E-Space

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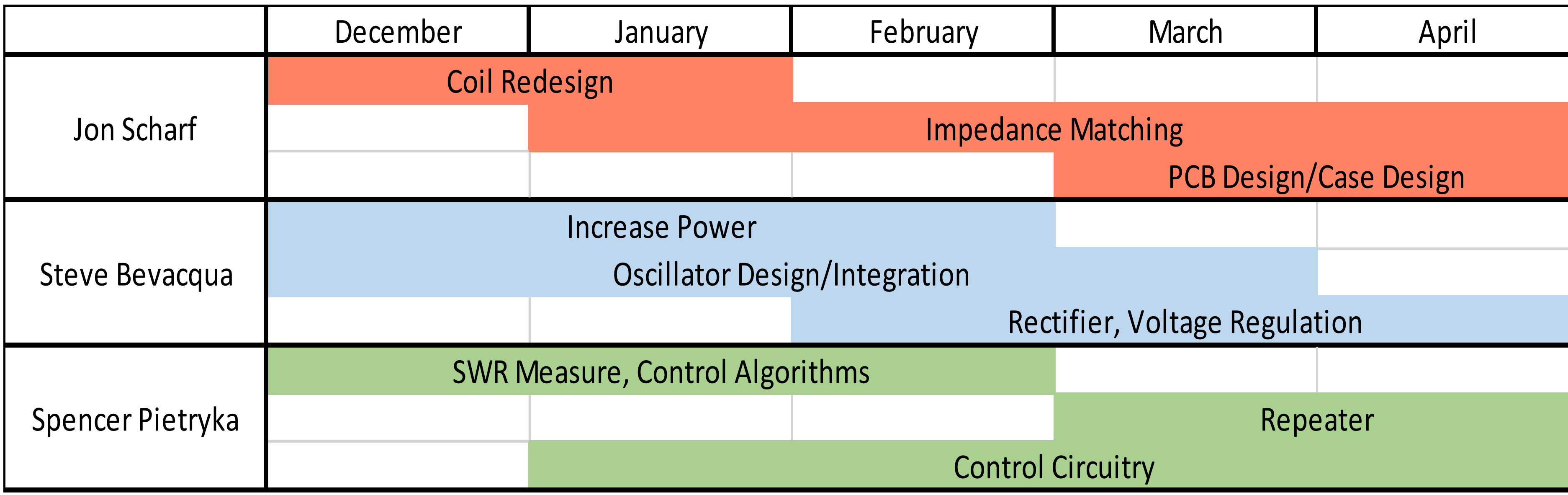
Revised System Requirements

- Changed minimum output power from 3.3W to 2.5W based on minimum USB charging requirements
- Changed final range to 10 cm

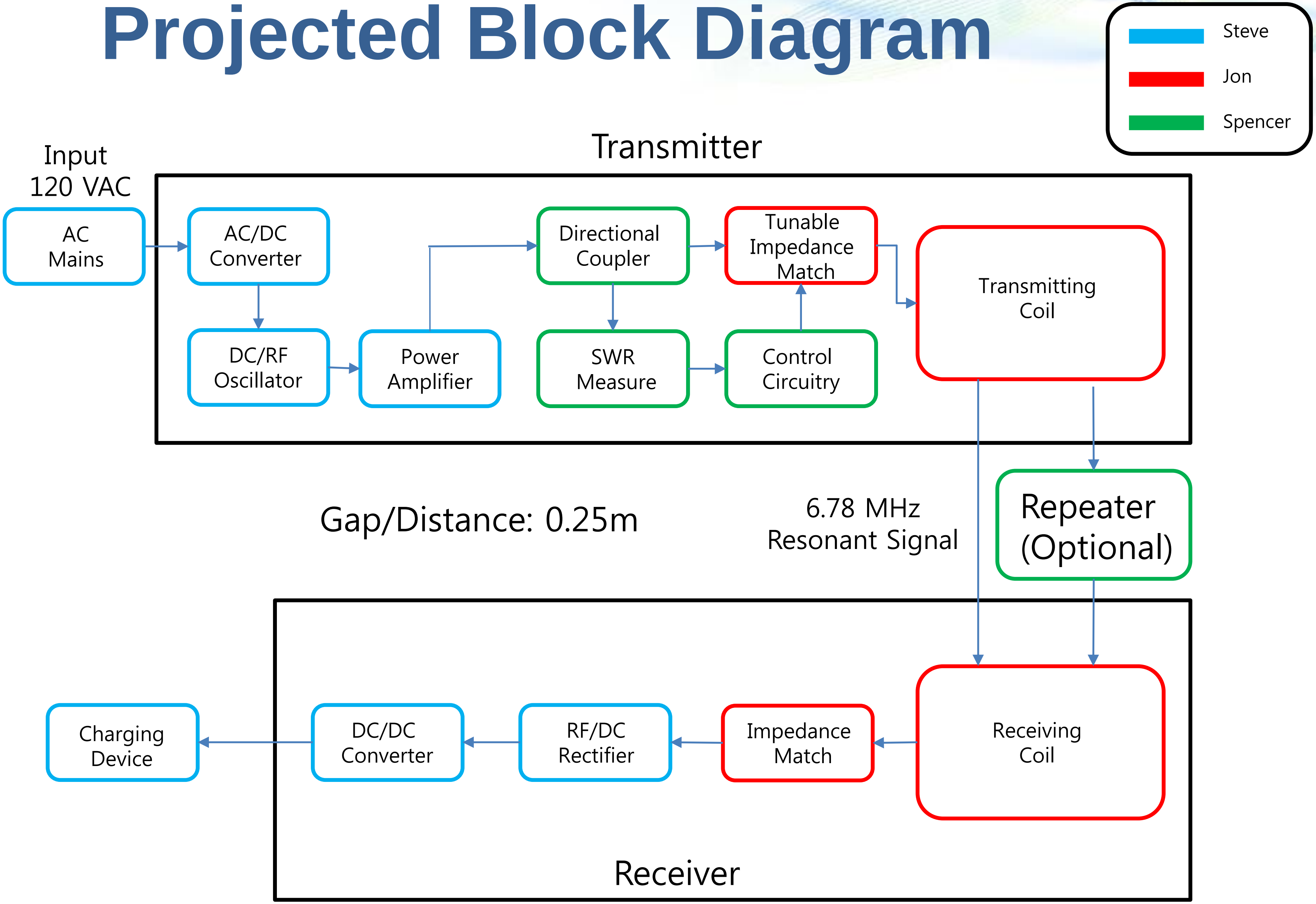
Input Specifications	120 VAC at 60Hz
Frequency	6.78 MHz
Distance/Range	10 cm
Minimum Output Power	2.5W
Minimum Wireless Transfer Efficiency	≥40%
Minimum Total System Efficiency	≥10%
Maximum Receiver Size	4.54 in X 2.31 in

Team Responsibilities



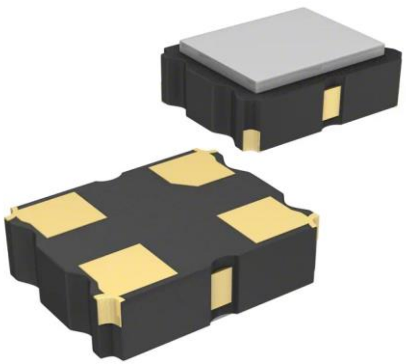
Gantt Chart from MDR

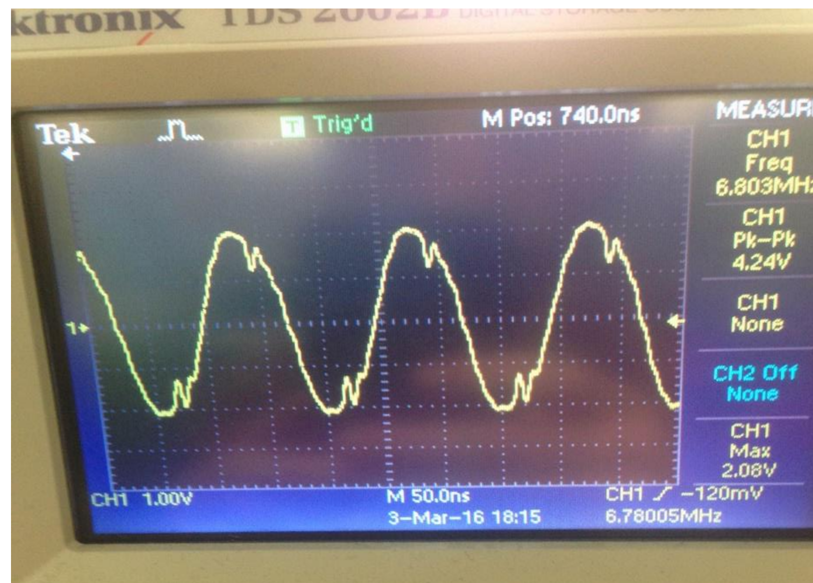
Projected Block Diagram



Oscillator

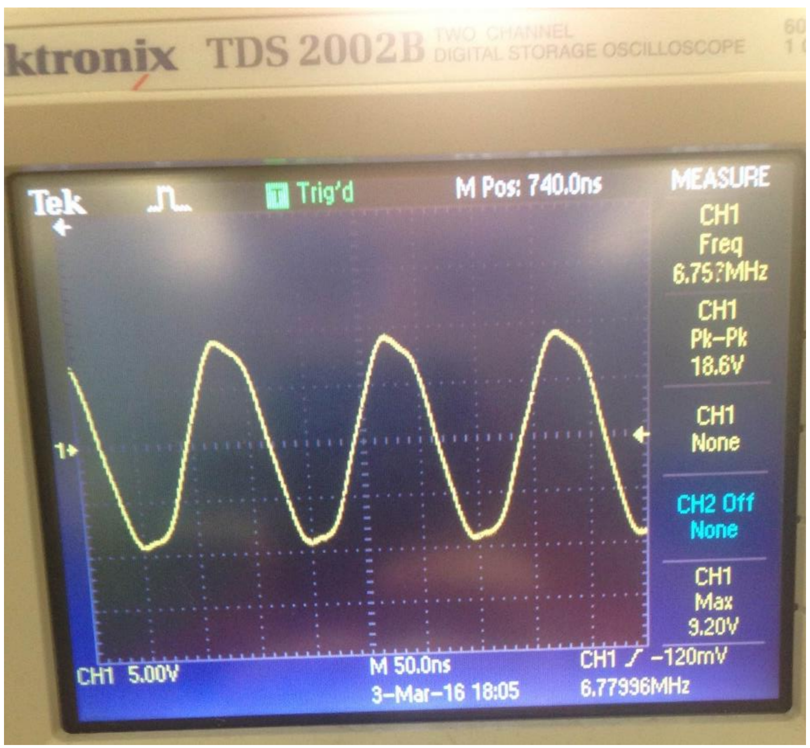
- Epson SG-210STF 6.7800ML Crystal Oscillator
- Stable 6.78 MHz frequency of oscillation
- Supply of 1.6V-3.6V and 1.8mA
- Output amplitude is directly proportional to supply voltage

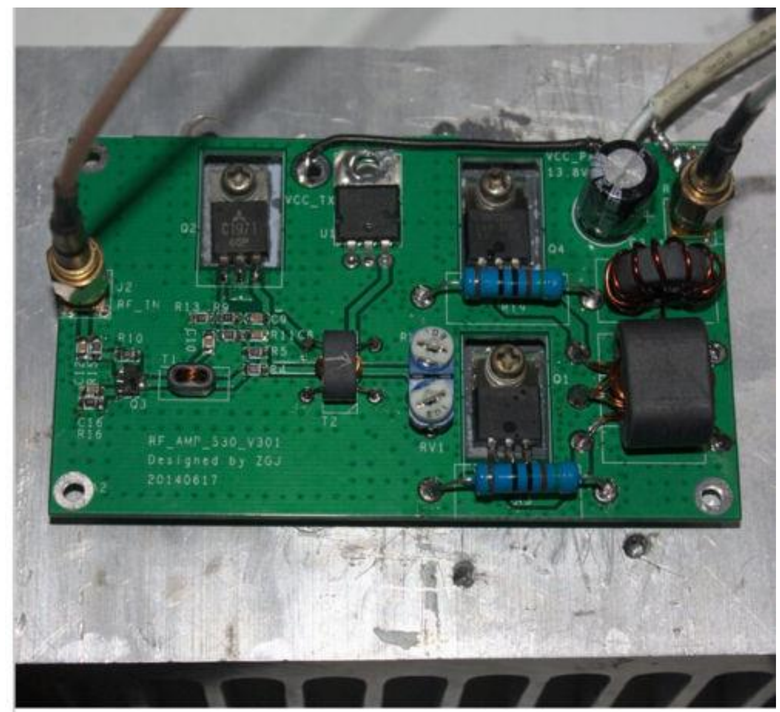




Power Amplifier

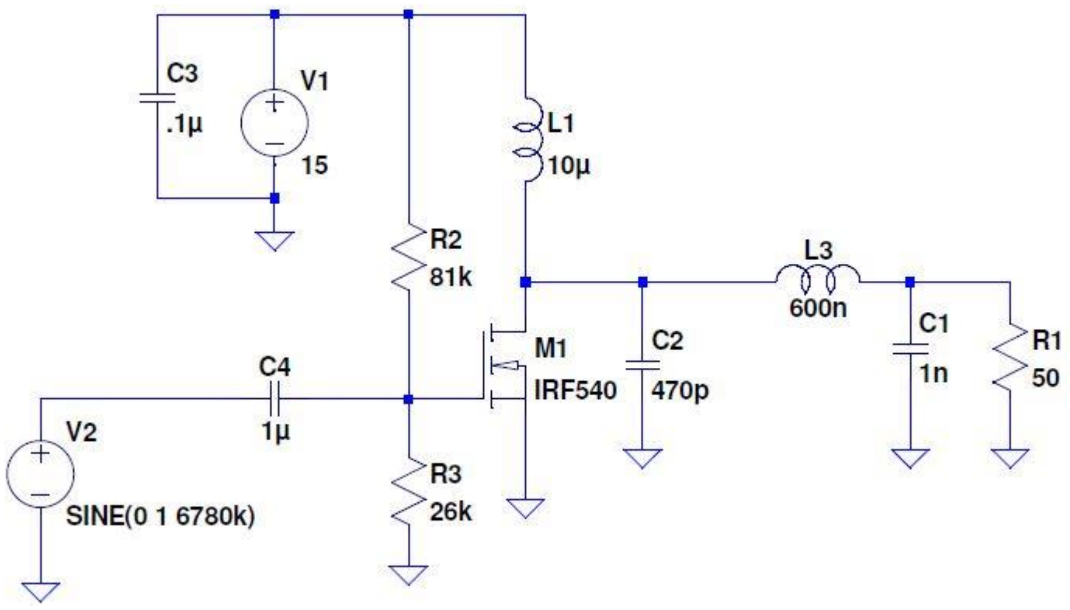
- Linear power amplifier
- Input 1mW-5mW
- 40dB gain, 45W max output power
- 3MHz-30MHz input frequency range
- SMA connectors on input and output

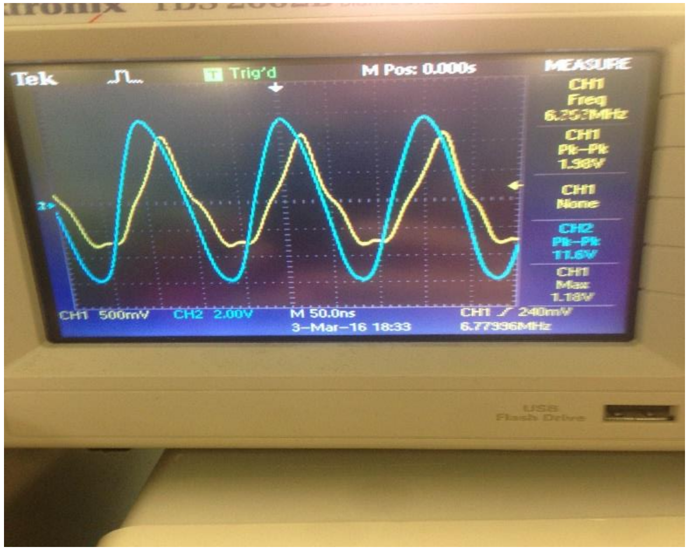




Power Amplifier

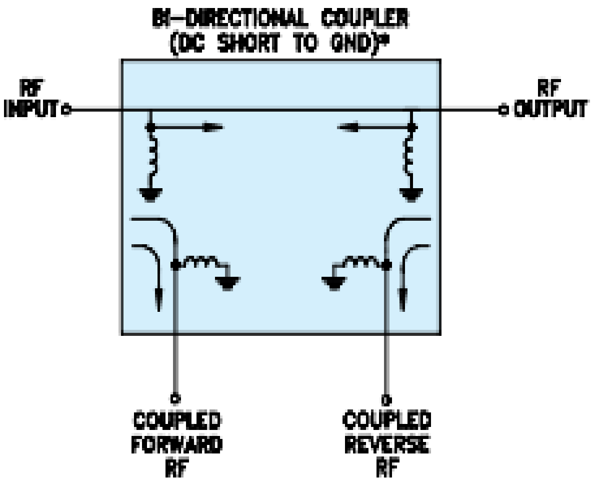
- Class E amplifier design
- ~15dB voltage gain
- Up to 40W output





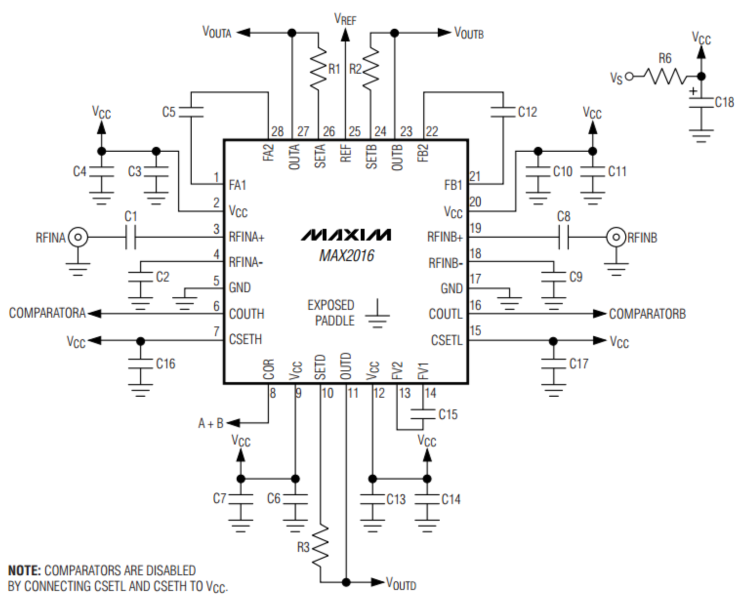
Directional Coupler

- Goal: Measure incident and reflected power from transmitting coil to quantify match
- Mini-Circuits SYDC-20-31HP+ Bi-directional Coupler
- 0.07 dB mainline loss
- 50 W power handling capability
- >41 dB directivity
- 20.4 dB coupling
- 36 dB return loss



SWR Measure

- Goal: Use coupled ports from bi-directional coupler to measure incident and reflected powers and provide proportional DC voltage
- Maxim Integrated MAX2016 LF-to-2.5GHz Dual Logarithmic Detector
- RF Input Power Range: -70 to +10 dBm



$$P_{RFIN\_} = \frac{V_{OUT\_}}{SLOPE} + P_{INT}$$

$$RL = P_{RFINA} - P_{RFINB}$$

$$VSWR = \frac{1 + 10^{-\left(\frac{RL}{20}\right)}}{1 - 10^{-\left(\frac{RL}{20}\right)}}$$

Coil Design

Recall Transmitter Limitation Due
To Reciever Size:

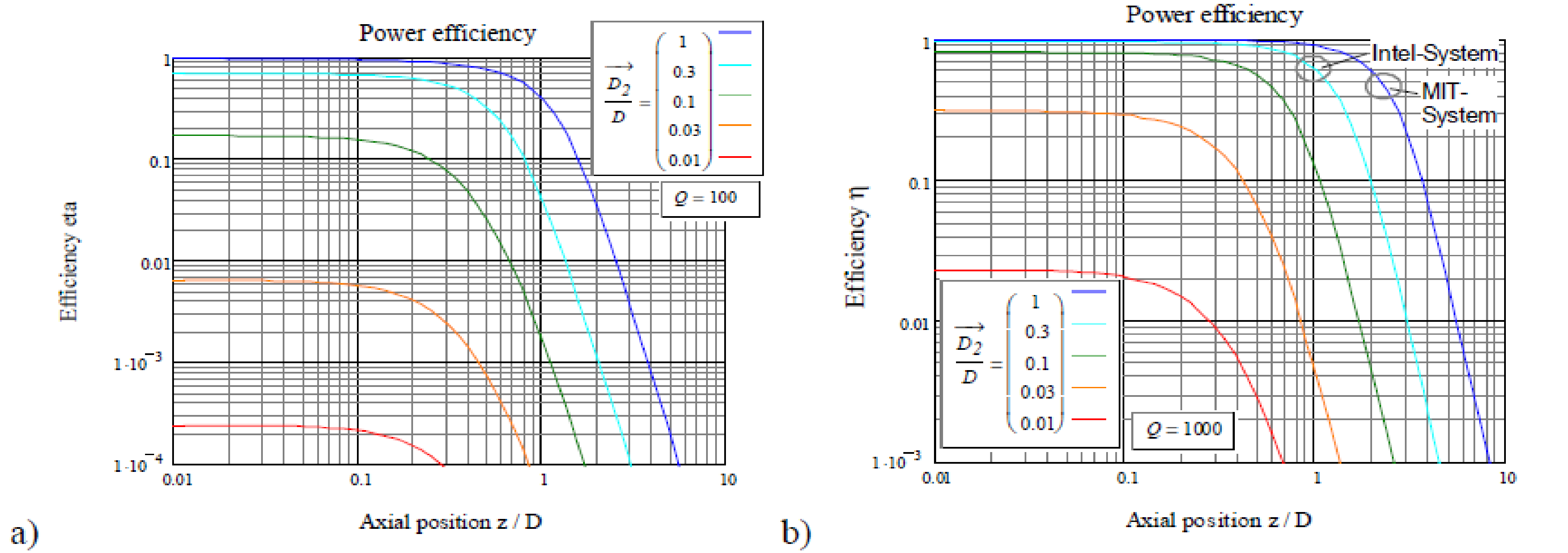


Figure 7: Power efficiency for an inductive power transfer system consisting of loop inductors in dependence on their axial distance z with size ratio as parameter. Calculated for a quality factor of a) Q = 100, b) Q = 1000

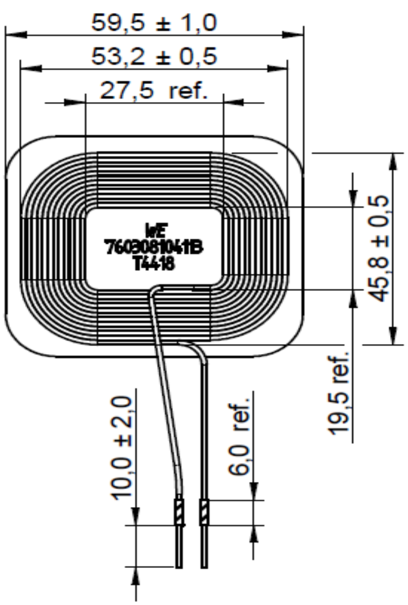
Waffenschmidt, Eberhard, and Toine Staring. "**Limitation of inductive power transfer for consumer applications**." In *Power Electronics and Applications, 2009. EPE'09. 13th European Conference on*, pp. 1-10. IEEE, 2009.

Coil Design

Coil Design Limited to ~175 mm Outer Diameter

Purchased Coil:

Dimensions: [mm]



Electrical Properties

Properties	Test conditions		Value	Unit	Tol.
Inductance	125 kHz/ 10 mA	L	12	µH	±10%
Q-factor	125 kHz/ 10 mA	Q	120		
Rated Current	$\Delta T = 40$ K	I_R	8	A	max.
Saturation Current		I_{SAT}	10	A	typ.
DC Resistance	@ 20°C	R_{DC}	0.06	Ω	typ.
DC Resistance	@ 20°C	R_{DC}	0.072	Ω	max.
Self Resonant Frequency		f_{res}	16	MHz	

Coil Design

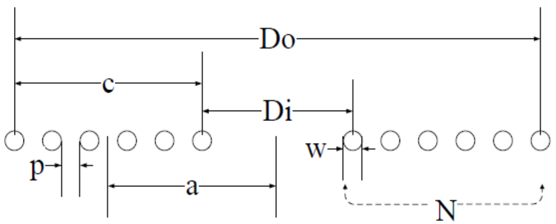


Fig. 1. Cross-sectional view of flat spiral coil.

$$D_i = D_o - 2N(w+p), \qquad l = \frac{1}{2}N\pi(D_o + D_i) \qquad (1)$$

$$a = \frac{1}{4}(D_o + D_i), \qquad c = \frac{1}{2}(D_o - D_i) \qquad (2)$$

N, number of turns
D_0, Outer Diameter
p, Spacing between turns
w, Wire Diameter
D_i, Inner Diameter
l, total wire length
a, winding radius
c, radial depth
f, Resonant Frequency

$$L(H) = \frac{N^2(D_o - N(w+p))^2}{16D_o + 28N(w+p)} \times \frac{39.37}{10^6} \qquad (3)$$

$$R_{DC} = \frac{l}{\sigma\pi(w/2)^2}, \qquad \delta = \frac{1}{\sqrt{\pi f \sigma \mu_o}} \qquad (5)$$

$$R = R_{DC}\frac{w}{4\delta} = \sqrt{\frac{f\pi\mu_o}{\sigma}}\,\frac{N(D_o - N(w+p))}{w} \qquad (6)$$

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{39.37}{10^6}\sqrt{\frac{f\pi\sigma}{\mu_o}}\,\frac{wN(D_o - N(w+p))}{8D_o + 14N(w+p)} \qquad (7)$$

B. H. Waters, B. J. Mahoney, Gunbok Lee and J. R. Smith, "***Optimal coil size ratios for wireless power transfer applications***," Circuits and Systems (ISCAS), 2014 IEEE International Symposium on, Melbourne VIC, 2014, pp. 2045-2048.

Coupling Factor and Coefficient Calculation

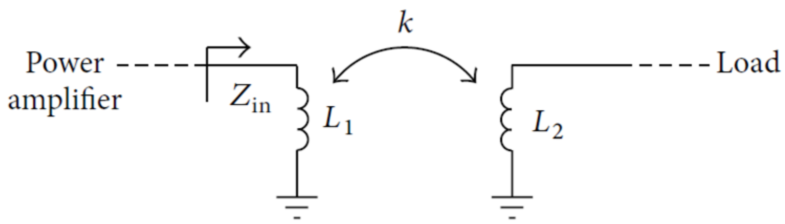


FIGURE 1: Inductive link schematic.

$$M = \frac{\mu\pi n_1 n_2 a^2 b^2}{\sqrt{(a+b)^2 + d^2}\left[(a-b)^2 + d^2\right]} \quad (14)$$

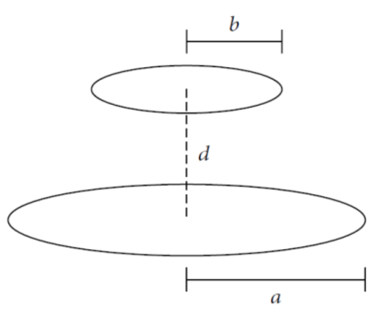


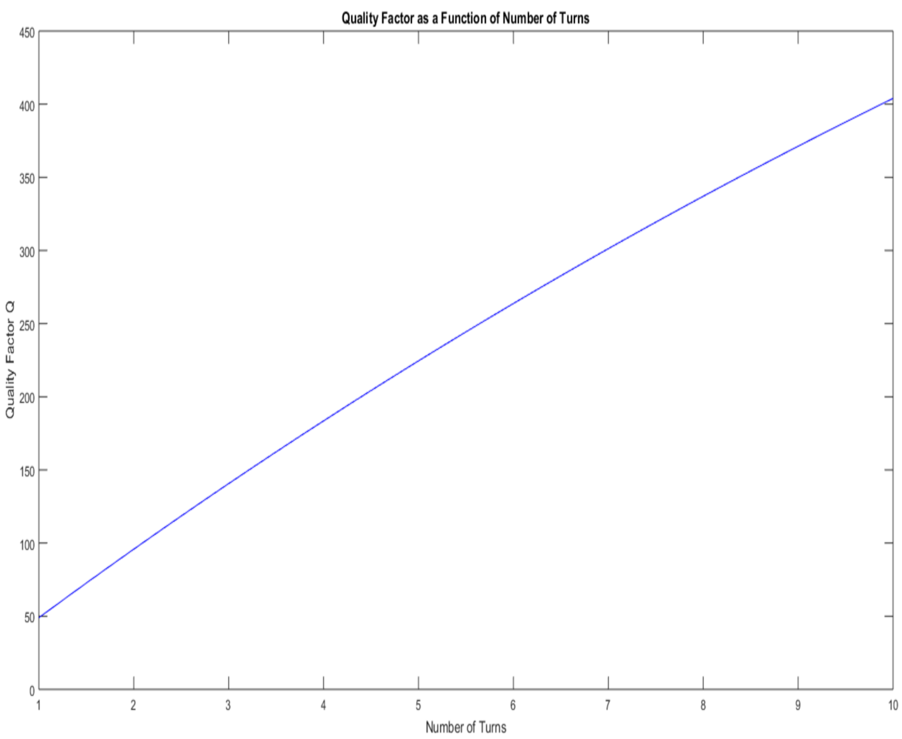
FIGURE 2: Two coaxial coils with radii a and b.

$$k = \frac{M}{\sqrt{L_i L_j}}$$

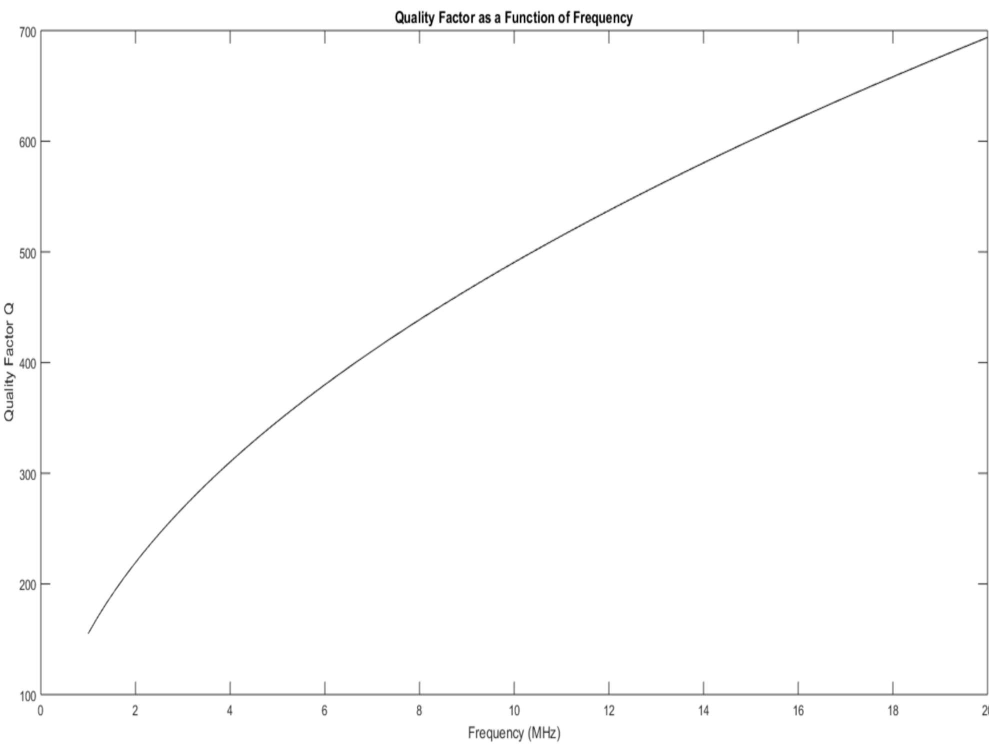
Rafael Mendes Duarte and Gordana Klaric Felic, "**Analysis of the Coupling Coefficient in Inductive Energy Transfer Systems," Active and Passive Electronic Components**, vol. 2014, Article ID 951624, 6 pages, 2014. doi:10.1155/2014/951624

Variable Effects

Quality Factor as a Function of Number of Turns

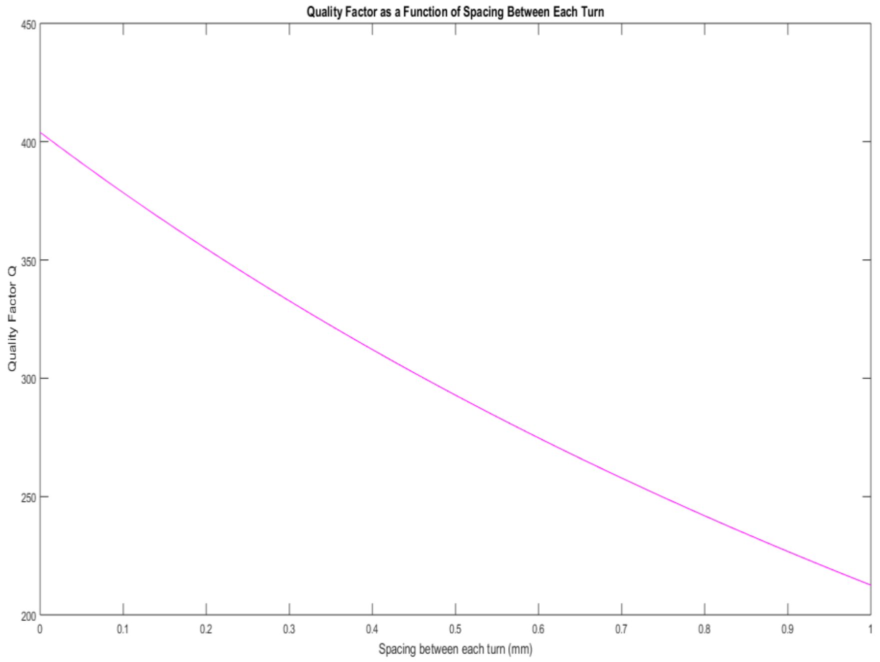


Quality Factor as a Function of Frequency

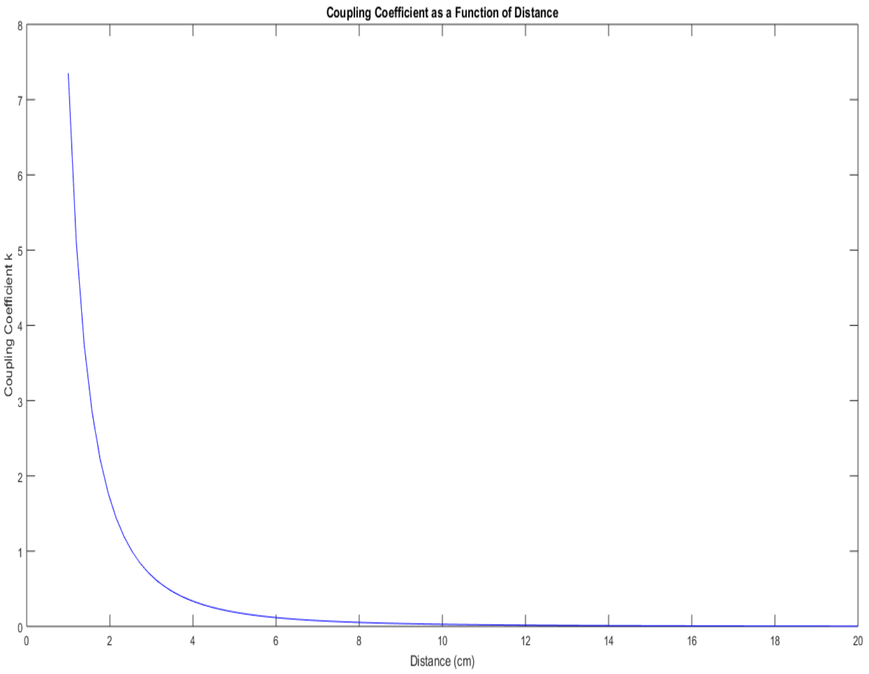


Variable Effects

Quality Factor as a Function of Turn Spacing

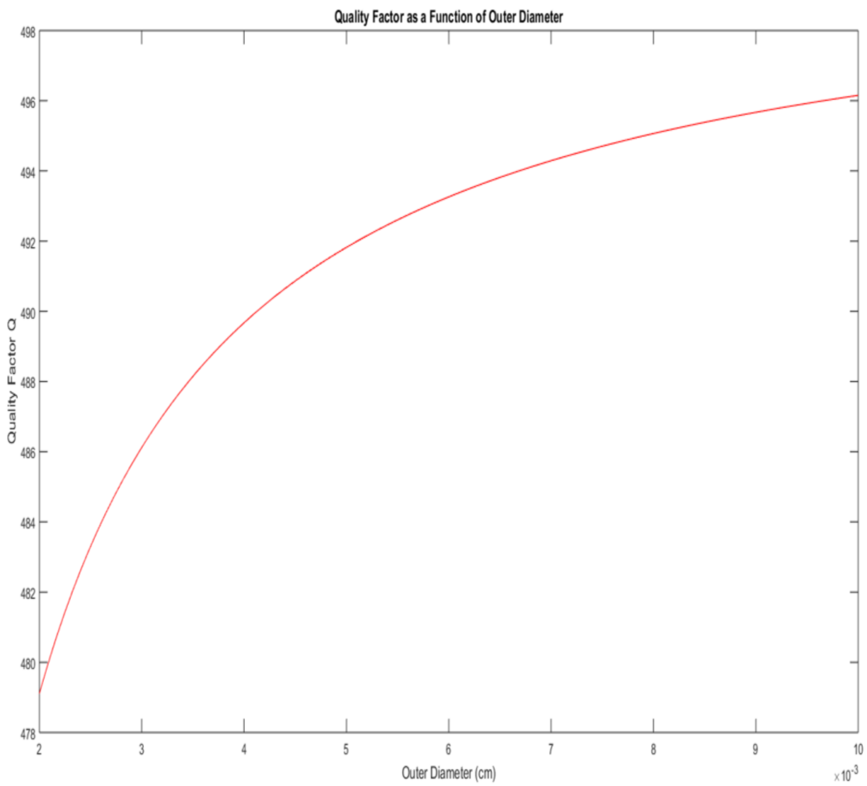


Coupling Coefficient as a Function of Distance

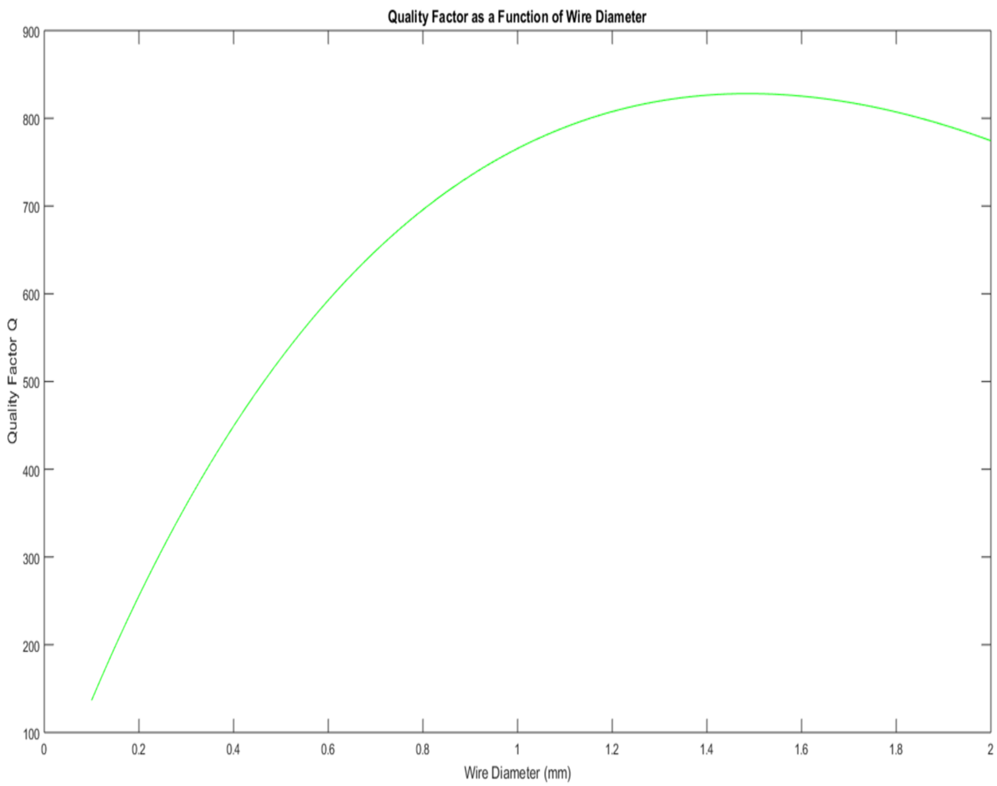


Variable Effects

Quality Factor as Function of Outer Diameter

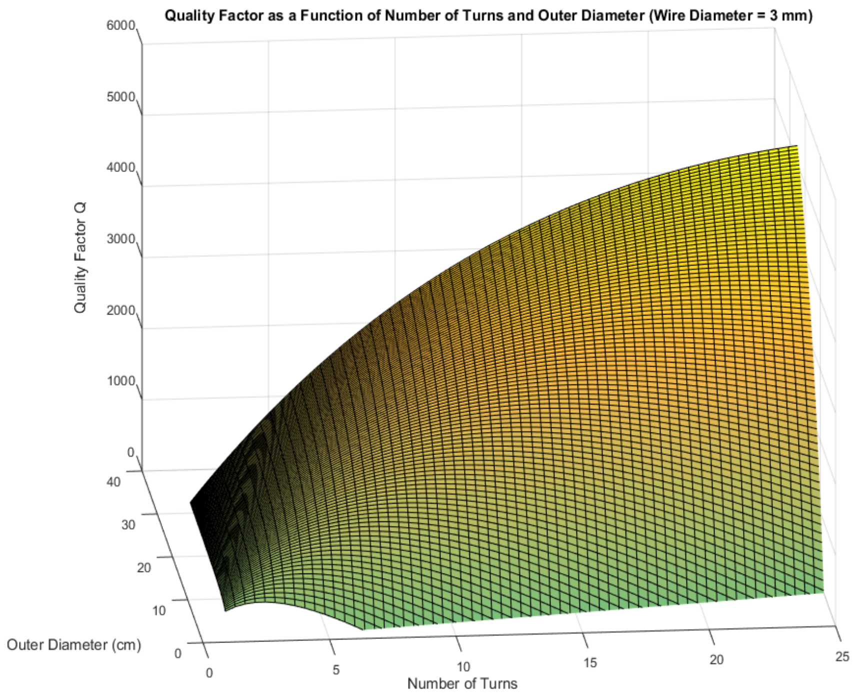


Quality Factor as Function of Wire Diameter

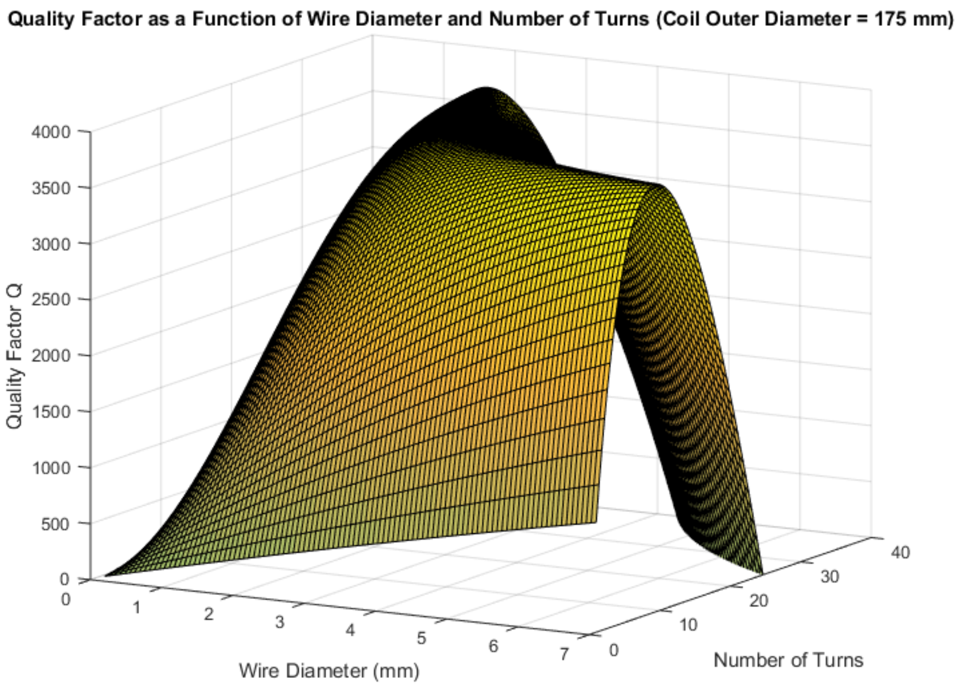


3 Dimensional Analysis on Variables

Quality Factor as Function of Turns and Outer Diameter

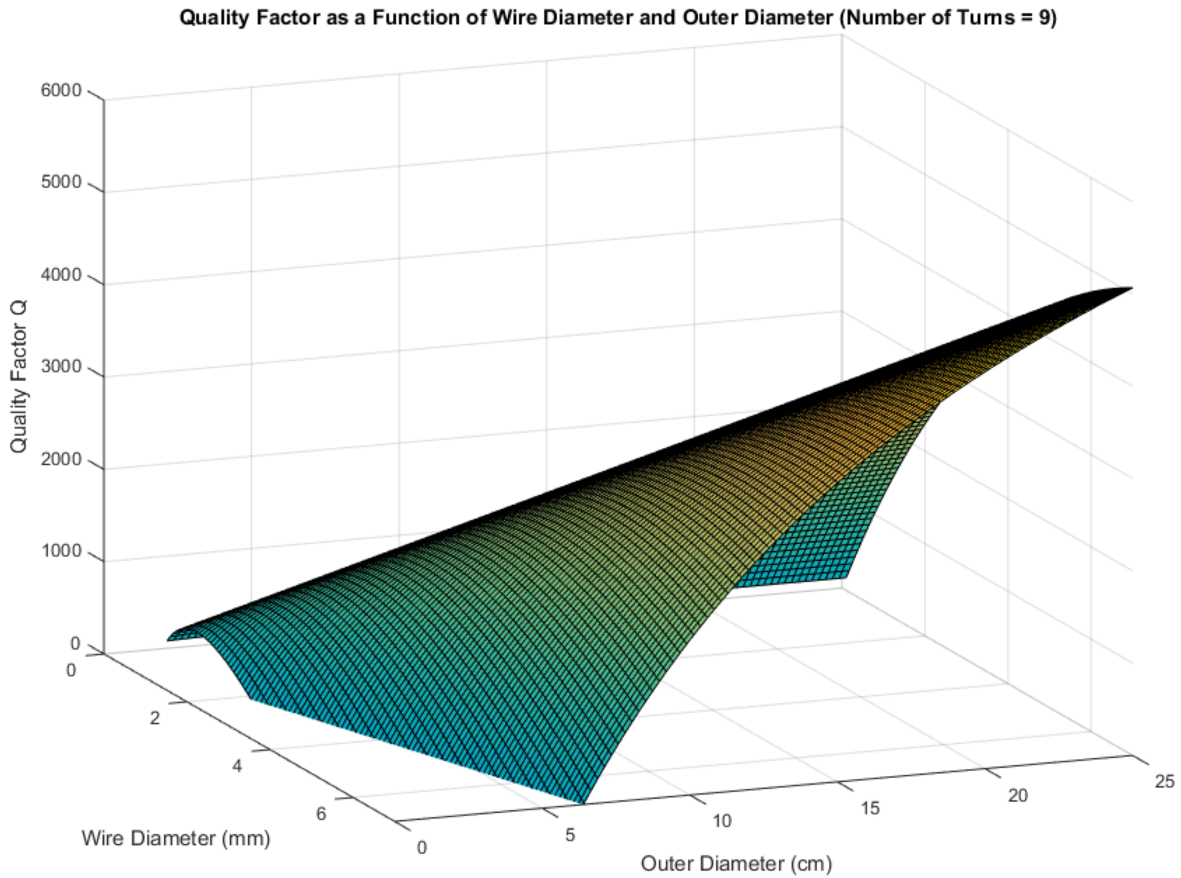


Quality Factor as Function of Turns and Wire Diameter



3 Dimensional Analysis on Variables

Quality Factor as Function of Outer Diameter and Wire Diameter



Real Vs. Theoretical (Transmitter)

Picked Values for Transmitting Coil

- D_0 = 175mm
- w = 2.05 mm (12AWG)
- N = 23 turns
- s = As close to zero as possible

Theoretical Values:

Q_Factor = 3544   C = 6.602 pF

L= 83.233 uH   R (AC) = .9440 ohms

Measured Values

Q_Factor = 5137.058   C = **assumed 0 F**

L = 61.5 uH   R(AC) = .51 ohms

Impedance Matching

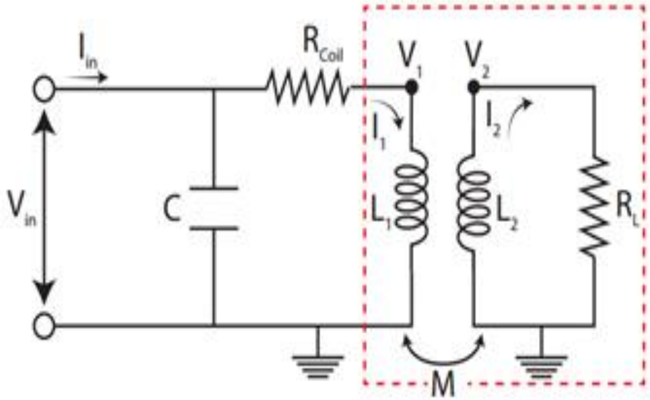


FIGURE 4. Circuit diagram of the driving coil and receiving coil

From Z_in, we calculated the impedance matching network values by setting Z_in to be our load (R_L+jX_L).

Where,

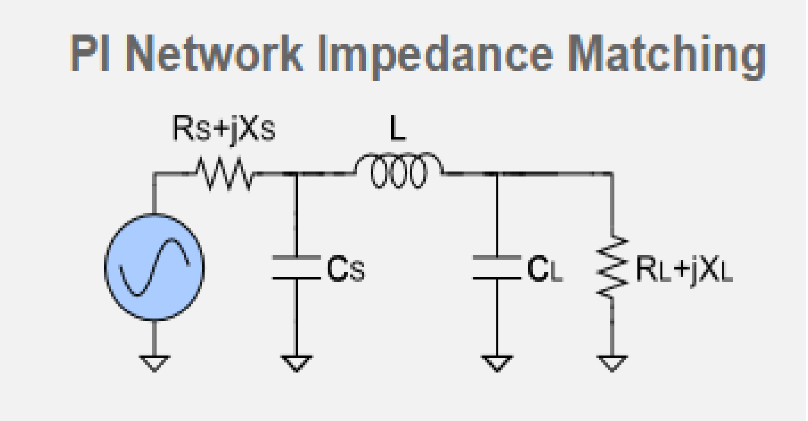
$$M = \frac{\mu_0}{4\pi}\oint_{C_{\text{emitter}}}\oint_{C_{\text{receiver}}}\frac{ds_{\text{receiver}}\cdot ds_{\text{emitter}}}{|R_{\text{emitter,receiver}}|} = k\sqrt{L_1L_2},$$

$$\frac{V_1}{I_1} = Z_{ind} = i\omega L_1 - \frac{\omega^2M^2}{R_L - i\omega L_2}.$$

$$Z_{eq} = \left[i\omega C + \frac{1}{R_C + Z_{ind}}\right]^{-1}$$

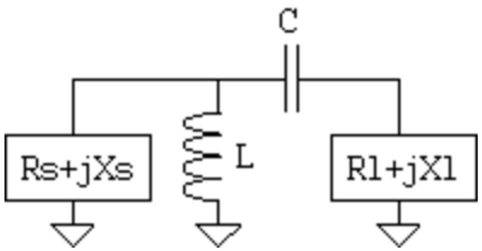
*Bhutada, Manasi, Vikaram Singh, and Chirag Warty. "**Transmission ofWireless Power in two-coil and four-coil systems using couple d mode theory**." In Aerospace Conference, 2015 IEEE, pp. 1-8. IEEE , 2015.*

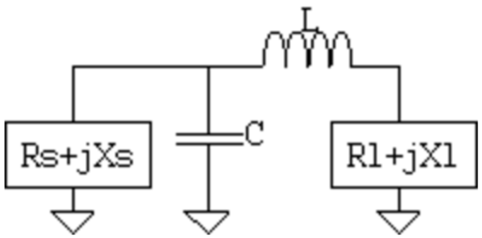
$$Z_{\text{in}} = R_{1S} + jwL_1 + \frac{w^2M^2}{jwL_2R_{2S} + Z_L},$$



Impedance Matching Networks

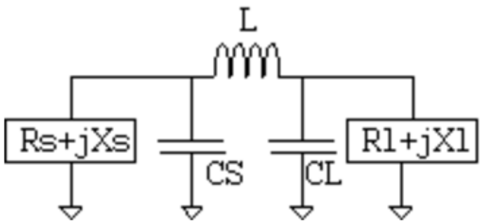
L-Model Networks





Several Impedance Matching Networks were created and the values determined through online calculators and matlab scripts.

Pi-Model Network



Self Capacitance of Transmitter Coil

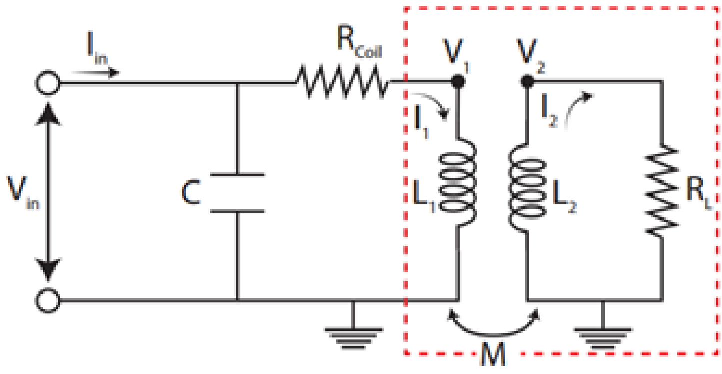


FIGURE 4. Circuit diagram of the driving coil and receiving coil

- Transmitting Coil Self Resonating Frequency is at 320 KHz
- C is actually 4.77 nF
- Impedance @6.78 MHz = -5.8492j
- Series inductance needed to tune to resonance

Receiver Coil Change

At Resonance

- L = 4.5 uH
- R = .1422
- Q Factor = 1359.2

Driving Coil

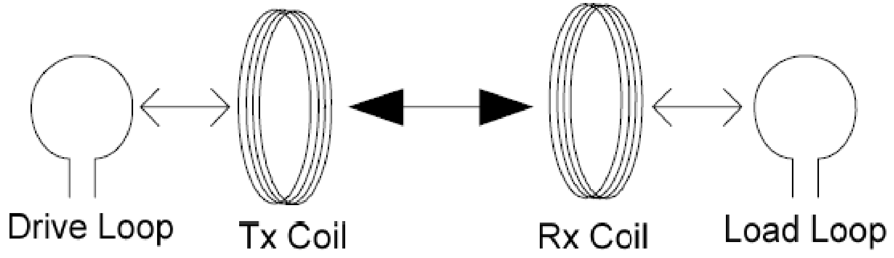


Figure 1. Magnetically coupled resonant wireless power system.

*Zhao, Qiang, Anna Wang, and Hao Wang. "**Structure Analysis of Magnetic Coupling Resonant for Wireless Power Transmission System**." (2015).*

- Used a 3 Coil System to better improve Matching
- Steps down voltage
- Driving Coil:
  55 turns & 22 AWG

Future: Impedance match to driving coil

Demonstration

- CDR Deliverables Met:
  - Implement impedance match network for 10 cm
  - Final coil sizes constructed
  - Effectively measure SWR on line

- CDR Deliverables Not Met:
  - Demonstrate system output: 2.5 W over 10 cm

Demo

FDR Goals

- Deliver 2.5W over 10 cm distance
- Deliver power through USB to phone's charging port
- Package transmitting circuitry and house receiving circuitry in a phone case
- Switchable impedance matching network dependent on SWR measurements
- Oscillator fully integrated
- Power supply selected and implemented

Questions and Comments