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# Design and Implementation of Multisite Stimulation System Using a Double-Tuned Transmitter Coil and Miniaturized Implants

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## Abstract

This letter presents a double-tuned dual input transmitter coil operating at 13.56 MHz and 40.68 MHz industrial, scientific, and medical (ISM) bands for multisite biomedical applications. The proposed system removes the need for two separate coils, which reduces system size and unwanted couplings. The design and analysis of the double-tuned transmitter coil using a lumped element frequency trap are discussed in this letter. The transmitter achieves measured matching of −26.2 dB and −21.5 dB and isolation of −17.7 dB and −11.7dB at 13.56 MHz and 40.68 MHz, respectively. A 3 mm × 15 mm flexible coil is used as an implantable receiver. This letter shows synchronized multisite stimulation of two flexible implants at a distance of 2 cm while covered with 1 cm chicken breast.

### Keywords

Wireless power transfer; dual-band; double-tuned; miniaturized implant; multisite stimulation

## I. Introduction

Traditional battery-powered implantable devices face limitations such as large size and compromised safety [1]–[4]. Wireless power transfer (WPT) is a popular solution to remove the implanted battery by adding an external wearable transmitter. Multisite powering and controlling a network of implants has different applications in biventricular heart pacing [5], [6], bilateral vagus nerve stimulation [7], [8], and spinal cord stimulation [9], [10].

In [6], the authors presented two Tx coils operating at 13.56 MHz and 40.68 MHz for biventricular heart pacing. The large system size and interference between coils are the main drawbacks of a two-Tx coil system [6], [11]–[13]. In Fig.1 (a), the system used in [6] is shown and Fig 1 (b) shows the proposed system, which uses a single dual input coil at 13.56MHz and 40.68 MHz. In [10], the authors presented a pattern detection

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scheme for multisite stimulation using a physical unclonable function (PUF). This scheme requires more power to recover the clock and data on the implant side. Another passcode detection scheme using chip pins is proposed in [7], which similarly requires more chip area and power. In [9], [14], multiple channel chips and electrode multiplexing are proposed; however, large implant and electrode sizes are not favorable in many applications, such as heart pacing and vagus nerve stimulation. In [13], a single coil, single input dual-band system using lumped element frequency trap is proposed. However, multi-band drivers and large coils cannot be easily realized for implantable or wearable devices. This work reports a double-tuned double input transmitter coil at 13.56 MHz and 40.68 MHz ISM bands. The transmitter coil has a matching of −21.7dB and an isolation of −11.7dB. The Tx coil can power up and control two implantable stimulators at a distance of 2 cm, including 1 cm of the chicken breast with 800 mW of power at each port. The implantable devices have a width of only 3mm, which makes them favorable for heart-pacing applications.

## II. Tx Coil Design

Tx multi-turn coil is fabricated in 1.6 mm FR4 substrate. The fabricated circular coil (diameter=62 mm) and matching network's schematic are shown in Fig. 2 (a) and (b), respectively. As shown in equation 1, the trap frequency has to be chosen to be within the two input frequencies [11], [13], [15]. The inductance ratio ($r_L = L1/L2$) between the coil and the trap is chosen to be close to 1 to maintain the same efficiency at two frequencies [13], [15]. The coil is designed to have an inductance close to 1$\mu H$. After fabrication, the coil S-parameters are extracted with VNA. The coil inductance varies from 1$\mu H$ to 1.25$\mu H$, as shown in Fig. 3 (a). The lumped inductance ($L_2$) is 1$\mu H$, and its SRF is 330 MHz (Johanson Technology Inc, L805W). In this work, $C_2$ is chosen to be 28 pF to put the trap frequency ($f_{LC2}$) at 30.08 MHz. The same principle applies to the series LC branch consisting of the coil ($L_1$) and $C_1$. In this work, $C_1$ is tuned to 21.8 pF, which puts $f_{LC1}$ at 34.1 MHz. High Q capacitors $C_3$ and $C_4$ are added to match the resonated inductors to 50Ω. Compared to [13], the limitation of this work is to maintain good isolation between ports. An additional capacitance of $C_5$ is added to improve high-frequency isolation between the two ports.

Fig.3 (b) to (d) presents the simulated and measured matching, and isolation results. Fig. 3 (b) and (c) show that low-frequency and high-frequency matching are better than −26.2 dB and −21.5 dB, and isolation between the ports is −17.7 dB and −11.7 dB, respectively (Fig. 3 (d)). The designed coil quality factor, self-resonance frequency (SRF), and matching network parameters are shown in table I.

$$13.56MHz < f_{LC_{1,2}} = \frac{1}{2\pi\sqrt{L_{1,2}C_{1,2}}} < 40.68MHz \quad (1)$$

## III. Implantable Stimulator Design

From the point of care perspective, miniaturized and wireless implants are highly preferred [1], [9], [16]. This work presents a multi-turn 4-layer 0.15mm flexible polyimide PCB for the implant. The coil on the PCB is used along with the chip to harvest the power from the Tx coil and store it on a storage capacitor. The geometry and size of the implantable coils are determined based on leadless pacing constraints. The notches in the wireless link are detected by the chip and define the duration of constant voltage stimulation. Chip design and internal circuitry details are presented at [2], [6].

The designed implant has a width of only 3 mm and a length of 41 mm. The implant can easily fit 24 french catheters, which shows its high potential for deployment in leadless heart pacing [6], [17]. The fabricated implantable device, the PCB schematic, and the flexibility of the implants are shown in Fig.4 (a) to (c). Due to the small size of implants, coil parameters such as L, Q, and SRF cannot be measured directly and are simulated in HFSS. The harvested power is a function of coil geometries and decreases with the inverse cube of the distance. Depending on the value of the tuning capacitor ($C_t$=82 pF/56 PF), the implant can operate at 13.56 MHz or 40.68 MHz for power harvesting. The rectified voltage is accumulated on the storage capacitor ($C_{str}$). The charge balancing is done using a blocking capacitor and discharge resistor ($C_{blk}$, $R_{dis}$), and a green LED is also used to indicate the pulses. Details of the implantable coil and component values are presented in table II.

## IV. System Verification

To test dual input wireless operation, two implants tuned at 13.56 MHz and 40.68 MHz, were put under 1 cm of chicken breast with a spacing of 5 mm. Two ports of the Tx coil were excited with 800 mW of power simultaneously. The pulse modulation on each port has a notch duration of 500 $\mu s$ and a repetition rate of 20 Hz and 10 Hz on 40.68 MHz and 13.56 MHz ports, respectively. The internal pulse modulation option on Agilent E4428C sources was used for modulation. Two power amplifiers for each port were used to reach an output power of 800 mW. Fig. 5 (a) presents real-time stimulation pulses for the implant tuned at 40.68 MHz at 20 Hz and for the implant tuned at 13.56 MHz at 10 Hz. Fig. 5 (b) shows a schematic of the measurement setup and how implants can get wirelessly powered and controlled at a distance of 2cm. This measurement demonstrates the successful WPT and control for two implantable devices using a single Tx coil at two frequencies. Table III summarizes and compares the performance of wireless multisite stimulation systems. This work features only 1 Tx coil and miniaturized low-power implantable devices suitable for biventricular pacing. The work in [6] used two Tx coils matched at 13.56 MHz and 40.68 MHz. Interference between coils and poor system scalability are the main drawbacks of this approach. The chip presented in [10] requires additional native layers for chip fabrication and complex circuitry to ensure PUF's stability. The work in [5] relied on two long ( 5 cm) electrodes to enable biventricular pacing, which makes it hard to deploy for leadless pacing. This letter proposes a single double-tuned Tx antenna and miniaturized implants operating at 13.56 MHz and 40.68 MHz ISM bands.

## V. Conclusion

A double-tuned dual input Tx coil and flexible miniaturized implants for multisite stimulation are presented in this letter. The Tx coil achieves −26.2 dB and −21.5 dB matching and isolation of −17.7 dB and −11.7 dB at 13.56 MHz and 40.68 MHz. The flexible implantable devices have a width of 3 mm, which makes them suitable for leadless pacing. The system's performance with two implants is verified in the presence of 1 cm of the chicken breast while wirelessly powered by 800 mW on each port. The measurements show successful power harvesting and data transfer using a single, dual input, double-tuned Tx coil.

## References

[1]. Piech DK, Johnson BC, Shen K, Ghanbari MM, Li KY, Neely RM, Kay JE, Carmena JM, Maharbiz MM, and Muller R, "A wireless millimetre-scale implantable neural stimulator with ultrasonically powered bidirectional communication," Nature Biomedical Engineering, vol. 4, no. 2, pp. 207–222, 2020.

[2]. Habibagahi I, Omidbeigi M, Hadaya J, Lyu H, Jang J, Ardell JL, Bari AA, and Babakhani A, "Vagus nerve stimulation using a miniaturized wirelessly powered stimulator in pigs," Scientific reports, vol. 12, no. 1, pp. 1–12, 2022. [PubMed: 34992227]

[3]. Ahn D and Ghovanloo M, "Optimal design of wireless power transmission links for millimeter-sized biomedical implants," IEEE transactions on biomedical circuits and systems, vol. 10, no. 1, pp. 125–137, 2015. [PubMed: 25616074]

[4]. Jang J, Habibagahi I, Rahmani H, and Babakhani A, "Wirelessly powered, batteryless closed-loop biopotential recording ic for implantable leadless cardiac monitoring applications," in 2021 IEEE Biomedical Circuits and Systems Conference (BioCAS). IEEE, 2021, pp. 1–4.

[5]. Gutruf P, Yin RT, Lee KB, Ausra J, Brennan JA, Qiao Y, Xie Z, Peralta R, Talarico O, Murillo A et al. , "Wireless, battery-free, fully implantable multimodal and multisite pacemakers for applications in small animal models," Nature communications, vol. 10, no. 1, pp. 1–10, 2019.

[6]. Lyu H, John M, Burkland D, Greet B, Post A, Babakhani A, and Razavi M, "Synchronized biventricular heart pacing in a closed-chest porcine model based on wirelessly powered leadless pacemakers," Scientific reports, vol. 10, no. 1, pp. 1–9, 2020. [PubMed: 31913322]

[7]. Habibagahi I, Jang J, and Babakhani A, "Miniaturized wirelessly powered and controlled implants for vagus nerve stimulation," in 2022 IEEE Radio Frequency Integrated Circuits Symposium (RFIC). IEEE, 2022.

[8]. Ardell JL, Rajendran PS, Nier HA, KenKnight BH, and Armour JA, "Central-peripheral neural network interactions evoked by vagus nerve stimulation: functional consequences on control of cardiac function," American Journal of Physiology-Heart and Circulatory Physiology, vol. 309, no. 10, pp. H1740–H1752, 2015. [PubMed: 26371171]

[9]. Lee B, Koripalli MK, Jia Y, Acosta J, Sendi M, Choi Y, and Ghovanloo M, "An implantable peripheral nerve recording and stimulation system for experiments on freely moving animal subjects," Scientific reports, vol. 8, no. 1, pp. 1–12, 2018. [PubMed: 29311619]

[10]. Yu Z, Chen JC, He Y, Alrashdan FT, Avants BW, Singer A, Robinson JT, and Yang K, "Magnetoelectric bio-implants powered and programmed by a single transmitter for coordinated multisite stimulation," IEEE Journal of Solid-State Circuits, vol. 57, no. 3, pp. 818–830, 2021. [PubMed: 36275505]

[11]. "Investigation of dual-band coil module for near-field wireless power transfer systems," in 2014 IEEE Wireless Power Transfer Conference. IEEE, 2014, pp. 265–268.

[12]. Dionigi M and Mongiardo M, "A novel resonator for simultaneous wireless power tranfer and near field magnetic communications," in 2012 IEEE/MTT-S International Microwave Symposium Digest. IEEE, 2012, pp. 1–3.

[13]. Kung M-L and Lin K-H, "Enhanced analysis and design method of dual-band coil module for near-field wireless power transfer systems," IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 3, pp. 821–832, 2015.

[14]. Jia Y, Guler U, Lai Y-P, Gong Y, Weber A, Li W, and Ghovanloo M, "A trimodal wireless implantable neural interface system-on-chip," IEEE transactions on biomedical circuits and systems, vol. 14, no. 6, pp. 1207–1217, 2020. [PubMed: 33180731]

[15]. Dabirzadeh A, "Rf coil design for multi-frequency magnetic resonance imaging and spectroscopy," Ph.D. dissertation, Texas A & M University, 2010.

[16]. Ye Z, Yang M, and Chen P-Y, “Multi-band parity-time-symmetric wireless power transfer systems for ism-band bio-implantable applications,” IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology, vol. 6, no. 2, pp. 196–203, 2021.

[17]. Sperzel J, Hamm C, and Hain A, “Nanostim—leadless pacemaker,” Herzschrittmachertherapie+ Elektrophysiologie, vol. 29, no. 4, pp. 327–333, 2018. [PubMed: 30341551]

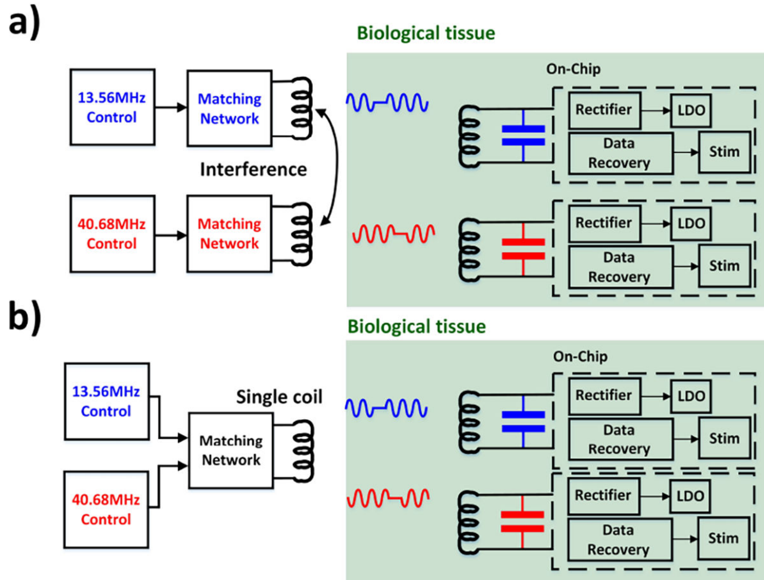


**Fig. 1.**

Conceptual representation of the multisite implantable system. (**a**) Two coil system presented in [6]. (**b**) Proposed single coil double tuned approach with less interference and compact size.

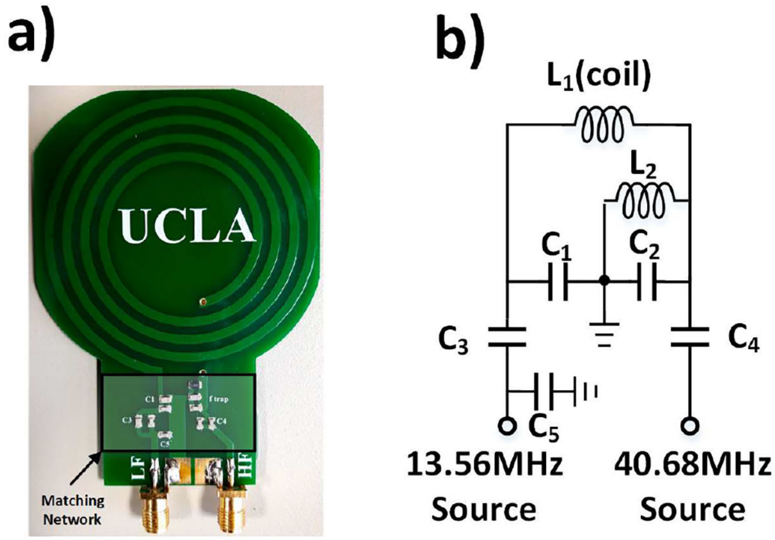


**Fig. 2.**

Tx double tuned coil. (**a**) Fabricated coil with matching networks. (**b**) Schematic of the double-tuned transmitter.

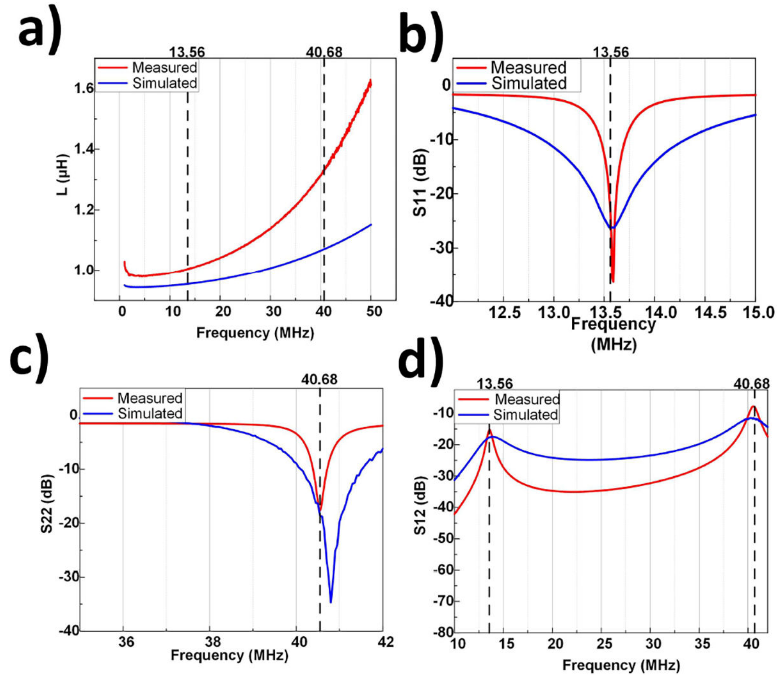


**Fig. 3.**

Characterization of the double-tuned coil. Measured and simulated (**a**) Inductance of the standalone coil (**b**) Low frequency port matching (**c**) High frequency port matching (**d**) Isolation between ports

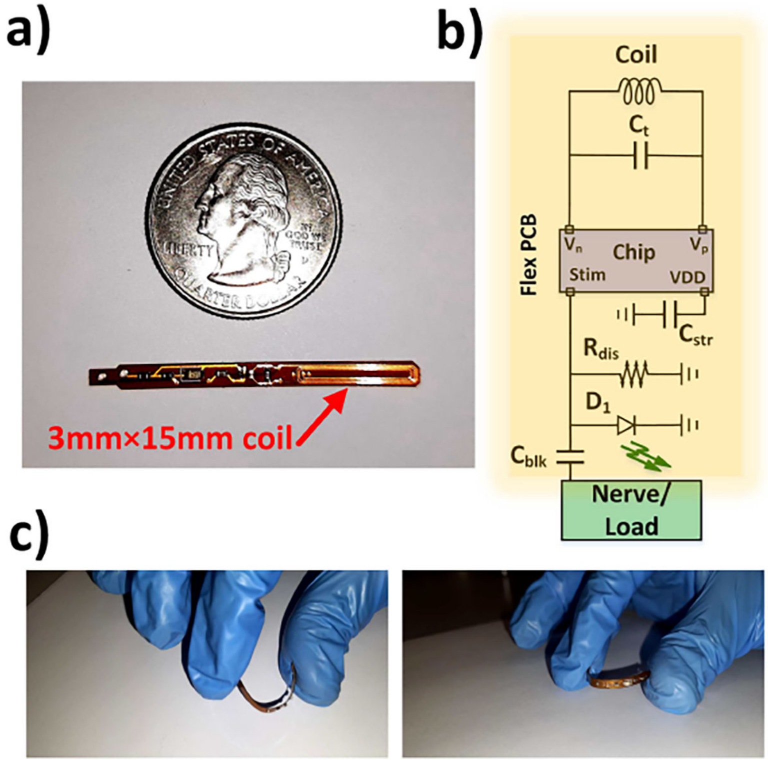


**Fig. 4.**

Implantable stimulator device. (**a**) Fabricated device compared to a dime coin. (**b**) Schematic of the implantable stimulator. (**c**) Demonstrated flexibility of the implantable device.

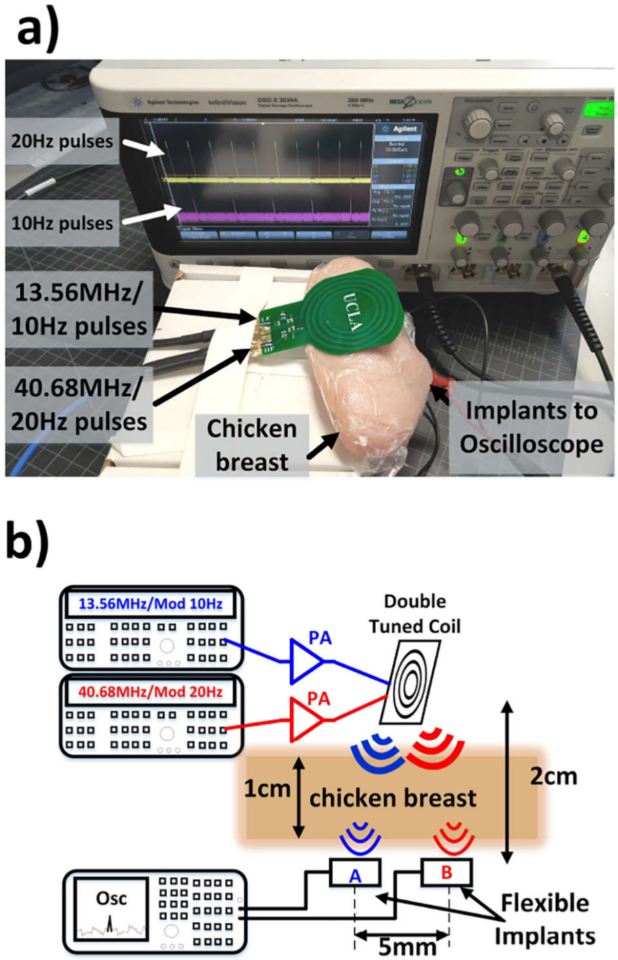


**Fig. 5.**

System verification setup (**a**) Double tuned coil is excited at two ports simultaneously with 10 Hz and 20 Hz pulse modulation, respectively. (**b**) Schematic of the measurement setup showing 2cm total distance including 1cm of chicken breast.

## TABLE I

Tx Coil parameters

| TX Coil Parameters | |
|---|---|
| Dimensions | 62mm diameter circular |
| # turns and layers | 4tums, Single layer |
| Q | 200~250 (measured) |
| Inductance | 1~1.25 μH |
| SRF | 78.7 MHz |
| **Matching Network Parameters** | |
| $L_2$,$C_1$,$C_2$ | 1 μH, 21.8 pF, 28 pF |
| $C_3$,$C_4$,$C_5$ | 39 pF, 6 pF, 330 pF |

**TABLE II**

IMPLANTABLE DEVICE PARAMETERS

| Implant Coil Parameters | |
|---|---|
| Dimensions | 3 mm × 15 mm |
| # turns and layers | 3turns, 4 layers |
| Q | 16~20(simulated) |
| Inductance | 1~1.447 μH (simulated) |
| SRF | 68.6 MHz (simulated) |
| **PCB Component Parameters** | |
| $C_t$,$C_{str}$ | 82 pF/56 pF, 22 μF |
| $R_{dis}$,$C_{blk}$ | 47 kΩ, 10 μF |

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## TABLE III

Performance comparison of wireless systems for multisite stimulation

| | **This work** | **Sci Rep 2020 [6]** | **JSSC 2021 [10]** | **Sci Rep 2019 [5]** | **J-ERM 2021 [16]** |
|---|---|---|---|---|---|
| # Tx Coils | **1** | 2 | 1 | 1 | 1 |
| Tx coil size($mm^2$) | **62 dia. (circular)** | 35×35, 45×45 | 60 dia. (circular) | 100×150 (estimate) | 15 dia. (circular) |
| Implant Size($mm^2$) | **3×15** | **11×11** | N/A (6$mm^2$ ME film) | 11 dia. (w/o electrodes) | 15 dia. (circular) |
| WPT Distance (mm) | **20** | 85 | 40 | ~30 | ~1 |
| Tx power (mW) | **800** | 1000 | N/A | 6000–10,000 | N/A |
| $f_{carrier}$ (MHz) | **13.56 / 40.68** | 13.56/ 40.68 | 0.33 | 13.56 | 27.12/ 40.68 |
| Multisite Validation | **Yes** | Yes | Yes | Yes | No |