Radio Frequencies Characteristics of Components

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Abstract

At radio frequencies, the inductance of connecting leads, the "skin" effect, and the capacitance between the conductors cannot be neglected especially at low frequencies. For this reason, an accurate equivalent circuit model may look quite different from the low-frequency circuit model that includes only the basic circuit element. It is important to understand these effects so that they can be accounted for when designing practical circuits.

Contents

1 Resistors

1.1 Introduction

[1] There are several types of resistors including carbon composition and thin film units. Over a fairly wide frequency range, the resistors can be modeled using the equivalent circuit shown below:

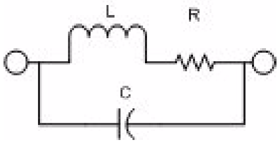

Figure 1: High Frequency Equivalent Circuit for Resistor

The inductance in the model shown in the above figure represents the inductance associated with the magnetic field generated by current flowing through the resistor, and the capacitance represents the shunt capacitance of the resistor structure. When the resistance is small ($\ll 100\Omega$), and the frequency is not too high, the capacitive reactance can usually be neglected leading to the simplified series RL model in Figure 2 below.

Figure 2: Equivalent Circuit for Small Resistance Resistor

Proof. If the frequency is not too high, we can assume $\omega \ll 1/\sqrt{LC}$ and $L/\left(R^2C\right) \gg 1$. The circuit impedance of the Figure 1 is:

$$\begin{aligned} Z\left(\omega\right) &= \mathrm{Re}\left(\omega\right) + \jmath\,\mathrm{Im}(\omega) \\ &= \left(\left(R+\jmath\omega L\right)^{-1} + \left(\frac{1}{\jmath\omega C}\right)\right)^{-1} \\ &= \frac{1}{\left(\omega^2LC-1\right)^2+\omega^2R^2C^2}\left(R+\jmath\omega L\left(1-\frac{R^2C}{L}-\omega^2LC\right)\right) \qquad (1) \end{aligned}$$

Using the assumption, we have:

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[1] There is a website for this project. All the material including the pictures, data, plots and circuit diagrams are available there. The website address is: http://www.ews.uiuc.edu/~cdcheng/Project/RF_Components_Characteristics/index.html

$$\begin{aligned} \omega^2 R^2 C^2 &= \omega^2 \cdot R^2 C \cdot C \\ &\ll \frac{1}{LC} \cdot L \cdot C \\ &= 1 \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{L}{R^2 C} &\gg 1 \\ 1 &\gg \frac{R^2 C}{L} \end{aligned} \tag{3}$$

$$\begin{aligned} \omega &\ll \frac{1}{\sqrt{LC}} \\ \omega^2 LC &\ll 1 \end{aligned} \tag{4}$$

i.e., the circuit impedance becomes:

$$Z\left(\omega\right) \approx R + \jmath \omega L \tag{5}$$

Hence, the circuit behaves like a series R-L combination, which is Figure 2.

When the resistance is large ($\gg 100\Omega$), and the frequency is not too high, the series inductance can be neglected, The equivalent circuit is simply as followed:

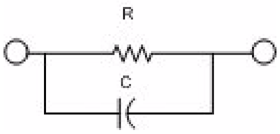


Figure 3: Equivalent Circuit for Large Resistance Resistor

Proof. If the frequency is not too high, we can assume $\omega \ll 1/\sqrt{LC}$ and $L/\left(R^2C\right) \ll 1$. The circuit impedance of the Figure 1 is:

$$\begin{aligned} Y(\omega) &= Z(\omega)^{-1} \\ &= (R + \jmath\omega L)^{-1} + \left(\frac{1}{\jmath\omega C}\right)^{-1} \\ &= \frac{1}{R\left(1 + \jmath\frac{\omega L}{R}\right)} + \jmath\omega C \end{aligned} \tag{6}$$

Using the assumption, we have:

$$\begin{aligned} \frac{\omega L}{R} &\ll \frac{L}{R} \cdot \frac{1}{\sqrt{LC}} \\ &= \sqrt{\frac{L}{R^2C}} \\ &\ll 1 \end{aligned} \tag{7}$$

i.e., the circuit impedance becomes:

$$Y(\omega) \approx \frac{1}{R} + \jmath\omega C \tag{8}$$

Hence, the circuit behaves like a parallel R-C combination, which is Figure 3.

In general, the resistor is connected to the metal for mounting on the circuit board. For example, the following resistor is connected by two metal wire.

Figure 4: Picture of a Leaded Resistor

These two wires will act as Transmission Line to the resistor component. Therefore, it is necessary to account this fact to the model we have just developed. The model now becomes:

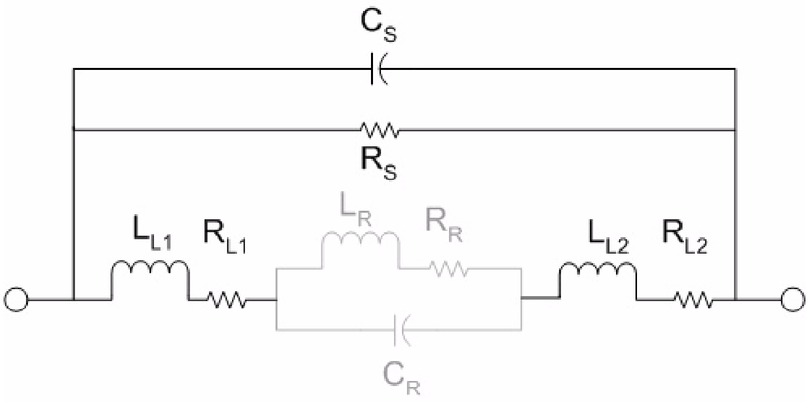


Figure 5: Complete Equivalent Circuit for Resistor(Grey Component: Resistor, Black Component: Transmission Line)

The black capacitor(C_S) on the upper part of the circuit represents the Shunt Capacitor, where the black inductors(L_{L1} and L_{L2}) at the bottom of both sides represent the Lead Inductors. Since the resistor has a non-ideal Transmission Line, a shunt resistor(R_S) is added in parallel to the Shunt Capacitor(C_S), and two leaded resistors(R_{L1} and R_{L2}) are added in series with the Lead Inductors(L_{L1} and L_{L2}). The leaded wires have the same material and their lengths are very closed. Therefore, the values of the L-R pairs at the bottom are very closed.

Usually the Shunt Resistor(R_3) has a large resistance, it can be ignored and it can be treated as an open circuit(i.e., $\mathrm{R}_3 \rightarrow \infty$). Also, the Leaded Resistors are small enough that can be ignored(i.e., $\mathrm{R}_{L1} \approx \mathrm{R}_{L2} \approx 0$) The Leaded Inductors at the bottom can be combined together, i.e.,

$$L_{\mathrm{L}} = L_{\mathrm{L1}} + L_{\mathrm{L2}} \tag{9}$$

The resistor model is now simplified as follow:

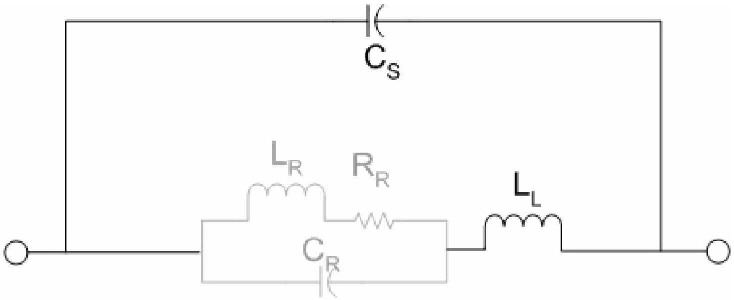
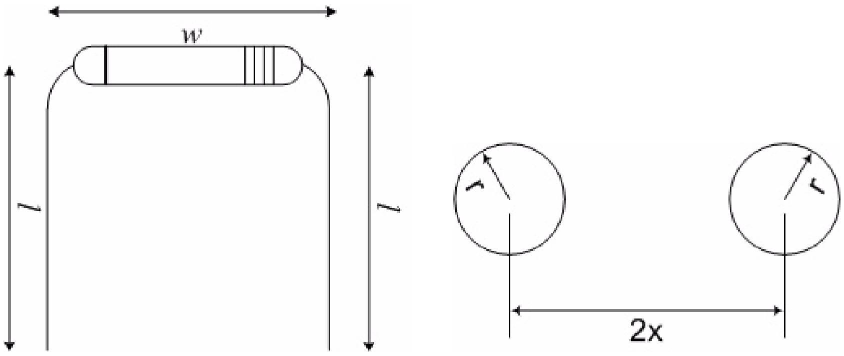


Figure 6: Simplified Equivalent Circuit for Resistor(Grey Component: Resistor, Black Component: Transmission Line)

1.2 Calculation on Transmission Line Components

The following pictures are the side view and bottom view of a Leaded Resistor respectively. The resistor is connected by two wires. By measuring the length(l), distance(w) and diameter(d) of two wires, it is possible to estimate the Transmission Line components.



Side view and bottom view of a Leaded Resistor

The Capacitance and Inductance per Unit Length are given by:

$$\begin{aligned}
\text{Capacitance per Unit Length} &= \frac{\pi\varepsilon}{\cosh^{-1}(x/a)} && (10)\\
\text{Inductance per Unit Length} &= \frac{\mu}{\pi}\cosh^{-1}\frac{x}{a} && (11)
\end{aligned}$$

where ε and μ are the permittivity and permeability respectively.

Since the energy is stored in free space, the relative permittivity(ε_r) and relative permeability(μ_r) are simply equal to 1. After substituting d and a by the measurement variables l, w, and d, the equations becomes:

$$\begin{aligned}
\text{Capacitance per Unit Length} &= \pi\varepsilon\left[\cosh^{-1}\left(\frac{(w-d)/2}{d/2}\right)\right]^{-1}\\
&= \pi\varepsilon\left[\cosh^{-1}\left(\frac{(w-d)}{d}\right)\right]^{-1} && (12)\\
\text{Inductance per Unit Length} &= \frac{\mu}{\pi}\cosh^{-1}\frac{x}{a}\\
&= \frac{\mu}{\pi}\cosh^{-1}\left(\frac{(w-d)}{d}\right) && (13)
\end{aligned}$$

Finally, the total capacitance and inductance are:

$$\begin{aligned}
C &= \pi\varepsilon\left[\cosh^{-1}\left(\frac{(w-d)}{d}\right)\right]^{-1}\cdot l && (14)\\
L &= \frac{\mu}{\pi}\cosh^{-1}\left(\frac{x}{a}\right)\cdot l && (15)
\end{aligned}$$

1.3 Analysis on Resistor

In general, a small resistance is known much smaller than 100Ω (i.e., $R \ll 100\Omega$), which means its resistance is smaller than one-tenth of 100Ω ($R < 10\Omega$). Similarly, a large resistance means it is larger than 10 times of 100Ω ($R > 1k\Omega$). What about the resistors outside these regions (e.g., 50Ω, 100Ω)? Which model should we apply on these resistors?

The characteristic of resistor depends on many things. For example, the type of material, power level and treatment has been done on the resistor can give a different result. How do these factors relate to the resistor performance? To find out the answer, I analyzed the following resistors:

Resistance (Ω)	Material	Power level (W)	Treatment
5.1	Film Leaded	1/4	None
5.1	Film Leaded	1/4	Wire is shortened
5.6	Carbon Composition Leaded	1/4	None
5.6	Carbon Composition Leaded	1/4	Wire is shortened
5.6	Thin-Film Chip	1/8	None
10.0	Film Leaded	1/4	None
10.0	Film Leaded	1/4	Wire is shortened
10.0	Thin-Film Chip	1/8	None
49.9	Thin-Film Chip	1/8	None
51.1	Film Leaded	1/4	None
51.1	Film Leaded	1/4	Wire is shortened
100.0	Film Leaded	1/4	None
100.0	Film Leaded	1/4	Wire is shortened
100.0	Film Leaded	1/2	None
100.0	Film Leaded	1/2	Wire is shortened
100.0	Thin-Film Chip	1/8	None
510.0	Film Leaded	1/4	None
510.0	Film Leaded	1/4	Wire is shortened
$1k$	Film Leaded	1/4	None
$1k$	Film Leaded	1/4	Wire is shortened
$1k$	Carbon Composition Leaded	1/2	None
$1k$	Carbon Composition Leaded	1/2	Wire is shortened
$1k$	Thin-Film Chip	1/8	None
$10k$	Film Leaded	1/2	None
$10k$	Film Leaded	1/2	Wire is shortened
$10k$	Carbon Composition Leaded	1	None
$10k$	Carbon Composition Leaded	1	Wire is shortened
$10k$	Thin-Film Chip	1/8	None

1.4 Measurement Step

1. Dimension of the sample resistor is recorded.

2. The impedance of the sample resistor is measured from 1 MHz to 501 MHz[2] using Hewlett-Packard 8753D Vector Network Analyzer(VNA). The VNA takes 201 sampling points. The data is smoothed and averaged with 999 Averaging Factors before it is downloaded to the computer.

3. After the measurement is done, the data is converted using Agilent Advanced Design System and the result is imported in Matlab. Matlab performs a non-linear data fitting to the model shown on Figure 6. The details of this step will be discussed in Appendix 1.

4. After the data fitting is done, Matlab plots the Real Impedance, Imaginary Impedance, Magnitude and Phase for the Measurement and Model in linear and logarithm scale, and Smith Chart.

5. Matlab calculates the R-Square values to show the agreement of the measurement data and model data.

6. An equivalent circuit is created using Agilent Advanced Design System.

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[2] The default value of the number of sampling point is 201. Therefore, if we measure from 1 MHz to 501 MHz, the sampling frequency is garantee to be integer. Although the maximum frequency of the fixture is 500 MHz, the result will still be acceptable.

1.5 Equipment List

Impedance Measurement

1. Hewlett-Packard Network Analyzer 8753D (30 kHz - 6 GHz)
2. Hewlett-Packard S-Parameter Test Set 85047A (300 kHz - 6 GHz)
3. Hewlett-Packard Spring Clip Fixture 16092A (MAX 500 MHz)

Resistance Measurement

1. Philips Multimeter PM2525

Dimension Measurement

1. Chicago Brand 6” Electronic Digital Caliper P.N. 50001

Software

1. Agilent Advanced Design System 2003
2. Matlab 6.5
3. Microsoft Excel XP
4. Microsoft Visio XP
5. Scientific WorkPlace2.50

1.6 Measurement Result

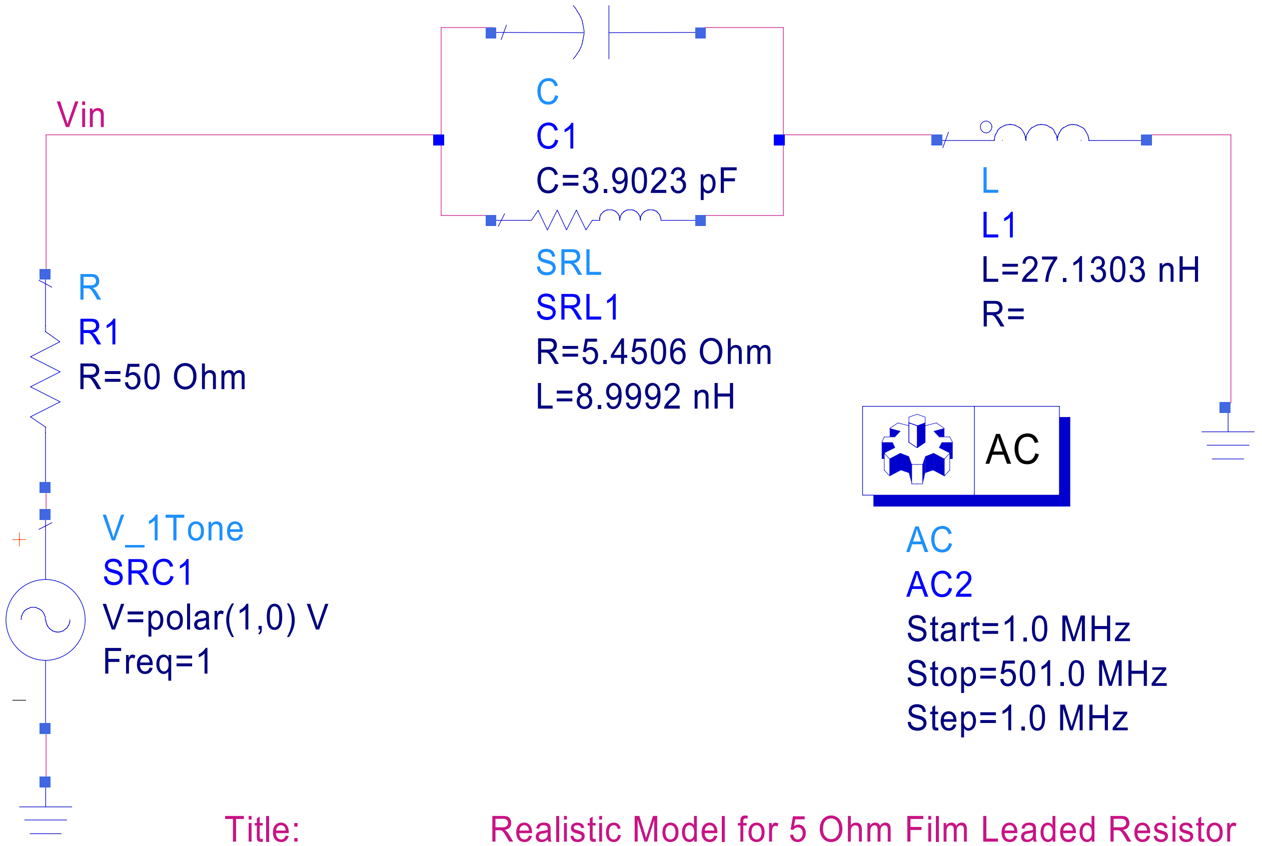
1.6.1 5.1Ω $0.25W$ Film Leaded Resistor

The following are the pictures of an original and after treatment 5.1Ω $0.25W$ Film Leaded Resistor.

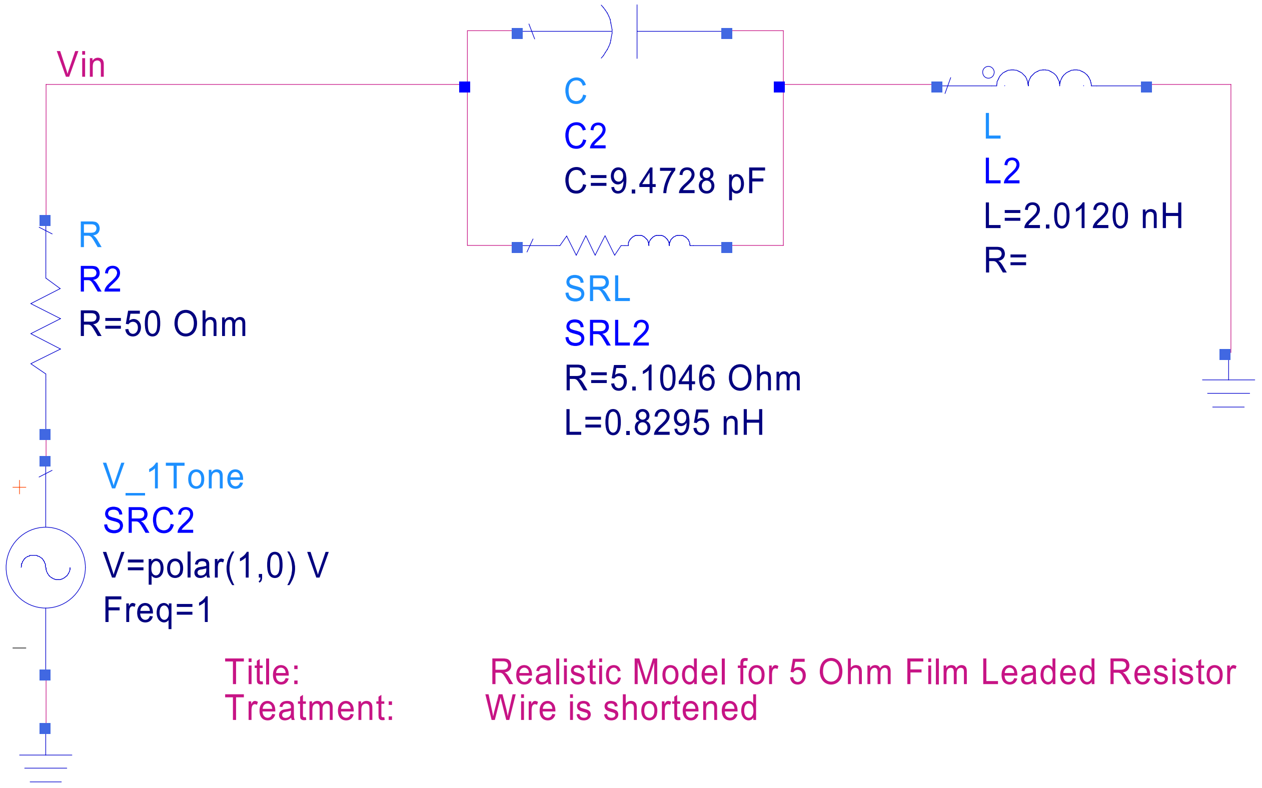
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

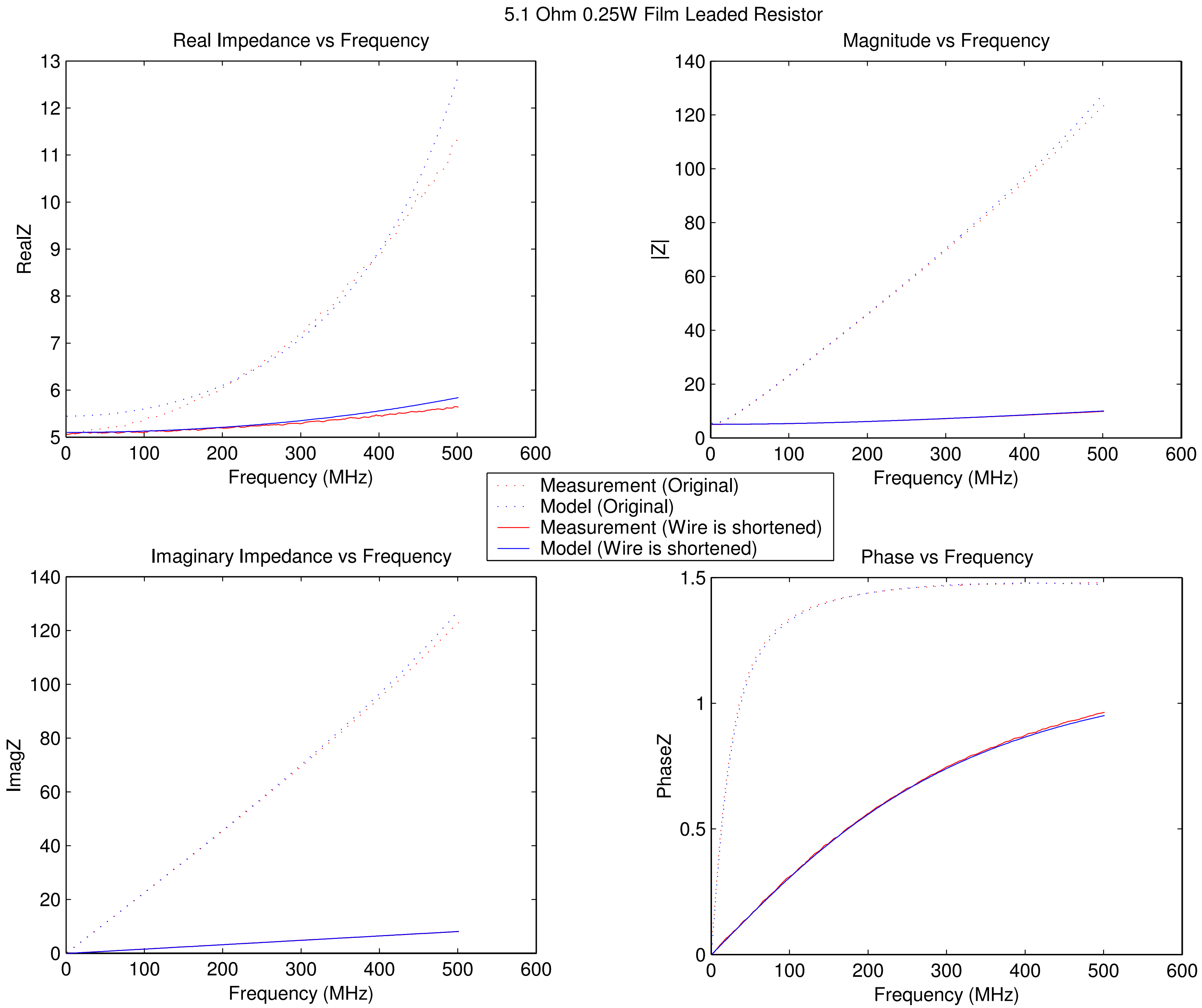
	Original	Wire is shortened
Measured Resistance (Ω)	5.13	5.13
Internal Resistance of Model (Ω)	5.4506	5.1047
Internal Inductance of Model (nH)	8.9993	0.8296
Internal Capacitance of Model (pF)	3.9024	9.4728
External Inductance from estimation (nH)	34.2129	0.0000
External Inductance of Model (nH)	27.1304	2.0120
External Capacitance from estimation (pF)	0.2128	0.0000
External Capacitance of Model (pF)	0.0000	0.0000
Legngth of Leaded Wire (mm)	25.60	0.00
Distance between two wires (mm)	8.48	8.76
Diameter of wire (mm)	0.5600	0.56
R-Square Value of Real Impedance	0.9793	0.9931
R-Square Value of Imaginary Impedance	0.9998	1.0000
R-Square Value of Magnitude	0.9998	0.9999
R-Square Value of Phase	0.9997	0.9999

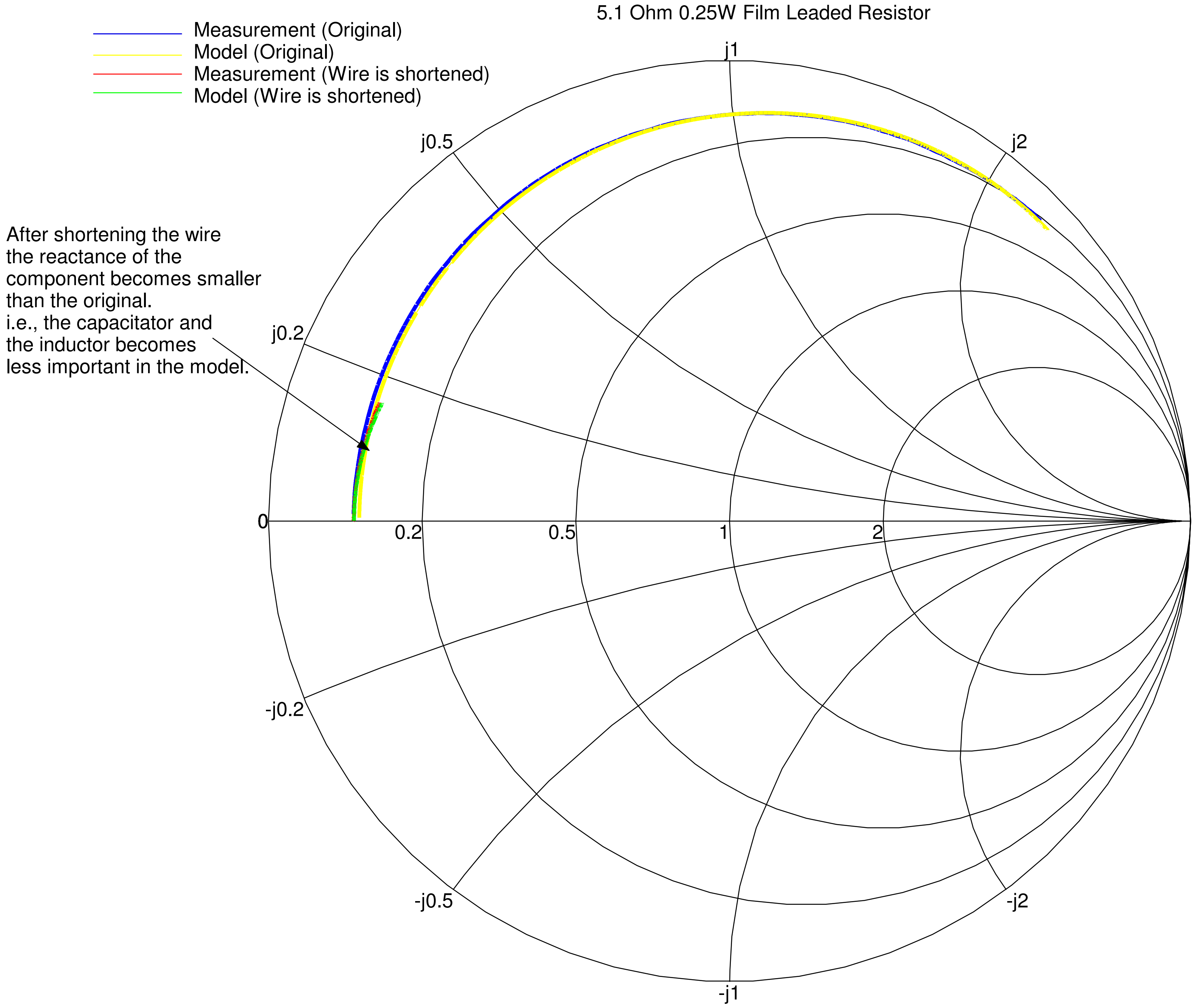


Title: Realistic Model for 5 Ohm Film Leaded Resistor
Treatment: None



Title: Realistic Model for 5 Ohm Film Leaded Resistor
Treatment: Wire is shortened


5.1 Ohm 0.25W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
13
12
11
10
9
8
7
6
5
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
1.5
1
0.5
0
0
100
200
300
400
500
600
Frequency (MHz)

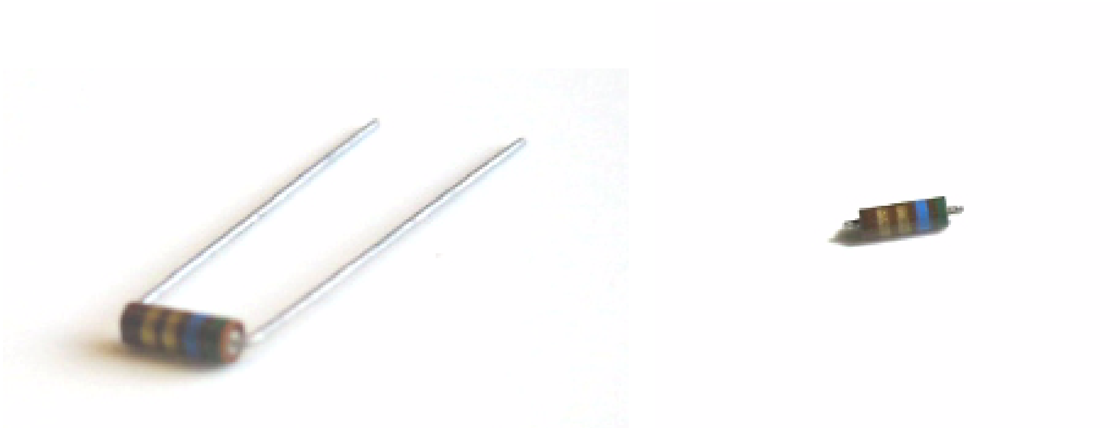


5.1 Ohm 0.25W Film Leaded Resistor

After shortening the wire the reactance of the component becomes smaller than the original.
i.e., the capacitator and the inductor becomes less important in the model.

1.6.2 5.6Ω $0.25W$ Carbon Composition Leaded Resistor

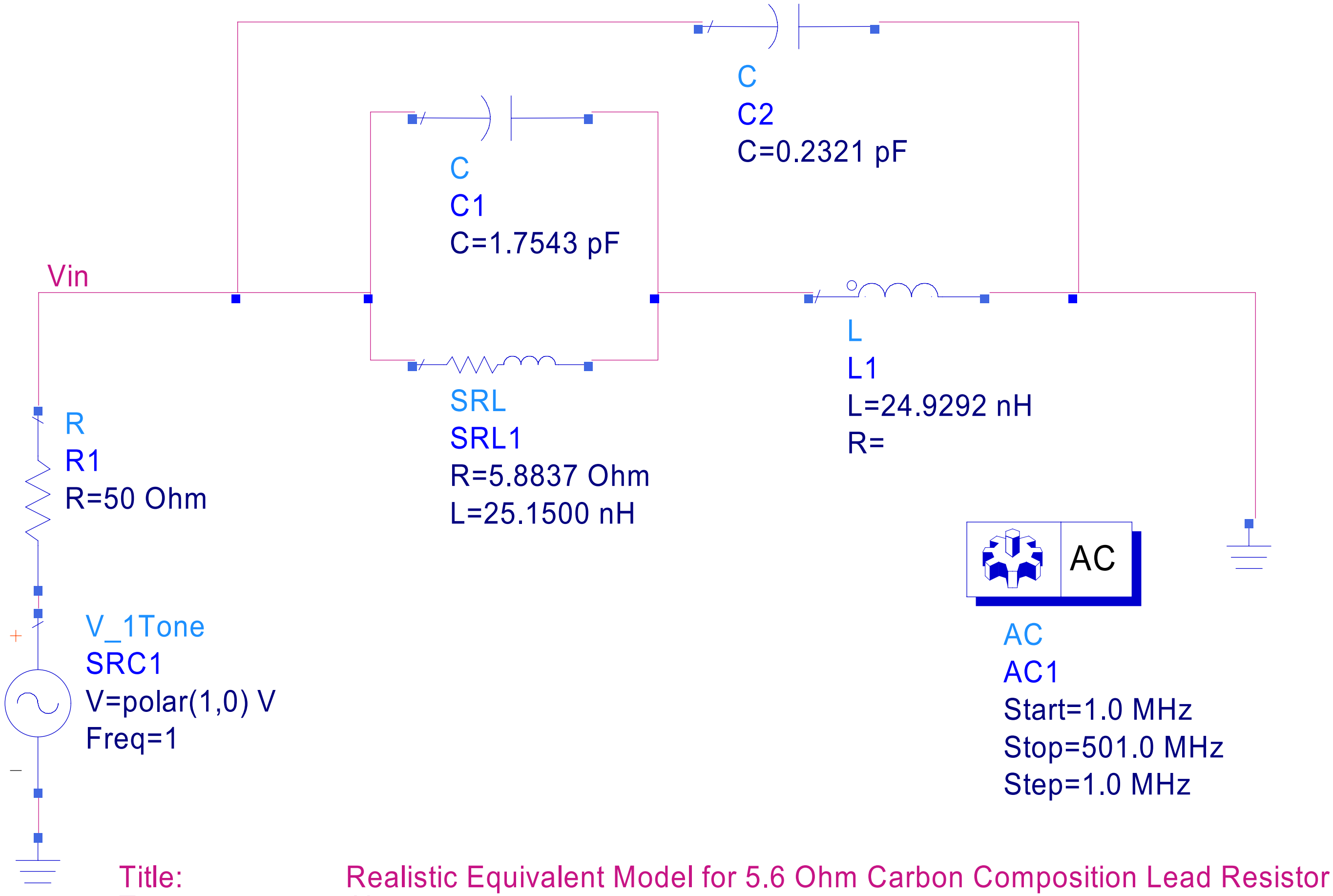
The following are the pictures of an original and after treatment 5.6Ω $0.25W$ Carbon Composition Leaded Resistor.



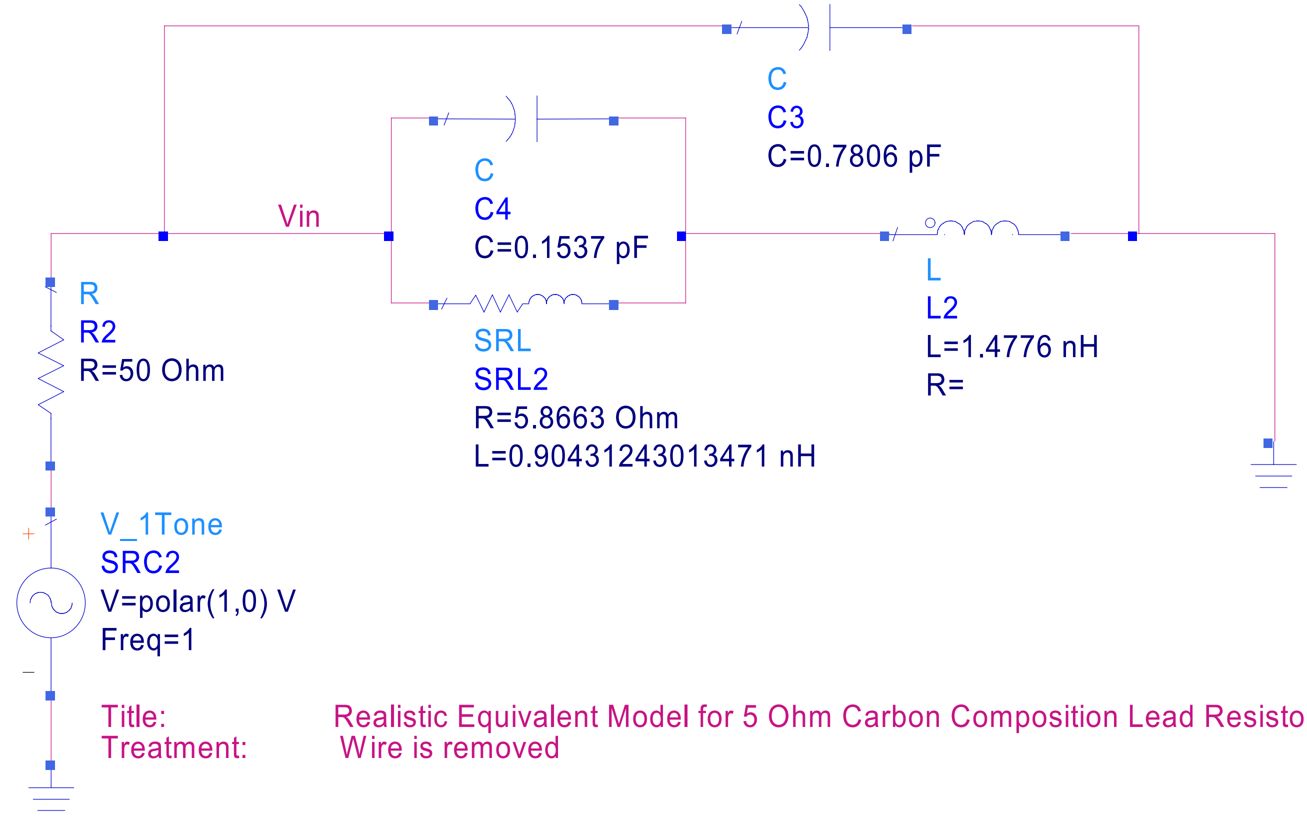
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

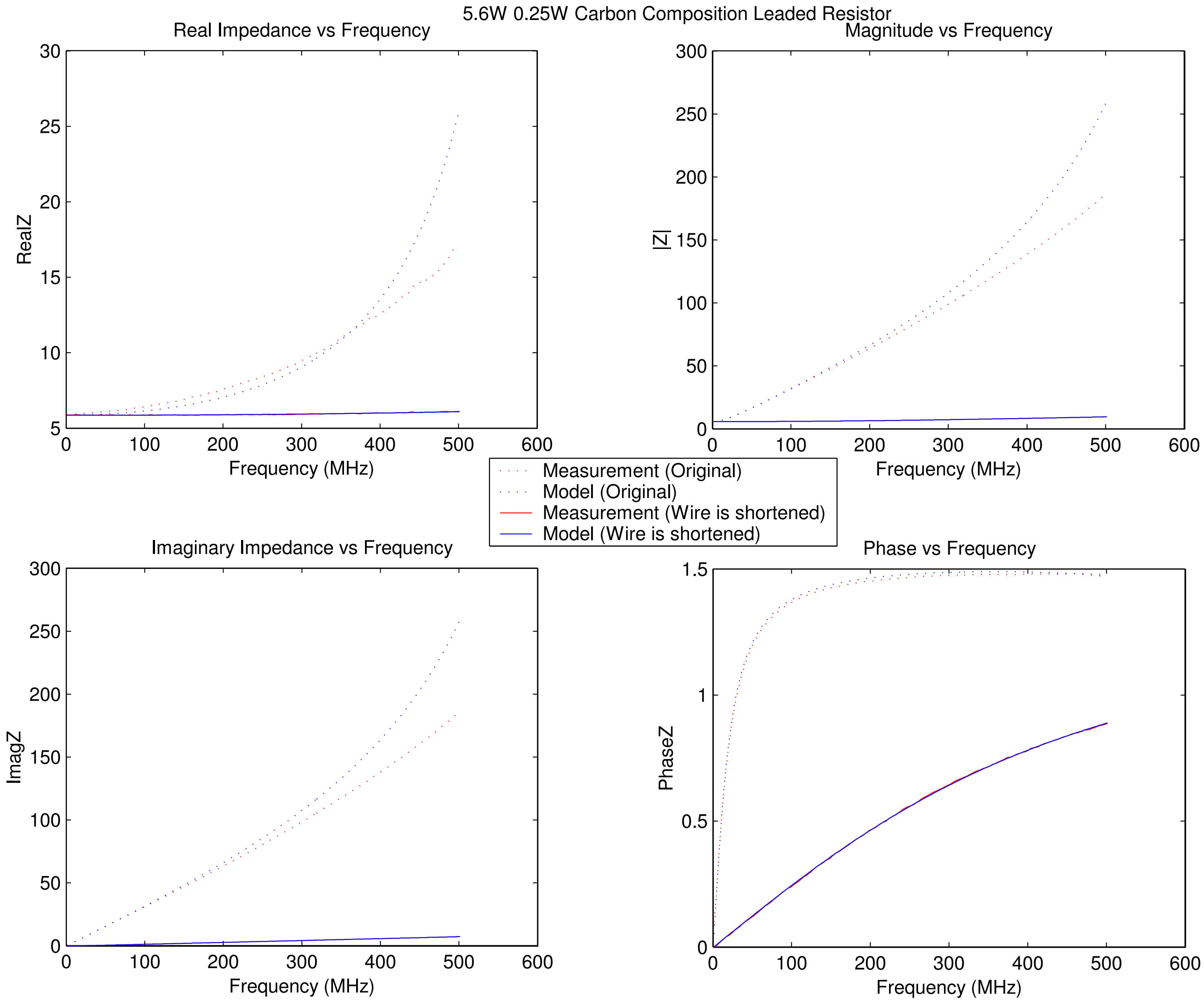
	Original	Wire is shortened
Measured Resistance (Ω)	5.97	5.96
Internal Resistance of Model (Ω)	5.8838	5.8663
Internal Inductance of Model (nH)	25.1501	0.9043
Internal Capacitance of Model (pF)	1.7544	0.1538
External Inductance from estimation (nH)	48.8282	0.0000
External Inductance of Model (nH)	24.9292	1.4777
External Capacitance from estimation (pF)	0.3277	0.0000
External Capacitance of Model (pF)	0.2321	0.7806
Legnth of Leaded Wire (mm)	37.95	0.00
Distance between two wires (mm)	8.23	8.34
Diameter of wire (mm)	0.61	0.61
R-Square Value of Real Impedance	0.9437	0.9579
R-Square Value of Imaginary Impedance	0.9858	1.0000
R-Square Value of Magnitude	0.9858	0.9999
R-Square Value of Phase	0.9992	0.9999



Title: Realistic Equivalent Model for 5.6 Ohm Carbon Composition Lead Resistor
Treatment: None



Title: Realistic Equivalent Model for 5 Ohm Carbon Composition Lead Resistor
Treatment: Wire is removed



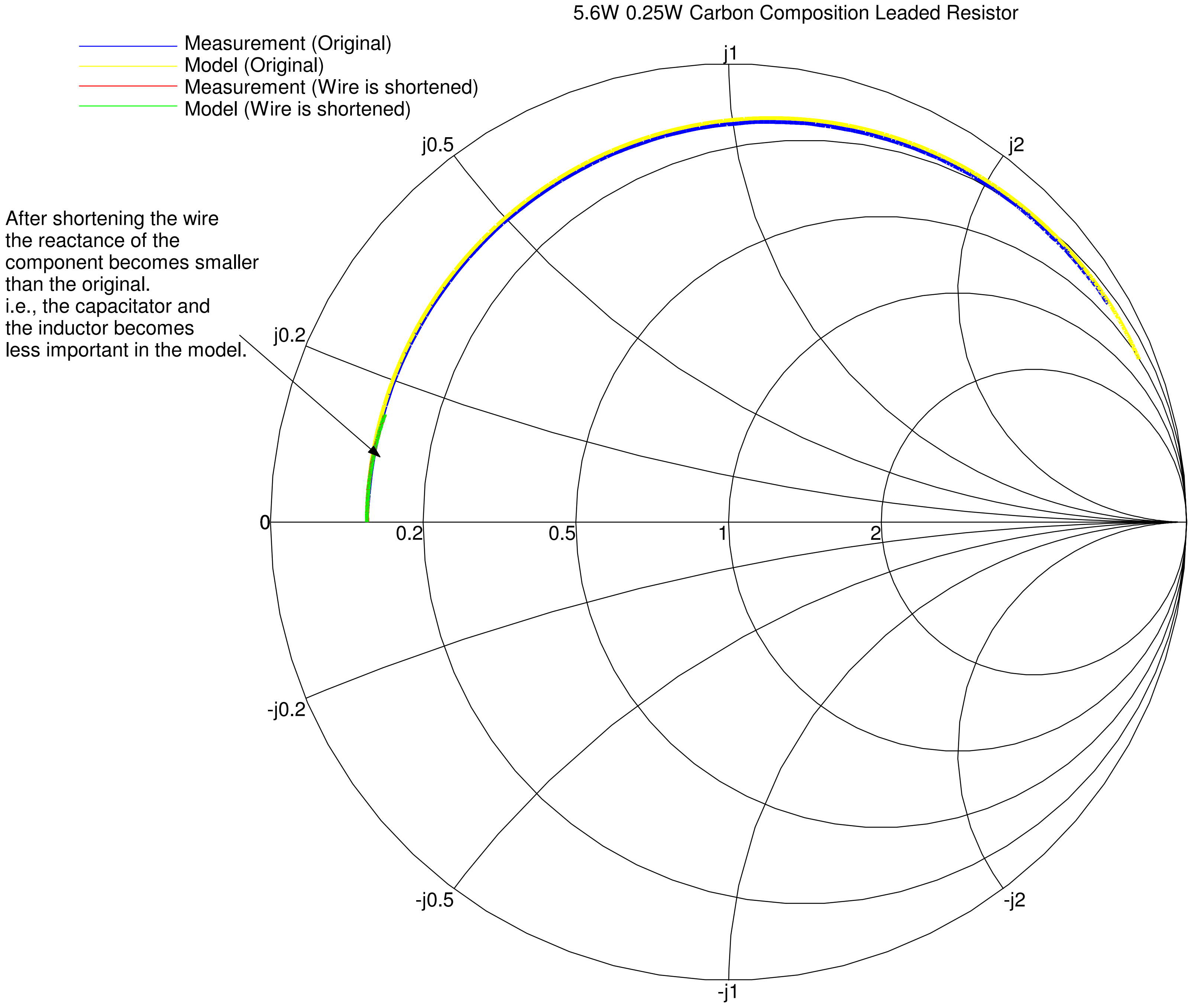
5.6W 0.25W Carbon Composition Leaded Resistor

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency



5.6W 0.25W Carbon Composition Leaded Resistor

After shortening the wire
the reactance of the
component becomes smaller
than the original.
i.e., the capacitator and
the inductor becomes
less important in the model.

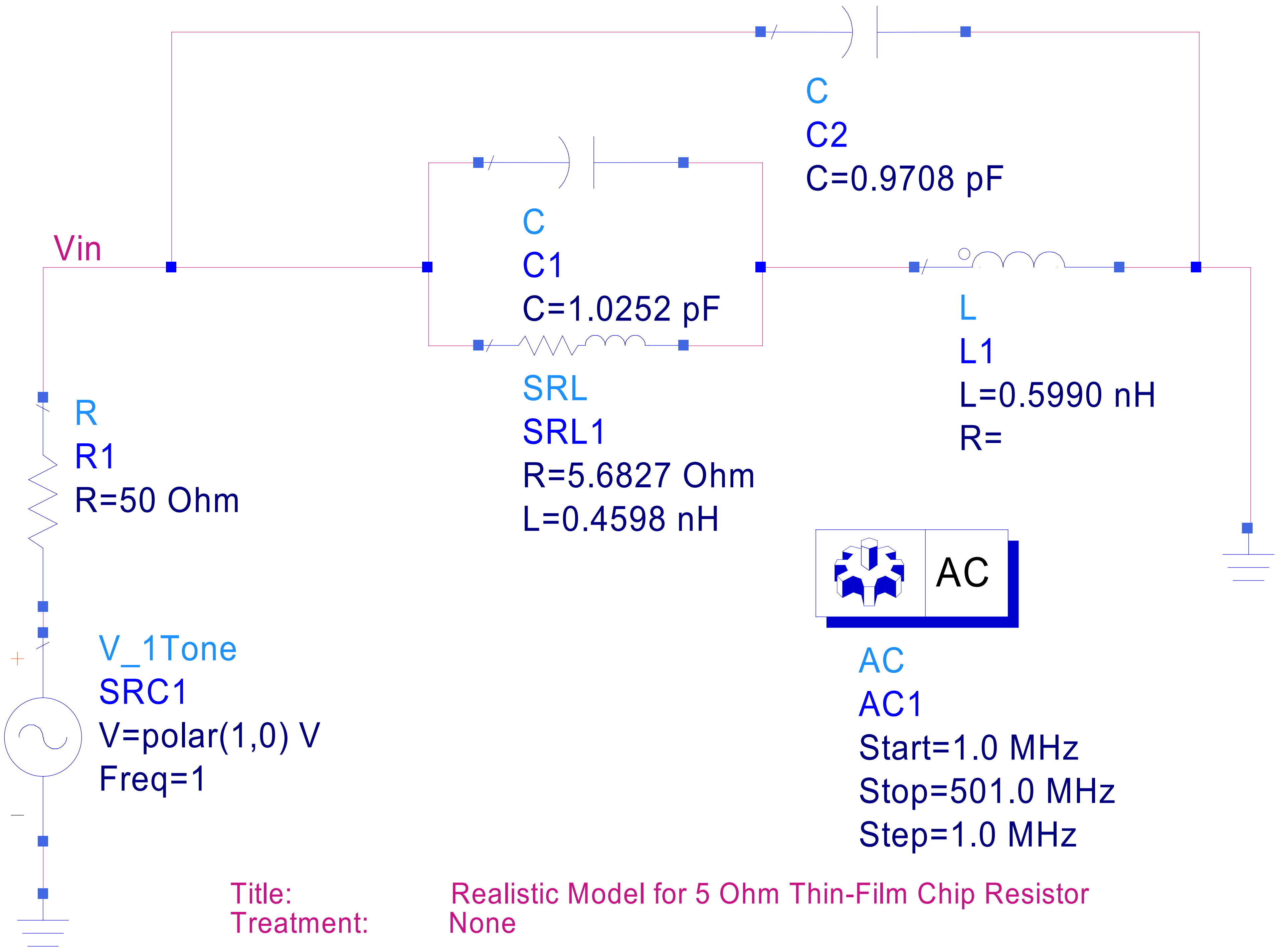
1.6.3 5.6Ω $0.125W$ Thin-Film Chip Resistor

The following is the picture of a 5.6Ω $0.125W$ Thin-Film Chip Resistor.

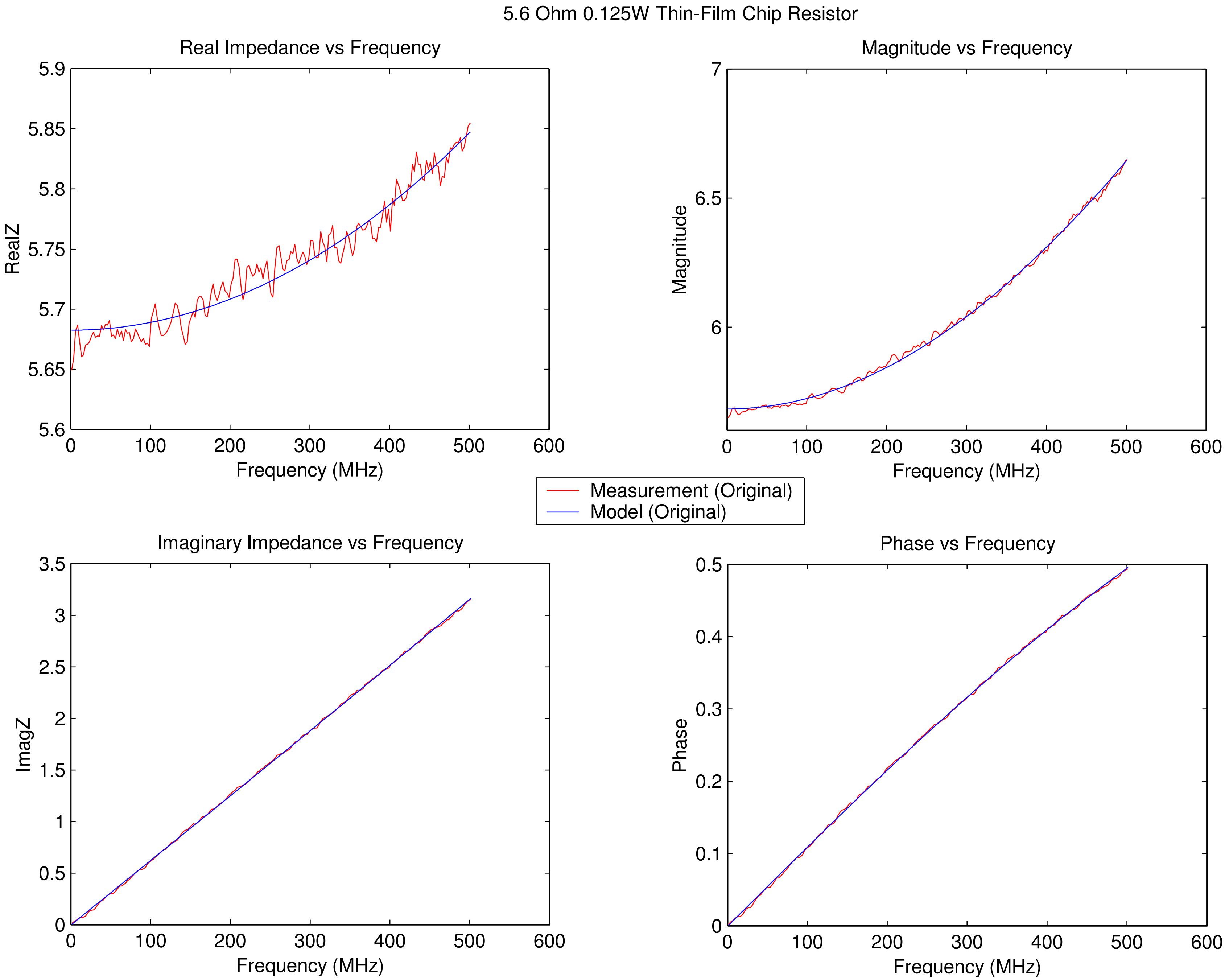
Word marked on the chip: `5R6`

This table summarizes measured data and simulation result:

	Original
Internal Resistance of Model (Ω)	5.6827
Internal Inductance of Model (nH)	0.4599
Internal Capacitance of Model (pF)	1.0253
External Inductance of Model (nH)	0.5991
External Capacitance of Model (pF)	0.9708
R-Square Value of Real Impedance	0.9474
R-Square Value of Imaginary Impedance	0.9998
R-Square Value of Magnitude	0.9982
R-Square Value of Phase	0.9998



Title: Realistic Model for 5 Ohm Thin-Film Chip Resistor
Treatment: None



5.6 Ohm 0.125W Thin-Film Chip Resistor

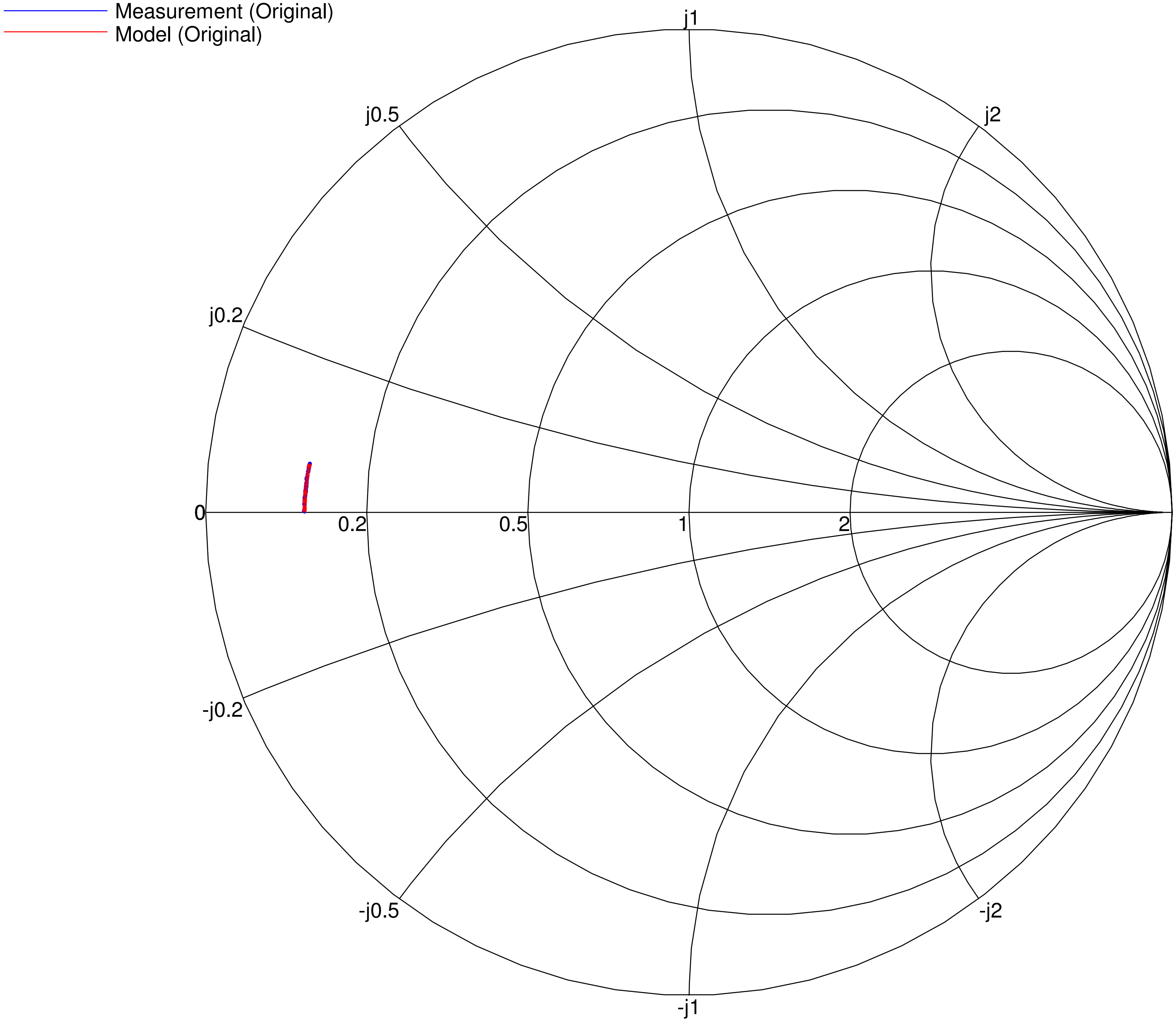
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

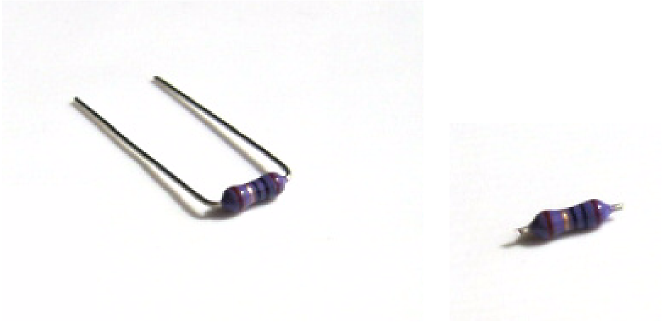
Phase vs Frequency

5.6 Ohm 0.125W Thin-Film Chip Resistor



1.6.4 10.0Ω $0.25W$ Film Leaded Resistor

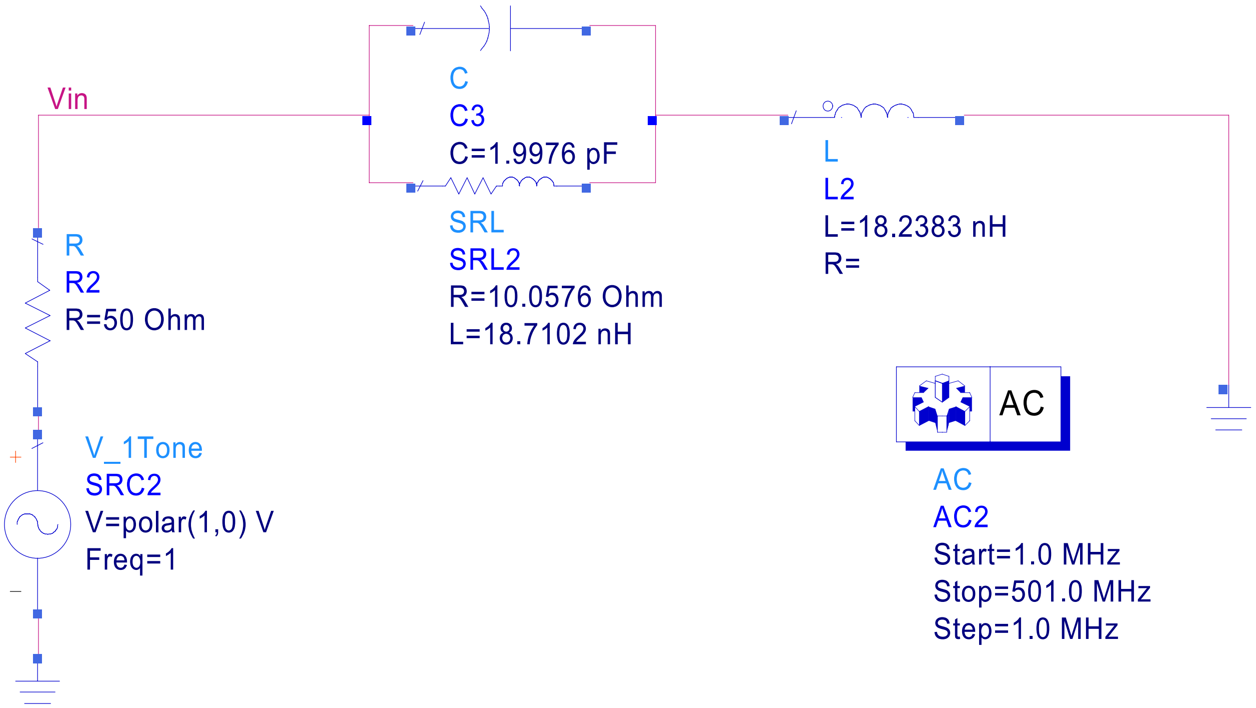
The following are the pictures of an original and after treatment 10.0Ω $0.25W$ Film Leaded Resistor.



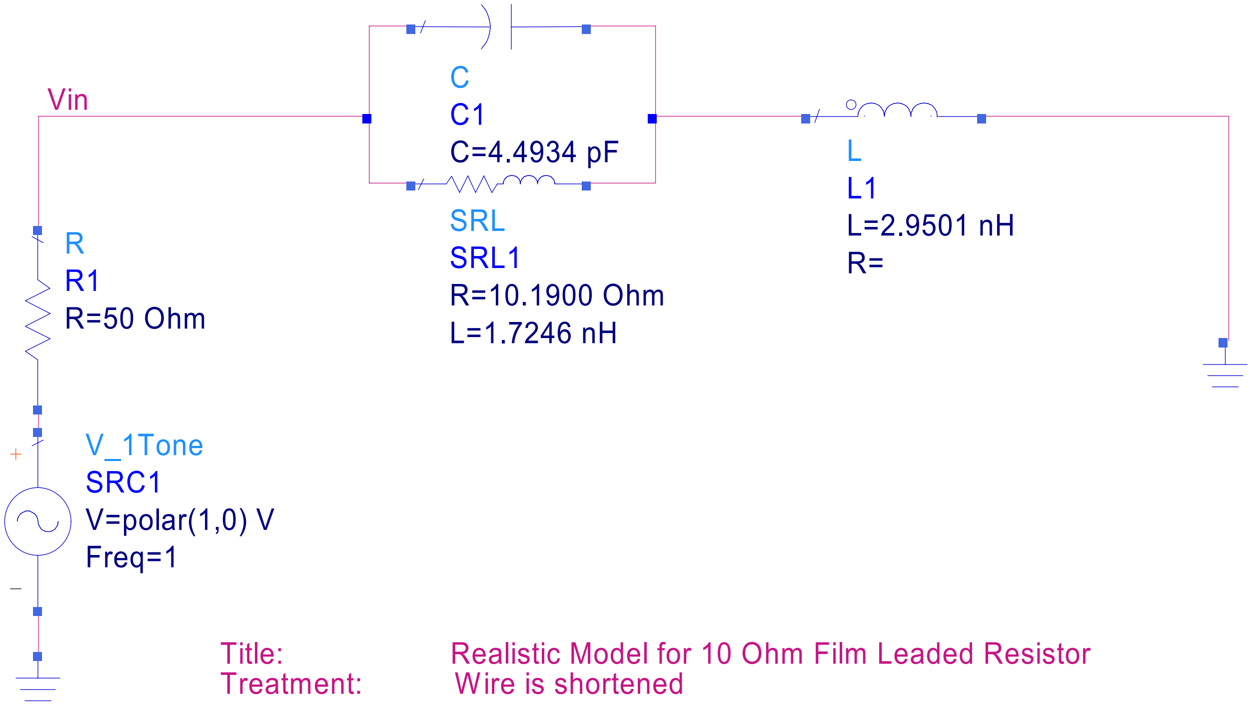
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

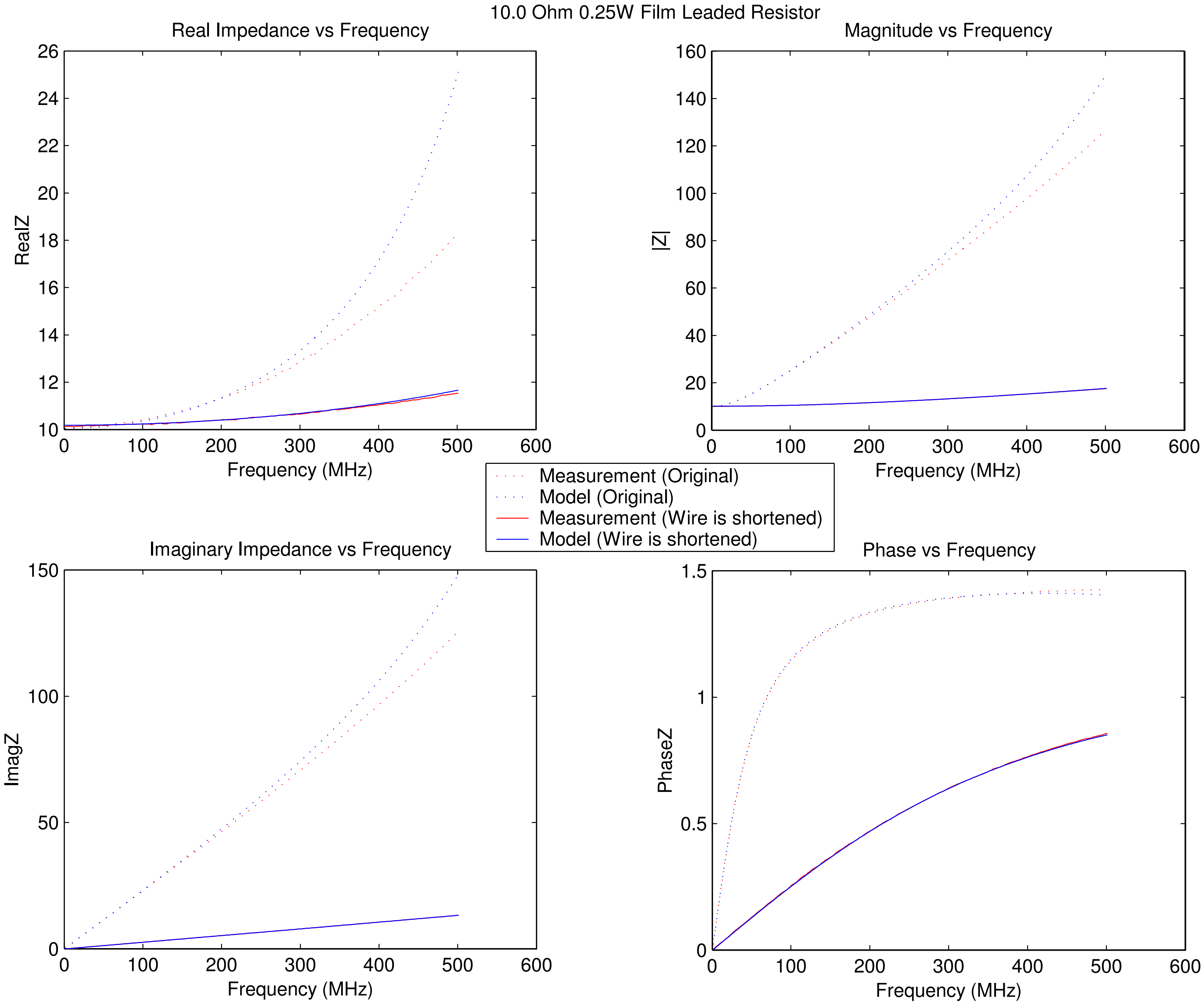
	Original	Wire is shortened
Measured Resistance (Ω)	10.13	10.11
Internal Resistance of Model (Ω)	10.0576	10.1900
Internal Inductance of Model (nH)	18.7102	1.7246
Internal Capacitance of Model (pF)	1.9976	4.4934
External Inductance from estimation (nH)	35.4384	0.0000
External Inductance of Model (nH)	18.2383	2.9501
External Capacitance from estimation (pF)	0.0000	0.0000
External Capacitance of Model (pF)	0.0000	0.0000
Legngth of Leaded Wire (mm)	26.14	0.00
Distance between two wires (mm)	8.87	9.14
Diameter of wire (mm)	0.56	0.56
R-Square Value of Real Impedance	0.9761	0.9975
R-Square Value of Imaginary Impedance	0.9961	1.0000
R-Square Value of Magnitude	0.9959	0.9999
R-Square Value of Phase	0.9994	1.0000

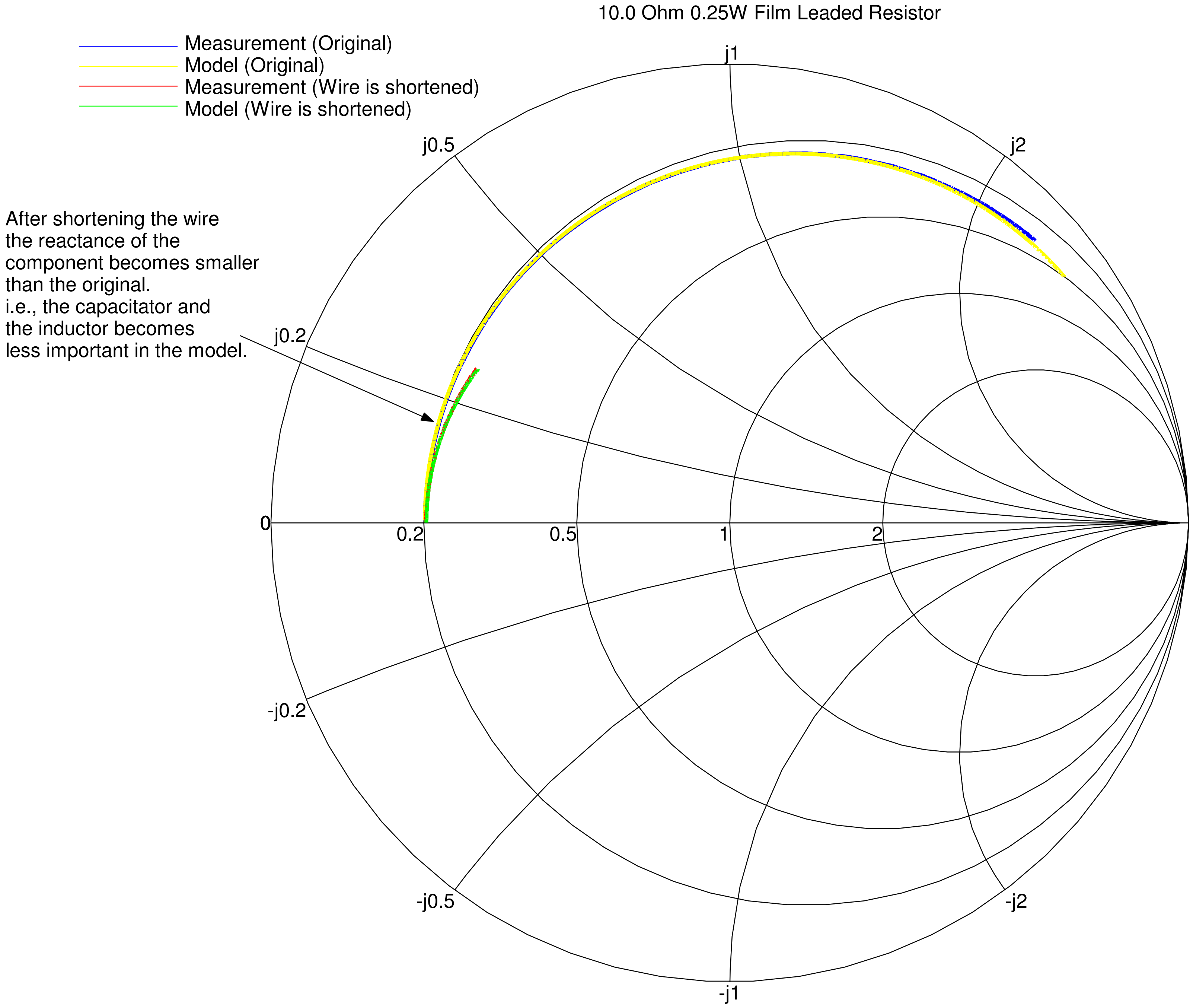


Title: Realistic Model for 10 Ohm Film Leaded Resistor
Treatment: None



Title: Realistic Model for 10 Ohm Film Leaded Resistor
Treatment: Wire is shortened

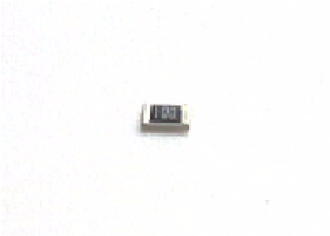

10.0 Ohm 0.25W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
10
12
14
16
18
20
22
24
26
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
0
50
100
150
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
0
0.5
1
1.5
0
100
200
300
400
500
600
Frequency (MHz)



After shortening the wire
the reactance of the
component becomes smaller
than the original.
i.e., the capacitator and
the inductor becomes
less important in the model.

1.6.5 10.0Ω $0.125W$ **Thin-Film Chip Resistor**

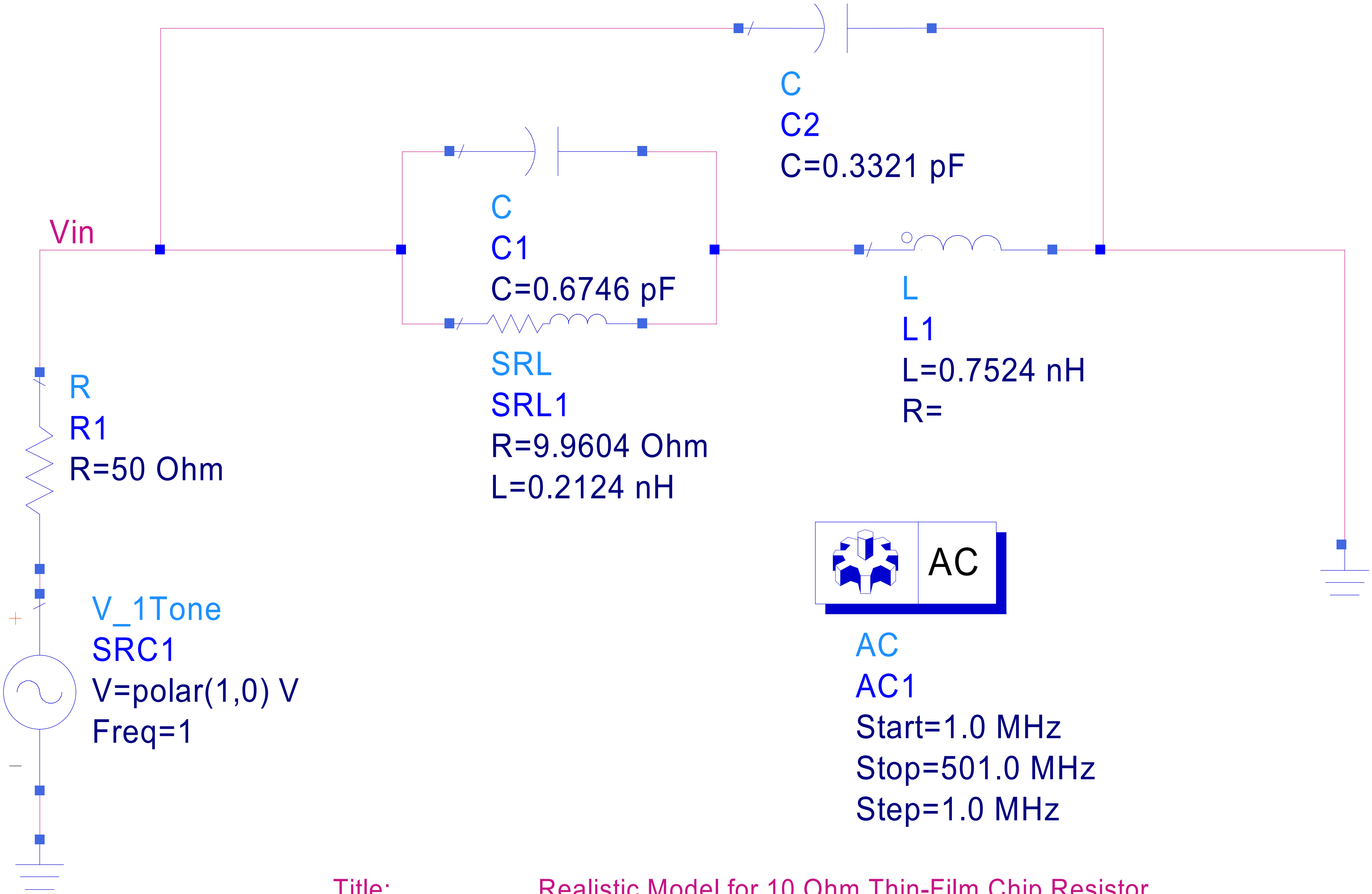
The following is the picture of a 10.0Ω $0.125W$ Thin-Film Chip Resistor.



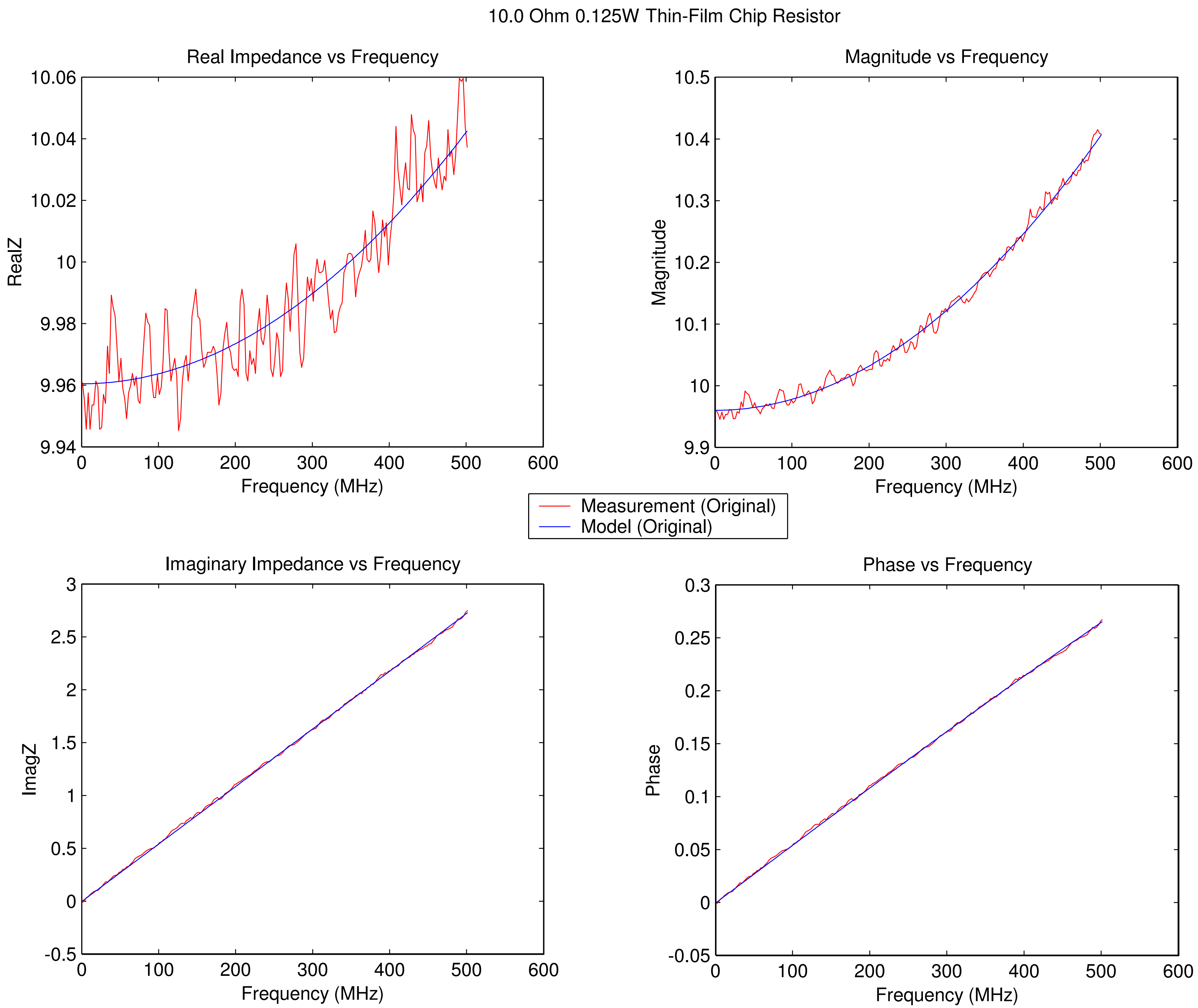
Word marked on the chip: `100`

This table summarizes measured data and simulation result:

	Original
Internal Resistance of Model (Ω)	9.9605
Internal Inductance of Model (nH)	0.2124
Internal Capacitance of Model (pF)	0.6747
External Inductance of Model (nH)	0.7525
External Capacitance of Model (pF)	0.3321
R-Square Value of Real Impedance	0.8572
R-Square Value of Imaginary Impedance	0.9998
R-Square Value of Magnitude	0.9941
R-Square Value of Phase	0.9998



Title: Realistic Model for 10 Ohm Thin-Film Chip Resistor
Treatment: None



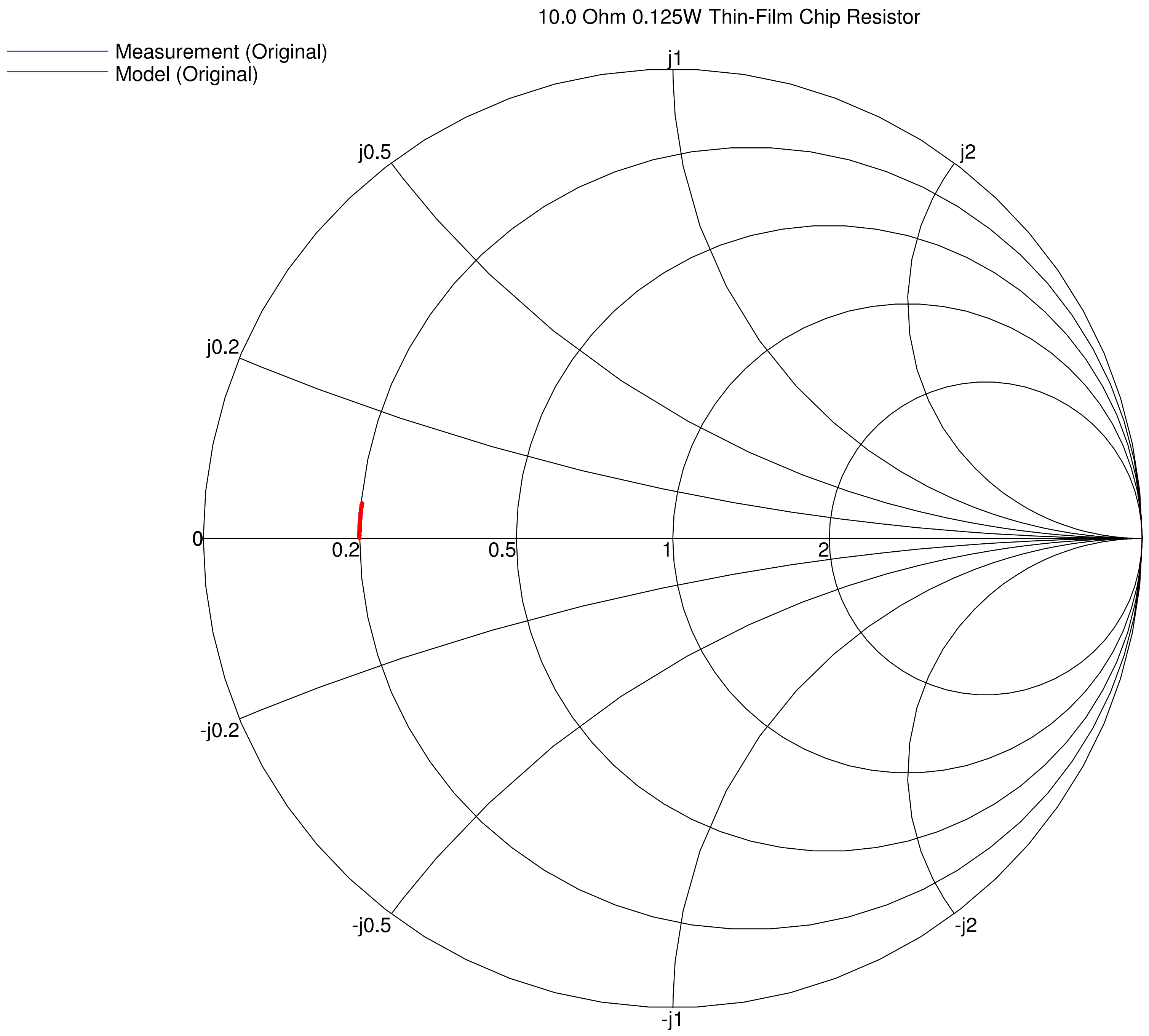
10.0 Ohm 0.125W Thin-Film Chip Resistor

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


10.0 Ohm 0.125W Thin-Film Chip Resistor

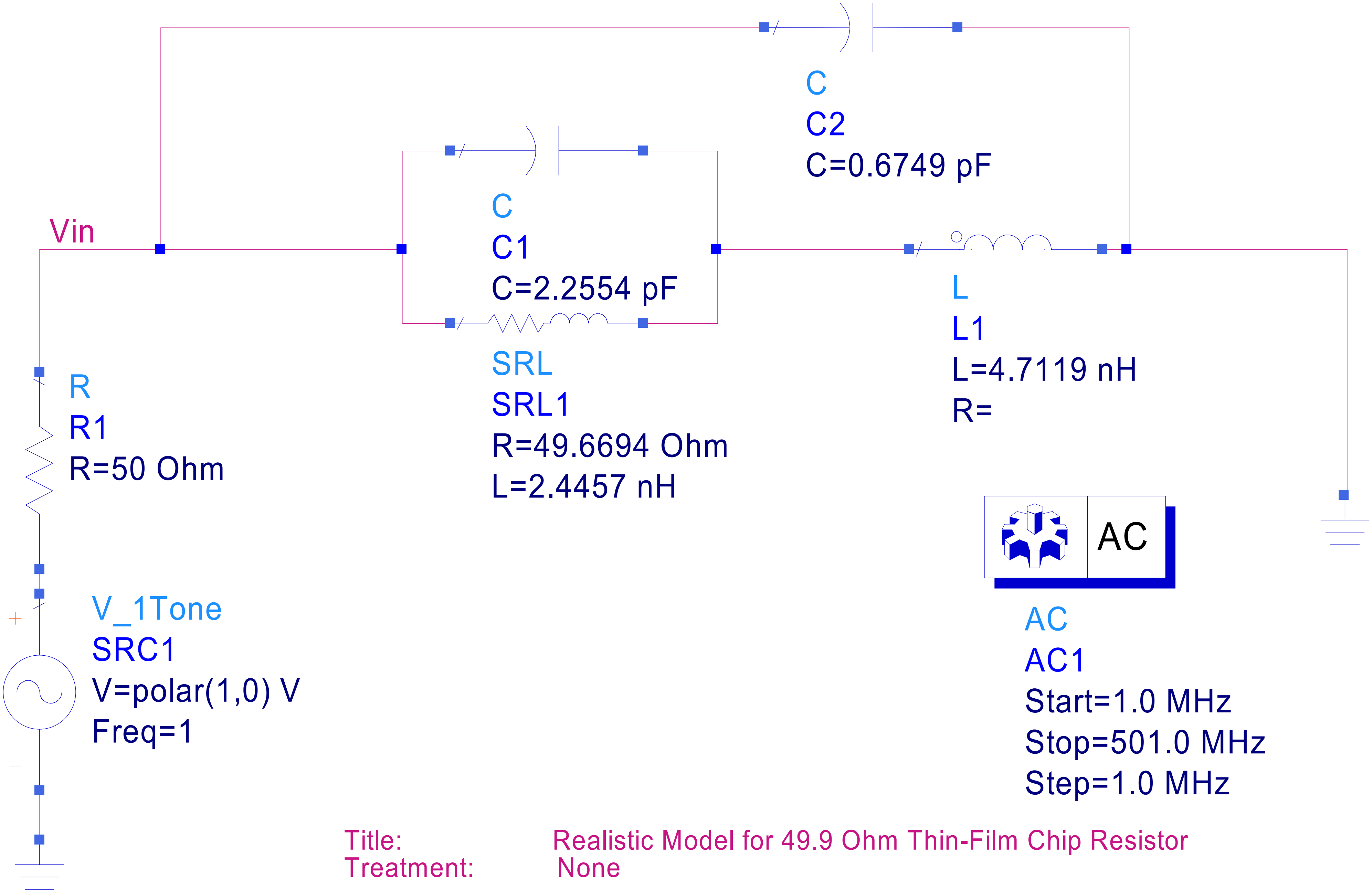
1.6.6 49.9Ω $0.125W$ Thin-Film Chip Resistor

The following is the picture of a 49.9Ω $0.125W$ Thin-Film Chip Resistor.

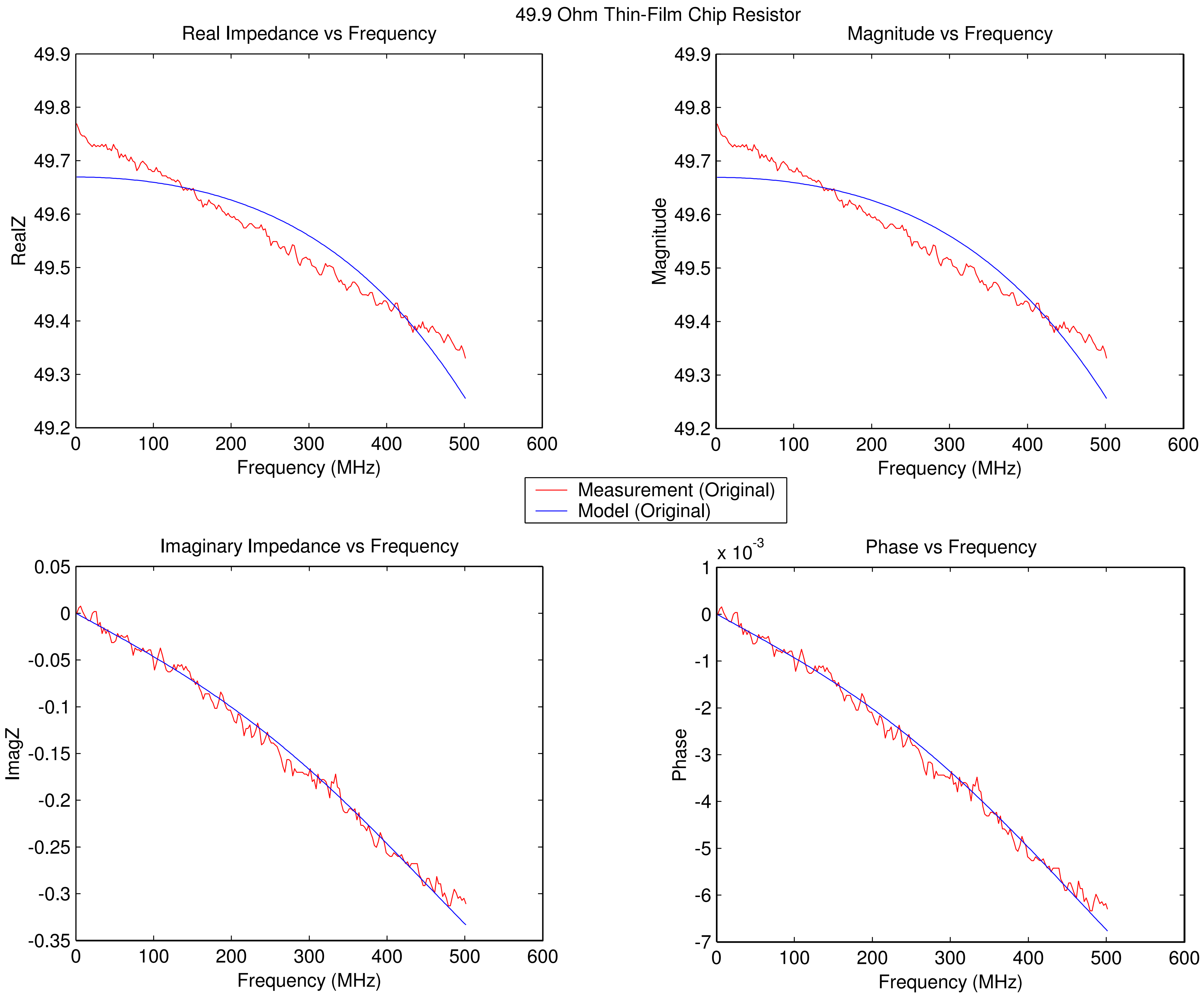
Word marked on the chip: `49R9`

This table summarizes measured data and simulation result:

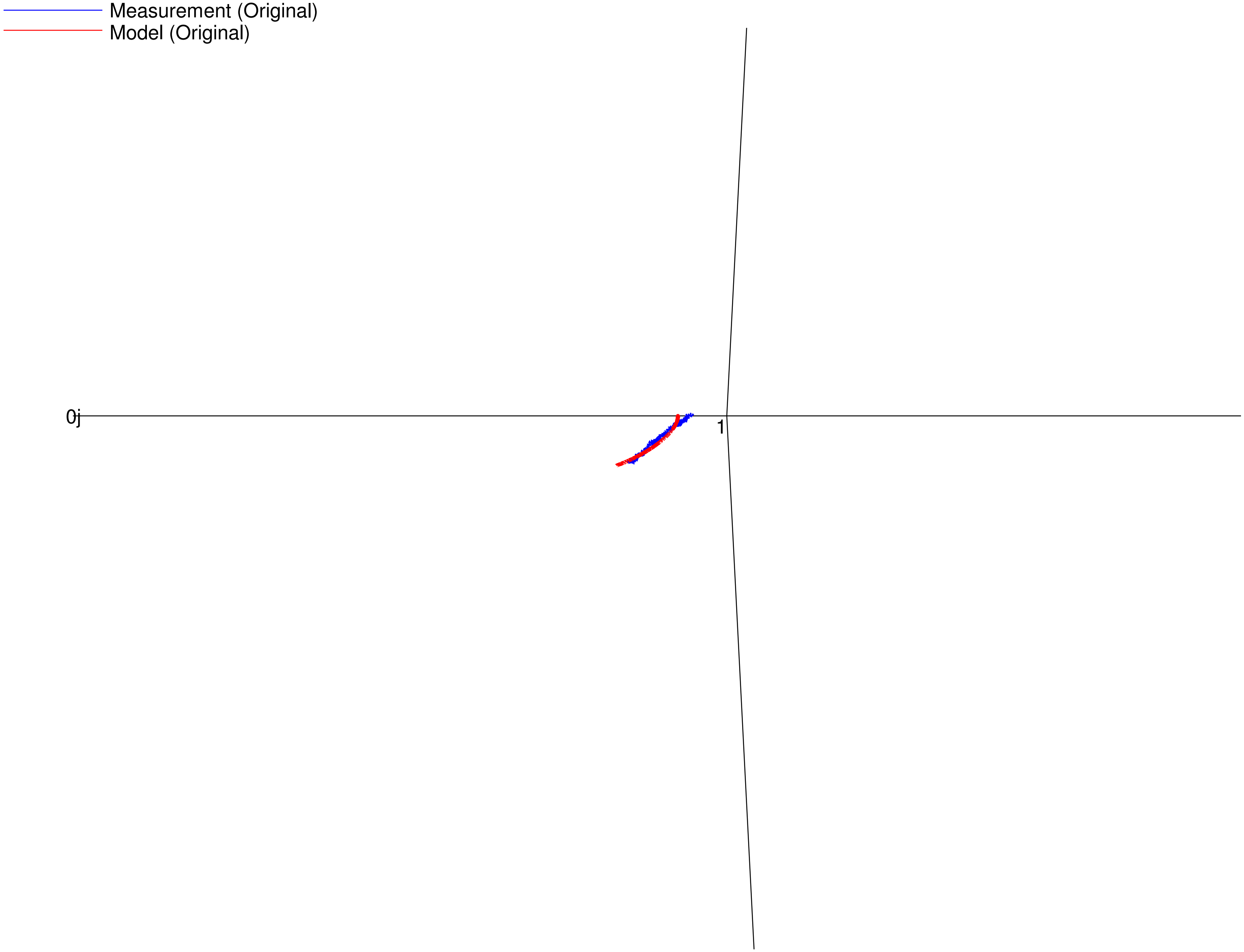
	Original
Internal Resistance of Model (Ω)	49.6695
Internal Inductance of Model (nH)	2.4457
Internal Capacitance of Model (pF)	2.2555
External Inductance of Model (nH)	4.7120
External Capacitance of Model (pF)	0.6749
R-Square Value of Real Impedance	0.8851
R-Square Value of Imaginary Impedance	0.9913
R-Square Value of Magnitude	0.8846
R-Square Value of Phase	0.9912



Title: Realistic Model for 49.9 Ohm Thin-Film Chip Resistor
Treatment: None


49.9 Ohm Thin-Film Chip Resistor
Real Impedance vs Frequency
RealZ
49.9
49.8
49.7
49.6
49.5
49.4
49.3
49.2
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
49.9
49.8
49.7
49.6
49.5
49.4
49.3
49.2
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Imaginary Impedance vs Frequency
ImagZ
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
x 10^-3
1
0
-1
-2
-3
-4
-5
-6
-7
0
100
200
300
400
500
600
Frequency (MHz)

49.9 Ohm Thin-Film Chip Resistor



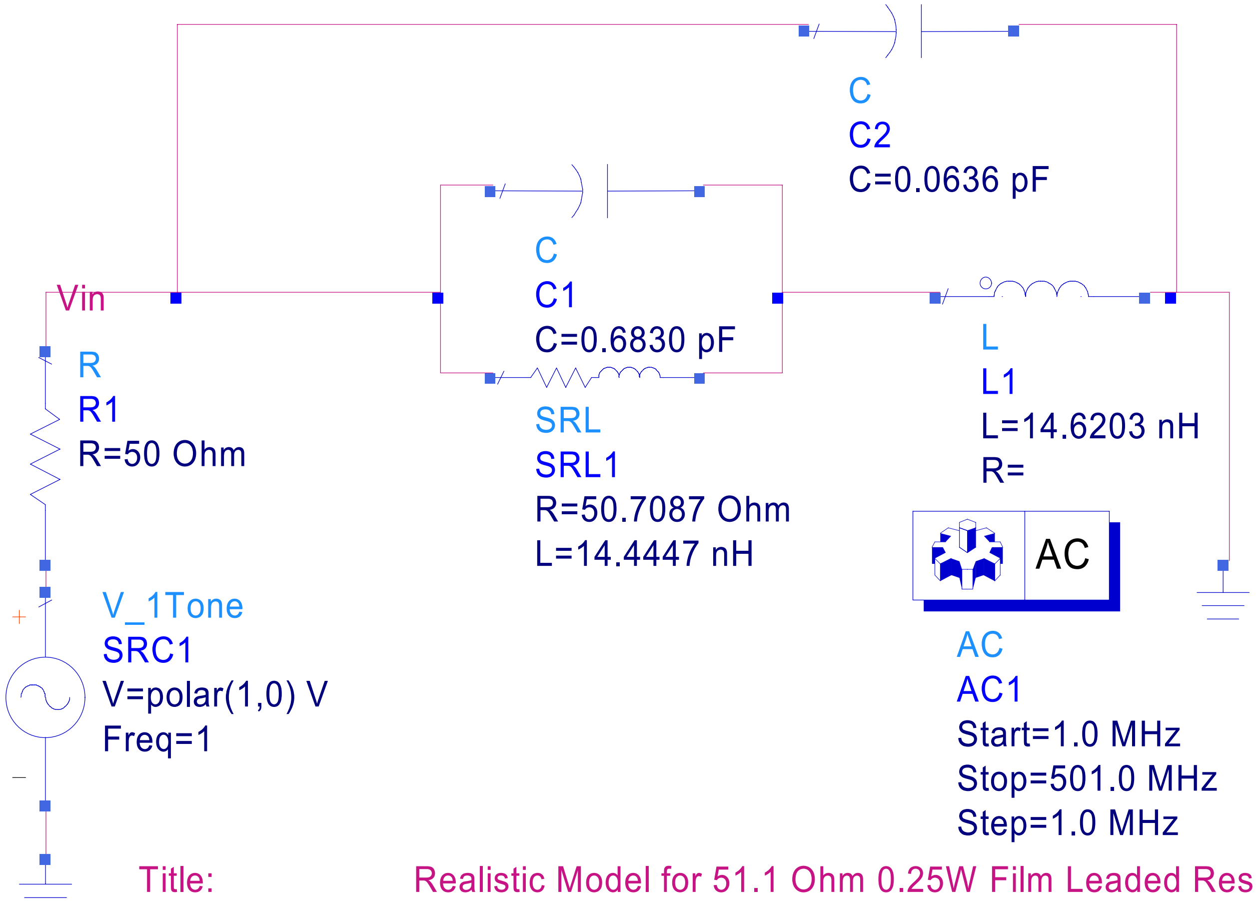
1.6.7 51.1Ω $0.25W$ Film Leaded Resistor

The following are the pictures of an original and after treatment 51.1Ω $0.25W$ Film Leaded Resistor.

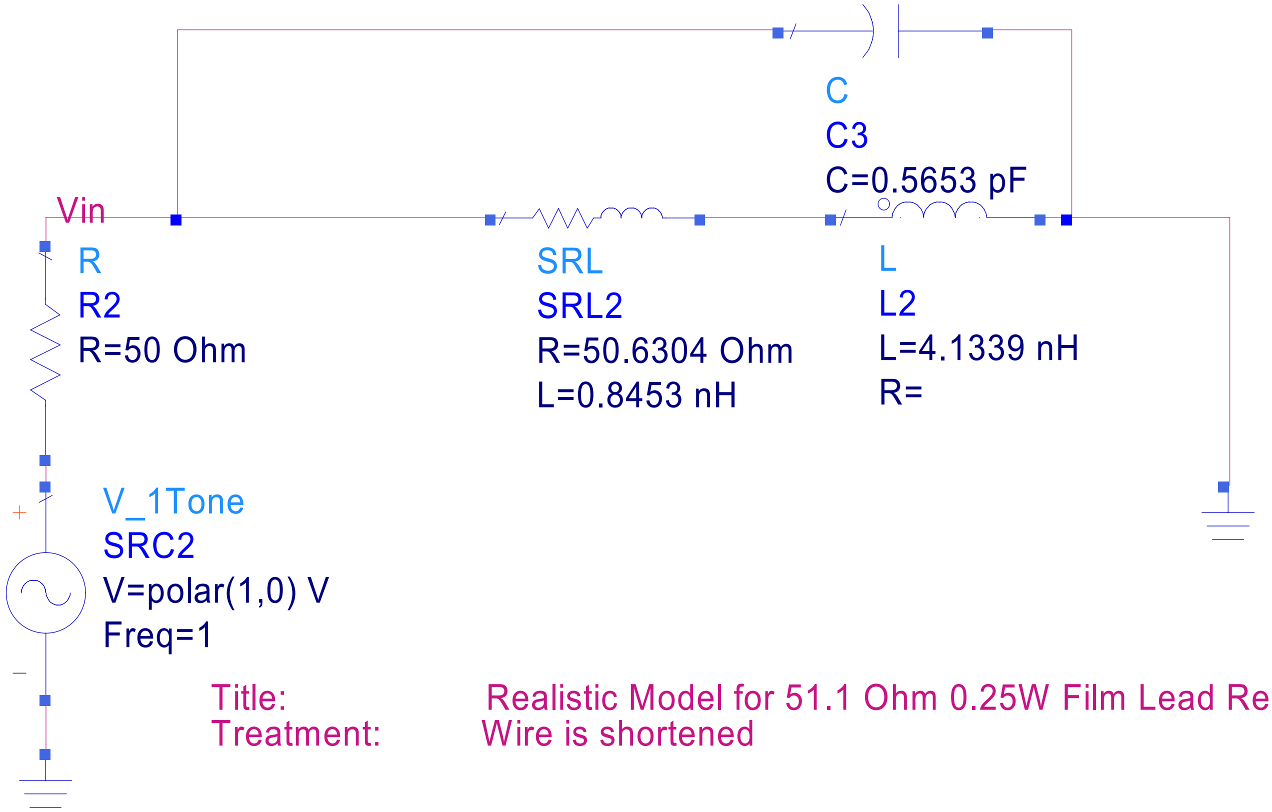
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

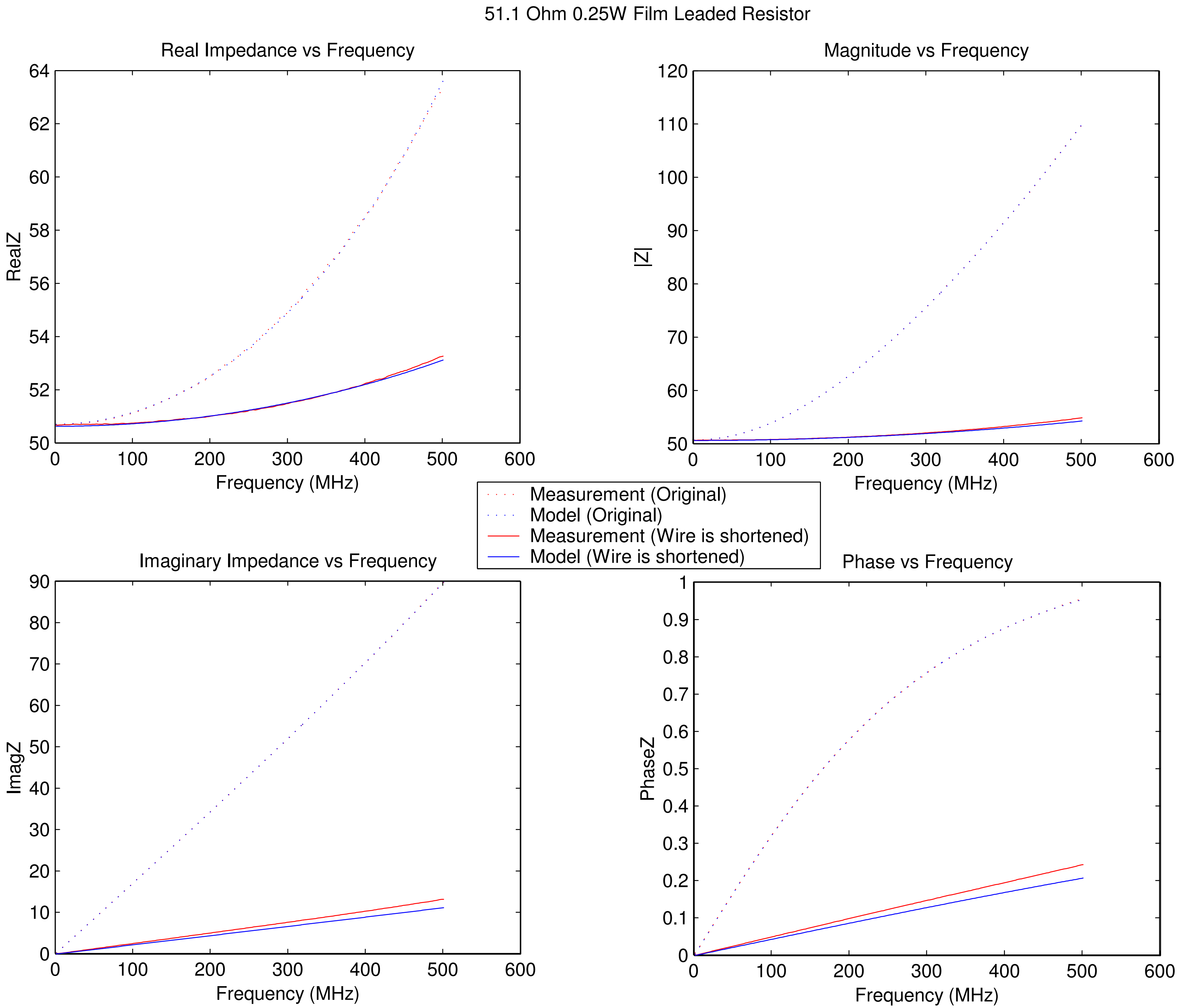
	Original	Wire is shortened
Measured Resistance (Ω)	50.94	50.94
Internal Resistance of Model (Ω)	50.7088	50.6305
Internal Inductance of Model (nH)	14.4447	0.8453
Internal Capacitance of Model (pF)	0.6830	0.0000
External Inductance from estimation (nH)	27.7244	0.0000
External Inductance of Model (nH)	14.6204	4.1339
External Capacitance from estimation (pF)	0.1868	0.0000
External Capacitance of Model (pF)	0.0637	0.5653
Legnth of Leaded Wire (mm)	21.59	0.00
Distance between two wires (mm)	7.78	7.87
Diameter of wire (mm)	0.58	0.58
R-Square Value of Real Impedance	0.9998	0.9974
R-Square Value of Imaginary Impedance	1.0000	0.9997
R-Square Value of Magnitude	1.0000	0.9986
R-Square Value of Phase	1.0000	0.9998

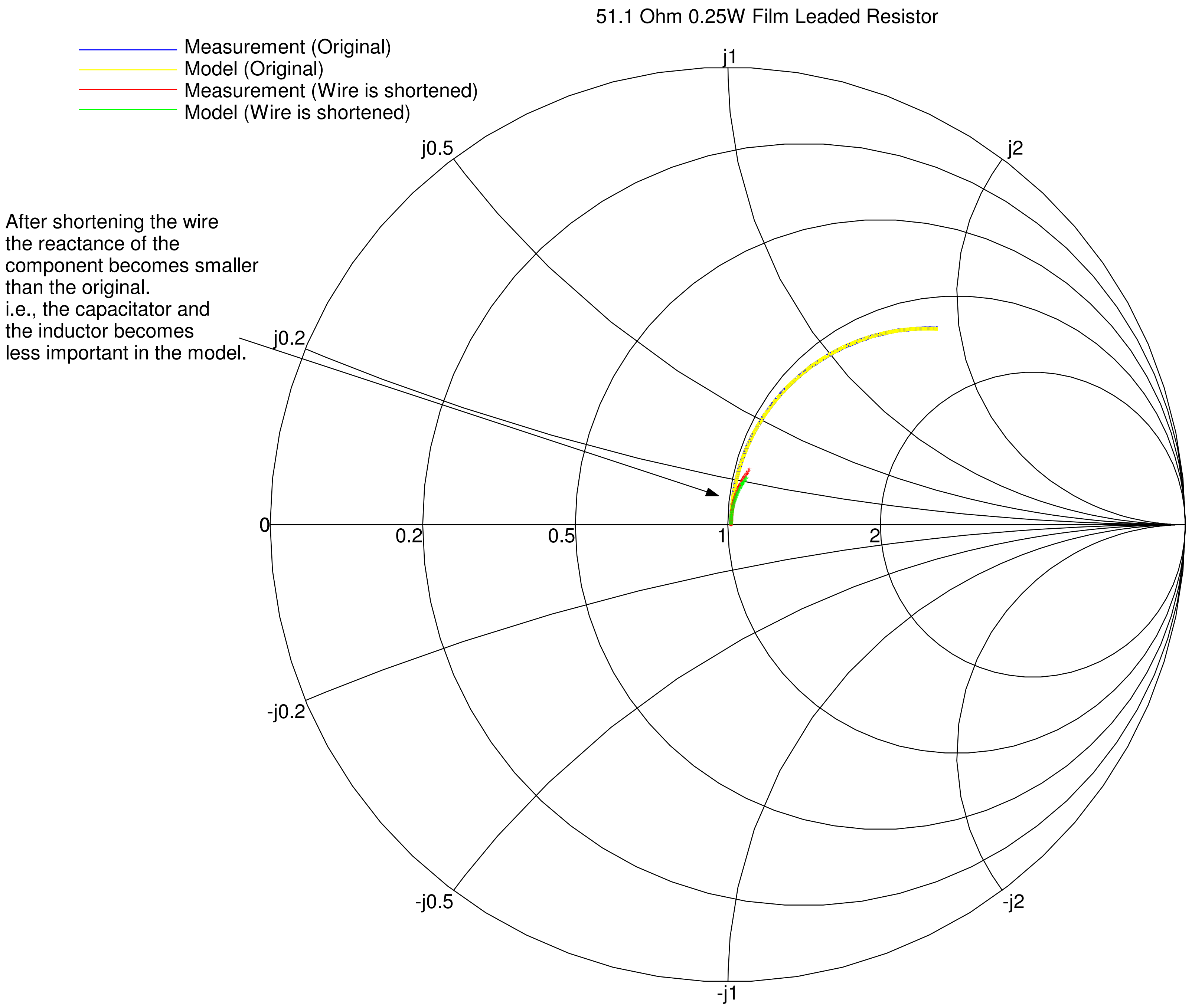


Title: Realistic Model for 51.1 Ohm 0.25W Film Leaded Resistor
Treatment: None



Title: Realistic Model for 51.1 Ohm 0.25W Film Lead Resistor
Treatment: Wire is shortened


51.1 Ohm 0.25W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
64
62
60
58
56
54
52
50
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
120
110
100
90
80
70
60
50
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
Frequency (MHz)



51.1 Ohm 0.25W Film Leaded Resistor

After shortening the wire
the reactance of the
component becomes smaller
than the original.
i.e., the capacitator and
the inductor becomes
less important in the model.

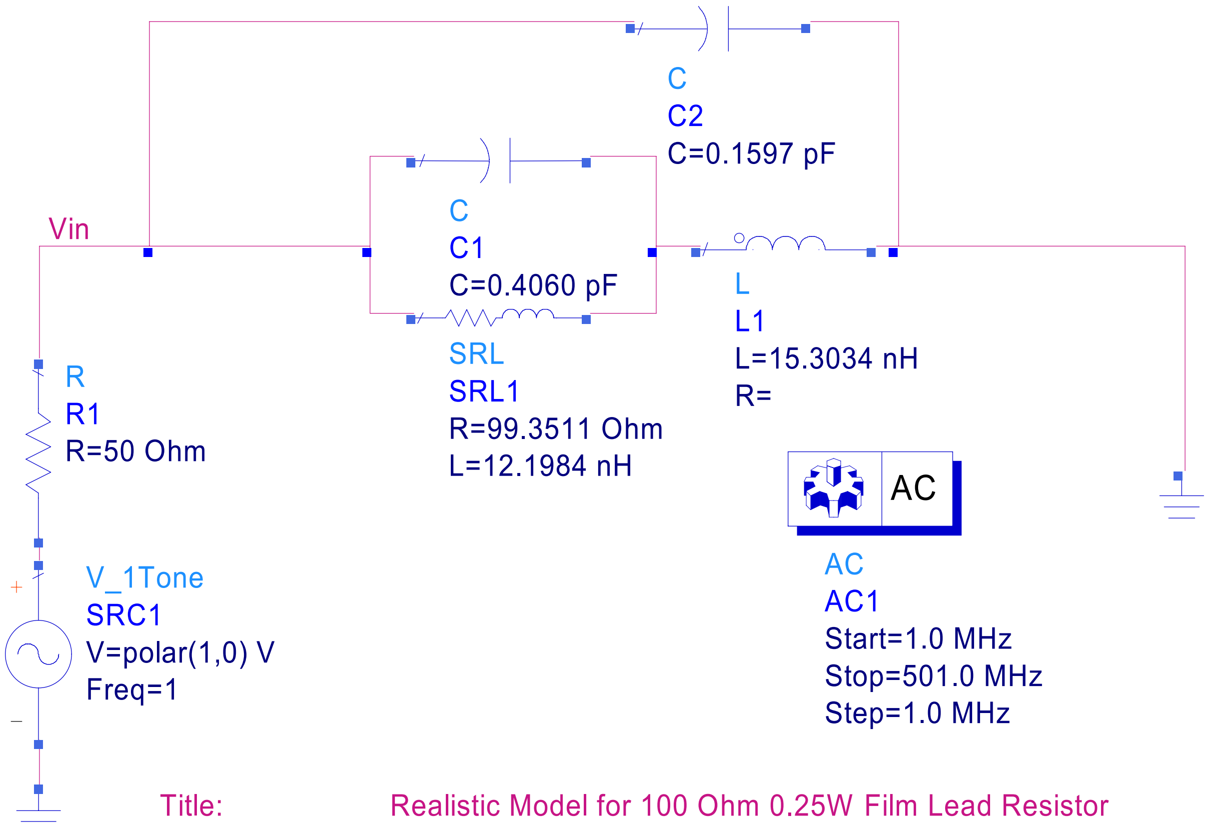
1.6.8 100.0Ω $0.25W$ Film Leaded Resistor

The following are the pictures of an original and after treatment 100.0Ω $0.25W$ Film Leaded Resistor.

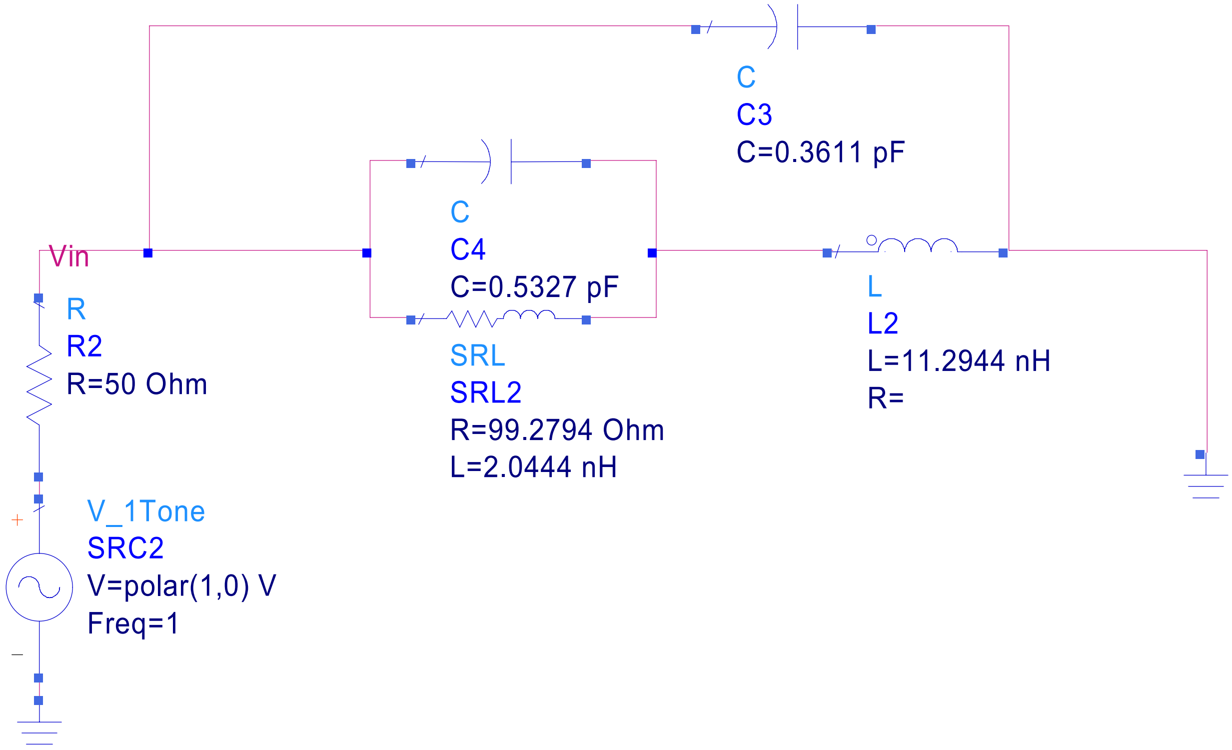
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

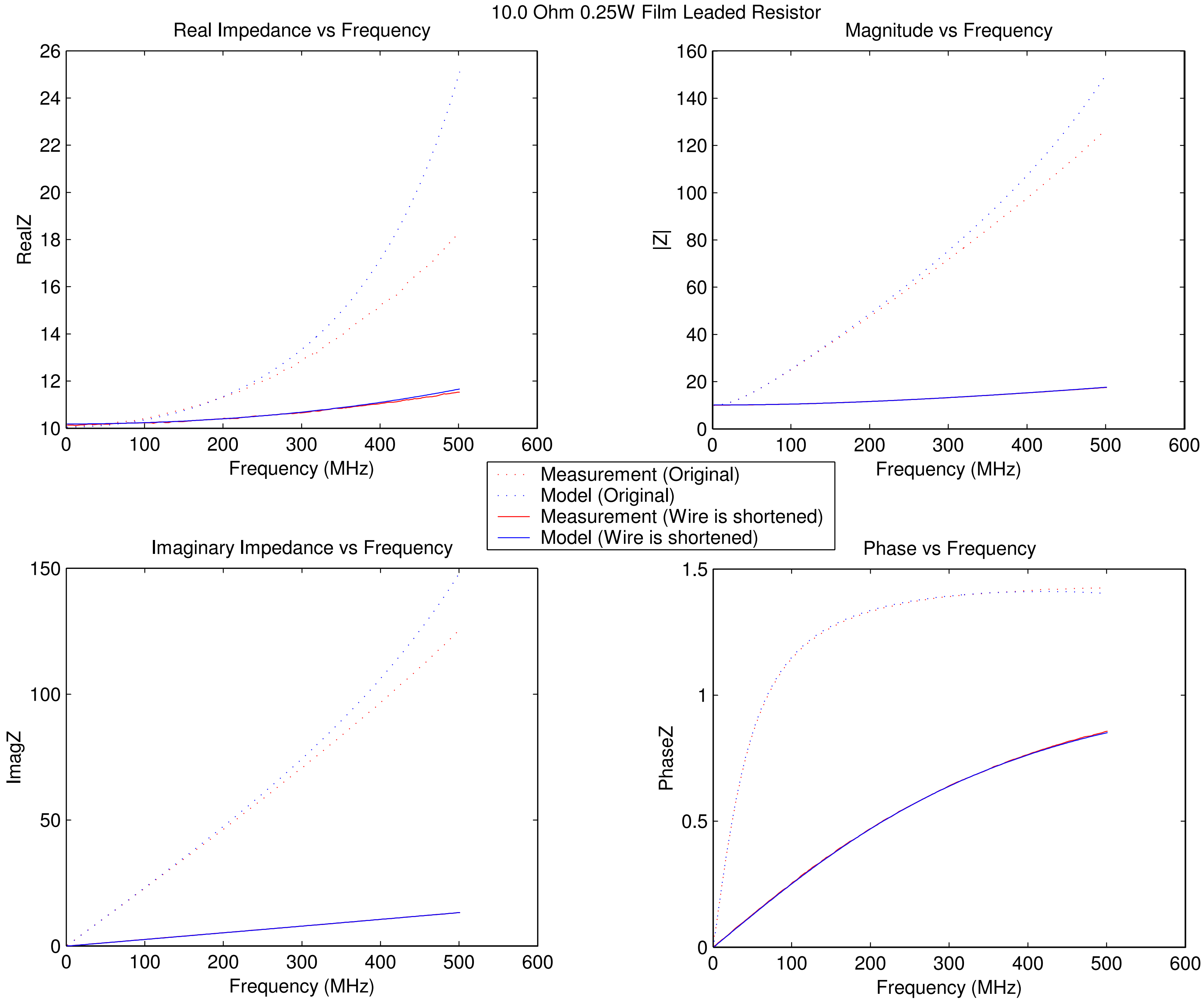
	Original	Wire is shortened
Measured Resistance (Ω)	99.90	99.89
Internal Resistance of Model (Ω)	99.3511	99.2795
Internal Inductance of Model (nH)	12.1984	2.0444
Internal Capacitance of Model (pF)	0.4060	0.5328
External Inductance from estimation (nH)	21.9506	0.1457
External Inductance of Model (nH)	15.3034	11.2945
External Capacitance from estimation (pF)	0.0000	0.0000
External Capacitance of Model (pF)	0.1597	0.3611
Legngth of Leaded Wire (mm)	16.97	0.00
Distance between two wires (mm)	7.95	7.90
Diameter of wire (mm)	0.58	0.58
R-Square Value of Real Impedance	0.9997	0.9952
R-Square Value of Imaginary Impedance	1.0000	0.9998
R-Square Value of Magnitude	1.0000	0.9970
R-Square Value of Phase	1.0000	0.9997

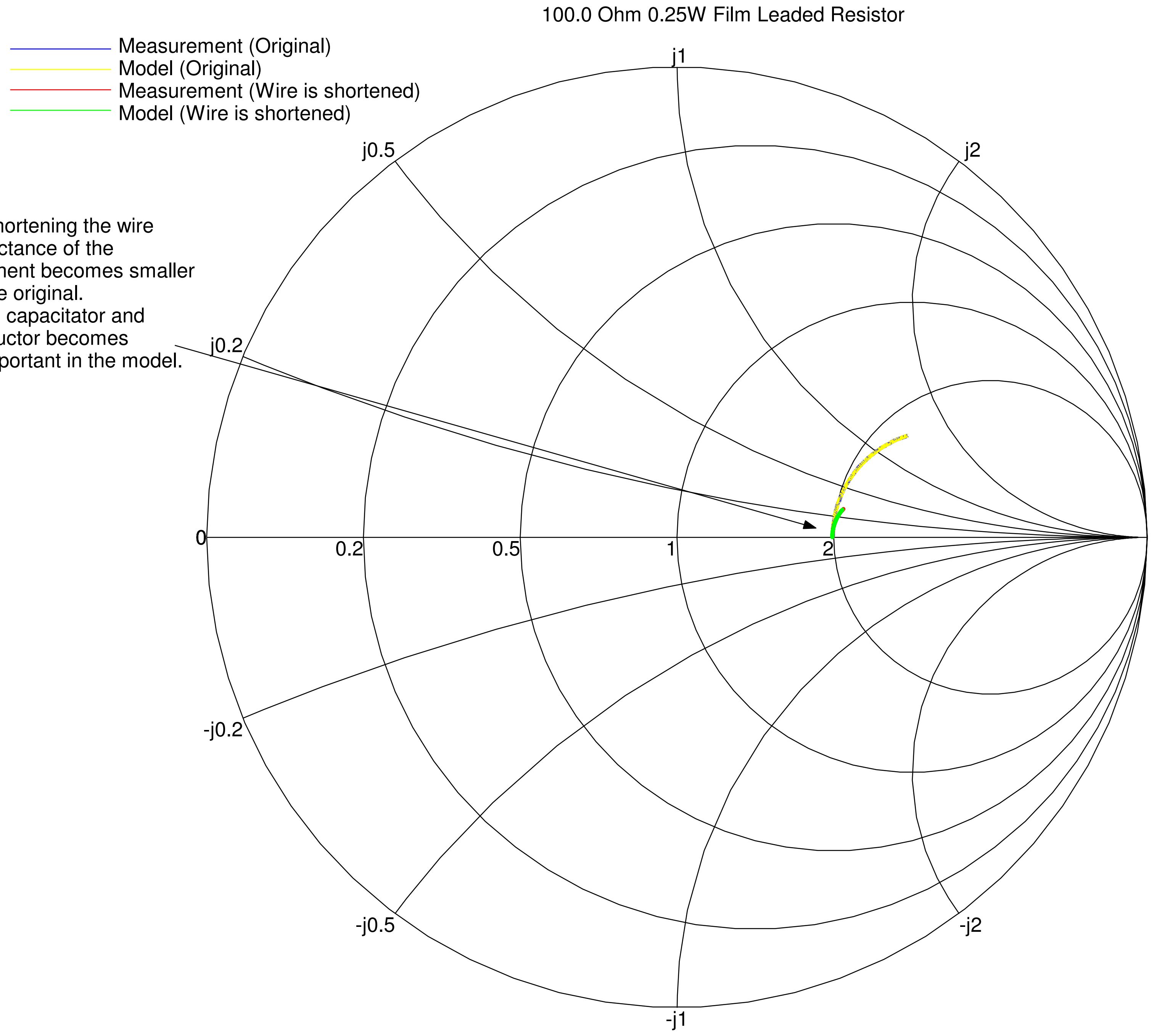


Title: Realistic Model for 100 Ohm 0.25W Film Lead Resistor
Treatment: None



Title: Realistic Model for 100 Ohm 0.25W Film Lead Resistor
Treatment: Wire is shortened


10.0 Ohm 0.25W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
10
12
14
16
18
20
22
24
26
Frequency (MHz)
0
100
200
300
400
500
600
Magnitude vs Frequency
|Z|
0
20
40
60
80
100
120
140
160
Frequency (MHz)
0
100
200
300
400
500
600
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
0
50
100
150
Frequency (MHz)
0
100
200
300
400
500
600
Phase vs Frequency
PhaseZ
0
0.5
1
1.5
Frequency (MHz)
0
100
200
300
400
500
600



100.0 Ohm 0.25W Film Leaded Resistor

After shortening the wire
the reactance of the
component becomes smaller
than the original.
i.e., the capacitator and
the inductor becomes
less important in the model.

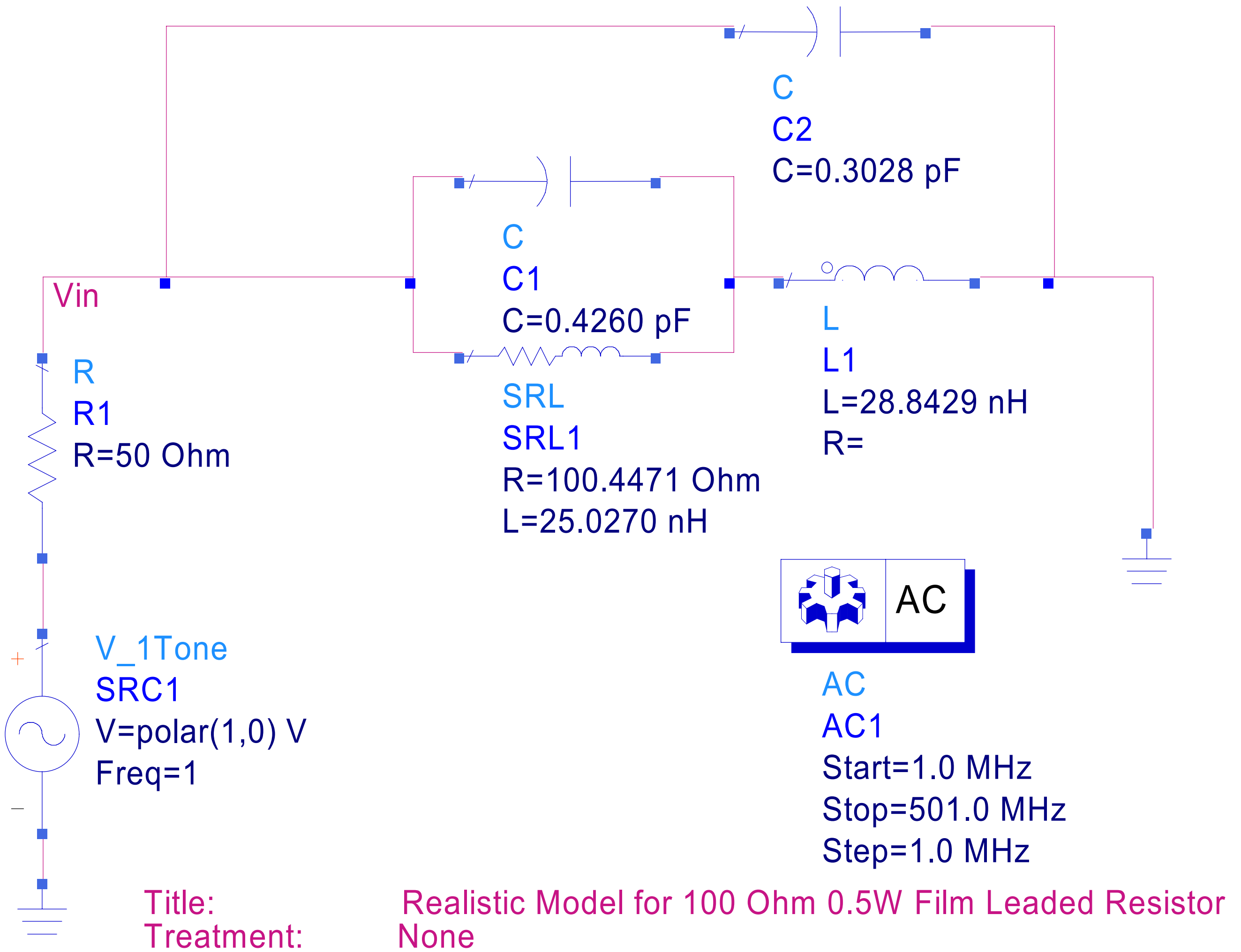
1.6.9 100.0Ω $0.50W$ Film Leaded Resistor

The following are the pictures of an original and after treatment 100.0Ω $0.50W$ Film Leaded Resistor.

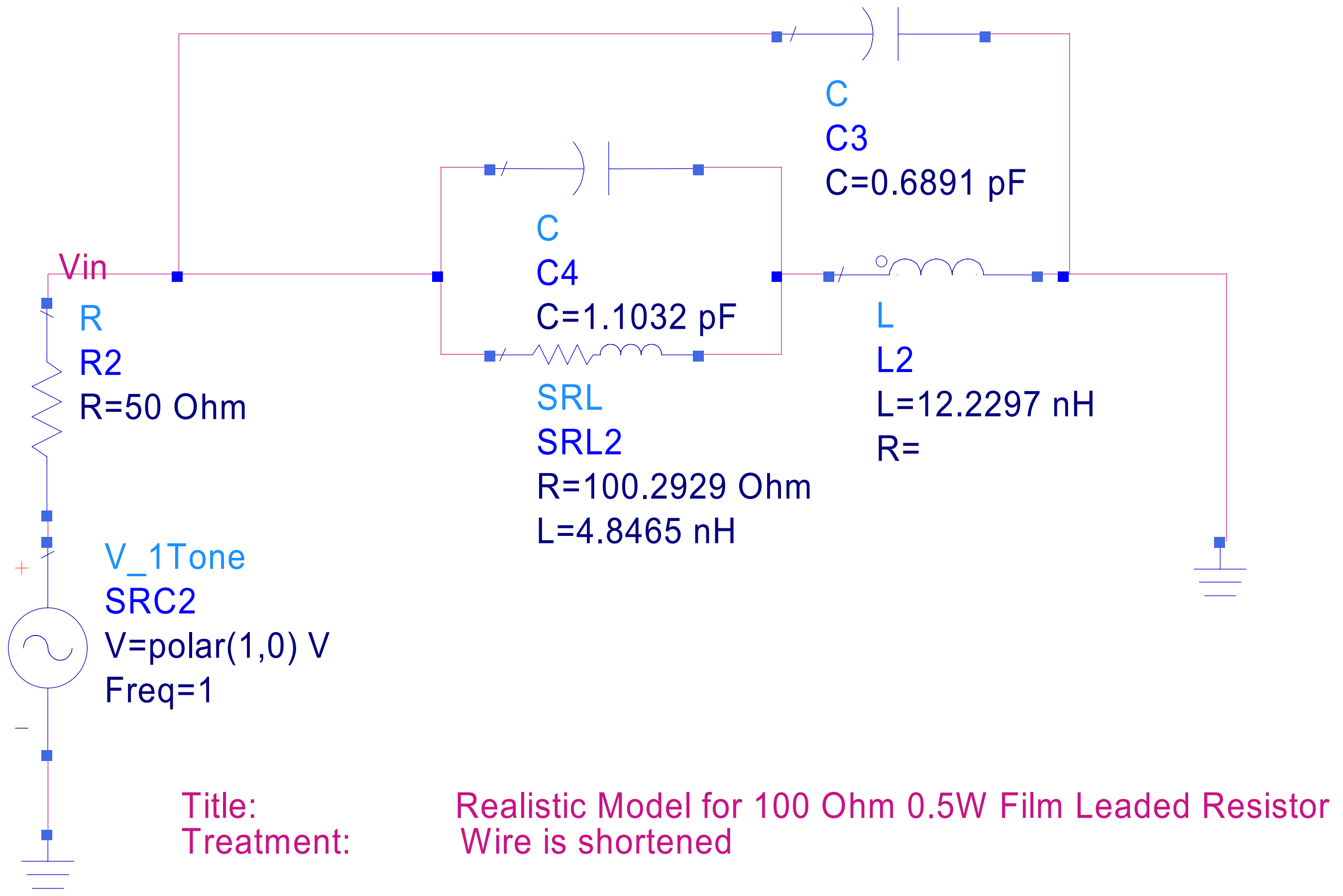
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

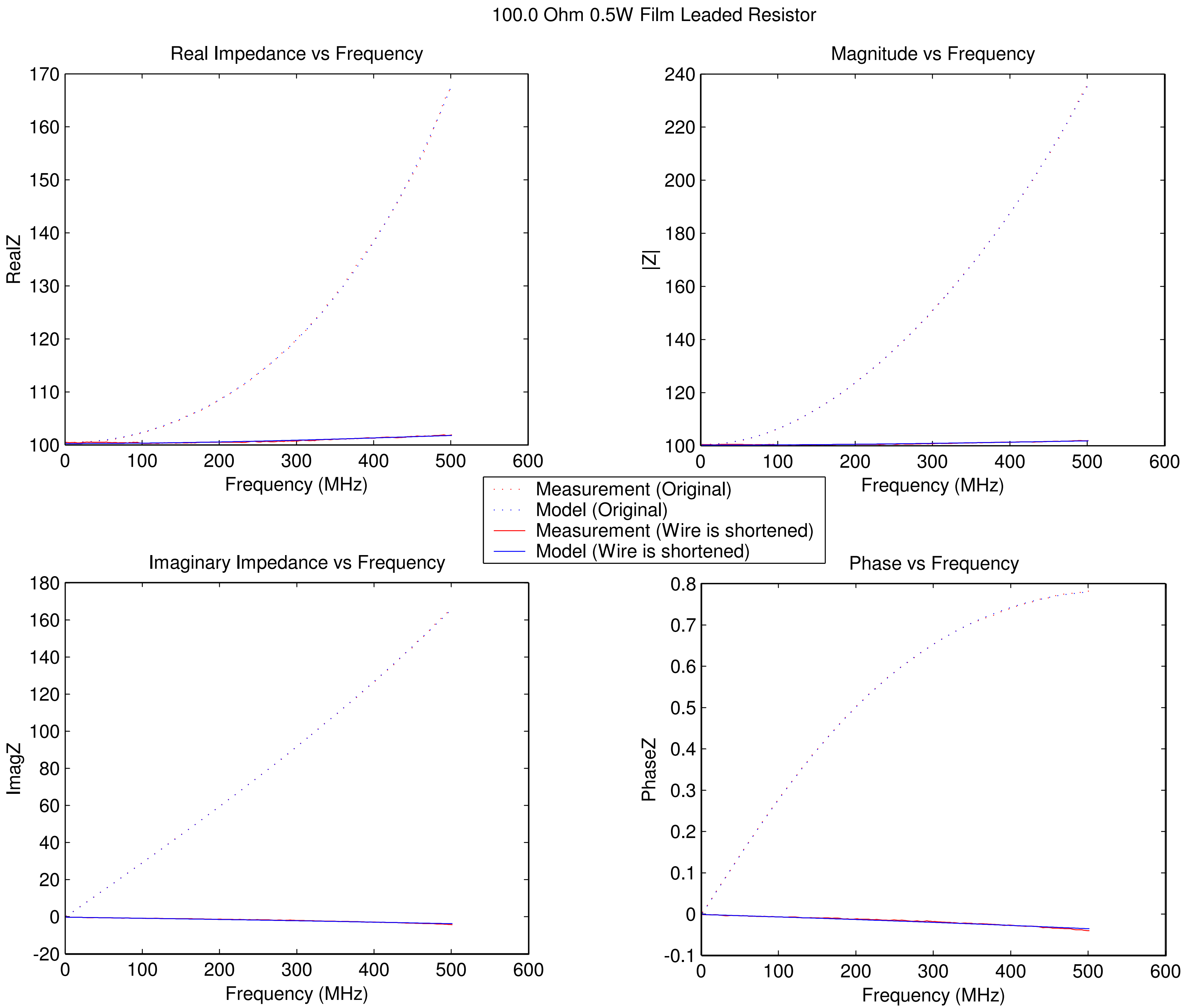
	Original	Wire is shortened
Measured Resistance (Ω)	100.42	100.41
Internal Resistance of Model (Ω)	100.4471	100.2930
Internal Inductance of Model (nH)	25.0270	4.8465
Internal Capacitance of Model (pF)	0.4260	1.1032
External Inductance from estimation (nH)	55.8467	0.0000
External Inductance of Model (nH)	28.8430	12.2297
External Capacitance from estimation (pF)	0.2971	0.0000
External Capacitance of Model (pF)	0.3029	0.6891
Legnth of Leaded Wire (mm)	38.65	0.00
Distance between two wires (mm)	12.31	12.11
Diameter of wire (mm)	0.63	0.63
R-Square Value of Real Impedance	0.9999	0.9447
R-Square Value of Imaginary Impedance	1.0000	0.9836
R-Square Value of Magnitude	1.0000	0.9473
R-Square Value of Phase	1.0000	0.9836

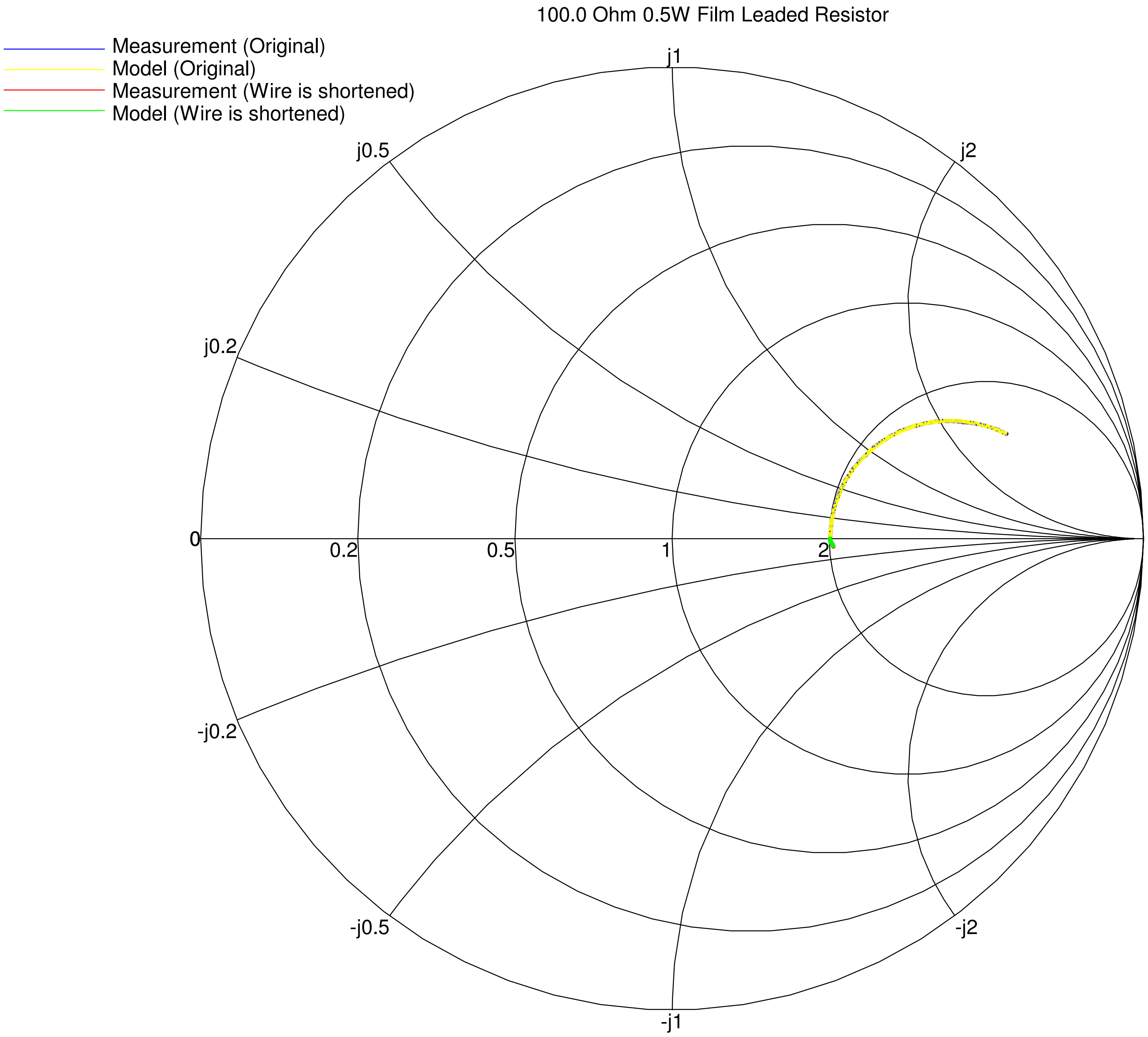


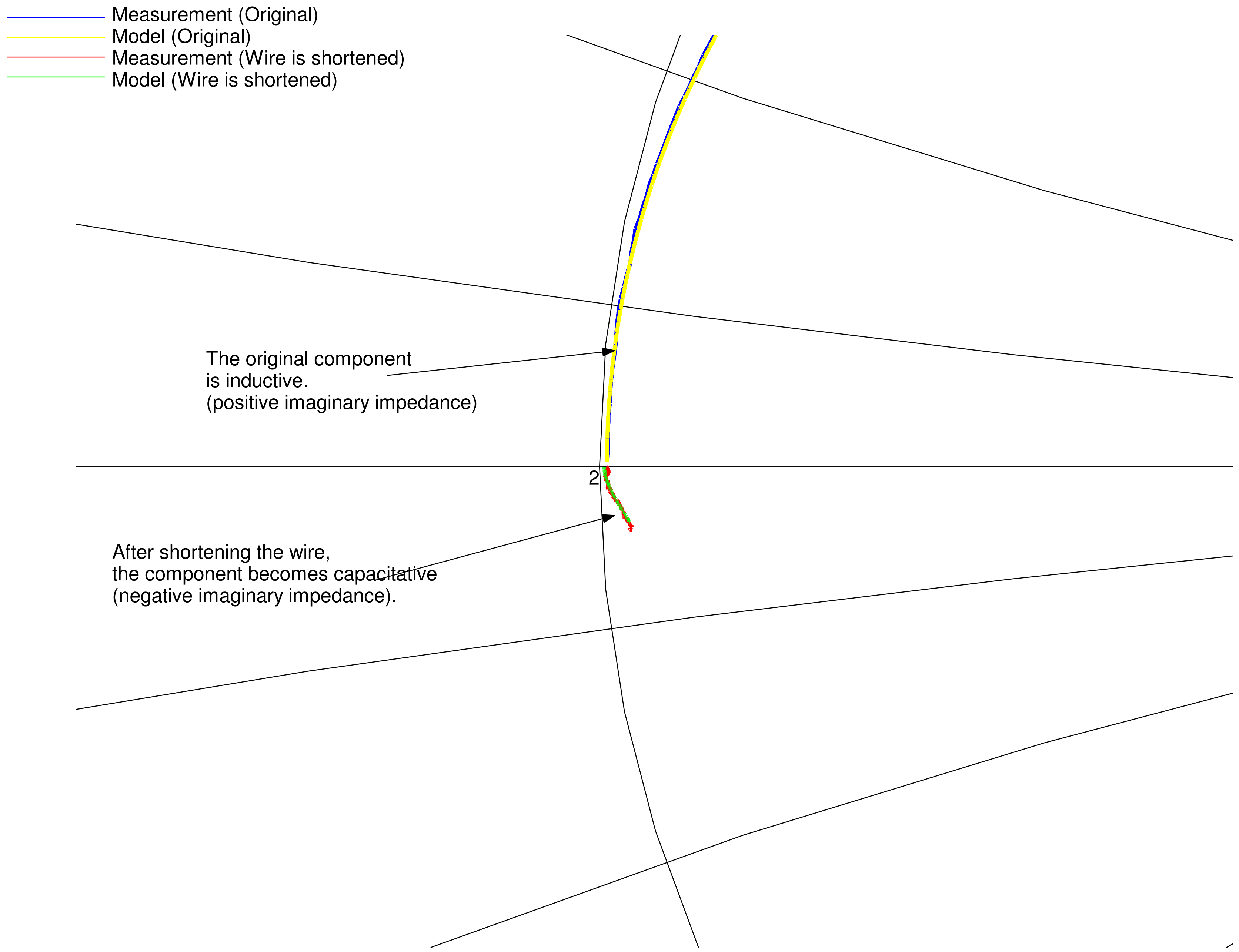
Title: Realistic Model for 100 Ohm 0.5W Film Leaded Resistor
Treatment: None



Title: Realistic Model for 100 Ohm 0.5W Film Leaded Resistor
Treatment: Wire is shortened


100.0 Ohm 0.5W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
170
160
150
140
130
120
110
100
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
240
220
200
180
160
140
120
100
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
180
160
140
120
100
80
60
40
20
0
-20
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
100
200
300
400
500
600
Frequency (MHz)

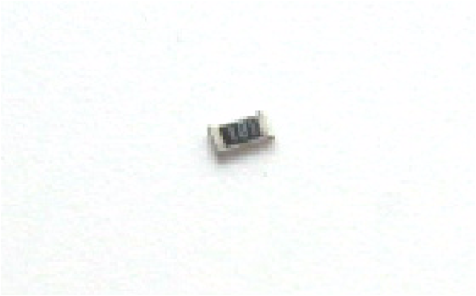

100.0 Ohm 0.5W Film Leaded Resistor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1



100.0 Ohm 0.5W Film Leaded Resistor (Zoom-in)

1.6.10 100.0Ω $0.125W$ Thin-Film Chip Resistor

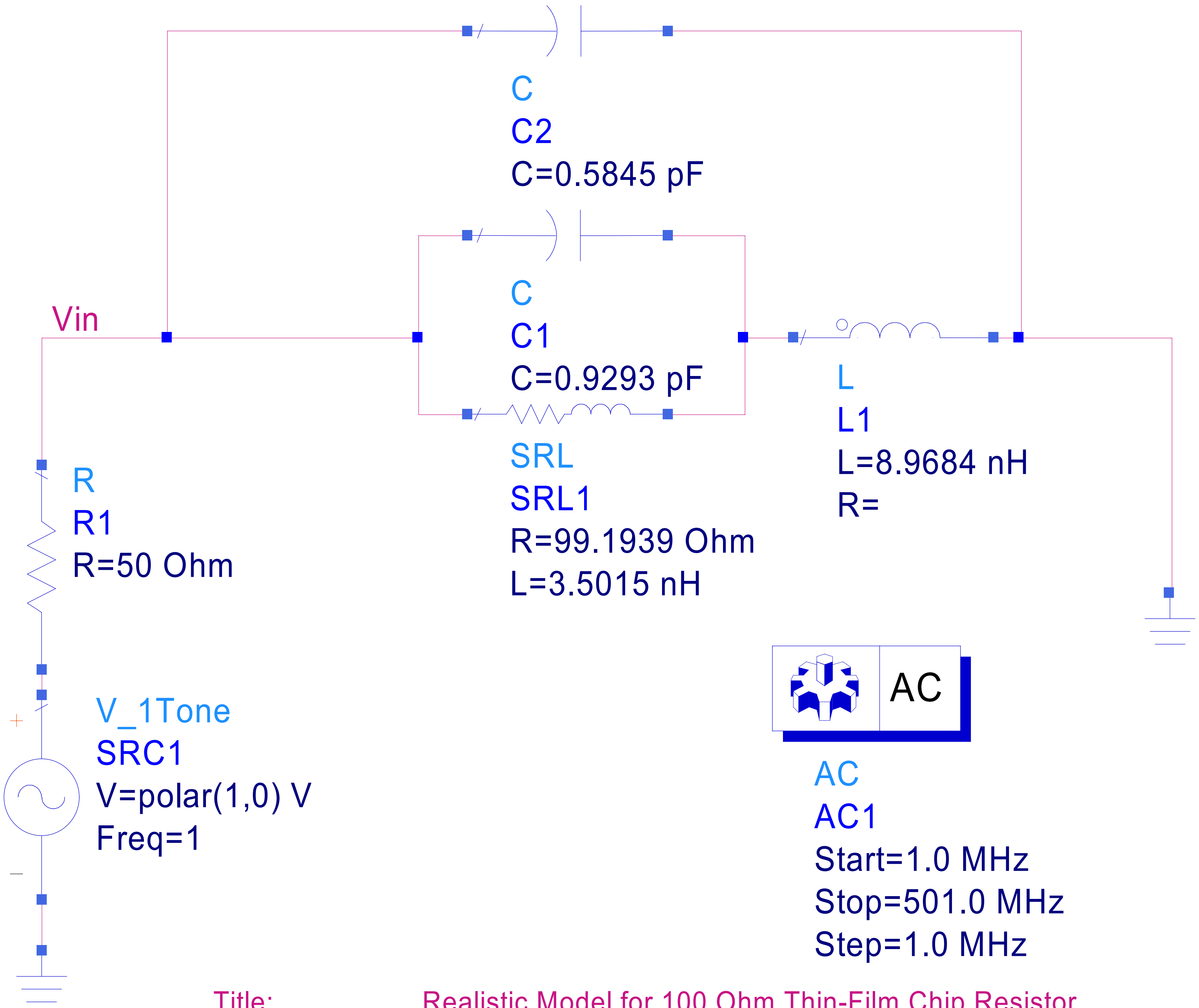
The following is the picture of a 100.0Ω $0.125W$ Thin-Film Chip Resistor.



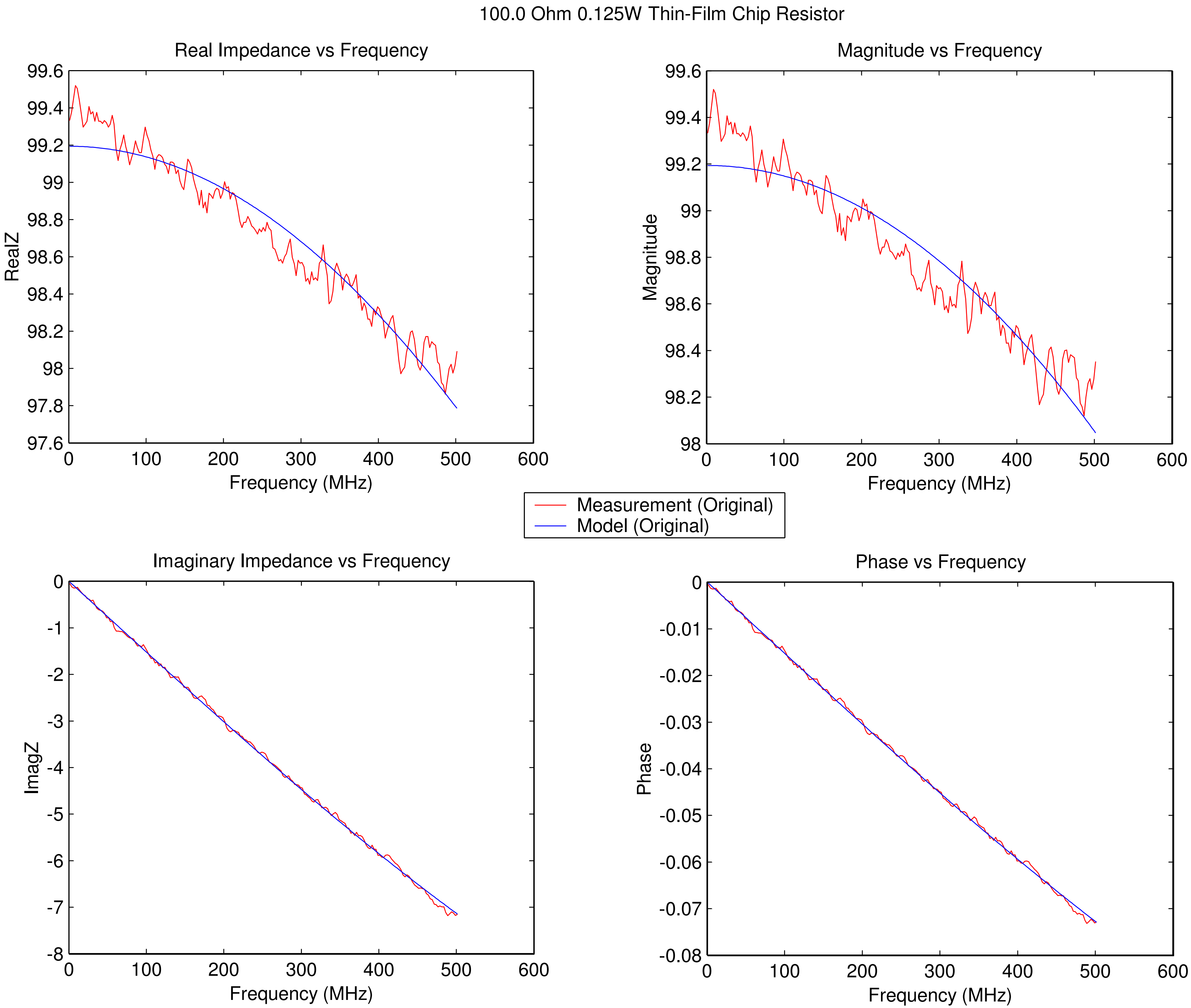
Word marked on the chip: `101`

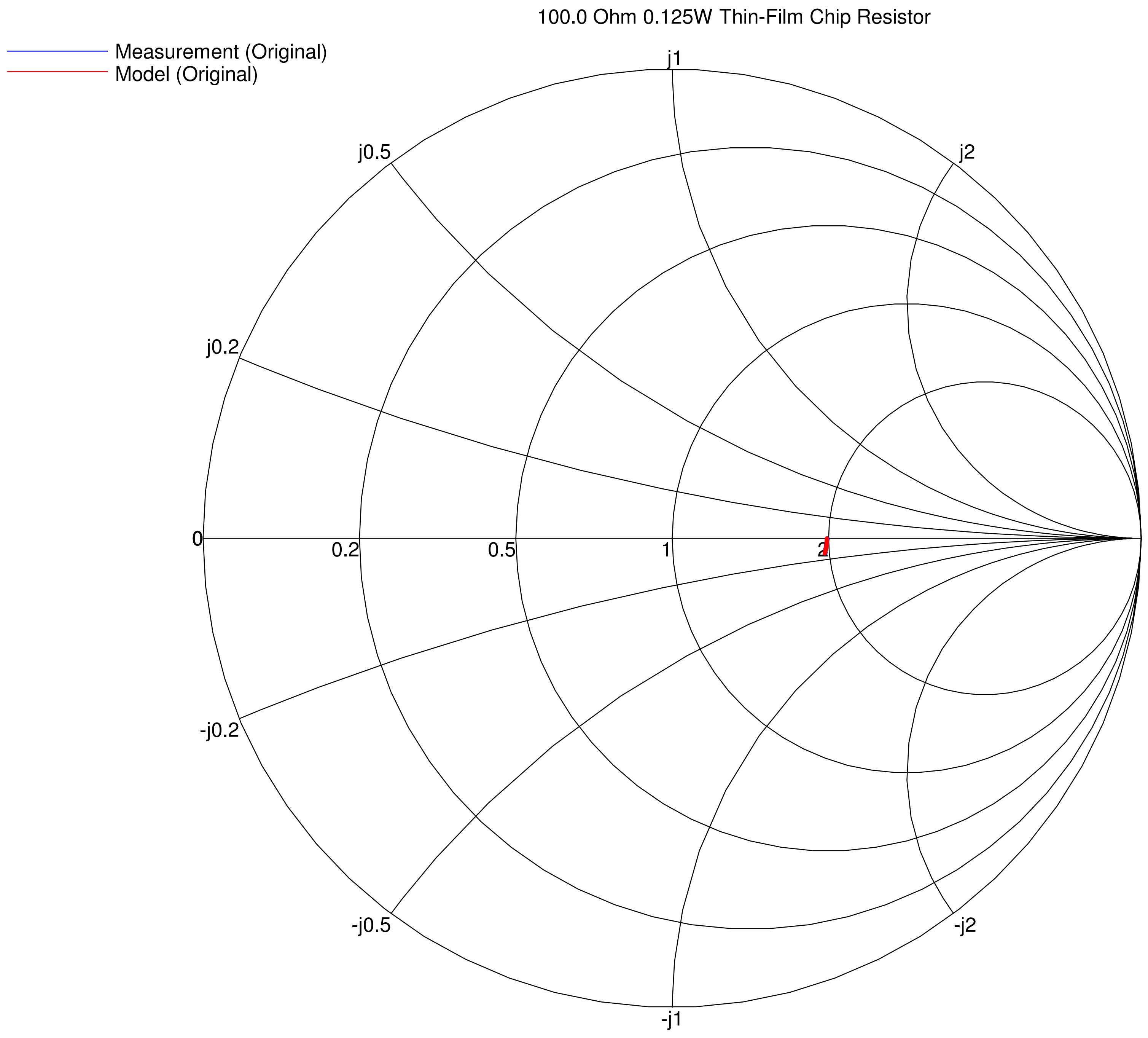
This table summarizes measured data and simulation result:

	Original
Internal Resistance of Model (Ω)	99.1939
Internal Inductance of Model (nH)	3.5015
Internal Capacitance of Model (pF)	0.9293
External Inductance of Model (nH)	8.9684
External Capacitance of Model (pF)	0.5845
R-Square Value of Real Impedance	0.9327
R-Square Value of Imaginary Impedance	0.9992
R-Square Value of Magnitude	0.8993
R-Square Value of Phase	0.9993

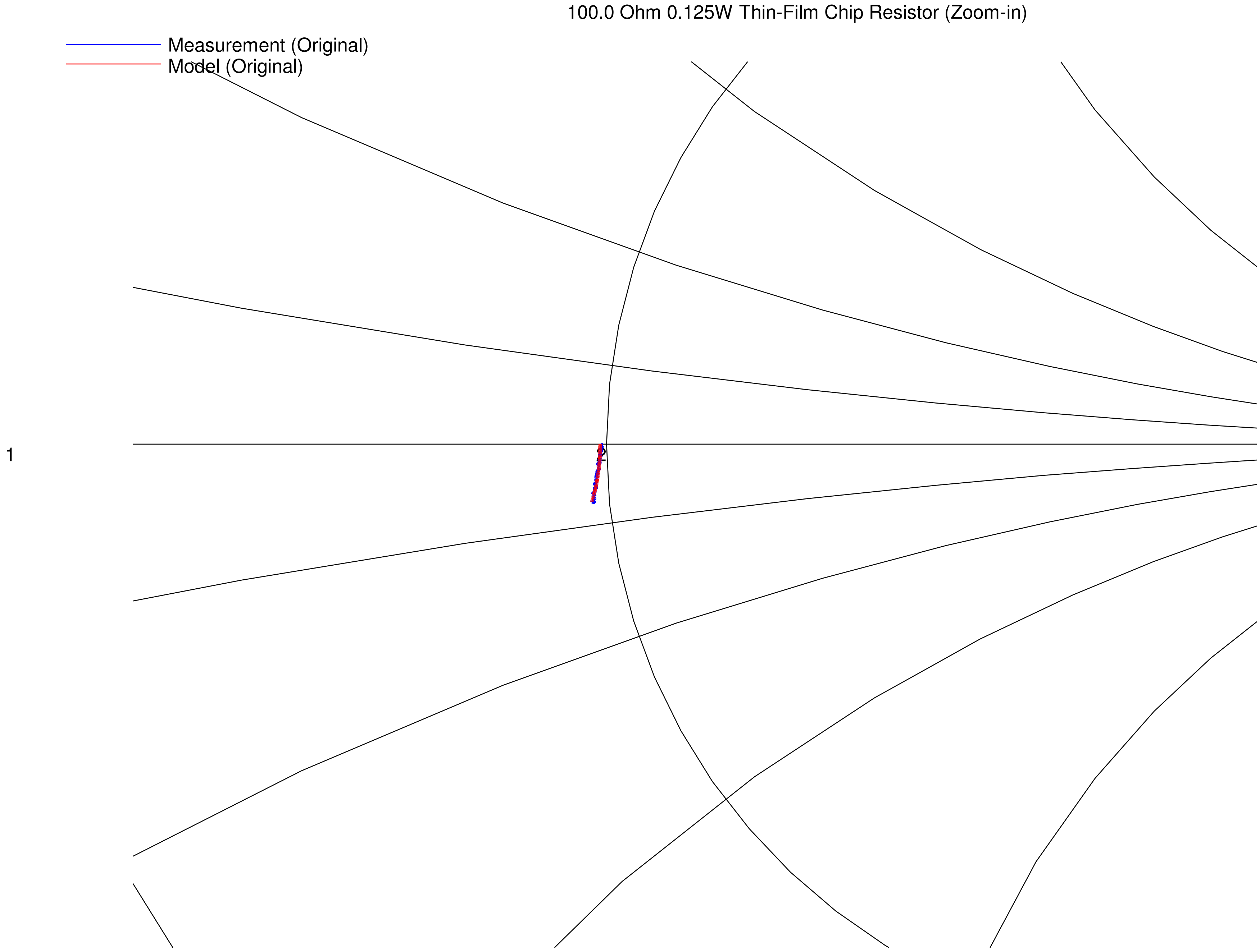


Title: Realistic Model for 100 Ohm Thin-Film Chip Resistor
Treatment: None


100.0 Ohm 0.125W Thin-Film Chip Resistor
Real Impedance vs Frequency
RealZ
99.6
99.4
99.2
99
98.8
98.6
98.4
98.2
98
97.8
97.6
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
99.6
99.4
99.2
99
98.8
98.6
98.4
98.2
98
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Imaginary Impedance vs Frequency
ImagZ
0
-1
-2
-3
-4
-5
-6
-7
-8
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
0
100
200
300
400
500
600
Frequency (MHz)



100.0 Ohm 0.125W Thin-Film Chip Resistor



100.0 Ohm 0.125W Thin-Film Chip Resistor (Zoom-in)

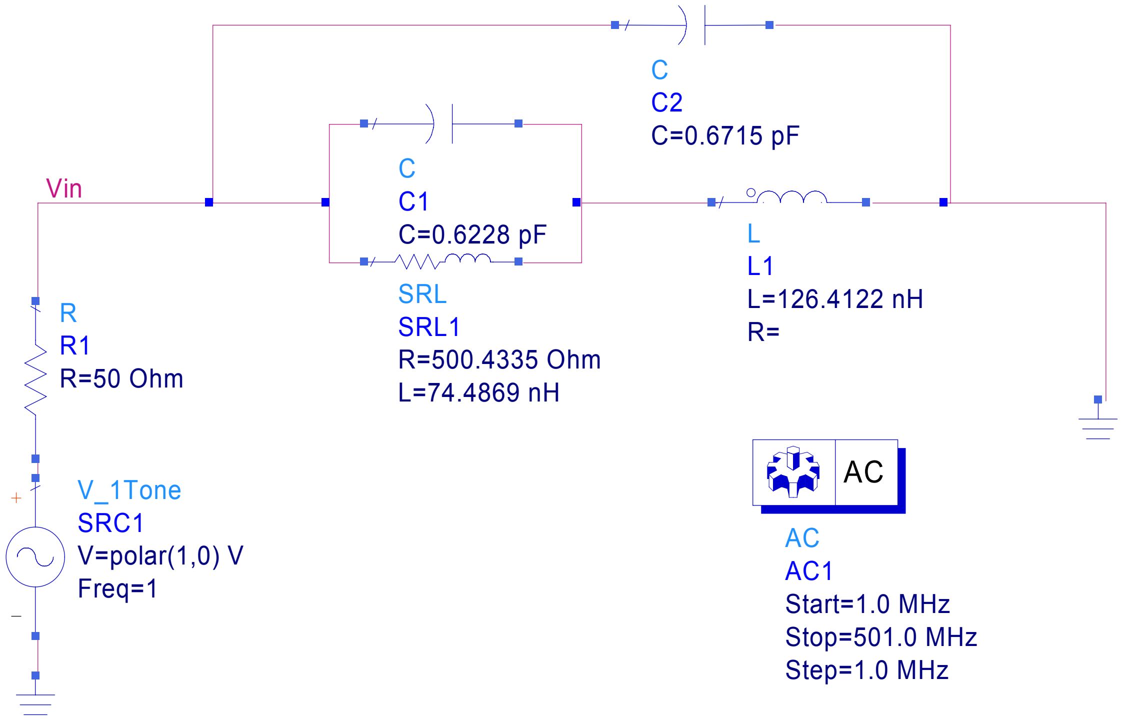
1.6.11 510.0Ω $0.25W$ **Film Leaded Resistor**

The following are the pictures of an original and after treatment 510.0Ω $0.25W$ Film Leaded Resistor.

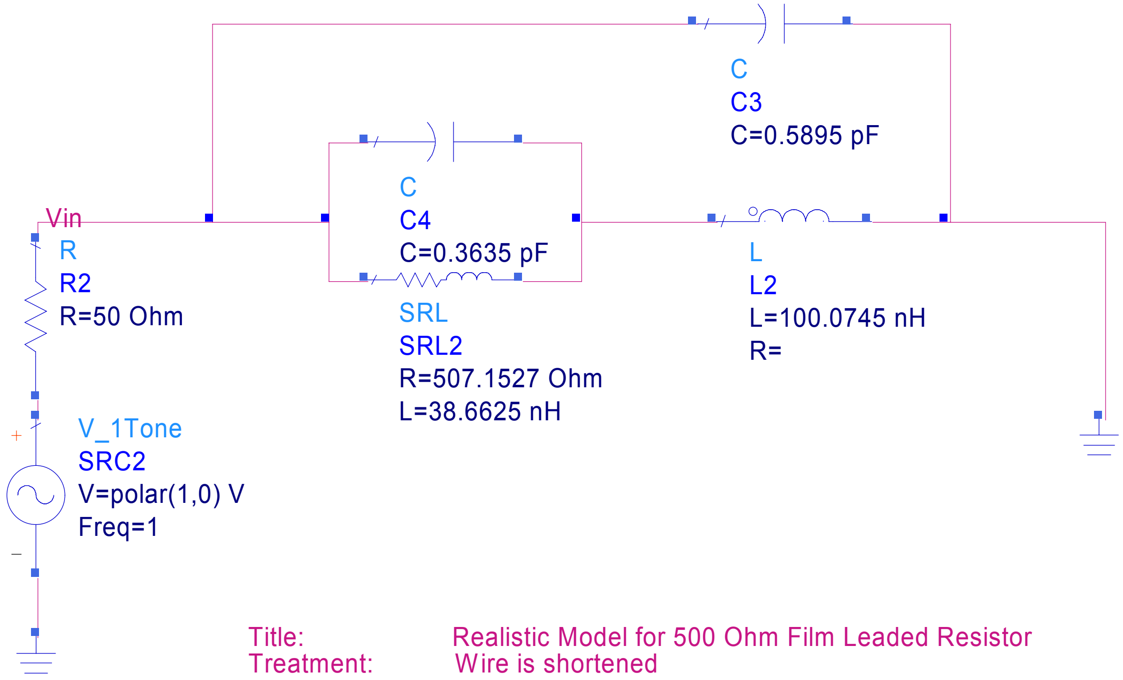
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

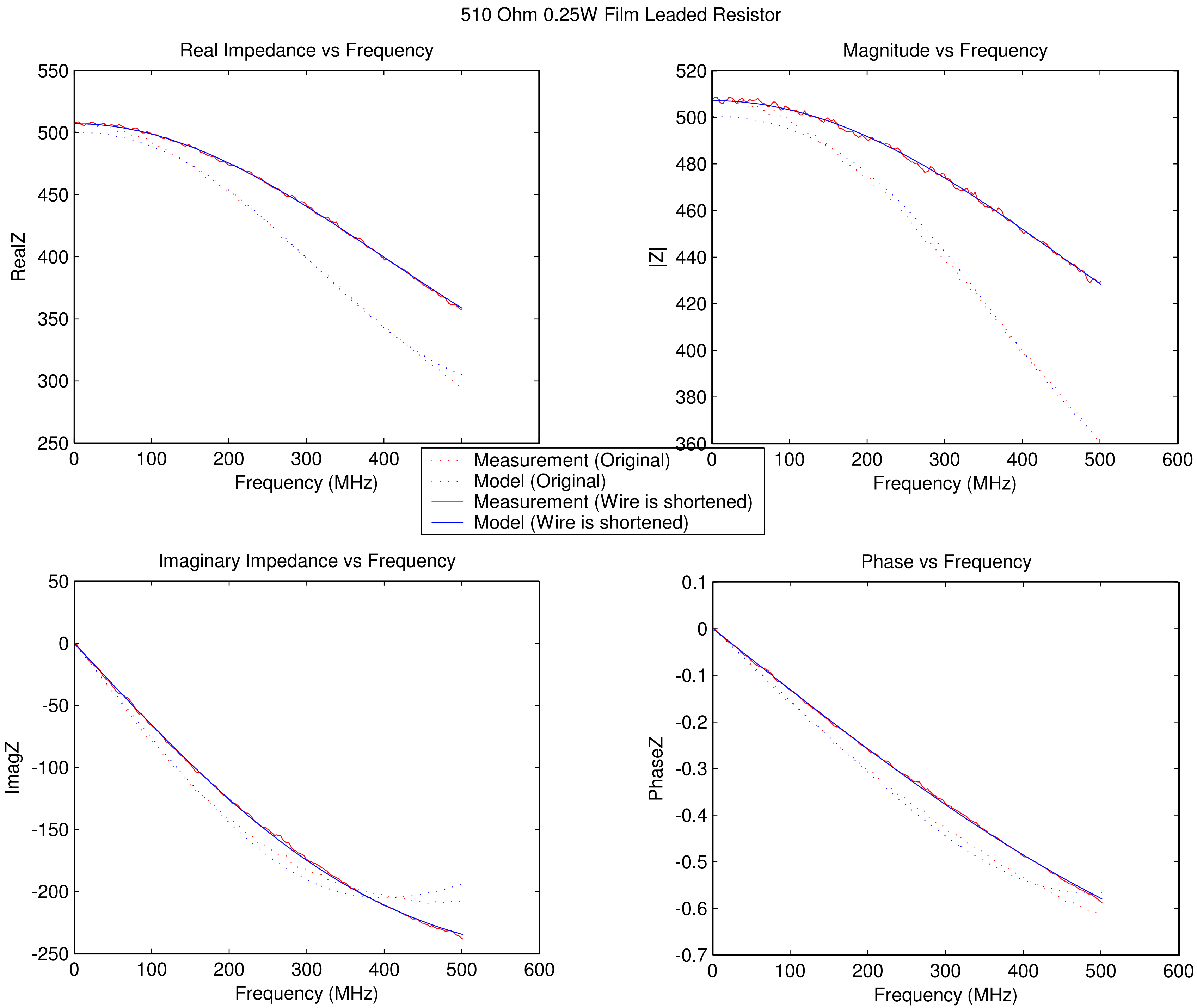
	Original	Wire is shortened
Measured Resistance (Ω)	510.21	510.20
Internal Resistance of Model (Ω)	500.4335	507.1527
Internal Inductance of Model (nH)	74.4869	38.6625
Internal Capacitance of Model (pF)	0.6228	0.3635
External Inductance from estimation (nH)	27.4921	0.0000
External Inductance of Model (nH)	126.4122	100.0745
External Capacitance from estimation (pF)	0.1887	0.0000
External Capacitance of Model (pF)	0.6715	0.5895
Legnth of Leaded Wire (mm)	21.61	0.00
Distance between two wires (mm)	7.83	7.87
Diameter of wire (mm)	0.60	0.60
R-Square Value of Real Impedance	0.9983	0.9995
R-Square Value of Imaginary Impedance	0.9927	0.9996
R-Square Value of Magnitude	0.9952	0.9984
R-Square Value of Phase	0.9939	0.9997

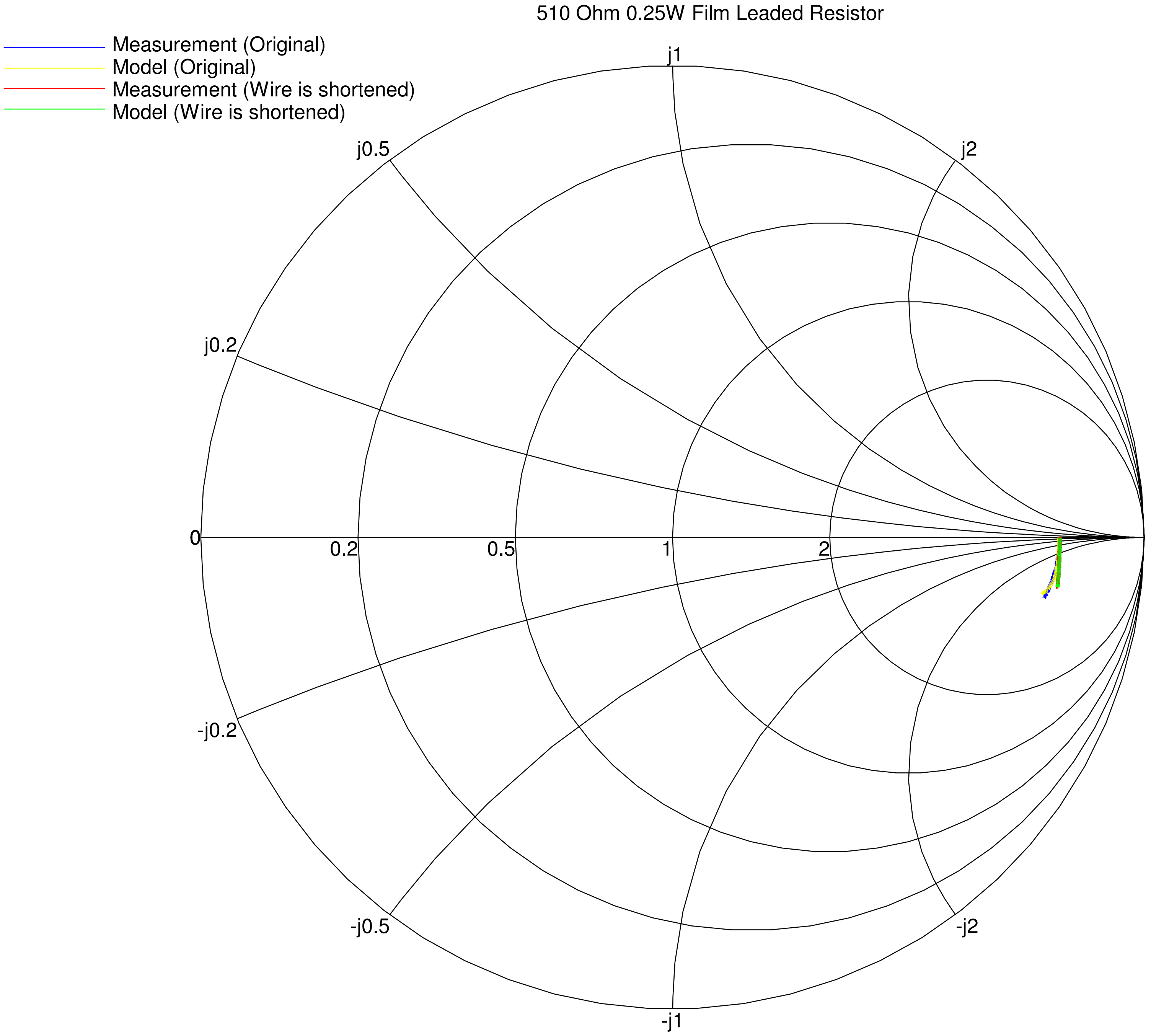


Title: Realistic Model for 500 Ohm Film Leaded Resistor
Treatment: None

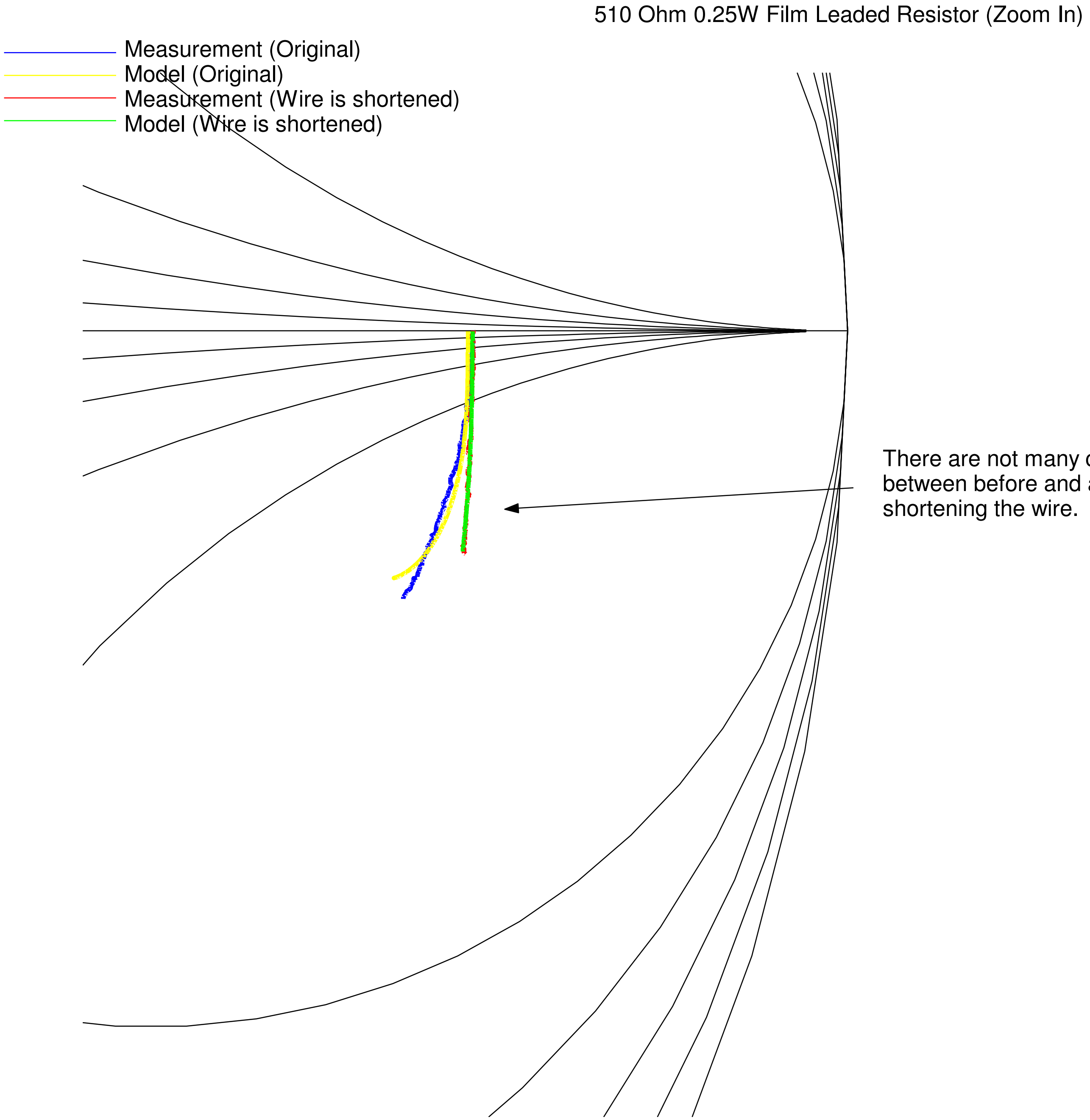


Title: Realistic Model for 500 Ohm Film Leaded Resistor
Treatment: Wire is shortened


510 Ohm 0.25W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
550
500
450
400
350
300
250
0
100
200
300
400
Frequency (MHz)
Magnitude vs Frequency
|Z|
520
500
480
460
440
420
400
380
360
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
50
0
-50
-100
-150
-200
-250
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
100
200
300
400
500
600
Frequency (MHz)



510 Ohm 0.25W Film Leaded Resistor



There are not many changes between before and after shortening the wire.

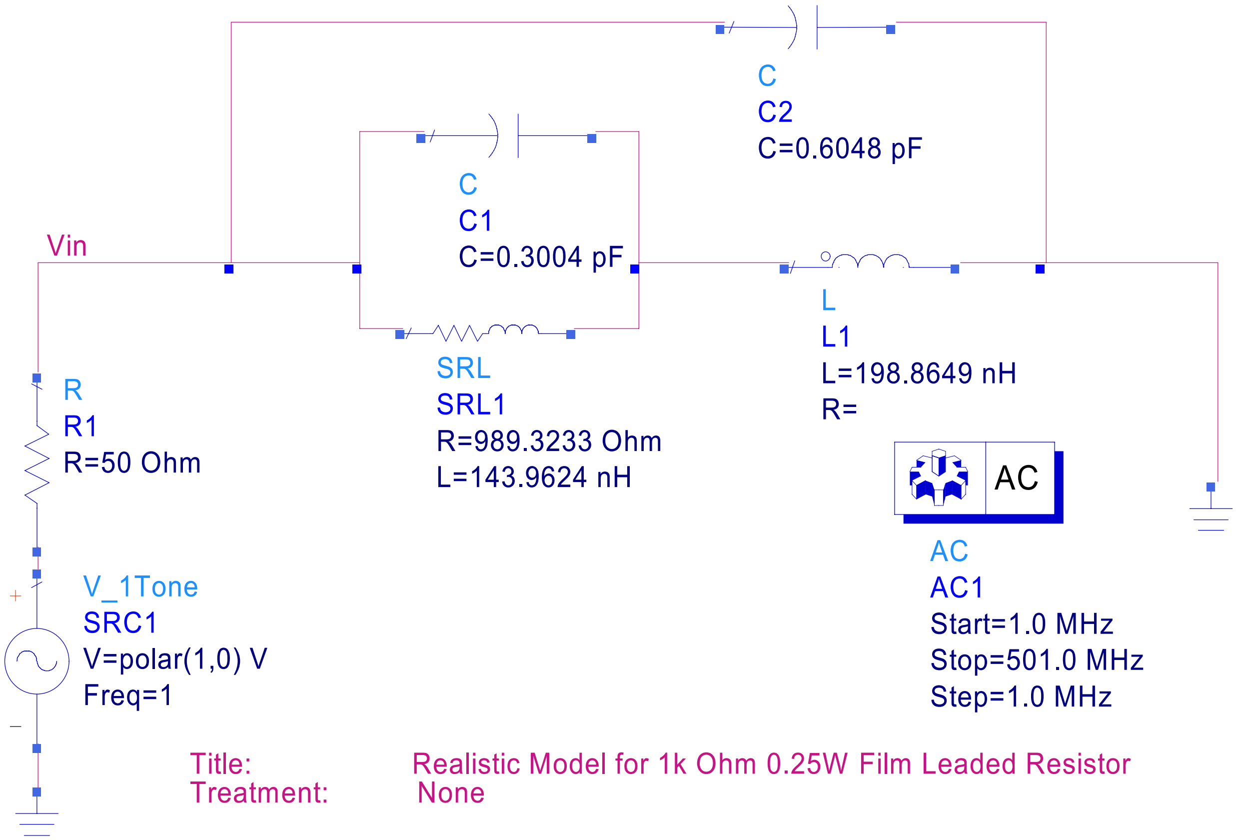
1.6.12 1kΩ $0.25W$ Film Leaded Resistor

The following are the pictures of an original and after treatment 1kΩ $0.25W$ Film Leaded Resistor.

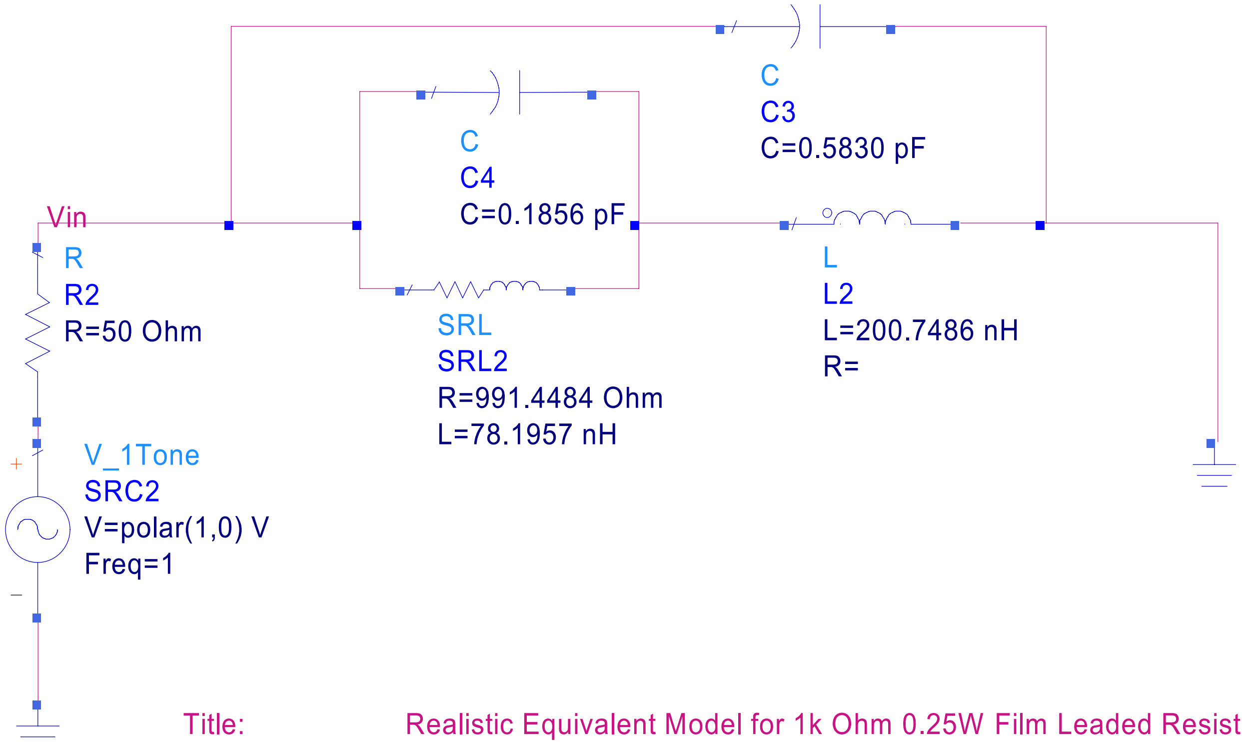
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

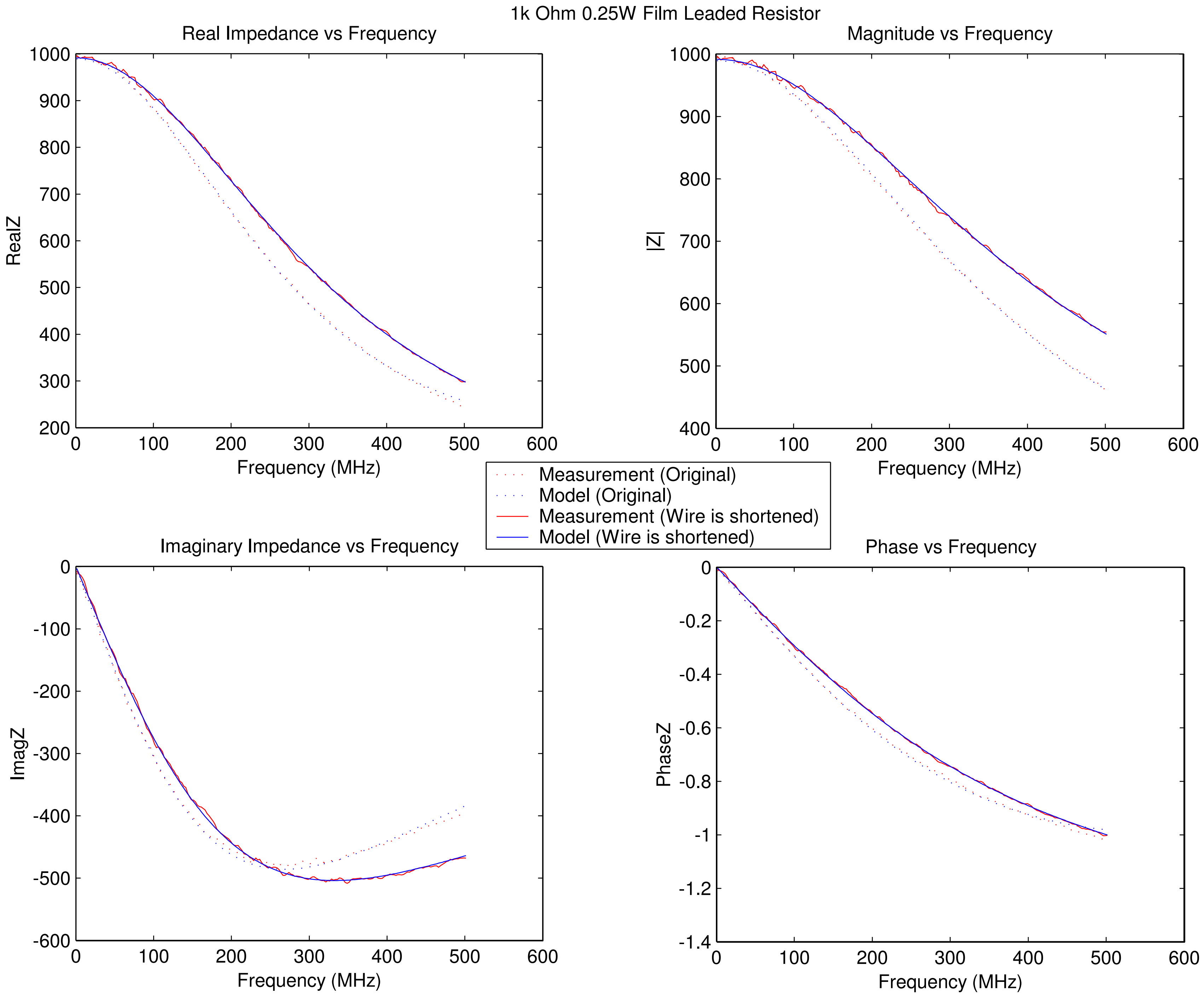
	Original	Wire is shortened
Measured Resistance (Ω)	994.60	994.60
Internal Resistance of Model (Ω)	989.3234	991.4484
Internal Inductance of Model (nH)	143.9624	78.1957
Internal Capacitance of Model (pF)	0.3005	0.1857
External Inductance from estimation (nH)	35.1204	0.0000
External Inductance of Model (nH)	198.8649	200.7487
External Capacitance from estimation (pF)	0.2245	0.0000
External Capacitance of Model (pF)	0.6049	0.5831
Legnth of Leaded Wire (mm)	26.64	0.00
Distance between two wires (mm)	7.84	8.41
Diameter of wire (mm)	0.54	0.54
R-Square Value of Real Impedance	0.9997	0.9998
R-Square Value of Imaginary Impedance	0.9982	0.9995
R-Square Value of Magnitude	0.9995	0.9995
R-Square Value of Phase	0.9987	0.9998

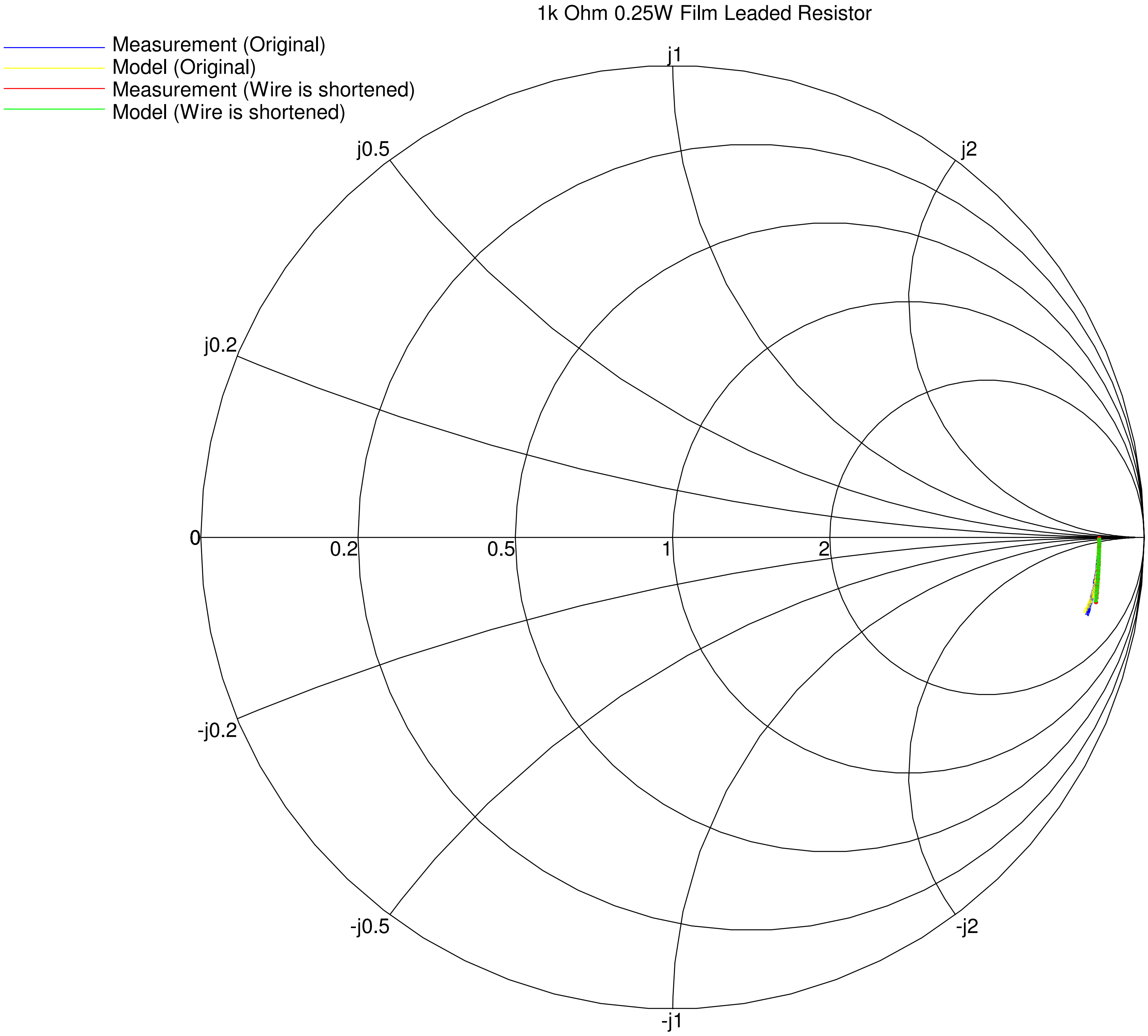


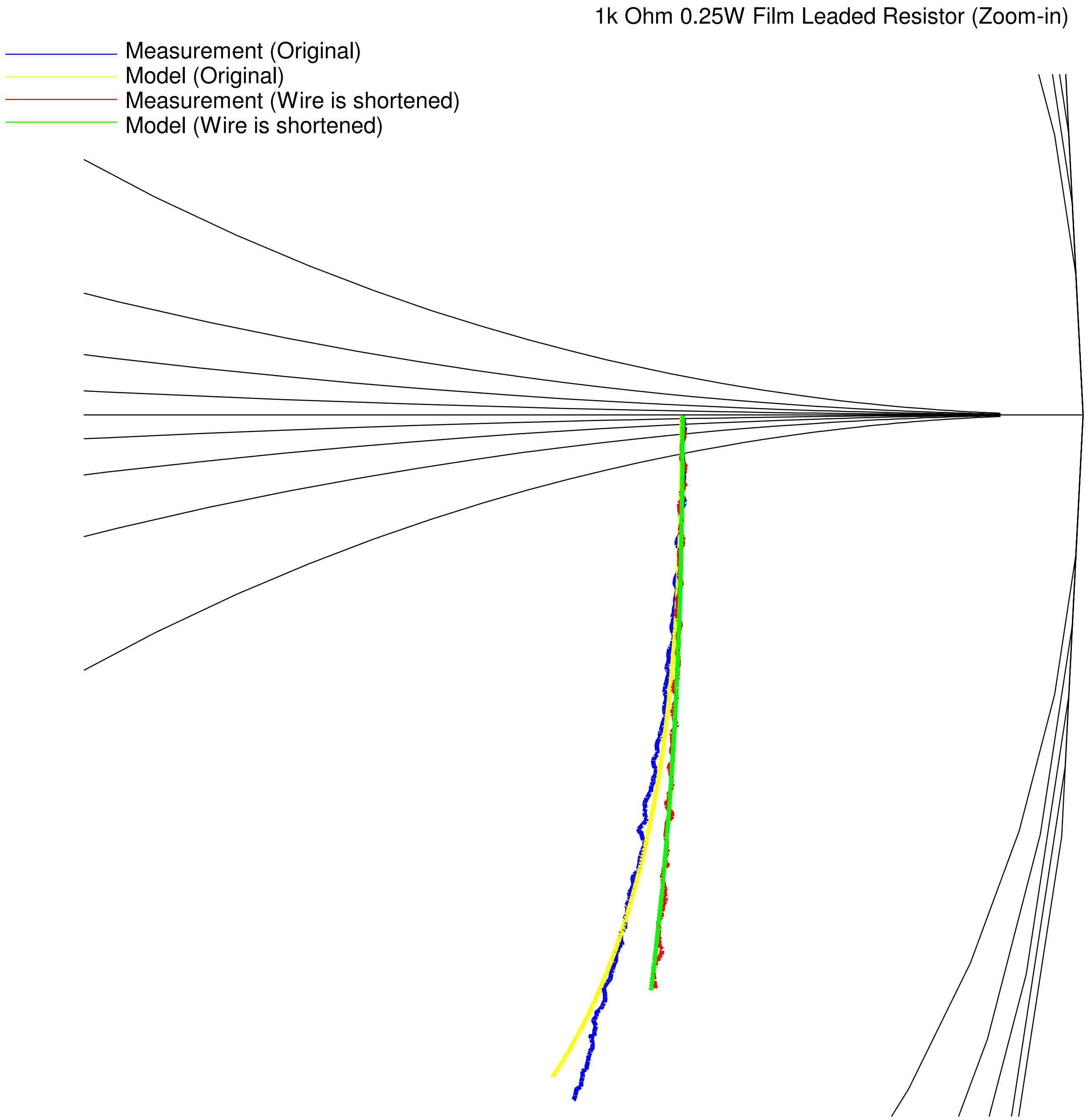
Title: Realistic Model for 1k Ohm 0.25W Film Leaded Resistor
Treatment: None



Title: Realistic Equivalent Model for 1k Ohm 0.25W Film Leaded Resistor
Treatment: Wire is shortened


1k Ohm 0.25W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
1000
900
800
700
600
500
400
300
200
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
1000
900
800
700
600
500
400
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
0
-100
-200
-300
-400
-500
-600
Frequency (MHz)
Phase vs Frequency
PhaseZ
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Frequency (MHz)


1k Ohm 0.25W Film Leaded Resistor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


1k Ohm 0.25W Film Leaded Resistor (Zoom-in)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)

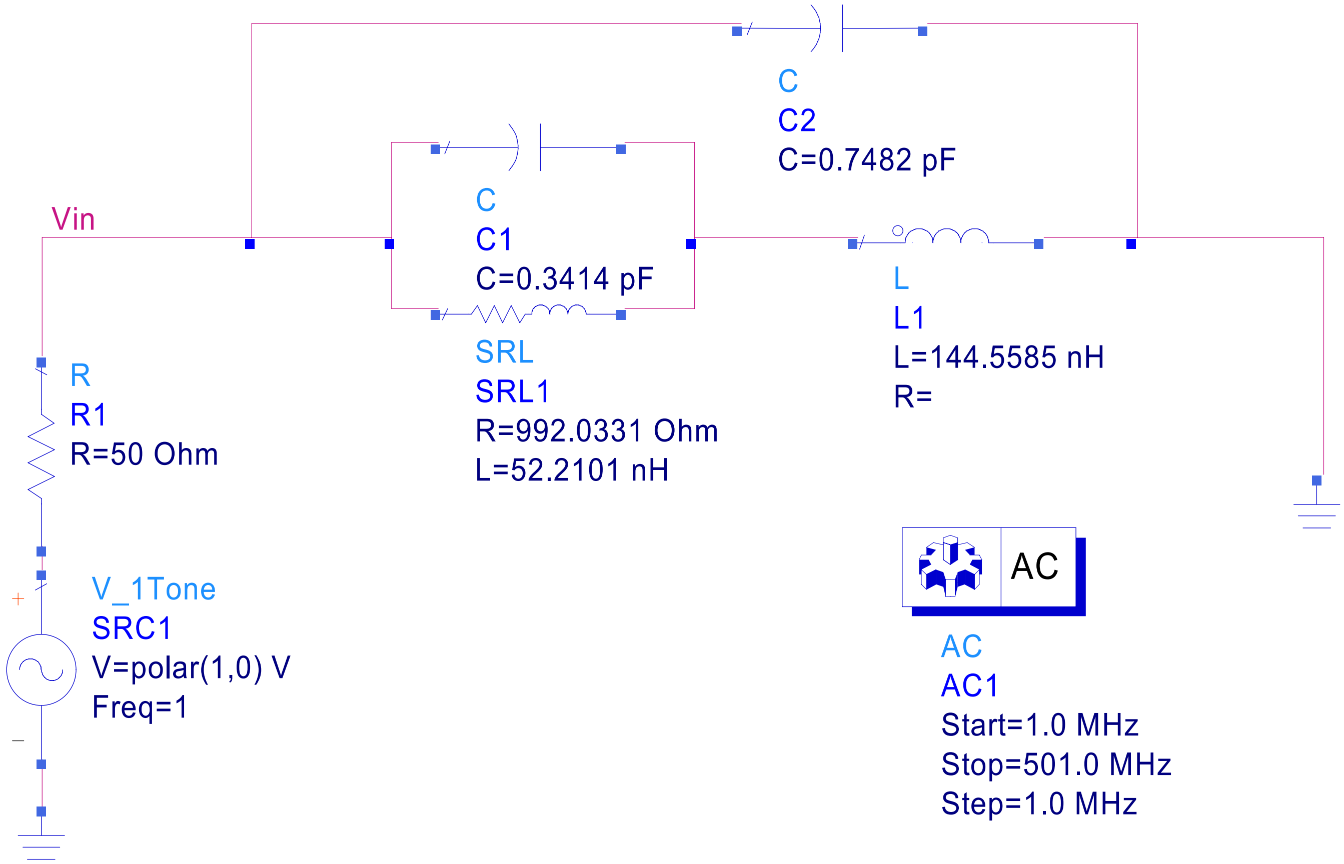
1.6.13 1kΩ $0.50W$ Carbon Composition Leaded Resistor

The following are the pictures of an original and after treatment 1kΩ $0.50W$ Carbon Composition Leaded Resistor.

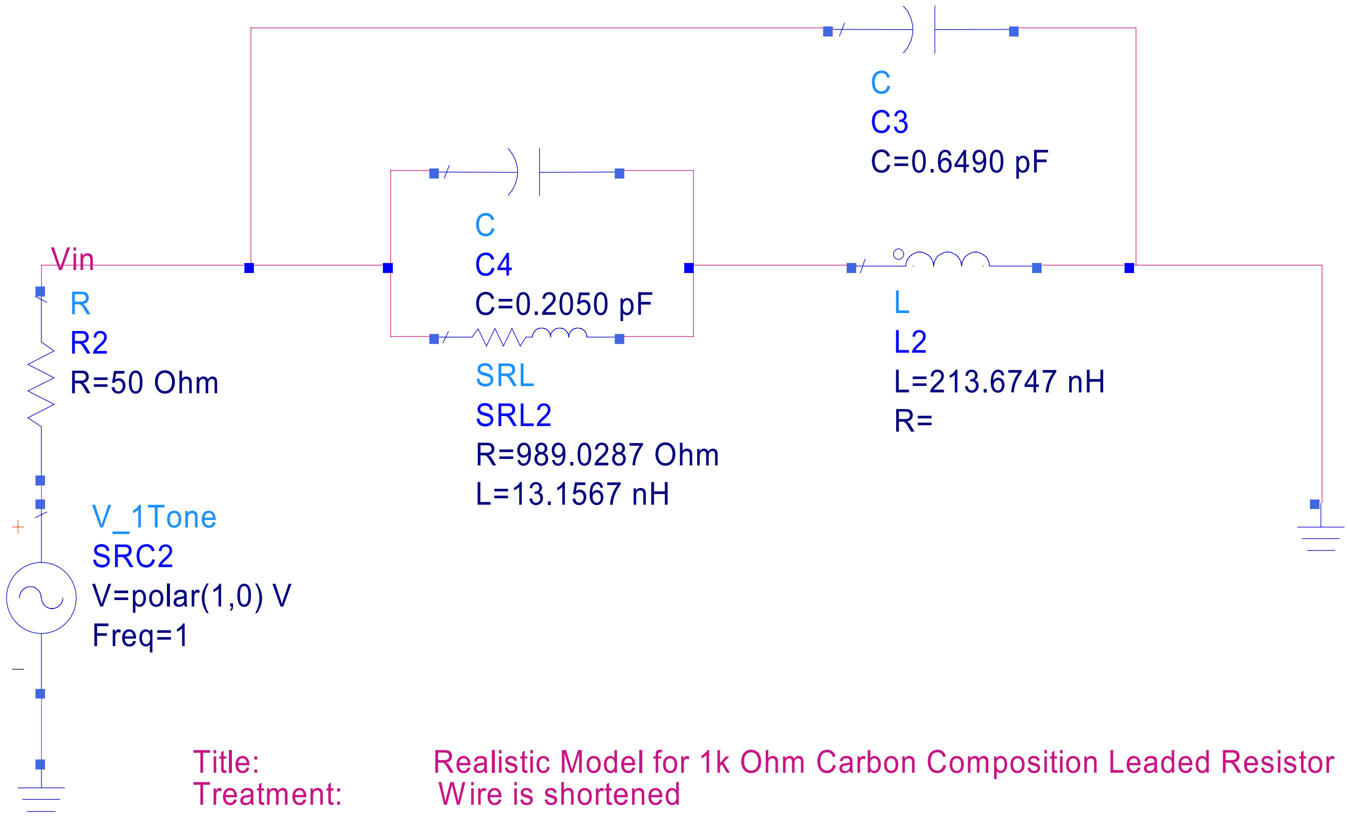
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

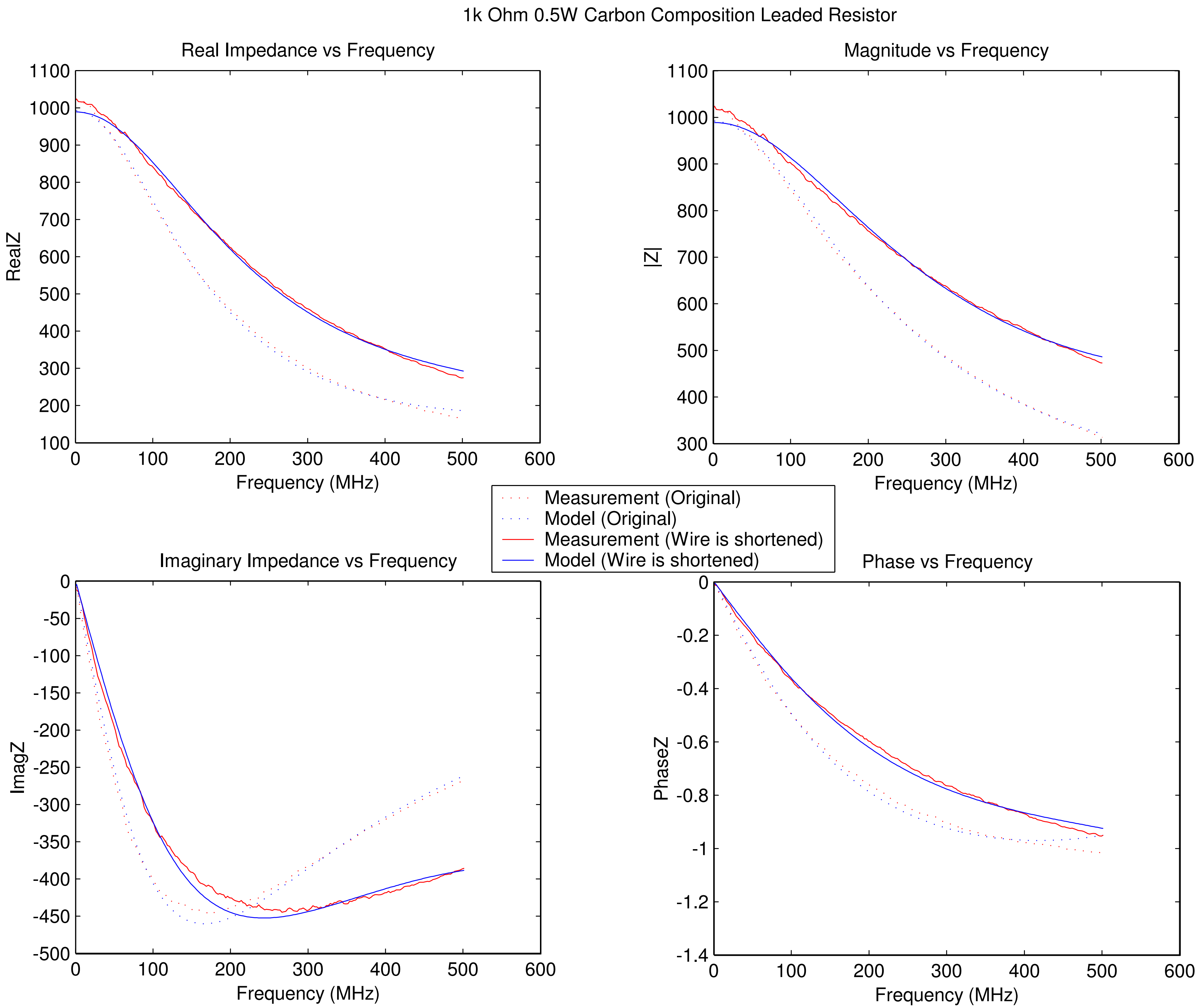
	Original	Wire is shortened
Measured Resistance (Ω)	1021.00	1020.80
Internal Resistance of Model (Ω)	992.0331	989.0287
Internal Inductance of Model (nH)	52.2101	13.1568
Internal Capacitance of Model (pF)	0.3415	0.2050
External Inductance from estimation (nH)	51.1756	0.0000
External Inductance of Model (nH)	144.5586	213.6748
External Capacitance from estimation (pF)	0.3092	0.0000
External Capacitance of Model (pF)	0.7483	0.6490
Legnth of Leaded Wire (mm)	37.74	0.00
Distance between two wires (mm)	12.68	13.21
Diameter of wire (mm)	0.80	0.80
R-Square Value of Real Impedance	0.9985	0.9981
R-Square Value of Imaginary Impedance	0.9967	0.9940
R-Square Value of Magnitude	0.9987	0.9966
R-Square Value of Phase	0.9929	0.9963



Title: Realistic Model for 1k Ohm Carbon Composition Leaded Resistor
Treatment: None



Title: Realistic Model for 1k Ohm Carbon Composition Leaded Resistor
Treatment: Wire is shortened



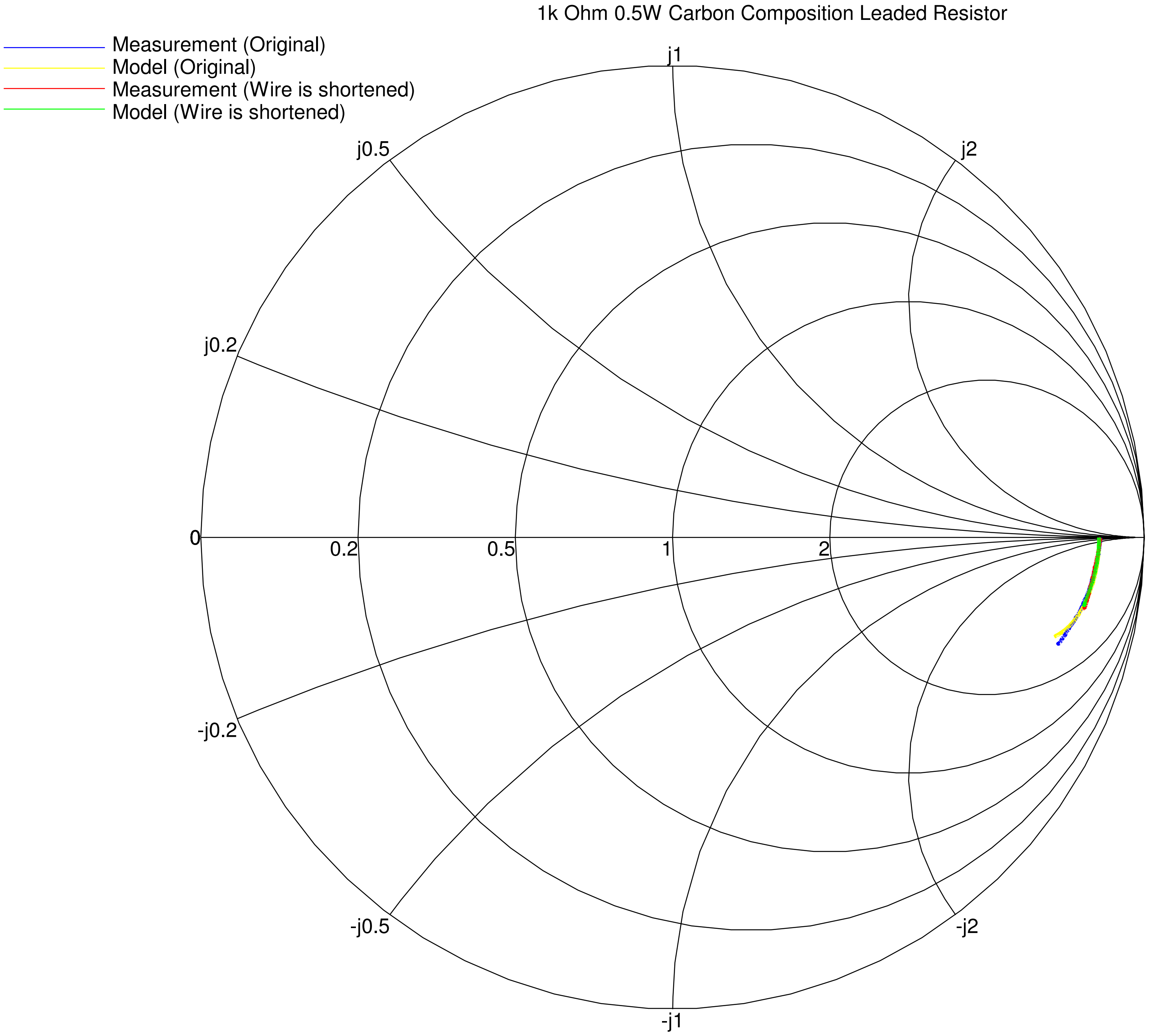
1k Ohm 0.5W Carbon Composition Leaded Resistor

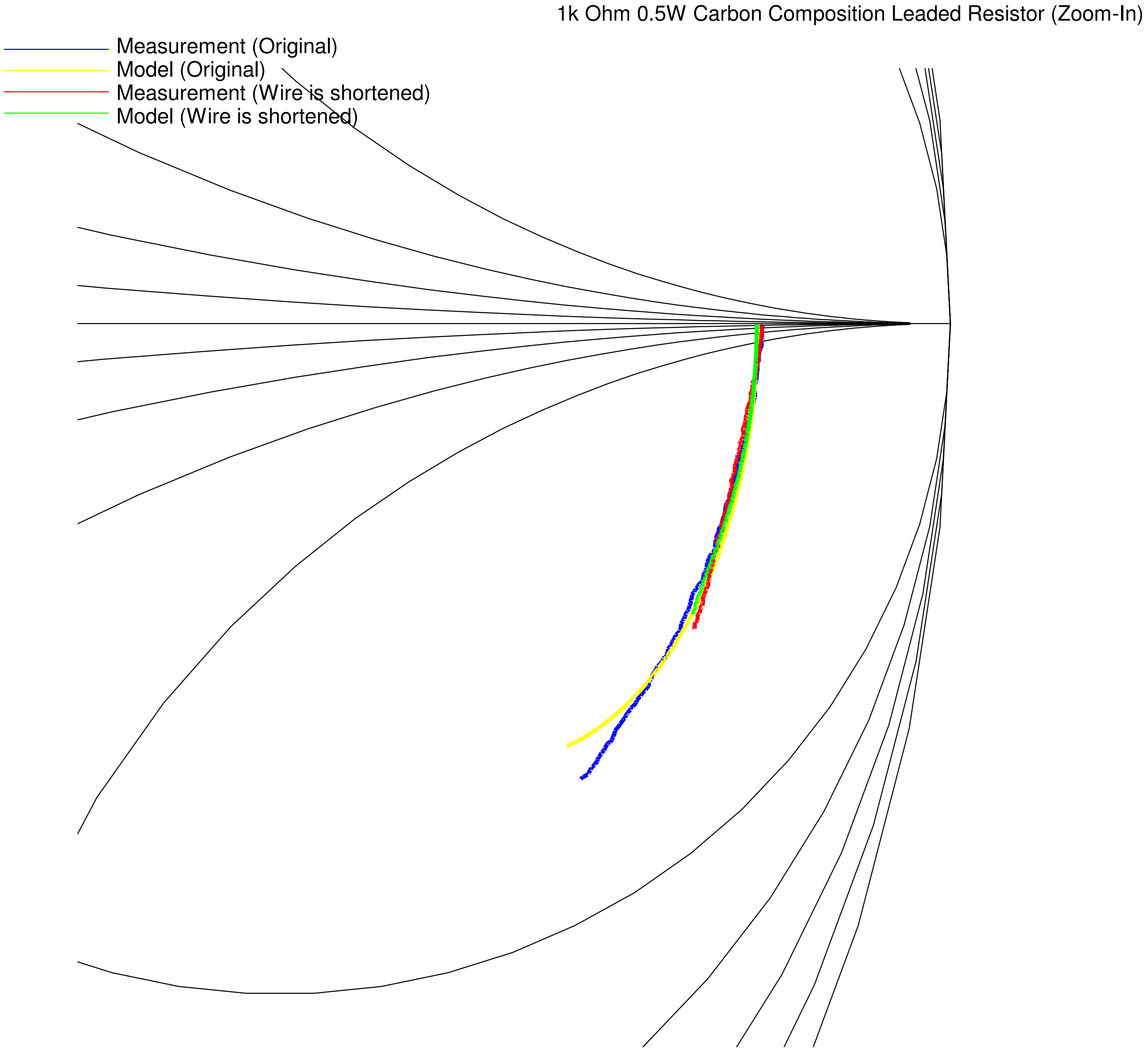
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


1k Ohm 0.5W Carbon Composition Leaded Resistor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


1k Ohm 0.5W Carbon Composition Leaded Resistor (Zoom-In)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)

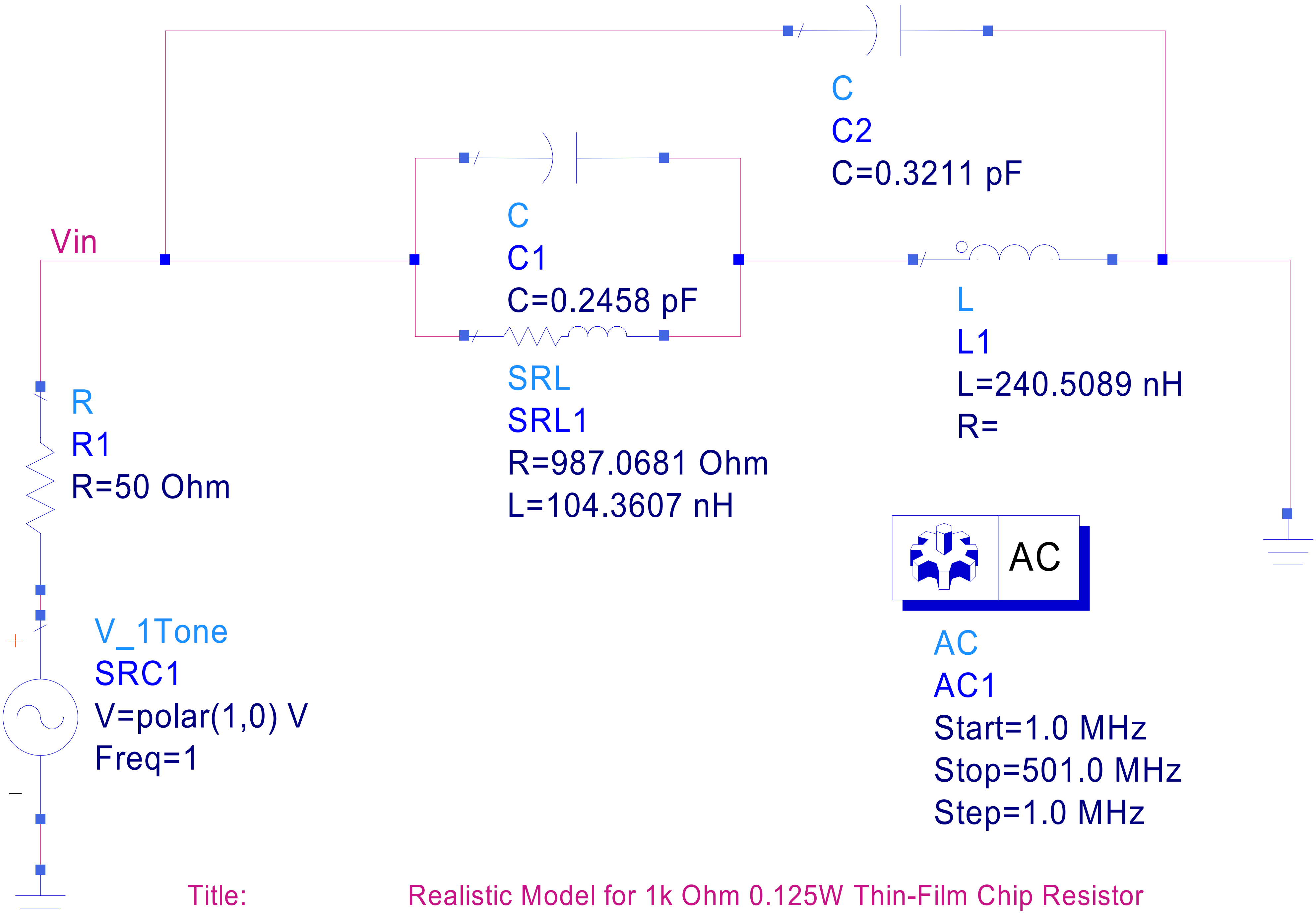
1.6.14 1kΩ $0.125W$ Thin-Film Chip Resistor

The following is the picture of a 1kΩ $0.125W$ Thin-Film Chip Resistor.

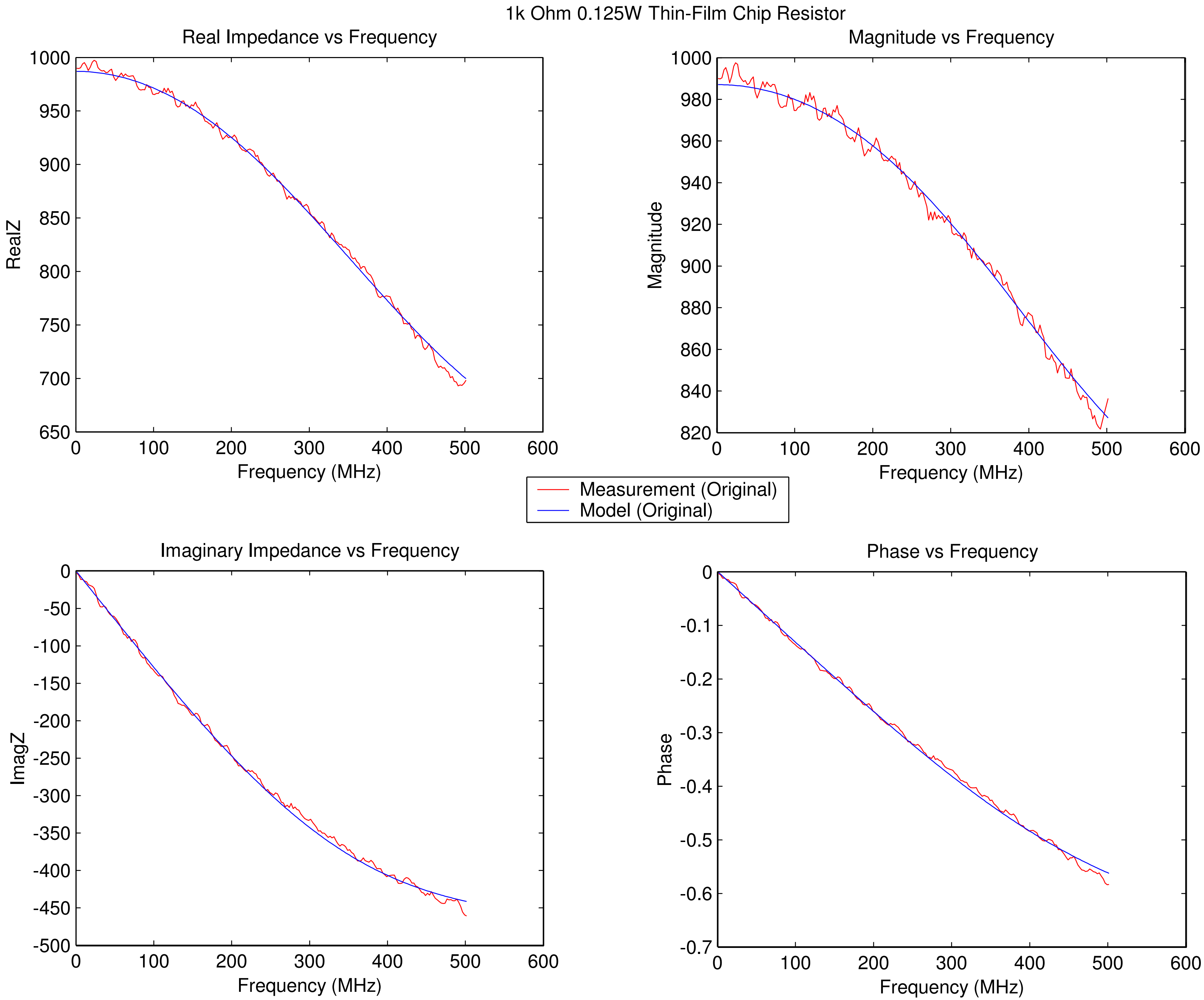
Word marked on the chip: `102`

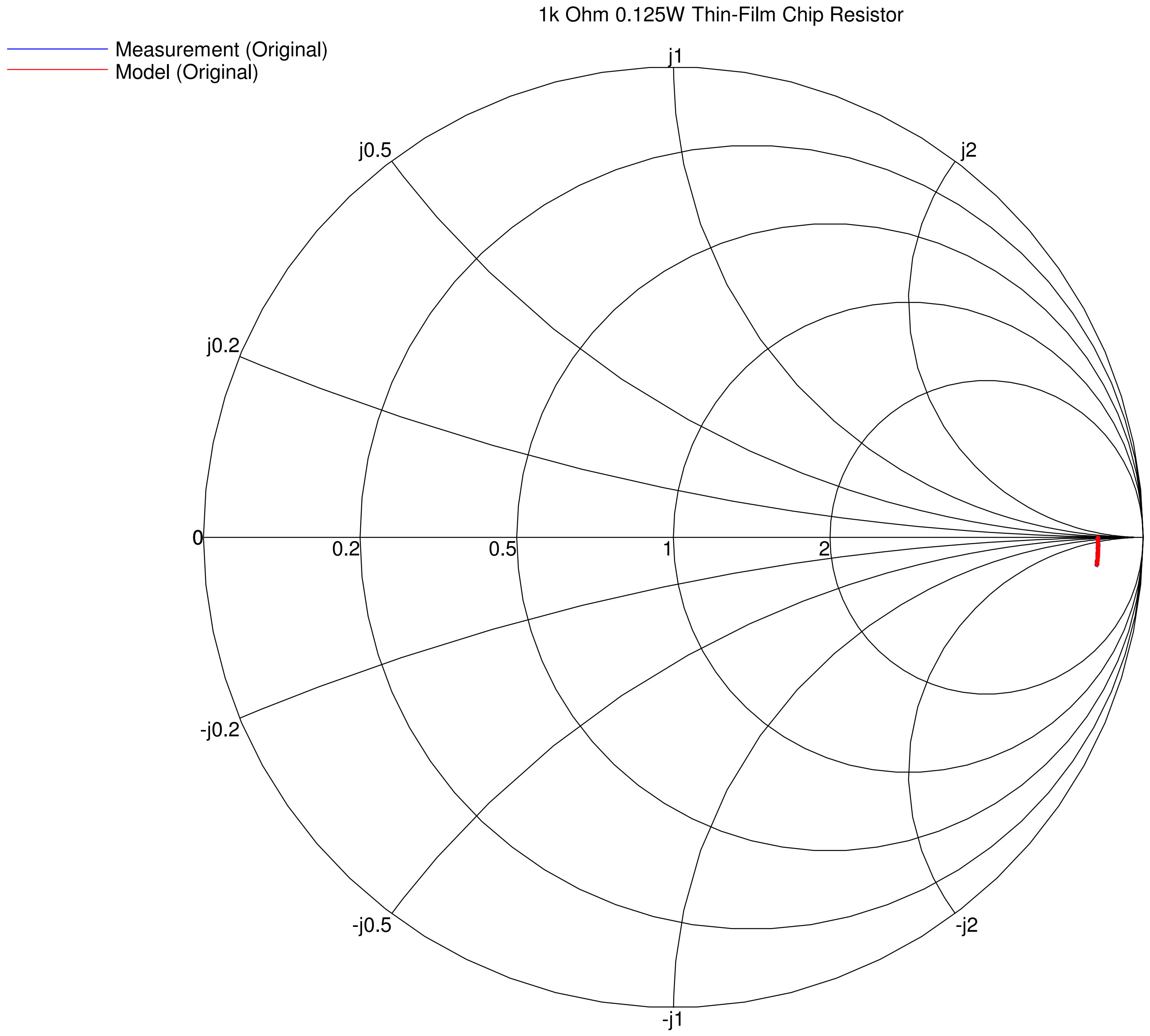
This table summarizes measured data and simulation result:

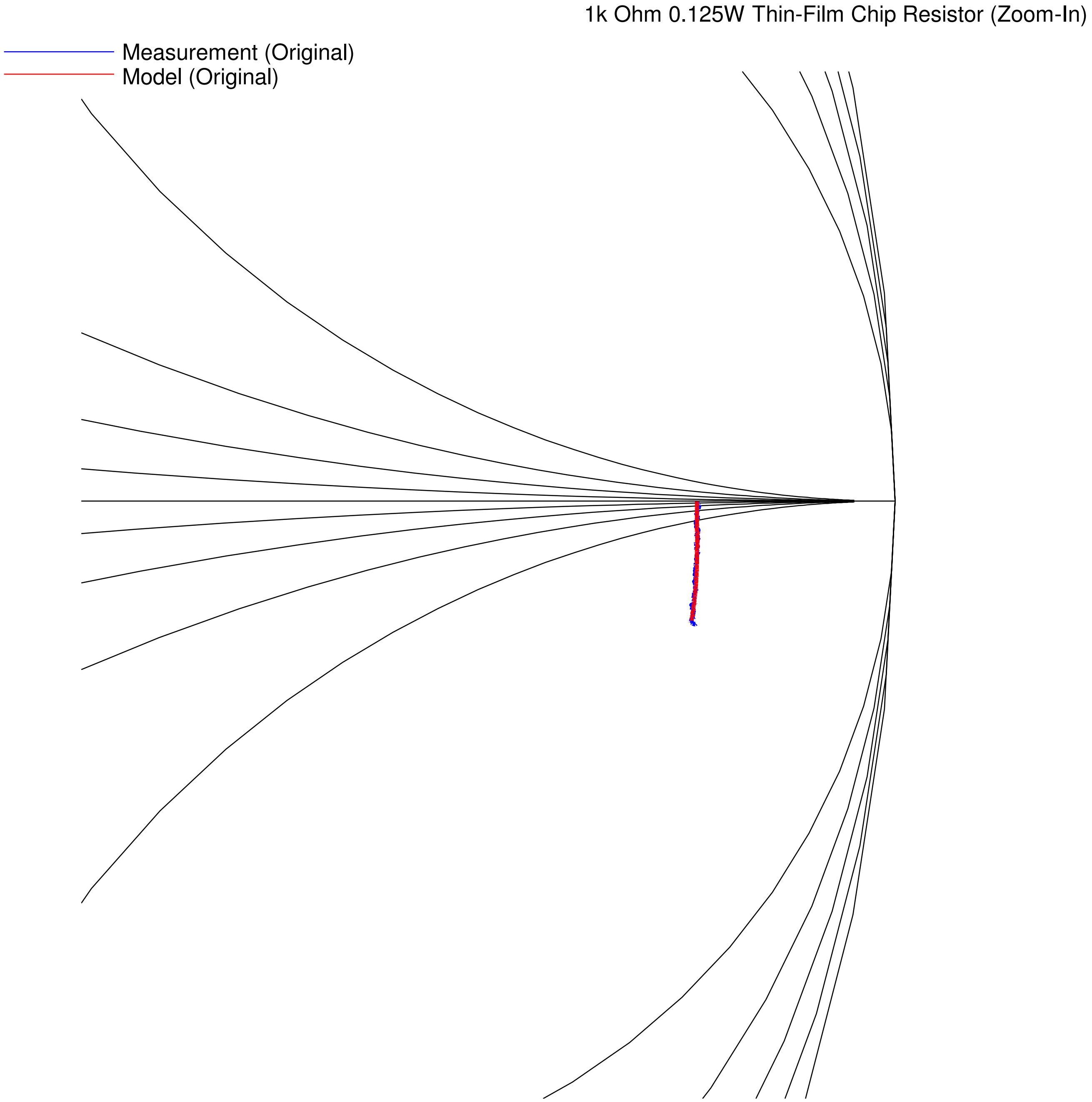
	Original
Internal Resistance of Model (Ω)	987.0682
Internal Inductance of Model (nH)	104.3608
Internal Capacitance of Model (pF)	0.2458
External Inductance of Model (nH)	240.5089
External Capacitance of Model (pF)	0.3212
R-Square Value of Real Impedance	0.9977
R-Square Value of Imaginary Impedance	0.9983
R-Square Value of Magnitude	0.9945
R-Square Value of Phase	0.9983



Title:	Realistic Model for 1k Ohm 0.125W Thin-Film Chip Resistor
Treatment:	None

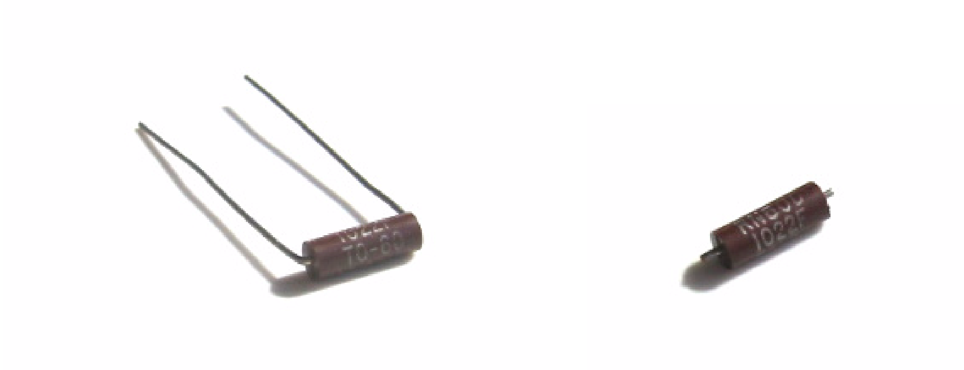

1k Ohm 0.125W Thin-Film Chip Resistor
Real Impedance vs Frequency
RealZ
1000
950
900
850
800
750
700
650
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
1000
980
960
940
920
900
880
860
840
820
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Imaginary Impedance vs Frequency
ImagZ
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
100
200
300
400
500
600
Frequency (MHz)


1k Ohm 0.125W Thin-Film Chip Resistor
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


1k Ohm 0.125W Thin-Film Chip Resistor (Zoom-In)
Measurement (Original)
Model (Original)

1.6.15 10kΩ $0.5W$ Film Leaded Resistor

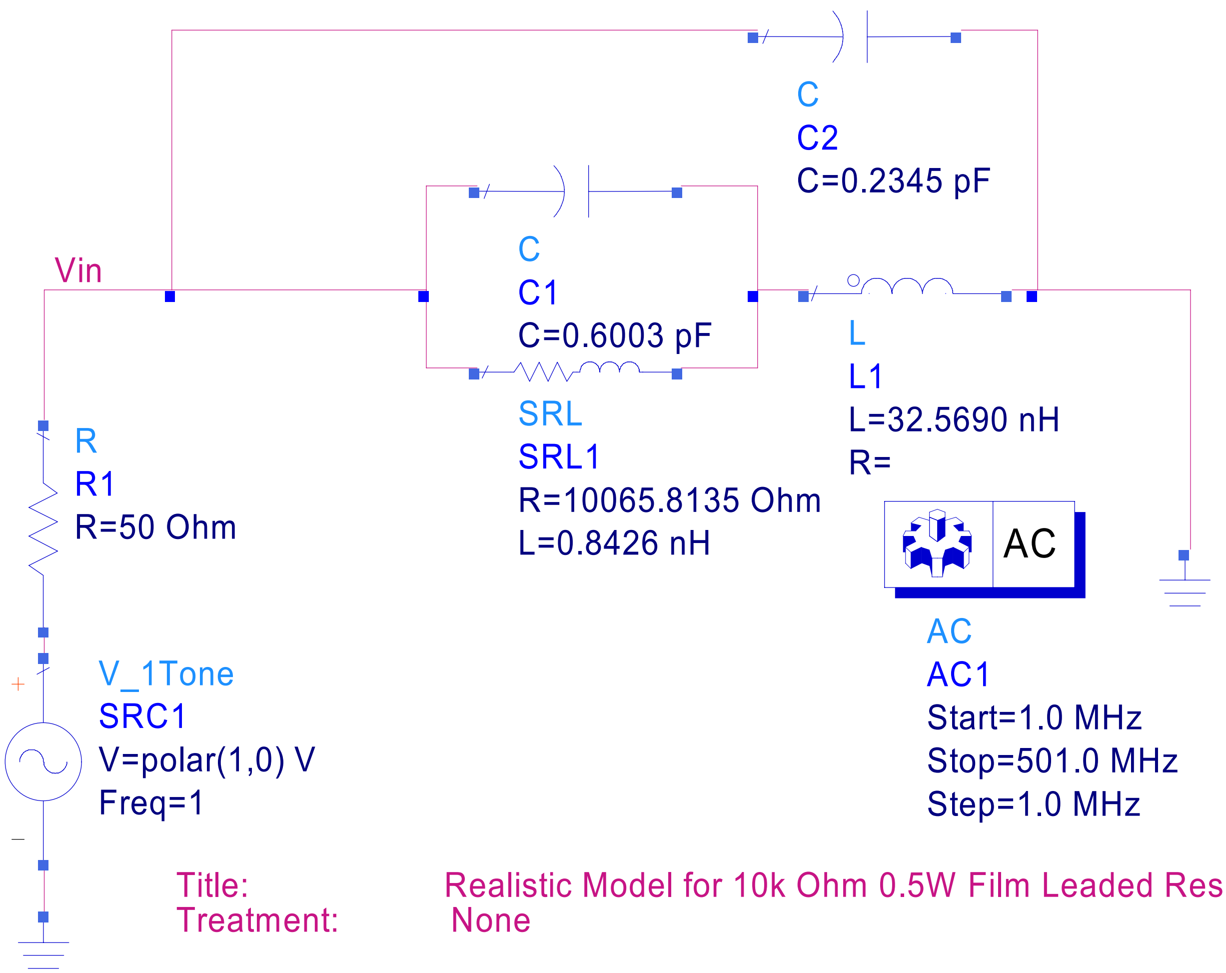
The following are the pictures of an original and after treatment 10kΩ $0.5W$ Film Leaded Resistor.



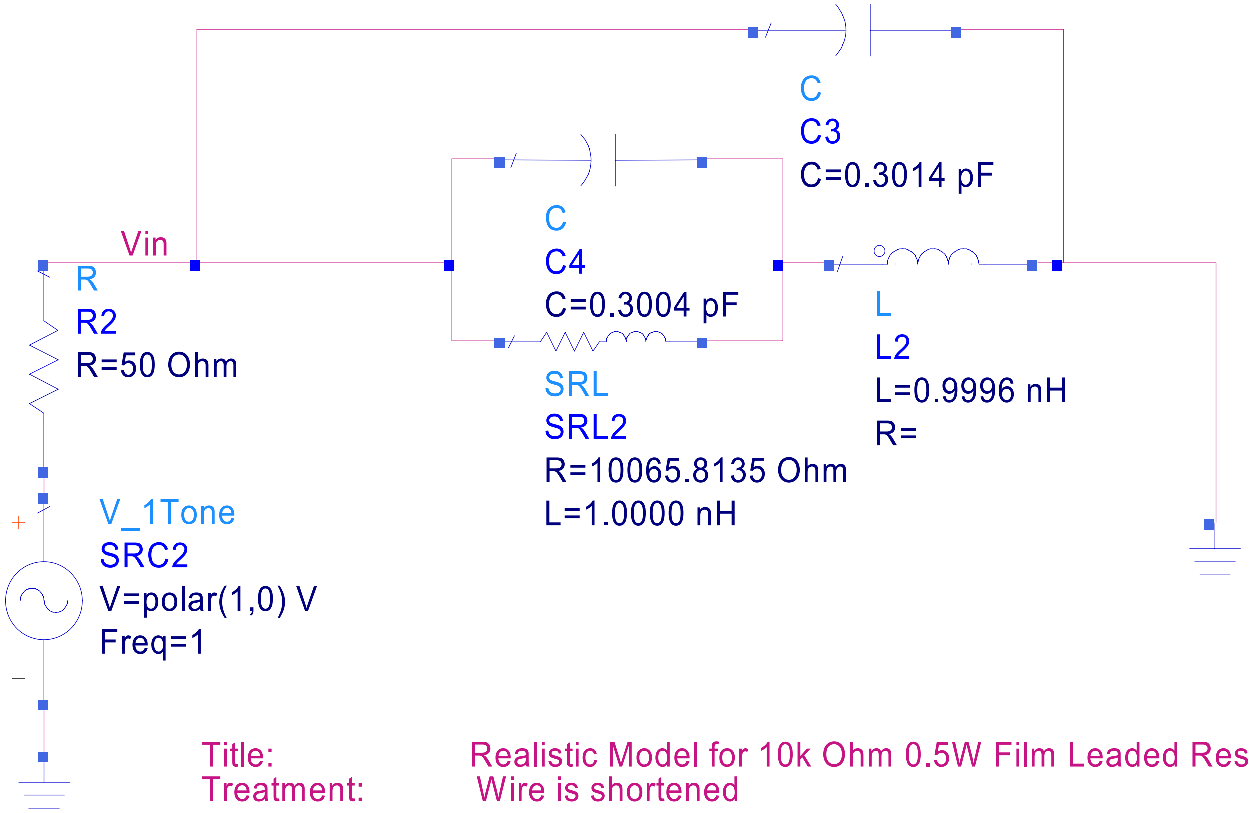
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

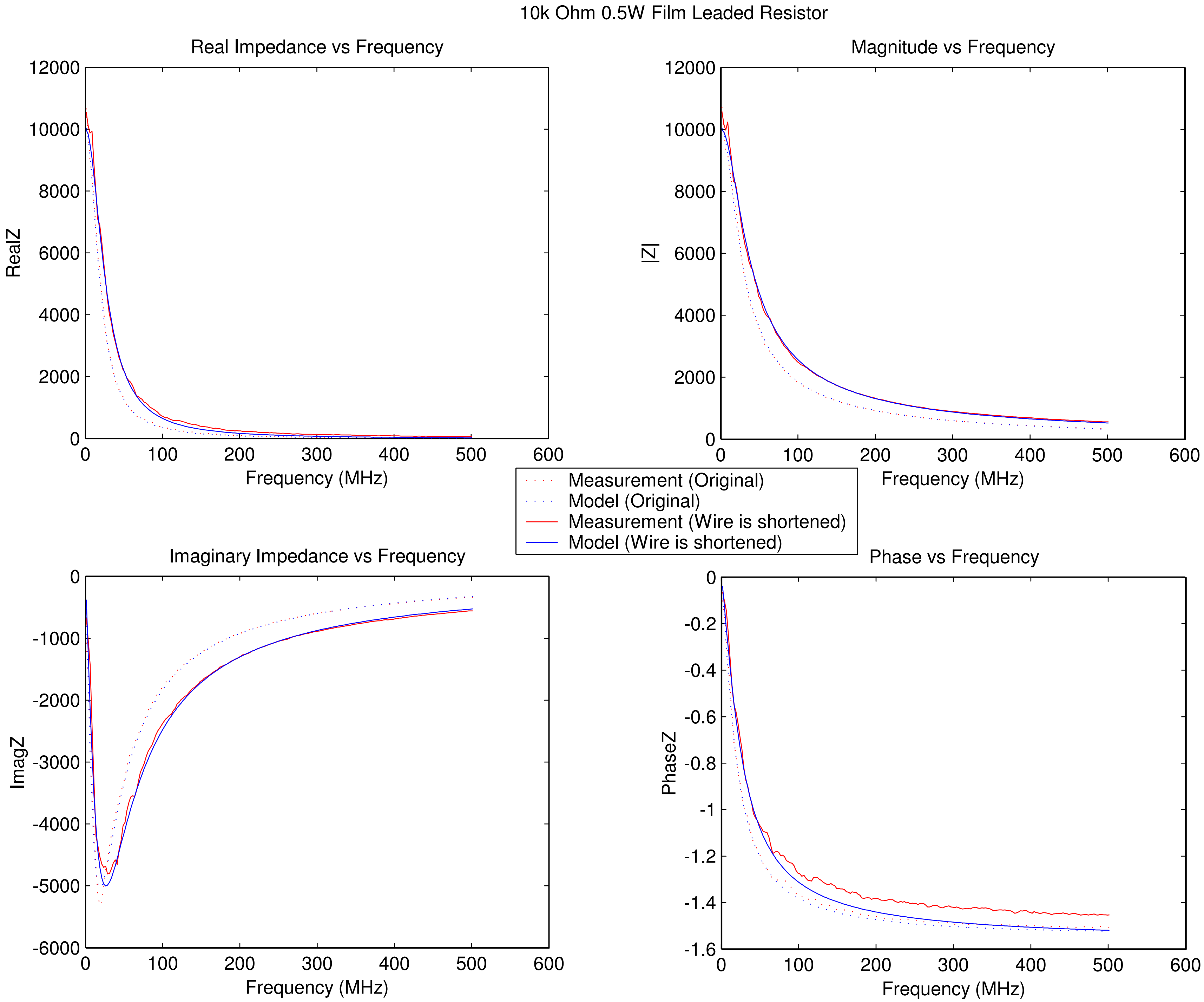
	Original	Wire is shortened
Measured Resistance (Ω)	10166.00	10166.00
Internal Resistance of Model (Ω)	10065.8135	10000.0000
Internal Inductance of Model (nH)	0.8427	1.0000
Internal Capacitance of Model (pF)	0.6004	0.3005
External Inductance from estimation (nH)	55.9076	0.0000
External Inductance of Model (nH)	32.5690	0.9996
External Capacitance from estimation (pF)	0.2936	0.0000
External Capacitance of Model (pF)	0.2346	0.3015
Legnth of Leaded Wire (mm)	38.44	0.00
Distance between two wires (mm)	12.19	13.35
Diameter of wire (mm)	0.61	0.61
R-Square Value of Real Impedance	0.9991	0.9983
R-Square Value of Imaginary Impedance	0.9957	0.9963
R-Square Value of Magnitude	0.9986	0.9982
R-Square Value of Phase	0.9986	0.9970

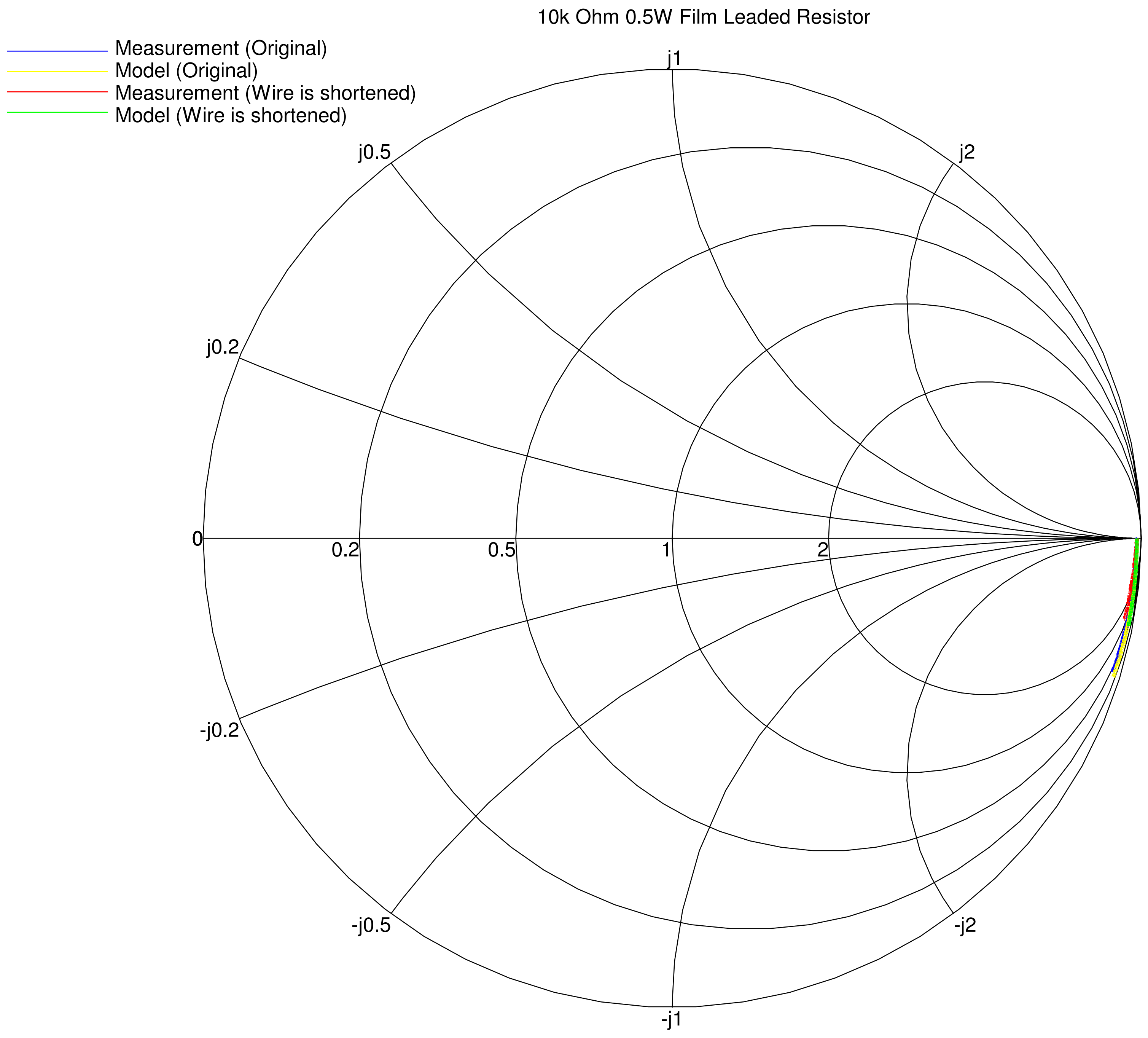


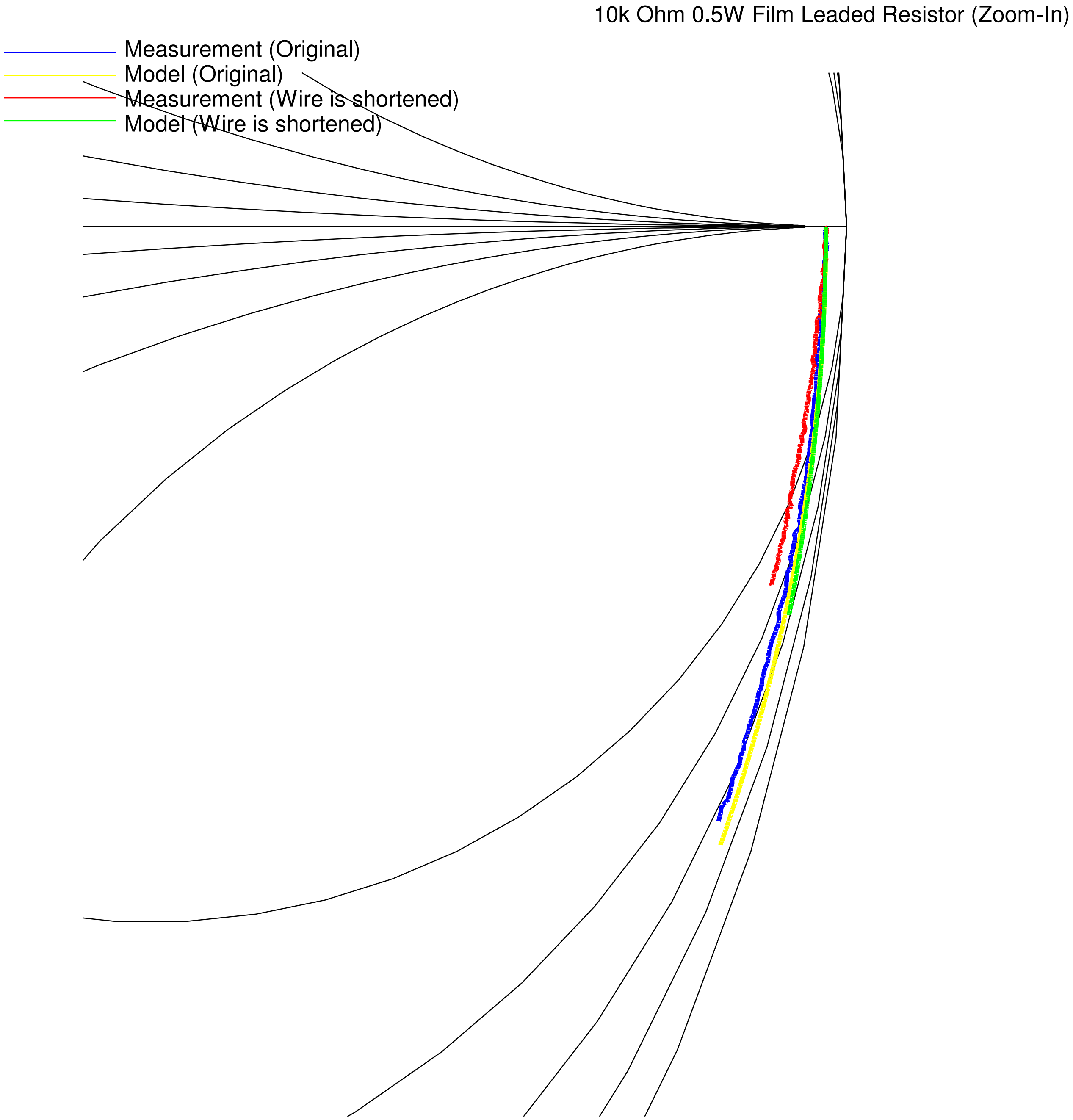
Title: Realistic Model for 10k Ohm 0.5W Film Leaded Resistor
Treatment: None



Title: Realistic Model for 10k Ohm 0.5W Film Leaded Resistor
Treatment: Wire is shortened


10k Ohm 0.5W Film Leaded Resistor
Real Impedance vs Frequency
RealZ
0
2000
4000
6000
8000
10000
12000
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
0
2000
4000
6000
8000
10000
12000
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
0
-1000
-2000
-3000
-4000
-5000
-6000
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
0
100
200
300
400
500
600
Frequency (MHz)


10k Ohm 0.5W Film Leaded Resistor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


10k Ohm 0.5W Film Leaded Resistor (Zoom-In)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)

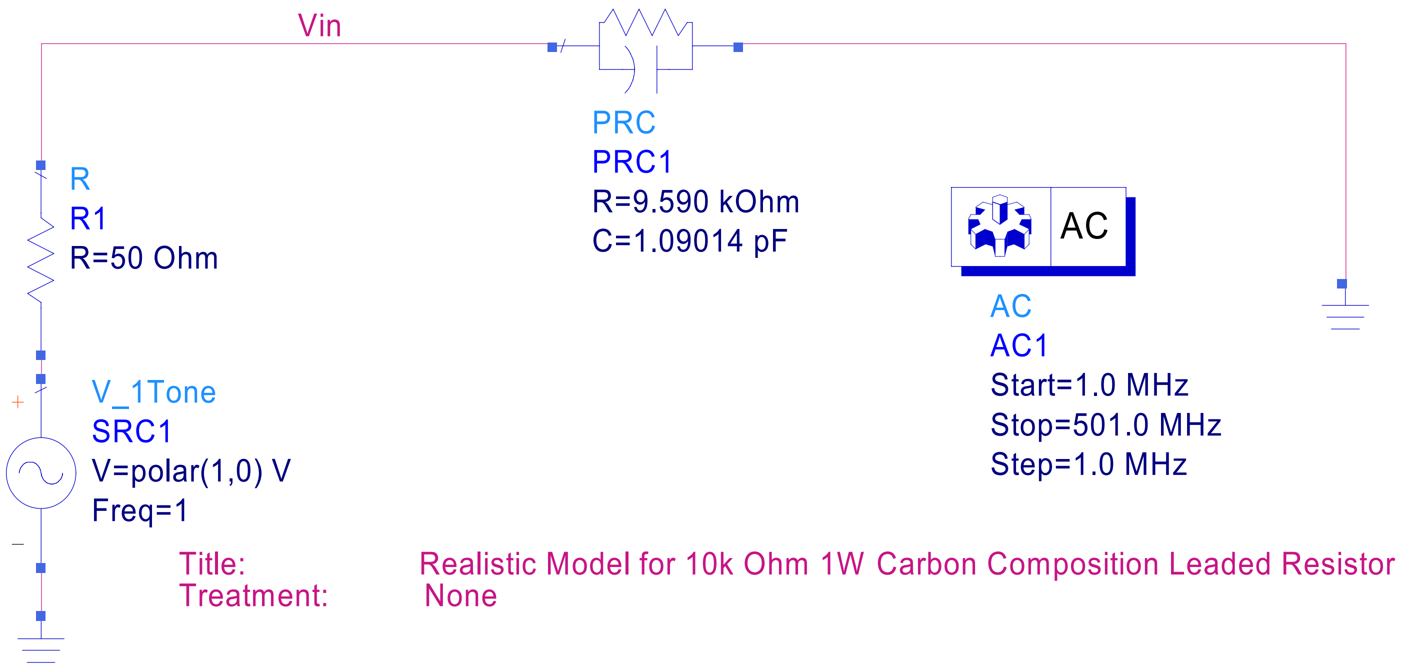
1.6.16 10kΩ 1.0W Carbon Composition Leaded Resistor

The following are the pictures of an original and after treatment 10kΩ 1.0W Carbon Composition Leaded Resistor.

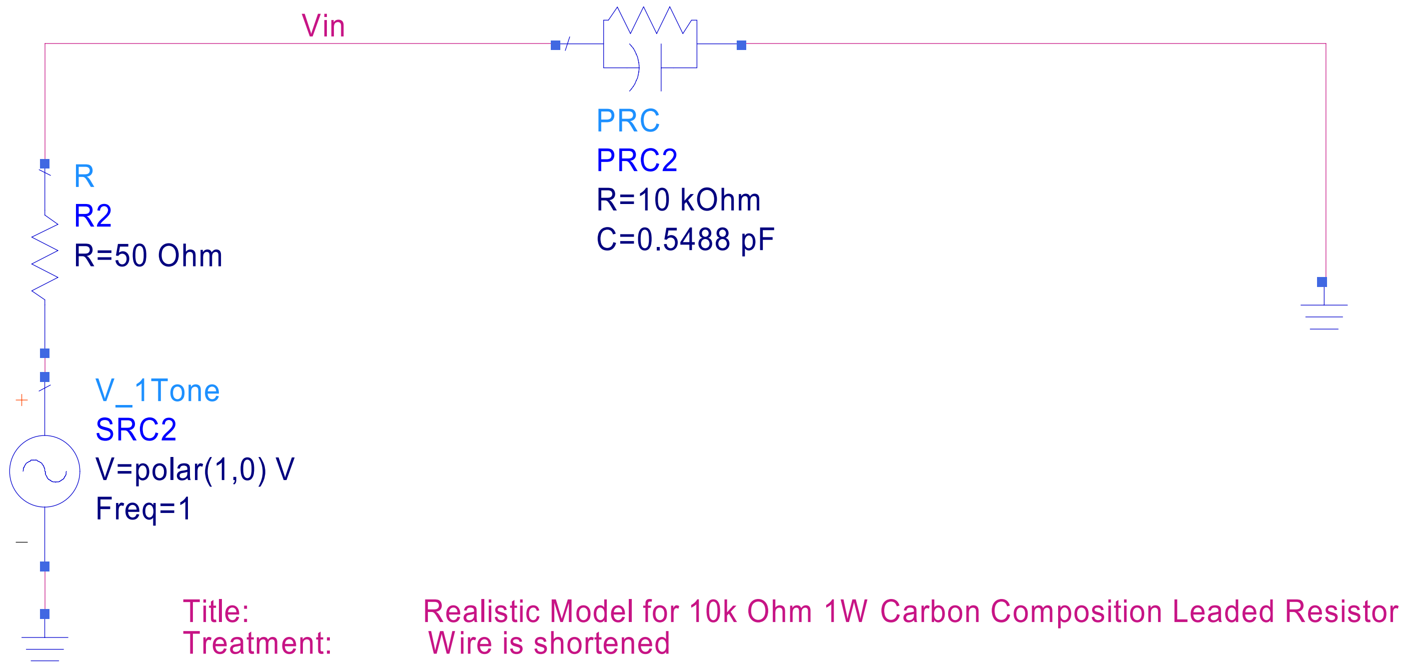
Picture of an original resistor and a shortened wire resistor

This table summarizes measured data and simulation result:

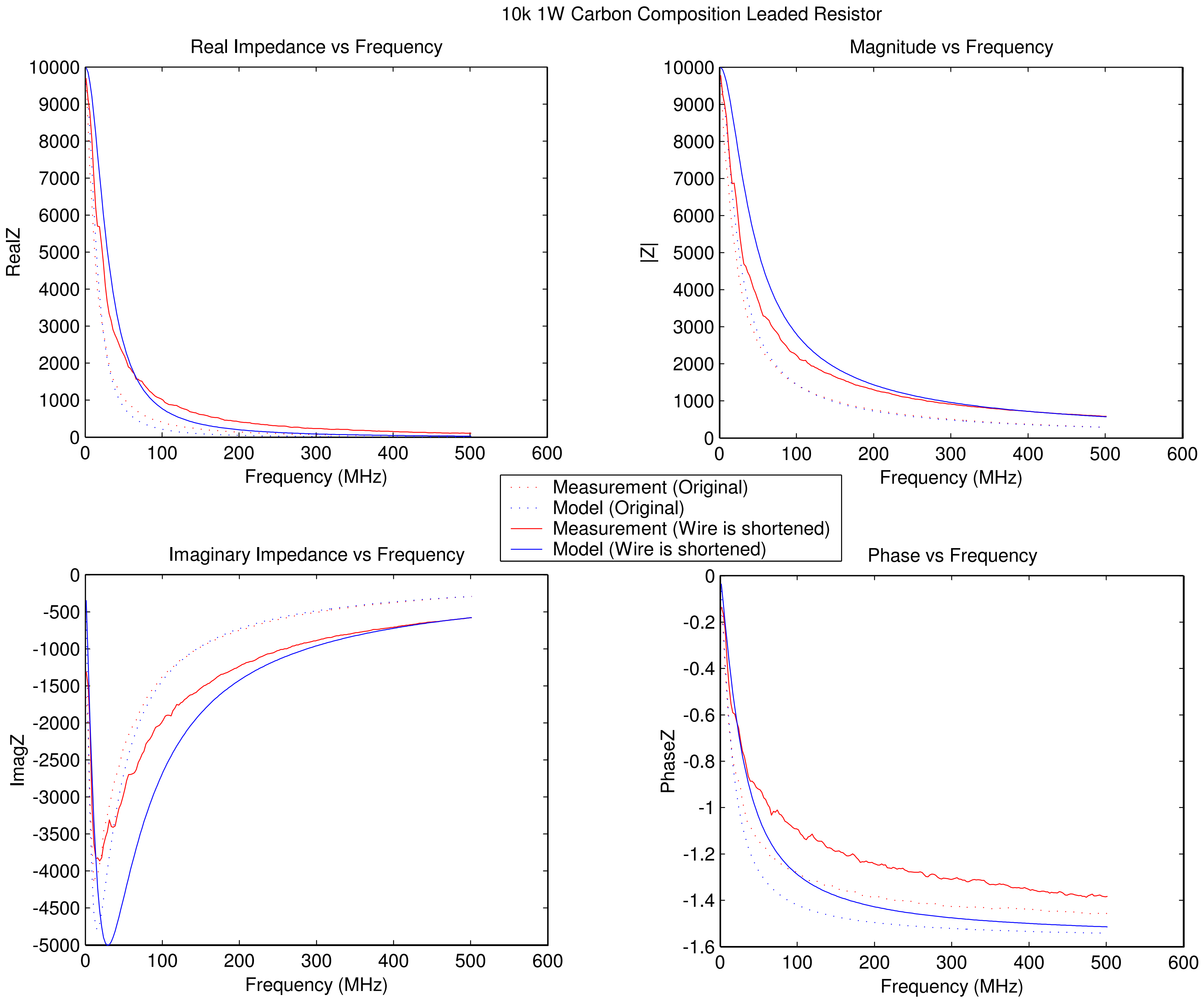
	Original	Wire is shortened
Measured Resistance (Ω)	10152.00	10414.00
Internal Resistance of Model (Ω)	9590.0000	9999.9999
Internal Inductance of Model (nH)	0.0000	0.0000
Internal Capacitance of Model (pF)	0.0000	0.0000
External Inductance from estimation (nH)	53.6965	0.0000
External Inductance of Model (nH)	0.0000	0.0000
External Capacitance from estimation (pF)	0.2975	0.0000
External Capacitance of Model (pF)	1.0901	0.5488
Legngth of Leaded Wire (mm)	37.92	0.00
Distance between two wires (mm)	18.25	19.99
Diameter of wire (mm)	1.00	1.00
R-Square Value of Real Impedance	0.9916	0.9828
R-Square Value of Imaginary Impedance	0.9872	0.9820
R-Square Value of Magnitude	0.9950	0.9946
R-Square Value of Phase	0.9860	0.9571



Title: Realistic Model for 10k Ohm 1W Carbon Composition Leaded Resistor
Treatment: None



Title: Realistic Model for 10k Ohm 1W Carbon Composition Leaded Resistor
Treatment: Wire is shortened



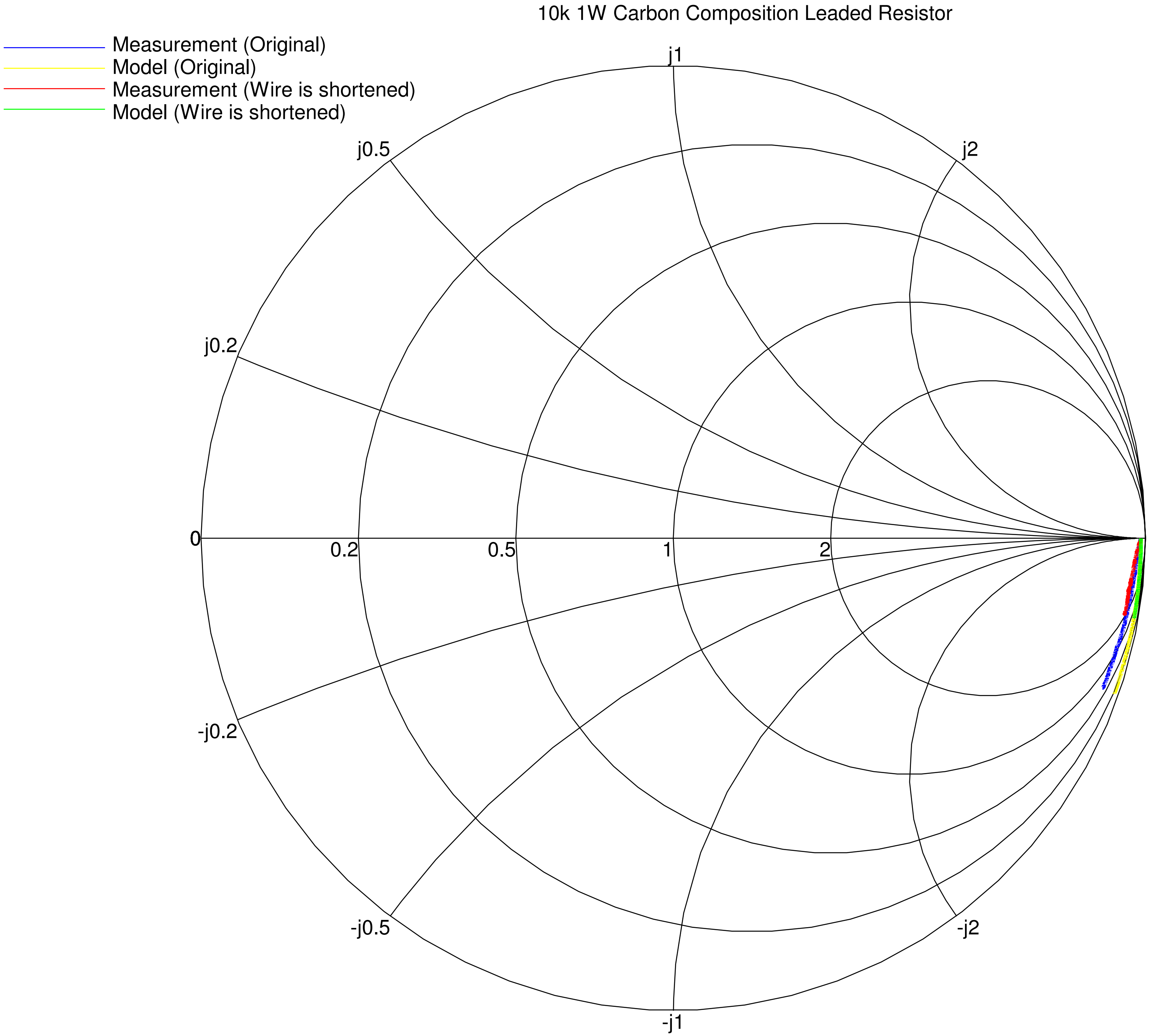
10k 1W Carbon Composition Leaded Resistor

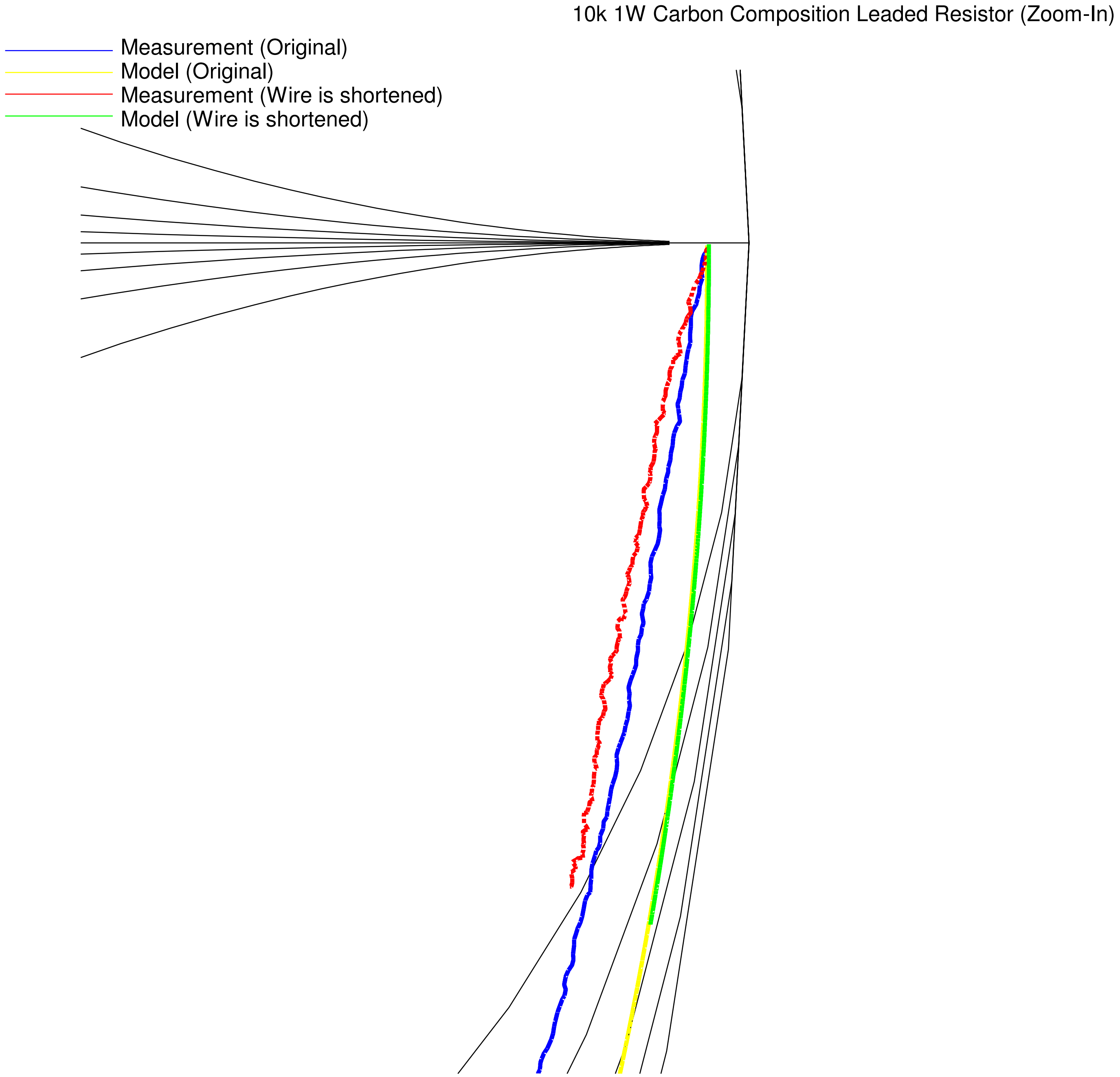
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


10k 1W Carbon Composition Leaded Resistor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


10k 1W Carbon Composition Leaded Resistor (Zoom-In)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)

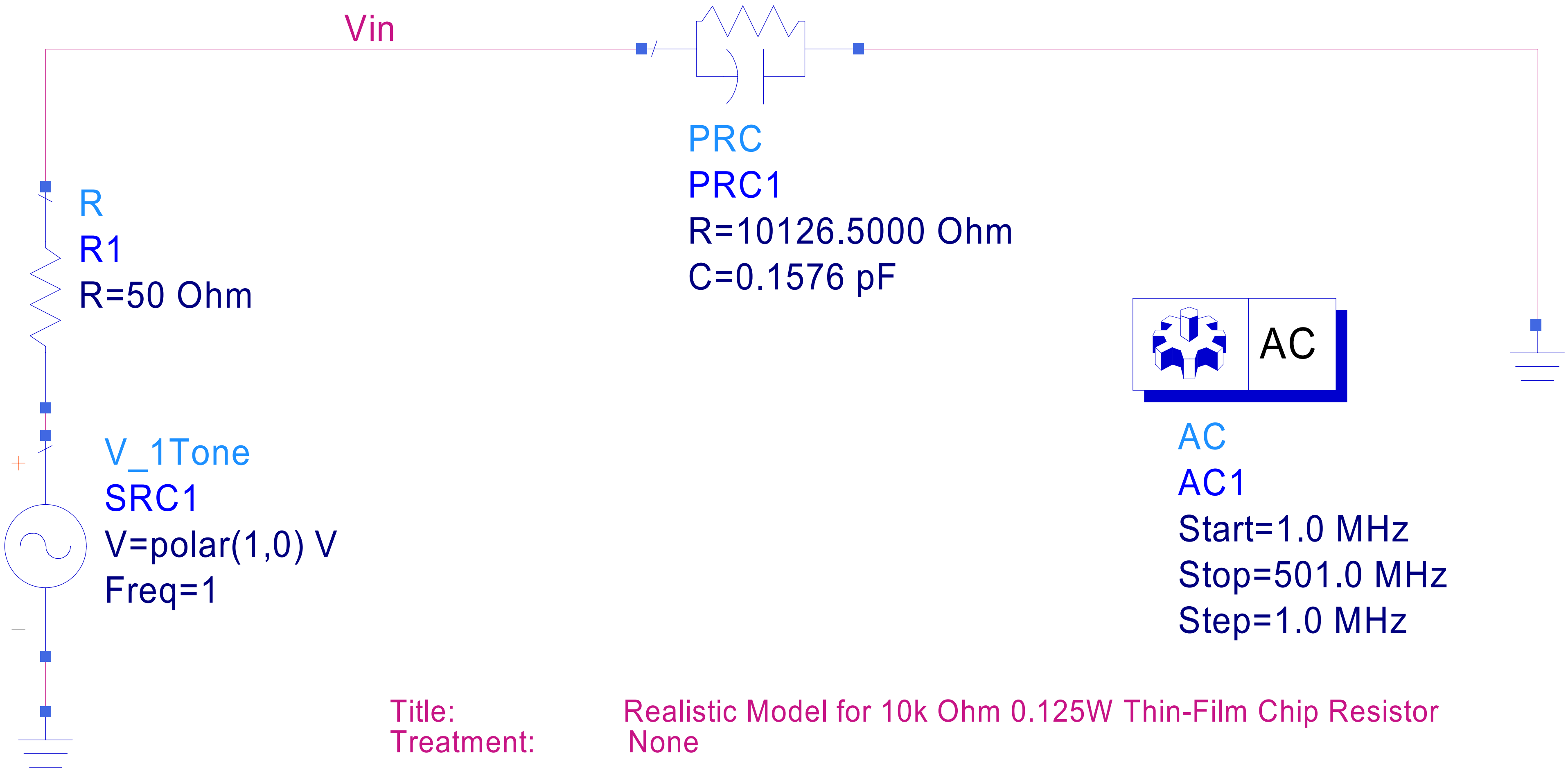
1.6.17 10kΩ 0.125W Thin-Film Chip Resistor

The following is the picture of a 10kΩ 0.125W Thin-Film Chip Resistor.

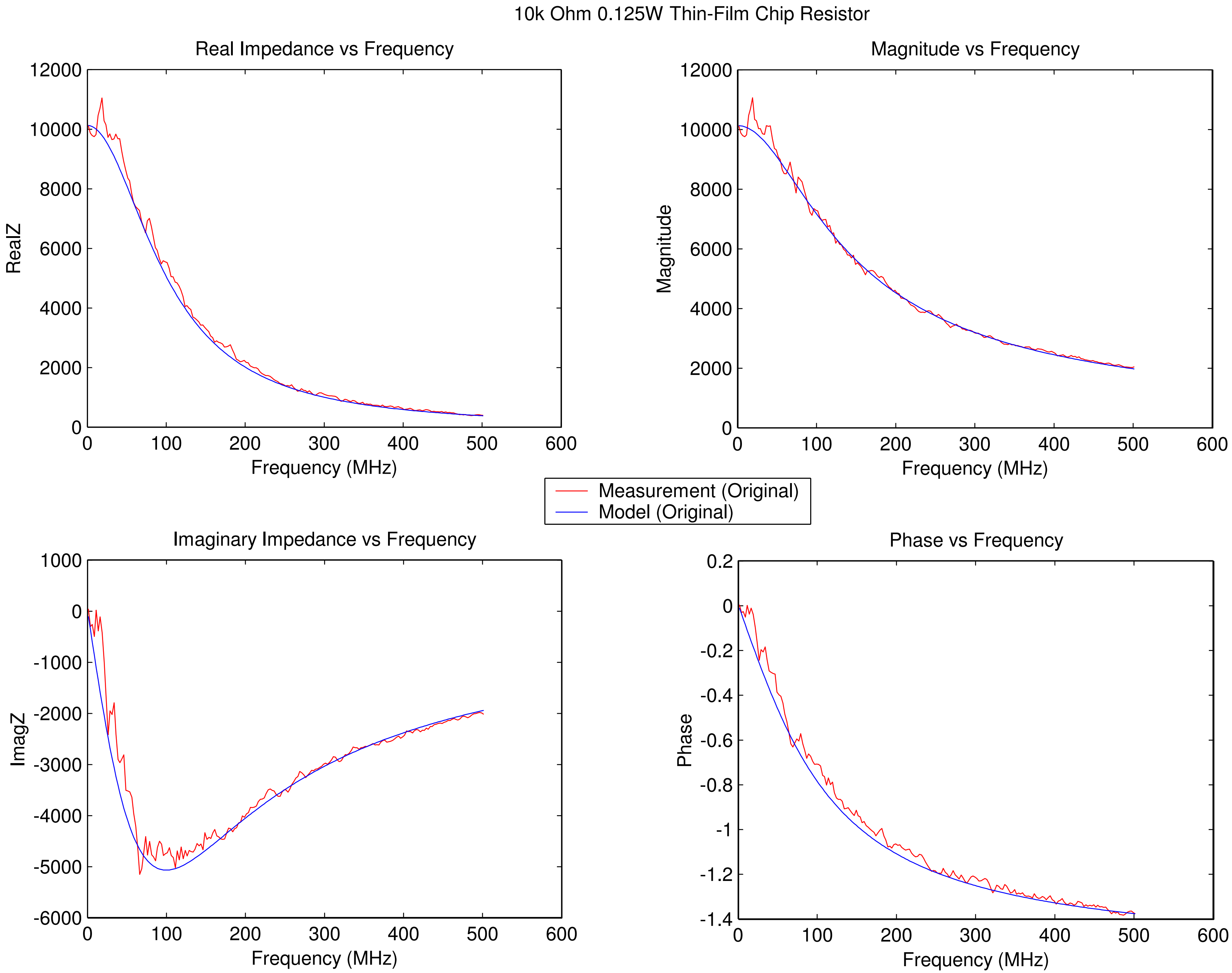
Word marked on the chip: `103`

This table summarizes measured data and simulation result:

	Original
Internal Resistance of Model (Ω)	10126.5000
Internal Inductance of Model (nH)	0.0000
Internal Capacitance of Model (pF)	0.0000
External Inductance of Model (nH)	0.0000
External Capacitance of Model (pF)	0.1577
R-Square Value of Real Impedance	0.9967
R-Square Value of Imaginary Impedance	0.9368
R-Square Value of Magnitude	0.9960
R-Square Value of Phase	0.9961



Title: Realistic Model for 10k Ohm 0.125W Thin-Film Chip Resistor
Treatment: None



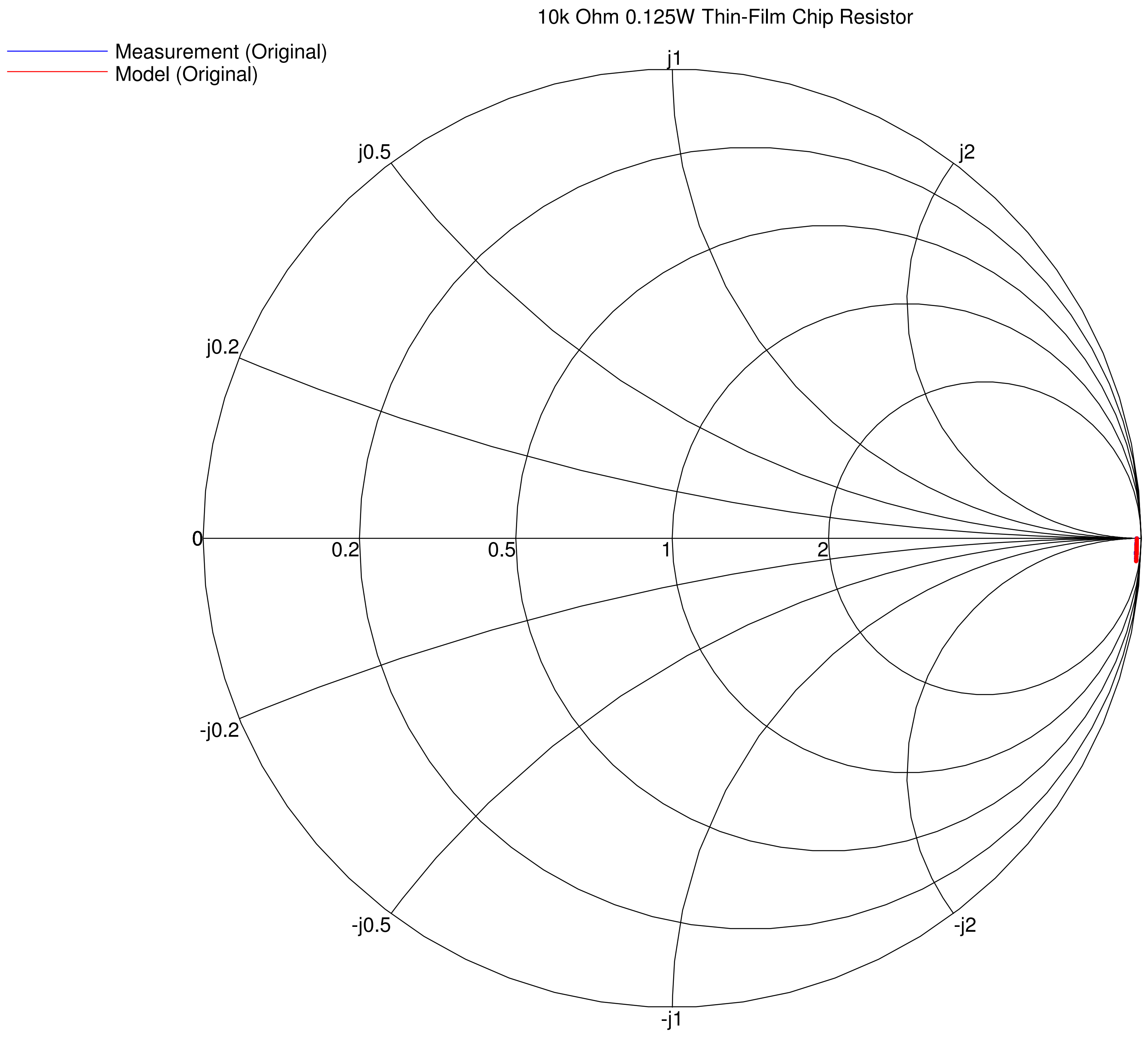
10k Ohm 0.125W Thin-Film Chip Resistor

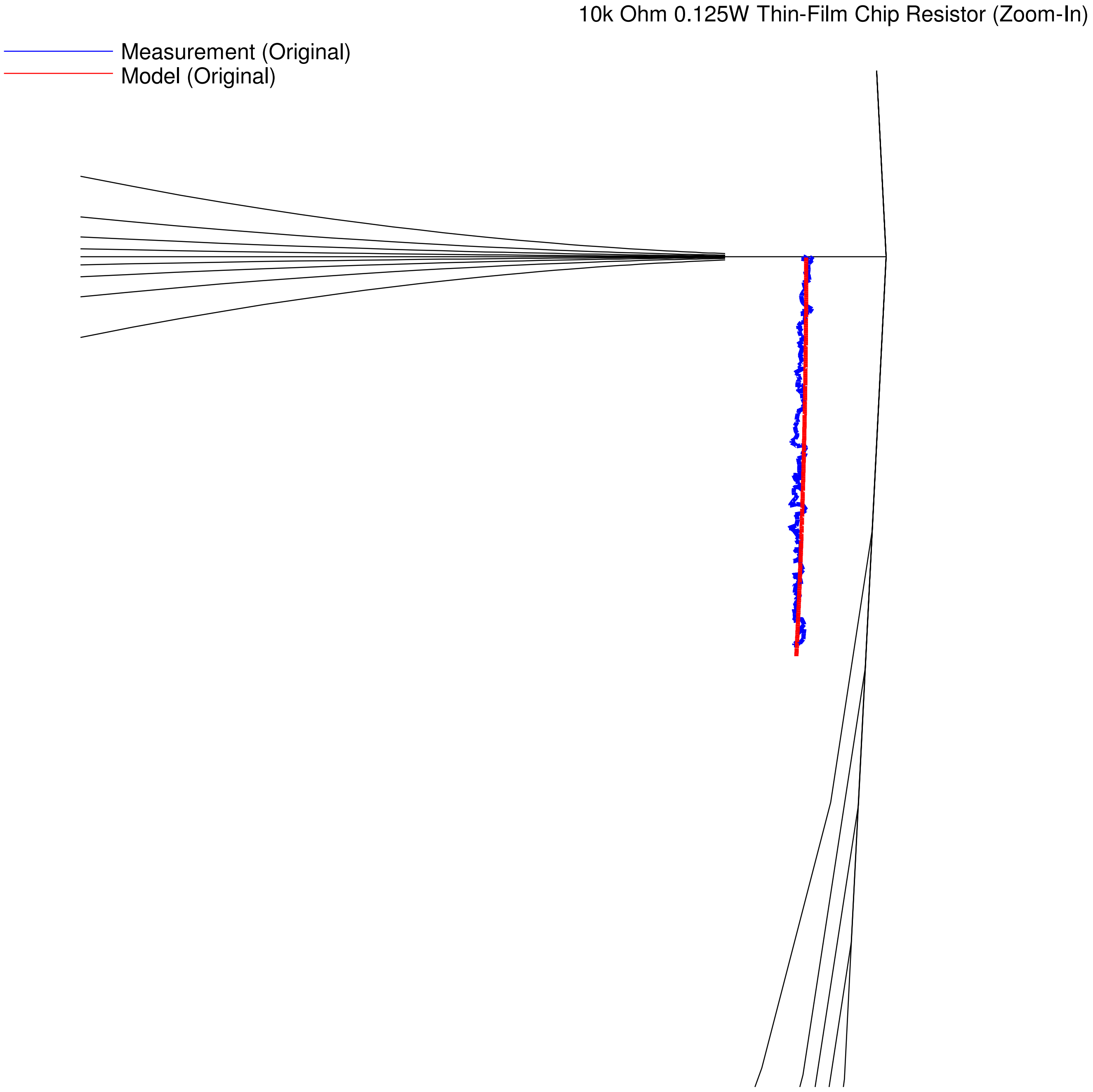
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


10k Ohm 0.125W Thin-Film Chip Resistor


10k Ohm 0.125W Thin-Film Chip Resistor (Zoom-In)
Measurement (Original)
Model (Original)

1.7 Analysis on Disagreement between the Model and Measurement

Most models agrees with their measurement data, and the mean of four R-Square values are above 0.95. The result is summarized below:

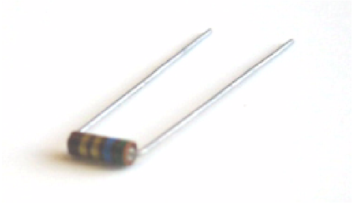
Resistance (Ω)	Material	Treatment	Mean of R^2
5.1	Film Leaded	None	0.9946
5.1	Film Leaded	Wire is shortened	0.9982
5.6	Carbon Composition Leaded	None	0.9786
5.6	Carbon Composition Leaded	Wire is shortened	0.9894
5.6	Thin-Film Chip	None	0.9863
10.0	Film Leaded	None	0.9919
10.0	Film Leaded	Wire is shortened	0.9993
10.0	Thin-Film Chip	None	0.9627
49.9	Thin-Film Chip	None	0.9380
51.1	Film Leaded	None	0.9999
51.1	Film Leaded	Wire is shortened	0.9989
100.0	Film Leaded	None	0.9999
100.0	Film Leaded	Wire is shortened	0.9979
100.0	Film Leaded	None	1.0000
100.0	Film Leaded	Wire is shortened	0.9648
100.0	Thin-Film Chip	None	0.9576
510.0	Film Leaded	None	0.9950
510.0	Film Leaded	Wire is shortened	0.9993
$1k$	Film Leaded	None	0.9990
$1k$	Film Leaded	Wire is shortened	0.9997
$1k$	Carbon Composition Leaded	None	0.9967
$1k$	Carbon Composition Leaded	Wire is shortened	0.9963
$1k$	Thin-Film Chip	None	0.9972
$10k$	Film Leaded	None	0.9980
$10k$	Film Leaded	Wire is shortened	0.9974
$10k$	Carbon Composition Leaded	None	0.9899
$10k$	Carbon Composition Leaded	Wire is shortened	0.9791
$10k$	Thin-Film Chip	None	0.9814

However, some models are failed to agree in some regions. The failure are discussed below:

1.7.1 Disagree in Real Impedance at High frequency

In this situation, the model disagrees with the measurement data in Real Impedance starting at High frequency (> 400 MHz). It happens in the small resistance leaded resistors:

1

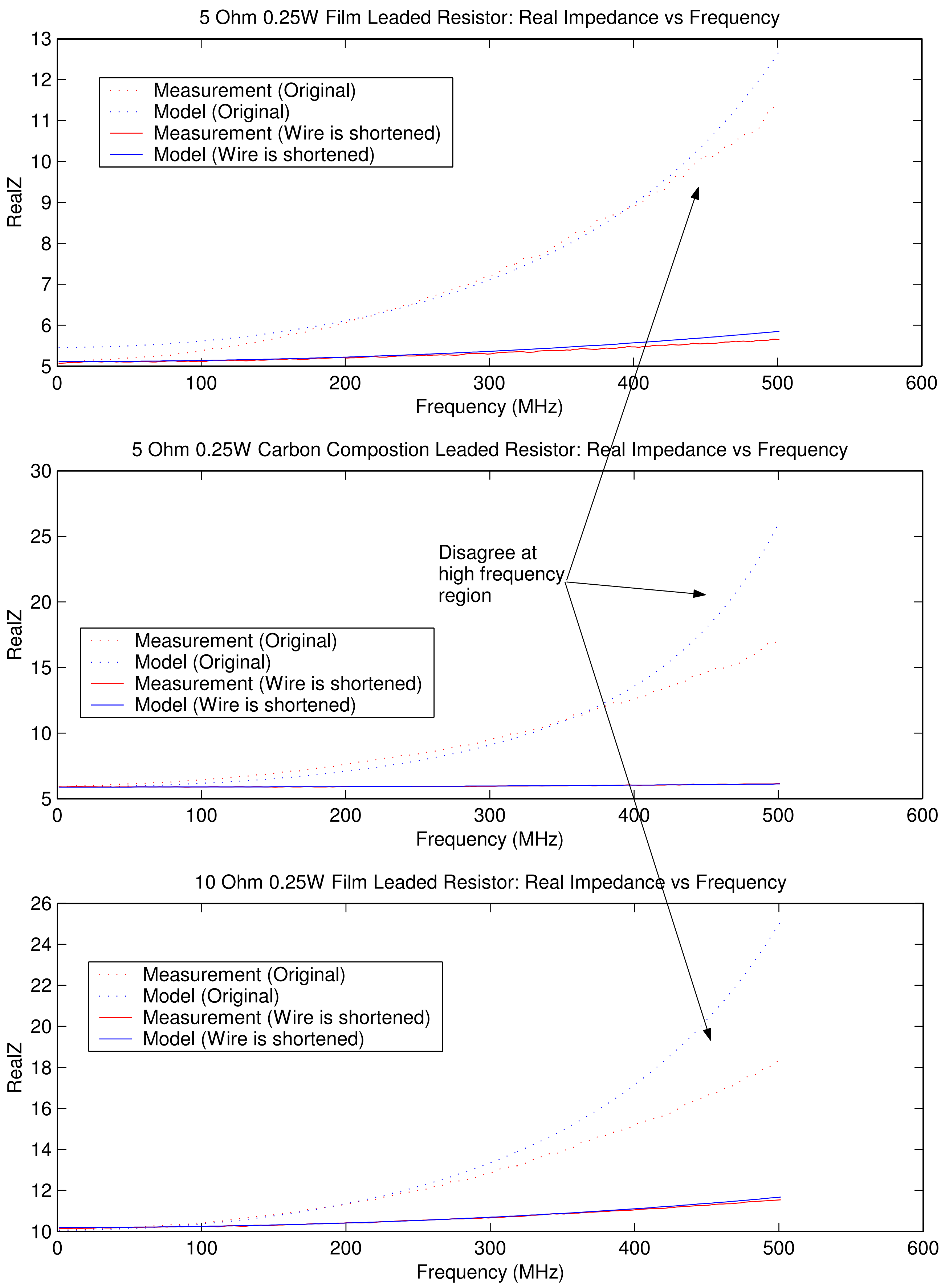


2

3

1. 5.1Ω 0.25W Film Leaded Resistor(Original)
2. 5.6Ω 0.25W Carbon Composition Leaded Resistor(Original)
3. 10Ω 0.25W Film Leaded Resistor(Original)

However, there is an improvement after shortening the wire. Therefore, we can conclude that the disagreements are caused by the unmatched Leaded Inductance and the Shunt Capacitance.


5 Ohm 0.25W Film Leaded Resistor: Real Impedance vs Frequency
RealZ
13
12
11
10
9
8
7
6
5
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
5 Ohm 0.25W Carbon Compostion Leaded Resistor: Real Impedance vs Frequency
RealZ
30
25
20
15
10
5
0
100
200
300
400
500
600
Frequency (MHz)
Disagree at high frequency region
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
10 Ohm 0.25W Film Leaded Resistor: Real Impedance vs Frequency
RealZ
26
24
22
20
18
16
14
12
10
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)

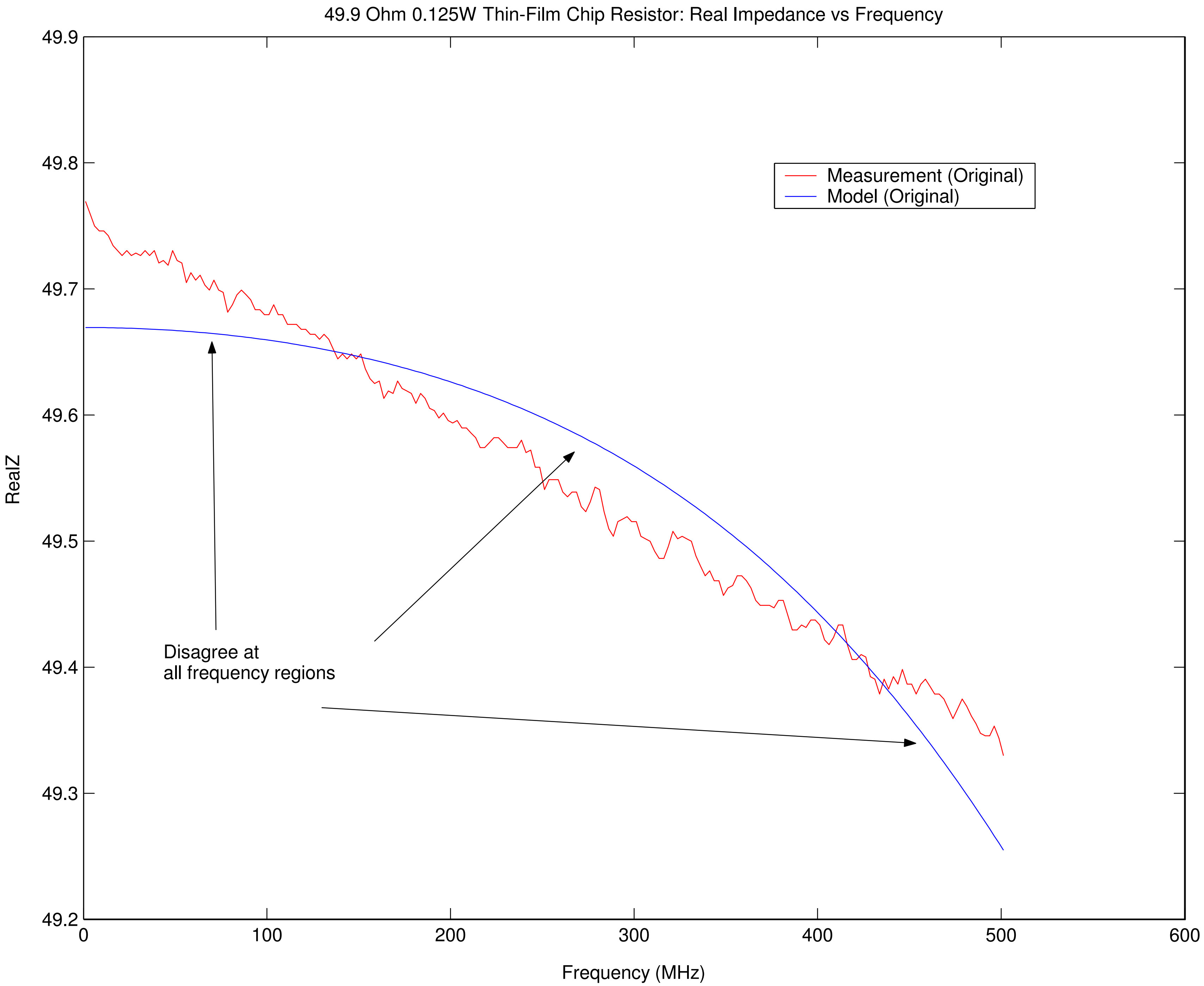
1.7.2 Disagree in Real Impedance at Sampling frequency

In this problem, the model fails to agree with the measurement in the sampling frequency range (i.e., 1 MHz - 501 MHz). This problem happens in the 49.9Ω 0.125W Thin-Film Chip Resistor.

Figure 7: A 49.9Ω 0.125W Thin-Film Chip Resistor

The measured real impedance behaves a down-slope straight line from 1 MHz to 501 MHz, while the model decreases non-linearly. It is unlikely that the suggested model could not describe the structure of Chip resistor, because the other resistance chip resistor models give good agreements with their measured value.

This problem is possibly caused by the inaccurate calibration. A 49.9Ω 0.125W Thin-Film Chip Resistor is used for calibrating the Network Analyzer. Since the calibration result will be kept in the memory after each calibration, it may cause error when measuring the same sample. Also, the fixture sometimes gives an unexpected error. A discussion on the calibration error will be given in the appendix..


49.9 Ohm 0.125W Thin-Film Chip Resistor: Real Impedance vs Frequency
Measurement (Original)
Model (Original)
Disagree at
all frequency regions
RealZ
Frequency (MHz)
49.9
49.8
49.7
49.6
49.5
49.4
49.3
49.2
0
100
200
300
400
500
600

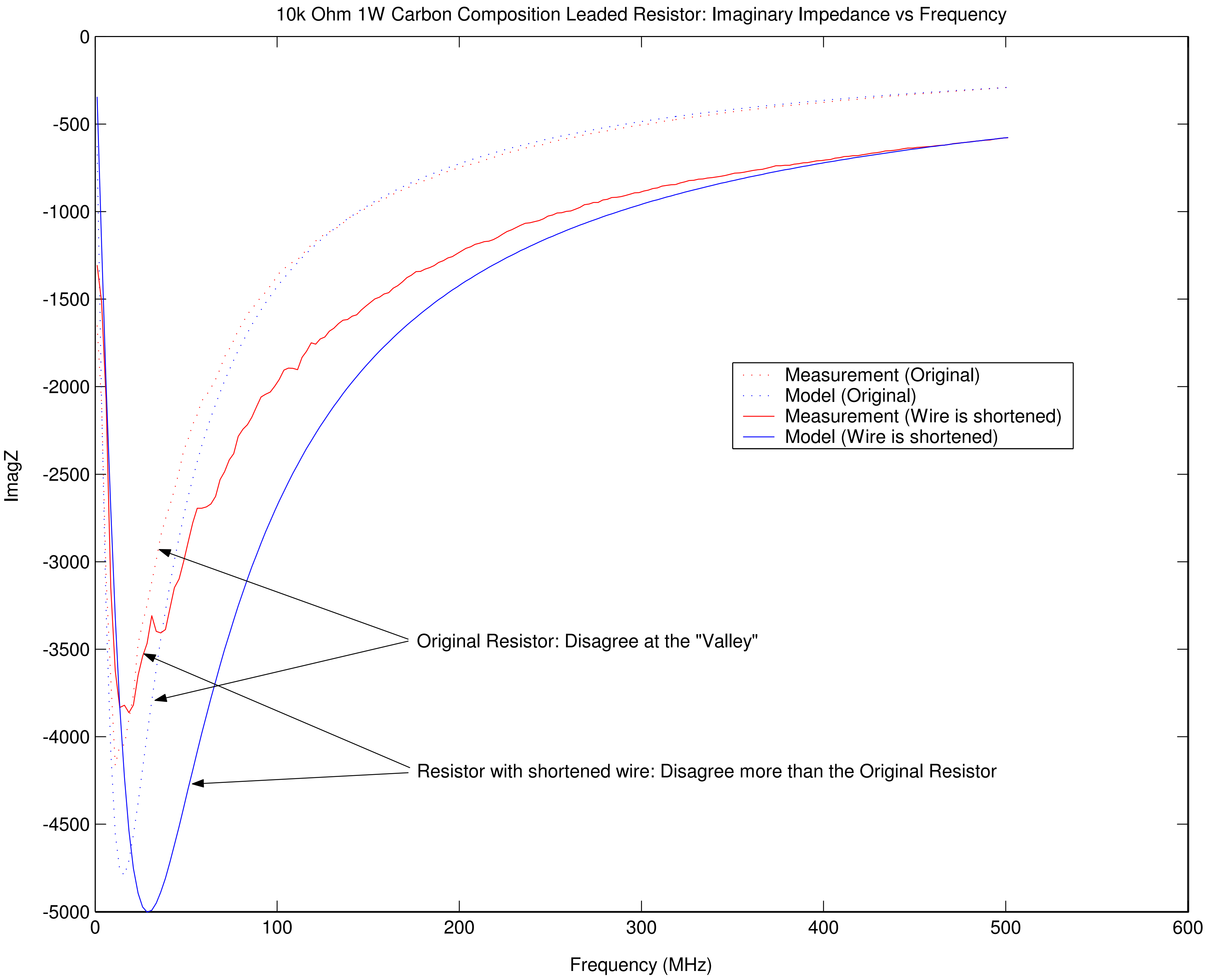
1.7.3 Disagree in Imaginary Impedance at the "Valley"

This problem happens in the 10kΩ 1W Carbon Composition Leaded Resistor. In the imaginary impedance, the resistor behaves like a "valley" at low frequency (30MHz - 50MHz). The model is unable to agree the "valley" with the measurement. Among these two samples(Original and after shortening the wire), it is surprised that the original model agrees better than the other one. Since the Transmission Line effect are reduced after shortening the wire, and the Internal Capacitor dominates the other components in large resistance resistor(10kΩ), which make the models involve only two components (Internal Resistor and Capacitor). Therefore, it is not easy to improve the agreement at the "valley" by just adjusting these two components.

1

2

	Original	Wire is shortened
Internal Resistance (Ω)	9590.0000	9999.9999
Shunt/Internal Capacitance (pF)	1.0901	0.5488
R-Square Value of Imaginary Impedance	0.9872	0.9820


10k Ohm 1W Carbon Composition Leaded Resistor: Imaginary Impedance vs Frequency
ImagZ
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Original Resistor: Disagree at the "Valley"
Resistor with shortened wire: Disagree more than the Original Resistor

1.8 Analysis on Material of Leaded Resistor

In this section, I will analysis the effect of material on the leaded resistor. The sample resistors I selected are listed below:

1

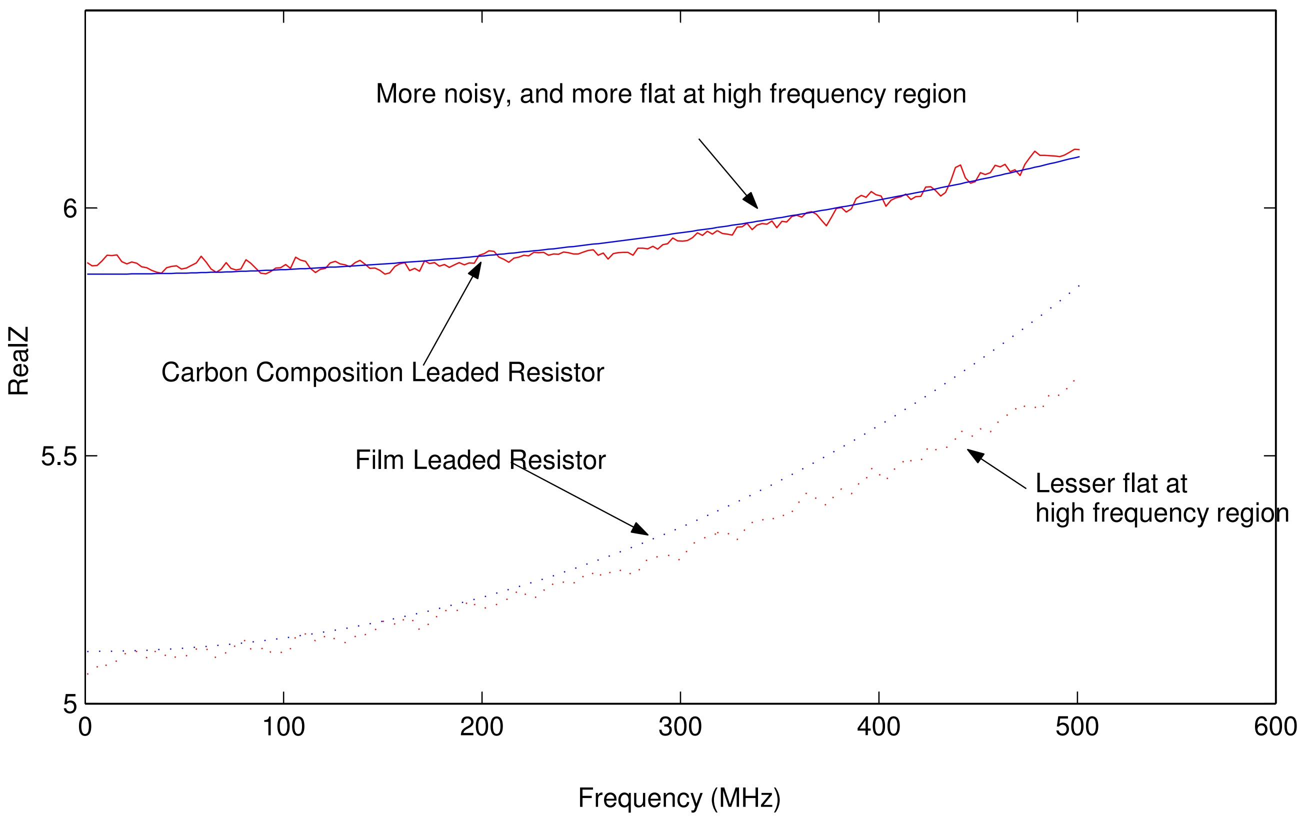
2

1. 5.1Ω 0.25W Film Leaded Resistor with shortened wire
2. 5.6Ω 0.25W Carbon Composition Leaded Resistor with shortened wire

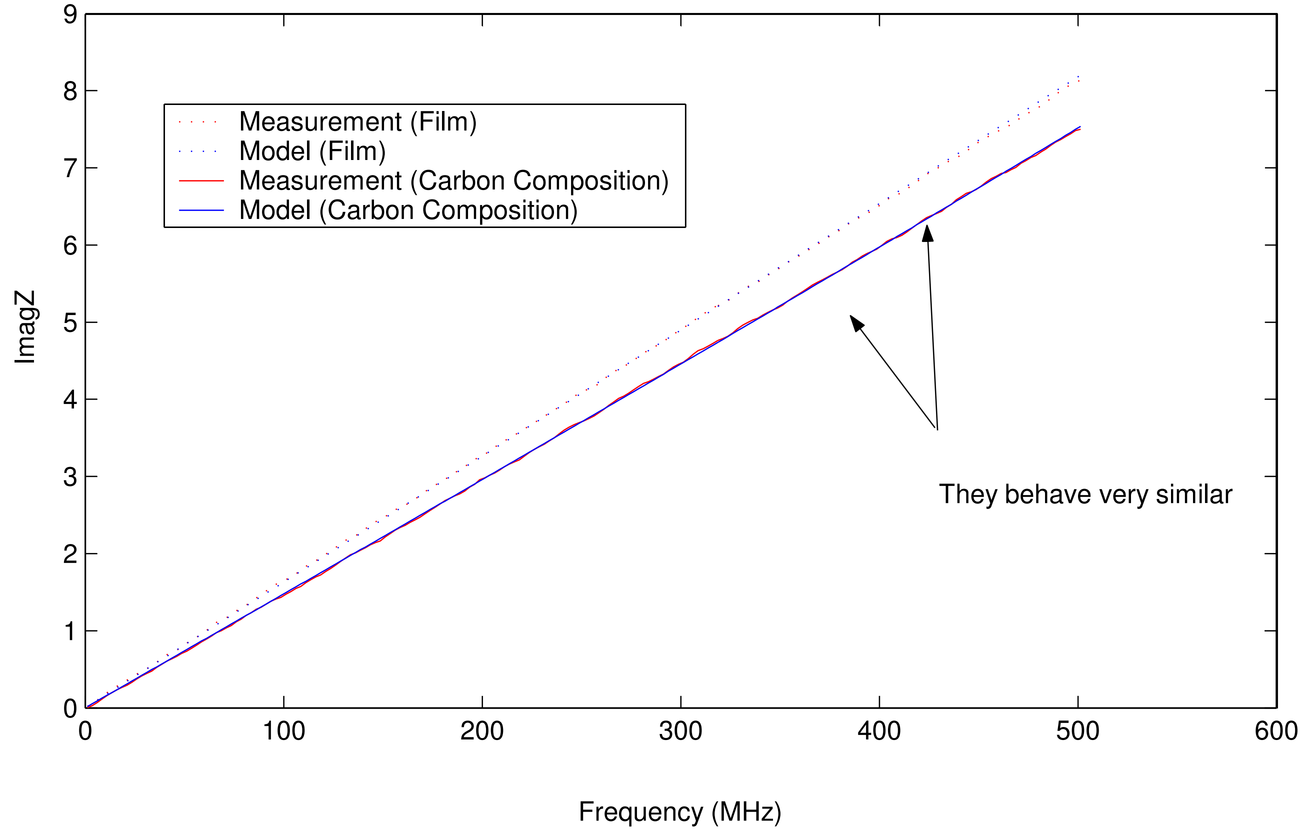
In general, Film Resistors are used when a high tolerance is needed. They are much more accurate in value than carbon composition resistors. They have about ±0.05% tolerance. This type of resistor is used for low-noise analog signal circuits. Carbon Composition Resistors are for the most general purpose, cheap resistor. The tolerance value is about ±5%. It has a disadvantage: it tends to be electrically noisy.

The next page shows the real impedance and imaginary impedance of two resistors. It is clear that the Carbon Composition Resistor is more noisy than the Film Resistor in the real impedance region. In the imaginary impedance region, they are very similar and they both behave inductively.

	Film	Carbon Composition
Internal Resistance of Model (Ω)	5.1047	5.8663
Internal Inductance of Model (nH)	0.8296	0.9043
Internal Capacitance of Model (pF)	9.4728	0.1538
External Inductance of Model (nH)	2.0120	1.4777
External Capacitance of Model (pF)	0.0000	0.7806



5.1 Ohm 0.25W Film Leaded Resistor & 5.6W 0.25W Carbon Composition Leaded Resistor: Real Impedance vs Frequency



Imaginary Impedance vs Frequency

1.9 Analysis on Power Level of Leaded Resistor

In this section, I will analysis the effect of power level on the leaded resistor. The sample resistors I selected are listed below:

1

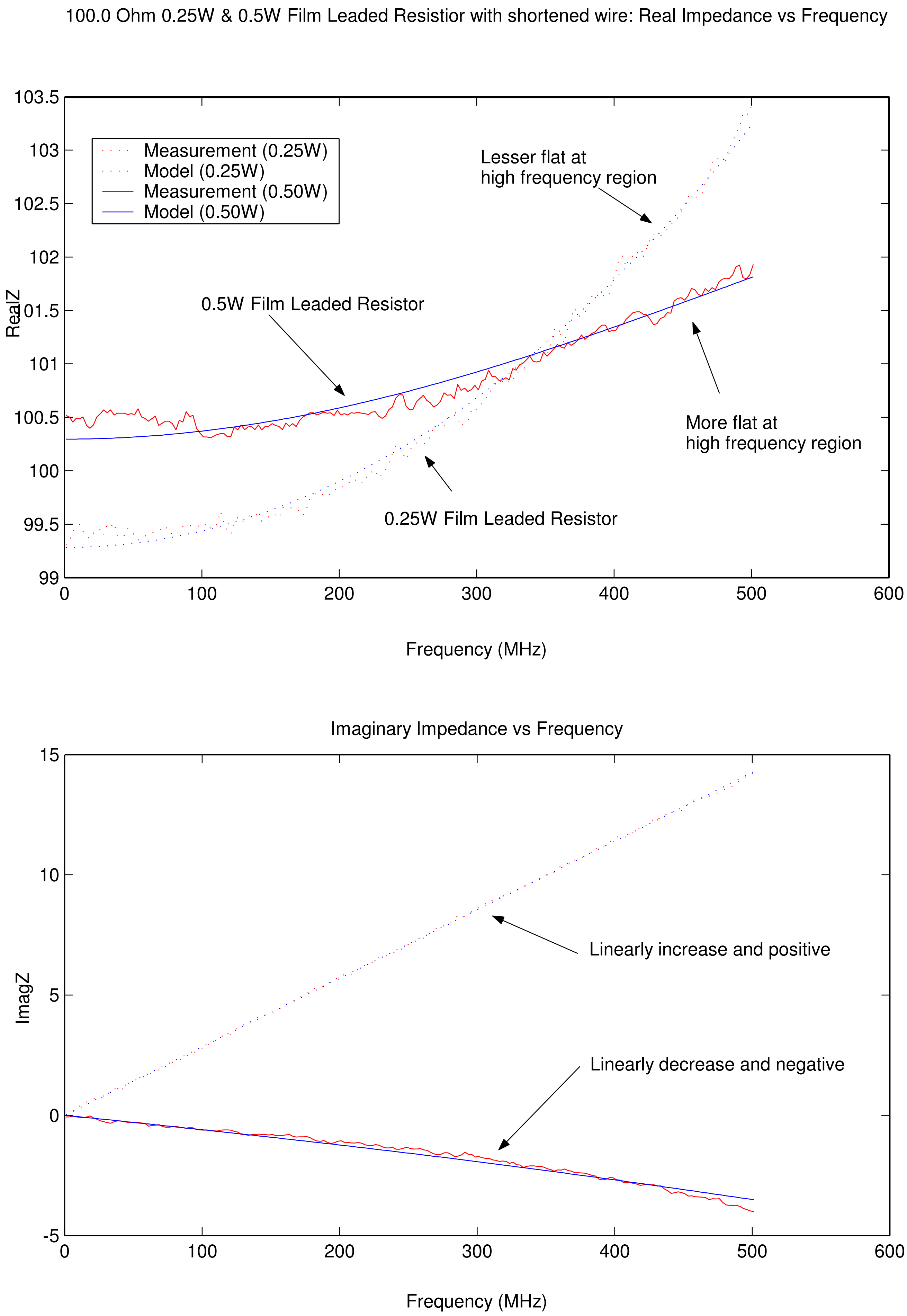
2

1. 100.0Ω 0.25W Film Leaded Resistor with shortened wire
2. 100.0Ω 0.50W Film Leaded Resistor with shortened wire

In the real impedance region, the 0.25W resistor is lesser flat at high frequency (> 300 MHz) than the 0.50W resistor. In the imaginary impedance region, the 0.25W resistor increases linearly and it is inductive, while the 0.50W resistor decreases linearly and it is capacitive.

The following table summarizes the model values of two resistors:

	0.25W	0.50W
Internal Resistance of Model (Ω)	99.2795	100.2930
Internal Inductance of Model (nH)	2.0444	4.8465
Internal Capacitance of Model (pF)	0.5328	1.1032
External Inductance of Model (nH)	11.2945	12.2297
External Capacitance of Model (pF)	0.3611	0.6891


100.0 Ohm 0.25W & 0.5W Film Leaded Resistior with shortened wire: Real Impedance vs Frequency
Measurement (0.25W)
Model (0.25W)
Measurement (0.50W)
Model (0.50W)
Lesser flat at
high frequency region
0.5W Film Leaded Resistor
More flat at
high frequency region
0.25W Film Leaded Resistor
RealZ
103.5
103
102.5
102
101.5
101
100.5
100
99.5
99
0
100
200
300
400
500
600
Frequency (MHz)
Imaginary Impedance vs Frequency
Linearly increase and positive
Linearly decrease and negative
ImagZ
15
10
5
0
-5
0
100
200
300
400
500
600
Frequency (MHz)

1.10 Analysis on the Shape of Impedance

In this section, I plot the real impedance, imaginary impedance and Smith Chart of the following resistors.

1. 5.1Ω 0.25W Film Lead Resistor with shortened wire
2. 10.0Ω 0.25W Film Lead Resistor with shortened wire
3. 51.1Ω 0.25W Film Lead Resistor with shortened wire
4. 100.0Ω 0.25W Film Lead Resistor with shortened wire
5. 510.0Ω 0.25W Film Lead Resistor with shortened wire
6. $1k\Omega$ 0.25W Film Lead Resistor with shortened wire
7. $10k\Omega$ 0.50W Film Lead Resistor with shortened wire

The first four samples (5.1Ω, 10.0Ω, 51.1Ω and 100Ω) have similar shapes in real and imaginary regions. Their imaginary impedances increase linearly and they are positive. It is because their internal inductors dominate the internal capacitors. However, the last three samples (500Ω, $1k\Omega$ and $10k\Omega$) behave differently than the first four samples. Their real impedances decrease and stay constant at high frequency, and their imaginary impedances decrease linearly and they are negative. It is because their internal capacitors dominate the inductors. These observations agree with the models we developed in the beginning of chapter.

Inductor dominates capacitance for small resistance resistor ($\ll 100\Omega$),

Figure 8: Equivalent Model for Small Resistance Resistor

and capacitor dominates inductor for large resistance resistor ($\gg 100\Omega$).

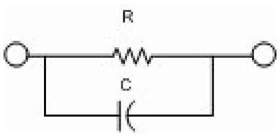


Figure 9: Equivalent Model for Large Resistance Resistor

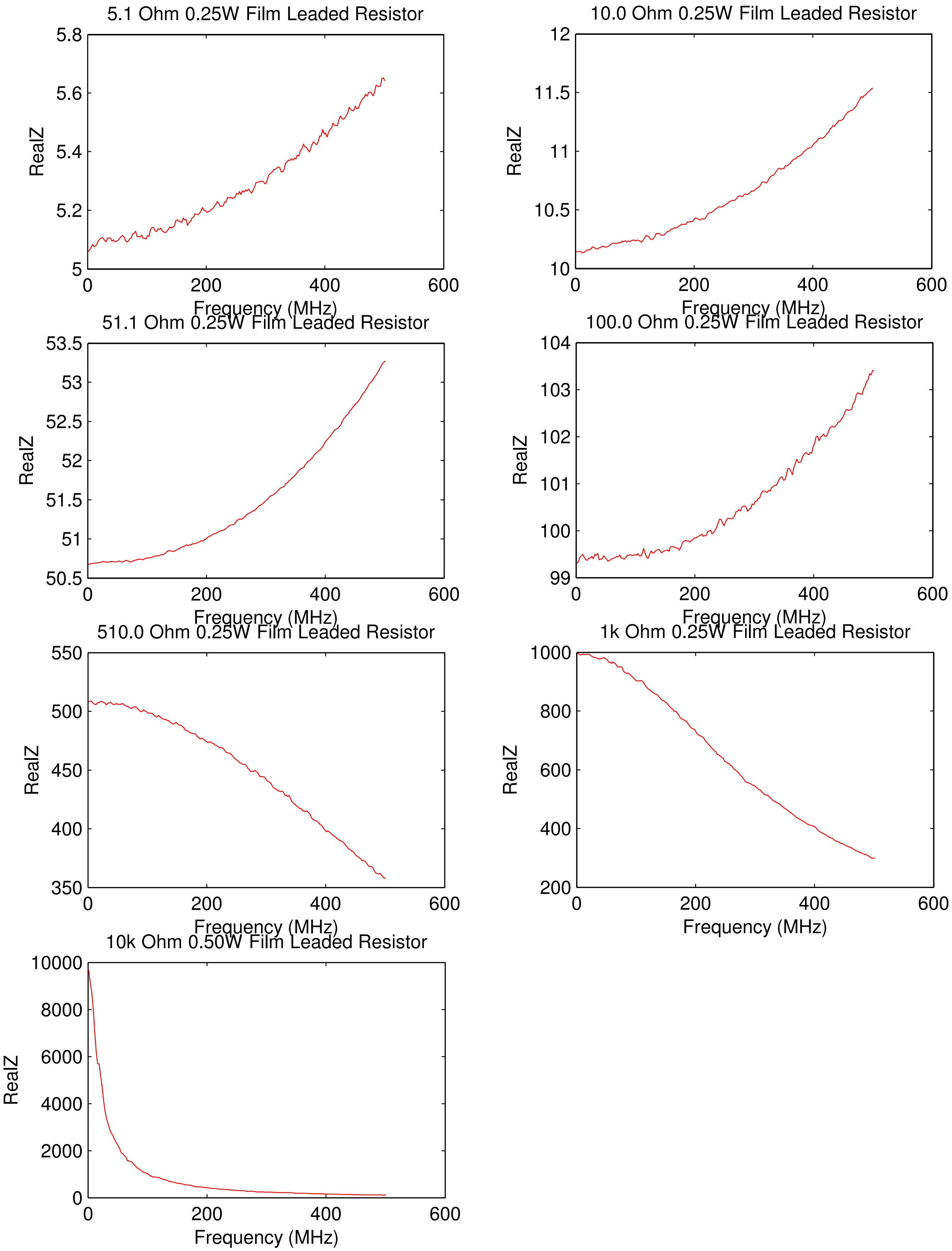
The table below summarizes the model component values of the samples[3].

	5.1Ω	10.0Ω	51.1Ω	100.0Ω	510.0Ω	1kΩ	10kΩ
Internal Resistance (Ω)	5.1047	10.1900	50.6305	99.2795	507.1527	991.4484	10000
Internal Inductance (nH)	0.8296	1.7246	0.8453	2.0444	38.6625	78.1957	1.0000
Internal Capacitance (pF)	9.4728	4.4934	0.0000	0.5328	0.3635	0.1857	0.3005
External Inductance (nH)	2.0120	2.9501	4.1339	11.2945	100.0745	200.7487	0.9996
External Capacitance (pF)	0.0000	0.0000	0.5653	0.3611	0.5895	0.5831	0.3015

---

[3] The assumption of the domination may not agree with the model component values, because it is hard to tell the Internal Inductance (or Capacitance) and External Inductance (or Capacitance).

Real Impedance of Selected Resistor (Measurement, with shortened Wire)



5.1 Ohm 0.25W Film Leaded Resistor

10.0 Ohm 0.25W Film Leaded Resistor

51.1 Ohm 0.25W Film Leaded Resistor

100.0 Ohm 0.25W Film Leaded Resistor

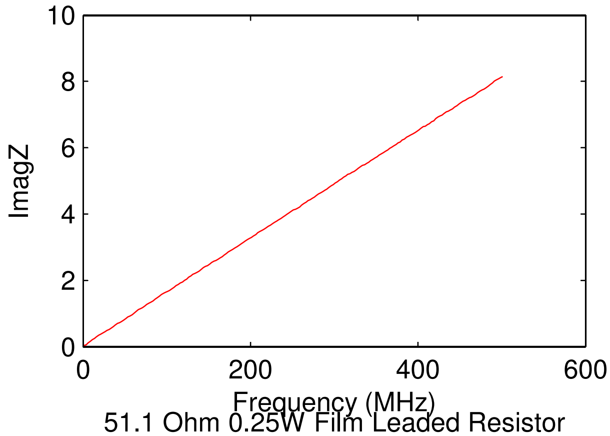
510.0 Ohm 0.25W Film Leaded Resistor

1k Ohm 0.25W Film Leaded Resistor

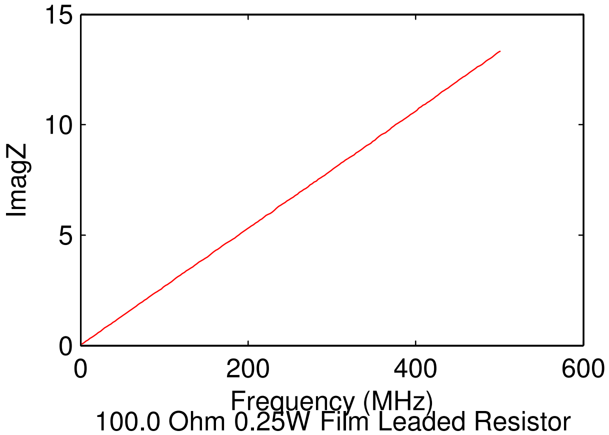
10k Ohm 0.50W Film Leaded Resistor

Imaginary Impedance of Selected Resistor (Measurement, with shortened Wire)

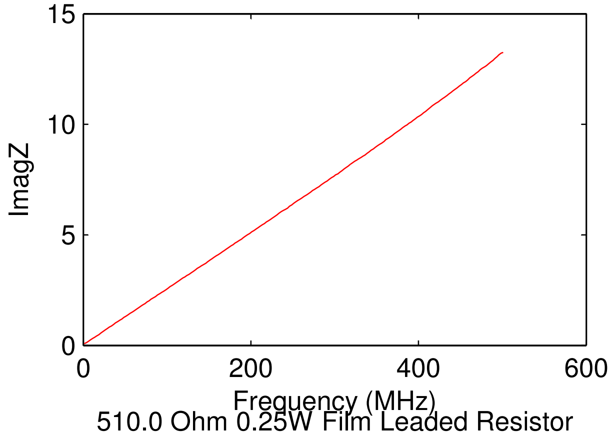
5.1 Ohm 0.25W Film Leaded Resistor



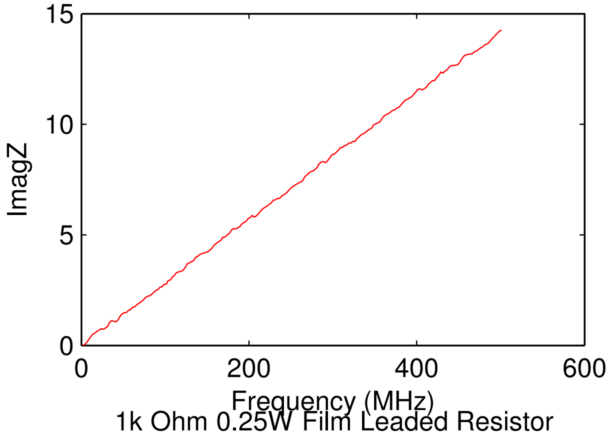
10.0 Ohm 0.25W Film Leaded Resistor



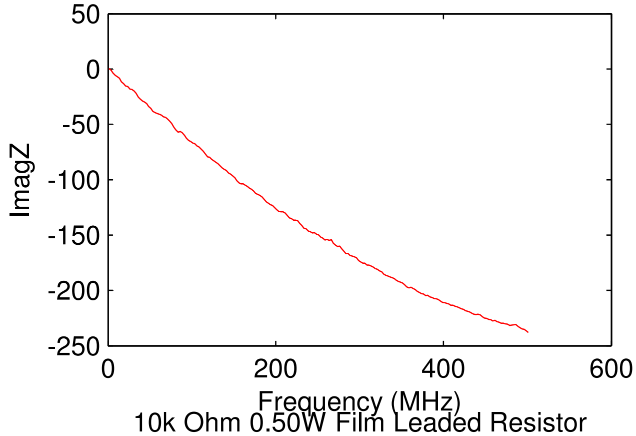
51.1 Ohm 0.25W Film Leaded Resistor



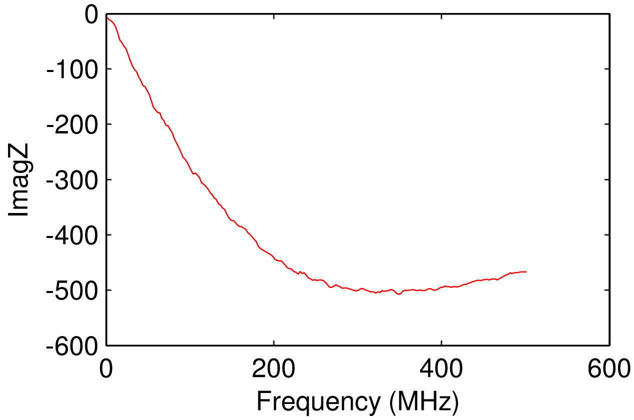
100.0 Ohm 0.25W Film Leaded Resistor



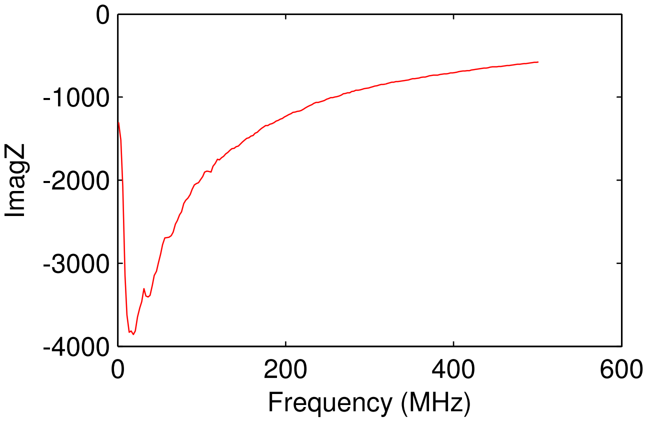
510.0 Ohm 0.25W Film Leaded Resistor

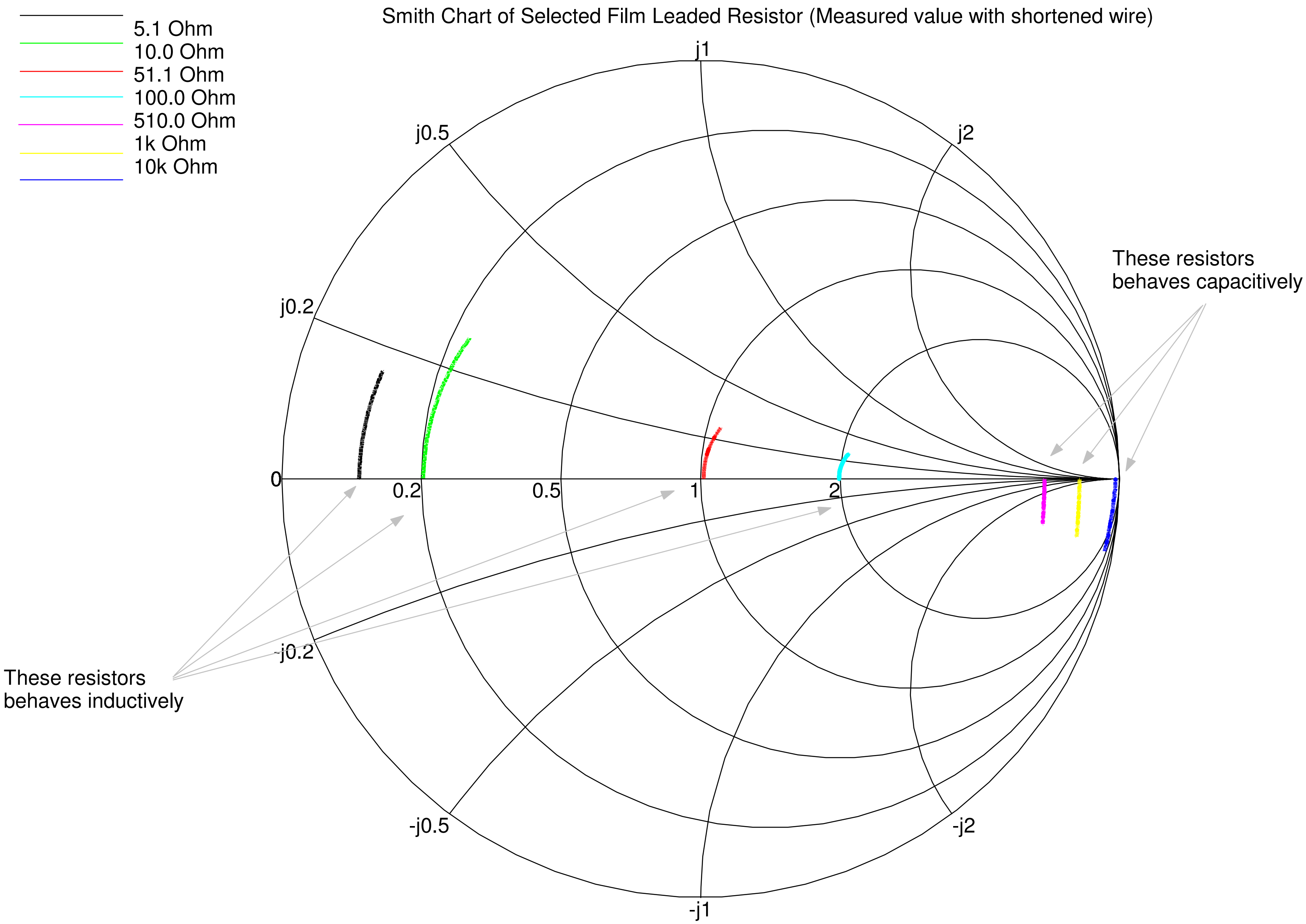


1k Ohm 0.25W Film Leaded Resistor



10k Ohm 0.50W Film Leaded Resistor





Smith Chart of Selected Film Leaded Resistor (Measured value with shortened wire)

These resistors behaves capacitively

These resistors behaves inductively

2 Capacitor

2.1 Introduction

An ideal capacitor can be described by the following loss-less model:

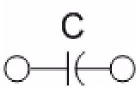


Figure 10: Equivalent circuit model for Ideal Capacitor

Generally, capacitors have small losses, and the model can be modified to the following circuit:

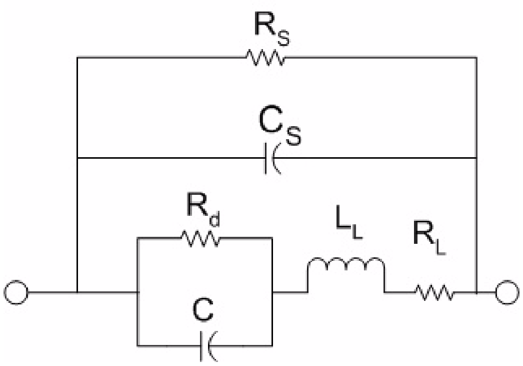


Figure 11: Equivalent circuit model for Lossy Capacitor with Transmission Line Components

where the resistor R_d accounts for the dielectric loss to the capacitor. The series R_L-L_L components and the parallel R_S-C_S components represent the leaded loss and the shunt loss of the Transmission Line respectively.

However, this model is not enough to describe the real impedance for large capacitance capacitor (e.g., 0.01μF) of the measurement. Therefore, it is necessary to re-develop the model from the physical points for view.

A Capacitor can be considered as two parallel plates:

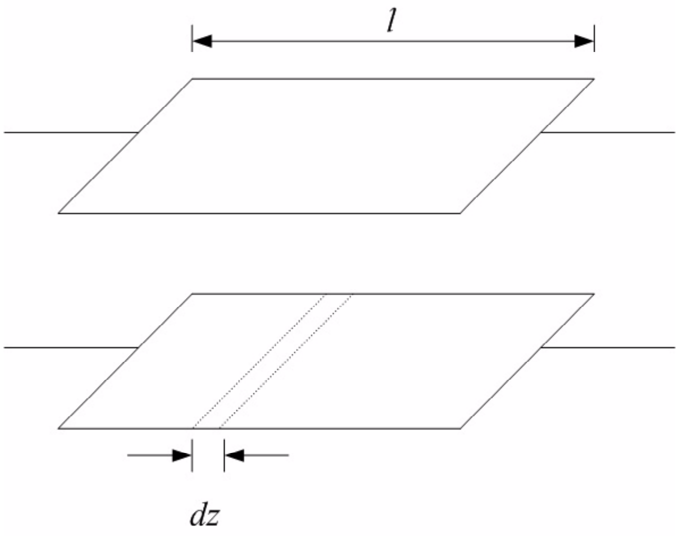


Figure 12: Two Parallel Plates

If dz is l, then the parallel plates is simply the following circuit:

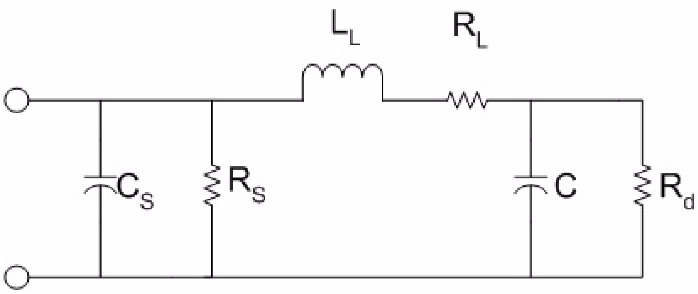


Figure 13: Equivalent Circuit Model of Two Parallel Plates

If dz is very small and it is closed to zero, then the series R_L-L_L components and the parallel R_S-C_S can be divided into infinity parts, i.e.,

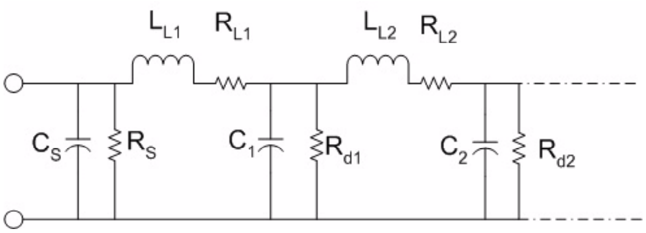


Figure 14: Equivalent Circuit Model of Two Parallel Plates

where

$$\begin{aligned} L_L &= L_{L1} + L_{L2} + ... \quad (16)\\ R_L &= R_{L1} + R_{L2} + ... \quad (17)\\ C &= C_1 + C_2 + ... \quad (18)\\ \frac{1}{R_d} &= \frac{1}{R_{d1}} + \frac{1}{R_{d2}} + ... \quad (19) \end{aligned}$$

In our case, we consider only two parts. From the imaginary impedance measurement, I observed that capacitor is capacitive (Negative slope) at low frequency region (1 MHz - 50 MHz). Beyond this region, the capacitor becomes inductive (Positive slope). I think this behavior is caused by a series L-C pair component. After recombining R_L, C and R_d, and we rearrange the components. The circuit becomes:

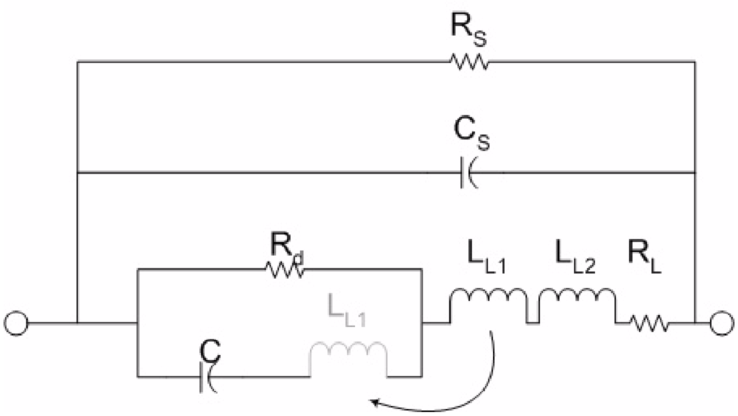


Figure 15: Equivalent Circuit Model of Two Parallel Plates (Black: Original, Grey: After Modification)

Generally, the Shunt Resistor R_S is large to be ignored. Finally, the circuit becomes:

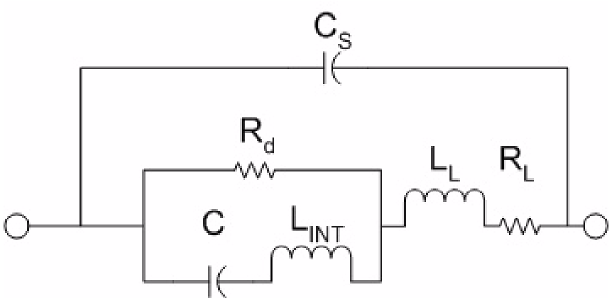


Figure 16: Equivallent Circuit Model of Capacitor

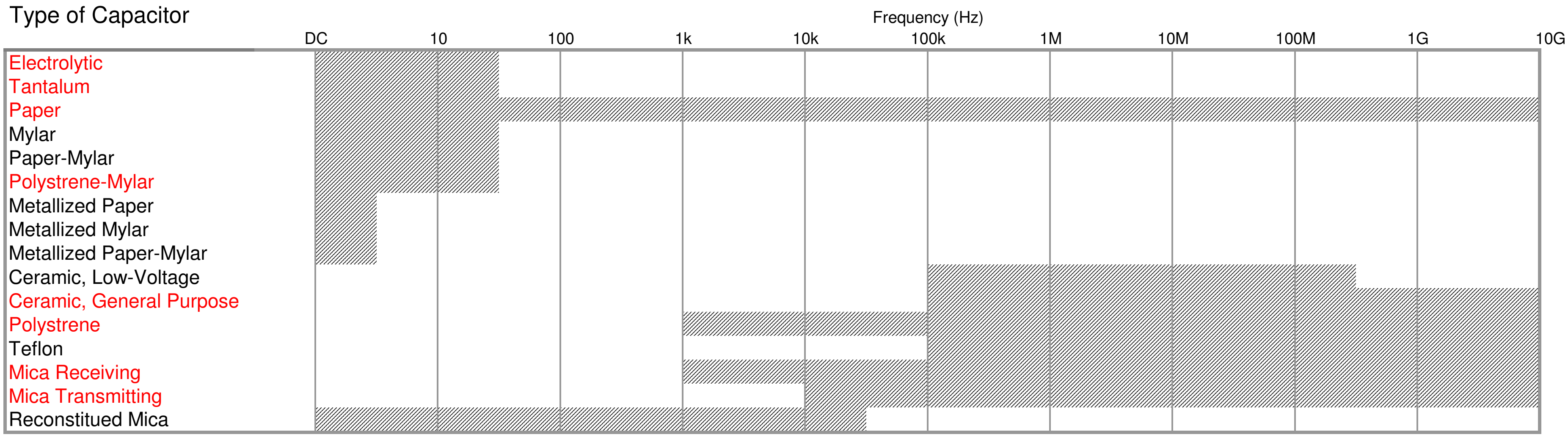
where the Inductor L_{INT}(Formally L_{L1}) can be treated as the Internal Inductor, and L_L can be treated as the External Inductor.

2.2 Analysis on Capacitor

There are many types of capacitors that made of different material. Each material behaves differently in different frequency bands. For example, electrolytic leaded capacitor is widely used in the digital circuit, but not in R.F. circuit. To study their frequency characteristics, the following capacitors are chosen:

Capacitance	Material	Voltage (V)	Treatment
1pF	Ceramic Disk Leaded	–	None
1pF	Ceramic Disk Leaded	–	Wire is shortened
1pF	SilverMica Leaded	–	None
1pF	SilverMica Leaded	–	Wire is shortened
100pF	SilverMica Leaded	–	None
100pF	SilverMica Leaded	–	Wire is shortened
100pF	Polystrene Leaded	–	None
100pF	Polystrene Leaded	–	Wire is shortened
0.01μF	Ceramic Disk Leaded	–	None
0.01μF	Ceramic Disk Leaded	–	Wire is shortened
0.01μF	Monolithic Leaded	–	None
0.01μF	Monolithic Leaded	–	Wire is shortened
0.01μF	Tantalum Chip	–	None
1μF	Minilytic Leaded	–	None
1μF	Minilytic Leaded	–	Wire is shortened
1μF	Monolithic Leaded	–	None
1μF	Monolithic Leaded	–	Wire is shortened
1μF	Electrolytic Leaded	50	None
1μF	Electrolytic Leaded	50	Wire is shortened
1μF	Paper Leaded	–	None
4.7μF	Electrolytic Leaded	25	None
4.7μF	Electrolytic Leaded	25	Wire is shortened
4.7μF	Electrolytic Leaded	63	None
4.7μF	Electrolytic Leaded	63	Wire is shortened
100μF	Tantalum Surface-Mounted	–	None

A frequency chart of the capacitance material is shown on next page.



Remark: The colored capacitors are selected in the measurement

2.3 Measurement Step

The steps of capacitor measurement are similar to the resistor measurement except for the normalization process. In general, capacitor can be treated as loss-less component because of its very low resistance. Due to the measuring error, negative real impedance may exist in the measurement if the noise is higher than the amplitude. Therefore, it is necessary to normalize the data before further analysis.

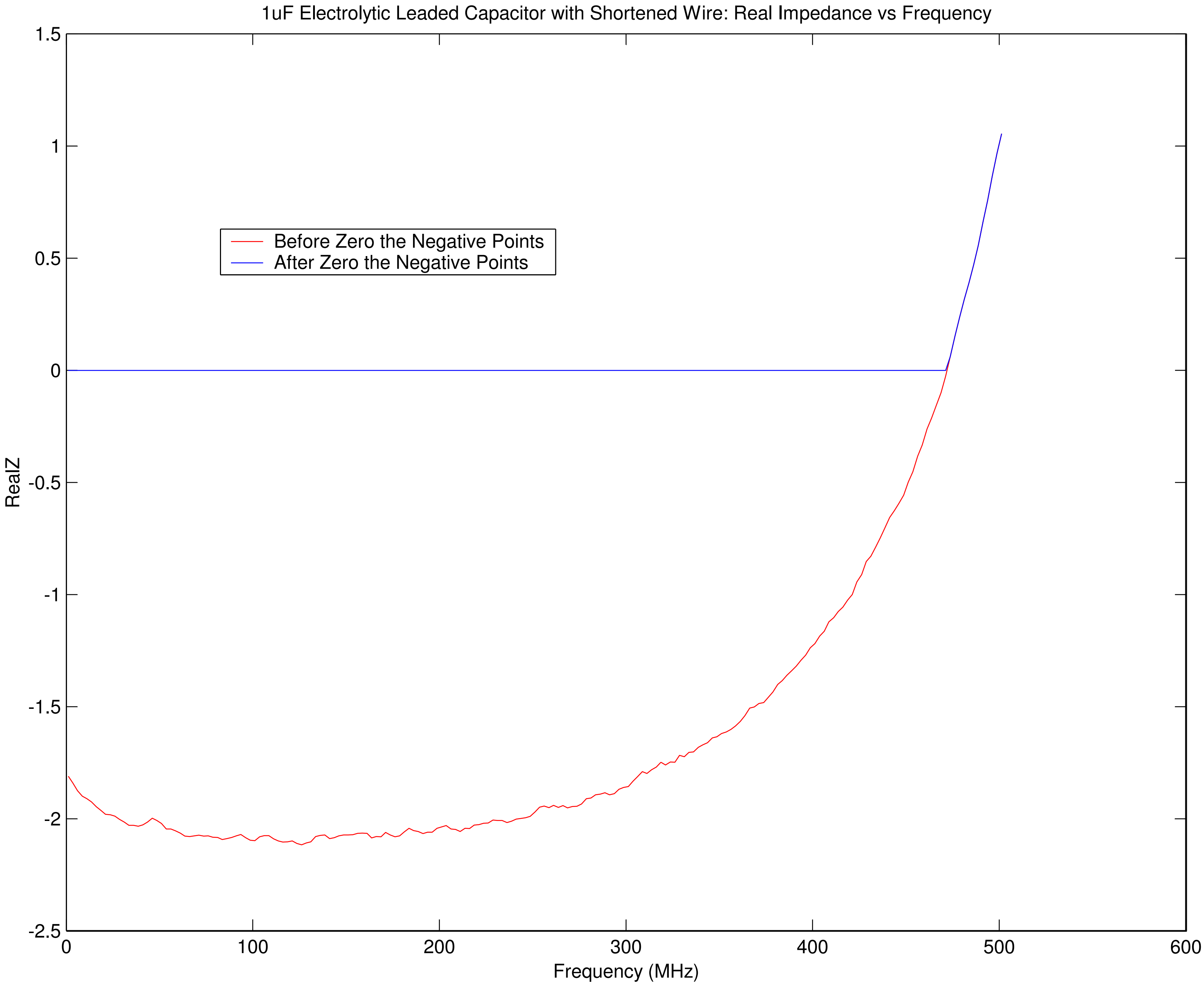
Partially Zero the Negative Point only

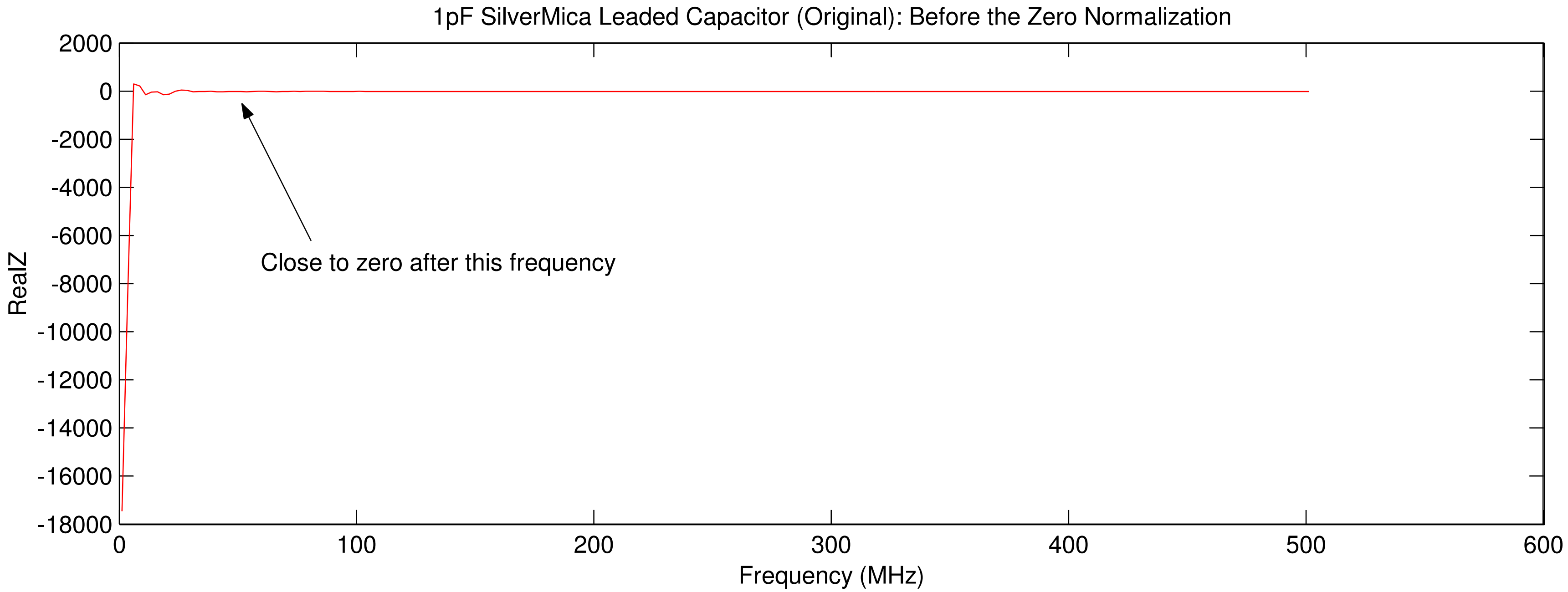
If the original data is positive and closed to zero, and it ends up negative because of the noisy measurement environment. This normalization method is good because it helps to eliminate the incorrect data.

Completely Zero the Real Impedance

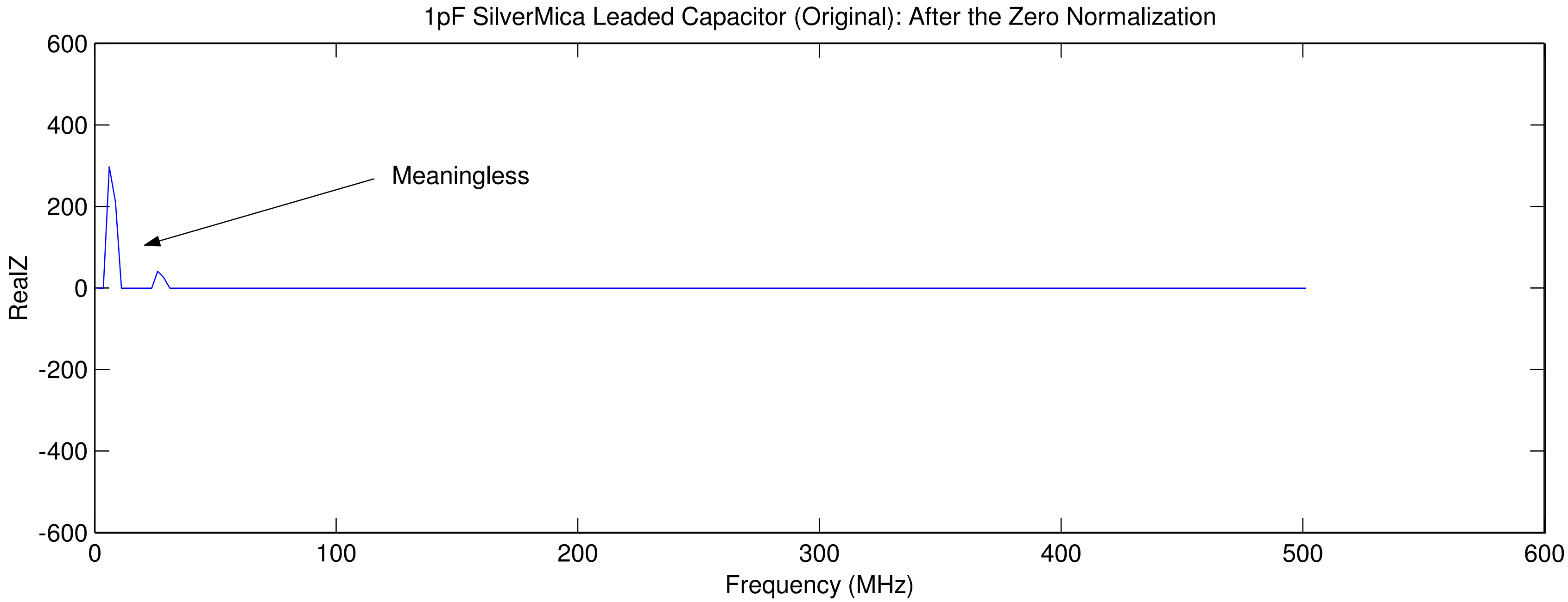
Sometimes, the negative real impedance is caused by unknown error. For example, the whole curve is shifted down for certain units, and it ends up part of the curve is above the axis, and the other part is below the axis. It is not a good idea to zero the negative parts, otherwise the remain curve will be meaningless. Instead, it is better to zero the whole real impedance data. In the other words, it is better to treat the capacitor as a loss-less component.

The next two pages show the results of before the normalization and after the normalization using the first method. It is clear that the result is meaningless and the data is hard to be fit to the current capacitor model.


1uF Electrolytic Leaded Capacitor with Shortened Wire: Real Impedance vs Frequency
Before Zero the Negative Points
After Zero the Negative Points
RealZ
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
100
200
300
400
500
600
Frequency (MHz)



1pF SilverMica Leaded Capacitor (Original): Before the Zero Normalization



1pF SilverMica Leaded Capacitor (Original): After the Zero Normalization

2.4 Measurement Result

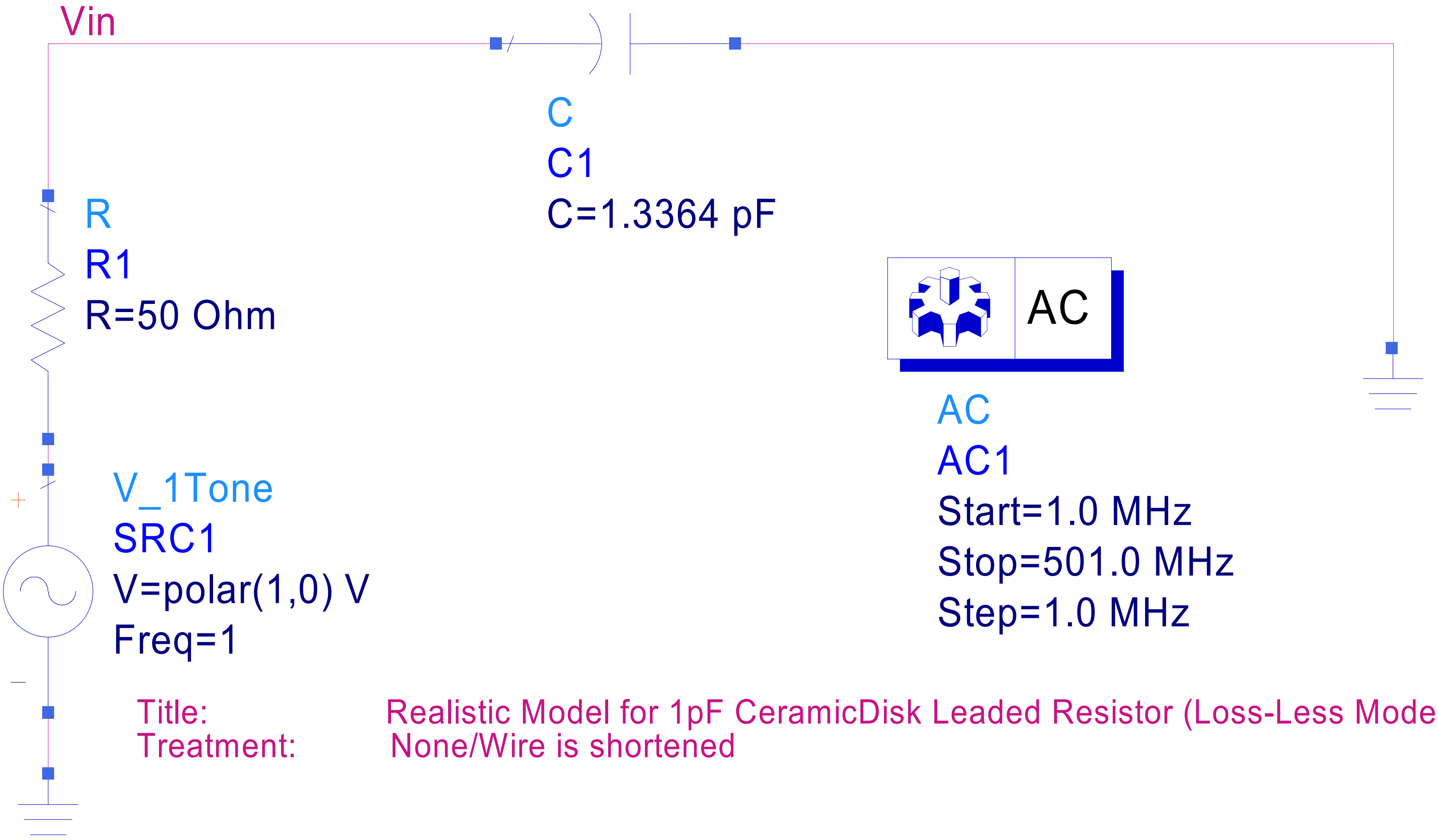
2.4.1 1pF Ceramic Disk Leaded Capacitor

The following are the pictures of an original and after treatment 1pF Ceramic Disk Leaded Capacitor.

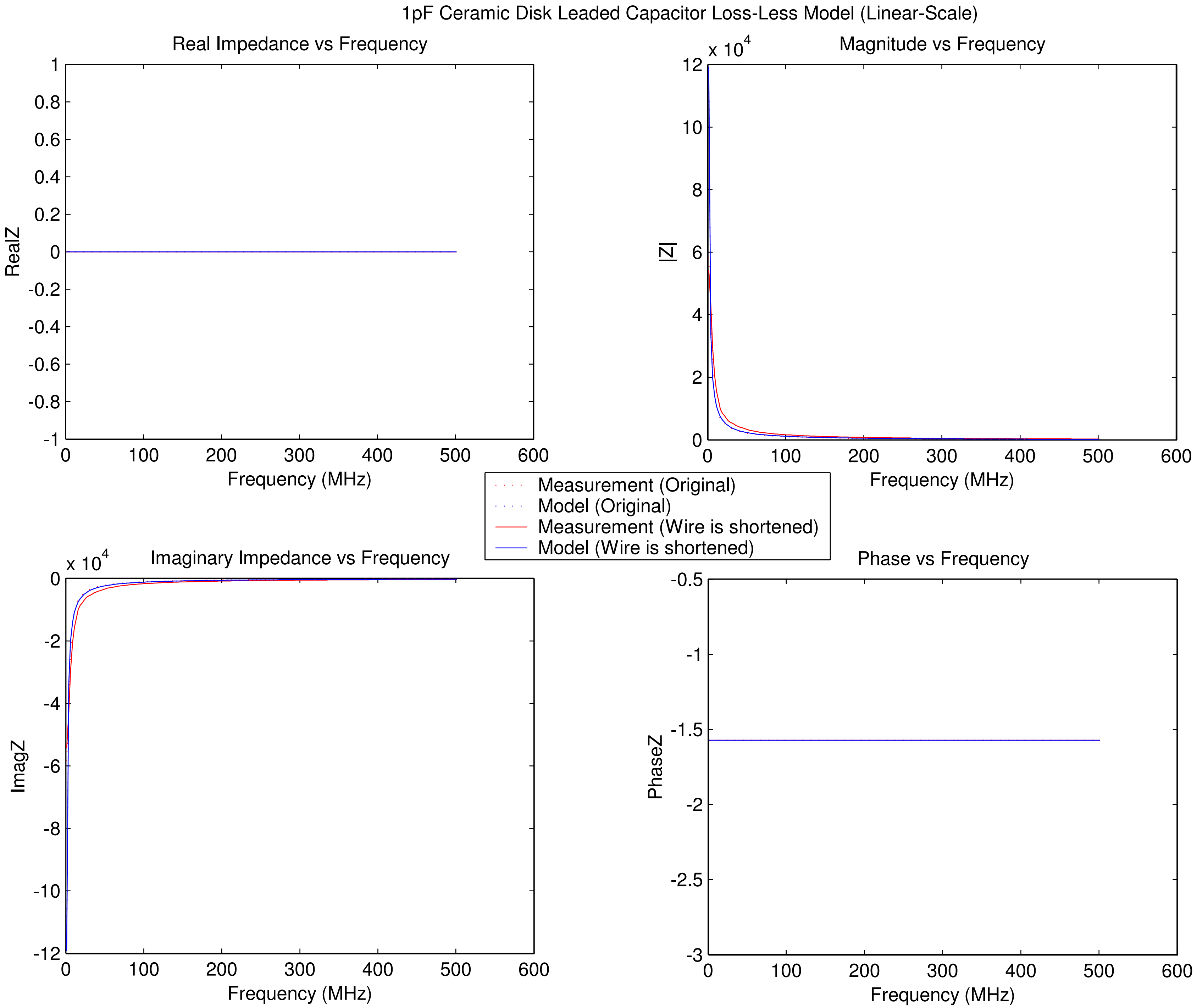
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result. Notice that both samples are treated as loss-less components and share the same model.

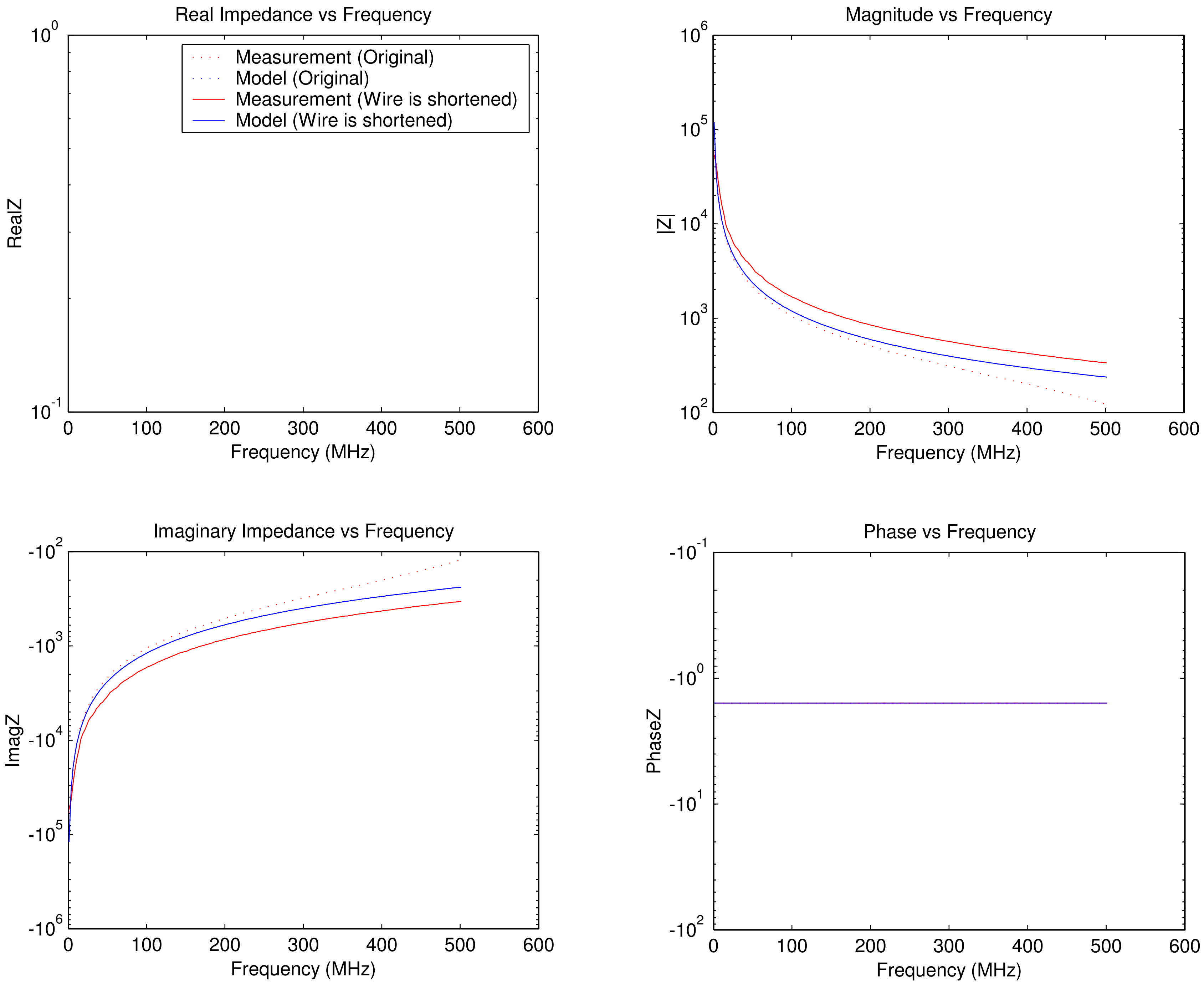
	Original	Wire is shortened
Normalization Treatment	Loss-Less	Loss-Less
Internal Resistance of Model (Ω)	∞	∞
Internal Inductance of Model (nH)	0.0000	0.0000
Internal Capacitance of Model (pF)	1.3364	1.3364
External Resistance of Model (Ω)	0.0000	0.0000
External Inductance from estimation (nH)	54.3739	3.3461
External Inductance of Model (nH)	0.0000	0.0000
External Capacitance from estimation (pF)	0.3553	0.0219
External Capacitance of Model (pF)	0.0000	0.0000
Legnth of Leaded Wire (mm)	41.7000	2.5700
Distance between two wires (mm)	6.7400	6.7100
Diameter of wire (mm)	0.4800	0.4800
R-Square Value of Real Impedance	1.0000	1.0000
R-Square Value of Imaginary Impedance	0.8654	0.7749
R-Square Value of Magnitude	0.8654	0.7749
R-Square Value of Phase	1.0000	1.0000

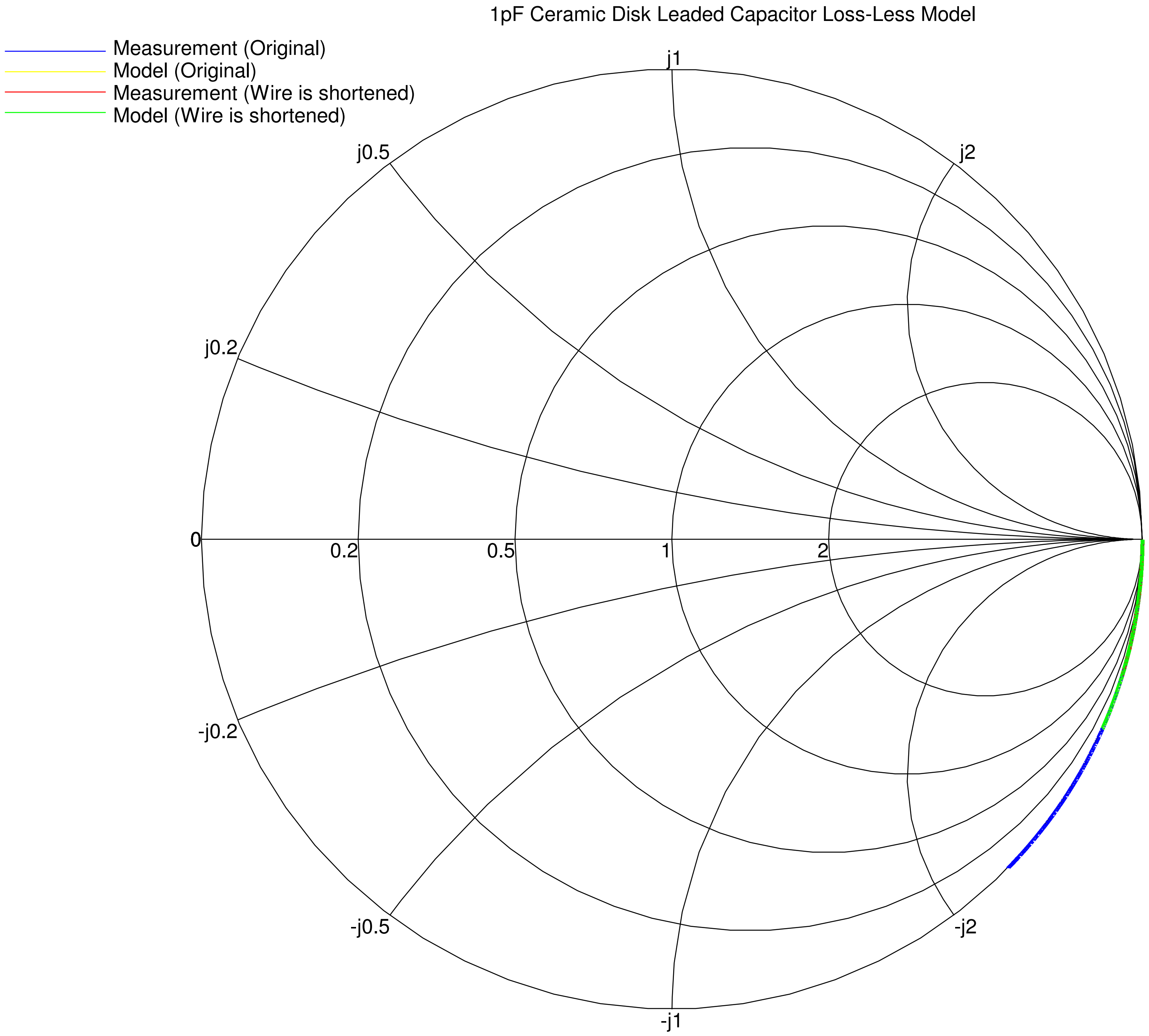


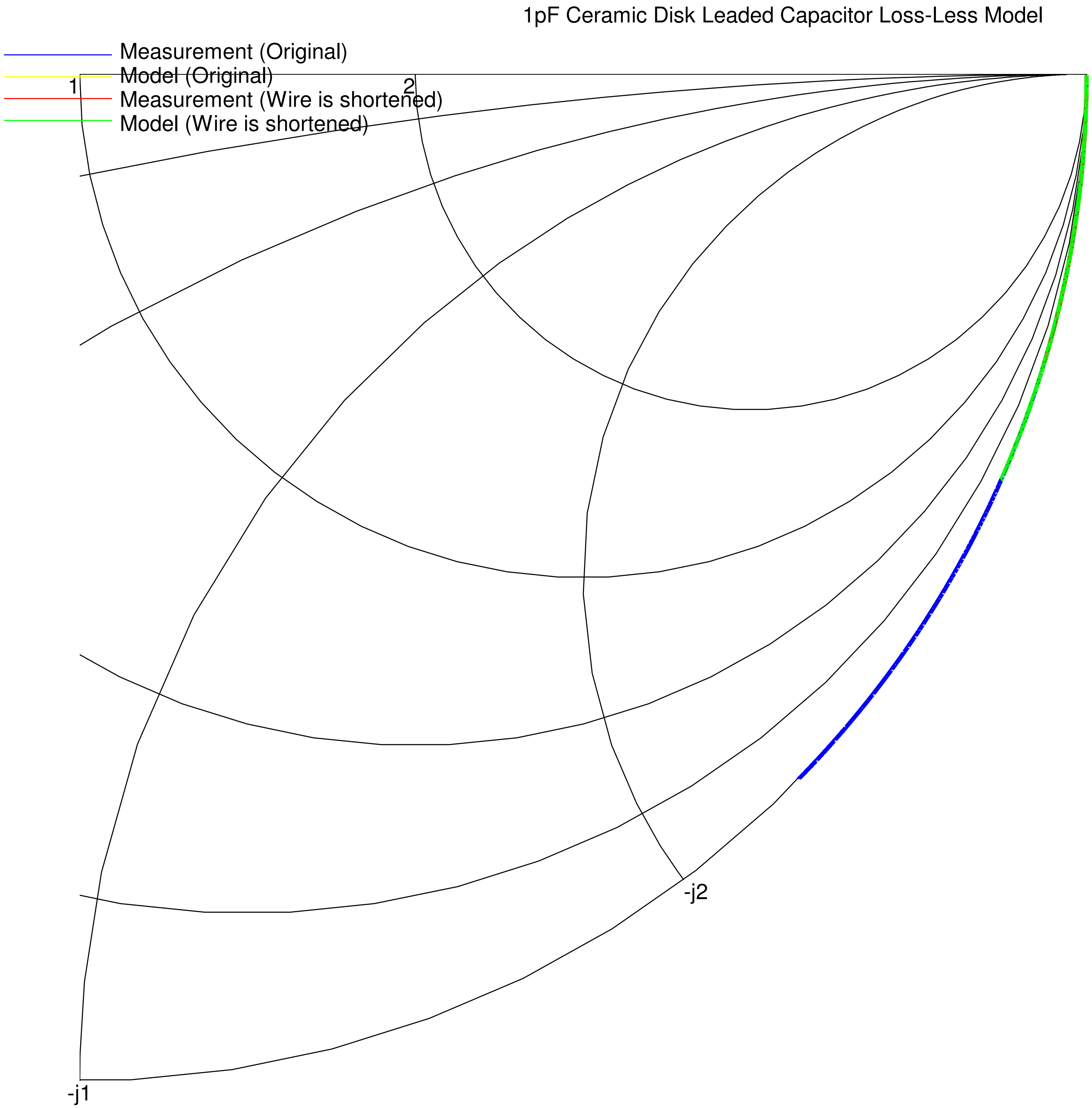
Title: Realistic Model for 1pF CeramicDisk Leaded Resistor (Loss-Less Model)
Treatment: None/Wire is shortened


1pF Ceramic Disk Leaded Capacitor Loss-Less Model (Linear-Scale)
Real Impedance vs Frequency
RealZ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
x 10^4
|Z|
12
10
8
6
4
2
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
x 10^4
ImagZ
0
-2
-4
-6
-8
-10
-12
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
-0.5
-1
-1.5
-2
-2.5
-3
0
100
200
300
400
500
600
Frequency (MHz)

1pF Ceramic Disk Leaded Capacitor Loss-Less Model (Log-Scale)



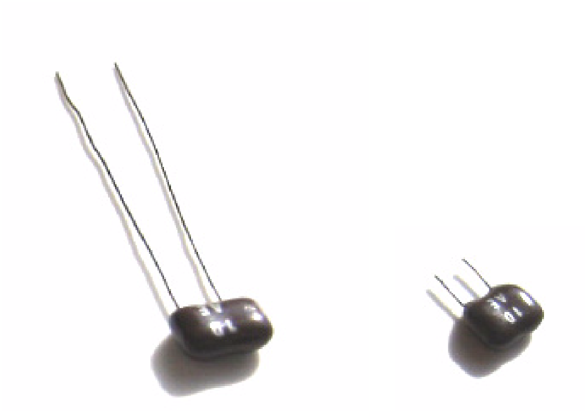

1pF Ceramic Disk Leaded Capacitor Loss-Less Model



1pF Ceramic Disk Leaded Capacitor Loss-Less Model

2.4.2 1pF SilverMica Leaded Capacitor

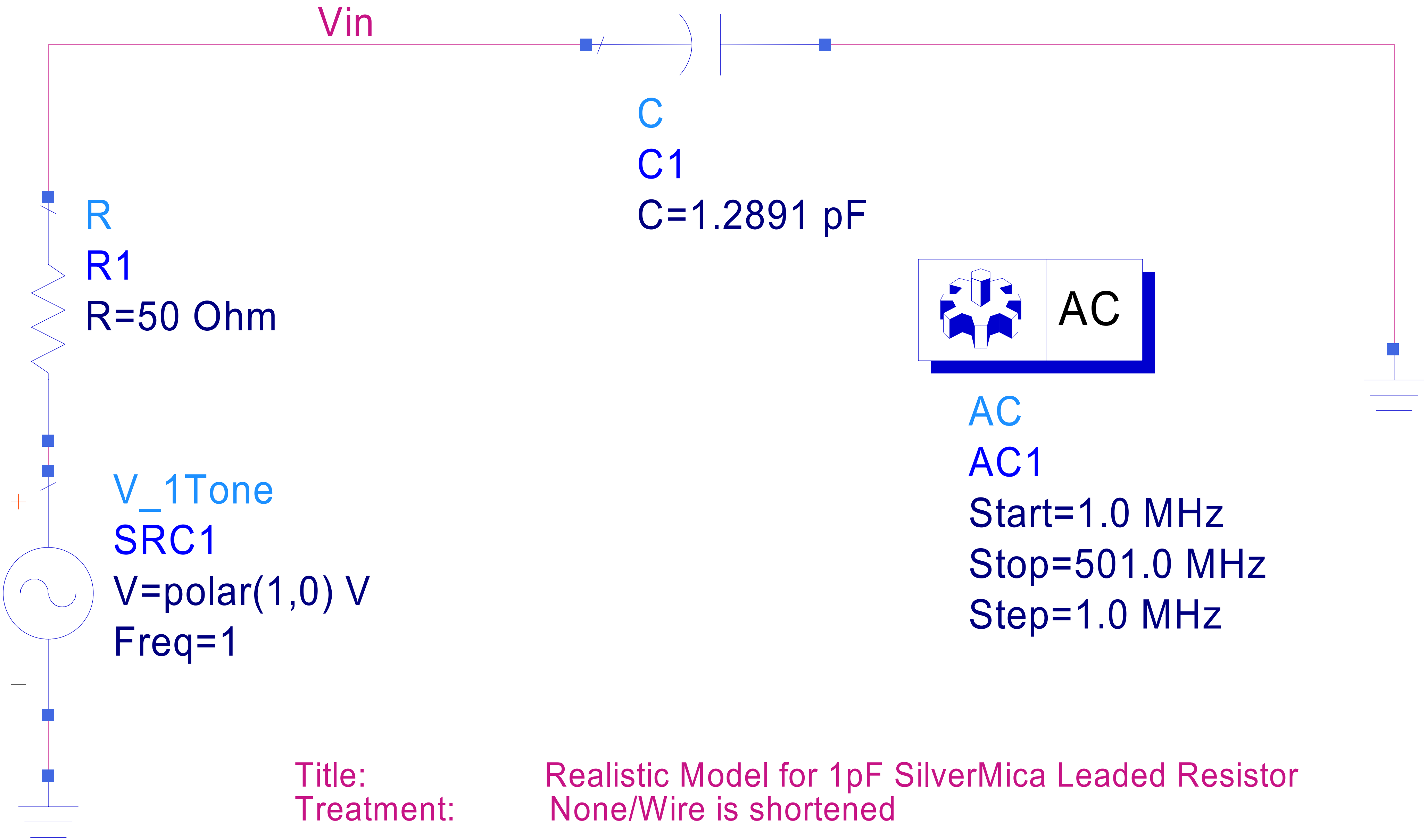
The following are the pictures of an original and after treatment 1pF SilverMica Leaded Capacitor.



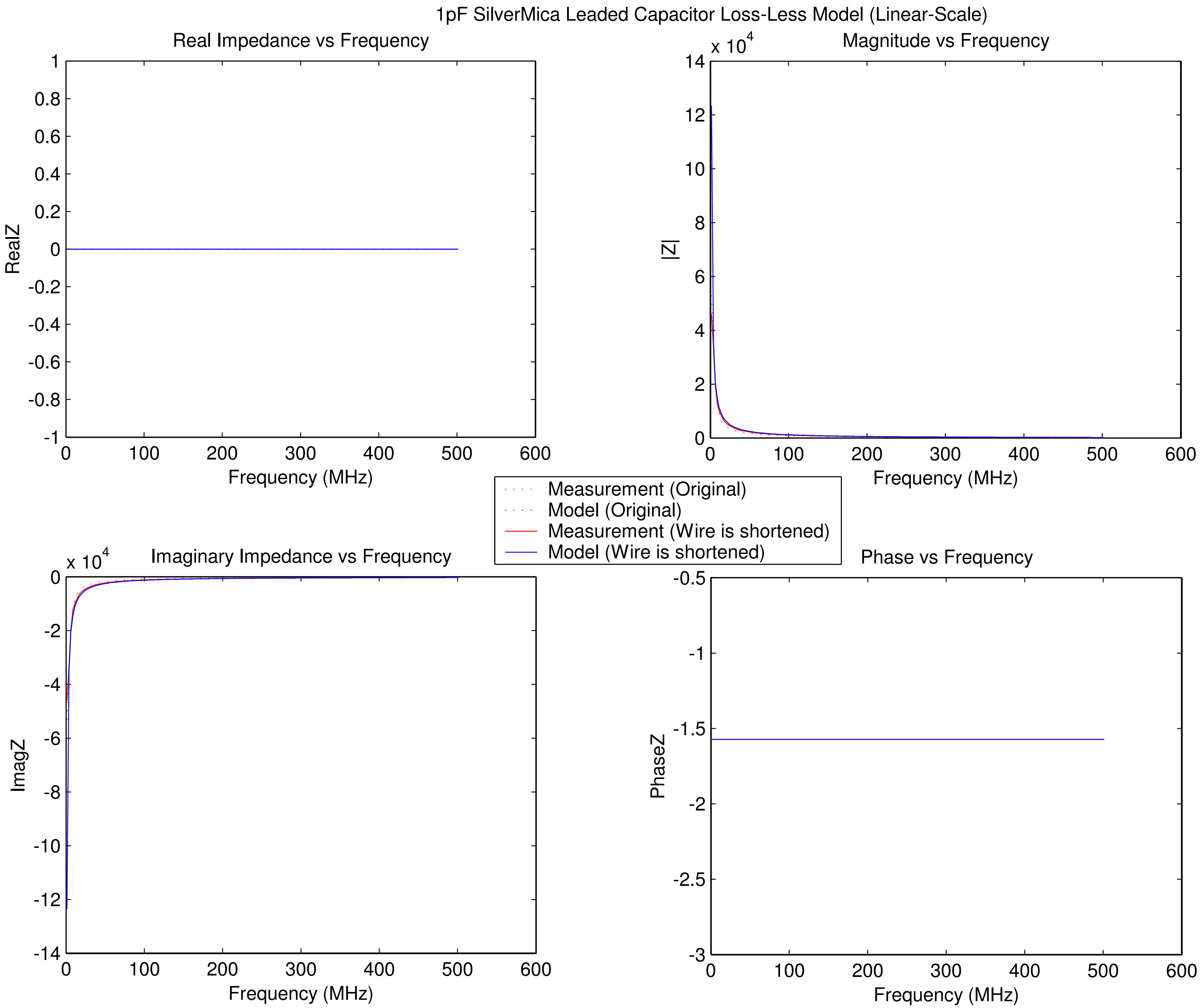
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result. Notice that both samples are treated as loss-less components and share the same model.

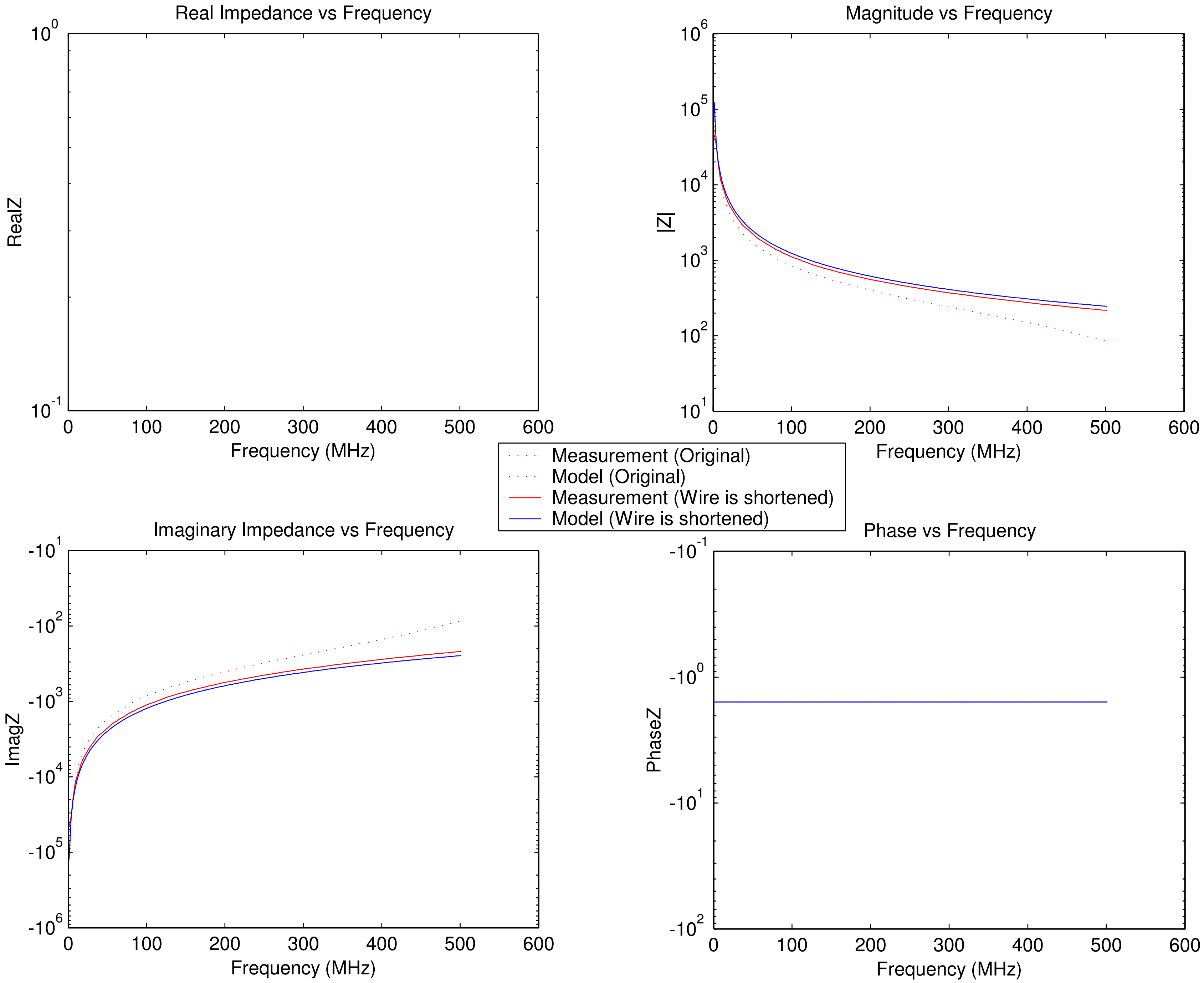
	Original	Wire is shortened
Normalization Treatment	Loss-Less	Loss-Less
Internal Resistance of Model (Ω)	∞	∞
Internal Inductance of Model (nH)	0.0000	0.0000
Internal Capacitance of Model (pF)	1.2891	1.2891
External Resistance of Model (Ω)	0.0000	0.0000
External Inductance from estimation (nH)	47.8615	0.2512
External Inductance of Model (nH)	0.0000	0.0000
External Capacitance from estimation (pF)	6.0809	0.0319
External Capacitance of Model (pF)	0.0000	0.0000
Legnth of Leaded Wire (mm)	32.9000	4.1800
Distance between two wires (mm)	7.6000	7.6000
Diameter of wire (mm)	0.3800	0.3800
R-Square Value of Real Impedance	1.0000	1.0000
R-Square Value of Imaginary Impedance	0.8791	0.8440
R-Square Value of Magnitude	0.8791	0.8440
R-Square Value of Phase	1.0000	1.0000

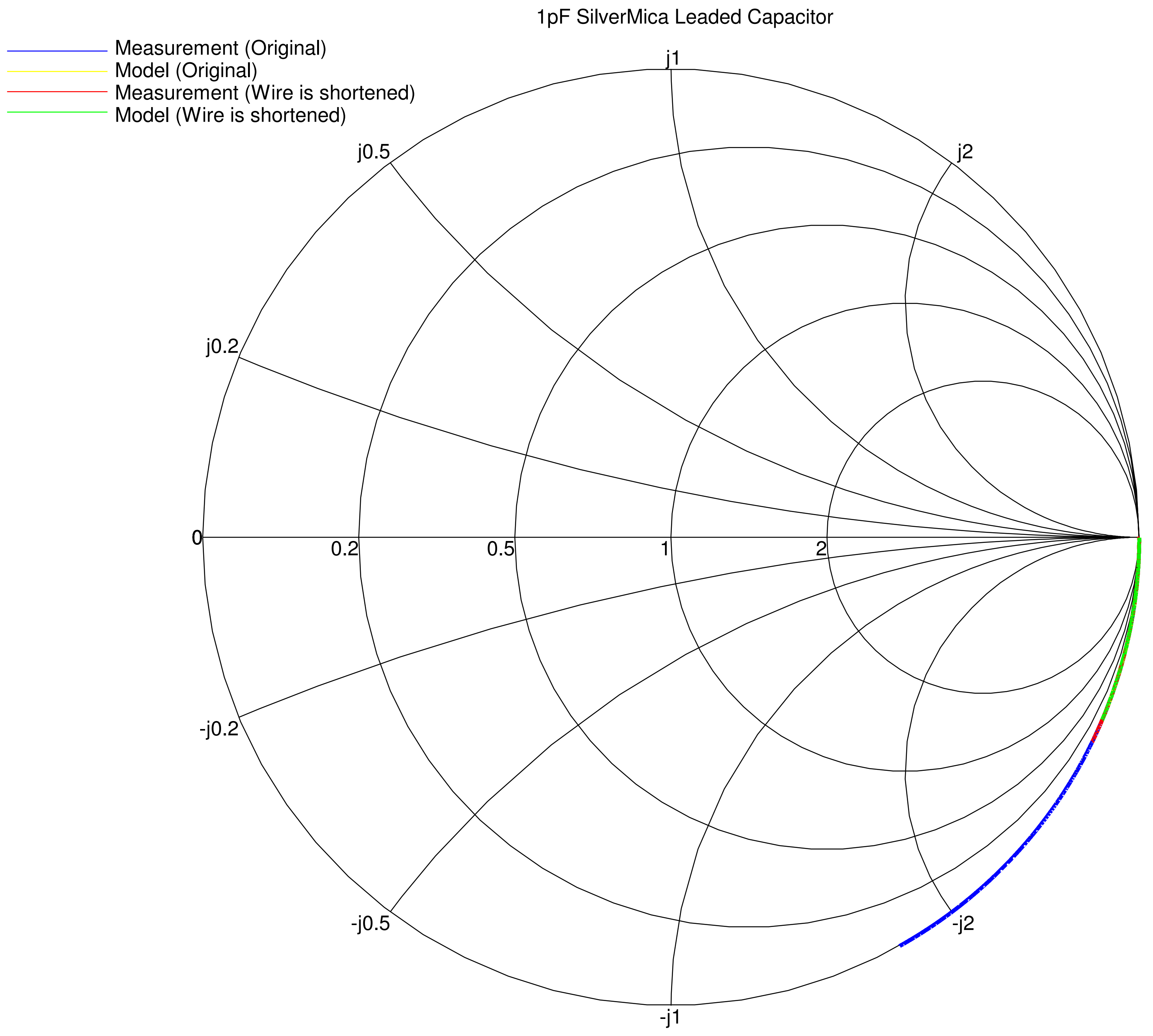


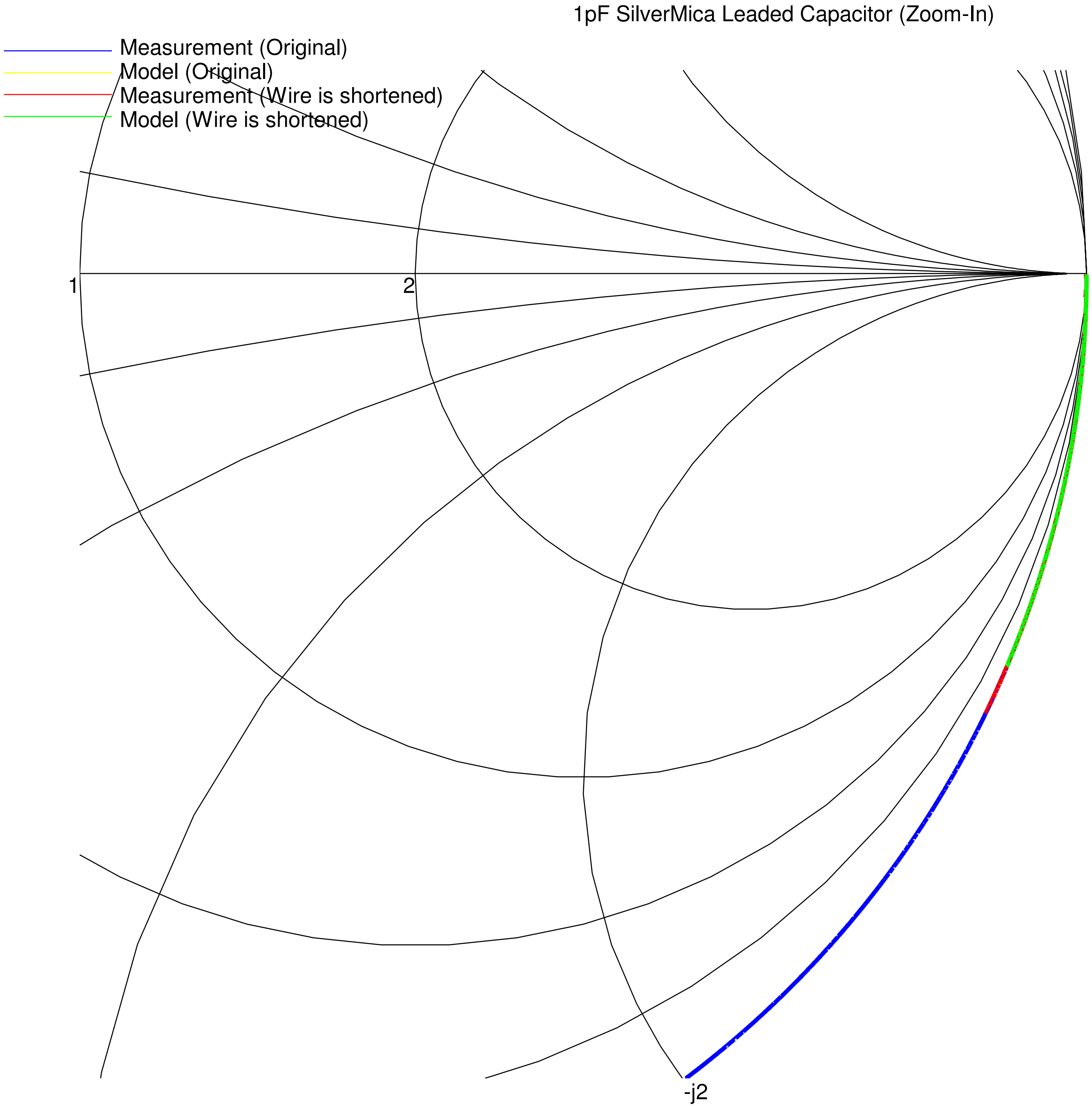
Title: Realistic Model for 1pF SilverMica Leaded Resistor
Treatment: None/Wire is shortened


1pF SilverMica Leaded Capacitor Loss-Less Model (Linear-Scale)
Real Impedance vs Frequency
RealZ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
x 10^4
|Z|
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
x 10^4
ImagZ
0
-2
-4
-6
-8
-10
-12
-14
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
-0.5
-1
-1.5
-2
-2.5
-3
0
100
200
300
400
500
600
Frequency (MHz)

1pF SilverMica Leaded Capacitor Loss-Less Model (Log-Scale)




1pF SilverMica Leaded Capacitor


1pF SilverMica Leaded Capacitor (Zoom-In)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
1
2
-j2

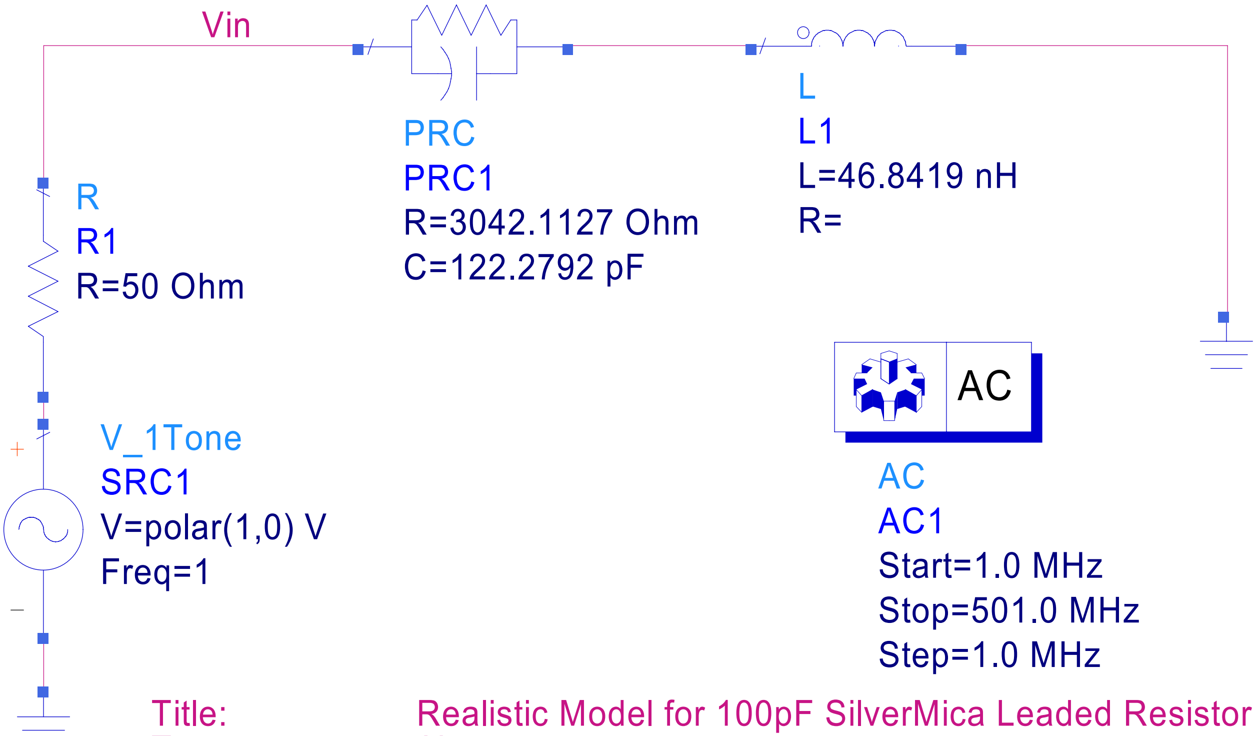
2.4.3 100pF SilverMica Leaded Capacitor

The following are the pictures of an original and after treatment 100pF SilverMica Leaded Capacitor.

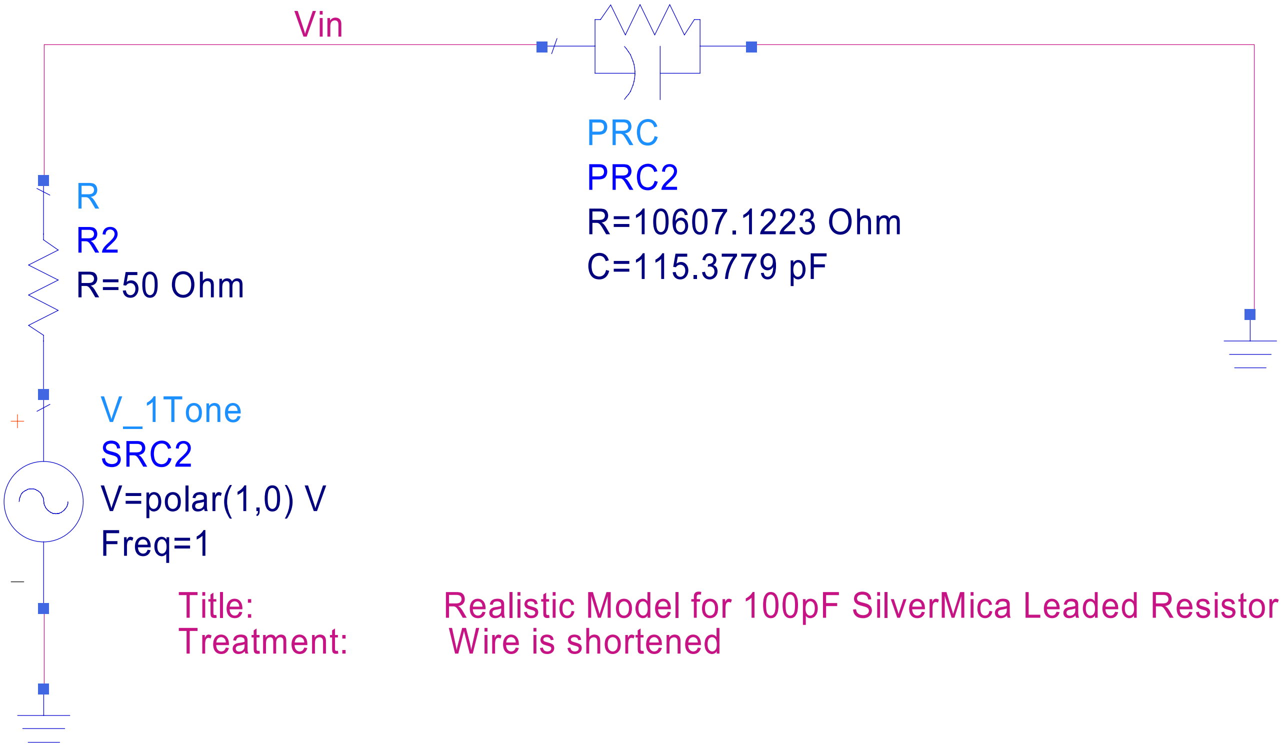
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result:

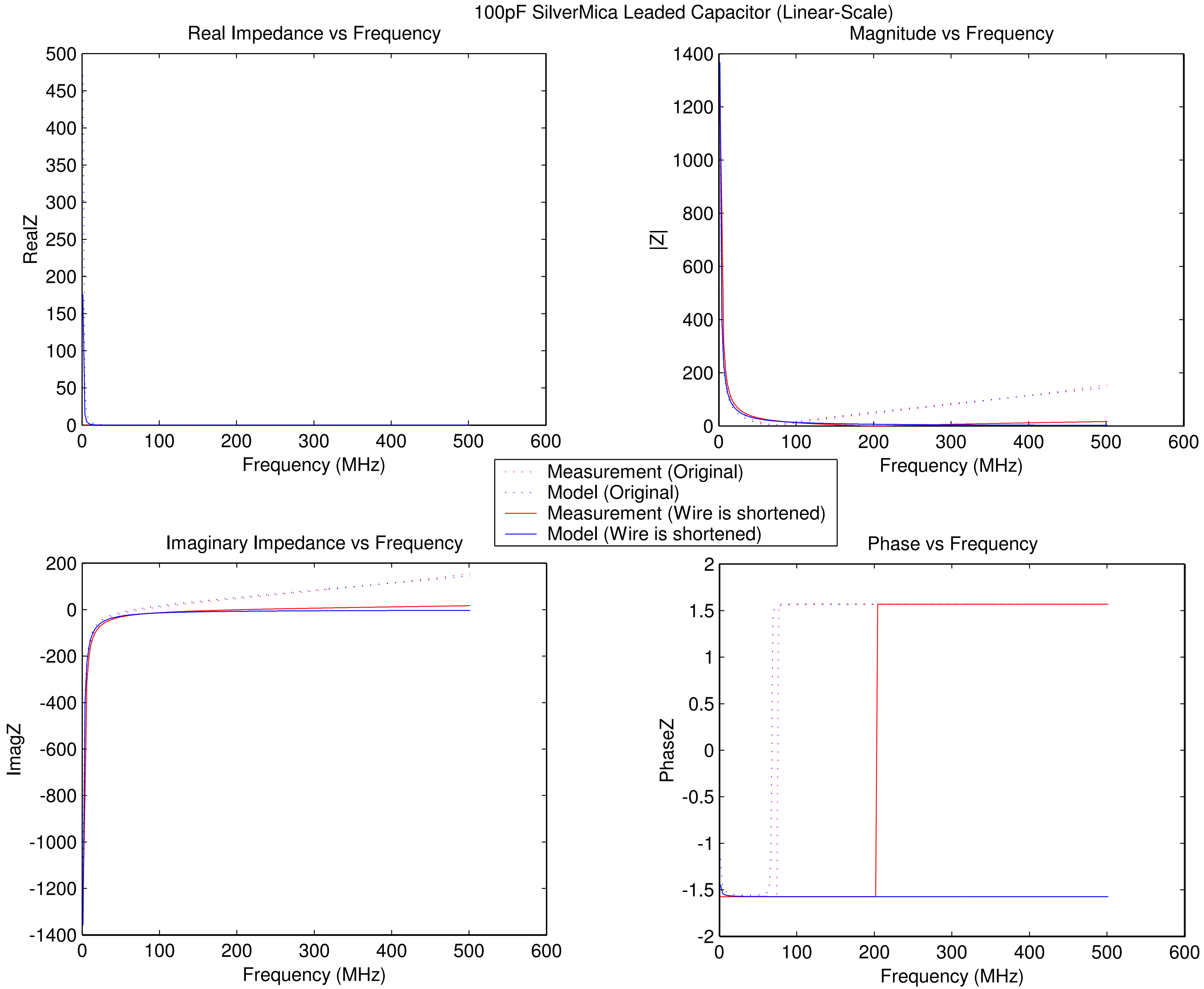
	Original	Wire is shortened
Normalization Treatment	Partial	Partial
Internal Resistance of Model (Ω)	3042.1127	10607.1223
Internal Inductance of Model (nH)	0.0000	0.0000
Internal Capacitance of Model (pF)	122.2792	115.3779
External Resistance of Model (Ω)	0.0000	0.0000
External Inductance from estimation (nH)	48.7589	5.2195
External Inductance of Model (nH)	46.8420	0.0000
External Capacitance from estimation (pF)	0.2577	0.0276
External Capacitance of Model (pF)	0.0000	0.0000
Legnth of Leaded Wire (mm)	33.6300	3.6000
Distance between two wires (mm)	7.7100	7.7100
Diameter of wire (mm)	0.3900	0.3900
R-Square Value of Real Impedance	0.1454	0.8780
R-Square Value of Imaginary Impedance	0.9623	0.9166
R-Square Value of Magnitude	0.9294	0.9178
R-Square Value of Phase	0.8864	0.0426

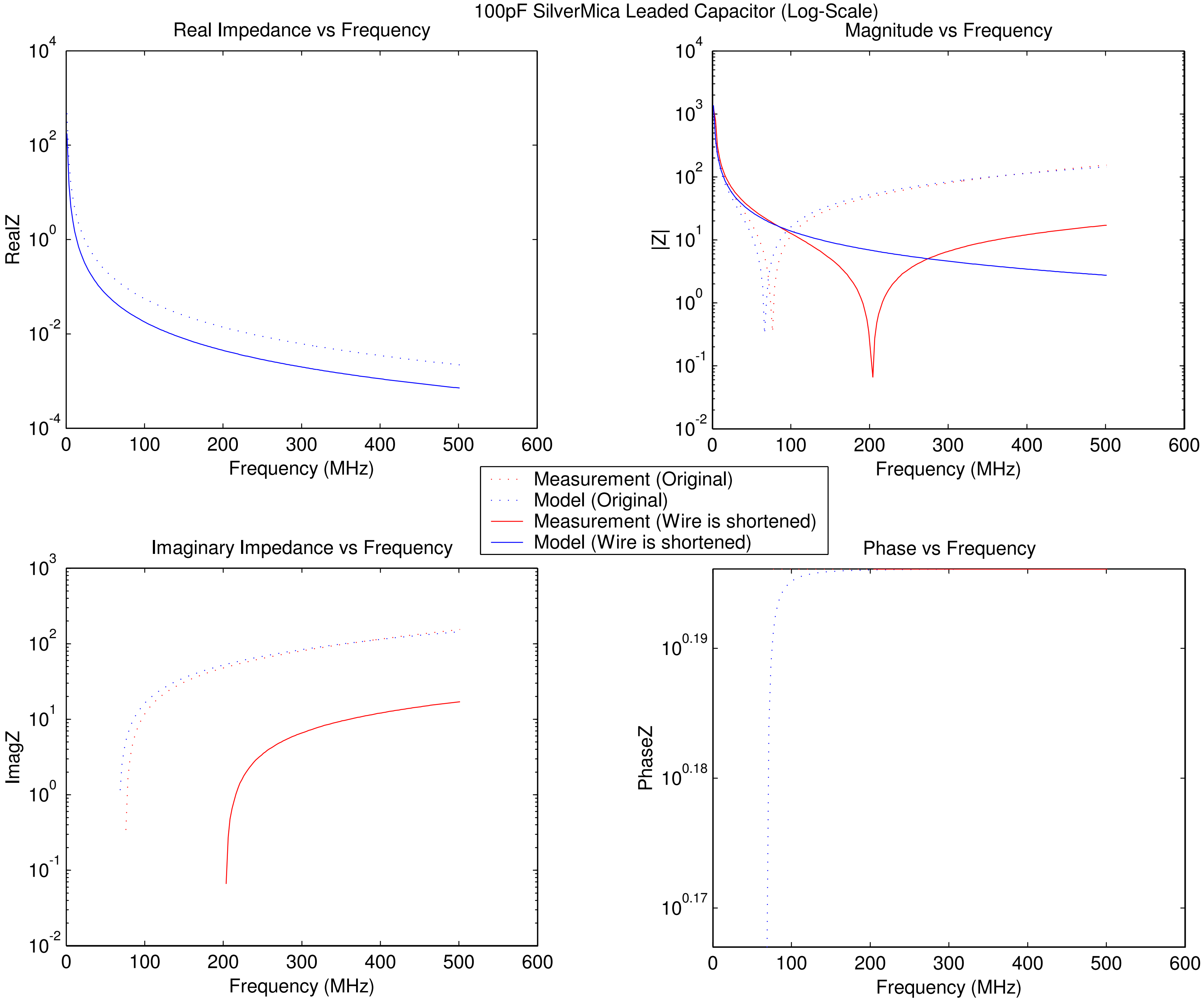


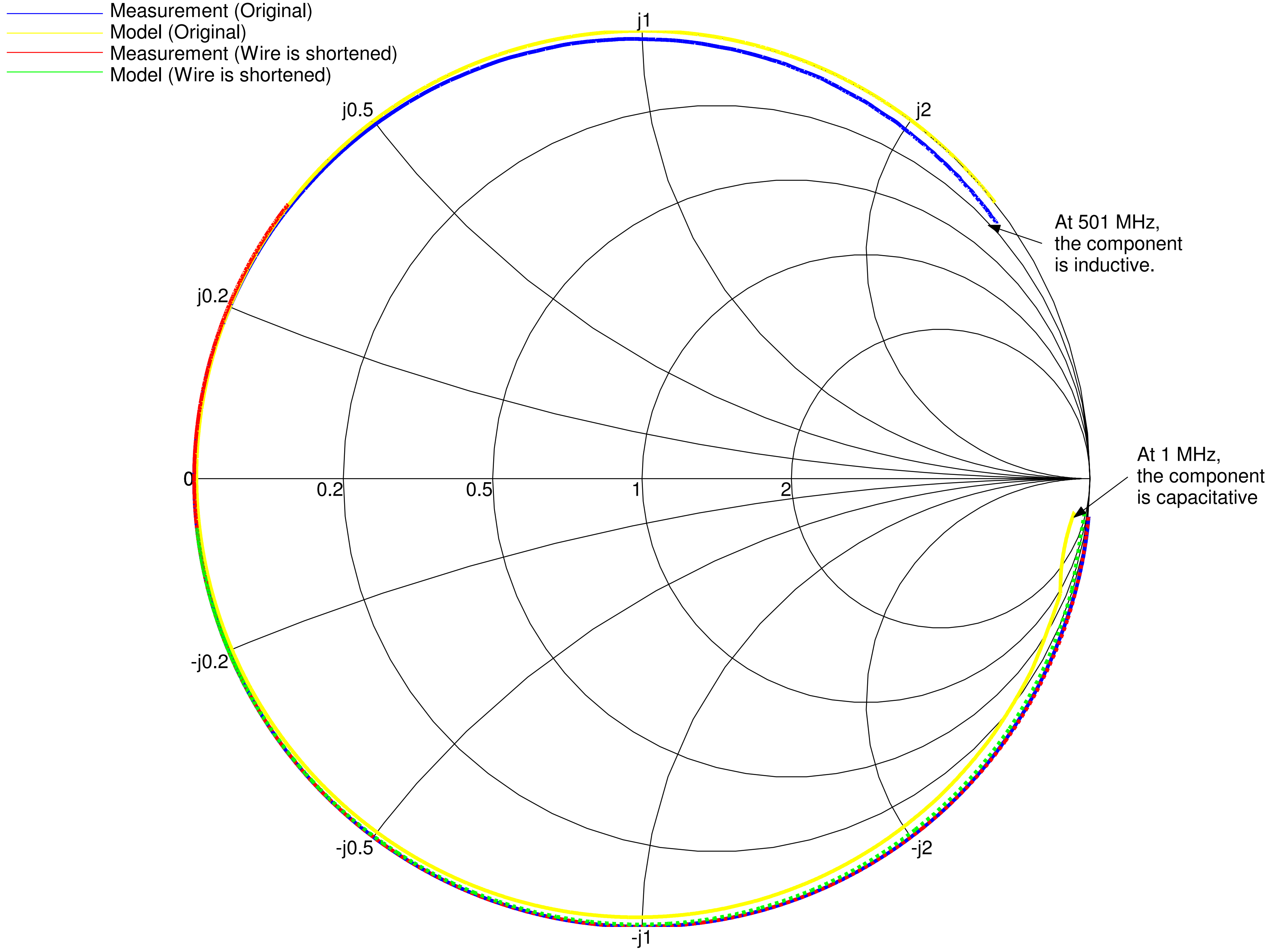
Title: Realistic Model for 100pF SilverMica Leaded Resistor
Treatment: None



Title: Realistic Model for 100pF SilverMica Leaded Resistor
Treatment: Wire is shortened


100pF SilverMica Leaded Capacitor (Linear-Scale)
Real Impedance vs Frequency
RealZ
500
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
200
0
-200
-400
-600
-800
-1000
-1200
-1400
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)


100pF SilverMica Leaded Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
$10^{0.19}$
$10^{0.18}$
$10^{0.17}$
0
100
200
300
400
500
600
Frequency (MHz)



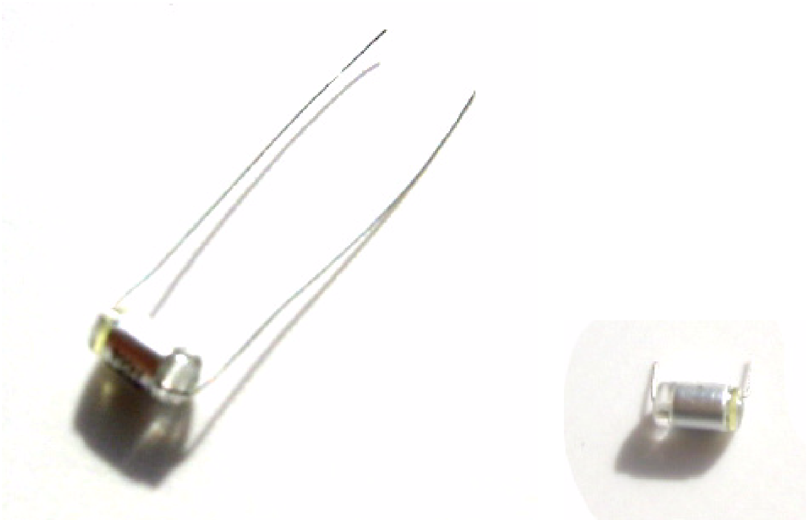
100pF SilverMica Leaded Capacitor

At 501 MHz, the component is inductive.

At 1 MHz, the component is capacitative

2.4.4 100pF Polystene Leaded Capacitor

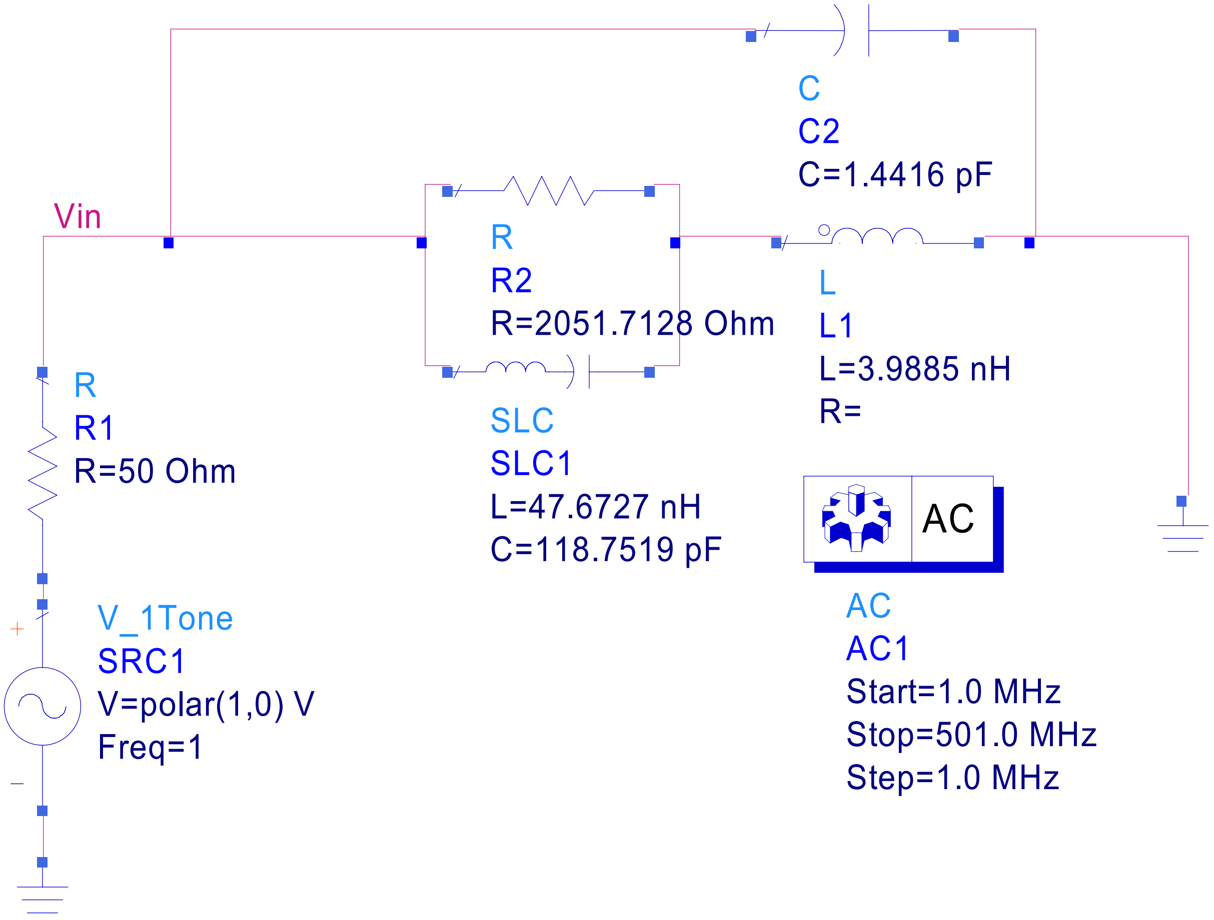
The following are the pictures of an original and after treatment 100pF Polystrene Leaded Capacitor.



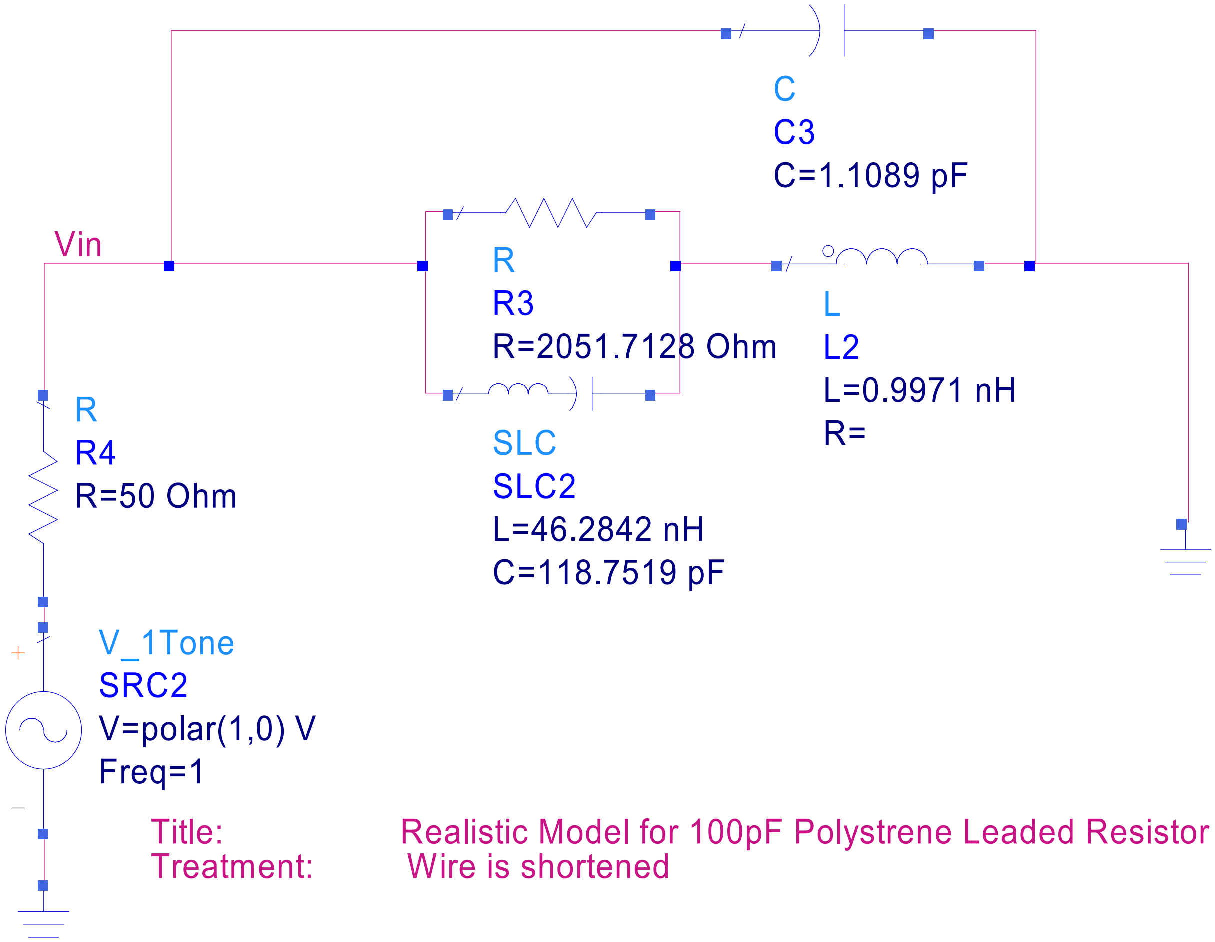
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result:

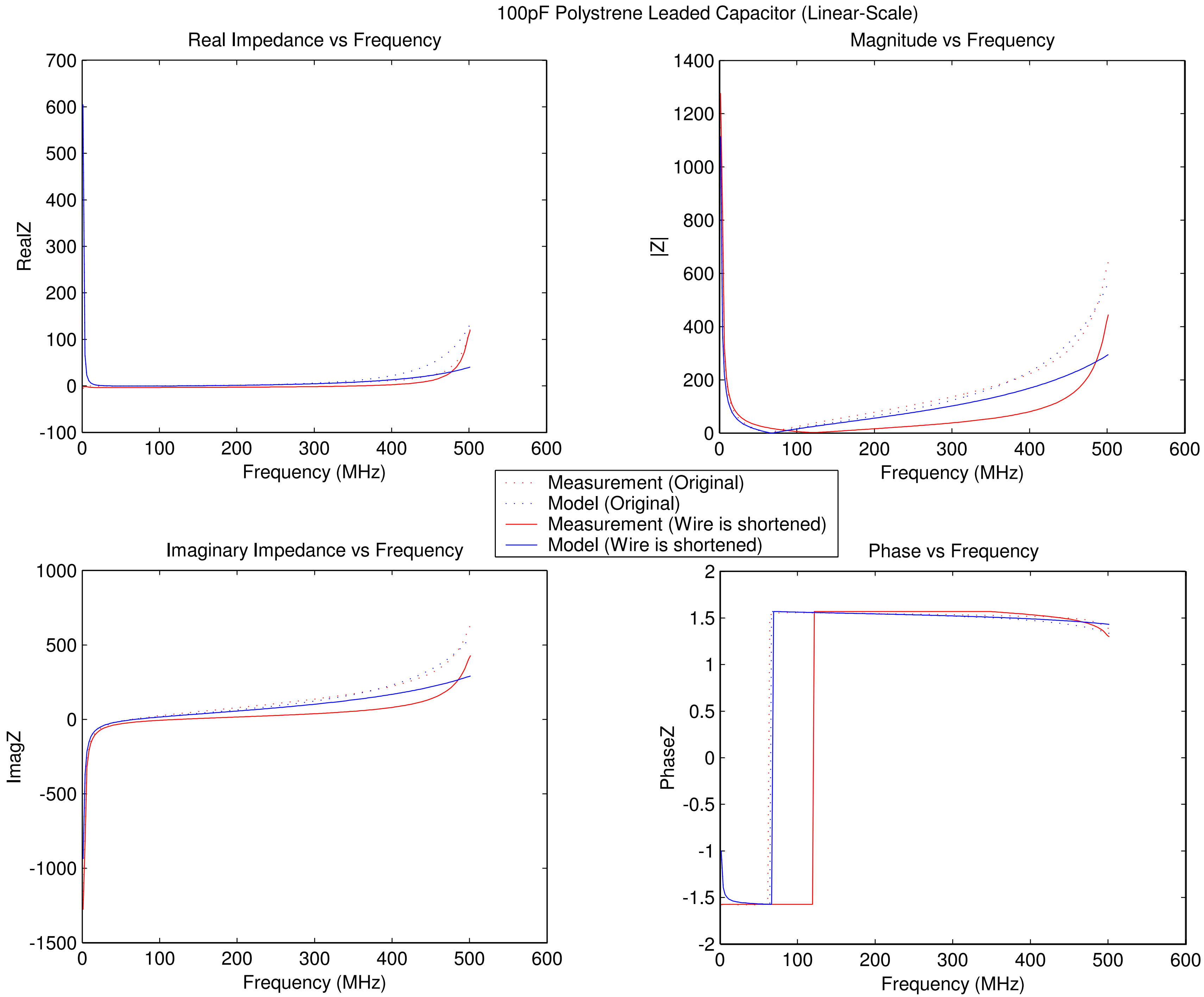
	Original	Wire is shortened
Normalization Treatment	Partial	Partial
Internal Resistance of Model (Ω)	2051.7128	2051.7128
Internal Inductance of Model (nH)	47.6727	46.2842
Internal Capacitance of Model (pF)	118.7519	118.7519
External Resistance of Model (Ω)	0.0000	0.0000
External Inductance from estimation (nH)	55.6054	7.0416
External Inductance of Model (nH)	3.9885	0.9971
External Capacitance from estimation (pF)	0.2386	0.0305
External Capacitance of Model (pF)	1.4416	1.1089
Legnth of Leaded Wire (mm)	34.5600	4.4000
Distance between two wires (mm)	7.8100	7.6500
Diameter of wire (mm)	0.2700	0.2700
R-Square Value of Real Impedance	0.2102	0.0235
R-Square Value of Imaginary Impedance	0.9620	0.8961
R-Square Value of Magnitude	0.9557	0.8085
R-Square Value of Phase	0.9531	0.4789



Title: Realistic Model for 100pF Polystrene Leaded Resistor
Treatment: None



Title: Realistic Model for 100pF Polystrene Leaded Resistor
Treatment: Wire is shortened



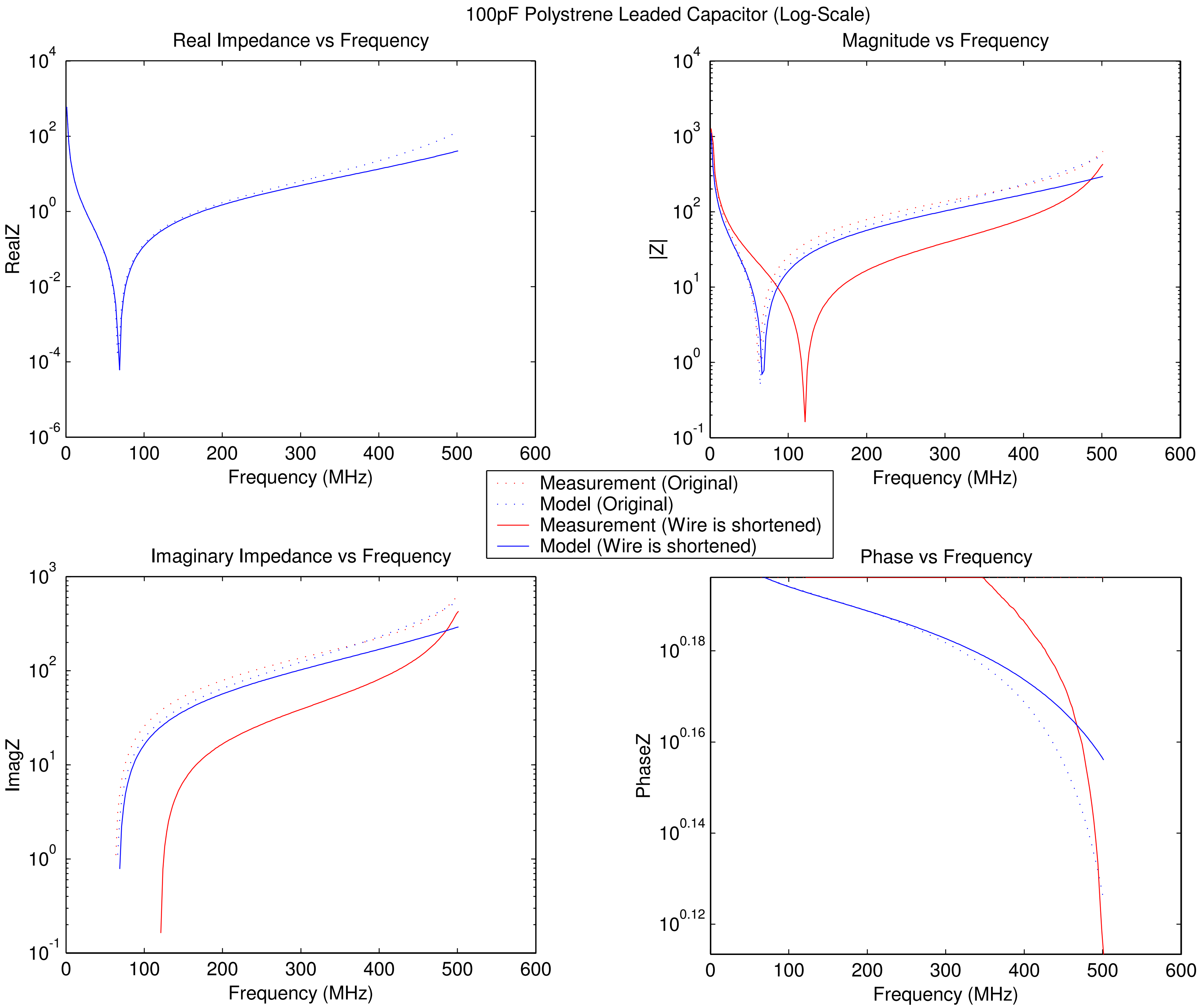
100pF Polystrene Leaded Capacitor (Linear-Scale)

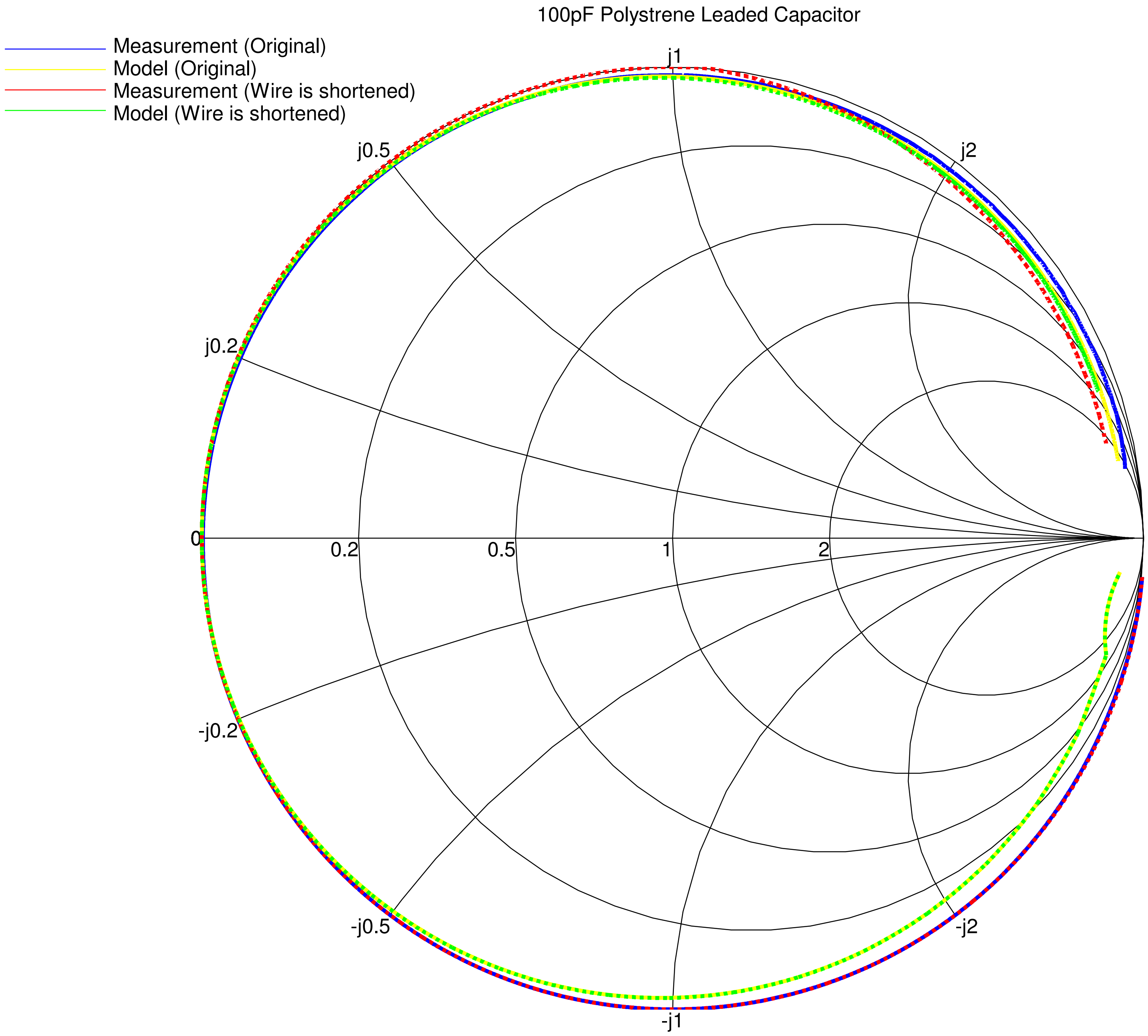
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

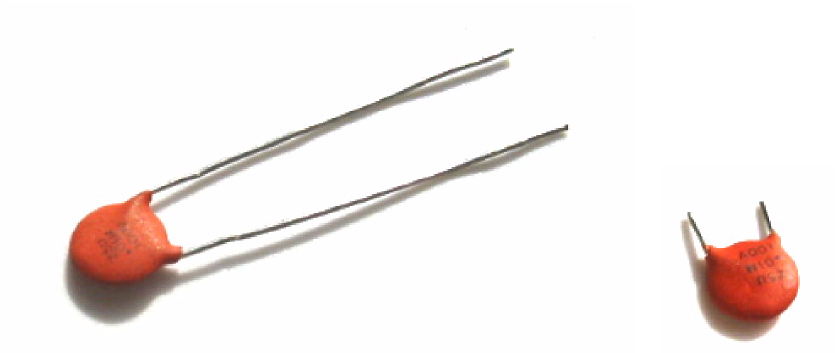
Phase vs Frequency


100pF Polystrene Leaded Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
10^4
10^3
10^2
10^1
10^0
10^{-1}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
10^3
10^2
10^1
10^0
10^{-1}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
$10^{0.18}$
$10^{0.16}$
$10^{0.14}$
$10^{0.12}$
0
100
200
300
400
500
600
Frequency (MHz)


100pF Polystrene Leaded Capacitor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

2.4.5 0.01μF Ceramic Disk Leaded Capacitor

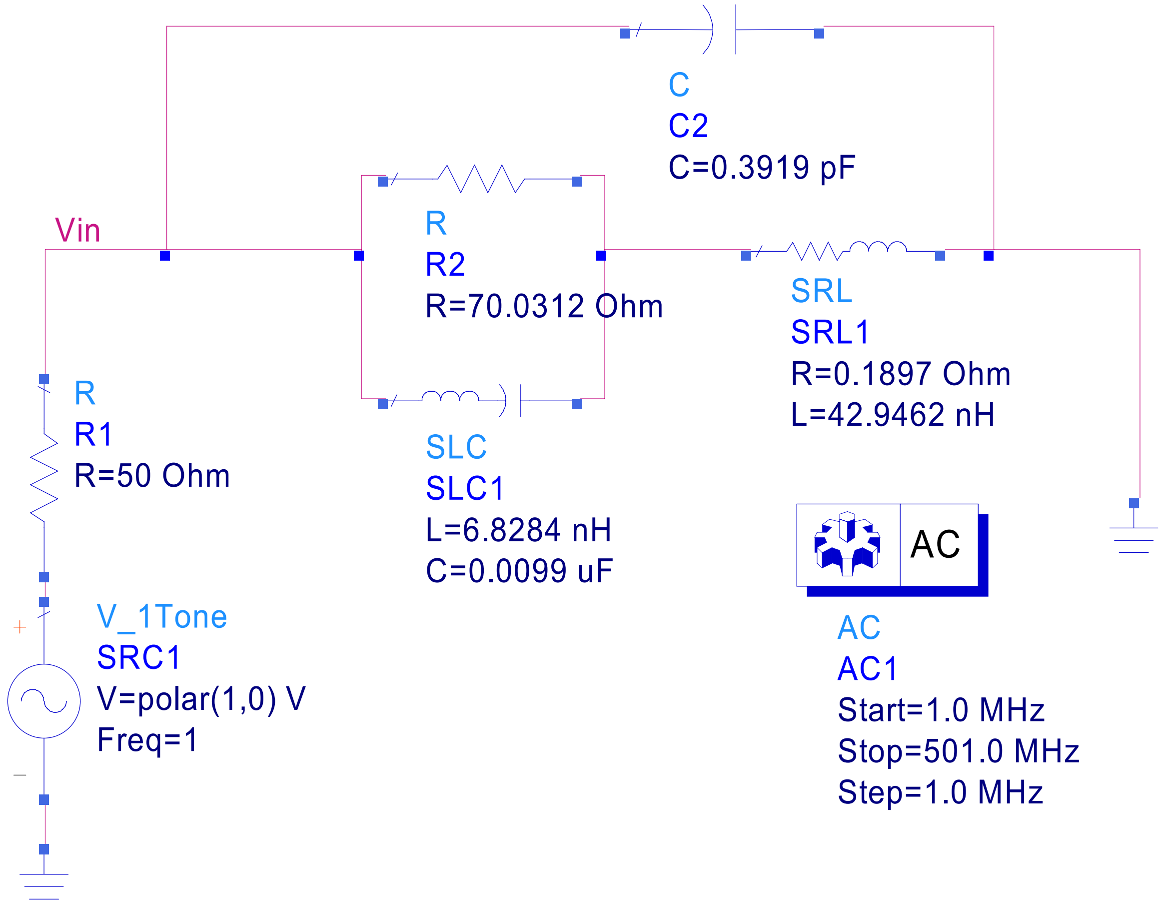
The following are the pictures of an original and after treatment 0.01μF Ceramic Disk Leaded Capacitor.



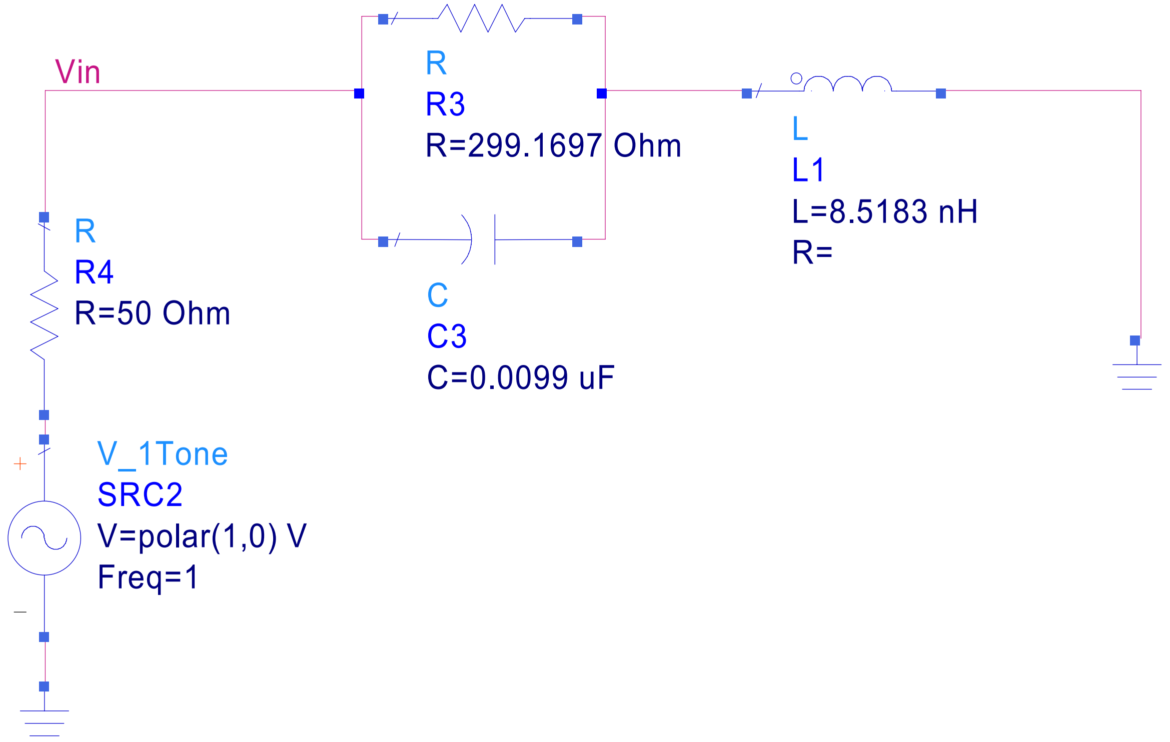
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

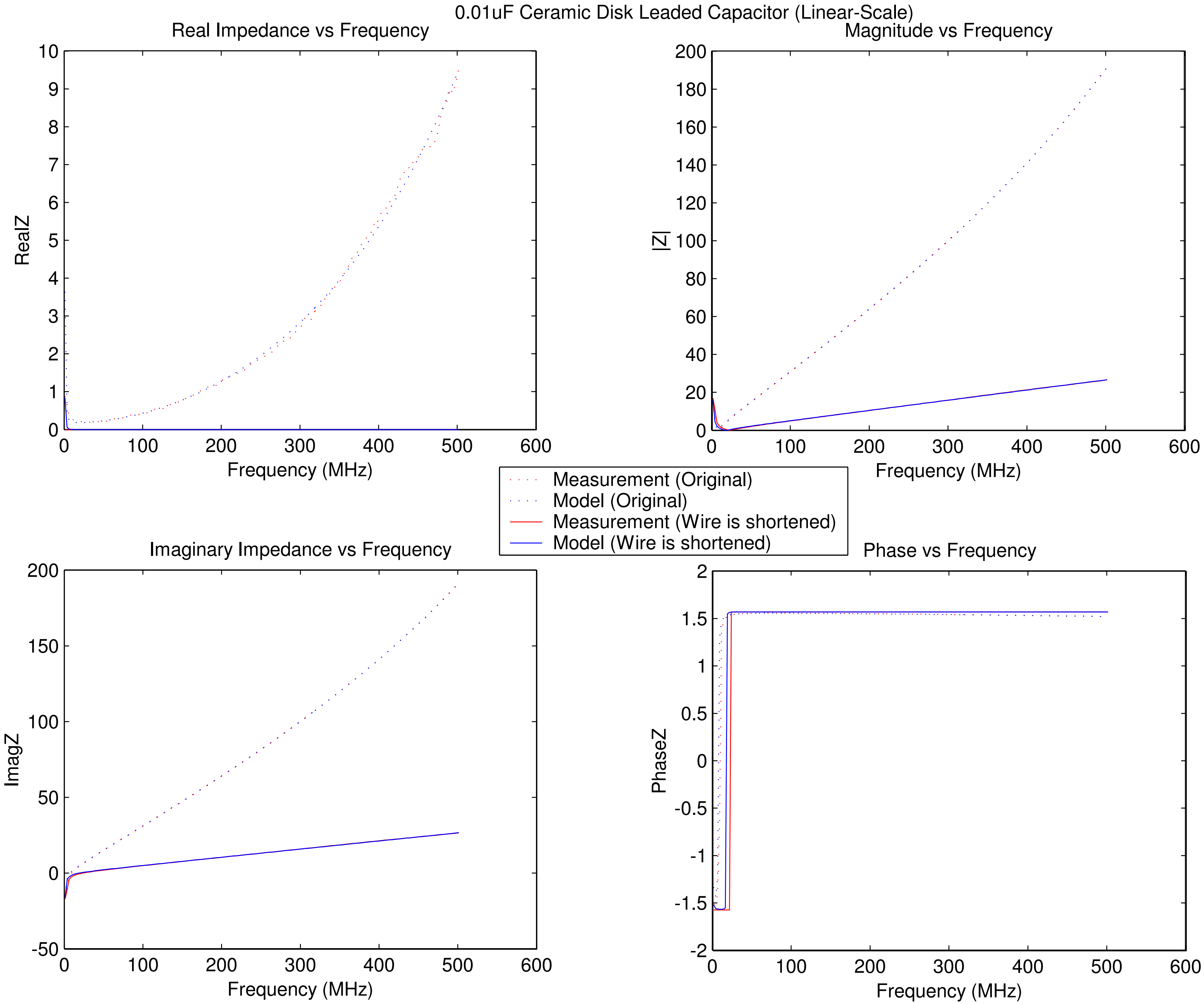
	Original	Wire is shortened
Normalization Treatment	None	Partial
Internal Resistance of Model (Ω)	70.0312	299.1697
Internal Inductance of Model (nH)	6.8284	0.0000
Internal Capacitance of Model (pF)	0.00995	0.00995
External Resistance of Model (Ω)	0.1898	0.0000
External Inductance from estimation (nH)	48.6216	0.3287
External Inductance of Model (nH)	42.9463	8.5183
External Capacitance from estimation (pF)	7.2426	0.0490
External Capacitance of Model (pF)	0.3919	0.0000
Legnth of Leaded Wire (mm)	37.9300	5.6500
Distance between two wires (mm)	8.1400	8.1400
Diameter of wire (mm)	0.6100	0.6100
R-Square Value of Real Impedance	0.9924	0.0000
R-Square Value of Imaginary Impedance	0.9999	0.9971
R-Square Value of Magnitude	0.9999	0.9958
R-Square Value of Phase	0.8824	0.8238



Title: Realistic Model for 0.01uF CeramicDisk Leaded Resistor
Treatment: None



Title: Realistic Model for 0.01uF CeramicDisk Leaded Resistor
Treatment: Wire is shortened

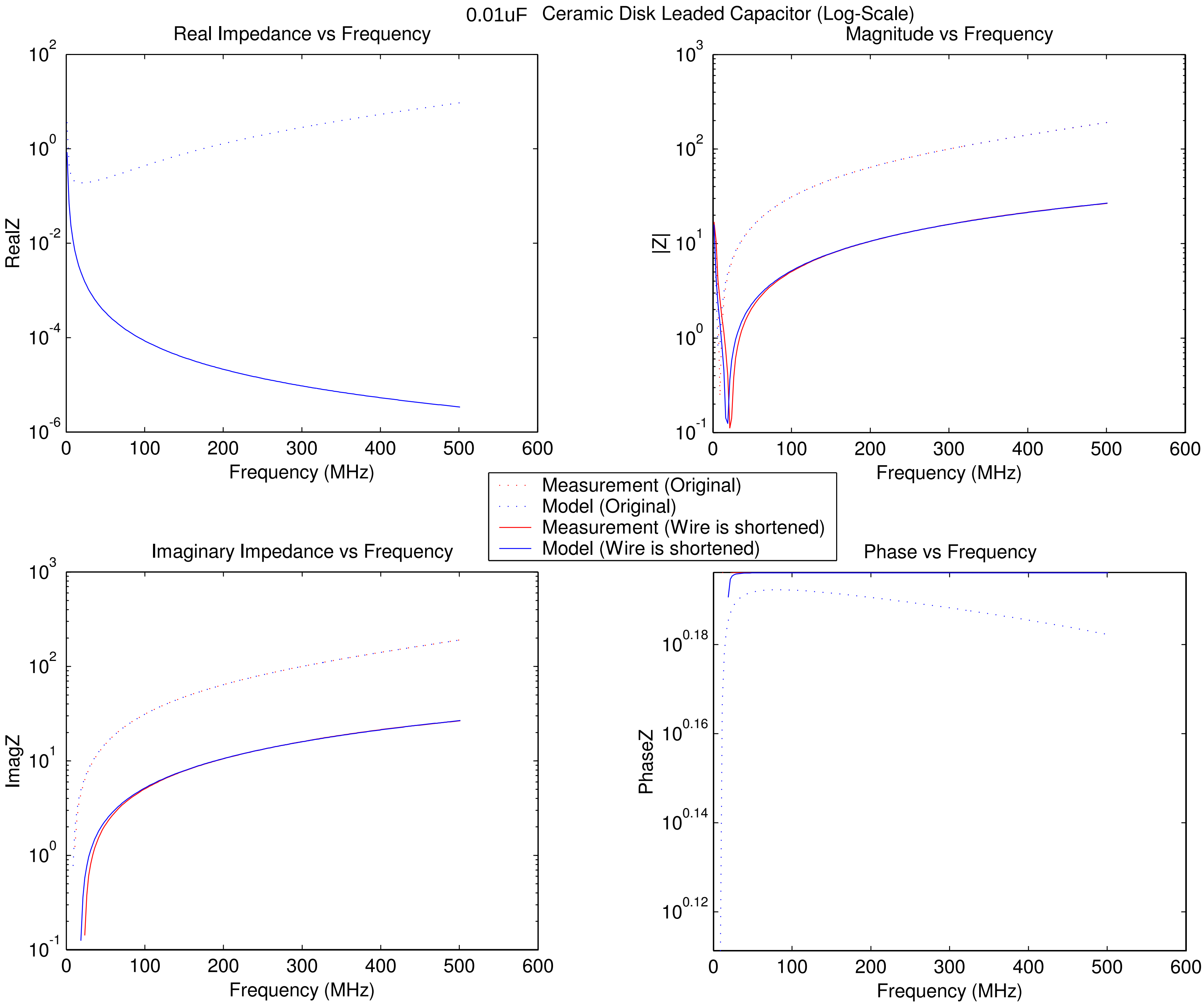

0.01uF Ceramic Disk Leaded Capacitor (Linear-Scale)

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency



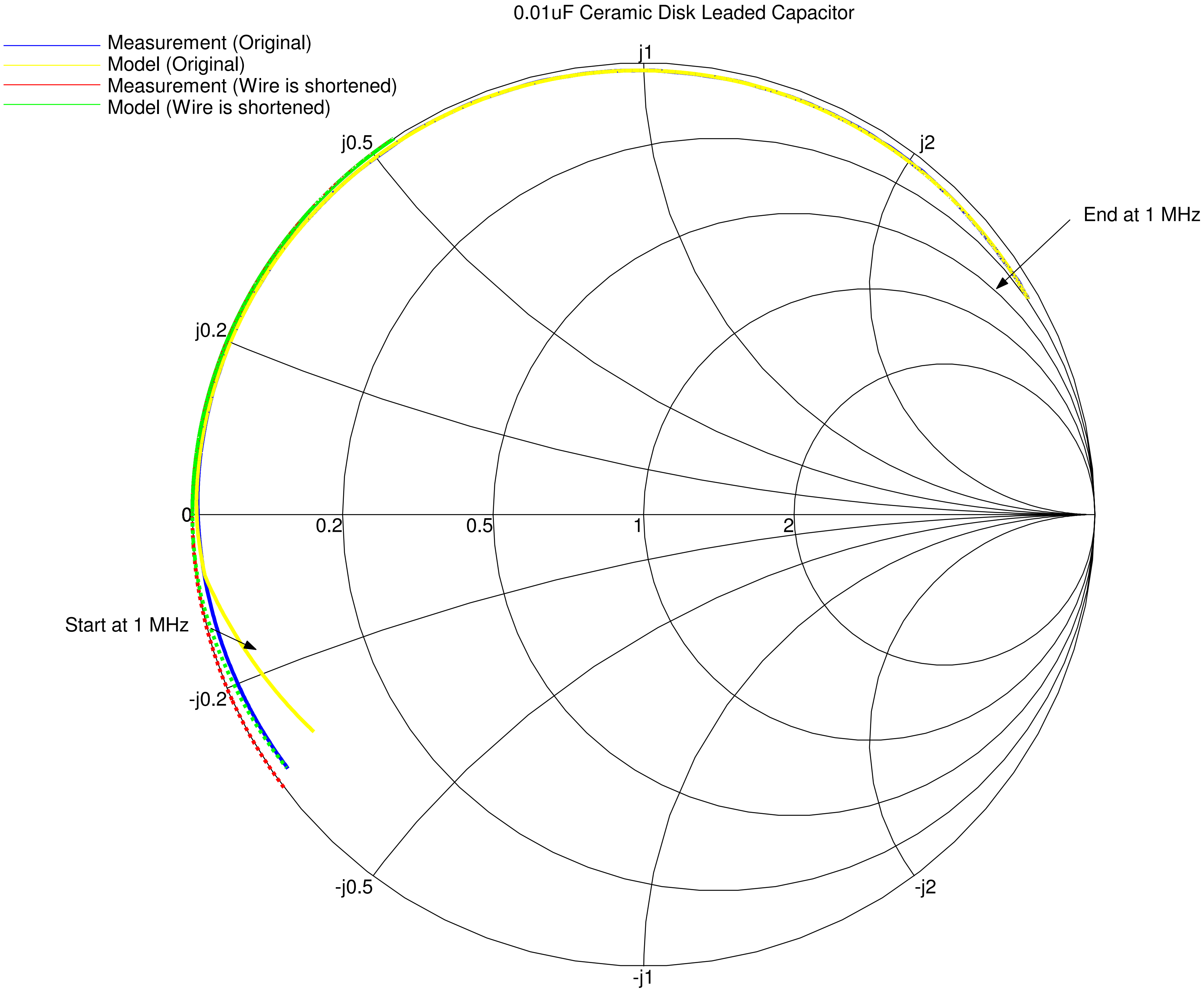
0.01uF Ceramic Disk Leaded Capacitor (Log-Scale)

Real Impedance vs Frequency

Magnitude vs Frequency

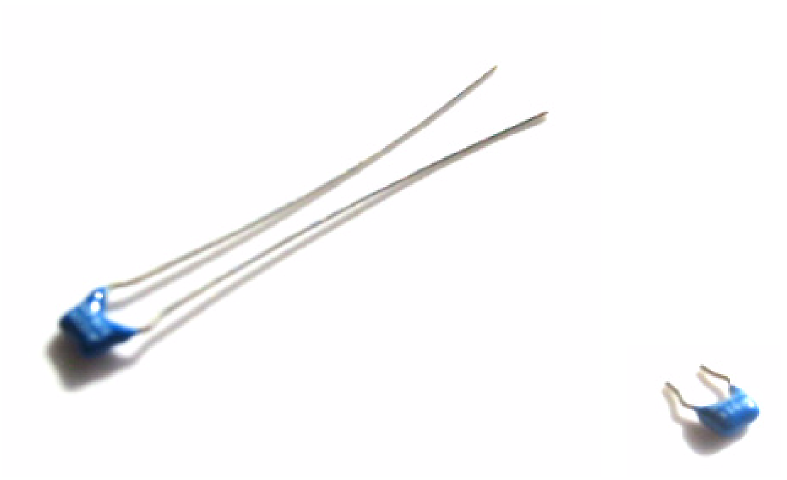
Imaginary Impedance vs Frequency

Phase vs Frequency


0.01uF Ceramic Disk Leaded Capacitor

2.4.6 0.01μF Monolithic Leaded Capacitor

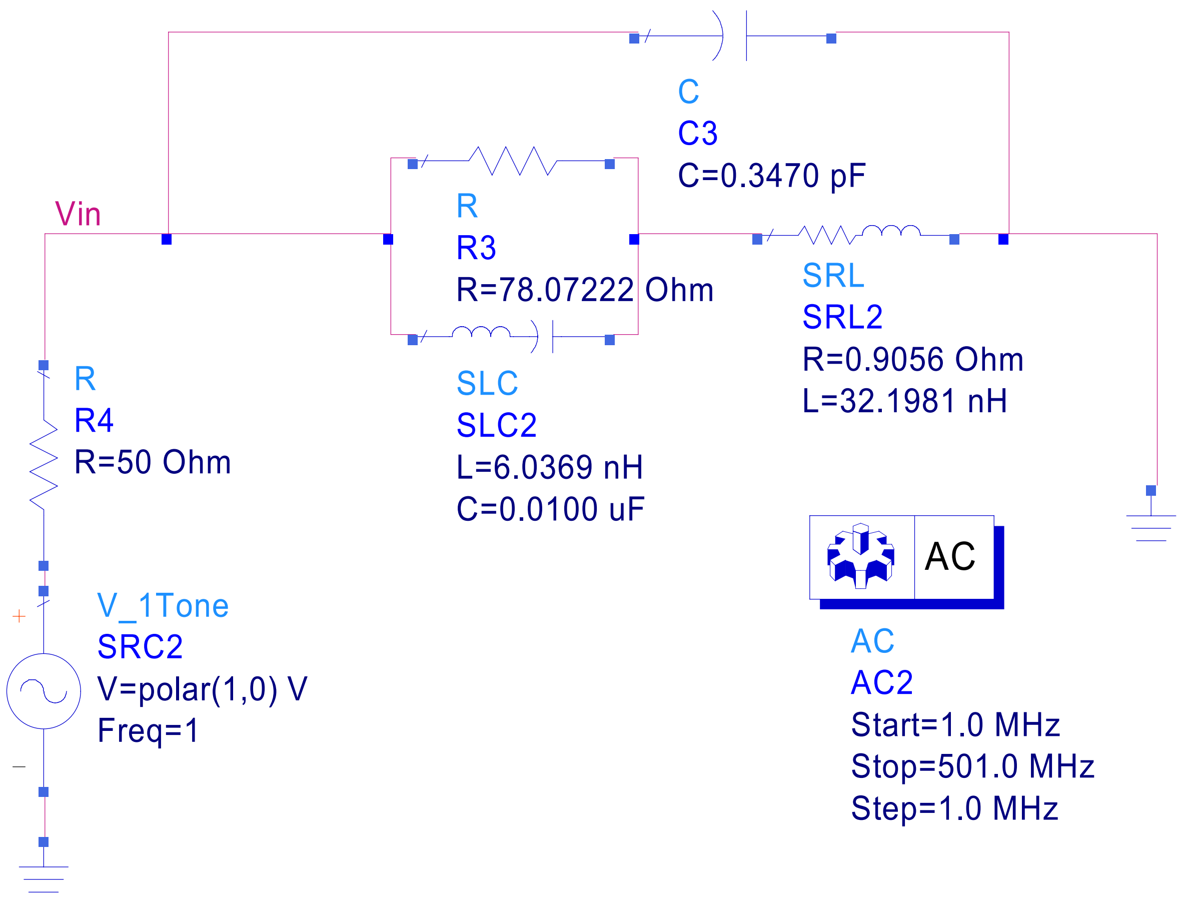
The following are the pictures of an original and after treatment 0.01μF Monolithic Leaded Capacitor.



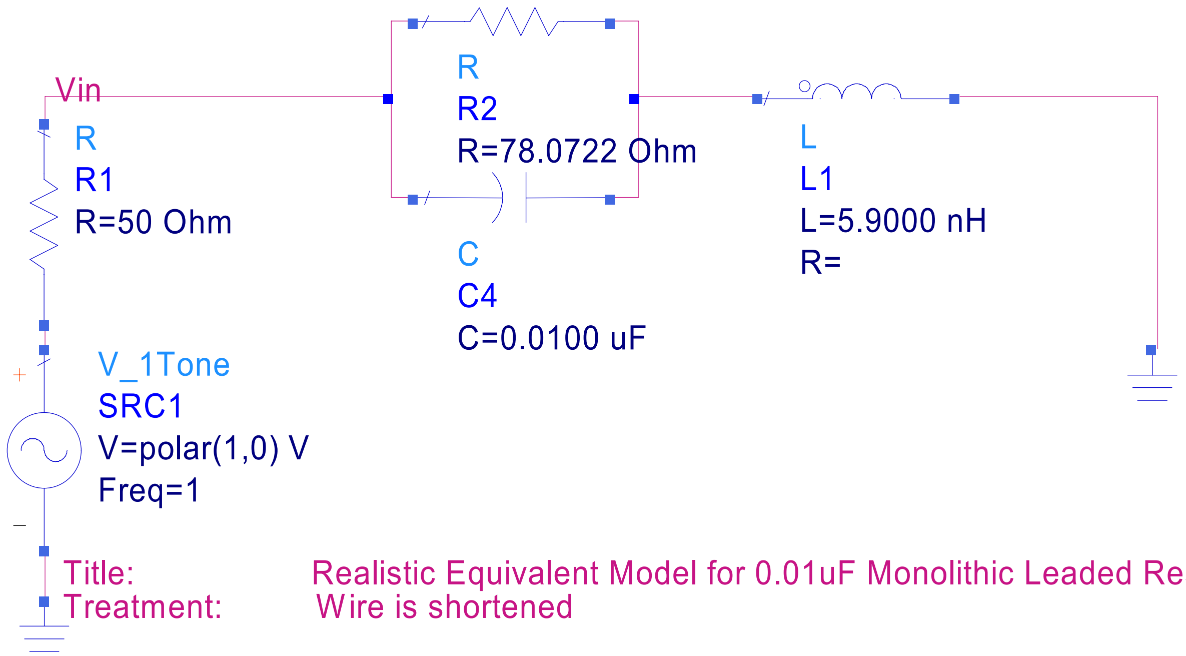
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

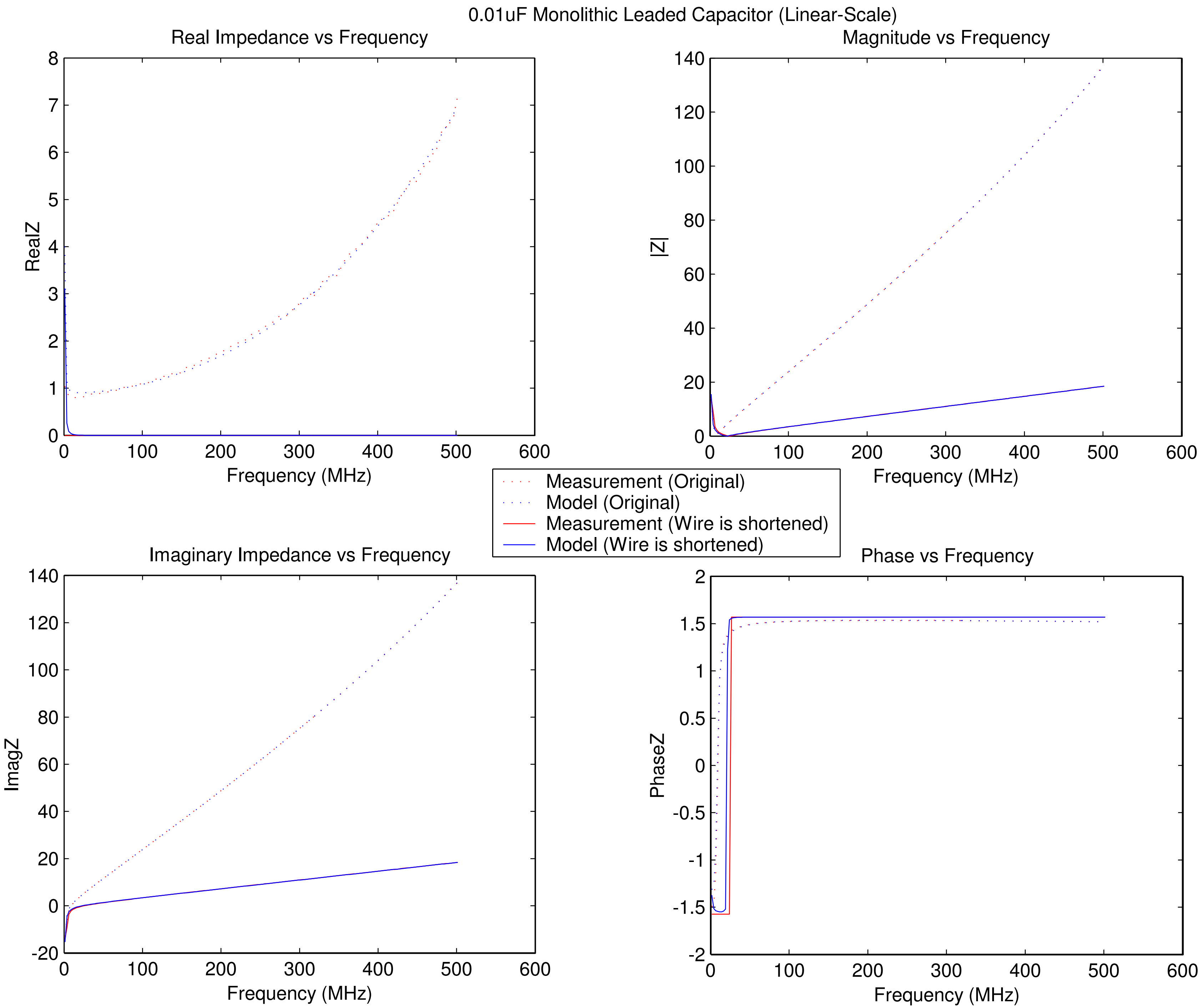
	Original	Wire is shortened
Normalization Treatment	Partial	Partial
Internal Resistance of Model (Ω)	78.0722	78.0722
Internal Inductance of Model (nH)	6.0370	0.0000
Internal Capacitance of Model (μF)	0.0100013835	0.0100013835
External Resistance of Model (Ω)	0.9057	0.0000
External Inductance from estimation (nH)	32.6019	0.1566
External Inductance of Model (nH)	32.1981	5.9000
External Capacitance from estimation (pF)	6.4714	0.0312
External Capacitance of Model (pF)	0.3471	0.0000
Legnth of Leaded Wire (mm)	21.4400	4.2600
Distance between two wires (mm)	11.2300	11.1900
Diameter of wire (mm)	0.4800	0.4800
R-Square Value of Real Impedance	0.9843	0.0000
R-Square Value of Imaginary Impedance	0.9999	0.9967
R-Square Value of Magnitude	0.9999	0.9957
R-Square Value of Phase	0.9972	0.8861

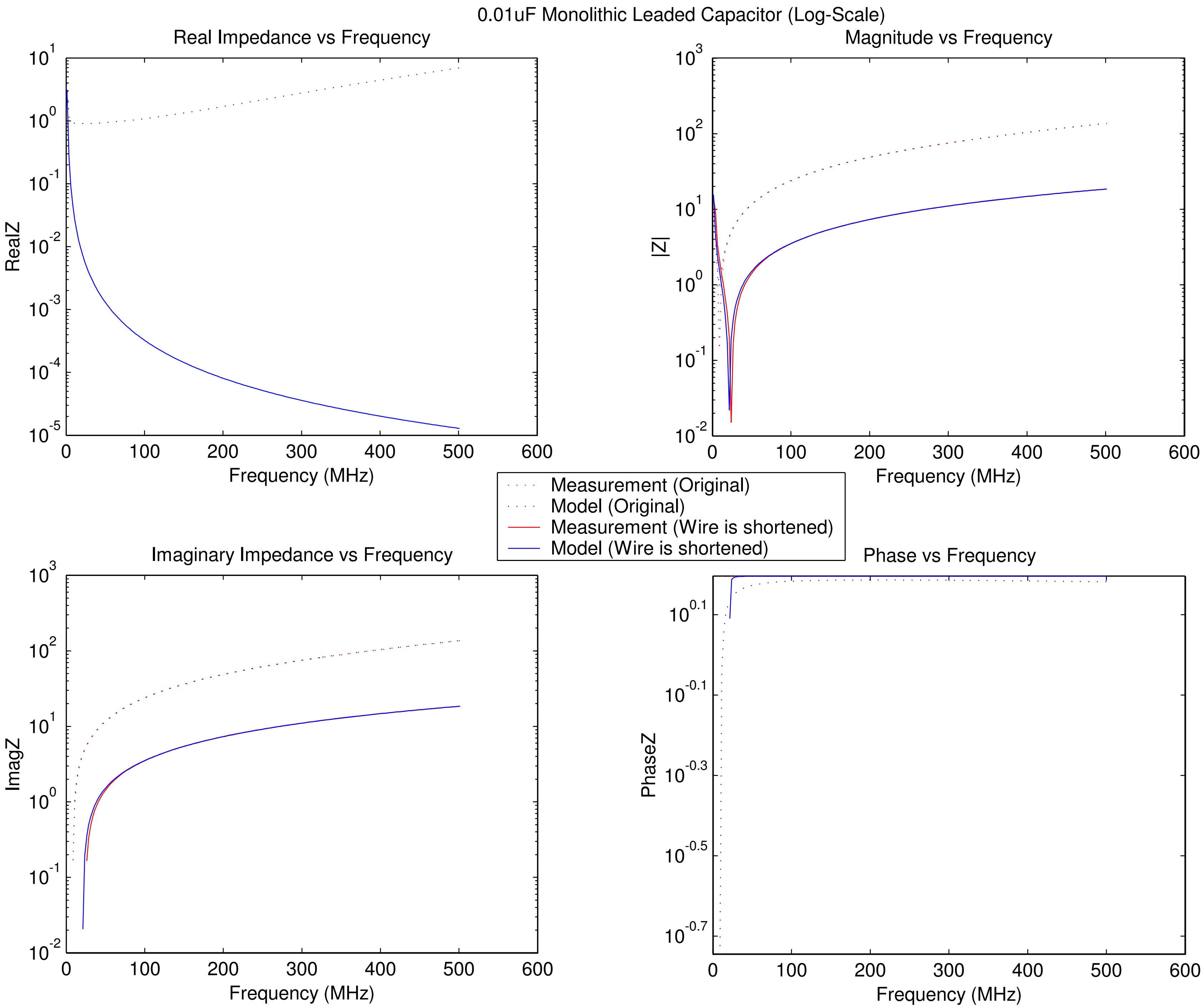


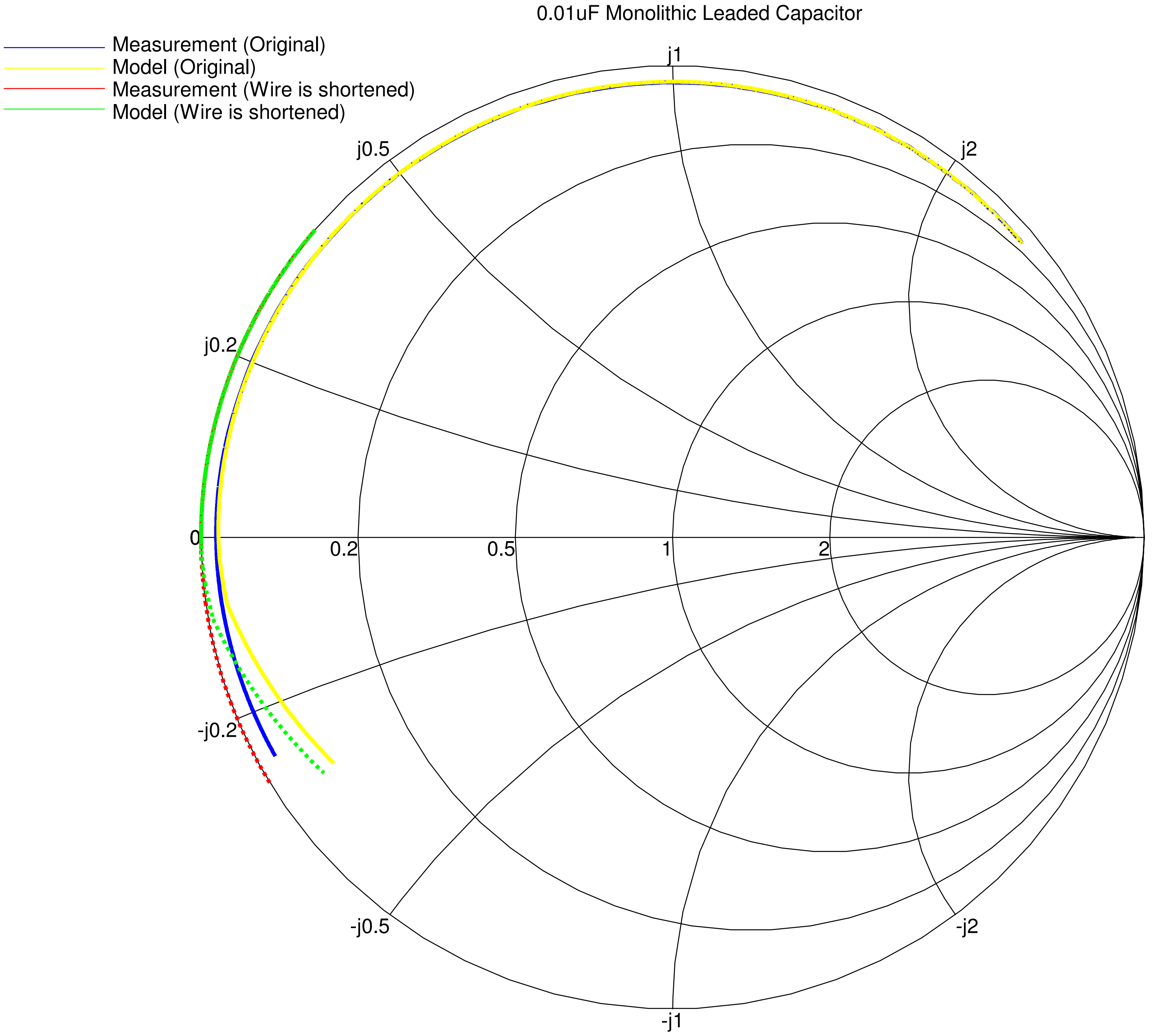
Title: Realistic Model for 0.01uF Monolithic Leaded Resistor
Treatment: None



Title: Realistic Equivalent Model for 0.01uF Monolithic Leaded Resistor
Treatment: Wire is shortened

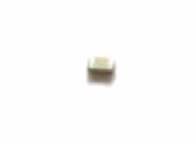

0.01uF Monolithic Leaded Capacitor (Linear-Scale)
Real Impedance vs Frequency
RealZ
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
140
120
100
80
60
40
20
0
-20
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)


0.01uF Monolithic Leaded Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
$10^{0.1}$
$10^{-0.1}$
$10^{-0.3}$
$10^{-0.5}$
$10^{-0.7}$
0
100
200
300
400
500
600
Frequency (MHz)


0.01uF Monolithic Leaded Capacitor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

2.4.7 0.01μF Tantalum Chip Capacitor

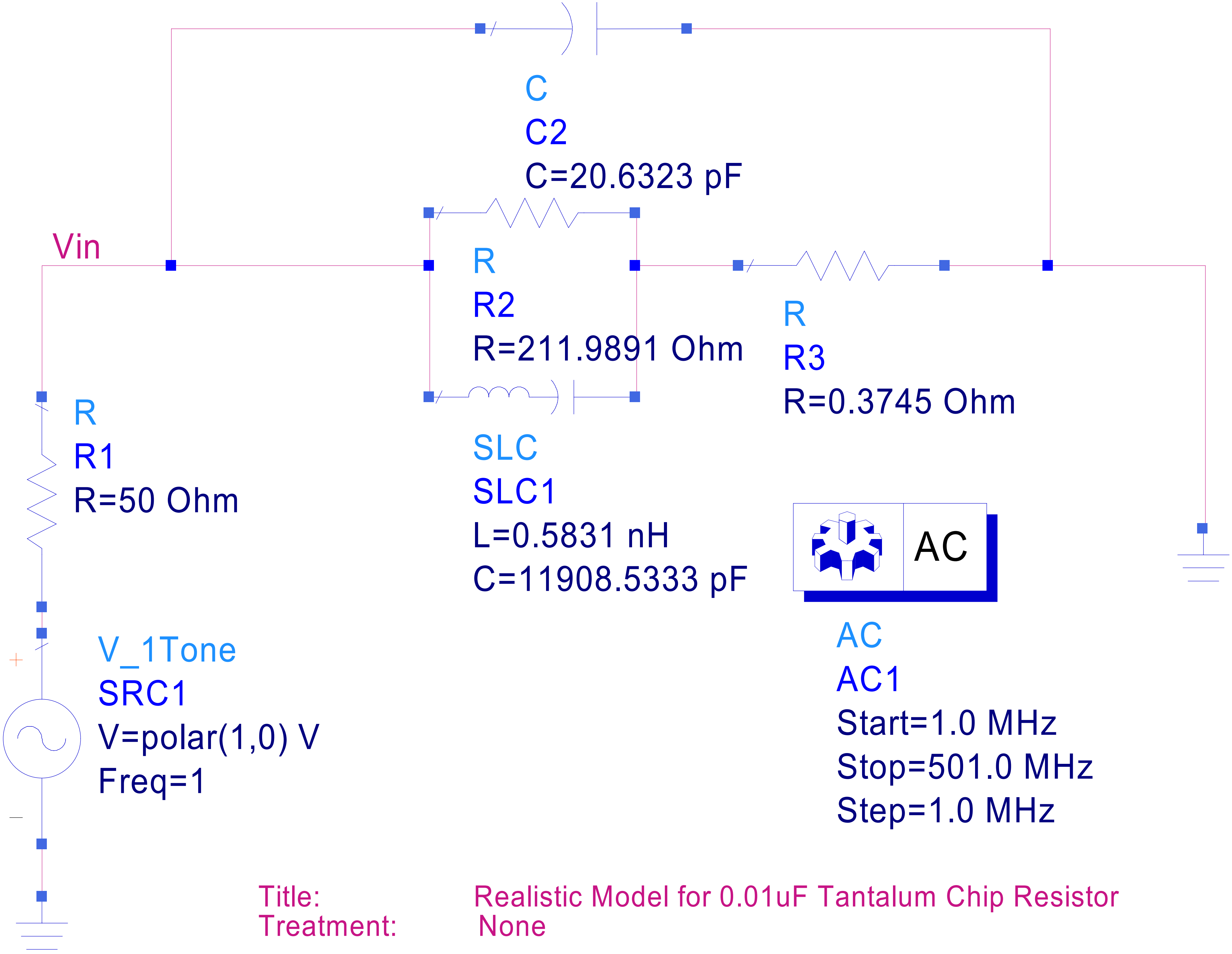
The following is the picture of a 0.01μF Tantalum Chip Capacitor.



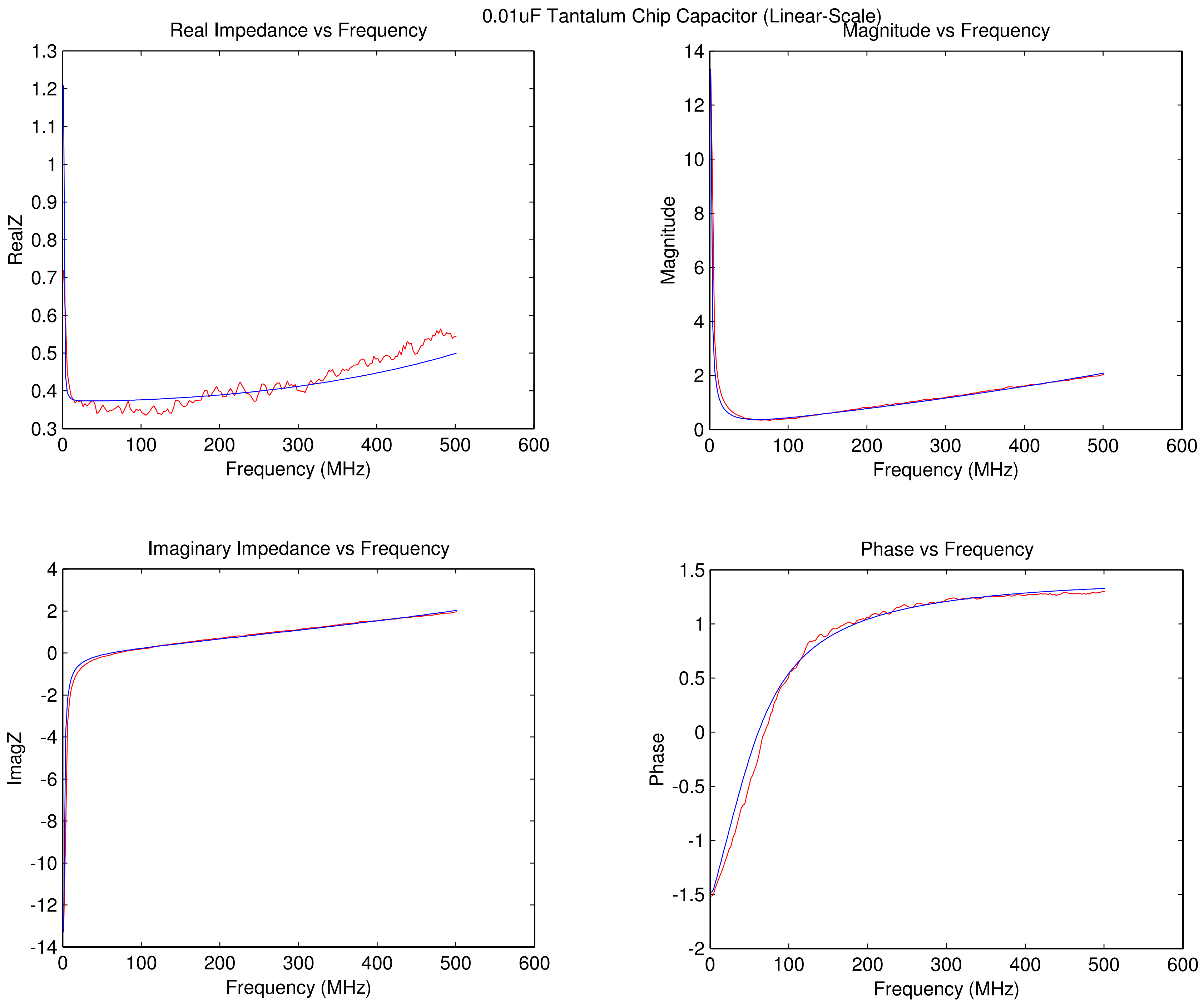
No word is marked on the Chip

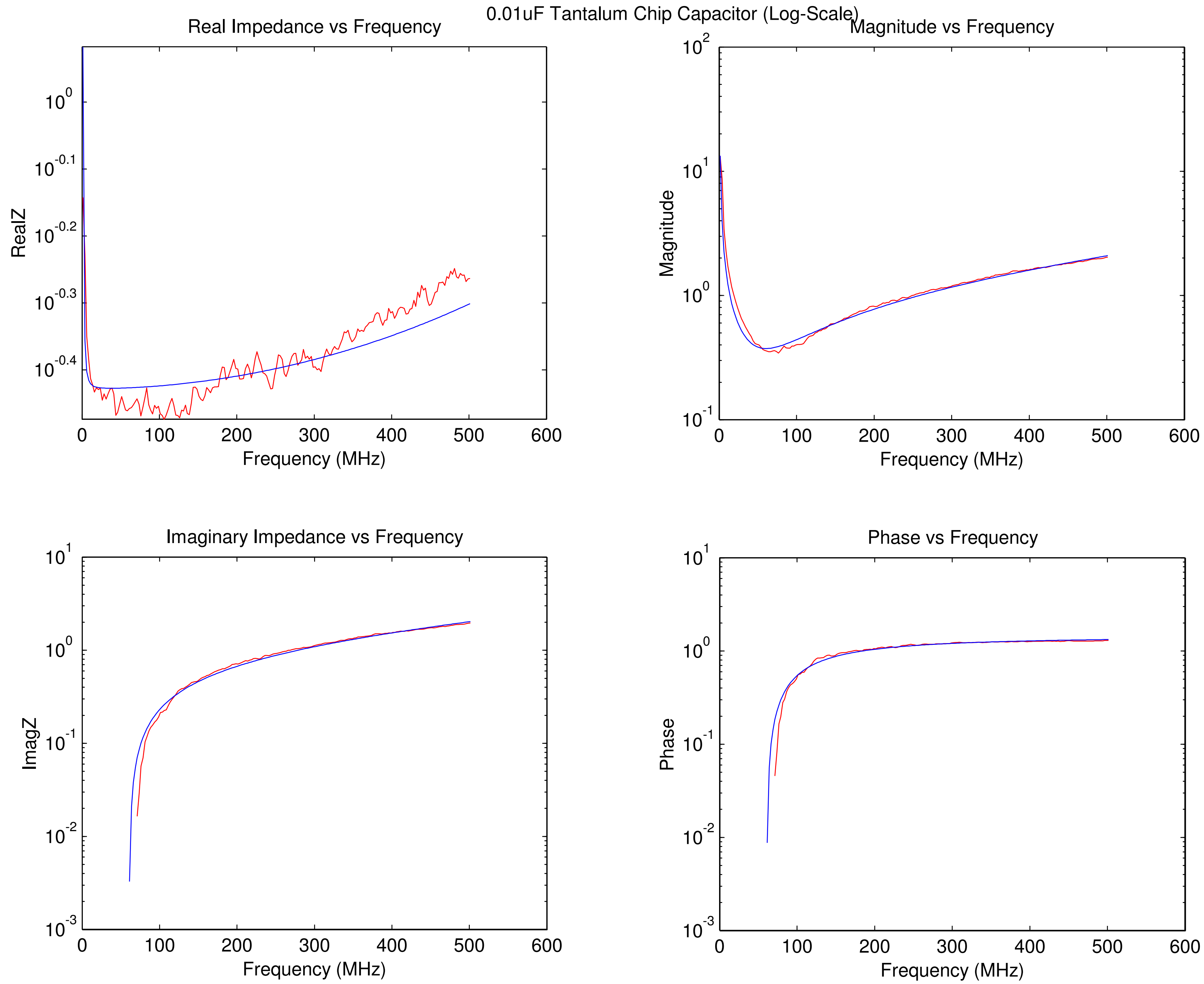
This table summarizes the measured data and simulation result.

	Original
Normalization Treatment	Partial
Internal Resistance of Model (Ω)	211.9891
Internal Inductance of Model (nH)	0.5831
Internal Capacitance of Model (μF)	0.0119
External Resistance of Model (Ω)	0.3745
External Inductance of Model (nH)	0.0000
External Capacitance of Model (pF)	20.6323
R-Square Value of Real Impedance	0.5848
R-Square Value of Imaginary Impedance	0.9476
R-Square Value of Magnitude	0.9105
R-Square Value of Phase	0.9941

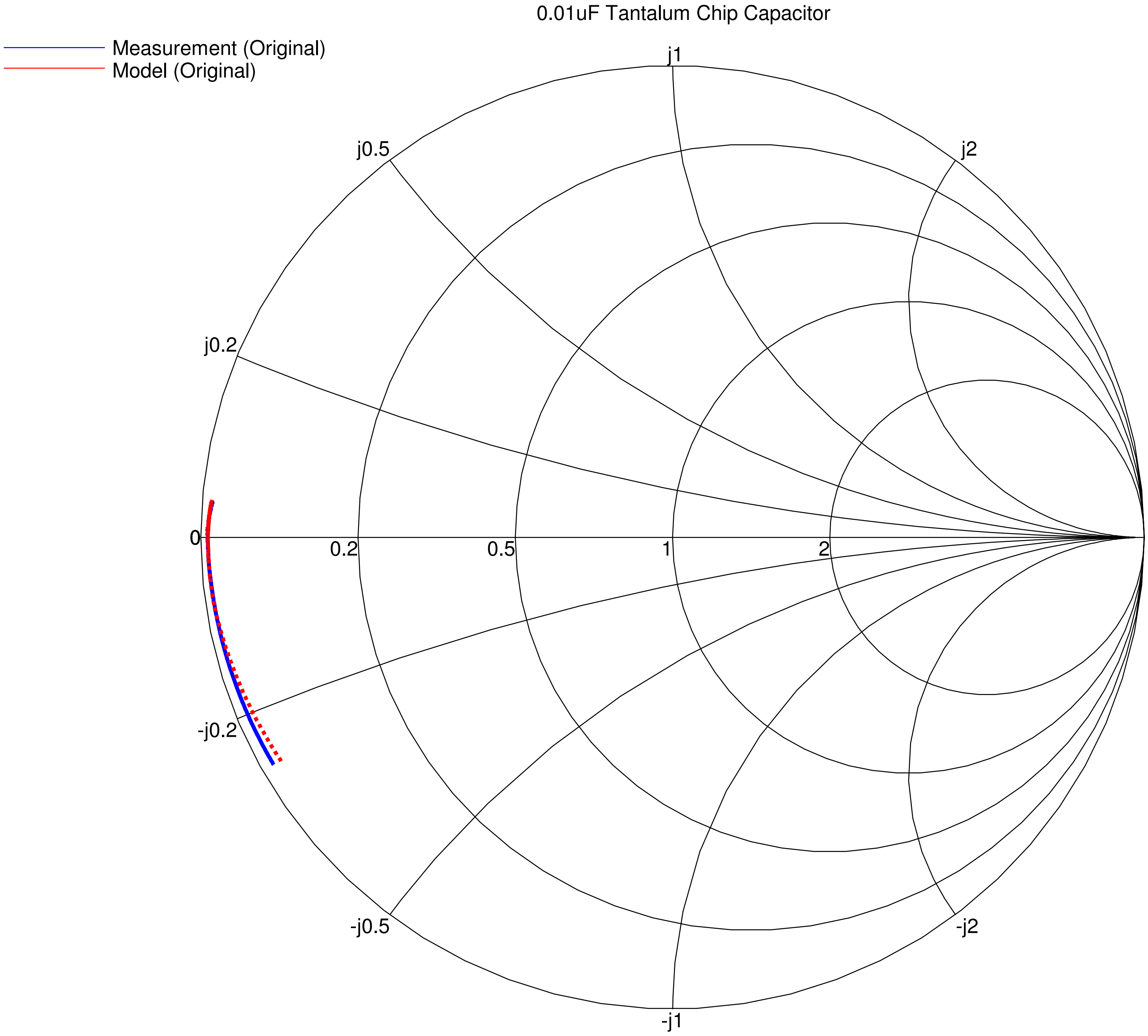


Title: Realistic Model for 0.01uF Tantalum Chip Resistor
Treatment: None


0.01uF Tantalum Chip Capacitor (Linear-Scale)
Real Impedance vs Frequency
RealZ
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600
Frequency (MHz)
Imaginary Impedance vs Frequency
ImagZ
4
2
0
-2
-4
-6
-8
-10
-12
-14
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)

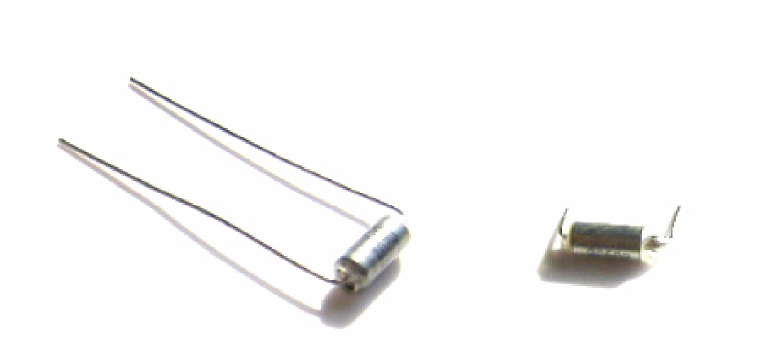


0.01uF Tantalum Chip Capacitor (Log-Scale)


0.01uF Tantalum Chip Capacitor
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

2.4.8 1μF Minilytic Leaded Capacitor

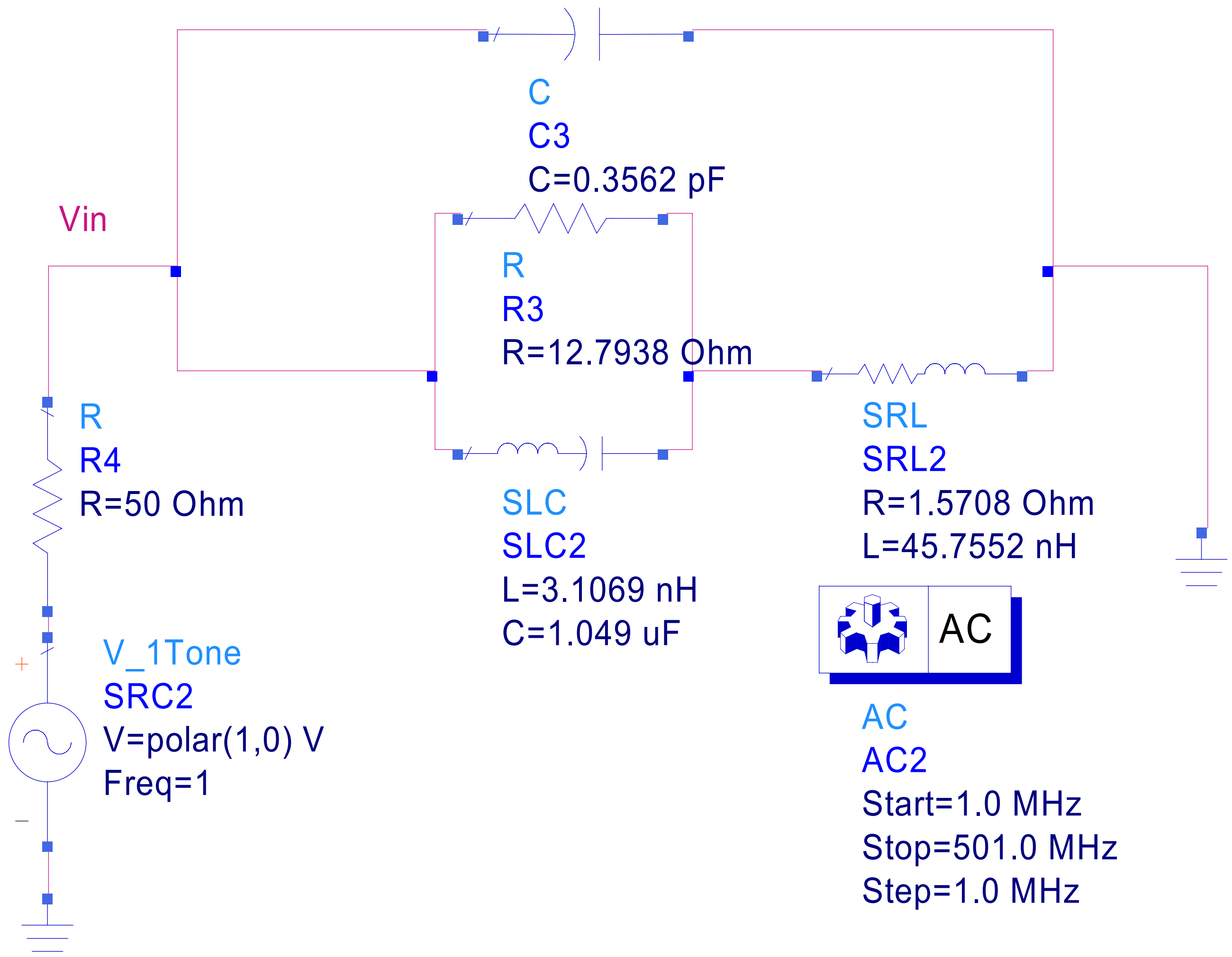
The following are the pictures of an original and after treatment 1μF Minilytic Leaded Capacitor.



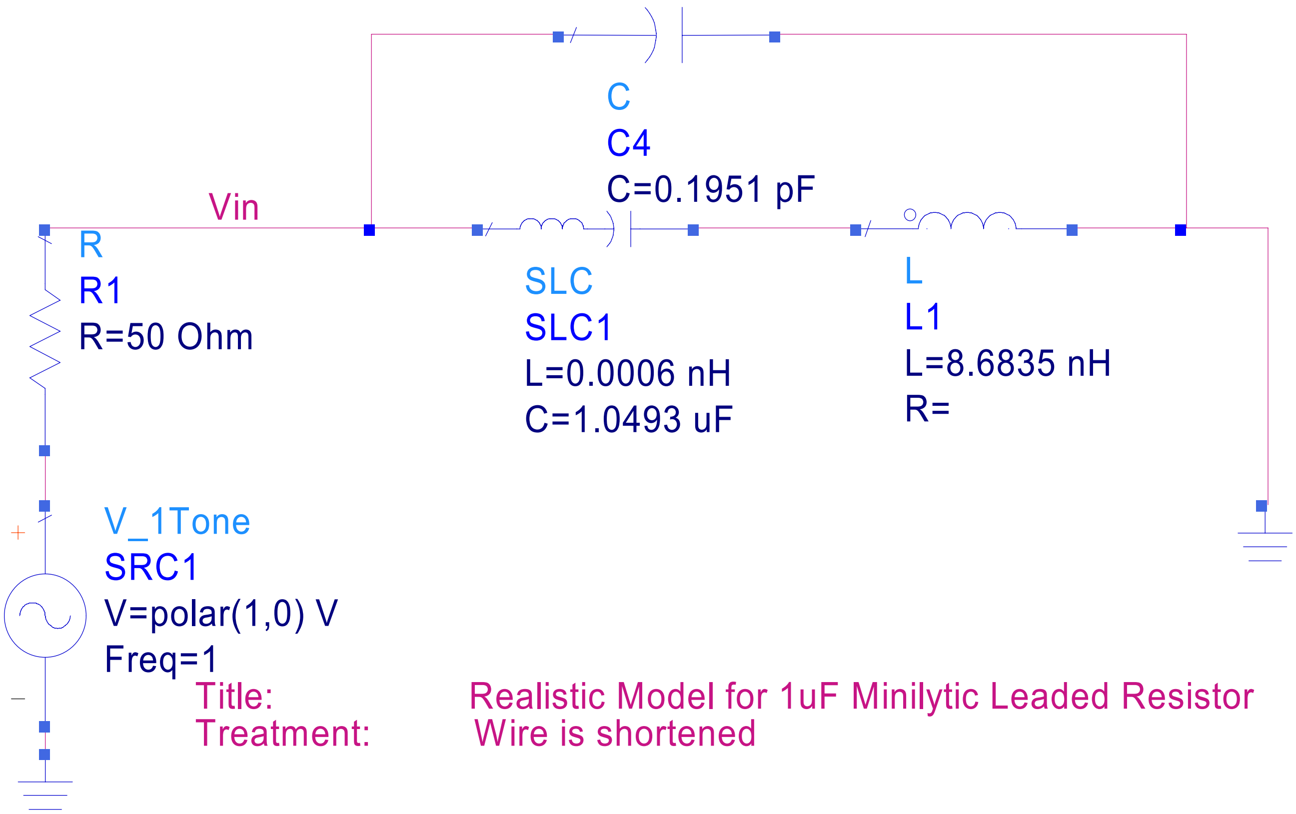
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

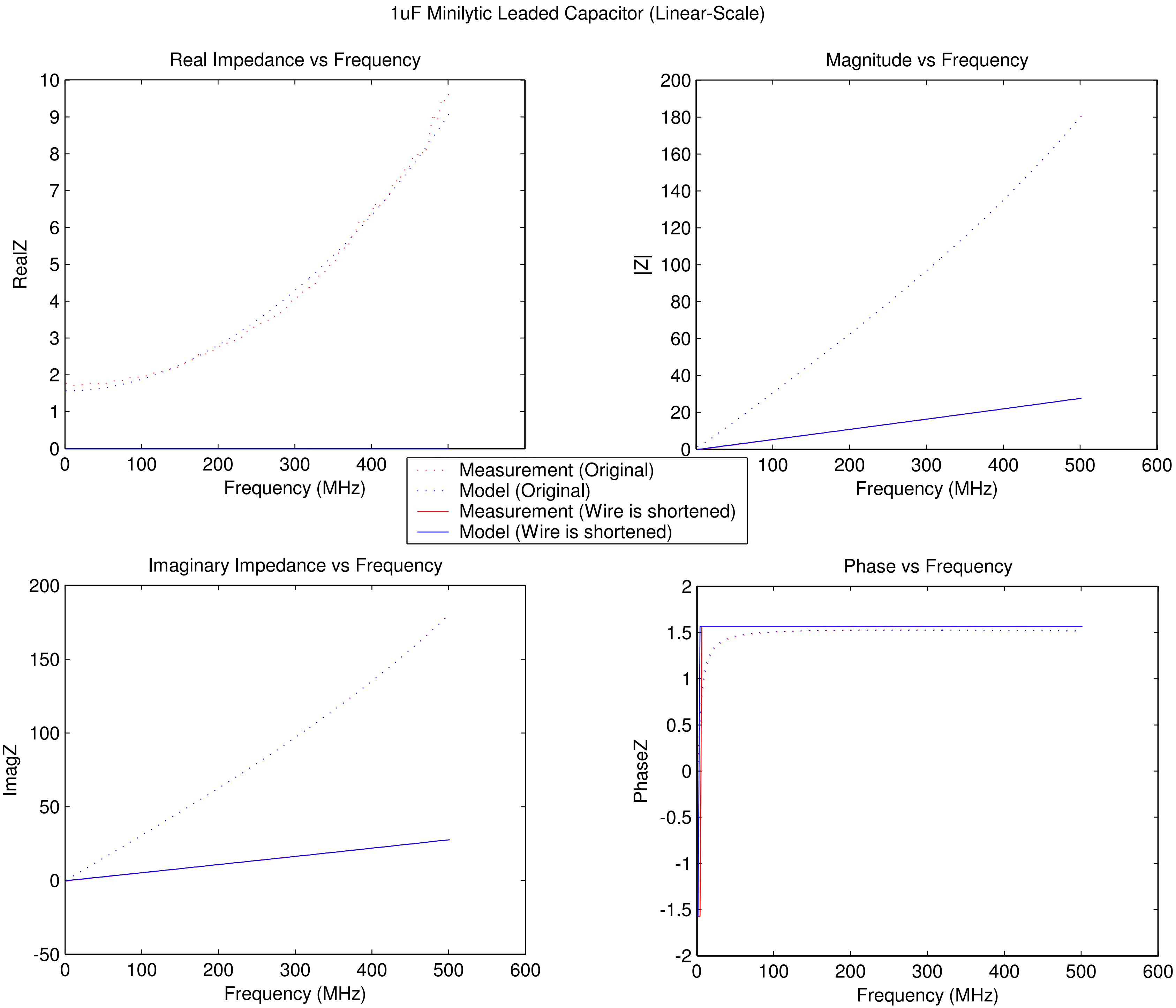
	Original	Wire is shortened
Normalization Treatment	Partial	Loss-Less
Internal Resistance of Model (Ω)	12.7939	∞
Internal Inductance of Model (nH)	3.1069	0.0006
Internal Capacitance of Model (μF)	1.0493	1.0493
External Resistance of Model (Ω)	1.5708	0.0000
External Inductance from estimation (nH)	49.9479	8.7303
External Inductance of Model (nH)	45.7552	8.6835
External Capacitance from estimation (pF)	0.2456	0.0425
External Capacitance of Model (pF)	0.3562	0.1951
Legnth of Leaded Wire (mm)	33.2300	5.7800
Distance between two wires (mm)	10.7700	10.9600
Diameter of wire (mm)	0.4800	0.4800
R-Square Value of Real Impedance	0.9939	1.0000
R-Square Value of Imaginary Impedance	1.0000	1.0000
R-Square Value of Magnitude	1.0000	1.0000
R-Square Value of Phase	0.9931	0.4975

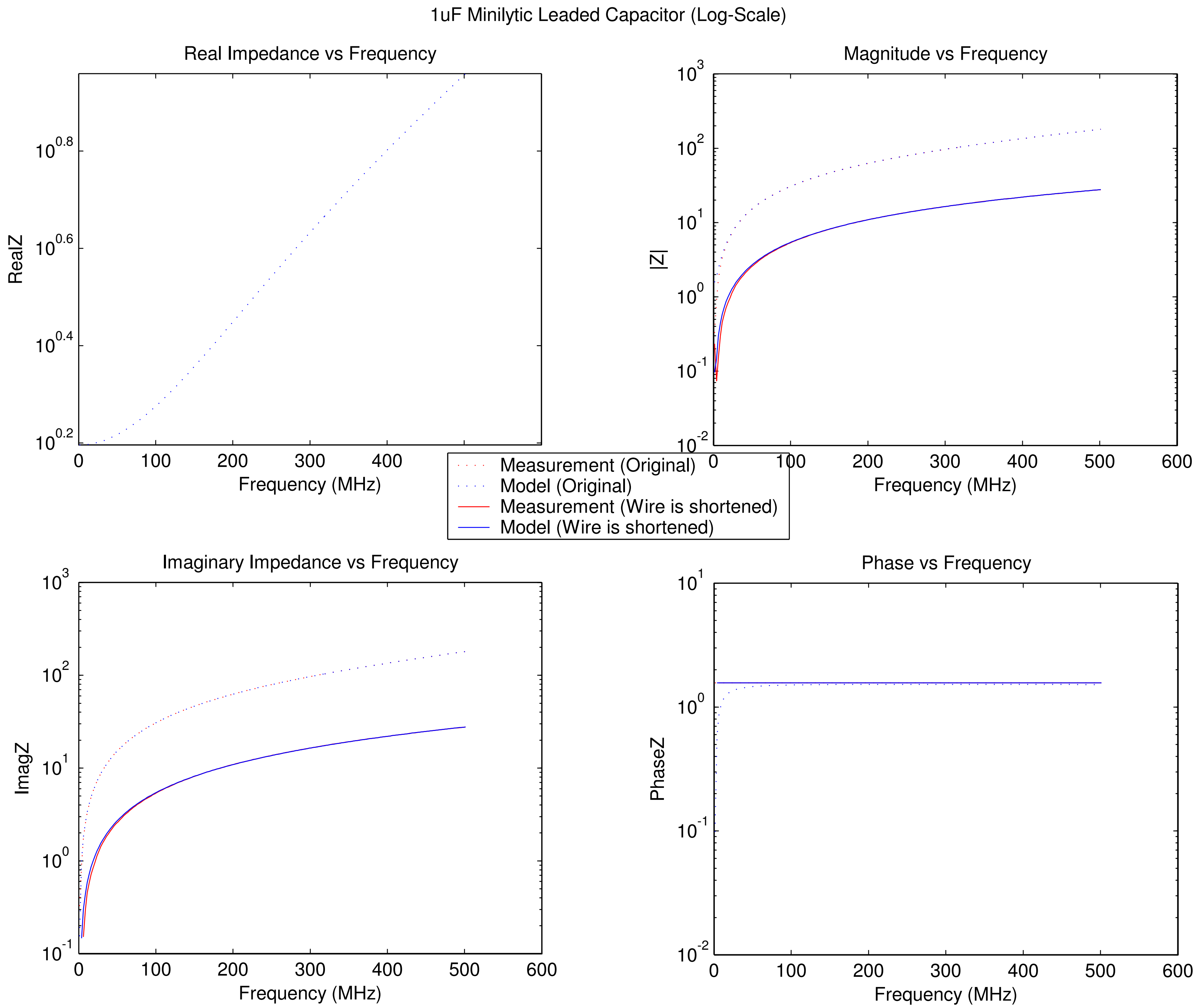


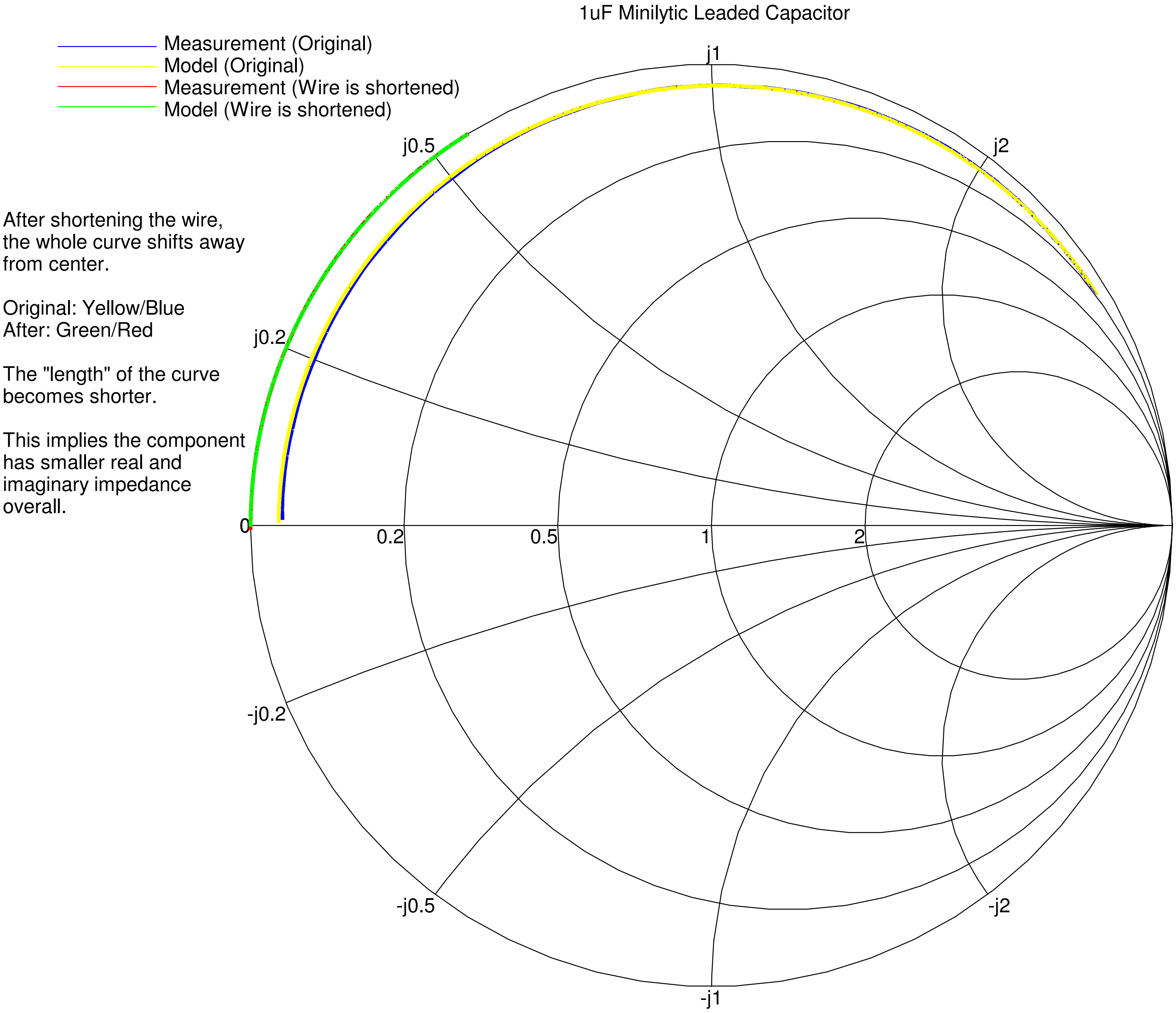
Title: Realistic Model for 1uF Minilytic Leaded Resistor
Treatment: None



Title: Realistic Model for 1uF Minilytic Leaded Resistor
Treatment: Wire is shortened


1uF Minilytic Leaded Capacitor (Linear-Scale)
Real Impedance vs Frequency
RealZ
10
9
8
7
6
5
4
3
2
1
0
100
200
300
400
Frequency (MHz)
Magnitude vs Frequency
|Z|
200
180
160
140
120
100
80
60
40
20
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
200
150
100
50
0
-50
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)


1uF Minilytic Leaded Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
$10^{0.2}$
$10^{0.4}$
$10^{0.6}$
$10^{0.8}$
0
100
200
300
400
Frequency (MHz)
Magnitude vs Frequency
|Z|
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
10^{-2}
10^{-1}
10^{0}
10^{1}
0
100
200
300
400
500
600
Frequency (MHz)



After shortening the wire, the whole curve shifts away from center.

Original: Yellow/Blue
After: Green/Red

The "length" of the curve becomes shorter.

This implies the component has smaller real and imaginary impedance overall.

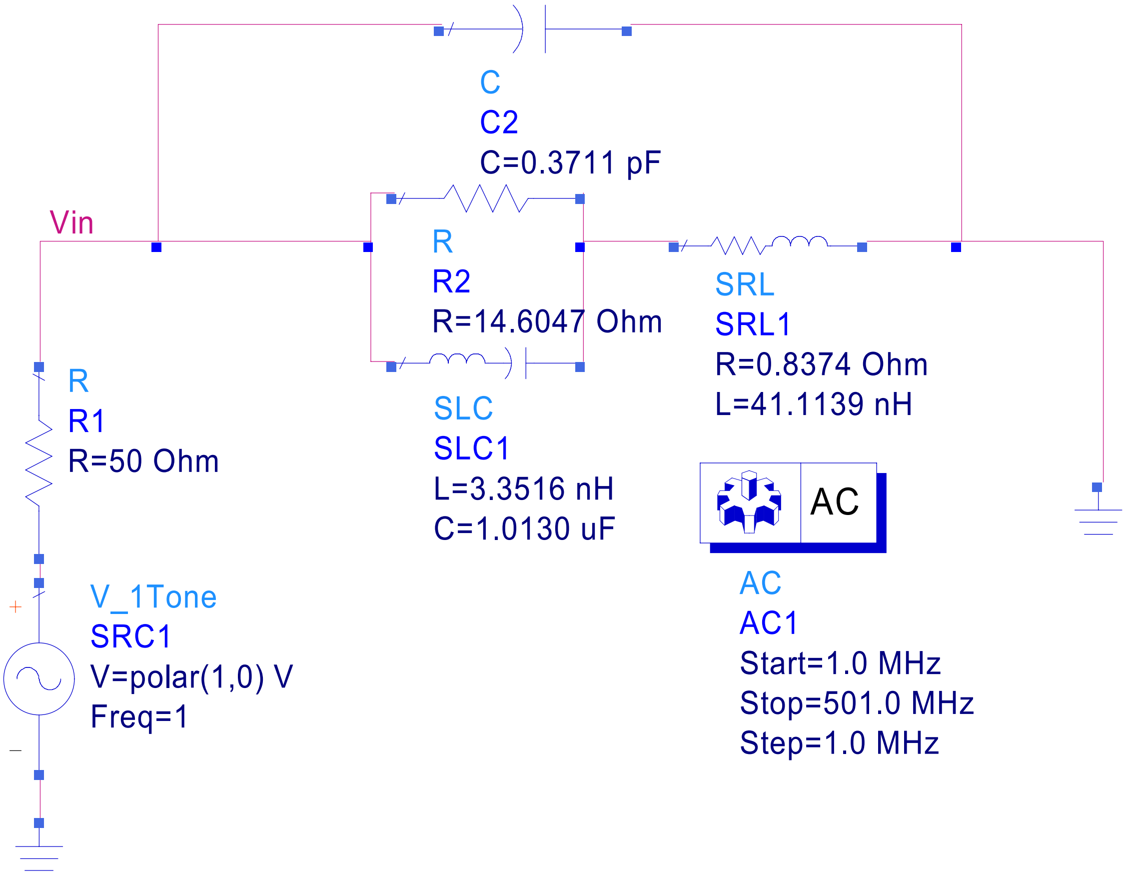
2.4.9 1μF Monolithic Leaded Capacitor

The following are the pictures of an original and after treatment 1μF Monolithic Leaded Capacitor.

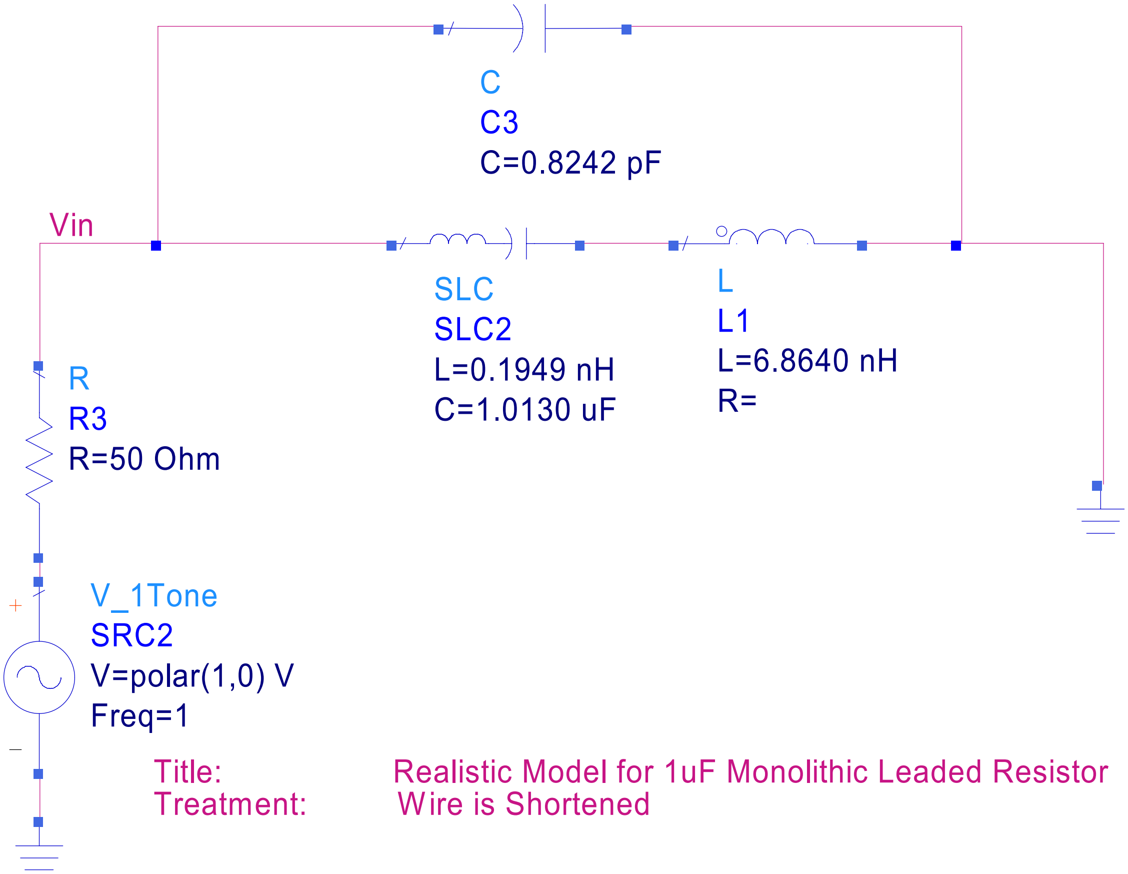
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

	Original	Wire is shortened
Normalization Treatment	Partial	Loss-Less
Internal Resistance of Model (Ω)	14.6047	∞
Internal Inductance of Model (nH)	3.3516	0.1949
Internal Capacitance of Model (μF)	1.0130	1.0130
External Resistance of Model (Ω)	0.8374	0.0000
External Inductance from estimation (nH)	42.9158	3.3375
External Inductance of Model (nH)	41.1139	6.8640
External Capacitance from estimation (pF)	0.3146	0.0250
External Capacitance of Model (pF)	0.3711	0.8242
Legnth of Leaded Wire (mm)	34.8600	2.7400
Distance between two wires (mm)	5.8200	5.6500
Diameter of wire (mm)	0.4900	0.4900
R-Square Value of Real Impedance	0.9968	1.0000
R-Square Value of Imaginary Impedance	1.0000	0.9995
R-Square Value of Magnitude	1.0000	0.9995
R-Square Value of Phase	0.9768	1.0000

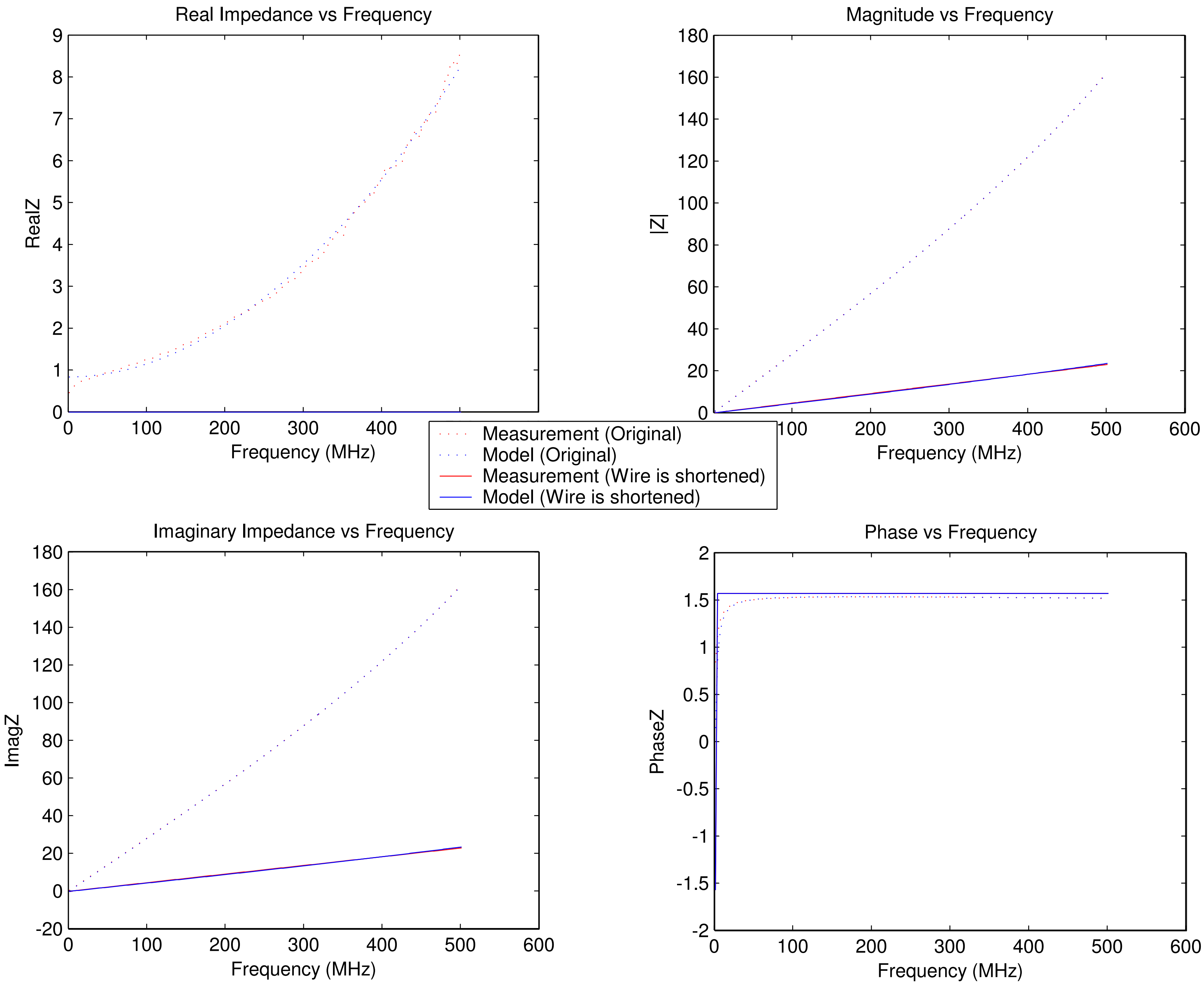


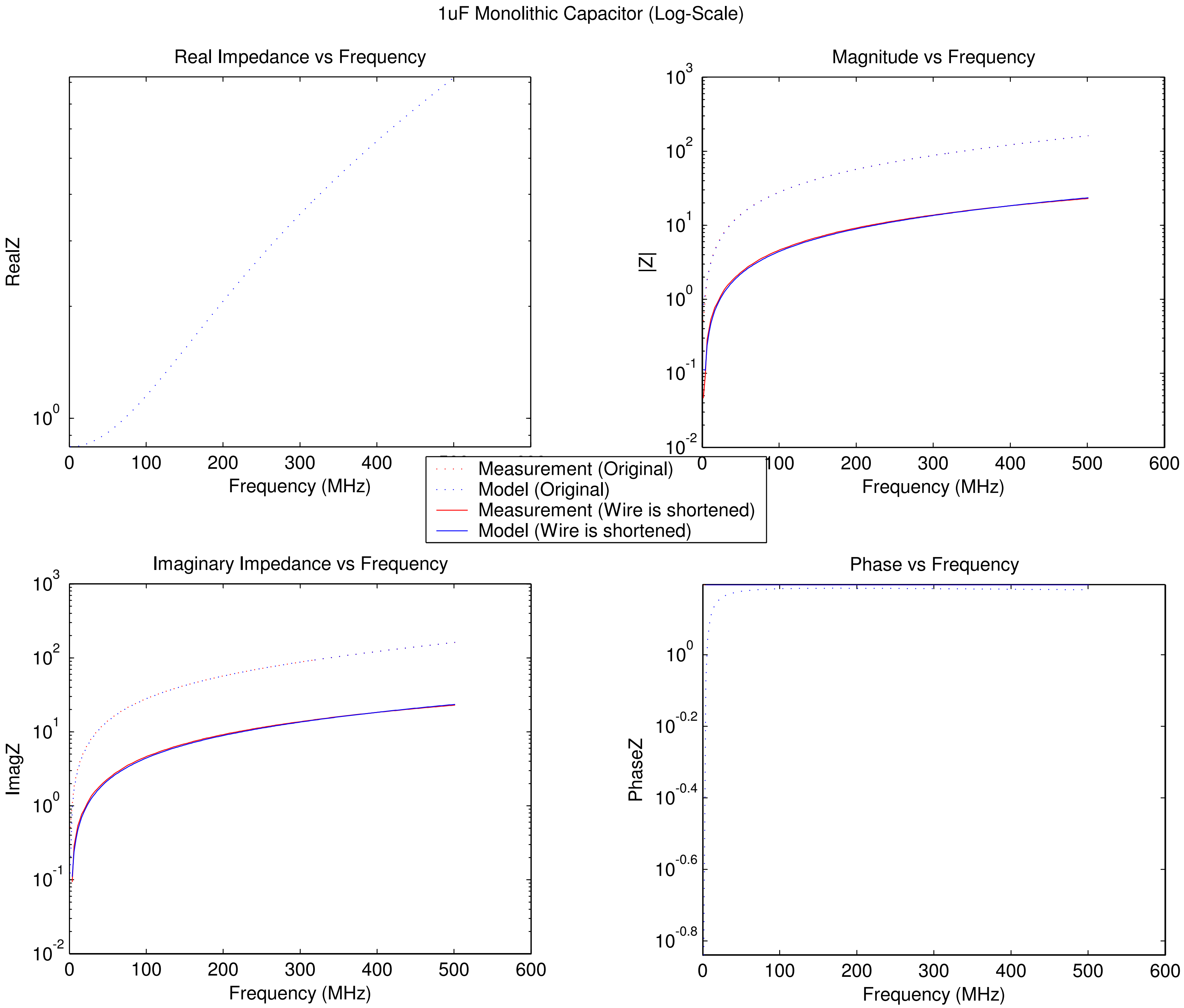
Title: Realistic Model for 1uF Monolithic Leaded Resistor
Treatment: None

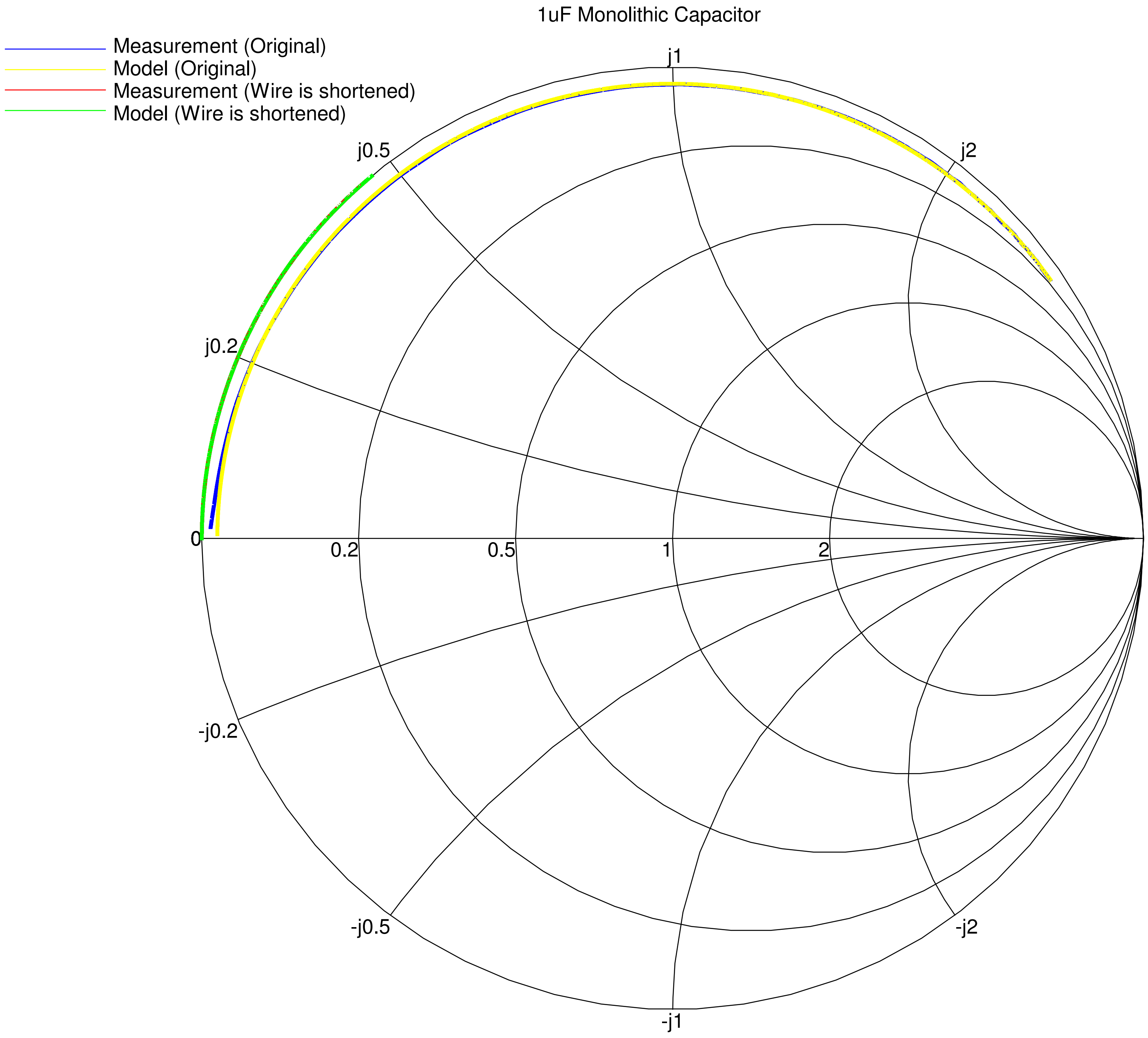


Title: Realistic Model for 1uF Monolithic Leaded Resistor
Treatment: Wire is Shortened

1uF Monolithic Capacitor (Linear-Scale)

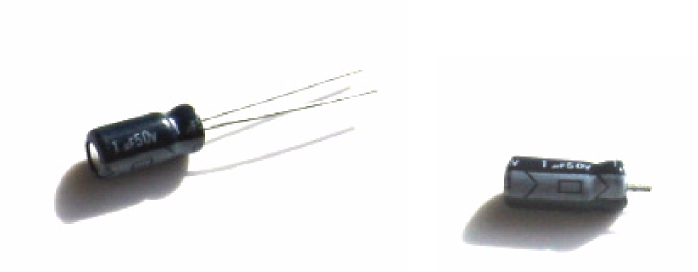



1uF Monolithic Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
10^0
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
10^0
$10^{-0.2}$
$10^{-0.4}$
$10^{-0.6}$
$10^{-0.8}$
0
100
200
300
400
500
600
Frequency (MHz)


1uF Monolithic Capacitor

2.4.10 1μF 50V Electrolytic Leaded Capacitor

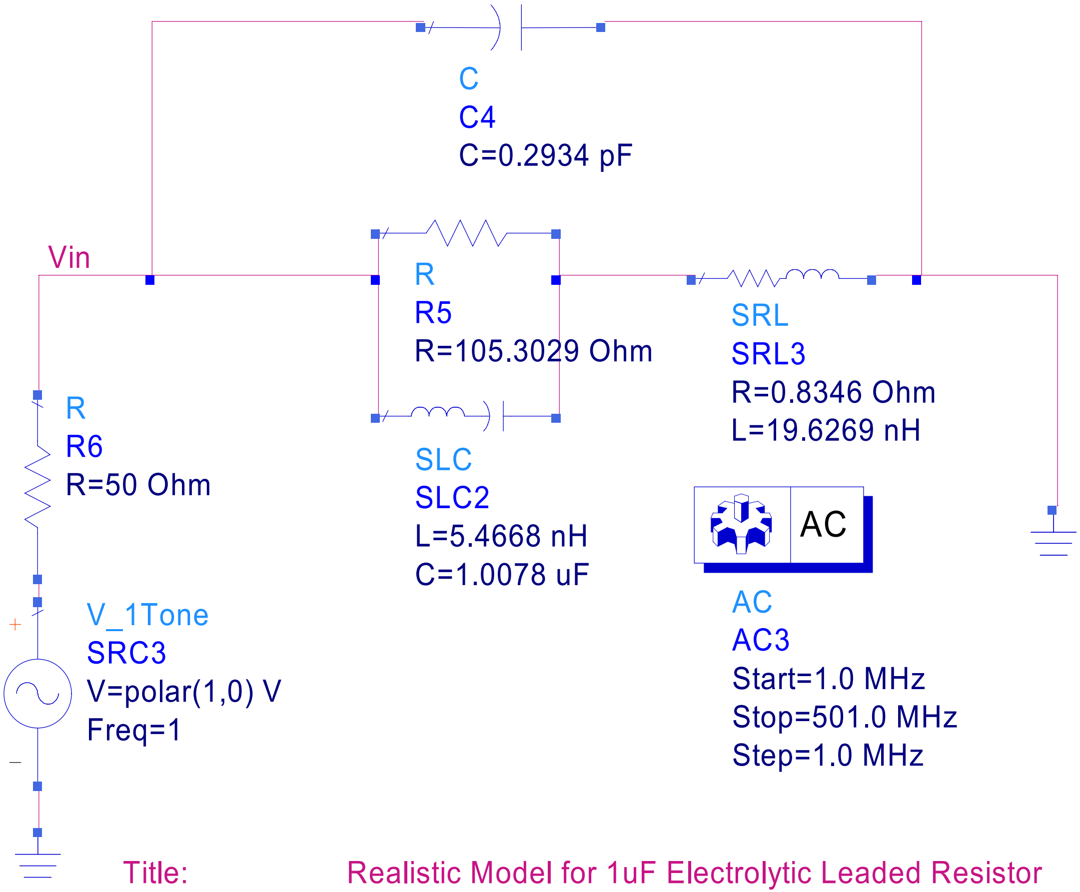
The following are the pictures of an original and after treatment 1μF 50V Electrolytic Leaded Capacitor.



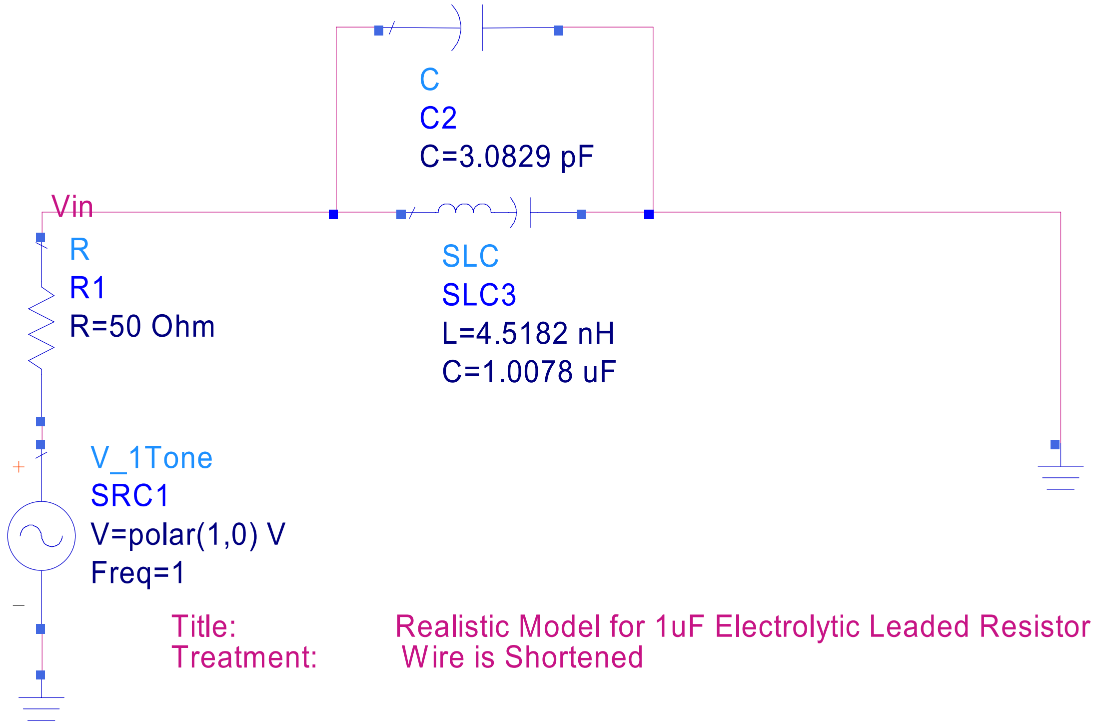
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

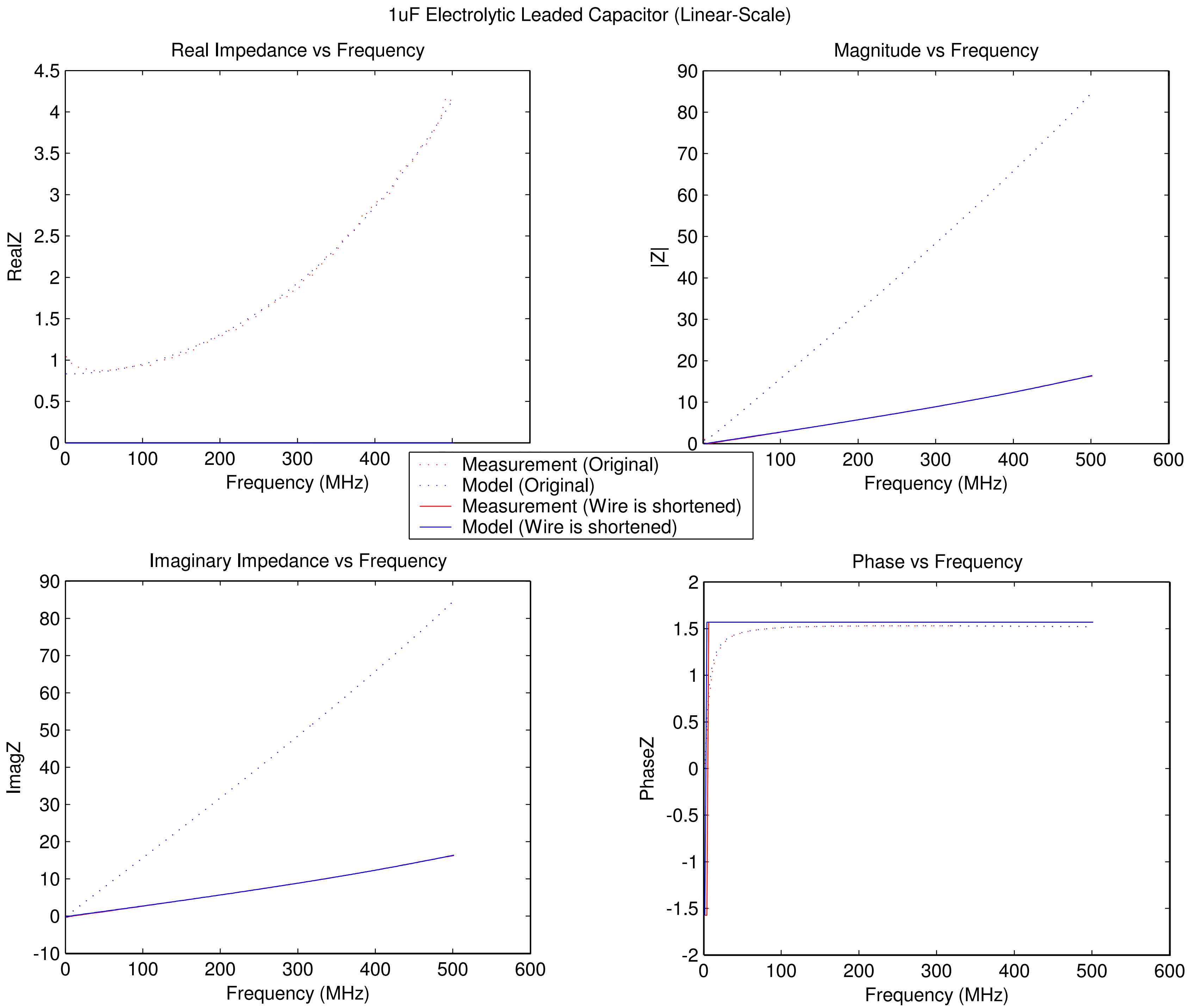
	Original	Wire is shortened
Normalization Treatment	Partial	Loss-Less
Internal Resistance of Model (Ω)	105.3029	∞
Internal Inductance of Model (nH)	5.4668	4.5182
Internal Capacitance of Model (μF)	1.0078	1.0078
External Resistance of Model (Ω)	0.8347	0.0000
External Inductance from estimation (nH)	26.7406	0.2003
External Inductance of Model (nH)	19.6269	0.0000
External Capacitance from estimation (pF)	3.1295	0.0234
External Capacitance of Model (pF)	0.2934	3.0829
Legnth of Leaded Wire (mm)	21.9600	2.5700
Distance between two wires (mm)	5.5300	5.5300
Diameter of wire (mm)	0.4700	0.4700
R-Square Value of Real Impedance	0.9980	1.0000
R-Square Value of Imaginary Impedance	1.0000	0.9999
R-Square Value of Magnitude	1.0000	0.9999
R-Square Value of Phase	0.9891	0.7456



Title: Realistic Model for 1uF Electrolytic Leaded Resistor
Treatment: None



Title: Realistic Model for 1uF Electrolytic Leaded Resistor
Treatment: Wire is Shortened



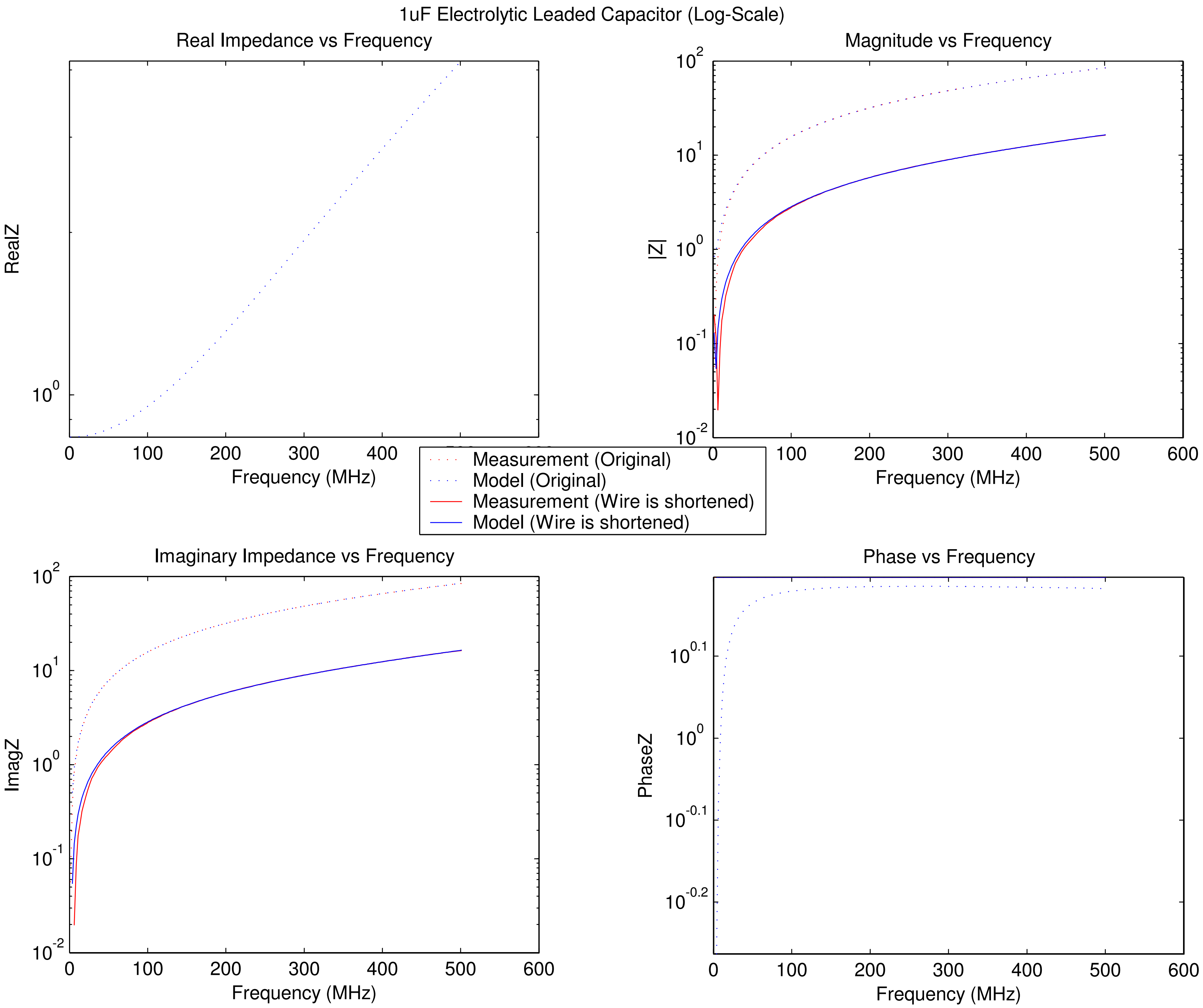
1uF Electrolytic Leaded Capacitor (Linear-Scale)

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency

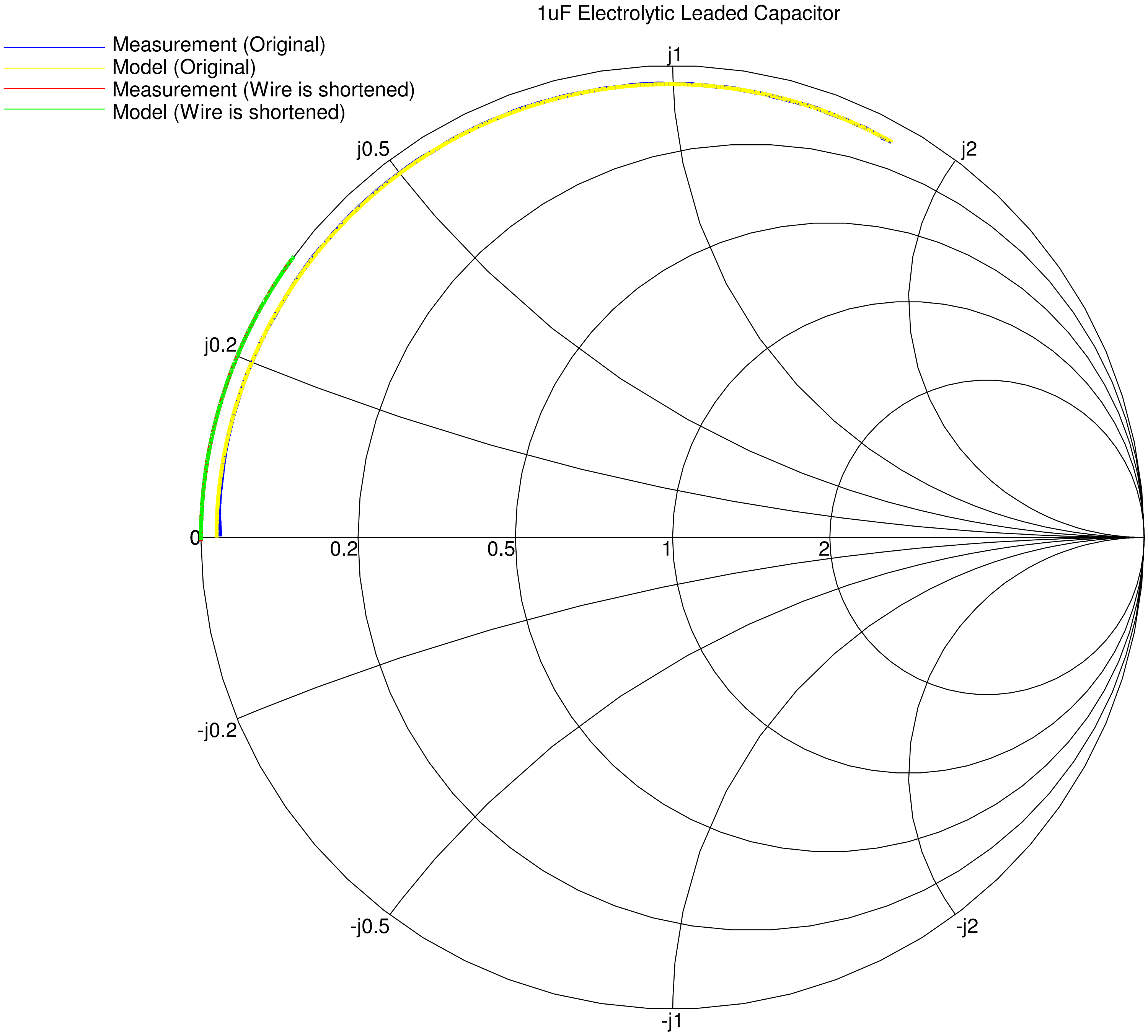

1uF Electrolytic Leaded Capacitor (Log-Scale)

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


1uF Electrolytic Leaded Capacitor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

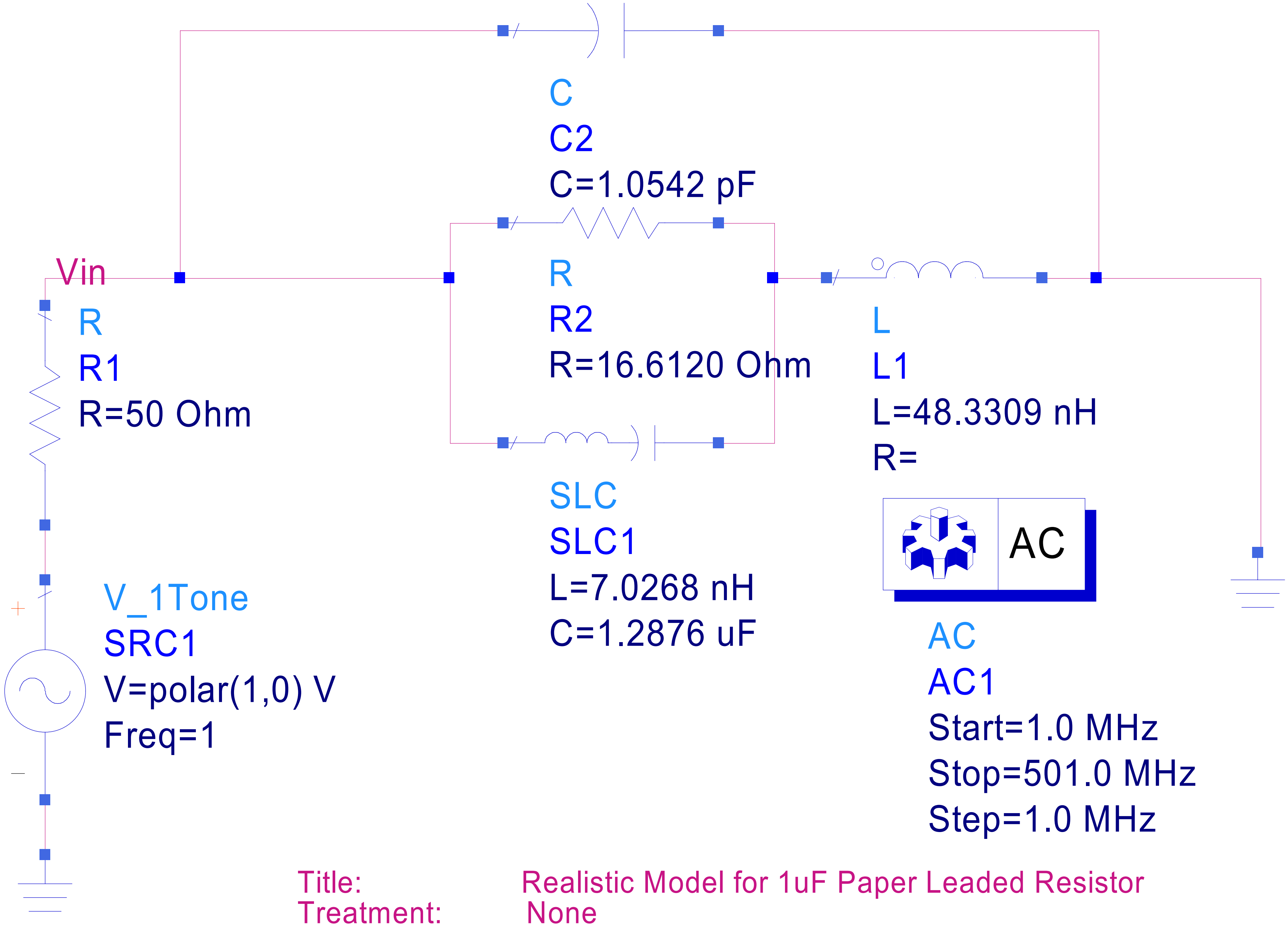
2.4.11 1μF Paper Leaded Capacitor

The following are the pictures of an original 1μF Paper Leaded Capacitor.

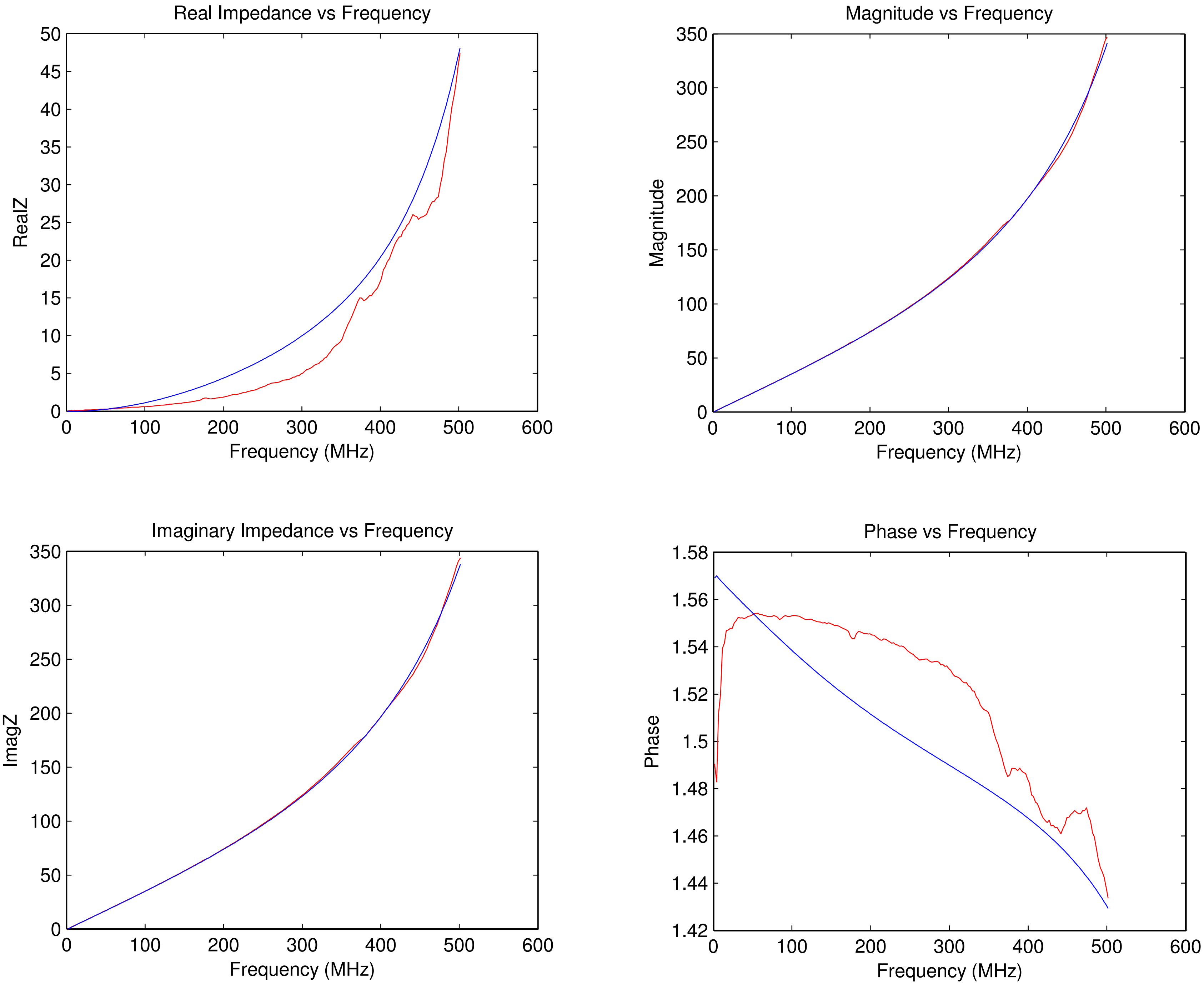
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

	Original
Normalization Treatment	Partial
Internal Resistance of Model (Ω)	16.6120
Internal Inductance of Model (nH)	7.0268
Internal Capacitance of Model (μF)	1.2876
External Resistance of Model (Ω)	0.0000
External Inductance from estimation (nH)	66.7770
External Inductance of Model (nH)	48.3309
External Capacitance from estimation (pF)	0.2277
External Capacitance of Model (pF)	1.0542
Legnth of Leaded Wire (mm)	37.0000
Distance between two wires (mm)	46.0900
Diameter of wire (mm)	0.9900
R-Square Value of Real Impedance	0.9775
R-Square Value of Imaginary Impedance	0.9995
R-Square Value of Magnitude	0.9995
R-Square Value of Phase	0.7238

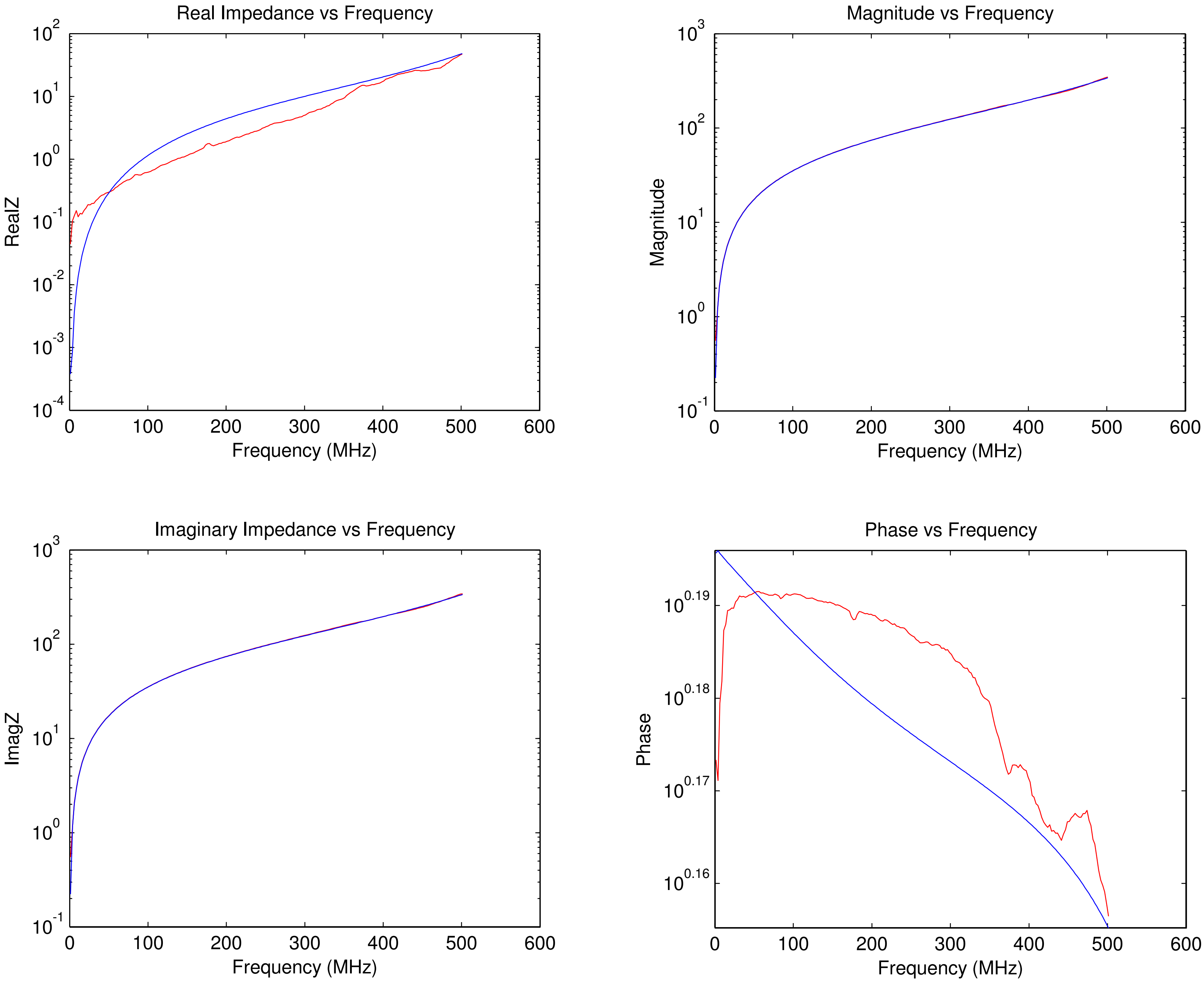


Title: Realistic Model for 1uF Paper Leaded Resistor
Treatment: None



1uF Paper Leaded Capacitor (Linear-Scale)

1uF Paper Leaded Capacitor (Log-Scale)

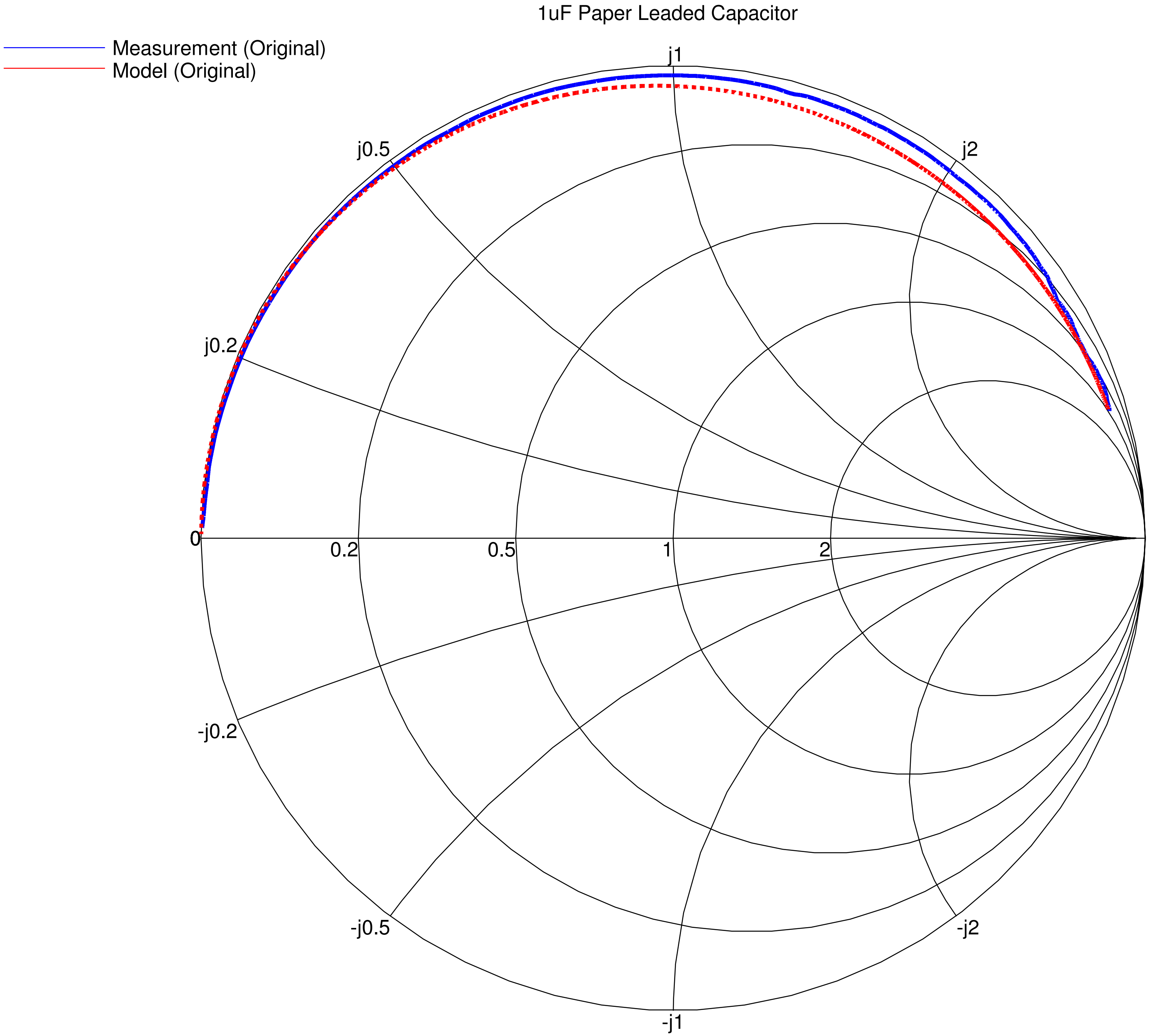


Real Impedance vs Frequency

Magnitude vs Frequency

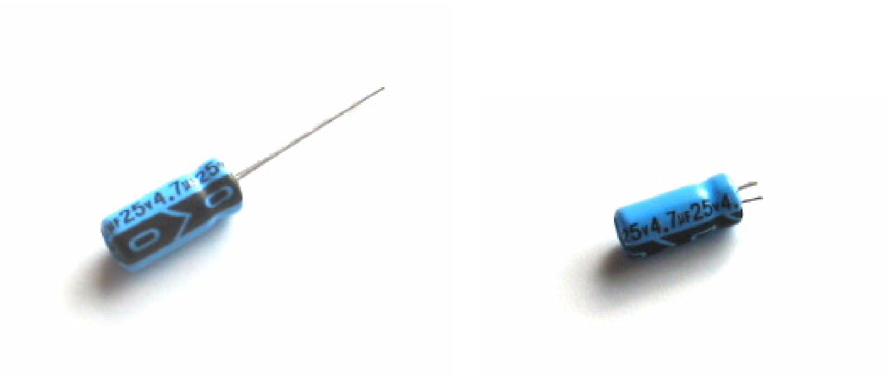
Imaginary Impedance vs Frequency

Phase vs Frequency


1uF Paper Leaded Capacitor
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j1
-j2

2.4.12 4.7μF 25V Electrolytic Leaded Capacitor

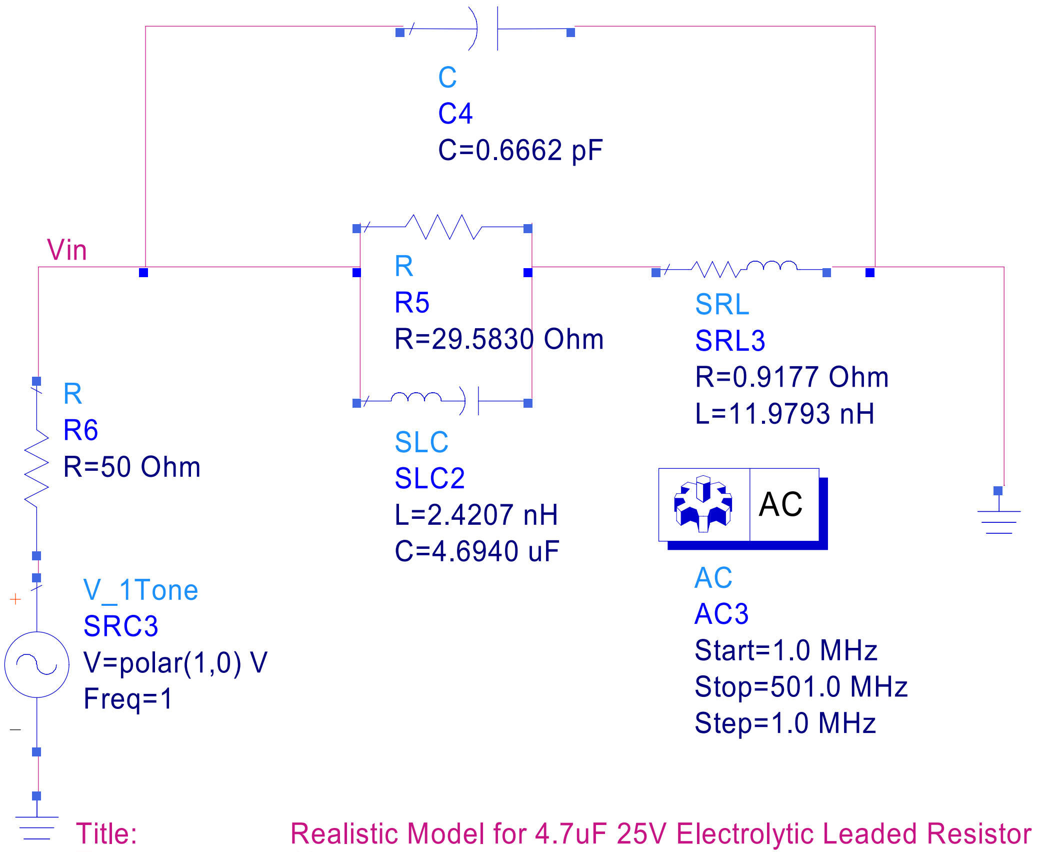
The following are the pictures of an original and after treatment 4.7μF 25V Electrolytic Leaded Capacitor.



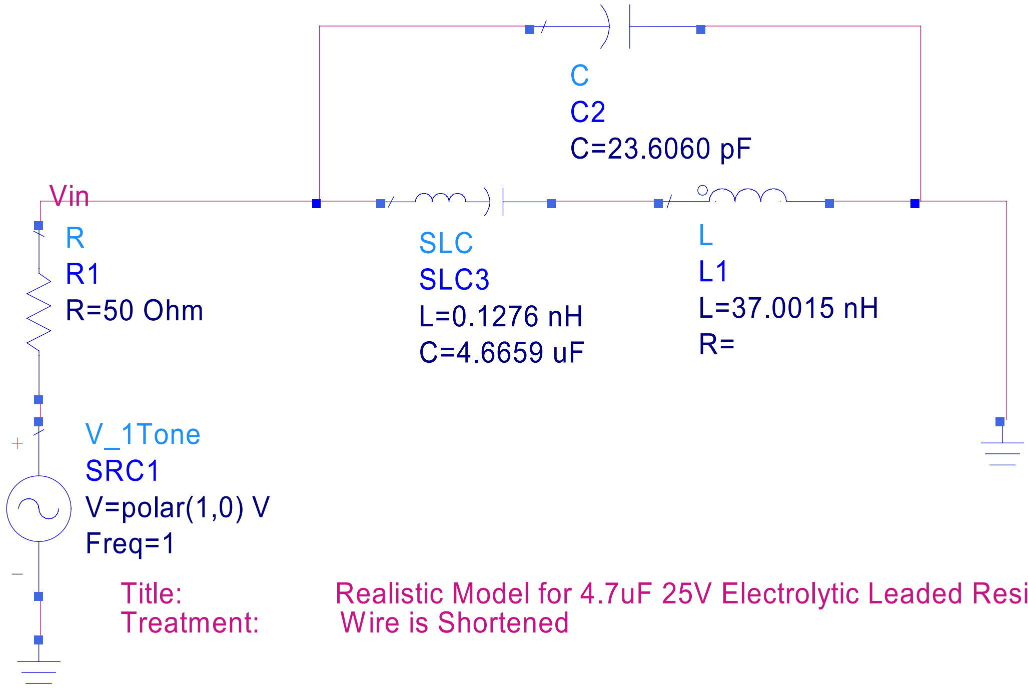
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

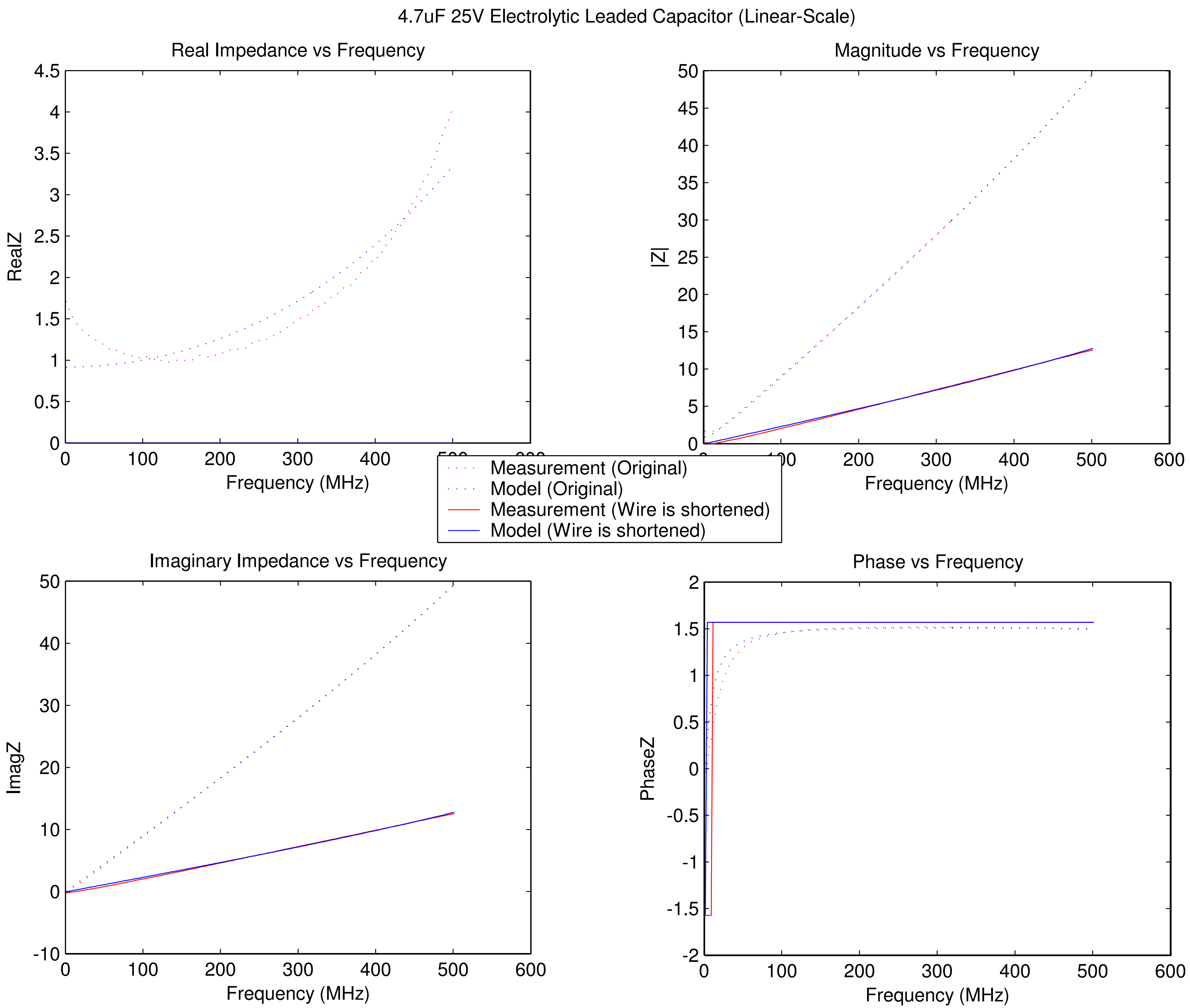
	Original	Wire is shortened
Normalization Treatment	Partial	Loss-Less
Internal Resistance of Model (Ω)	29.5830	∞
Internal Inductance of Model (nH)	2.4207	0.1276
Internal Capacitance of Model (μF)	4.6940	4.6659
External Resistance of Model (Ω)	0.9177	0.0000
External Inductance from estimation (nH)	27.0416	2.6060
External Inductance of Model (nH)	11.9793	37.0015
External Capacitance from estimation (pF)	0.2045	0.0197
External Capacitance of Model (pF)	0.6662	23.6060
Legnth of Leaded Wire (mm)	22.3100	2.1500
Distance between two wires (mm)	5.4600	5.4600
Diameter of wire (mm)	0.4800	0.4800
R-Square Value of Real Impedance	0.8903	1.0000
R-Square Value of Imaginary Impedance	1.0000	0.9993
R-Square Value of Magnitude	0.9999	0.9992
R-Square Value of Phase	0.9724	0.2463



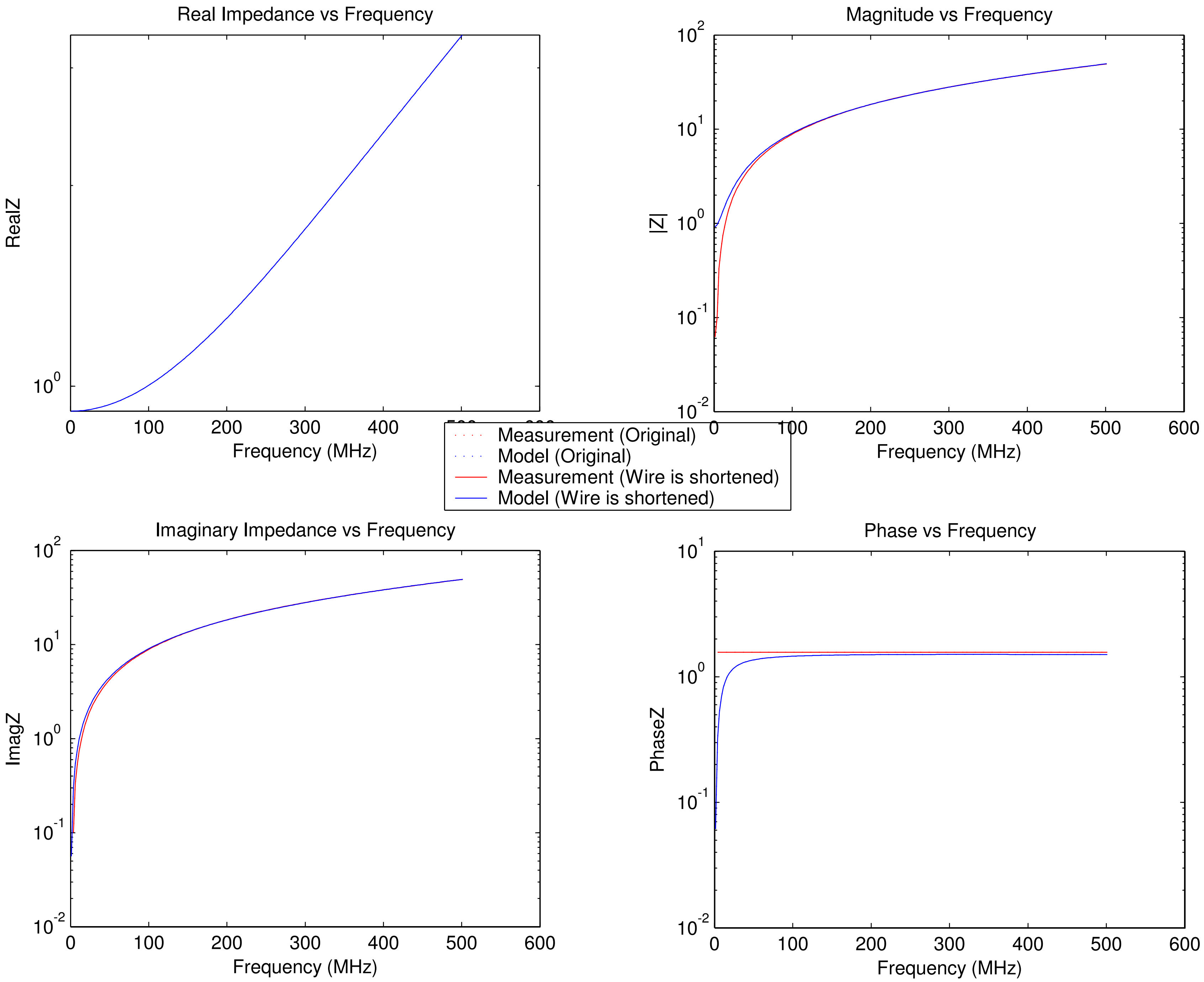
Title: Realistic Model for 4.7uF 25V Electrolytic Leaded Resistor
Treatment: None

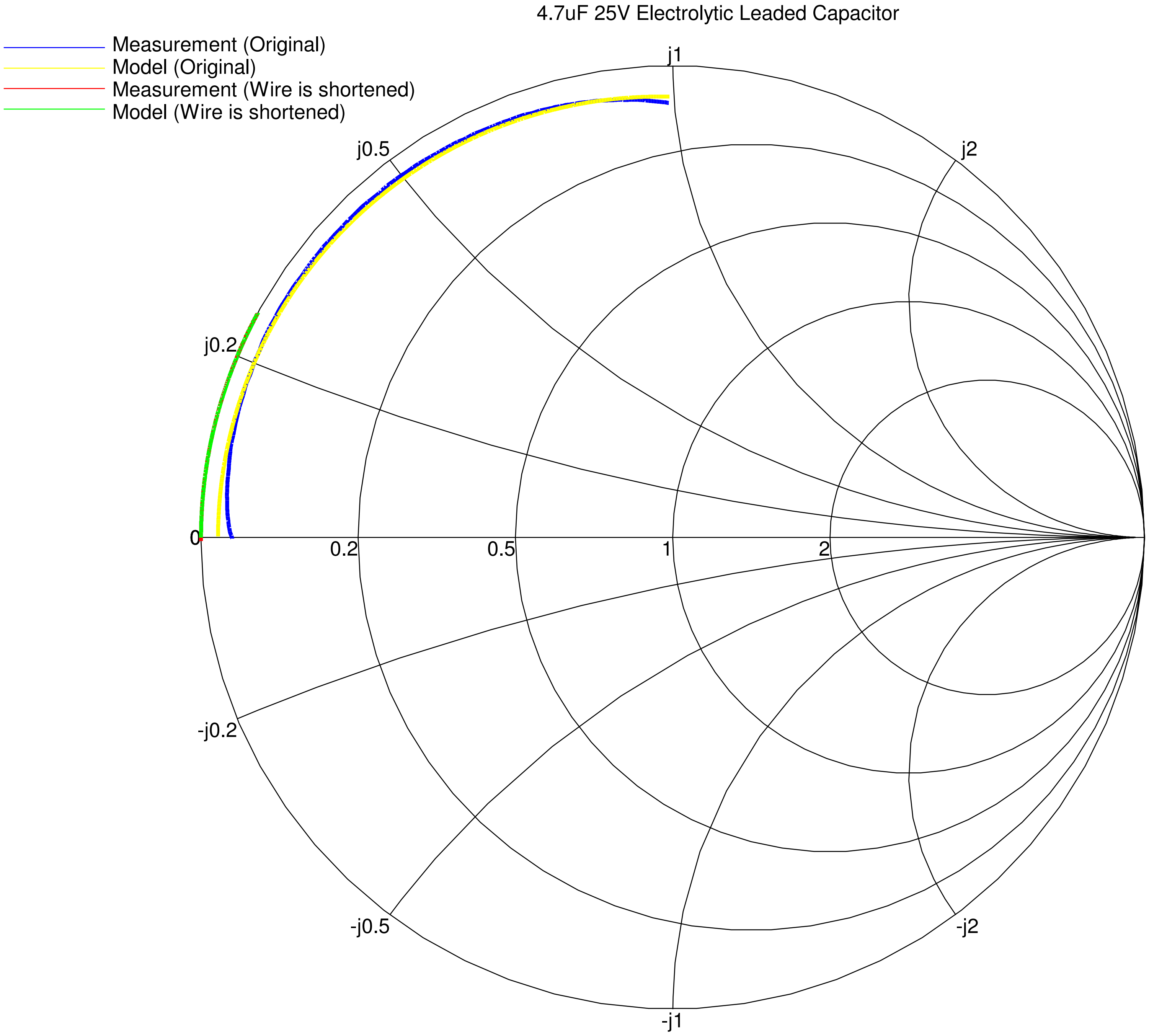


Title: Realistic Model for 4.7uF 25V Electrolytic Leaded Resistor
Treatment: Wire is Shortened


4.7uF 25V Electrolytic Leaded Capacitor (Linear-Scale)
Real Impedance vs Frequency
RealZ
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
50
40
30
20
10
0
-10
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)

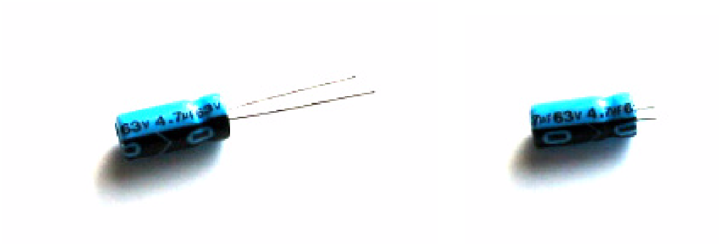
4.7uF 25V Electrolytic Leaded Capacitor (Log-Scale)




4.7uF 25V Electrolytic Leaded Capacitor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

2.4.13 4.7μF 63V Electrolytic Leaded Capacitor

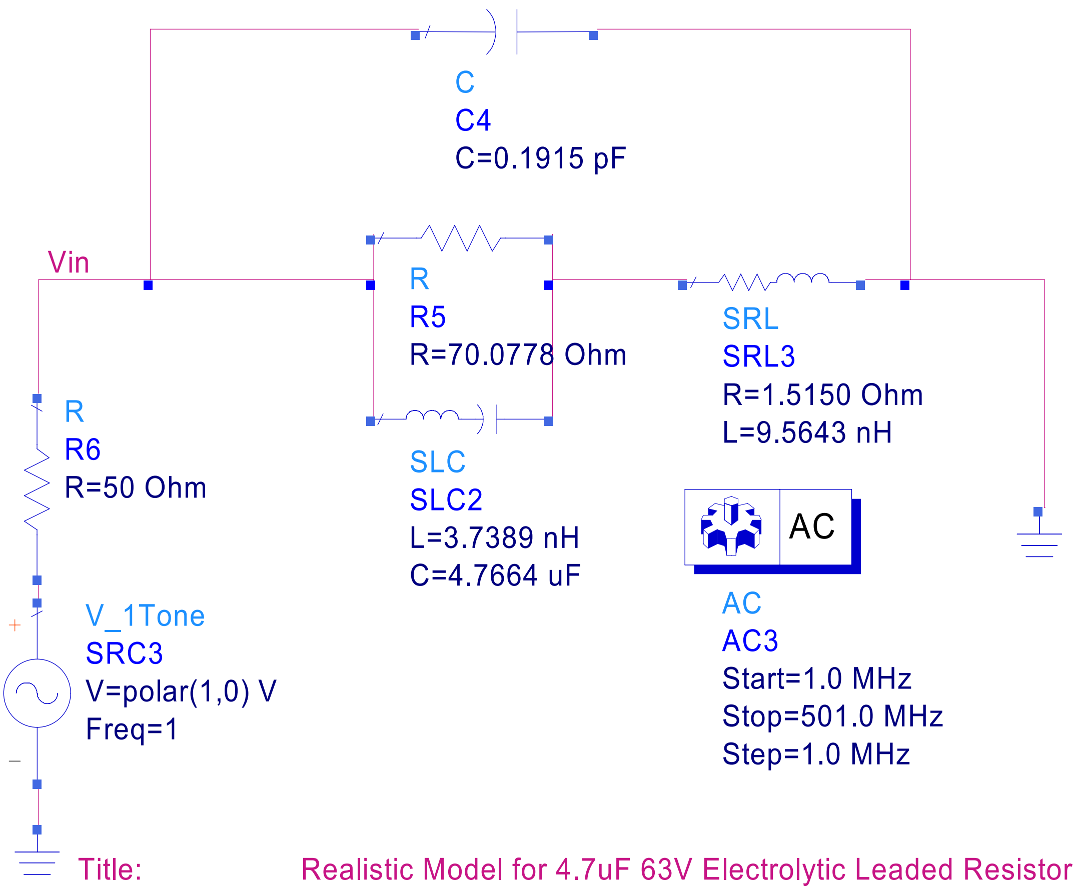
The following are the pictures of an original and after treatment 4.7μF 63V Electrolytic Leaded Capacitor.



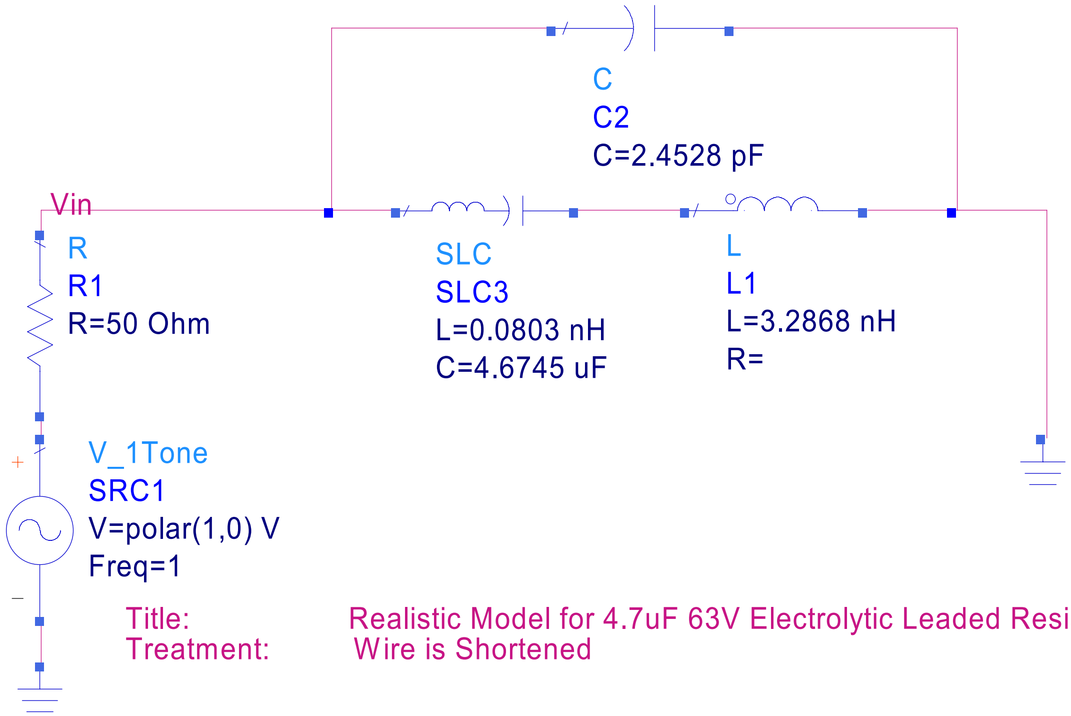
Picture of an original capacitor and a shortened wire capacitor

This table summarizes the measured data and simulation result.

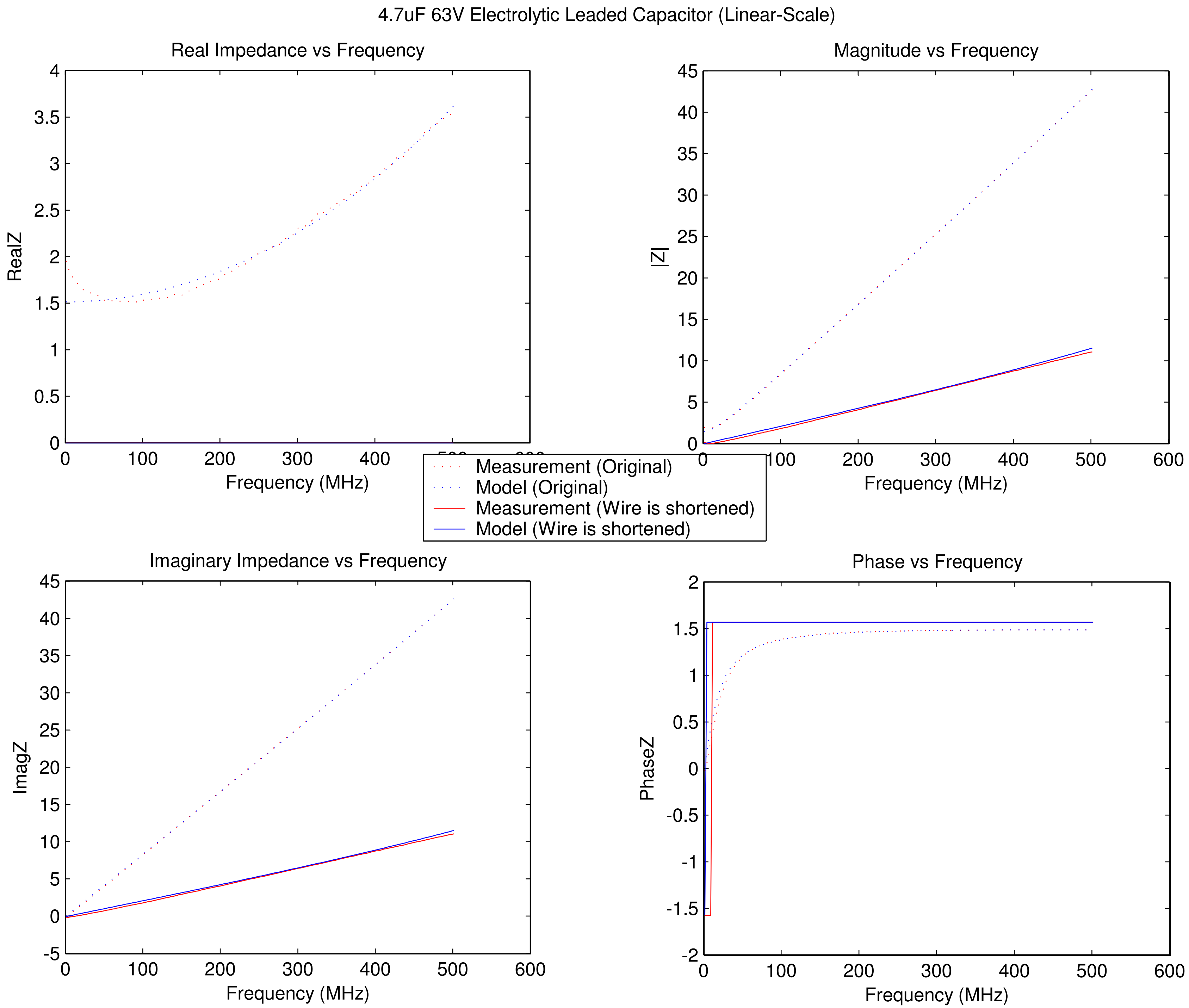
	Original	Wire is shortened
Normalization Treatment	Partial	Loss-Less
Internal Resistance of Model (Ω)	70.0778	∞
Internal Inductance of Model (nH)	3.7389	0.0803
Internal Capacitance of Model (μF)	4.7664	4.6745
External Resistance of Model (Ω)	1.5150	0.0000
External Inductance from estimation (nH)	26.7907	3.2470
External Inductance of Model (nH)	9.5643	3.2868
External Capacitance from estimation (pF)	0.2012	0.0244
External Capacitance of Model (pF)	0.1915	2.4528
Legnth of Leaded Wire (mm)	22.0300	2.6700
Distance between two wires (mm)	5.5100	5.5100
Diameter of wire (mm)	0.4800	0.4800
R-Square Value of Real Impedance	0.9850	1.0000
R-Square Value of Imaginary Impedance	1.0000	0.9993
R-Square Value of Magnitude	1.0000	0.9993
R-Square Value of Phase	0.9973	0.2463

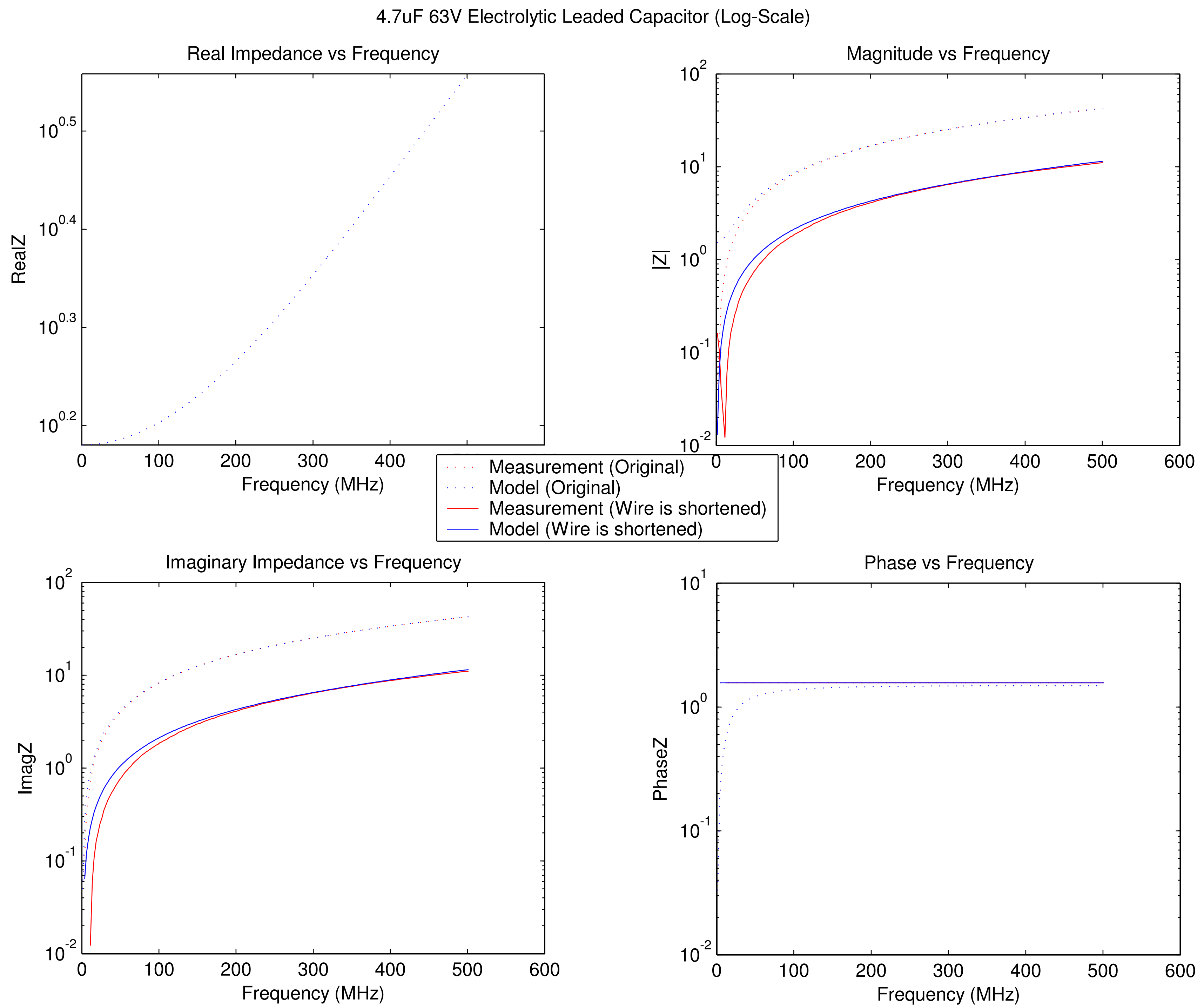


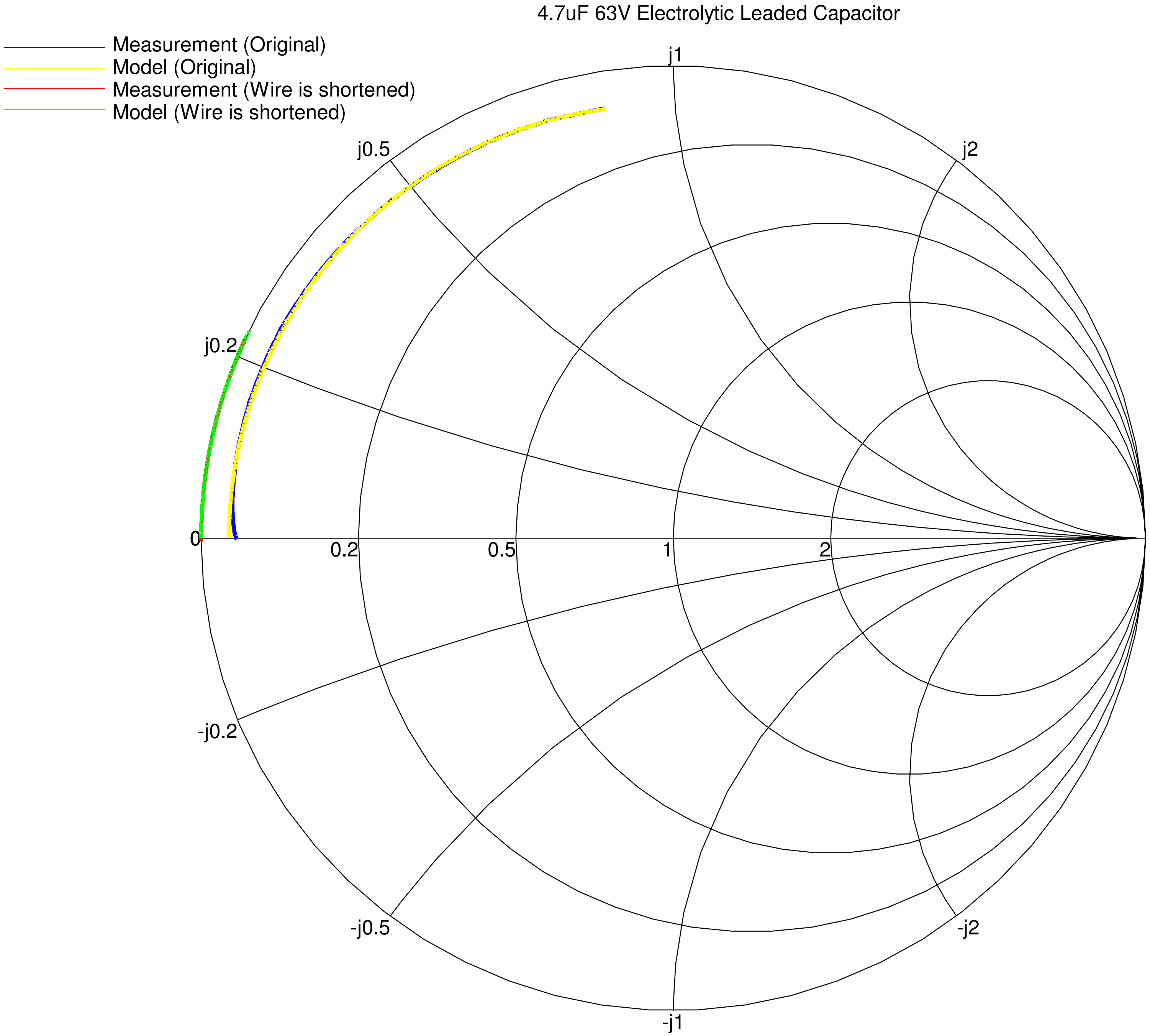
Title: Realistic Model for 4.7uF 63V Electrolytic Leaded Resistor
Treatment: None



Title: Realistic Model for 4.7uF 63V Electrolytic Leaded Resistor
Treatment: Wire is Shortened

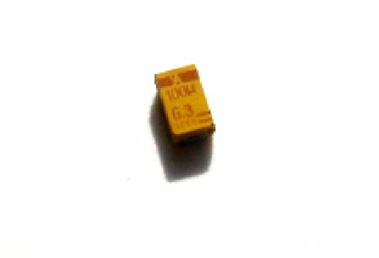

4.7uF 63V Electrolytic Leaded Capacitor (Linear-Scale)
Real Impedance vs Frequency
RealZ
0
0.5
1
1.5
2
2.5
3
3.5
4
Frequency (MHz)
0
100
200
300
400
500
600
Magnitude vs Frequency
|Z|
0
5
10
15
20
25
30
35
40
45
Frequency (MHz)
0
100
200
300
400
500
600
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
-5
0
5
10
15
20
25
30
35
40
45
Frequency (MHz)
0
100
200
300
400
500
600
Phase vs Frequency
PhaseZ
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Frequency (MHz)
0
100
200
300
400
500
600


4.7uF 63V Electrolytic Leaded Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
$10^{0.5}$
$10^{0.4}$
$10^{0.3}$
$10^{0.2}$
0
100
200
300
400
Frequency (MHz)
Magnitude vs Frequency
|Z|
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
Imaginary Impedance vs Frequency
ImagZ
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)


4.7uF 63V Electrolytic Leaded Capacitor
Measurement (Original)
Model (Original)
Measurement (Wire is shortened)
Model (Wire is shortened)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

2.4.14 100μF Tantalum Surface-Mounted Capacitor

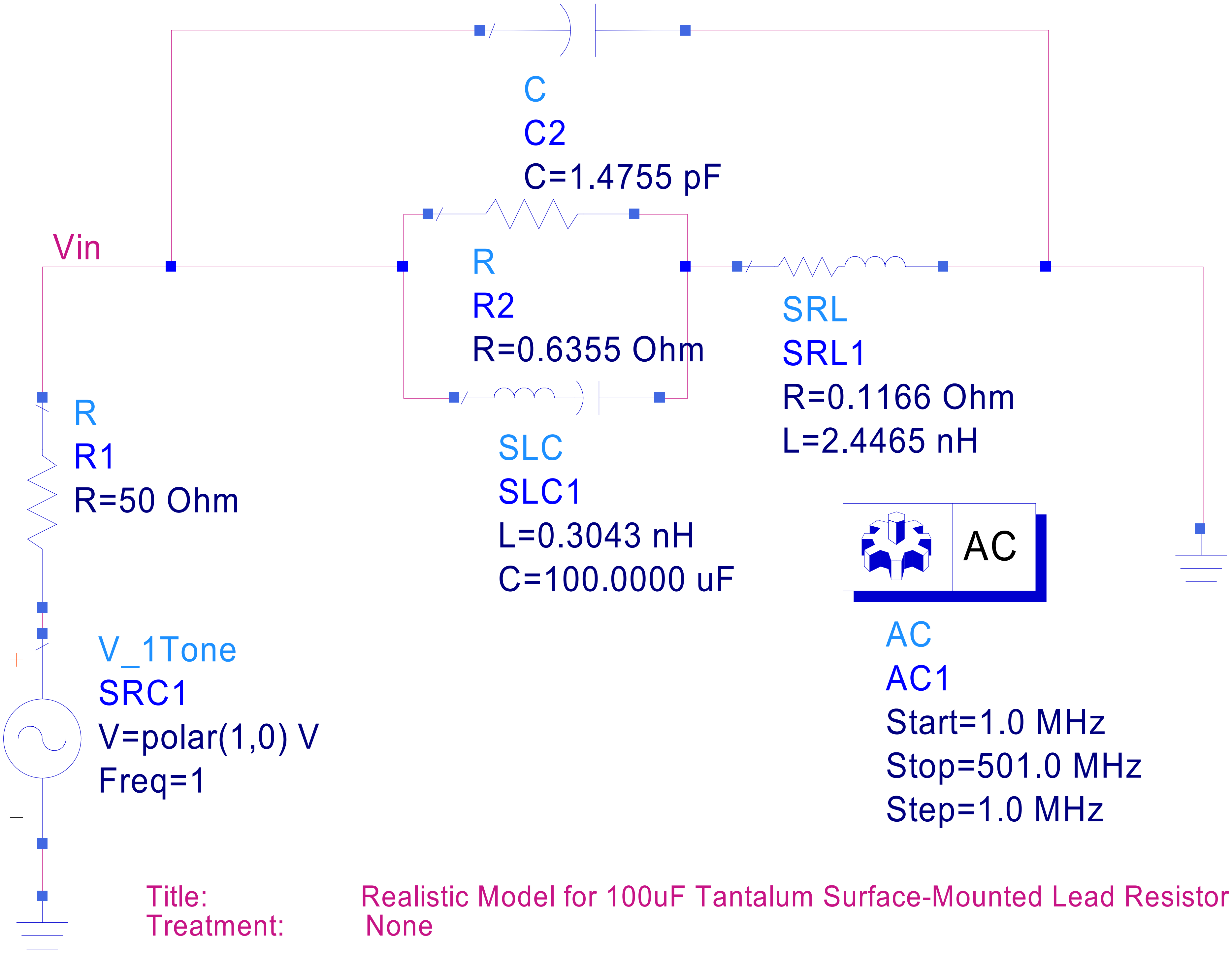
The following is the picture of a 100μF Tantalum Surface-Mounted Capacitor.



Word marked on the chip: `100`μ

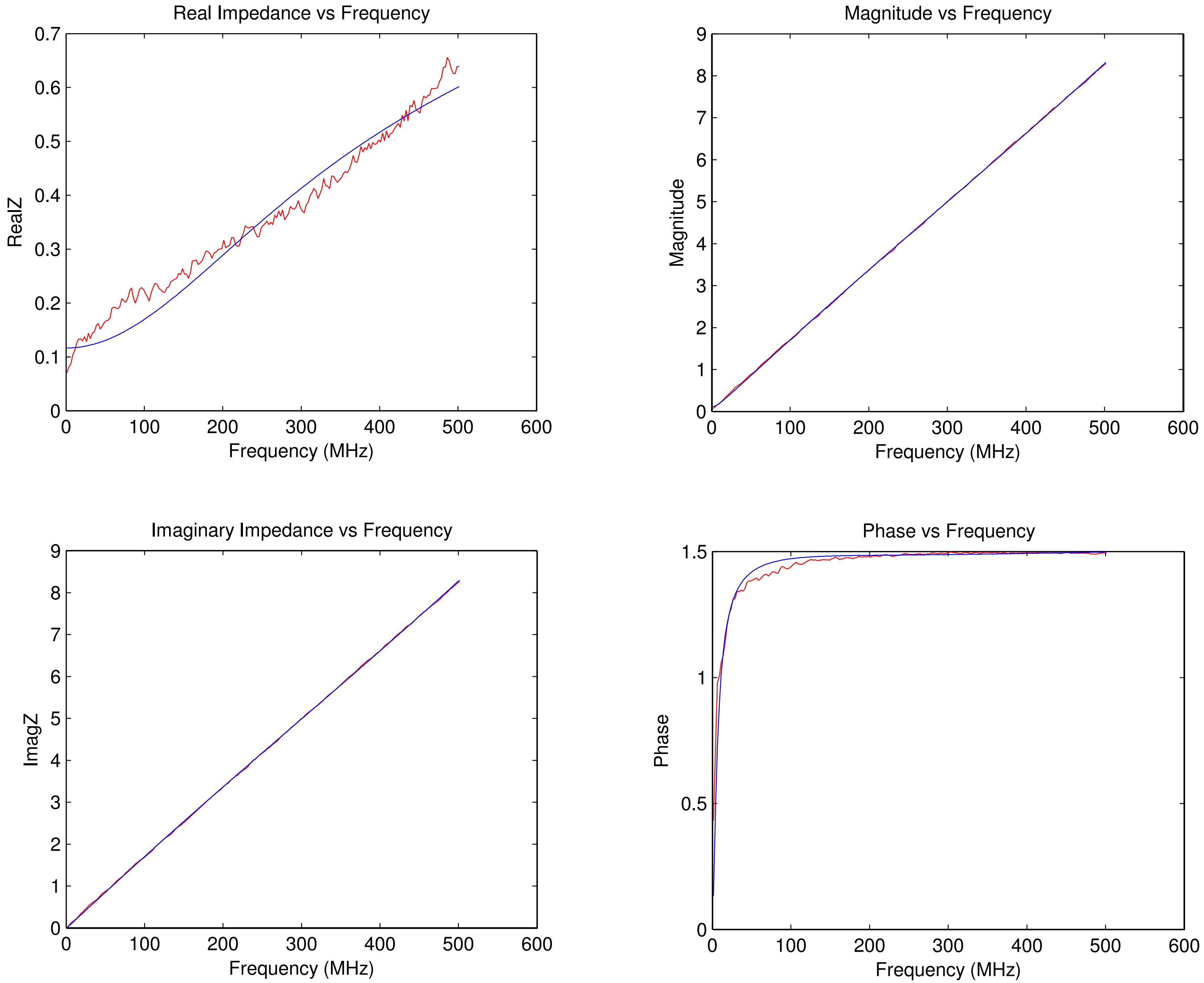
This table summarizes the measured data and simulation result.

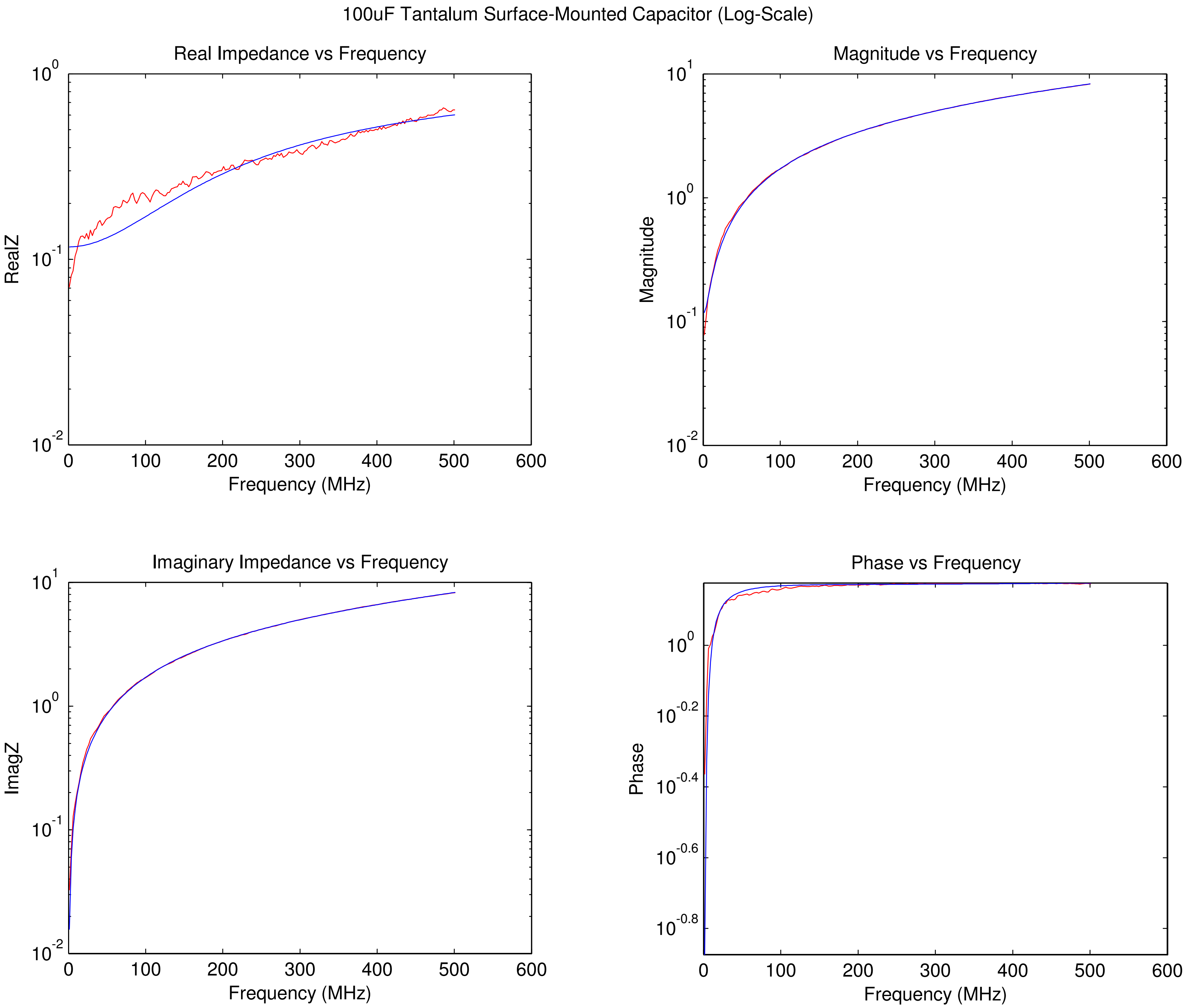
	Original
Normalization Treatment	None
Internal Resistance of Model (Ω)	0.6355
Internal Inductance of Model (nH)	0.3043
Internal Capacitance of Model (μF)	100.0000
External Resistance of Model (Ω)	0.1167
External Inductance of Model (nH)	2.4466
External Capacitance of Model (pF)	1.4756
R-Square Value of Real Impedance	0.9687
R-Square Value of Imaginary Impedance	0.9999
R-Square Value of Magnitude	0.9999
R-Square Value of Phase	0.9643

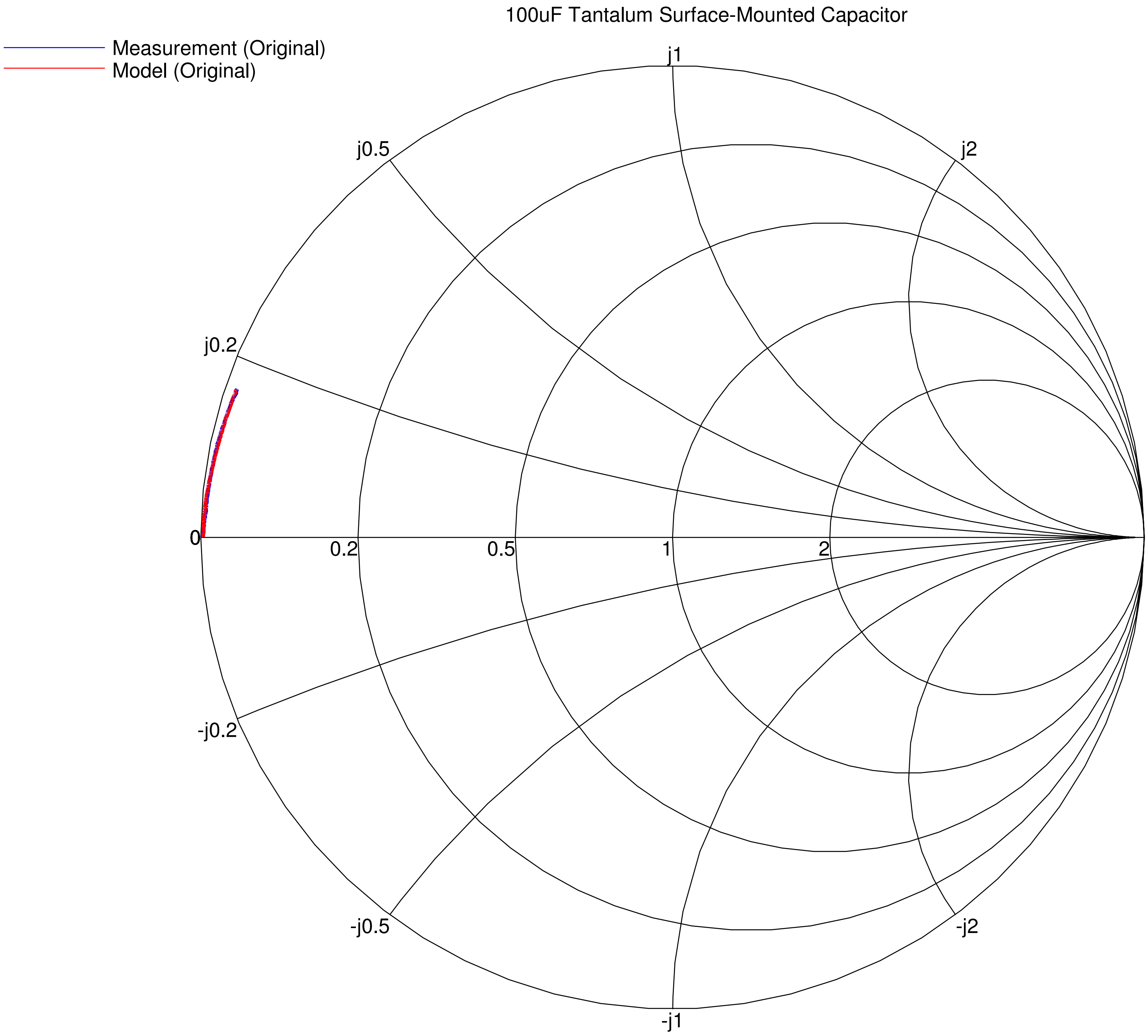


Title: Realistic Model for 100uF Tantalum Surface-Mounted Lead Resistor
Treatment: None

100uF Tantalum Surface-Mounted Capacitor (Linear-Scale)




100uF Tantalum Surface-Mounted Capacitor (Log-Scale)
Real Impedance vs Frequency
RealZ
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Imaginary Impedance vs Frequency
ImagZ
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
10^{0}
$10^{-0.2}$
$10^{-0.4}$
$10^{-0.6}$
$10^{-0.8}$
0
100
200
300
400
500
600
Frequency (MHz)


100uF Tantalum Surface-Mounted Capacitor
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

2.5 Analysis on Disagreement between the Model and Measurement

Most models agrees with their measurement data (R-Square value > 0.90).

Capacitance	Material	Voltage (V)	Treatment	Mean of R^2
1pF	Ceramic Disk Leaded	–	None	0.9327
1pF	Ceramic Disk Leaded	–	Wire is shortened	0.8874
1pF	SilverMica Leaded	–	None	0.9396
1pF	SilverMica Leaded	–	Wire is shortened	0.9220
100pF	SilverMica Leaded	–	None	0.7309
100pF	SilverMica Leaded	–	Wire is shortened	0.6887
100pF	Polystrene Leaded	–	None	0.7703
100pF	Polystrene Leaded	–	Wire is shortened	0.5518
0.01μF	Ceramic Disk Leaded	–	None	0.9687
0.01μF	Ceramic Disk Leaded	–	Wire is shortened	0.7042
0.01μF	Monolithic Leaded	–	None	0.9954
0.01μF	Monolithic Leaded	–	Wire is shortened	0.7196
0.01μF	Tantalum Chip	–	None	0.8592
1μF	Minilytic Leaded	–	None	0.9968
1μF	Minilytic Leaded	–	Wire is shortened	0.6597
1μF	Monolithic Leaded	–	None	0.9934
1μF	Monolithic Leaded	–	Wire is shortened	0.9997
1μF	Electrolytic Leaded	50	None	0.9968
1μF	Electrolytic Leaded	50	Wire is shortened	0.7457
1μF	Paper Leaded	–	None	0.9251
4.7μF	Electrolytic Leaded	25	None	0.9657
4.7μF	Electrolytic Leaded	25	Wire is shortened	0.8112
4.7μF	Electrolytic Leaded	63	None	0.9956
4.7μF	Electrolytic Leaded	63	Wire is shortened	0.8112
100μF	Tantalum Surface-Mounted	–	None	0.9832

However, some models are failed to agree in some regions. These regions are summarized below:

2.5.1 Disagree in Real Impedance at Low frequency

For the small capacitance capacitors($\leqslant$ 100pF), the models are failed to match the measurement data at the low frequency region (< 5 MHz). This problem happens in the following capacitors:

1. 100 pF SilverMica Leaded Capacitor (Original)
2. 100 pF Polystrene Leaded Capacitor (Original)

Related plots will be shown on the next page.

Considering the following capacitor model:

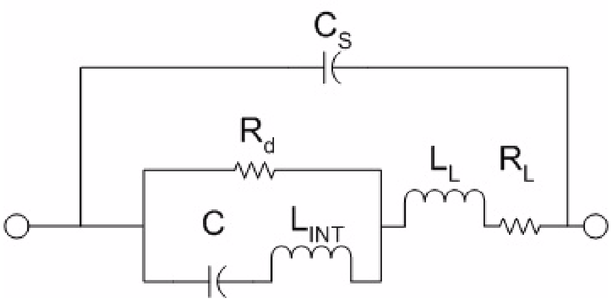
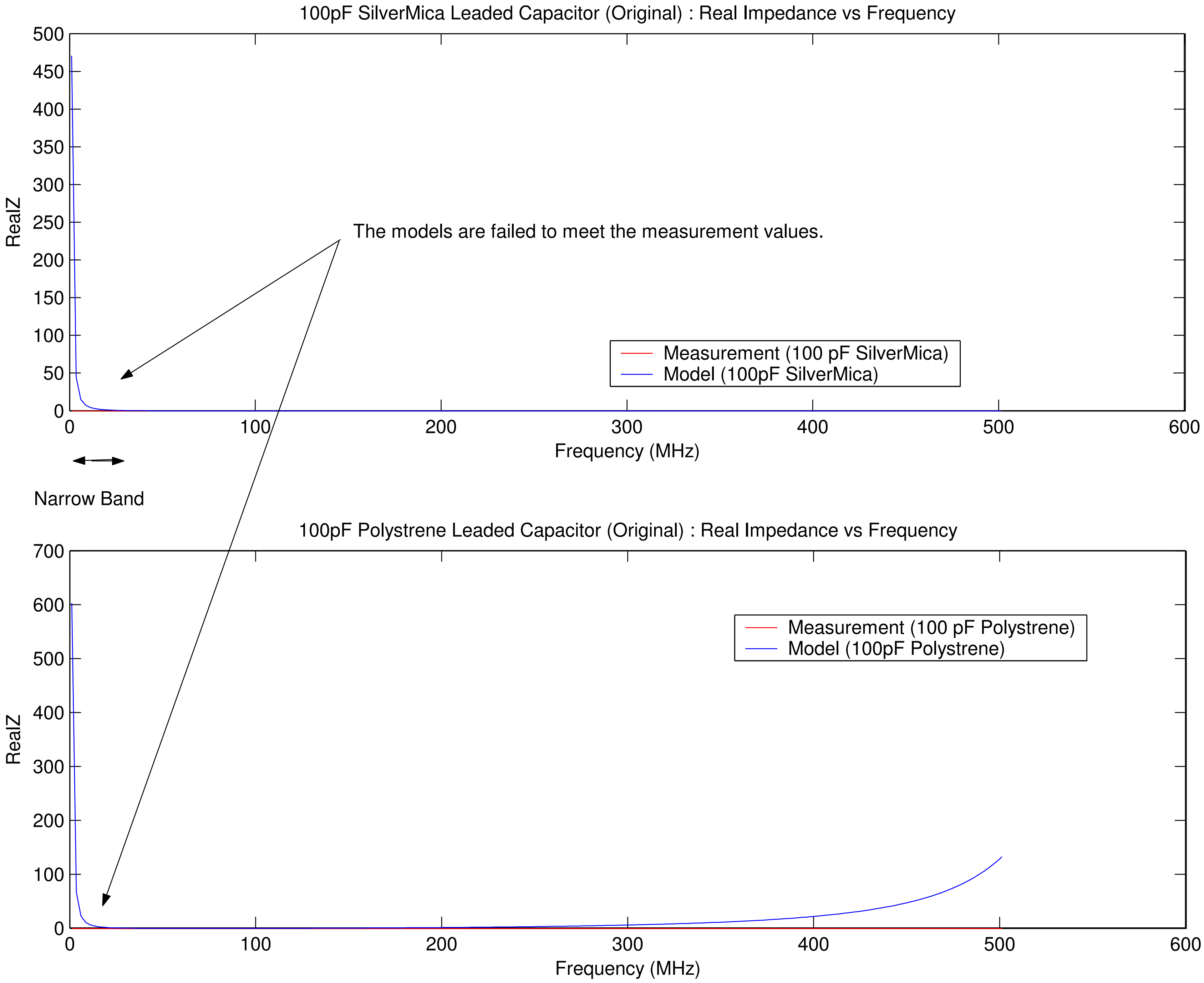


Figure 17: Equivallent Circuit Model of Capacitor

At the very low frequency (closed to DC), the capacitor and inductor can be ignored. Therefore, the circuit is simply the resistor R_d and R_L in serial. According to the plots, the real impedance is about 450Ω.

The real impedance of both samples drop significantly from 1MHz to 10 MHz. Beyond 10 MHz, the real impedance is very closed to zero and can be considered as a loss-less circuit. In our model it is not easy to model the drop in such a narrow band (10 MHz).


100pF SilverMica Leaded Capacitor (Original) : Real Impedance vs Frequency
RealZ
500
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Frequency (MHz)
The models are failed to meet the measurement values.
Measurement (100 pF SilverMica)
Model (100pF SilverMica)
Narrow Band
100pF Polystrene Leaded Capacitor (Original) : Real Impedance vs Frequency
RealZ
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement (100 pF Polystrene)
Model (100pF Polystrene)

2.6 Analysis on Breakdown Voltage

Breakdown Voltage is the maximum voltage that the capacitor can handle. The breakdown voltage depends on the kind of capacitor being used. If it exceeds, it will cause the dielectric material inside the capacitor to break down and conduct.

Electrolytic Capacitor is commonly used in bypassing the signal. Therefore, I selected the following samples to compare the frequency characteristics of different breakdown voltages.

1

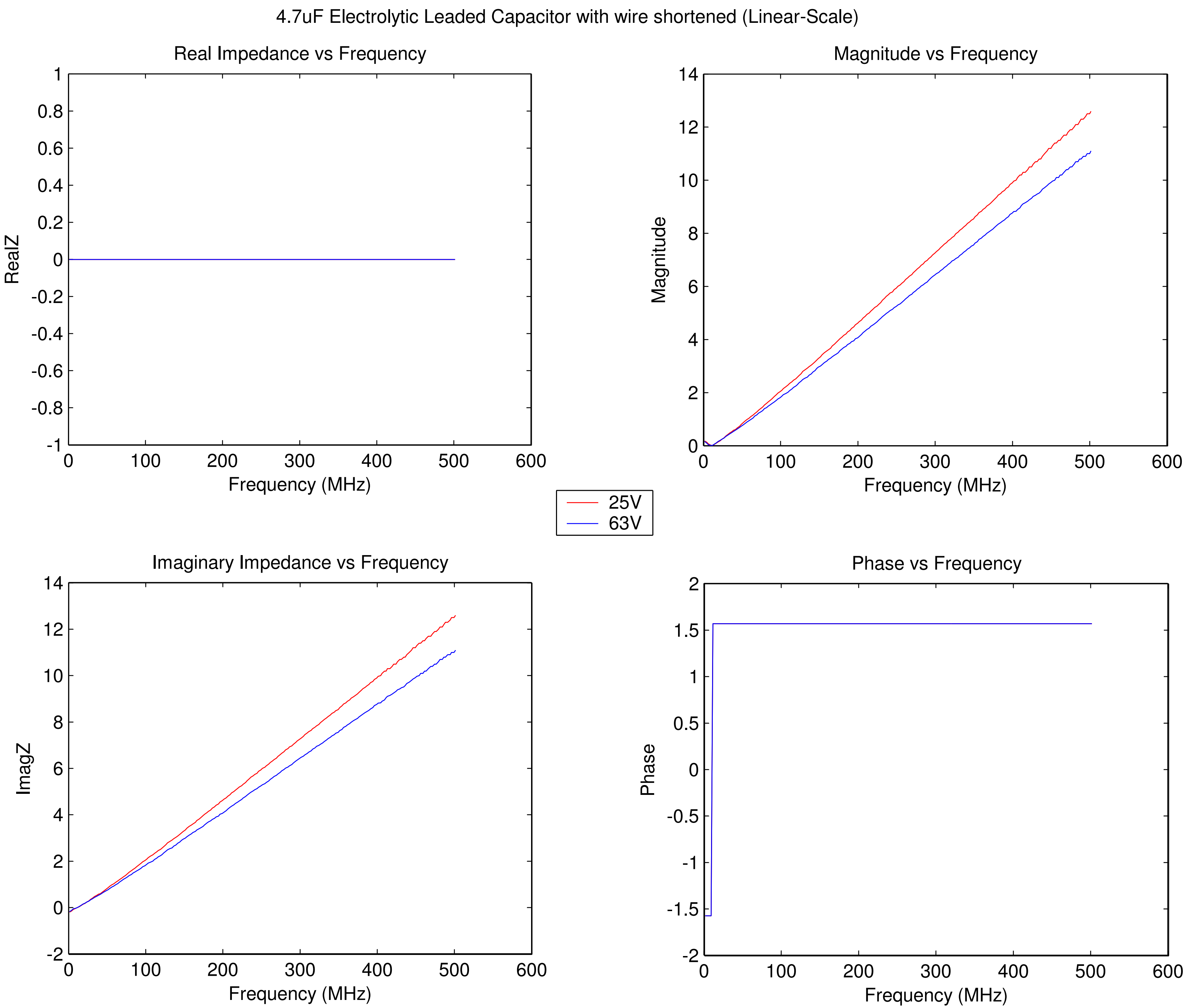
2

1. 4.7μF 25V Electrolytic Leaded Capacitor (Wire is shortened)
2. 4.7μF 63V Electrolytic Leaded Capacitor (Wire is shortened)

The plots are shown on the next page.

Both samples have similar frequency characteristics. Both of them are loss-less, and the 25V one is more inductive than the other one. It is clearly that their inductive components dominate the capacitive components. Here are their equivalent models values:

	25V	63V
Internal Resistance of Model (Ω)	∞	∞
Internal Inductance of Model (nH)	0.1276	0.0803
Internal Capacitance of Model (μF)	4.6659	4.6745
External Resistance of Model (Ω)	0.0000	0.0000
External Inductance of Model (nH)	37.0015	3.2868
External Capacitance of Model (pF)	23.6060	2.4528



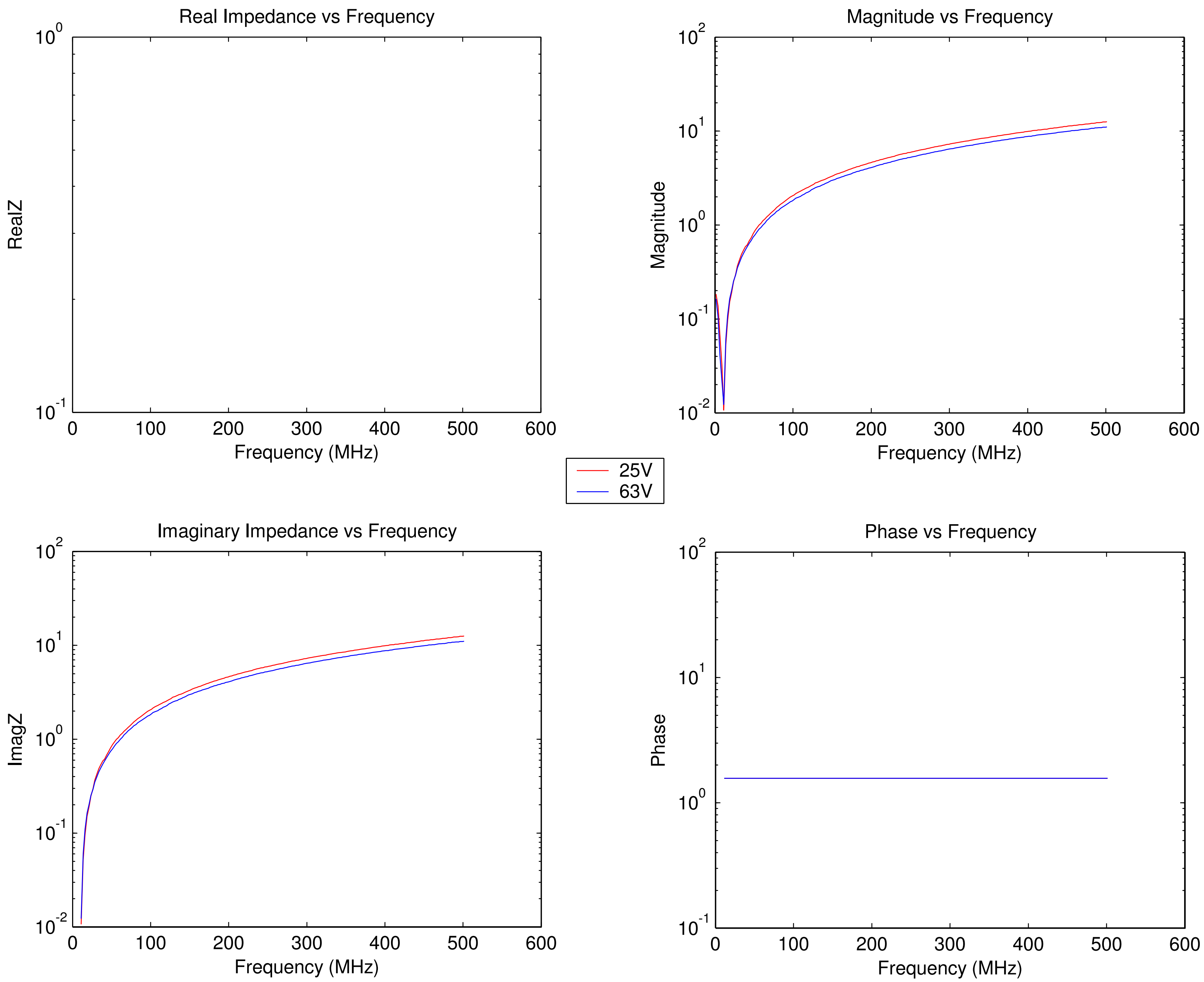
4.7uF Electrolytic Leaded Capacitor with wire shortened (Linear-Scale)

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


4.7uF Electrolytic Leaded Capacitor with wire shortened (Log-Scale)

2.7 Analysis on Common Type of Leaded Capacitor

In aerospace application, the physical property of capacitor itself is very important. Since the physical environment in space is very extreme, for example, it can be very hot if it is exposed under the sun light, or it can be very cold if it is behind the earth. Also, the pressure and gravity will be closed to zero in space. Therefore, not every type of capacitor can perform normally in such environment.

Gel is used as a dielectric material in Electrolytic Capacitor, which has a high potential to explode in vacuum. Therefore, it is necessary to replace it with the other type capacitor which is safe in vacuum.

These are the common type of the Leaded Capacitors I select:

1

2

3

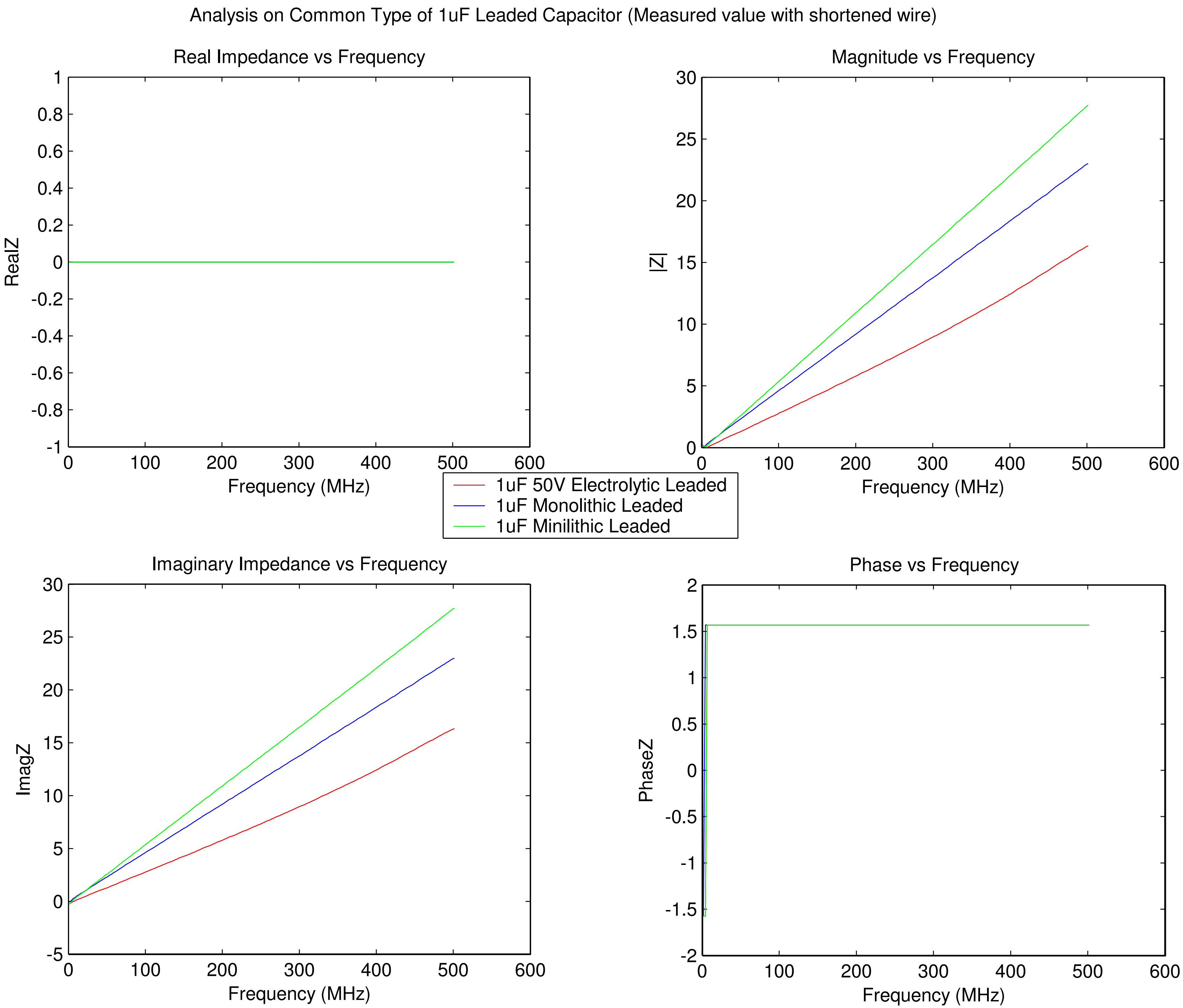
1. 1μF 50V Electrolytic Leaded Capacitor (Wire is shortened)
2. 1μF Monolithic Leaded Capacitor (Wire is shortened)
3. 1μF Minilytic Leaded Capacitor (Wire is shortened)

The plots will be shown on next page.

From the plots, all of three capacitors behaves similar in impedances and phase. They are relatively low-loss, and they are inductive. Overall, the electrolytic capacitor is more inductive than the other two capacitors.

The following are their models components.

	Electrolytic	Monolithic	Minilytic
Internal Resistance of Model (Ω)	∞	∞	∞
Internal Inductance of Model (nH)	4.5182	0.1949	0.0006
Internal Capacitance of Model (μF)	1.0078	1.0130	1.0493
External Resistance of Model (Ω)	0.0000	0.0000	0.0000
External Inductance of Model (nH)	0.0000	6.8640	8.6835
External Capacitance of Model (pF)	3.0829	0.8242	0.1951


Analysis on Common Type of 1uF Leaded Capacitor (Measured value with shortened wire)
Real Impedance vs Frequency
RealZ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
|Z|
30
25
20
15
10
5
0
0
100
200
300
400
500
600
Frequency (MHz)
1uF 50V Electrolytic Leaded
1uF Monolithic Leaded
1uF Minilithic Leaded
Imaginary Impedance vs Frequency
ImagZ
30
25
20
15
10
5
0
-5
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
PhaseZ
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)

2.8 Analysis on the Shape of Impedance

In this section, I plot the real impedance, imaginary impedance and Smith Chart of the following resistors:

1. 1pF SilverMica Leaded Capacitor with wire shortened
2. 100pF SilverMica Leaded Capacitor with wire shortened
3. 0.01μF Monolithic Leaded Capacitor with wire shortened
4. 1μF Monolithic Leaded Capacitor with wire shortened
5. 100μF Tantalum Surface-Mounted Capacitor

1

2

3

4

5

2.8.1 Real Impedance

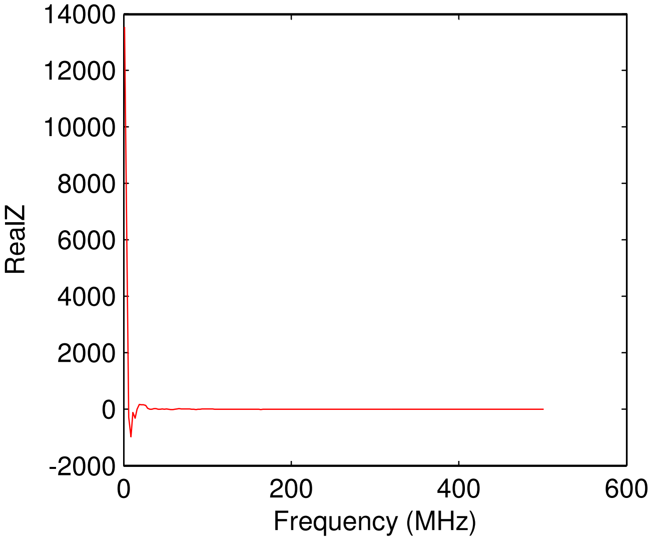
From the plots on next page, it is clear that small capacitance SilverMica capacitors (1pF, 100pF) have high real impedances in low frequency region (1 MHz - 10 MHz), and becomes loss-less beyond this region.

For the middle size of the capacitance Monolithic capacitors (0.01μF, 1μF), the plots are not accurate because they have negative real impedance due to the measurement error. However, their shapes are meaningful. I think their real impedances behaves in this shape, but with a extremely small magnitude.

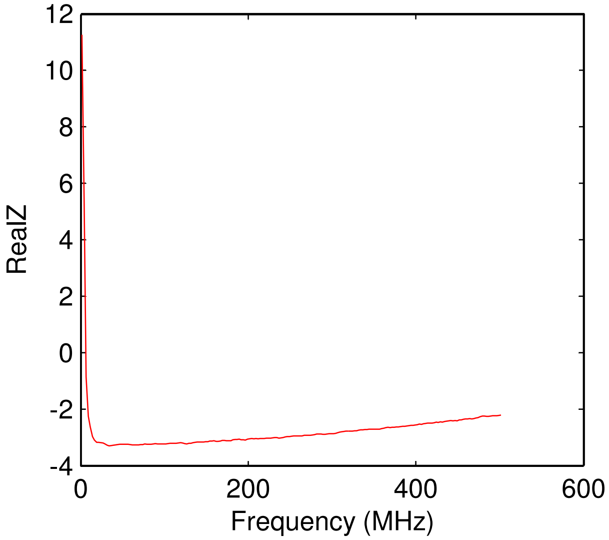
For the large capacitance Tantalum capacitor (100pF), it increases linearly through the sampling frequency range.

Real Impedance of Selected Capacitor (Measurement with wire shortened)

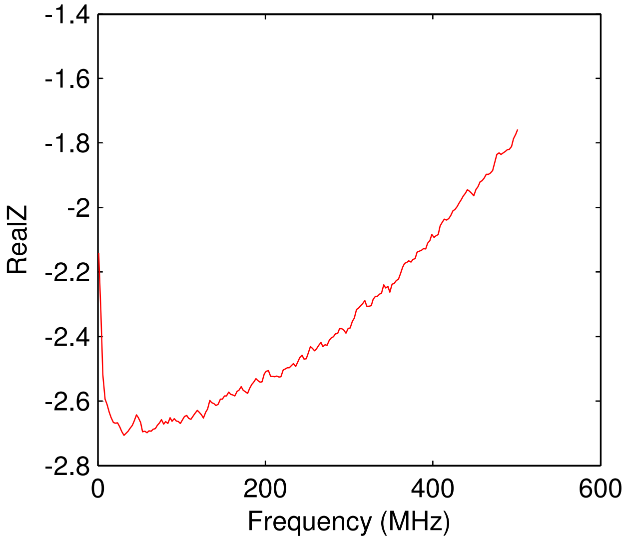
1pF SilverMica Leaded Capacitor



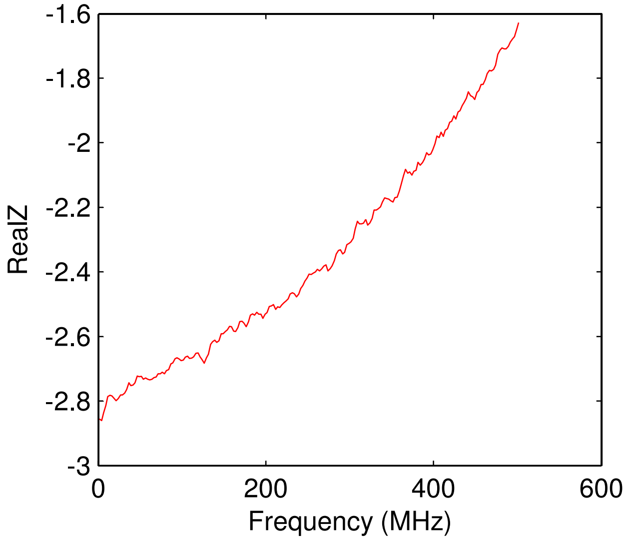
100pF SilverMica Leaded Capacitor



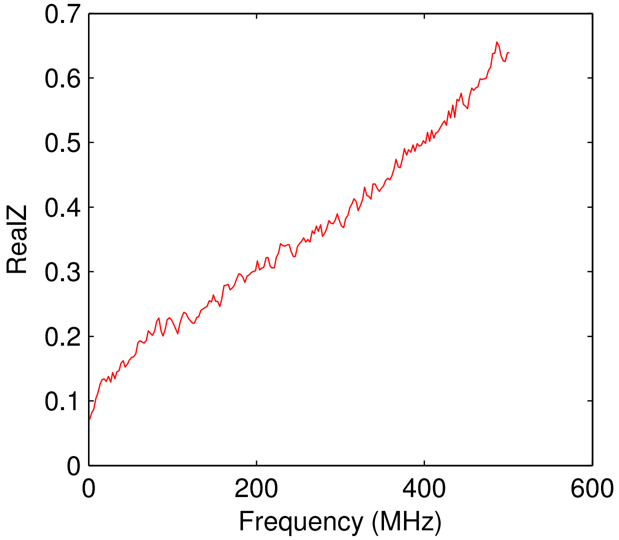
0.01uF Monolithic Leaded Capacitor



1uF Monolithic Leaded Capacitor



100uF Tantalum Surface-Mounted Capacitor

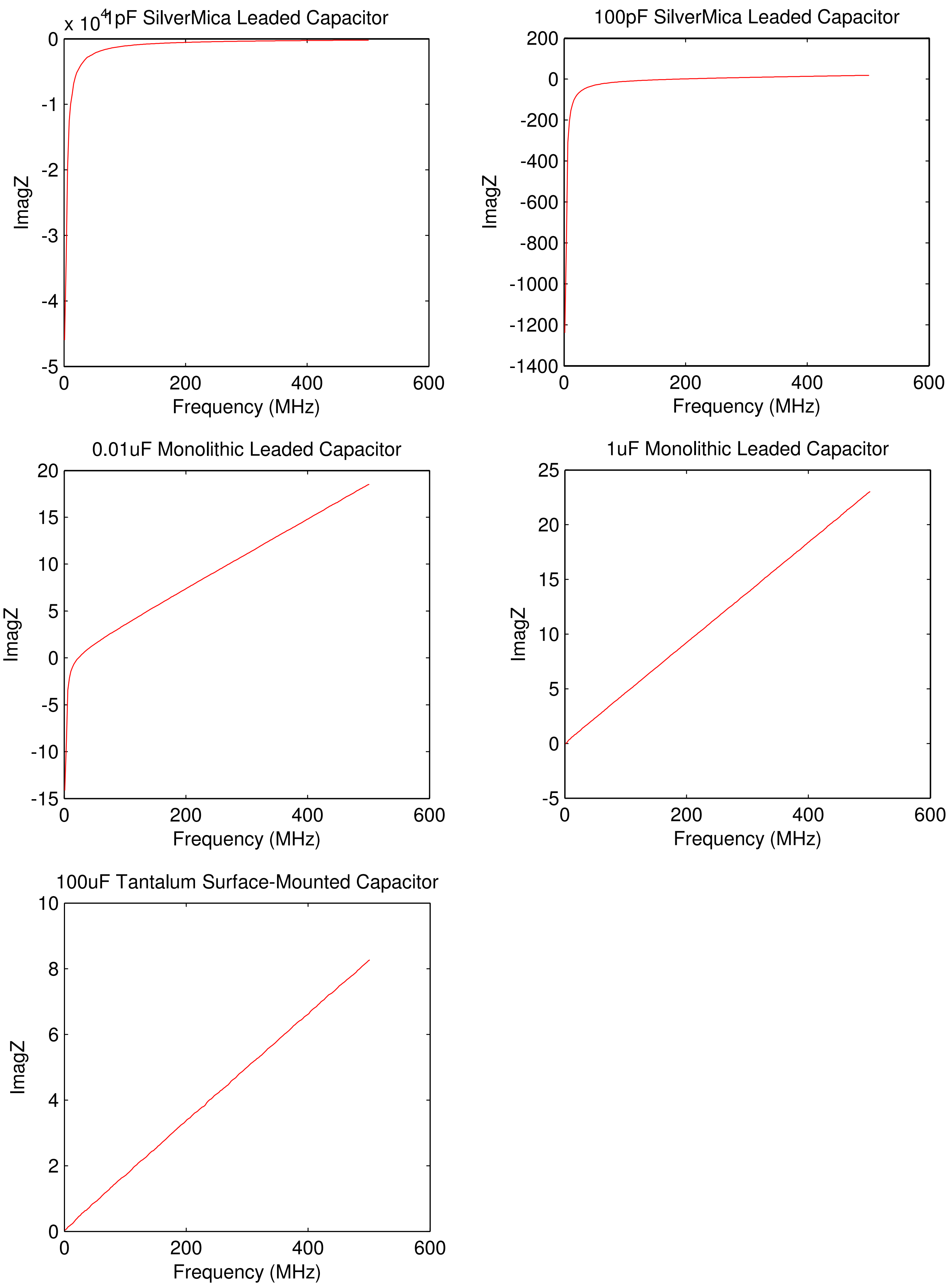


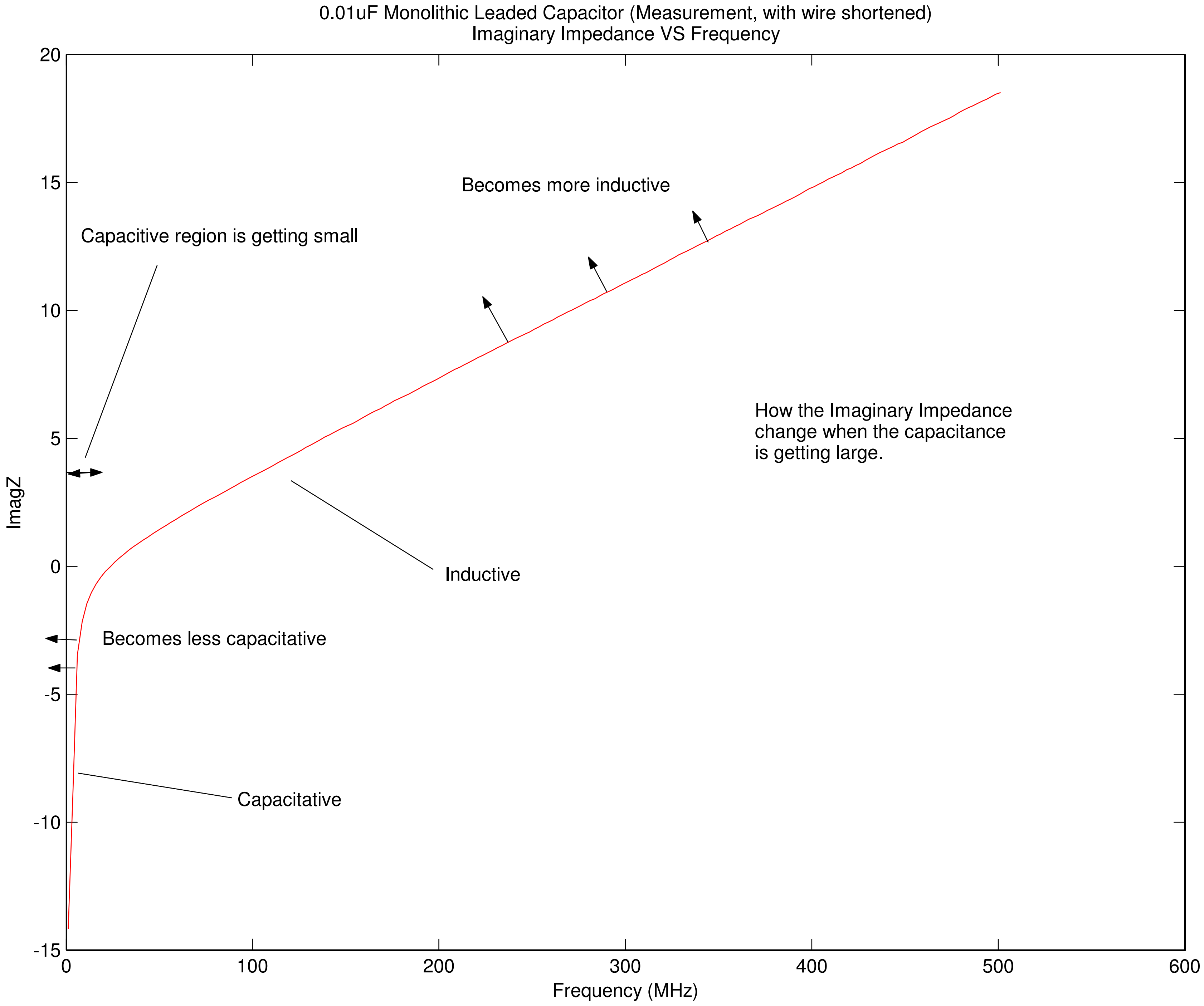
2.8.2 Imaginary Impedance

Overall, the capacitor becomes capacitative if the capacitance is small. It becomes less capacitive and more inductive when the capacitance increases. Finally, it becomes purely inductive. A 0.01μF Monolithic Leaded Capacitor with wire shortened is selected to express this idea graphically on next page

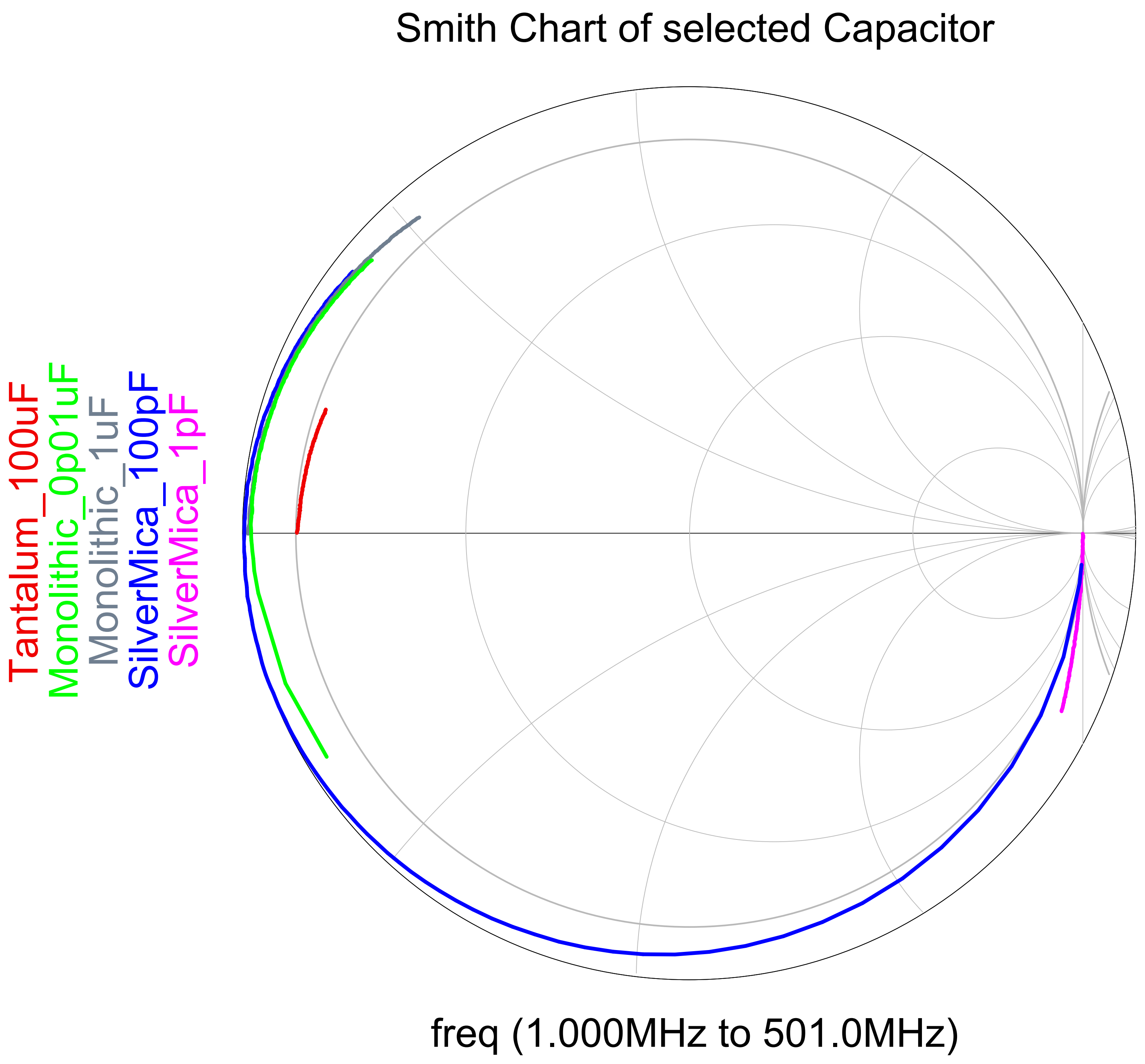
A 0.01μF Monolithic Leaded Capacitor with wire shortened

Imaginary Impedance of Selected Capacitor (Measurement with wire shortened)





0.01uF Monolithic Leaded Capacitor (Measurement, with wire shortened)
Imaginary Impedance VS Frequency


Smith Chart of selected Capacitor
Tantalum_100uF
Monolithic_0p01uF
Monolithic_1uF
SilverMica_100pF
SilverMica_1pF
freq (1.000MHz to 501.0MHz)

3 Inductor

3.1 Introduction

Inductor can be treated as a resistor. It has the same equivalent model as resistor but with a different component values. Therefore the model is simply:

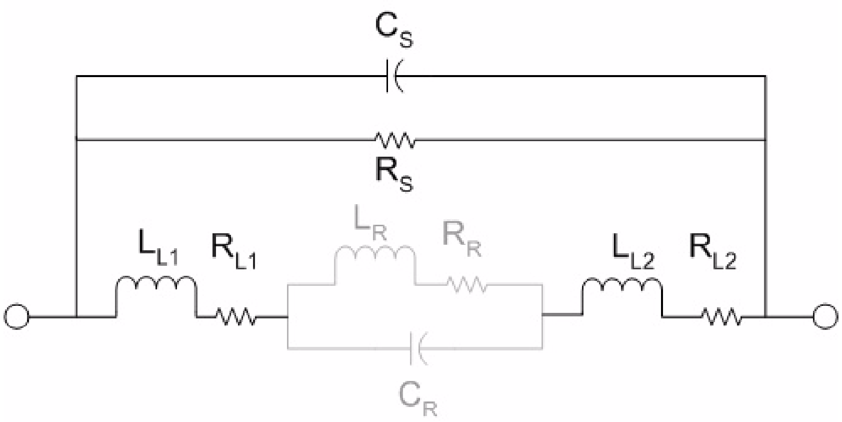


Figure 18: Complete Equivalent Model for Inductor

Since the resistive component of the transmission line could be ignored, the model can be simplified to:

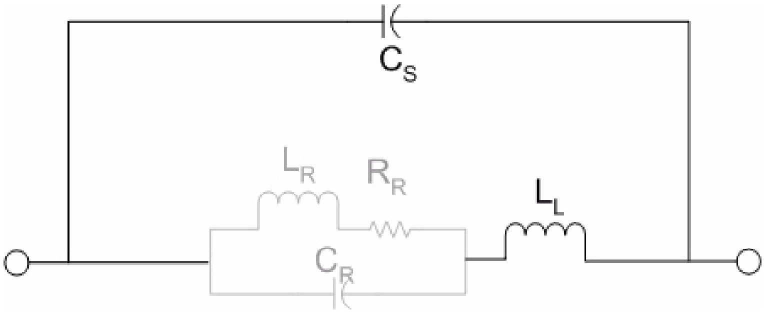


Figure 19: Simplified Equivalent Model for Inductor

In this project, I analysis two common types of the inductor: Air-Core and Toroidal Core Inductors.

In general, the estimation on the number of turns can be given by the following equations:

For Air-Core Inductor:

$$N = \frac{\sqrt{L\,(9r + 10l)}}{r} \tag{20}$$

where
N = Number of turns,
L = Inductance in μH,
r = Radius of coil in inches,
l = Length of coil in inches.

For Iron Powder Toroidal Inductor:

$$N = 100\sqrt{\frac{L\,(\mu H)}{A_L}} \tag{21}$$

For Ferrite Toroidal Inductor:

$$N = 1000\sqrt{\frac{L\,(mH)}{A_L}} \tag{22}$$

where
A_L = Toroidal Core parameter.

3.2 Analysis on Inductor

There are many types of Toroidal Core. Each of them have different frequency characteristics. Therefore, I built the inductors with the same inductance using these Toroidal Cores.

Inductance	Type	Material[4]	Suggested Operating Frequency
0.1μH	Iron Powder Toroidal Core	T-30-00	50 MHz - 300 MHz
0.1μH	Iron Powder Toroidal Core	T-30-02	1 MHz - 30 MHz
0.1μH	Iron Powder Toroidal Core	T-30-06	2 MHz - 50 MHz
0.1μH	Iron Powder Toroidal Core	T-30-07	5 MHz - 35 MHz
0.1μH	Iron Powder Toroidal Core	T-30-10	10 MHz - 100 MHz
0.1μH	Iron Powder Toroidal Core	T-30-12	20 MHz - 200 MHz
1μH	Iron Powder Toroidal Core	T-50-02	1 MHz - 30 MHz
1μH	Iron Powder Toroidal Core	T-50-03	0.05 Hz - 0.5 MHz
1μH	Iron Powder Toroidal Core	T-50-06	5 MHz - 35 MHz
1μH	Iron Powder Toroidal Core	T-50-07	2 MHz - 50 MHz
1μH	Iron Powder Toroidal Core	T-50-10	10 MHz - 100 MHz
10μH	Ferrite Toroidal Core	FT-82-43	1 MHz - 50 MHz
10μH	Ferrite Toroidal Core	FT-82-61	10 MHz - 200 MHz
10μH	Ferrite Toroidal Core	FT-82-63	25 MHz - 200 MHz
0.1μH	Air-Core	#8079	N.A.
1μH	Air-Core	#8079	N.A.

Remark 1 *10μH Air-Core Inductor was not built because it required too many turns, which was too large to fit in the spring clip fixture.*

---

[4] All Toroidal Core Inductors are made by Amidon and they are wired using Copper #8079.

3.3 Measurement Step

The measurement procedure of inductor is similar to the resistor and capacitor measurement except for removing the oxide layer of the copper wire. The material of the wire is Copper, which will form a Copper Oxide layer on the surface when it is exposed in air. This layer will cause a bad connection, which may result an invalid measurement. For example, an inductor without this treatment may behave like a capacitive component in low frequency range, which is not what we expect. Therefore, it is necessary to remove this layer.

During the first time I made the measurement, I had a hard time to come up a good agreement with the model and the measurement data. The problem is possibly caused by the sampling frequency. Since the sampling frequency ranges from 1 MHz to 501 MHz. It is hard to come up a model that fit all the points in this wide frequency range. Therefore, I made the second measurement with a different frequency range[5]. The new range is the values suggested by the manufacture. For example, there are two sets of measurement for Iron Powder Toroidal Core T-30-02 Inductor: One of them is from 1 MHz to 501 MHz, and the other one is from 1 MHz - 30 MHz.

---

[5] Calibration is necessary to be repeated when the sampling frequency is changed.

3.4 Measurement Result

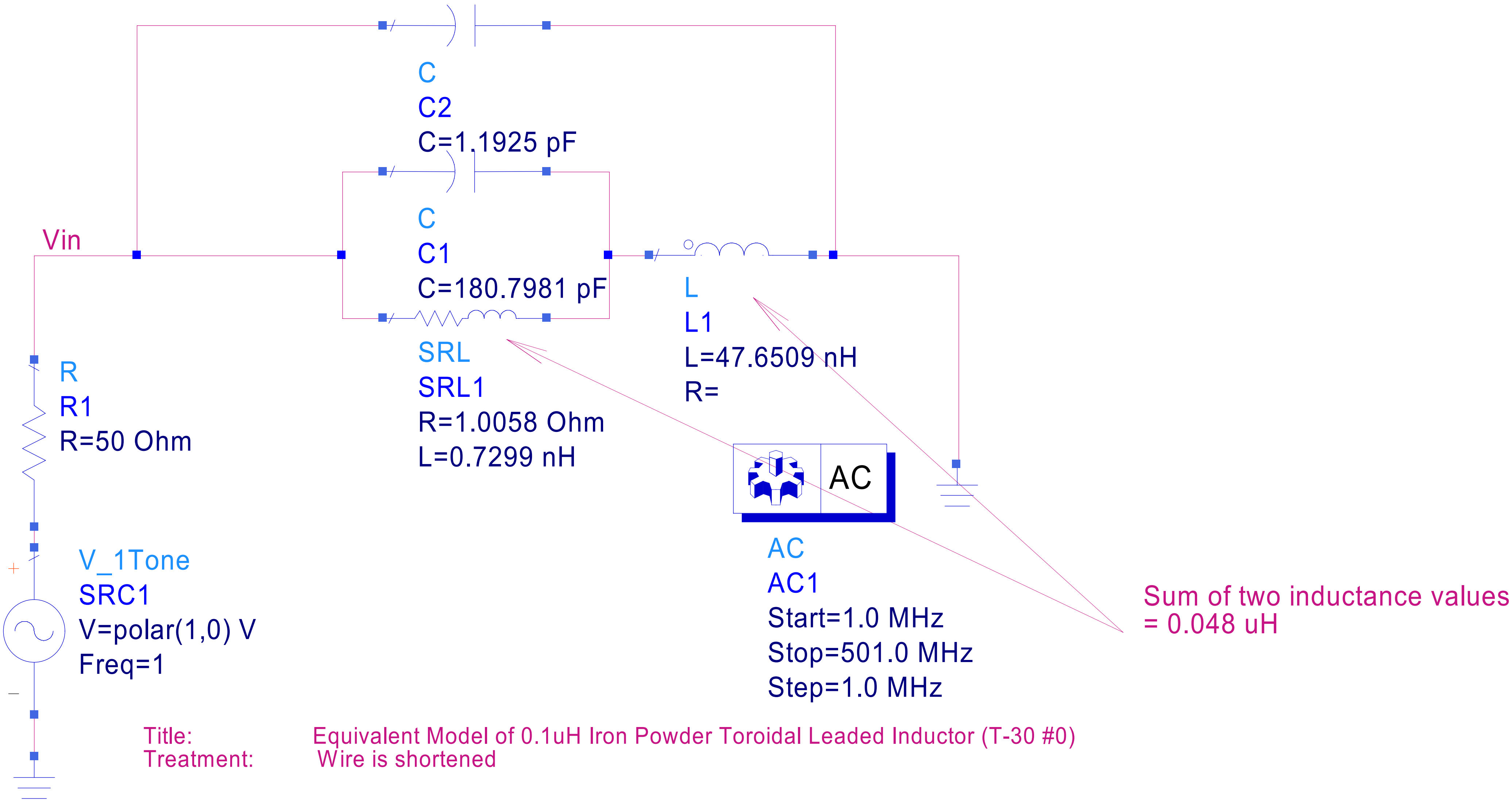
3.4.1 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #0)

The following is the picture of a 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #0)

Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

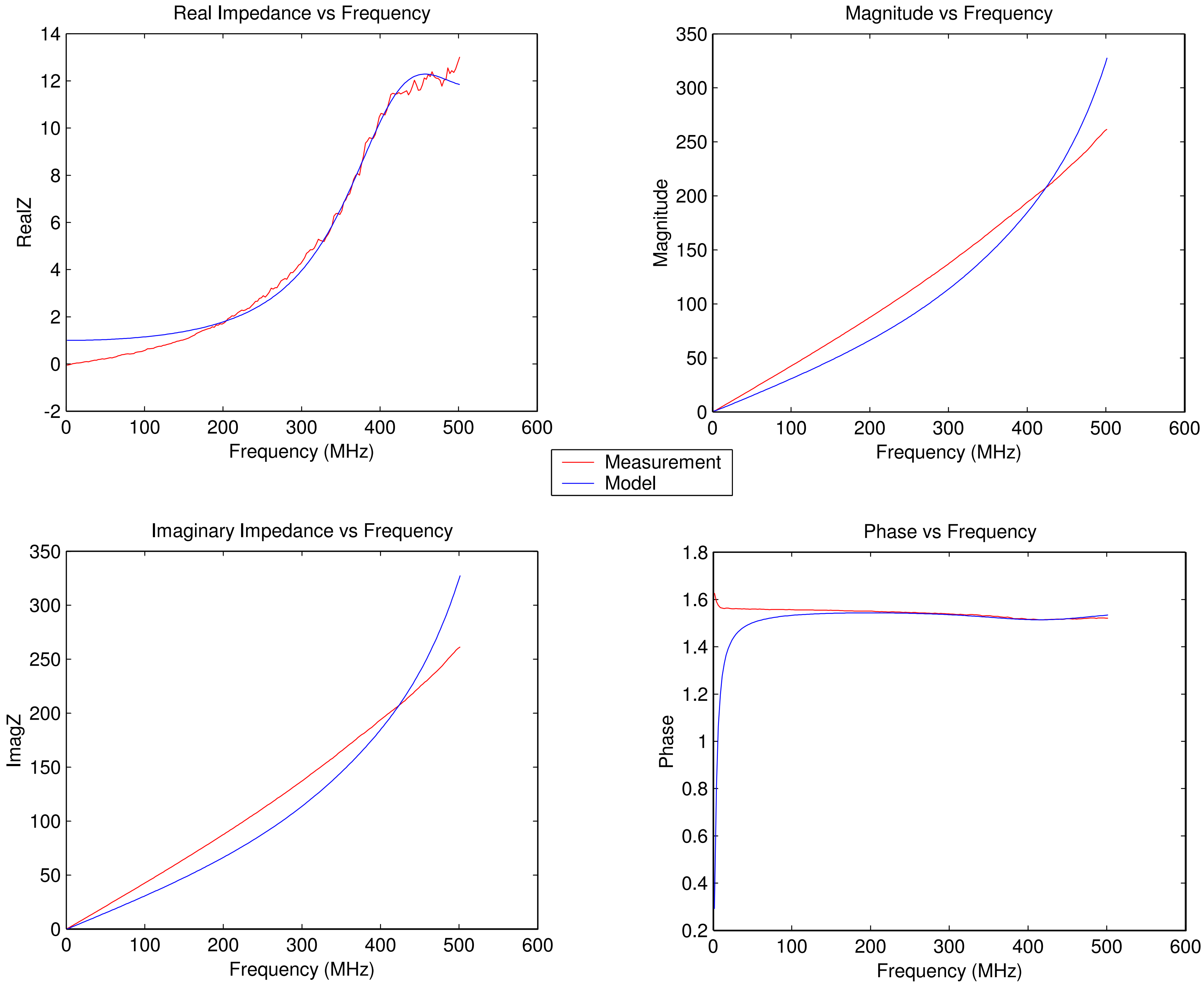
	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	0.0000
Internal Resistance of Model (Ω)	1.0058
Internal Inductance from estimation (μH)	0.1300
Internal Inductance of Model (nH)	0.7299
Internal Capacitance from estimation (pF)	0.1556
Internal Capacitance of Model (pF)	180.7981
External Inductance from estimation (nH)	4.4845
External Inductance of Model (nH)	47.6509
External Capacitance from estimation (pF)	0.0183
External Capacitance of Model (pF)	1.1925
Resonant Frequency (MHz)	1119.0445
A_L	6
Number of turns from estimation	12.910
Number of turns	7
Legnth of Leaded Wire (mm)	2.7200
Distance between two wires (mm)	12.1000
Diameter of wire (mm)	0.3800
R-Square Value of Real Impedance	0.9915
R-Square Value of Imaginary Impedance	0.9639
R-Square Value of Magnitude	0.9640
R-Square Value of Phase	0.2089



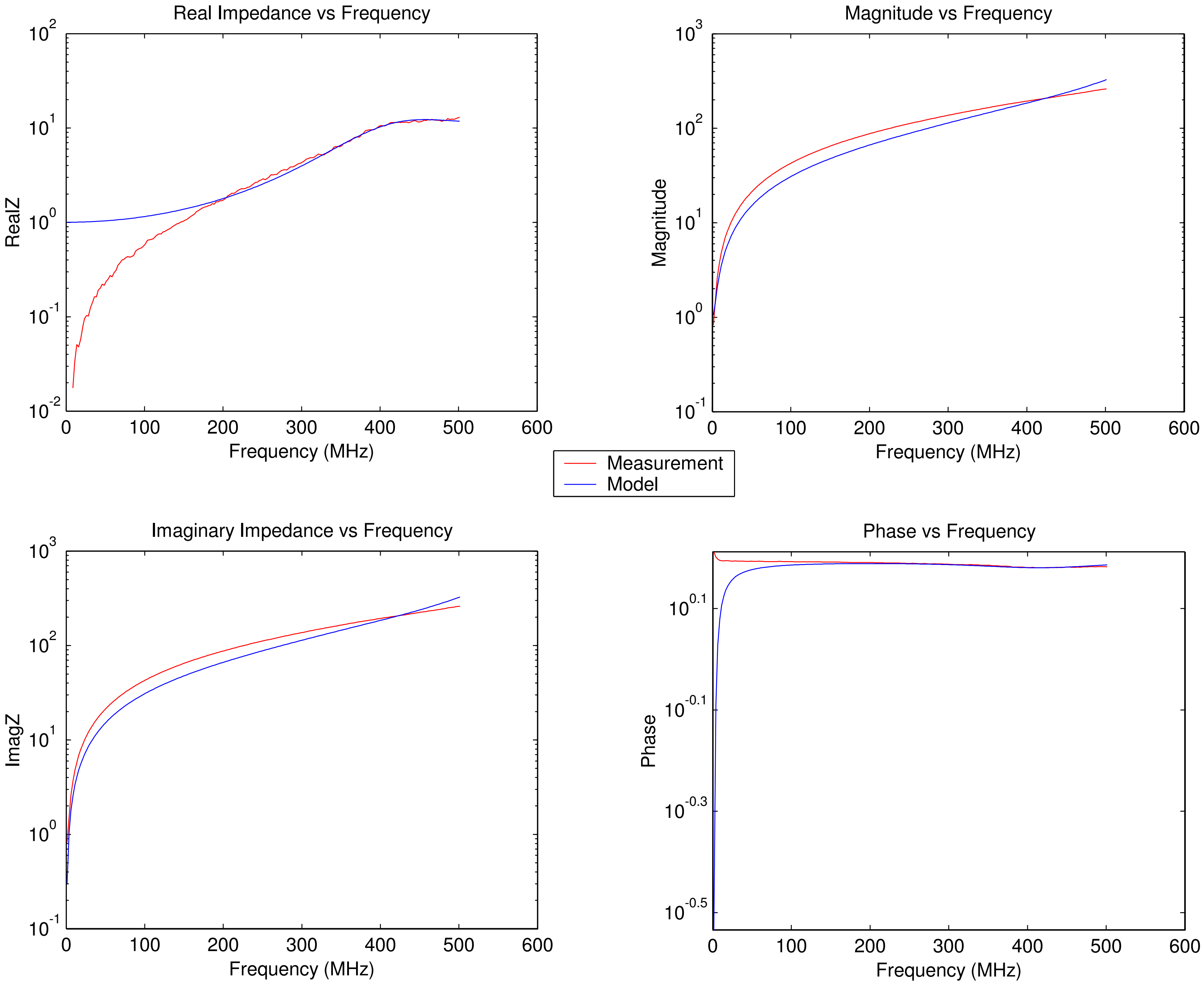
Sum of two inductance values = 0.048 uH

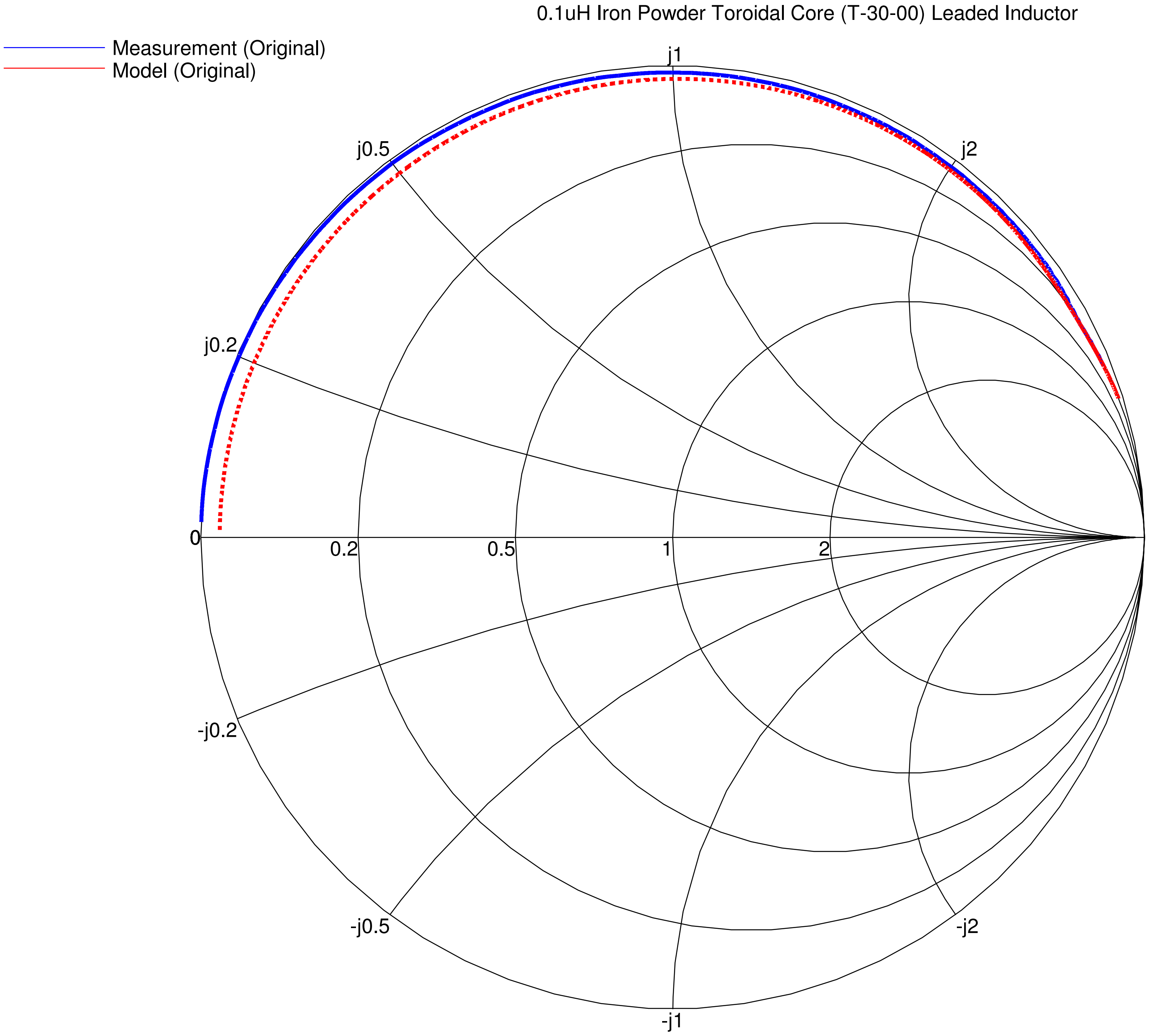
Title: Equivalent Model of 0.1uH Iron Powder Toroidal Leaded Inductor (T-30 #0)
Treatment: Wire is shortened

0.1uH Iron Powder Toroidal Core (T-30-00) Leaded Inductor with Wire Shortened (Linear-Scale)



0.1uH Iron Powder Toroidal Core (T-30-00) Leaded Inductor with Wire Shortened (Log-Scale)




0.1uH Iron Powder Toroidal Core (T-30-00) Leaded Inductor
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

3.4.2 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #2)

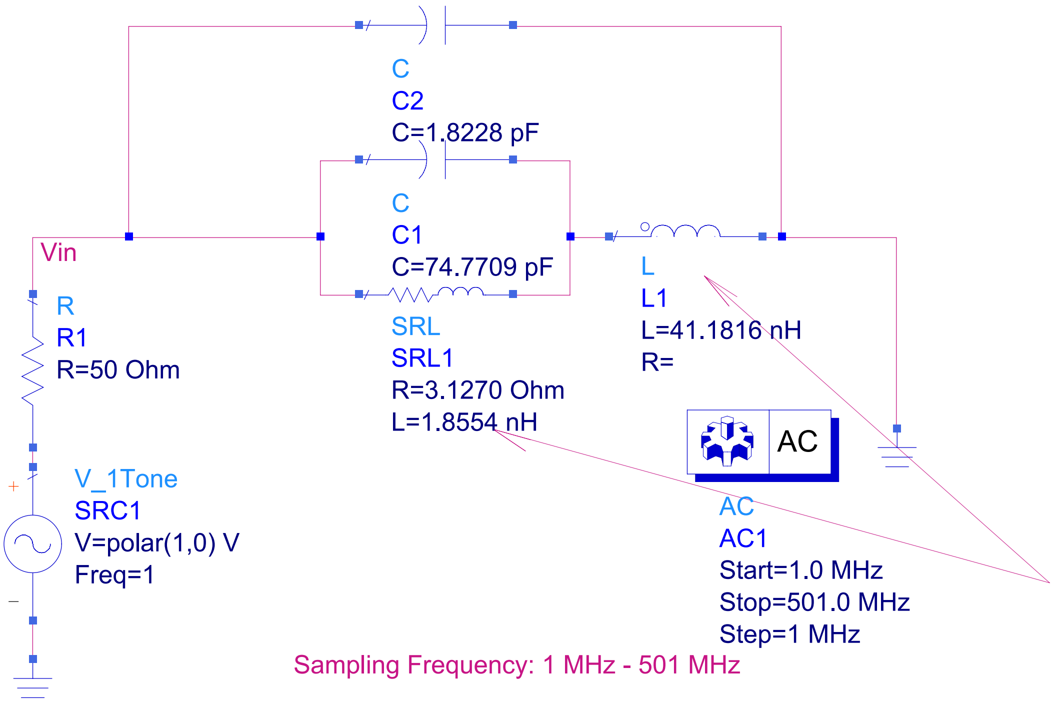
The following is the picture of a 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #2)

Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

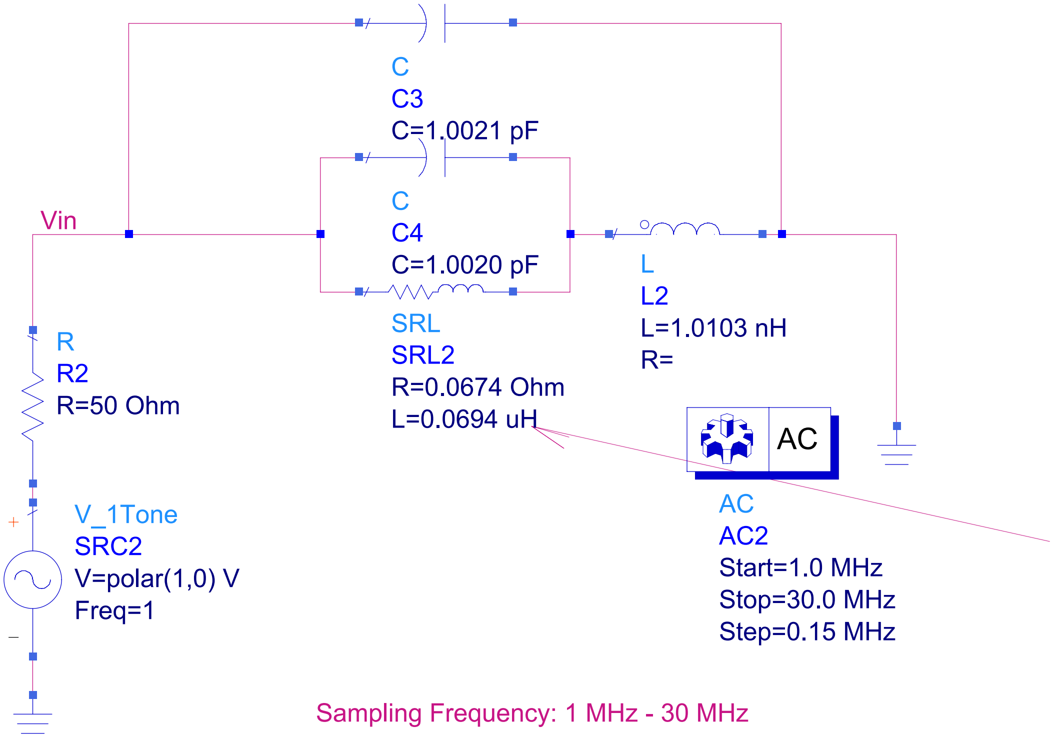
	1 MHz - 501 MHz	1 MHz - 30 MHz
Internal Resistance from estimation (Ω)	0.0082	0.0082
Internal Resistance of Model (Ω)	3.1270	0.0675
Internal Inductance from estimation (μH)	0.1355	0.1355
Internal Inductance of Model	1.8554 nH	0.0695μH
Internal Capacitance from estimation (pF)	0.1691	0.1691
Internal Capacitance of Model (pF)	74.7709	1.0021
External Inductance from estimation (nH)	7.3019	7.3019
External Inductance of Model (nH)	41.1816	1.0103
External Capacitance from estimation (pF)	0.0297	0.0297
External Capacitance of Model (pF)	1.8228	1.0021
Resonant Frequency (MHz)	1051.4721	1051.4721
A_L	43	43
Number of turns from estimation	4.822	4.822
Number of turns	3	3
Legnth of Leaded Wire (mm)	4.4200	4.4200
Distance between two wires (mm)	13.1600	13.1600
Diameter of wire (mm)	0.4100	0.4100
R-Square Value of Real Impedance	0.9894	0.7766
R-Square Value of Imaginary Impedance	0.9067	1.0000
R-Square Value of Magnitude	0.9099	1.0000
R-Square Value of Phase	0.1377	0.7775

Equivalent Model of 0.1uH Iron Powder Toroidal Leaded Inductor (T-30 #2)



Sum of two inductance values
= 0.04 uH

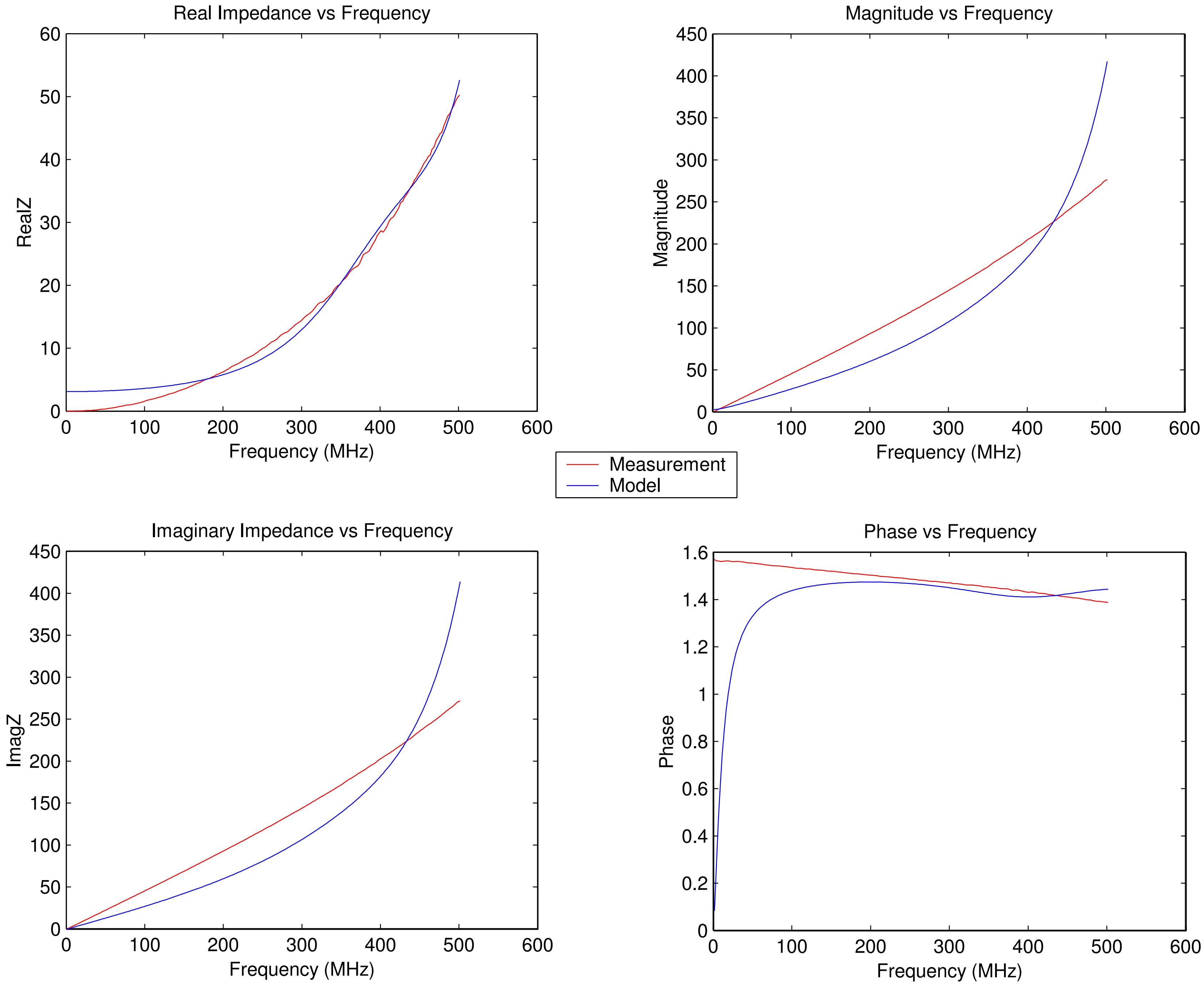
Sampling Frequency: 1 MHz - 501 MHz

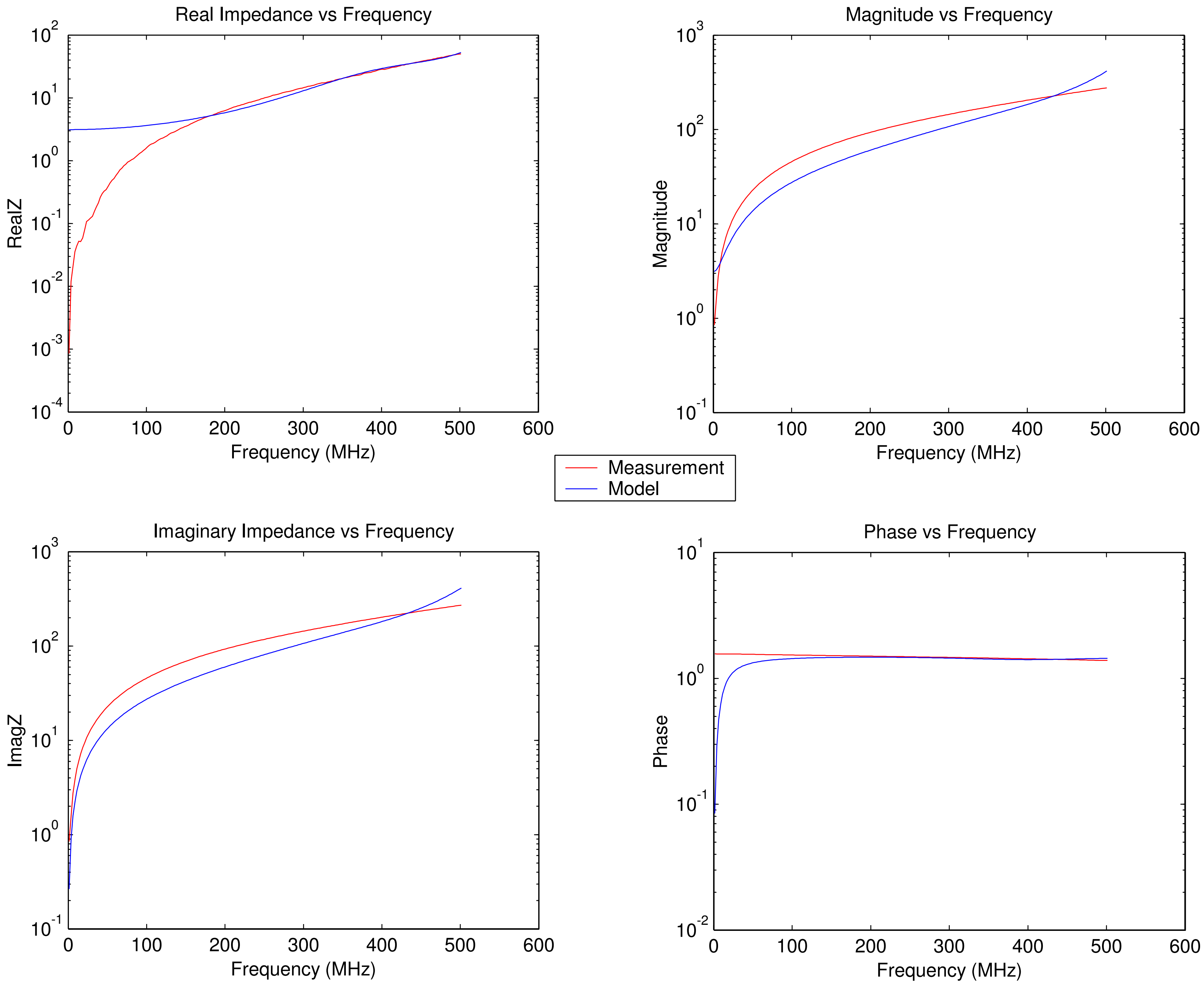


Closed to the goal: 0.1 uH

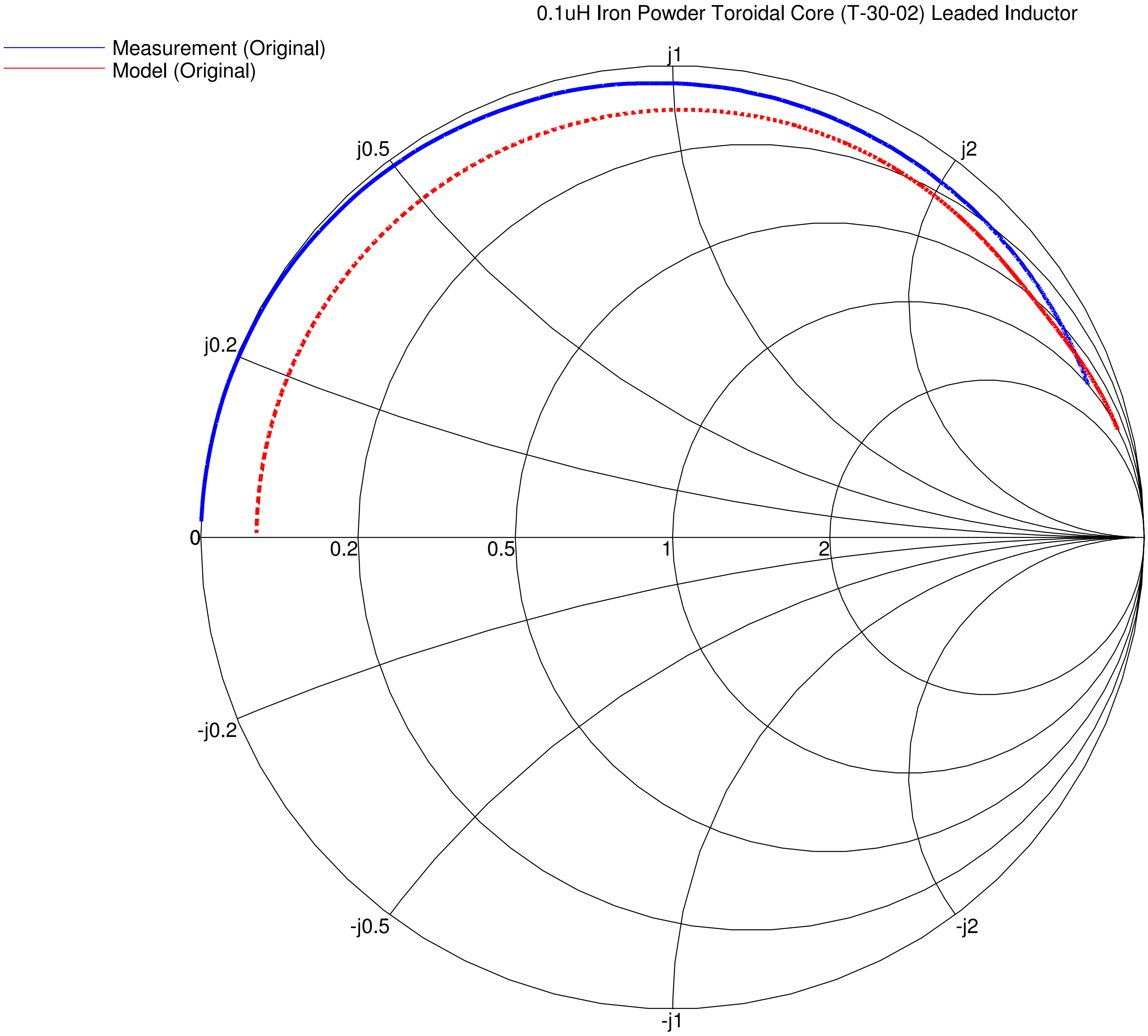
Sampling Frequency: 1 MHz - 30 MHz

0.1uH Iron Powder Toroidal Core (T-30-02) Leaded Inductor with Wire Shortened (Linear-Scale)

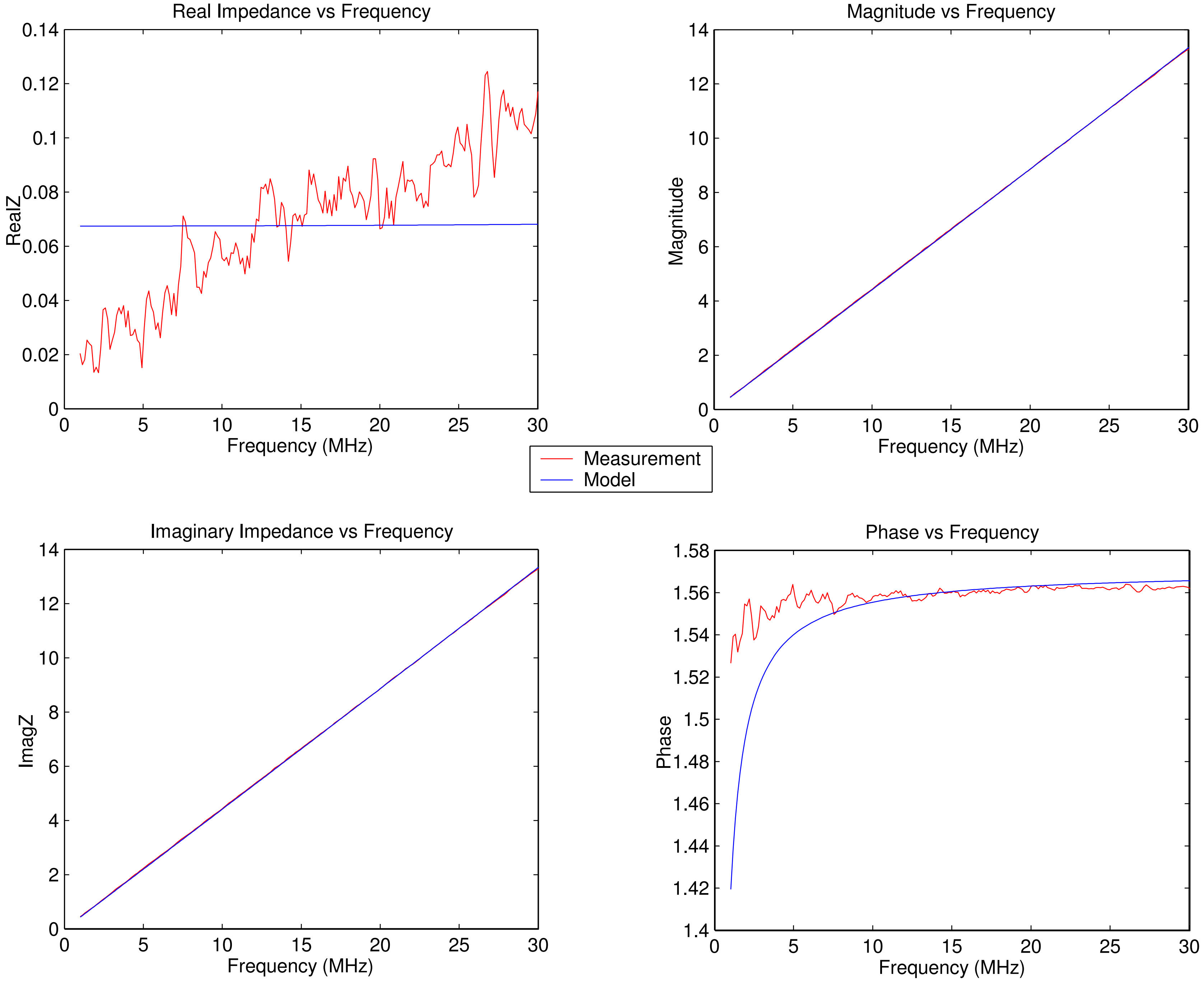




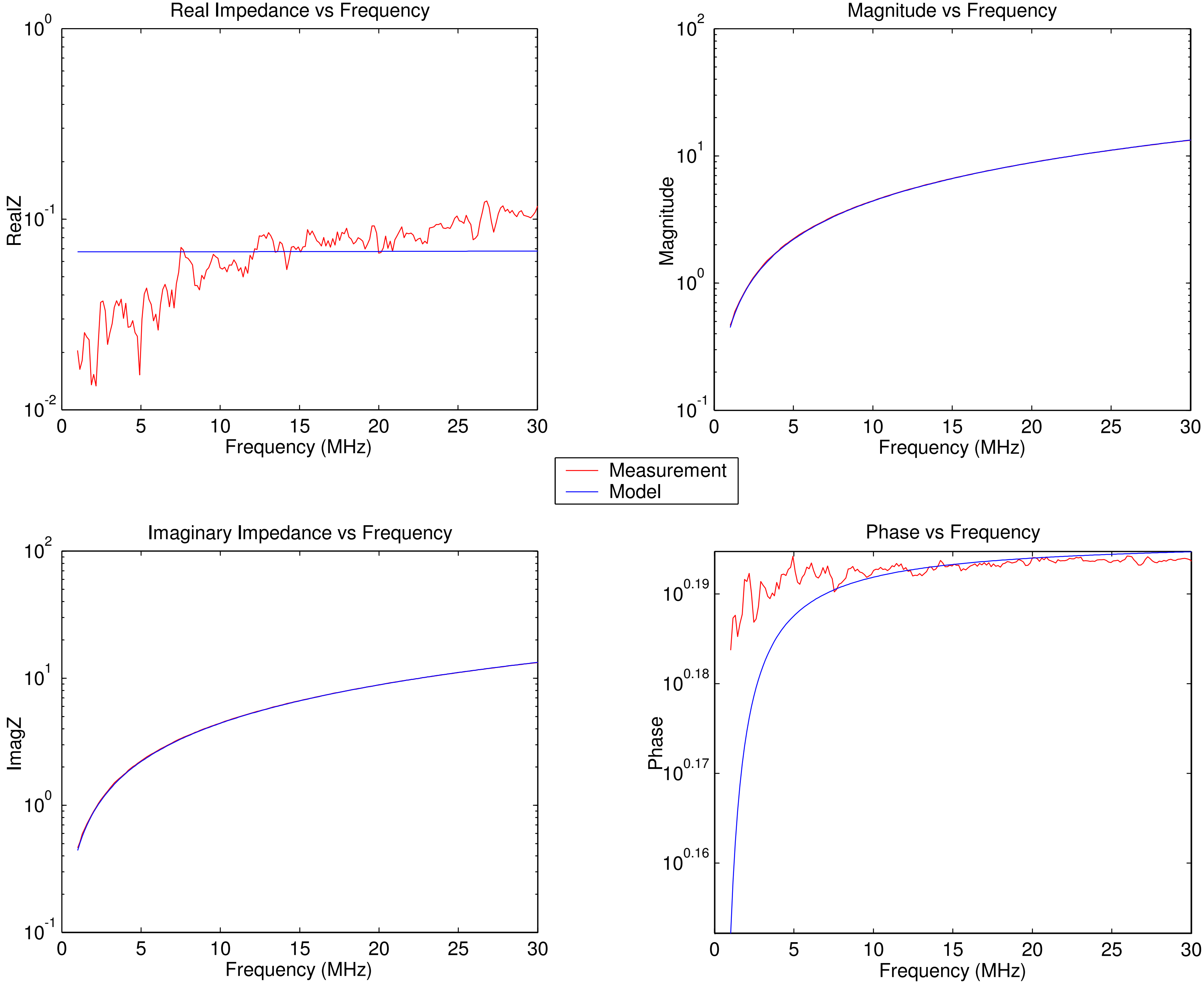
0.1uH Iron Powder Toroidal Core (T-30-02) Leaded Inductor with Wire Shortened (Log-Scale)

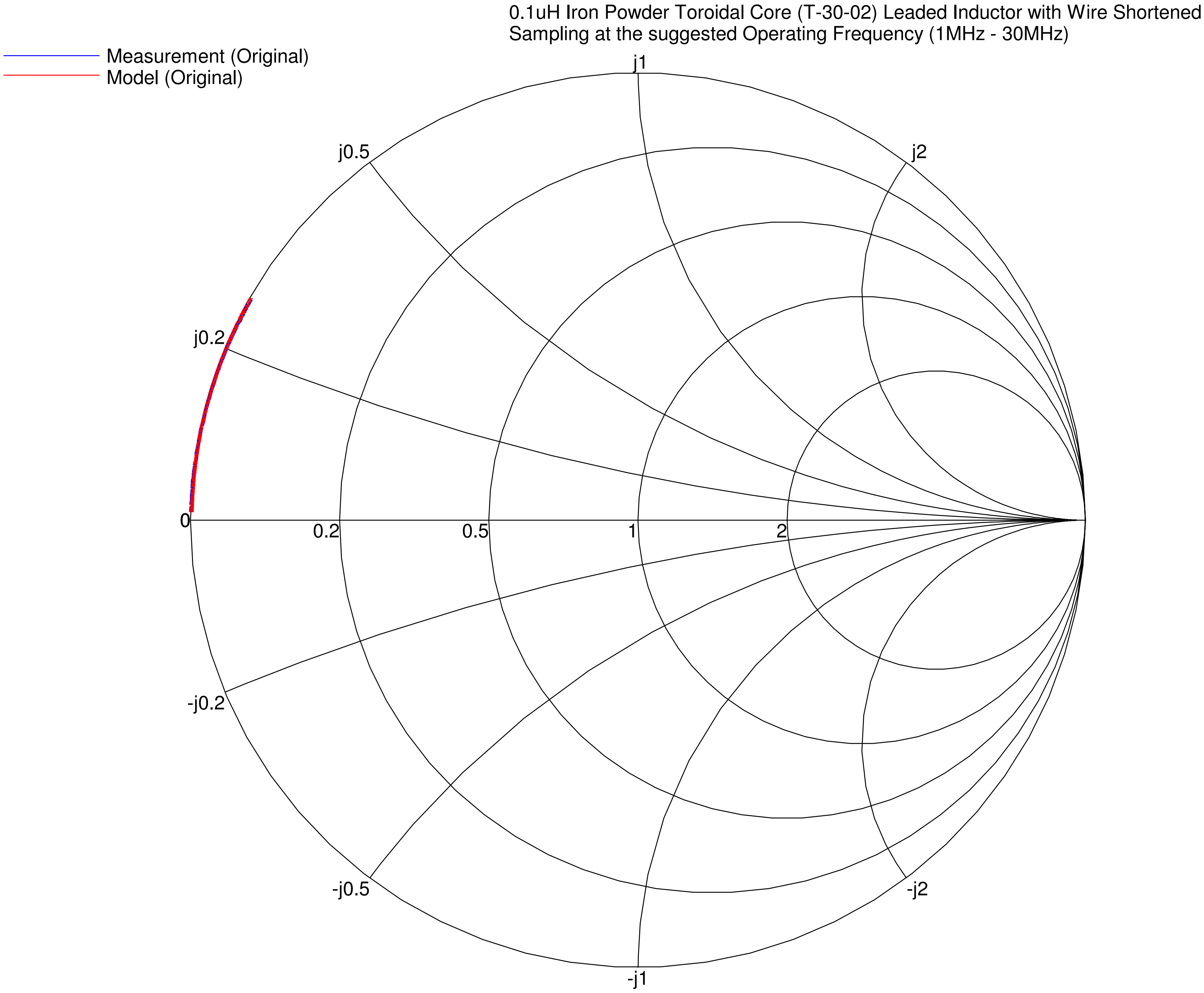

0.1uH Iron Powder Toroidal Core (T-30-02) Leaded Inductor
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

0.1uH Iron Powder Toroidal Core (T-30-02) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (1MHz - 30MHz)



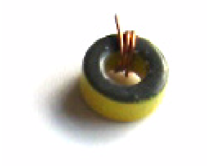
0.1uH Iron Powder Toroidal Core (T-30-02) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (1MHz - 30MHz)




0.1uH Iron Powder Toroidal Core (T-30-02) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (1MHz - 30MHz)
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

3.4.3 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #6)

The following is the picture of a 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #6)

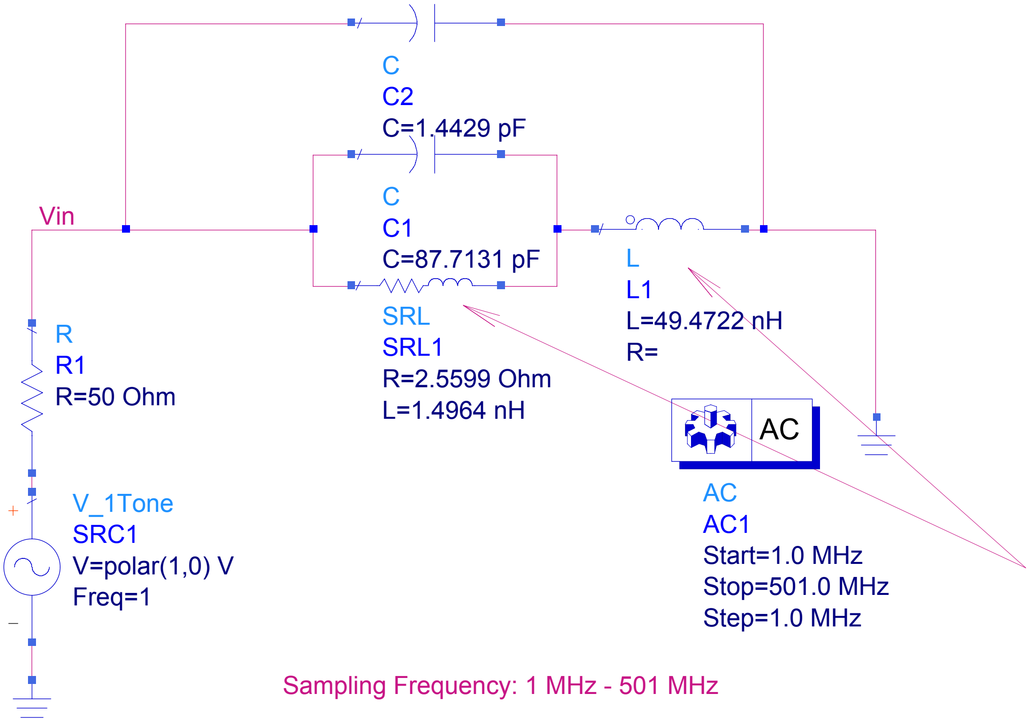


Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

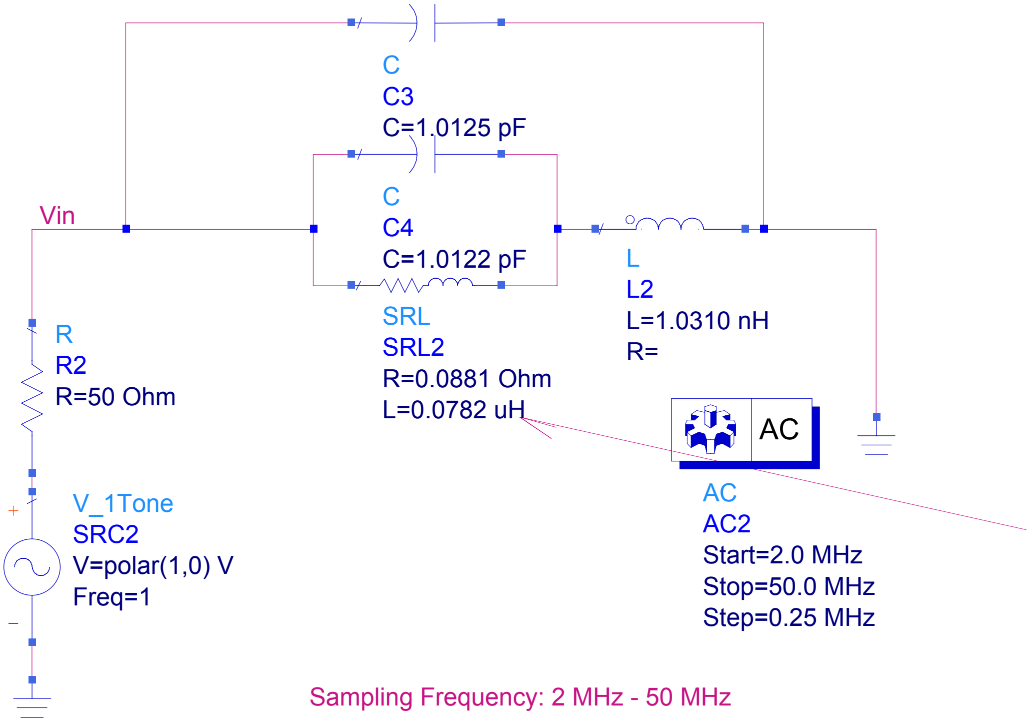
	1 MHz - 501 MHz	2 MHz - 50 MHz
Internal Resistance from estimation (Ω)	0.0000	0.0000
Internal Resistance of Model (Ω)	2.5599	0.0882
Internal Inductance from estimation (μH)	0.1476	0.1476
Internal Inductance of Model	1.4964 nH	0.0783 μH
Internal Capacitance from estimation (pF)	0.1430	0.1430
Internal Capacitance of Model (pF)	87.7131	1.0123
External Inductance from estimation (nH)	2.3426	2.3426
External Inductance of Model (nH)	49.4722	1.0311
External Capacitance from estimation (pF)	0.0149	0.0149
External Capacitance of Model (pF)	1.4429	1.0126
Resonant Frequency (MHz)	1095.2243	1095.2243
A_L	36	36
Number of turns from estimation	5.270	5.270
Number of turns	3	3
Legnth of Leaded Wire (mm)	1.7700	1.7700
Distance between two wires (mm)	5.2900	5.2900
Diameter of wire (mm)	0.3600	0.3600
R-Square Value of Real Impedance	0.9892	0.9467
R-Square Value of Imaginary Impedance	0.9213	1.0000
R-Square Value of Magnitude	0.9228	1.0000
R-Square Value of Phase	0.1189	0.9076

Equivalent Model of 0.1uH Iron Powder Toroidal Leaded Inductor (T-30 #6)



Sum of two inductance values = 0.050 uH

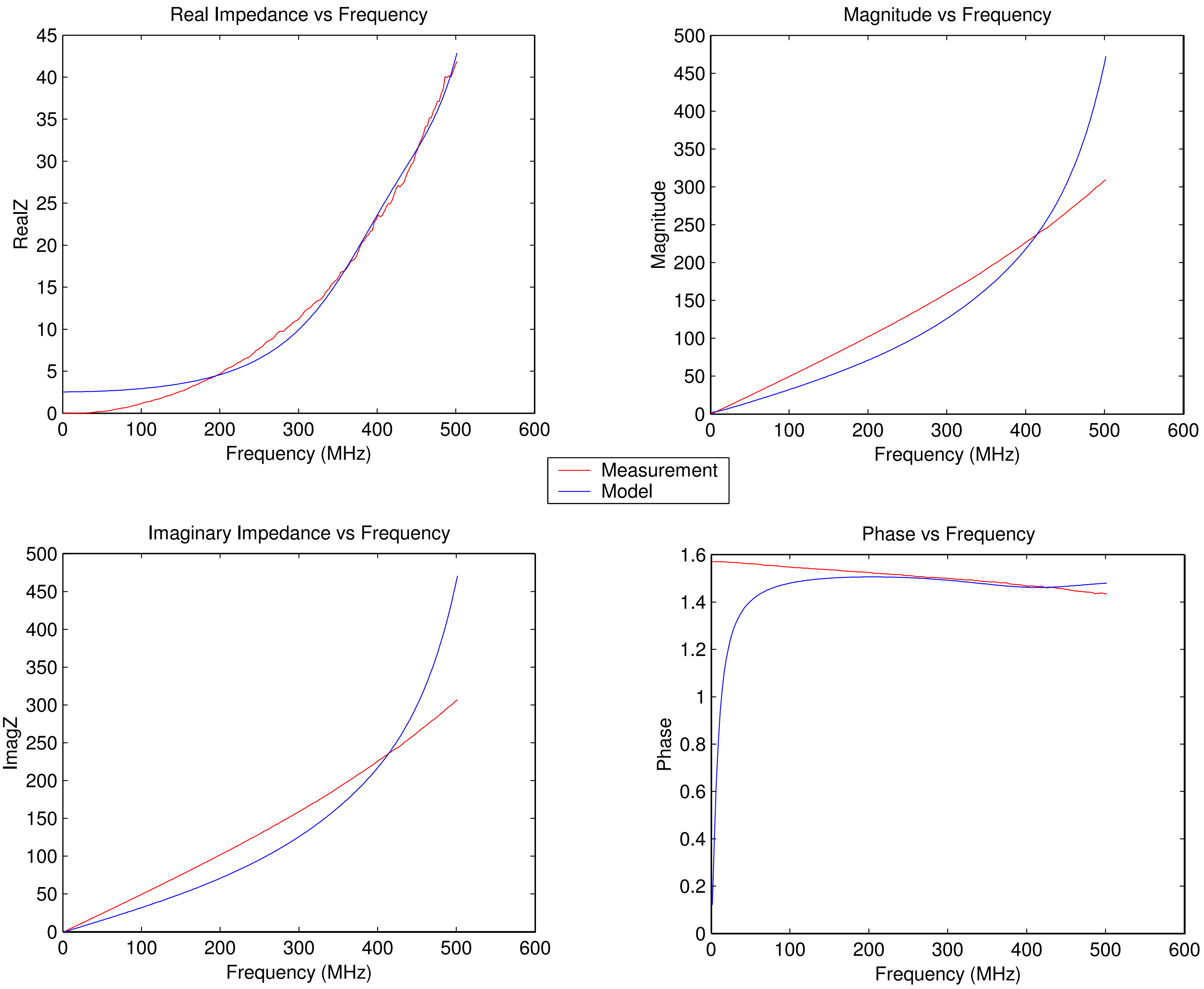
Sampling Frequency: 1 MHz - 501 MHz



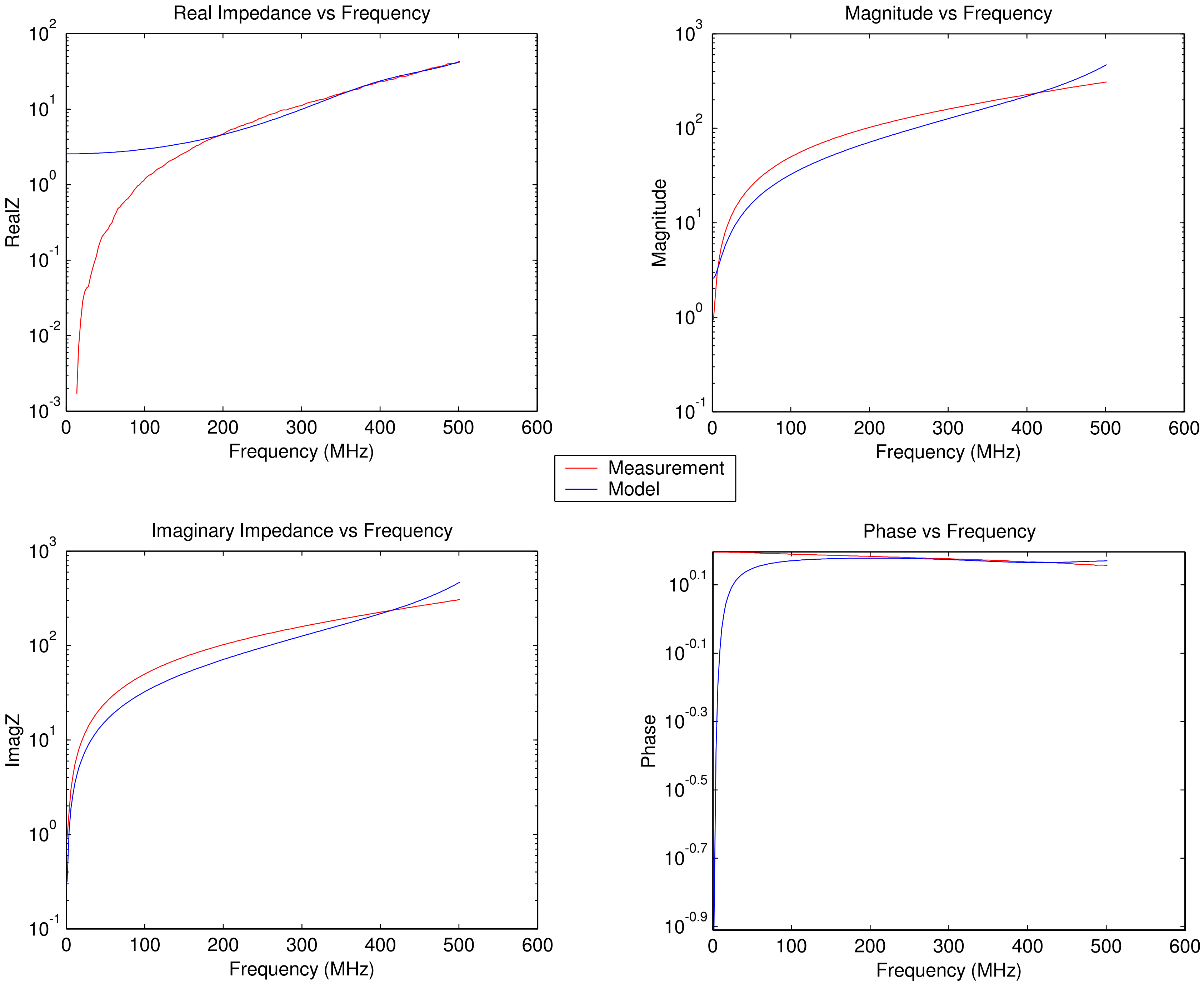
Closed to the goal: 0.1 uH

Sampling Frequency: 2 MHz - 50 MHz

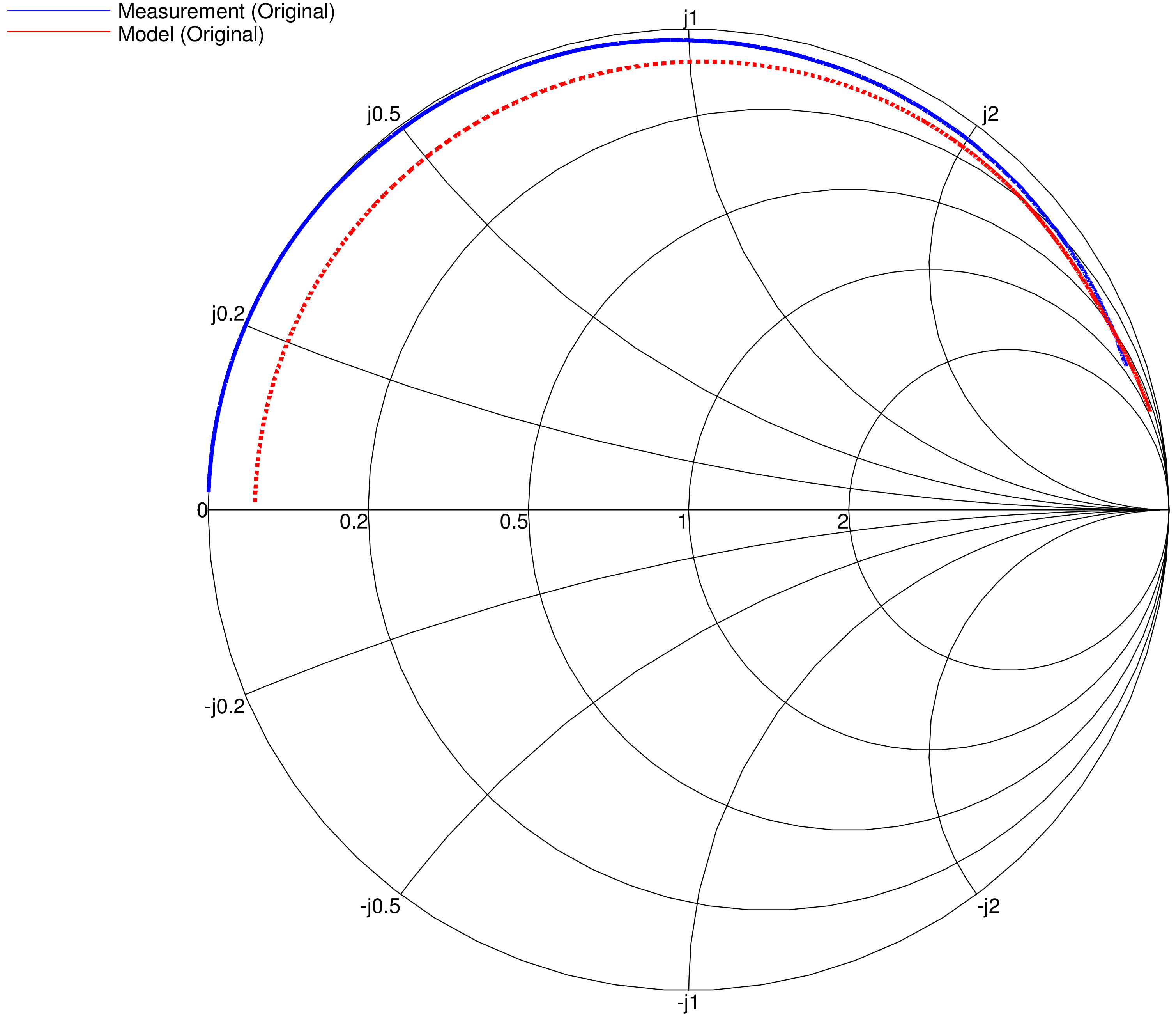
0.1uH Iron Powder Toroidal Core (T-30-06) Leaded Inductor with Wire Shortened (Linear-Scale)

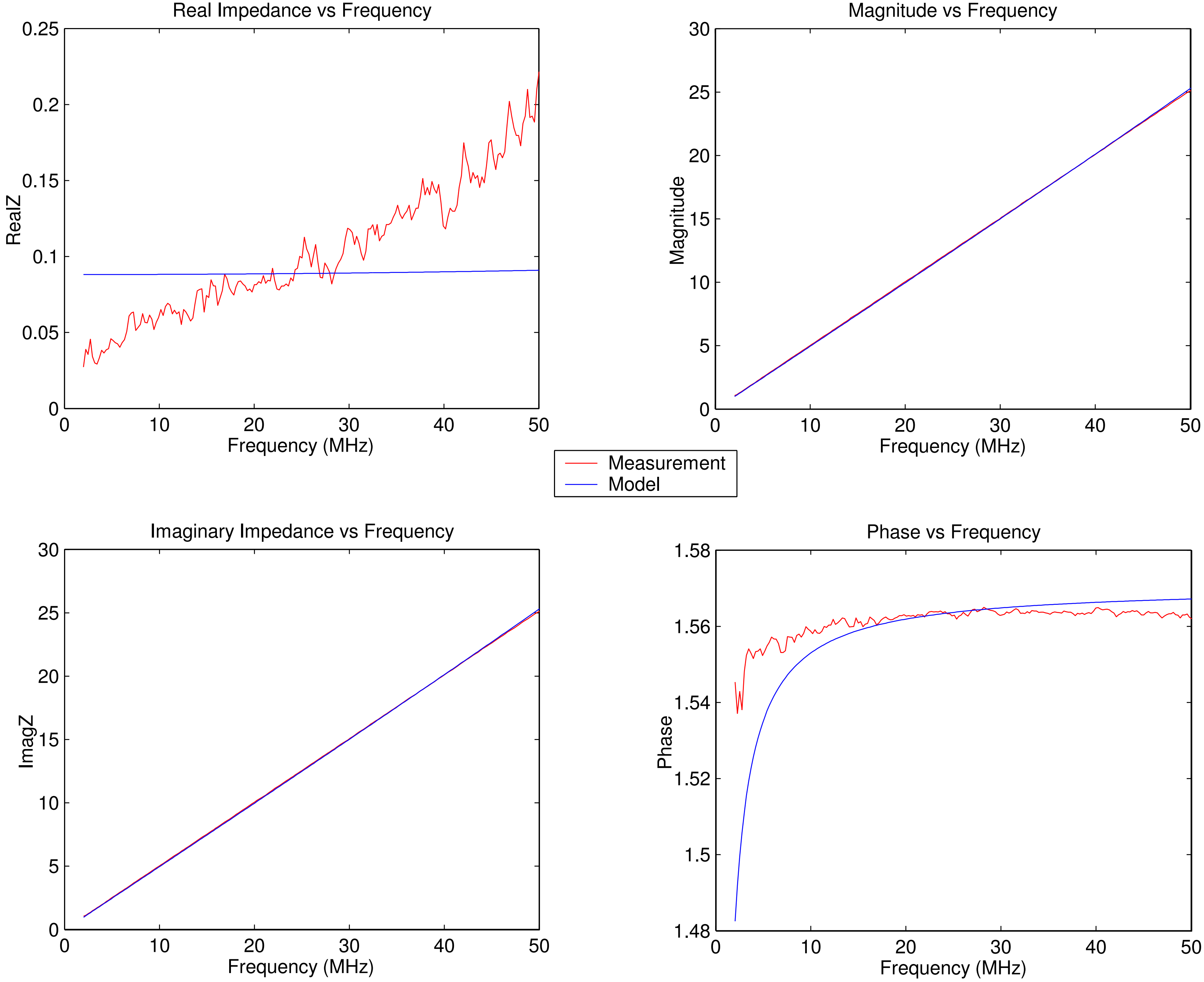


0.1uH Iron Powder Toroidal Core (T-30-06) Leaded Inductor with Wire Shortened (Linear-Scale)



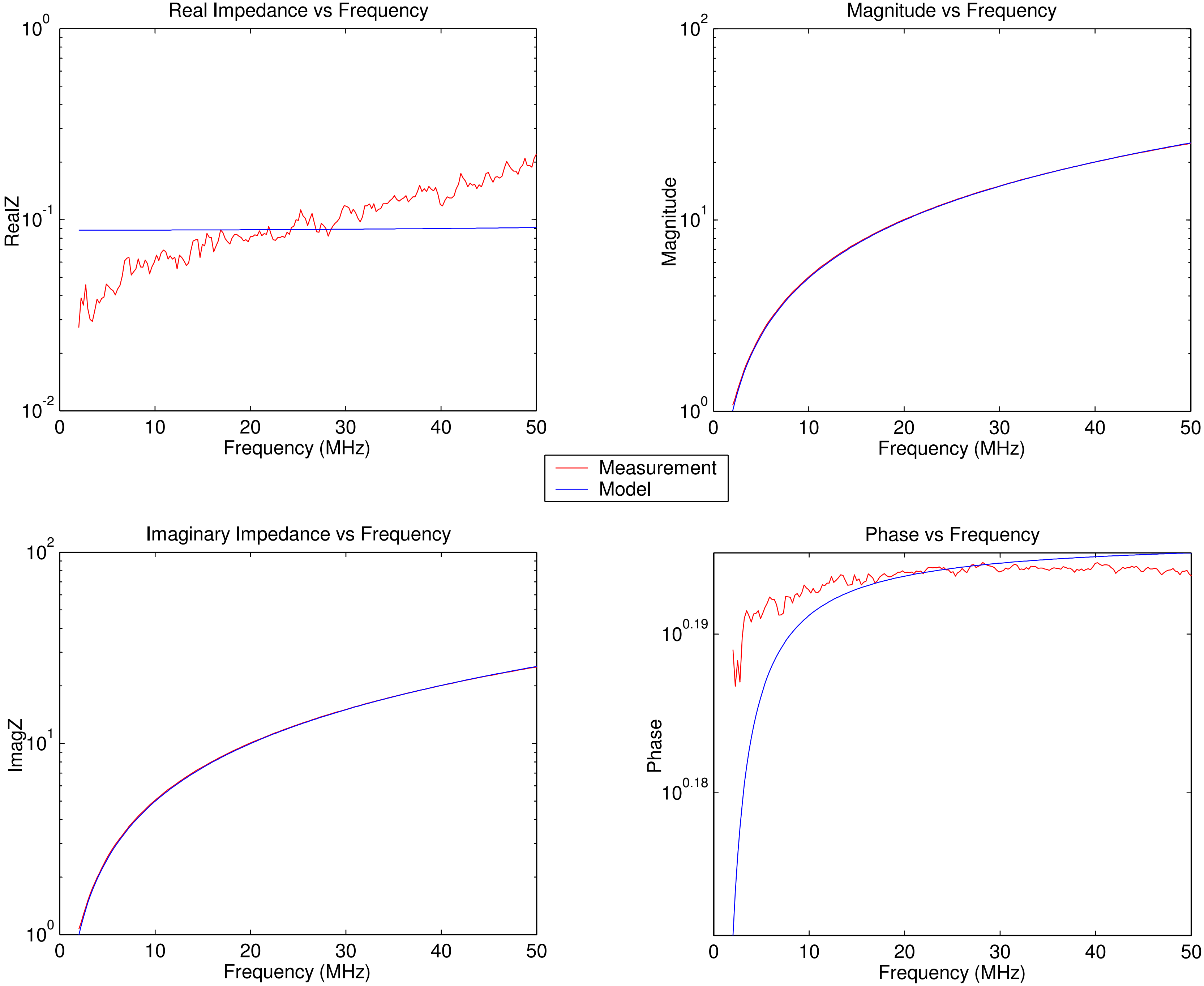
0.1uH Iron Powder Toroidal Core (T-30-06) Leaded Inductor with Wire Shortened



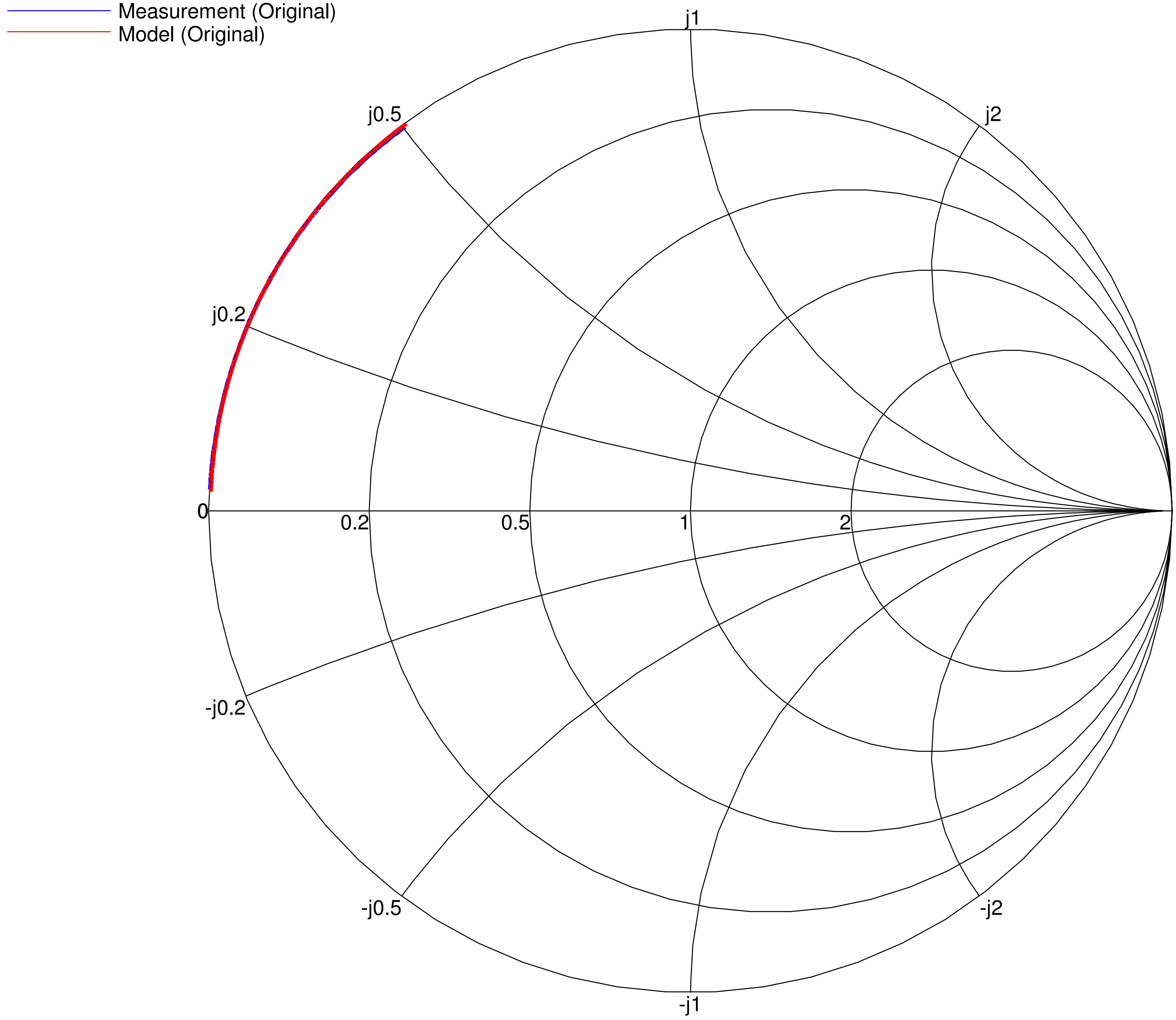


0.1uH Iron Powder Toroidal Core (T-30-06) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (2MHz - 50MHz)

0.1uH Iron Powder Toroidal Core (T-30-06) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (2MHz - 50MHz)



0.1uH Iron Powder Toroidal Core (T-30-06) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (2MHz - 50MHz)



3.4.4 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #7)

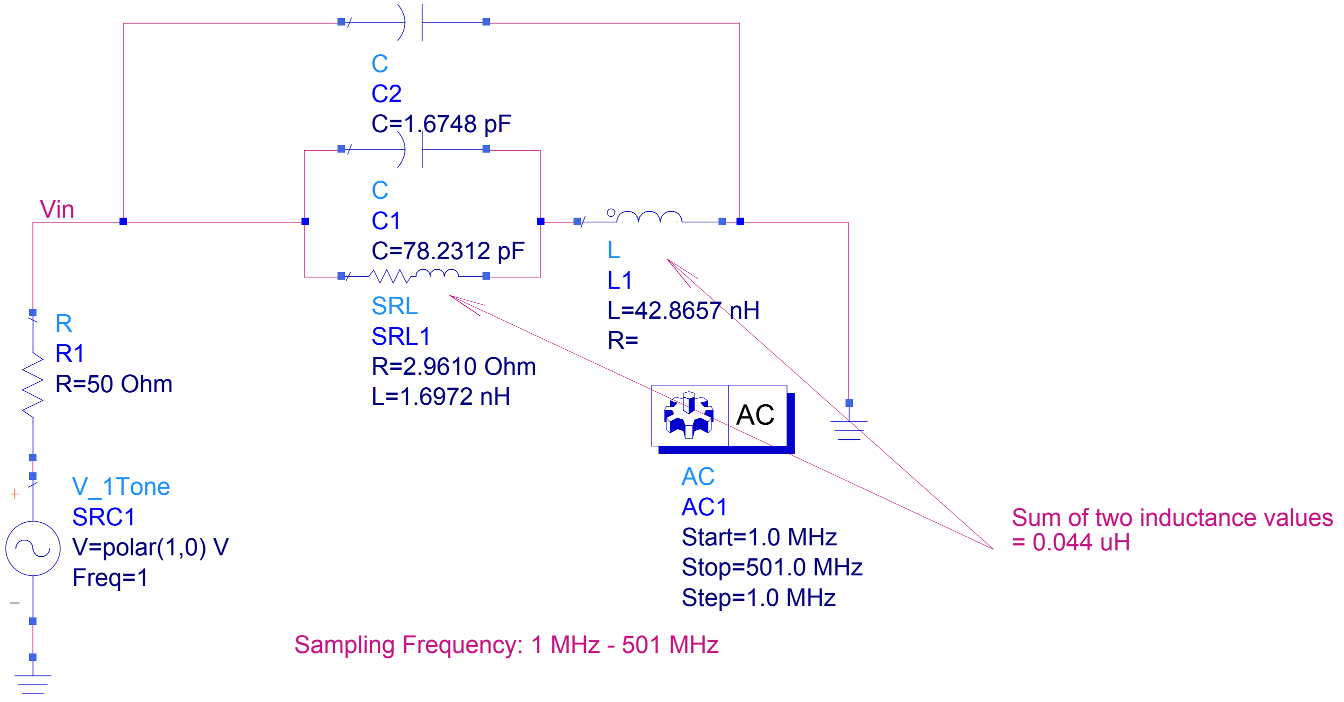
The following is the picture of a 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #7)

Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

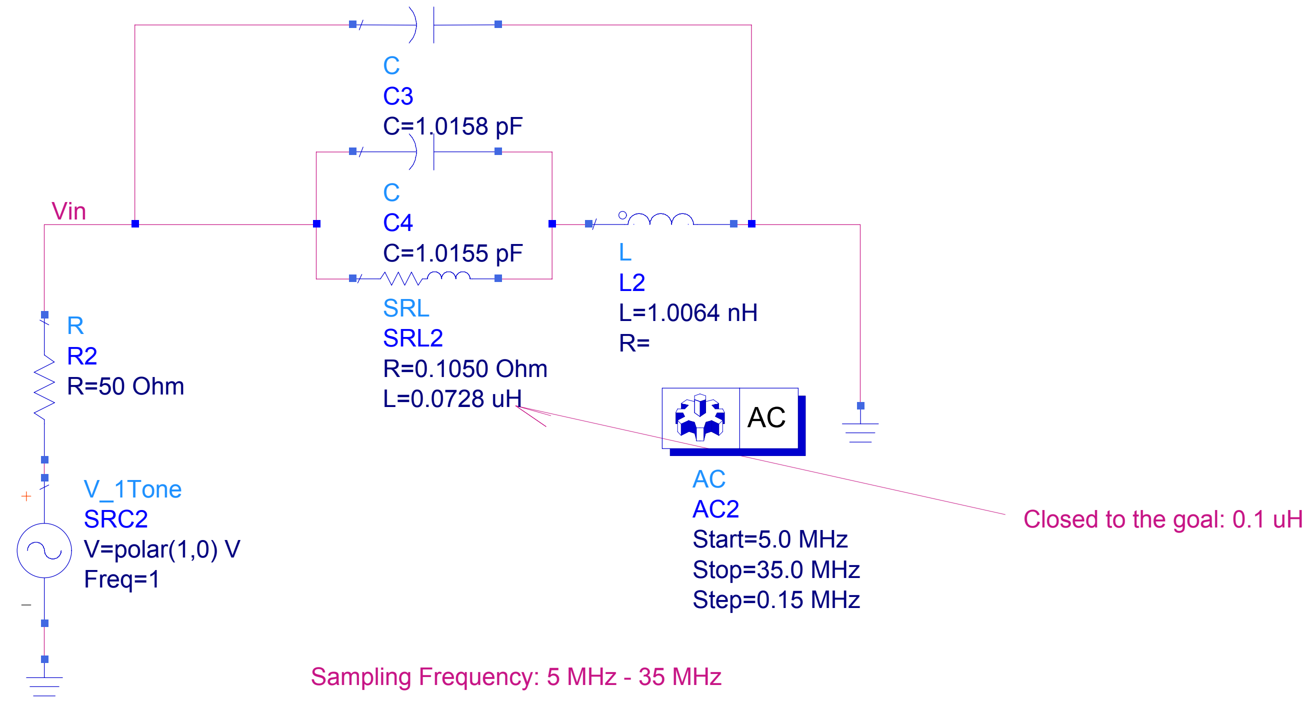
	1 MHz - 501 MHz	5 MHz - 35 MHz
Internal Resistance from estimation (Ω)	0.0000	0.0000
Internal Resistance of Model (Ω)	2.9610	0.1050
Internal Inductance from estimation (μH)	0.1347	0.1347
Internal Inductance of Model	1.6972 nH	0.0729 μH
Internal Capacitance from estimation (pF)	0.1340	0.1340
Internal Capacitance of Model (pF)	78.2312	1.0155
External Inductance from estimation (nH)	3.6347	3.6347
External Inductance of Model (nH)	42.8657	1.0064
External Capacitance from estimation (pF)	0.0176	0.0176
External Capacitance of Model (pF)	1.6748	1.0158
Resonant Frequency (MHz)	1184.8041	1184.8041
A_L	37	37
Number of turns from estimation	5.199	5.199
Number of turns	3	3
Legnth of Leaded Wire (mm)	2.4000	2.4000
Distance between two wires (mm)	8.5300	8.5300
Diameter of wire (mm)	0.3700	0.3700
R-Square Value of Real Impedance	0.9889	0.8585
R-Square Value of Imaginary Impedance	0.9189	1.0000
R-Square Value of Magnitude	0.9210	1.0000
R-Square Value of Phase	0.2113	0.8301

Equivalent Model of 0.1uH Iron Powder Toroidal Leaded Inductor (T-30 #7)



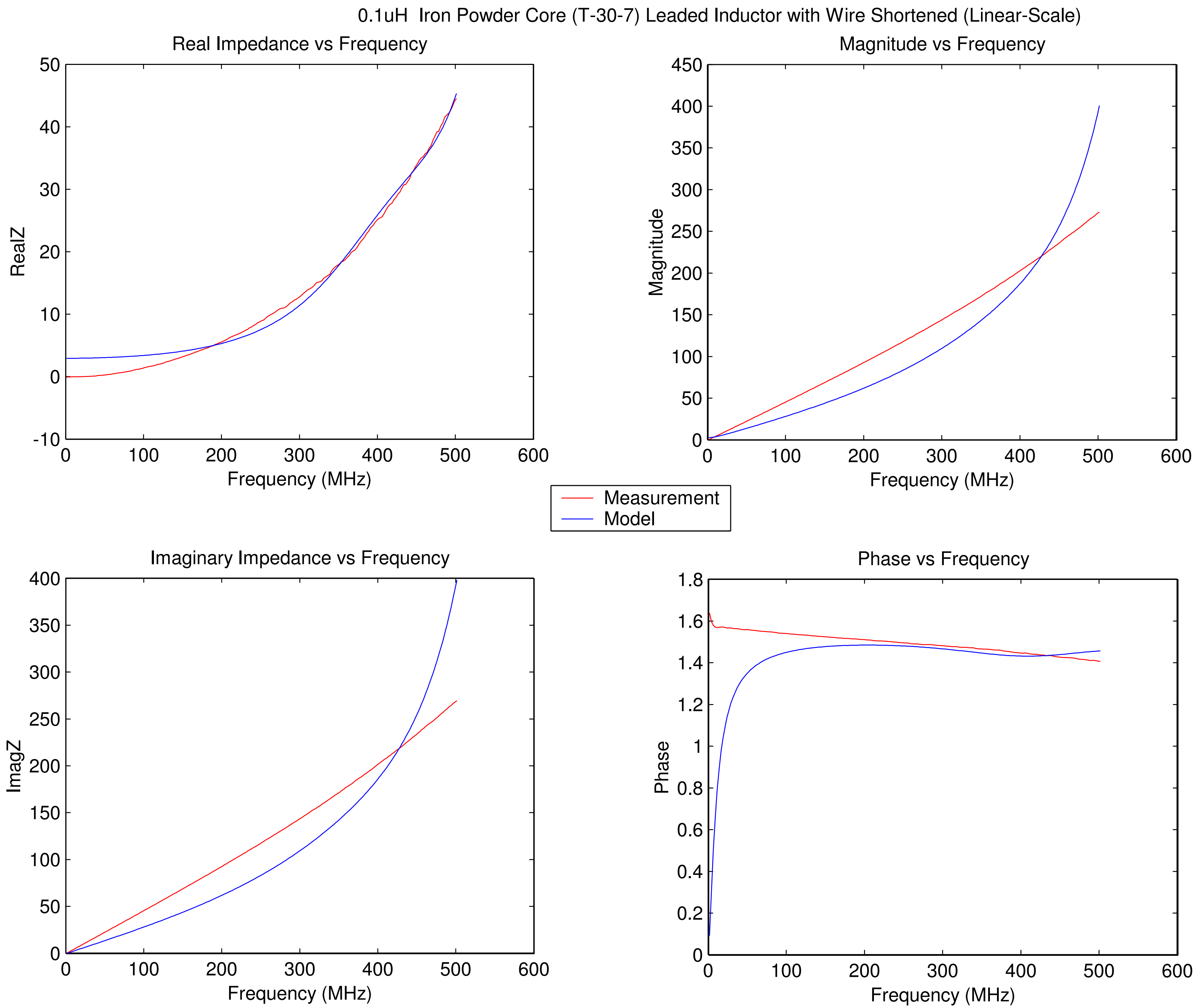
Sum of two inductance values = 0.044 uH

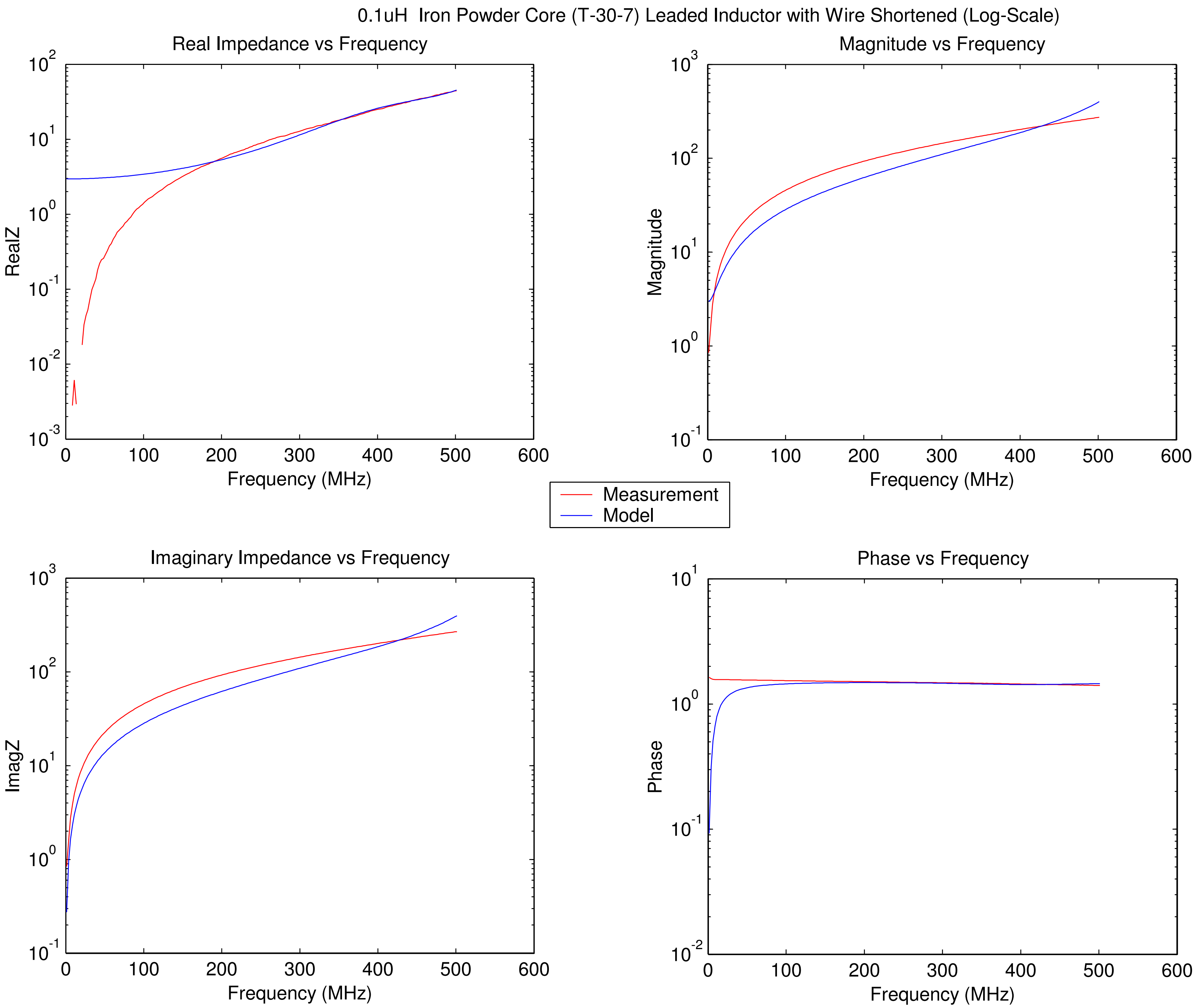
Sampling Frequency: 1 MHz - 501 MHz



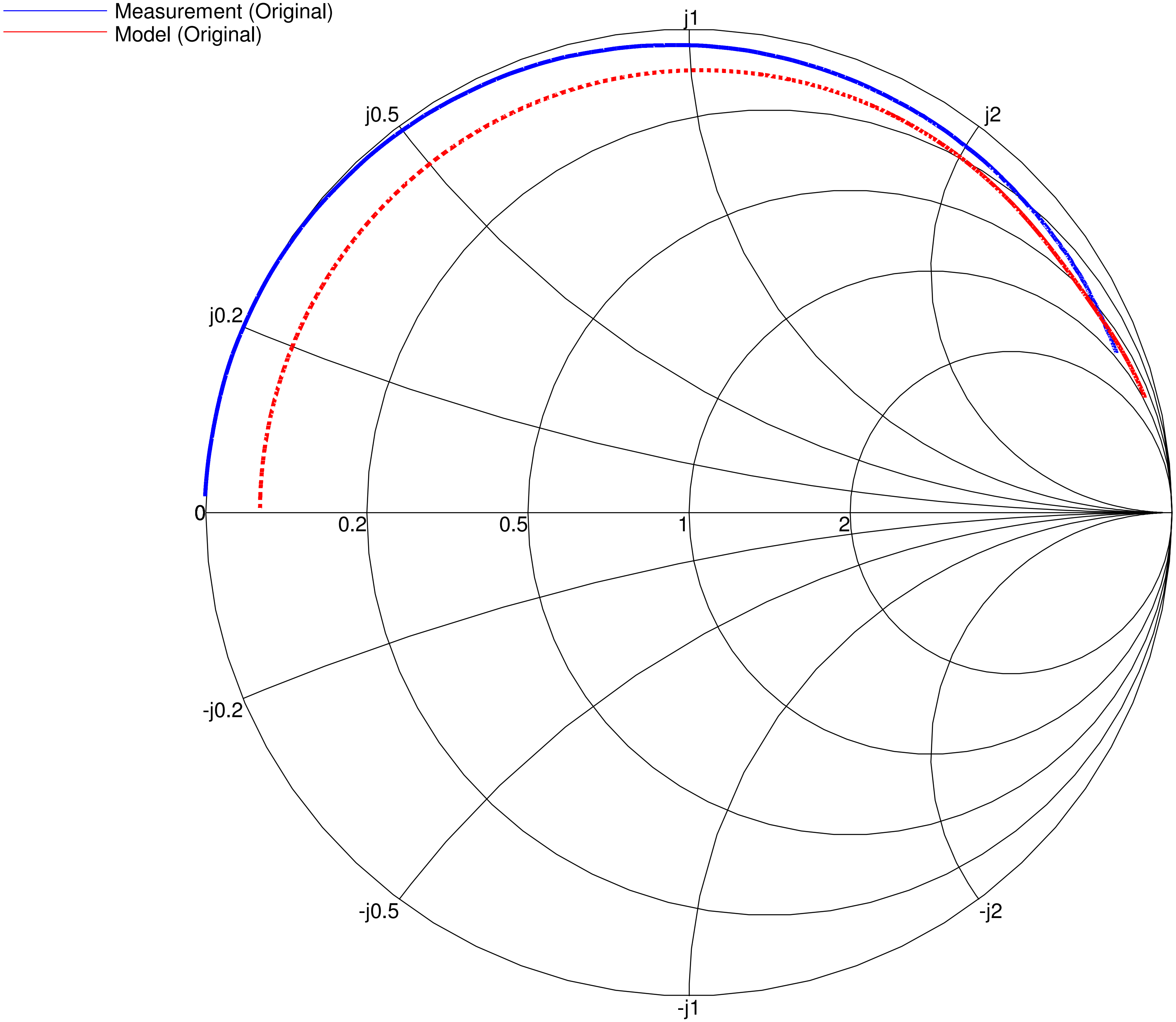
Closed to the goal: 0.1 uH

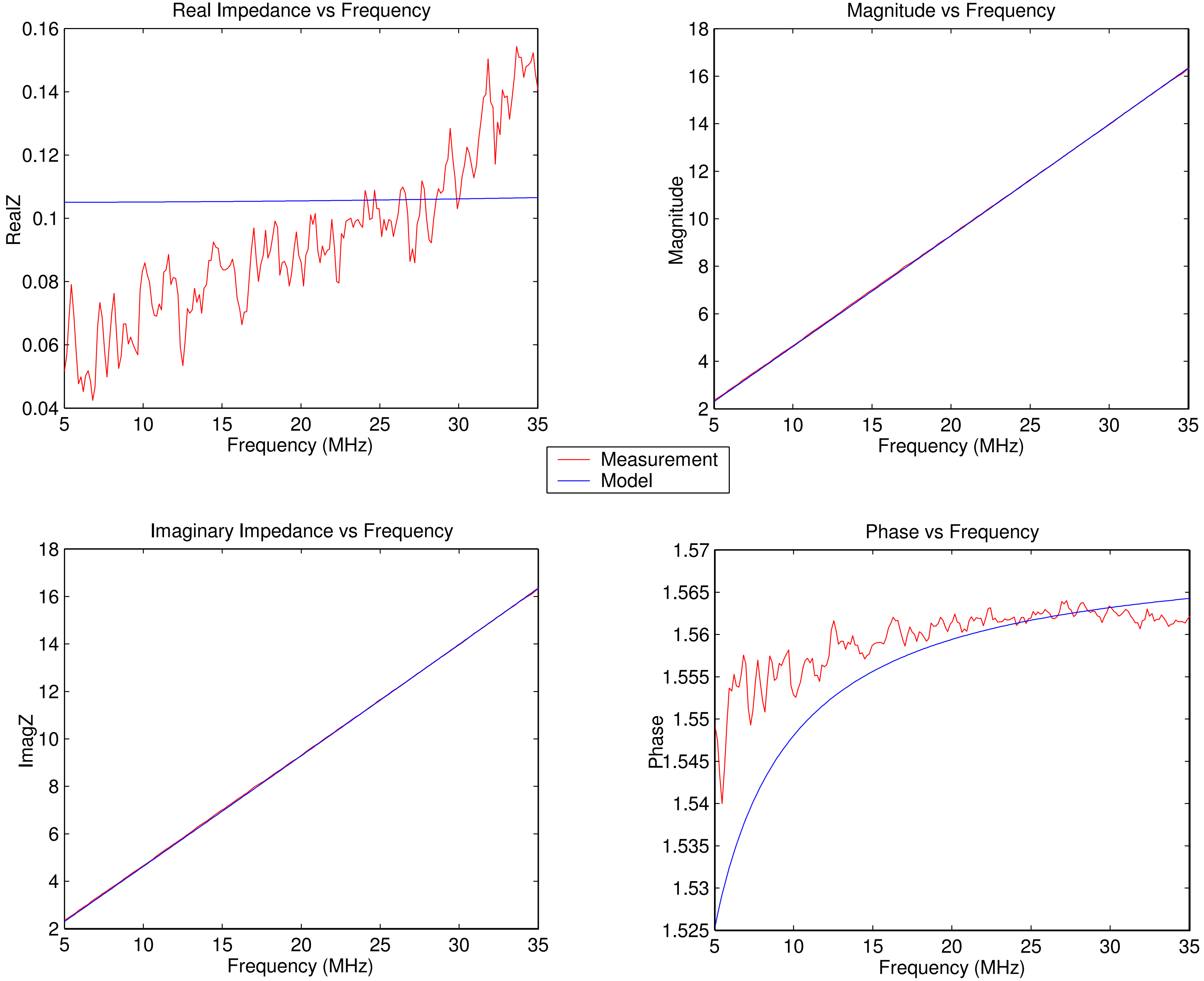
Sampling Frequency: 5 MHz - 35 MHz


0.1uH Iron Powder Core (T-30-7) Leaded Inductor with Wire Shortened (Linear-Scale)
Real Impedance vs Frequency
RealZ
50
40
30
20
10
0
-10
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement
Model
Imaginary Impedance vs Frequency
ImagZ
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
Frequency (MHz)


0.1uH Iron Powder Core (T-30-7) Leaded Inductor with Wire Shortened (Log-Scale)
Real Impedance vs Frequency
RealZ
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement
Model
Imaginary Impedance vs Frequency
ImagZ
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)

0.1uH Iron Powder Core (T-30-7) Leaded Inductor with Wire Shortened





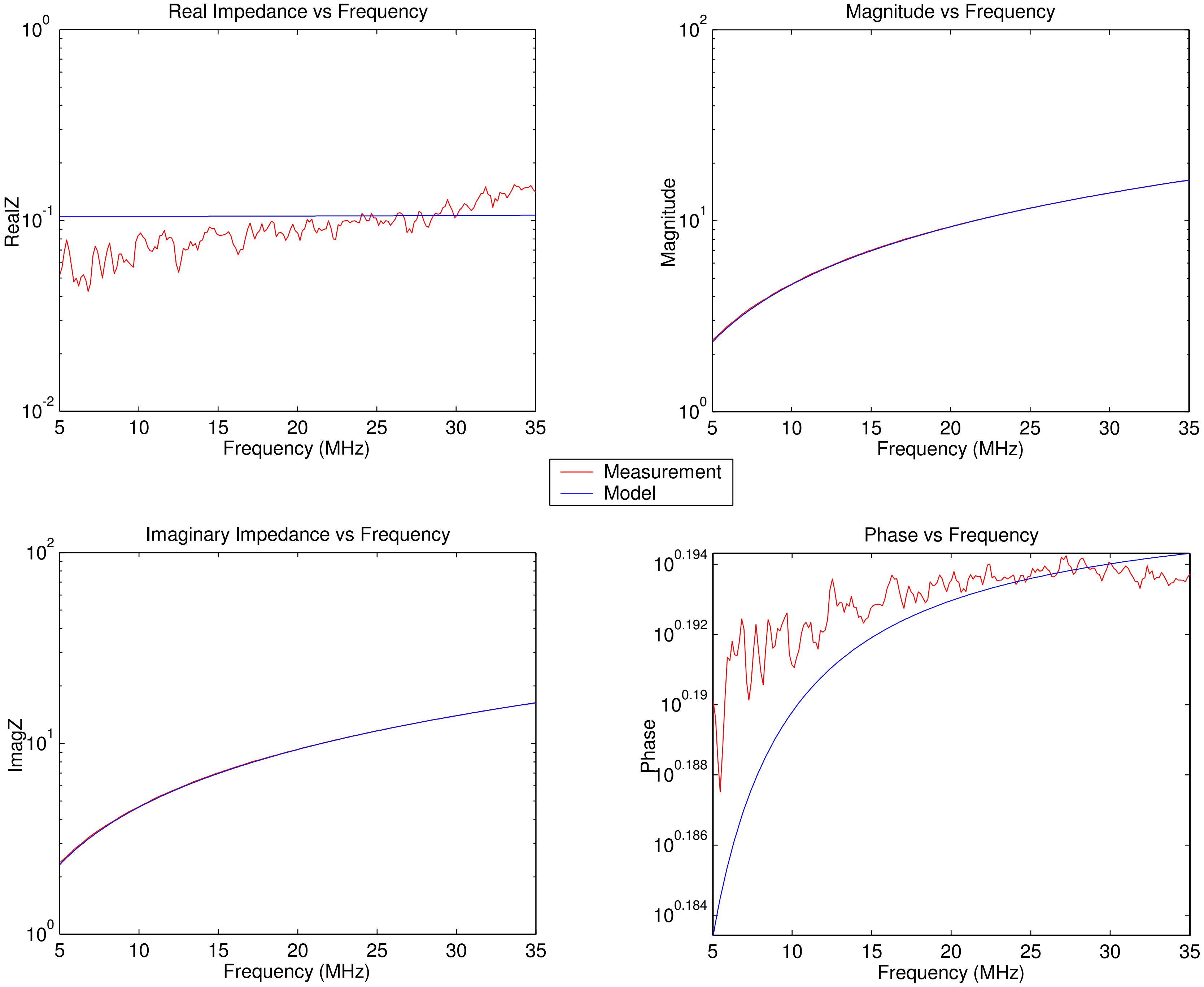
0.1uH Iron Powder Toroidal Core (T-30-07) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (5MHz - 35MHz)

Real Impedance vs Frequency

Magnitude vs Frequency

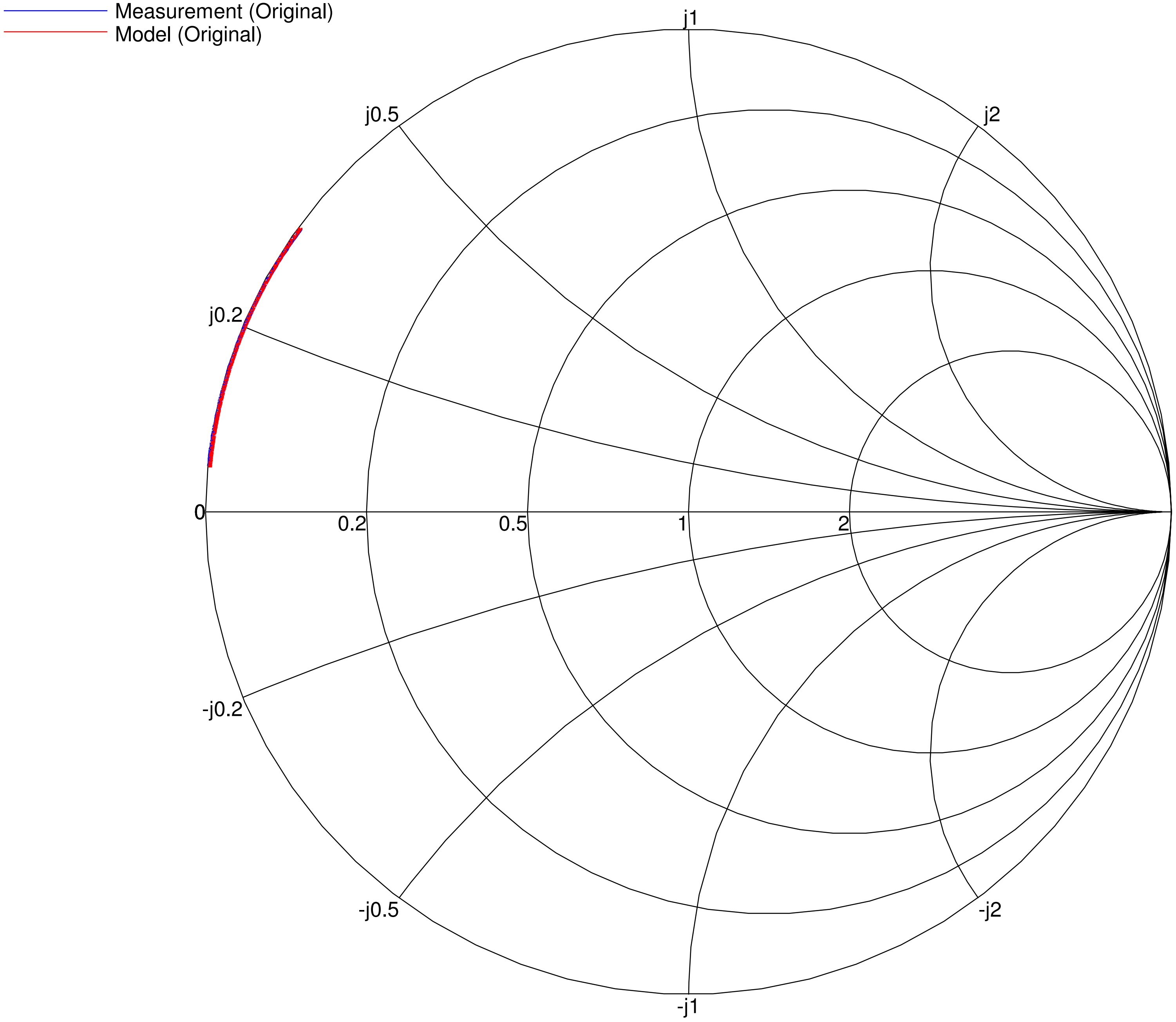
Imaginary Impedance vs Frequency

Phase vs Frequency



0.1uH Iron Powder Toroidal Core (T-30-07) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (5MHz - 35MHz)

0.1uH Iron Powder Toroidal Core (T-30-07) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (5MHz - 35MHz)



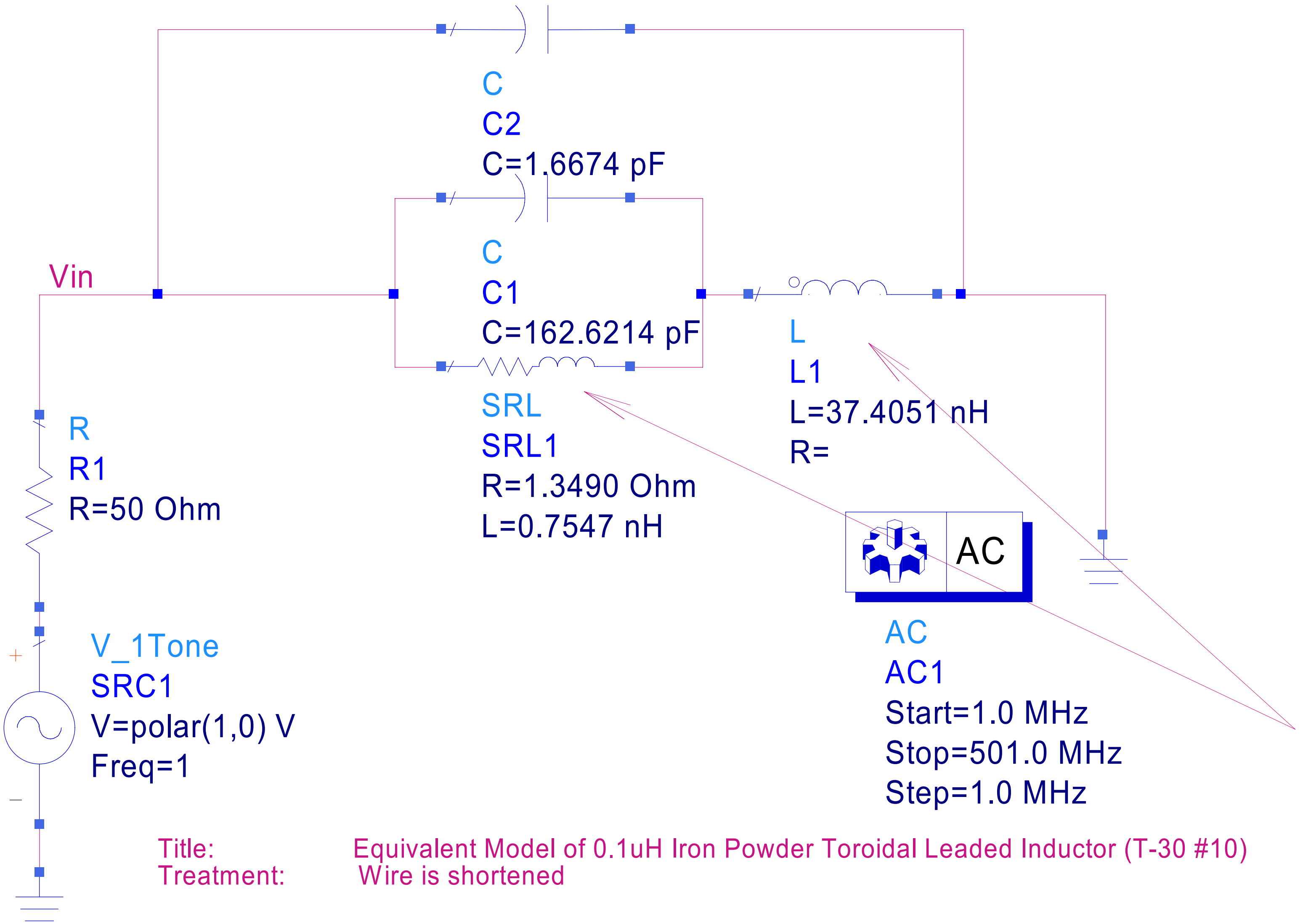
3.4.5 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #10)

The following is the picture of a 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #10)

Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

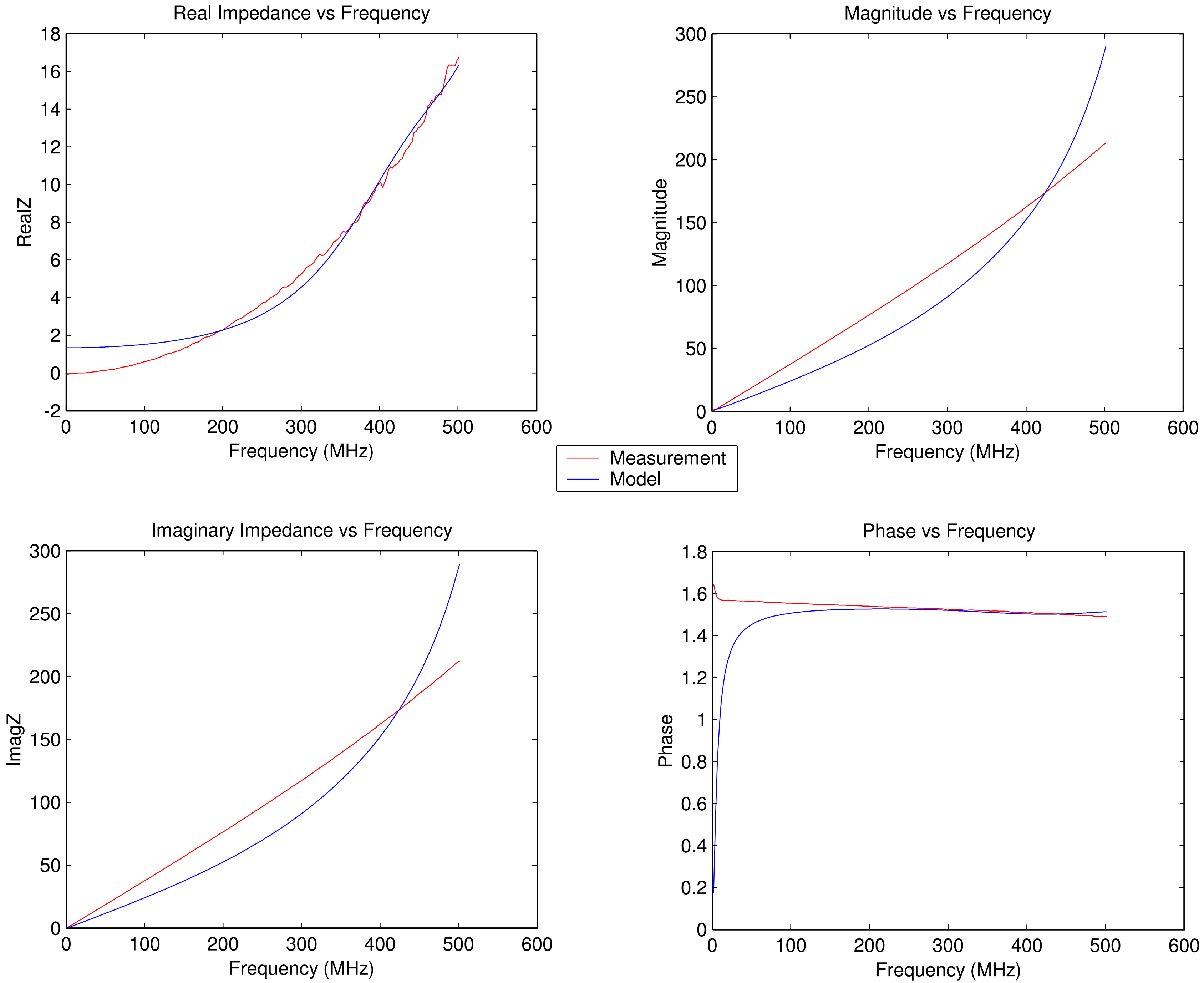
	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	0.0000
Internal Resistance of Model (Ω)	1.3490
Internal Inductance from estimation (μH)	0.1127
Internal Inductance of Model (nH)	0.7547
Internal Capacitance from estimation (pF)	0.1164
Internal Capacitance of Model (pF)	162.6214
External Inductance from estimation (nH)	4.8162
External Inductance of Model (nH)	37.4051
External Capacitance from estimation (pF)	0.0245
External Capacitance of Model (pF)	1.6674
Resonant Frequency (MHz)	1389.6536
A_L	25
Number of turns from estimation	6.325
Number of turns	3
Legnth of Leaded Wire (mm)	3.2600
Distance between two wires (mm)	8.2300
Diameter of wire (mm)	0.3900
R-Square Value of Real Impedance	0.9832
R-Square Value of Imaginary Impedance	0.9352
R-Square Value of Magnitude	0.9355
R-Square Value of Phase	0.2906



Sum of two inductance values = 0.038 uH

Title: Equivalent Model of 0.1uH Iron Powder Toroidal Leaded Inductor (T-30 #10)
Treatment: Wire is shortened

0.1uH Iron Powder Toroidal Core (T-30-10) Leaded Inductor with Wire Shortened (Linear-Scale)



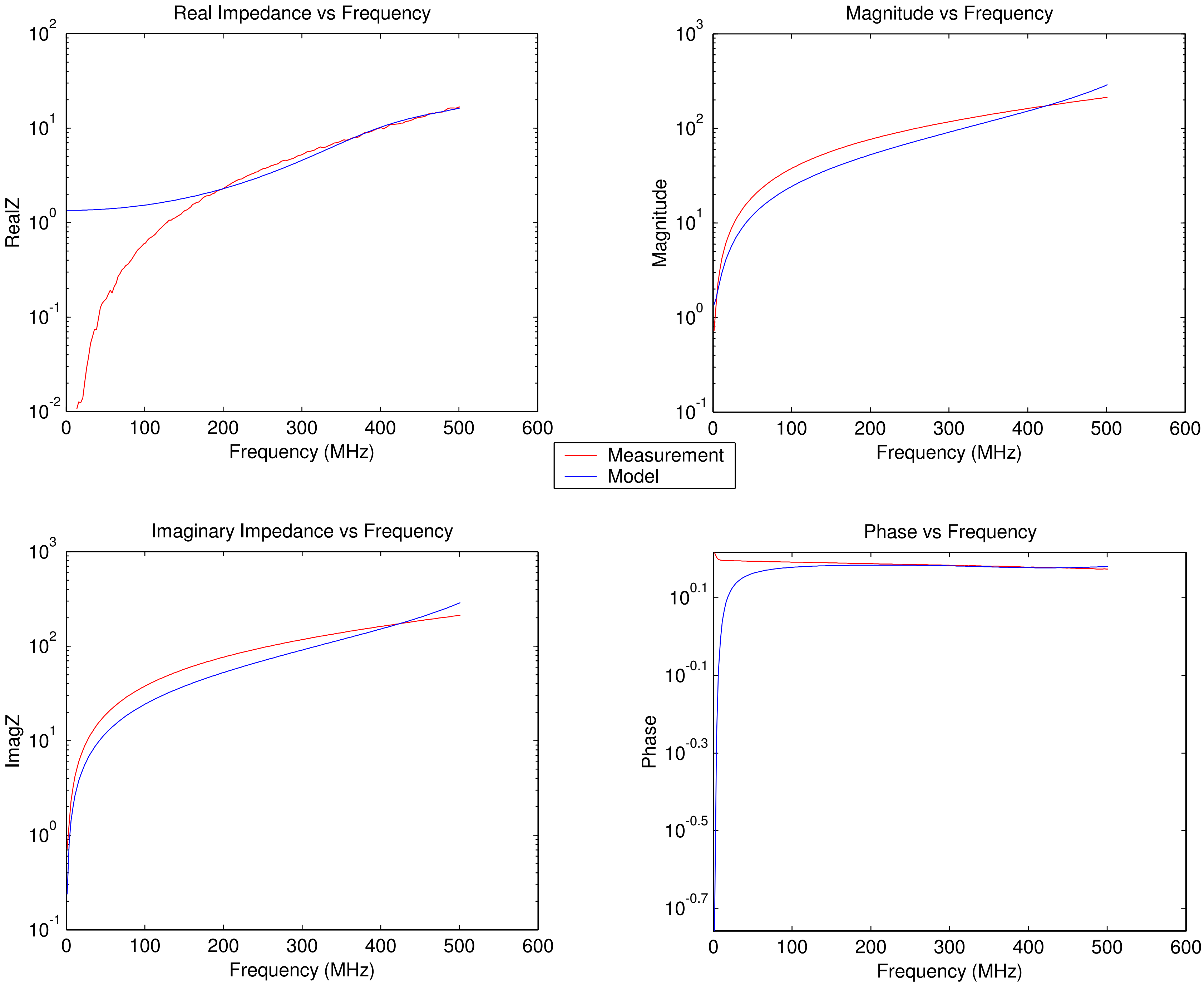
Real Impedance vs Frequency

Magnitude vs Frequency

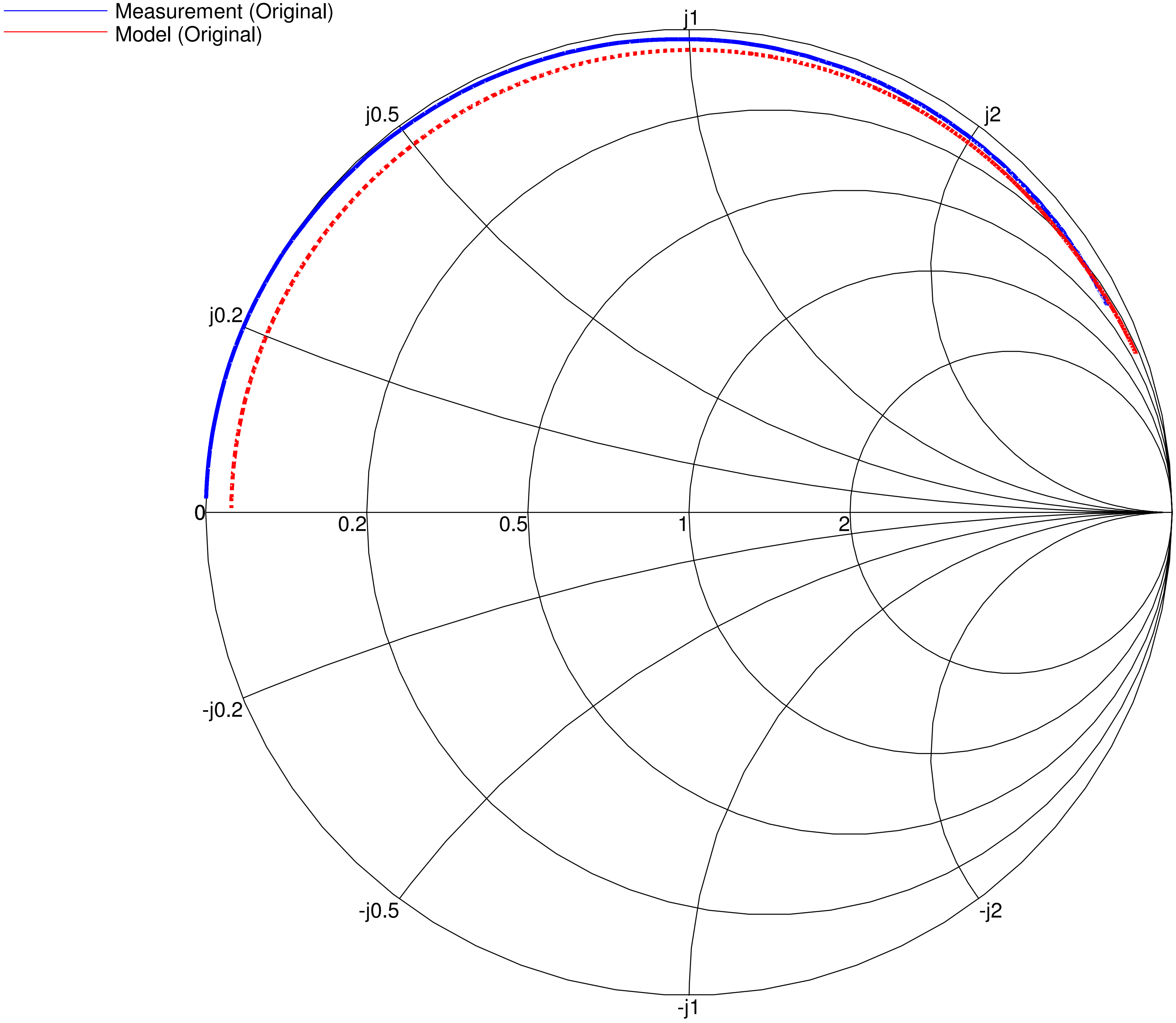
Imaginary Impedance vs Frequency

Phase vs Frequency

0.1uH Iron Powder Toroidal Core (T-30-10) Leaded Inductor with Wire Shortened (Log-Scale)



0.1uH Iron Powder Toroidal Core (T-30-10) Leaded Inductor with Wire Shortened



3.4.6 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #12)

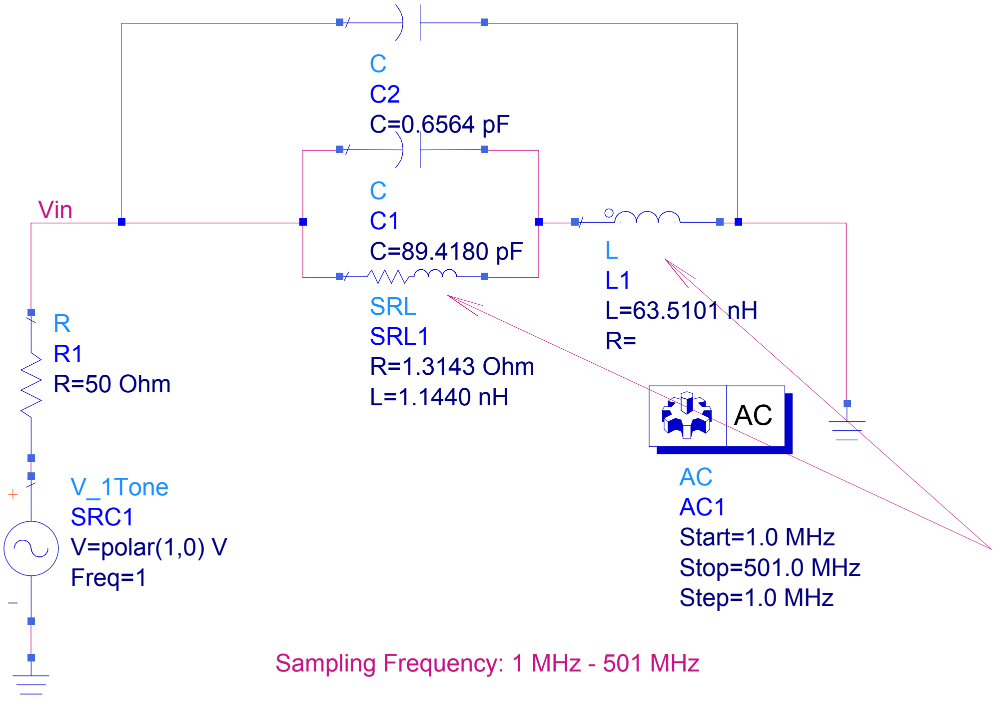
The following is the picture of a 0.1μH Iron Powder Toroidal Leaded Inductor (T-30 #12)

Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

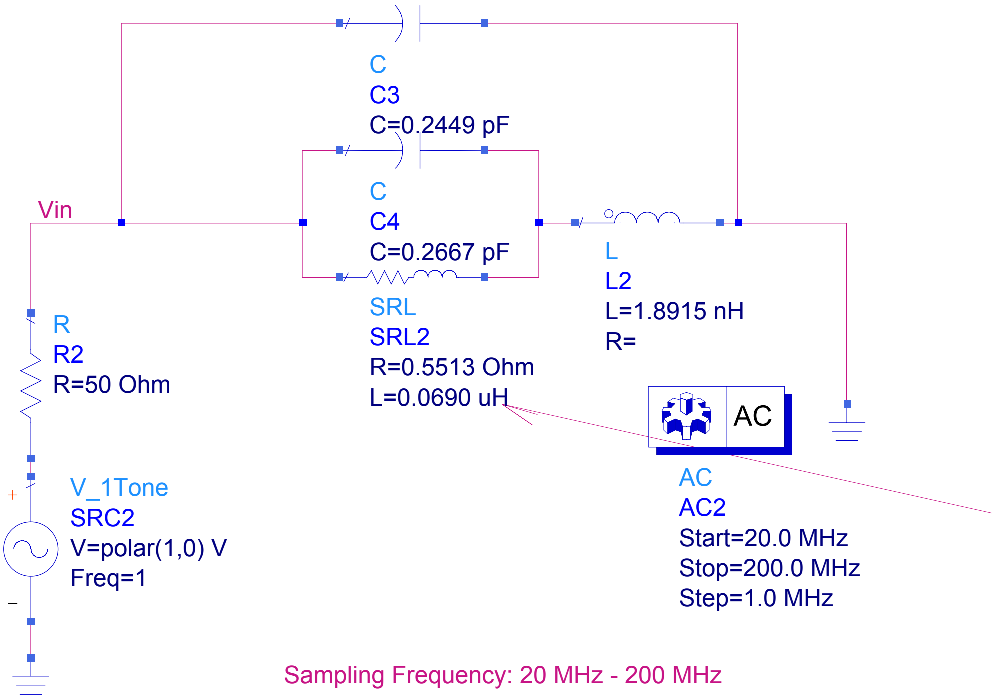
	1 MHz - 501 MHz	20 MHz - 200 MHz
Internal Resistance from estimation (Ω)	0.0000	0.0000
Internal Resistance of Model (Ω)	1.3143	0.5513
Internal Inductance from estimation (μH)	0.1408	0.1408
Internal Inductance of Model	1.1440 nH	0.0691 μH
Internal Capacitance from estimation (pF)	0.1733	0.1733
Internal Capacitance of Model (pF)	89.4180	0.2668
External Inductance from estimation (nH)	3.0494	3.0494
External Inductance of Model (nH)	63.5101	1.8916
External Capacitance from estimation (pF)	0.0156	0.0156
External Capacitance of Model (pF)	0.6564	0.2449
Resonant Frequency (MHz)	1018.8403	1018.8403
A_L	16	16
Number of turns from estimation	7.906	7.906
Number of turns	4	4
Legnth of Leaded Wire (mm)	2.0700	2.0700
Distance between two wires (mm)	7.7300	7.7300
Diameter of wire (mm)	0.3700	0.3700
R-Square Value of Real Impedance	0.9919	0.9939
R-Square Value of Imaginary Impedance	0.9947	0.9999
R-Square Value of Magnitude	0.9948	0.9999
R-Square Value of Phase	0.0102	0.3371

Equivalent Model of 0.1uH Iron Powder Toroidal Leaded Inductor (T-30 #12)



Sum of two inductance values
= 0.065 uH

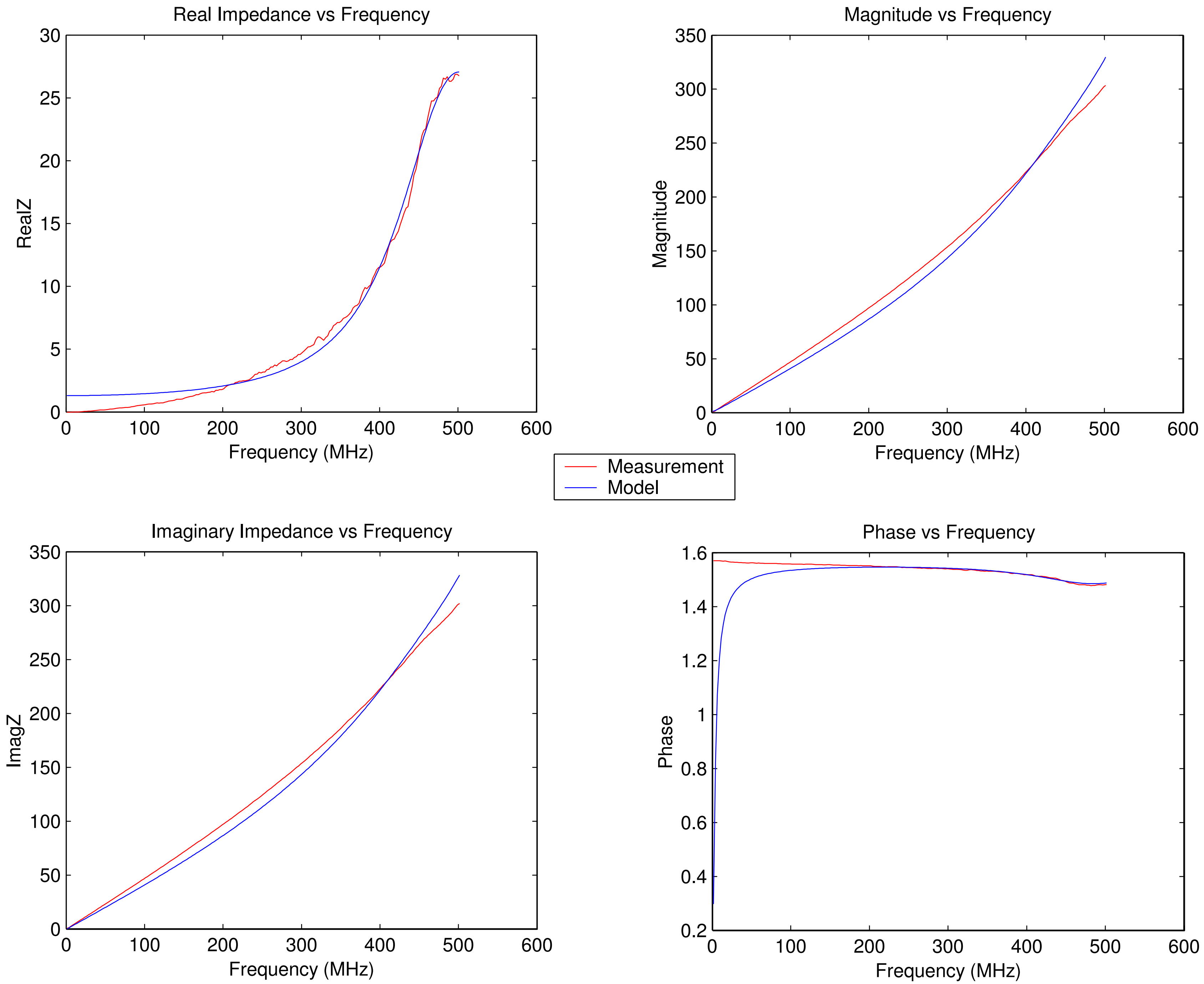
Sampling Frequency: 1 MHz - 501 MHz



Closed to the goal: 0.1 uH

Sampling Frequency: 20 MHz - 200 MHz

0.1uH Iron Powder Toroidal Core (T-30-12) Leaded Inductor with Wire Shortened (Linear-Scale)

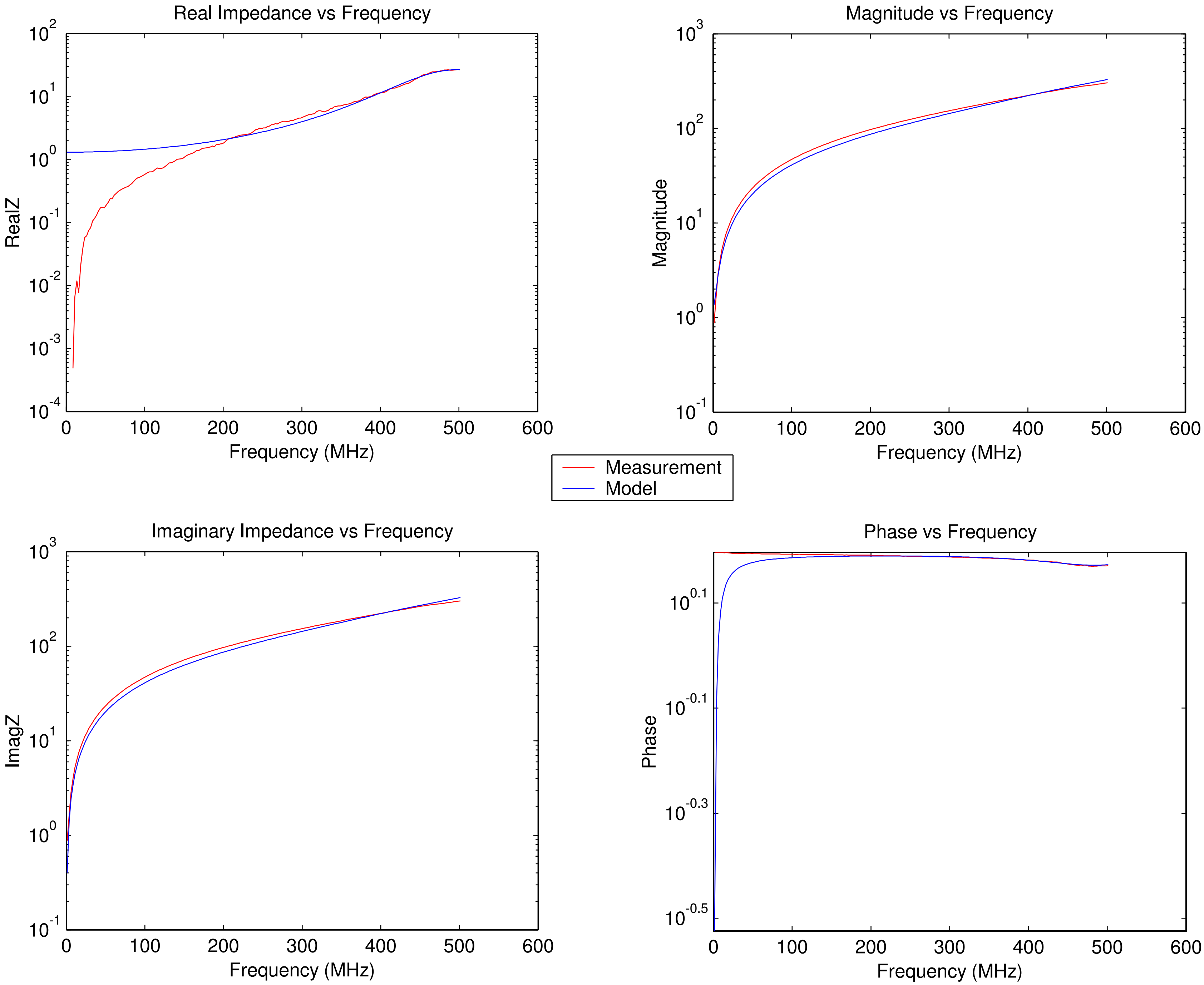

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency

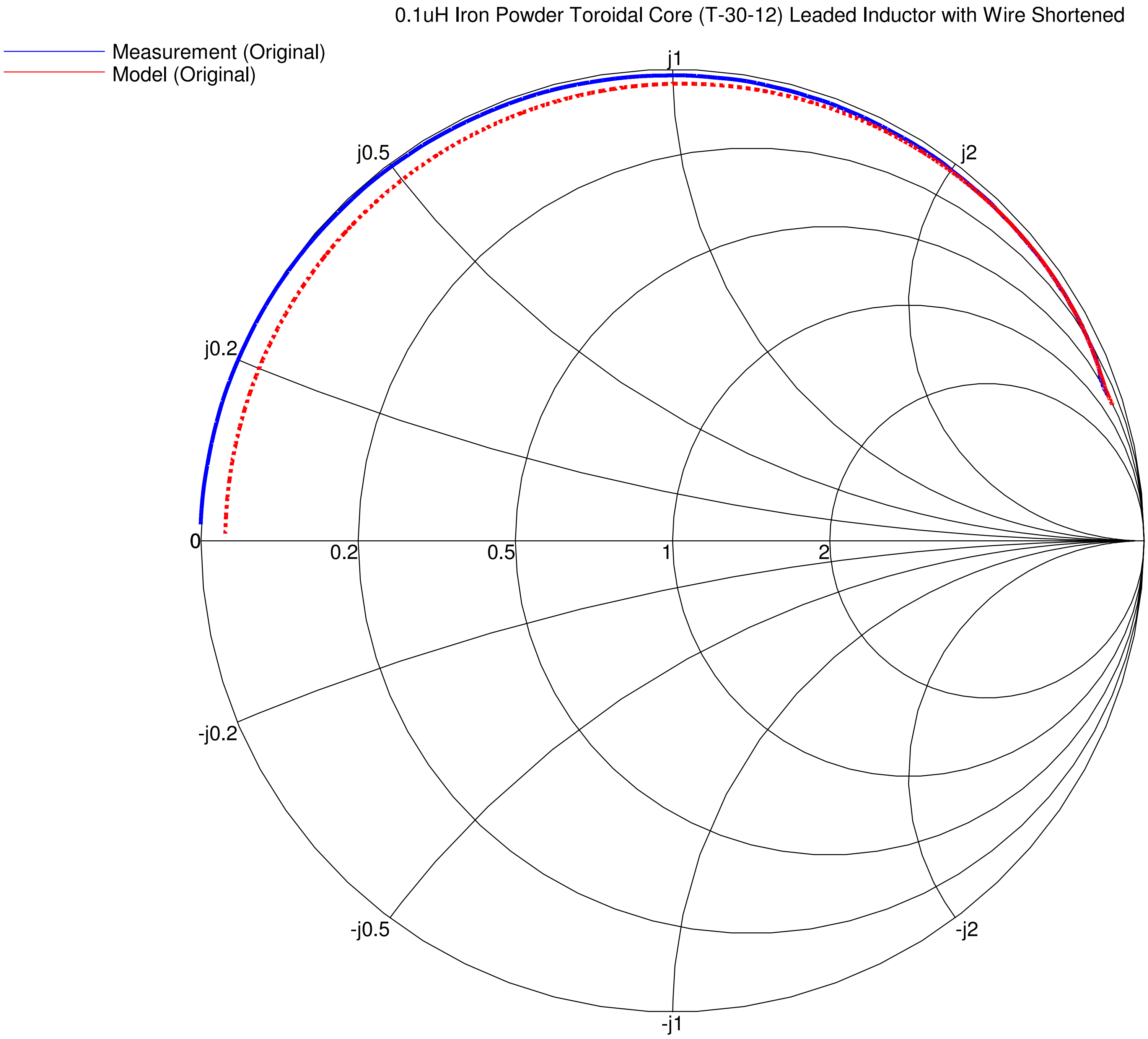
0.1uH Iron Powder Toroidal Core (T-30-12) Leaded Inductor with Wire Shortened (Log-Scale)


Real Impedance vs Frequency

Magnitude vs Frequency

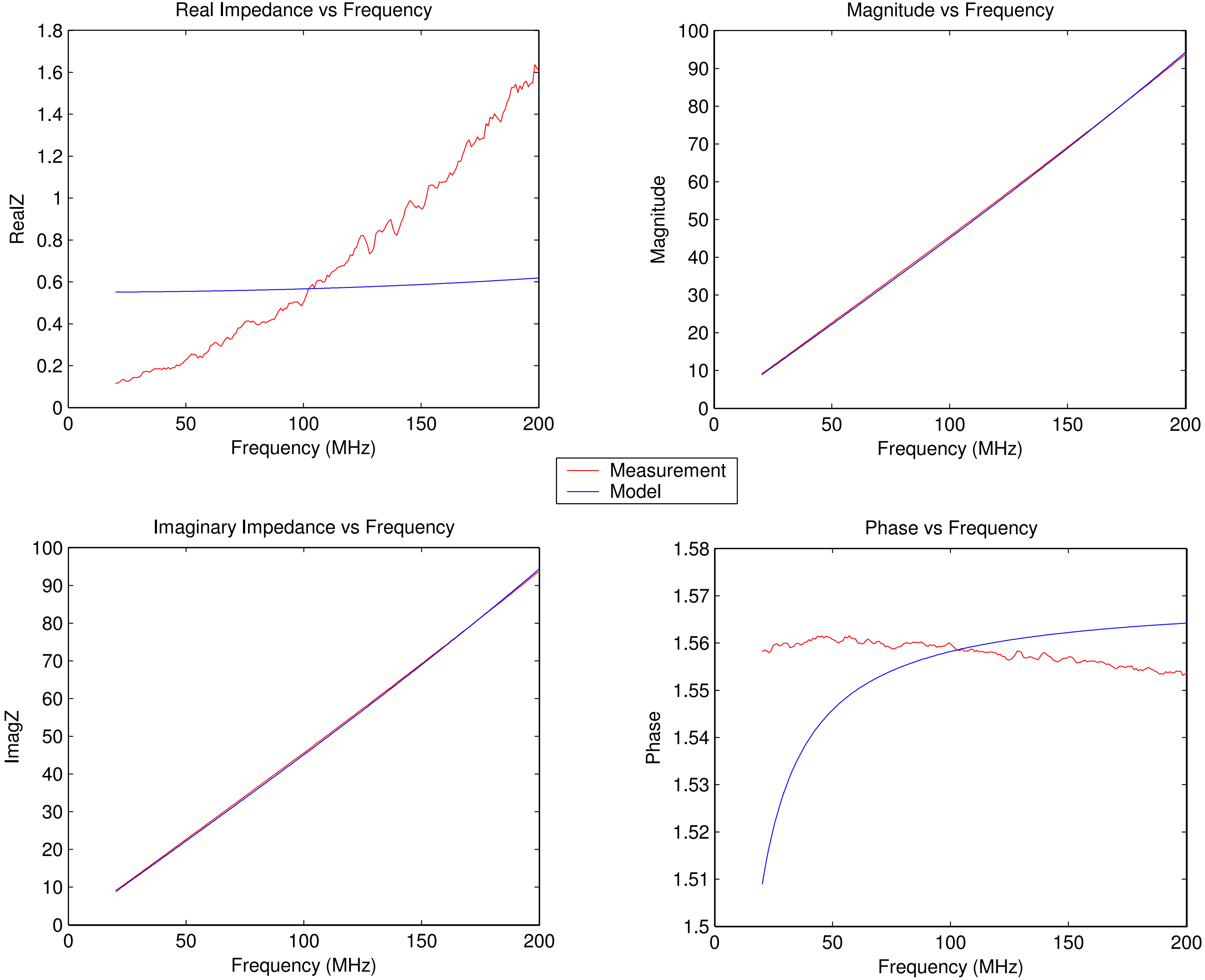
Imaginary Impedance vs Frequency

Phase vs Frequency

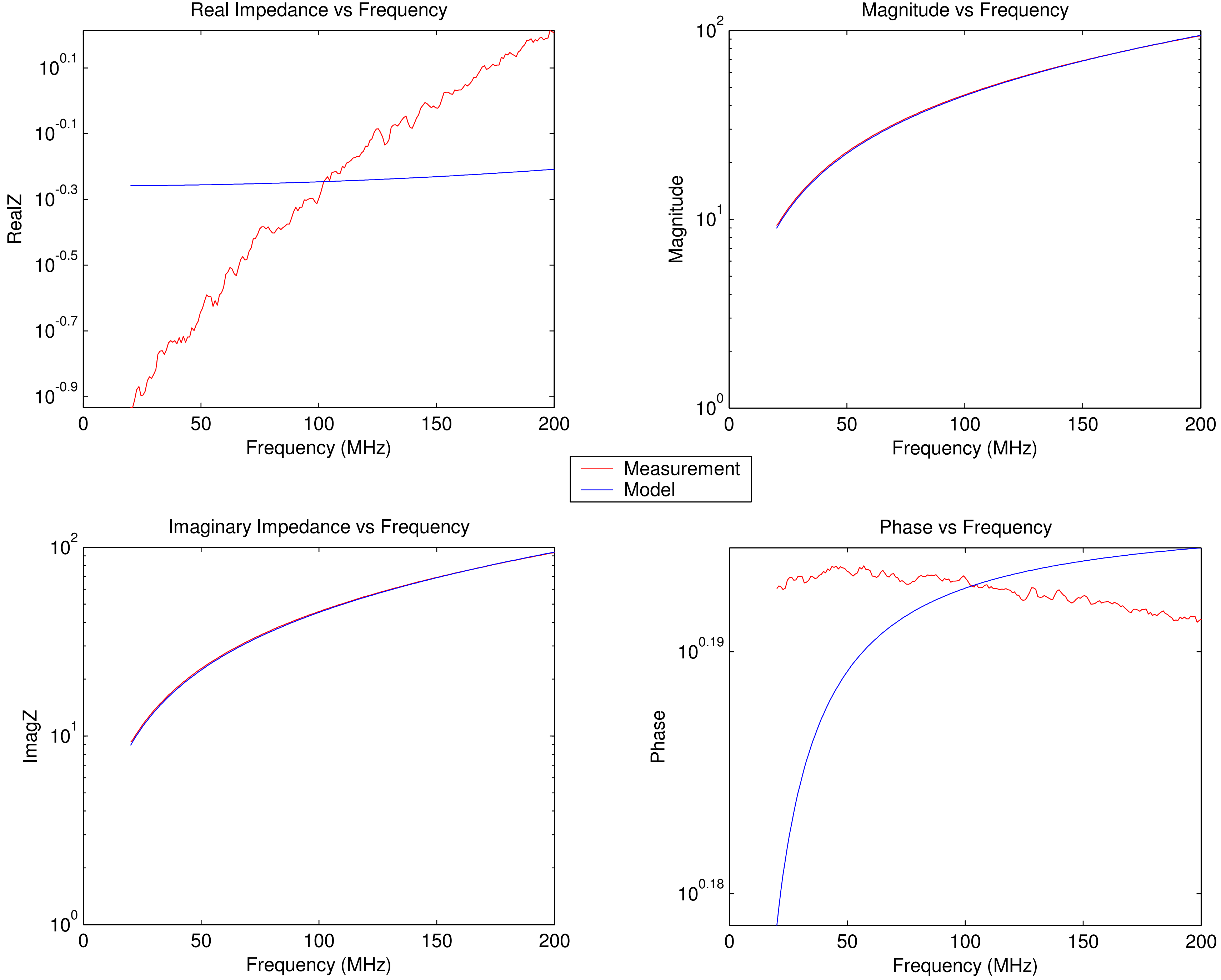


0.1uH Iron Powder Toroidal Core (T-30-12) Leaded Inductor with Wire Shortened

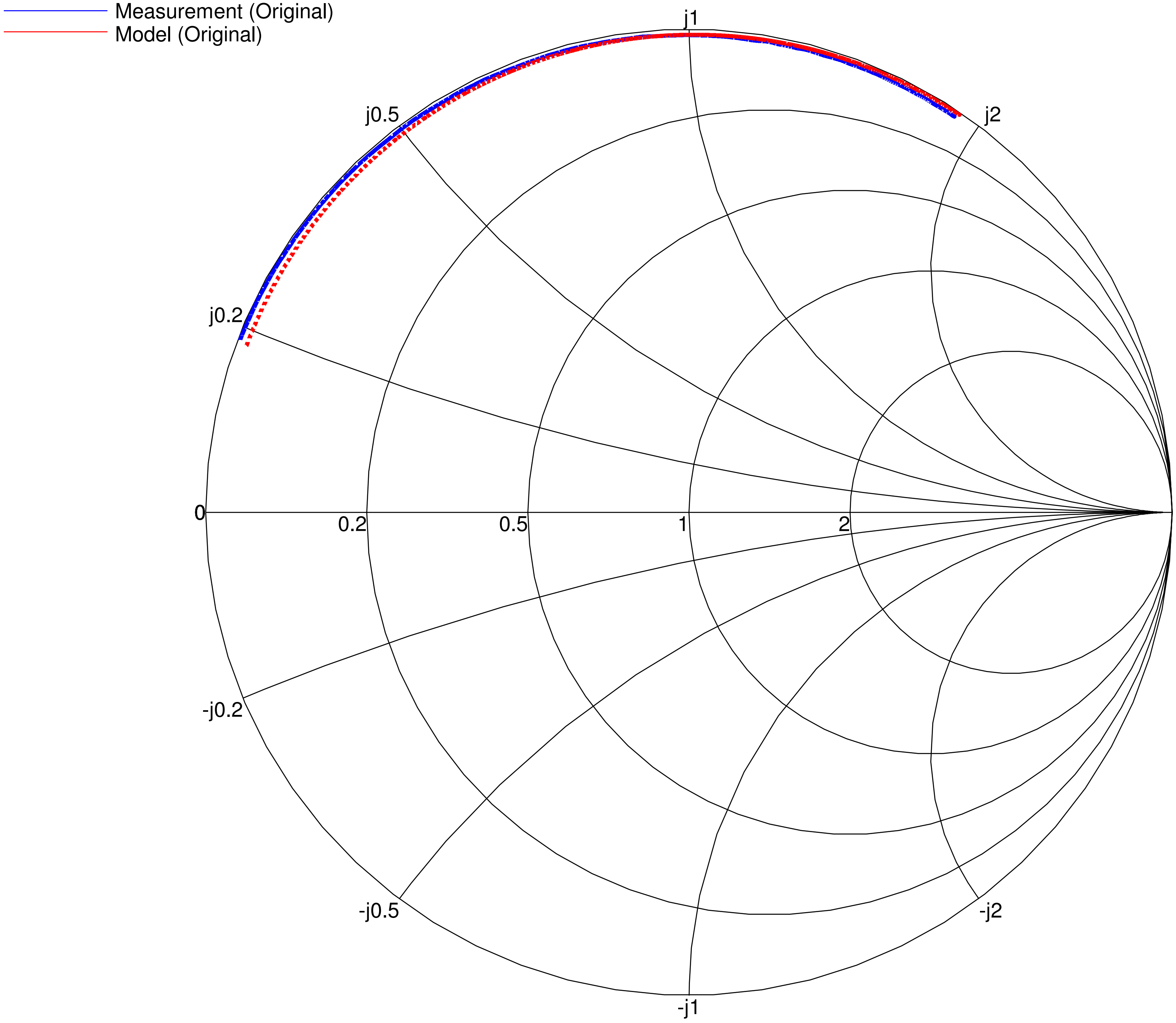
0.1uH Iron Powder Toroidal Core (T-30-12) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (20MHz - 200MHz)



0.1uH Iron Powder Toroidal Core (T-30-12) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (20MHz - 200MHz)



0.1uH Iron Powder Toroidal Core (T-30-12) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (20MHz - 200MHz)



3.4.7 1μH Iron Powder Toroidal Leaded Inductor (T-50 #2)

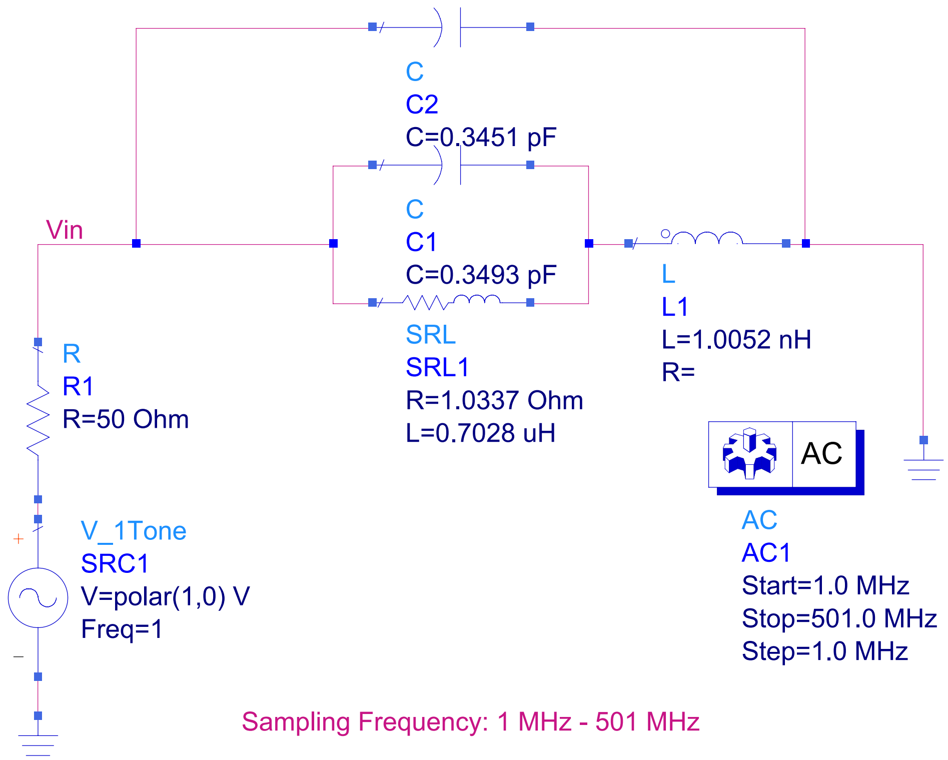
The following is the picture of a 1μH Iron Powder Toroidal Leaded Inductor (T-50 #2)

Picture of a shortened wire inductor

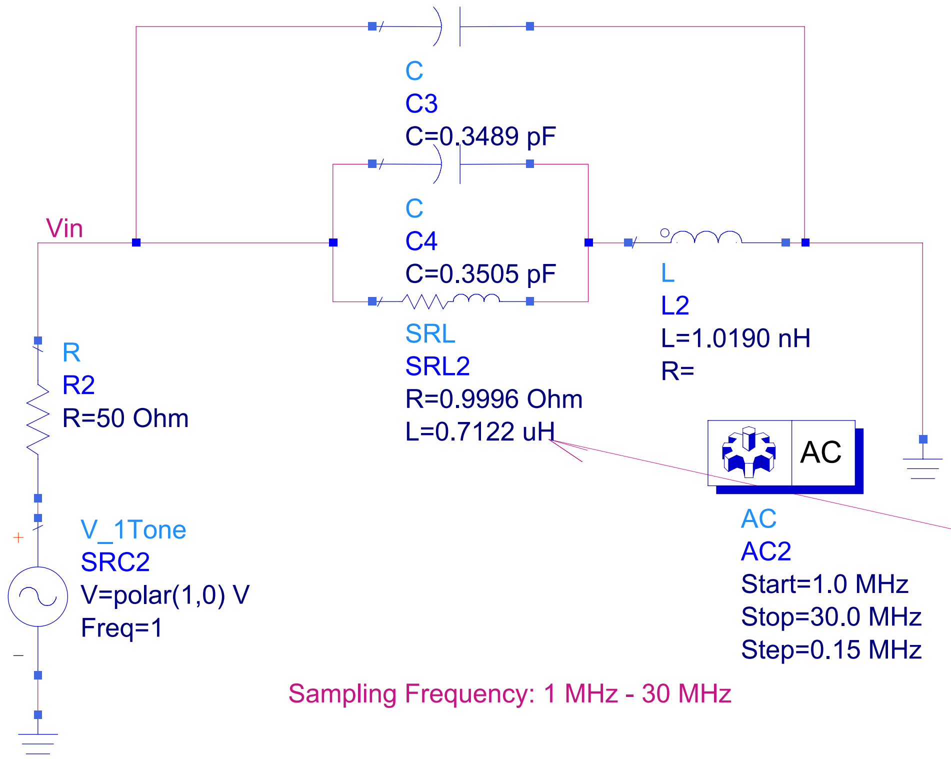
This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz	1 MHz - 30 MHz
Internal Resistance from estimation (Ω)	0.0990	0.0990
Internal Resistance of Model (Ω)	1.0337	0.9996
Internal Inductance from estimation (μH)	1.3021	1.3021
Internal Inductance of Model (μH)	0.7028	0.7122
Internal Capacitance from estimation (pF)	0.3729	0.3729
Internal Capacitance of Model (pF)	0.3493	0.3506
External Inductance from estimation (nH)	12.4680	12.4680
External Inductance of Model (nH)	1.0052	1.0190
External Capacitance from estimation (pF)	0.0485	0.0485
External Capacitance of Model (pF)	0.3451	0.3490
Resonant Frequency (MHz)	228.4057	228.4057
A_L	49	49
Number of turns from estimation	14.286	14.286
Number of turns	11	11
Legnth of Leaded Wire (mm)	7.3800	7.3800
Distance between two wires (mm)	14.4100	14.4100
Diameter of wire (mm)	0.4100	0.4100
R-Square Value of Real Impedance	0.1974	0.7403
R-Square Value of Imaginary Impedance	0.0688	1.0000
R-Square Value of Magnitude	0.3531	1.0000
R-Square Value of Phase	0.9674	0.9955

Equivalent Model of 1uH Iron Powder Toroidal Leaded Inductor (T-50 #2)



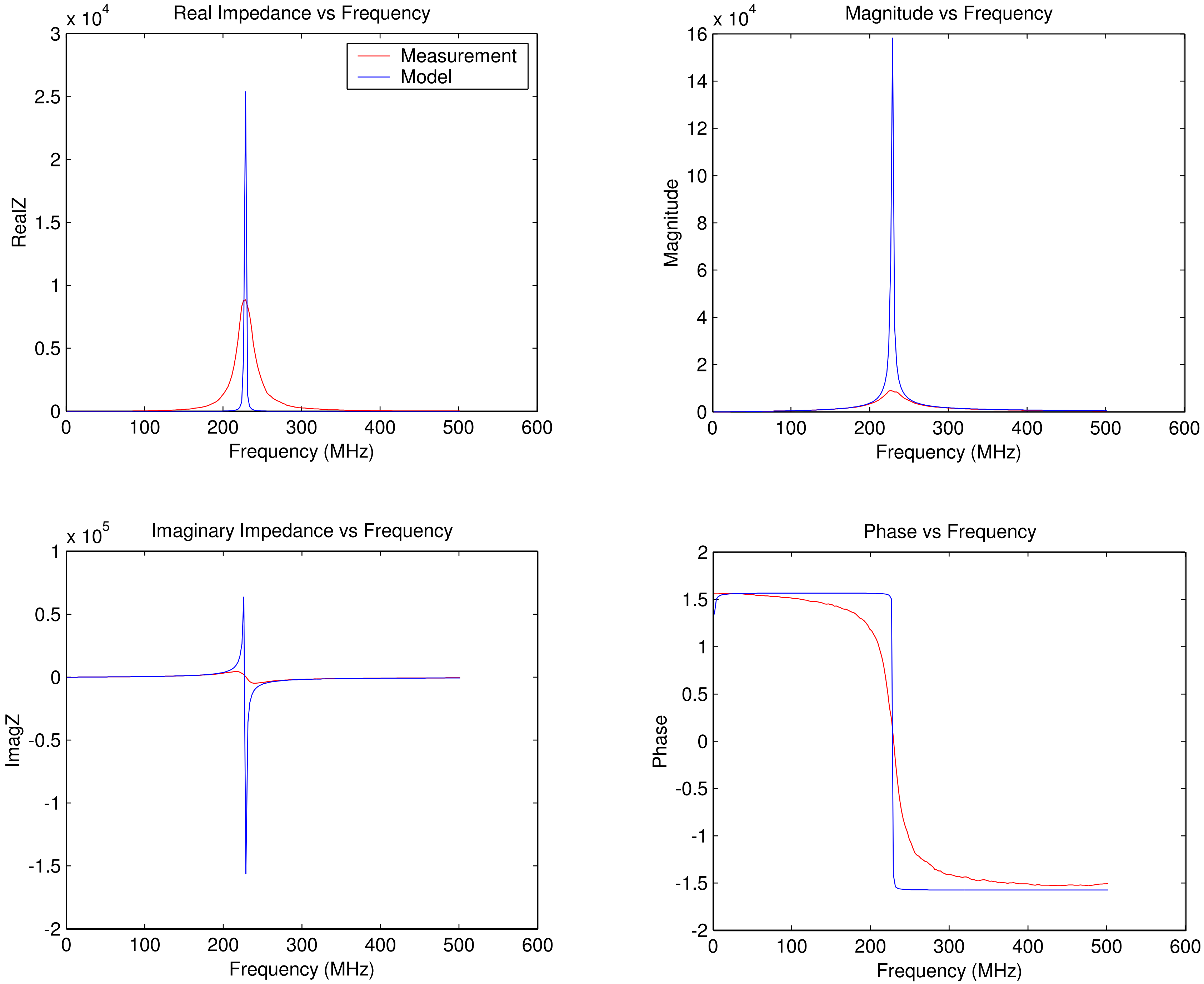
Sampling Frequency: 1 MHz - 501 MHz



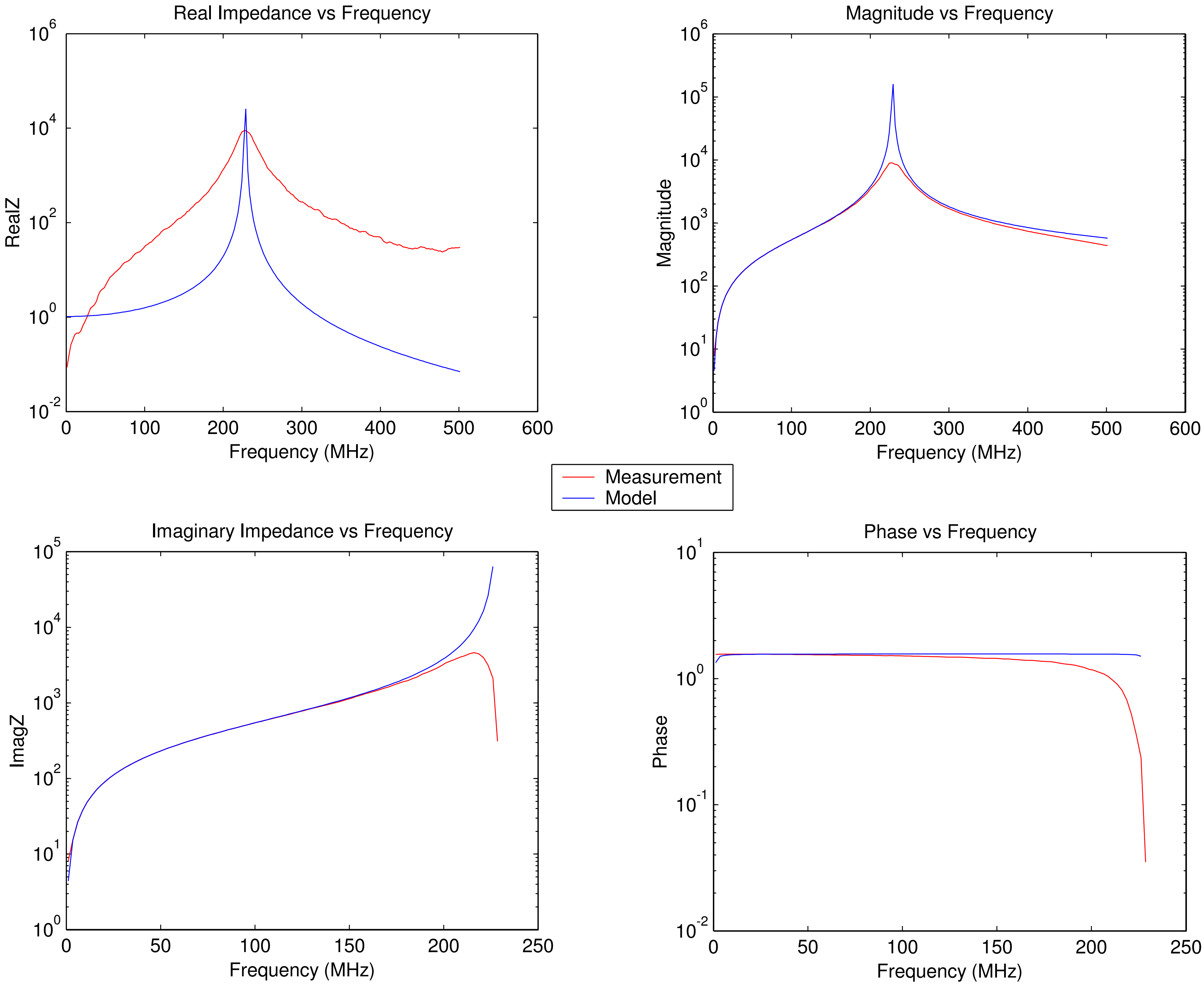
Closed to the goal: 1 uH

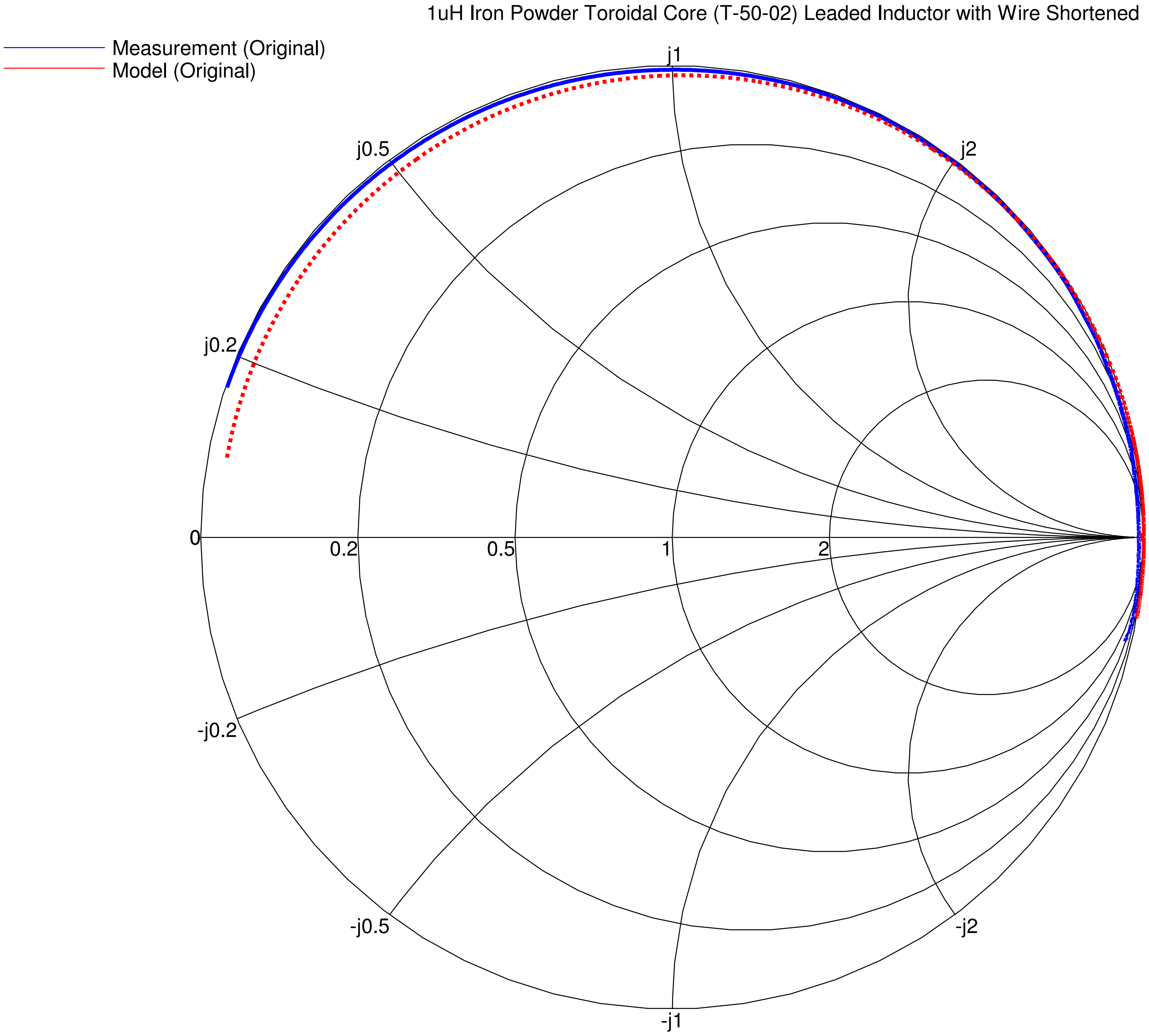
Sampling Frequency: 1 MHz - 30 MHz

1uH Iron Powder Toroidal Core (T-50-02) Leaded Inductor with Wire Shortened (Linear-Scale)



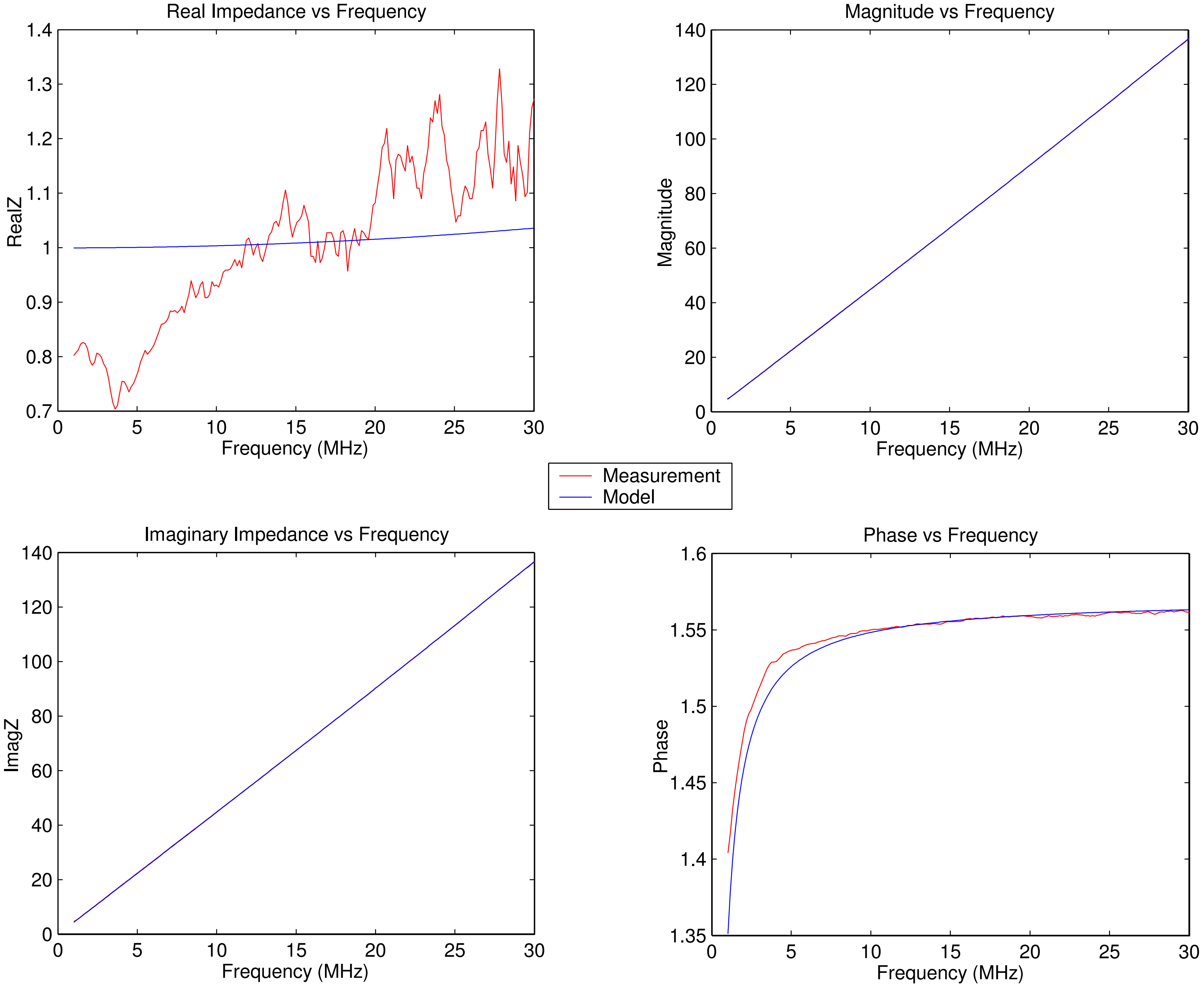
1uH Iron Powder Toroidal Core (T-50-02) Leaded Inductor with Wire Shortened (Log-Scale)



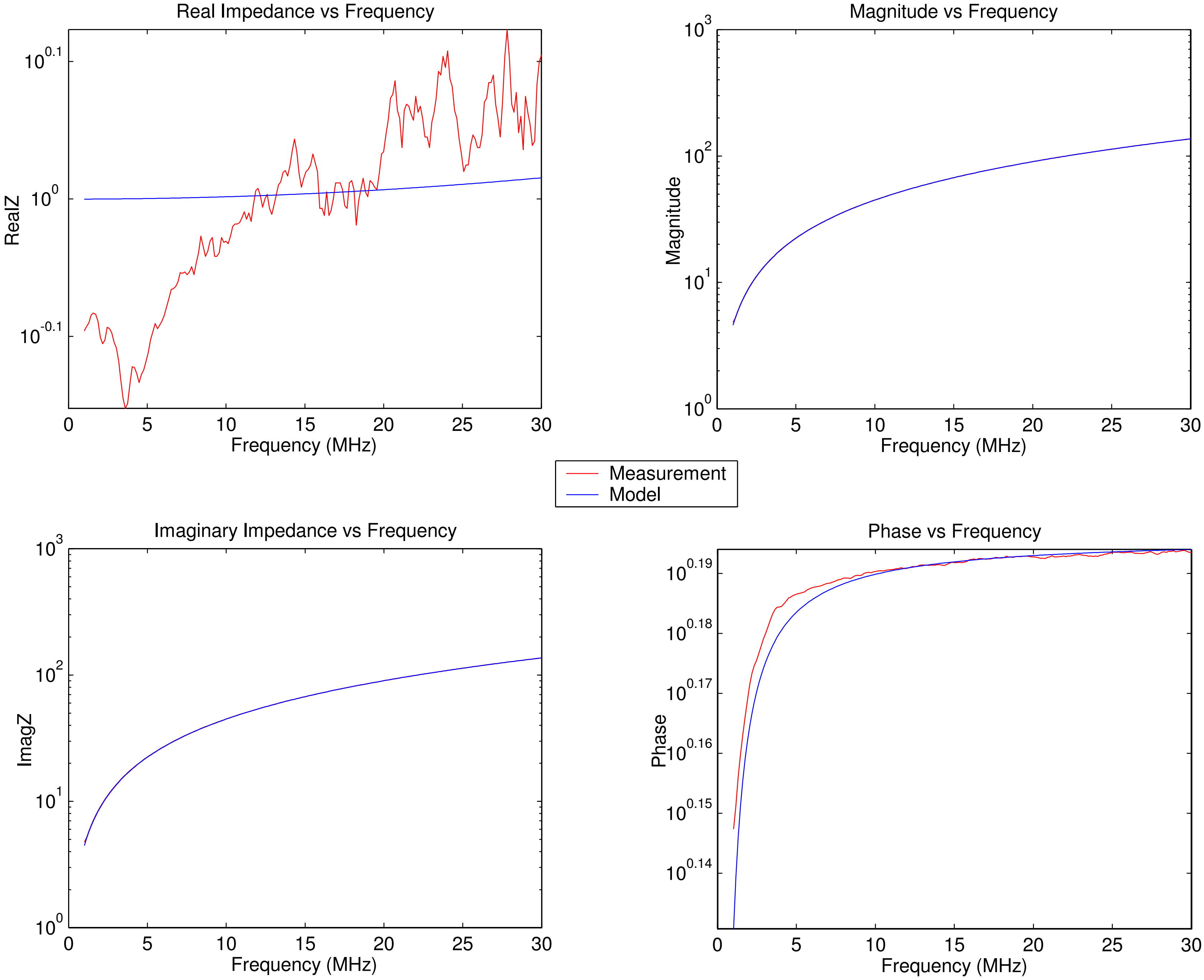


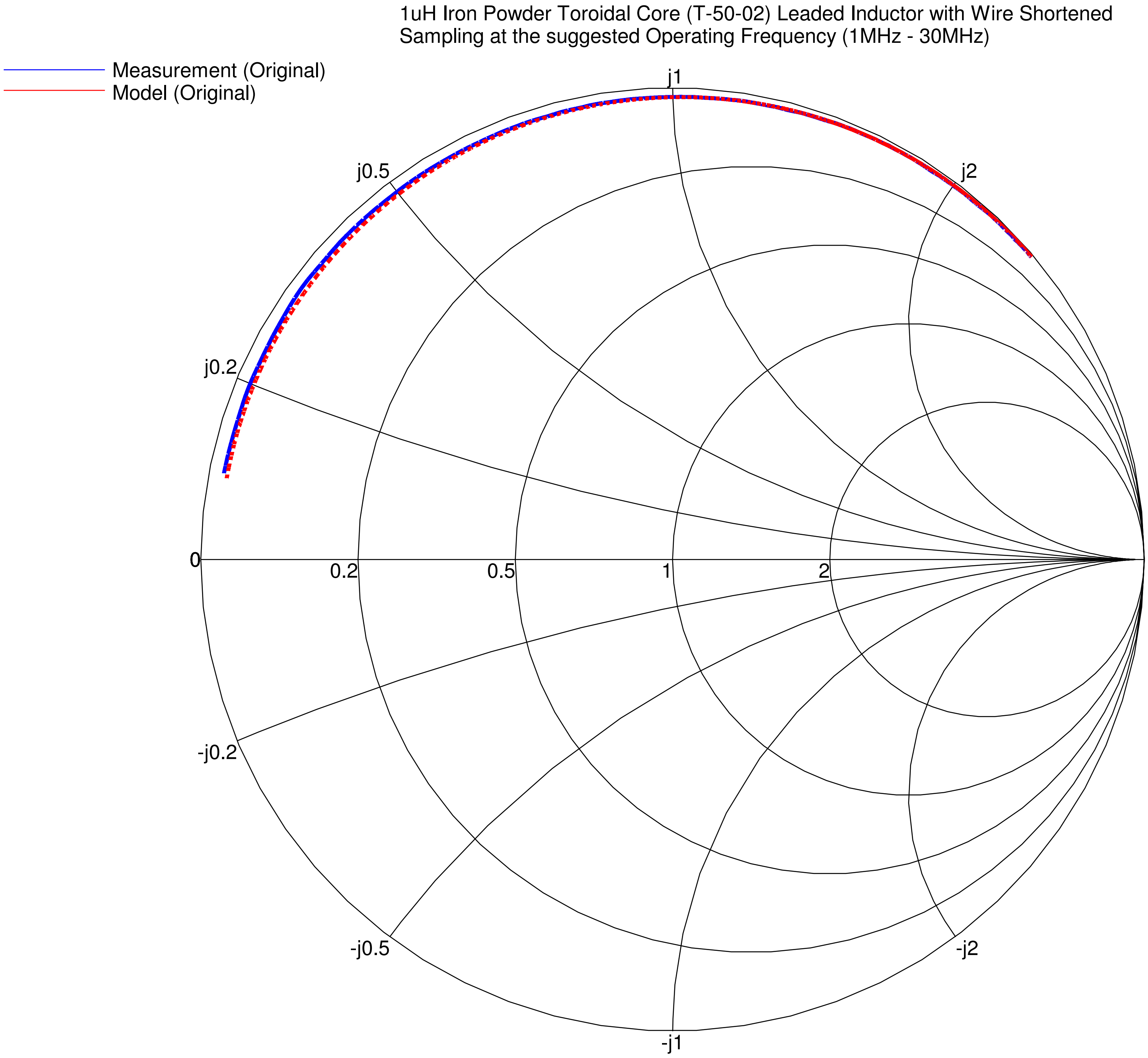
1uH Iron Powder Toroidal Core (T-50-02) Leaded Inductor with Wire Shortened
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

1uH Iron Powder Toroidal Core (T-50-02) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (1MHz - 30MHz)



1uH Iron Powder Toroidal Core (T-50-02) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (1MHz - 30MHz)





1uH Iron Powder Toroidal Core (T-50-02) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (1MHz - 30MHz)

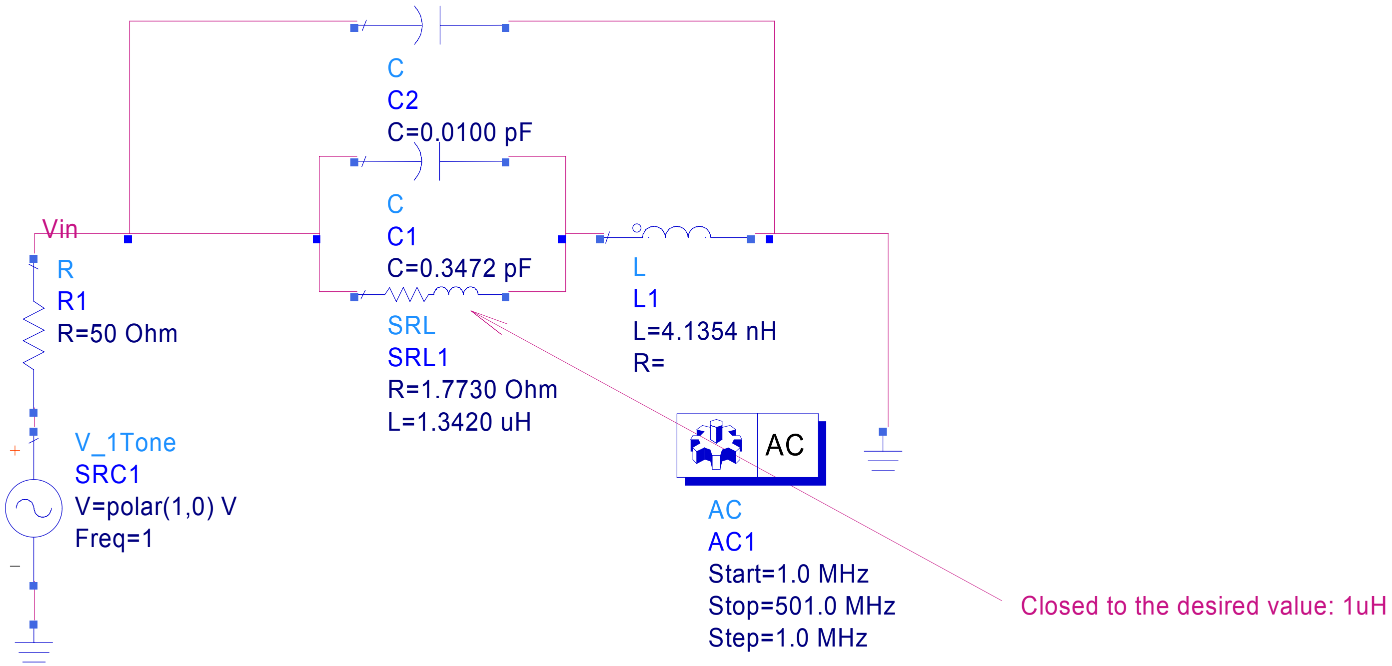
3.4.8 1μH Iron Powder Toroidal Leaded Inductor (T-50 #3)

The following is the picture of a 1μH Iron Powder Toroidal Leaded Inductor (T-50 #3)

Picture of a shortened wire inductor

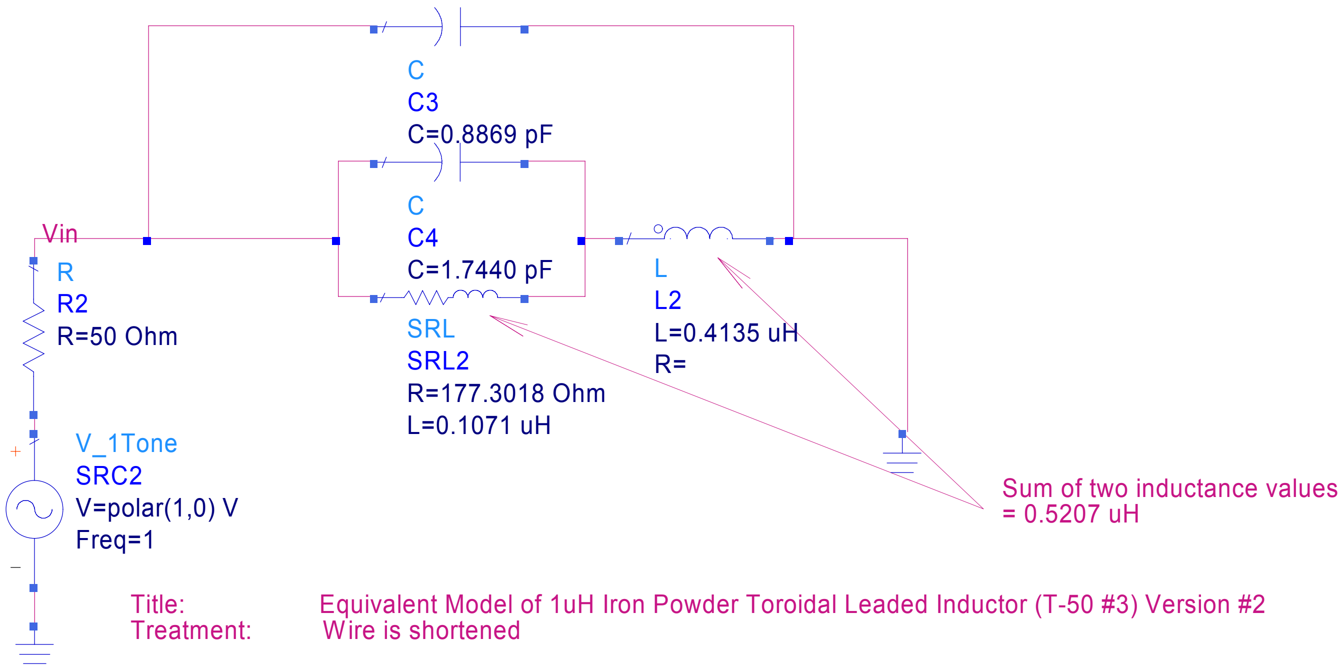
I offered two different models for this inductor. Both of them are measured from 1 MHz to 501 MHz. The internal inductance of the first version is very closed to our desired value, while the second one has better agreements (R-Square value) overall. Although Version #2 gives a better R-Square value overall, Version #1 matches the measurement result better in the Smith Chart.

	Version #1	Version #2
Internal Resistance from estimation (Ω)	0.1170	0.1170
Internal Resistance of Model (Ω)	1.7730	177.3018
Internal Inductance from estimation (μH)	1.3626	1.3626
Internal Inductance of Model (μH)	1.3421	0.1072
Internal Capacitance from estimation (pF)	0.3472	0.3472
Internal Capacitance of Model (pF)	0.3472	1.7440
External Inductance from estimation (nH)	4.7009	4.7009
External Inductance of Model (nH)	4.1354	413.5449
External Capacitance from estimation (pF)	0.0203	0.0203
External Capacitance of Model (pF)	0.0100	0.8869
Resonant Frequency (MHz)	231.4017	231.4017
A_L	175	175
Number of turns from estimation	7.559	7.559
Number of turns	6	6
Legnth of Leaded Wire (mm)	2.9300	2.9300
Distance between two wires (mm)	11.7300	11.7300
Diameter of wire (mm)	0.4100	0.4100
R-Square Value of Real Impedance	0.0566	0.9650
R-Square Value of Imaginary Impedance	0.0201	0.9872
R-Square Value of Magnitude	0.1377	0.9433
R-Square Value of Phase	0.8536	0.8965



Closed to the desired value: 1uH

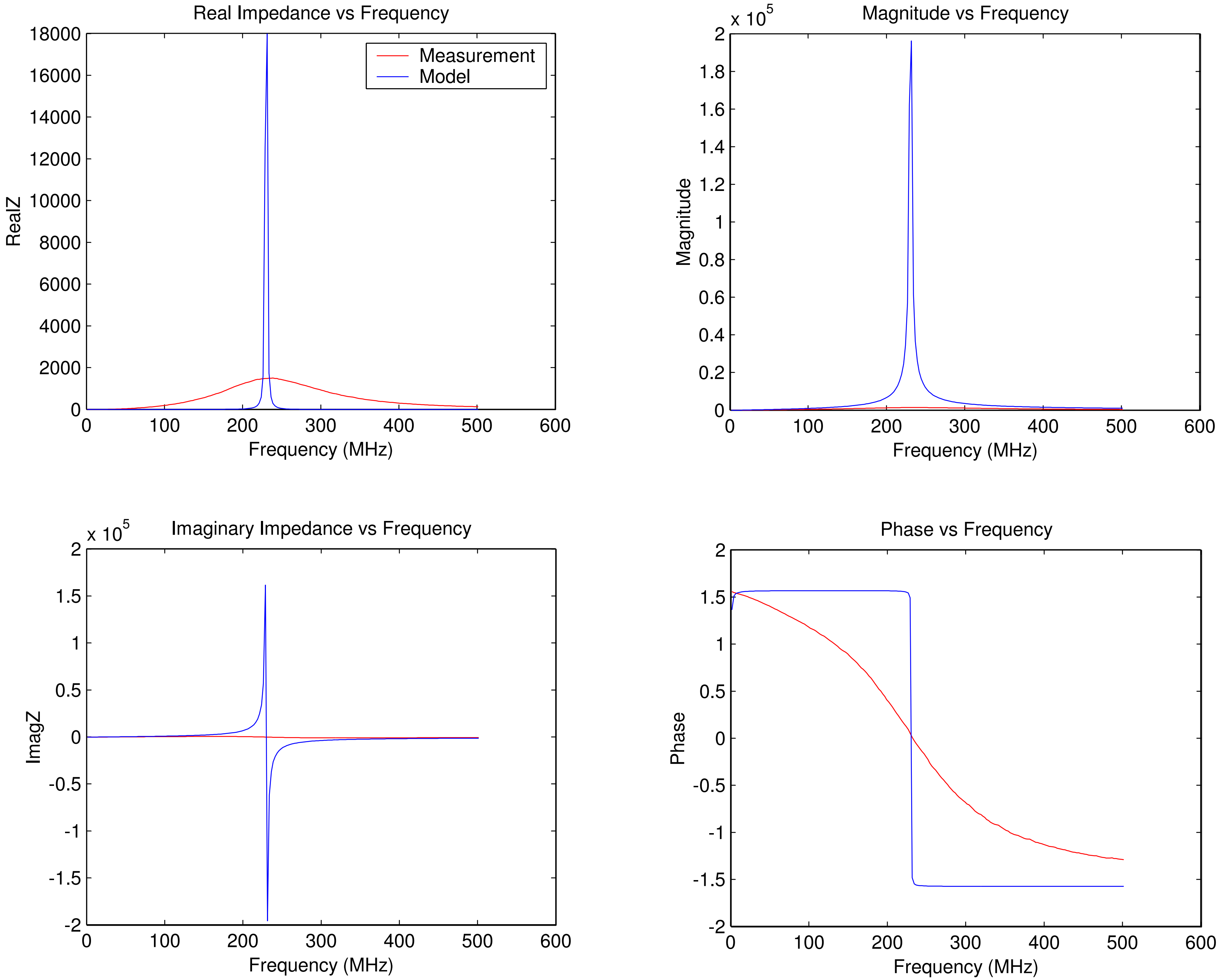
Title: Equivalent Model of 1uH Iron Powder Toroidal Leaded Inductor (T-50 #3) Version #1
Treatment: Wire is shortened



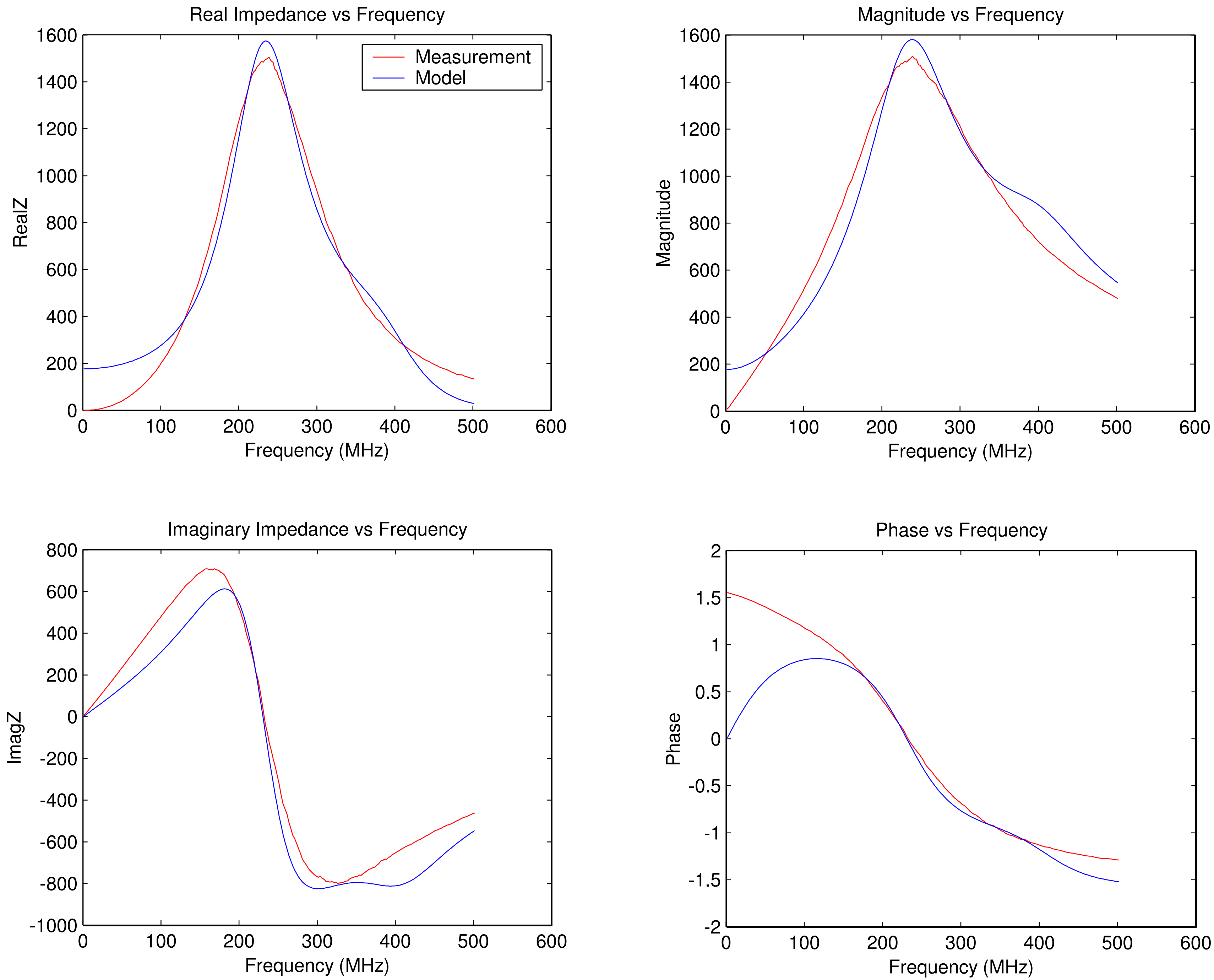
Sum of two inductance values
= 0.5207 uH

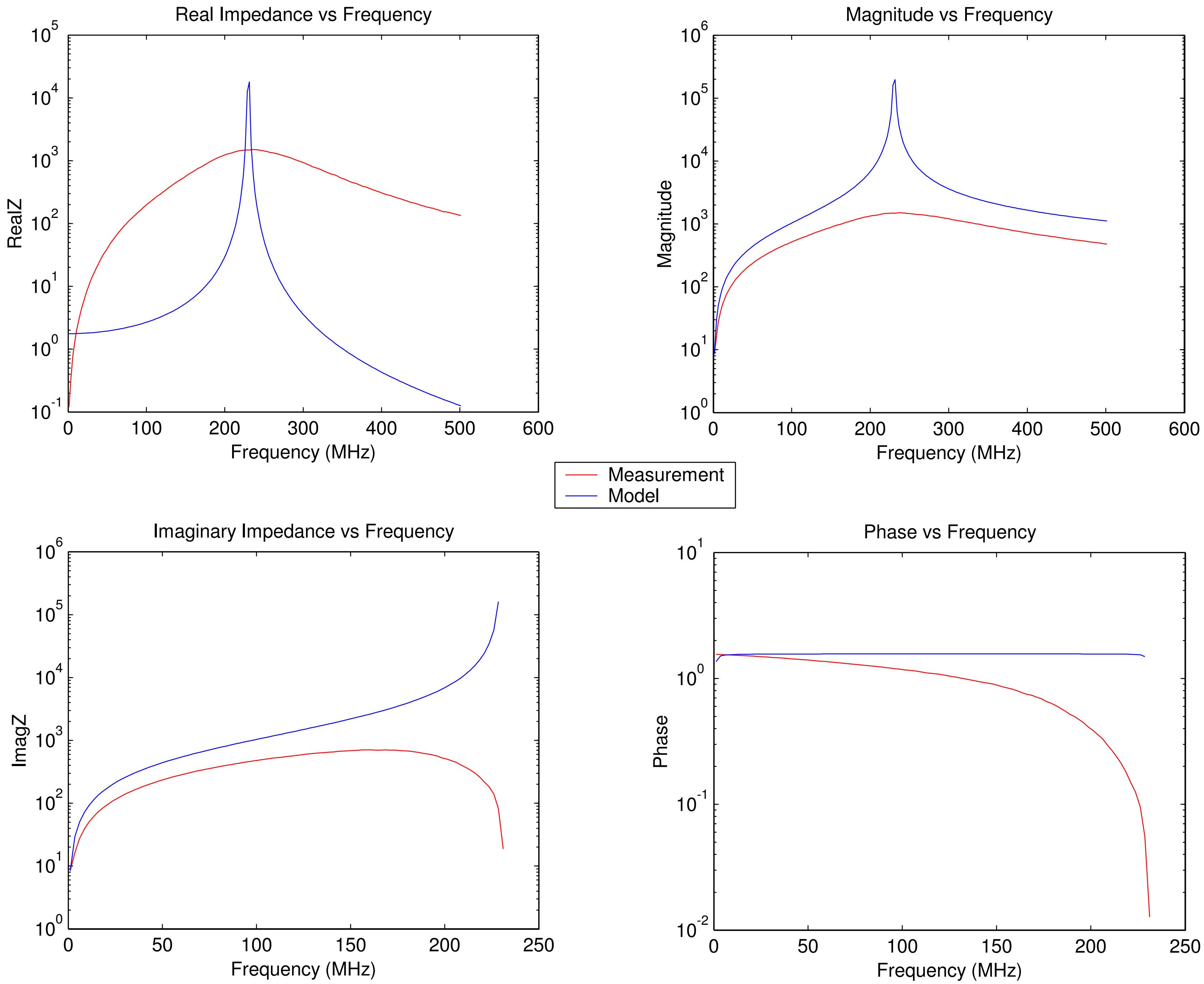
Title: Equivalent Model of 1uH Iron Powder Toroidal Leaded Inductor (T-50 #3) Version #2
Treatment: Wire is shortened

1uH Iron Powder Toroidal Core (T-50-03) Leaded Inductor with Wire Shortened (Linear-Scale) Version #1

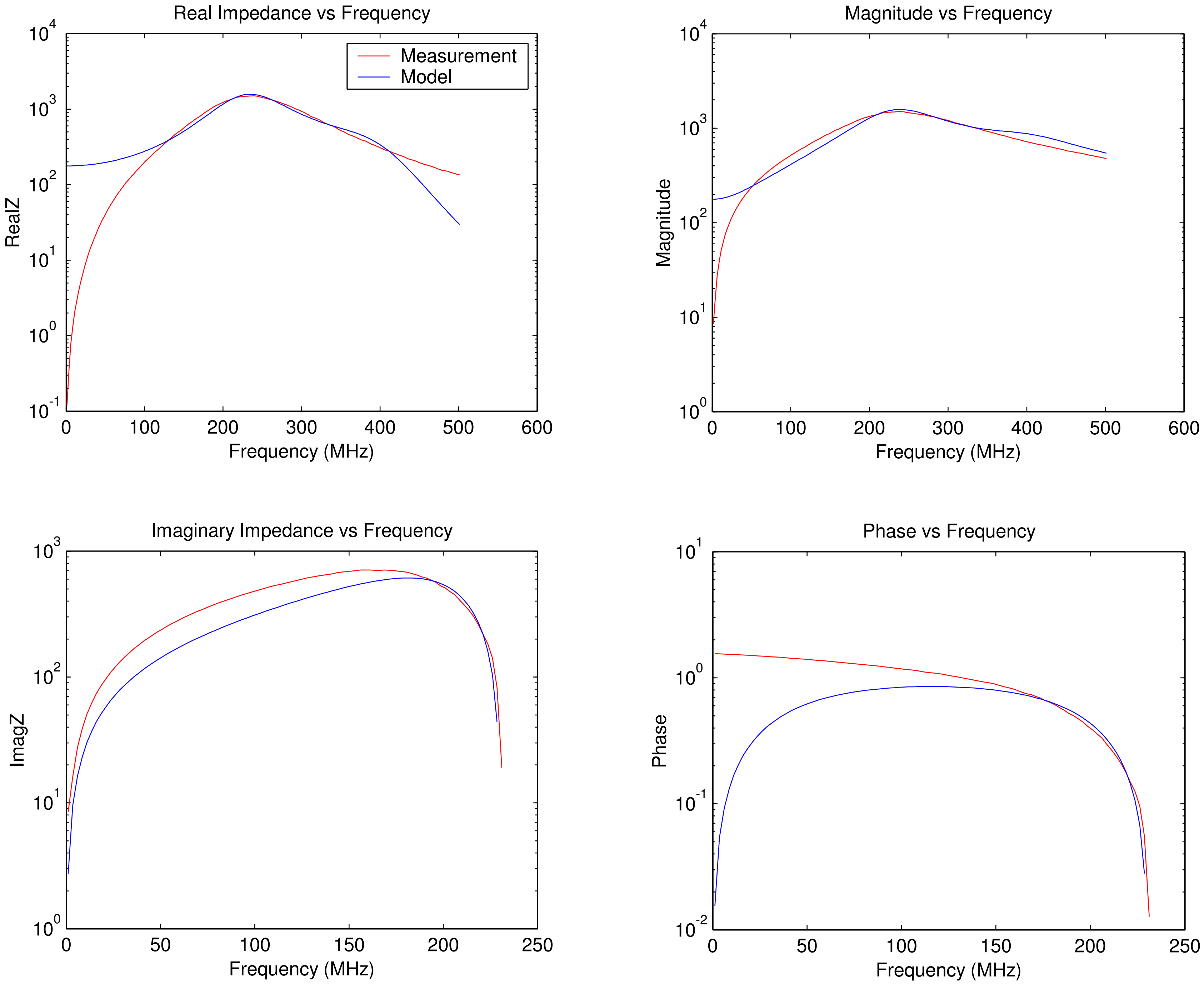


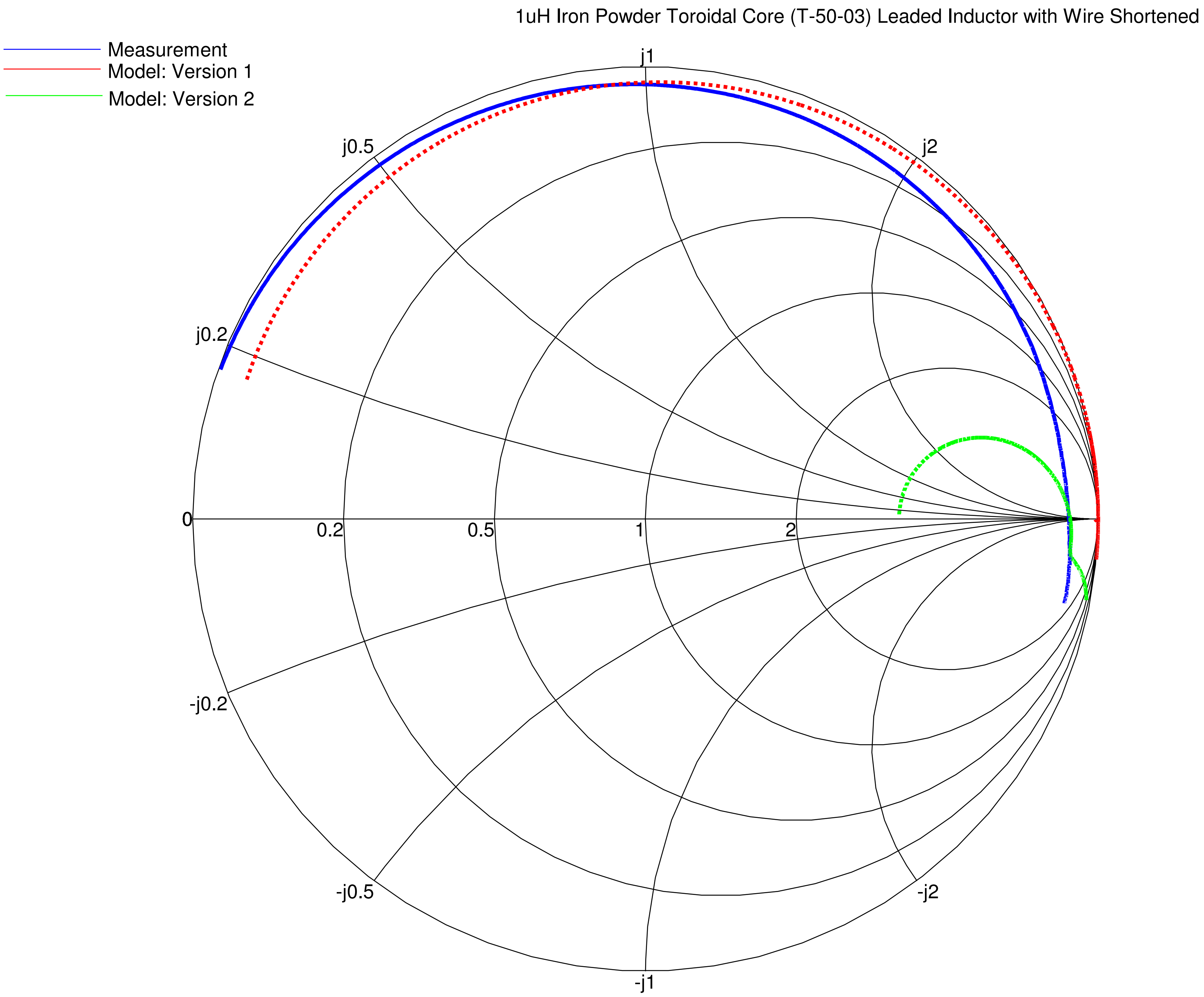
1uH Iron Powder Toroidal Core (T-50-03) Leaded Inductor with Wire Shortened (Linear-Scale) Version #2




1uH Iron Powder Toroidal Core (T-50-03) Leaded Inductor with Wire Shortened (Log-Scale) Version #1

1uH Iron Powder Toroidal Core (T-50-03) Leaded Inductor with Wire Shortened (Log-Scale) Version #2




1uH Iron Powder Toroidal Core (T-50-03) Leaded Inductor with Wire Shortened
Measurement
Model: Version 1
Model: Version 2
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

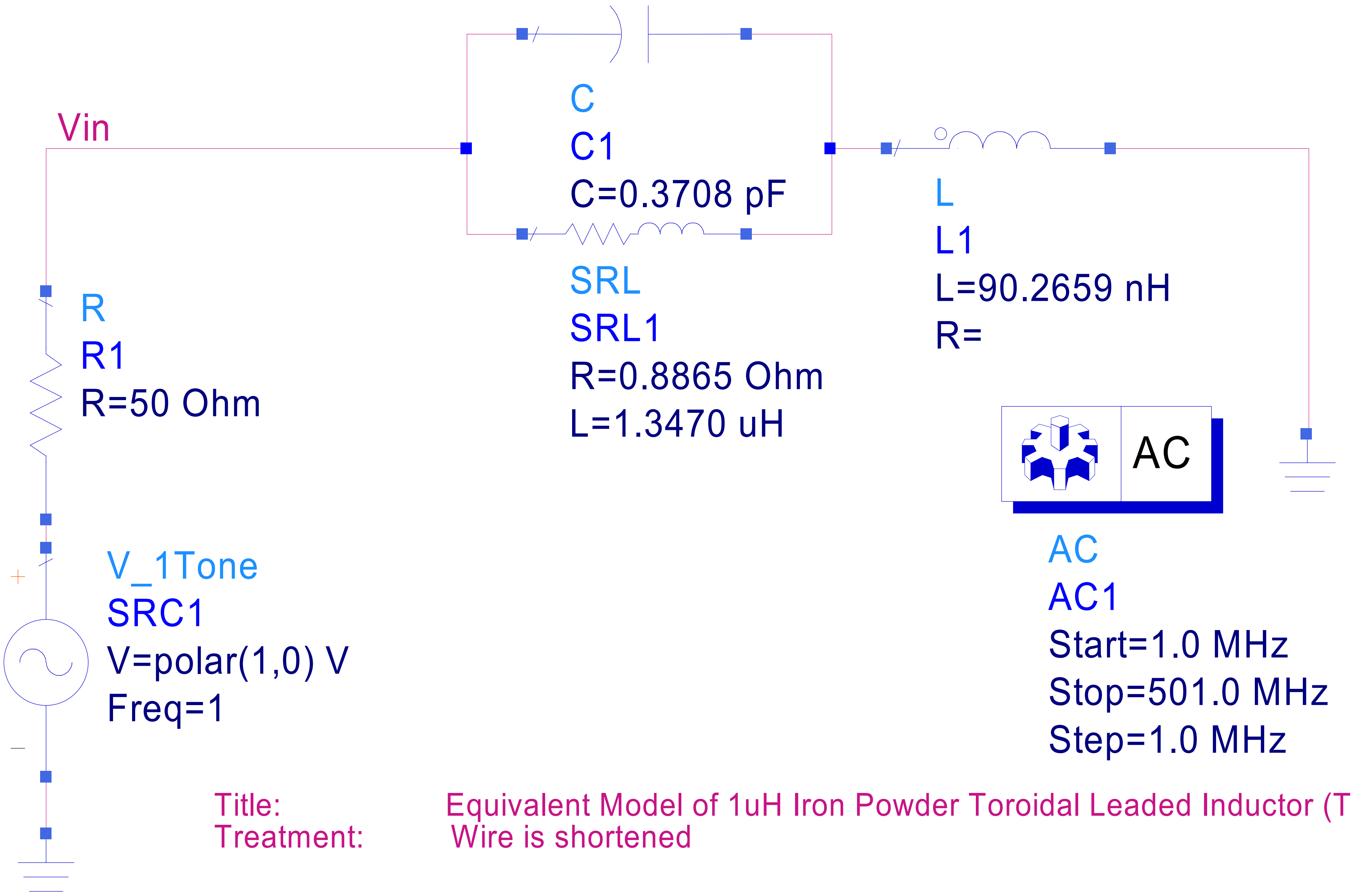
3.4.9 1μH Iron Powder Toroidal Leaded Inductor (T-50 #6)

The following is the picture of a 1μH Iron Powder Toroidal Leaded Inductor (T-50 #6)

Picture of a shortened wire inductor

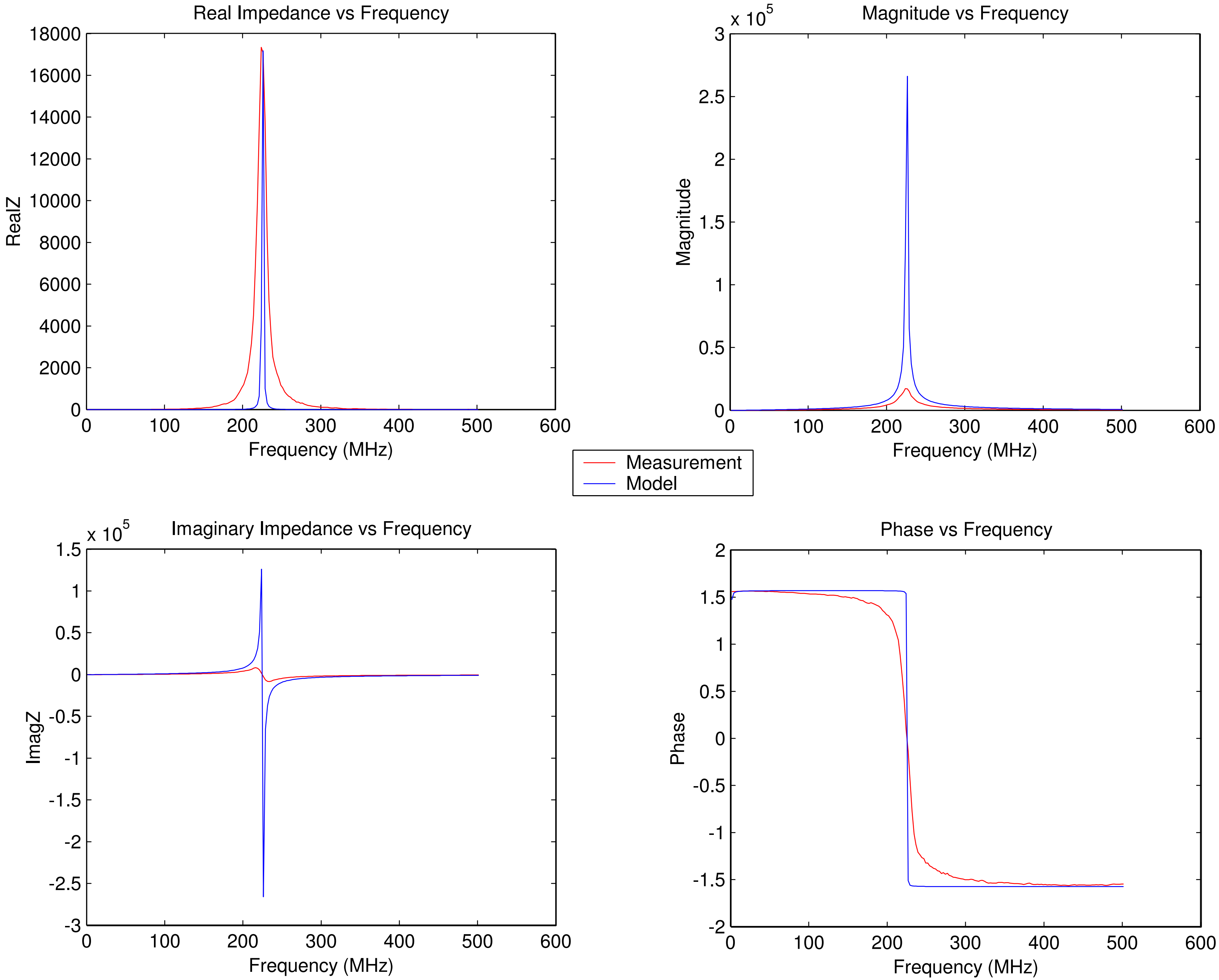
This table summarizes the measured data and simulation result.

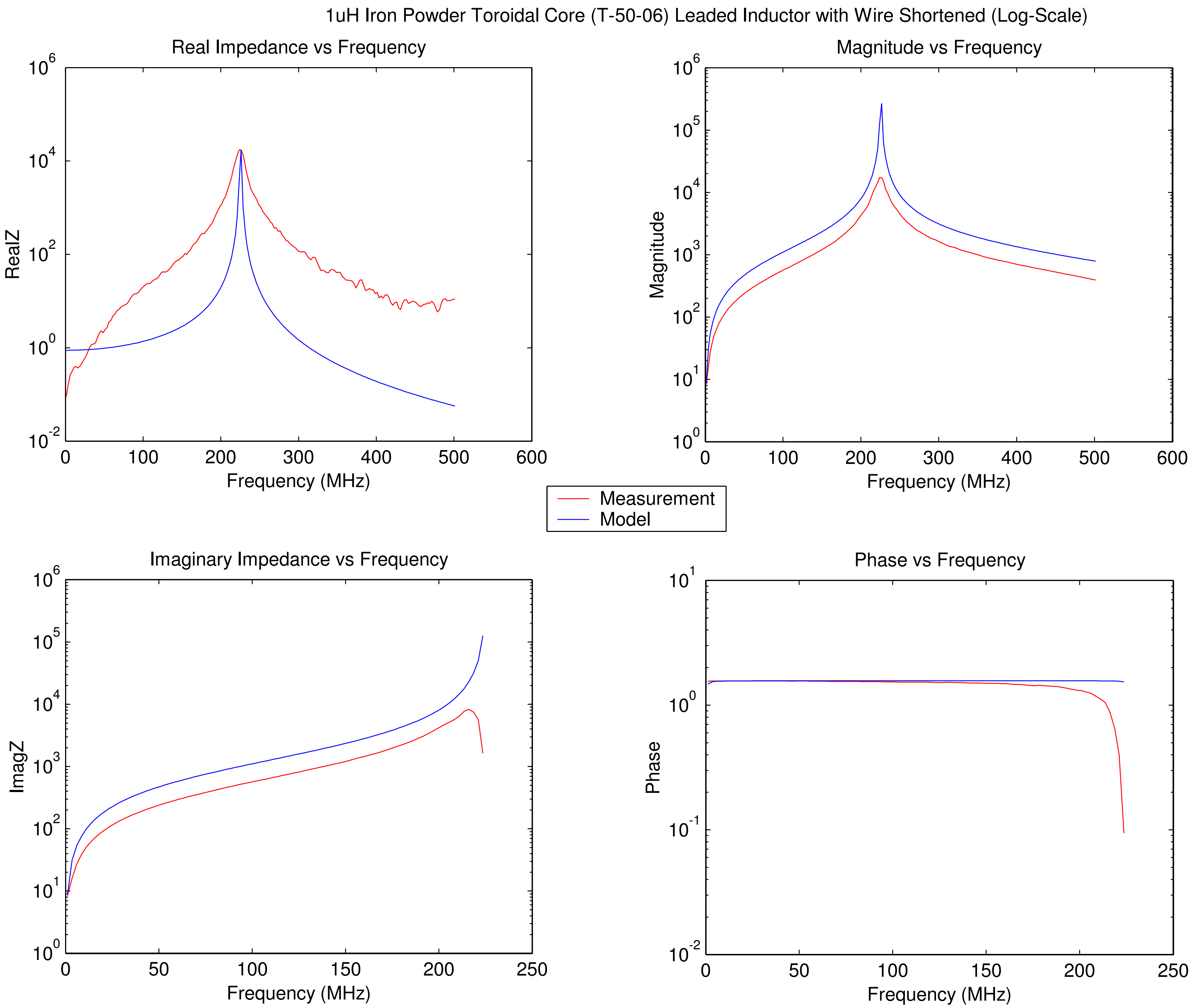
	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	0.0993
Internal Resistance of Model (Ω)	0.8865
Internal Inductance from estimation (μH)	1.3512
Internal Inductance of Model (μH)	1.3471
Internal Capacitance from estimation (pF)	0.3708
Internal Capacitance of Model (pF)	0.3708
External Inductance from estimation (nH)	5.4590
External Inductance of Model (nH)	90.2660
External Capacitance from estimation (pF)	0.0258
External Capacitance of Model (pF)	0.0000
Resonant Frequency (MHz)	224.8645
A_L	43
Number of turns from estimation	15.250
Number of turns	12
Legnth of Leaded Wire (mm)	3.5600
Distance between two wires (mm)	9.6500
Diameter of wire (mm)	0.4000
R-Square Value of Real Impedance	0.3845
R-Square Value of Imaginary Impedance	0.1490
R-Square Value of Magnitude	0.5598
R-Square Value of Phase	0.9790

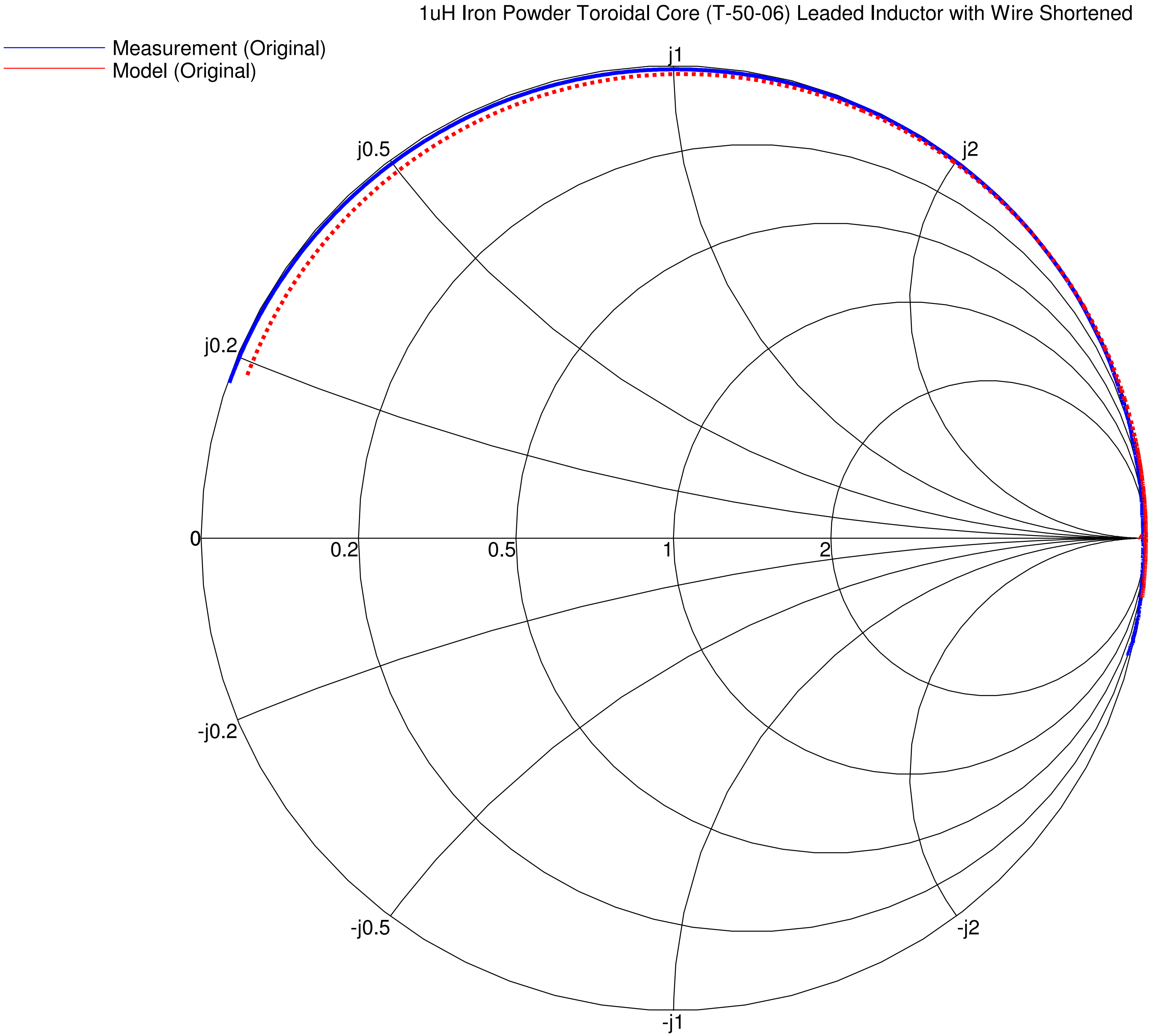


Title: Equivalent Model of 1uH Iron Powder Toroidal Leaded Inductor (T-50 #6)
Treatment: Wire is shortened

1uH Iron Powder Toroidal Core (T-50-06) Leaded Inductor with Wire Shortened (Linear-Scale)




1uH Iron Powder Toroidal Core (T-50-06) Leaded Inductor with Wire Shortened (Log-Scale)


1uH Iron Powder Toroidal Core (T-50-06) Leaded Inductor with Wire Shortened
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

3.4.10 1μH Iron Powder Toroidal Leaded Inductor (T-50 #7)

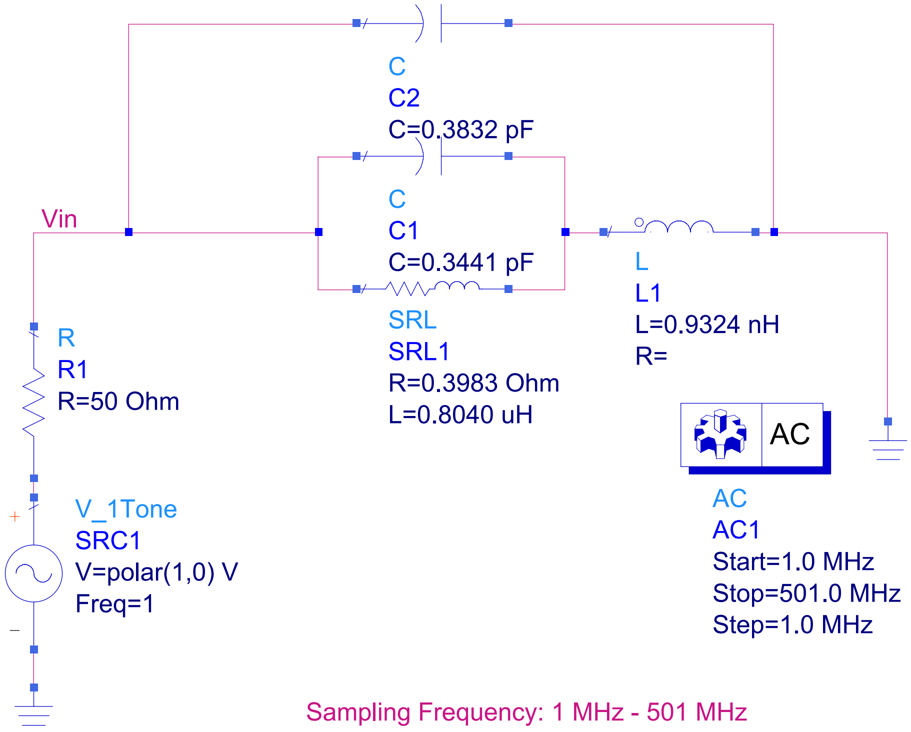
The following is the picture of a 1μH Iron Powder Toroidal Leaded Inductor (T-50 #7)

Picture of a shortened wire inductor

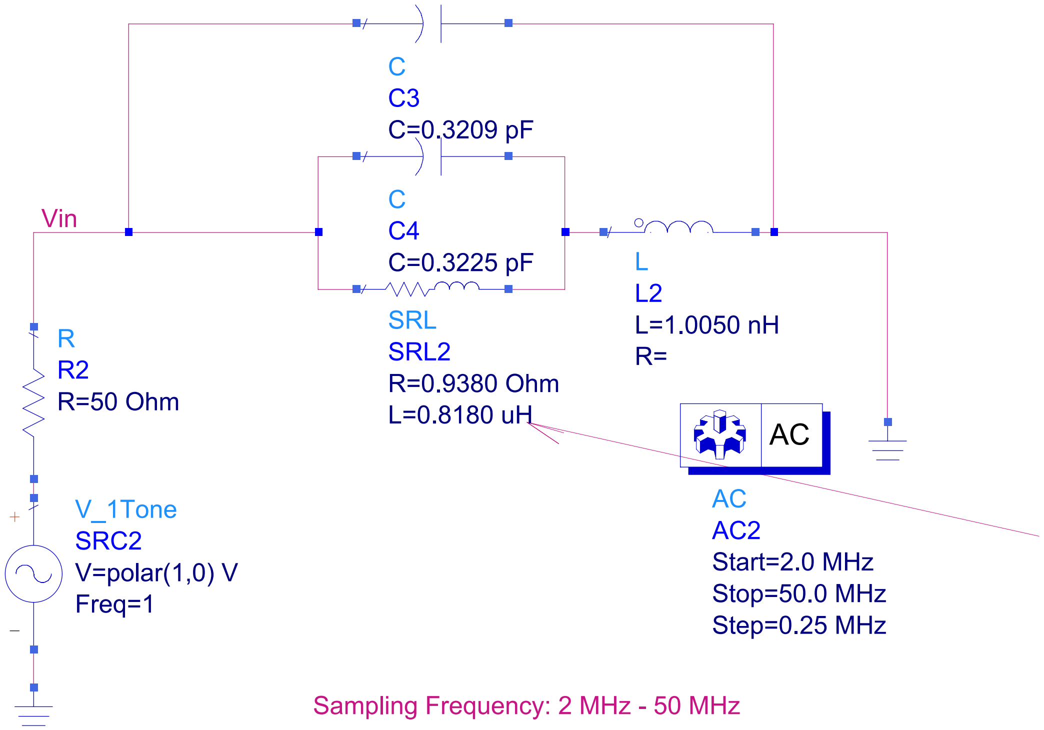
This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz	2 MHz - 50 MHz
Internal Resistance from estimation (Ω)	0.1209	0.1209
Internal Resistance of Model (Ω)	0.3983	0.9381
Internal Inductance from estimation (μH)	1.4925	1.4925
Internal Inductance of Model (μH)	0.8040	0.8180
Internal Capacitance from estimation (pF)	0.3913	0.3913
Internal Capacitance of Model (pF)	0.3441	0.3225
External Inductance from estimation (nH)	6.8600	6.8600
External Inductance of Model (nH)	0.9324	1.0051
External Capacitance from estimation (pF)	0.0280	0.0280
External Capacitance of Model (pF)	0.3832	0.3209
Resonant Frequency (MHz)	208.2628	208.2628
A_L	40	40
Number of turns from estimation	15.811	15.811
Number of turns	12	12
Legnth of Leaded Wire (mm)	4.1600	4.1600
Distance between two wires (mm)	12.1100	12.1100
Diameter of wire (mm)	0.3800	0.3800
R-Square Value of Real Impedance	0.1708	0.9799
R-Square Value of Imaginary Impedance	0.0234	1.0000
R-Square Value of Magnitude	0.2532	1.0000
R-Square Value of Phase	0.9719	0.9748

Equivalent Model of 1uH Iron Powder Toroidal Leaded Inductor (T-50 #7)

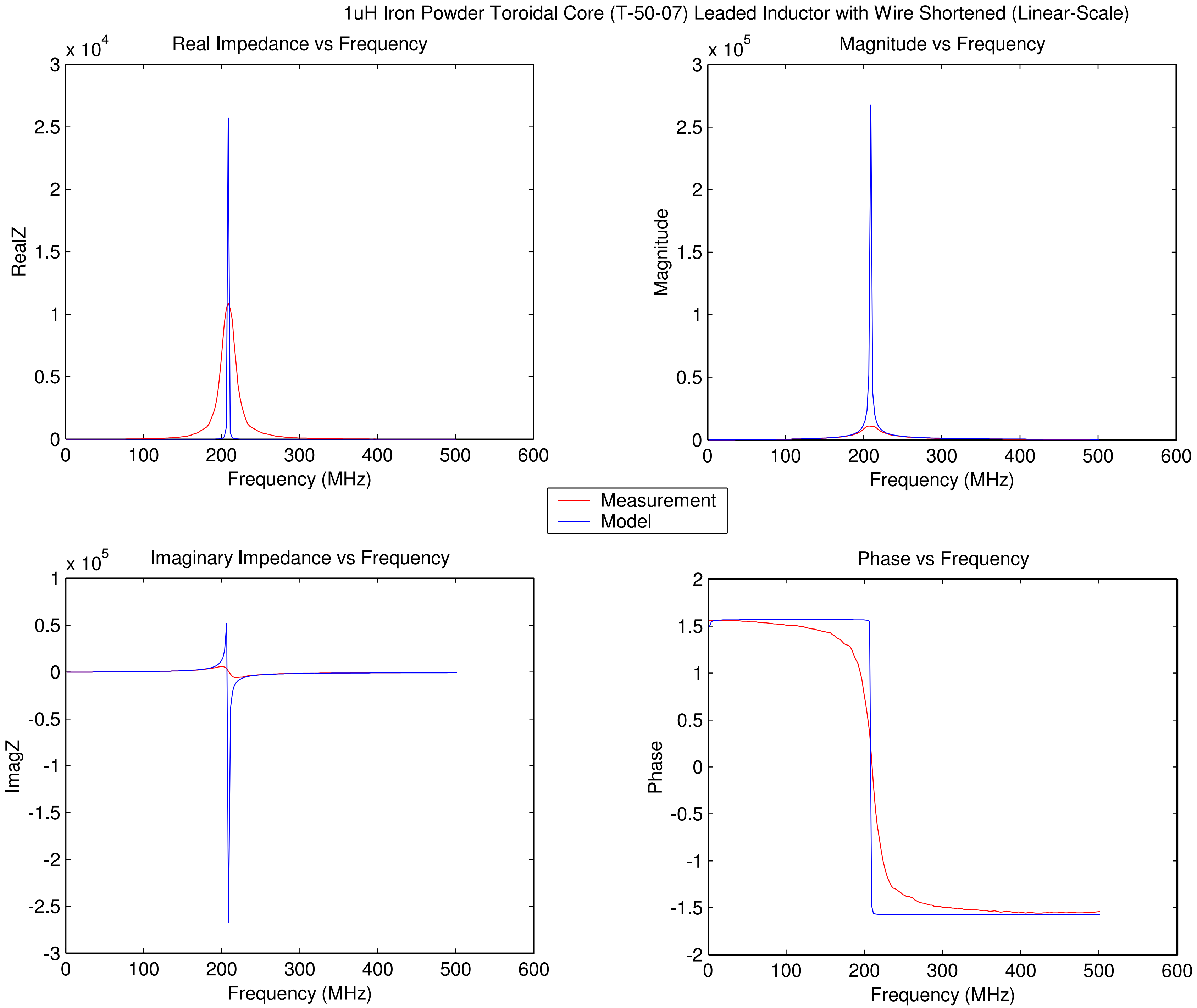


Sampling Frequency: 1 MHz - 501 MHz

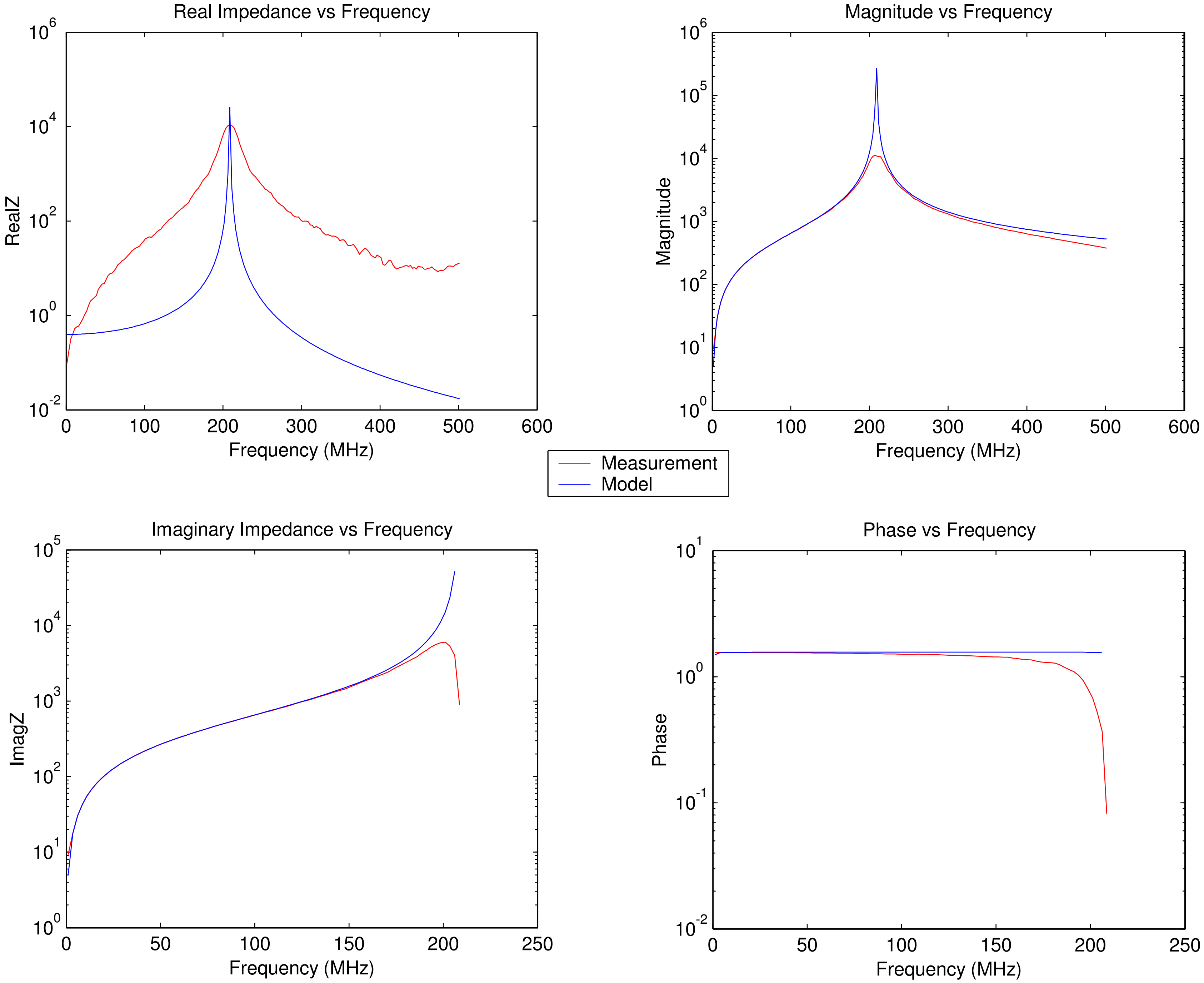


Closed to the goal: 1 uH

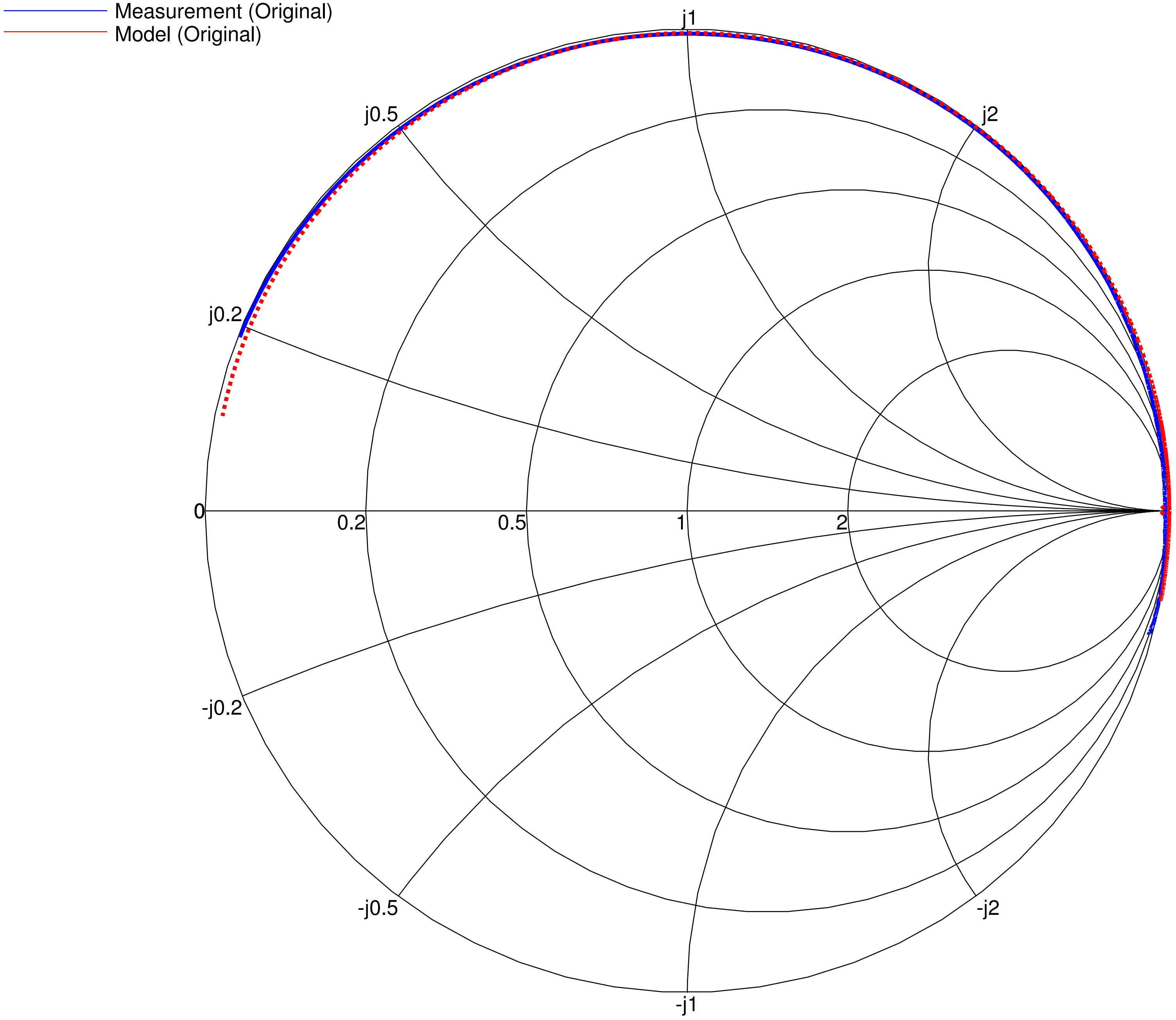
Sampling Frequency: 2 MHz - 50 MHz

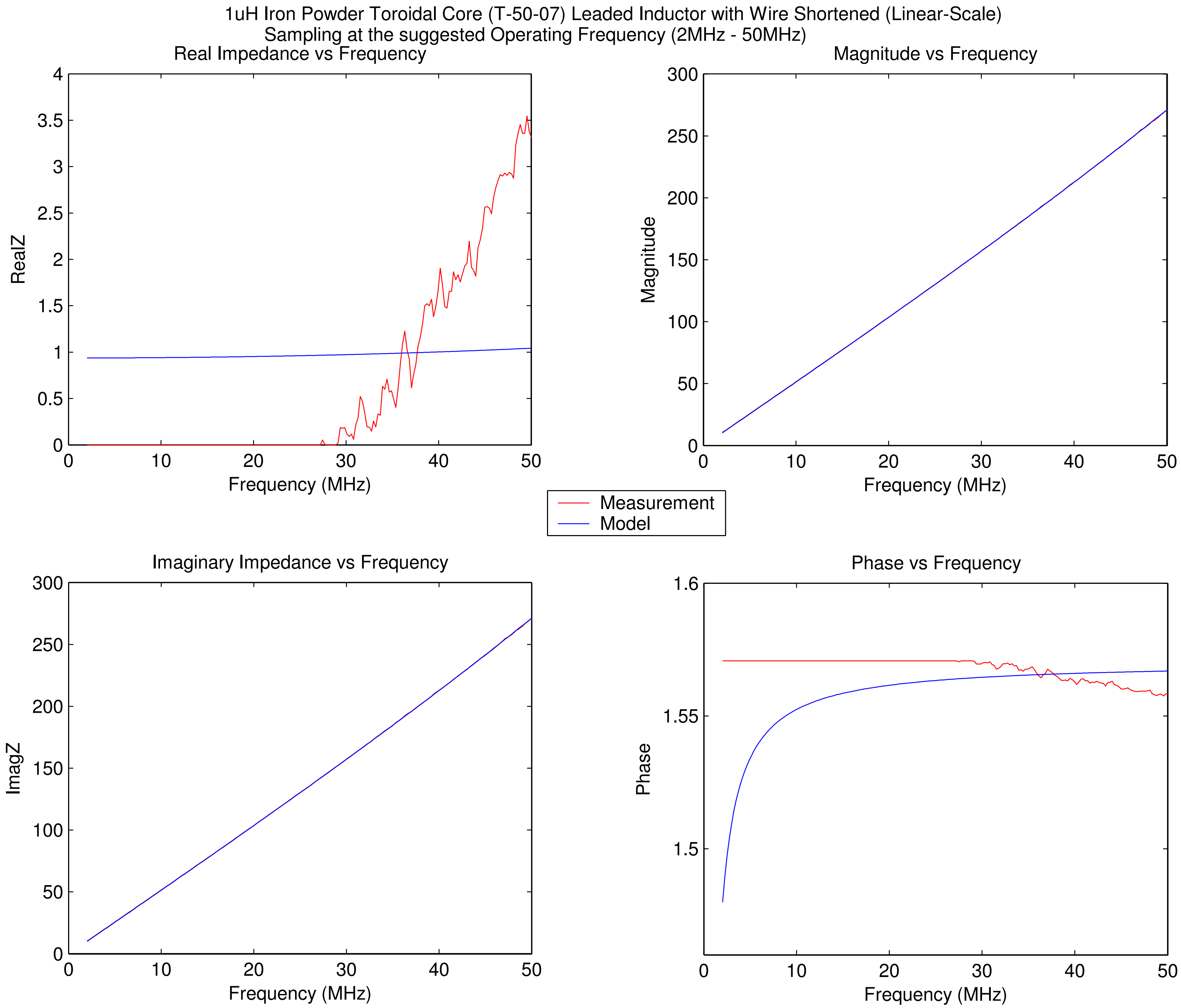

1uH Iron Powder Toroidal Core (T-50-07) Leaded Inductor with Wire Shortened (Linear-Scale)
Real Impedance vs Frequency
x 10^4
RealZ
3
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
x 10^5
Magnitude
3
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement
Model
Imaginary Impedance vs Frequency
x 10^5
ImagZ
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)

1uH Iron Powder Toroidal Core (T-50-07) Leaded Inductor with Wire Shortened (Log-Scale)



1uH Iron Powder Toroidal Core (T-50-07) Leaded Inductor with Wire Shortened





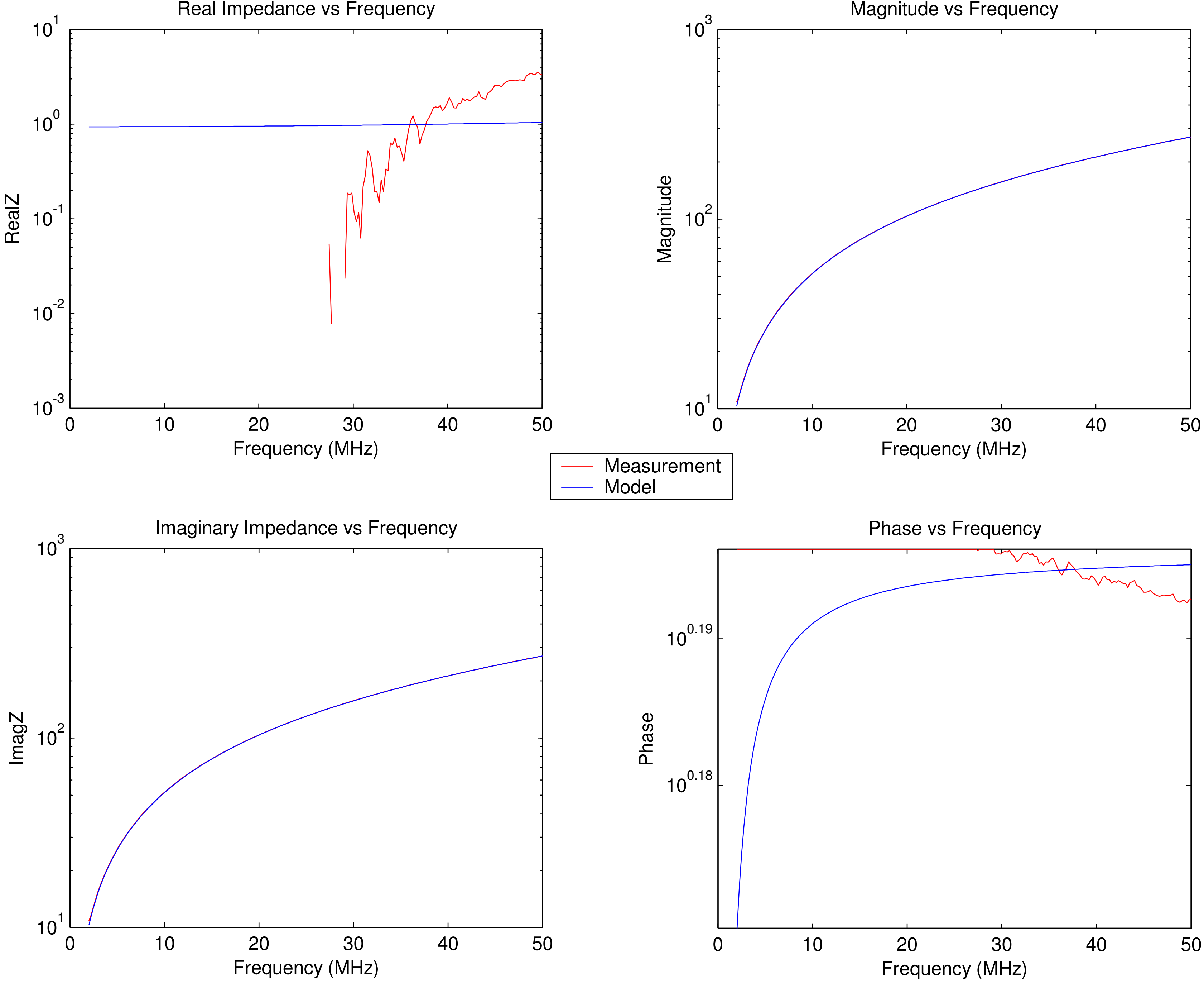
1uH Iron Powder Toroidal Core (T-50-07) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (2MHz - 50MHz)

Real Impedance vs Frequency

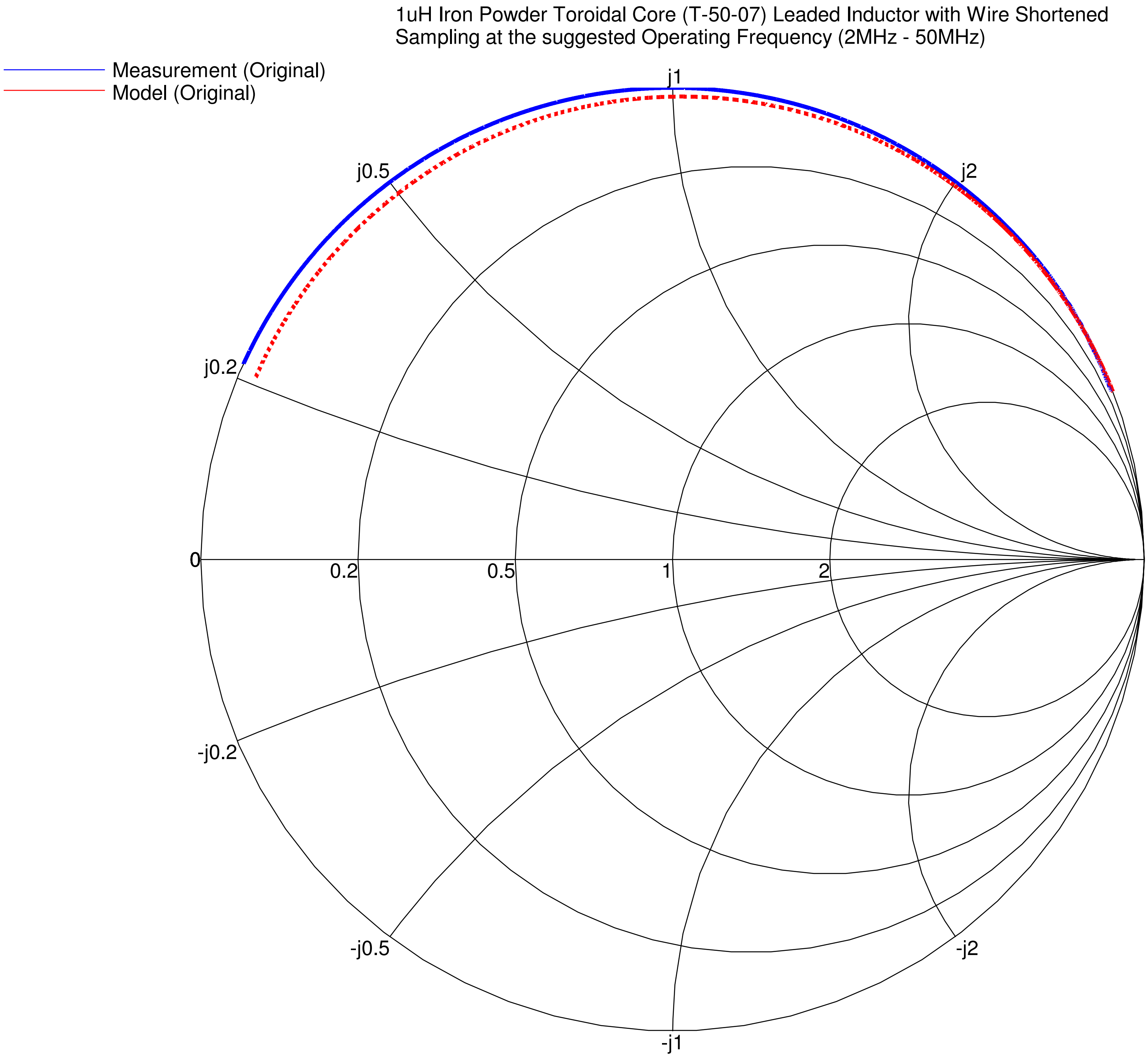
Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency



1uH Iron Powder Toroidal Core (T-50-07) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (2MHz - 50MHz)



1uH Iron Powder Toroidal Core (T-50-07) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (2MHz - 50MHz)

3.4.11 1μH Iron Powder Toroidal Leaded Inductor (T-50 #10)

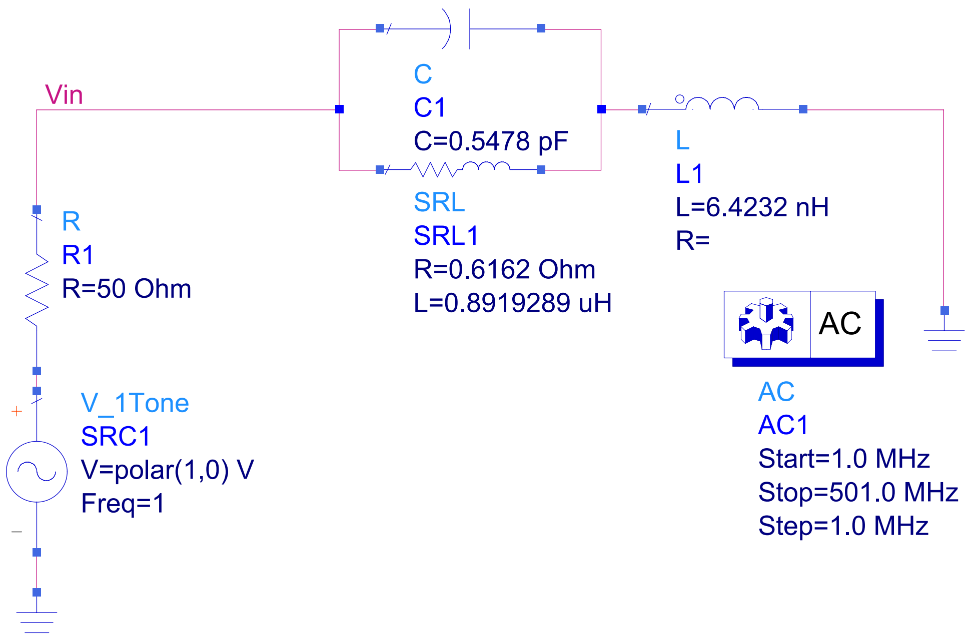
The following is the picture of a 1μH Iron Powder Toroidal Leaded Inductor (T-50 #10)

Picture of a shortened wire inductor

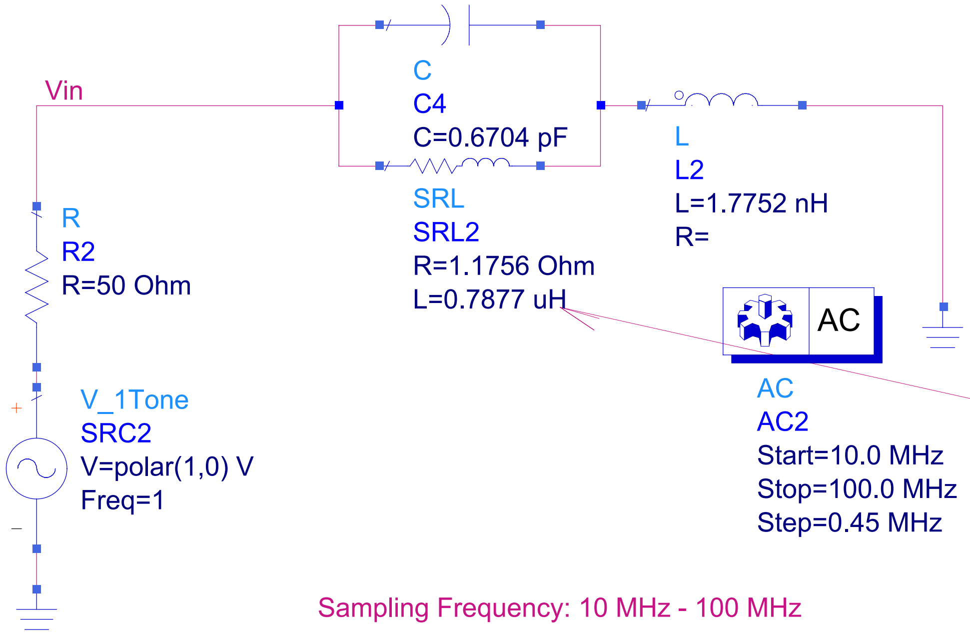
This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz	10 MHz - 100 MHz
Internal Resistance from estimation (Ω)	0.1211	0.1211
Internal Resistance of Model (Ω)	0.6162	1.1757
Internal Inductance from estimation (μH)	1.4868	1.4868
Internal Inductance of Model (μH)	0.8919	0.7878
Internal Capacitance from estimation (pF)	0.3445	0.3445
Internal Capacitance of Model (pF)	0.5478	0.6705
External Inductance from estimation (nH)	7.2469	7.2469
External Inductance of Model (nH)	6.4232	1.7752
External Capacitance from estimation (pF)	0.0251	0.0251
External Capacitance of Model (pF)	0.0000	0.0000
Resonant Frequency (MHz)	222.3684	222.3684
A_L	31	31
Number of turns from estimation	17.961	17.961
Number of turns	14	14
Legnth of Leaded Wire (mm)	4.0500	4.0500
Distance between two wires (mm)	16.1400	16.1400
Diameter of wire (mm)	0.3600	0.3600
R-Square Value of Real Impedance	0.2593	0.9681
R-Square Value of Imaginary Impedance	0.1900	1.0000
R-Square Value of Magnitude	0.5262	1.0000
R-Square Value of Phase	0.9772	0.3396

Equivalent Model of 1uH Iron Powder Toroidal Leaded Inductor (T-50 #10)

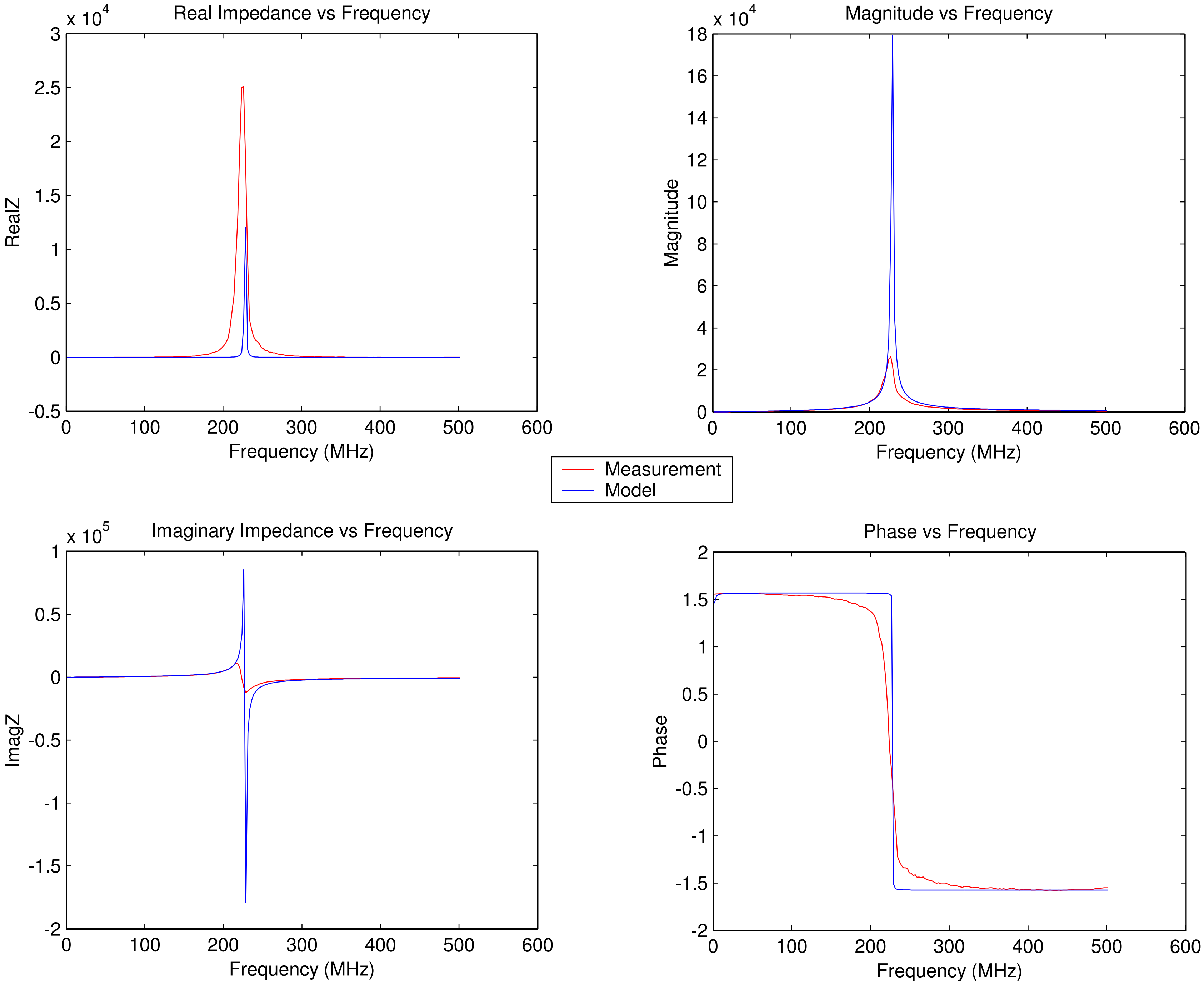


Sampling Frequency: 1 MHz - 501 MHz

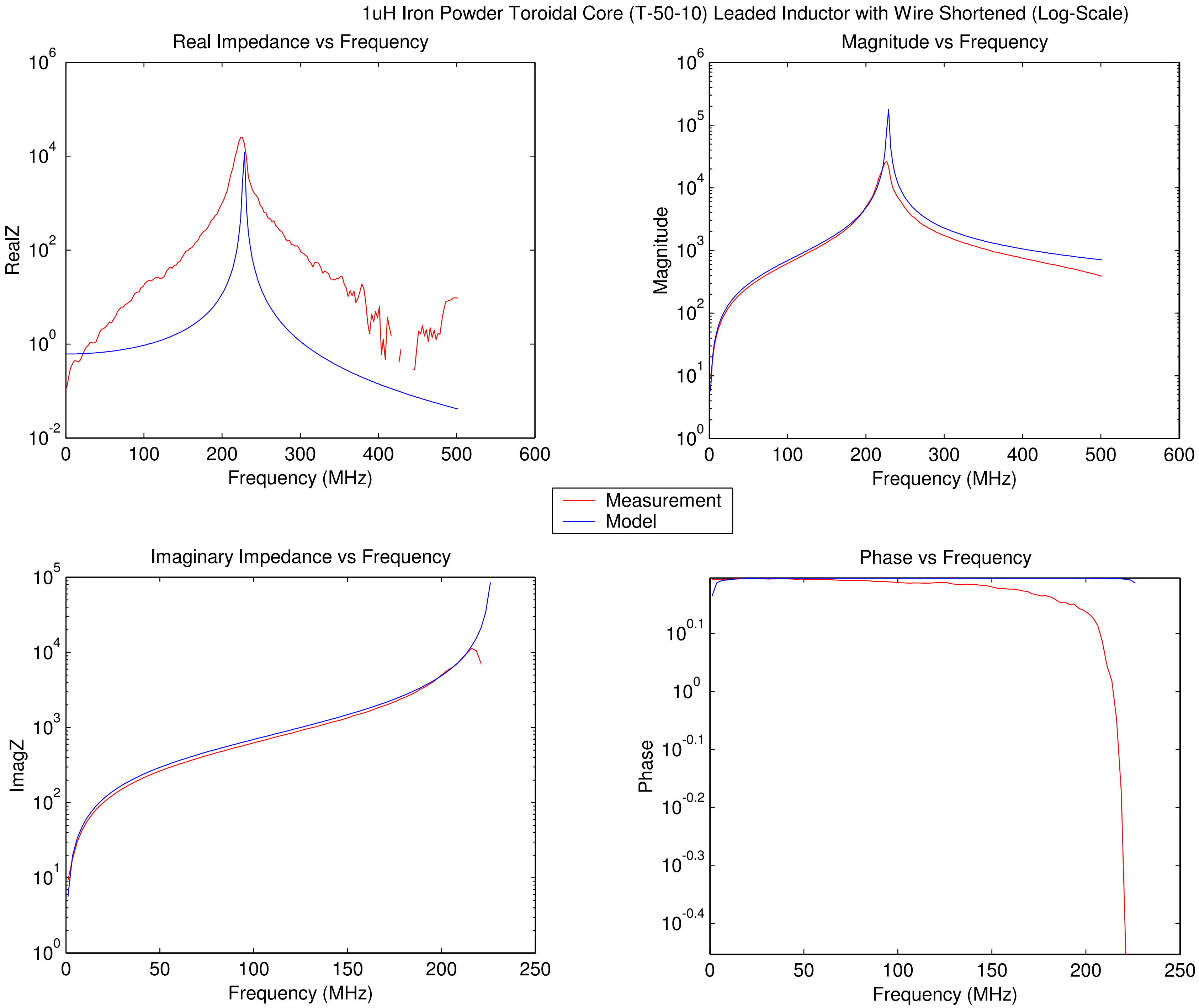


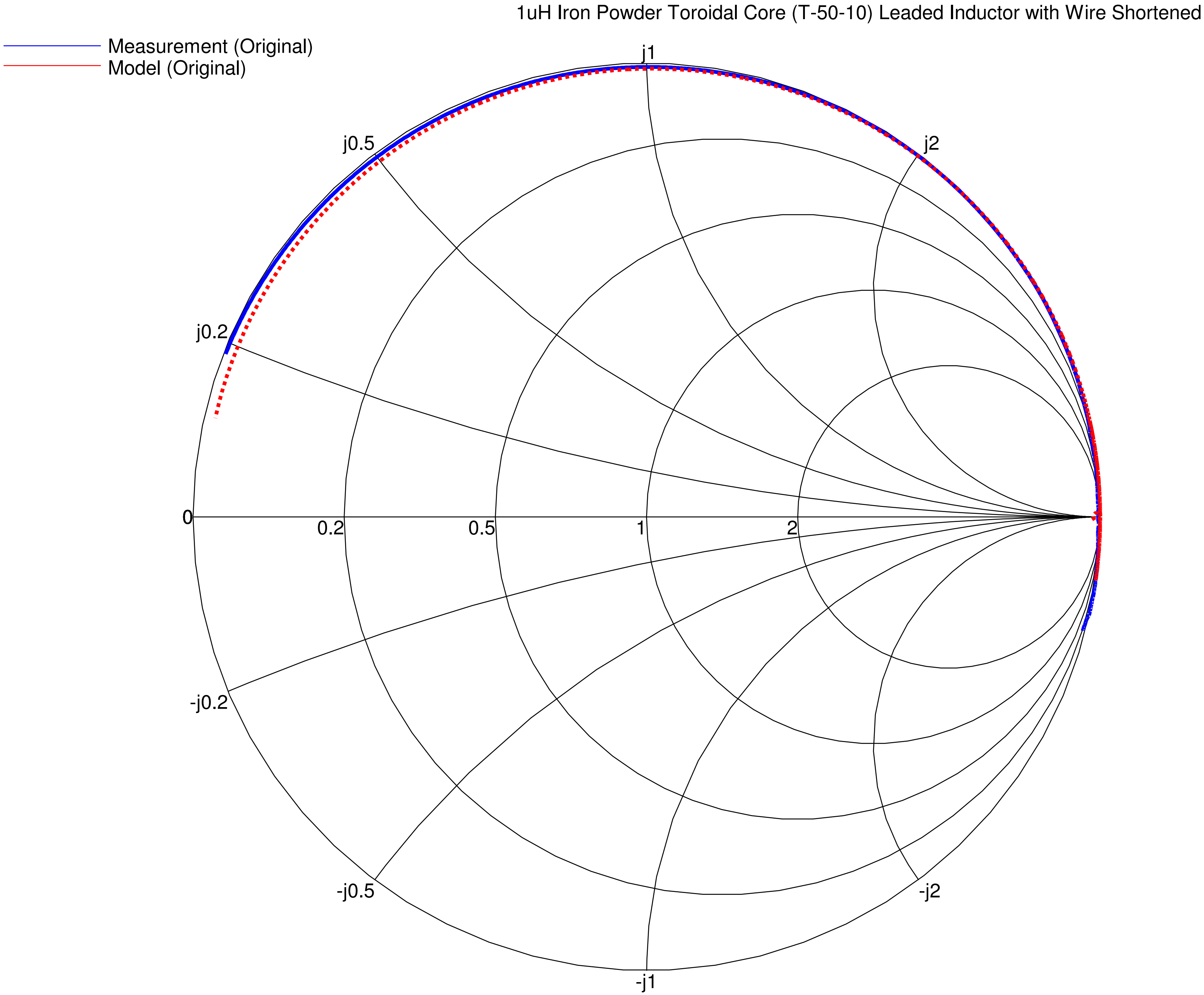
Closed to the goal: 1 uH

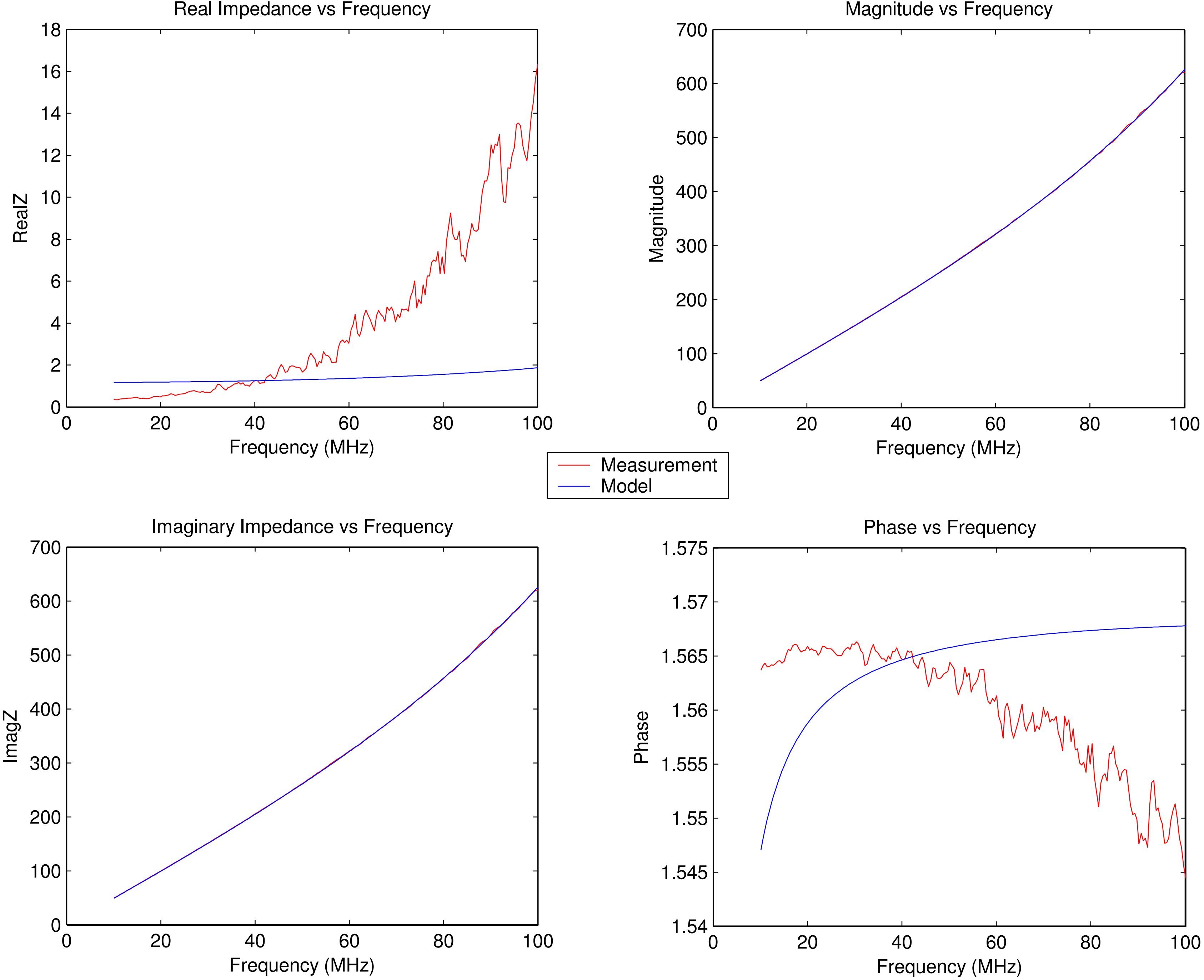
Sampling Frequency: 10 MHz - 100 MHz



1uH Iron Powder Toroidal Core (T-50-10) Leaded Inductor with Wire Shortened (Linear-Scale)

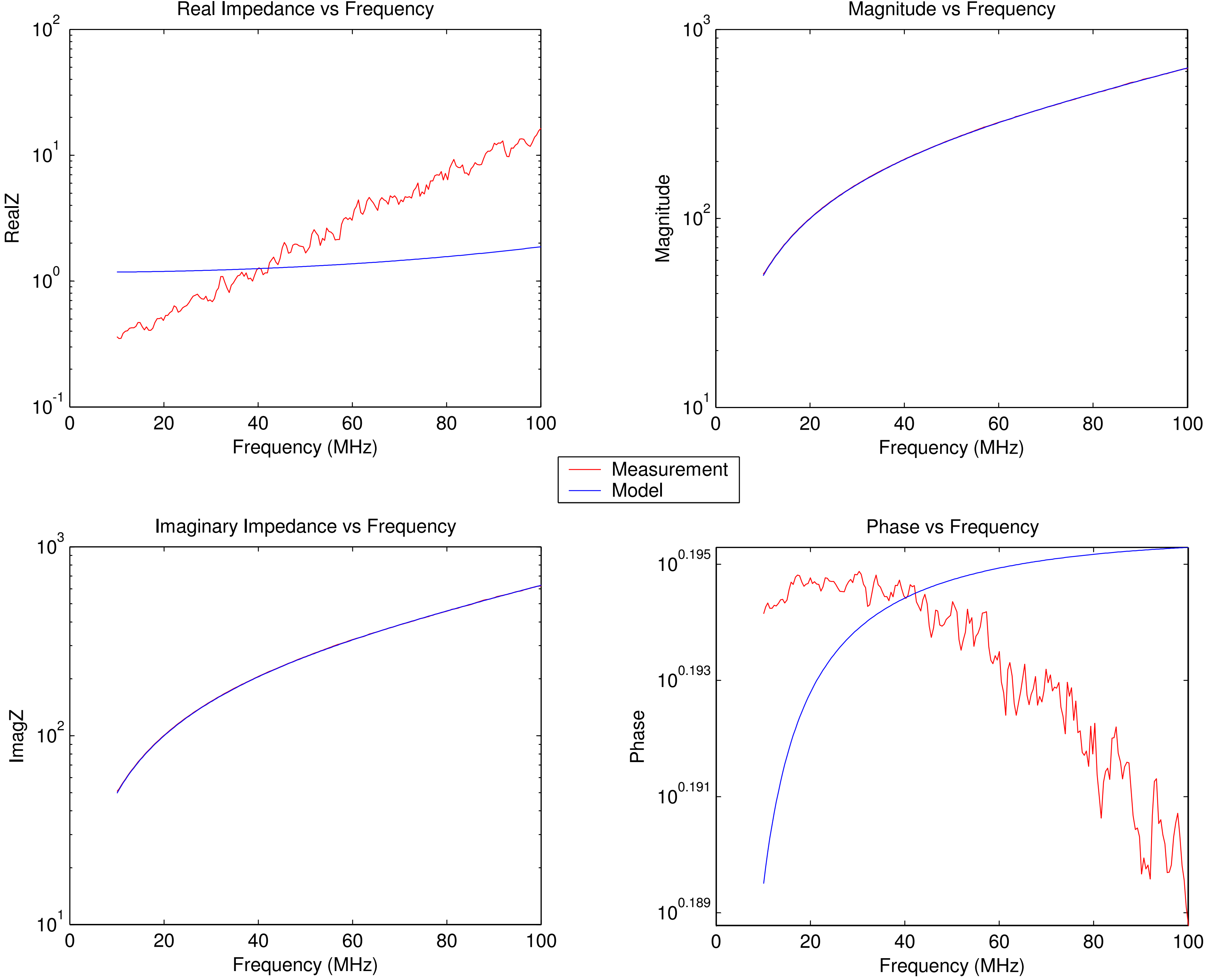

1uH Iron Powder Toroidal Core (T-50-10) Leaded Inductor with Wire Shortened (Log-Scale)
Real Impedance vs Frequency
RealZ
10^6
10^4
10^2
10^0
10^{-2}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement
Model
Imaginary Impedance vs Frequency
ImagZ
10^5
10^4
10^3
10^2
10^1
10^0
0
50
100
150
200
250
Frequency (MHz)
Phase vs Frequency
Phase
$10^{0.1}$
10^0
$10^{-0.1}$
$10^{-0.2}$
$10^{-0.3}$
$10^{-0.4}$
0
50
100
150
200
250
Frequency (MHz)

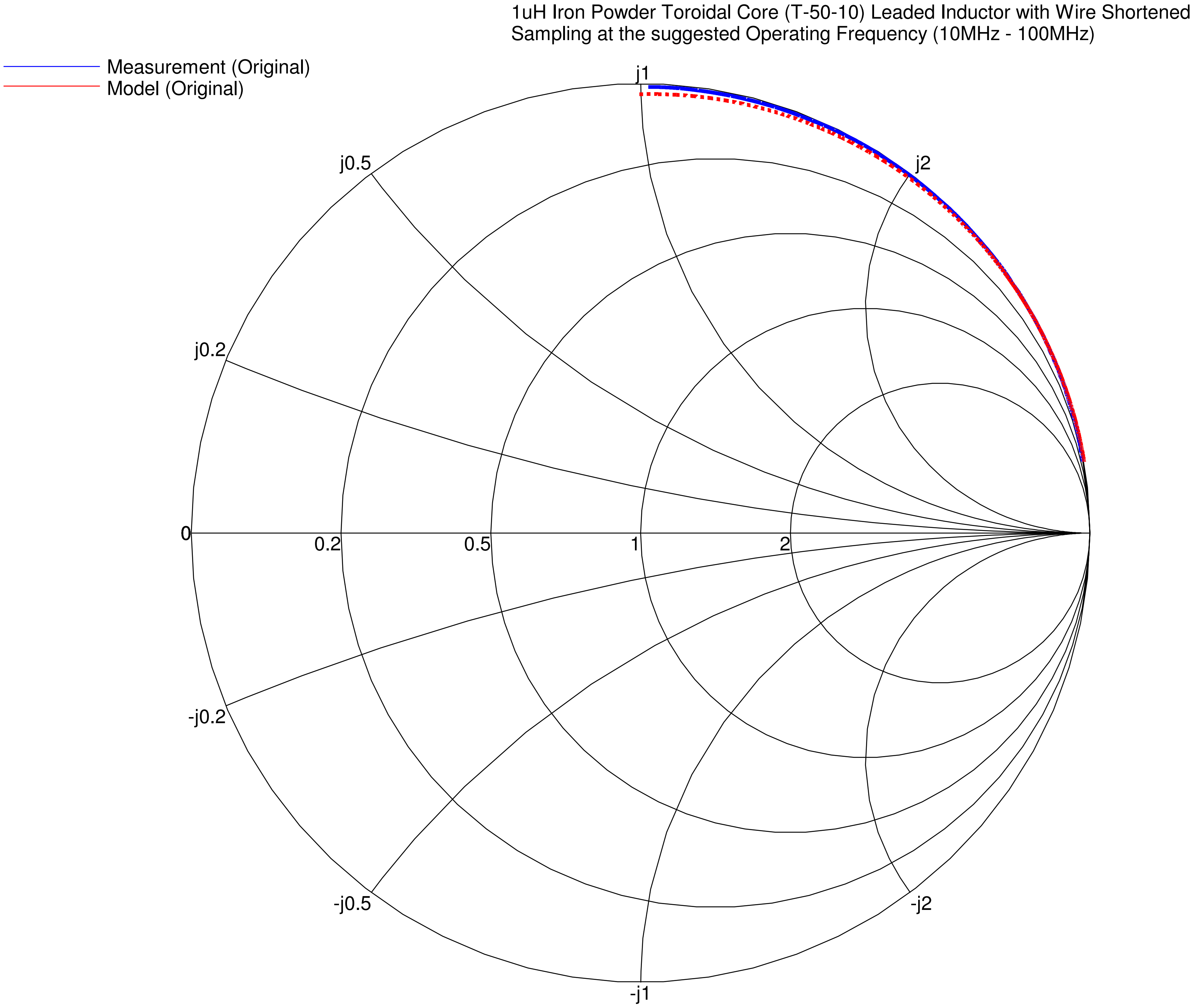

1uH Iron Powder Toroidal Core (T-50-10) Leaded Inductor with Wire Shortened
Measurement (Original)
Model (Original)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1



1uH Iron Powder Toroidal Core (T-50-10) Leaded Inductor with Wire Shortened (Linear-Scale)
Sampling at the suggested Operating Frequency (10MHz - 100MHz)

1uH Iron Powder Toroidal Core (T-50-10) Leaded Inductor with Wire Shortened (Log-Scale)
Sampling at the suggested Operating Frequency (10MHz - 100MHz)





1uH Iron Powder Toroidal Core (T-50-10) Leaded Inductor with Wire Shortened
Sampling at the suggested Operating Frequency (10MHz - 100MHz)

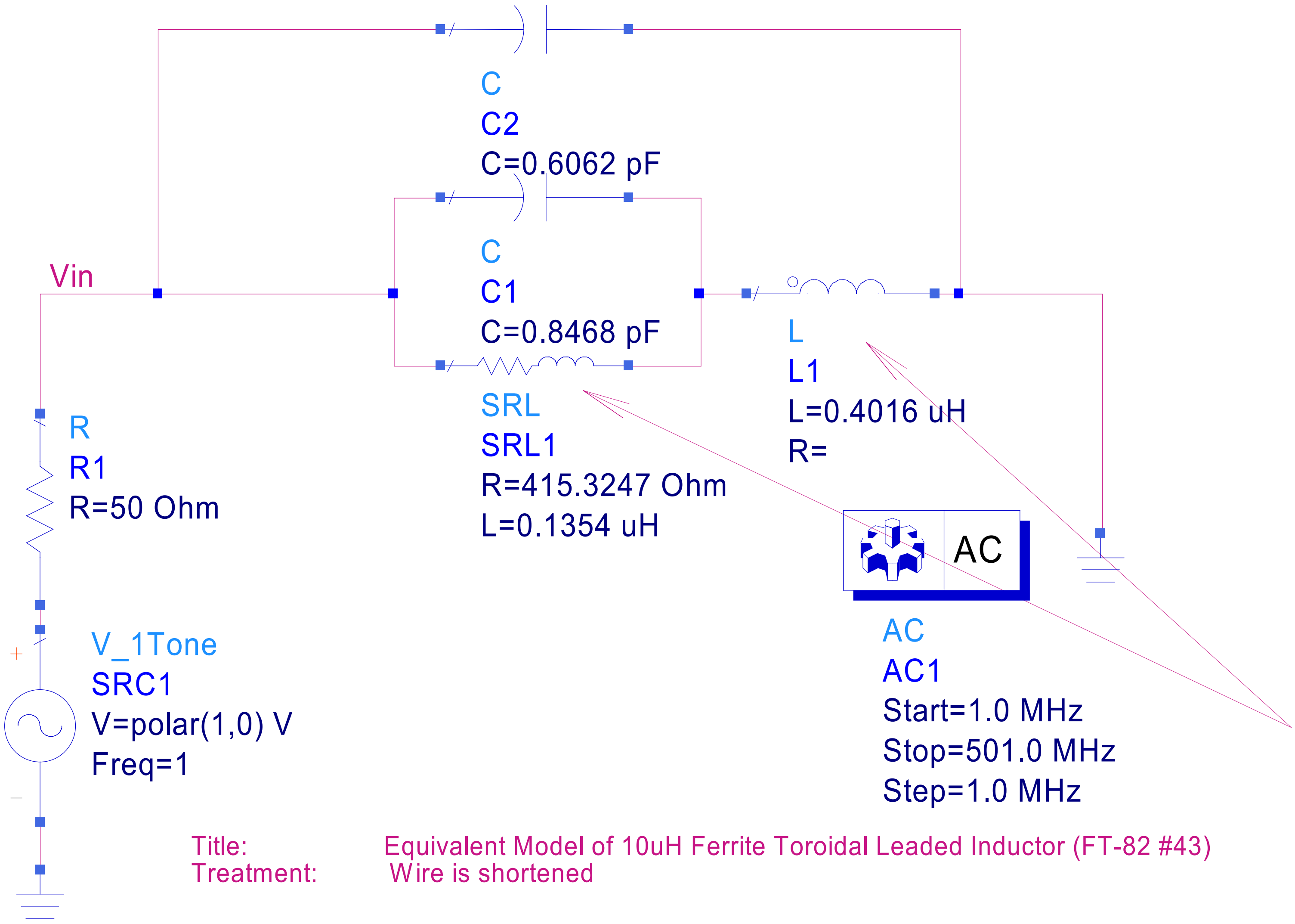
3.4.12 10μH Iron Powder Toroidal Leaded Inductor (FT-82 #43)

The following is the picture of a 10μH Iron Powder Toroidal Leaded Inductor (FT-82 #43)

Picture of a shortened wire inductor

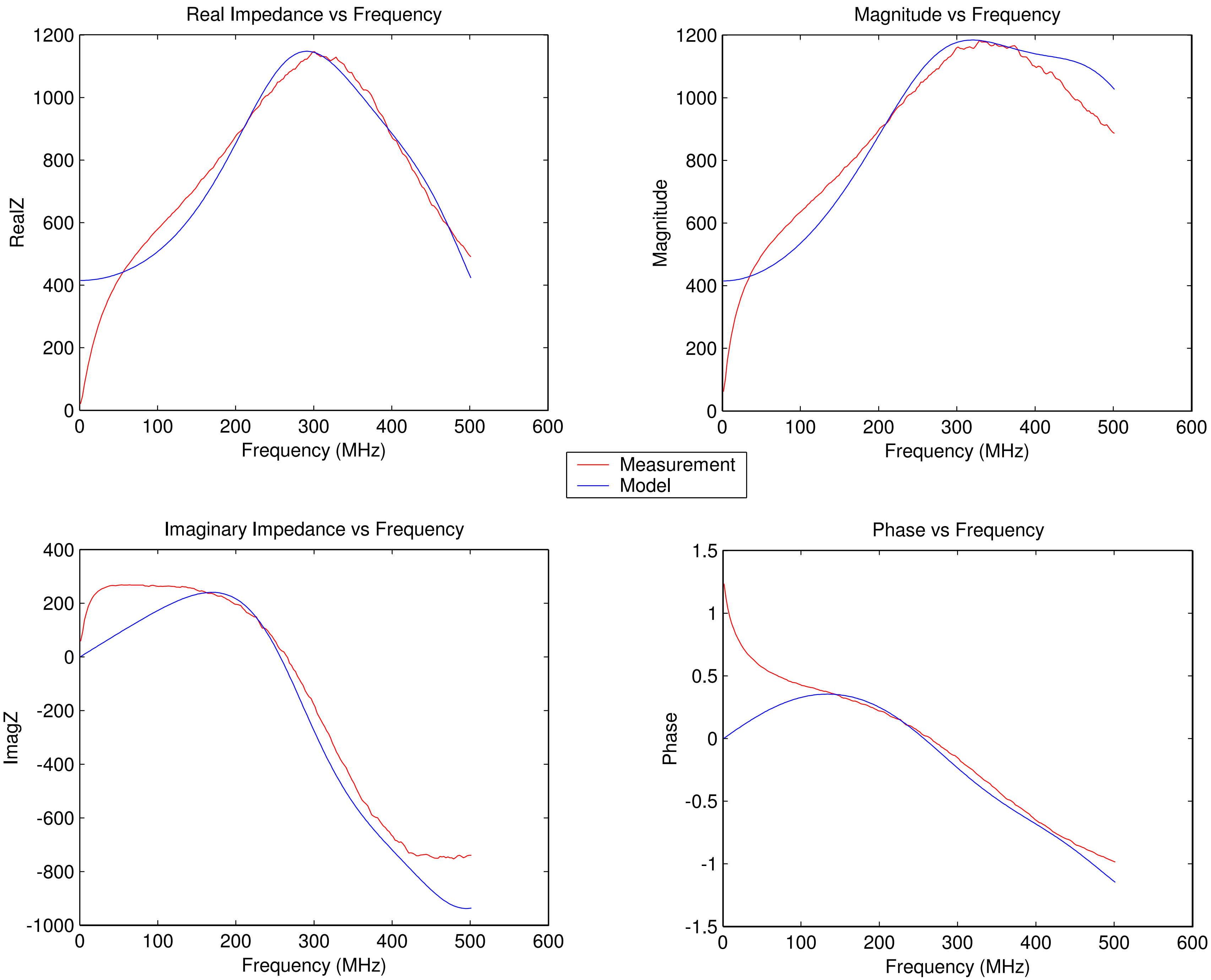
This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	21.4030
Internal Resistance of Model (Ω)	415.3247
Internal Inductance from estimation (μH)	9.4573
Internal Inductance of Model (μH)	0.1354
Internal Capacitance from estimation (pF)	0.0371
Internal Capacitance of Model (pF)	0.8468
External Inductance from estimation (nH)	9.2001
External Inductance of Model (nH)	401.6431
External Capacitance from estimation (pF)	0.0313
External Capacitance of Model (pF)	0.6062
Resonant Frequency (MHz)	268.6960
A_L	557
Number of turns from estimation	4.2371
Number of turns	4
Legnth of Leaded Wire (mm)	5.0900
Distance between two wires (mm)	17.3400
Diameter of wire (mm)	0.3700
R-Square Value of Real Impedance	0.9230
R-Square Value of Imaginary Impedance	0.9778
R-Square Value of Magnitude	0.9191
R-Square Value of Phase	0.8481

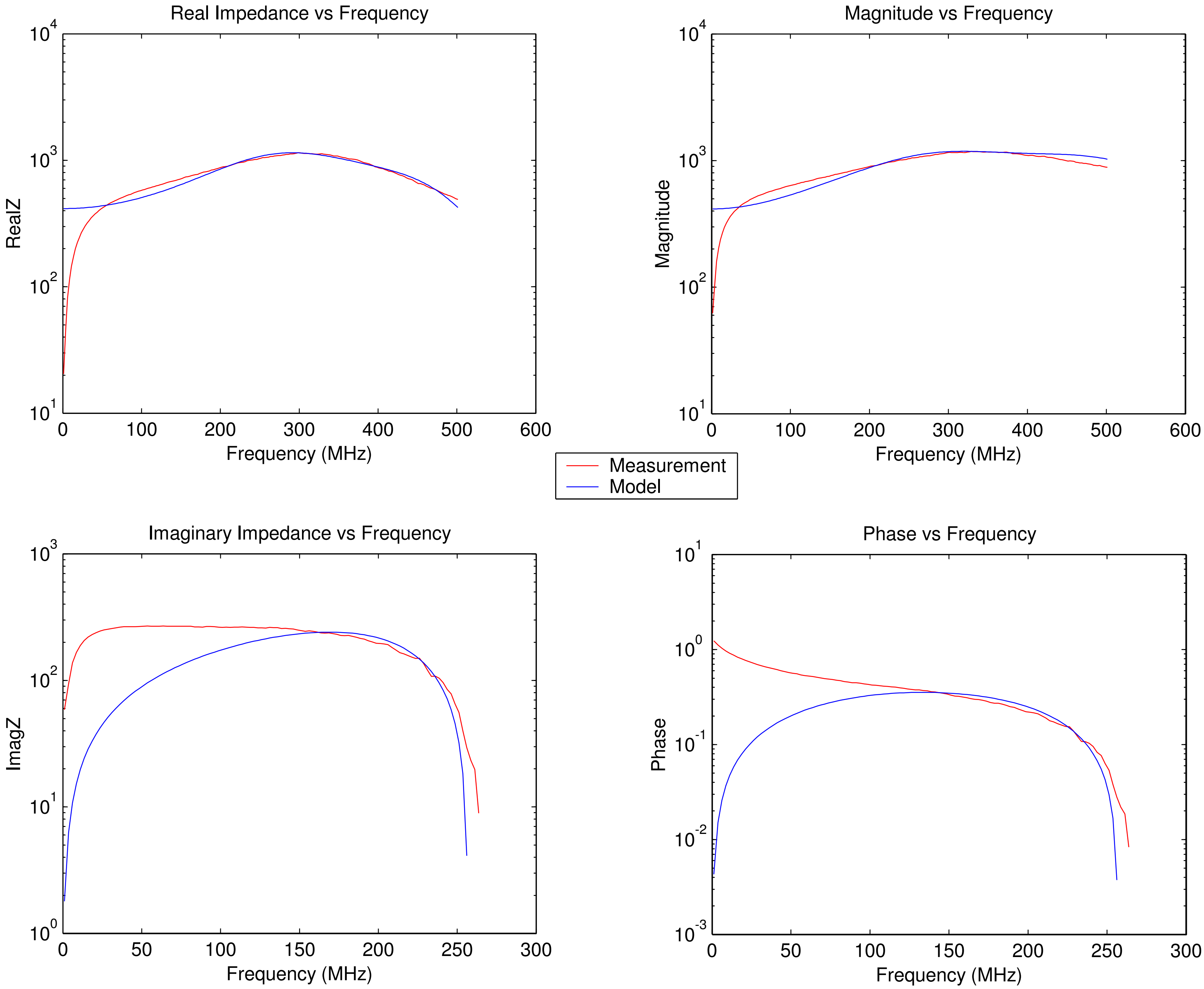


Sum of two inductance values
= 0.50 uH

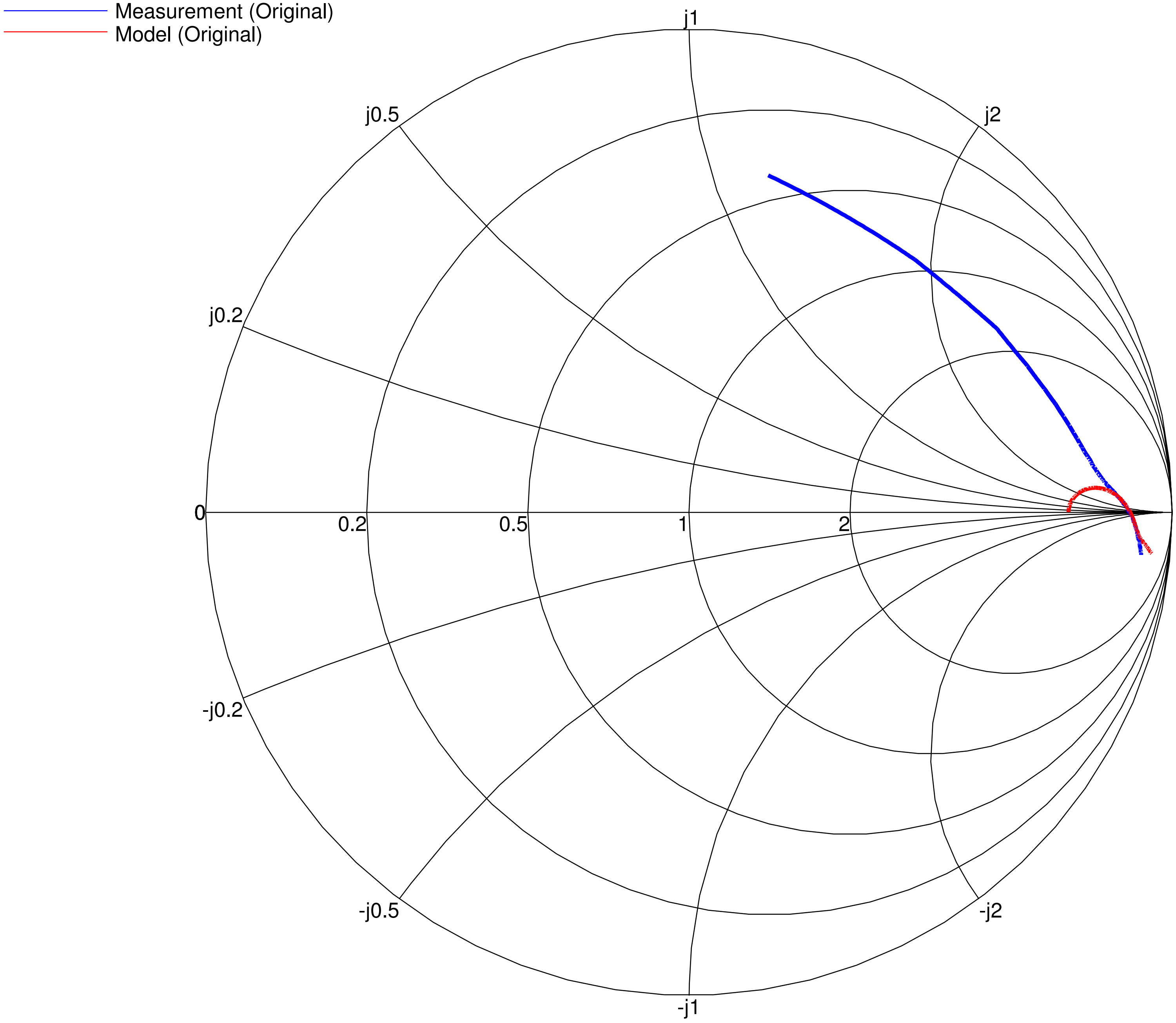
Title: Equivalent Model of 10uH Ferrite Toroidal Leaded Inductor (FT-82 #43)
Treatment: Wire is shortened



10uH Ferrite Toroidal Core (FT-82-43) Leaded Inductor with Wire Shortened (Linear-Scale)


10uH Ferrite Toroidal Core (FT-82-43) Leaded Inductor with Wire Shortened (Log-Scale)

10uH Ferrite Toroidal Core (FT-82-43) Leaded Inductor with Wire Shortened



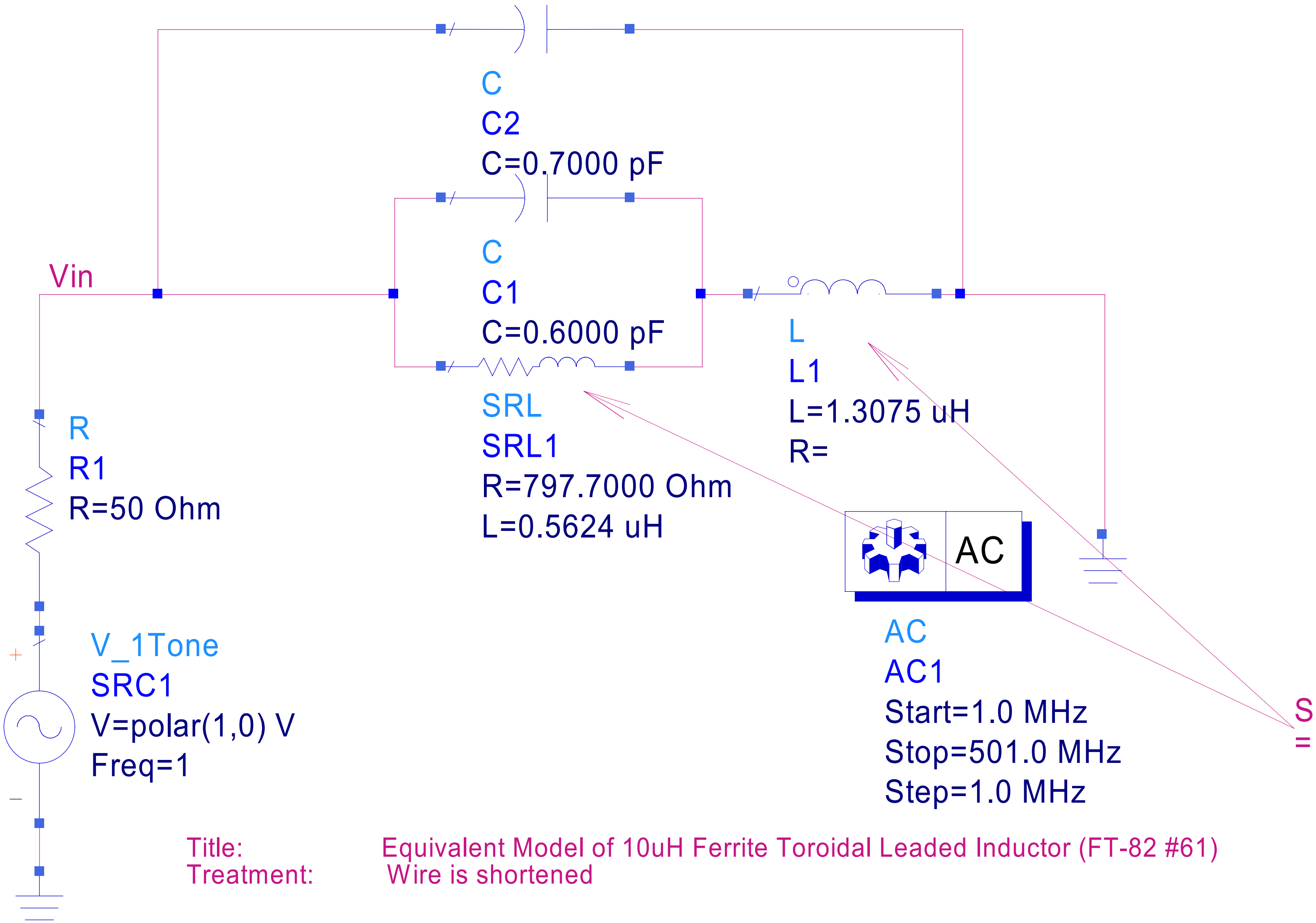
3.4.13 10μH Iron Powder Toroidal Leaded Inductor (FT-82 #61)

The following is the picture of a 10μH Iron Powder Toroidal Leaded Inductor (FT-82 #61)

Picture of a shortened wire inductor

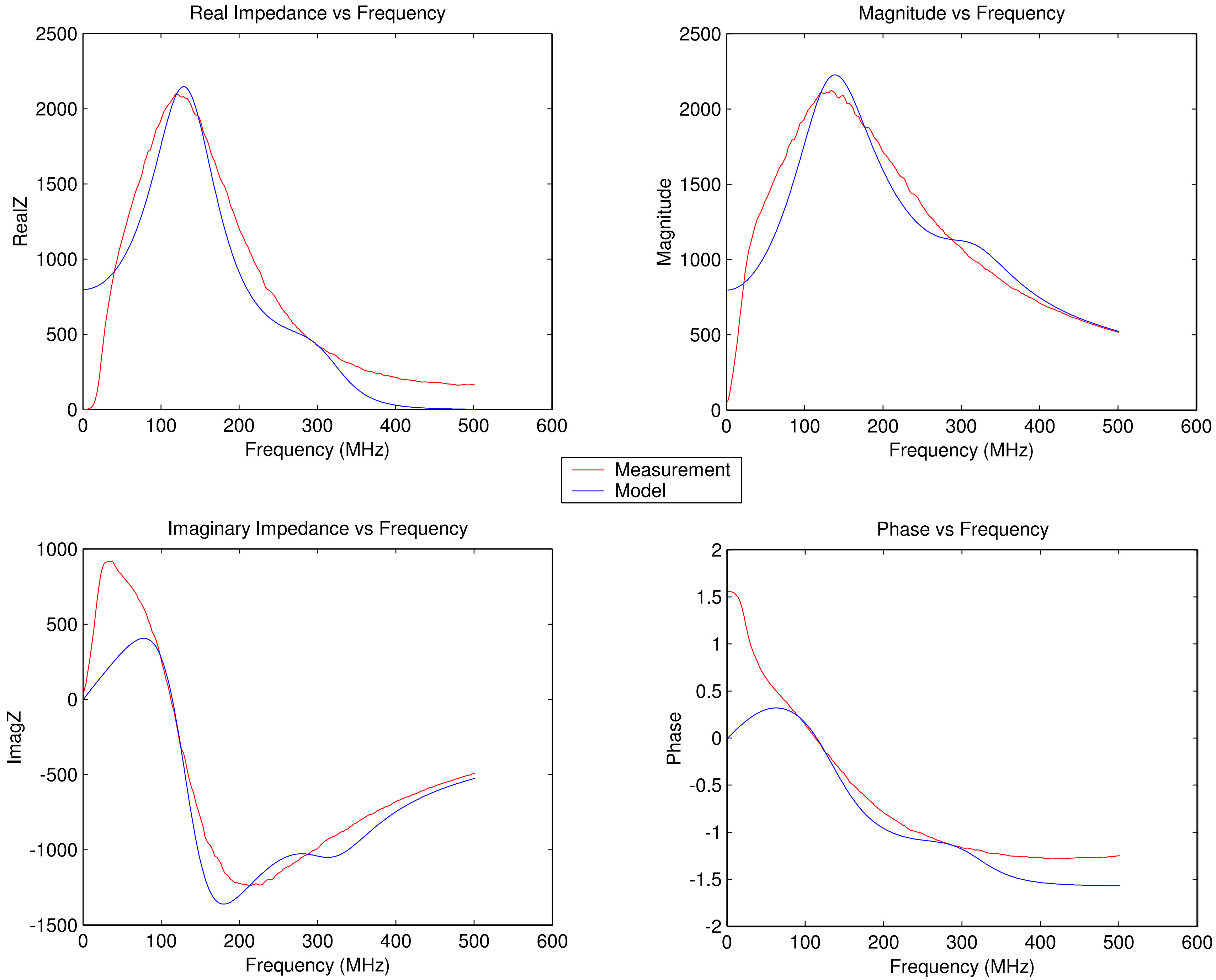
This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	0.6973
Internal Resistance of Model (Ω)	797.7000
Internal Inductance from estimation (μH)	8.6717
Internal Inductance of Model (μH)	0.5624
Internal Capacitance from estimation (pF)	0.2266
Internal Capacitance of Model (pF)	0.6000
External Inductance from estimation (nH)	7.4391
External Inductance of Model (nH)	1307.5000
External Capacitance from estimation (pF)	0.0255
External Capacitance of Model (pF)	0.7000
Resonant Frequency (MHz)	113.5413
A_L	73
Number of turns from estimation	11.6801
Number of turns	8
Legnth of Leaded Wire (mm)	4.1300
Distance between two wires (mm)	18.0000
Diameter of wire (mm)	0.3900
R-Square Value of Real Impedance	0.8940
R-Square Value of Imaginary Impedance	0.9370
R-Square Value of Magnitude	0.8983
R-Square Value of Phase	0.8693



Sum of two inductance values
= 1.8 uH

Title: Equivalent Model of 10uH Ferrite Toroidal Leaded Inductor (FT-82 #61)
Treatment: Wire is shortened



10uH Ferrite Toroidal Core (FT-82-61) Leaded Inductor with Wire Shortened (Linear-Scale)

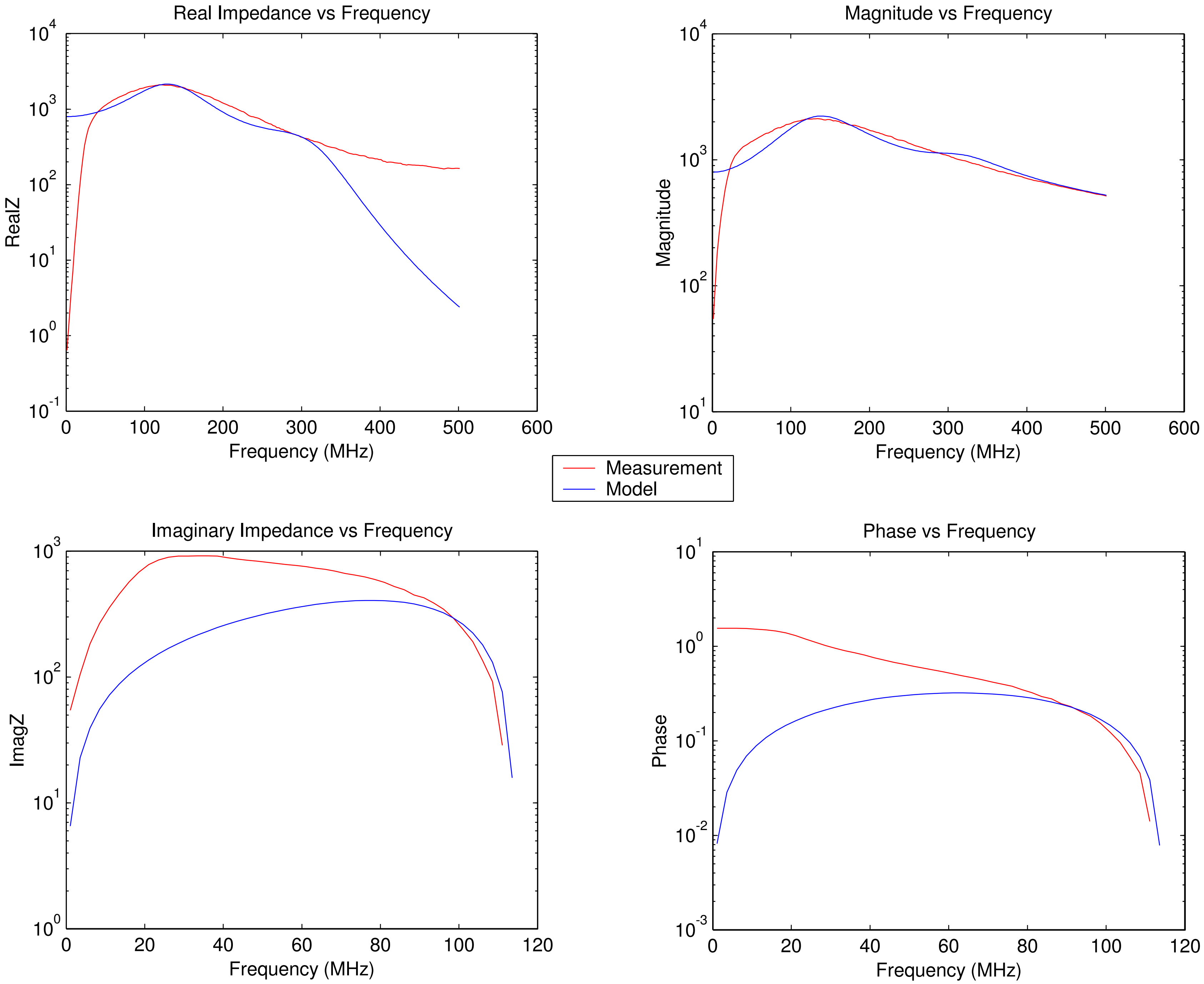
Real Impedance vs Frequency

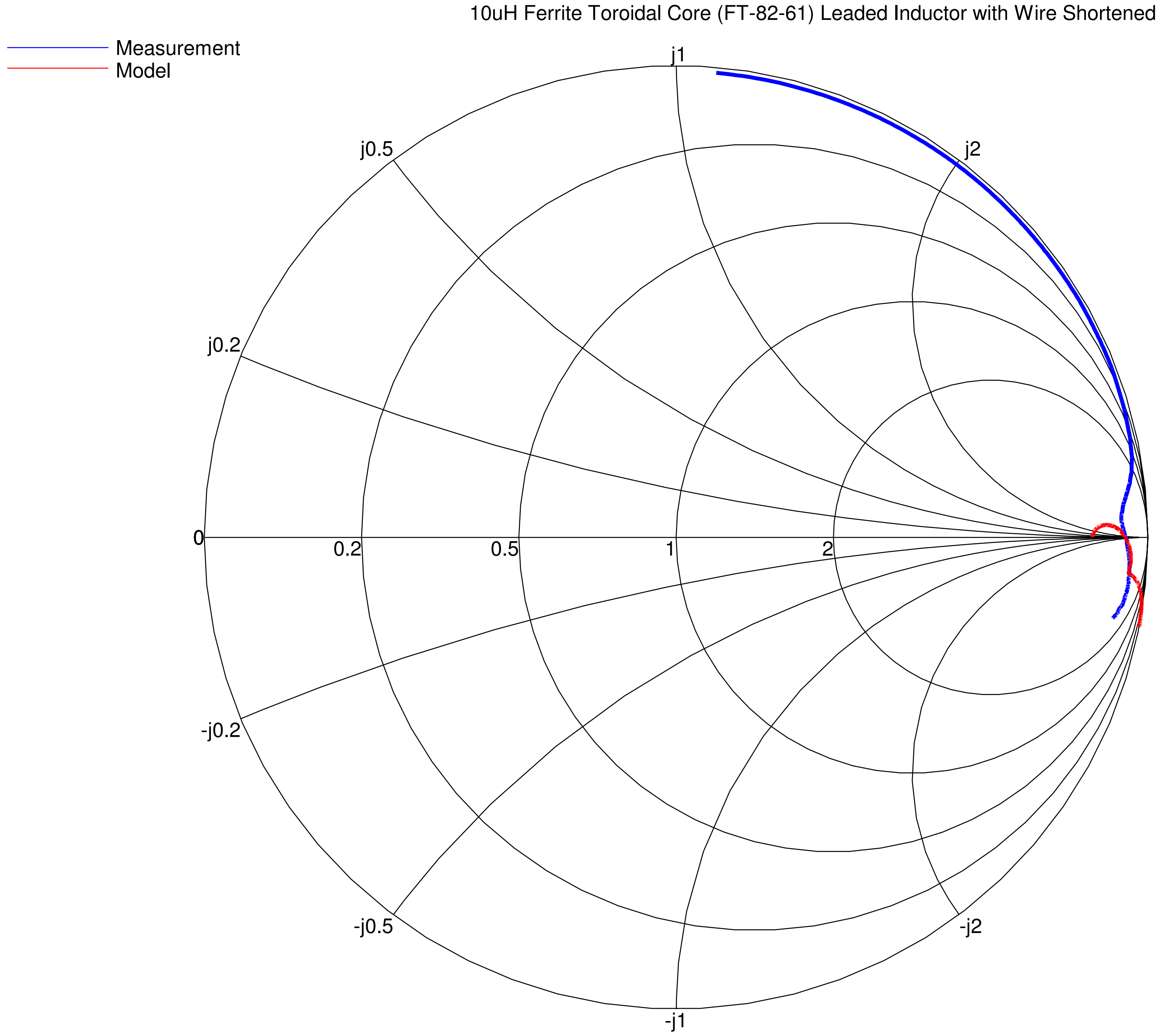
Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency

10uH Ferrite Toroidal Core (FT-82-61) Leaded Inductor with Wire Shortened (Log-Scale)




10uH Ferrite Toroidal Core (FT-82-61) Leaded Inductor with Wire Shortened

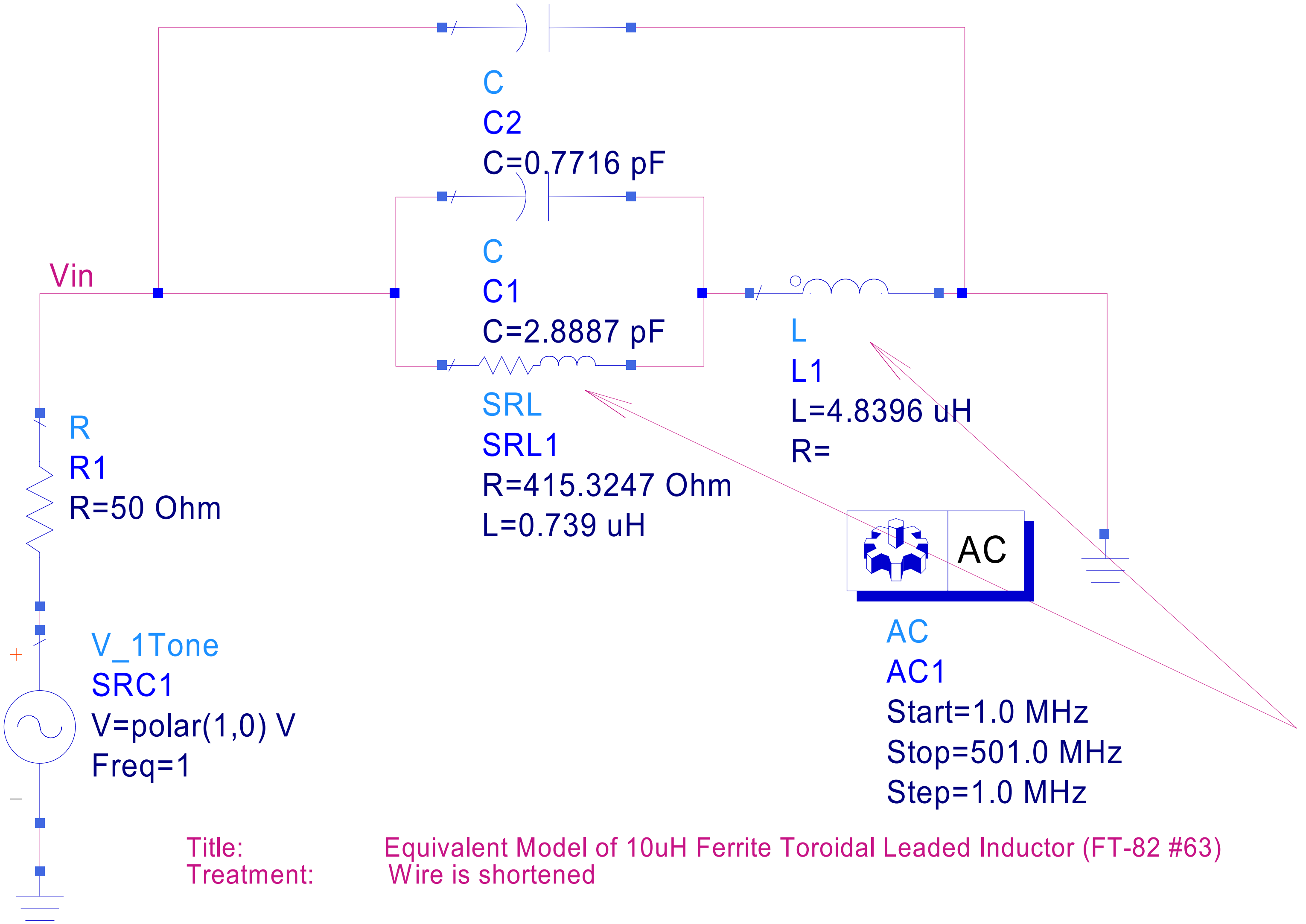
3.4.14 10μH Iron Powder Toroidal Leaded Inductor (FT-82 #63)

The following is the picture of a 10μH Iron Powder Toroidal Leaded Inductor (FT-82 #63)

Picture of a shortened wire inductor

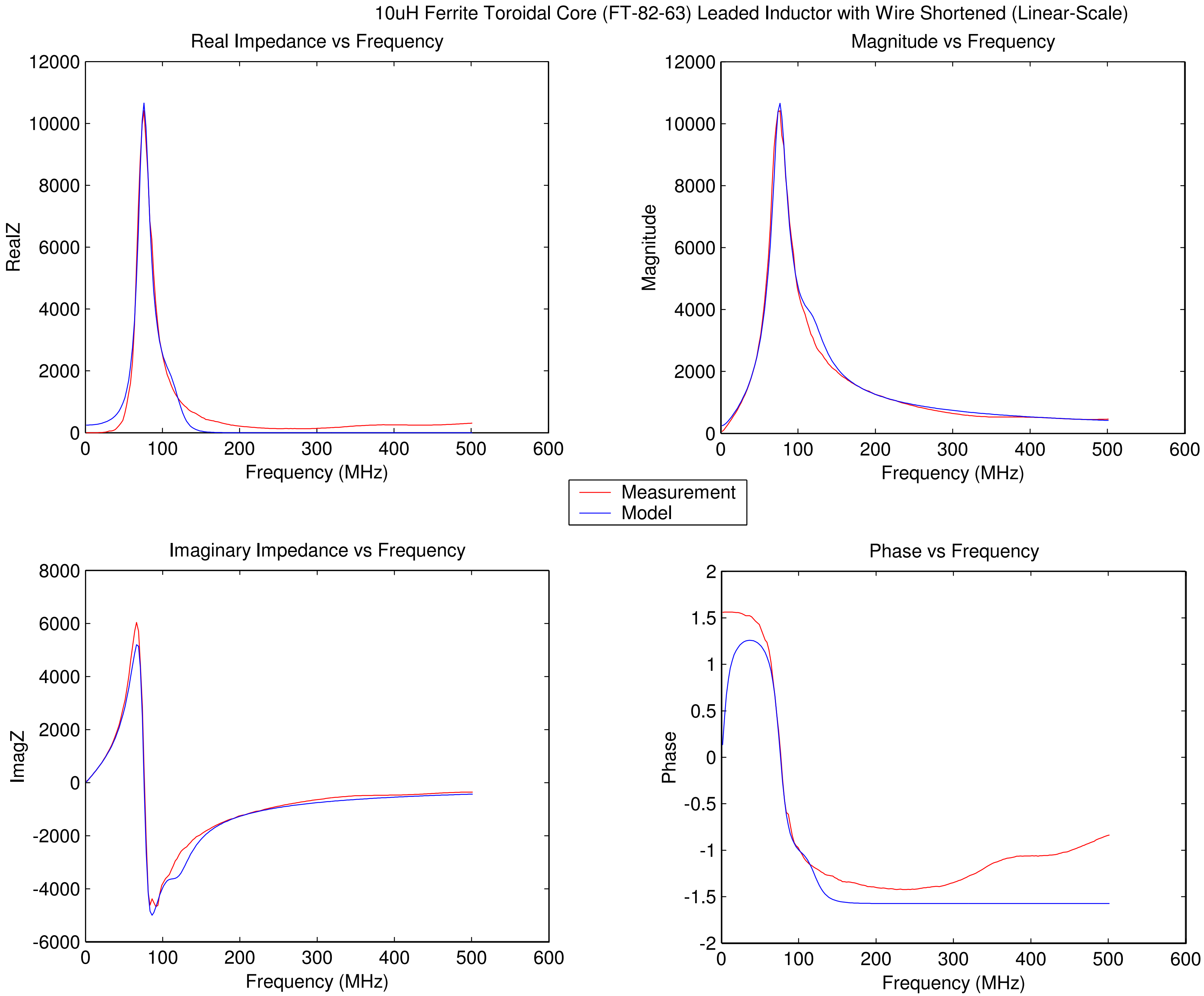
This table summarizes the measured data and simulation result.

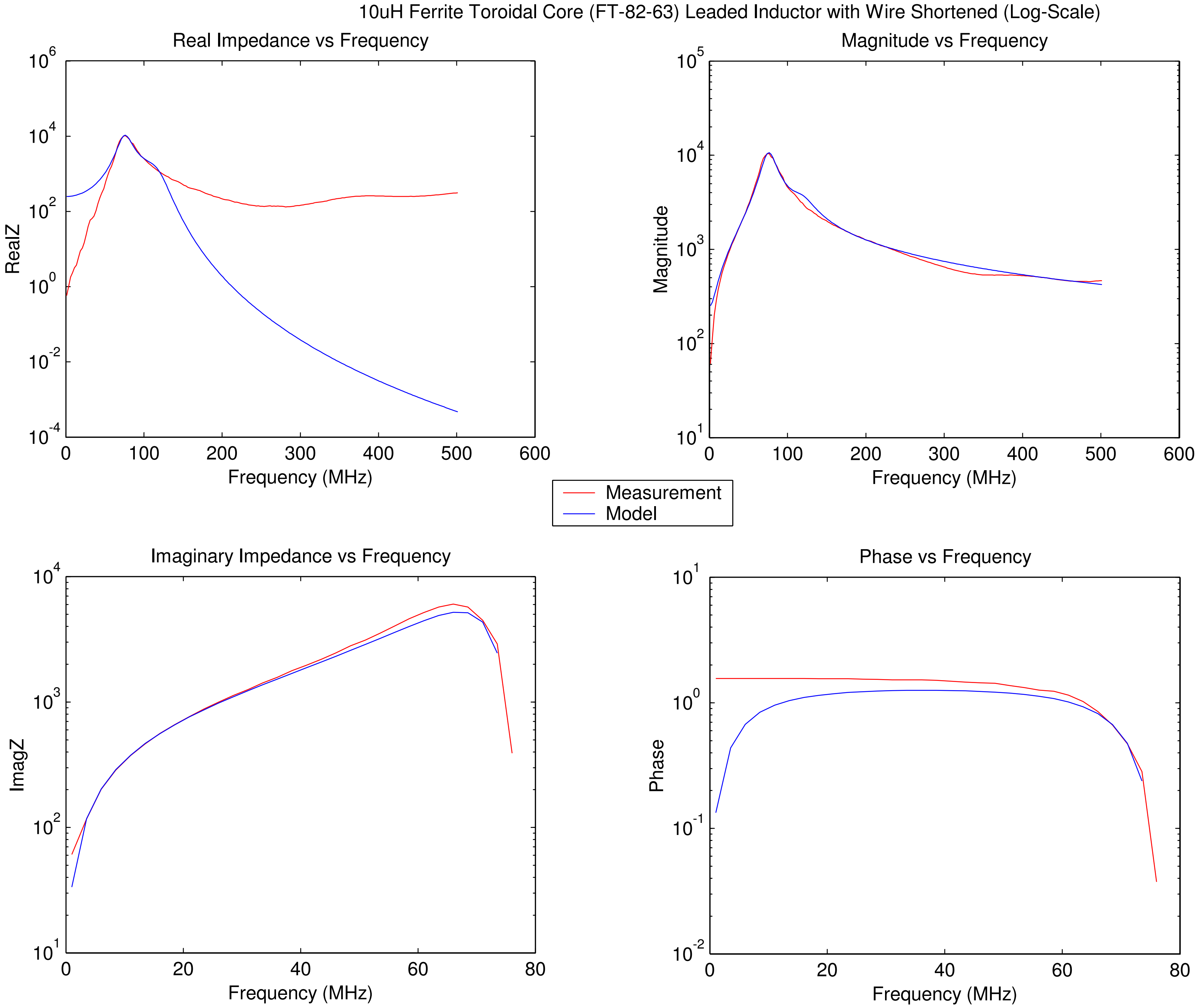
	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	1.4166
Internal Resistance of Model (Ω)	250.0655
Internal Inductance from estimation (μH)	9.7532
Internal Inductance of Model (μH)	0.7394
Internal Capacitance from estimation (pF)	0.4307
Internal Capacitance of Model (pF)	2.8887
External Inductance from estimation (nH)	7.4013
External Inductance of Model (nH)	4839.6917
External Capacitance from estimation (pF)	0.0257
External Capacitance of Model (pF)	0.7716
Resonant Frequency (MHz)	77.6513
A_L	22
Number of turns from estimation	21.1289
Number of turns	15
Legnth of Leaded Wire (mm)	4.1400
Distance between two wires (mm)	16.9700
Diameter of wire (mm)	0.3800
R-Square Value of Real Impedance	0.9809
R-Square Value of Imaginary Impedance	0.9888
R-Square Value of Magnitude	0.9914
R-Square Value of Phase	0.9423



Sum of two inductance values
= 5.5 uH

Title: Equivalent Model of 10uH Ferrite Toroidal Leaded Inductor (FT-82 #63)
Treatment: Wire is shortened


10uH Ferrite Toroidal Core (FT-82-63) Leaded Inductor with Wire Shortened (Linear-Scale)
Real Impedance vs Frequency
RealZ
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
Frequency (MHz)
Measurement
Model
Imaginary Impedance vs Frequency
ImagZ
8000
6000
4000
2000
0
-2000
-4000
-6000
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
Frequency (MHz)

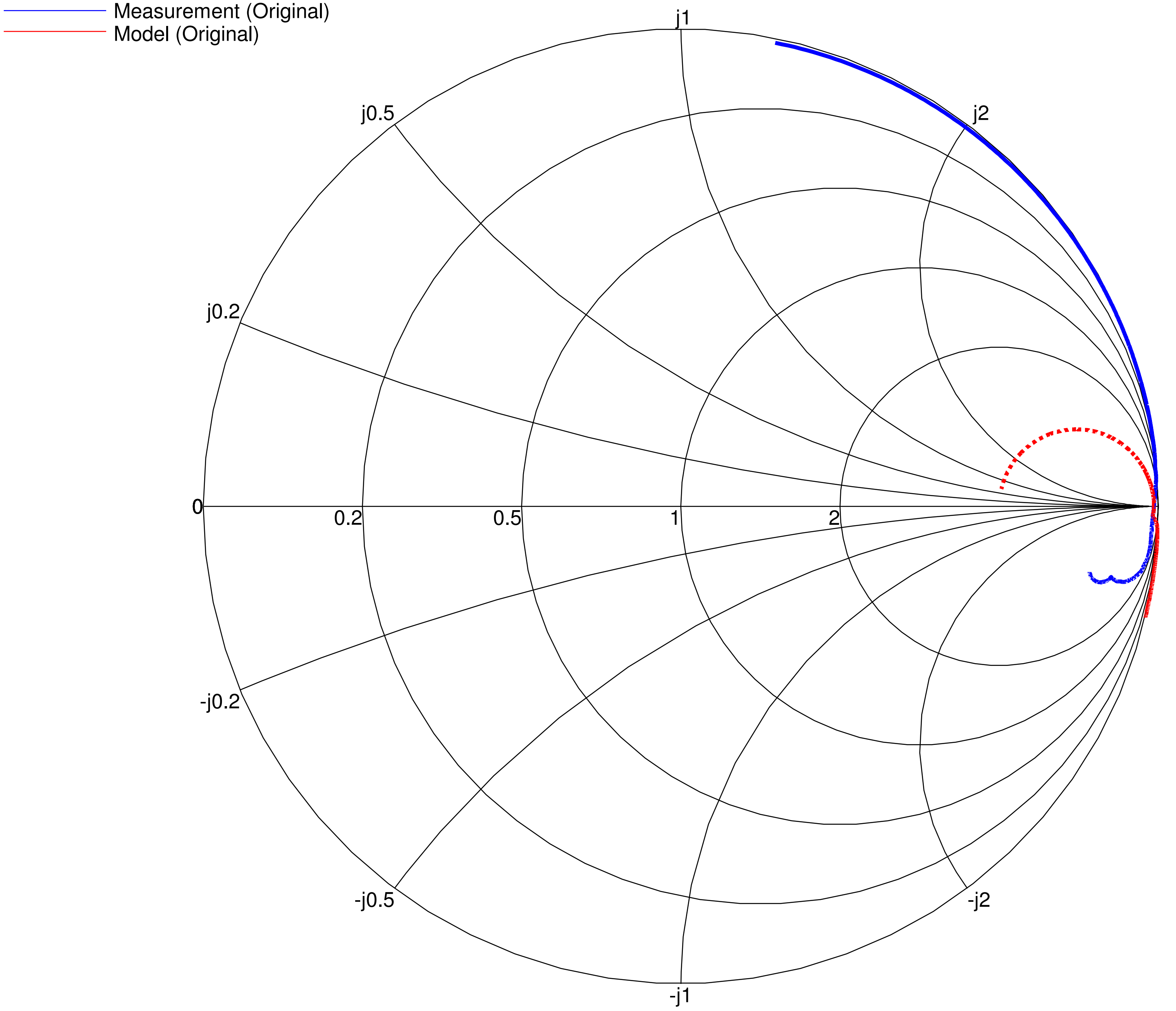

10uH Ferrite Toroidal Core (FT-82-63) Leaded Inductor with Wire Shortened (Log-Scale)

Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency



10uH Ferrite Toroidal Core (FT-82-63) Leaded Inductor with Wire Shortened

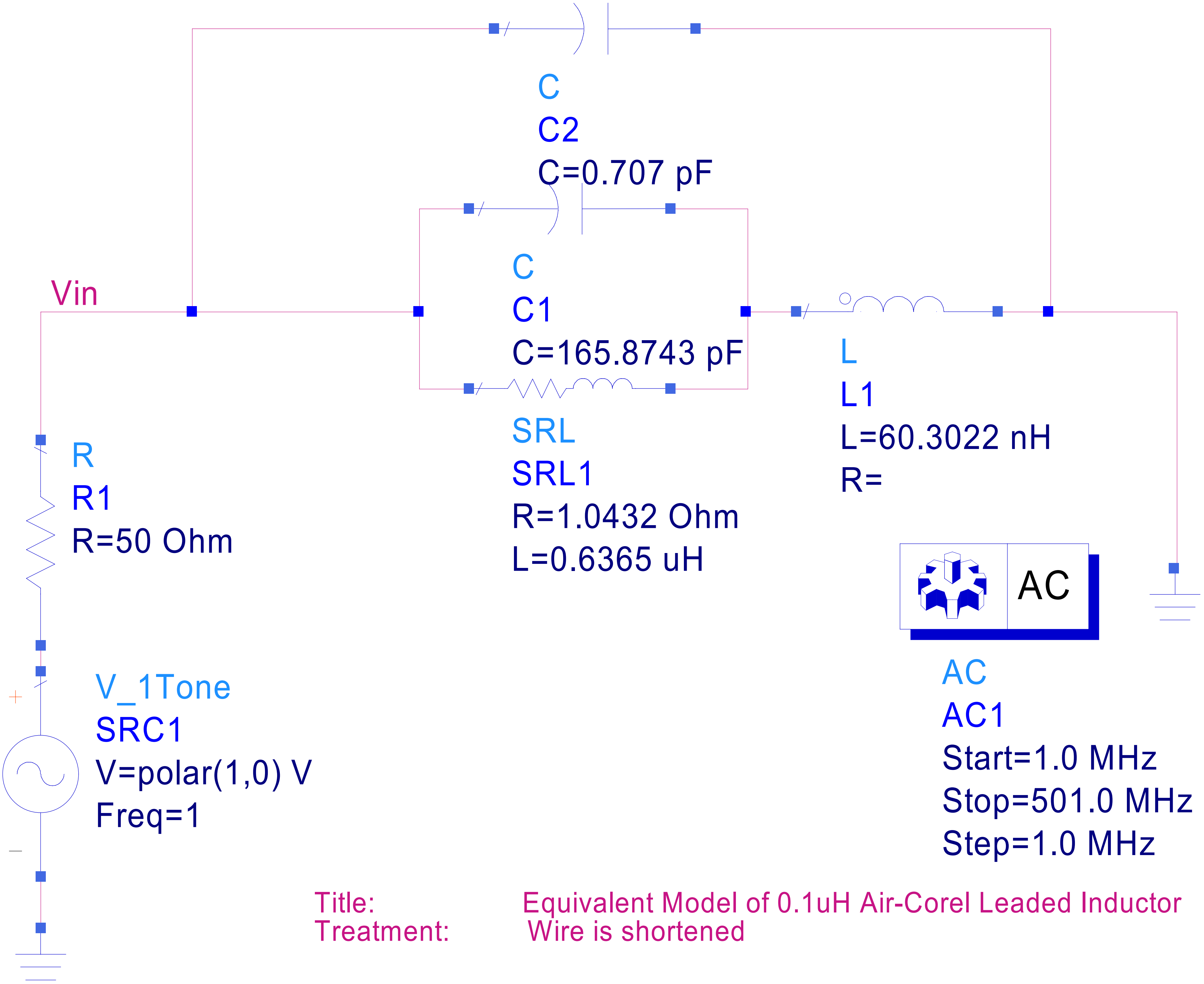
3.4.15 0.1μH Air-Core Leaded Inductor

The following is the picture of a 0.1μH Air-Core Leaded Inductor

Picture of a shortened wire inductor

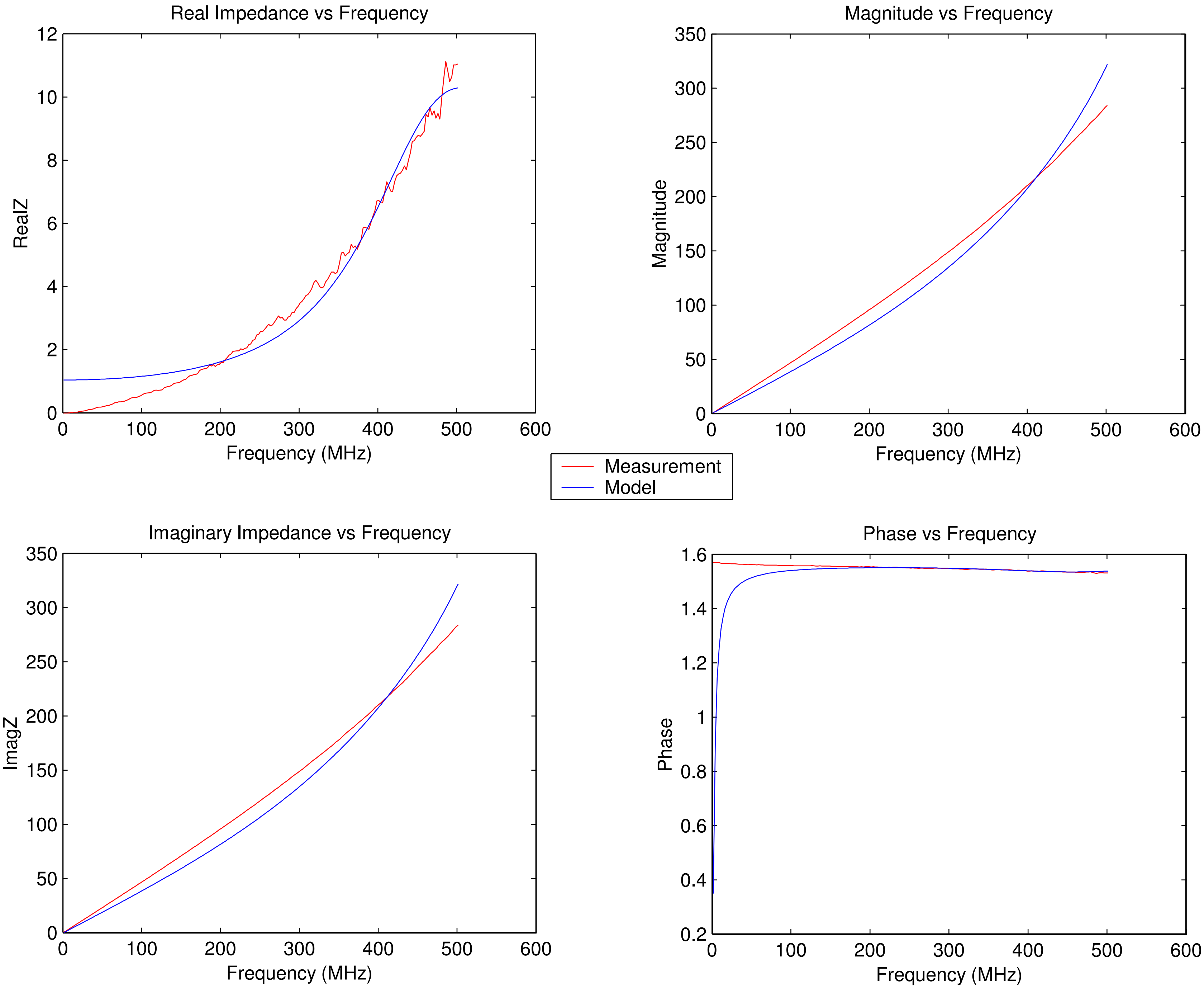
This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	0.0000
Internal Resistance of Model (Ω)	1.0432
Internal Inductance from estimation (nH)	0.1417
Internal Inductance of Model (μH)	0.6365
Internal Capacitance from estimation (pF)	0.1669
Internal Capacitance of Model (pF)	165.8743
External Inductance from estimation (nH)	4.8585
External Inductance of Model (nH)	60.3022
External Capacitance from estimation (pF)	0.0308
External Capacitance of Model (pF)	0.707
Resonant Frequency (MHz)	1034.9363
Number of turns	4
Legngth of Leaded Wire (mm)	3.6700
Distance between two wires (mm)	5.0000
Diameter of wire (mm)	0.3400
R-Square Value of Real Impedance	0.9761
R-Square Value of Imaginary Impedance	0.9880
R-Square Value of Magnitude	0.9880
R-Square Value of Phase	0.3582

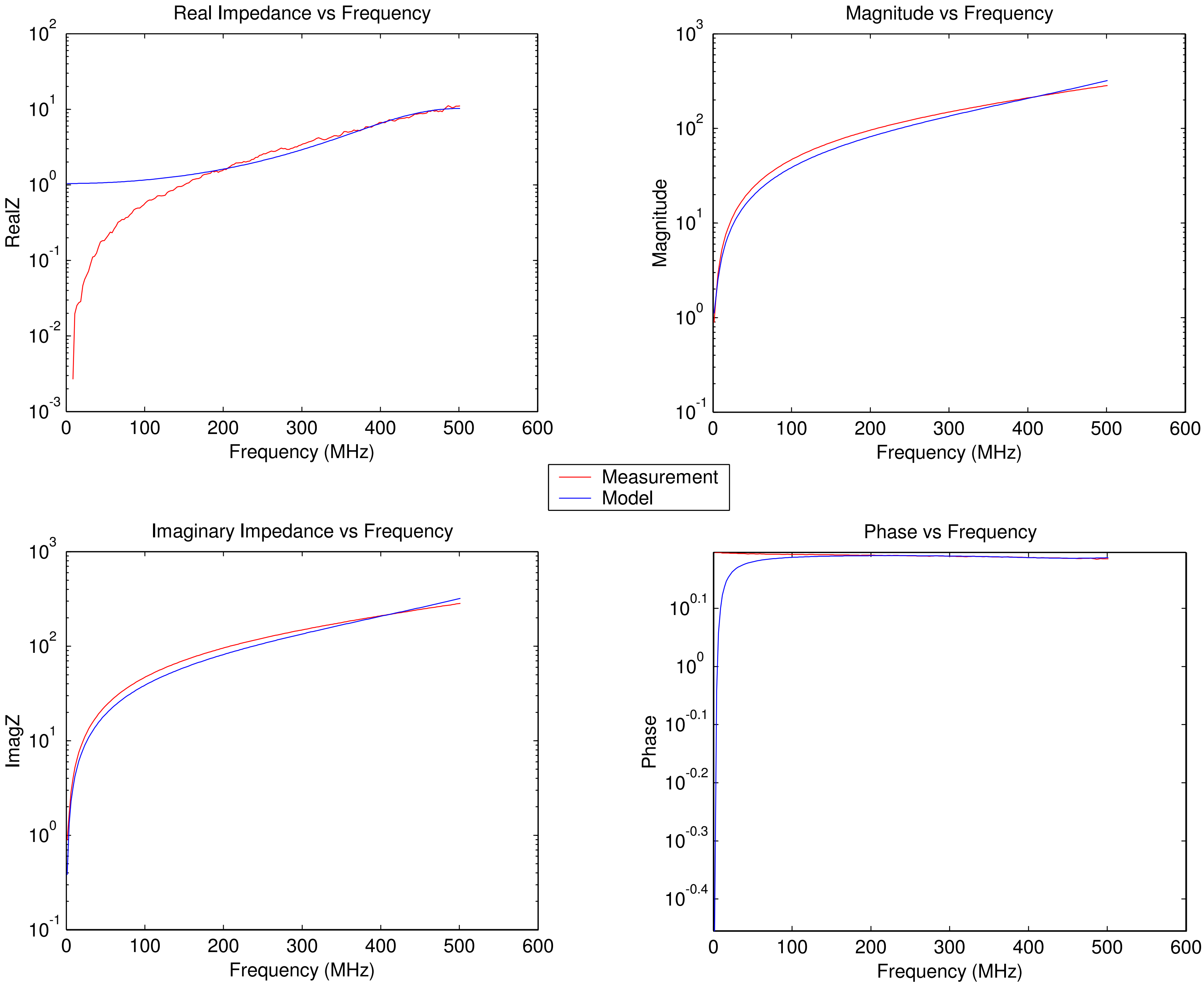


Title: Equivalent Model of 0.1uH Air-Corel Leaded Inductor
Treatment: Wire is shortened

0.1uH Air-Core Leaded Inductor with Wire Shortened (Linear-Scale)



0.1uH Air-Core Leaded Inductor with Wire Shortened (Log-Scale)



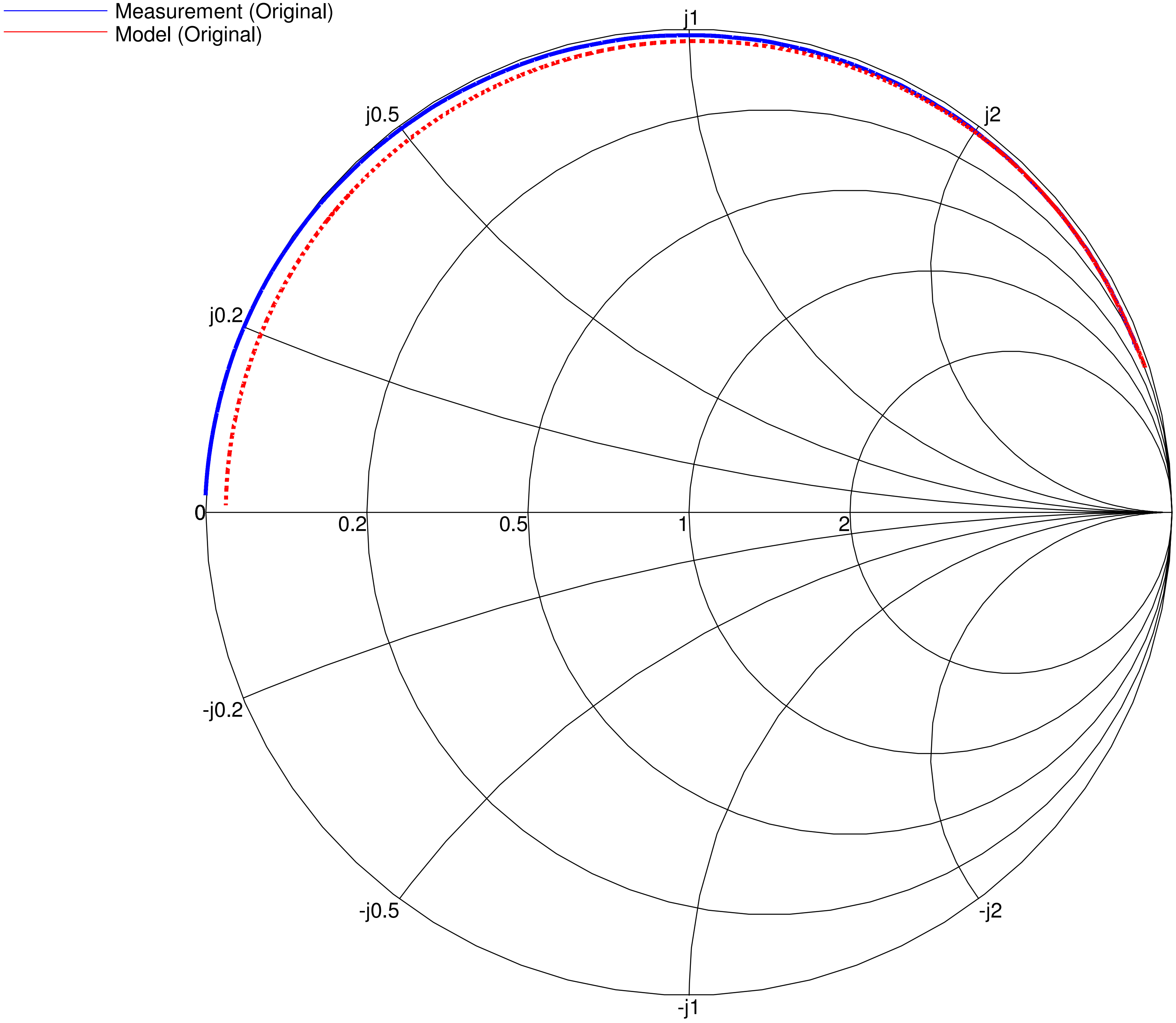
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

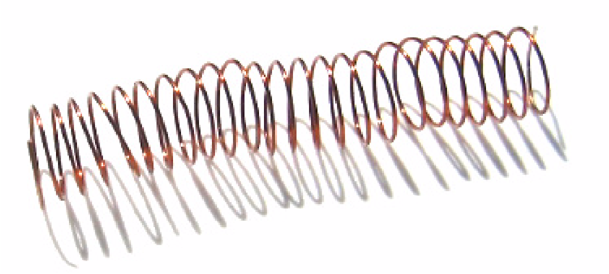
Phase vs Frequency

0.1uH Air-Core Leaded Inductor with Wire Shortened



3.4.16 1μH Air-Core Leaded Inductor

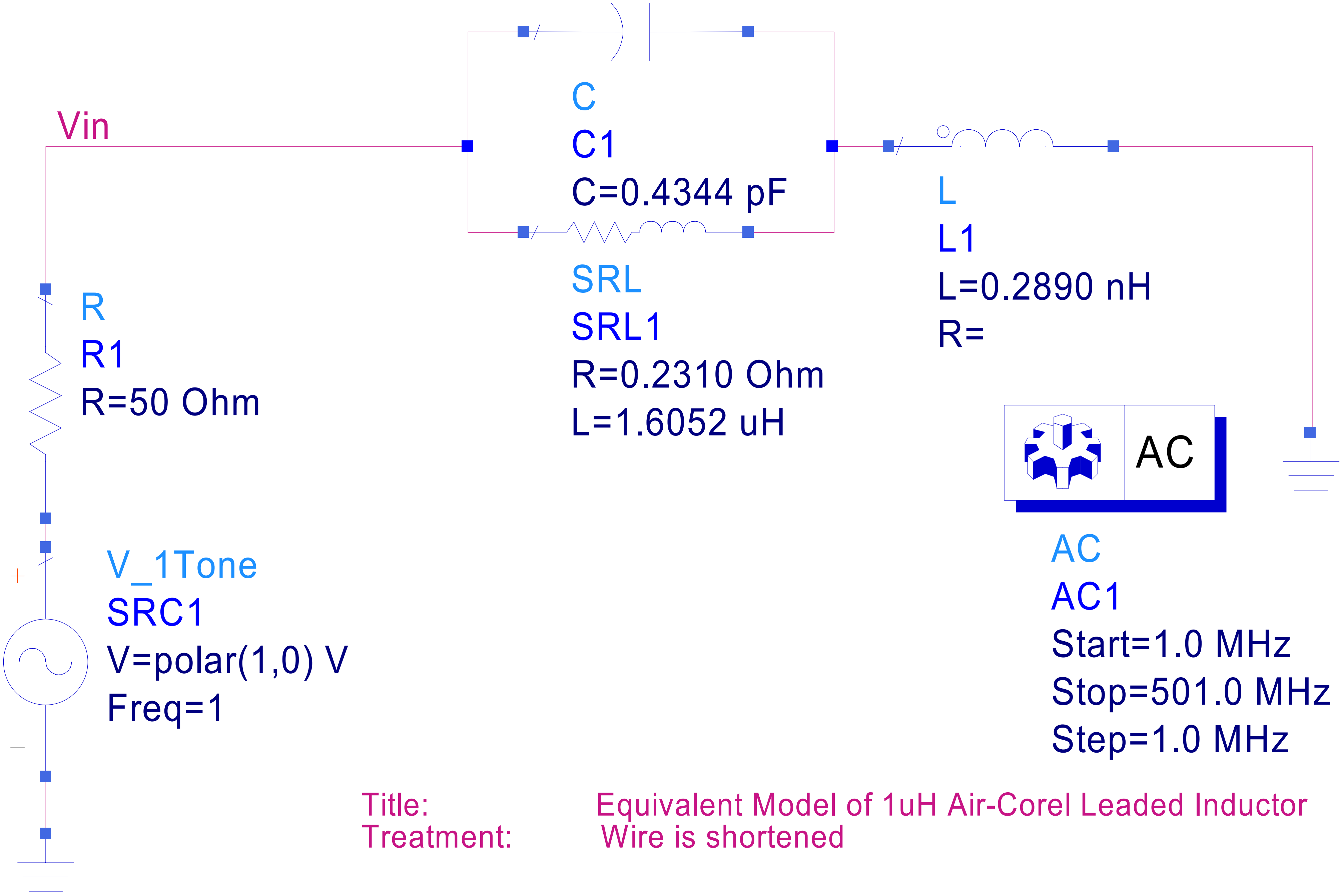
The following is the picture of a 1μH Air-Core Leaded Inductor



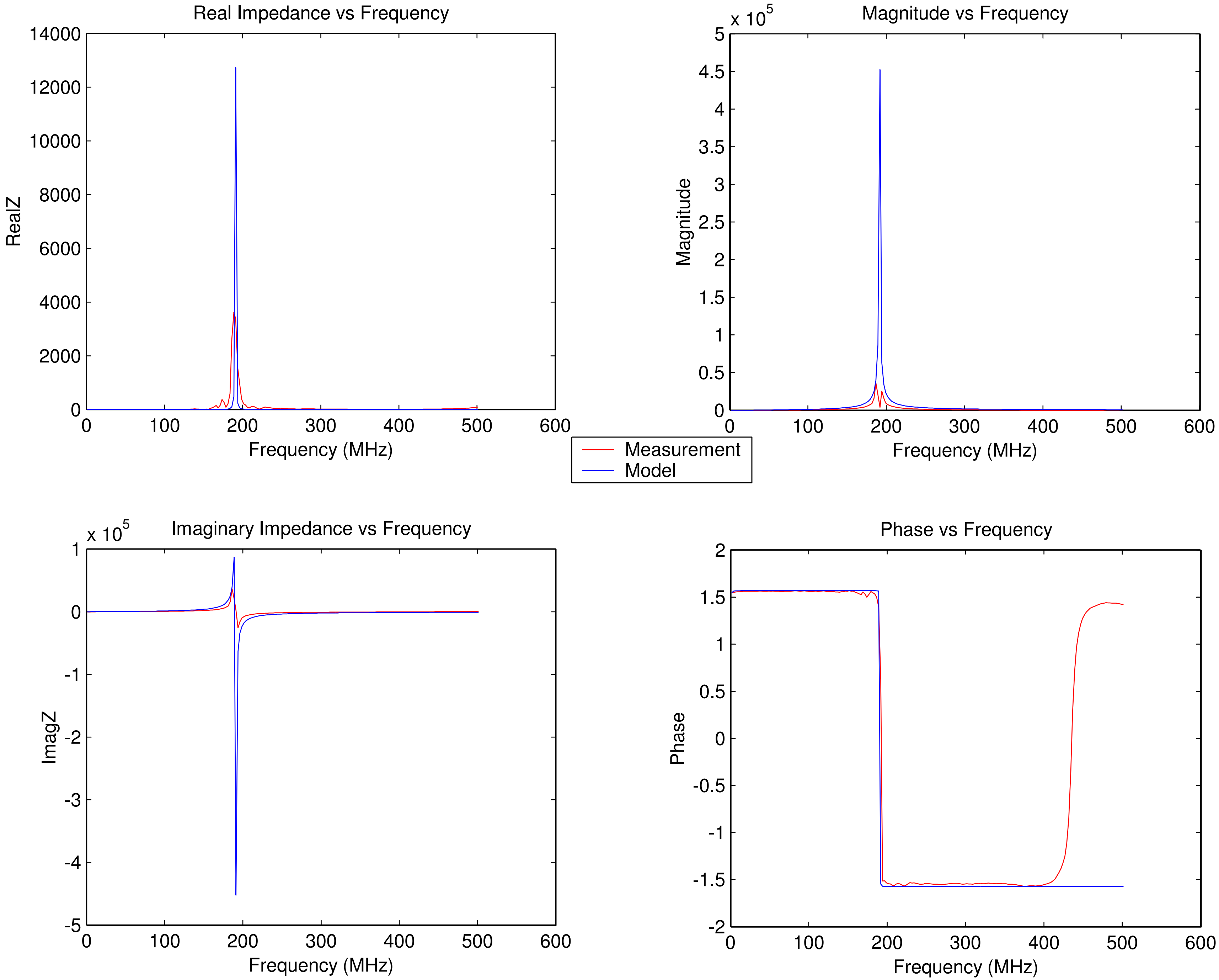
Picture of a shortened wire inductor

This table summarizes the measured data and simulation result.

	1 MHz - 501 MHz
Internal Resistance from estimation (Ω)	0.2310
Internal Resistance of Model (Ω)	0.2310
Internal Inductance from estimation (nH)	1.6052
Internal Inductance of Model (μH)	1.6052
Internal Capacitance from estimation (pF)	0.4344
Internal Capacitance of Model (pF)	0.4344
External Inductance from estimation (nH)	7.4014
External Inductance of Model (nH)	0.2890
External Capacitance from estimation (pF)	0.0172
External Capacitance of Model (pF)	0.0000
Resonant Frequency (MHz)	190.5923
Number of turns	25
Legnth of Leaded Wire (mm)	3.3900
Distance between two wires (mm)	47.3400
Diameter of wire (mm)	0.4000
R-Square Value of Real Impedance	0.3537
R-Square Value of Imaginary Impedance	0.0495
R-Square Value of Magnitude	0.0787
R-Square Value of Phase	0.6183



Title: Equivalent Model of 1uH Air-Corel Leaded Inductor
Treatment: Wire is shortened



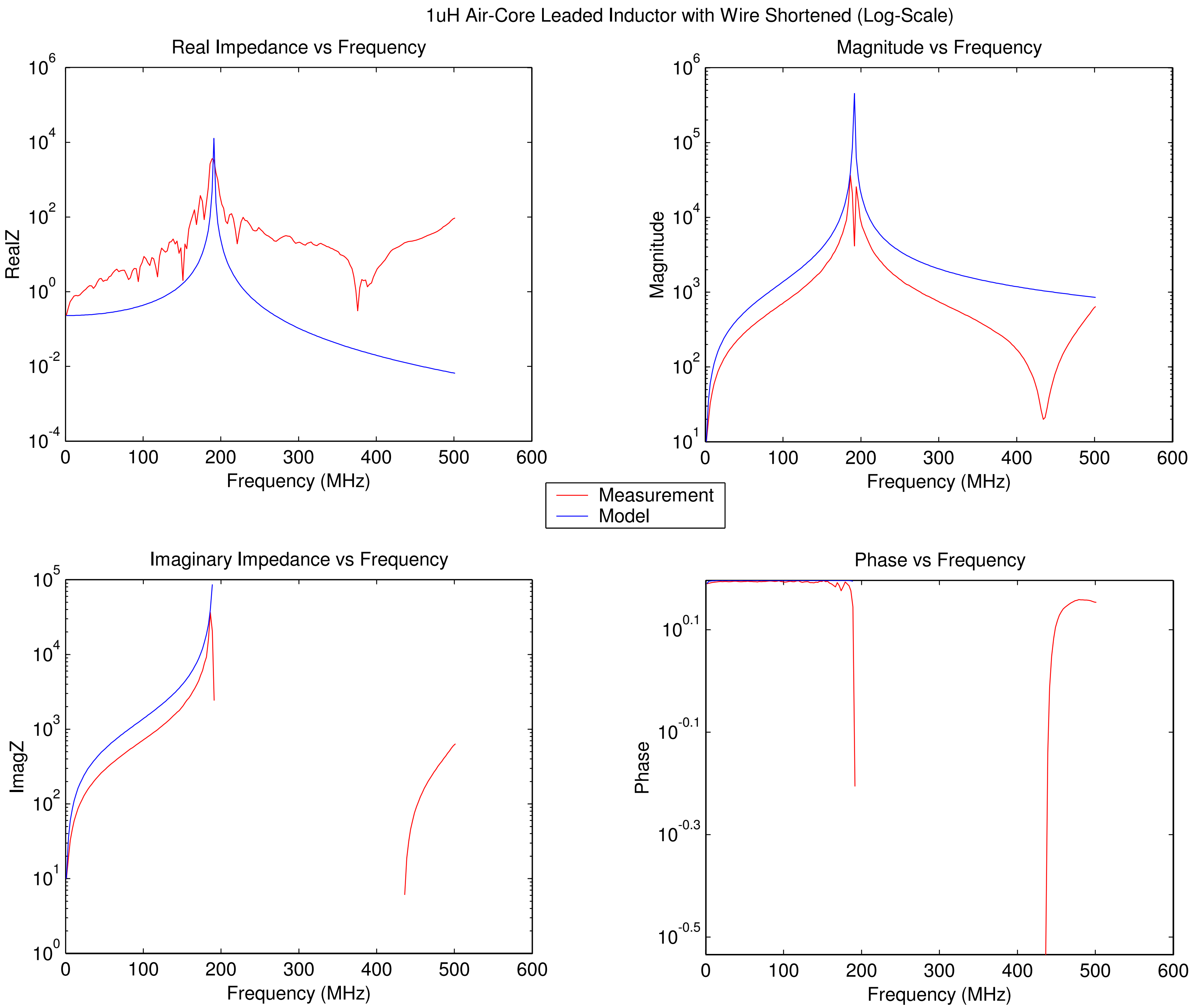
1uH Air-Core Leaded Inductor with Wire Shortened (Linear-Scale)

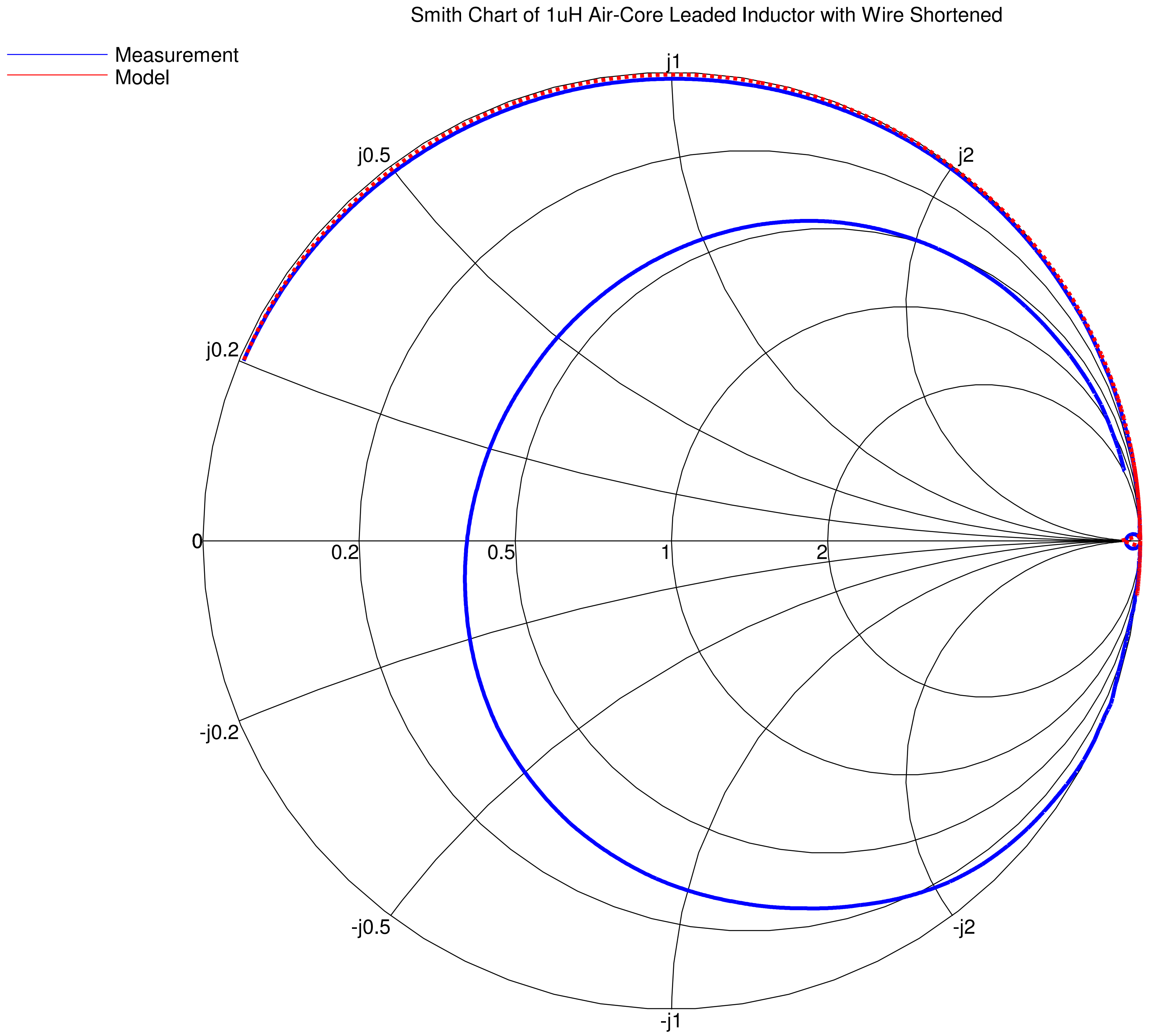
Real Impedance vs Frequency

Magnitude vs Frequency

Imaginary Impedance vs Frequency

Phase vs Frequency


1uH Air-Core Leaded Inductor with Wire Shortened (Log-Scale)
Real Impedance vs Frequency
RealZ
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
0
100
200
300
400
500
600
Frequency (MHz)
Magnitude vs Frequency
Magnitude
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
0
100
200
300
400
500
600
Frequency (MHz)
Measurement
Model
Imaginary Impedance vs Frequency
ImagZ
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
0
100
200
300
400
500
600
Frequency (MHz)
Phase vs Frequency
Phase
$10^{0.1}$
$10^{-0.1}$
$10^{-0.3}$
$10^{-0.5}$
0
100
200
300
400
500
600
Frequency (MHz)


Smith Chart of 1uH Air-Core Leaded Inductor with Wire Shortened
Measurement
Model
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1

3.5 Analysis on Disagreement between the Model and Measurement

Most models fails to give a good agreement to the measurement. We can divide them into two cases. For the first case, the model fails to agree the measurement from 1 MHz to 501 MHz, but there is a significant improvement after narrowing the frequency range (The Suggested Operating Frequency). For the second case, the mode fails to give good agreements in both case. For some samples, the narrow frequency range measurement is even worse than the original one. Therefore, I do not list the result in this report.

As I mentioned earlier, the reason of the unsuccessful modeling is caused by the wide frequency range. After the second measurement, the agreement becomes better. However, there is no improvement in the second case. One reason is the inaccurate model. The model is not enough to describe the behavior of the measurement. More components should be invited to the model.

A physical Inductor circuit is very similar to the two plates model of capacitor.

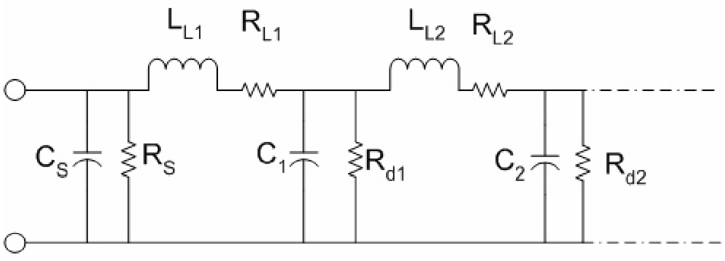


Figure 20: Equivalent Model for Inductor with Infinity Transmission Components

This model also explains why there are multiple resonant frequencies in the imaginary impedance region.

$$f_i = \frac{1}{2\pi\sqrt{L_{\mathrm{L}i}C_i}} \tag{23}$$

However, our model is unable to describe the multiple resonant frequencies. Therefore, our model fails to give a good agreement with some samples.

3.6 Analysis on "Splitting" Internal Inductance

The following is our inductor model:

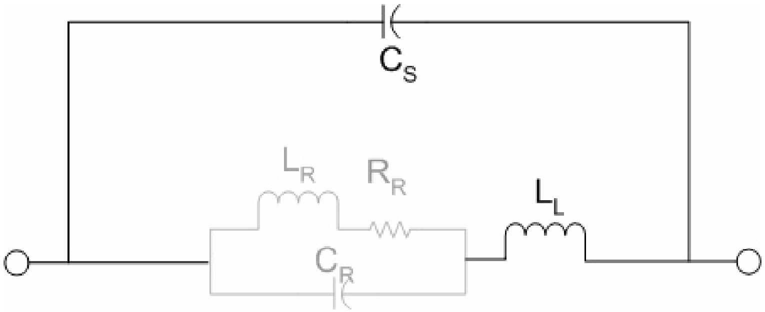


Figure 21: Equivalent Model for Inductor

The inductor L_R represents the marked inductance, while the inductor L_L represents the leaded inductance due to the transmission line effects. For the measurement on the Iron Power Toroidal Core Inductors (T-30), I found that the inductor L_R is too small to represents the desired inductance (0.1 μH). However, the inductor L_L is too large compared to the estimated values. Therefore, I think the inductor is spilt into two. The following table gives a summary on this observation:

Material	Estimated L_R (μH)	L_R (nH)	L_L (nH)	L_R+L_L (μH)
T-30 #0	0.1300	0.7299	47.6509	0.0484
T-30 #2	0.1355	1.8554	41.1816	0.0430
T-30 #6	0.1476	1.4964	49.4722	0.0510
T-30 #7	0.1347	1.6972	42.8657	0.0446
T-30 #10	0.1127	0.7547	37.4051	0.0382
T-30 #12	0.1408	1.1440	63.5101	0.0647

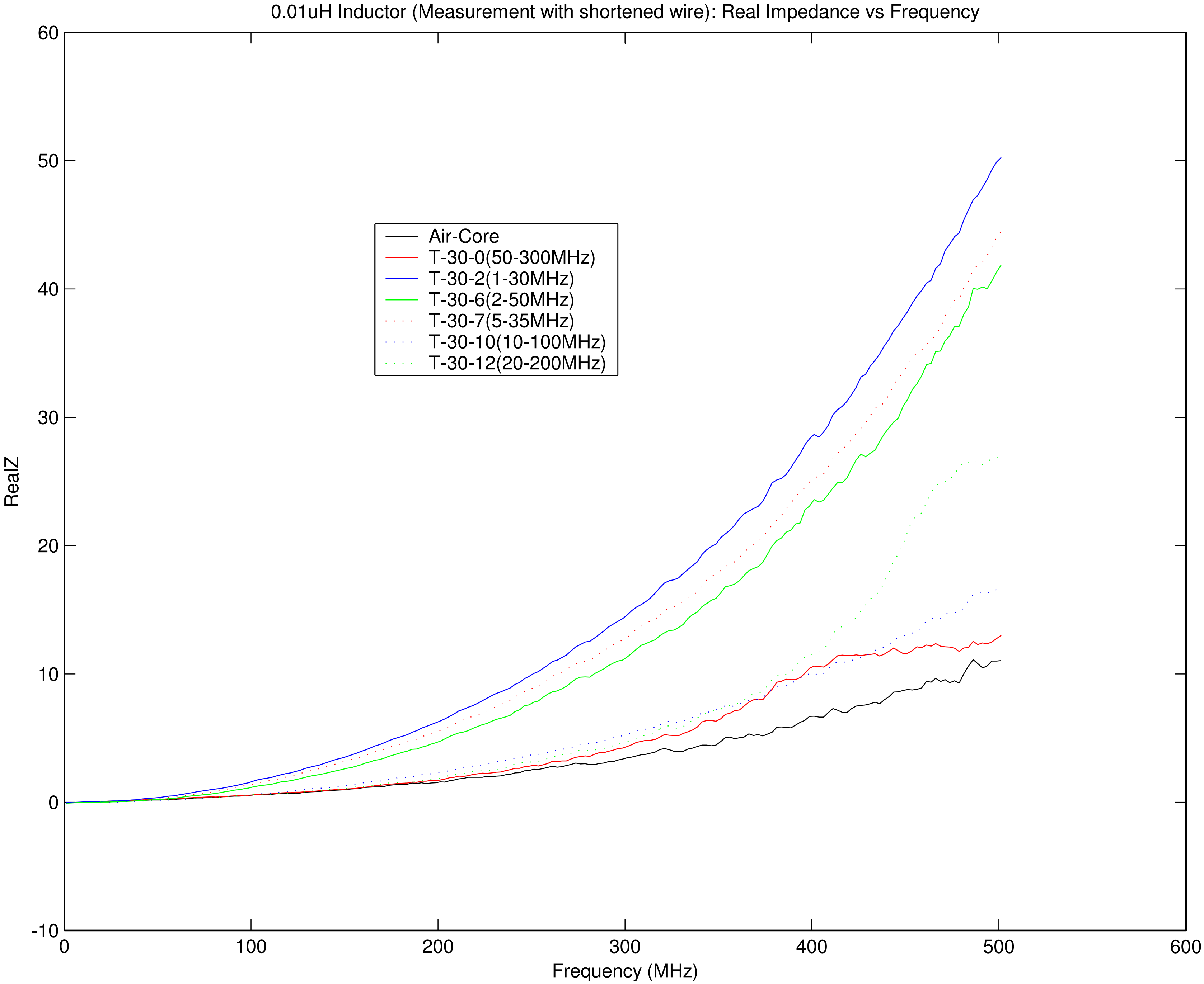
0.1μH Iron Powder Toroidal Inductor

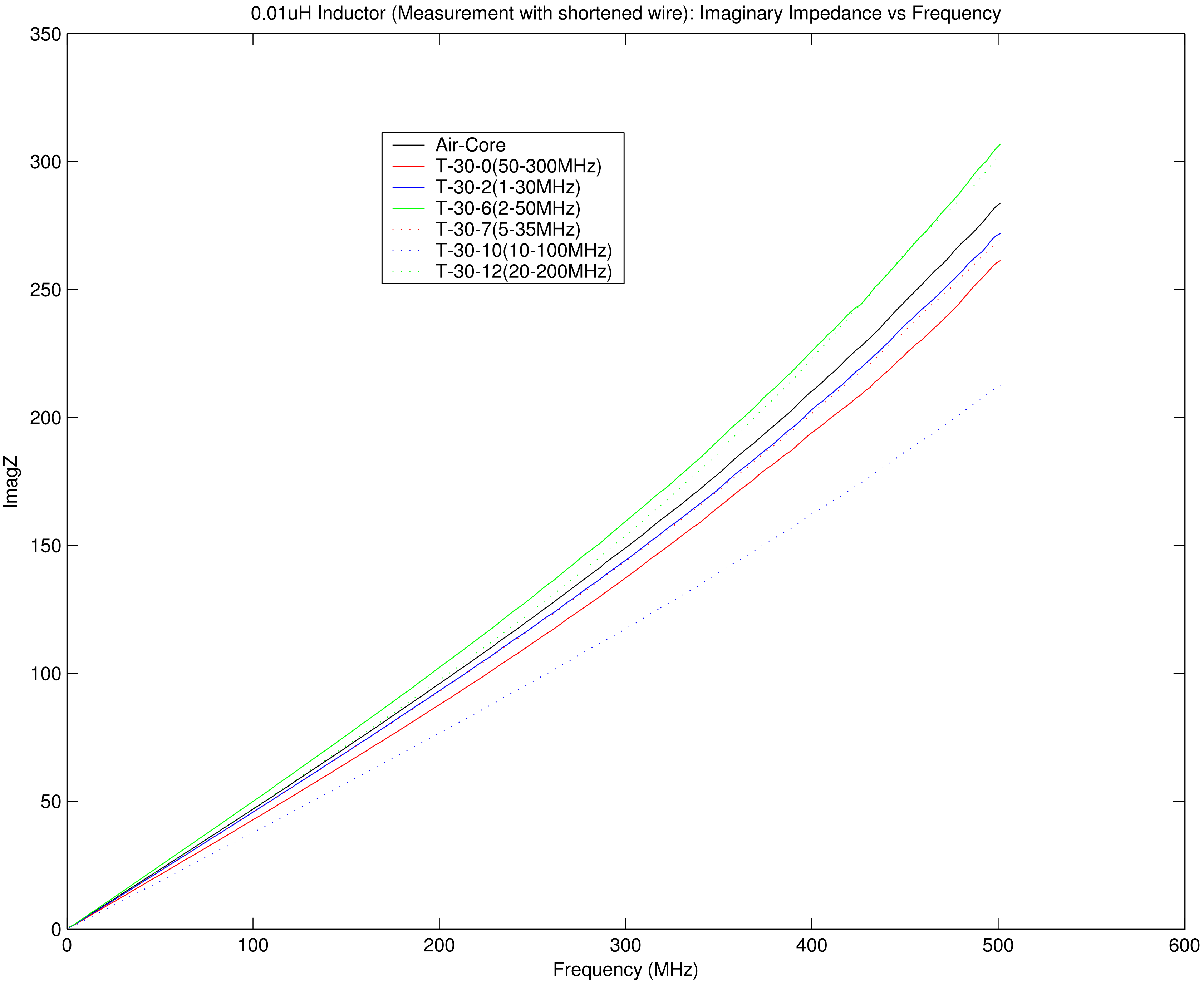
3.7 Analysis on the Shape of Impedance

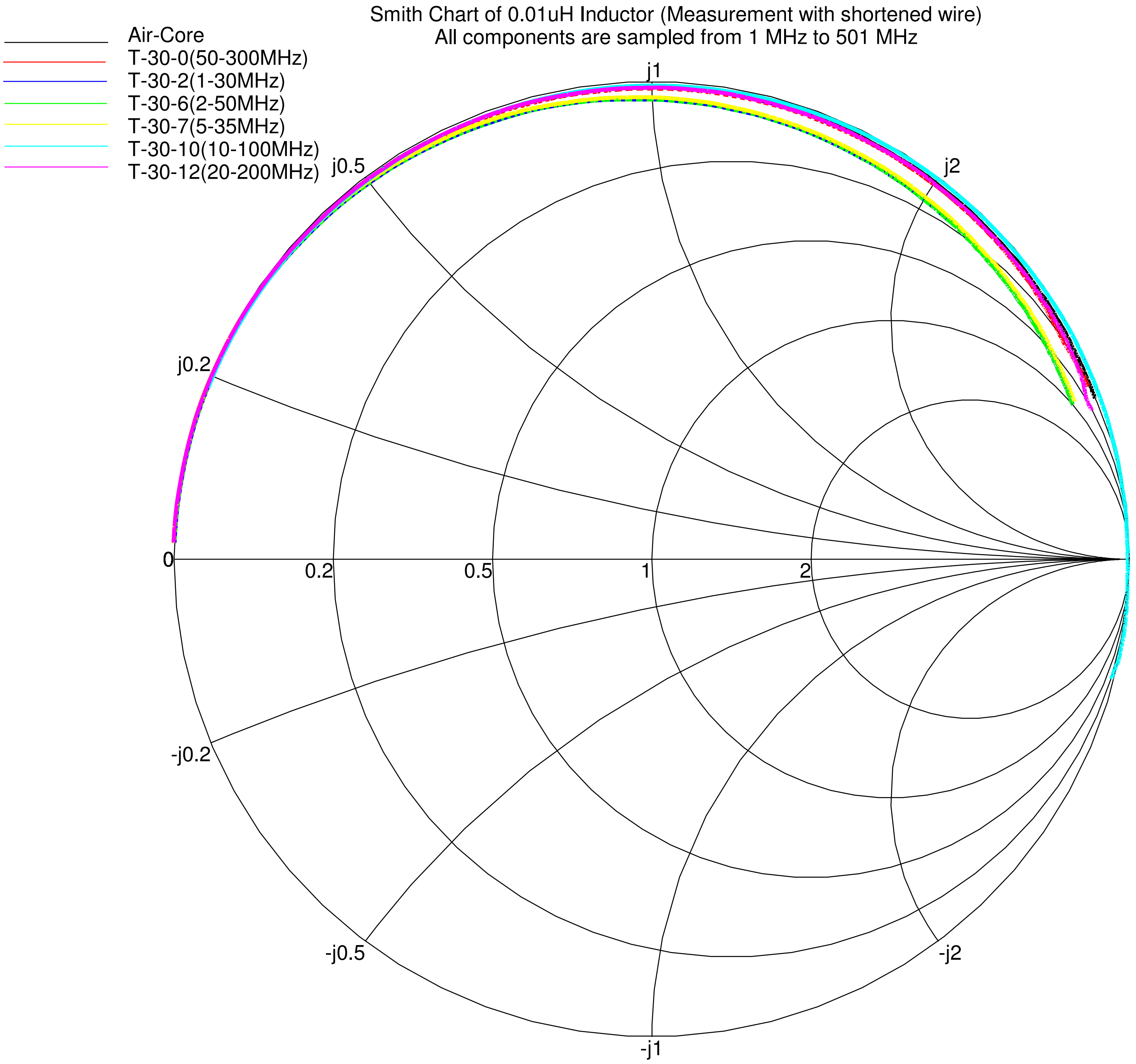
In this section, I plots the samples with the same inductance on the same plots. The frequency next to the line is the recommended operating frequency range of the material.

From the plots, I found that the resonant frequency is getting smaller when the inductance increases. It is because the resonant frequency is based on the following equation:

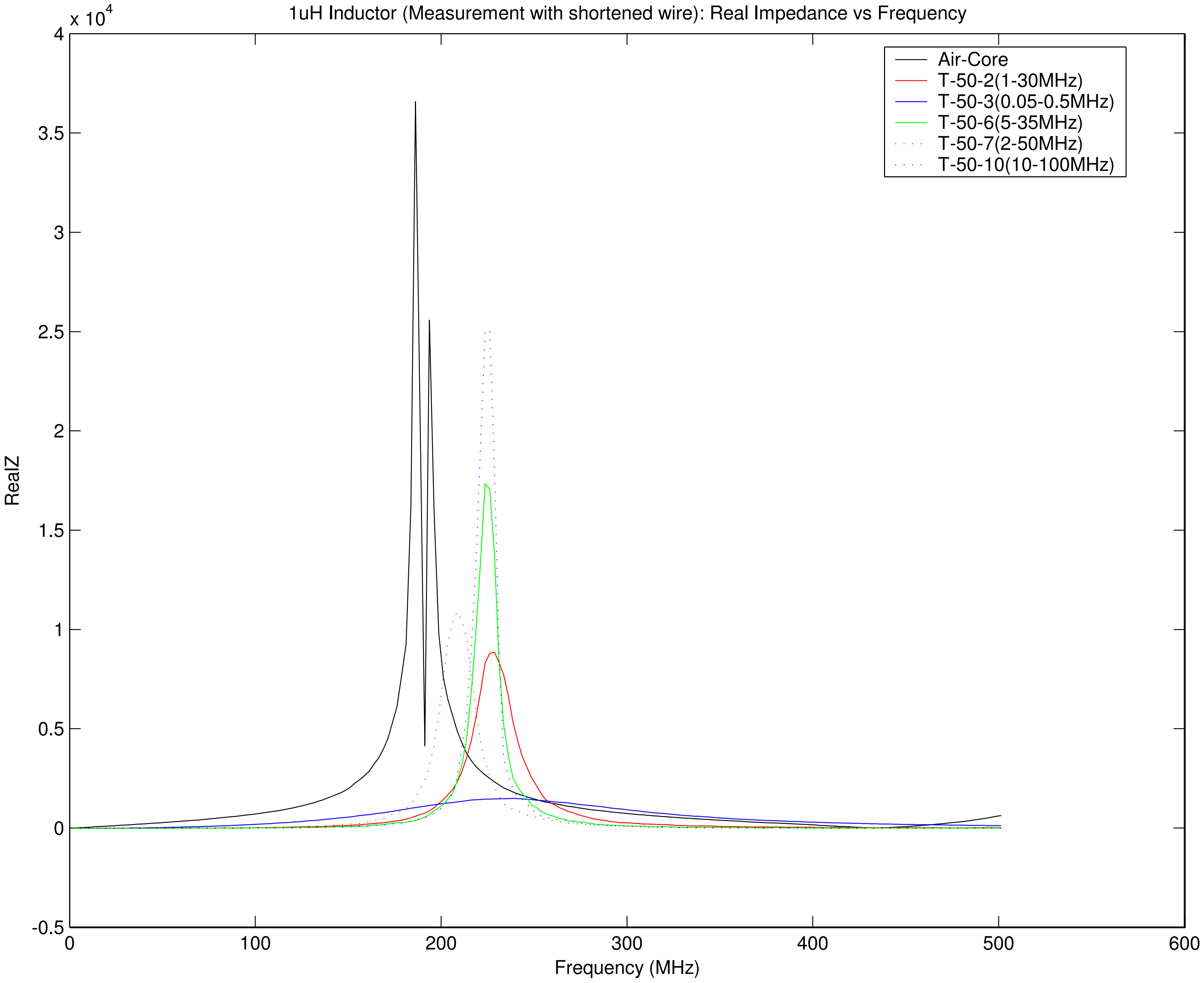
$$f = \frac{1}{2\pi\sqrt{LC}} \tag{24}$$

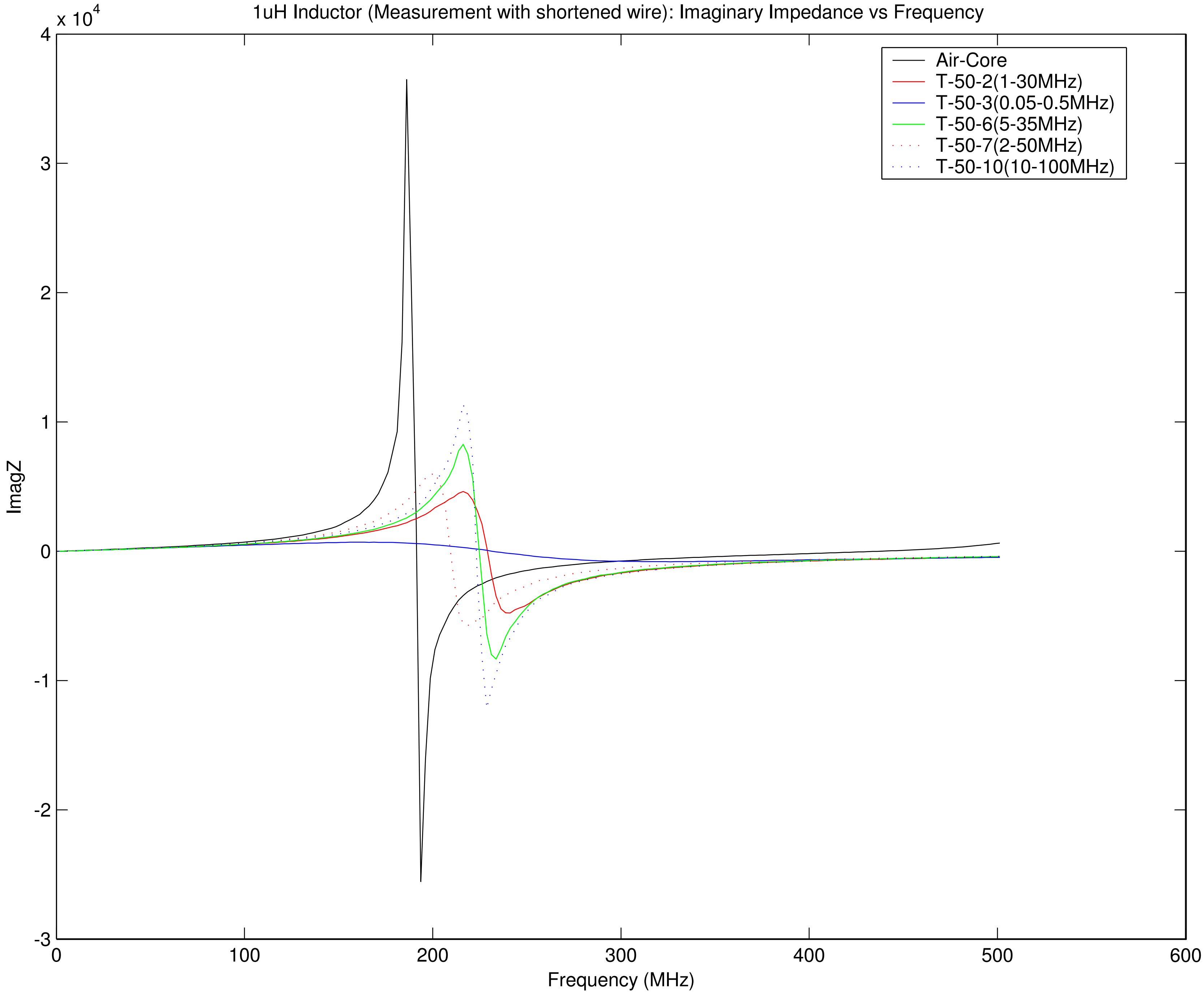

0.01uH Inductor (Measurement with shortened wire): Real Impedance vs Frequency
RealZ
Frequency (MHz)
60
50
40
30
20
10
0
-10
0
100
200
300
400
500
600
Air-Core
T-30-0(50-300MHz)
T-30-2(1-30MHz)
T-30-6(2-50MHz)
T-30-7(5-35MHz)
T-30-10(10-100MHz)
T-30-12(20-200MHz)

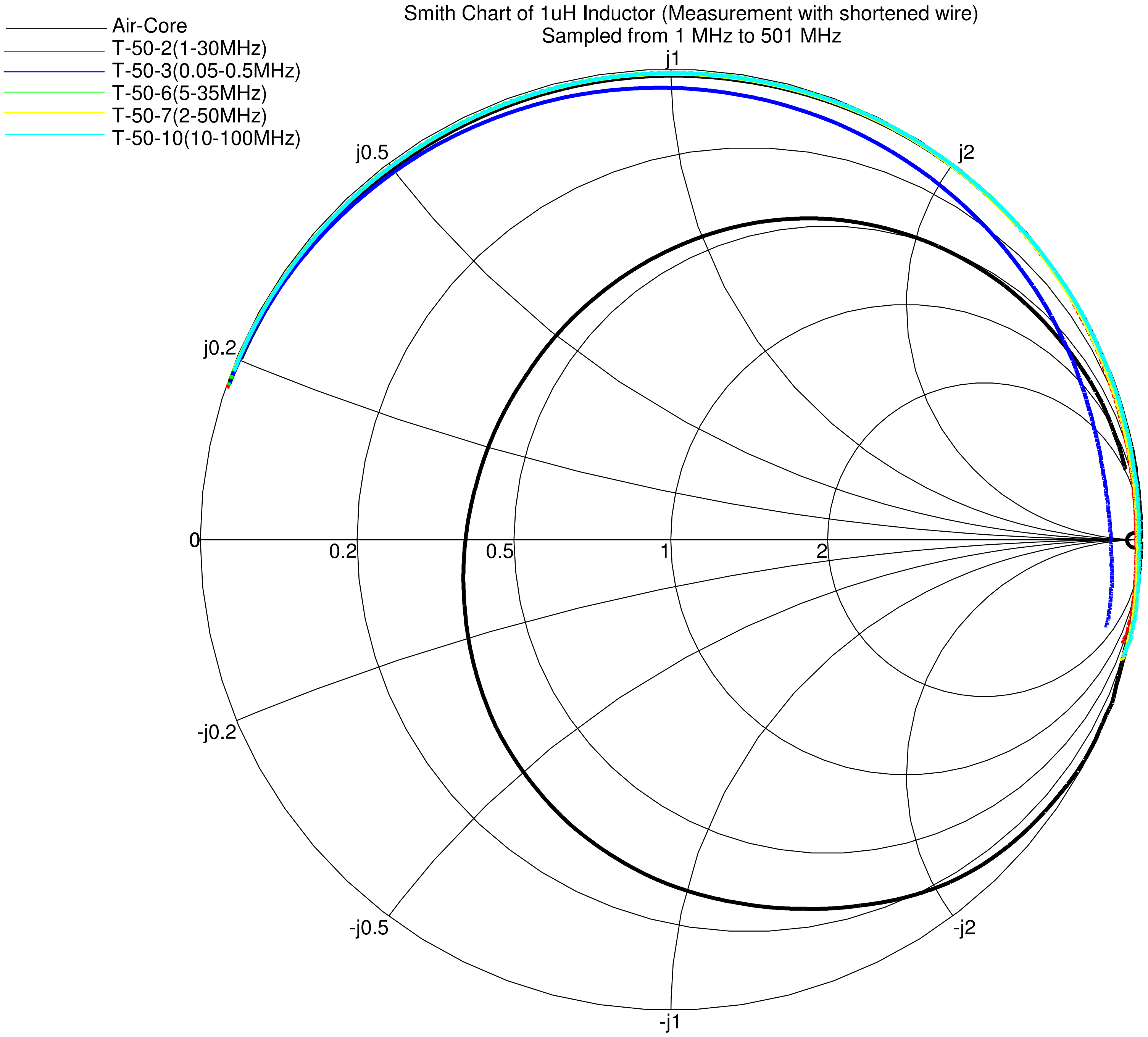

0.01uH Inductor (Measurement with shortened wire): Imaginary Impedance vs Frequency
Air-Core
T-30-0(50-300MHz)
T-30-2(1-30MHz)
T-30-6(2-50MHz)
T-30-7(5-35MHz)
T-30-10(10-100MHz)
T-30-12(20-200MHz)
ImagZ
Frequency (MHz)
0
50
100
150
200
250
300
350
0
100
200
300
400
500
600

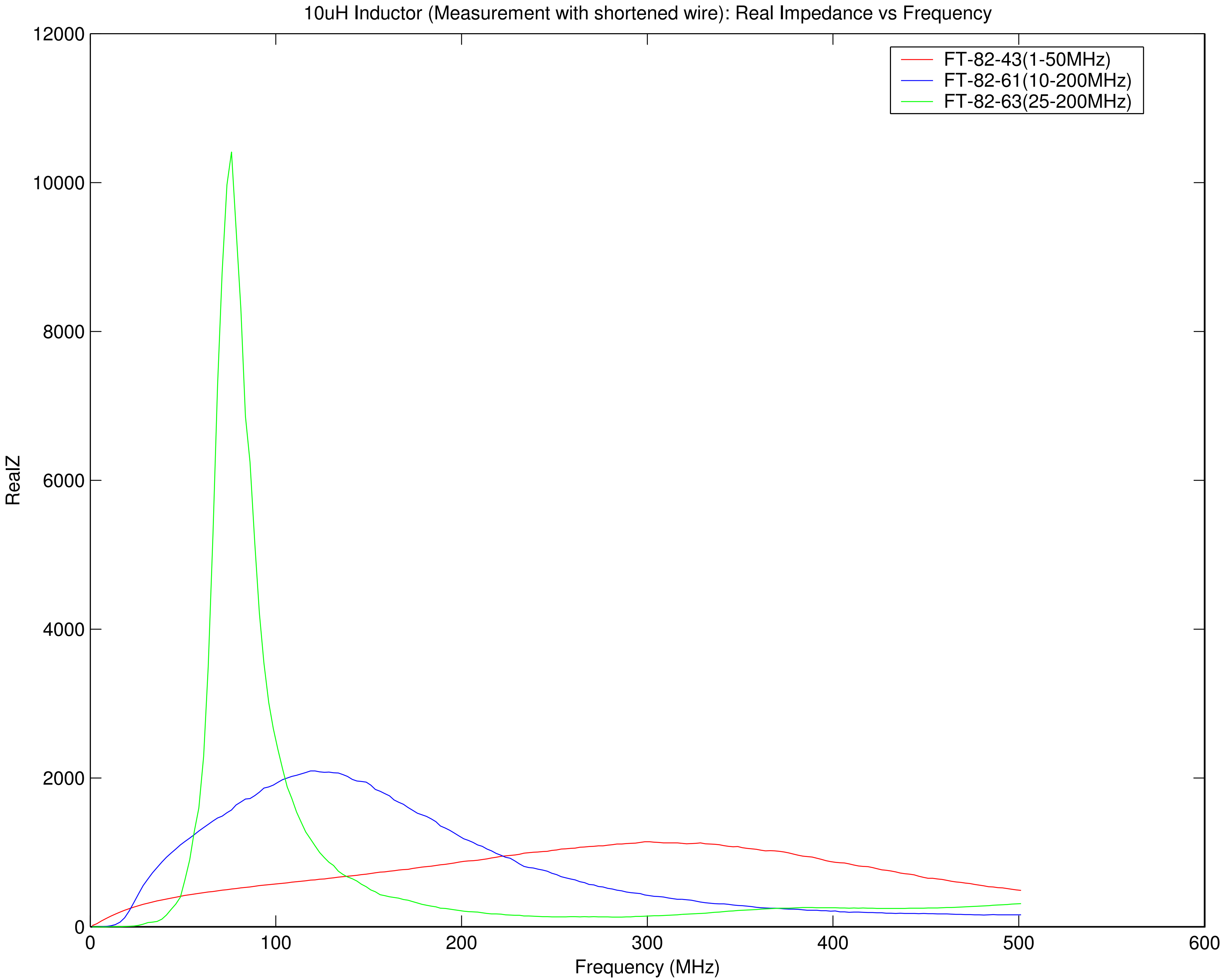


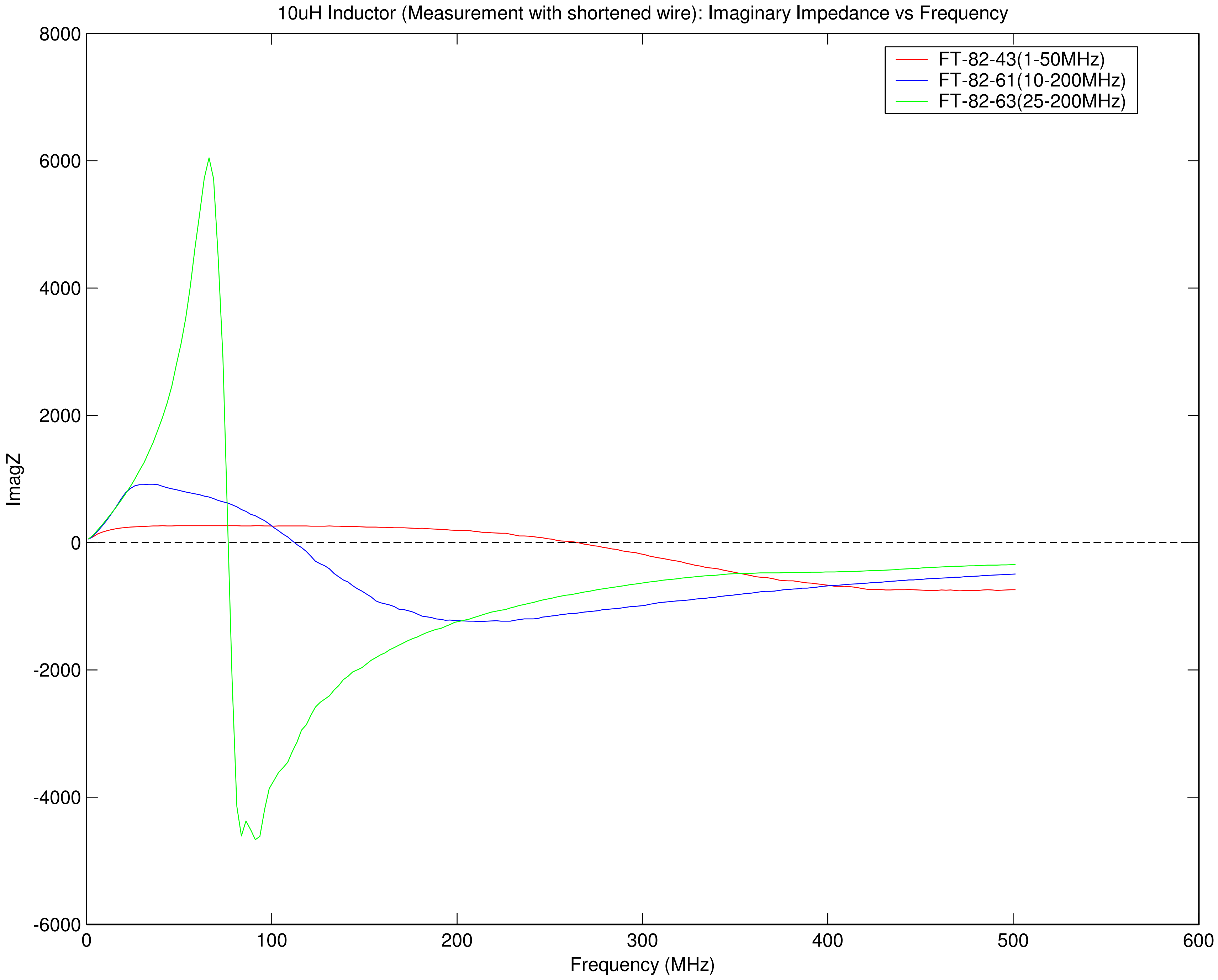
Smith Chart of 0.01uH Inductor (Measurement with shortened wire)
All components are sampled from 1 MHz to 501 MHz

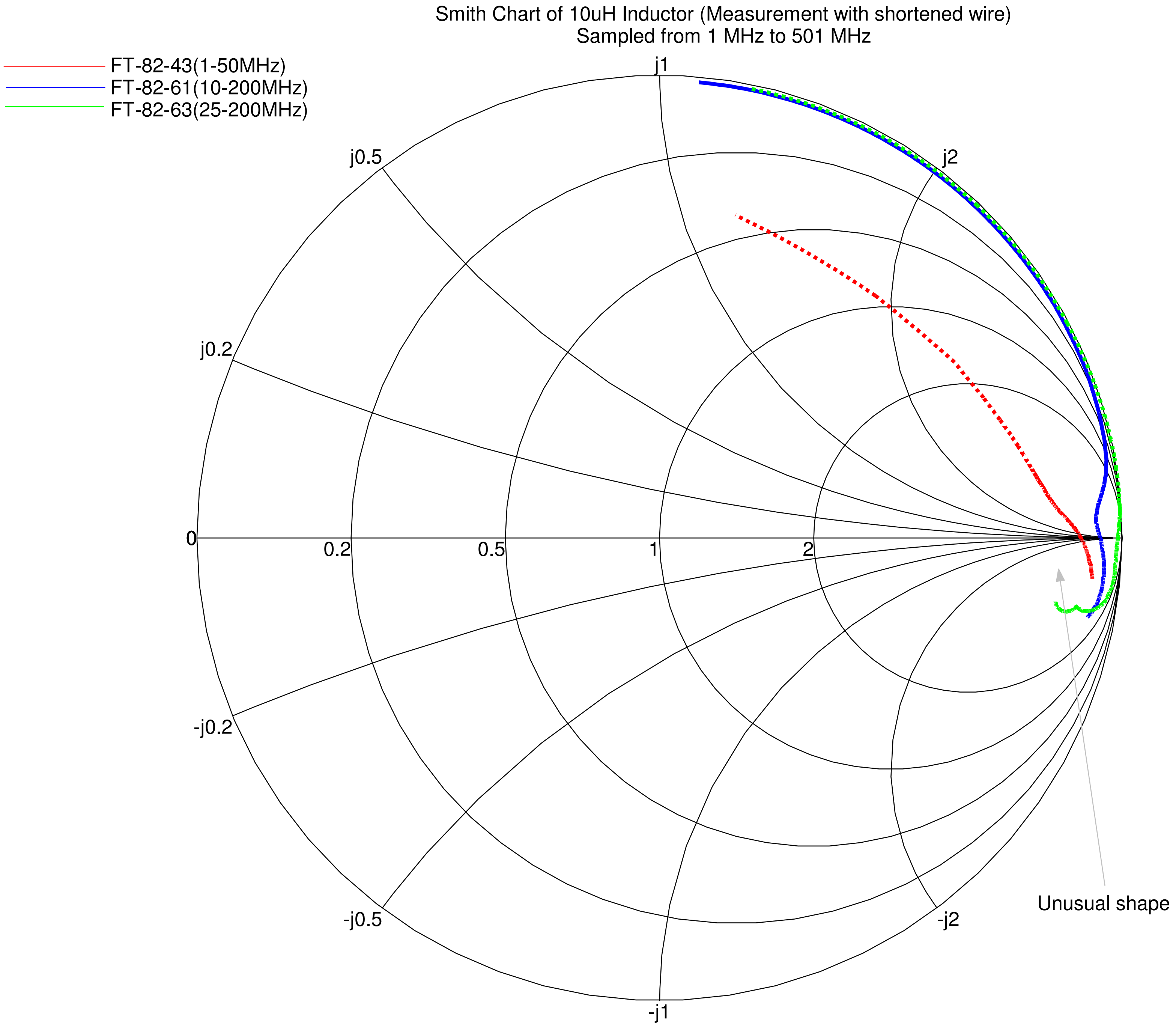

1uH Inductor (Measurement with shortened wire): Real Impedance vs Frequency
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
RealZ
0
100
200
300
400
500
600
Frequency (MHz)
Air-Core
T-50-2(1-30MHz)
T-50-3(0.05-0.5MHz)
T-50-6(5-35MHz)
T-50-7(2-50MHz)
T-50-10(10-100MHz)


1uH Inductor (Measurement with shortened wire): Imaginary Impedance vs Frequency
x 10^4
4
3
2
1
0
-1
-2
-3
ImagZ
0
100
200
300
400
500
600
Frequency (MHz)
Air-Core
T-50-2(1-30MHz)
T-50-3(0.05-0.5MHz)
T-50-6(5-35MHz)
T-50-7(2-50MHz)
T-50-10(10-100MHz)


Smith Chart of 1uH Inductor (Measurement with shortened wire)
Sampled from 1 MHz to 501 MHz
Air-Core
T-50-2(1-30MHz)
T-50-3(0.05-0.5MHz)
T-50-6(5-35MHz)
T-50-7(2-50MHz)
T-50-10(10-100MHz)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


10uH Inductor (Measurement with shortened wire): Real Impedance vs Frequency
FT-82-43(1-50MHz)
FT-82-61(10-200MHz)
FT-82-63(25-200MHz)
RealZ
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
Frequency (MHz)


10uH Inductor (Measurement with shortened wire): Imaginary Impedance vs Frequency
FT-82-43(1-50MHz)
FT-82-61(10-200MHz)
FT-82-63(25-200MHz)
ImagZ
8000
6000
4000
2000
0
-2000
-4000
-6000
0
100
200
300
400
500
600
Frequency (MHz)


Smith Chart of 10uH Inductor (Measurement with shortened wire)
Sampled from 1 MHz to 501 MHz
FT-82-43(1-50MHz)
FT-82-61(10-200MHz)
FT-82-63(25-200MHz)
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1
Unusual shape

3.8 Analysis on the Toroidal Core parameter and the resonant frequency

I found that the Toroidal Core parameter, $\mathrm{A_L}$ relates to the resonant frequency. When the resonant frequency is large when $\mathrm{A_L}$ is small.

Recall the equation for calculating the Number of Turns for Toroidal Core Inductor:

$$N = x\sqrt{\frac{L}{A_L}} \tag{25}$$

where x is either 100 or 1000. It depends on the type of the material.

Resonant frequency is given by the following equation:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{26}$$

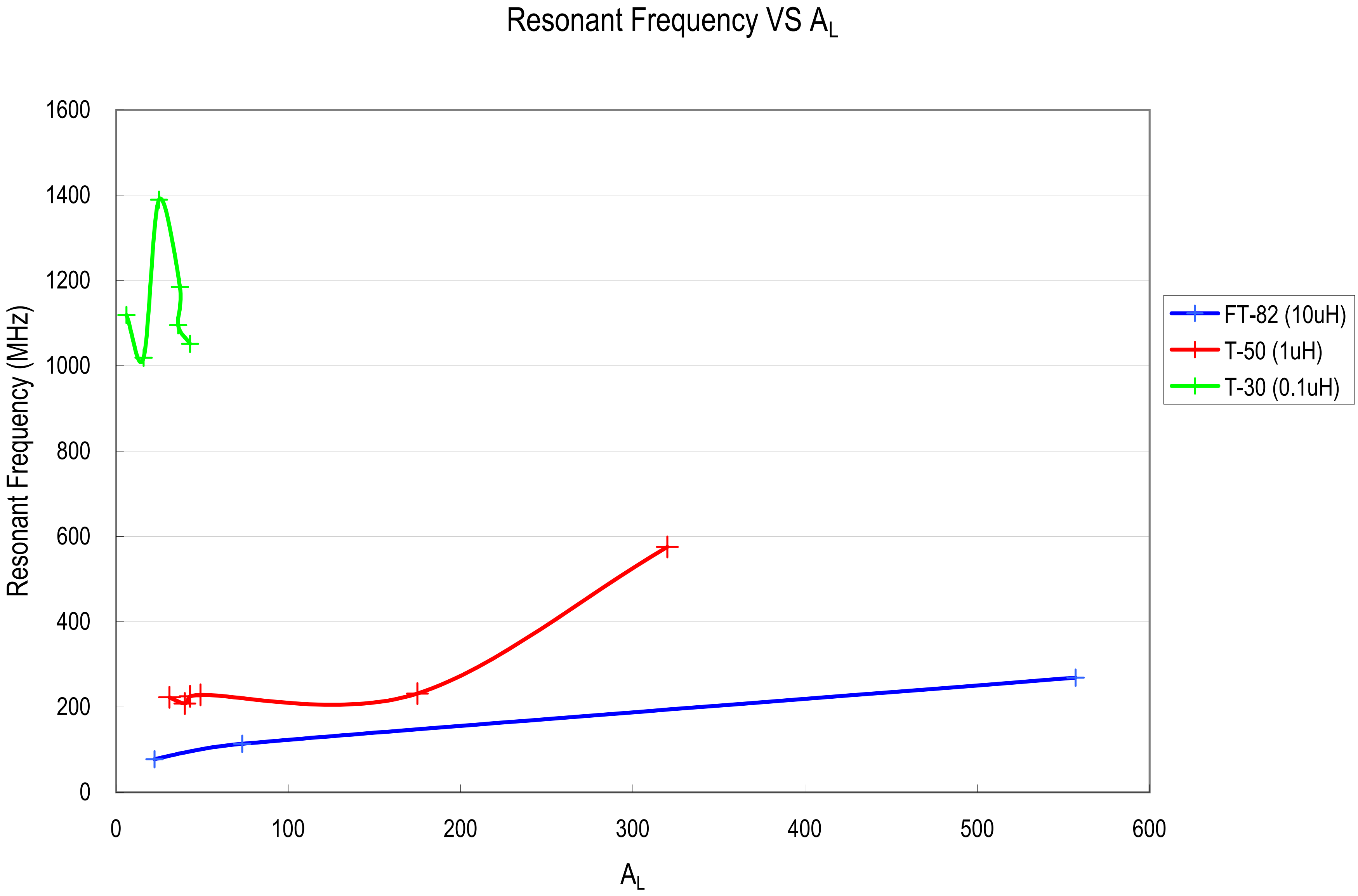
If we rearrange the Equation 25,

$$L = \left(\frac{N}{x}\right)^2 A_L \tag{27}$$

and we substitute the result to Equation 26:

$$\begin{aligned} f &= \frac{1}{2\pi\sqrt{\left(\frac{N}{x}\right)^2 A_L C}} \\ &= \frac{x}{2\pi N\sqrt{A_L C}} \end{aligned} \tag{28}$$

which explains the behavior of the samples.


Resonant Frequency VS A_L
Resonant Frequency (MHz)
1600
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500
600
A_L
FT-82 (10uH)
T-50 (1uH)
T-30 (0.1uH)

4 Conclusion

The models of resistor, capacitor and inductor are similar. Can we use a single model to describe all of them?

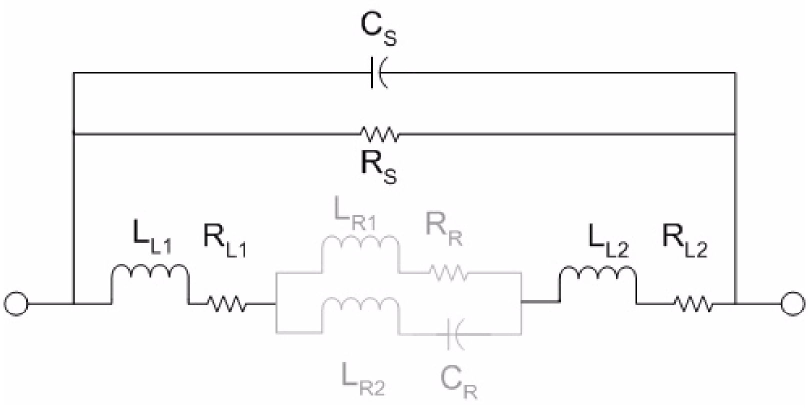


Figure 22: An equivalent model that represents resistor, capacitor and inductor.

If the resistor L_{R2} is zero, it becomes a resistor or inductor model that we introduced earlier:

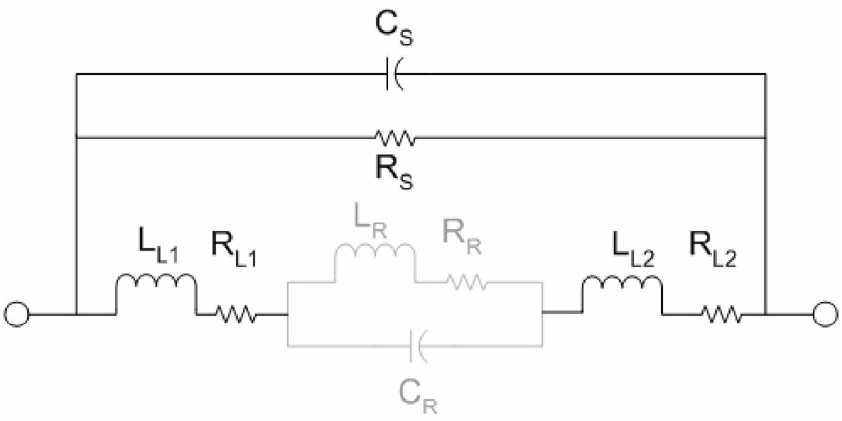


Figure 23: An equivalent model for Resistor and Inductor

If the resistor L_{R1} is zero, it becomes a capacitor model:

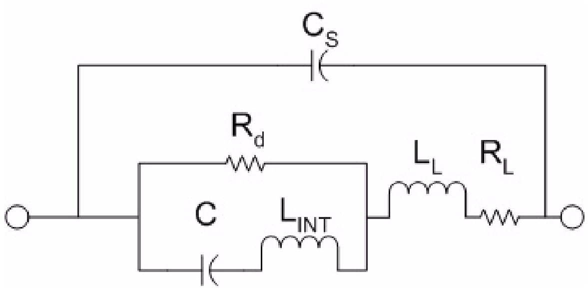


Figure 24:

This "convenient" model may give a good mathematical agreement with our measurement, but it is not realistic. In physical points of view, it is not possible to have such arrangement. Therefore, this is not a solution to improve this experiment.

In the Appendix, a discussion on the material of capacitor and inductor will be given. These information is helpful to analysis the frequency characteristics for the samples I selected.

5 Appendix

5.1 Discussion on the material of capacitor

Common capacitor material includes Electrolytic, Tantalum, Ceramic, Monolithic, Polystyrene and Silver Mica. Each of them have different characteristic, which make them behave differently in Frequency regions.

5.1.1 Electrolytic Capacitor

The electrode of Electrolytic Capacitor is made with aluminum. Generally, it capacitance ranges from 1μF to 1000μF. This type of capacitor is mainly used as a ripple filter in a power supply circuit, or as a filter to bypass the low frequency signals. Since electrolytic capacitor is similar to the nature of a coil in construction, it is not possible to be used for high-frequency circuits. It is known that its frequency characteristics is bad.

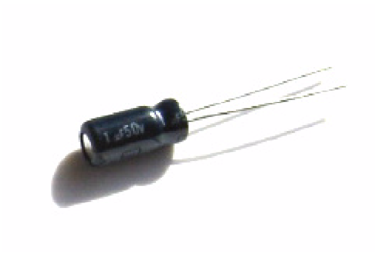


Figure 25: A 1μF 50V Electrolytic Leaded Capacitor

5.1.2 Tantalum Capacitor

Tantalum Capacitor is a type of Electrolytic Capacitor that the electrode is made with tantalum. It is more expensive than Aluminum Electrolytic Capacitor, because it behaves better than the Aluminum Electrolytic Capacitor in temperature and frequency.

Tantalum capacitor is very stable. Therefore, it is used for circuits which demand high stability in the capacitance values. It is used in analog signal system very often, because the current-spike noise that occurs with aluminum electrolytic capacitor does not appear.

Figure 26: A 100μF Tantalum Surface-Mounted Capacitor

5.1.3 Ceramic Capacitor

Ceramic Capacitor is made with Titanium Acid Barium, which is used as the dielectric material. Internally, the capacitor is not constructed as a coil. Therefore, it can be used in high frequency applications. Typically, the Ceramic Capacitor is used in bypassing the high frequency signals. The following capacitor has the shape of disk. Its capacitance is usually small.

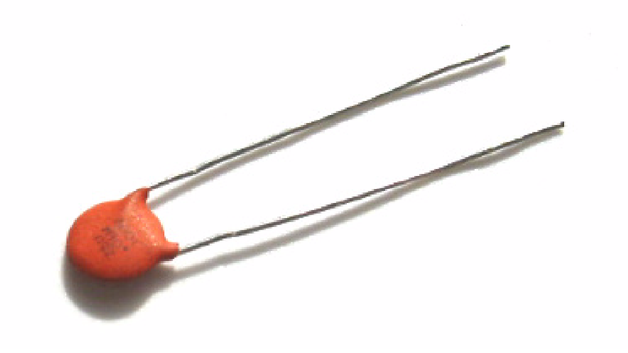


Figure 27: A 0.01μF CeramicDisk Leaded Capacitor

5.1.4 Monolithic Capacitor

The word Monolithic stands for “One-Stone”. It implies that the entire circuit is contained in a single component. Monolithic Capacitor is Ceramic Capacitor with multilayer of dielectric. The Monolithic Capacitor is small in size, and have good temperature and frequency characteristics. Usually, Monolithic Capacitor is used to bypass the high frequency. It is also employed in Digital circuit system because it has a good response with Square wave signal.

Figure 28: A 0.01uF Monolithic Leaded Capacitor

5.1.5 Polystyrene Capacitor

Polystrene Capacitor contains polystyrene as the dielectric material. It is not for use in high frequency circuit, because it is constructed like a coil inside. Instead, Polystrene Capacitor is widely used in the filter circuit and timing circuit, which run at several hundred kHz or less.

Figure 29: A 100pF PolyStrene Leaded Capacitor

5.1.6 SilverMica Capacitor

SilverMica Capacitor uses silver mica for the dielectric material. SilverMica capacitor has good stability because of its small temperature coefficient. Since it has a good frequency characteristic, and it is used for resonance circuit and high frequency filter. Also, SilverMica Capacitor has good insulation, and it can be utilized in high voltage circuit.

Figure 30: A 100pF SilverMica Leaded Capacitor

5.2 Discussion on Iron Powder Toroidal Core

Common Iron Powder Toroidal Core is made with the following material: #0, #2, #3, #6, #7, #10 and #12. They have different physical characteristics, which make their inductors have different properties.

5.2.1 Material #0

Material #0 ($\mu_r = 1$) is commonly used for frequencies above 100 MHz. Due to the nature of this material, the actual inductance may different from the calculating using its $\mathrm{A_L}$ value.

Figure 31: A 0.1μH T30-0 Iron Powder Toroidal Core Inductor

5.2.2 Material #2

Material #2 ($\mu_r = 10$) is a Carbonyl 'E' iron powder material which have a high volume resistivity. It has a high 'Q' from 2 MHz to 20 MHz. It is available in toroidal form and shielded coil form.

Figure 32: A 1μH T50-2 Iron Powder Toroidal Core Inductor

5.2.3 Material #3

Material #3 ($\mu_r = 35$) is a Carbonyl 'HP' material that have excellent stability and excellent 'Q' from 50 kHz to 500 kHz. It is available in toroidal form and shielded coil form.

Figure 33: A 1μH T50-3 Iron Powder Toroidal Core Inductor

5.2.4 Material #6

Material #6 ($\mu_r = 8$) is a Carbonyl 'SF' material. It has a high 'Q' and excellent temperature stability from 20 MHz to 50 MHz. It is available in toroidal form and shielded coil form.

Figure 34: A 1μH T50-6 Iron Powder Toroidal Core Inductor

5.2.5 Material #7

Material #7 ($\mu_r = 9$) is a Carbonyl 'TH' material. It is very similar to material #2 and #6, and it has a better temperature stability than the other two. It is available in toroidal form and shielded coil form.

Figure 35: A 1μH T50-7 Iron Powder Toroidal Core Inductor

5.2.6 Material #10

Material #10 ($\mu_r = 6$) is a powdered iron 'W' material. It has a high 'Q' and a high stability from 40 MHz to 100 MHz. It is available in toroidal form and shielded coil form.

Figure 36: A 1μH T50-10 Iron Powder Toroidal Core Inductor

5.2.7 Material #12

Material #12 ($\mu_r = 4$) is a Synthetic Oxide material which has a good 'Q' and moderate stability from 50 MHz to 200 MHz. It is available in toroidal form only.

Figure 37: A 0.1μH T30-12 Iron Powder Toroidal Core Inductor

5.3 Matlab code for Resistor Model

The Matlab script is designed to fit the data to the following Resistor Model:

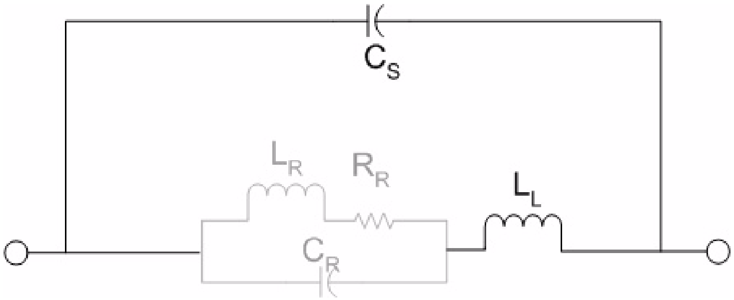


Figure 38: Simplified Realistic Resistor Model

Before performing the data fitting, it is necessary to import the data of interested sample in Matlab. The data file is in text format. Each data file contains three different measurements: Frequency(MHz), Real Impedance(Ω) and Imaginary Impedance(Ω). They should be stored using the following variable name: **freq**, **RealZ** and **ImagZ**.

After importing the data, run the following command:

```
testCompleteR
ModelR
```

After the command is done, the results are store in the variable **x**. **x** is an 1 by 5 array. It stores the following variable:

$$\begin{pmatrix} R_1(\Omega) \\ L_1(\mathrm{nH}) \\ C_1(\mathrm{pF}) \\ L_2(\mathrm{nH}) \\ C_2(\mathrm{pF}) \end{pmatrix}$$

where R_1,L_1 and C_1 are the Internal Components (The grey components), L_2 and C_2 are the Transmission Line Components.

5.3.1 testCompleR.m

This function is the core function. It performs a non-linear data fitting using Least Square Method. By calling a Matlab build-in function, LSQNONLIN and self-defined function, fitCompleteR, this function will generate an array that contain the best guess of the values.

```
% R1, L1, C1:  Resistor Internal Components
% L2, C2:  Transmission Line Components
%
% Unit of Component
% R1:  Ω
% L1, L2:  nH
% C1, C2:  pF
%
% Define and initialize the data sets
w = freq*2*pi;
RealZExp = RealZ;
ImagZExp = ImagZ;
ZExp = RealZExp + j*ImagZExp;

% Initialize the guess values of the function.
% [R1 L1 C1 L2 C2]
X0=[1 1 1 1 1]’;

% Set an options file for LSQNONLIN
options = optimset(’Largescale’,’off’,
’MaxFunEvals’,inf,’MaxIter’,inf,’DiffMinChange’,1e-3,
’MaxPCGIter’,inf,’DerivativeCheck’,’on’,’LevenbergMarquardt’,’on’);

% Calculate the new coefficients using LSQNONLIN.
x=lsqnonlin(’fitCompleteR’,X0,[],[],options,w,ZExp);

% Z1Model:  Impedance of the Internal Component
Z1Model = (j*w.*x(3)*1e-12 + (x(1) + j*w.*x(2)*1e-9).^-1 ).^-1;

% ZOverall:  Overall impedance
ZOverall = (j*w.*x(5)*1e-12 + (Z1Model + j*w.*x(4)*1e-9).^-1 ).^-1;

% ModelR is a function that plots the Complex Impedance, Magnitude and
Phase in linear scale.
m=x;
ModelR;


% End of file
```

5.3.2 fitCompleteR.m

This function calculates the difference between the data of the measurement and the model. The difference, $diff$ is defined as following:

$$diff = \sqrt{(\mathrm{Re}\,\mathrm{Z})^2 + (\mathrm{Im}\,\mathrm{Z})^2 + (\mathrm{Magnitude})^2 + (\mathrm{Phase})^2} \tag{29}$$

```
function diff = fitCompleteR(x,X,Y)


% Define the variable
R1=x(1);
L1=x(2);
C1=x(3);
L2=x(4);
C2=x(5);


% Z1 represents the following components:  R1, C1 and L1.
Z1 = (j*X.*C1*1e-12 + (R1 + j*X.*L1*1e-9).^-1 ).^-1;
ZR = real((j*X.*C2*1e-12 + (Z1 + j*X.*L2*1e-9).^-1 ).^-1);
ZI = imag((j*X.*C2*1e-12 + (Z1 + j*X.*L2*1e-9).^-1 ).^-1);
ZMag = sqrt(ZR.^2 + ZI.^2);
ZPhase = phase(ZR + j*ZI);


% Model data
YR = real(Y);
YI = imag(Y);
YMag = sqrt(YR.^2 + YI.^2);
YPhase = phase(Y);


% Calculate the diff
diffR = ZR - YR;
diffI = ZI - YI;
diffMag = ZMag - YMag;
diffPhase = ZPhase - YPhase;


% Return the diff
diff = sqrt(diffR.^2 + diffI.^2 + diffMag.^2 + diffPhase.^2);

% End of file
```

5.3.3 ModelR.m

This function plots the Real Impedance, Imaginary Impedance, Magnitude and Phase in linear scale. It also calculate the R-square value for each plot.

```
w = freq*2*pi;
RealZExp = RealZ;
ImagZExp = ImagZ;
R1=m(1);
L1=m(2);
C1=m(3);
L2=m(4);
C2=m(5);

Z_1 = (j*w.*C1*1e-12 + (R1 + j*w.*L1*1e-9).^-1 ).^-1;
Z_Overall = ((j*w.*C2*1e-12 + (Z_1 + j*w.*L2*1e-9).^-1 ).^-1);
RealZModel = real(Z_Overall);
ImagZModel = imag(Z_Overall);
MagZModel = sqrt((real(Z_Overall)).^2 + (imag(Z_Overall)).^2);
PhaseZModel = phase(Z_Overall);
freqM = freq/1e6;

% Plotting the Real Impedance
subplot(2,2,1);
plot(freqM,RealZExp,'r',freqM,real(Z_Overall),'b')
title('Real Impedance vs Frequency');
ylabel('RealZ');
xlabel('Frequency (MHz)');

% Plotting the Imaginary Impedance
subplot(2,2,3);
plot(freqM,ImagZExp,'r',freqM,imag(Z_Overall),'b')
title('Imaginary Impedance vs Frequency');
ylabel('ImagZ');
xlabel('Frequency (MHz)');

% Plotting the Magnitude
subplot(2,2,2);
plot(freqM,abs(ZExp),'r',freqM,abs(Z_Overall),'b')
title('Magnitude vs Frequency');
ylabel('Magnitude');
xlabel('Frequency (MHz)');
```

```
% Plotting the Phase
subplot(2,2,4);
plot(freqM,phase(ZExp),'r',freqM,phase(Z_Overall),'b')
title('Phase vs Frequency');
ylabel('Phase');
xlabel('Frequency (MHz)');

% R-square value calulation
RealZExp = RealZ;
ImagZExp = ImagZ;
MagZExp = abs(RealZExp + j*ImagZExp);
PhaseZExp = phase(RealZExp + j*ImagZExp);

RealZR = corrcoef(RealZExp, RealZModel);
RealZRSquare = RealZR(2)^2

ImagZR = corrcoef(ImagZExp, ImagZModel);
ImagZRSquare = ImagZR(2)^2

MagZR = corrcoef(MagZExp, MagZModel);
MagZRSquare = MagZR(2)^2

PhaseZR = corrcoef(PhaseZExp, PhaseZModel);
PhaseZRSquare = PhaseZR(2)^2


% End of File
```

5.4 Matlab code for Capacitor Model

The code for finding the capacitor component is very similar to the resistor, except for calculating the internal impedance.

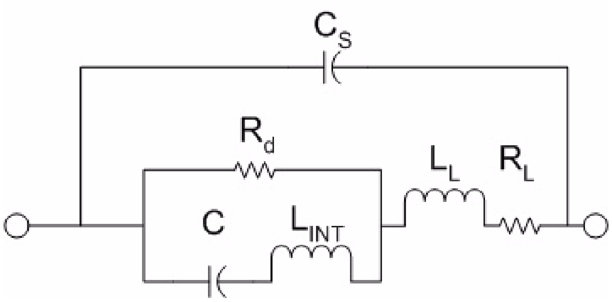


Figure 39: Equivalent Model for Capacitor

5.4.1 testCompleC.m

```
% R1, L1, C1:  Resistor Internal Components
   % R2, L2, C2:  Transmission Line Components
   %
   % Unit of Component
   % R1, R2:  Ω
   % L1, L2:  nH
   % C1, C2:  pF
   %
   % Define and initialize the data sets
   w = freq*2*pi;
   RealZExp = RealZ;
   ImagZExp = ImagZ;
   ZExp = RealZExp + j*ImagZExp;

   % Initialize the guess values of the function.
   % [R1 L1 C1 R2 L2 C2]
   X0=[1 1 abs(1/(ImagZ(1)*w(1))*1e12) 1 1 1]’;

   % Set an options file for LSQNONLIN
   options = optimset(’Largescale’,’off’,
   ’MaxFunEvals’,inf,’MaxIter’,inf,’DiffMinChange’,1e-3,
   ’MaxPCGIter’,inf,’DerivativeCheck’,’on’,’LevenbergMarquardt’,’on’);

   % Calculate the new coefficients using LSQNONLIN.
```

```
   x=lsqnonlin('fitCompleteR',X0,[],[],options,w,ZExp);
   % Z1Model:  Impedance of the Internal Component
   Z1Model = ((j*w.*x(3)*1e-12)^-1 + j*w.*x(2)*1e-9).^-1 + x(1).^-1).^-1

   % ZOverall:  Overall impedance
   ZOverall = (j*w.*x(6)*1e-12 + (Z1Model + x(4) + j*w.*x(5)*1e-9).^-1 ).^-1;

   % ModelR is a function that plots the Complex Impedance, Magnitude and
Phase in linear scale.
   m=x;
   ModelC;


   % End of file
```

5.4.2 fitCompleteC.m

This function calculates the difference between the data of the measurement and the model. The difference, $diff$ is defined as following:

$$diff = \sqrt{(\mathrm{Re}\,\mathrm{Z})^2 + (\mathrm{Im}\,\mathrm{Z})^2 + (\mathrm{Magnitude})^2 + (\mathrm{Phase})^2} \tag{30}$$

```
function diff = fitCompleteR(x,X,Y)


% Define the variable
R1=x(1);
L1=x(2);
C1=x(3);
R2=x(4);
L2=x(5);
C2=x(6);


% Z1 represents the following components:  R1, C1 and L1.
Z1 = (((j*X.*C1*1e-12).^-1 + j*X.*L1*1e-9)).^-1 + R1.^-1).^-1;
ZR = real((j*X.*C2*1e-12 + (Z1 + R2 + j*X.*L2*1e-9).^-1 ).^-1);
ZI = imag((j*X.*C2*1e-12 + (Z1 + R2 + j*X.*L2*1e-9).^-1 ).^-1);
ZMag = abs(ZR + j*ZI);
ZPhase = phase(ZR + j*ZI);


% Model data
YR = real(Y);
YI = imag(Y);
YMag = abs(Y);
YPhase = phase(Y);


% Calculate the diff
diffR = ZR - YR;
diffI = ZI - YI;
diffMag = ZMag - YMag;
diffPhase = ZPhase - YPhase;


% Return the diff
diff = sqrt(diffR.^2 + diffI.^2 + diffMag.^2 + diffPhase.^2);
% End of File
```

5.4.3 ModelC.m

This function plots the Real Impedance, Imaginary Impedance, Magnitude and Phase in linear scale. It also calculate the R-square value for each plot.

```
w = freq*2*pi;
RealZExp = RealZ;
ImagZExp = ImagZ;
R1=m(1);
L1=m(2);
C1=m(3);
R2=m(4);
L2=m(5);
C2=m(6);

Z_1 = (((j*w.*C1*1e-12).^-1 + j*w.*L1*1e-9).^-1 + R1.^-1).^-1;
Z_Overall = ((j*w.*C2*1e-12 + (Z_1 + R2 + j*w.*L2*1e-9).^-1 ).^-1);
RealZModel = real(Z_Overall);
ImagZModel = imag(Z_Overall);
MagZModel = abs(Z_Overall);
PhaseZModel = phase(Z_Overall);
freqM = freq/1e6;

% Plotting the Real Impedance
subplot(2,2,1);
plot(freqM,RealZExp,'r',freqM,real(Z_Overall),'b')
title('Real Impedance vs Frequency');
ylabel('RealZ');
xlabel('Frequency (MHz)');

% Plotting the Imaginary Impedance
subplot(2,2,3);
plot(freqM,ImagZExp,'r',freqM,imag(Z_Overall),'b')
title('Imaginary Impedance vs Frequency');
ylabel('ImagZ');
xlabel('Frequency (MHz)');

% Plotting the Magnitude
subplot(2,2,2);
plot(freqM,abs(ZExp),'r',freqM,abs(Z_Overall),'b')
title('Magnitude vs Frequency');
ylabel('Magnitude');
xlabel('Frequency (MHz)');
```

```
% Plotting the Phase
subplot(2,2,4);
plot(freqM,phase(ZExp),'r',freqM,phase(Z_Overall),'b')
title('Phase vs Frequency');
ylabel('Phase');
xlabel('Frequency (MHz)');

% R-square value calulation
RealZExp = RealZ;
ImagZExp = ImagZ;
MagZExp = abs(RealZExp + j*ImagZExp);
PhaseZExp = phase(RealZExp + j*ImagZExp);

RealZR = corrcoef(RealZExp, RealZModel);
RealZRSquare = RealZR(2)^2

ImagZR = corrcoef(ImagZExp, ImagZModel);
ImagZRSquare = ImagZR(2)^2

MagZR = corrcoef(MagZExp, MagZModel);
MagZRSquare = MagZR(2)^2

PhaseZR = corrcoef(PhaseZExp, PhaseZModel);
PhaseZRSquare = PhaseZR(2)^2


% End of File
```

5.5 Matlab code for Inductor Model

Since inductor and resistor share the same model, it is okay find the component of inductor models using the code of resistor.

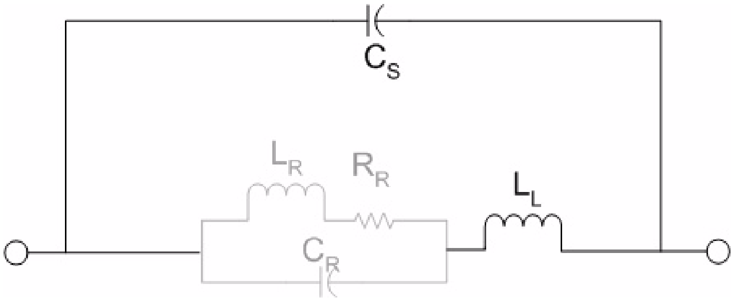


Figure 40: Equivalent of Inductor Model

However, it would be better to change the initial guess value. The Low-Frequency Approximation can be used to find the guess value of the internal components.

$$\begin{aligned} \mathrm{R}_R &= \mathrm{real\,Z}\left(f = 1\mathrm{MHz}\right) && (31) \\ L &= \frac{\mathrm{imagZ}\left(f = 1\mathrm{MHz}\right)}{2\pi\left(1\mathrm{MHz}\right)} && (32) \\ C &= \frac{1}{\left((2\pi f_r)^2\right) L} && (33) \end{aligned}$$

where f_r is the resonant frequency. If f_r is beyond the sampling frequency (i.e., $f_r > 501\mathrm{MHz}$), it is not possible to locate the resonant frequency. Since it is required to calculate the capacitance. Therefore, I use another Network Analyzer (Sampling from 1 MHz to 2 GHz) to find out the resonant frequency[6]. Since the maximum frequency of the fixture is 500 MHz, the resonant frequency is not reliable. It is only good for reference. The modification is given followed:

On line 17 of testCompleteR.m, the initial guess value should be changed to be:

```
% Initialize the guess values of the function.
% [R1 L1 C1 L2 C2]
fr = The measured Resonant frequency in Hz;
Lint = ImagZ(1)/w(1);
Cint = 1/((2*pi*fr)^2*Lint);
% The default units of Inductance and Capacitance
% are in uH and pF respectively.
X0=[RealZ(1) Lint*1e9 Cint*1e12 1 1]';
```

---

[6] Calibration is necessary if frequency has been changed. To avoid the inconvenience, it is better to use multiple Network Analyzers.

5.6 Matlab code for plotting Smith Chart

The built-in library Matlab 6.5 does not support the Smith Chart. Therefore, I used the code provided by Mathworks, the manufacture of Matlab. However, the provided function can only draw a line between two points. Therefore, I write an addition function, such that the it can plot my samples with 201 sampling points.

5.6.1 sss.m

This function go through every data points and join them together. Therefore, it can plot all the sampling points in a single Smith Chart.

```
i = 1;
while (i < 201)
 smiim(ZExp1(i)/50, ZExp1(i+1)/50);
 i = i + 1;
end
```

The file will call a function, *smiim* to generate the Smith Chart. The parameters are the Real Impedance and Imaginary Impedance respectively. Both data are normalized by dividing $Z_0(= 50\Omega)$ before passing into the function.

For more information about the smiim.m, please refer to the following website:

http://www.mathworks.com/support/solutions/data/4565.shtml

5.7 Matlab code for Normalization

As mentioned in earlier sections, it is necessary to normalize the data before running the simulation. It is impossible to have negative points in the real impedance. The following function will zero all the negative points.

5.7.1 NormalizeRealZ.m

The function will search the negative point of Real Impedance. If the value is smaller than zero, then it will be replaced by zero.

```
i = 1;
while(i < 202)
 if RealZ(i) < 0
 RealZ(i) = 0;
 end
 i = i + 1;
end
```

5.7.2 signFunction.m

Sometimes, Matlab gives the negative value for the Resistor Model component(e.g., Negative resistance), which is not possible in realistic world. Therefore, it is necessary to eliminate this error during data fitting. This function accepts a real value. It returns 1 if it is positive, otherwise it returns 0.

```
function resultVal = signFunction(Val)
if Val < 0
 resultVal = 0;
else
 resultVal = 1;
end
% End of file
```

This function is used during the curve fitting. Even Matlab generates a negative value, it will not affect the overall result because it is zero. By doing this, the result of simulation will fall into an acceptable range.

5.8 Notes on Calibration Error

Calibration is important to the impedance measurement using Network Analyzer, because it accounts the fact of the measurement environment. For example, when we do the short measurement, we expect to see a zero impedance. However, a non-zero impedance will appear on screen if we "short" the fixture. Therefore, it is important to calibrate the Network Analyzer before doing any measurement.

In this project, we only consider the One Port Calibration (S11 1-Port). We only calibrate three standards: Open, Short and Load. For the "Load" Calibration, we use a 49.9Ω Thin-Film Chip Resistor as a 50Ω reference resistance. The Network Analyzer will take it as a reference in the user's sampling frequency range.

One way to determine whether the calibration is successful or not is by observing the Real Impedance. At the low frequency (e.g., 1 MHz), the component usually behaves like its marked value because the effect from capacitor and inductor is small. Therefore, we expect the real impedance of 49.9Ω Thin-Film Chip Resistor is around 50Ω.

The plot on the next pages show a successful calibration along with several unsuccessful calibrations. Every calibration is performed using the same equipment, sample (only for same marked value) and same frequency range. The following is the specification of the calibrations:

Equipment

1. Hewlett-Packard Network Analyzer 8753D (30 kHz - 6 GHz)
2. Hewlett-Packard S-Parameter Test Set 85047A (300 kHz - 6 GHz)
3. Hewlett-Packard Spring Clip Fixture 16092A (MAX 500 MHz)

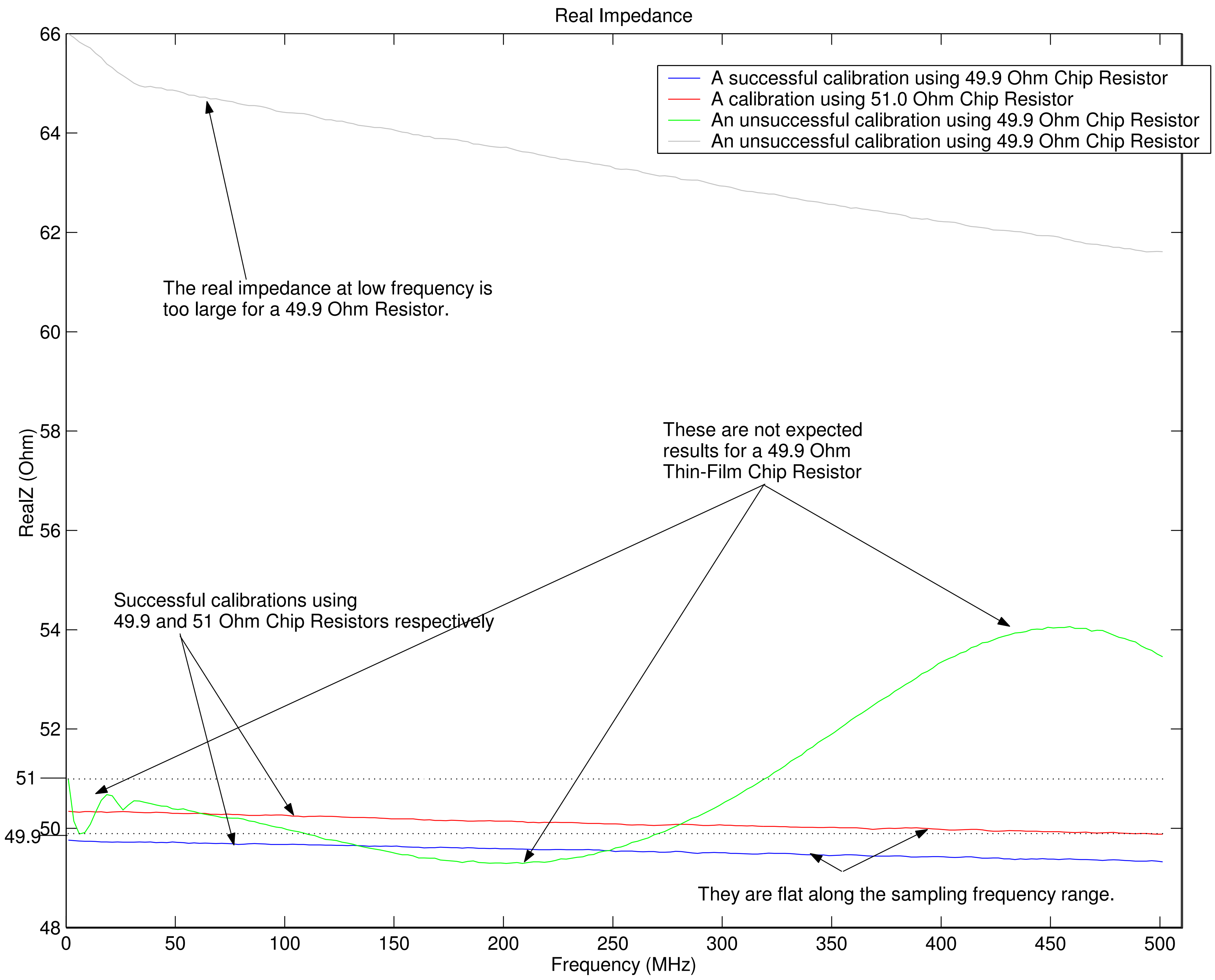
Samples

1. 49.9Ω Thin-Film Chip Resistor
2. 51.0Ω Thin-Film Chip Resistor

Calibration Setting

1. Sampling Frequency Range: 1 MHz to 501 MHz
2. Type of Calibration: One-Port Calibration on Short, Open and Load.

The next pages show the plots of real impedance, imaginary impedance and Smith Chart of the Calibration result. Calibration has to be repeated if the result is incorrect. Therefore, a good calibration is important because it affects the result of rest measurements.

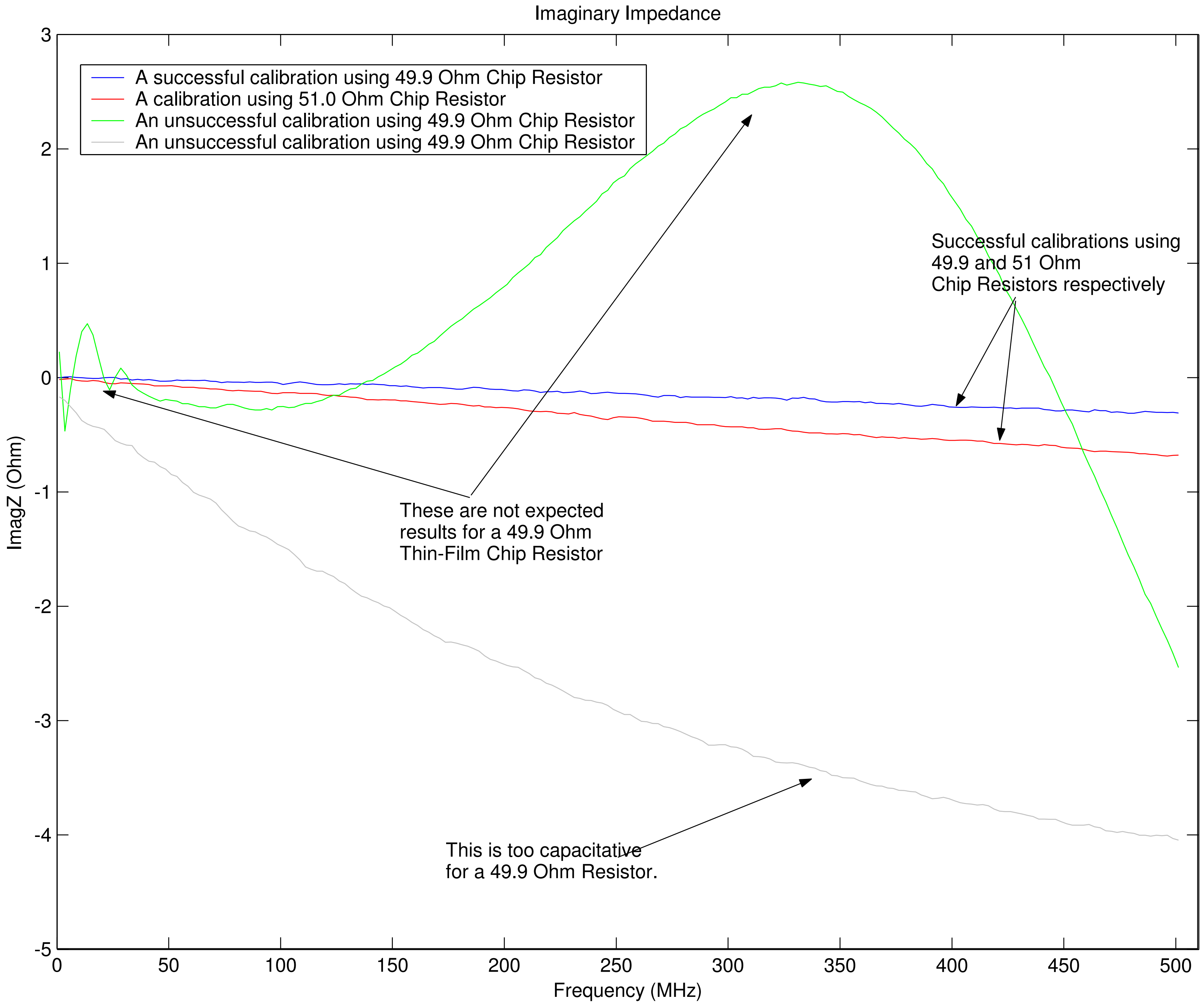


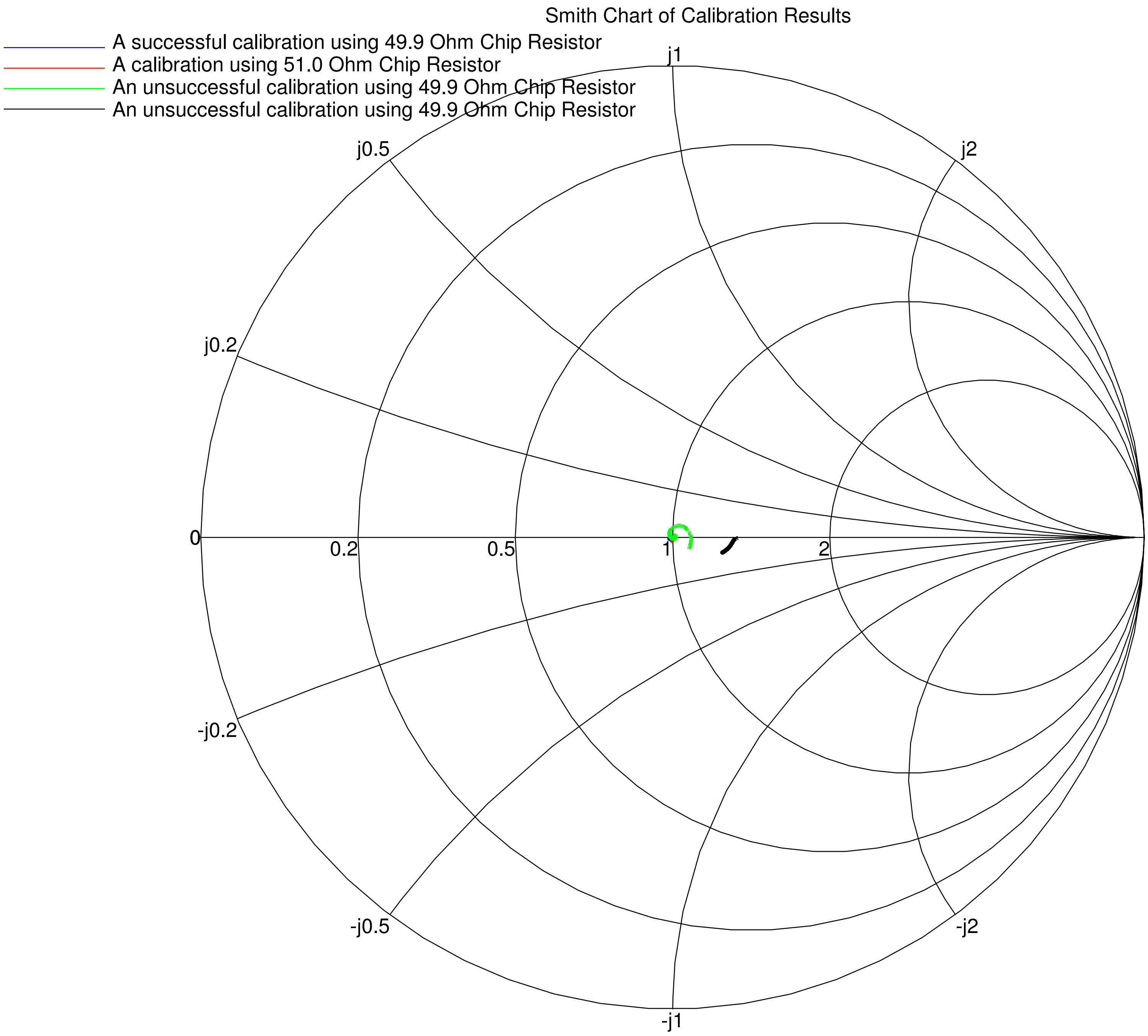
The real impedance at low frequency is too large for a 49.9 Ohm Resistor.

These are not expected results for a 49.9 Ohm Thin-Film Chip Resistor

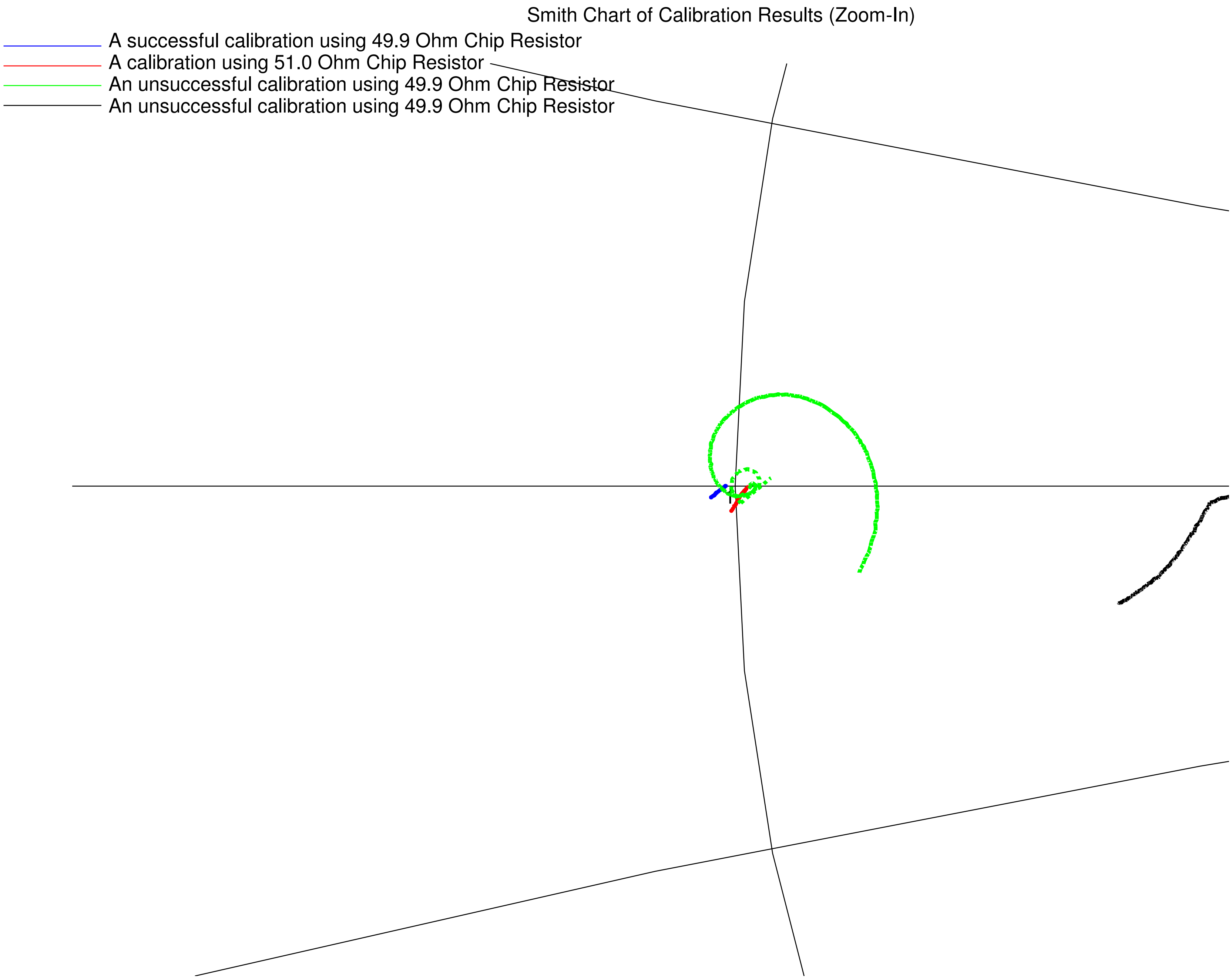
Successful calibrations using 49.9 and 51 Ohm Chip Resistors respectively

They are flat along the sampling frequency range.


Imaginary Impedance
A successful calibration using 49.9 Ohm Chip Resistor
A calibration using 51.0 Ohm Chip Resistor
An unsuccessful calibration using 49.9 Ohm Chip Resistor
An unsuccessful calibration using 49.9 Ohm Chip Resistor
Successful calibrations using
49.9 and 51 Ohm
Chip Resistors respectively
These are not expected
results for a 49.9 Ohm
Thin-Film Chip Resistor
This is too capacitative
for a 49.9 Ohm Resistor.
ImagZ (Ohm)
Frequency (MHz)
3
2
1
0
-1
-2
-3
-4
-5
0
50
100
150
200
250
300
350
400
450
500



Smith Chart of Calibration Results
A successful calibration using 49.9 Ohm Chip Resistor
A calibration using 51.0 Ohm Chip Resistor
An unsuccessful calibration using 49.9 Ohm Chip Resistor
An unsuccessful calibration using 49.9 Ohm Chip Resistor
j1
j0.5
j2
j0.2
0
0.2
0.5
1
2
-j0.2
-j0.5
-j2
-j1


Smith Chart of Calibration Results (Zoom-In)
A successful calibration using 49.9 Ohm Chip Resistor
A calibration using 51.0 Ohm Chip Resistor
An unsuccessful calibration using 49.9 Ohm Chip Resistor
An unsuccessful calibration using 49.9 Ohm Chip Resistor

References

[1] C. D. Cheng, "Lab #1: High Frequency Characteristics of Components", *ECE 353 Lab Report*, 2003

[2] C. D. Cheng, "Lab #2: RF Oscillator", *ECE 353 Lab Report*, 2003

[3] C. D. Cheng, "Lab #3: Broadband RF Amplifier", *ECE 353 Lab Report*, 2003

[4] CWS ByteMark, *Iron Powder Toroidal Cores (for resonant circuits)*. Retrieved on July 2003, from: http://www.bytemark.com/products/iptcres.htm.

[5] Elna Magnetics, *Ferroxcube 2002 Data Handbook*. Retrieved on July 2003, from: http://www.elnamagnetics.com/literature/catalogs/ferroxcube/2002_handbook

[6] S. J. Franke, *ECE 353 Radio Communication Circuits*, University of Illinois at Urbana-Champaign, IL 2003.

[7] S. Inoue, *Basic knowledge of Electronic parts*. Retrieved on July 2003, from: http://www.interq.or.jp/japan/se-inoue/e_parts.htm.

[8] Mathworks, *Technical Notes #1504: How Do I Fit a Function to Data Using LSQNONLIN?*. Retrieved on July, 2003, from: http://www.mathworks.com/support/tech-notes/1500/1504.shtml.

[9] Mathworks, *Solution Notes #4565: Can I generate a Smith Chart with MATLAB or any of the Toolboxes?*. Retrieved September, 2003, from: http://www.mathworks.com/support/solutions/data/4565.shtml

[10] N. N. Rao, *Elements of Engineering Electromagnetics*, Prentice Hall, 1999.

[11] R. Rhea, "Filters and an Oscillator Using a New Solenoid Model", *Applied Microwave & Wireless*, November 2000.

[12] Welwyn Components Ltd, *Application Specific Electronic Components.* Retrieved on July 2003, from: http://www.welwyn-tt.co.uk/products/index.html.

[13] Welwyn Components Ltd, *An Introduction to Carbon Composition Resistors.* Retrieved on July 2003, from: http://www.welwyn-tt.co.uk/products/index.html.