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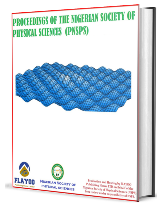

Leveraging EBG integration for microstrip patch antenna performance enhancement

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ABSTRACT

This article proposed a design of an Electromagnetic Band Gap (EBG) integrated Microstrip Patch Antenna (MPA) at the 2.45 GHz ISM band. The design employed the use of two quarter-wavelength ($\lambda/4$) resonators coupled close to a radiating patch for bandwidth enhancement. The proposed design is made of polydimethylsiloxane (PDMS) flexible substrate with a dielectric constant of 2.7, loss tangent of 0.02, and thickness of 2.5 mm. Zelt, a nylon-based material, with a surface resistivity of 0.01 ohm/sq and thickness of 0.063 mm was used as the radiating patch. The designed antennas were studied and analyzed using CST (Computer Simulation Technology) Microwave Studio. Different parameters such as Return Loss, Bandwidth, Gain, and Efficiency were studied and compared for the antenna with and without EBG. The antenna achieved a fractional bandwidth of 9.4%. To improve other parameters, EBG was used thereby improving the gain of the antenna from 4.03dBi to 4.58dBi, and radiation efficiency from 52% to 53.2%. Such improvement showed that this antenna offers better performance compared to existing solutions, which often face limitations in bandwidth of 4%. The proposed antenna can be utilised in various wearable devices operating in the Industrial, Scientific and Medical (ISM) band of 2.45 GHz for healthcare monitoring, military communications, and implantable medical tools.

Keywords: Patch antenna, $\lambda/4$ resonators, Flexible substrates, Efficiency.

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1. INTRODUCTION

Wearable antennas designed to operate in the 2.4 GHz band were found useable in wearable electronic devices for healthcare monitoring systems, military communications, implantable medical tools, etc [1]. Microstrip patch antennas (MPAs) have gained significant attention due to their low profile, ease of fabrication, and compatibility with microwave integrated circuits. However, their inherent narrow bandwidth and low gain and efficiency limitations have hindered their widespread application [1, 2]. To improve the bandwidth of microstrip patch antennas with ease and less cost of fabrication, a single-layer capacitive-fed technique is recommended in many research, most of which utilize a dual-resonance idea [3]. With this concept, bandwidth is expected to increase whenever another resonance is introduced near the resonance of a patch. This paper adopts the strategy utilized in Ref. [3, 4] by placing a couple of quarter wavelength ($\lambda/4$) resonators near the rectangular patch to accomplish wideband radiation on a single, thin substrate. In addition, researchers have explored the integration of Electromagnetic Band Gap (EBG) structures

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in the antenna community. EBG is a periodic structure that prevents the propagation of surface waves in a specified band of frequency, thereby improving antenna parameters such as gain and efficiency [5]. This structure is compact and has good potential to design a low profile with a highly efficient antenna.

Due to the irregular shape of the human body, conformable substrates are recently used instead of rigid ones in microstrip patch antenna design and fabrication. Flexible antennas made from flexible polymer substrates are employed in antenna designs and fabrications [1, 6]. Polydimethylsiloxane (PDMS) introduced in Refs. [7, 8] is a good candidate for wearable antenna designs due to its low cost, high flexibility, and biocompatibility. On the other hand, the radiating planes for wearable antenna should have high conductivity, be flexible, and have less resistivity among others. Performance characteristics of different conducting materials such as Zelt, Shieldit, and Flectron were studied in Ref. [9] with zelt having the best performance. Zelt is made from copper and tin as a nylon-based conducting material with a low surface resistivity (<0.01 ohm/sq.) and high conductivity of 10^6 S/m [10].

The combination of EBG integration with flexible material presents a novel design that enhances the performance and applicability of microstrip patch antennas in wearable technology. This study successfully integrates EBG structures into the design of a microstrip patch antenna, which enhances the performance parameters such as gain and radiation efficiency. This contrasts with many traditional designs that do not leverage EBG technology. The choice of flexile substrate addresses the need for flexibility and biocompatibility in wearable devices, which is a significant development over existing rigid designs typically used in microstrip antennas. This paper aimed to design and analyse a wideband, flexible microstrip patch antenna incorporating EBG structures for wearable applications. The rest of the paper discusses the dimensions and designs of the antenna and EBG in section II, the result analysis in section III, and the conclusion in section IV.

2. ANTENNA GEOMETRY AND DESIGN

2.1. ANTENNA DESIGN

The proposed design of the microstrip patch antenna with enhanced bandwidth is depicted in Figure 1. The design is made of a rectangular patch at a distance (d) from two quarter-wavelength ($\lambda/4$) resonators attached to the microstrip line. The $\lambda/4$ resonators share a shorting via with radius (r). PDMS is used as a substrate with a dielectric constant (ε_r) of 2.7, loss-tangent of 0.02 and thickness (h) of 2.5 mm [6]. Zelt is used as a conducting material for radiating planes (patch, ground, resonators and microstrip feeding line). It has a conductivity of 10^6 S/m, a thickness of 0.063 mm with a manufacturer-specified surface resistance of less than 0.01 ohm/sq [10]. The antenna is designed for a resonant frequency (f_r) of 2.45 GHz. The dimensions of the antenna patch and $\lambda/4$ resonators are obtained using the design equations (1)-(5) [11] for resonant frequency (f_r) of 2.45 GHz, dielectric constant (ε_r) of 2.7, substrate thickness (h) of 2.5 mm and velocity of light (c_o) of 3.0×10^8 m/s. CST Microwave Studio

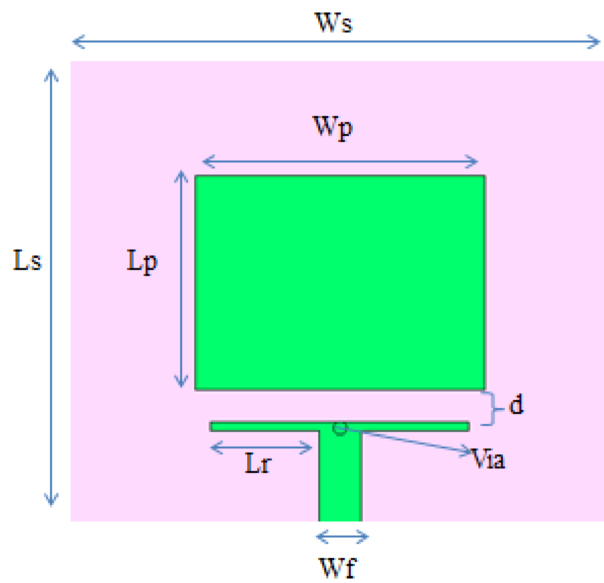

Figure 1. Antenna geometry.

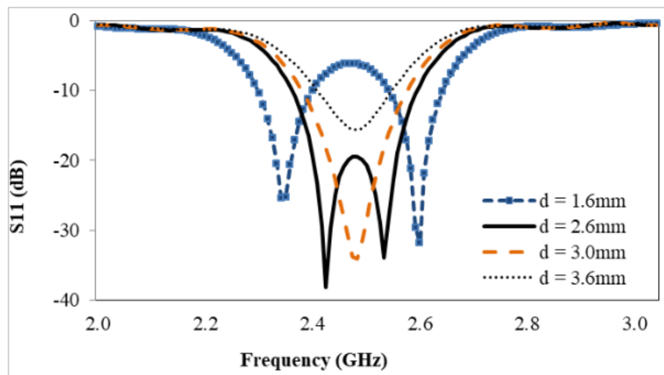

Figure 2. Effect of distance (d) on the reflection coefficient (S11).

is used to carry out the design and simulations.

$$Wp = \frac{c_o}{2f_r}\sqrt{\frac{2}{1+\varepsilon_{ep}}}, \tag{1}$$

$$Lp = \frac{c_o}{2f_r\sqrt{\varepsilon_{ep}}} - 2\Delta L, \tag{2}$$

$$\Delta L = 0.412h\frac{\left(\varepsilon_{ep} + 0.3\right)\left(\frac{Wp}{h} + 0.264\right)}{\left(\varepsilon_{ep} - 0.258\right)\left(\frac{Wp}{h} + 0.8\right)}, \tag{3}$$

$$Lr = \frac{c_o}{4f_r\sqrt{\varepsilon_{er}}}, \tag{4}$$

where Wp is patch width, Lp is patch length, Lr is the resonator's length, ΔL is the change in patch's length due to a fringing effect and f_r is the antenna resonant frequency. ε_{ep} and ε_{er} are the effective permittivity for the patch and $\lambda/4$ resonators respectively, obtained using (5).

$$\varepsilon_{ex} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{Wx}\right]^{-1/2}; \quad x = p,\ r. \tag{5}$$

Table 1. Proposed antenna dimensions.

Parameters	Value (mm)
Length of the Patch (Lp)	34.3
Width of the Patch (Wp)	44
Feedline Width (Wf)	6.53
$\lambda/4$ Length (Lr)	20.3
$\lambda/4$ Width (Wr)	0.6
Via Radius (r)	0.6
Distance (d)	2.6
Substrate Length (Ls)	70
Substrate Width (Ws)	80

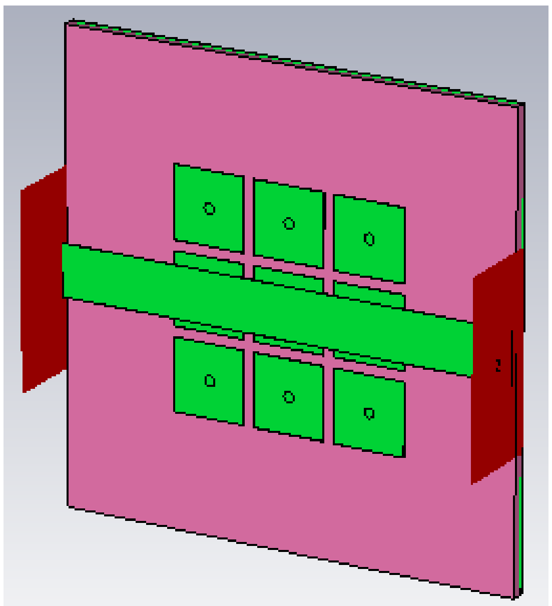

Figure 3. Design of 3 by 3 EBG structure using suspended transmission line.

Table 2. Optimized dimensions of EBG structure.

Parameter	Dimension (mm)
EBG patch width (We)	14
Gap between the patches (g)	2
Substrate height (hs)	2.5
Via radius (r)	1

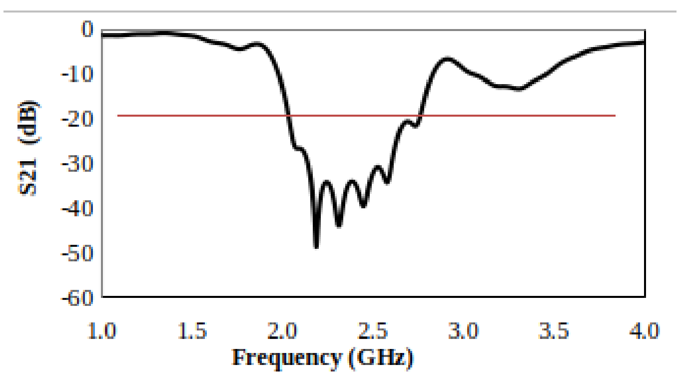

Figure 4. Transmission Coefficient (S21) of EBG structure.

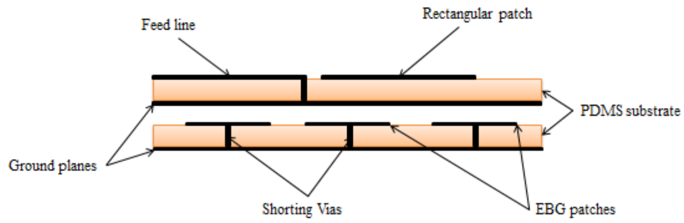

Figure 5. Designed antenna and EBG integration setup.

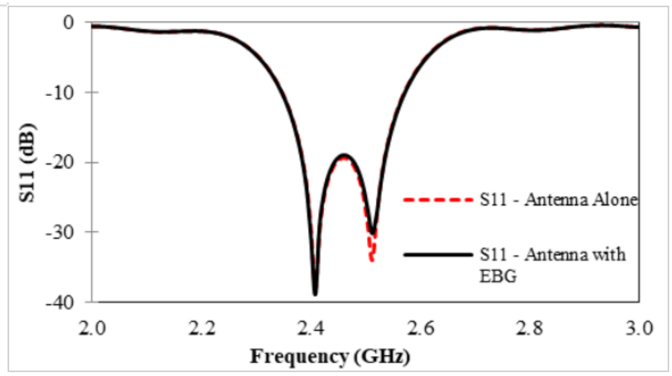

Figure 6. S11 plots of the antenna with and without EBG.

Table 3. Result summaries.

Parameters	Without EBG	With EBG
Bandwidth (GHz)	2.34 - 2.57 (9.4%)	2.34 - 2.57 (9.4%)
Directivity (dBi)	6.85	7.32
Gain (dBi)	4.03	4.58
Efficiency (%)	52	53.3
3dB Beamwidth (degree)	90.6	79.8

The PDMS substrate is backed by a full ground plane of zelt material so that both the antenna ground and substrate have the same dimensions of length (Ls) and Width (Ws) given by [12]:

$$Ls = 6 * h + L_p + L_f, \tag{6}$$

$$Ws = 6 * h + W_p. \tag{7}$$

After calculations and optimizations, the antenna dimensions are obtained such that Lp = 34.3 mm, Wp = 44 mm, Ls = 70 mm, Ws = 80 mm and Wf = 6.53 mm. A parametric study is performed on the distance (d) to obtain the best acceptable bandwidth by combining the dual bands due to the $\lambda/4$ resonators and patch.

It can be observed from Figure 2 that, by placing the $\lambda/4$ resonators at d = 1.6 mm from the patch, two resonances emerged; one at 2.33 GHz and the other at 2.57 GHz. By increasing the distance d, the two resonances try to merge and form a wideband. When d = 2.6 mm, a wideband response is obtained covering the frequency range from 2.34 GHz to 2.57 GHz taken at a return loss value below -10 dB. At a certain point of the distance (here, at d = 3.0 mm), a single resonance emerged with narrow bandwidth resonating at 2.46 GHz. When d is further increased beyond 3.0 mm, poor impedance matching is observed.

The optimized calculated values of the antenna dimensions are summarized in Table 1.

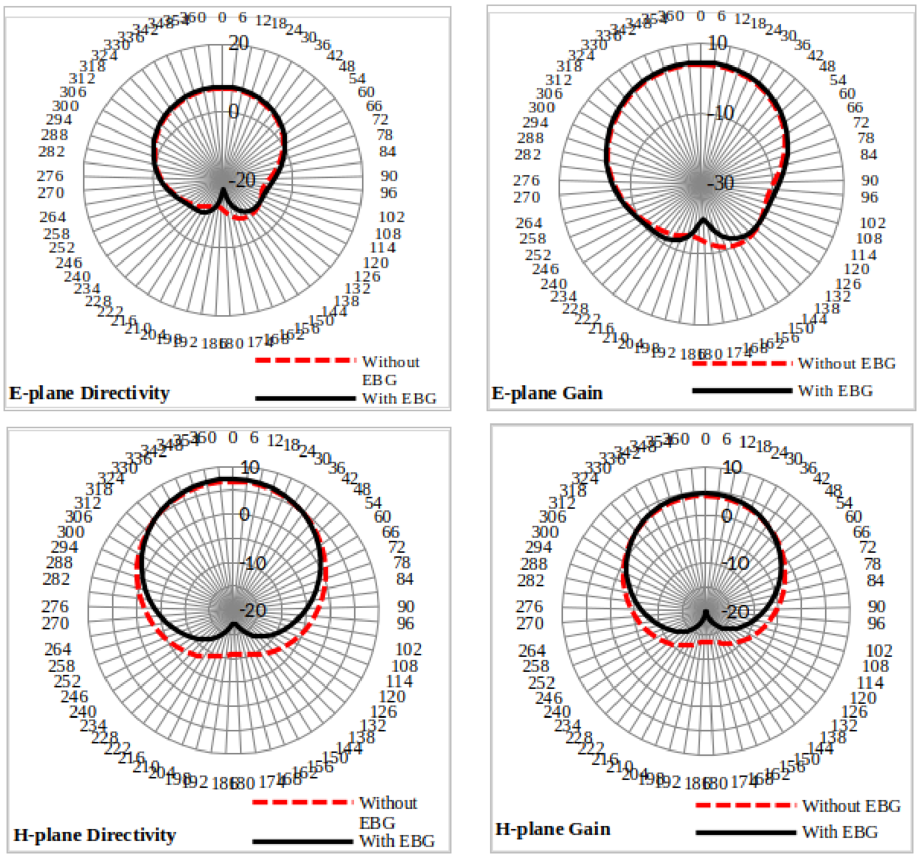

Figure 7. E-plane and H-plane co-polarization radiation pattern for directivity and gain with and without EBG.

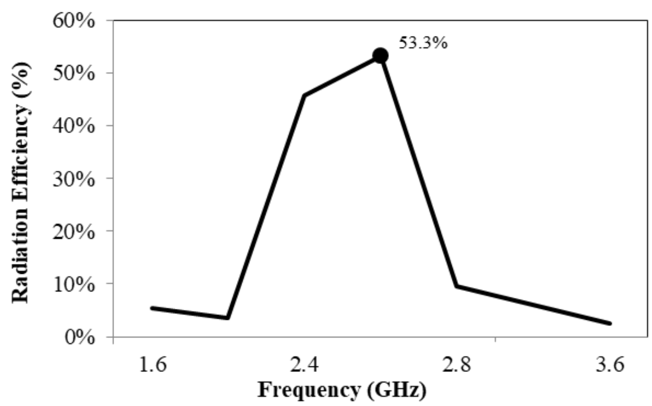

Figure 8. Radiation efficiency of the EBG integrated antenna.

2.2. ELECTROMAGNETIC BAND GAP (EBG) STRUCTURE

Mushroom electromagnetic band gap (EBG) structure which can prevent the propagation of surface waves along the operating frequency of the proposed antenna is adopted and depicted in Figure 3. The same PDMS substrate and Zelt conducting material are used as substrate and radiating planes respectively. Shorted EBG patch array is designed on top of a fully grounded dielectric substrate with a height (he) of 2.5 mm. A suspended transmission line technique is used to analyse the EBG design to determine the band gap frequency. A thin 50 ohms transmission line is placed on a 1.6 mm thickness substrate and the ends are connected by two ports to send and receive electromagnetic waves. With this arrangement, transmission loss (S21) indicating the band gap frequency for the EBG structure is determined.

The transmission loss (S21) of the 3×3 EBG arrays depends on the width of the patch (We), via radius (r) and the spaces between the patches (g) [5, 13, 14]. Hence, a parametric study is performed for these parameters to get the desired frequency band gap. A good result is obtained when the patch width (We) is 14 mm, the space between the patches (g) is 2 mm and radius of via (r) is 1 mm. The size of the transmission line is 80 mm x 10 mm for an impedance matching of 50 ohms. The optimized dimensions of the EBG structure are listed in Table 2.

The transmission coefficient (S21) of the EBG showing the frequency ranges of the band gap is depicted in Figure 4 with a bandwidth of 750 MHz (2.0 GHz to 2.75 GHz) taken at a transmission loss (S21) value below -20 dB. This indicates that the EBG structure effectively reflects significant energy within this frequency range. As a result, it minimizes unwanted surface wave propagation, which would otherwise degrade the antenna's efficiency. The presence of a well-defined band gap means that the antenna operates more efficiently at its target resonant frequency of 2.45 GHz, thereby improving overall performance.

2.3. INTEGRATION OF THE DESIGNED ANTENNA WITH EBG

The integration of the proposed antenna with the EBG involves combining individually designed components into a single structure using a low-dielectric material as a separation layer. This configuration ensures electrical isolation, mechanical support, and optimal interaction between the antenna and EBG for enhanced performance. Here, 1 mm air space is used between the two components, and the setup is depicted in Figure 5.

3. RESULTS AND DISCUSSION

3.1. REFLECTION COEFFICIENT (S11)

The Reflection coefficient (S11) plot of the antenna with and without EBG structure is presented in Figure 6. The operating frequency of the antenna ranges from 2.34 GHz to 2.57 GHz measured with a return-loss value of less than -10 dB which gives a fractional bandwidth of 9.4%. The bandwidths for both antennas remain closely the same for the fact that we used a small array of EBG cells, which do not give much effect on the bandwidth of the antenna.

3.2. RADIATION PATTERN

The co-polarizing radiation pattern of the E-plane and the H-plane of the antenna with and without EBG structure is depicted in Figure 7. The simulated results of the EBG integrated antenna achieved a directivity of 7.32 dBi and a gain of 4.58 dBi at 2.45 GHz operational frequency. The effect of the EBG structure when integrated with the antenna can be seen when these results are compared with that of the antenna without EBG which achieved a directivity of 6.85 dB and a gain of 4.03 dBi at 2.45 GHz. This is for the fact that the EBG have the capability of reducing the surface wave radiations thereby improving the antenna's gain, and efficiency. It can be seen that the antenna is highly directional as most of the signals are radiated toward one direction, normal to the radiating patch. The EBG integrated antenna radiates in a narrower angular width with a beamwidth of 79.8° when compared with that of the antenna without EBG having a beamwidth of 90.6°.

3.3. RADIATION EFFICIENCY

The simulated results of the EBG integrated antenna achieved a radiation efficiency of 53.3% at 2.45 GHz operational frequency as shown in Figure 8. The effect of the EBG structure when integrated with the antenna can be seen when these results are compared with that of the antenna without EBG which achieved a radiation efficiency of 52% at 2.45 GHz. The improvement in radiation efficiency from 52% to 53.3% shows the benefit of introducing EBG structure into patch antenna design.

3.4. RESULT SUMMARY

Table 3 summarizes the results of the proposed antenna for free-space and on-body analysis. The gain and efficiency of the non-EBG antenna are greatly affected by the presence of human tissues. On the other hand, the integration of the antenna with the EBG structure helps to overcome the effect of human tissues on the performance of the antenna.

4. CONCLUSION

This paper discussed on performance improvement of wearable microstrip patch antenna at 2.45 GHz. Flexible materials, PDMS and Zelt, were used for the designs. The antennas were designed and analysed in CST Microwave studio software. The antenna achieved a fractional bandwidth of 9.4%. To improve other parameters of the antenna, EBG was used, thus improving the antenna gain from 4.03 dBi to 4.58 dBi, and radiation efficiency from 52% to 53.2%. The paper indicates that the EBG-integrated antenna is well-suited for deployment in various wearable electronic devices that operates in 2.45 GHz, thereby contributing to advancements in wearable communication technology.

DATA AVAILABILITY

The data will be available on request from the corresponding author.

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