An Efficient and Robust Antenna Combined with Electromagnetic Band-Gap Structure for Wearable Medical Application

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Abstract. A low-profile and robust inversely E-shaped antenna (IESA) combined with electromagnetic band-gap (EBG) is introduced for wearable medical application at 2.4 GHz. It has an overall size of $46 \times 46 \times 2.4 \text{ mm}^3$. The EBG presented in this research is to isolate the antenna from the body. Thus, the performance of the antenna is not affected by the body. Contrarily, it reveals better performance compared to antenna in free space. The numerical and experiment results show that the integrated design shows good performance under bending and loading the human body. Moreover, the gain and the bandwidth were improved by 7.8 dBi and 27\%, respectively. In addition, the SAR values were complied with standard. The reduction is more than 90.

1. Introduction

As people become more interested in the use of technology in their daily lives, the potential for using wearable wireless devices in multiple areas is rapidly increasing, such as healthcare, sports, child monitoring, military, emergency, consumer electronics, and more. These wearable devices must be small, low-powered and able to connect to a hub or gateway device for access to internet or cloud. Antenna is one of the major components in these wearable devices. It has a direct impact on the size, shape and performance of the system. The physical integration of antennas in this device is a major issue for the designers as they must deal with additional features like safety and regulation constraints [1]-[5].

Human body acts as a large inhomogeneous object with high loss and permittivity which affects the performance of the antenna such as shifting in the resonant frequency, drop in the efficiency, FBR, and gain, increases in the radiation towards the body and the SAR. These affects may vary with the characteristics of fat, skin tissue and muscle with respect to the heating effects of the electric field. The location of an antenna in the body also has major control on the size and shape of antenna [6]-[7].
The major challenge in designing a wearable antenna is the performance of the on-body antenna design should be maintained for various bending condition therefore it may suit the body curvature or body movement. Hence, a flexible substrate that has deformation capability is required [8].

More than a few kinds of design such as, inverted-F antennas, microstrip patch antenna, substrate integrated waveguide antenna, CPW antenna, and cavity-backed antenna [9]-[13] have been studies for their appropriateness as wearable antennas. But these configurations owned some disadvantages such narrow bandwidth, high SAR, large lateral size, low FBR and high back radiation.

In recent years, several works have been carried out to alleviate antenna-human interactions. In line with earlier research, quite a few configurations such as HIS, MTM, EBG, AMC, full ground plane [14]-[18], located under the antenna have been presented to improve antenna performances while decreasing the back radiation towards the body. However, these structures still have disadvantages such as electrically large and poor FBR.

In this paper, we present further findings from a study of a novel fabric antenna incorporated with EBG that was originally outlined in [19]. The overall dimension of the design is 46×46×2.4 mm$^3$. This configuration has the novelty of showing EBG (Suppression of Surface Wave) and AMC (In-phase) that improve the antenna features such as FBR, bandwidth, gain and reduces the SAR levels.

2. Design Methodology

The proposed inversely E-shaped antenna (IESA) was briefly documented in [19]. The structure was formed by introducing a specific slot into the conducting patch. These slots increased the patch current causes the resonant frequency to drop to lower band, which corresponds to a decrement in antenna size. The details of the design and the investigation study of the IESA structure are obviously presented in [11].

![Figure 1. EBG unit cell (a) conventional square patch, (b) Square loop, and (c) Modified square loop](image)

The EBG unit design process was developed based on three stages. It started with conventional square patch that shows an overall dimension of 46.90 x 46.90 x 0.7 mm$^3$ at 0$^\circ$ reflection phase 2.4 GHz. Then, a rectangular cut is introduced in the square patch to form a square loop with an overall dimension of 32×32×0.7 mm$^3$ at 0$^\circ$ reflection phase 2.4 GHz. Both designs only can demonstrate the in-phase feature, because of the absent of via that control the band-gap feature.

![Figure 2. EBG characteristics (a) reflection phase, and (b) Band-gap](image)
It is worth mentioning that, the introduction of via in the design will increase the effective inductance, so four strip lines in the form of a T-shaped are added to the square loop to be equivalent to the via. This will ease the fabrication process compared to exist of via. The final design will consist of square loop with four T-shaped connected as shown in Figure 1. With these four strip lines, the effective inductance is increased demonstrating the features of band-gap and in-phase as well as reduces the area size by 75.95% and 48.34% compared to the conventional square patch and square loop configurations, respectively.

The new modified square loop EBG unit cell was studied by two techniques. The reflection phase that illustrates the feature of in-phase crossing $0^\circ$ at 2.4 GHz which imitative the feature of PMC that is not available in nature. The band-gap that covers from 2.18 GHz to 2.8 GHz which indicates the suppression of surface wave within this range. Figure 2(a) present the reflection phase of the three configurations: conventional square patch, square loop and the new modified square loop while Figure 2(b) illustrates the bandgap feature of new modified square loop.

The new modified square loop was experimentally verified by using suspended transmission line method. The suspended transmission line was placed above 2 x 2 EBG array and connected with two 50-ohm SMA connector as shown in Figure 3(a). The measured transmission coefficients ($S_{21}$) is shown in Figure 3 (b). It can be realized that the covers a band range from 1.92 GHz to 2.67 GHz.

The square loop and the new modified square loop configurations were modelled as equivalent circuit to show the impact of the introducing the four strip lines as depicted in Figure 4. The strip of the square and the strip of T-shapes causes the inductance whereas the gap between the square loop, the neighboring unit cells, and the strip T-shaped causes the capacitance. The values of each components can be determined based on the equations given in [17].
3. EBG and Antenna Fabrication
The IESA is fabricated based on highly flexible fabric material that have a permittivity of 1.7 and a thickness of 0.7 mm. It was located above 2×2 EBG array. A foam was inserted between them to avoid any short circuit. It has a thickness of 1 mm and tangent loss of 0.0003. The incorporated design is shown in Figure 5. The initial studies in [19] reveals that the integrated IESA with new modified square loop configuration in free space, establish a superior performance with a gain of 7.8 dBi (simulated), bandwidth of 27 % (measured), and the FBR of 15.5 dB (measured).

Figure 5. Photo of the fabricated design (a) front view and (b) back view

Figure 6. Bending measurement methodology (a)y-axis,(b) x-axis,(c) y+45° axis, and (d) y-45° axis
4. Further studies

4.1. Deformation Assessment

In many applications, flexible antennas are anticipated to deform or load onto the surface of the human body during operation. Therefore, before investigating the effects of human tissue load, it is necessary to check the performance of the proposed design in a few degrees of structural deformation in free space to confirm its reliability. Four different scenarios performed x-axis, the y-axis, y+45° and y-45° as illustrated in Figure 6. The investigation was conducted with more than a few diameters \((d)\) of 70 mm x 80 mm, 100 mm and 140 mm. These diameters are selected to correspond different sizes of the human legs and arms.

Figure 7 illustrates the experimental results of the four scenarios. It is seen that the shifted resonant frequencies among all scenarios is not more than 30 MHz even at extremely degree of bending. These shifted consider negligible, since all still maintain below -10 dB. In general, \(S_{11}\) and bandwidth are comparable even if the diameters of the cylinders are different. Furthermore, the radiation pattern under deformation of the four scenarios were experimentally conducted at diameter of 140 mm as illustrated in Figure 8. The results were compared with measured normal case (no bending). It is seen that there is no much different between them. A minor reduction of FBR was also observed especially at ±45° this effect could because of the non-ideal uniformity of the bending diameters across the structure as well as the effects of cable during the measurements.

![Figure 7. \(S_{11}\) based on bending (a) y-axis, (b) x-axis, (c) y+45°axis, and (d) y-45°axis](image)

4.2. Effects of Human Tissues Loading

The EBG shield the antenna in this design to immune it from the impact of the body. Therefore, the resonant frequency is not shifting and other performances are maintaining as in the case of free space. To validate this, the design was tested experimentally by placing the design on the arm and thigh model of a volunteer male as illustrated in Figure 9. The results are shown in Figure 9(c). It
demonstrates that the $S_{11}$ is reasonable stable and covers the desired range. This indicates that EBG isolate the antenna from the body that has high neutral dielectric which can affect the antenna performance.

Figure 9. (a) On arm, (b) on thigh, and (c) $S_{11}$ measurement of the integrated antenna with EBG positioned on chest and back of real body

The radiation patterns of the antenna performance alone and with the incorporated EBG were tested and compared with the free space condition. It is realized the body absorb significant power when the antenna placed on the model without EBG compared to the free space as shown in Figure 10. Furthermore, it is seen in the case of adding EBG the absorb power is less as shown in Figure 11. This indicates the usefulness of introducing EBG in antenna design.

Figure 10. Simulated radiation patterns of the antenna alone on arm model (a) E-plane, and (b) H-plane.

Figure 11. Simulated radiation patterns of the antenna with EBG on arm model (a) E-plane, and (b) H-plane.
4.3. SAR Assessment

It is necessary to evaluate the SAR value of the design to ensure the safety level is satisfied with standard. SAR is typically averaged over the entire body or over a small sample volume and is proportional to the conductivity of the radiation-absorbing tissue and inversely proportional to its density. It is expressed as the power absorbed per unit mass of tissue in watts per kilogram (W/Kg). Based on the guideline given by the FCC, the SAR values should be less than 1.6 W/kg averaged over 1 g of human tissues [17], [19].

| Different distances between the design model | Antenna with EBG | Antenna alone |
|-----------------------------------------------|-----------------|---------------|
| 1 mm                                          | 2 mm            | 3 mm          |
| Arm y-axis                                    | 0.037           | 0.023         | 0.02          | 6.19 | 5.36 | 5.26 |
| Arm x-axis                                    | 0.061           | 0.033         | 0.024         | 5.76 | 5.67 | 5.53 |

The SAR values is determined based on IEEE C95.1 standard provided in the CST. The input power was set as 100 mW. A multi-layer model was designed to represent the arm for SAR assessment. The designed model has four layer which muscle, bone, skin, and fat. The model has diameter of 80 mm and 150 mm length. The data and thickness of each layer is taken from [8], [19]. The designed was analyzed with different distance from the model. Figure 12, displays the simulated SAR at 1 mm away from the arm. The result of the antenna alone and with EBG at 2.4 GHz over 10 g is tabulated in Table 1. It shows that when the antenna is alone, the SAR level is greatly exceeding the limits. On the other hand, when the antenna is isolated from the body by using EBG, the SAR levels greatly drop compared to the antenna alone which comply with standards. The drop is more than 90%.

**Figure 12.** SAR values at 1 mm far from the chest model for: (a) Antenna alone along y-axis (b) Antenna with EBG along y-axis, and (c) Antenna with EBG along x-axis (both at 1mm away from the tissue model).
5. CONCLUSION

A robust, fully integrated textile antenna integrated with EBG for wearable medical applications has been designed and experimentally tested. The useful of introducing EBG is to isolate the antenna from the body. Hence the performances of the antenna are improved compared to the case without EBG. Based on the numerical and experimental result, the incorporated design shows superior result. The bandwidth and the gain are improved to 27% and 7.8 dBi. The SAR level of design comply with the standard, it reduced by more than 90%. Furthermore, the radiation towards the body was minimized by 15 dB. These achievements indicate the suitability of the design for wearable medical applications

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