# Design, Modeling, and Simulation of a 2.4 GHz Near-field Phased-Array based Wireless Power Transfer System for Brain Neuromodulation Applications

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***Abstract*—To avoid interruption of experiment and risk of infection, wireless power transfer (WPT) techniques have been used to eliminate the bulky wires and batteries attached to the animals in rodent electrophysiological applications for long-term in-vivo electrophysiological recordings. Headstage-based neuromodulation device has become one of the most popular methods for neural stimulation in recent times. In this work, a wireless power transfer system is designed which provides a constant power to a headstage based optogenetic stimulator. The proposed research is composed of two parts: i) a unidirectional 28 cm × 21 cm phased array transmitter antenna, and ii) an electrically small bi-directional 2.4 cm × 2.4 cm receiver antenna. A phased array transmitter antenna is designed to provide a uniform power transmission over the 27 cm × 23 cm × 16 cm rat behavioral cage area. The proposed WPT scheme utilizes a near-field power transmission scheme at 2.4 GHz frequency. Simulation results show that the transmitter antenna achieves a -24 dB and receiver antenna achieves a -27 dB return loss ($S_{11}$) at the resonating frequency. The proposed WPT system shows a maximum of 24.5% power transfer efficiency (PTE) when the receiver is in the center position and is 10 cm distance apart from the transmitter, which is much higher compared to the other state-of-the-art works. The transmitter antenna steers beam from -21° to 27° in $\phi$ axis and -108° to 74° in $\theta$ axis which covers the maximum 6.27 $cm^2$ area of the cage. The preliminary simulation results of the proposed WPT module show a better prospect for future optogenetics based applications.**

***Index Terms*—Wireless power transfer (WPT), Electrophysiological, Optogenetic, Receiving antennas, Transmitting antennas, Phased array antenna.**

## I. Introduction

Wireless power transfer has become the alternative solution to current electronic devices that depend on bulky batteries to supply the power and energy. With the recent advancement and progress in the field of WPT, there is an expanding demand for accomplishing a high power transfer efficiency (PTE). Optogenetics has established a new platform for the study of neuroscience especially in biomedical applications [1]–[3].There are usually two techniques for WPT system for transferring power: far-field and near-field [4]. For far-field WPT, microwave power beaming can transfer power from a long distance [5]. Microwave power beaming is not appropriate for optogenetic implants for two reasons. The first reason is that the WPT for optogenetics application needs low-power transmission and thus short-distance telemetry [5]. The second reason is due to the power density surpassing the Specific Absorption Rate (SAR) value 1.6 W/kg from IEEE standard safety guidelines. Beam steering is used for different applications such as Wireless Power Transfer to Micro Aerial Vehicle (MAV) [6].

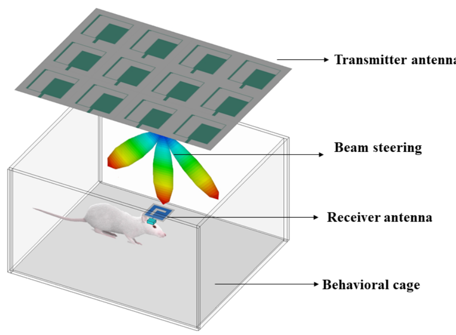


Fig. 1. Overview of the overall system

The WPT system proposed in this work implements nearfield resonant coupling for supplying power. A head-stage mount is proposed to be used for freely moving rodents that includes the receiver, and the transmitter is placed on the top/bottom of the 27 × 23 × 16 $cm^3$ cage. The receiver is placed on the headstage on the top of the head of the rodent. In our prior works, we implemented a near-field inductive coupling based WPT scheme, where the resonating planar coil-based transmitter was placed underneath the cage, and the receiver was mounted inside a 3D printed headstage [7]. The drawback of the prior works was that the magnetic field was not focused to the receiver only, and also not evenly distributed throughout the cage, which reduced the PTE at multiple

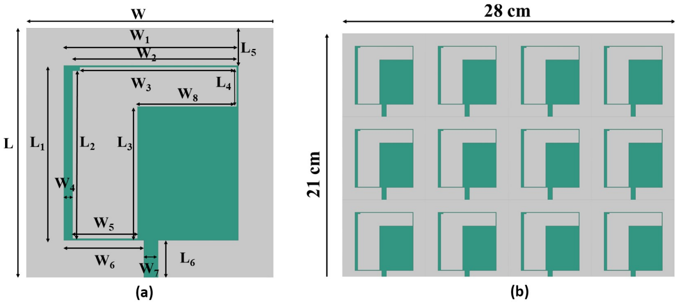


Fig. 2. (a) Transmitter antenna layout (b) Layout of the Transmitter antenna array

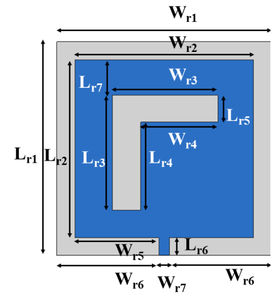


Fig. 3. Receiver antenna layout

TABLE I
TRANSMITTER ANTENNA DESIGN PARAMETERS

| Parameter | Value (mm) | Parameter, | Value (mm), |
|---|---|---|---|
| L | 70 | $W_1$ | 49 |
| W | 70 | $W_2$ | 46.52 |
| $L_1$ | 49 | $W_3$ | 44 |
| $L_2$ | 47 | $W_4$ | 2.55 |
| $L_3$ | 37 | $W_5$ | 18.2 |
| $L_4$ | 11 | $W_6$ | 22.5 |
| $L_5$ | 10.5 | $W_7$ | 4 |
| $L_6$ | 10.5 | $W_8$ | 27.8 |

TABLE II
RECIEVER ANTENNA DESIGN PARAMETERS

| Parameter | Value (mm) | Parameter, | Value (mm), |
|---|---|---|---|
| $L_{r1}$ | 24 | $Wr_1$ | 24 |
| $L_{r2}$ | 20 | $Wr_2$ | 20 |
| $L_{r3}$ | 12.90 | $Wr_3$ | 11.80 |
| $L_{r4}$ | 9.90 | $Wr_4$ | 8.6 |
| $L_{r5}$ | 3 | $Wr_5$ | 9.40 |
| $L_{r6}$ | 2 | $Wr_6$ | 11.43 |
| $Lr_7$ | 3.55 | $Wr_7$ | 1.20 |

locations. To overcome this challenge, here we proposed a phased-array antenna based near-field radiative WPT scheme, where the power beam can be steered electronically towards the headstage of the freely moving rodent. As the height of the cage is 16 cm and the rodent's height is 6-8 cm, the main focus is to designing a system which will continuously supply power to the receiver that is located in 10 cm distance. The overall view of the design is given in Fig. 1.

The rodents are freely moving animals, so the position of the receiver changes with time. In this work, the power transfer efficiency is analyzed in three different positions of the receiver antenna inside the cage, and the beam steering is shown to cover the maximum area. The main contributions of this paper are design of the proposed WPT system which supplies power at a large transfer distance with comparatively higher power transfer efficiency (24.5%) which is suitable to be implemented in the behavioral cage of the rodents for electrophysiological recording applications The maximum beam steering range achieved for this work is -21° to 27° in $\phi$ axis and -108° to 74° in $\theta$ axis which covers a large area of the behavioral cage. The paper is organized as follows: section II discusses the design and modeling of the antennas; section III presents the simulation results, followed by a concluding remark presented in section IV.

## II. WIRELESS POWER TRANSFER MODULE

The WPT Module is illustrated by its fundamental parts: a transmitter (TX) and a receiver (RX) module as shown in Fig. 2 and 3. Optogenetic implants need a miniaturized receiver module that should not weigh more than 10% of the mass of the animal [8]. A thin substrate of 0.8 mm is used to reduce the weight.

### A. Transmitter antenna design

The proposed WPT system is designed for the TX and RX antennas to resonate at the 2.4 GHz ISM band which is suitable for biomedical applications. The 2.4 GHz band uses longer waves, which makes it better suited for longer ranges. The TX antenna is a 4 × 3 phased array antenna which is designed to transmit wireless power through a unidirectional beam. The proposed antenna array is designed on a 2.4 mm thick FR4 substrate with a dielectric constant of 4.3 and a loss tangent of 0.02. Copper (Cu) with a thickness of 0.018 mm has been chosen as the conductor for both the radiating patch and the ground patch. The array consists of twelve 7 cm × 7 cm single unit antenna which is shown in Fig. 2(a). The design parameters of the TX antenna is presented in Table I.

Different shaped slots are cut in patch antennas for different operations in certain frequency such as Quad-Band Operation [9], wireless local area network (WLAN) applications [10], Microwave Power Transmission [11], Wireless Electrophysiological Recording Application [12] etc. In this work, the patch antenna is modified with L-shaped slot and full ground plate to create a unidirectional radiation pattern. The optimization of the design was done by changing the length, width, and thickness of the slots of the radiating patch. The slots are created in such a way that the antenna can resonate in 2.4 GHz frequency. The width of the horizontal slot of the L shape is proportional to the frequency and the return loss. On the other hand, the height of the vertical slot of the L shape is inversely proportional to the frequency. The measurements of the slots are designed to achieve high return loss and gain in 2.4 GHz frequency. The spacing between the unit antennas is chosen to be $\lambda/2$ considering the 2.4 GHz operating frequency.

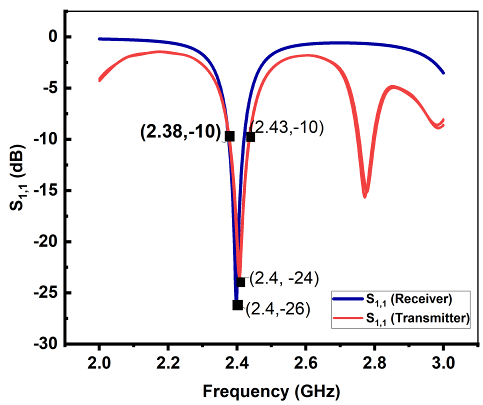


Fig. 4. $S_{11}$ parameter of the transmitter and receiver

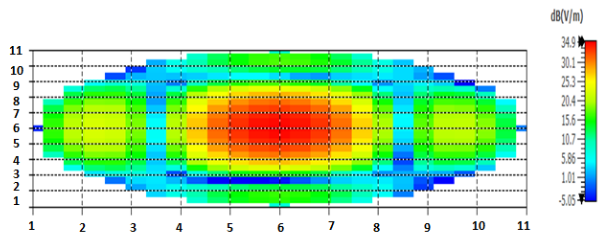


Fig. 5. E-field distribution (in cm) at the center position of the receiver, 10 cm away from the transmitter antenna

The overall dimension of the 4×3 array is 28 ×21 $cm^2$ which is convenient to be placed at the top or the bottom of the behavioral cage.

### B. Receiver antenna design

The dimension of the receiver antenna is 2.4 cm × 2.4 cm, which is shown in Fig. 3. The antenna is small enough to be placed it horizontally in the headstage on the head of the rodent. It is also designed and fabricated on an FR4 substrate and copper (Cu) has been used in patch and ground. The slot which has been cut in the patch, creates the bidirectional beam, and resonates at 2.4 GHz. The transmitter antenna can be placed at the top or the bottom of the behavioral cage.

pattern is convenient for placing two transmitter antennas at the top or the bottom of the behavioral cage. The design parameters are given in Table II.

## III. SIMULATION RESULTS

The computer simulation Technology (CST) software is used to carry out the simulation process. All performance parameters such as reflection coefficient $S_{11}$, gain, and radiation patterns are evaluated for both the TX and RX antennas. The measured $S_{11}$ are found to be -24 dB at 2.4 GHz for the 4×3 transmitter array antenna as shown in Fig. 4. The 2D polar plot of the RX antenna is presented in Fig. 7. Moreover, at the same center frequency of 2.4 GHz, the simulated $S_{11}$ of the receiver antenna is -27 dB and it's radiation pattern

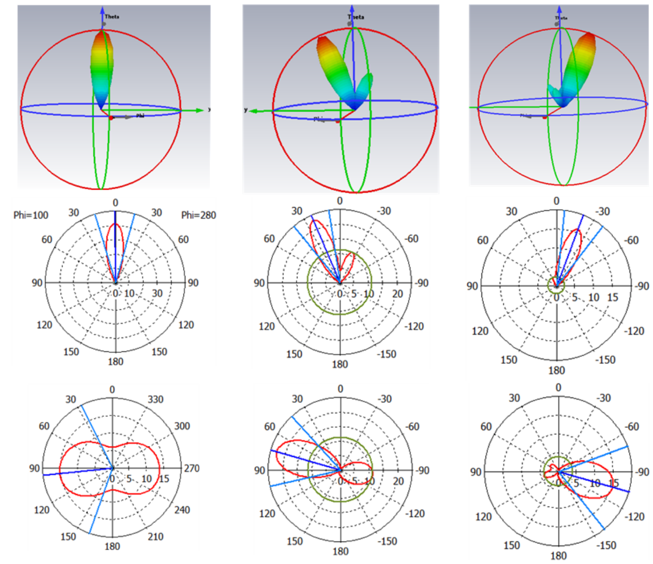


Fig. 6. Beam steering along (a)center (b) left and (c)right position of the receiver along  and  axis in 10 cm distance from the transmitter antenna.

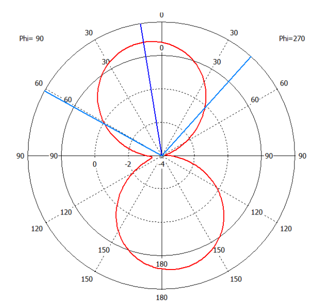


Fig. 7. 2D radiation pattern of the receiver antenna

is bidirectional which is convenient for receiving the signals from the transmitter antennas If they are placed at the top and the bottom of the cage. The gain of the TX and RX antennas are 13.4 dBi and 3.48 dBi respectively. As the radiation beam is of narrow bandwidth, it cannot illuminate the entire area of the cage. So, the beam steering is need for covering the maximum area of the cage. The maximum HPBW of the antenna is 81°. This angular width can cover 6.27 $cm^2$ area but the area of the cage is 28×21 $cm^2$. So, beam steering is needed to cover the whole area of the cage. The electric field is perfectly focused on the receiver when it is in the center position to the transmitter. The E field is simulated 34.9 V/m when the receiver is 10 cm apart from the transmitter which is demonstrated in Fig. 5. The radiation pattern of the transmitter antenna presents that it steers beam from is -21° to 27° in $\phi$ axis and -108° to 74° in $\theta$ axis for the phase conditions given in table III. The results are shown in Fig. 6. All the simulation results are presented keeping the reference distance 10 cm which is in the receiver plane and basically the simulations are representing near field simulation.

$$Reactive\ nearfield \leq 0.62 \times D^2/\lambda \quad (1)$$

TABLE III
BEAM STEERING RESULTS ALONG THE $\phi$ AND $\theta$- AXIS FOR DIFFERENT PHASE SHIFTS

| | | | | | | | | | | | | Phi($\phi$) | | Theta($\theta$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Beam Dir. | HPBW | Beam Dir. | HPBW |
| $0°$ | $337.5°$ | $22.5°$ | $315°$ | $45°$ | $450°$ | $67.5°$ | $270°$ | $90°$ | $247.5°$ | $112.5°$ | $180°$ | $-21°$ | $32.3°$ | $-108°$ | $81°$ |
| $0°$ | $337.5°$ | $22.5°$ | $315°$ | $45°$ | $480°$ | $67.5°$ | $270°$ | $90°$ | $247.5°$ | $135°$ | $225°$ | $23°$ | $31.2°$ | $74°$ | $60.4°$ |
| $0°$ | $180°$ | $22.7°$ | $90°$ | $67.5°$ | $225°$ | $112.5°$ | $270°$ | $157.5°$ | $-145°$ | $58.4°$ | $-13°$ | $20.3°$ | $20.4°$ | $20.4°$ | $20.4°$ |

TABLE IV
COMPARISON WITH THE STATE-OF-THE-ART

| Parameters | [13] | [14] | [15] | This work |
|---|---|---|---|---|
| Frequency | 13.56 MHz | 7.15 MHz | 70.47 kHz | 2.4 GHz |
| RX size | 10 × 10 $mm^2$ | 6 × 6 $mm^2$ | 352 $mm^3$ | 2.4 × 2.4 × $cm^2$ |
| TX size | 100 × 100 $cm^2$ | 10.5 × 10.5 $mm^2$ | – | 28 × 21 $cm^2$ |
| Distance | – | 5 mm | – | 10 cm |
| Transmitter Type | Planar spiral | Planar spiral | Helmholtz coil | Planar patch |
| Efficiency | 0.56% | 4.10% | 0.12% | 25.4% |

$$Radiating\ nearfield \leq 2D^2/\lambda \tag{2}$$

Here, D is Antenna dimensions and  is wavelength. As per equation, the proposed transmitter antenna can cover maximum 26 cm. The input power provided in the simulation is 1W and the fixed impedance is 50 Ω. The power transfer efficiency (PTE) is calculated as the following equations:

$$V = Ed \tag{3}$$

$$P_{out} = V^2/R \tag{4}$$

$$PTE = \frac{P_{out}}{P_{in}} \times 100\% \tag{5}$$

The V, E, d, and R denotes the potential difference in volts, electric field strength (in newtons per coulomb), distance between the antennas, and the resistance respectively. This work is compared with other works in terms of size and efficiency in Table IV. The proposed work achieves higher PTE than the compared works and the transfer distance is higher compared to the other works.

## IV. CONCLUSION

Wireless Power Transfer (WPT) makes it possible to transfer power through an air gap, without any requirement of current-carrying wires. The proposed WPT system is designed with the aim of utilizing it in a neuromodulation system which will be implemented in the future works. The transmitter antenna can uniformly send the signal and steer the beam which is suitable for this application. The proposed WPT system achieves higher PTE with smaller size of the antennas which is the novelty of this work.

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