Ultra-Wideband Steerable Antenna Array Based on EBG Structure for Millimeter Wave 5G Applications

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***Abstract*—An ultra-wideband miniature antenna array based on electromagnetic band gab (EBG) has been presented for the five generation of wireless communication (5G) applications. The proposed antenna array is fed by a 3dB hybrid coupler. Simulation results show that two beams steering toward $\pm 13°$ with 7.35 dB maximum gain magnitude in E-plane at 28 GHz, are achieved. Thus, by using EBG structure, the proposed antenna array achieves an ultra-wideband (UWB) behavior, that covers 23.28-35.78 GHz (44.64%) frequency range.**

***Index Terms*—Beam steering, EBG, millimeter wave, multi-layer structure, ultra-wideband, 3dB hybrid coupler, 5G.**

I. Introduction

One of the major goals of the 5G is to deliver data transfer rates or capacity two to three orders of magnitude higher than those currently available [1]. So, to address this challenge, according to Shannon's theorem, the capacity of a channel requires a commensurate large bandwidth and large signal power [1]. For this, the millimeter wave (mmwave) frequencies (30 GHz to 300 GHz), are very attractive to achieve the 5G goals due to its available bandwidths [2-3]. However, in the mmwave, there are many applications, such as the ISM band (24 GHz), the upper region of K-band, the Ka-band (27-40 GHz), the mmwave 5G communication (26 GHz, 28 GHz, and 38 GHz), and the 60 GHz high-speed wireless communication [4]. Thus, the development of a UWB antenna is very crucial for 5G technology [5]. Hence, various research works have been done to achieve a UWB behavior by using different techniques. Indeed, a slotted antenna or ground plane, a truncated or partial ground plane and stacking parasitic patches, are presented [4]-[10]. However, despite the achieved UWB behavior, the gain achieved by the proposed antennas in [4]-[6]-[8] cannot meet the need of 5G applications due to the high path loss [11]. According to the Friis equation, in the higher frequencies, the path loss will be increased due to the small wavelength in the higher frequencies [12]. However, in [7]-[9]-[10], antenna arrays are presented, and a narrow beam is synthesized resulting in limited area coverage. Thus, using antenna array with beam steerable remains an important technique that provides good area coverage [10-12].

In this paper, we propose a microstrip antenna array with beam steerable capability by using a 3dB hybrid coupler. Therefore, To achieve an ultra-wideband, we have used an EBG substrate. However, the miniaturization of the proposed antenna has been achieved by using a multi-layer structure.

The organisation of this paper is as follow, an antenna design is presented in Section II, in Section III, simulation results will be presented and discussed, and in Section IV, a conclusion will be presented.

II. Antenna Design

The proposed antenna array is printed on Rogers RT Duroid 5880 dielectric substrate with a relative permittivity ε_r=2.2, loss tangent tanδ=0.009 and a thickness h=0.254 mm. For the conductor material, we have used a copper material with 17 µm thickness.

A. Design of 3dB hybrid coupler

As shown in Fig 1, the 3dB hybrid coupler is composed by four ports in which the input energy in port 1 is uniformly divided between port 2 and port 3, with a 90° phase shift. However, port 4 is an isolated port in which no energy is coupled [13].

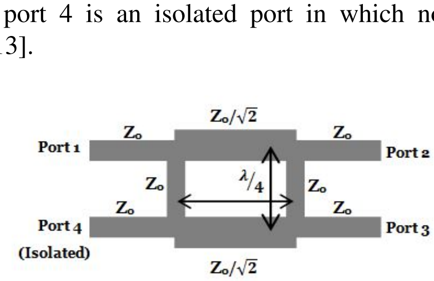
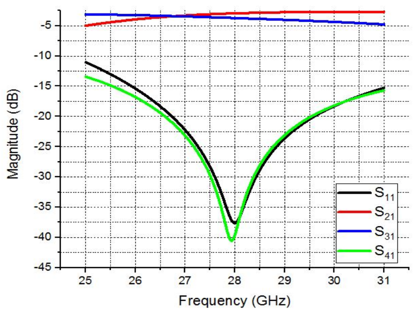


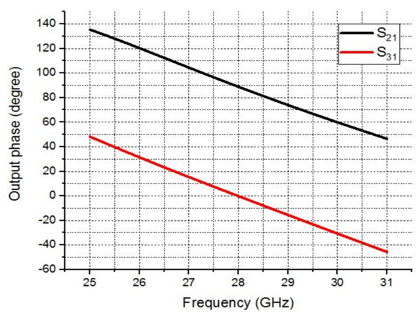
Fig. 1. Geometry of a branch-line coupler.

The design of 3dB coupler is based on two quarter-wavelength strip lines impedances: the first is Z_0 and the second is $\frac{Z_0}{\sqrt{2}}$ [13]. Thus, we have used Z_0=50 Ω, so $\frac{Z_0}{\sqrt{2}}$ =35.35 Ω.

As shown in the Fig 2a, the simulated S_{11} and S_{41} shows a good return loss at the frequency 28 GHz, which are respectively 37.5 dB and -40 dB. Thus, the simulated S_{21} and S_{31} at the frequency 28 GHz are 2.8 dB (≈ 3dB) and 3.8 dB respectively. These results are not exactly equal to 3dB due to some losses in the substrate material. However, the simulated output phases of the S_{21} and S_{31} parameters at 28 GHz are 77.77° and 11.33° respectively with a phase difference of 89.1° ≈ 90° as illustrated in Fig 2b.



(a)



(b)

Fig. 2. Simulated S-parameters (a) magnitudes (b) output phases of the 3dB coupler.

B. Design of EBG unit cell

The operation mode of the EBG is explained by a LC filter in which the parameter L (inductance) results from the current that flow through the vias (with a radius r) and the C (capacitance) is due to the gap (g) effect between the neighboring patches (with a width W_s) as shown in Fig 3 [14]. All the parameter that are shown in Fig 3 are related in the equations below [14]:

$$L = \mu_0 h \tag{1}$$

$$C = \frac{W_s \varepsilon_0 (1+\varepsilon_r)}{\pi} cosh^{-1}(\frac{W_s + g}{g}) \tag{2}$$

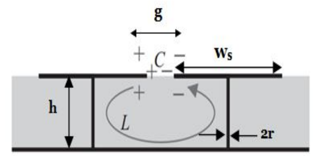


Fig. 3. Lumped LC model for EBG analysis [14-15].

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

With h is the substrate thickness, ε_r is the dielectric constant and f_0 is the resonance frequency. The design of the EBG unit cell is shown in Fig 4. The dimensions of the EBG unit cell, calculated by using the equation (1)-(3), are presented in Table I.

TABLE I
EBG UNIT CELL DIMENSIONS

Parameter	Ws	r	g
Value (mm)	1.6	0.1	0.2

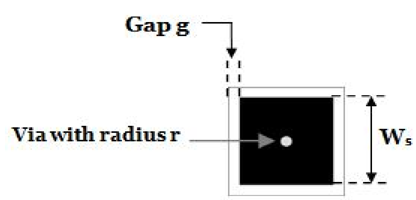


Fig. 4. EBG unit cell design.

By using the method of suspended transmission line, the S_{21} value was measured. Thus, the simulation results show that the proposed EBG unit cell has a wide stop band of over 5 GHz ranging from 26 GHz to 31 GHz as shown in the Fig 5.

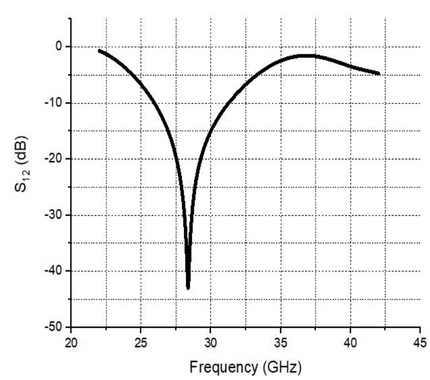


Fig. 5. Simulated S_{12} of the EBG structure: design with suspended transmission line.

III. Configuration of the Antenna Array

To attend a compact antenna, we have used a multi-layer antenna structure, in which the 3dB coupler is implemented in a layer and the antenna radiation in another layer, as shown in the Fig 6.

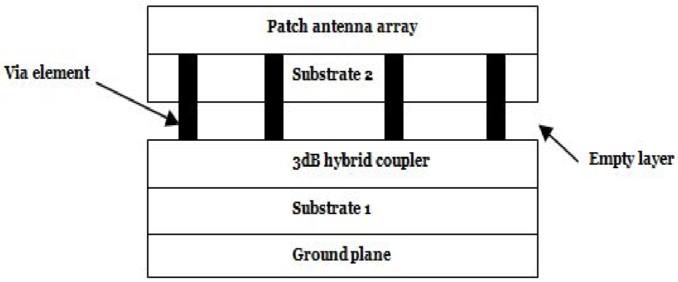


Fig. 6. Side view of the configuration of the proposed UWB beam switching antenna array.

Fig 7 shows the 3dB coupler with the two transmission lines to connect the two patches by using via elements.

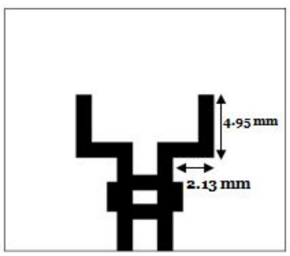


Fig. 7. 3dB hybrid coupler with two transmission lines.

Fig 8 gives the top layer of the proposed antenna structure with and without EBG.

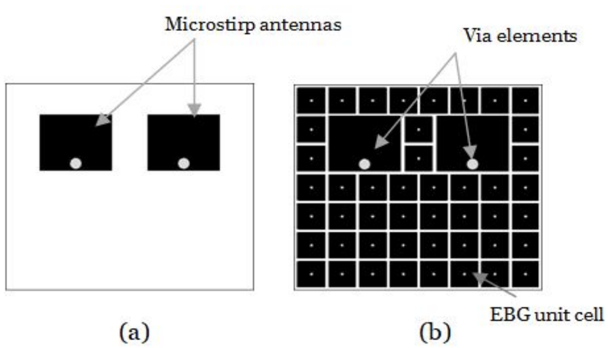
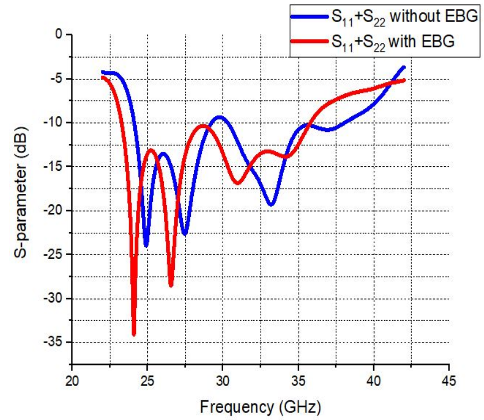


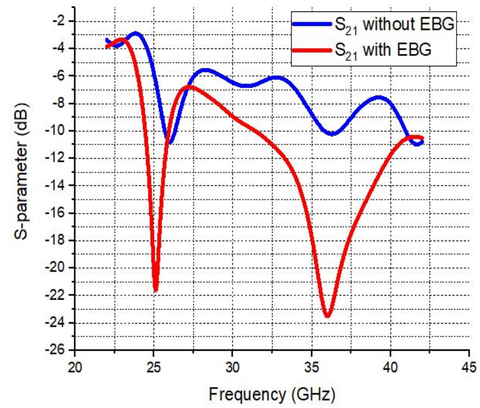
Fig. 8. Antenna array configuration (a) with and (b) without EBG structure.

IV. Simulation results

As shown in the Fig 9a, the bandwidth of the antenna, without EBG structure, is 24.12-29.18 GHz and 30.32-37.98 GHz for S_{11} $\leq$-10 dB. However, by the implementation of the EBG structure an ultra-wideband of 44.64 % (23.28-35.78 GHz) is attended. In addition, the mutual coupling between the two ports is enhanced since the S_{11} and S_{22} parameters levels are improved due to the suppression of the surface waves by the EBG substrate [15] as shown in Fig 9b.



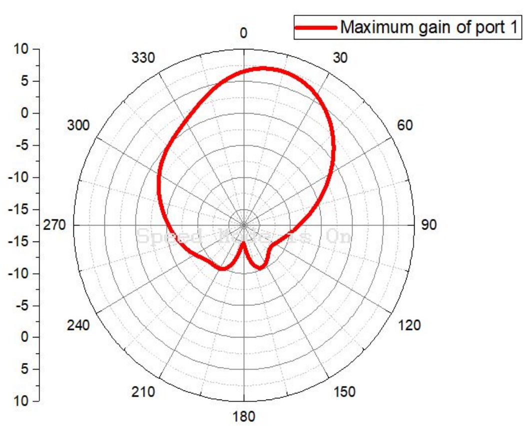
(a)



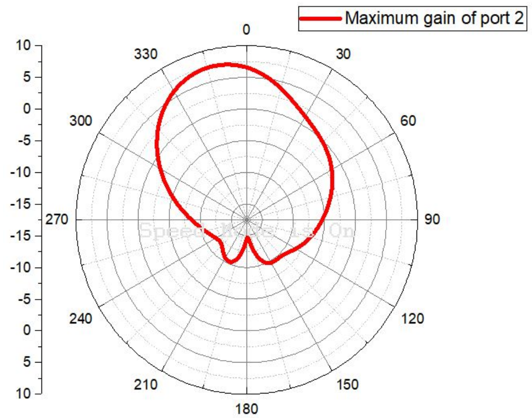
(b)

Fig. 9. Simulation results of the (a) S_{11} and (b) S_{21} with and without EBG structure.

As shown in Fig 10, two beams steering at ±13° with 7.35 dB maximum gain magnitude, have been achieved at 28 GHz.



(a)



(b)

Fig. 10. Simulated radiation patterns of the proposed antenna array system with the excitation of (a) port 1 and (b) port 2.

Table II gives the comparison of our proposed antenna with the state of the art.

TABLE II
COMPARISON OF OUR PROPOSED ANTENNA WITH THE STATE OF THE ART

Ref	Nbre of patches	Bandwidth (GHz)	Gain
4	1	23.5 - 65	5.66 dBi
6	1	24.75-27.5 and 37-42.5	3.4 and 2.4 dBi
7	3	26-40	10.1 dBi
8	1	16-40	3.1-5.5 dBi
9	2	15.6/24.7/41.4	4.6/6.95/7.7 dB
10	16	24.35–31.13	18.7 dBi
This work	2	23.28-35.78	7.35 dB

V. Conclusion

A UWB antenna array with beam steering capabilities is presented. However, by using a multi layer structure, the size of the antenna array is reduced. Thus, by the implementation of EBG structure, an ultra-wideband that covers 23.28-35.78 GHz frequency range with an impedance bandwidth of 44.64% at the center frequency 28 GHz, is attended. Hence, two beams pointing at $\pm 13°$ with 7.35 dB maximum gain magnitude at 28 GHz are achieved. So, the antenna array performances are very crucial to achieve the 5G requirement in both ISM and ka-band.

Our research prospects will focus on reduction of the mutual coupling in beamforming antenna array.

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