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New Integrated Dual-Band Dipole Antenna with EBG Structures Designed for Wireless Communications

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Abstract—**This paper presents a new technique that resides on the use of electromagnetic bandgap (EBG) structures under a half-wave dipole antenna suitable for wireless communication systems. The implementation of the EBG electromagnetic band gap structures and superstrate creates a new frequency descent of half-wave dipole antenna of 73 ohms, simultaneously we are capable to operating at 2.6 and 3.5 GHz bands with only one antenna and also enhances its performance (gain, directivity), and improve the antenna efficiency. This is manifested by a very low dipole antenna return loss, besides improving the efficiency of the radiation pattern, by using the EBG structure in the proposed configuration. This technique also allows to the low profile antenna (26% reduction) contribution for cell phones. The dipole antenna initially operates at a frequency range of 3.5 GHz, but with the introduction of the EBG electromagnetic band gap structures, it resonates in two frequency of sub-6 GHz 5G bands 3.5 GHz and 2.6 GHz, which is well suited for 5G mobile applications. The design parameters of the antenna were optimized.**

Index Terms—**Dual-band Half-wave dipole antenna, radiation pattern, Electromagnetic Band Gap (EBG)**

I. INTRODUCTION

Man has always needed to transmit information over long distances. The evolution of systems that can transmit communication data started hundreds of years ago, they went through several stages. The evolution of systems that can transmit communication data has begun hundreds of years ago, they have progressed through several stages. The antennas are important devices in the transmission chain, they are used to transmit and receive the signal radiated into free space. Depending on the area of application and the characteristic of the radiation pattern, several types of antennas can be distinguished, each with its own properties. Several techniques have been used to increase the directivity of an antenna and to reduce it size and side lobes. Among these techniques, the use of electromagnetic bandgap structures EBG will be described. The electromagnetic band gap (EBG) structures birth comes from the optics area [1], called photonic crystals in this field. The Bragg mirror was developed in 1915 by the English physicist William Lawrence Bragg [2]. Thanks to constructive interference phenomena, this mirror is able to reflect the incident energy more than 99.5%, whereas no other mirror can match. The condition for this is that the incident wave and the normal incidence are close to each other. The concept of two- and three-dimensional Bragg mirrors was extended in 1987 by Eli Yablonovitch for any incidence and to microwave frequencies. EBG structures are dielectric or metallic structures composed of a periodic assembly of two or more materials. This periodicity can be present in one, two or three dimensions. The electromagnetic field that propagates in these structures is the solution of an equation similar to the Schrödinger equation giving birth to frequency bands in semiconductors.

The EBG structures have a band of forbidden frequency where no electromagnetic wave can propagate through the material. They have the property of controlling the propagation of electromagnetic waves, as well as frequency and spatial filtering. In the telecommunications field, and particularly in the electromagnetic field, several research activities are being carried out on EBG structures, In the telecommunications field, and particularly in the electromagnetic field, several research activities are being carried out on EBG structures, which are being extensively used for different applications such as the suppression of surface waves for diverse antenna designs, increasing the gain of the antenna and reducing the back lobes [3], [4], In addition, they are used to reduce the mutual coupling level [5]-[7] Designing Low Profile Efficient Wire Antennas [8], [9], Multiband Reconfigurable Antennas [10] and the design of wide band antennas[11], as well as being used in miniaturized antenna designs [12], [13] and the concept of resonator antennas with high gain [14]. A new configuration of dual-band dipole antenna incorporating with electromagnetic bandgap EBG structures is proposed in this paper, with this configuration we can create a new frequency down the half-wave dipole antenna of 73 ohm, on one hand, and one the other hand to enhance the dipole antenna performance (gain, directivity) and reducing by about 32% its size. There are several techniques to have miniaturized multiband

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antennas mentioned in [15]-[17] as mentioned the structure of multiband antennas usually supports a selective frequency band. On the contrary, in this paper, the EBG structure technique allows the antenna to operate simultaneously in both 2.6 and 3.5 GHz bands, with the smallest size. Hence the choice of this technique. The principle novelty of the proposed work resides in the use of two frequency bands simultaneously (3.5GHz, 2.6GHz), and also reduce the size of the antenna with an important percentage. In this paper the simulation results are presented and discussed.

II. DIPOLE ANTENNA WITHOUT EBG STRUCTURE

A. Dipole Antenna Design

The dipole antenna, developed by Heinrich Rudolph Hertz around 1886 [18], is a device consisting of two metal rods, which are fed in the middle and designed to transmit or receive electromagnetic radiation. This type of antenna is the simplest to study from an analytical point of view and is certainly the simplest antenna to realize. The application of EBG structures to cell phones in fifth-generation (5G) wireless communication systems could receive a lot of attention. This is due to the fact that the dimensions of the EBG structures are comparable to the wavelength, so they can be small enough for a cell phone at 3.5 GHz. In this letter, the feasibility of a dipole antenna on top of the EBG substrate has been studied for 5G cell phones.

The geometry and parameters of the proposed antenna are shown in Fig. 1. This dipole antenna is designed to operate around 3.5GHz, with a copper rod length, l=38.84mm and a width e=1mm, its input impedance is set to 73 ohms.

For a thin dipole, when the length of the dipole L is equal to $\lambda/2$ (half wave dipole), the antenna is then in resonance, its resonance frequency is therefore equal to:

$$L = \frac{\lambda}{2} \leftrightarrow f = \frac{C}{2L} \tag{1}$$

The obtained S-parameter simulation results, illustrated in Fig. 2, show a high resonant frequency around 3.5GHz (down to −41dB) with a wide bandwidth of about 580MHz which corresponds to WiMAX applications.

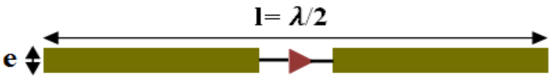


Fig. 1. Proposed half-wave dipole antenna.

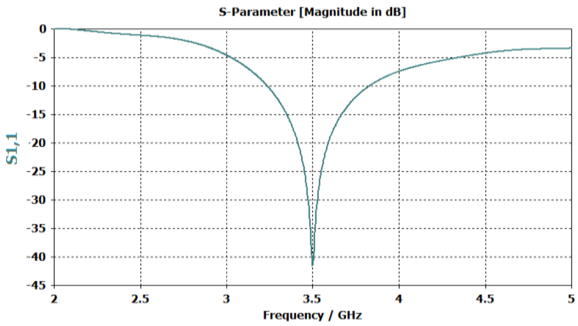


Fig. 2. S parameters of the half-wave dipole antenna.

B. EBG Structure

The slotted EBG structure used in this paper is the SHI (High Impedance Surface) structure. It is a new type of electromagnetic bandgap structure that is designed by adding slots in the metal plates of conventional mushroom like EBG as shown in Fig. 3. These slots affect the current distribution on the plates, resulting in a longer current path, and also create additional capacitance formed between the edges of the slots. In this paper, we designed a new slotted EBG structure four square rings with three small rings of size 0.8mm×0.8mm, while the large ring is 5.65mm×5.65mm, which are deposited on a substrate Rogers RO3010 because they are priced competitively with excellent mechanical and electrical stability. This stability allows the material to be used in a variety of applications over a very wide frequency range. The characteristics of this material make Rogers RO3010 excellent for circuit miniaturization. Its relative permittivity is 10.2 and its thickness is 1.27 mm. The unit cell of the EBG structure is shown in Fig. 4 and the summary of the parametric values of this cell is presented in Table I.

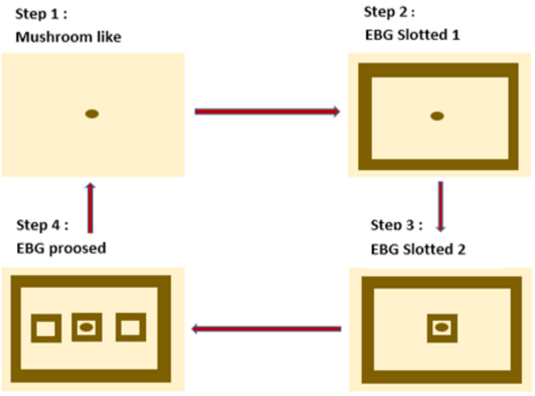


Fig. 3. Design steps of the EBG unit cell.

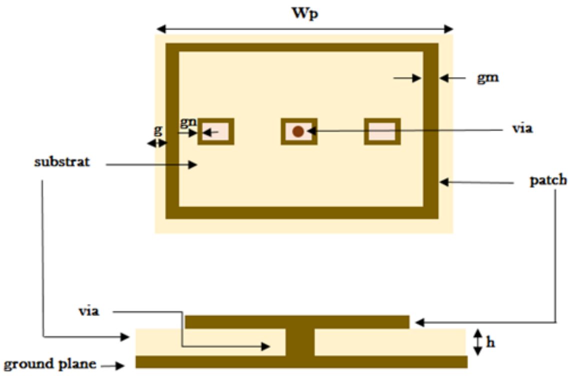


Fig. 4. The EBG unit cell.

TABLE I: THE EBG UNIT CELL DIMENSION (IN MM)

Parameter	Description	Values (mm)
g_n	thickness of the small square rings	0.38
g_m	Thickness of large square ring	0.5
r	Via radius	0.2
w_p	Unit cell length or width	6.37
h	Substrate thickness	1.27
m	Ground plane thickness	0.0175
g	The space between the unit cells	0.36

Different methods have been implemented to analyze the characteristics of the SHI structure. They can be classified into three categories: a model based on the equivalent circuit [19], [20], a model based on the transmission line [21], [22], and a model based on the periodic boundary conditions [23]. It is considered that the equivalent circuit model is the simplest to describe the SHI structure as an LC resonant circuit. The geometry of the SHI is used to determine the values of the inductance L and capacitance C, and its resonant behavior is used to explain the bandgap characteristic of the SHI structure. The understanding of this model is simple, but the simplified approximation of L and C does not allow to obtain very accurate results.

Fig. 5 explains the mechanism of the SHI structure. The capacitance C is caused by the fringing electric fields between the adjacent metal plates, while the inductance L is generated by the current flux through the metal surface and via.

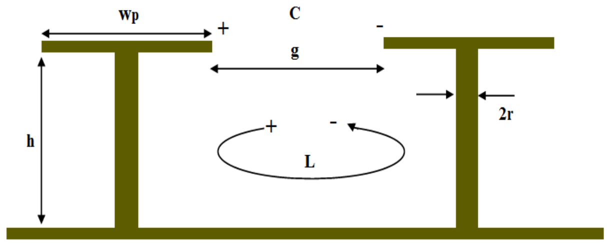


Fig. 5. Electrical equivalent model.

The inductance L and capacitance C initial of the conventional structure mushroom-like

$$L = \mu_0 \mu_r h \tag{2}$$

$$C = \frac{w_p \varepsilon_0 (1+\varepsilon_r)}{\pi} \cosh^{-1}\left(\frac{w_p + g}{g}\right) \tag{3}$$

where w represents the patch width and g the spacing between the EBG structure elements, μ_0 and ε_0 are the permeability and permittivity of the free space, respectively. The inductance and capacitance equivalents are identical to those of the conventional mushroom-like structure, besides the new L and C created by the slots. By introducing the slots, the initial L and C value does not change, while it will increase and provide a lower resonant frequency and, therefore, a compact structure.

The corresponding resonant frequency of the equivalent circuit is expressed by:

$$\omega = \frac{1}{\sqrt{LC}} \tag{4}$$

The bandwidth of the band gap frequency is given by the following expression:

$$B_W = \frac{\Delta\omega}{\omega} = \frac{1}{\eta}\sqrt{\frac{L}{C}} \tag{5}$$

where η represents the free space impedance.

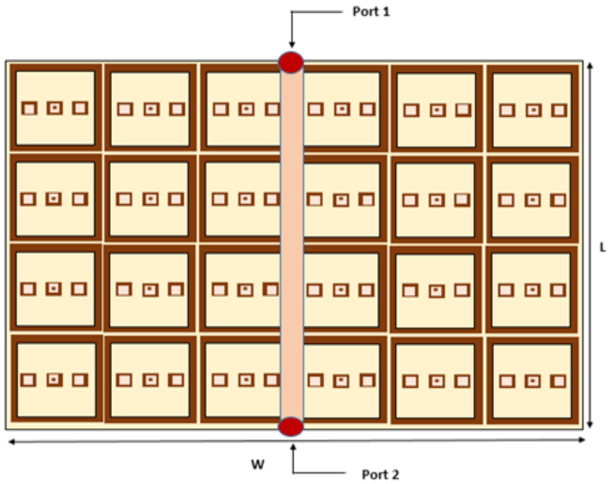


Fig. 6. EBG structure: *W*= 40.7mm, *L*= 27.3mm.

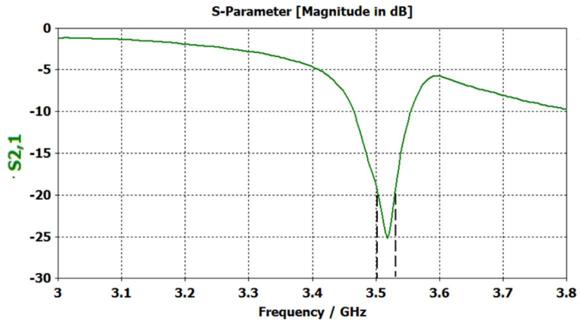


Fig. 7. Transmission coefficient S21 of the EBG structure.

III. DIPOLE ANTENNA WITH EBG STRUCTURE

A. Design of the EBG Model Based on the Transmission Line

The model approach based on the transmission line shown in Fig. 6 is applied to obtain the band gap characteristic of the SHI structure. The microstrip transmission line is placed at a distance of 0.5mm above the rectangular SHI cells (their dimensions are presented in the previous section), which are repeated periodically (EBG structure is formed by 4×6 cells) and separated by *g*=0.36mm, the transmission line is fed by two wave receiving and transmitting ports [24]. This structure is built on a Roger 3010 substrate of thickness 1.27 mm and surface area 40.7mm×27.3mm.The SHI structure is designed to act as a bandstop filter [25], the dimensions of the SHI cells is optimized to obtain a rejection of the WiMax band from 3.5GHz to 3.53GHz. Fig. 7 illustrates the variation of the S-parameters of the SHI cell, we can see that the transmission coefficient S21 lower than –20dB for a frequency band around 3.5GHz indicates the band gap behavior of the structure. The width of the band gap can be adjusted by changing the dimensions of the structure.

B. Parametric Study

To determine the electromagnetic properties of an EBG structure, the physical dimensions of the structure are used. However, there are three principal parameters for this EBG slotted structure shown in Fig. 6 that affect its performance [26], which are the substrate permittivity ε_r, the substrate thickness h, and the superstrate effect. In this section, the effects of these parameters are studied one by one to obtain some engineering guidelines for the design of EBG surfaces. Knowing that the radius *r* of the vias has a banal effect as it is thinner compared to the operating wavelength.

1) *Effect of substrate permittivity*

In the telecommunications field, the relative permittivity ε_r of a substrate, also known as the dielectric constant, is an important parameter used to monitor the frequency behavior. Some commercial materials generally used such as RT/duroid substrates and TMM substrates are studied. The EBG structure analyzed in this section is the structure shown in Fig. 6, the same parameters are conserved, and only the permittivity is modified. The transmission coefficients of the EBG structure with different permittivities are shown in Fig. 8.

Using Rogers TMM 10 with permittivity $\varepsilon_r = 9.2$ as the substrate, the EBG surface has the highest resonant frequency and the largest bandwidth. On the other hand, as the permittivity increases, the resonant frequency decreases, as well as the bandwidth, see Table II Therefore, to reduce the size of the EBG cells, we can always use a substrate with a high dielectric constant. A narrow bandwidth is the price to pay. In the rest of simulation we will choose Rogers RO3010 with a permittivity of $\varepsilon_r = 10.2$ as substrate.

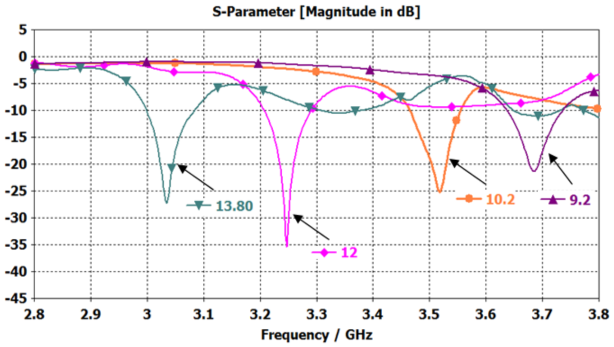


Fig. 8. Effect of substrate permittivity ε_r on the S21 transmission coefficient of the EBG structure.

TABLE II: THE SUBSTRATE PERMITTIVITY ER EFFECT ON THE RESONANT FREQUENCY OF THE STUDIED STRUCTURE.

Permittivity ε_r	Frequency (GHz)	Bandwidth MHz
13.80	3.03	83
12	3.24	83.7
10.2	3.51	90
9.2	3.68	99.1

2) *Effect of substrate thickness*

It can be seen in the previous study that the bandwidth evolves according to the resonance frequency. With a decrease in frequency, the bandwidth also becomes narrower. The question that arises, it is possible to decrease the resonance frequency and simultaneously increase the bandwidth? This is possible by adjusting the thickness of the substrate *h*. The EBG structure analyzed in the following simulation is the structure shown in Fig. 6. The same parameters are kept, except that the substrate thickness is changed.

The substrate thickness is always considered to be small relative to the wavelength since a thin EBG surface is more suitable for practical applications. The effect of substrate thickness *h* on EBG structure transmission coefficient S21 is presented in Fig. 9. It can be observed that as the substrate thickness increases, the frequency reduces and the bandwidth increases as shown in Table III. This is also explained by the LC model. As the substrate thickness increases, the equivalent inductance L also increases. Thus, the frequency decreases and bandwidth increases. We chose *h* = 1.27 mm for the rest of the design.

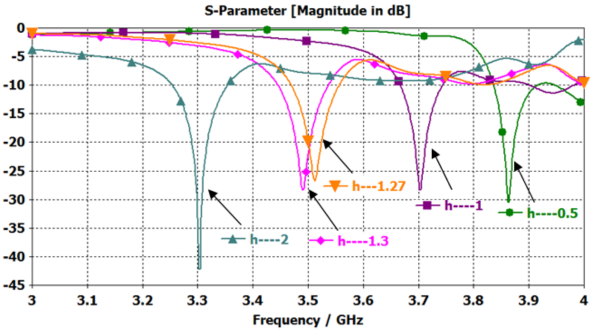


Fig. 9. Effect of substrate thickness *h* on EBG structure transmission coefficient S21.

TABLE III: THE EFFECT OF THE SUBSTRATE THICKNESS H ON THE STUDIED EBG STRUCTURE FREQUENCY AND BANDWIDTH

Substrate thickness *h*	Frequency (GHz)	Bandwidth (MHz)
2	3.30	105
1.3	3.49	95
1.27	3.51	89.9
1	3.70	77.8
0.5	3.86	77.7

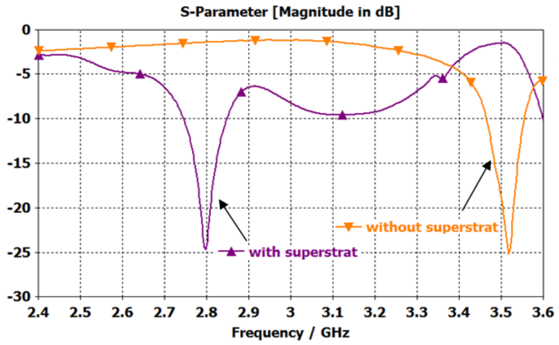


Fig. 10. Transmission coefficient S21 of the EBG structure with and without superstrate.

3) *Superstrate effect*

Dielectric superstrate layers, or more commonly known as cover layers, are often used to protect printed antennas from environmental risks. The superstrate plays a vital role in antenna design, it can affect several basic antenna performance characteristics such as gain [27], [28], directivity [29], bandwidth [30], and resonant frequency, and it also contributes to the reduction of mutual coupling between the radiating elements. The transmission coefficient S21 of the proposed EBG structure, with and without superstrate, is presented in Fig. 10. It can be seen that by covering the proposed EBG structure with a superstrate, the band gaps shift to a lower frequency, see Fig. 10, which allows for a reduction in the expected size of the initial EBG without a superstrate.

Thus, the proposed structure maintains a device with a low profile.

C. Half Wave Dipole Antenna Design with EBG Structure

A In this section, the previously presented 4×6 EBG cells (Fig. 6) will be inserted under the dipole antenna.

A Rogers RO 3010 substrate with a relative permittivity of 10.2 and a thickness of 1.27mm is chosen for the design of the antenna. The same material is used as both substrate and superstrate. The final configuration of the proposed structure (dipole antenna with EBG) is shown in Fig. 11.

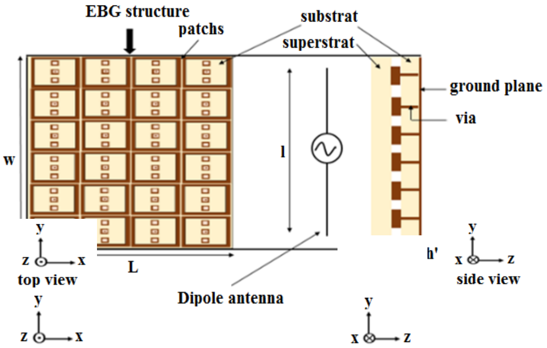


Fig. 11. Dipole antenna design with EBG structure mounted with the superstrate: L= 27.3mm; W=40.7mm; h'=1.27mm; h=2h'+ 0.0175; g = 0.36mm; l = 38.84mm.

4) Effect of EBG unit cell type

In this part, the antenna design is optimized by studying the used EBG structure effect. First Mushroom like unit cells are inserted under the dipole antenna, then EBG slotted 1, EBG slotted 2 and finally EBG Proposed. Fig. 12 shows the reflection coefficient S11 depending on the type of EBG unit cells used.

Through Fig. 12, if we compare the four EBG structures, we can see that by adding slots in the conventional Mushroom like EBG structure, the antenna resonance frequency decreases, i.e. the creation of slots will lead to a compact structure, as well as an improvement of the reflection coefficient. The comparisons between the four EBG structures are summarized in Table IV.

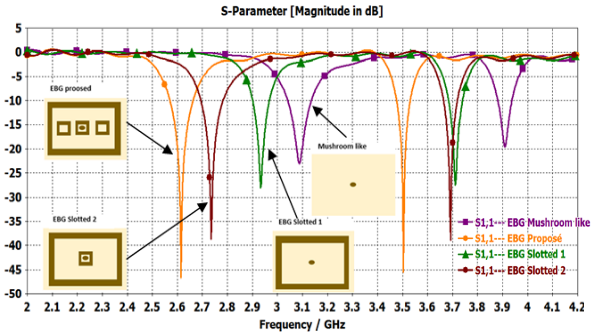


Fig. 12. Reflection coefficients of a dipole antenna: on a structure EBG Mushroom like (Purple squares), EBG slotted 1 (Green triangles), EBG slotted 2 (Red circles), EBG proposed (Orange diamonds).

Table IV shows that the proposed structure achieves the best reduction percentage of about 32% compared to the conventional Mushroom structure which achieves only 20%, thus a better adaptation is obtained, hence the choice of the proposed EBG structure for the rest of the design.

TABLE IV: COMPARISON BETWEEN FOUR TYPES OF EBG STRUCTURES

Parameter /EBG	Resonance frequency (GHz)		reflection coefficient (dB)		Percentage reduction
EBG Mushroom like	3.08	3.90	-23.04	-19.55	20 %
EBG slotted1	2.93	3.71	-28.04	-27.25	24 %
EBG slotted 2	2.73	3.69	-38.72	-38.92	29 %
EBG proposed	2.61	3.50	-46.72	-45.50	32 %

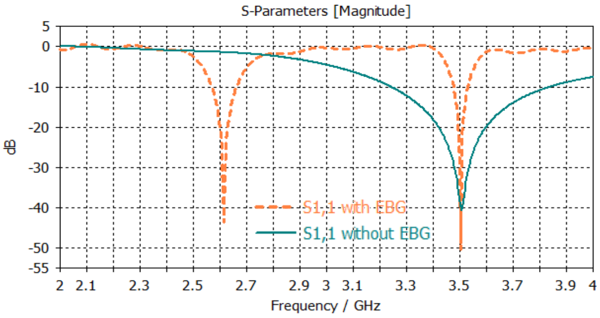


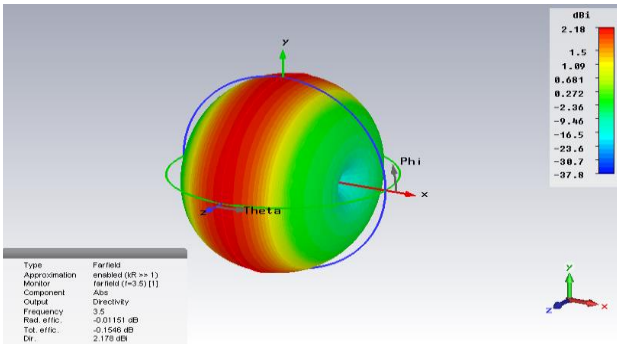
Fig. 13. S-parameters of the antenna without and with EBG structure.

The coefficient S_{11} of the dipole antenna with and without EBG structure is shown in Fig. 13.

From Fig. 13, the creation of a new resonant frequency towards the bottom of the dipole antenna can be seen, allowing the creation of a dual band antenna (2.6GHz, 3.5GHz). This new configuration has another significant advantage in achieving a miniaturization of the antenna size with 32% (reduction of the resonant frequency from 3.5GHz to 2.6GHz). For the frequency bands of 3.5GHz and 2.6GHz, the reflection coefficient of the antenna structure with and without EBG structure shows a good adaptation. The bandwidth of the dipole antenna without EBG structure is 580 while with EBG it decreases to 65 MHz for the frequency 3.5 GHz and 50 MHz for 2.6 GHz.

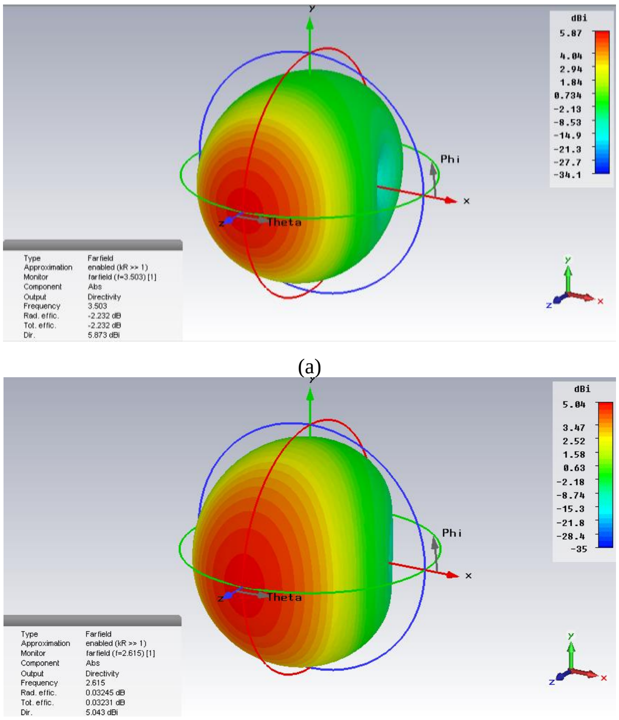
D. Radiation Pattern

In this part of simulation, the radiation pattern of the dipole antenna without EBG structure will be compared with that obtained in the presence of EBG cells for understanding of EBG structure behavior. The gain patterns of the dipole antenna with and without EBG structure at 3.5GHz and 2.6GHz resonances are shown in Fig. 14 and Fig. 15.



Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=3.5) [1]
Component Abs
Output Directivity
Frequency 3.5
Rad. effic. -0.01151 dB
Tot. effic. -0.1546 dB
Dir. 2.178 dBi

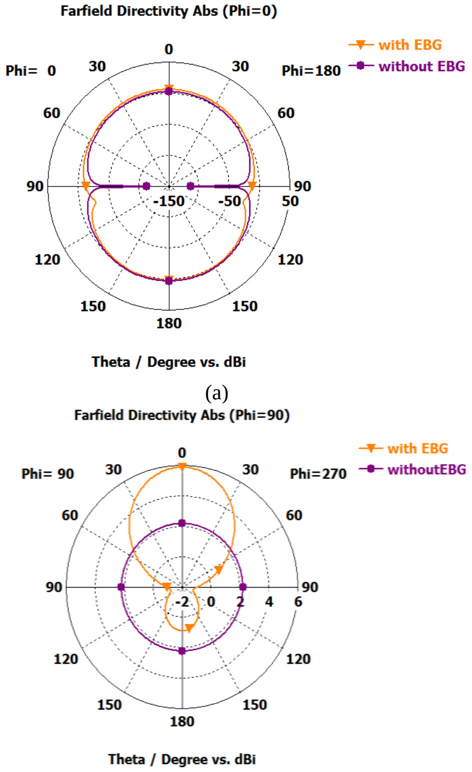
Fig. 14. Conventional dipole antenna far field radiation pattern at 3.5 GHz.



(a)

(b)

Fig. 15. Dipole antenna with EBG far field radiation pattern: (a) at 3.5 GHz; (b) at 2.6 GHz.

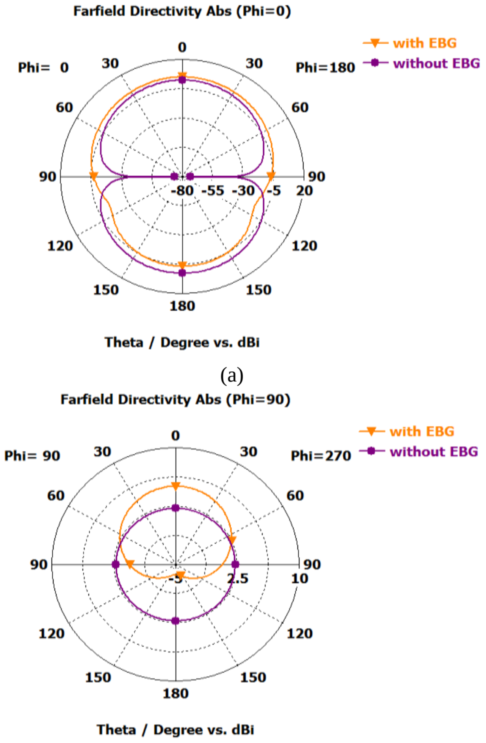


(a)

(b)

Fig. 16. Radiation pattern of the dipole antenna with and without EBG structure at 3.5GHz in horizontal and vertical section (a) phi=0 (b) phi=90.

The conventional antenna directivity and gain at 3.5GHz are 2.18dB and 2.17dB respectively, while the directivity and gain of the dipole antenna with EBG are (5.85dB, 3.29dB) at 3.5 GHz and (5.03dB, 4.91dB) at 2.6GHz respectively. In addition to creating a dual-band antenna and reducing the size of the antenna, which is indicated by reducing the resonant frequency from 3.5GHz to 2.6GHz, this new technique improves the performance of the antenna in terms of radiation which has become directional with a decrease in back radiation, see Fig. 16 and Fig. 17.



(a)

(b)

Fig. 17. Radiation pattern of the dipole antenna with and without EBG structure at 2.6GHz in horizontal and vertical section (a) phi=0 (b) phi=90.

From the Table V, the comparison between the conventional antenna and the proposed one is summarized. In terms of antenna performance, it can be seen that when EBG unit cells are added under the dipole antenna, the latter becomes more adapted and more directive.

The parameters of the proposed antenna compared to various antenna configurations reported in [23], [24]-[27] are summarized in Table VI. From the provided study, the effectiveness of the designed antenna structure is confirmed. It can be seen that our configuration has the smallest volume among all of them. The advantages and novelty of our proposed design reside in the ability of our antenna to operate in two frequencies of the sub-6 GHz 5G bands simultaneously, 3.5 GHz and 2.6 GHz, which are the smallest for 5G mobile applications.

TABLE V: SUMMARY OF DIPOLE ANTENNA PERFORMANCE WITH AND WITHOUT EBG

Parameters	Dipole antenna		
	Conventional structure (without EBG)	Proposed structure (with EBG)	
Frequency (GHz)	3.5	3.5	2.6
Return Loss S11 (dB)	-40	-45.50	-46.72
Gain (dB)	2.17	3.64	5.07
directivity (dBi)	2.18	5.85	5.03
bandwidth (MHz)	580	65	100

TABLE VI: THE COMPARISON BETWEEN THE PROPOSED ANTENNA AND SOME OTHER WORKS

References	Antenna size (mm^2)	Resonance frequency GHZ	Gain dBi	Employed techniques
This work	40.7×27.3	2.6 & 3.5	4.91-3.29	EBG structure -Superstrate
2018 [31]	40×40	3.15 & 4.56	3.5-2.6	MTM - Fractals
2019 [32]	51×51	3.33 to 3.63	6.4-6.57	Capacitive Loading
2021 [33]	60 × 40	2.332 4.02 5.23	2.23 2.81 1.91	loaded with a via-less MTM
2018 [34]	180×90	2.4–3.1 5.1–5.8	5 6	metamaterial structure
2021 [15]	120 × 60	2.2–2.7 3.3–4.02	3.7 dBi at 2.7 GHz	RF PIN Diode
2019 [16]	100×60	2.5–3.6	1.9 dBi at 3.5 GHz	SP4T Switch
2019 [17]	100×100	2.4–2.7 3.4–3.6	7.41dBi at 3.5GHz	RF PIN Diode
2018 [35]	40×30	3.4–3.8 3.7–4.2	2.24 2.76	Slot antenna with Two PIN diodes

IV. CONCLUSION

A new design of a dual-band antenna based on electromagnetic bandgap structure EBG has been presented in this paper. The introduction of Electromagnetic Band Gap EBG structures under the conventional dipole antenna, previously operating at a single frequency of 3.5 GHz, has provided two resonant frequencies of (3.5 GHz and 2.6 GHz). A very good radiation characteristic is achieved at each resonant frequency, including a clear enhancement in directivity and gain. This technique also reduces the size of the proposed antenna by 26%. Therefore, for modern wireless communication applications, the antenna can be easily integrated due to its small size. In perspective, the proposed antenna will be fabricated and the simulation results will be validated by the experimental results.

CONFLICT OF INTEREST

The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS

Author's contribution to this work: Sara Said and Abdenacer Es-salhi conducted the research and analyzed the data; all authors had approved the final version.

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