Magnetic-Resonance-Coupling-Based Wireless Power Transfer System for Battery-free Miniaturized Medical Implants

APPLIED PHYSICAL SCIENCES
Joint Department of BIOMEDICAL ENGINEERING

Sicheng Xing[1,2], Lin Zhang[3], Wubin Bai[1,3]

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Introduction

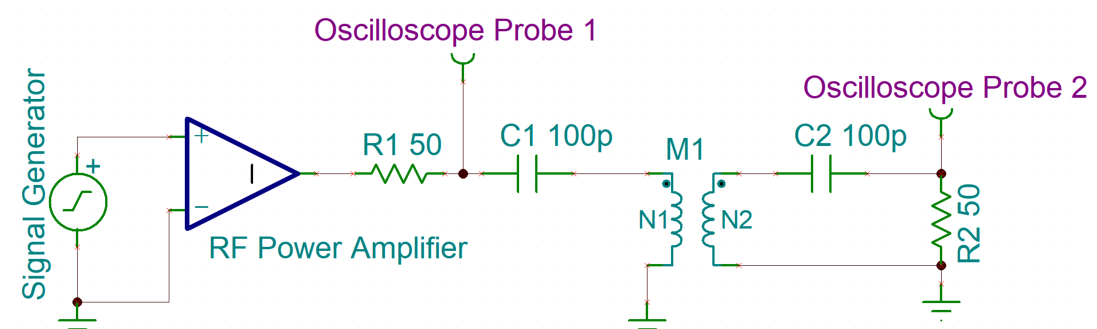
Miniaturized medical implants that perform localized sensing, electrical therapy, or drug delivery functions hold great potential to innovate treatment and improve patient outcomes. However, traditional tethered implants create risks of infections, and battery power devices come with increased weight, a limited life span, and reduced overall device flexibility, all of which may lead to bulky devices and potential complications. Therefore, better means of power delivery are needed for implants to improve overall patient outcomes.

Here, we present a flexible, wireless power transfer (WPT) system based on magnetic resonance coupling (MRC) made of commercially available materials that can be integrated with medical implants to eliminate the need for batteries or wiring to an external power supply, thereby reducing potential complications, as well as improving patient comfort and overall quality of life. This device is characterized by the following features:

- Lightweight with size at the centimeter scale
- Delivery of high power up to 1.3W at the efficiency of 80% with Minimal heat dissipation in coils
- Minimal changes in resonance frequency due to distortion, bending, or twisting

Methods

- **Circuit Diagram of Experimental Measurement**



- **Derivation of Time-Averaged Apparent Power and Transmission Efficiency:**

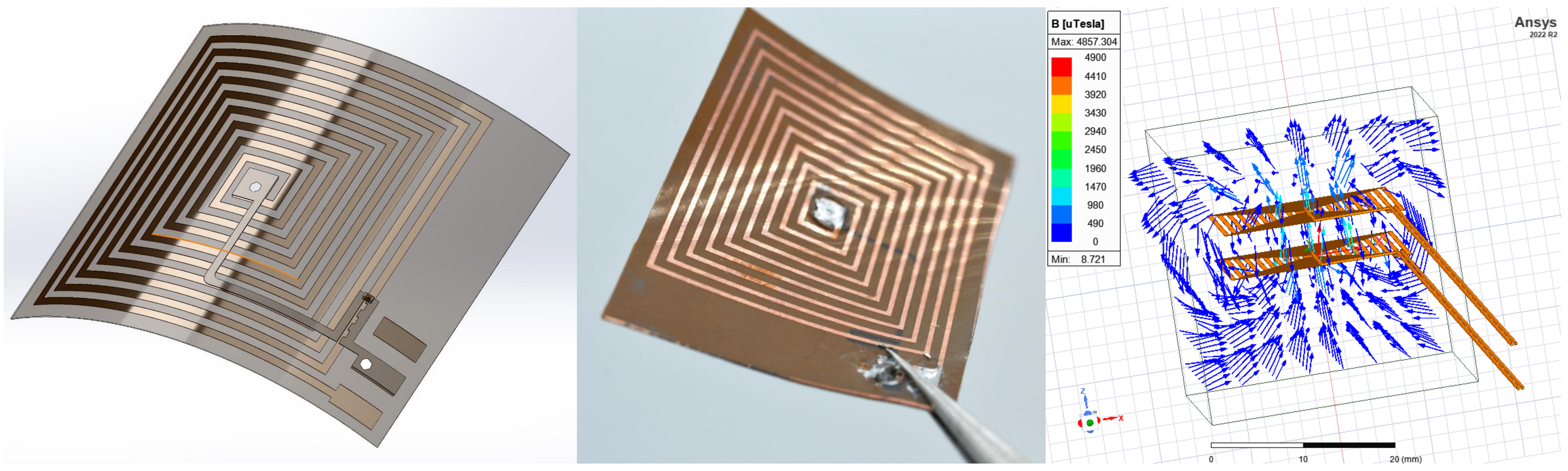
$$P_{Tx} = I_{Tx_{RMS}} V_{Tx_{RMS}} = \left(\frac{\frac{\sqrt{2}}{4} A V_{PP_{Drive}} - V_{RMS_1}}{R}\right) V_{RMS_1},$$

$$P_{Rx} = \frac{V_{RMS_2}^2}{R},$$

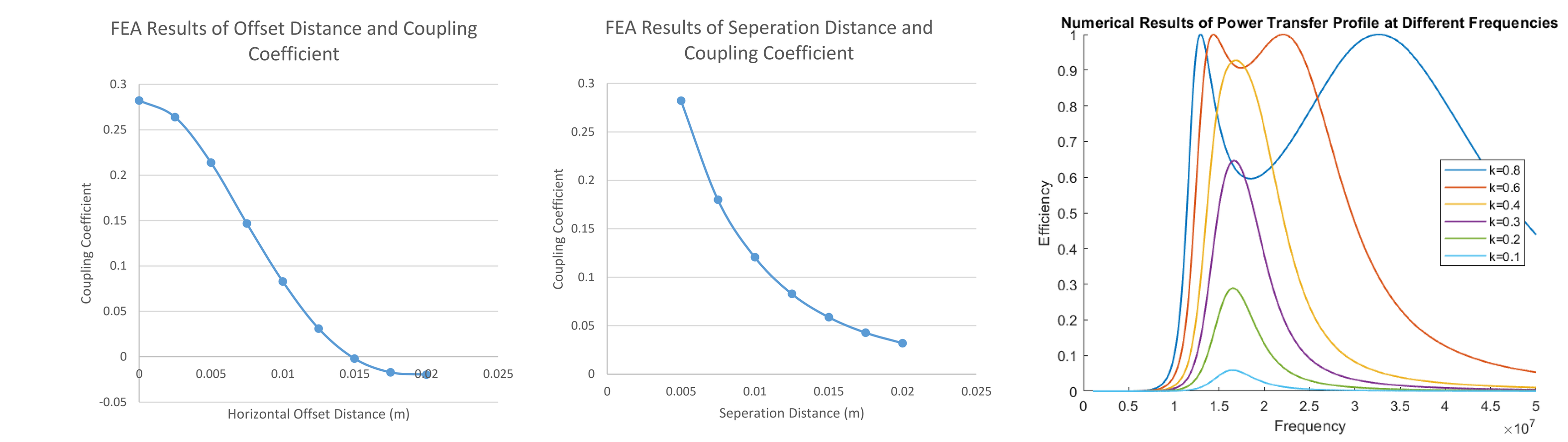
$$\eta = \frac{P_{Rx}}{P_{Tx}},$$

Where A is the Amplifier Gain and $40dB = 20\log_{10} A$.

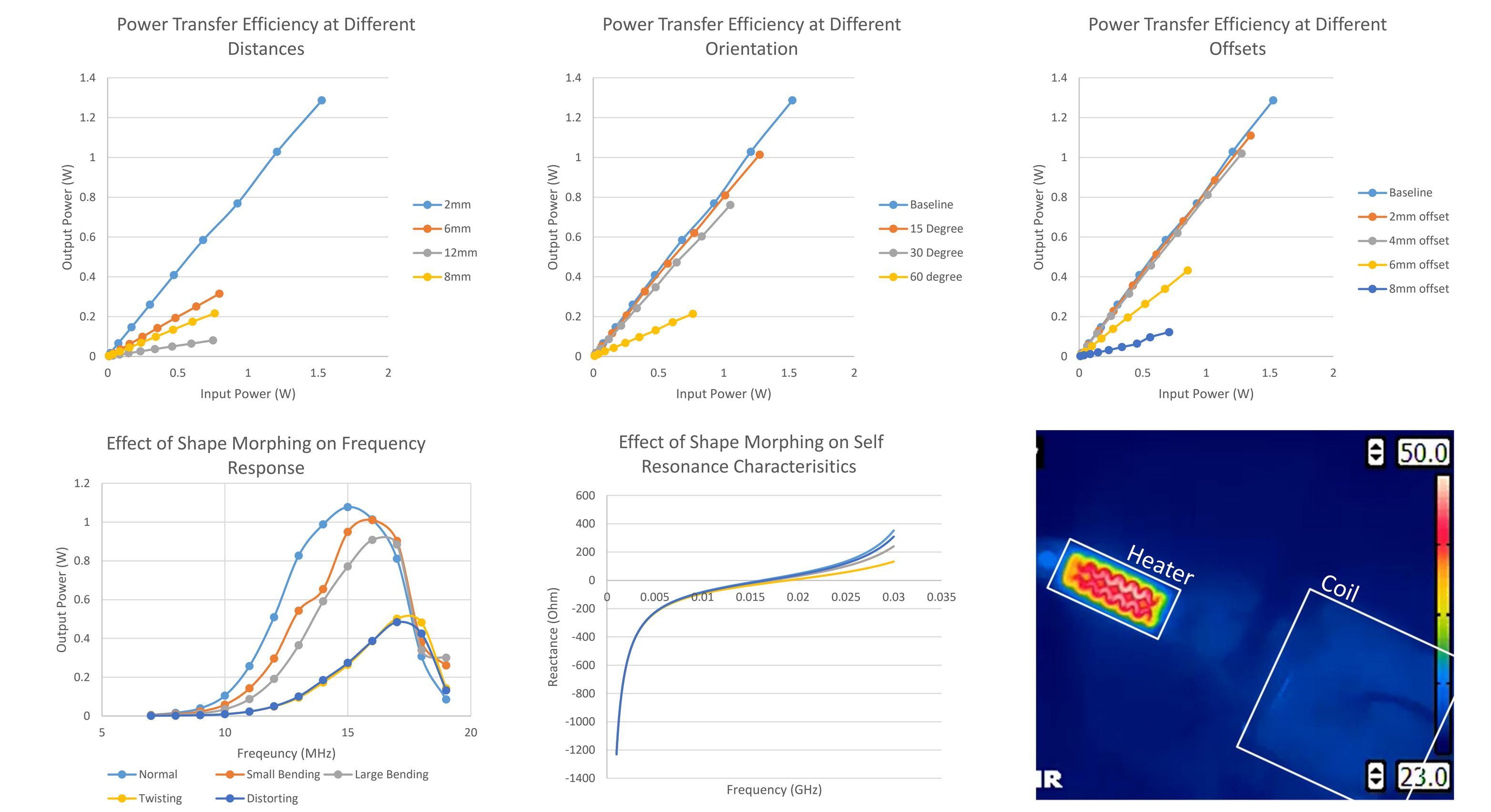
- **Design, Fabrication, and Electromagnetic Finite Element Analysis of Flexible, Miniaturized Power Transfer Coil**



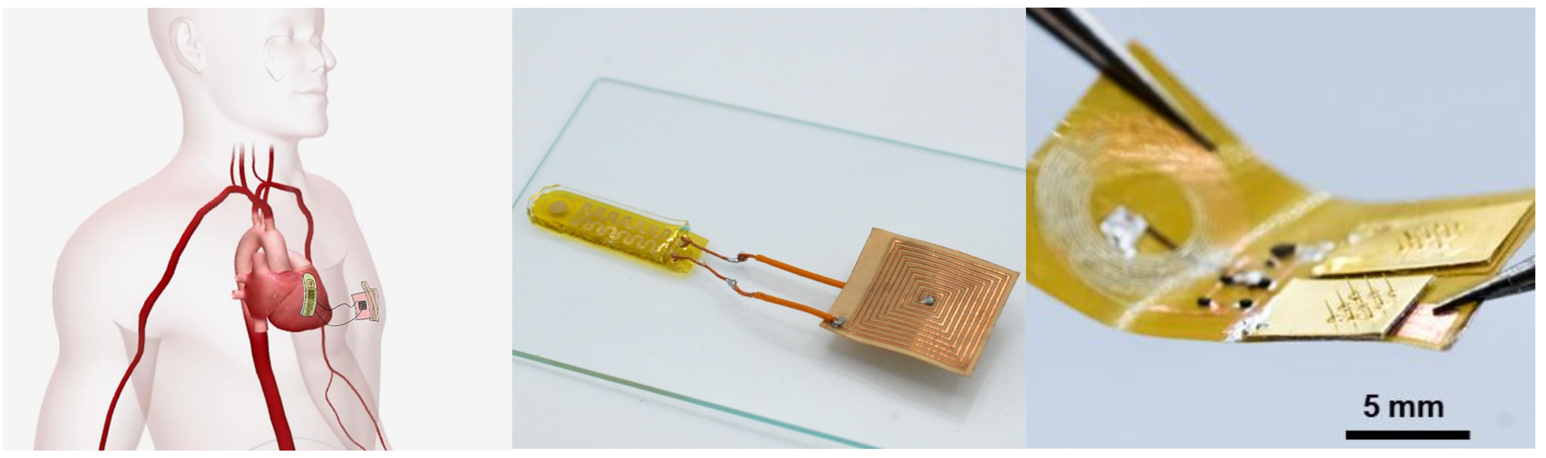
Results



Finite Element Analysis Results: *Figures 1 and 2 present the FEA results of horizontal offset and Separation distance effect on the Coupling Coefficient. Figure 3 shows the transfer efficiency as a function of frequency at different coupling coefficients.*



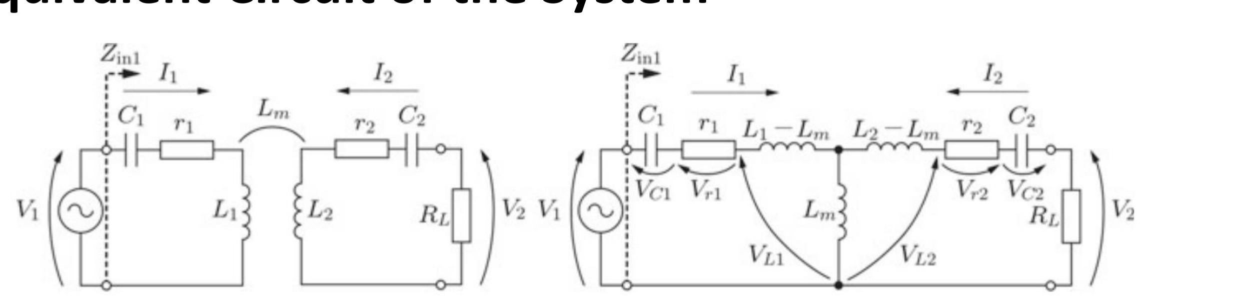
Experimental Characterization Results: *Figures 1,2 and 3 show the effect of separation distances, orientation angles, and horizontal offsets between coils on power transfer efficiency. Figures 4 and 5 show the effect of shape changes on frequency response and self-resonant characters. The infrared image in figure 6 shows minimal heat was dissipated by the coil with the majority of power delivered to the load.*



Biomedical Applications: *Figure 1 and 2 shows the integration of the system with a sensory soft-robot implant for localized monitoring and electrotherapy. Figure 3 shows the integration of the system with a microneedle drug delivery implant for targeted drug delivery in human brain*

Theoretical Background

- **The Equivalent Circuit of the System**



a) The Idealized Circuit of the System *b) The T-Transformation of the Equivalent Circuit*

- **The Characteristic Impedance of the Circuit**

The Impedance of a the RLC circuit in the load can be modeled as:

$$Z_p = j\omega(1-k)L + \frac{1}{j\omega C} + R.$$

The Impedance after R1 can be modeled as:

$$Z_{eq} = \frac{1}{\frac{1}{Z_p}+\frac{1}{jkL\omega}} + Z_p = \frac{\left(j\omega L+\frac{1}{j\omega C}+R\right)^2 + k^2\omega^2L^2}{\left(j\omega L+\frac{1}{j\omega C}+R\right)}.$$

Where k is the coupling coefficient. Due to the transmission and the receiving coil, share the same L, the mutual inductance can be modeled as $M = k\sqrt{L_1 L_2} = kL$.

- **Voltage across the Load Resistor**

Using KVL and KCL in the frequency domain, the voltage across the load resistor can be expressed as:

$$V_L = V_s e^{j\omega t} \frac{1}{\left(\frac{1}{Z_p}+\frac{1}{jkL\omega}\right)} \cdot \frac{1}{Z_{eq}} \cdot \frac{R}{Z_p}.$$

The steady-state voltage across the load resistor can therefore be calculated numerically using MATLAB at different coupling factors as a function of frequency. This generates a maximum power transfer efficiency at the near-resonant frequency with slight decreases at closer coupling states.

- **Voltage, Power, and Efficiency at the Resonance Frequency**

At resonance, the reactance $X = j\omega L + \frac{1}{j\omega C}$ goes to 0, rendering V_L as

$$V_L = V_s e^{j\omega t} \frac{jk\omega L Z_p}{\left(j\omega L+\frac{1}{j\omega C}+R\right)} \cdot \frac{\left(j\omega L+\frac{1}{j\omega C}+R\right)}{\left(j\omega L+\frac{1}{j\omega C}+R\right)^2+k^2\omega^2L^2} \cdot \frac{R}{Z_p} = V_s e^{j\omega t}\left(\frac{jk\omega LR}{R^2+k^2\omega^2L^2}\right),$$

$$= V_s e^{j\omega t}\left(\frac{j}{\frac{1}{kQ}+kQ}\right).$$

The power delivered by the load resistor now becomes

$$P_L = V_{S_{RMS}}^2 \left(\frac{1}{\frac{1}{kQ}+kQ}\right)^2 \cdot \frac{1}{R}.$$

This equation has shown that when k and Q are relatively small (kQ<1) due to the small size of the coil, increasing Q and increasing k will lead to greater power delivered to the receiving coil at resonant frequency. For larger kQ values, deviation from the resonance frequency, known as frequency split, was observed.

Bibliography

[1] M. Kiani and M. Ghovanloo, "The circuit theory behind coupled-mode magnetic resonance-based wireless power transmission," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 59, no. 9, pp. 2065–2074, 2012.

[2] S. D. Barman, A. W. Reza, N. Kumar, M. E. Karim, and A. B. Munir, "Wireless powering by magnetic resonant coupling: Recent trends in Wireless Power Transfer System and its applications," *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1525–1552, 2015.

[3] T. Imura, *Wireless Power Transfer: Using magnetic and electric resonance coupling techniques*. S.l., Singapore: Springer Nature Singapore Pte Ltd., 2021.

1. Joint Department of Biomedical Engineering, University of North Carolina at Chapel Hill
2. Department of Physics and Astronomy, University of North Carolina at Chapel Hill
3. Department of Applied Physical Sciences, University of North Carolina at Chapel Hill