2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI) | 978-1-6654-4228-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/USNC-URSI52151.2023.10238083

# Modeling and Optimization of the Steering Range of a Phased Array Antenna for Neuromodulation Applications in the Near-Field Region

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***Abstract*—This paper presents modeling and optimization of the steering range of a microstrip planar phased array antenna to steer the unidirectional near-field focused beam towards a certain direction. This antenna can be implemented in headstage-based neural stimulation system and wireless recording system for optogenetic neuromodulation applications. The proposed phased-array antenna consists of sixteen elements that are designed to provide a uniform power transmission over the 27 cm × 23 cm × 16 cm rat behavioral cage area. The proposed transmitter (TX) antenna implements a near-field-based wireless power transmission system operating at 2.4 GHz frequency. The phased array antenna steers the beam from –30° to 60° in the elevation plane by feeding the individual elements with different phases using four 4-bit phase shifters. A design analysis of the beam-steering approach of the phased array antenna is presented and the corresponding simulation and measurement results are included in this paper.**

***Index Terms*—Phased array antenna , phase shifters, near-field focused beam, optogenetic, neuromodulation.**

## I. Introduction

The advancement of microwaves in medical applications, for both diagnosis and treatment of the diseases has introduced a new pathway to transfer continuous power to the low-power circuits such as implantable medical devices. The wireless power transfer technique is becoming popular to avoid the use of bulky wires and batteries attached to the animals for long-term $in-vivo$ electrophysiological recordings. Electromagnetic (EM) power needs to be concentrated towards the dynamic target (freely moving animal) in order to acieve a high power transfer efficiency (PTE).

Researchers have investigated various techniques to achieve near-field focused beams in previous years [1], [2]. In WPT system where the receiver is dynamic such as rodents, UAV [3] etc., it is important to scan the beam to radiate power towards the accurate direction. In our prior work, a phased-array antenna-based near-field wireless power transfer (WPT) system, where the power beam can be steered electronically towards the headstage of the freely moving rodent has been proposed [4]. To achieve better performance, here the design has been improved to a 4×4 phased array antenna by placing the subarrays side by side in a plane and keeping the spacing between the unit antennas $\sim \lambda/3$ considering the operating frequency as of 2.4 GHz. The unit element design of the phased array antenna and RX is the same for this work. The analysis of the steering range was not done which is a limitation of the prior work. In this paper, a study of designing the TX phased array antenna for beam steering and transferring the power to the RX antenna is presented. The contributions of this work are- 1) Analysis of the beam steering approach in the behavioral cage. 2) Validation of the simulated results with measurement results.

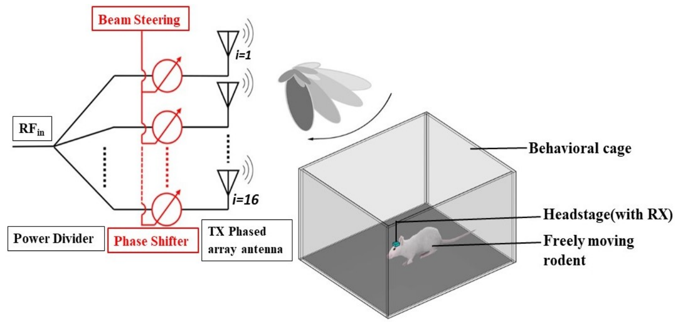


Fig. 1. A 3D rendered overview of the proposed wireless power transfer system

## II. Design Analysis of phased array antenna

The TX antenna resonates at 2.4 GHz industrial, scientific, and medical radio band (ISM band) which is suitable for biomedical applications. The overview of the system is shown in Fig. 1. The proposed antenna array is designed on a FR4 substrate with a dielectric constant of 4.3. Copper (Cu) with a thickness of 0.018 mm has been chosen as the conductor for both the radiating patch and the ground patch [4]. Assuming, there are $N$ column subarrays are placed linearly in a plane and $m$ and $n$ are the row and column numbers of the antenna. The radius vector of the $(m, n)$ element with respect to origin is [5],

$$\rho_{mn} = x(m-1)d_h + z(n-1)d_v \quad (1)$$

Here, $d_h$ denotes the spacing between the adjacent elements, and the subscript 'h' and 'v' indicates "horizontal and vertical respectively. The wavenumber vector is determined as,

$$kR_{mn} = kr - kd_h(m-1)sin\theta cos\phi - kd_v(n-1)cos\theta \quad (2)$$

Here, $k$ is the wavenumber vector, $R_{mn}$ is the radius vector going from the $(m, n)_{th}$ element to the target point (rodent). $\theta$ and $\phi$ denotes the elevation and azimuth angles respectively. Hence, to point the beam in the direction ($\theta_o$, $\phi_o$), the array elements have to bc phase shifted as follows:

$$w_{mn} = e^{-jkd_h(m-1)sin\theta_o cos\phi_o} e^{-jkd_v(n-1)cos\theta_o} \quad (3)$$

Thus, the radiation pattern of the beam-steering planar array, consisting of $N$ linear subarrays of $M$ patch radiators is given by the product of the element pattern and the space factor of the planar array, as follows:

$$F_{pl}(\theta, \phi) = F_1(\theta, \phi) \sum_{n=1}^{N} e^{jkd_v(n-1)(cos\theta - cos\theta_o)}$$

$$[\textstyle\sum_{n=1}^{N} e^{jkd_h(m-1)(sin\theta cos\phi - sin\theta_o cos\phi_o)}](4)$$

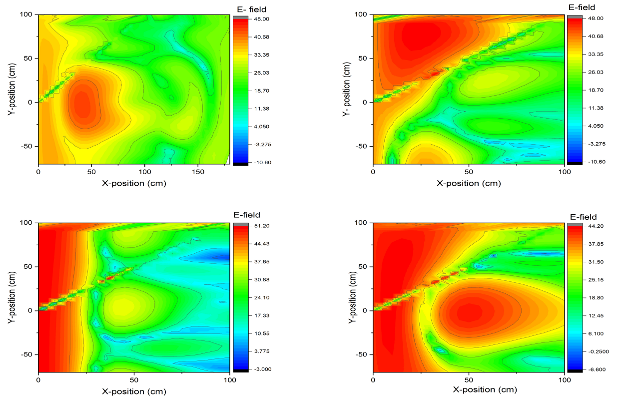


Fig. 2. E-field pattern distribution for different beam steering

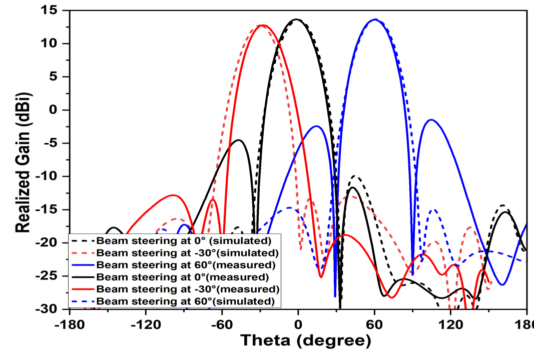


Fig. 3. Representation of simulated and measured radiation patterns in the elevation plane

TABLE I
BEAM STEERING ALONG THE $\theta$- AXIS FOR DIFFERENT PHASES

| Input phases | | | | Beam Direction | HPBW | Gain (dBi) |
|---|---|---|---|---|---|---|
| **Q1-Q8** | **Q9-Q12** | **Q13-Q14** | **Q15-Q16** | | | |
| 157.5° | 45° | 11.25° | 337.5° | -30° | 25.4° | 13.6 |
| 45° | 202.5° | 135° | 225° | 0° | 24.8° | 13.1 |
| 78.25° | 180° | 0° | 11.25° | 60° | 25.6° | 12.8 |

The height of the behavioral cage is 16 cm and the height of a rodent is typically 6-8 cm. So, the main goal is to design a system that will continuously supply power to the receiver that is located at a 10 cm distance. To calculate the coverage area by the unidirectional beam, the radius of the coverage area is considered as $a_r$. The 2D surface plane area (p$\times q$) cm$^2$ of the cage can be represented as,

$$\int_{x_1}^{x_2} \int_{y_1}^{y_2} dxdy = \pi {a_r}^2 = (p \times q)cm^2 \tag{5}$$

Calculating from the maximum HPBW (25.4°) of the antenna, a radiated beam covers 4.5 diameters at the 10 cm distance plane. As per calculation, to transfer power all over the 27 cm × 23 cm × 16 cm rat behavioral cage area, the scanning range is $\sim$120° and the unidirectional beam needs to be steered at a resolution of 24.22°. To achieve precise radiation and to eliminate the blind spots, the beam requires to be steered with a steering resolution of less than 24.22°. The radiated beam from the phased array antenna is able to cover 15.9 $cm^2$ area of the cage at a 10 cm distance. As the dimension of the RX antenna is smaller than this area, the beam is capable of radiating power to the RX antenna properly and accurately. To steer the unidirectional beam into different angles toward the rodent, different phases are needed to be provided into the ports of the TX antenna and the input phases are represented in Table I.

## III. SIMULATION AND MEASUREMENT RESULTS

The computer simulation Technology (CST) software has been used to perform all the simulation processes. The electric field distribution with beam steering is shown in Fig. 2. The electric field indicates the strength of the radiated wave that is being transmitted from the antenna at the 10 cm height plane. The results indicate that the radiated beam covers the maximum area of the behavioral cage by steering the beam in different directions. The simulated and measured radiation patterns in the elevation plane of the phased array antenna are represented in Fig. 3. Fig. 3 shows that the attainable scanning range of the unidirectional beam is from -30° to 60° for the phase conditions given in the table I with a maximum sidelobe level (SLL) below 10 dB.

## IV. CONCLUSION

This paper presents the optimization of the steering range of the phased array antenna to supply wireless power to the receiver of the neural stimulation system. The proposed antenna can cover the maximum area of the 2D surface plane of the behavioral cage. In the future, we will continue to increase the steering range to transfer power more precisely to the receiver.

## ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. ECCS 1943990.

## REFERENCES

[1] J. C. Lantis, K. L. Carr, R. Grabowy, R. J. Connolly, and S. D. Schwaitzberg, “Microwave applications in clinical medicine,” Surg. Endosc., vol. 12, pp. 170–176, 1998.

[2] A. Rosen, M. A. Stuchly, and A. V. Vorst, “Applications of RF/microwaves in medicine,” IEEE Trans. Microw. Theory Tech., vol. 50, no. 3, pp. 963–974, Mar. 2002.

[3] A. B. Patwary and I. Mahbub, ”Design and Simulation of UWB Phased Array Antenna For Wireless Power Transfer to Micro Aerial Vehicle (MAV) Through Beam Steering,” 2022 IEEE Radio and Wireless Symposium (RWS), Las Vegas, NV, USA, 2022, pp. 111-114, doi: 10.1109/RWS53089.2022.9719990.

[4] N. Saha and I. Mahbub, ”Design, Modeling, and Simulation of a 2.4 GHz Near-field Phased-Array based Wireless Power Transfer System for Brain Neuromodulation Applications,” 2022 IEEE Texas Symposium on Wireless and Microwave Circuits and Systems (WMCS), 2022, pp. 1-5

[5] V. Kallnichev, ”Analysis of beam-steering and directive characteristics of adaptive antenna arrays for mobile communications,” in IEEE Antennas and Propagation Magazine, vol. 43, no. 3, pp. 145-152, June 2001, doi: 10.1109/74.934915.