E-shape metamaterials embedded implantable antenna for ISM-band biomedical applications

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Received: 22 February 2021 / Accepted: 25 November 2021 / Published online: 22 January 2022
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Abstract
Purpose This paper presents a compact antenna based on two different metamaterial resonators, the E-shape resonators and the interdigital resonators, suitable for biomedical implant applications.
Methods The proposed antennas operate in the industrial, scientific, and medical (ISM) bands in the frequency band of 2.4–2.5 GHz. The integration of metamaterial (MTM) into the design led to the reduced size of these antennas and gaining enhancement. The overall size of the proposed antennas is $8 \times 7 \times 1.27 \text{mm}^3$. The implantable antennas contain two layers of the substrate; the lower layer comprises the MTM resonators and the upper, superstrate layer. The antennas are designed and simulated by the software simulator HFSS.
Results To study the performance of the proposed antennas, the reflection coefficient and gain are determined. In order to observe the exposure of electromagnetic energy to human tissues, the specific absorption rates (SARs) of the proposed antennas are also calculated in the layer model.
Conclusion The results of the proposed antennas are acceptable and suitable for biomedical applications and human body safety through the values obtained from SARs.

Keywords Antenna · Design · Metamaterial · E-shape resonator · ISM bands · Miniature

Introduction
Implantable medical devices (IMDs) play an important role in telemetry. They allow the transmission of information from inside the human body to the base station (Fig. 1) (Alrawashdeh. 2005). The antenna is the important element in IMDs which is responsible for the transmission of this information between the IMDs and the external equipment (Kiourti et al. 2012). An antenna design has become one of the most active areas of communications studies and must be adapted to meet the requirements of the new applications (Nouri et al. 2016; Abes et al. 2020).

The design of the implantable antenna must meet some essential requirements, such as compact size, biocompatibility, patient safety, flexibility, and low value of specific absorption rate (SAR) (Kiourti et al. 2014). One of the key challenges is the miniaturization of the patch antenna. A variety of techniques have been proposed, like a high dielectric constant material (Xu et al. 2012), loading shorting pins to connect the patch and the ground (Waterhouse. 1995), and metamaterial split ring resonator (SRR) (Ali and Birdar 2017).

The design steps needed to design implantable antennas are described in Kim and Rahmat-Samii (2004). The implantable antenna is used in the medical implant communication service (MICS) band, which is between 402 and 405 MHz, and in the industrial, scientific, and medical (ISM) bands (433.1–434.8 MHz, 868–868.6 MHz, 902.8–928 MHz, and 2400–2500 MHz) (Kiourti and Nikita. 2012).

Metamaterials (MTMs) are engineered materials with extraordinary properties not usually found in nature, such as negative permittivity, permeability, and the refractive index (Barrett and Cummer. 2015; Becharef and al. 2020). The theoretical properties of this material were first introduced by the Russian scientist Victor Veselago in 1968. Researchers
are interested in metamaterials and their follow-up in many fields, especially in the microwave field (Jarchi et al. 2017; Dong and Itoh 2012). Several forms of metamaterials have been introduced, such as split ring resonators (SRRs) circular and square (Becharef et al. 2019), complementary SRRs (Becharef et al. 2017), S-shape (Khan and Mughal. 2009) and G-shape (Dadgarpour et al. 2015)…

The use of metamaterials in the design of implantable antennas has become interesting: in some work, MTM-loaded CP implantable antenna (Zada et al. 2019), a compact SRR based antenna (Chaturvedi, and Raghavan. 2019), and a metamaterial-inspired CP antenna for implantable application (Goswami and Karia. 2020).

In this paper, two metamaterial resonators embedded in antennas are proposed, E-shape and E-interdigital resonators, to study these forms of metamaterial in contrast to the familiar forms. These antennas are for use in multiple bio-telemetry applications in the upper-frequency band of ISM 2.4–2.5 GHz. Adding, the two proposed resonators are designed on the substrate layer of the proposed antenna and simulated in different human layer tissues such as skin, fat, and muscle.

Antenna with four E-shape resonators

Antenna design specifications

The proposed antenna loaded with four E-shape MTM resonators modeled and analyzed in HFSS is shown in Fig. 2. The overall size of the proposed antenna is $8 \times 7 \times 1.27 \text{mm}^3$. The antenna contains a radiation patch, full ground, and two layers of substrate, the first layer consisting of patch radiation and the four MTM E-shape resonators, and the second, the superstrate layer. The designed antenna is standardized at 50 ohms and is fed by a coaxial cable and a shorting pin with a 0.15mm and 0.1mm diameter, respectively. A RO3010 with a dielectric permittivity constant ($\varepsilon_r = 10.2$) and a loss tangent ($\tan\delta = 0.0035$) and a 0.635mm thickness is used as the substrate and superstrate layer. The proposed antenna operates at a 2.45-GHz resonance frequency.

Metamaterial unit cell

In this work, the design of the MTM resonator is formed by the E-shape resonator as shown in Fig. 3. This structure
is treated by High Frequency Structure Simulator (HFSS) software. The perfect electric conductor (PEC) boundary is applied along the Y-axis and the perfect magnetic conductor (PMC) boundaries are applied along the X-axis. Electromagnetic waves pass through port 1 and port 2, which are perpendicular to the boundaries of PEC and PMC, along the Z-axis, as shown in Fig. 3-(b). The value parameters of the E-shape resonator are \( e = d = 1.5 \text{mm}, \ g = 0.3 \text{ mm}, \) and \( k = 1 \text{ mm}. \)

To check the presence of metamaterial in the proposed E-shape, the Nicolson Ross Weir (NRW) method is used to extract the effective parameters of the MTM: permeability, permittivity, and refractive index (Dhillon and Dimri. 2015). This method uses the following equations:

\[
V_1 = S_{21} + S_{11} \\
V_2 = S_{21} - S_{11} \\
\mu_{\text{eff}} = \frac{2}{(jK_0d)(1 + V_2)} (1 - V_2) \\
\varepsilon_{\text{eff}} = \frac{2}{(jK_0d)(1 + V_1)} (1 - V_1) \\
n_{\text{eff}} = \sqrt{\mu_{\text{eff}} \times \varepsilon_{\text{eff}}}
\]

where:
- \( K_0 \) is wave number in free space \( (K_0 = \frac{\omega}{c}) \), \( \omega \) is the angular frequency, and \( c \) is the speed of light in free space, \( c = 3 \times 10^8 \text{ m/s} \).
- \( d \): the thickness of the substrate.
- \( S_{11}, S_{21} \): the S-parameters.
- \( \varepsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) are effective permittivity and effective permeability.
- \( n_{\text{eff}} \) is the refractive index.

Figure 4 illustrates the reflection coefficient \( S_{11} \) and the transmission coefficient \( S_{21} \) of the proposed E-shape resonator concerning frequency.

From the S-parameters, we extracted the values of permittivity, permeability, and refractive index, as shown in Fig. 5.

From the results, the MTM resonator has a negative value for the real parts of permittivity, permeability, and refractive index at 2.45 GHz.
Fig. 5 The real and imaginary part of (a) permittivity, (b) permeability, and (c) refractive index
Design and simulation environments of MTM planar antenna based on E-shaped unit cells

The proposed antenna loaded with four MTM E-shape resonators was modeled and analyzed in HFSS. Firstly, the proposed antenna is operated in free space by two steps. In the first step, the dimensions of the patch antenna are calculated by the following equations in terms of the resonant frequency and the relative permittivity of the dielectric material (Balanis. 2015):

\[
W_p = \frac{c}{2 f_0 \sqrt{\varepsilon_r + 1/2}} \tag{6}
\]

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \frac{1}{\sqrt{1 + 12 \left( \frac{h}{w} \right)^2}} \right] \tag{7}
\]

\[
L_p = \frac{c}{2 f_0 \sqrt{\varepsilon_{\text{eff}}}} - 0.824b \left( \frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}} - 0.258} \left( \frac{w}{b} + 0.264 \right) \right) \tag{8}
\]

where:

- \(W_p\) and \(L_p\): the width and the length of the patch.
- \(\varepsilon_{\text{eff}}\): the effective dielectric constant of the patch.

Free space

To get the desired frequency, we have a study and an optimization of the positions of pin and via, and each time we also minimize the dimensions of this antenna until we get the following dimensions as shown in Fig. 6:

- \(W_g = 12\) mm, \(L_g = 11\) mm, \(W_p = 10.4\) mm, \(L_p = 9.4\) mm, and \(d = 7.4\) mm.

In the second step, the antenna is simulated by adding the four MTM E-shape resonators (Fig. 6.b). The addition of the MTM to the antenna results in a frequency shift which enables the reduction of the antenna dimensions to obtain the desired frequency.

Human body phantom

For the second operation, the proposed antenna is simulated in a one-layer tissue model (skin) and in a three-layer tissue model (skin, fat, and muscle). Because of the high values of the dielectric properties of human tissues, the simulation frequency shifts. Therefore, the antenna parameters are reduced to reach the desired frequency with the values from Table 1.

The proposed antenna is deep in the upper layer of the skin tissue model, with dimensions of 100 mm × 100 mm × 4 mm for the single model and 100 mm × 100 mm × 23 mm for the three-layer tissue model.

Table 1 The value parameters of the proposed antenna

| Variable | Value(mm) | Variable | Value(mm) |
|----------|-----------|----------|-----------|
| \(W_g\)  | 8         | \(a\)    | 0.5       |
| \(L_g\)  | 7         | \(b\)    | 3         |
| \(W_p\)  | 6.7       | \(c\)    | 1.4       |
| \(L_p\)  | 6         | \(d\)    | 5.1       |

Fig. 6 The proposed antenna. (a) Antenna without MTM resonators. (b) Antenna with four E-shape MTM resonators
surrounded by a radiation box, as shown in Fig. 7 (a) and (b). Table 2 shows the relative permittivity, conductivity, and density for skin, fat, and muscle simulated at 2.45 GHz (Yang et al. 2017). In other simulations, the proposed antenna is simulated at different heights in fat and muscle.

**Results and analysis**

**Antenna in free space**

Figure 8 shows the simulated return loss of the proposed antenna in free space with and without the four E-shape MTM resonators. The simulation results are shifted from 2.44 GHz to 2.45 GHz and it seems that the size of the antenna is reduced, as can be seen from the figure. The return loss is $-22.57 \, \text{dB}$ and $-25.90 \, \text{dB}$ without and with the addition of the E-shape resonators, respectively.

The different values of the bandwidth (BW) in free space are presented in Table 3. The bandwidth value is $f_{\text{max}} - f_{\text{min}}$ for $|S_{11}| < 10 \, \text{dB}$.

Figure 9 illustrates Farfields gain pattern in free space before and after adding the four MTM E-shape resonators, for both principal planes E plane ($\phi = 0$) and H plane ($\phi = 90^\circ$). As can see from the figure, the radiation pattern is nearly omnidirectional for both the E and H planes, without and with MTM resonators.

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**Table 2** Dielectric properties of different tissues at 2.45 GHz

| Tissues  | Thickness (mm) | $\varepsilon_r$ | $\sigma (S/m)$ | Density (kg/m$^3$) |
|----------|----------------|----------------|----------------|--------------------|
| Skin     | 4              | 38.0           | 1.44           | 1100               |
| Fat      | 4              | 5.28           | 0.1            | 910                |
| Muscle   | 15             | 52.7           | 1.74           | 1041               |

**Table 3** The bandwidth values

|                        | BW (MHz) |
|------------------------|----------|
| Without four E-shape   | 20       |
| With four E-shape      | 30       |
The maximum gain values of the proposed antenna are about $-14.7 \, \text{dB}$ at 2.45 GHz for without and with the four E-shape resonators, as shown in Fig. 10.

As can be seen from the results, the addition of the four E-shape resonators improves the bandwidth and the coefficient of reflection, and the gain is almost for the two MTM resonators of the proposed antenna.

Antenna in one-layer and three-layer tissue models

We have studied the performance of the proposed antenna in one-layer and three-layer tissue models. The simulated result of the reflection coefficient of the proposed MTM E-shape embedded antenna is presented in Fig. 11 for the two tissue models. For one-layer, the simulated return loss is $-37.96 \, \text{dB}$
at 2.45 GHz, and about the three-layer model, the return loss is −22.01 dB at 2.44 GHz.

The electromagnetic field passing through the human body depends on the thickness and exact composition of biological tissues, the change in frequency from the skin to three-layer due to the increase in the values of the properties of the layers (one-layer to three-layer).

Table 4 illustrates the bandwidth values of the proposed antenna in different layer models.

Figure 15 shows Farfields radiation gain pattern for the two planes E and H in the one-layer and three-layer tissue models.

The maximum gain values are −25.4 dB and −28.2 dB for one-layer and three-layer, respectively (Fig. 12).

As can be seen from these plots, the back value of the maximum gain is low in the presence of the human tissues compared to the free space (Fig. 10). The low gain is due to the size of the antenna compared to the size of the human body and also due to its loss environment.

**Antenna with MTM E-interdigital resonators**

**Antenna design specifications**

In this part, we replace the four MTM E-shape resonators with another shape of E-interdigital, as shown in Fig. 13. This structure is also modeled and simulated by using HFSS software with the same value parameters of the proposed antenna and the same process as indicated in § II.2. The value parameters of the E-shape resonator are $e = d = 1.5$ mm and the others are shown in Fig. 13.b.

To verify the existence of metamaterial in the proposed E-interdigital, we use the same method of Nicolson Ross Weir (NRW) to extract the effective parameters of the MTM: permeability, permittivity, and refractive index by using Eqs. (1)–(4) in § II.B.

From the results, the MTM resonator has a negative value for the real parts of permittivity, permeability, and refractive index at 2.45 GHz.

The $S_{11}$ and $S_{21}$ of the MTM E-interdigital resonator are presented in Fig. 14.

From the S-parameters, we extracted the values of permittivity, permeability, and refractive index, as shown in Fig. 16.

The proposed antenna is also simulated in free space, in one- and three-layer human models.

**Results and analysis**

**Antenna in free space**

As shown in Fig. 17, the reflection coefficient of the proposed antenna with E-interdigital MTM resonators is −22.7 dB at 2.45 GHz, and as we indicated before the simulation without MTM resonators is −22.57 dB at 2.44 GHz. The simulation
frequency is shifted from without to with MTM resonators and it looks like the antenna size has been reduced.

Table 5 illustrates the bandwidth values of the proposed antenna in free space.

Figure 18 shows the Farfields gain pattern at 2.45 GHz in free space in the two planes E and H.

The 3D gain values are presented in Fig. 19. The maximum gain is $-14.74$ dB and $-15.24$ dB for without and with MTM resonators, respectively.
Antenna in one- and three-layer model

The proposed antenna with the resonators E-interdigital takes the same parameter values as indicated in the previous section and Table 1.

Figure 20 shows the return loss in one-layer and three-layer tissue models. From the figure, the value of the S-parameters is $-33.44$ dB and $-21.18$ dB at about 2.46 GHz in the one-layer and three-layer tissue model, respectively.

The bandwidth values are presented in Table 6 for one-layer and three-layer models.

Figure 21 illustrates the Farfields radiation pattern for the two planes E and H in the one-layer and three-layer tissue models.

Layer simulation at various depths

We simulated the proposed antenna with the two MTM resonators in different deep tissue models (fat and muscle) as shown in Fig. 23. The results of reflection coefficients are shifted as shown in Fig. 24. This shift is due to the change in the values of permittivity and conductivity from skin to fat and muscle.

The proposed antenna with the two MTM resonators, E-shape and E-interdigital, is simulated with different deep-layer tissue models (fat and muscle). Simulation results are
shifted whenever the antenna is deeply in the tissue. As shown in the figure, the simulation in the fat-layer is changed from 2.46 GHz to 2.12 GHz for $d_p = 0.5$ mm and $d_p = 1.5$ mm, respectively. The simulation frequency has been changed from 1.37 GHz to 0.97 GHz for the muscle layer for $d_p = 0$ mm and $d_p = 4$ mm, respectively.

**Patient safety (biocompatibility) and SAR**

The implantable medical devices contain not only the antenna but also other components like sensors, batteries... So, to eliminate direct contact with the human body, all components of the IMD are encased in biocompatible materials. There are many biocompatible materials in literature: silica (Ali et al. 2017), ceramic alumina ($Al_2O_3$) (Nachiappan and Azhagarsamy. 2017; Challa, S. Raghavan. 2016), zirconia ($ZrO_2$) (Kaka and Toycan. 2015), Parylene-C (Duan et al. 2014)...

The specific absorption rate (SAR) is evaluated to observe the sensitivity of human tissues to electromagnetic energy. It is necessary to specify the maximum acceptable input power to the antenna (Nadh et al. 2019). The SAR limit specified in IEEE C95.1: 1999 is 1.6 W/kg in a SAR 1-g averaging mass, while that specified in IEEE C95.1: 2005 has been updated to 2 W/kg in a 10-g averaging mass (Bailey et al. 2019).
SAR is calculated by:

\[
SAR = \frac{\sigma}{\rho} |E| \quad \text{(V/m)}
\]

where \( E \) is the root mean square RMS of the induced electric field (V/m) and \( \rho \) is the mass density of the tissue (kg/m\(^3\)).

**Table 5** The bandwidth values

|                  | BW (MHz) |
|------------------|----------|
| Without MTM      | 20       |
| E-interdigital   | 24.4     |

**Fig. 17** Variation of S-parameters with frequency with MTM E-interdigital in free space

**Fig. 18** Farfields radiation pattern in free space at 2.45 GHz (a) without four E-shape resonators and (b) with four E-shape resonators

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The SAR is calculated first with the default input power of 1 W in HFSS for the two proposed MTM resonators, four E-shape and E-interdigital resonators at a frequency of 2.45 GHz.

Figures 25 and 26 show the distribution of SAR for the two MTM resonators, E-shape and E-interdigital resonators, in one-layer skin. The maximum SAR values are presented in Table 7. These values are not acceptable and harm human tissues. So we need to change the reference power values to preserve the standards.

So, to get the standard values, we have to change the reference power value. The input power values for the two MTM resonators (E-shape and E-interdigital) become 2 mW. The new values of the SAR are 1.52 W/kg and 0.16 W/kg for 1 g and 10 g, respectively, for the MTM E-shape
resonators, and for the MTM E-interdigital are 1.51 W/kg and 0.16 W/kg for 1 g and 10 g, respectively.

Table 8 illustrates the different values of the size, the gain, and the SAR in the literature and our work of E-shape and E-interdigital MTM resonators on average for 1 g and 10 g of tissue with a default input power of 1 W.

As shown in the following table, the different values in the results, like the gain and the SAR, are due to the different forms of the antennas and to the different dimensions of the tissue model where these proposed antennas are implanted. For example, the dimensions of the antenna in reference (Zada et Al. 2019) are almost the same as our proposed antenna, but the difference in performance is due
to different forms (the MTM in the superstrate layer) and due to the different dimensions of the skin tissue model. Also, in this reference, the study is about antenna systems (containing sensor packs, micro-electronics, and two alkaline batteries).

**Discussion**

In this study, to design a miniature implantable antenna, we added metamaterial resonators, a short pin that is an electrical connection between the ground and the patch, and we used a dielectric material with a high value of permittivity. The result of the reflection coefficient of the proposed antenna with MTM is better compared to that without MTM.

The results of the proposed antenna with four E-shape MTM resonators are almost the same as the results of the antenna with E-interdigital MTM resonators. For detailed information, we will make a table (Table 9) comparing the proposed antenna with the two MTM resonators in one-layer and three-layer tissue models.

From the table, the simulated values of the gain in the single-layer are better compared to the multi-layer and that is due to the increase in the values of permittivity and conductivity of the tissue layers.

Biological tissues usually have high permittivities. This will change the resonant frequency of the antennas.
coupled with them. Depending on the working frequency of the antenna, the human body can generate large losses caused by power absorption, which will reduce the performance of the antenna. The electromagnetic field passing through the human body depends on the thickness and exact composition of biological tissues.

As previously stated in the simulation of the different deeps in the different layer tissue models, the S-parameters are shifted as we go deeper into the layers (from skin to muscle). The results depend on the thickness, the dimensions, and the values of the properties of each layer (like the muscle has a high value of permittivity).

### Conclusion

This paper presents the proposed antenna with two different metamaterial resonators, the first one with four E-shapes resonators and the second with E-interdigital resonators. Due to the use of a high-dielectric substrate/superstrate, shorting pin, and MTM resonators, the proposed antennas have reached the size of $8 \times 7 \times 1.27$ mm$^3$, operating at 2.45 GHz for ISM bands. The two proposed antennas are simulated in free space, one-layer and

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**Table 7** Simulated SAR in 1 g and 10 g of skin tissue for 1 W

| Mass of tissue | SAR (W/kg) | SAR (W/kg) |
|---------------|------------|------------|
| 1 g-Avrg      | 760        | 10 g-Avrg  |
| Four E-shape  | 758        | 80.9       |
| E-interdigital| 758        | 80.5       |
three-layer tissue models. The simulation results are reasonable and we show small differences in the results. The gain value of the proposed antennas is reduced from the free space to the human body because of the lossy nature. The SAR values are simulated in the skin tissue, and these values are acceptable by IEEE C95.1: 1999 regulation. The proposed antennas present good performance in the presence of human body models that are suitable for biomedical applications.

Funding  This work was financially supported by the Directorate General of Scientific Research and Technological Development (DGRSDT) under the authority of the Ministry of higher education and scientific research MESRS.

Table 8 Comparison of the proposed antenna with some works in literature

|                  | Ref                | Freq (GHz) | Size (mm²) | Gain (dBi) | SAR (W/kg) |
|------------------|--------------------|------------|------------|------------|------------|
|                  | (Zada et al. 2019) | 2.45       | 7 × 6 × 0.256 | −9.81      | 524.3      |
|                  | (Wang et al. 2020) | 0.92       | 58 × 40 × 0.8 | −34        | 881.5      |
|                  | (Faisal et al. 2019) | 2.45       | 12 × 12 × 0.635 | −22.29    | 591.40     |
| This work        | 4-E                | 2.45       | 8 × 7 × 0.635 | −25.3      | 758        |
|                  | E-inter            | //         | //          | −25        | 751        |

4-E: four E-shape resonators
E-inter: E-interdigital

Table 9 Comparison of the proposed antenna with the two MTM resonators

|                  | E-shape | E-interdigital |
|------------------|---------|----------------|
|                  | One-L   | Three-L        | One-L | Three-L |
| S11 (dB)         | −37.96  | −22.01         | −33.34 | −21.18 |
| Gain (dB)        | −25.45  | −28.29         | −25.09 | −28.04 |
| BW (MHz)         | 94.20   | 100            | 93.30  | 100     |
| SAR              | 1 g     | 1.52           | /      | 1.51    |
|                  | 10 g    | 0.16           | /      | 0.16    |

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