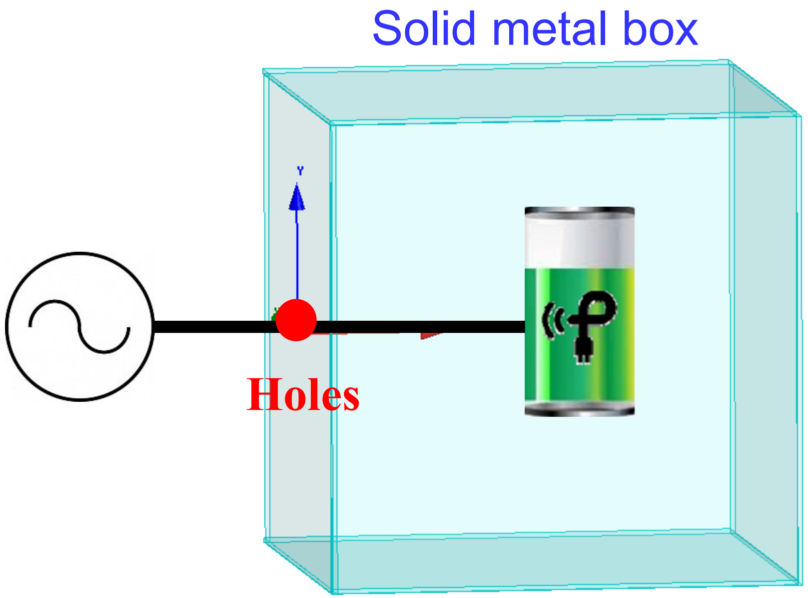
Through-metal communications and power transfer

Juan Romero and Anh-Vu Pham
Microwave Microsystems Laboratory, University of California
Department of Electrical and Computer Engineering
Davis, CA 95616
Phone: 530-752-7472 and Email: pham@ece.ucdavis.edu

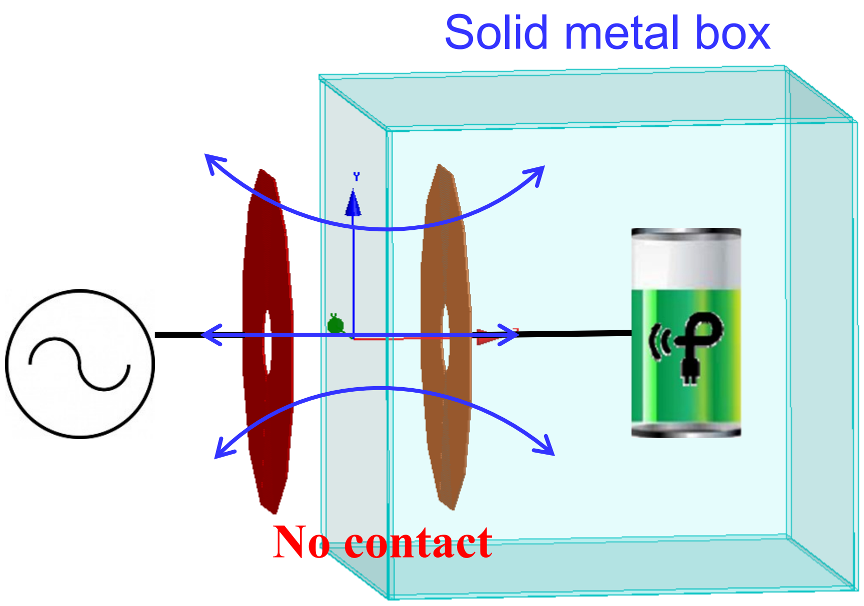
UC DAVIS ELECTRICAL AND COMPUTER ENGINEERING

Through Metal Energy Harvesting

- Drilling holes cause leakage and reduce structural integrity.
- No contact allowed with metallic plate.
- Inductive power coupling can transfer power through common metals, but efficiency is very poor.



Conventional through-wire solutions

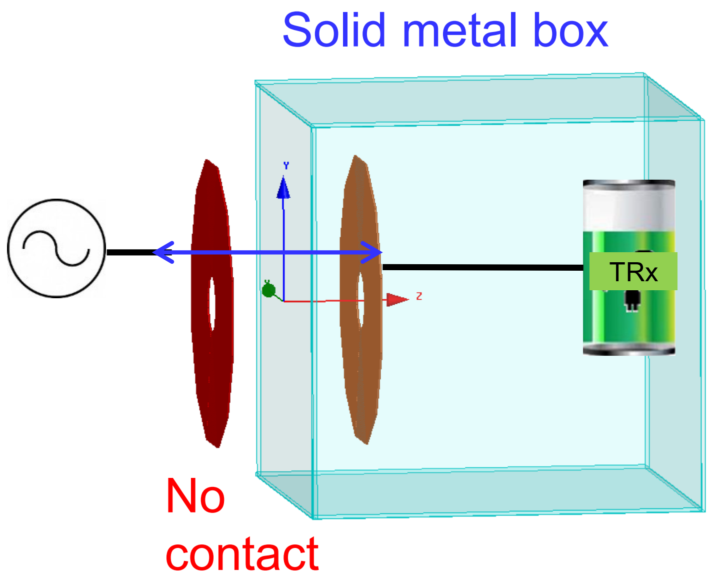


Proposed inductive power transfer

System requirements

- Sensor enclosed in metal box of 3mm thick aluminium.
- No batteries allowed inside sensor box: power up entirely from outside.
- Simultaneous power and data transmission is required
- No contact allowed with metallic box, i.e. no PZTs or EMATs.
- Bidirectional communications between inside and outside units.

- Received power should be >3W.
- Very high efficiency: PTE>2%
- Data rate >4.8 kbps.
- Coil/size limitations:
  - Diameter < 50mm
  - Height < 76mm



Proposed IPT system

State of the art performance of IPT systems through metal

- Most of the research focuses on poor conductive materials such as stainless steel or tin.

Design	Frequency (Hz)	Structure	Tx/Rx coil outer diameter (mm)	Metal thickness	Skin depth (mm) @50Hz	PTE (%)	Data rate (bps)
[1]	50	Solenoid with ferrite	211/234	5 mm stainless steel pipe	59	10	NA
[2]	50-50000	Solenoid	24/30	14 mm stainless steel pipe	59	Not provided	Not provided
[3]	50	Loop coil	120/120	12 mm steel open disk	59	4.6	NA
[4]	50-3000	Helix	220/220	3.1 mm aluminium plate	12	4	NA
[5]	30-1000	Stacked Helix	150/50	3.1 mm aluminium tank	12	3.4	NA
[This work]	200	Stack and Flat Coil	195/195	3.1 mm aluminium tank	12	9	4800

[1] M. Yamakawa, Y. Mizuno, J. Ishida, K. Komurasaki and H. Koizumi, "Wireless Power Transmission into a Space Enclosed by Metal Walls Using Magnetic Resonance Coupling," *Wireless Engineering and Technology*, Vol. 5 No. 1, 2014, pp.19-24.

[2] H. Zangl, A. Fuchs, T. Bretterklieber, M. J. Moser and G. Holler, "Wireless Communication and Power Supply Strategy for Sensor Applications Within Closed Metal Walls," in *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 6, pp. 1686-1692, June 2010.

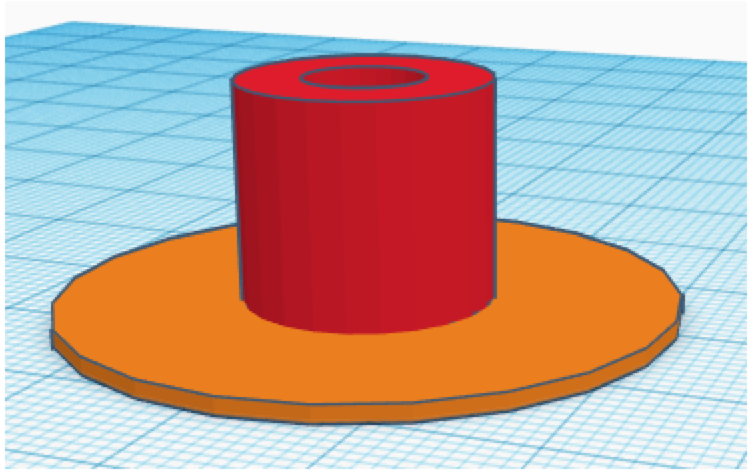
[3] D. J. Graham, J. A. Neasham and B. S. Sharif, "Investigation of Methods for Data Communication and Power Delivery Through Metals," in *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4972-4980, Oct. 2011.

[4] C. Van Pham, A. Pham and C. S. Gardner, "Development of Helical circular coils for wireless through-metal inductive power transfer," *2017 IEEE Wireless Power Transfer Conference (WPTC)*, Taipei, 2017, pp. 1-3.

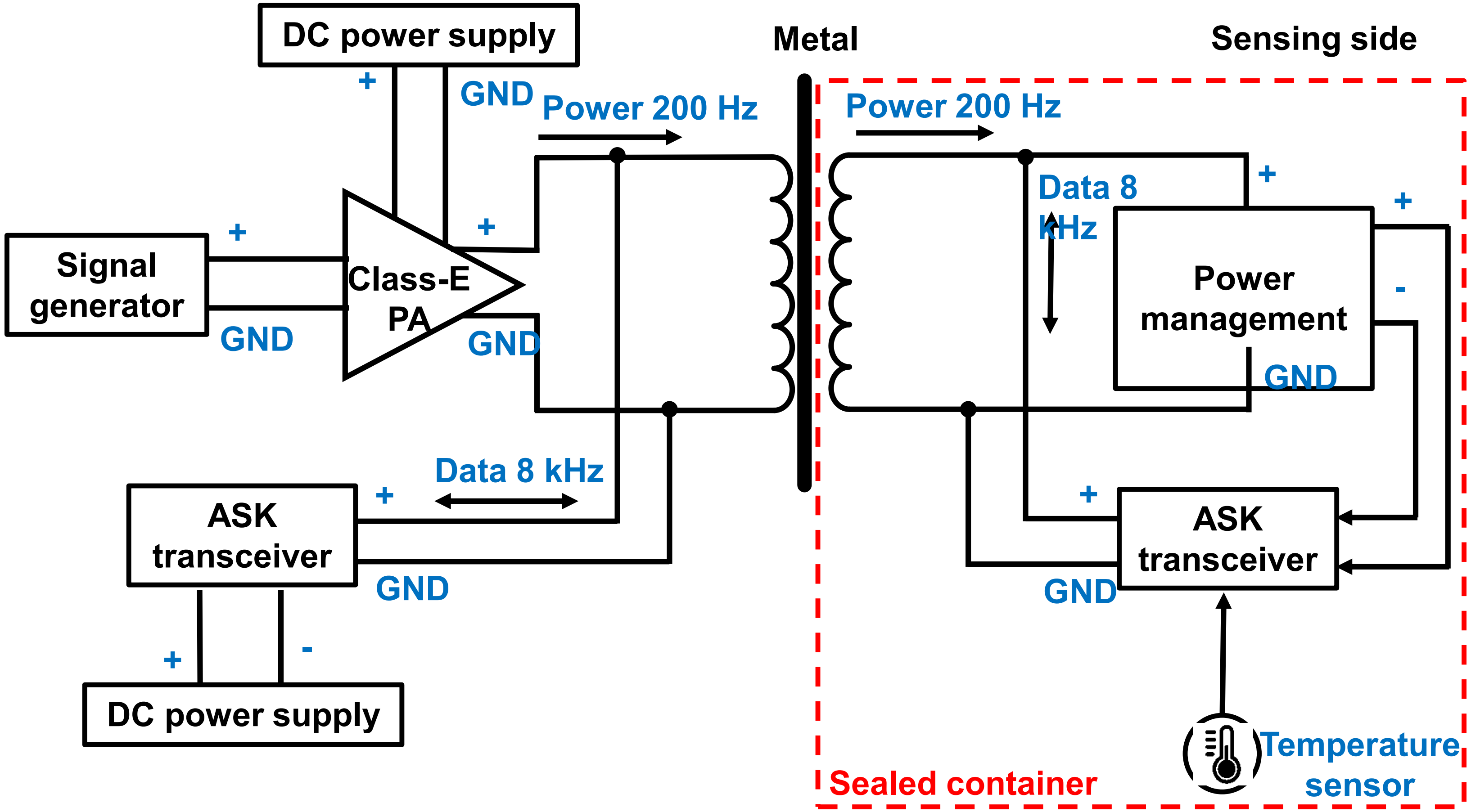
[5] C. V. Pham, T. A. Vu, W. Tran, A. Pham and C. S. Gardner, "Wireless Energy Harvesting System Through Metal for Aerospace Sensor," *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*, Long Beach, CA, 2018, pp. 545-549.

System Overview

- Novel Stack-Flat Coil structure for high PTE and data rate.
- Custom designed Power Amplifier, Power Management Module and ASK TRx allows bidirectional 4800 bps communication link.
- PTE=9%.



Novel Stack – Flat coil structure



POWER TRANSFER

Power Coils

- Coil requirements:
  - Diameter < 50mm
  - Height < 76mm
  - Rx Power > 3W
  - PTE > 2%
  - 3mm thick Al

- To meet the requirements a custom helix stacked coil with **ferrite core** was designed.

Without ferrite | **With ferrite**

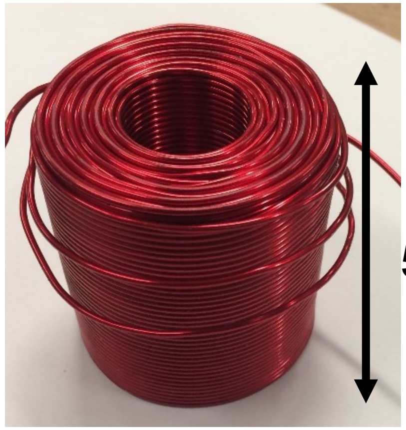
Helix 1 (Rx)
(~ 635 turns AWG 17)

70 mm

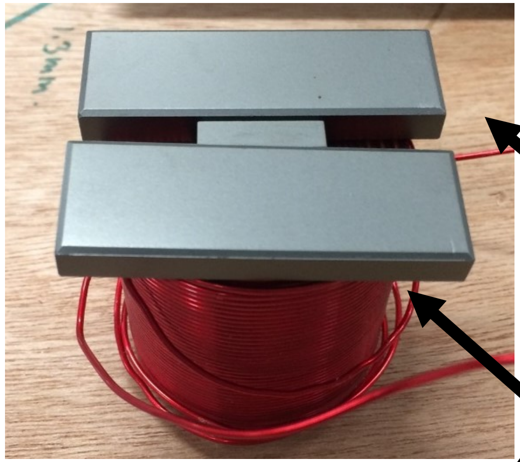
16 Rods

rout< 50 mm

Helix 2 (Tx)
(~ 514 turns AWG 17)



51 mm



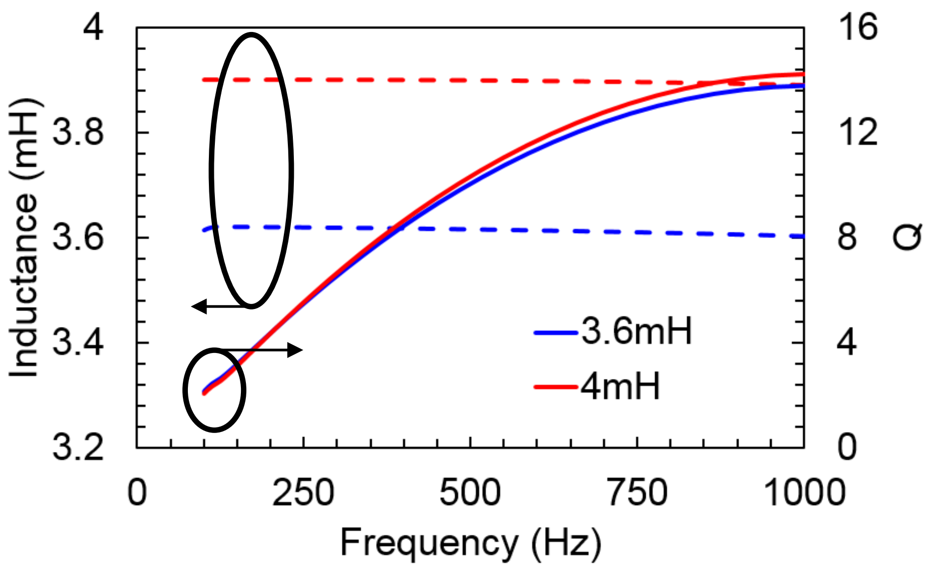
Ferrite

4 rods

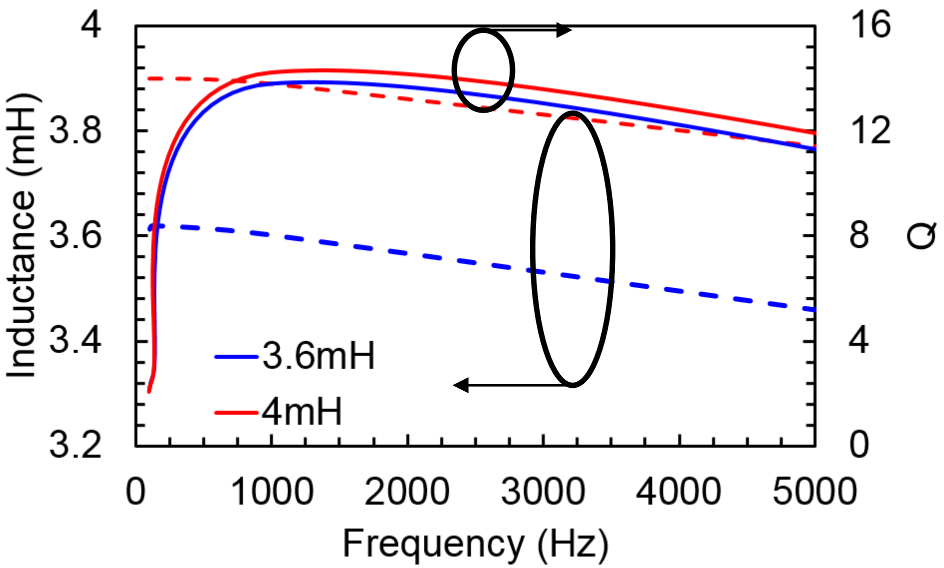
Coils Parameters (without ferrite)

- Coil measured parameters comply with expected values.
  - Helix 1 without ferrite: L= 3.9 mH, Q= 2.456 at 120 Hz
  - Helix 2 without ferrite: L= 3.62 mH, Q= 2.578 at 120 Hz
- Parameters not enough to comply with the requirements → Ferrite Core is critical!

***f*: 100- 1000 Hz**



***f*: 100- 5000 Hz**



Effect of Ferrite Core on Coils Parameters

Coil parameters	Helix 1 No ferrite	Helix 1 Ferrite	Helix 2 No Ferrite	Helix 2 Ferrite
Inductance (L)	3.90 mH	25.7 mH	3.62 mH	23.533 mH
Quality factor (Q)	2.456	9.502	2.578	9.001
DC resistance (R)	1.202 Ω	2.0352 Ω	1.040 Ω	1.976 Ω
Coil turns	635	635	514	514
Ferrite type	None	Rods	None	Rods and bar

$$\eta = \frac{P_{in}}{P_{out}} = \frac{V_1 I_1}{V_2^2 / R_L} \Rightarrow \eta \cong \frac{1}{2 + \frac{4}{k^2 Q_1 Q_2}}$$

- ✓ Using ferrite core tremendously improves inductance and quality factor of helix stacked coils.
  - ✓ >6.5x Inductance and >3x Quality factor.
- ✓ However, the effect of the metal plate has not been considered.

Parasitic Effect of Metal Plate

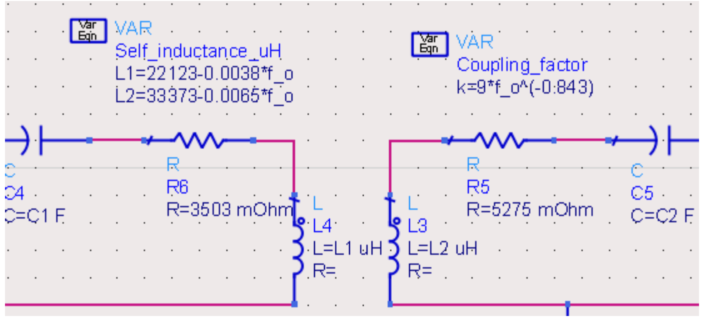
- The metal barrier will increase in the parasitic resistance of the coil which decreases the quality factor and decreases the PTE.
  - ↑Rs, ↓Q, ↓PTE

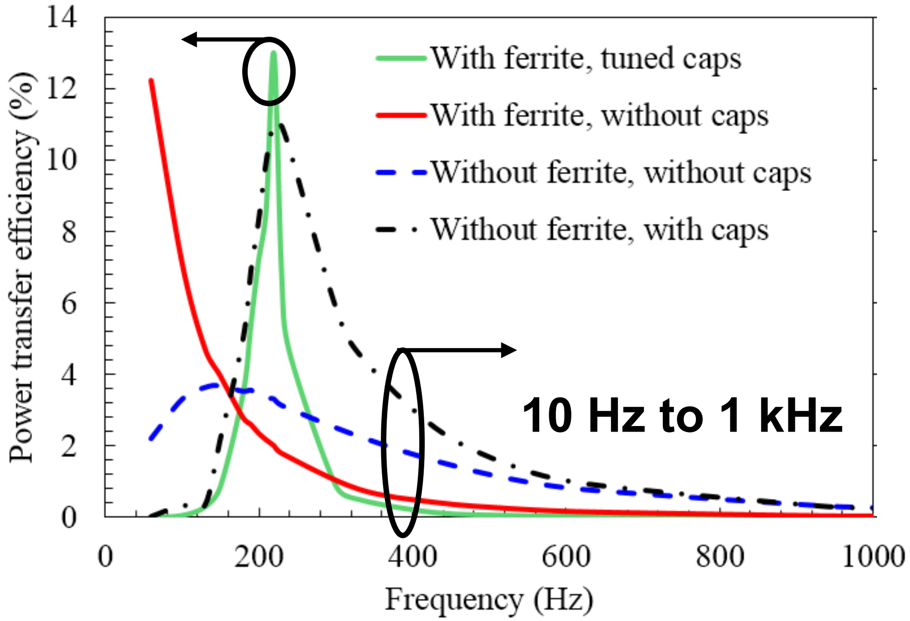
Coil implementations	Q	L (mH)	ESR (Ω)
Helix 1 with ferrite in air	9.502	25.698	2.039
Helix 1 with ferrite on metal	3.858	23.461	4.592
Helix 2 with ferrite in air	9.001	23.533	1.976
Helix 2 with ferrite on metal	3.168	21.304	5.071

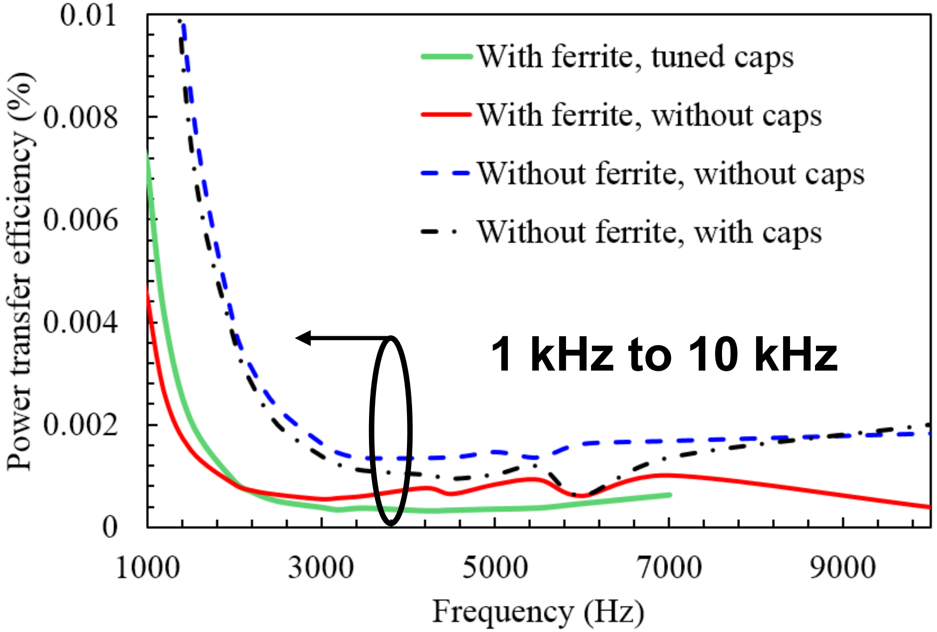
- Ferrites are required to counteract the parasitic effect of the metal plate and meet the requirements of PTE and Prx.

Resonant Capacitors

- To enhance power transfer capability the coils need to be compensated capacitively.
  - Higher PTE.
  - Resonant effect ~filter



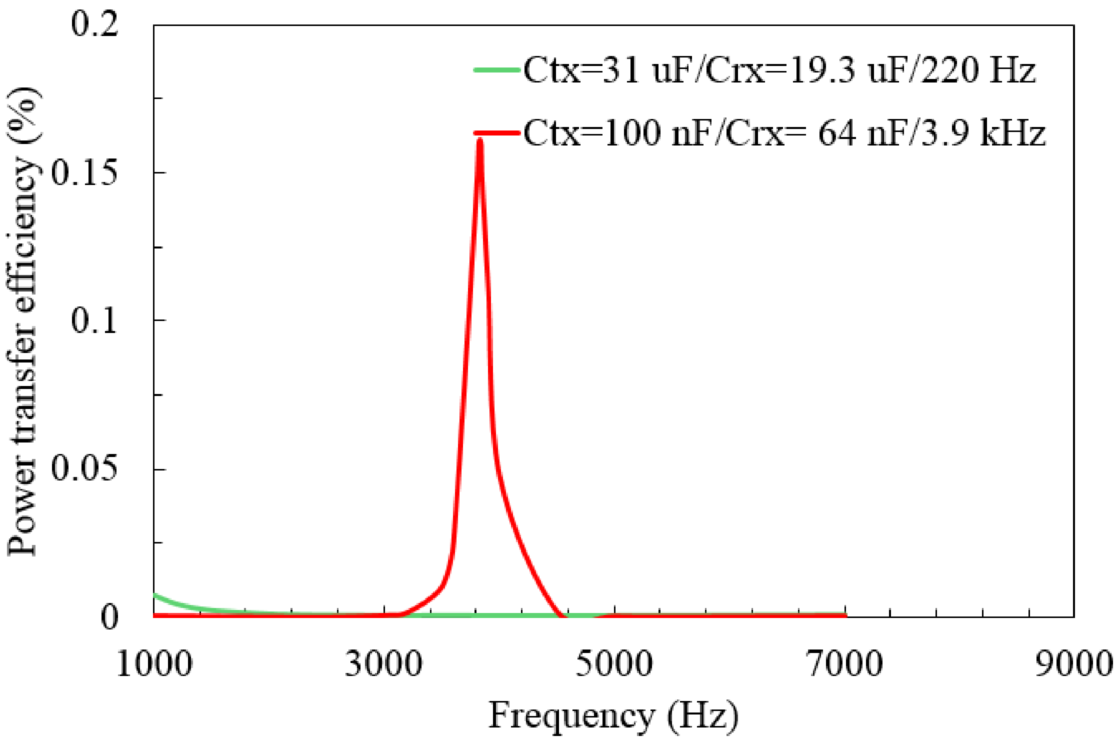


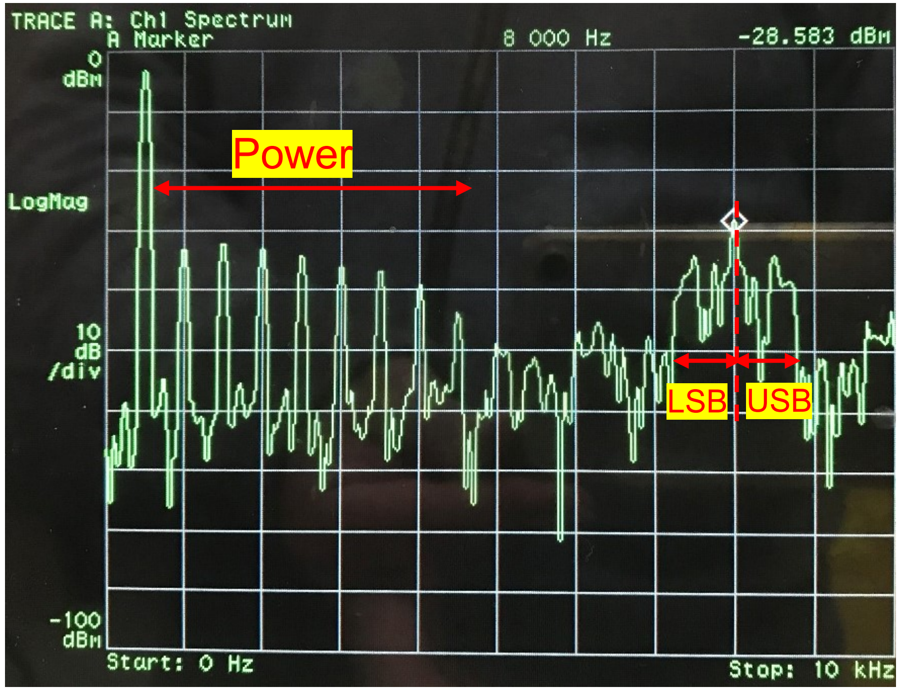


- Capacitors allowed for easier impedance matching while maintaining PTE.

Blocking effect for data transfer

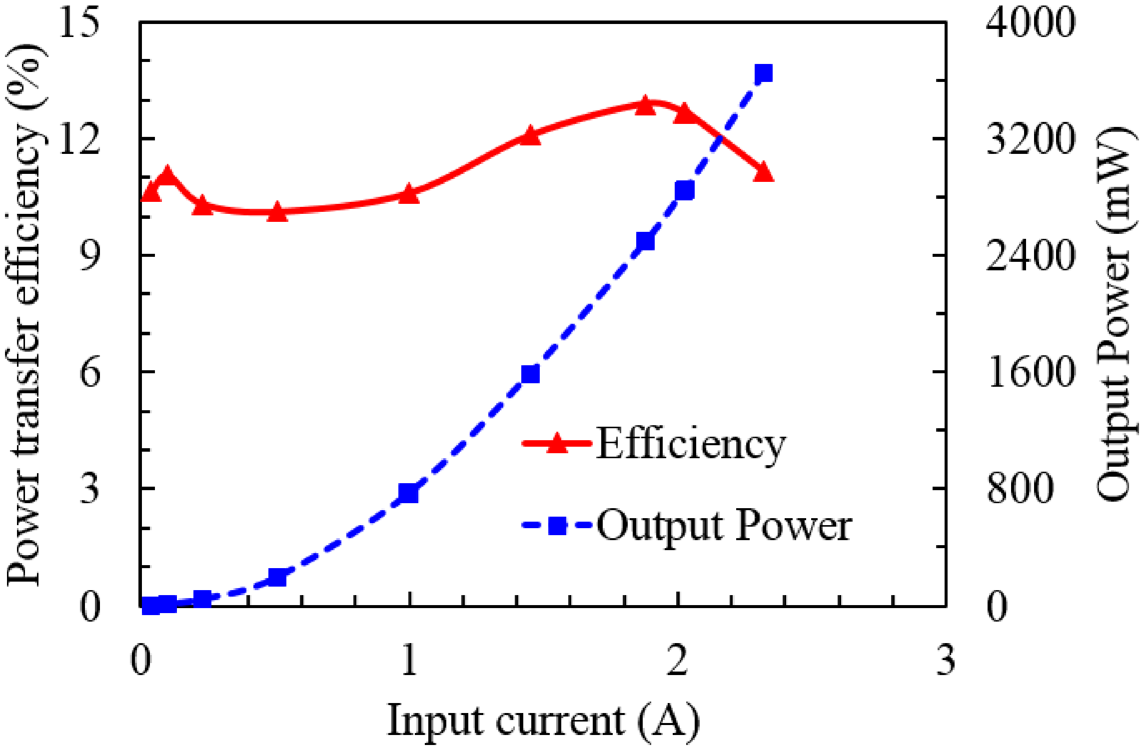
- Interference from power signal to data signal is considerable.
  - Even when fc=4 kHz for data transfer → shift to 8 kHz.
- Resonant capacitors serve as LPF so PTE@ 3.9 kHz is only 0.00032 %.





Power Transfer Efficiency

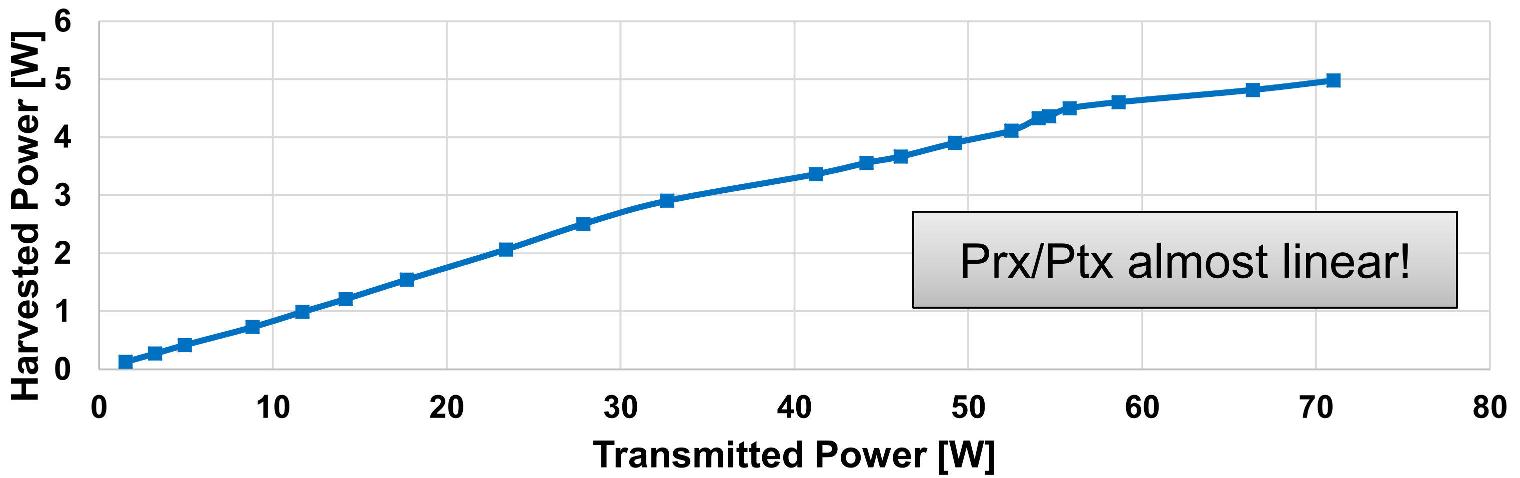
- Efficiency does not necessarily translates to more harvested power but must aim to max PTE.
  - Higher PTE allows to keep input power moderately low, reduce the effect of parasitic and simplify circuit design. E.g. +/- 2% PTE ~ +/- 20 W Pin

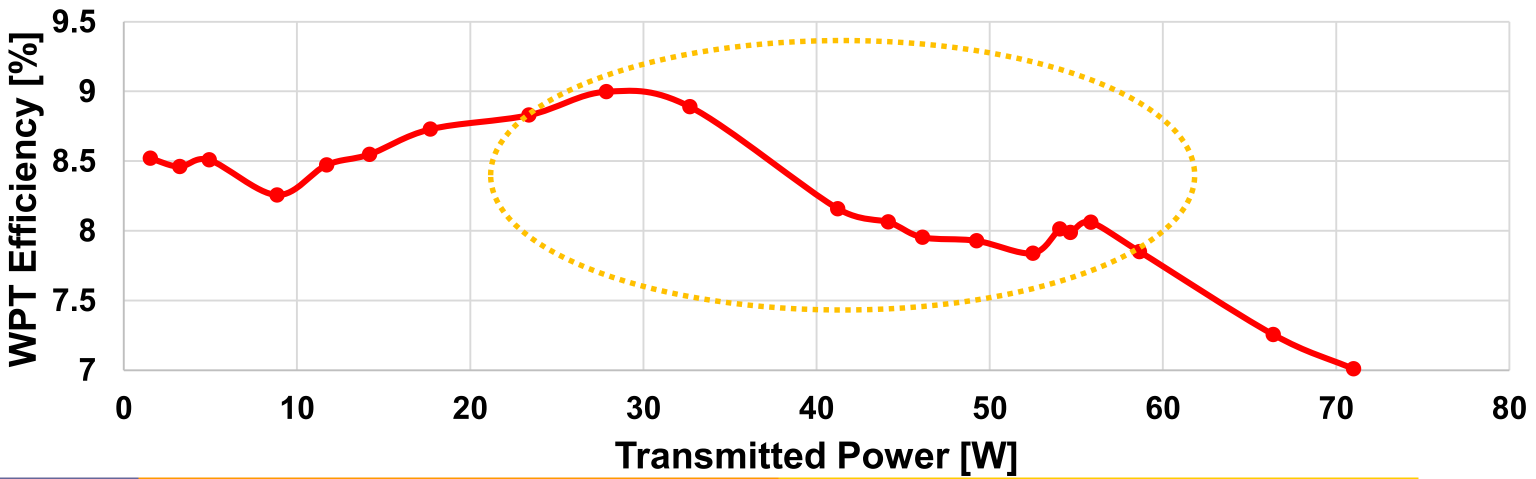


- Output power linearly increases with input current.
- Output power is more than 3.5 W and efficiency peaks ~12%.

Power transfer through metal

- Custom coil design allowed high PTE at very high Pin.





DATA TRANSFER

System requirements

- Simultaneous power and data transfer.
- No batteries allowed on the inside.
- No contact with metal allowed, i.e. no PZTs or EMATs.
- Data rate > 4.8 kbps.

State of the art data rate for IPT systems

Design	Metal thickness	Data rate (bps)
[1]	0.5 mm tin tank	20000 *
[2]	20 mm stainless steel pate	>100

- Goal:
  - Maximize bandwidth to achieve highest data rate.
  - High SNR to enable error free communications.
- Proposal:
  - Helix technology of large BW and good PTE.

* theoretical estimations

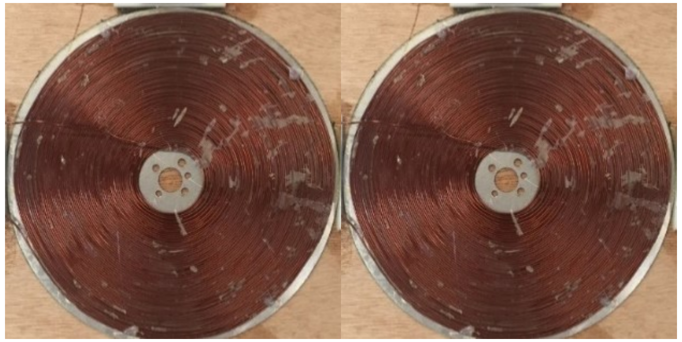
[1] Zangl H., Fuchs A., Bretterklieber T., Moser M., Holler G. An Investigation on Wireless Communication and Power Supply Through Metal Tank Walls; Proceedings of the 2008 IEEE Instrumentation and Measurement Technology Conference Proceedings; Victoria, BC, Canada. 12–15 May 2008; pp. 1452–1457.

[2] Graham D.J. Ph.D. Thesis. University of Newcastle upon Tyne; Newcastle upon Tyne, UK: 2012. Investigation of Methods for Data Communication and Power Delivery through Metals.

Coils prototypes

- Higher bandwidth coils: compromise between a low Q and moderate PTE.
- Helix flat coils proved to be the most efficient coils for this application.

Helix 1 (AWG 16)



Helix 2 (AWG 16)

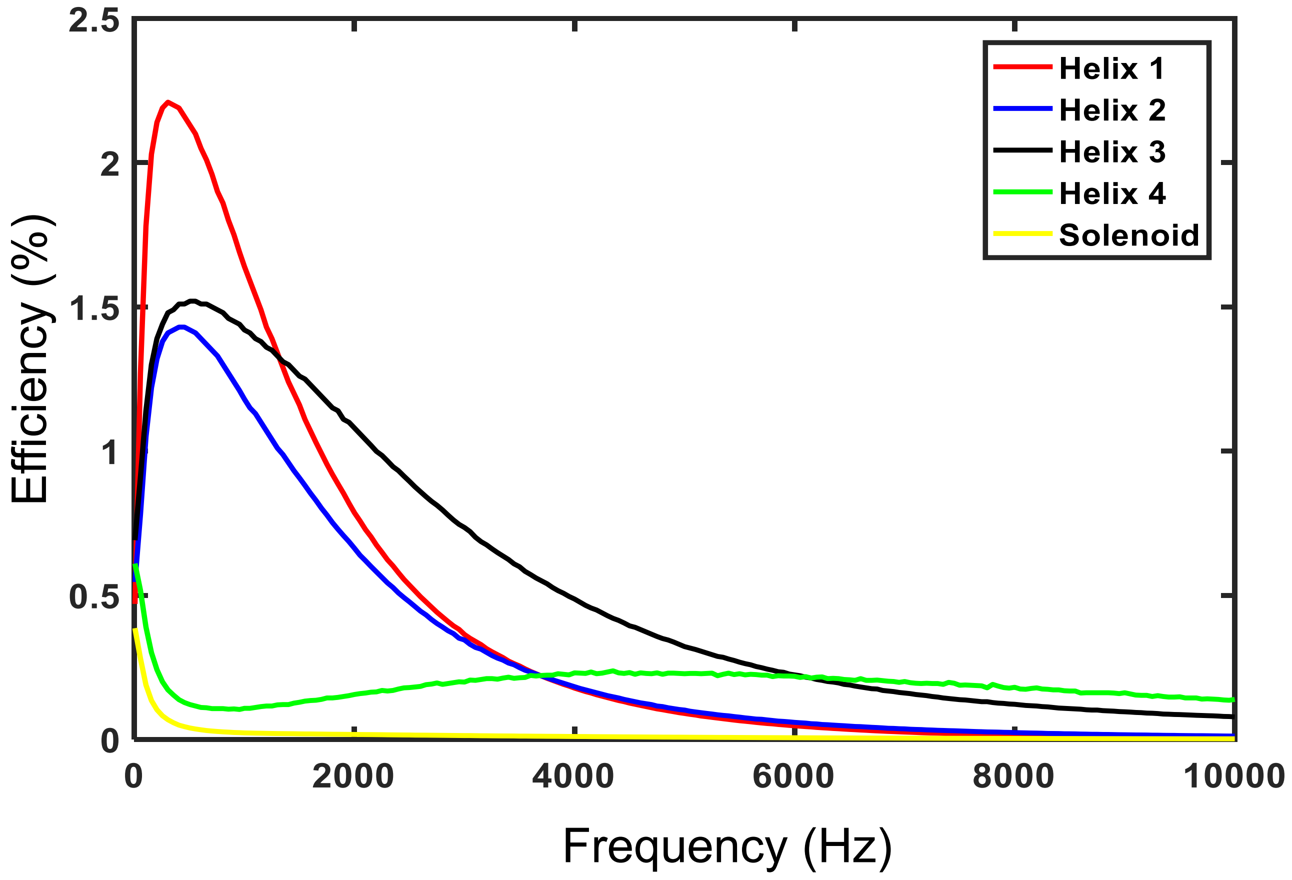
Helix 3 (AWG 18)

Helix 4 (AWG 16)

Solenoid (AWG 16)

PTE of Data Flat Coils

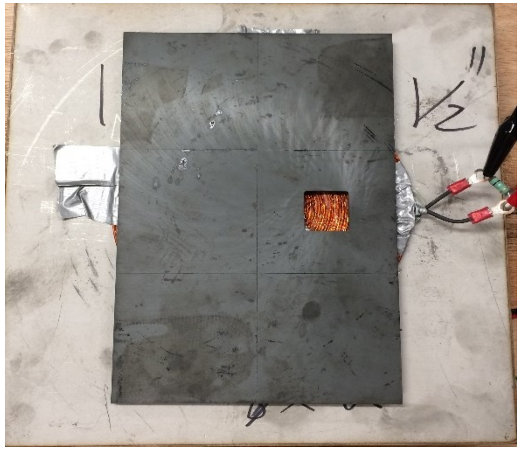
- Flat coils designed at UC Davis provide advantages for data transmission:
  - Moderate PTE.
  - Larger Bandwidth.
- Critical to achieve higher data rate.



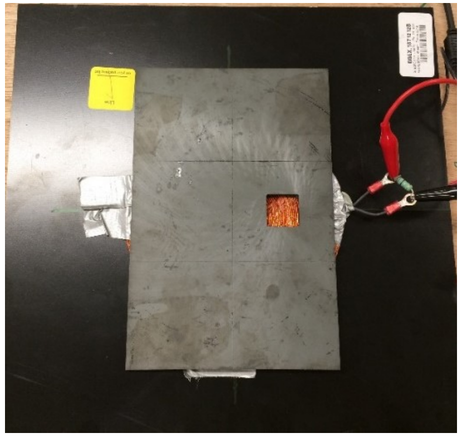
Coil designs	Helix 1 (D_{out}=195 mm)	Helix 2 (D_{out}=150 mm)	Helix 3 (D_{out}=150 mm)	Helix 4 (D_{out}=120 mm)	Solenoid (D_{out}=131 mm)
Peak efficiency (%)	2.16	1.36	1.52	0.141	0.06

Flat Coils performance with different materials

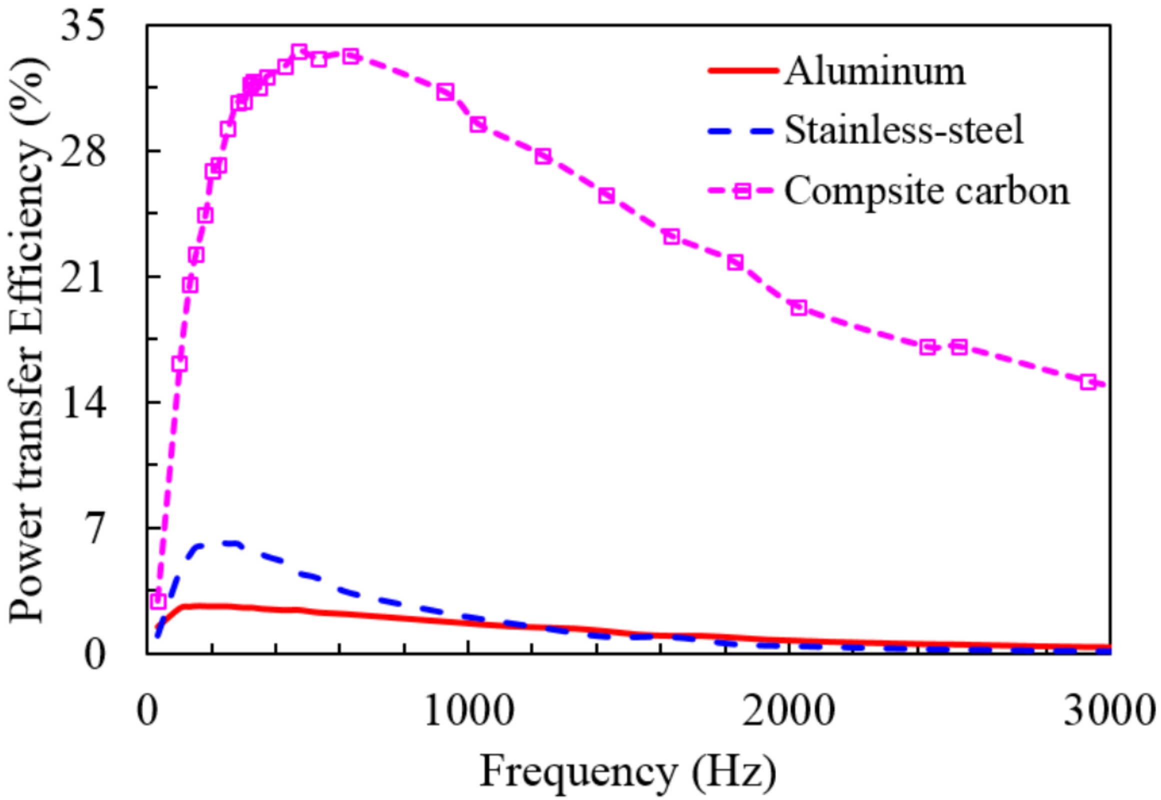
- Even higher performance for other materials.



Stainless-steel: 12.7 mm thick



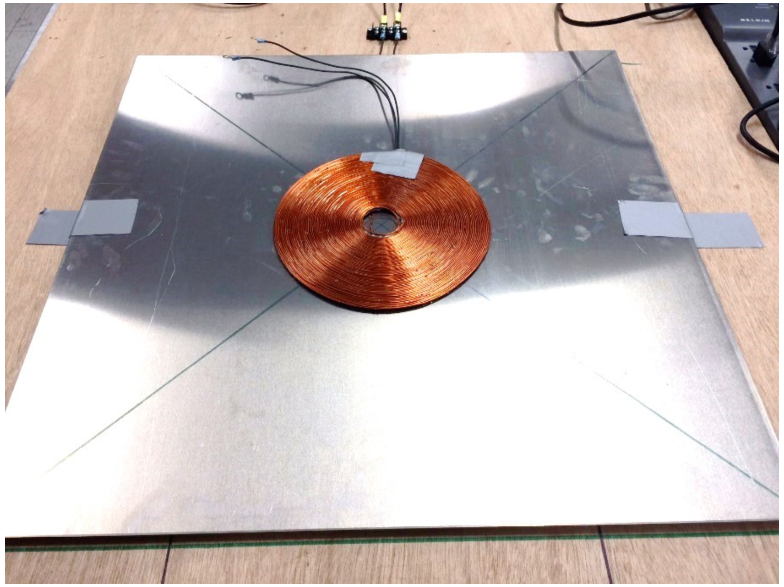
Composite carbon: 5 mm thick



Materials	Aluminum	Steel	Carbon
Conductivity (MS/m)	38	2.1	1
Peak efficiency (%)	2.68	6.25	34
Optimal frequency	200 Hz	230 Hz	480 Hz

Data and Power Simultaneous Transmission

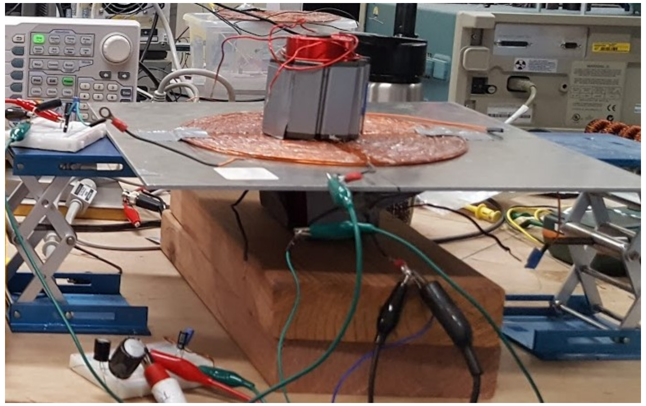
- Coils had to be modified to create combined structure for simultaneous power and data transfer.
  - Din=44mm → Din=55mm.
- Reduce interference of power signal.

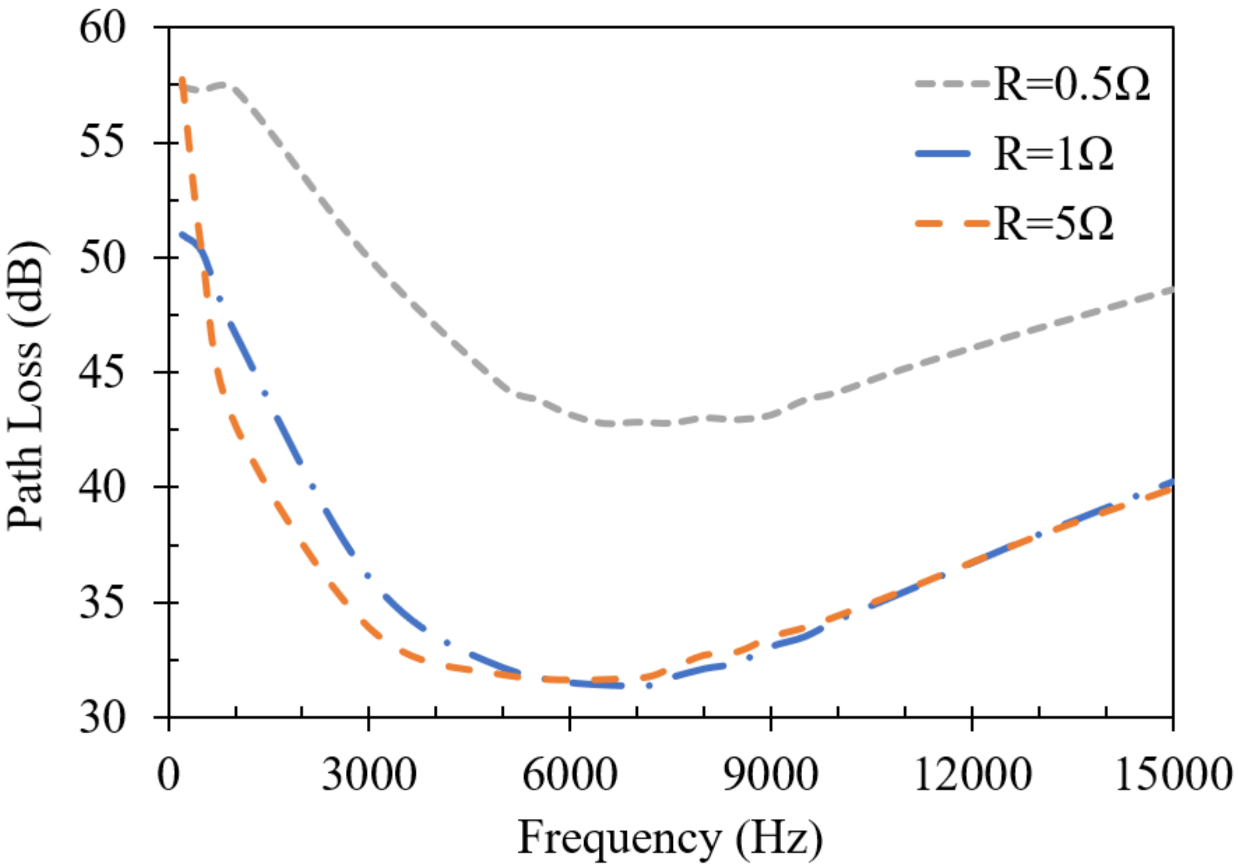


Designs	Wire size	D_{in}	D_{out}	N_{tx}	N_{rx}
Helix 2	AWG 16	44 mm	195 mm	63	63

Summary: Performance of Helix 195mm for Data Transfer

	New Structure	
Parameters	**Tx-Flat Coil**	**Rx-Flat Coil**
L	29.77 uH	29.11 uH
Q	2.07	2.14
Rs	0.899	0.851
DCR	0.48	0.41



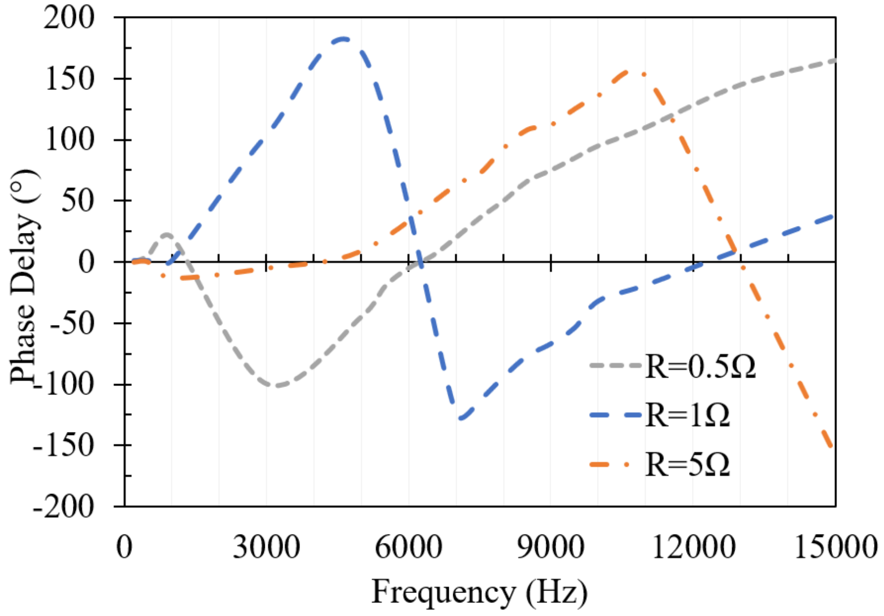


- Flat Coils were resonated for 8 KHz operation
- Flat response around BW of interest: 5-9 kHz → higher data rate.

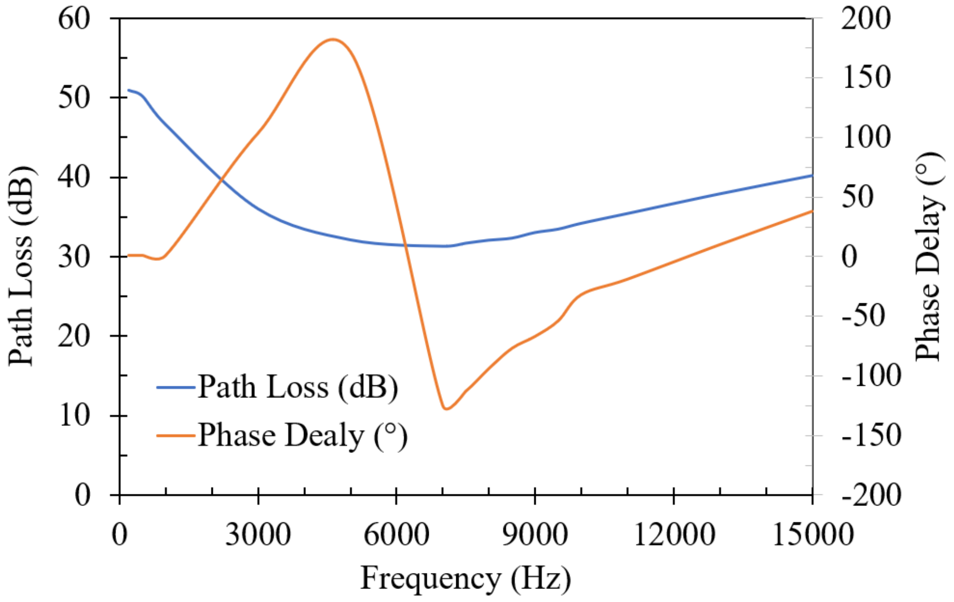
Summary: Performance of Helix 195mm for Data Transfer

- ✓ Flat Coils show a linear Phase Delay response despite being within the new structure.
- ✓ Coil has good characteristics for data transfer and can support higher order communication schemes.

Phase Delay Comparison

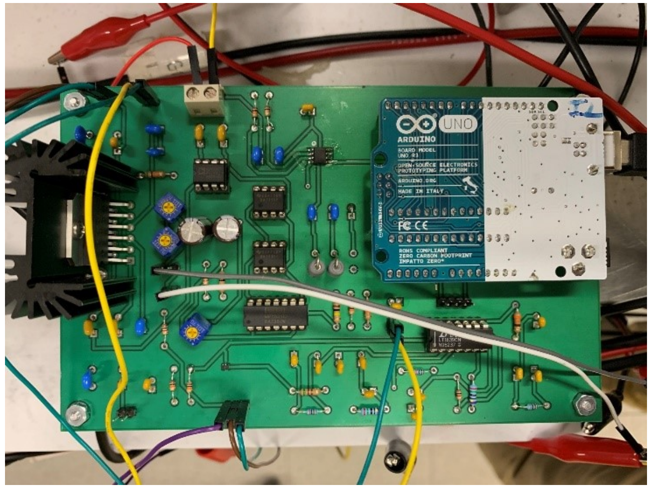


Best Case: R= 1 Ω

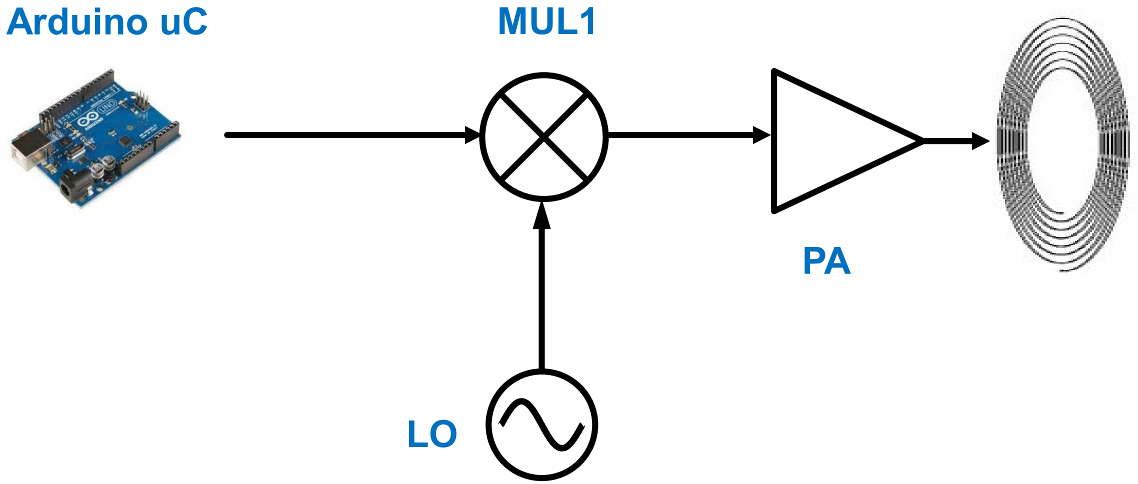


ASK transceiver

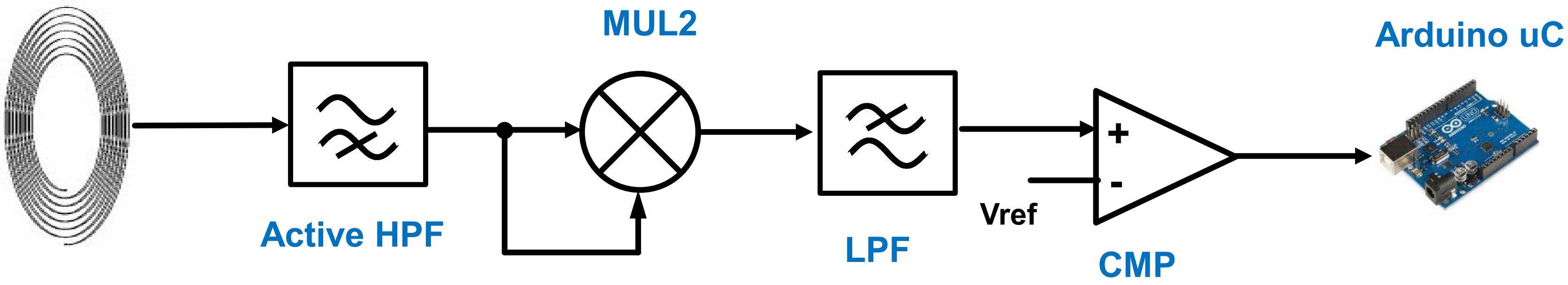
- ASK modulation was the most efficient technique for this case.
  - The performance of FSK and BPSK were considered.



ASK modulator

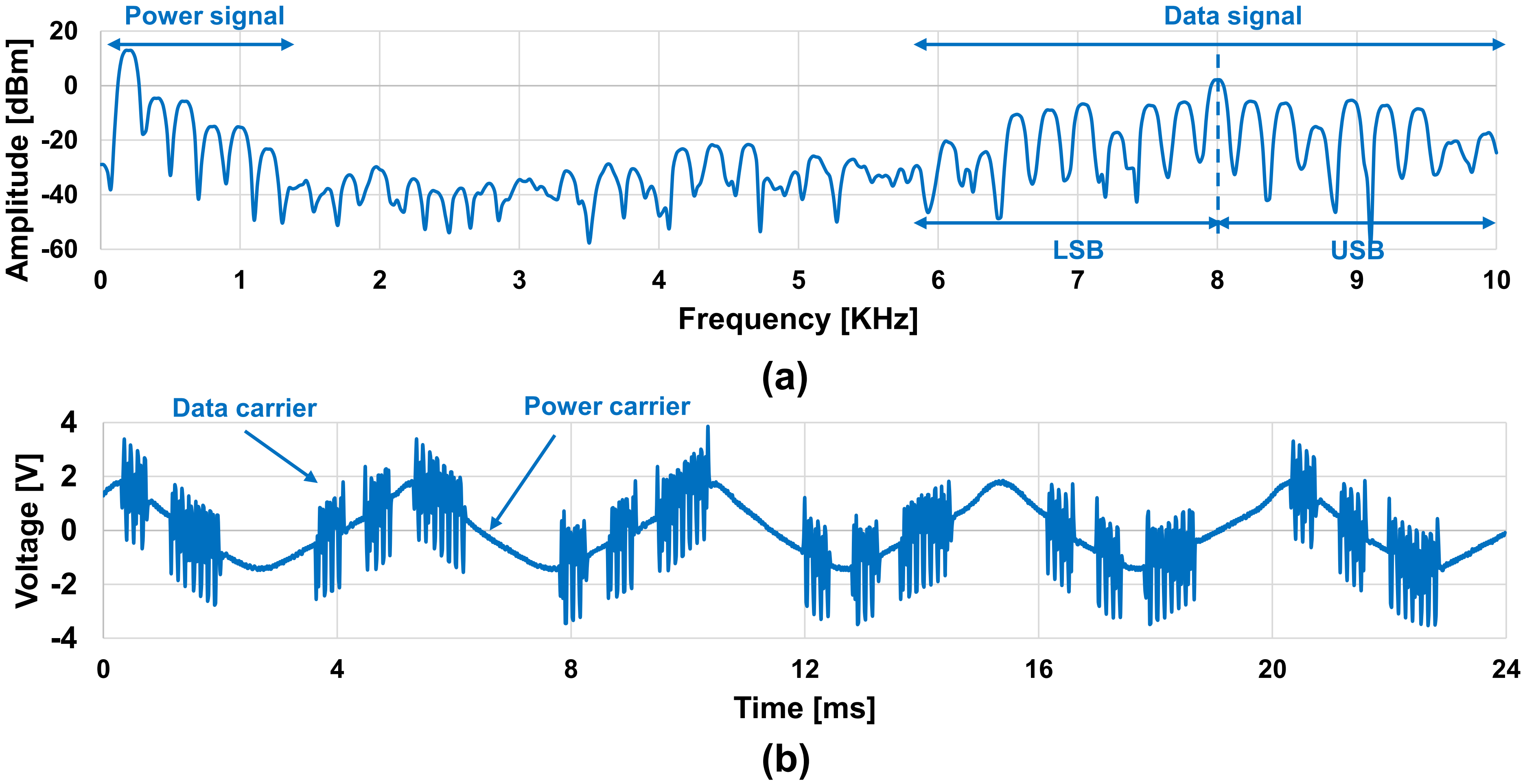


ASK demodulator



Data rate: 2.4 kbps

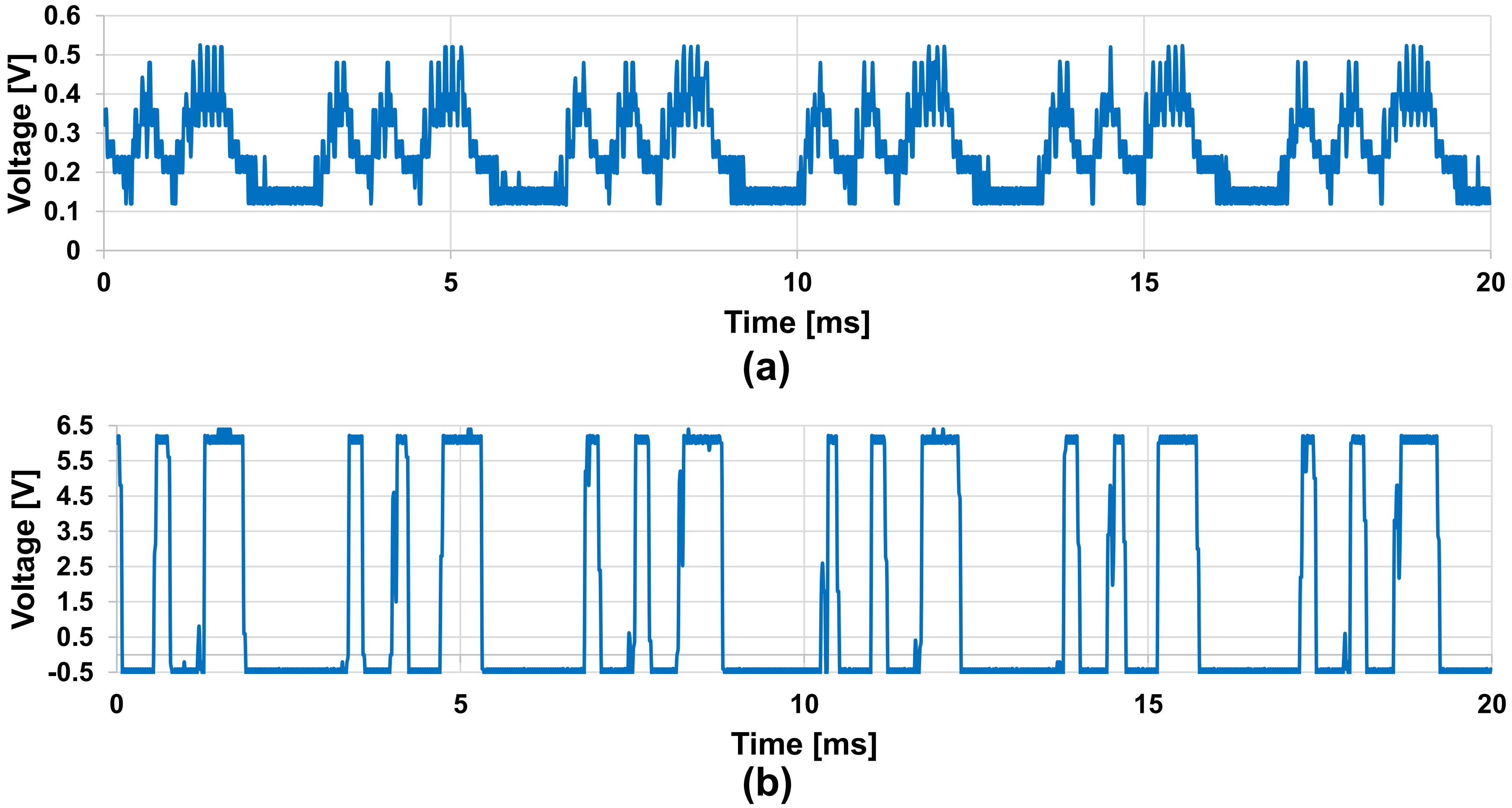
- Power and data signal do not interfere with each other.



Measured transmitting signals across the flat coil in (a) frequency domain and (b) time domain.

Data rate: 2.4 kbps

- Data signal successfully received and demodulated.

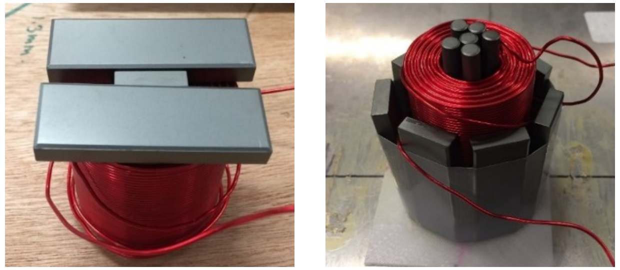


(a) Received signal after low-pass filtering; (b) Received digital data after thresholding.

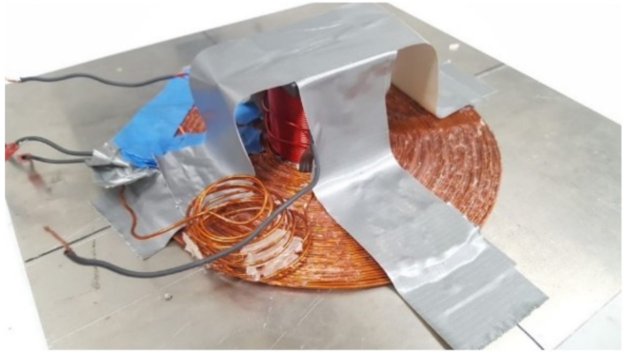
SYSTEM INTEGRATION

Coil Structure and Performance

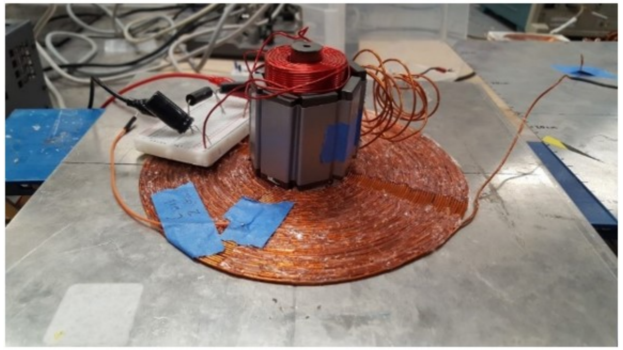
- High PTE Stack coils together with large bandwidth Flat coils enable state of the art data transmission through metal.



Stacked coils used for power transfer



(a)

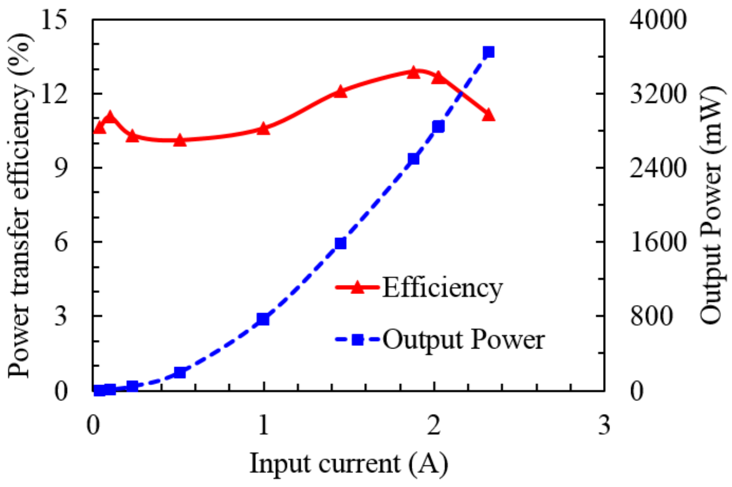


(b)

Flat coils used for data transfer

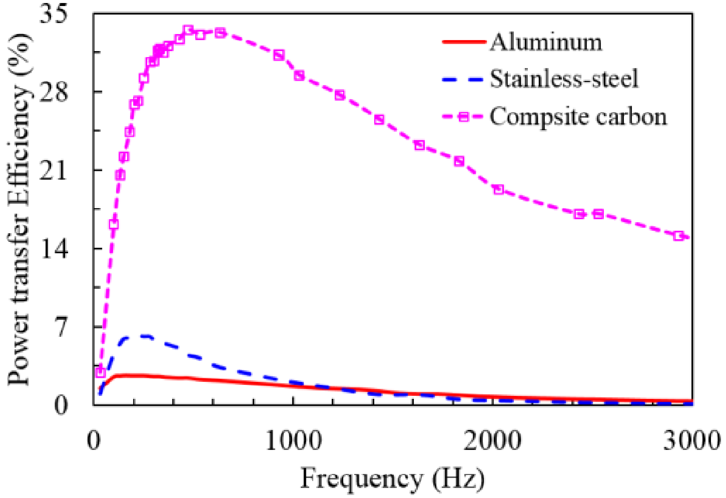
(a) Transmitting coil (b) Receiving coil

Stack coils PTE



Output power is more than 5W and max. efficiency ~12%.

Flat coils PTE

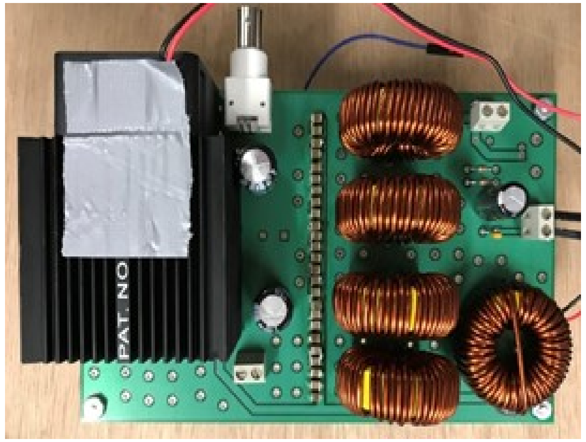


Materials	Aluminum	Steel	Carbon
Peak efficiency (%)	2.68	6.25	34
Optimal frequency (Hz)	200	230	480
Barrier Thickness (mm)	3	5	12.7

Additional circuitry

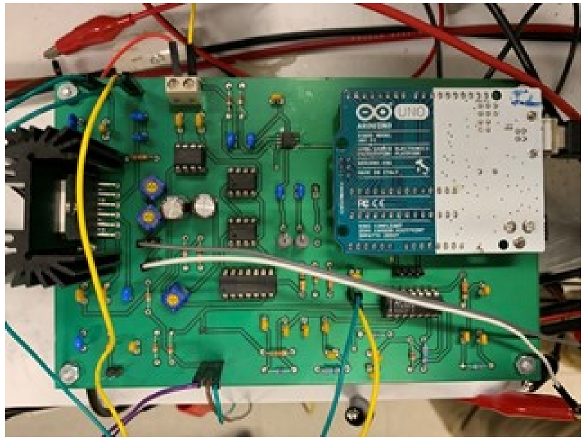
- Precise circuits design is also important because of complex impedance matching due to transformer-like network.
  - Power Amplifier of high conversion efficiency (~90%) matched with small impedance from stacked coil: ~3-6 Ω.
  - Power Management Circuit capable of +/- 5V and 12V output. Supplies stable impedance to Coil-Power Amplifier network.
  - ASK transceiver enables bidirectional communication using **only harvested power through metal barrier**.

Class-E power amplifier



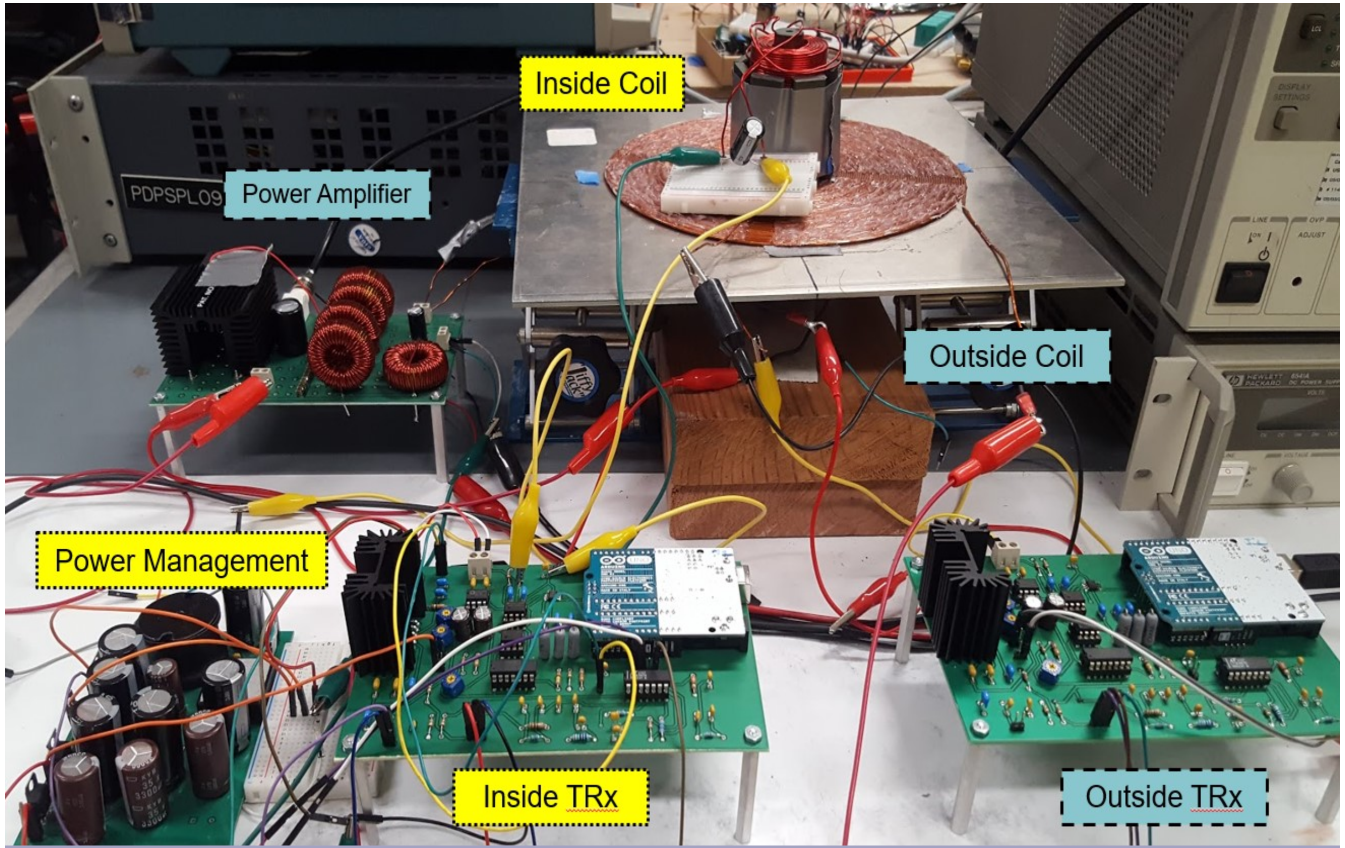
Power management circuit

ASK data transfer circuit



Current Record

- More than 9% PTE efficiency is achieved through 3mm thick aluminum plate.
- Harvested power on the inside of the metal barrier is larger than 5W.
- Data transfer rate is 4800 bps free of errors.

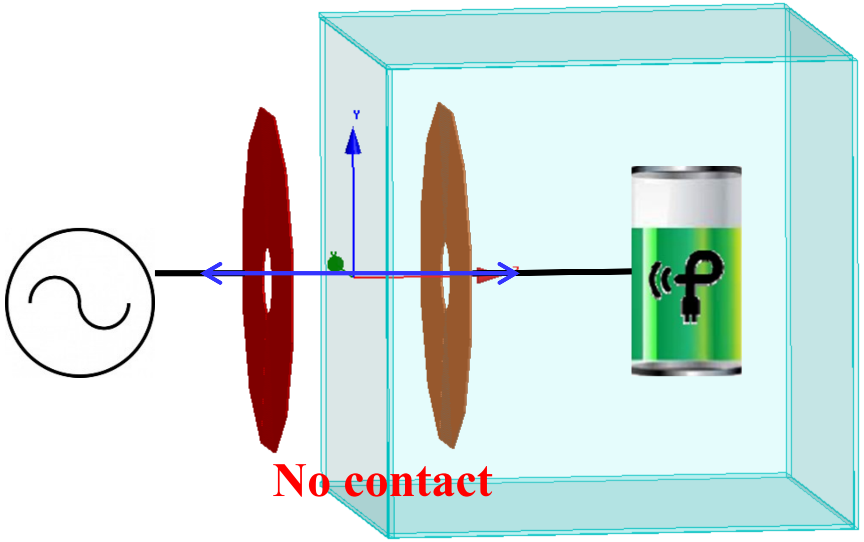


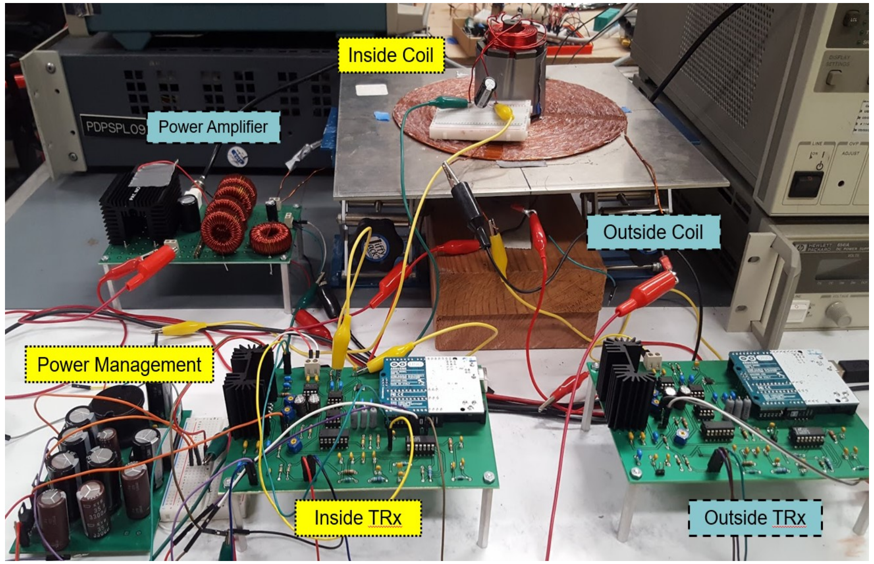
System Integration

4.8 kbps waveforms – Inside-Outside

Conclusion

- Enclosed sensor inside meta box successfully communicates with external transceiver.
  - 3mm thick **Aluminium**.
- There is no mean of communication between transceivers.
  - No cables, no opening, no contact, etc.
- Power is limited: no batteries allowed.
  - 5W harvested power.
- High data rate enables high throughput applications.
  - 4800 bps (highest known).
- System can work in different scenarios without changes of structure.
  - Stainless steel, carbon composite, etc.





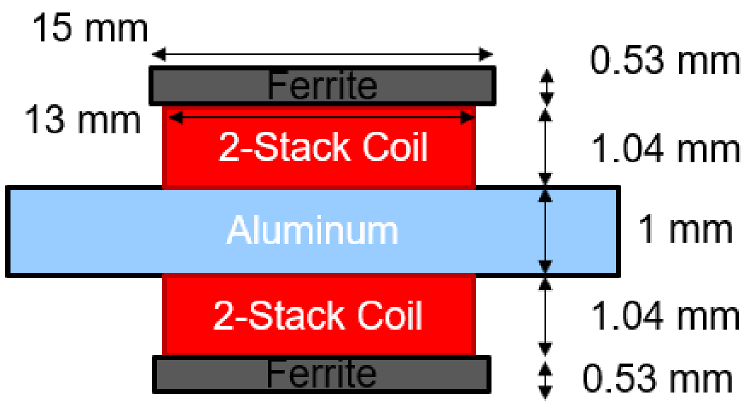
MOBILE COIL

Mobile Application Coil

- Requirement of miniature WPT system:

Parameter	Objectives
Peak efficiency (η)	≤ 1.0%
Metal Thickness (t)	Al, 1 mm
Height of coil (h)	≤ 2 mm
Diameter of coil (d)	≤ 15 mm
Power handling	≥ 10 mW received

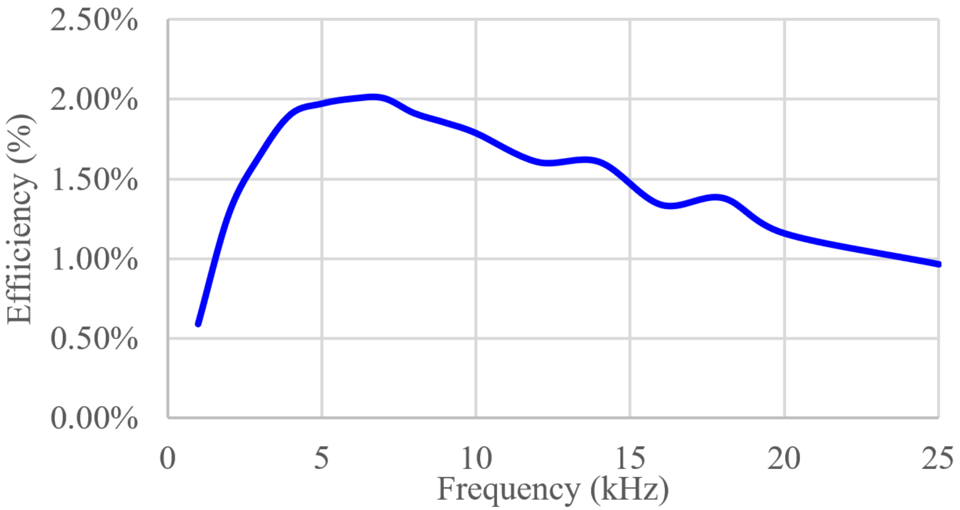
- Solution proposed:



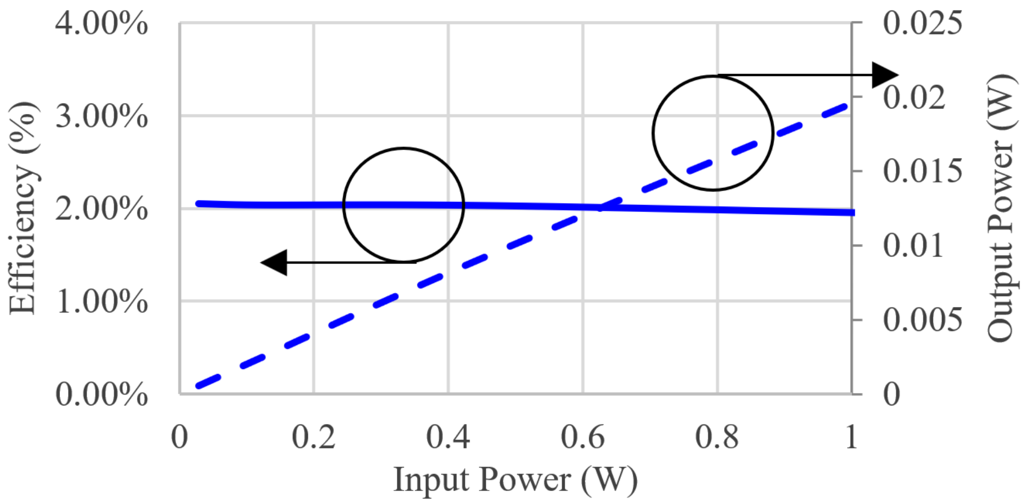
24AWG wire
n= 12 turns
2 stacks
Ferrite μ_r=220

Performance

- Enough harvested power from mini coils to power up any ultra-low power system:
  - Prx=20 mW.
  - PTE=2% with max. Pin=1W when f=6 kHz and RL=0.2 Ω



Coil-to-coil efficiency for R_{Load} = 0.200 Ω



Coil-to-coil efficiency and output power versus varying input power at f = 6 kHz, R_{Load} = 0.2 Ω.

Thank you

Anh-Vu Pham and Juan Romero
Microwave Microsystems Laboratory, University of California
Department of Electrical and Computer Engineering
Davis, CA 95616
Phone: 530-752-7472 and Email: pham@ece.ucdavis.edu

This work is supported by Lawrence Livermore National Laboratory.

UCDAVIS
ELECTRICAL AND COMPUTER ENGINEERING