Optimize Wireless Power Transfer Link Efficiency

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In attempting to improve the efficiency of wireless power transfer it is essential to consider the losses associated with the proximity effects of the transmit and receive coils. Optimizing the link efficiency, and how the two coils interact with each other, requires that measurements be made with the coils close to each other, preferably with the separation expected in the specific application.

The July 2011 issue of Power Electronics Technology included an article entitled “Wireless Power Minimizes Interconnect Problems,” which offered an overview of the wireless link’s efficiency. This efficiency is primarily the result of the resonant link efficiency and the secondary linear voltage regulator.

The link efficiency is a function of the Q of the transmit and receive coils. This leads to several important questions:

- How do we determine the associated link efficiency and what influences it?
- How do we effectively and efficiently measure and simulate wireless power
- How do we optimize the efficiency?

Here, we will present a technique for measuring the inductance and Q of the coils and, more importantly, how the two coils interact due to proximity effects. The key to improving the link efficiency is to understand the interaction between the elements within the coil and the relationship between the two coils.

The first step is to measure each of the coils independently. To do so, we can use an OMICRON-LAB Bode-100 vector network analyzer; an inexpensive, low frequency (1Hz-40MHz) VNA/Impedance analyzer, which in conjunction with the B-WIC impedance adapter simplifies accurate measurements of the coil parameters, L and R, as well as the self resonant frequency (SRF) over a wide range of frequency.

Figure 1 shows a typical transmit and receive coil along with the Bode 100 and B-WIC adapter used to measure the coils.

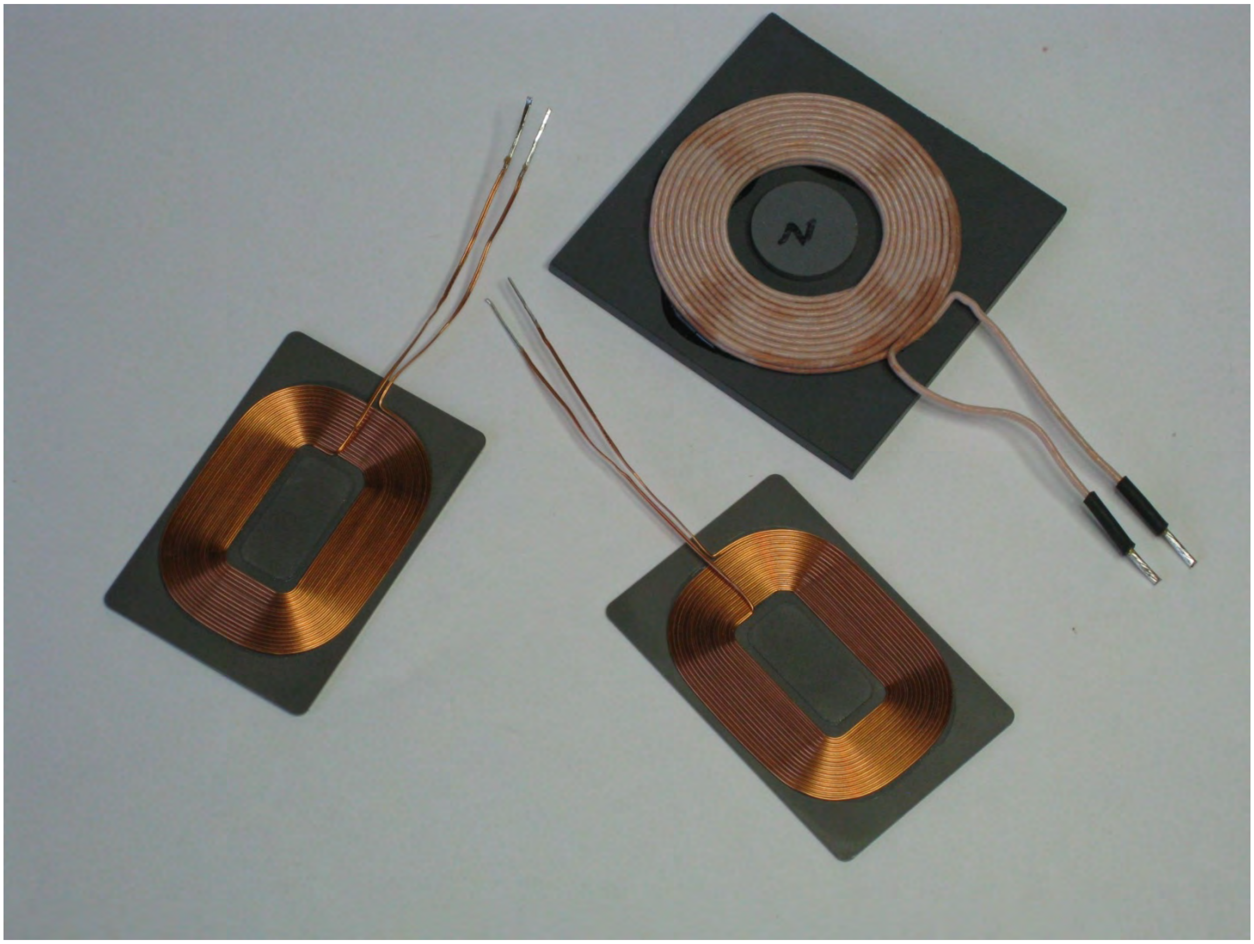


Figure 1 - Typical transmit and receive coils.

Measuring the Transmit Coil

The lowest and highest Q from a set of four receive coils was measured. The results, shown in Figure2, indicate a flat inductance (10.8µH) over a wide frequency range, a flat Q (~40 over a wide frequency range) and an SRF of approximately 20MHz. Both coils measured 10.8µH with a low Q device of 35.8 and a high Q device of 44. Both coils displayed a resonant frequency of approximately 20MHz.

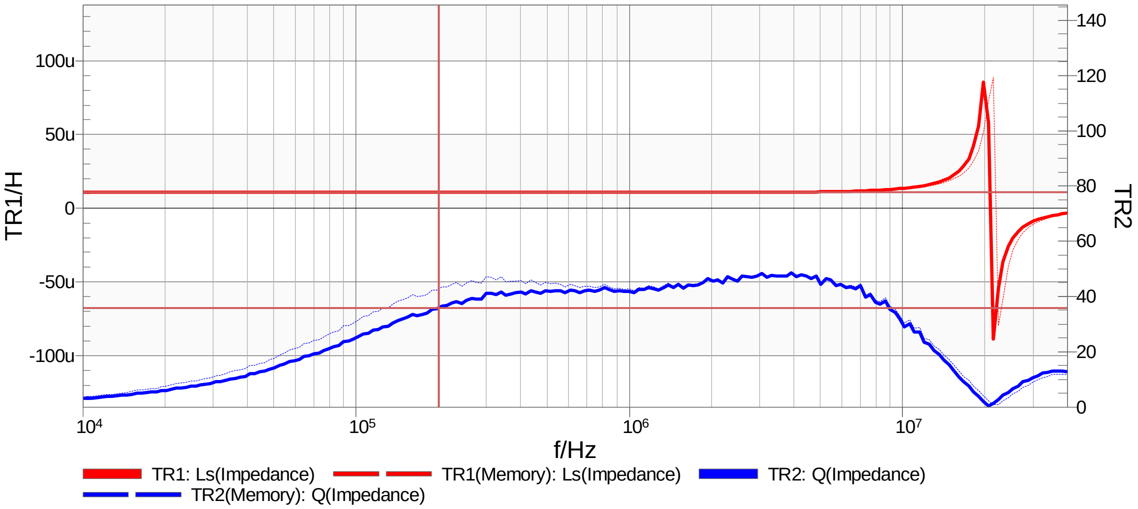
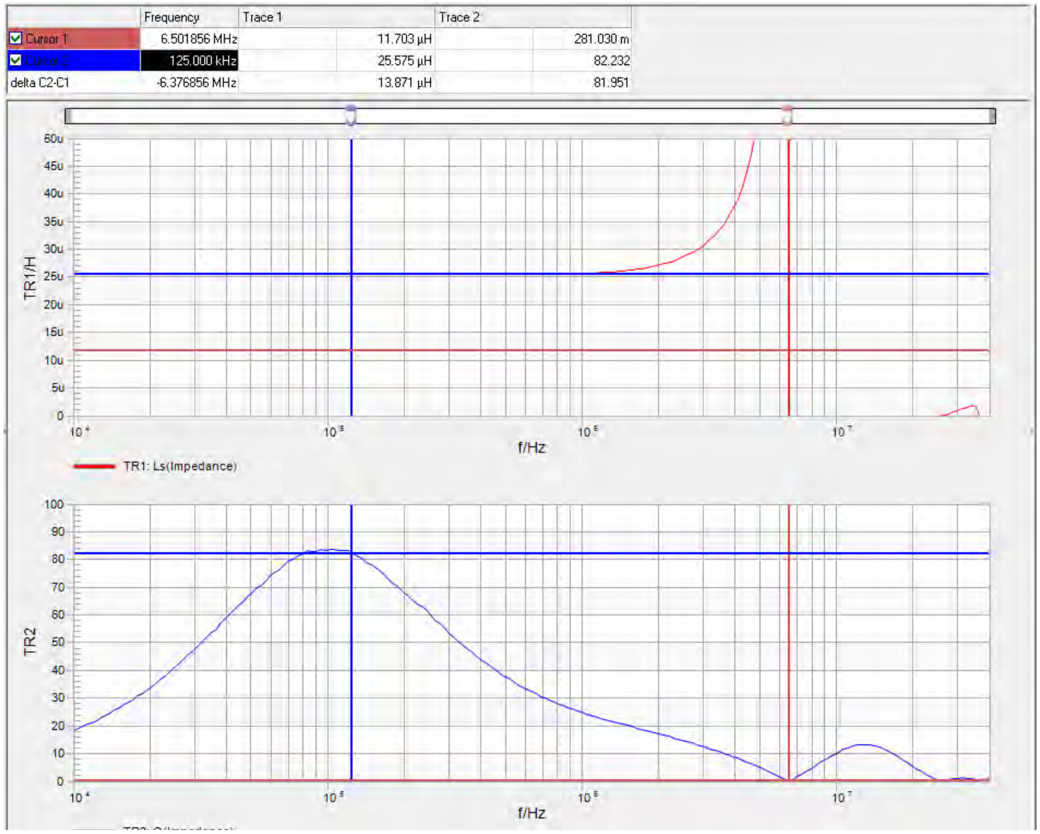


Figure 2. Measurement of the highest and lowest Q devices from a sample of four devices.

Similarly, a measurement of the transmit coil, shown in Figure 3 indicates an inductance of approximately 25uH with a Q of 82 at 125kHz, falling to 70 at 200kHz.



	Frequency	Trace 1	Trace 2
☑ Cursor 1	6.501856 MHz	11.703 µH	281.030 m
☑ Cursor 2	125.000 kHz	25.575 µH	82.232
delta C2-C1	-6.376856 MHz	13.871 µH	81.951

Figure 3. Nominal transmit inductance is 25.575uH with a Q = 82.2 (RS = 0.244Ω) at 125kHz. SRF is 6.5MHz.

If the transmit and receive coils were perfectly coupled, the coupling factor, k, would simply be 1. In this simple case the "transformer" formed by $L_{TRANSMIT}$ and $L_{RECEIVE}$ has a turns ratio of:

$$\sqrt{\frac{L_{RECIEVE}}{L_{TRANSMIT}}} \qquad (1)$$

We can measure the coupling, k, by measuring the voltage ratio of the "transformer":

$$k = \sqrt{\frac{L_{RECIEVE}}{L_{TRANSMIT}}} \times \frac{V_{TRANSMIT}}{V_{RECEIVE}} \qquad (2)$$

Using a value of 10.8µH for the receive coil and 25.7µH for the transmit coil results in a ratio based on the inductance value of 0.648. The voltage gain is measured with several values of separation between the two aligned coils, allowing a calculation of k as a function of separation, as listed in Table 1.

Table 1. Coupling factor k as a function of separation and transmit coil inductance.

$\sqrt{\frac{L_{RECIEVE}}{L_{TRANSMIT}}}$	Gain	Separation (mm)	Gain	k
0.648254165	0.543	0	0.543	0.837634
0.648254165	0.4	4	0.4	0.617042
0.648254165	0.275	8	0.275	0.424216
0.648254165	0.194	12	0.194	0.299265
0.648254165	0.177	16	0.177	0.273041

Figure 4 shows the relationship between separation and coupling factor, k.

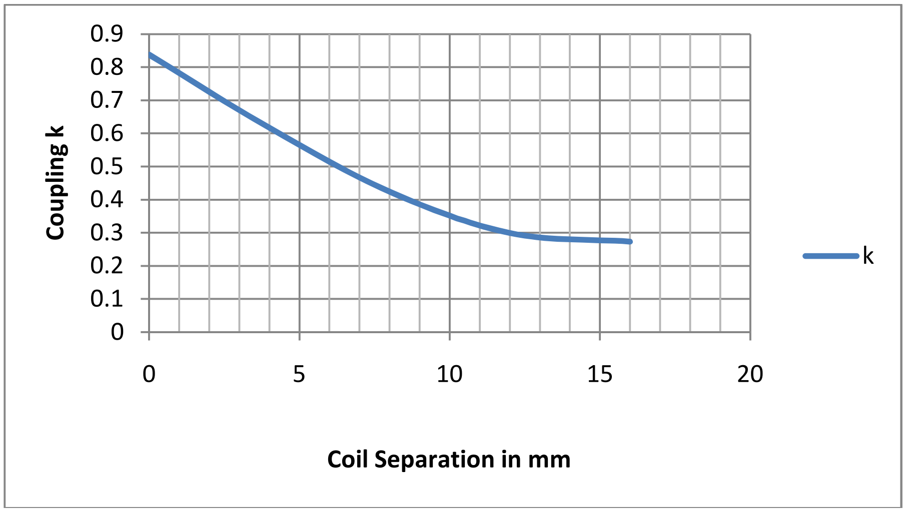
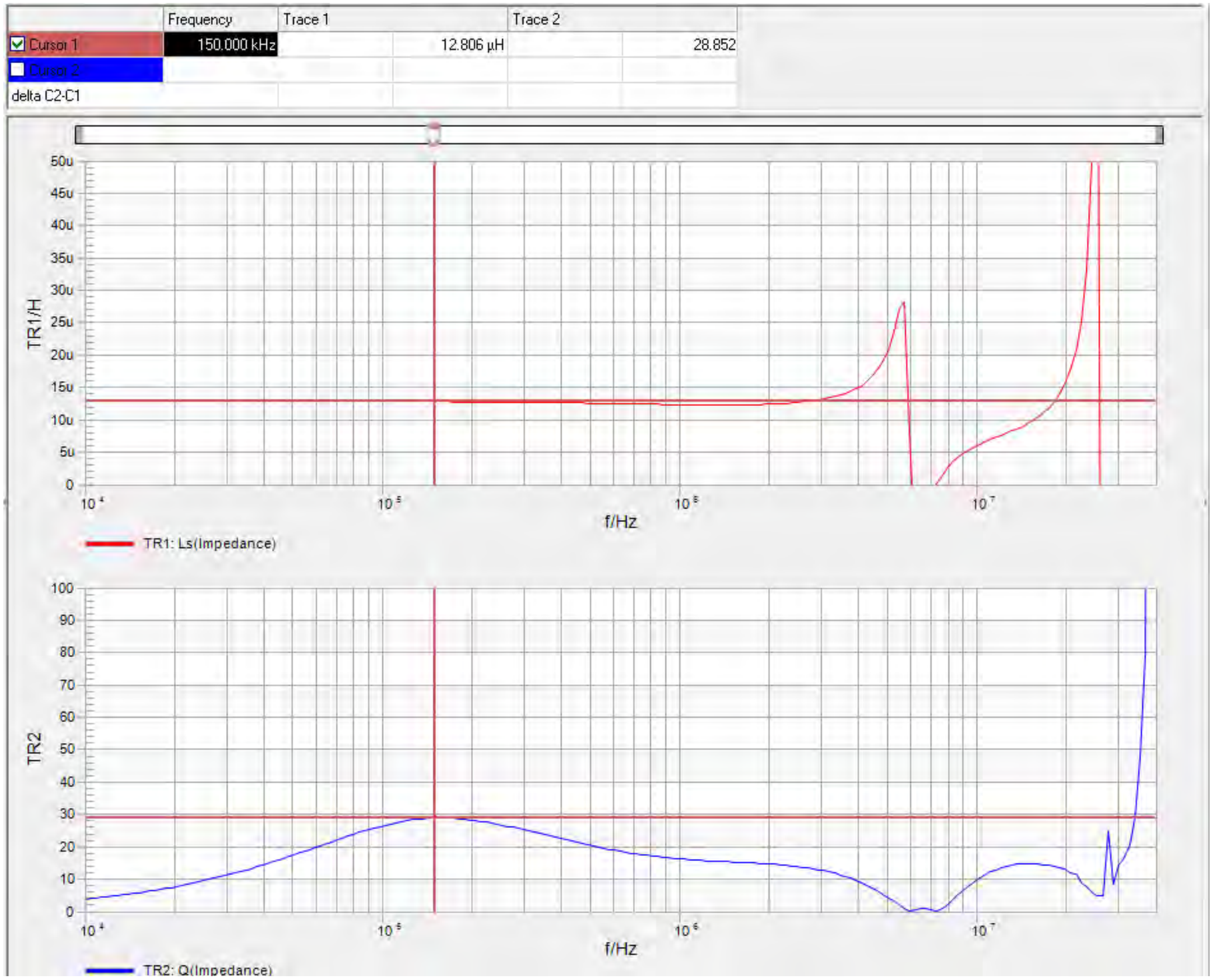


Figure 4. Relationship between the transmit and receive coil separation in mm and coupling factor k.

Figure 5 shows the transmit coil inductance and Q with a 4 mm separation as a function of frequency.



	Frequency	Trace 1		Trace 2	
☑ Cursor 1	150.000 kHz		12.806 µH		28.852
☐ Cursor 2					
delta C2-C1					

Figure 5. Transmit coil inductance and Q at 4 mm separation.

Using the measured data for the inductance and Q of each coil, as well as the coupling factor versus coil separation, we can now calculate the optimum line efficiency using the relationship:

$$Q = \sqrt{Q_{\mathrm{TRANSMIT}} \times Q_{\mathrm{RECEIVE}}} \qquad (3)$$

$$\eta_{\mathrm{OPT}} = \frac{(kQ)^2}{\left[1+\sqrt{1+(kQ)^2}\right]^2} \qquad (4)$$

Referring to the figure, and using the typical inductor Q values of 40 and 82, results in a Q of 56, which can be used to determine the optimum efficiency.

$$\eta_{\mathrm{OPT}} = 0.932 \qquad (5)$$

The efficiency is not nearly this high. To understand why the measured efficiency is significantly lower than this calculated value, we need to look at the losses associated with the interaction of the two coils. In order to do so, we again align the coils and measure the inductance and the Q (or series resistance, RS) of each coil as a function of the coil separation (Figure 6).

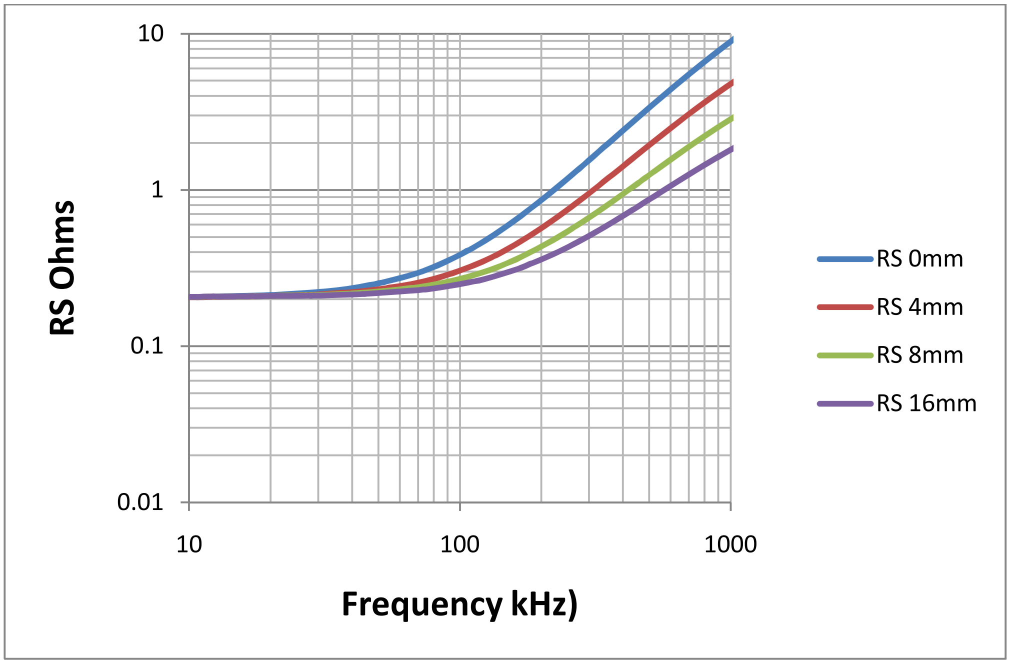


Figure 6. Receiver coil RS as a function of frequency and separation.

Receiver Coil

Table 2. Receiver coil inductance vs. (separation)

Frequency	L (0 mm)	L (4 mm)	L (8 mm)	L (16 mm)
125 kHz	1.58E-05	1.28E-05	1.18E-05	1.12E-05
Q	26	28.35	30.7	32.5

Evaluating the optimum efficiency with the inductance and Q values obtained in close proximity (4 mm) to each other results in an optimum efficiency of 90%, 3% lower than obtained from the individual coil measurements.

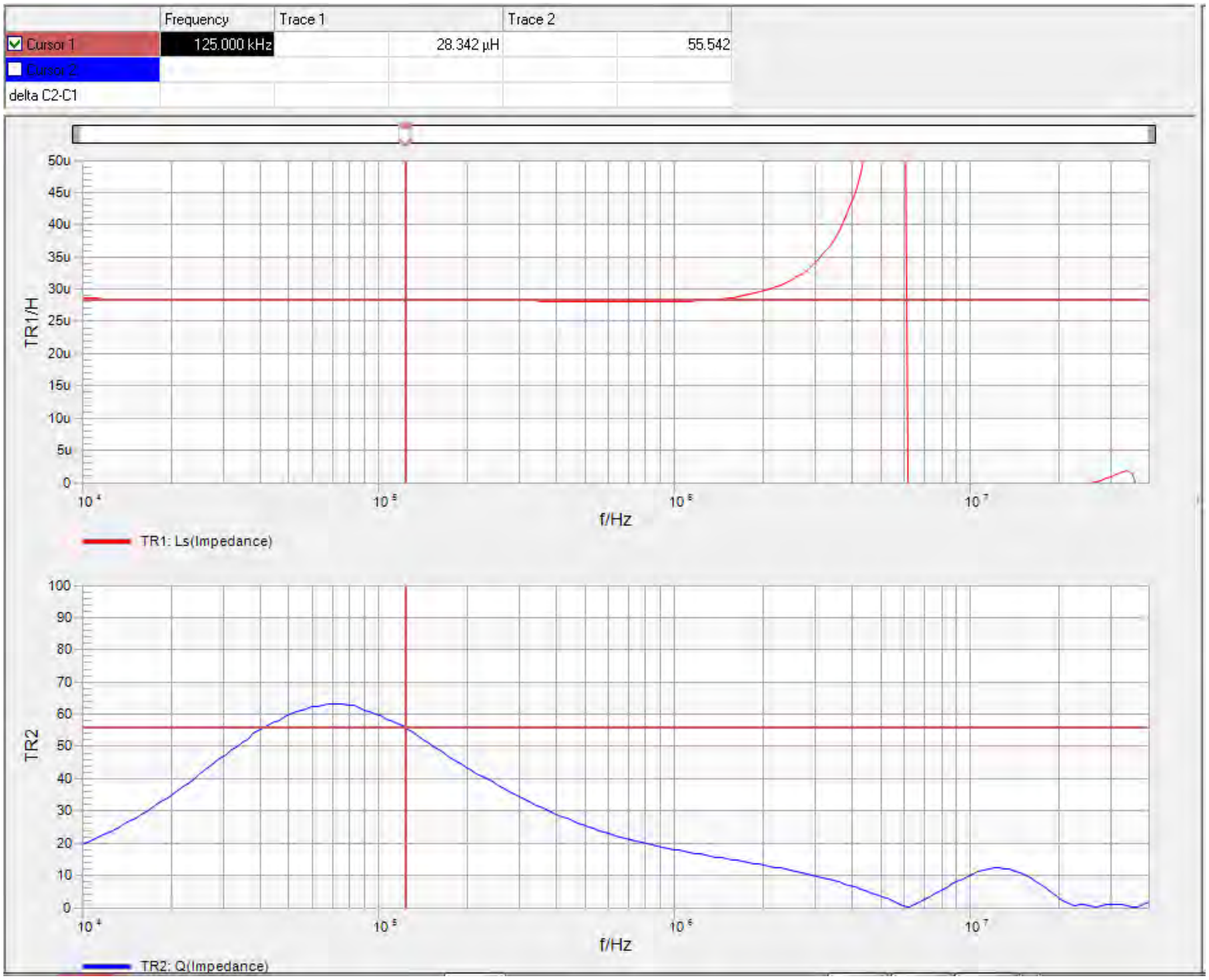
Note that there is significant proximity loss associated with the two coils (along with ferrite back plates and alignment magnets) being placed close together. At a separation of 4 mm and 150kHz the AC loss is double the DC loss. This is magnified as the frequency increases.

Transmit Coil

Table 3. Transmit coil inductance vs. (separation)

Frequency	L (0 mm)	L (4 mm)	L (8 mm)	L (16 mm)
125 kHz	33.4E-05	2.8E-05	2.66E-05	2.58E-05
Q	36.7	55.5	69.6	79.3

Again note that the Q of the transmit coil is also greatly reduced when it is in close proximity to the transmit coil. RS also varies with frequency and separation, as shown in Figure 8.



	Frequency	Trace 1		Trace 2	
☑ Cursor 1	125.000 kHz		28.342 µH		55.542
☐ Cursor 2					
delta C2-C1					

Figure 7. Transmit coil inductance and Q at 4 mm separation.

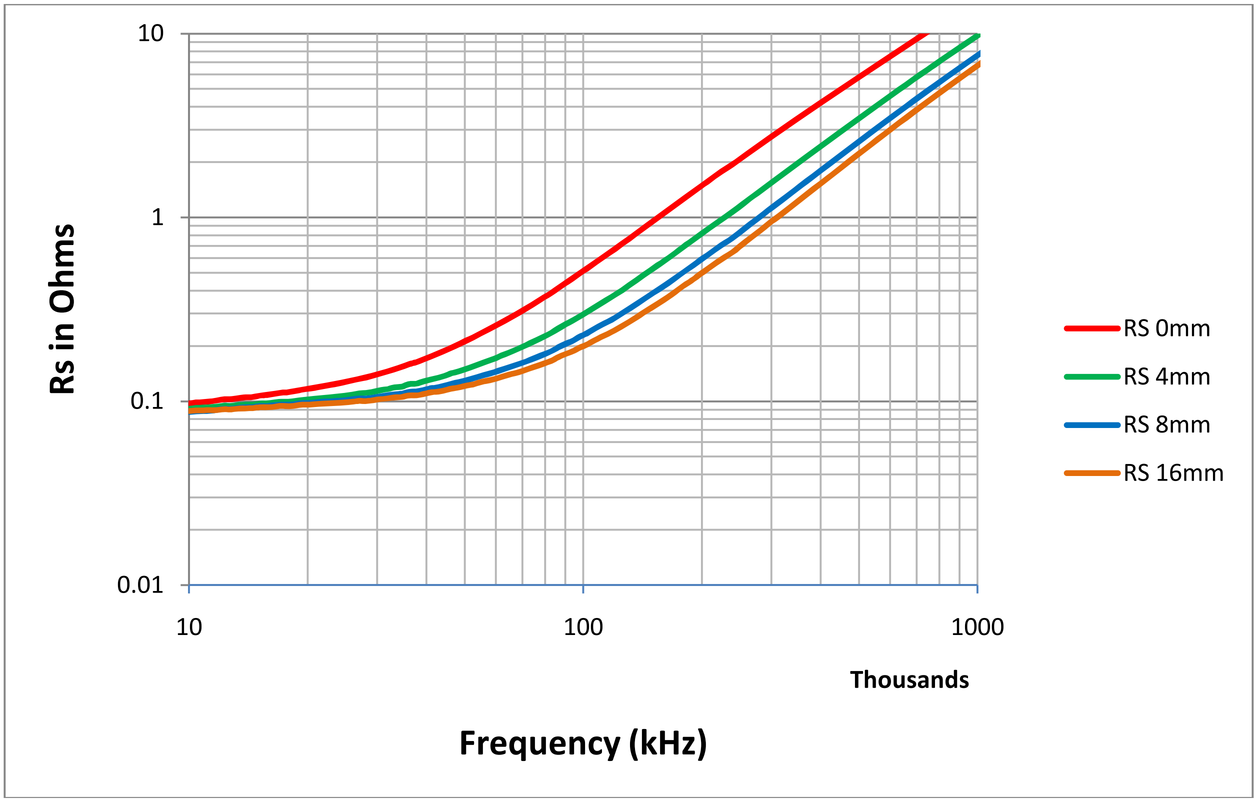


Figure 8. Receiver coil RS as a function of frequency and separation.

The link efficiency is determined by Q's of the transmit and receive coils and is greatly influenced by AC losses related to proximity effect as well as to the magnet and ferrite shields. We can effectively measure the coil Q and coupling, k, with the Bode 100, allowing us to calculate the link efficiency.

The efficiency is optimized by minimizing the proximity effects including the removal of the alignment magnets. It is also essential that the resonant frequency be kept as low as possible, as the AC losses increase rapidly with frequency.

In part 2 of this article we will construct a high fidelity model of the coupled link and compare the simulation of the wireless link using the ADS simulator and with SPICE. We'll also look at simulating the overall losses and further ways that efficiency can be improved.

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References

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