Wide-band Felt Antenna with 6-Cells Electromagnetic Band Gap Jeans Array for Wireless Area Network Applications

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ABSTRACT

This study proposed a 20 mm x 30 mm x 1mm wearable antenna constructed of fabric (felt) substrate, making it the most suitable candidate for wearable applications, and fit for embedding in cloths for use in telemedicine applications. In addition, an electromagnetic band gap (EBG) array comprised of 6 square copper loopsattached to a fabric substrate (jeans) with a slotted ground structure was proposed. The proposed antenna design combined with the EBG array had a total dimension of 60 mm x 60 mm x 2 mm and operated at 2.4 GHz with low specific absorption rate (SAR) of 1.55 watts per kilogram (W/kg) and 0.77 W/kg per 10 g. The simulation and measurement results indicated that the antenna performed better when coupled with the 6-cells EBG array constructed on a substrate different from that of the antenna and featuring slots on the EBG partial ground. This new approach of using a different substrate for the antenna and EBG array significantly increased theantenna's bandwidth from 7.5% to 25 %, that can overcome the problem of frequency shifting and reduced the negative effect of the human body on the performance of the antenna. Furthermore, the partial slotted EBG ground increased the antenna gain from 1.4 dBi to 6.7 dBi. Additionally, the antenna's performance was measured on a real human body arm. The measurement results showed a good agreement with the simulation results, making the proposed design reliable for wearable telemedicine applications.

Keywords: Bandwidth, EBG-Array, Fabric Substrate, Reflection Coefficient, SAR, Wearable Antennas.

1 Introduction

We are now experiencing a rapid development of technology in general and wearable devices in particular, as these devices have become an effective and essential element in our lives, as they have entered the field of medicine and monitoring the health status of the patient, such as checking the level of blood sugar and blood pressure and in tracking applications, and military, etc.

These devices are easy to embed in clothing such as hats or shirts and even in shoes and accessories such as smart watches and bracelets. Wearable antennas used in this type of applications, especially those manufactured for inclusion in smart clothing, have been developed. These antennas can be manufactured from fabrics such as cotton, jeans, polyester and other fabrics used in the clothing industry. However, despite the excellence of wearable antenna with its high flexibility and its ability to adapt to the curves of the human body, the fabrics used in its manufacture have a low dielectric constant, which affects the antenna size inversely. Therefore, wearable antennas face a real challenge in the issue of efficiency, as the manufacture of a high-efficiency, small-sized antenna has become a challenge [1,2,3,4,5]. Since these devices are associated with human activities, they have been designed and developed to be wearable and occasionally embedded in clothing [6,7].

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Numerous techniques have been developed to mitigate the effect on antenna performance, including the use of EBG structures. The EBG structure is a well-known technology that is used in the majority of modern antenna designs. Its benefits include a high level of isolation from the human body [8]. Additionally, the specific absorption rate (SAR) level is reduced significantly to meet International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Federal Communications Commission (FCC) standards [9]. On the other hand, these structures have number of disadvantages, the most significant of which is that they are typically quite thick for Medical Body Area Network (MBAN) Applications [6,9]. Moreover, the main disadvantage of EBG designs is their narrow bandwidth, which results in frequency shifts [10]. This defect is most frequently encountered when the antenna is in contact with the human body. The antenna's radiation is absorbed by the body's tissues, distorting the pattern and reducing the antenna's effectiveness. A large bandwidth is one way to overcome the sensitivity of frequency shifts, as itwill have little effect on the desired band, which will remain within a 10 dB bandwidth. Furthermore, a large amount of bandwidth is required for high data rates and short-range indoor communications [11].

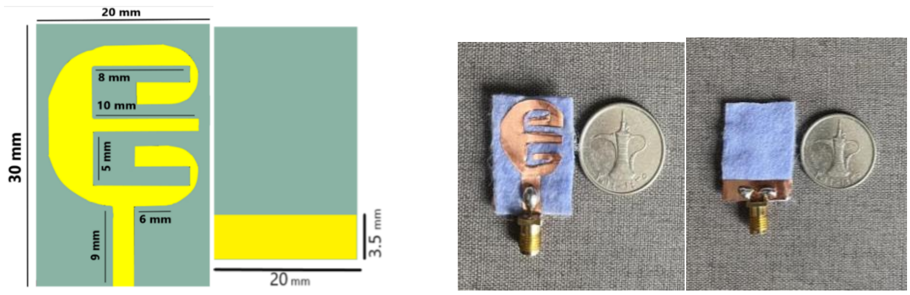
In [12], a defected ground structure (DGS) was etched on the back of an EBG array to overcome the narrow bandwidth of the EBG antenna design. Although this study achieved a wide bandwidth, adding a supported technique like DGS is not an evaluation of the EBG technique itself. This technique still suffers from a narrow bandwidth when attaching it alone to the antennas. Moreover, adding a (DGS) structure to the proposed design increased its sizeand weight. In [13], an E-shaped Microstrip patch antenna using Rogers RT/duroid 5880 substrate. The proposed antenna operated at (90.97/1.6/2.8) GHz with bandwidth (0.22% / 8.5% / 2.49%) respectively. In [14] HFSS 14V software uses to design and simulate E patch antenna at 28 GHz with the FR4 epoxy substrate material. The optimized proposed antenna's results of dual-band and wideband have been resonating at frequencies of 29.12 GHz and 31.35 GHz, and impedance bandwidth 3.2 GHz respectively.

As a result, this study introduced a new approach and distinct substrate into the EBG structure and antenna to overcome the narrow bandwidth with slots on EBG partial ground to enhance the antenna gain for a high-performance antenna. The bandwidth improvement was not made at the expense of any antenna parameter, but rather on the structure of the EBG technique itself, allowing it to operate with wide bandwidth and high performance without the addition of a supported technique.

2 Parametric study of the proposed Antenna and EBG unit cells

A. Antenna Design and parametric study

The antenna was designed with a small size and lightweight in mind, measuring 20 mm x 30 mm x 1 mm. Due to the widespread design of letter-shaped antenna patches, an epsilon-shaped patch of copper material with a thickness of 0.17 mm was attached to a 0.7 mm thick fabric substrate. On the back of the fabric substrate a partial ground with a thickness of 0.17 mm to increase the antenna's gain while maintaining a lightweight antenna. The proposed antenna is depicted in Figure 1, along with the measurements. The antenna was evaluated using various fabric substrates, including felt, jeans, and polyester.



(a) Simulated felt substrate antenna (b) *Manufactured felt substrate antenna*

Figure 1: *Proposed Antenna*

The S11 for the fabric substrates are shown in Figure 2, with the felt substrate providing the best results in terms of wide bandwidth and operating frequency at 2.4 GHz. In that regard, this study aimed to obtain a wide bandwidth frequency for one of the industrial, scientific and medical (ISM) band frequencies. The variation in the feed length had significant effect on line impedance as it varies from 5 mm to10 mm, the line impedance of the proposed antenna was 50 Ohm at 3 mm to present themaximum transfer of the electromagnetic waves. By varying the feed width from 1 mm to 4 mm, the return loss (<-10 dB) is also varying from 2.4 GHz to 5.5 GHz frequencies.

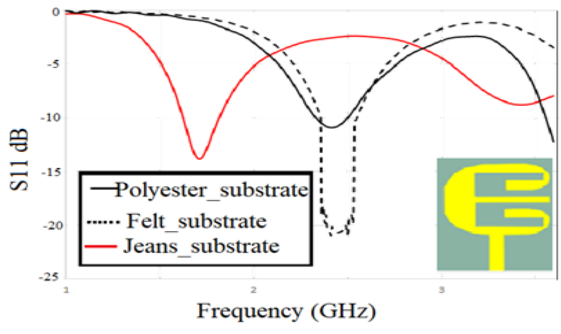
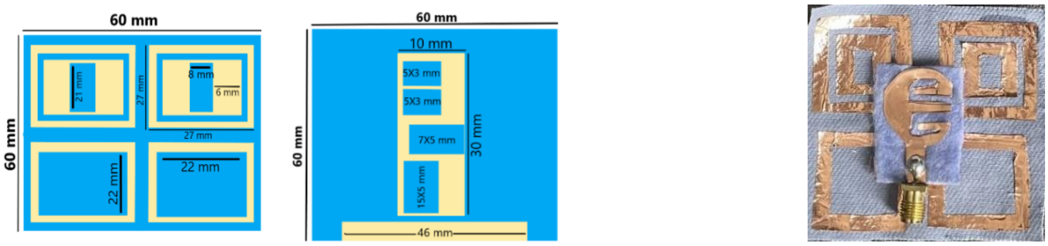


Figure 2: *S11 for the different substrate fabric*

B. EBG Design and Parametric study

In this study, the proposed EBG was designed with easy of fabrication in mind. The square loop is the simplest shape to choose for an EBG array. Figure 3 depicts the EBG array as proposed in this study. The EBG array consistedof 6 square copper loops attached to the jeans substrate and a partial copper ground consisting of two pieces, one vertical and one horizontal, with four slots on the vertical piece. The total EBG array dimension was 60 mm x 60 mm x 1 mm. As described in the following sections, this proposed design was evaluated to determine its effectiveness in expanding the antenna's bandwidth.



(a) Simulated EBG- Jeans substrate array (b)*Manufactured EBG Jeans-substrate array*

Figure 3: *EBG Array*

The specifications for the EBG array were determined by their effect on the operating frequency and bandwidth. The number of EBG cells has a significant impact on the frequency ofthe antenna. This study showed that four and five cells had a negative effect on the frequency, as it shifted to higher frequencies, compared to six cells, which provide a fixed 2.4 GHz frequency as shown in figure 4.

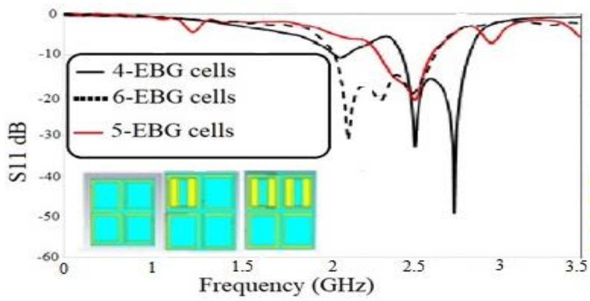


Figure 4:*S 11 antenna over different number of EBG cells*

Additionally, the material of the substrate had a direct effect on the operating frequency, with the felt material having a slightly shifting to the higher frequency as shown in figure 5, and with Polyester substrate the frequency shifted to 1.8 GHz which is not lower frequency, as the jeans substrate showed fixed operating frequency at 2.4 GHz and wider bandwidth. The addition of ground slots increased the antenna gain and maintained the wide bandwidth of the jeans substrate for the EBG array.

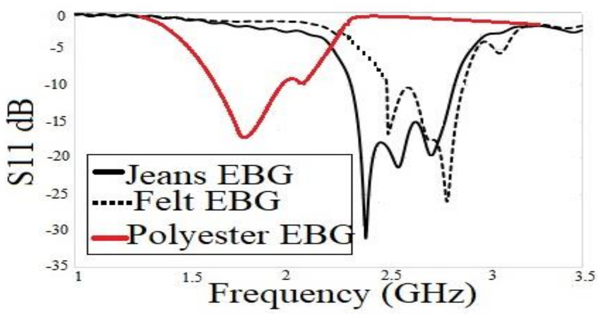


Figure 5: *S11 antenna over different EBG substrate*

3 Antenna Performance over a Different EBG Substrate in Free Space and on human body

The antenna's size must be considered to meetthe requirements of modern devices. Specifically, the antenna's size must be compact and characterized by a wide bandwidth to overcome any sensitivity to resonant frequencies when the antennas are applied to the human body. Therefore, this study proposed a wearable antenna designed of a felt substrate over a 6-EBGcells array designed of jeans substrate and a partial slotted ground. When testing the antenna over the EBG array, a 1 mm layer of foam was used to isolate the EBG array from the antenna, preventing short circuits and minimizing mismatches. The foam had a permittivity (€r) of 1.05 and a conductivity of 0.0003.

Figure 6 shows the S-parameters of the antenna with and without the 6-EBG cells array with jeans substrate. The S11 parameter indicated that the antenna over the EBG-jeans substrate had a wider bandwidth than the antennawithout EBG array.

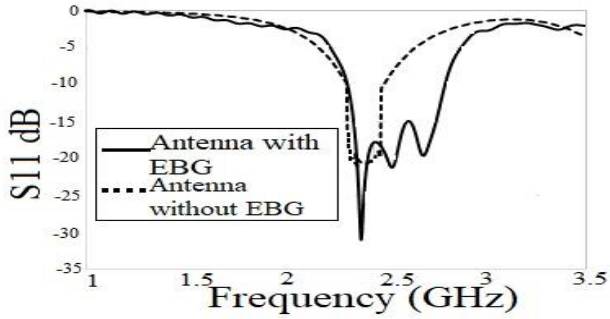


Figure 6: *Antenna S11 with and without EBG array*

Figure 7 illustrates the agreement between measured S-parameter test and simulated results of the antenna over EBG array in free spaces.

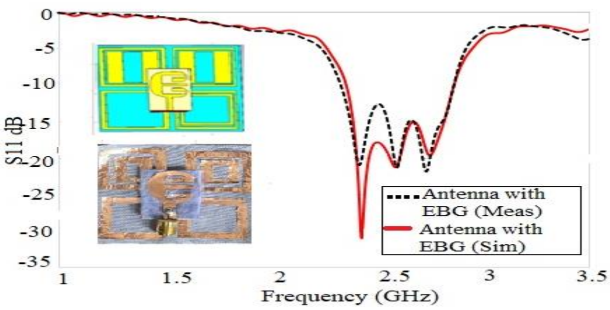


Figure 7: *S11 EBG and Antenna results in free space*

This could be explained by the new approachof using a different substrate for the antenna andthe EBG array and the fact that the EBG array's vertical and horizontal partial ground disrupts theground plane's current distribution. In addition, it could be explained by a decrease in the surfacewave excitation. By reducing surface wave excitation, the Q factor and stored energy decrease, resulting in increased bandwidth [20]. The measured results agree with the simulated results, with slight discrepancies that could be due to fabrication or soldering process. This wider bandwidth is useful in wearable antennas because it ensures that the desired frequency band is covered regardless of frequency shifts caused by human body deformation.

As shown in Figure 8, the S11 results of the antenna with the proposed EBG when placed on a body were compared to prove the effectivenessof introducing the different substrate EBG array with a partial slotted ground in free space. The antenna with the proposed EBG array demonstrated a wide bandwidth sufficient to cover the resonant frequency at 2.4 GHz without shifting and was found to be consistent with the antenna-EBG performance measurements in freespace.

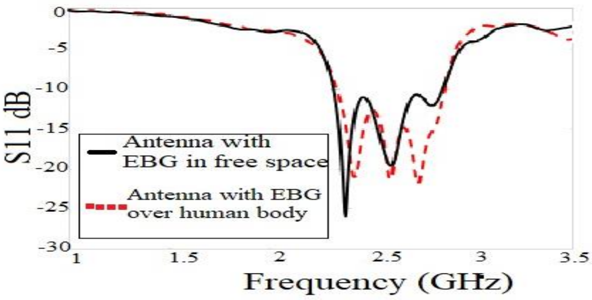


Figure 8: *S11antenna over EBG array on human body (measured result)*

The combination of the antenna and the EBG performed well, indicating that the EBG acted as an insolation layer between the antenna and body. Additionally, by using a different substrate than the antenna, the design bandwidth was increased, making the design more robust acrossall body curvatures. As a result, the antenna over the 6-EBG cells array-jeans substrate with a slotted ground structure is a good candidate for body-worn systems. the measured results agree with the simulated due to fabrication or soldering mistakes.

results, with slight discrepancies that could be

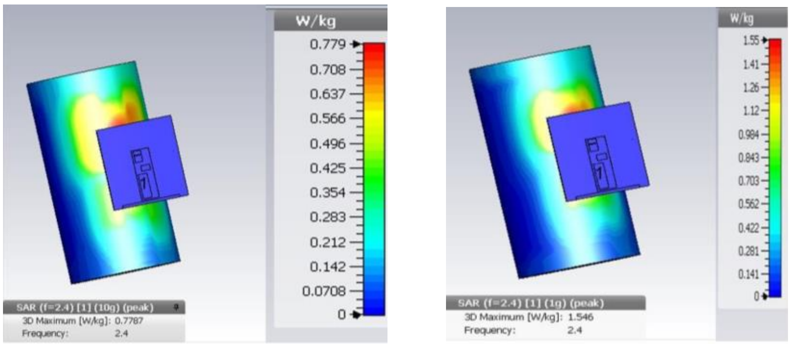
4 SAR evaluation

The arm model was simulated using CST (Computer Simulation Technology) software to evaluate the proposed antenna performance. Four-layer model was designed to mimic the human body. A cylindrical with a diameter of 80 mm and a length of 150 mm was used to represent the arm. Table 1 summarises the four layers of arm model.

Table 1: *Properties of multilayer body tissues [18,19]*

	Fat	Muscle	Bone	Skin
Density (kg/m^3)	900	1006	1008	1001
Permittivity(€r)	5.27	52.67	18.49	37.95
Conductivity (s/m)	0.11	1.77	0.82	1.49
Thickness (mm)	5	20	13	2

The antenna was evaluated at various distances to ensure that it was safe to use on the human bodyin accordance with international standards [18,19]. The scenario of the antenna over the 6-EBG cells array patch facing the model brought SAR valuesbelow the safe level of 1.6 W/kg under the FCC average and 2 W/kg under the ICNIRP average. Results obtained shows that as the designed antenna was moved away from the models, the SAR values decreased dramatically. Figure 9 shows the SAR values at 10 mm away from the model over 1 g average tissue and over 10 g of tissue, while Table 2 summarises all the distance results.



(a) SAR for 10 grams (b) SAR for 1 gram

Figure 9: *SAR evaluation*

Table 2: *SAR test evaluation*

Distance between antenna and arm model (mm)						
	0	2	4	6	8	10
SAR (1g)	6.4	4.8	2.8	1.8	1.68	1.55
SAR (10g)	3.1	2.7	1.7	1.4	0.95	0.779

5 Conclusion

A wearable epsilon-patch antenna with a felt substrate over a 6-EBG cells jeans substrate wasproposed for telemedicine applications operatingat 2.4 GHz. The design was validated in free space and on a human body. The proposed design' effectiveness was demonstrated through standard antenna evaluation methods: free spaceand human body testing. In comparison to the 6-EBG cells on a felt substrate, the antenna over the6-EBG cells on jeans substrate demonstrated better performance and wider bandwidth. Furthermore, the results in free space and on thehuman body were satisfactory and in great agreement with those obtained from simulations.The human body test demonstrated high performance, with a bandwidth of 21% and a gain of 6.7 dBi. The results demonstrated that the proposed felt substrate antenna over 6-EBG cells-jeans substrate was capable of mitigating the negative frequency shifting effect of the human body on the antenna radiation. The SAR obtained for human activity applications was 1.55 W/kg for 1 g and 0.779 W/kg for 10 g, making design safe to use and suitable for wearable applications. In table 3 a comparison of this work with resent published researches.

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Table 3: *The proposed antenna results compared with recent researches*

Work	Bandwidth (%)	No.of unit cells	Substrate	Size (mm)
2021 [20]	5.3	-	Rogers 4360G2	-
2021 [21]	5.71	3X3	Jeans	45 x 45 x 2.4
2020 [22]	8.16	3x4	textile	25 x 82.5 x 7.6
2019 [23]	7.5	5x5	Rogers 6002	30 x 30
2018 [24]	8.3	2x2	Jeans	60 x 60
2017 [25]	6.26	2x2	-	40 x 40 x 4
2016 [26]	4.8	2x1	semiflexible RT/duroid 5880	68 x 38 x 1.57
This work	25	3X3	Jeans (EBG) , felt (antenna)	60 x 60 x 2

6 Declarations

6.1 Competing Interests

There is no conflict of interest.

6.2 Publisher's Note

AIJR remains neutral with regard to jurisdiction claims in published maps and institutional affiliations.

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