Metamaterial-Loaded Compact High-Gain Dual-Band Circularly Polarized Implantable Antenna System for Multiple Biomedical Applications

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Abstract—This communication presents a metamaterial (MTM) loaded compact dual-band circularly polarized (CP) antenna system suitable for multiple bio-telemetric applications. The proposed antenna system operates in the industrial, scientific, and medical (ISM) bands with center frequencies: 915 MHz (902–928 MHz) and 2450 MHz (2400–2480 MHz). The integration of an MTM structure with epsilon very large property on the superstrate layer of the antenna produces significant gain enhancement and strong CP behavior at both the operating frequencies. The key features of the proposed antenna system are its compact size (7 mm × 6 mm × 0.254 mm), dual-band CP characteristics, significantly high gain values (-17.1 and -9.81 dBi in the lower and upper bands, respectively), and slot-less ground plane that reduces the complexity and backscatter radiation. The performance of the MTM-loaded antenna system is validated experimentally. The antenna is fabricated and integrated with dummy electronics and batteries and is enclosed in a 3D printed device. The hermetically sealed device is tested in minced pork muscle to validate the simulation results. The measured impedance bandwidths of 35.8% and 17.8% are obtained in the lower and upper ISM bands, respectively. The specific absorption rate of the antenna system is evaluated at both frequencies in different tissues. Additionally, to determine the wireless communication range, the link margin is estimated at data rates of 100 kbps and 1 Mbps.

Index Terms—Axial ratio, circular polarization, ISM bands, link margin, miniaturization, metamaterial.

I. INTRODUCTION

Recent research advances have enabled the use of wirelessly linked implantable medical devices (IMDs) as control devices (e.g., implanted sensors, drug infusion devices, artificial vision, and organ control) or stimulators (nerve stimulators, defibrillators, cochlear implants, and leadless pacemaker) to improve the lifestyle of patients [1]. A key component of the wirelessly linked IMDs is the integrated implantable antenna, which facilitates bidirectional communication with the external control equipment. The design of implantable antennas has attracted significant research interest, as they must satisfy the requirements of miniaturization, biocompatibility, patient safety, sufficient radiation efficiency, and circular polarization (CP). The CP characteristic of an antenna is essential for high-quality communication with the external environment to compete human activities and postural movements. In order to fit easily within the devices used in bio-telemetric applications, the antenna must be designed with minimum size and volume. However, miniaturization degrades the antenna’s gain and efficiency. Many researchers have proposed and developed various antenna designs to meet these requirements [1]–[6], [9], [10]. Recently in [11], we designed a triple band antenna system that was intended for biotelemetry and wireless power transfer system. The miniaturization, impedance matching, and bandwidth enhancement of the antenna were achieved by inserting a slot in the ground plane. However, small gain values were observed in the desired direction of propagation at all the frequency bands due to the dominant backscatter radiations from the ground slot. The backscatter radiations can severely detune the antenna when integrated with microelectronics [12].

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Various techniques were proposed for the gain enhancement of the implantable antennas. In [2], a relatively large size planar dipole with a high gain of -23.7 dBi and low specific absorption rate (SAR) in the Med-Radio band (401–406 MHz) was proposed. However, its achieved gain value still need to be improved and the antenna size should be miniaturized to fit easily within small implantable devices. In some other works, the implantable antenna gain was improved by using a combination of hemispherical lenses and parasitic rings [3] or by introducing external structures such as printed grid surfaces [4]. This inclusion of external structures, however, restricted the implantation of the entire antenna system inside the human body. An alternative approach was proposed by Das et al. [5] wherein 3-dB gain improvement and good impedance matching was achieved by the inclusion of metamaterial (MTM) structures. However, in their work, the antenna communicated over a single frequency band (2.45 GHz) only, which was a busy band. Hence, the antenna operating in this band could suffer significant losses during propagation in tissues compared to the lower frequency bands. Moreover, the antenna was linearly polarized, which could create polarization mismatch with the external controlling device. Additionally, the study lacked system-level consideration and coupling with the device components used for bio-telemetric applications. In [6], the authors used a reactive impedance substrate, which widened the impedance bandwidth and

![Fig. 1. Overview of human anatomy and the proposed MTM-loaded antenna system.](image-url)
improved the axial ratio (AR) behavior in both the operating bands. However, the antenna exhibited low gain values of -31.8 and -27.6 dBi at 920 and 2450 MHz, respectively, and had a relatively large size.

In this communication, a compact dual-band implantable antenna system with enhanced gain and circular polarization characteristics in the 915 and 2450 MHz industrial, scientific, and medical (ISM) bands is presented for use in multiple bio-telemetric applications. The MTM technique [5], [7]–[10], [13] is used to improve the gain and AR behavior of the proposed planar inverted-F antenna (PIFA) system. An MTM unit cell consisting of a $2 \times 2$ array with epsilon-near-zero (ENZ) property is designed on the superstrate layer of the proposed antenna. In addition to the improvement in AR behavior with the MTM surface, gain improvements of approximately 2 and 1.5 dB are observed at 915 and 2450 MHz, respectively. To the best of our knowledge, the achieved gain is the highest value obtained to date, for implantable antennas with the smallest size of 7 mm $\times$ 6 mm $\times$ 0.254 mm (10.6 mm$^3$). A detailed comparison with recent studies is presented in Table I. The MTM-loaded PIFA is integrated with dummy electronic components for demonstrating the practical usability of the device in bio-telemetric applications, as shown in Fig. 1. The device is simulated inside a homogeneous phantom and in different body tissues of a realistic human model. The integrated antenna system’s performance is validated experimentally in the minced pork muscles, and the measured results are found to be in reasonable agreement with the simulated results. Additionally, the link-budget analysis of the antenna system is estimated for different tissues, to investigate its capability for communication in bio-telemetric applications.

## II. METHODOLOGY

### A. Design of the MTM-Loaded Antenna System

The schematic of MTM-loaded CP implantable antenna is presented in Fig. 2. The antenna has a compact size of 7 mm $\times$ 6 mm $\times$ 0.254 mm and consists of a serpentine-shaped radiating patch with a full ground plane. The coaxial feed and shorting pin with diameters of 0.6 and 0.4 mm, respectively, are placed at appropriate positions on the ground plane. The designed antenna is employed on substrate and superstrate layers. A Rogers RT/duriod 6010 with a dielectric constant ($\varepsilon_r$) of 10.2, loss tangent (tan$\delta$) of 0.0035, and thickness 0.127 mm is used as the substrate and superstrate layer. The high-dielectric superstrate material decouples the antenna from the lossy surroundings and stabilizes the effective permittivity fluctuations around the antenna [5]. Moreover, to improve the antenna gain and AR behavior, a finite array of MTMs consisting of $2 \times 2$ unit cells is designed on the existing superstrate layer of the proposed antenna. An additional dielectric slab is not required to load the MTM unit cell, which ensures a greater level of compactness to fit inside the IMDs used for bio-telemetric applications. The detailed design parameters of the antenna are presented in Table II.

In practical scenarios, the IMDs contain not only the antenna, but also microelectronic components such as sensors, circuitry, and power sources (batteries). Therefore, the designed antenna is integrated with dummy electronic components to constitute the device architecture. Fig. 3 shows the integration of the antenna with the device components. The device contains an implantable antenna, sensor packs, micro-electronics, and two alkaline batteries of height 2.1 mm and diameter 6.5 mm. The electronic components and batteries are considered to be perfect electric conductors and the sensor pack is of Roger RT/duriod 6010. All components of the device are encased in a biocompatible ceramic alumina ($\text{Al}_2\text{O}_3$) container with $\varepsilon_r$ of 9.8 and thickness 0.2 mm.
surrounded by a radiation box of dimensions 300 mm × 300 mm. The properties (permittivity and conductivity) of the skin tissues were set to be frequency dependent for the entire band used in the simulations. The antenna system was then implanted at different body tissue locations such as the scalp, heart, stomach, and small and large intestines of a realistic human model in Remcom, as shown in Fig. 3(a). The simulation results were validated by fabricated prototype of the antenna system. The fabricated MTM-loaded antenna was integrated with dummy circuitry and two batteries enclosed in a 3D printed device. The reflection coefficient, AR behavior, and gain patterns were measured by placing the hermetically sealed device in the minced pork muscle, as depicted in Fig. 3(b).

C. Operating Principal of the MTM-Loaded Antenna System

As discussed in detail by Lovat et al. [7] that MTM superstrate with EVL ($|\varepsilon_r| \gg 1$) and mu very large ($|\mu_r| \gg 1$) properties are required to improve the directivity and broadside gain of the magnetic dipole and electric dipole sources, respectively. Moreover, work presented in [8] described that if a grounded MTM structure of permittivity $\varepsilon_r$ and permeability $\mu_r$ is excited by a wave source, the normalized broadside power $P_N(0)$ can be expressed as

$$P_N(0) = \frac{K^2_0}{8\pi^2 \rho_0 \eta^2}$$  \hspace{1cm} (1)

where

$$K_0 = \omega \sqrt{\mu_0 \varepsilon_0}$$  \hspace{1cm} (2)

these equations show that if we made high the relative permittivity of the MTM structure or low the characteristic/intrinsic impedance, directive radiation can be obtained, which leads to gain enhancement in the desired direction of propagation. Thus, high effective permittivity values are suitable for enhancing directivity and gain of the antennas based on the leaky wave concept [7]. Furthermore, MTM structure has been applied to circular polarized micro-strip antennas in the free space to enhance the antenna gain and AR behavior [9], [10]. These enhancements are due to two factors. First, placing the MTM structure above the radiating patch results in additional electromagnetic coupling between the radiating patch and the meta-surface, thus enhancing the AR bandwidth. Second, the MTM improves the field distribution, which enlarge the effective aperture of the antenna [13].

In this study, the unit cell of the MTM structure was analyzed by applying two perfect electric and magnetic conductive boundaries each to the walls of the radiation box, which was placed at a distance of 1 mm from each side of the skin phantom, as illustrated in Fig. 4(a). As described in [5], [7]–[10], a grounded MTM superstrate with EVL properties is required to improve the broad-side gain of the magnetic dipole source. Here, we simulated the MTM-loaded implantable antenna in a homogeneous skin phantom. The characteristics and effective medium parameters of the unit cell, such as the effective permittivity and permeability were extracted using the Kramers–Kronig algorithm [14]. It can be seen from Fig. 4(b) that in the desired frequency range, the effective permittivity values of the MTM superstrate are very high, and they vary in the range of 20 to 30. Thus, this MTM structure with these EVL properties can be used for improving the gain and AR behavior of the antenna.

III. RESULTS AND DISCUSSION

The simulated and measured results for the return loss characteristics of the MTM-loaded implantable antenna system are illustrated...
Fig. 7. Distributions of the simulated surface currents on the radiating patch of the MTM-loaded antenna system at different phases: 0°, 90°, 180°, and 270°. (a) 915 MHz. (b) 2450 MHz.

**TABLE III**

TRANSMISSION PARAMETERS FOR THE WIRELESS LINK-BUDGET ANALYSIS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_r$</td>
<td>Resonance frequency (MHz)</td>
<td>915/2450</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Tx input power (dBW)</td>
<td>-46</td>
</tr>
<tr>
<td>$G_r$</td>
<td>Gain of the Rx antenna (dBi)</td>
<td>2</td>
</tr>
<tr>
<td>$G_t$</td>
<td>Gain of the Tx antenna (dBi)</td>
<td>-17.1/-9.81</td>
</tr>
<tr>
<td>$P_L$</td>
<td>Path loss (dB)</td>
<td>Distance dependent</td>
</tr>
<tr>
<td>$d$</td>
<td>Distance (m)</td>
<td>1-20</td>
</tr>
</tbody>
</table>

in Fig. 5. As can be seen from the figure, the system resonates in the 915 and 2450 MHz bands, with maximum measured impedance bandwidths of 17.8% and 35.8% in the lower and upper ISM bands, respectively. The simulation setups for the proposed antenna system in a homogeneous skin box and in different tissues (scalp, heart, stomach, small intestine, and large intestine) of a realistic human model are shown in Fig. 3(a). The heterogeneous environment has negligible effect in the lower frequency band (915 MHz), while a small shift occurs in the upper band (2450 MHz), which may be due to the variations in the electrical properties and asymmetrical load effect red of the body tissues [12].

The simulated and measured AR and gain comparisons between the implantable PIFA and MTM-loaded PIFA are illustrated in Fig. 6(a) and (b). The integration of the MTM structure leads to considerable CP behaviors at the corresponding frequency bands, as shown in Fig. 6(a). The simulated 3-dB AR bandwidths of the unloaded antenna are observed to be 15.3% and 11.8% in the lower and upper ISM bands, respectively. The MTM-loaded antenna system exhibits AR bandwidths of 21.3% and 17.14% in the lower and upper bands, respectively. The measured AR behavior is closely correlated with the simulated scenarios. The simulated and measured gain versus frequency analysis is shown in Fig. 6(b), the gain enhancement upon loading the MTM structure can be observed clearly. Gain enhancements of approximately 2 and 1.5 dB are observed at the lower and upper frequency bands, respectively. A similar gain enhancement can be observed from the measured gain behavior at both the resonance frequencies.

Regardless of the axial behavior, the CP mechanism can also be realized by analyzing the surface current distributions. Fig. 7 represents the simulated current distributions on the radiating patch of the MTM-loaded antenna at the corresponding resonance frequencies (915 and 2450 MHz) for four different phases (0°, 90°, 180°, and 270°). At both the operating frequencies for 0° phase, the current density is dominant in +Y direction (upward), while for the 90° phase, the dominant currents are toward +X direction (rightward). However, the predominant currents for the 180° and 270° are found in equal magnitude and opposite phase with 0° and 90°, respectively. Thus, the predominant currents are rotating in clockwise direction, which shows that the polarization sense for the proposed MTM-loaded antenna is left-hand circular polarization.

Fig. 8 demonstrates the radiated far-field gain patterns in the realistic human scalp, heart, stomach, and small and large intestines, and those measured in the minced pork muscle at the corresponding operating frequencies. As can be seen from the figure, the gain patterns are nearly omnidirectional in both E and H planes; however, the maximum direction of propagation is outside from the anatomical model as required for the implantable antenna systems. The gain-patterns were measured in an anechoic-chamber, as shown in Fig. 3(b). The maximum realized gain values of the MTM-loaded antenna system were observed in the skin phantom as -17.1 and -9.81 dBi in the lower and upper ISM bands, respectively, which are the highest gain values obtained to date with the smallest antenna size compared to the recently published implantable antennas.

The link-budget was calculated to determine the communication ability of the proposed antenna system. The proposed implantable antenna system was considered as a transmitter (Tx) with an input power of 25 µW, and a dipole antenna with a constant gain ($G_r$) of
TABLE IV

<table>
<thead>
<tr>
<th>Tissue category</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>Gain (dBi)</th>
<th>1-g Net-input power without MTM (mW)</th>
<th>1-g Net-input power with MTM (mW)</th>
<th>10-g Net-input power without MTM (mW)</th>
<th>10-g Net-input power with MTM (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin /Scalp</td>
<td>915</td>
<td>101</td>
<td>-17.13</td>
<td>2.776</td>
<td>4.052</td>
<td>36.67</td>
<td>48.97</td>
</tr>
<tr>
<td>Small Intestine</td>
<td>2450</td>
<td>163</td>
<td>-9.81</td>
<td>3.052</td>
<td>4.853</td>
<td>39.82</td>
<td>58.10</td>
</tr>
<tr>
<td>Heart</td>
<td>915</td>
<td>84</td>
<td>-19.78</td>
<td>2.752</td>
<td>3.948</td>
<td>31.56</td>
<td>44.88</td>
</tr>
<tr>
<td>Large Intestine</td>
<td>2450</td>
<td>144</td>
<td>-12.3</td>
<td>3.313</td>
<td>5.071</td>
<td>36.91</td>
<td>51.63</td>
</tr>
<tr>
<td>Stomach</td>
<td>2450</td>
<td>151</td>
<td>-14.4</td>
<td>3.664</td>
<td>5.579</td>
<td>38.27</td>
<td>60.04</td>
</tr>
</tbody>
</table>

2 dBi was considered as a receiver located at a distance $d$ from the Tx. The additional parameters used for the link-budget calculation are presented in Table III. The Friis formula was used to calculate the link budget, considering various losses [15]. Figs. 9(a) and (b) demonstrate the distance versus margin for the proposed antenna system in different body tissues at 915 MHz with bit rates of 100 kbps and 1 Mbps, respectively. It has been observed that the antenna system exhibits successful transmission for $d > 10$ and $d > 6$ m at bit rates of 100 kbps and 1 Mbps, respectively. Thus, the proposed antenna system fulfills the requirements of low and high-data rate applications and can be used in multiple implantable biomedical applications.

To evaluate the safety of the proposed MTM-loaded antenna system, the SAR distributions over 1-g of tissues in the scalp and heart of a realistic human model without and with MTM structure were evaluated and shown in Figs. 10(a) and (b), respectively. For an input power of 1 W, the maximum 1-g average SAR in the heart tissues at 915 MHz was observed to be 405.2 and 581.1 W/kg with and without MTM, respectively. The SAR reduction and gain enhancement with MTM structure is due to the formation of displacement currents in the surrounding tissues of the antenna system [16]. The detailed performance of the MTM-loaded antenna, e.g., bandwidth, gain, and maximum allowable net input power with and without MTM in different human tissues using the XFtdtd-based simulator Remcom are presented in Table IV. According to Table 2, the 1-g net input power for the heart without and with MTM structure are 2.75 and 3.94 mW, which are very far from the 25 µW value specified for implantable antennas under the IEEE safety regulations.

IV. Conclusion

This paper addressed the design, analysis, and experimental validation of an MTM-loaded compact CP implantable antenna system with enhanced gain and AR characteristics, for multiple bio-telemetric applications. Gain enhancement and substantial AR bandwidth were achieved at the desired frequency bands, with a compact size of 7 mm × 6 mm × 0.254 mm compared to the other implantable antennas. The integrated antenna with dummy electronics and batteries was simulated in different tissues of a realistic human model to demonstrate its use in multiple applications. The simulation results were validated experimentally by placing a hermetically sealed device containing the MTM-loaded antenna, dummy circuitry, and batteries in minced pork muscles. The measured results (reflection coefficients and gain patterns) were found to be in reasonable agreement with the simulated results.

REFERENCES