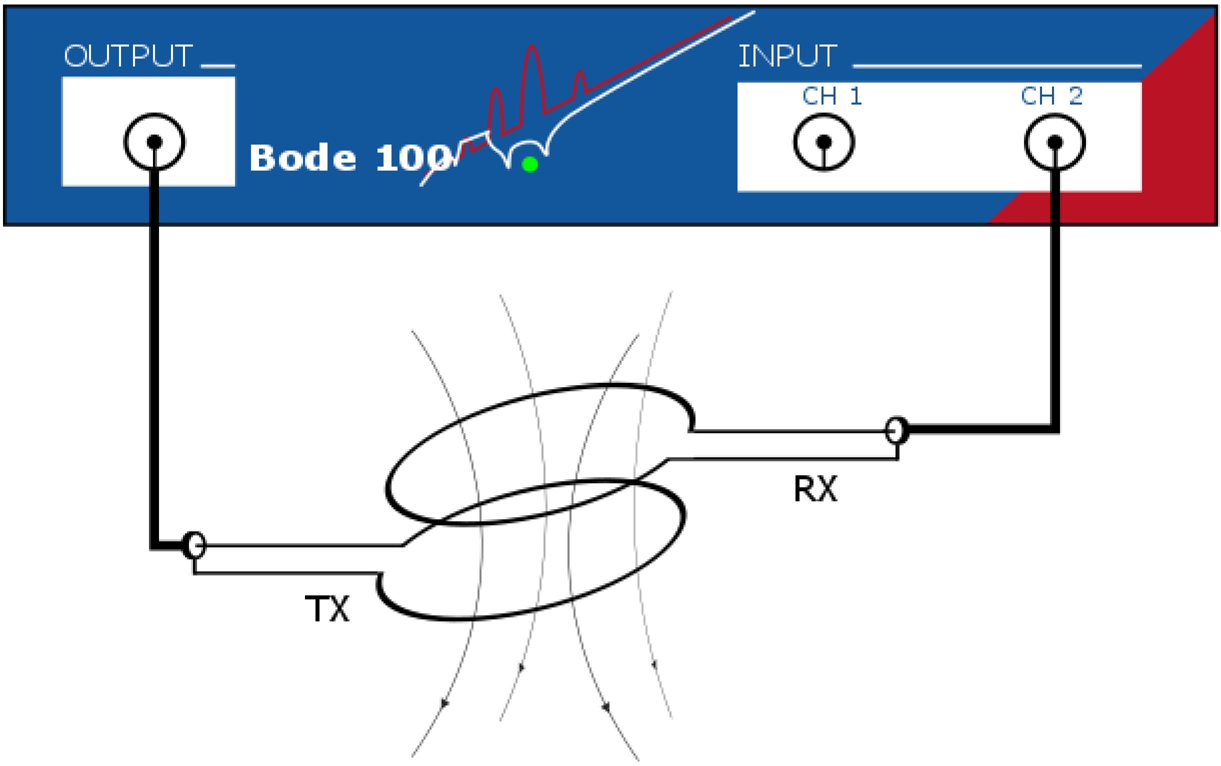
Bode 100 - Application Note

Modelling Wireless Power Transfer Link



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Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at www.omicron-lab.com/bode-100/downloads#3

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.23. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

1 Introduction

This application note describes how to derive a model for WPT[1] coil link using the Bode 100 vector network analyzer. In modern devices, WPT becomes more and more relevant. There are different use cases for a WPT connection. In one use case, users want to have a very easy way to charge a mobile device e.g. a smartphone. And on another use case, mobile devices for very rough environments need to be sealed and have no opportunity to get a wired charging connection. In all these cases a simulation model is very useful for a designer and gives him a lot of advantages in the design stage. Therefore, a wideband simulation model for a wireless power transfer coil link is derived in this document.

Figure 1 shows a basic block diagram of a WPT link. In this application note, the focus will be on the magnetic link of the two coils.

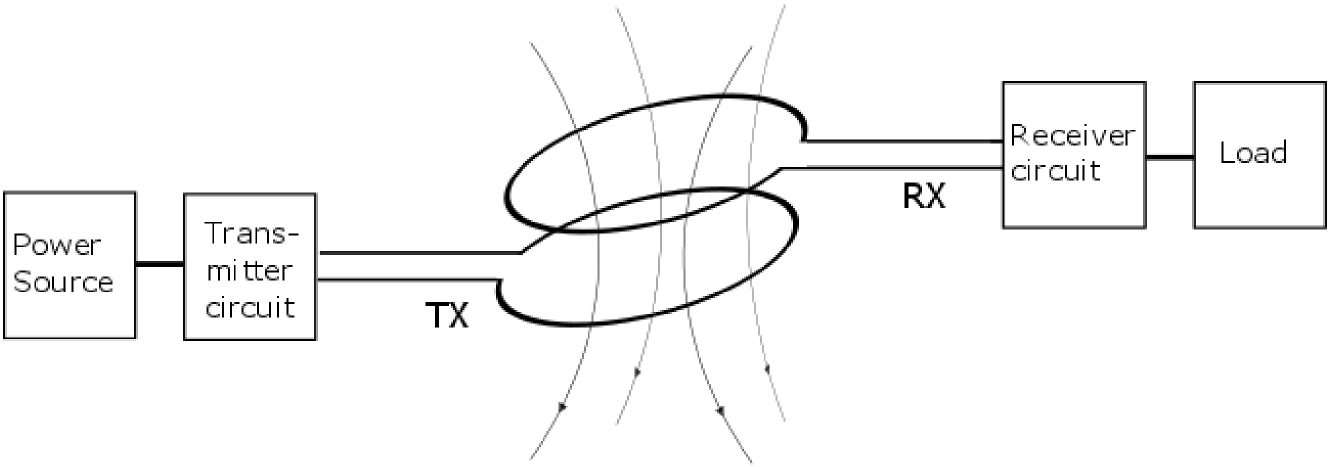

Figure 1: WPT system

The following picture shows the coils that were used for the measurements outlined in this document. The TX coil is shown on the left side and the RX coil on the right side of the picture.

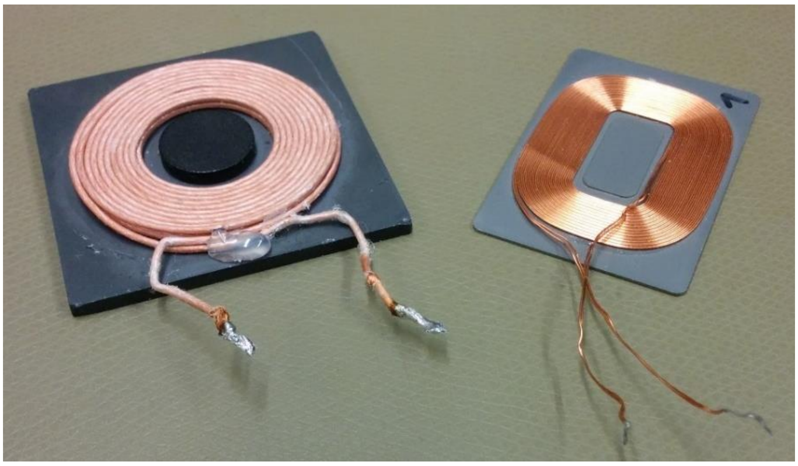

Figure 2: TX and RX coil

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[1] WPT…Wireless Power Transfer

2 Deriving the Model Parameters

To derive the model of the wireless power link, three impedance measurements have to be performed. The first and the second one are the measurements of the primary and the secondary coil. The third one is the coupling factor measurement.

The following model is used to model the coil link.

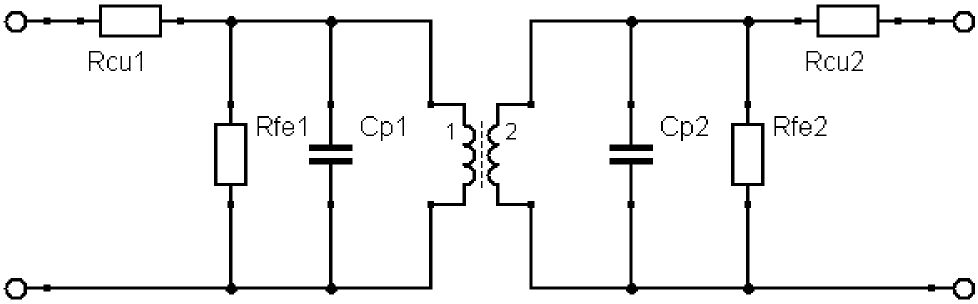
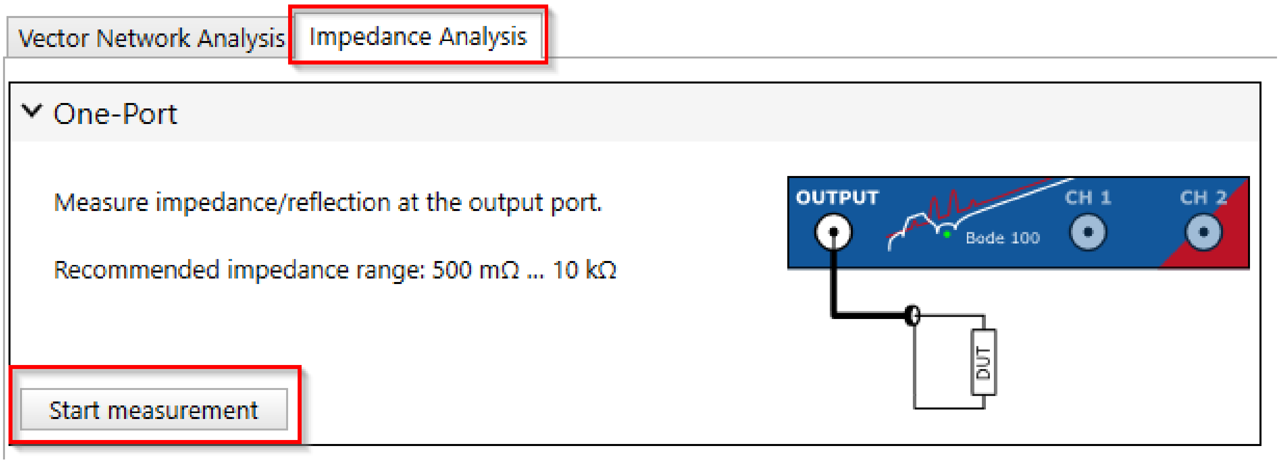


Figure 3: Coil link model

The left half is the TX and the right half is the RX coil. RCU1 and RCU2 represent the copper losses. RFE1 and RFE2 describe the magnetization losses. CP1 and CP2 represent the parasitic capacitance of both coils. The magnetic link between both coils is described by two coupled inductors.

2.1 Measurement Setup & Calibration

To perform the impedance measurements, the One-Port impedance measurement method is used.

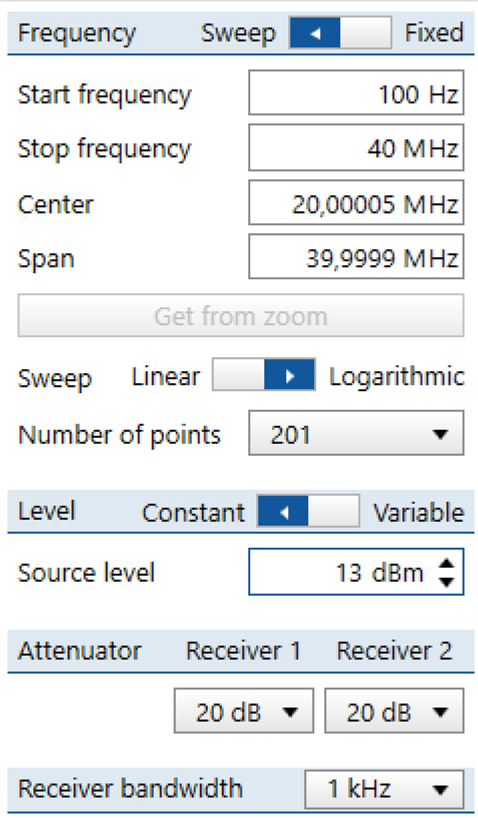


Measure impedance/reflection at the output port.

Recommended impedance range: 500 mΩ ... 10 kΩ

Figure 4: One-Port impedance measurement mode

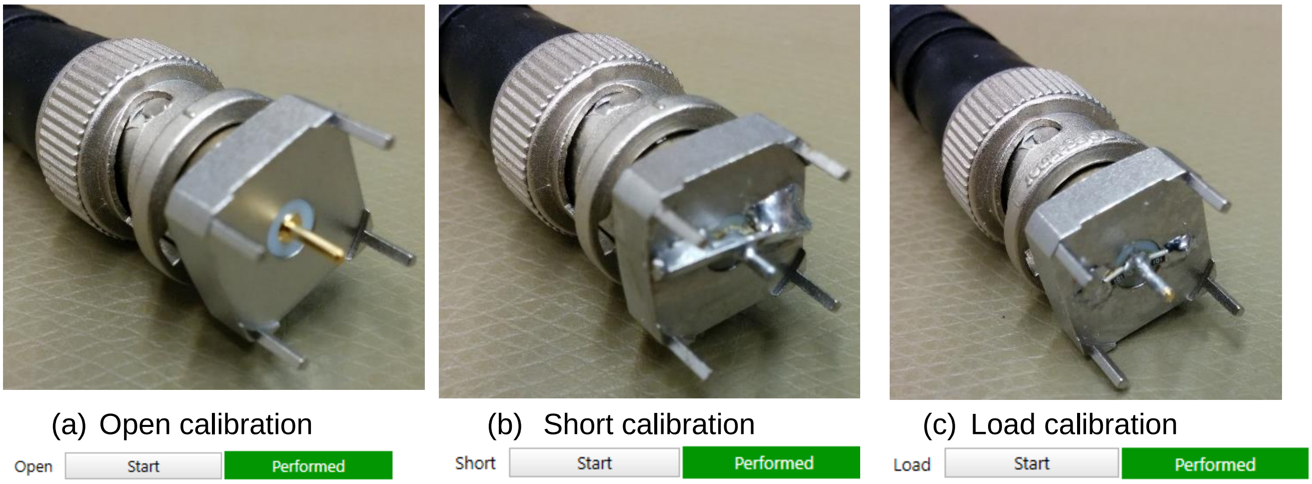
The following sweep settings are applied:



Frequency: Sweep ◀ Fixed
Start frequency: 100 Hz
Stop frequency: 40 MHz
Center: 20,00005 MHz
Span: 39,9999 MHz
Get from zoom
Sweep: Linear ▶ Logarithmic
Number of points: 201 ▼
Level: Constant ◀ Variable
Source level: 13 dBm
Attenuator: Receiver 1: 20 dB ▼ Receiver 2: 20 dB ▼
Receiver bandwidth: 1 kHz ▼

Figure 5: Sweep and configuration settings

Before the measurement is done, a calibration of the Bode 100 is performed (Full-Range Impedance Calibration). To achieve the highest accuracy, the calibration elements were built using the same connectors as used for DUT connection.



(a) Open calibration (b) Short calibration (c) Load calibration

Open: Start, Performed
Short: Start, Performed
Load: Start, Performed

Figure 6: One-port impedance calibration

2.2 Measuring the Transmitter Coil

At first, the TX coil is measured. Therefore, the coil is connected to the Bode 100 output using a BNC connector.

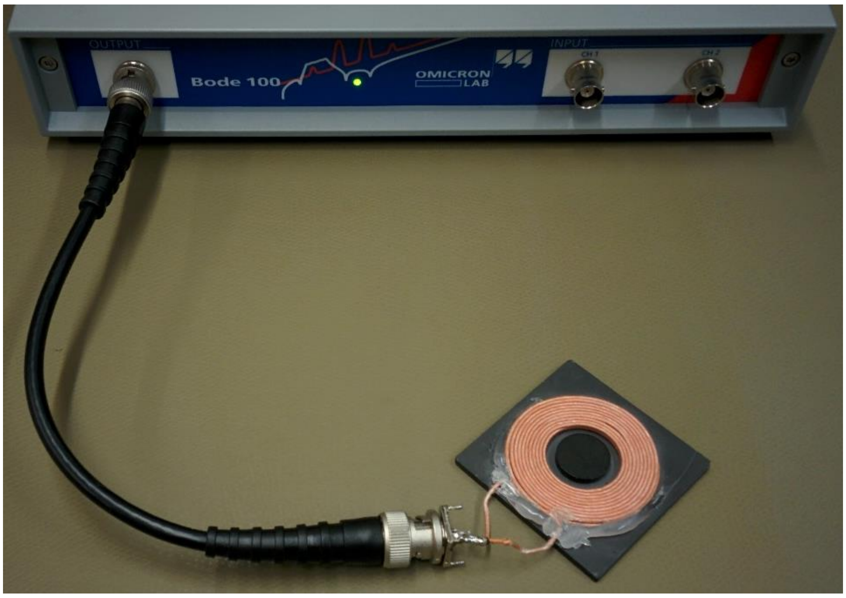
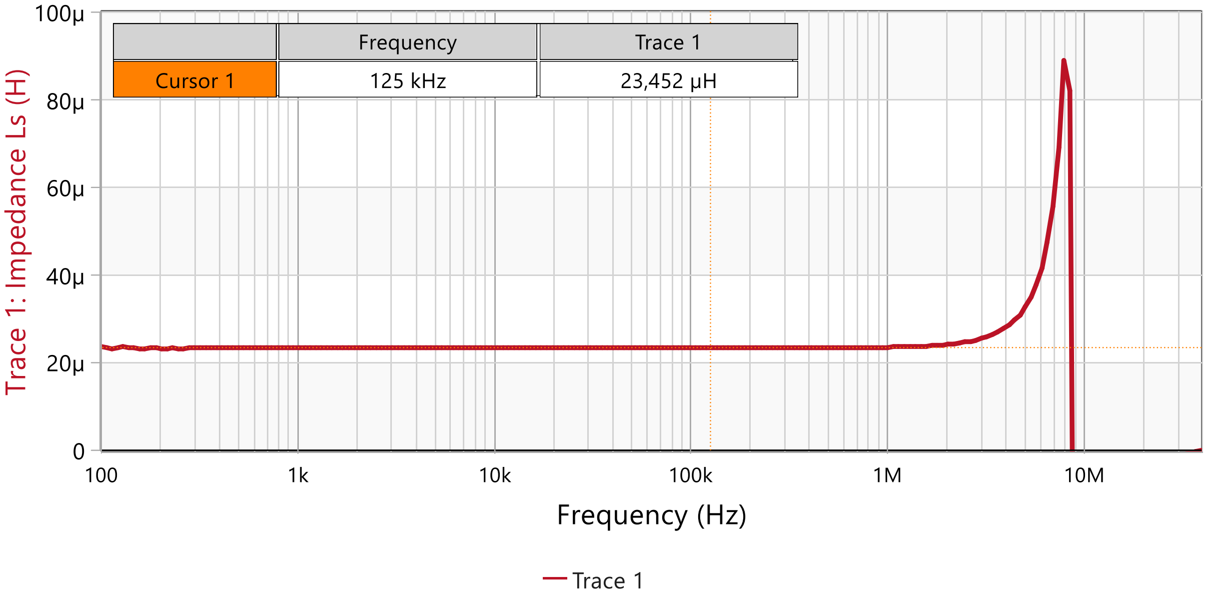


Figure 7: TX coil measurement setup

Trace 1 is set to Ls. With a single sweep  the following result was obtained:



	Frequency	Trace 1
Cursor 1	125 kHz	23,452 µH

Figure 8: Measurement result TX – Ls

From the cursor at 125 kHz it can be seen that the inductance of the coil is:

$$L_{TX} = 23.45\ \mu H \tag{1}$$

Trace 1 is now set to “Magnitude” and Trace 2 to “Phase”.

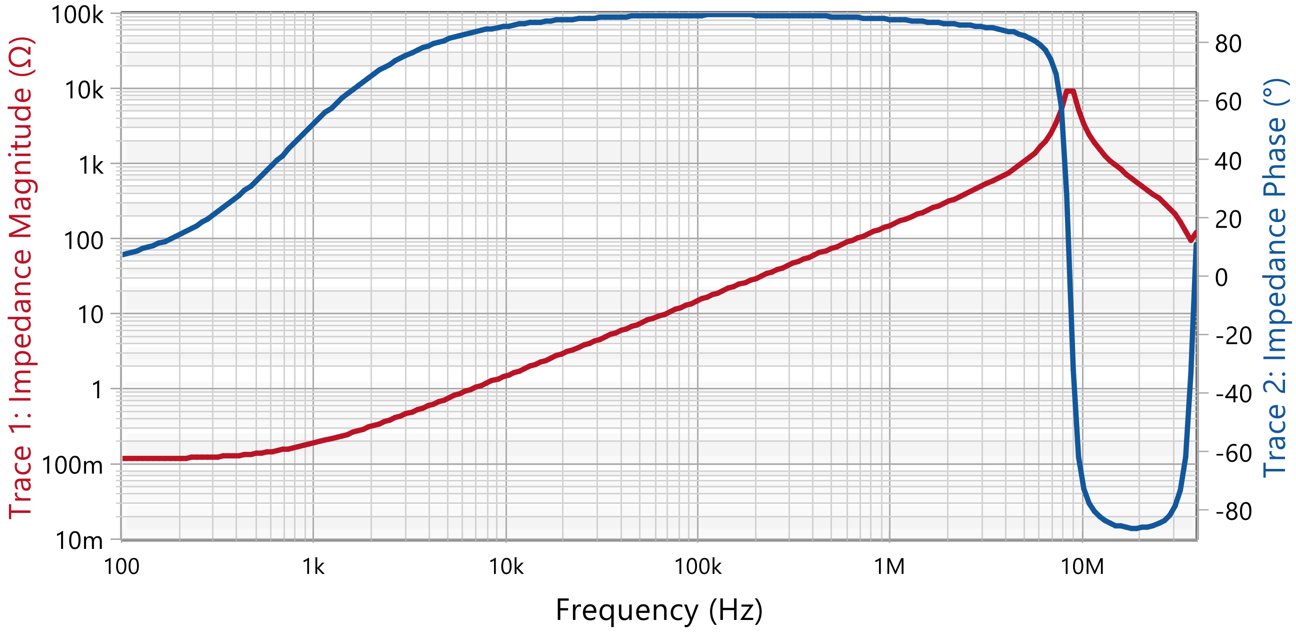
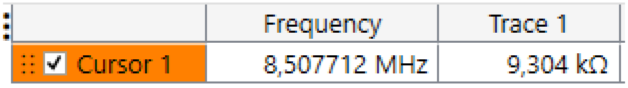


Figure 9: Measurement result TX - Magnitude and Phase



	Frequency	Trace 1
☑ Cursor 1	8,507712 MHz	9,304 kΩ

Figure 10: Cursor Table TX - Impedance at resonance

The resistance of the transmitter coil at resonance frequency (8.5 MHz) is:

$$R_{fe1} = 9.304\ k\Omega$$

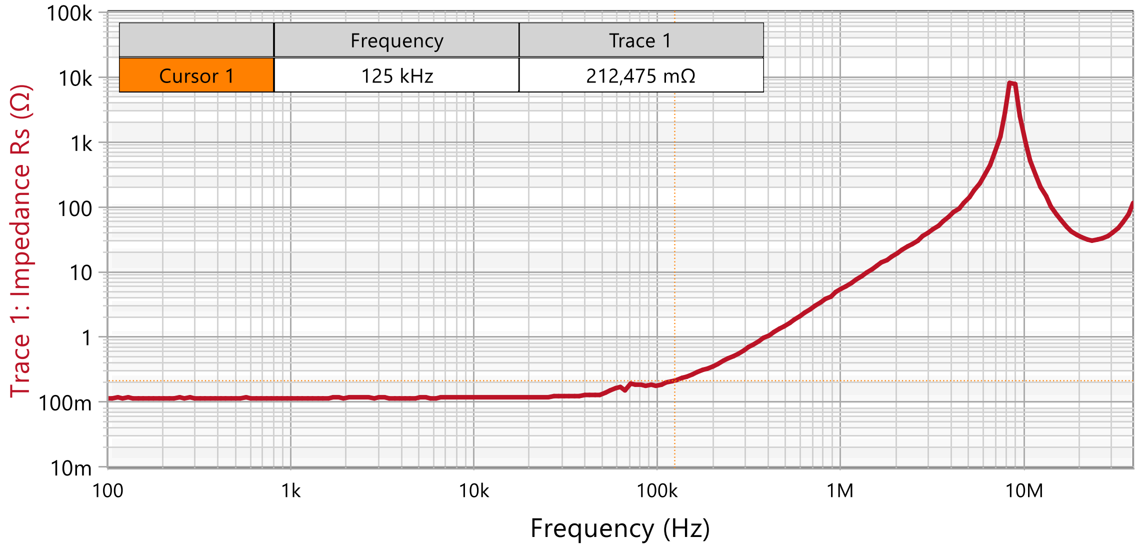
The self-resonance frequency of the transmitter coil is at $f_{rTX} = 8.507\ MHz$. Using the resonance frequency, the parasitic capacitance of the coil can now be calculated:

$$f_{rTX} = \frac{1}{2 \cdot \pi \cdot \sqrt{C_{TX} \cdot L_{TX}}} \Rightarrow \tag{2}$$

$$C_{TX} = \frac{1}{4 \cdot \pi^2 \cdot f_{rTX}^2 \cdot L_{TX}} = \frac{1}{4 \cdot \pi^2 \cdot (8.507\ MHz)^2 \ \cdot 23.45\mu H} = 14.92\ pF \tag{3}$$

To measure the copper resistance, Trace 1 is set to Rs:

The coils used for these measurements usually operate at a resonance frequency of 125 kHz. Therefore, the series resistance of the coil is measured at this frequency. The trace format is set to Rs and the cursor to $125\ kHz$.



	Frequency	Trace 1
Cursor 1	125 kHz	212,475 mΩ

Figure 11: Measurement result TX – Rs

The resistance of the copper winding at $125\ kHz$ is:

$$R_{CU1} = 212\ m\Omega \tag{4}$$

2.3 Receiver Coil

Now the RX coil is measured using the same setup as in 2.2 above.

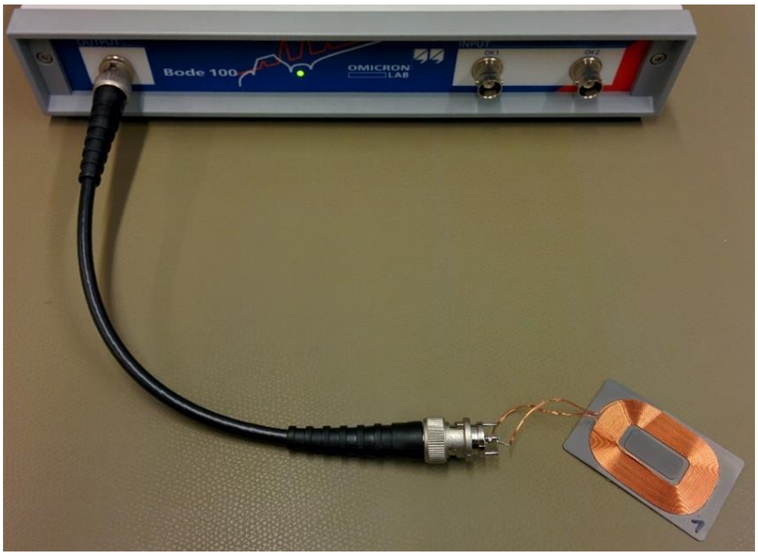
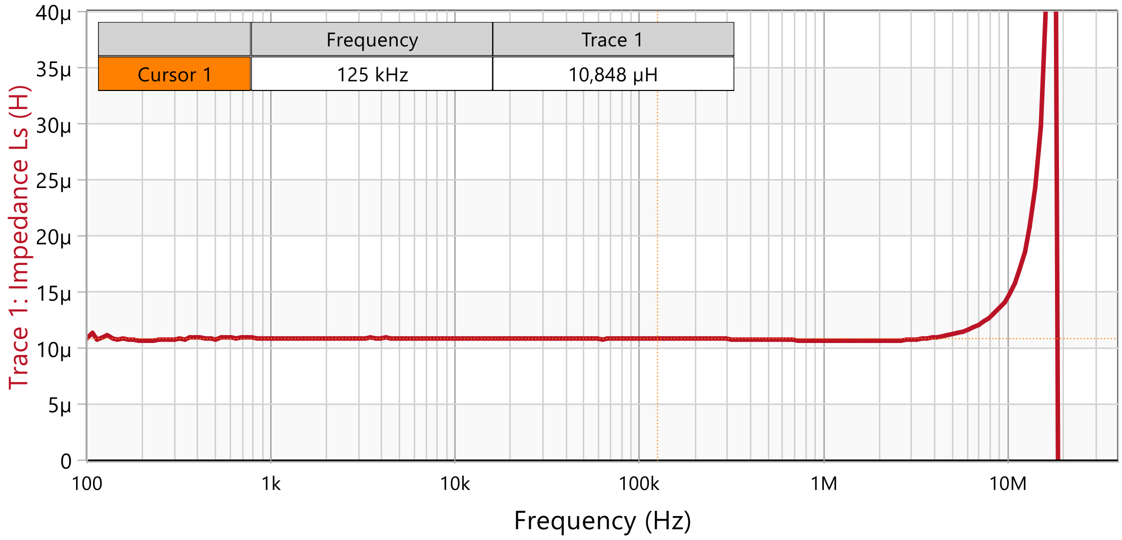


Figure 12: RX coil measurement setup

The inductance measurement shows the following result:



	Frequency	Trace 1
Cursor 1	125 kHz	10,848 µH

Figure 13: Measurement result RX – Ls

The inductance of the coil is:

$$L_{RX} = 10.85\ \mu H \tag{5}$$

Trace 1 is now set to Magnitude and Trace 2 to Phase(°).

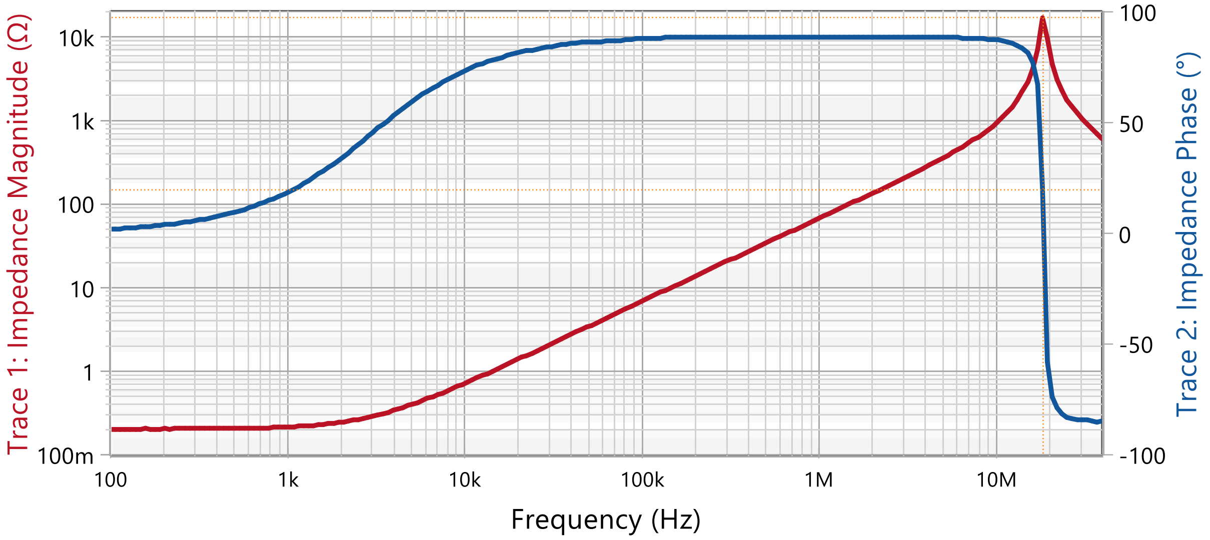
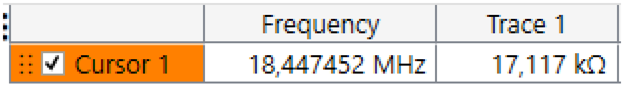


Figure 14: Measurement result RX - Magnitude and Phase



	Frequency	Trace 1
☑ Cursor 1	18,447452 MHz	17,117 kΩ

Figure 15: Cursor table RX - Magnitude

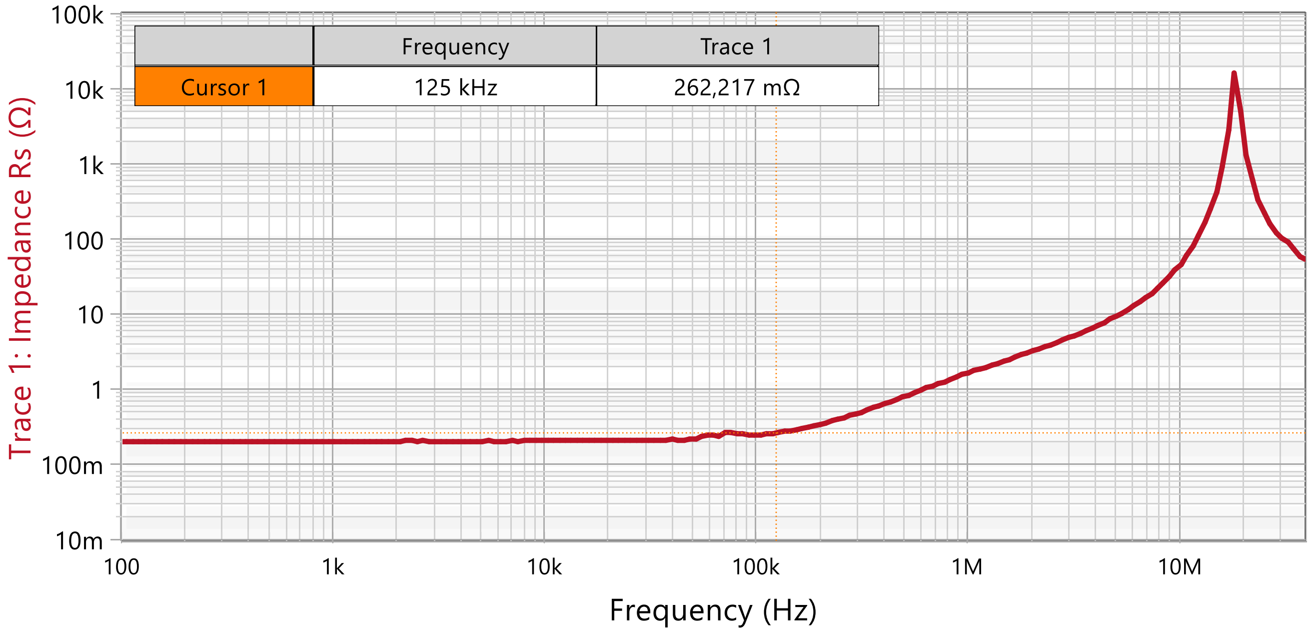
The resistance if the transmitter coil at resonance frequency is:

$$R_{fe2} = 17.117\ k\Omega \tag{6}$$

The resonance is at $f_{rRX} = 18.447\ MHz$. Therefore:

$$C_{RX} = \frac{1}{4 \cdot \pi^2 \cdot f_{rRX}^2 \cdot L_{RX}} = \frac{1}{4 \cdot \pi^2 \cdot (18.447\ MHz)^2 \cdot 10.85 \mu H} = 6.86\ pF \tag{7}$$

To measure the resistance of the copper winding at $f = 125\ kHz$ the trace format is set to Rs and the cursor is placed to $125\ kHz$.



	Frequency	Trace 1
Cursor 1	125 kHz	262,217 mΩ

Figure 16: Measurement result RX - Rs

The resistance of the copper winding at the desired resonance frequency is:

$$R_{CU2} = 262\ m\Omega \tag{8}$$

2.4 Coupling factor

To measure the coupling factor of the two coils, the coils are placed on a cardboard test rig. The test rig holds the coils at a constant distance of $1\ cm$ and therefore enables reproducible measurements. The cardboard material has a minimal influence on the measurement since its magnetic properties are similar to air. The two coils are connected in series such that the coupled field canceled and the resulting inductance of both coils are measured as shown in Figure 17.

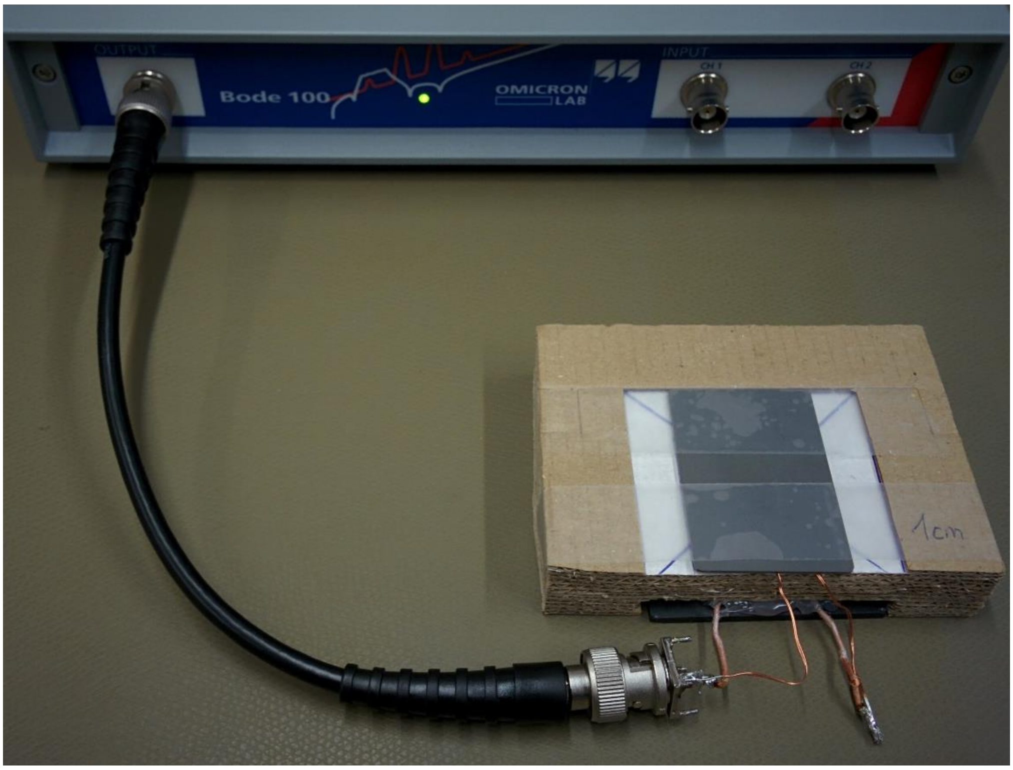


Figure 17: Coupling factor measurement setup

Connect the two coils as shown in the circuit below (Figure 18). The current flow is opposite in both coils such that the coupled fields cancel. The amount of coupled field depends on the coupling factor.

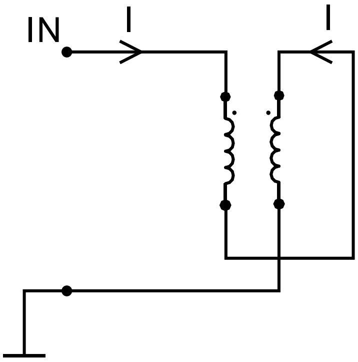


Figure 18: Coupling factor measurement setup circuit

The following measurement shows the measured inductance of the two coupled series-connected coils:

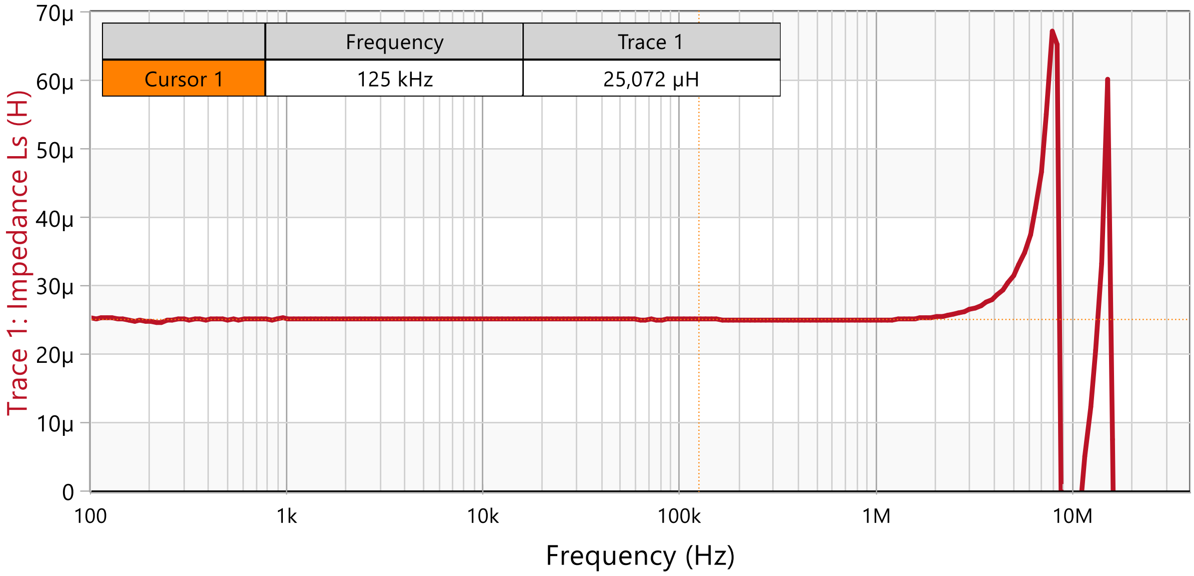


Figure 19: Measurement result TX&RX – Ls

The measured inductance of both coils in series is $L_S = 25.07\ \mu H$.

With the following formula, the mutual inductance M can be calculated:

$$L_S = L_{TX} + L_{RX} + 2 \cdot M \tag{9}$$

$$\Rightarrow M = \frac{L_{TX} + L_{RX} - L_S}{2} = \frac{23.45\ \mu H + 10.85\ \mu H - 26\ \mu H}{2} = 4.62\ \mu H \tag{10}$$

The coupling factor k is now calculated as shown below:

$$k = \frac{M}{\sqrt{L_{TX} \cdot L_{RX}}} = \frac{4.62\ \mu H}{\sqrt{23.45\ \mu H \cdot 10.85\ \mu H}} = 0.288 \tag{11}$$

3 Simulation

With the gathered data from the modeling process, the coil link can now be simulated. All the simulations are performed using *QUCS*[2]. The S21 parameters are simulated and compared to the measurement data. Qucs outputs the complex S21 parameter. To compare it to the Bode 100 measurement results the magnitude in dB is calculated as shown below.

$$\left|\underline{S_{21}}\right| = 20 \cdot \log_{10}\left(\left|\underline{S[2,1]}\right|\right) \tag{12}$$

The S21 parameters within the frequency range of $100\ Hz$ to $10\ MHz$ are simulated. The terminating impedances on port 1 and port 2 are set to $50\ \Omega$.

3.1 Direct Inductive Coil Link

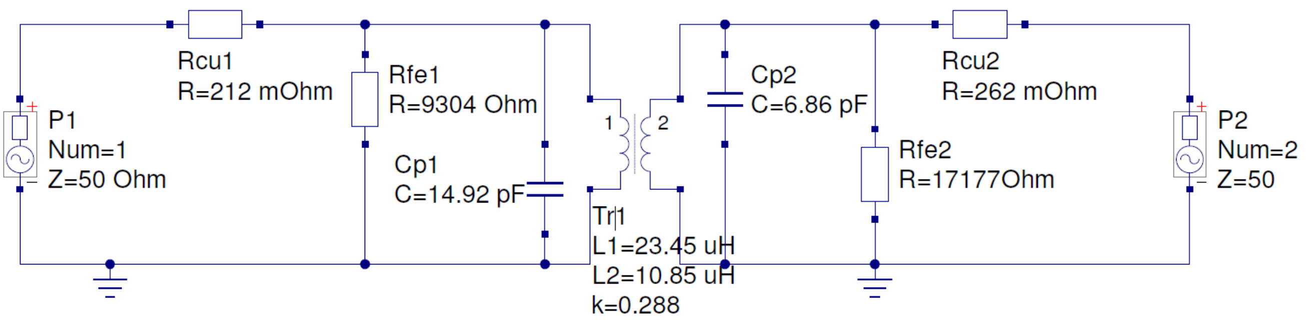


Figure 20: Coil link simulation

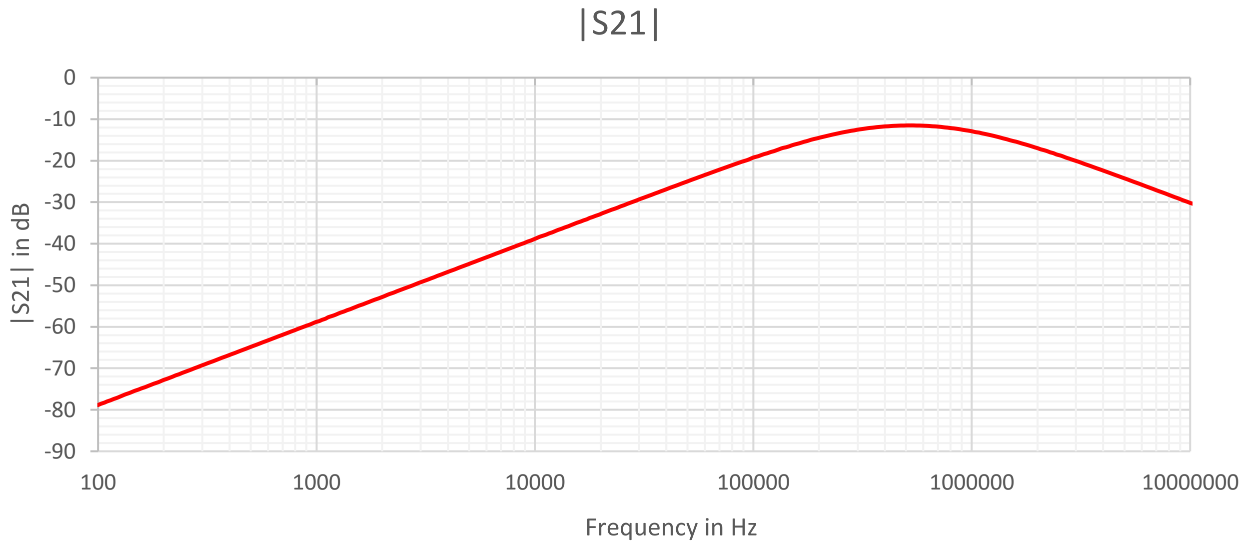


Figure 21: Coil link simulation

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[2] Qucs is an open-source electronic circuit simulator. Version 0.0.19 was used for the simulations.

3.2 Series Resonance

To improve the efficiency of the link, WPT coil links are usually operated in resonance. Therefore, two series capacitors on each coil are used to create a resonance at $f_r = 125\ kHz$.
The values of the series capacitors are calculated with the following formula:

$$C_{rTX} = \frac{1}{4 \cdot \pi^2 \cdot f_r^2 \cdot L_{TX}} = = \frac{1}{4 \cdot \pi^2 \cdot\ (125\ kHz)^2 \cdot 23.45\ \mu H} = 69\ nF \tag{13}$$

$$C_{rRX} = \frac{1}{4 \cdot \pi^2 \cdot f_r^2 \cdot L_{RX}} = = \frac{1}{4 \cdot \pi^2 \cdot (125\ kHz)^2 \cdot 10.85\ \mu H} = 149\ nF \tag{14}$$

The parasitic capacitances of the coils were neglected since they are significantly smaller.

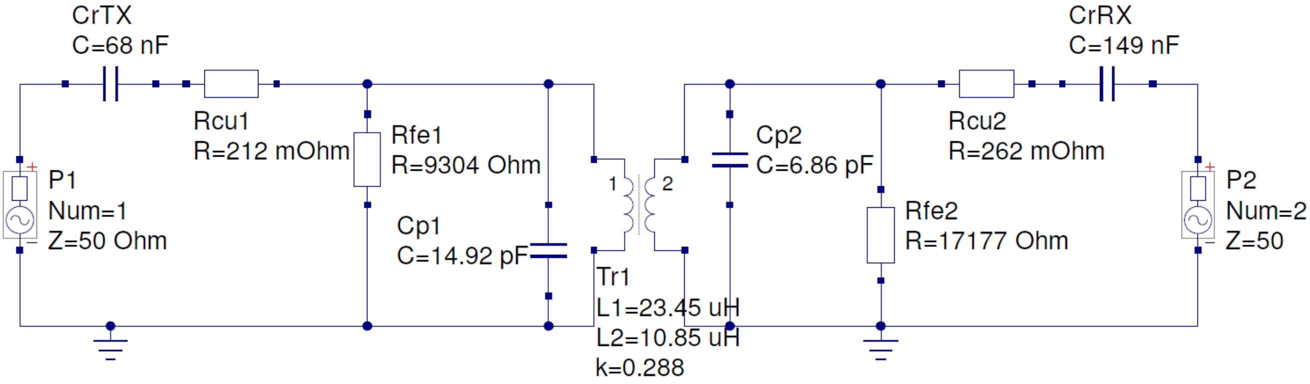


Figure 22: Series resonance simulation

The simulation shows the following result:

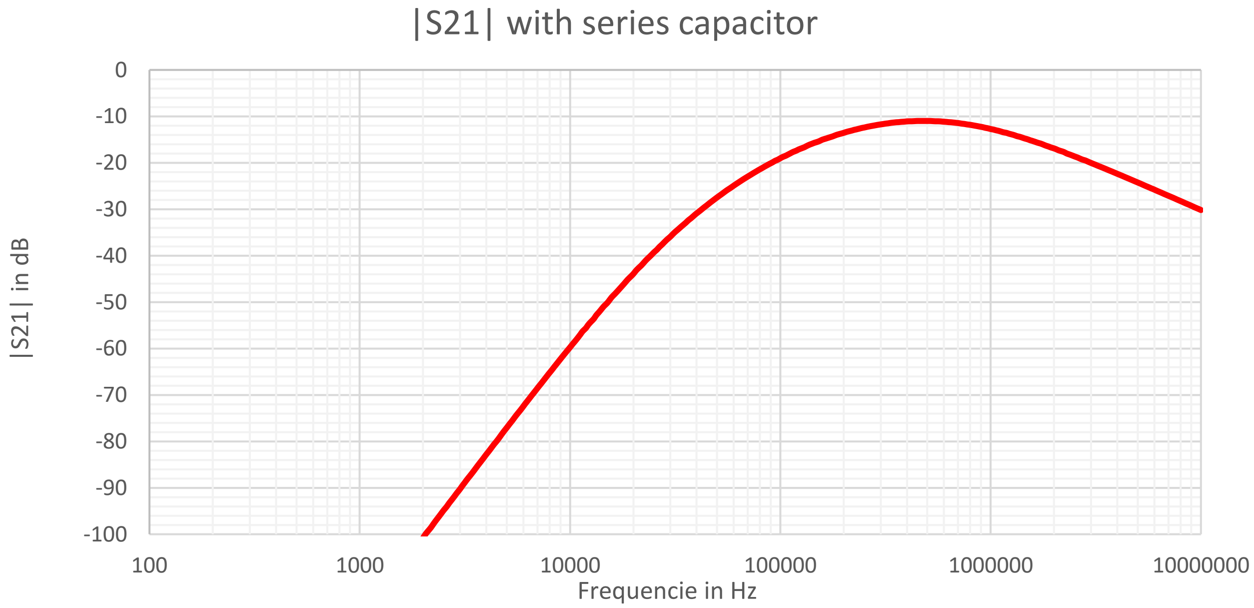
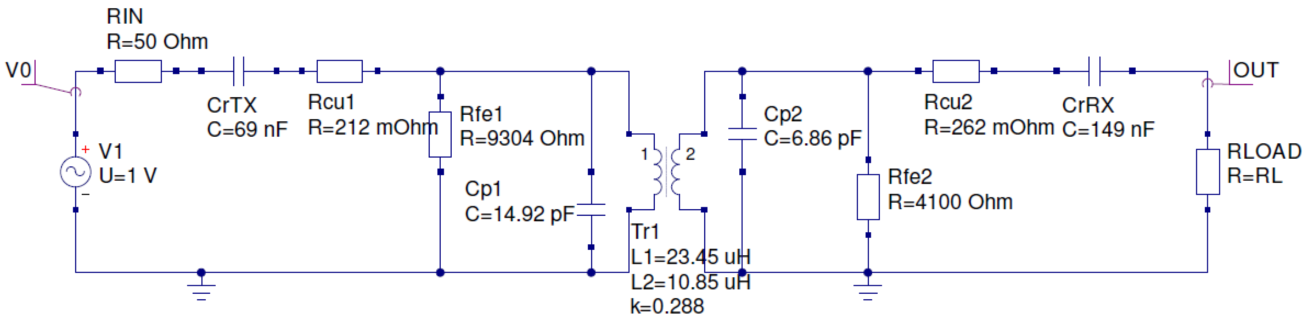


Figure 23: Series resonance simulation

For a more realistic simulation approach, the load impedance was varied. The load impedance is swept in the range of $1\ \Omega$ to $100\ \Omega$. In order to compare the simulated data and the measured data, the |S21| parameter is calculated as follows:

$$|S21| = 20 \cdot \log_{10}\left(\frac{V_{OUT}}{\frac{1}{2} \cdot V_0}\right) \tag{15}$$

An AC frequency sweep is simulated and the parameter R_{LOAD} is swept as well.



The simulation shows the following results:

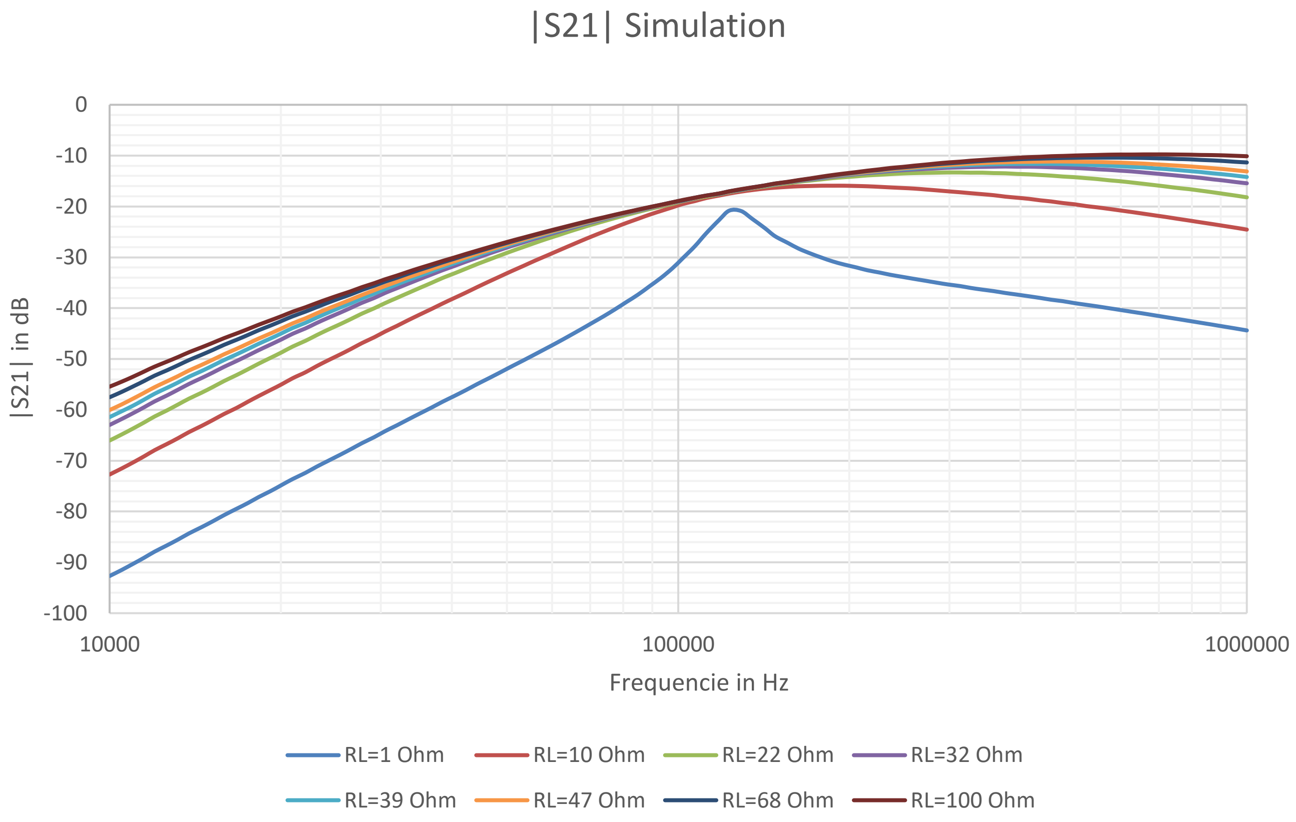


Figure 24: Series resonance simulation at different load impedance values

3.3 Parallel Resonance

The link is also simulated in a parallel resonance configuration. The same capacitors are used as in the series resonance configuration to achieve the same resonance frequency.

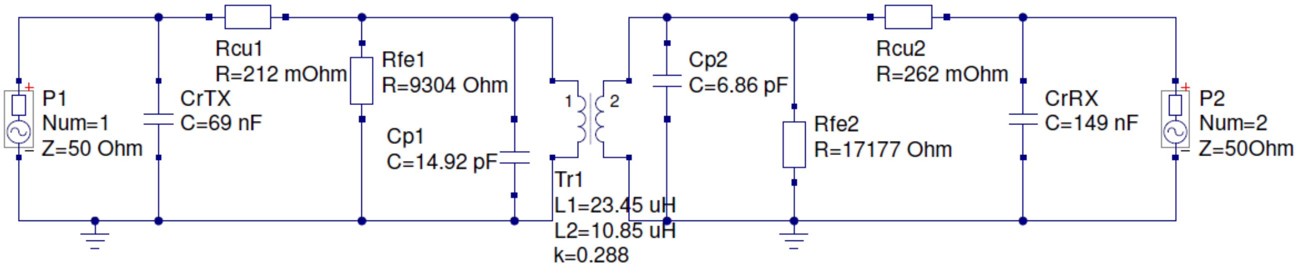


Figure 25: Parallel resonance simulation

The simulation shows a significantly smaller loss at resonance.

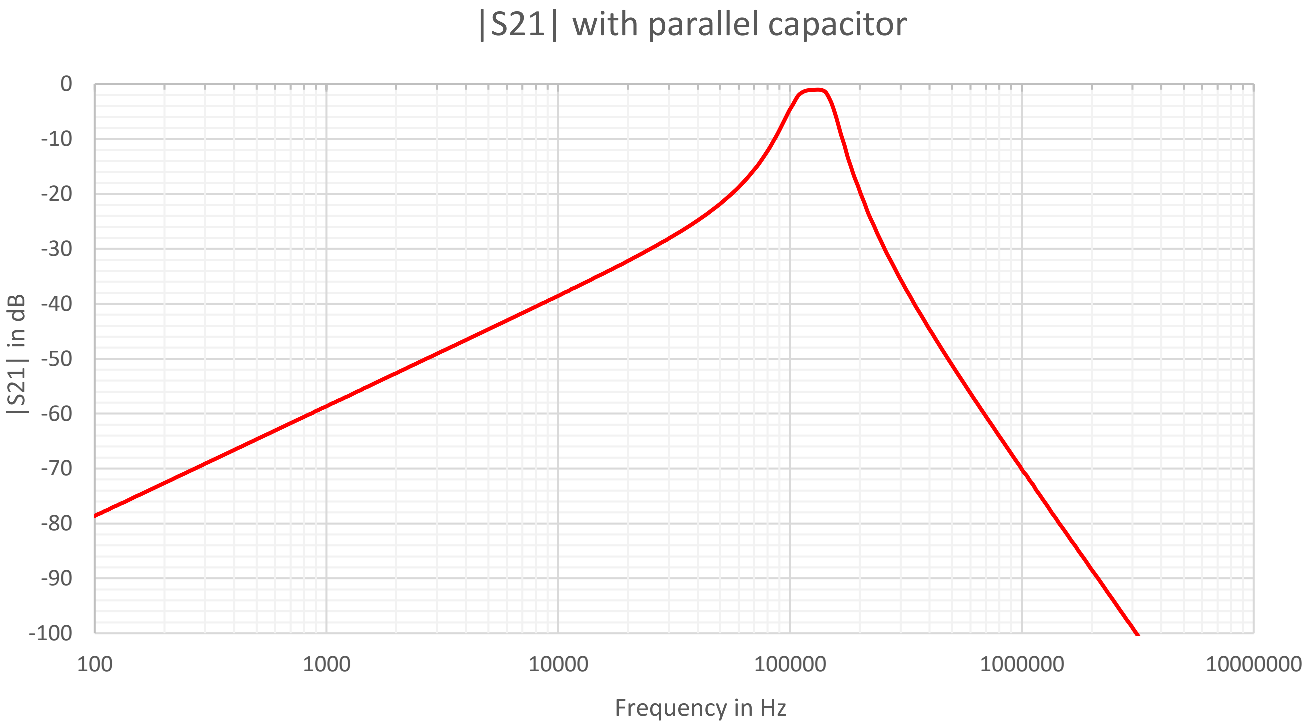


Figure 26: Parallel resonance simulation

The load resistance sweep is performed in the same way as explained in 3.2 above3.2 .

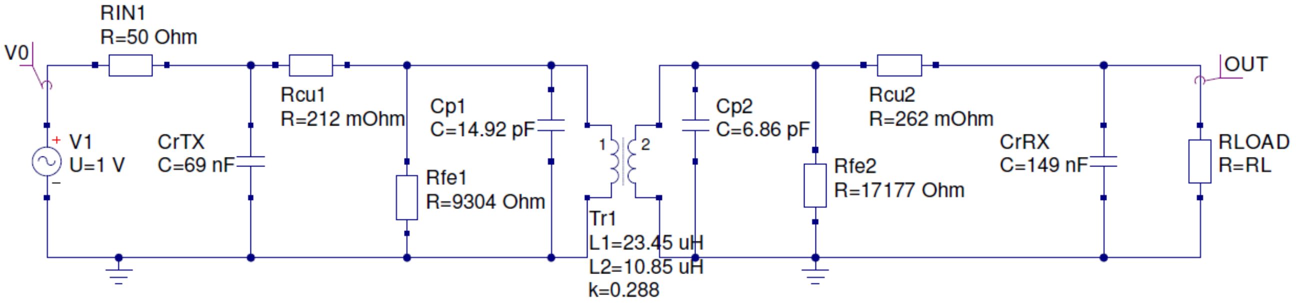


Figure 27: Parallel resonance configuration including Load resistance

The simulation shows the following results for varying load resistance:

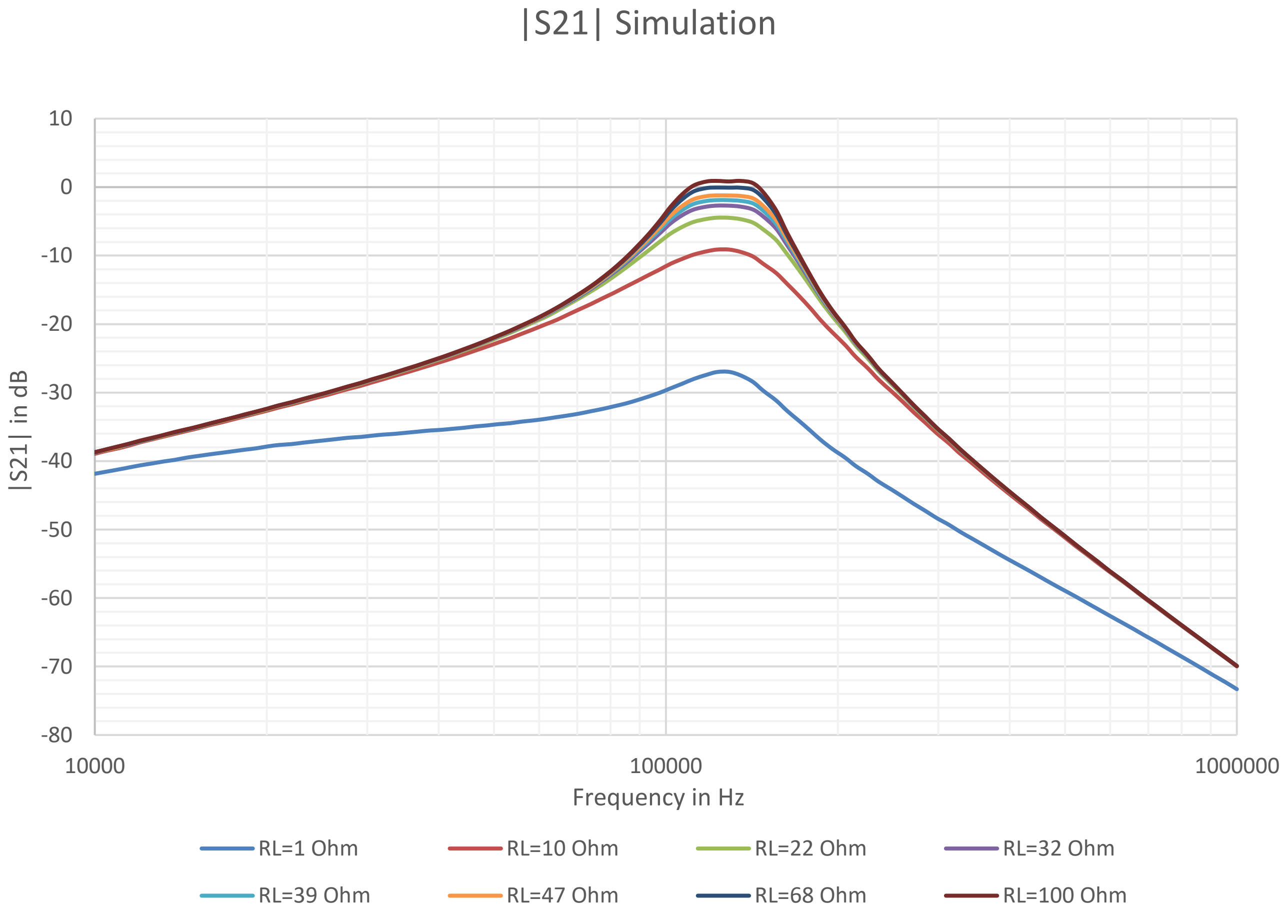


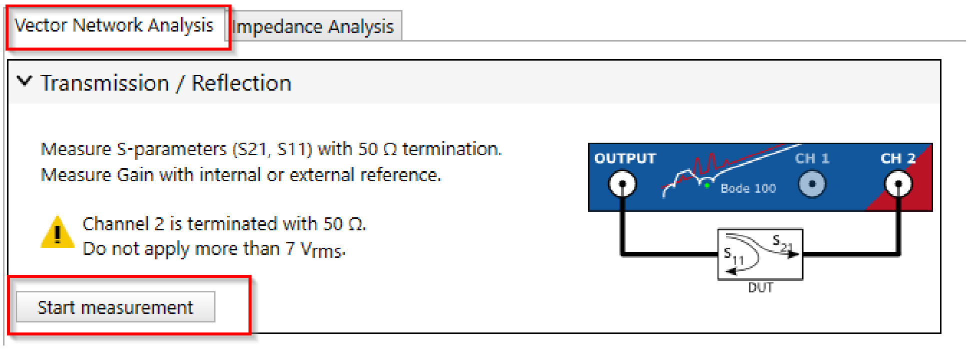
Figure 28: Parallel resonance simulation with varied load

4 Coil Link Measurement

To confirm the derived model, the gain of the coil link is measured using the Bode 100.

4.1 Measurement Setup & Configuration

First, a new Transmission/ Reflection measurement in opened in the Bode Analyzer Suite:



Measure S-parameters (S21, S11) with 50 Ω termination.
Measure Gain with internal or external reference.

Channel 2 is terminated with 50 Ω.
Do not apply more than 7 V_{rms}.

Figure 29: Device configuration

Figure 30 below shows the measurement setup:

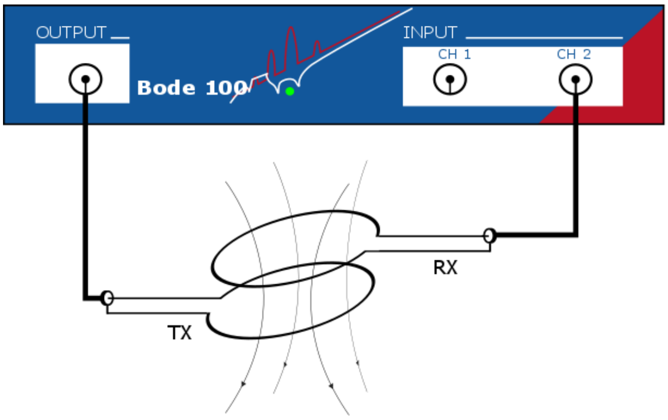


Figure 30: Measurement setup

Trace 1 is set to show the gain in dB. The start frequency is set to $100\ Hz$ and the stop frequency to $1\ MHz$. To measure the gain of the link the same cardboard rig as in 0is used.

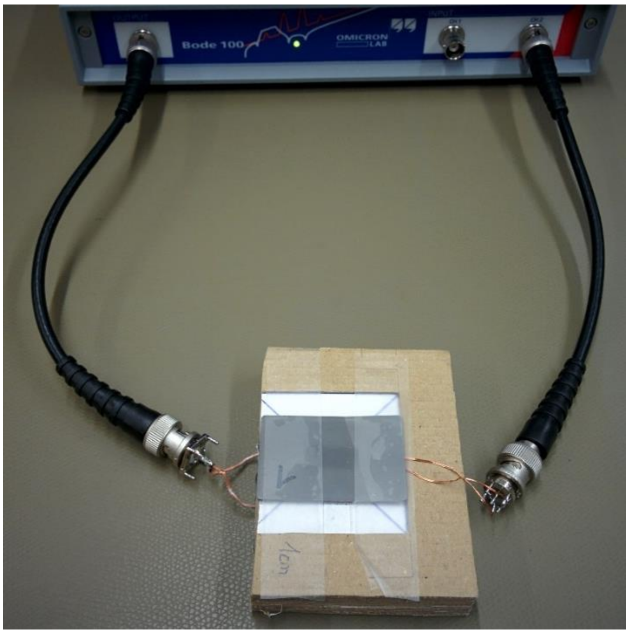


Figure 31: Measurement setup

But before the gain is measured, a Thru-calibration is performed. Figure 32 shows the connection during thru calibration.

Figure 32: Thru calibration

4.2 Coil Link without Capacitors

At first, the coil link itself is measured without resonance.

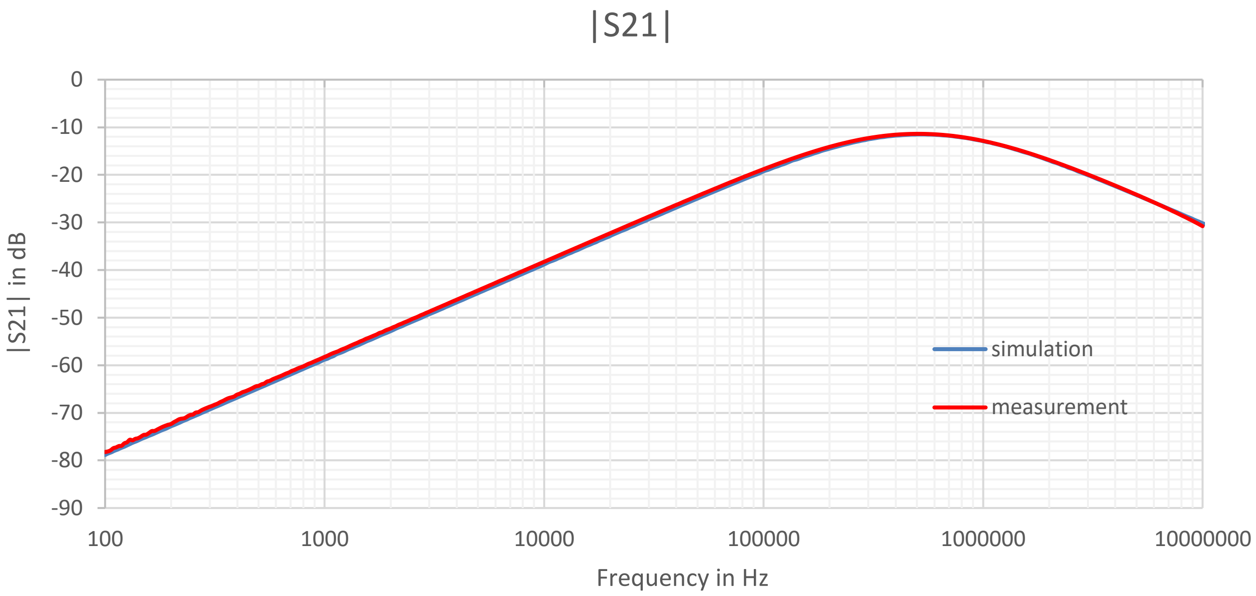


Figure 33: Coil link measurement

The simulated and measured data fit almost perfectly.

4.3 Series Resonance Configuration

Figure 34 shows the |S21| measurement in series resonance configuration.

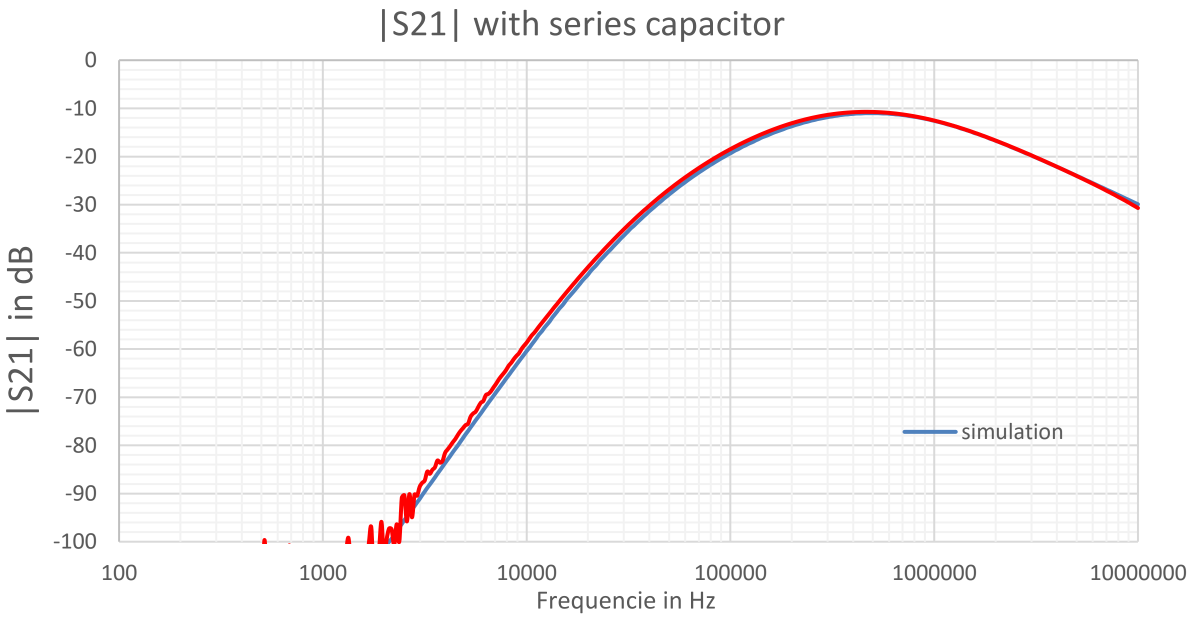


Figure 34: Series resonance configuration measurement

The measured data showed no unexpected behavior and matches the simulation.

4.4 Parallel Resonance Configuration

Figure 35 below shows the |S21| measurement in parallel resonance configuration.

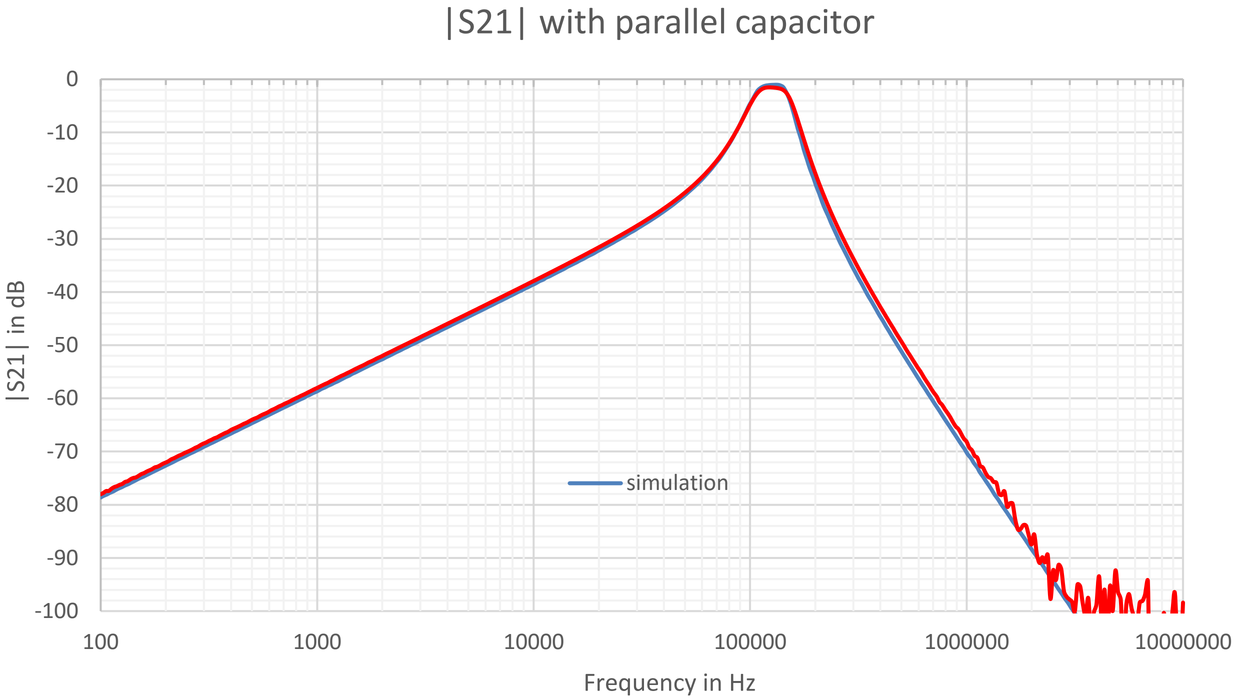


Figure 35: Parallel resonance configuration measurement

Also, the measurement with the parallel resonance shows the expected behavior from the simulation.

4.5 Load Impedance variation

Since the transfer link characteristic depends on the load, the gain is measured with different load impedances. Therefore, the impedance of CH2 is set to high impedance and the termination resistance (load resistance) is added externally.

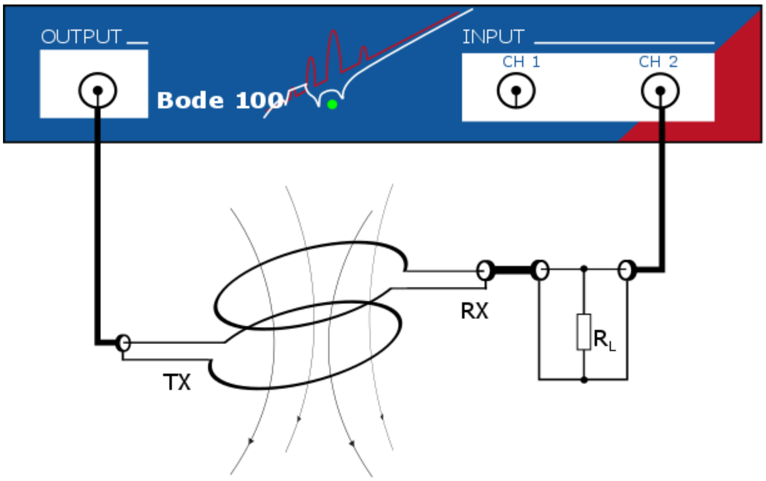


Figure 36: Gain measurement with a varying load resistor

Figure 37 and Figure 38 below show the load impedance adapter used to mount the resistors.

Figure 37: Load impedance adapter

Figure 38: 47 Ω (1206 chip resistor)

This new measurement setup allows us to measure the gain with different load resistors.

The measurement shows the following results:

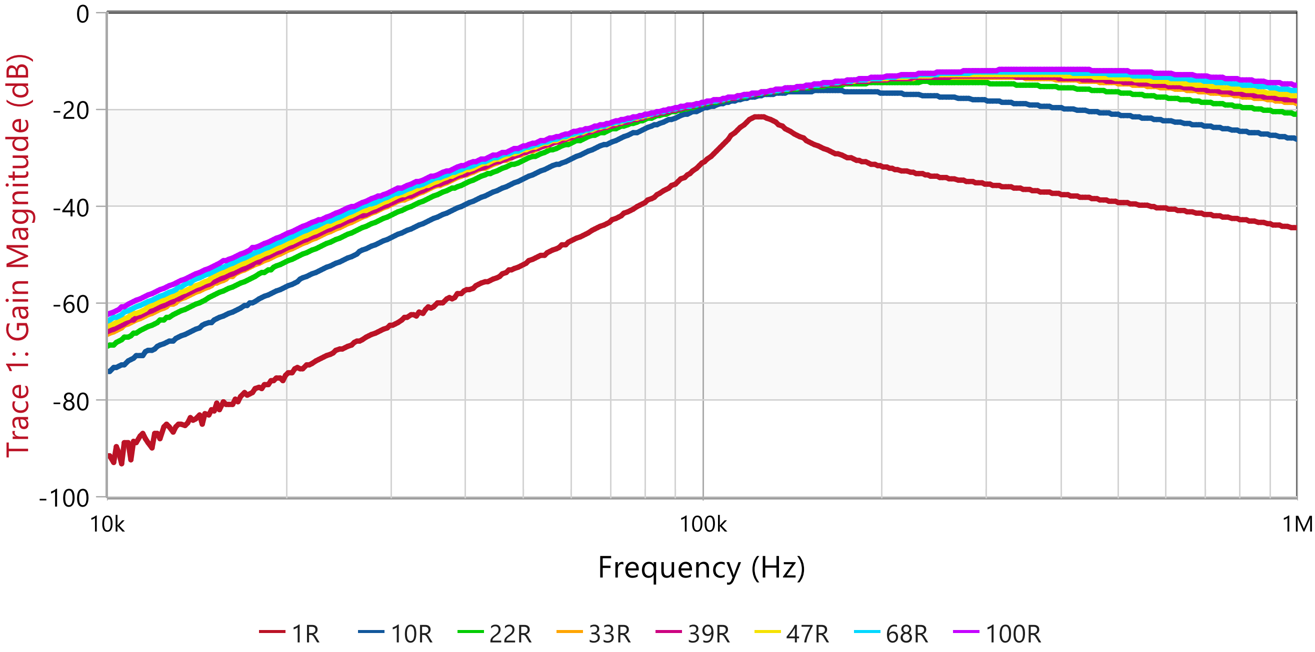


Figure 39: Series resonance gain measurement

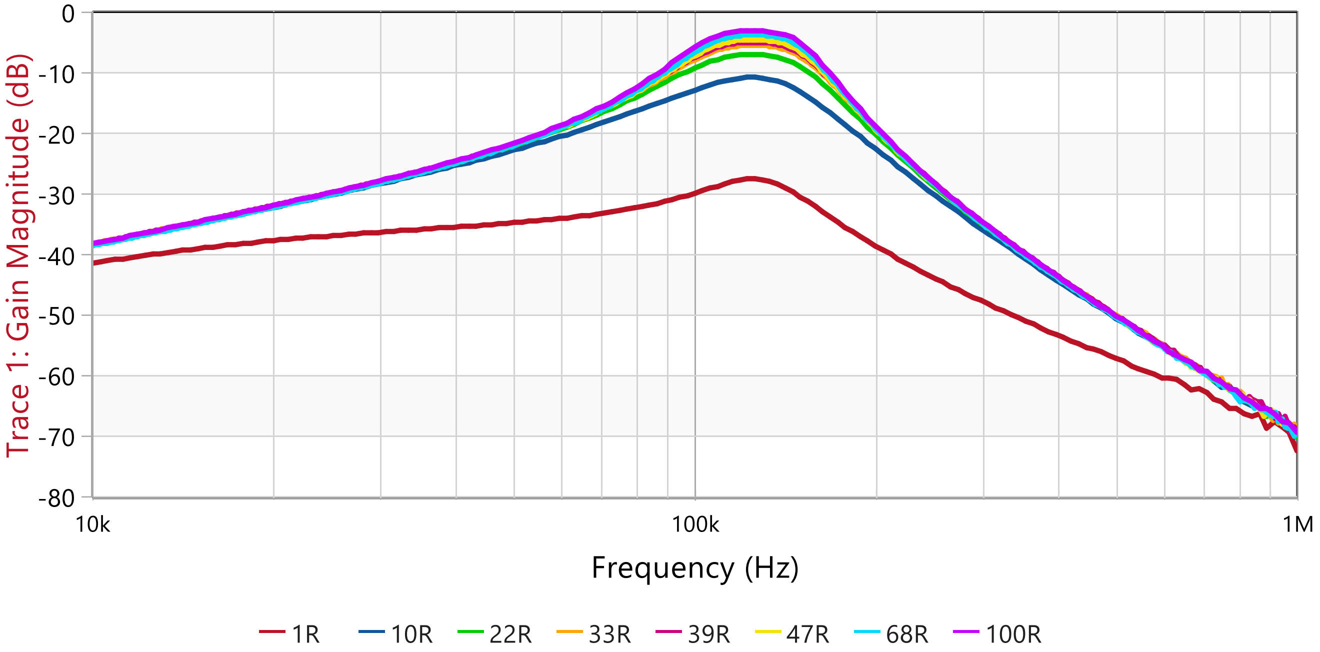


Figure 40: Parallel resonance gain measurement

The measurements fit very well to the simulation data as shown in the Graphs: Figure 23 and Figure 26.

5 Conclusion

This application note shows how to derive a simple but accurate model of a WPT coil link. With this model, WPT designers can easily simulate and optimize WPT systems.
With the automation interface of the Bode 100, it is also possible to measure the WPT link quality in production and ensure a constant high-quality level of the product.

The Bode 100 vector network analyzer is an ideal base for modeling electronic parts and a wide range of other measurements. The user-friendly handling of the Bode 100 enables a fast and cost-effective coverage of a wide spectrum of measurement applications.

OMICRON Lab is a division of OMICRON electronics specialized in providing Smart Measurement Solutions to professionals such as scientists, engineers and teachers engaged in the field of electronics. It simplifies measurement tasks and provides its customers with more time to focus on their real business.

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