A Novel Design Reconfigurable Antenna Based on the Metamaterial for Wearable Applications

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Abstract. A novel design of wearable antenna depending on metamaterials inspired-fractal Minkowski-shaped for industrial, scientific, and medical (ISM) applications is presented. The antenna consists of a conventional monopole and a Chebyshev transformer coupled with a unit cell of a fractal Minkowski curve to obtain three bands covering the ISM and Wireless Local Area Network (WLAN) applications. To enhance the antenna performance, the authors proposed the Electromagnetic Band Gap (EBG) layer of 3×4 array is introduced into the design structure. The authors used material FR4 dielectric as a substrate to design the antenna with dimensions of 51mm x 45mm x 1.6mm and fed by a 50 Ω port. The Antenna performance is analyzed numerically using CST Microwave Studio (CSTMS) depending the Finite Integral Technique (FIT). Various investigation analyses have carried out to verify optimum antenna performance. The proposed antenna realizes reconfiguration by using the PIN diode. In both cases (switching= ON, OFF) the antenna achieves good bandwidth, |S11|<-10dB, and excellent impedance matching.

1. Introduction
With the recent growth in microwave systems, more advanced materials in electromagnetic field applications are demanded. The emergence and development of the concept of "metamaterials" throughout the year led to a revolution and received great interest from researchers [1]. Metamaterial (MTM) is artificial composite materials that have been engineered in precise shape to give it smart properties have the ability to manipulate electromagnetic waves by enhancing, bending, absorbing or blocking waves, to achieve benefits unavailable in natural materials [2]. MTM structures have introduced in various antenna applications including defective ground planes, frequency selective surfaces, artificial magnetic conductors, and perfect lenses [3], to obtain a low profile, higher isolation, SAR Reduction, gain enhancement, improved radiation performance, and unidirectional antenna [4-8]. Moreover, MTMs possess unique features such as high absorbency capacity, distinctive stopbands, surface wave reduction, and negative effective constitutive parameters [9-12]. The antennas can be used for medical implants and in-vivo communication [32-36].

In the past, researchers have developed many articles [13-22] focusing on the different types of wearable antennas. In [13], the authors design a fractal Minkowski-shaped antenna based on the metamaterial for blood glucose test, the antenna consists of a four-unit cell from the Minkowski open-loop (MOL), coupled with an open-stub transmission line (OSTL) to increase the impedance matching and achieve the resonance frequency at 2.45GHz. In [14] the structure of fractal antenna has a significant role in applications of wave polarization through changing the direction of the transmission...
line of a meta-surface structure to achieve two different characteristics of polarization, circular polarization at 1.5 GHz and linear polarization at 2.45 GHz. In [15] the authors offered a manner to evaluate the performance of a handset's open-loop capacity in MIMO systems using Coefficient of Variation (CoV) at 2.45GHz. However, the antenna bandwidth in previous literature has extremely narrow. A flexible wearable antenna triangular-shaped based on Koch fractal geometry has designed for (WBAN) applications [16], however, the antenna covers only the band of range 2.36–2.55 GHz, and the radiation efficiency only 75%. In [17], the authors offered meandered structure wearable antenna printed on a polydimethylsiloxane (PDMS) flexible substrate for WBAN applications, however, the bandwidth is only 4% at resonant frequency 2.45 GHz. in [18], the authors introduced a wearable fractal antenna based on Koch structure backed with (EBG) layer of 2 x 2 array has designed for communications devices applications, however, large antenna dimensions are not suitable for utilizing in a compact environment, also, the bandwidth only 50MHz. The authors in [19] designed a compact wearable antenna reconfigurable suitable for smart glasses. The antenna operates at 2.4 GHz ISM band, using four PIN diodes reconfiguration is achieved, however, the antenna gain did not exceed 1.5 dBi and the efficiency of only 40%. The authors use a metamaterial-inspired Hilbert-shaped structure with EBG for MIMO applications, which is offered in [20], however, the boresight gain of only 2.1dBi at 2.45 GHz. in [21], the dual-band antenna consists of a traditional monopole with EBG array printed on the dielectric substrate Roger 3006 for GSM and Wi-Max applications. The antenna realized resonant frequency of 1.85 and 3.3 GHz, however, the radiation efficiency only 53.6% and 78% respectively. The authors of [22] presented a microstrip patch antenna square-shaped with a EBG layer 3 × 3 placed on FR4 dielectric substrate and full ground plane from copper for WLAN applications, however, bandwidth only 6.3 % at 5.88 GHz and weakness of aperture efficiency 38.8%, also, antenna size is 85 x 85 x 1.55 mm³ is not suitable for utilizing in a compact environment.

A critical issue in designing a wearable antenna is the choice of substrate material [23]. It is recommended that the substrate should be a low-loss material in order to increase the antenna performance with gain enhancement when used vicinity of the body. Due to the narrow bandwidth that is determined by the thickness of the substrate, Microstrip antennas are not favorable for applications demanding a high level of rolling, pressure, and bending [24]. Moreover, the human tissues are a high permittivity, dispersive material, and extremely lossy, when the human body is exposed to EM waves that radiate from patch antenna, the human tissues absorb amount of energy. Therefore, the wearable antenna performance are noticeably decreased by operates the antenna near of human body [25], which causes a deterioration of the wireless communication field. Also, the EM power absorbed by the human body have undesirable environmental and biological impacts [26].

In this article, the authors present a novel structure reconfigurable wearable antenna based on the metamaterial with radiation pattern end-fire at 2.4 GHz ISM band. The proposed antenna is consists of a traditional monopole coupled with a unit cell of a fractal Minkowski curve to generate three bands frequency spectra to cover different application bands. The proposed design realized a steerable radiation pattern in the frequency range from 2.32 to 2.82 GHz. The proposed antenna achieved reconfigurable by using a PIN diode. When the switch is turned ON, the ISM band is blocked, and the proposed antenna works at two bands 2.7 and 3.4GHz, while in the off mode, the antenna operates in three bands 2.4, 2.7, and 3.4GHz. The antenna was designed and analyzed using CST MWS.

The paper is arranged as follows: the proposed design structure and antenna geometry are presented in Section 2. The unit cell is analyzed and offers its characteristics in Section 3. In Section 4, the design methodology is explained in detail. Simulation results are provided and discussed in Section 5. Finally, a conclusion is presented in Section 6.

2. Antenna geometry

The proposed antenna is constructed from a traditional monopole and a fractal Minkowski-shaped with a Chebyshev transformer. The monopole antenna is fed by 50 Ω port that is located between the monopole conductor and right CPW side, see Figure 1, to keep the directivity toward a certain direction. This is considered to maintain the antenna radiation away from the human body which is a desirable requirement in the wearable applications [18, 19, 20, 21]. The other side of the other side of
the CPW is constructed as a Chebyshev transformer to improve the impedance matching as well as to enhance the antenna bandwidth. The proposed Chebyshev transformer is an impedance matching circuit that is constructed from 4 stages to maintain different impedances over a wide frequency bands. Now, to ensure the monopole directivity away from human body, the authors proposed an EBG layer of 3×4 array. Moreover, the proposed EBG layer is conducted to enhance the antenna gain [4, 6, 8, 22, 28], the quality factor [4], and the number of resonances in the frequency band of interest because the fractal geometry [7, 12]. Therefore, the proposed EBG is consistent of the Minkowski-shaped fractal unit cell of the 3rd order. The dimensions of the individual unit cell in terms of outer area is 8.5 x 8.5 mm² with separation distance between each consecutives is 0.5mm. The proposed EBG layer is placed at 2.5mm distance from the monopole edge to maintain a frequency band from 2.32GHz up to 2.82GHz.

The antenna substrate is considered as an FR4 layer with 1.6mm thickness. The antenna metal is printed on a single side from the substrate and the other side has be left without metallization as seen in Fig. 1. All dimensions are measured in millimetres (mm).

Figure 1. The antenna geometrical: (a) front view, (b) back view, and (c) side view, (d) unit cell structure
Table 1. Dimensions of the proposed antenna.

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| L         | 51         | Wm        | 4          |
| W         | 45         | W1        | 9.5        |
| h         | 1.6        | W2        | 7.7        |
| Lf        | 10         | W3        | 5.9        |
| Lc        | 14         | W4        | 4.1        |
| Wc        | 28.42      |           |            |

3. EBG Layer Characterizations
In this part, a single unit cell structure of the proposed antenna has examined. The unit cell is made of copper printed on a substrate thickness of 1.6mm. The unit cell is placed inside the waveguide, port on the right side, and another port on the left side to evaluate the S parameters (S12 and S11) and obtain the maximum (S11) and the minimum (S21) at the same time. CST MW package was used in the analysis and simulation of a unit cell. It was found that the unit cell operates at a frequency of 2.45 GHz as shown in Figure 2.

![Figure 2. S-parameters characterization](image)

4. Design Methodology
In this section, a numerical study based on an intensive parametric analysis is conducted by CST MWS [30]. In the proposed parametric study, the performance of the antenna in terms of radiation patterns, boresight gain, and S11 spectra are monitored to arrive the optimal design performance. Therefore, the antenna dimension parameters are swept to maintain two criteria: The first is to obtain three frequency bands around 2.4, 2.7, and 3.4GHz, for ISM band, WLAN, 5G, and IoT applications in portable systems. Then, the second criteria is to keep the antenna radiation away from the human body in specific of the SAR effects reductions on the human tissues. For this, the parametric study is conducted by changing the antenna parameters as following:

4.1. Monopole antenna design
The authors decided to investigate the stages of the proposed antenna formation. The antenna performance was checked with a conventional monopole and then developed the proposed design by introducing the Transformer into the antenna structure. It was found that the performance of the proposed antenna improved in terms of impedance matching and bandwidth and shift the center frequency towards 2.45 GHz. This is due to the high impedance of the Transformer. In order to
improve the parameters of the proposed antenna, the EBG structure has been introduced in the antenna structure. It has been observed that the EBG structure has a significant influence on antenna performance. This improvement is attributed to the reduction of the mutual coupling and surface waves due to the increase in the antenna impedance. As shown in Fig. 3 (a). On the other hand, the proposed design realized three bands at 2.4, 2.7, and 3.4 GHz, which increases the antenna operating range in wireless communication applications.

Now, the investigation study is applied to the proposed monopole length (L) and width (w) to realize their influence on the antenna performance. It is found that the monopole length plays a significant role in antenna performance, therefore, four different monopole lengths are examined, starting from (L = 51mm) to (L = 45 mm) with a step (2 mm) while keeping the other dimensions of the antenna to limit their impact on the performance of the antenna. Fig. 3 (b) presents the effects of the length change on the S11 spectra. It is observed from the results of the analysis in Fig. 3 (b) by reducing L, the antenna parameters such as bandwidth, resonant frequency, and impedance matching decrease, however, to obtain optimum condition and enhance resonance frequency and impedance matching as well as gain and efficiency in the three bands by tuning L at 51 mm.

![Figure 3](image)

**Figure 3.** (a) Effect of introducing Transformer and EBG structures on antenna design, (b) impact of changing the Monopole length on antenna design.

The Monopole width or length has a significant effect on antenna parameters [21], [37]. Therefore, the authors focus on studying varying of monopole width and effects on the antenna design in terms of, impedance matching, bandwidth, and gain. Therefore, we variated monopole width W from (5 to 3) mm by a step of (1mm), while keeping the other dimensions of the antenna to cancellate their influence on the antenna behavior. Fig. 4 offers the impacts of changing monopole width on the S11 spectra. From the results obtained, a variation in resonant frequency, impedance matching, and bandwidth in the three bands was found due to variation in the monopole impedance and the increase
in the mutual coupling between the antenna elements and, consequently, the desired enhance in monopole impedance, as well as the improvement of the antenna performance in the three bands, was achieved by setting W at 4 mm.

4.2. **CPW location effects**

In this part, we examined the impacts of changing the right-wing length on the antenna parameters. Therefore, four lengths have examined starting from (12 to 15) mm in a step of 1 mm, while respect the other antenna dimensions to cancel their influence on the antenna design. Fig. 5 displays the effect of the L change on the S11 spectra. The results of the investigation show that changing the CPW length directly affects the performance of the antenna, by increasing or decreasing the length L the resonant frequency is shifted as well as impedance matching was reduced due to the fringing from substrate edge [21], therefore to obtain the optimum condition in terms of impedance matching, bandwidth, and resonant frequency of the three bands when tuning L at 14 mm.

4.3. **Chebyshev transformer design**

In this part, the authors analyzed the effect of the Chebyshev transformer on antenna performance. It was found that the transformer has a positive effect on the performance of the antenna parameters. Fig. 6 (a) offers the impacts of the Chebyshev transformer on the antenna design. It is worth noting that introducing the Chebyshev transformer has a significant effect on the antenna parameters, therefore, the bandwidth and impedance matching significantly improved, furthermore, the antenna covered the entire ISM band due to the appearance of a resonant frequency at 2.4GHz. It is attributed that increased the antenna impedance and reduce mutual coupling [10]. Also, the authors examined the transformer configuration stages and their effects on the antenna behavior such as S11. The antenna performance was inspected with regard to adding four cases, starting in ascending order from the first
to the fourth cases, while keeping the other dimensions of the antenna to limit their impact on the antenna performance. Fig. 6 (b) offers the Influence of transformer inserting phases on the S11 spectra.

It was found that the optimum condition in terms of matching the impedance, bandwidth, and resonant frequency by adding the fourth case, which improves the antenna impedance then enhances the antenna performance, as in Fig. 6 (b).

![S-Parameters](image)

**Figure 6.** Transformer effect: (a) the impact of the transformer on the proposed antenna and (b) impact of transformer configuration stages on the antenna design.

### 4.4. Antenna performance based EBG layer

In this section, we decided to conduct a parametric study on antenna design in order to recognize the antenna performance without unit cell introduction. The results of a study concluded that the proposed antenna achieved good results with excellent matching in terms of resonant frequency at 2.45 GHz and bandwidth of 25.47% from (2.38_3) GHz, |S_{11}| < -10 dB, also, the maximum gain of 2.74 dBi and the antenna efficiency of 80%, see Figure 7 the proposed antenna without EBG. Also, the direction of the antenna radiation emitting from the patch is keeping away from the human body in specific of the SAR effects reductions on the human tissues. Table 2. The effect of inserting EBG on the performance of the proposed antenna.

On the other hand, after the introduction of EBG structures, it has observed a significant effect on antenna performance [22], where three frequency bands appeared at 2.4, 2.7, and 3.4 GHz, which increased the antenna operating ranges in wireless communication systems. Also, a significant improvement in the gain, efficiency, and directivity of the radiation pattern of the proposed antenna, as in Table 3.
MTM structure plays an important role in improving the antenna parameters [6], therefore, in order to recognize the benefits of introducing a cell unit to the performance of the antenna, the authors in this work conducted a parametric study focusing on the use of MTM structure in the design of the proposed antenna, the unit cell contains an electromagnetic bandgap (EBG), number of these gaps and their influence on antenna behavior has investigated in this section. Moreover, the authors examined the effects of 1, 2, 3, 4 rows, and 3 columns of the unit cell printed on the same substrate surface and located 2.5mm from the monopole edge. Due to the restriction of the substrate boundaries, the number of unit cell structures used in the proposed antenna design is four rows and three columns. Results: The use of the unit cell structure leads to enhance the performance antenna in terms of gain, efficiency, and operating range, which is attributed to the decrease in mutual coupling due to the high impedance in the unit cell thus the surface waves are reduced. Furthermore, it is found that the impedance matching has been improved by adding four arrays, see Figure 8. Because reflecting energy from the EBG structure toward the monopole antenna [12]. From the above discussion, the authors conclude that the antenna realized the required performance by using a 3x4 array of unit cell structures. Table 2 shows the effect of EBG on the proposed design.
Table 2. The effect of inserting EBG on the performance of the proposed antenna.

| Parameters       | Without EBG | With EBG |
|------------------|-------------|----------|
|                 | f1  | f2  | f1  | f2  | f3  |
| Frequency (GHz)  | 2.45 | 2.7  | 2.4 | 2.7 | 3.4 |
| Bandwidth (MHz)  | 620  |       | 500 | 80 |     |
| Gain (dBi)       | 2.74 | 2.61 | 4.93 | 5 | 1.5 |
| Antenna efficiency % | 80.6 | 95.5 | 93 | 93.8 | 60.3 |

After investigating the effect of metamaterial on antenna performance, we decided to examine the influence of the distance between monopole and unit cell arrays in terms of resonant frequency, bandwidth, and matching impedance on the behavior of the proposed antenna. Therefore, the distance (m) has changed from 2.5mm to 4.5mm with a step of 1 mm while keeping the other antenna dimensions to cancel their influence on the antenna design. From Fig. 9, it is found that the distance between the unit cell and the monopole has a significant effect on the S11 spectra, due to the effects of mutual coupling and the surface waves that decrease when the distance between the unit cell structure and the monopole edge small [20]. We point that the ideal state in terms of resonant frequency, impedance matching, and bandwidth when set distance (m) to 2.5mm.

Figure 9. Distance impact between unit cell structure and Monopole on S11 spectra.

4.5. Effect of a PIN diode on antenna performance

After analyzing the antenna performance to obtain the optimum condition of the design, now in this section, the authors have attempted to controllable the behavior of the proposed antenna by inserting a PIN diode into the lower edge between the monopole and the transformer. Using a PIN diode, the proposed antenna achieved the potential of reconfiguring the radiation pattern by blocking the ISM band frequencies (PIN diode ON) while maintaining $|S_{11}| < -10$dB and resonant frequency at two bands 2.7, 3.4 GHz, with an impedance bandwidth of 330 MHz (2.83 – 2.5GHz), 80MHz (3.346_3.4264GHz) respectively. Figure 10 presents the influence of PIN diode on S11 spectra. Lumped elements values were set and simulated using the CST MWS package, as shown in Table 3. Also, in the case of PIN diode (SW OFF), it was found that the performance of the proposed antenna has improved in terms of bandwidth, gain, and efficiency at two modes 2.4 and 2.7 GHz with maintaining the resonant frequency at 3.4GHz. This is due to the good insulation between the antenna.
elements and the PIN diode position, which plays an important role in reconfigurable the antennas [31]. Therefore, the antenna has achieved an impedance bandwidth of 500 MHz (2.32 - 2.82GHz) at 2.4GHz and radiation efficiency at the two modes (2.4, 2.7 GHz) of 96.2% and 94.2% respectively. This improvement is attributed to the increase in the impedance of the proposed antenna due to the decrease in the mutual coupling between the antenna and the transformer [10, 29]. Table 4 offers the effect of introducing the PIN diode on antenna performance.

The proposed antenna has a wide range and high efficiency, which makes it suitable for work in wireless communication systems applications, such as WBAN, Bluetooth, and WLAN.

Table 3. Lumped elements values.

| PIN diode status | Resistor (R) | Inductor (L)   | Capacitor (C) |
|------------------|-------------|----------------|---------------|
| ON               | 3Ω          | 2.6×10^-13H    | 0F            |
| OFF              | 20KΩ        | 0H             | 40pF          |

Table 4. Simulated the effect of the PIN diode on the antenna parameters.

| Antenna condition | Frequency (GHz) | $|s_{11}|$ (dB) | Bandwidth (MHz) | Gain (dBi) | Efficiency % |
|-------------------|-----------------|-------------|-----------------|------------|--------------|
| Without PIN diode | 2.4             | -19.38      | 470             | 4.73       | 87.63        |
| PIN diode (SW)    | 2.7             | -45.11      |                 | 4.85       | 92.21        |
| ON                | 3.4             | -16         | 80              | 1.5        | 60           |
| PIN diode (SW)    | 2.7             | -38.5       | 330             | 4.6        | 93.22        |
| ON                | 3.4             | -15.5       | 80              | 1.5        | 61.1         |
| PIN diode (SW)    | 2.4             | -18.3       | 500             | 4.93       | 92.87        |
| OFF               | 2.69            | -38.8       |                 | 5          | 93.87        |
|                   | 3.4             | -15.5       | 80              | 1.48       | 60.3         |

5. RESULTS AND DISCUSSION
In this section, the proposed antenna simulation results are presented in terms of radiation pattern, reflection coefficient, impedance bandwidth, efficiency, and gain. CST MWS package was used to simulate the antenna. Figure 10 shows the effect of introducing the PIN diode on the antenna designed in terms of impedance bandwidth and reflection coefficients under the PIN diode ON and OFF...
In the case of the (SW ON), the ISM band is isolated and the antenna covers two bands, the first, in Wi-Fi bands (2.5 - 2.83 GHz) with a center frequency of 2.7 GHz and an impedance bandwidth of 12.2%, and the second in WLAN bands with a resonant frequency at 3.4GHz. In the case (SW OFF), the proposed antenna operates in three bands 2.4, 2.7, and 3.4GHz, covering ranges (2.32 -2.82 GHz), (3.346-3.4264GHz) respectively. In both cases (switching ON and OFF) the proposed antenna achieved acceptable performance compared to previous related literature as shown in Table 5.

Figure 11 shows the radiation patterns of the designed antenna. The radiation patterns are evaluated based on E-plane (Phi = 0), and H-plane (Phi = 90) at (SW ON and OFF). The radiation patterns of the proposed antenna are found at (Phi = 0) and (Phi = 90) in the desired direction away from the human body, therefore electromagnetic waves travel in specific directions, thus reducing the specific absorption rate (SAR) and their effects on human tissues.

In the case of (SW ON), the proposed antenna realized a gain of 4.6 and 1.5 dBi at 2.7, 3.4 GHz with an efficiency of 93.2%, 61.1% respectively, while in the case of (SW OFF) the gain of the antenna reached 4.93, 5, and 1.48 dBi with an efficiency of 92.8%, 93.8%, 60.3% at three bands 2.4, 2.7, and 3.4 GHz, as in Figure 12. The improvement of the antenna gain is attributed to the role of EBG structure in reducing surface waves and the mutual coupling between the antenna elements.

The surface current distributions of the designed antenna are investigated. Therefore, it is observed that in the case of PIN diode switching ON at 2.7 and 3.4GHz, the surface current is concentrated at the lower edge of the monopole and moves towards the CPW structure, however, by switching OFF at 2.4, 2.7, and 3.4GHz, the surface current moves towards the transformer as seen in Figure 13.

| Reference | Dimension (mm²) | Frequency (GHz) | BW (MHz) | Boresight gain (dBi) | Radiation efficiency % | Radiation pattern |
|-----------|-----------------|-----------------|----------|----------------------|------------------------|------------------|
| [16]      | 39 x 39         | 2.45            | 190      | 2.06                 | 75                     | Omnidirectional  |
| [17]      | 33 x 30         | 2.45            | 100      | 2.76                 | 92                     | Omnidirectional  |
| [18]      | 83 x 83         | 2.38            | 50       | 7.8                  | 85                     | Almost Endfire   |
| [19]      | 35 x 35         | 2.4             | 120      | 1.9                  | 40                     | Omnidirectional  |
| [20]      | 40 x 50         | 2.45            | 300      | 2.1                  | 91                     | Broadside        |
| [21]      | 50 x 30         | 1.85, 3.3       | 221,201  | 2.88, 5.8            | 53, 78                 | End-Fire         |
| [22]      | 85x85           | 5.8             | 370      | 11.2                 | N                      | Omnidirectional  |
| [27]      | 280 x280        | 2.45            | 70       | 11                   | 88                     | Broadside        |
| [28]      | 240x240         | 2.45            | 50       | 13.4                 | N                      | Broadside        |
| [29]      | 95 x 50         | 2.45,5.8        | N        | 2.1,3.1              | N                      | Broadside        |
| Proposed  | 51x45           | 2.45,2.7,3.4    | 500,80   | 4.93, 5, 1.5         | 96.2,94.2, 63          | End-Fire         |
Figure 11. Simulated E-plane and H-plane radiation patterns of the proposed antenna: (a), (b), (c), (d) when PIN diode ON, while (e), (f), (g), (h), (i), (j) when PIN diode OFF.

(a)
Figure 12. Simulated 3D radiation patterns of the proposed antenna: (a) PIN diode SW=ON (2.7GHz, 3.4GHz), while (b) PIN diode SW=OFF (2.4GHz, 2.7GHz, and 3.4GHz)

Figure 13. Current distribution of the proposed antenna: (a), (b), (c) PIN diode SW=OFF (2.4, 2.7, and 3.4GHz) respectively, while (d) and (e) PIN diode SW=ON (2.7 and 3.4GHz).

6. Conclusion
A novel wearable reconfigurable antenna based on the metamaterial has been introduced for Wireless Body Area Network (WBAN) and WLAN applications. The antenna structure has been developed by introducing the Chebyshev Transformer in order to increase bandwidth and improve impedance matching. Antenna performance is improved by inserting the EBG structure array in the design of the proposed antenna. Several parametric studies were performed to obtain the optimum design using the CST Microwave Studio package. The proposed antenna is printed on an inexpensive and available
FR4 dielectric substrate in 51x 45 x1.6 mm$^3$ dimensions and fed to port 50-ohm SAM. The antenna achieved reconfiguration by introduced a PIN diode into the lower edge between the Transformer and the Monopole. The proposed antenna achieved good results and the end-fire radiation pattern in both cases (SW= ON, OFF). The antenna performance has compared with previous work. It was found that the performance of the proposed antenna is good and suitable for wearable applications.

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References

[1] M. R. I. Faruque, M. T. Islam, and N. Misran, “Design analysis of new metamaterial for EM absorption reduction,” Progress in Electromagnetics Research, vol. 124, pp. 119–135, 2012, doi:10.2528/PIER11112301.
[2] H. Nakano, Low-Profile Natural and Metamaterial Antennas, Hoboken, NJ, USA:Wiley, 2016.
[3] Engheta, N., & Ziolkowski, R. W. (2007). Electromagnetic metamaterials: Physics and engineering explorations. New York: Wiley.
[4] B.Hazarika, B.Basu, and A.Nandi, “Design of Dual-Band Conformal AMC Integrated Antenna for SAR Reduction in WBAN,” Progress In Electromagnetics Research C, Vol. 110, 91-102, 2021, doi:10.2528/PIERC20121202.
[5] Ayd, A. and R. Rad, “Low-profile MIMO antenna arrays with left-handed metamaterial structures for multiband operation,” Progress In Electromagnetics Research M, Vol. 89, 1–11, 2020, doi:10.2528/PIERM19112608.
[6] Moreira, E. C., R. O. Martins, B. M. S. Ribeiro, and A. S. B. Sombra, “A novel gain-enhanced antenna with metamaterial planar lens for long-range UHF RFID applications,” Progress In Electromagnetics Research B, Vol. 85, 143–161, 2019, doi:10.2528/PIERB19081501.
[7] Misra, P., S. S. Pattnaik, “Metamaterial loaded fractal based interdigital capacitor antenna for communication systems,” Progress In Electromagnetics Research M, Vol. 70, 127-134, 2018, doi:10.2528/PIERM18032801.
[8] Alnaiemy, Y. and, Lajos, N.”Further Investigation of The Feasibility of Using EBG Structure-Based Microstrip Antenna for Gain Enhancement,” IEEE International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET), 18-20 Nov. 2020, Indonesia, DOI: 10.1109/ICRAMET51080.2020.9298613.
[9] Hasar UC, Buldu G, Kaya Y, Ozturk G, “Determination of Effective Constitutive Parameters of Inhomogeneous Metamaterials with Biaisotropy,” IEEE Trans Microw Theory Tech, Volume: 66, Issue: 8, Aug. 2018, DOI: 10.1109/TMTT.2018.2846726.
[10] Jafargholi A, Jafargholi A, Choi JH, “Mutual Coupling Reduction in an Array of Patch Antennas Using CLL Metamaterial Superstrate for MIMO Applications,” IEEE Trans Antennas Propag. Volume: 67, Issue: 1, Jan. 2019, DOI: 10.1109/TAP.2018.2874747.
[11] Liu J, Zhou W, Long Y, “A Simple Technique for Open-Stopband Suppression in Periodic Leaky-Wave Antennas Using Two Nonidentical Elements Per Unit Cell,” IEEE Trans Antennas Propag. Volume: 66, Issue: 6, June 2018, DOI: 10.1109/TAP.2018.2819701.
[12] Al-Sabbagh HM, Elwi TA, Al-Naiemy Y and Al-Rizzo HM, “A compact triple-band metamaterial-inspired antenna for wearable applications,” Microwave and Optical Technology Letters, 04 October 2019.
[13] Obaid S, M Elwi TA, and Ilyas. M, “Fractal Minkowski-Shaped Resonator for Noninvasive Biomedical Measurements: Blood Glucose Test,” Progress In Electromagnetics Research C, Vol. 107, 143-156, 2021, doi:10.2528/PIERC20072603.
[14] Arka B, Amartya B, Sayan C and Bhaskar G, “Dual-Band Minkowski Fractal Patch Antenna with Polarization Diversity,” (2020) IEEE Calcutta Conference (CALCON), 02 June 2020, India.
[15] Al-Wahhamy A, Al-Rizzo HM, and Nicholas E. B., “The Coefficient of Variation as a Performance Metric of MIMO Antenna Systems Under Arbitrary Handset Orientations,” *Progress In Electromagnetics Research C*, Vol. 108, 171-185, 2021, doi:10.2528/PIERC20091603.

[16] Arif A, Zubair M, Ali M, Khan MU and Mehmood MQ., “A Compact, Low-Profile Fractal Antenna for Wearable On-Body WBAN Applications,” *IEEE Antennas and Wireless Propagation Letters*, Volume: 18, Issue: 5, May 2019, DOI: 10.1109/LAWP.2019.2906829.

[17] A T. Zerith M and M. Nesasudha, “A Compact Wearable 2.45 GHz Antenna for WBAN Applications,” IEEE (2020) 5th International Conference on Devices, Circuits and Systems (ICDCS), 23 April 2020, India.

[18] Arif A, Akram MR, Riaz K, Zubair M and Mehmood MQ., “Koch Fractal Based Wearable Antenna Backed with EBG Plane,” (2020) IEEE 17th International Bhurban Conference on Applied Sciences and Technology (IBCAST), Pakistan.

[19] E. Cil and S. Dumanli, “The Design of a Reconfigurable Slot Antenna Printed on Glass for Wearable Applications,” *IEEE Access*, 20 May, 2020, DOI: 10.1109/ACCESS.2020.2996020.

[20] Al-Dulaimi, Z., T. A. Elwi, and D. C. Attila, "Design of a meander line monopole antenna array based hillbert-shaped reject band structure for MIMO applications," *IETE Journal of Research*, Vol. 66, 1-10, 2020. doi:10.1080/03772063.2020.1743207.

[21] Al Naiemy, Y., T. A. Elwi, and L. Nagy, "An end fire printed monopole antenna based on electromagnetic band gap structure," *Automatika*, Vol. 61, No. 3, 482-495, 2020, doi:10.1080/00051144.2020.1785783.

[22] Al Naiemy, Y., and L. Nagy, “Improved Antenna Gain and Efficiency Using Novel EBG Layer,” 2020 IEEE 15th International Conference of System of Systems Engineering (SoSE), 01 July, Hungary, DOI: 10.1109/SoSE50414.2020.9130494.

[23] J. Yoo, L. Yan, S. Lee, H. Kim, and H.-J. Yoo, “A Wearable ECG Acquisition System With Compact Planar-Fashionable Circuit Board- Based Shirt,” IEEE Trans. Inf. Technol. Biomed., vol. 13, no. 6, pp. 897902, 2009.

[24] Khaleel, Haider R., Hussain M. Al-Rizzo, and Ayman I. Abbosh. "Design, fabrication, and testing of flexible antennas.” In Advancement in Microstrip Antennas with Recent Applications. IntechOpen, 2013.

[25] A. Abohmra, S. Ramani, A. Sharif, M. A. Imran, Q. Abbasi, W. Ahmad, “Novel Flexible and Wearable 2.4 GHz Antenna for Body-Centric Applications,” 2019 IEEE Intl Conf on Dependable, 04 November, Japan, DOI: 10.1109/DASC/PiCom/CBDCom/CyberSciTech.2019.00082.

[26] L. Belrhati, F. Riouch, A. Tribak, J. Terhzaz, and A. M. Sanchez, Flexible Antennas Design and Test for Human Body Applications Scenarios, J. Microwaves, Optoelectron. Electromagn. Appl., vol. 16, no. 2, pp. 494513, 2017.

[27] Al Naiemy, Y., T. A. Elwi, and L. Nagy, “Enhancing the Microstrip Antenna Gain Using a Novel EBG Lens Based on a Single Layer,” (2018) IEEE 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP), 27 September, Hungary, DOI: 10.1109/CSNDSP.2018.8471786.

[28] Al Naiemy, Y. and L. Nagy, “Electromagnetic Band Gap Structure for Microstrip Antenna Gain Enhancement at WLAN Band,” 2020 IEEE International RF and Microwave Conference (RFM), 12 February, Malaysia, DOI: 10.1109/RFM50841.2020.9344778.

[29] Y. Alnaiemy, T. A. Elwi, and L. Nagy, “Mutual Coupling Reduction in Patch Antenna Array Based on EBG Structure for MIMO Applications,” Period. Polytech. Electr. Eng. Comput. Sci., vol. 63, no. 4, pp. 332–342, Oct. 2019.

[30] Dassault Systèmes "CST Microwave Studio", [computer program] Available at: http://www.cst.com [Accessed: 11 January 2019.

[31] Y. Alnaiemy, and L. Nagy, “Design of a Controllable Antenna Based on Embedded Differential PSK Modulation,” *Progress In Electromagnetics Research*, Vol. 90, 43-62, 2021. Doi:10.2528/PIERB20100106.
[32] M. Mezher, M. Ilyas, O. Bayat, and Q. H. Abbasi, "Bit Error Rate Performance of In-vivo Radio Channel Using Maximum Likelihood Sequence Estimation," International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 28 August 2020, Istanbul, Turkey.

[33] M. Ilyas, O. Bayat, M. A. Imran, and Q. H. Abbasi, "UltraWideband In Vivo Channel Modelling with Respect to Ex Vivo Antenna Location," 2019 13th European Conference on Antennas and Propagation (EuCAP), Krakow, Poland, 2019, pp. 1-4.

[34] M. Ilyas, O. N. Ucan, O. Bayat, X. Yang, and Q. H. Abbasi, "Mathematical Modeling of Ultra Wideband In Vivo Radio Channel," in IEEE Access, vol. 6, pp. 20848-20854, 2018.

[35] M. Ilyas, O. N. Ucan, O. Bayat, A. A. Nasir, M. A. Imran, A. Alomainy and Q. H. Abbasi, "Evaluation of Ultra-Wideband In-vivo Radio Channel and its Effects on System Performance," in Transactions on Emerging Telecommunications Technologies, Aug 2018.

[36] M. Ilyas, O. Bayat, and Q. H. Abbasi, "Experimental analysis of ultra wideband in vivo radio channel," 2018 26th Signal Processing and Communications Applications Conference (SIU), Izmir, 2018, pp. 1-4.

[37] E. D. Hussein, N. Qasem, M. S. Jameel, M. Ilyas, and O. Bayat, "Performance Optimization of Microstrip Patch Antenna Using Frequency Selective Surfaces for 60 GHz", 2020 28th Signal Processing and Communications Applications Conference (SIU), 2020, pp. 1-4, Gaziantep, Turkey, DOI: 10.1109/SIU49456.2020.9302486.