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A design of a single element switched beam antenna on Mushroom-like EBG structures

***Abstract**. This paper proposes the low profile switched beam antenna that uses only a single element for 5G applications. The antenna is placed on mushroom-like EBG structures to suppress surface waves. Therefore, bandwidth and directive gain of the proposed antenna can be enhanced. To increase signal in the desired direction and reduce interference in undesired directions, switched beam technique is proposed. There are two directions of main beam antenna 0˚/180˚ and 90˚/270˚ by shorted circuit at terminal edges. The results in terms of bandwidth and gain are compared when the antenna is with and without EBG. The results confirm that the bandwidth and gain can be enhanced when the proposed switched beam antenna is placed on mushroom-like EBG.*

Streszczenie.** W artykule zaproponowano niskoprofilową antenę z przełączaną wiązką, która wykorzystuje tylko jeden element do zastosowań 5G. Antena jest umieszczona na przypominających grzyby konstrukcjach EBG, aby wytłumić fale powierzchniowe. W związku z tym można zwiększyć przepustowość i wzmocnienie kierunkowe proponowanej anteny. W celu zwiększenia sygnału w pożądanym kierunku i zmniejszenia zakłóceń w niepożądanych kierunkach proponuje się technikę wiązki przełączanej. Istnieją dwa kierunki anteny głównej 0˚/180˚ i 90˚/270˚ poprzez zwarcie na krawędziach zacisków. Wyniki pod względem szerokości pasma i wzmocnienia są porównywane, gdy antena jest zi bez EBG. Wyniki potwierdzają, że przepustowość i wzmocnienie można zwiększyć, gdy proponowana antena z przełączaną wiązką zostanie umieszczona na EBG w kształcie grzybka.*(***Projekt jednoelementowej anteny z przełączaną wiązką na konstrukcjach EBG typu Mushroom)

Keywords: switched beam, EBG, surface wave, shorted circuit, bandwidth
Słowa kluczowe: antena szerokopasmowa, przełączalna wiązka, EBG

Introduction

Recently, the demand for wireless communications has been dramatically increased. Several techniques were proposed to manage the request of users. One approach that can improve the performance of wireless communication systems is switched beam technique in smart antenna systems [1] - [2]. Switched beam systems consist of an antenna array, a simple beamforming network and a beam selector. The beamforming method is used to create the main beam pattern to the desired direction and nulling the pattern to interfering directions. Next, the beam having maximum signal strength is selected by the beam selector. Consequently, these antenna systems are interested as their implementation is not complicated and not costly. However, the size of the antenna, even for low profile switched beam antenna, remains a limiting factor for performance in the mobile terminal. Therefore, single element switched beam antennas are discussed.

Considerable literature reveals single element switched beam antenna such as the work presented in [3], single element switched beam antenna with a parasitic ring was delivered. Main beam directions were steered by a shorted circuit at the corner of the octagonal patch, while sidelobe level can be reduced using a parasitic ring. Furthermore, an active centre element that was surrounded by several symmetrically placed parasitic elements was presented in [4]. Beam steering in steps of 60 degrees each was achieved. Also, in work presented in [5], a single-arm rectangular spiral antenna was presented. The beam can be switched by changing the length of the spiral. In addition, switching the direction of the main beam by shorted circuit at different positions of the spiral arm was revealed in [6]. Also, a square loop antenna whose main beam directions can be steered by changing parts of feeding points was proposed in [7]. Moreover, the rectangular patch antenna with a centre feed was presented in [8], which the main beam can point by shorted circuit at the terminal edge. Also, in the works presented in [9] and [10], eight directions of the octagonal patch were proposed which main beam direction can be steered by shorted circuit at terminal edges. In the work presented in [11], the main beam direction can be switched in a dual-frequency band using only a single element which main beam direction can be controlled by shorted circuit at terminal edges. In addition, the main beam can be switched using parasitic elements surround the active patch was revealed in [12] and [13].

However, one problem of microstrip patch antenna can reduce the antenna efficiency and radiation pattern called a surface wave. One technique for suppressing surface waves in periodic structures or unit cells of resonance type is called Electromagnetic Band Gap (EBG) [14]. It does not allow the surface wave to propagate in the substrate around the antenna's resonant frequency. Therefore, all radiations go up in a vertical direction, and gain can be increased [15].

Several pieces of literature proposed the microstrip antenna with mushroom-like EBG structures, such as the work presented in [16]. Three columns of mushroom-like EBG were placed surround the patch antenna to increase the gain and directivity of the antenna. Also, in the work presented in [17], the antenna's bandwidth can be improved by using the mushroom-type EBG structure with glide-symmetric edge vias. Moreover, the increase of bandwidth by placing the EBG cells in the E-plane for surface wave reduction was revealed in [18]. The bandwidth of the microstrip patch antenna can be enhanced by adjusting the parameters such as the gaps between adjacent patches in two orthogonal directions, x-direction and y-direction, respectively, and the related vias' radii. In addition, double layer and edge-location via techniques were combined for EBG size reduction [19]. By applying these techniques, the size of the EBG mushroom was reduced while the mushrooms maintain the broad bandwidth operation and can suppress the surface wave modes. Also, the lowering of mutual coupling between the two radiating elements using EBG was presented in [20].

Recently, many metamaterial periodic structures have been introduced using their filtering behavior to enhance their characteristics, such as those in Electromagnetic bandgaps (EBGs) [21] – [23] and those in Frequency selective surfaces (FSSs) [24] – [25], and lastly, split-ring resonators (SRRs) [26] – [28].

Accordingly, this article proposes a design of the low profile switched beam antenna which using only a single element. The antenna is cooperated with mushroom-like

EBG structures to suppress surface waves. Therefore, the bandwidth and gain of the proposed antenna can be enhanced. The main beam of the proposed antenna can be steered into two directions by shorted circuit at terminal edges. Also, signal strength in the desired direction can be increased while interference signals can be reduced.

The rest of this article is as follows. After a brief introduction, the configuration of the antenna is discussed in the Design antenna section. After that, the design of mushroom-like EBG cooperate with the antenna is revealed in Mushroom-like EBG structures with the antenna section. Next, the shorted circuited to switched main beam direction is shown and analyzed in Switched beam slot antenna with mushroom-like EBG structures section. Finally, the Conclusion section has concluded the article.

Design of antenna

In this article, the advantages of the antenna from the work presented in [11] are adopted due to its simplicity and its ability to switch. Moreover, beam switching is simplified using only a single feeding point. From the work of [11] the square patch can be expressed by

$$\lambda_d = \frac{\lambda}{\sqrt{\varepsilon_r}} \tag{1}$$

where ε_r is the dielectric constant of substrate. The proposed antenna has been designed on FR4 with dielectric constant of 4.7 and substrate thickness (h) of 1.6 mm. The antenna patch and ground plane has been designed with thickness (t) of 0.03 mm. The antenna is designed based on the dimension of f which is adjusted to consider the resonant frequency at 2.6 GHz which is the one of 5G frequency band in Thailand. The SMA feed probe is attached from one side through another side at the patch center which is symmetrically positioned along the E-plane. The dimension of the antenna is shown in Fig. 1. S_{11} is shown in Fig. 2 which operating frequencies are changed when f is adjusted. Next, patch of the antenna is grooved to increase bandwidth as shown in Fig. 3 which parameters a_1 and a are considered. The parameters a_1 and a are adjusted which the maximum bandwidth is occurred, 125 MHz, when a_1 is 28.5 mm and a is 1.5 mm. S_{11} of the slot antenna after adjusted parameter is shown in Fig. 4. Please note that the resonant frequency is slightly shifted due to the area of the antenna patch is grooved. The radiation patterns are radiated in vertical plane which the maximum gain of 5.02 dBi as shown in Fig. 5.

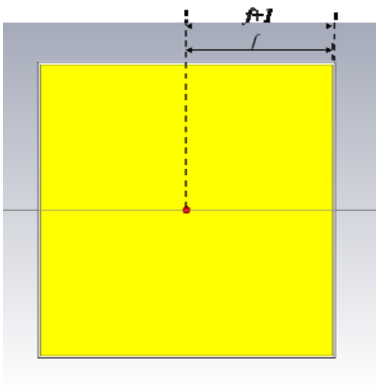


Fig.1. Configuration of the antenna.

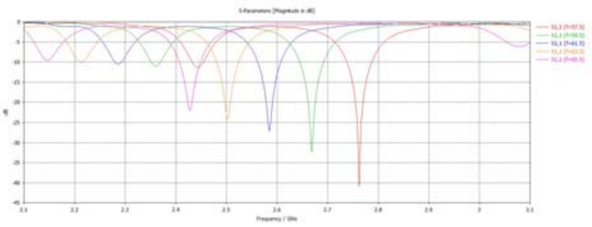


Fig.2. S_{11} of the antenna.

Mushroom-like EBG structures with the antenna

One problem of microstrip patch antenna is excitation of surface wave. Surface waves reduce the antenna efficiency and radiation pattern. One technique used for control of surface waves is using EBG structures which mushroom-like EBG is one simple type of EBG structures. Mushroom-like EBG is shown in Fig. 6 which its inductance and capacitance behaves as a parallel resonant LC circuit. The surface is inductive at below the resonance frequency, while the surface is capacity at above resonance frequency which can be express by [15], [29]

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{2}$$

where ω_0 is the surface impedance. The capacitance C is provided by

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

where w is the width of metallic pad, g is the gap width. ε_0 is the permittivity of free space. The inductance L is related to the thickness of the substrate given by

$$L = \mu_0 h \tag{4}$$

where μ_0 is the magnetic permeability and h is the thickness of substrate.

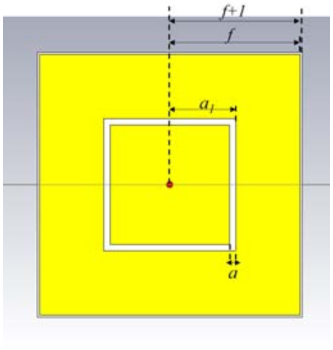


Fig.3. Configuration of the slot antenna.

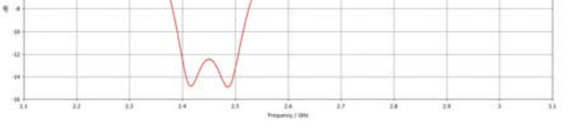


Fig.4. S_{11} of the slot antenna.

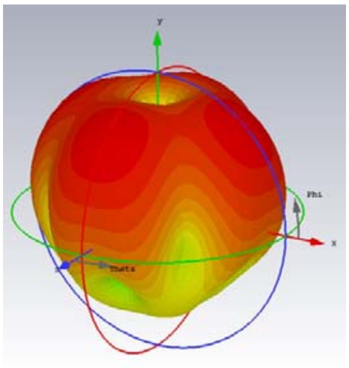
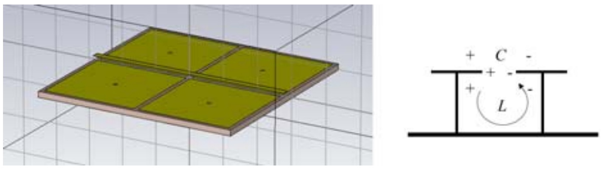


Fig.5. Radiation pattern of the slot antenna.

At its frequency band gap, a very high impedance is occured. Therefore, it does not allow an electromagnetic wave to trasmit through its surface but reflects it in phase with the main radiated wave. The reflection phase of EBG surface wave is zero degree. Consequently, the performance can be improved.

To determine the frequency band gap, unit of the mushroom structure is designed as shown in Fig. 7. The band gap of the mushroom-like EBG is adjusted by turning w and g which is the width and gap of band gap to cover the frequency of 2.6 GHz. S parameters are shown in Fig. 8 which w is 26.45 mm, g is 1.15 mm and via diameter of 1 mm. The EBG is design on FR4 substrate which the hight of 1.6 mm and ε_r of 4.7. It seems that the transmission coefficient in term of S_{21} and S_{12} are very low at desired band gap to confirm the EBG characteristic.



(a) (b)

Fig.6. (a) Mushroom like-EBG structure and (b) equivalent circuit model EBG unit cell.

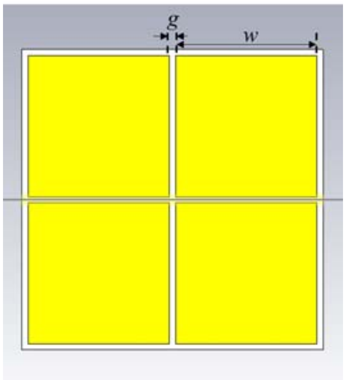


Fig.7. Structure of 2×2 cells EBG.

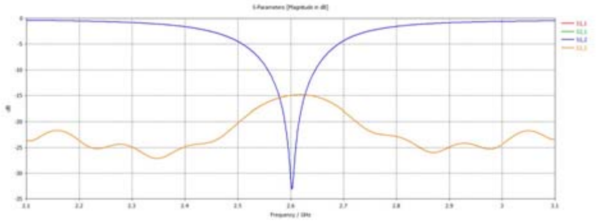


Fig.8. S parameters of EBG.

Next, the slot antenna is placed on mushroom-like EBG. The number of colums of mushroom EBG structures is increased to 5×5 which provide the same size with the antenna. Moreover, mushroom EBG structures are grooved to increase bandwidth of the antenna as shown in Fig. 9. Fig. 10 shows the configuration of the slot antenna which is placed on mushroom-like EBG structure. There are three significant parameters, b, c and i which are the length, the widgth of musgroom EBG and the distance between the slot antenna and EBG. The parameters are turned to achive the highest bandwidth which the result is shown in Fig. 11. As we can see, S_{11} seems wider than appling the slot antenna without EBG. Also, radiation pattern of the slot antenna with EBG structures is shown in Fig. 12 which the maximum gain of 6.03 dBi.

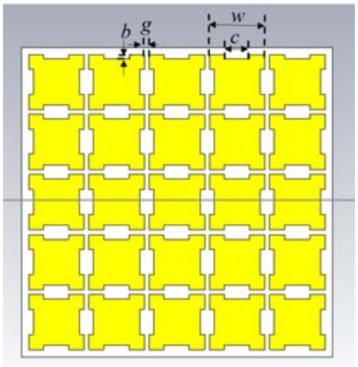


Fig.9. Structure of notched EBG.

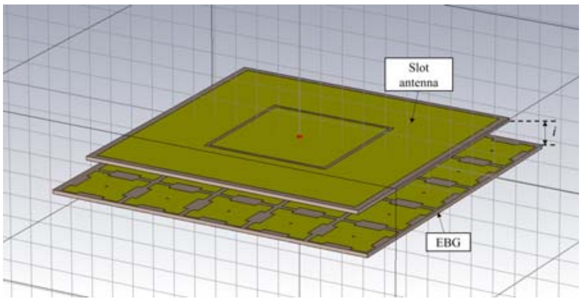


Fig.10. Configuration of the slot antenna with EBG structure.

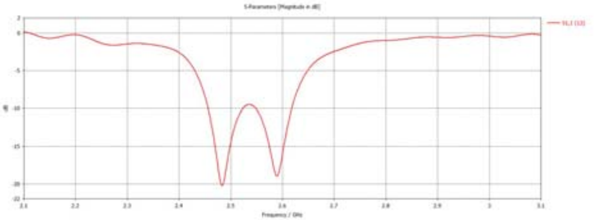


Fig.11. S_{11} of the slot antenna with EBG structure.

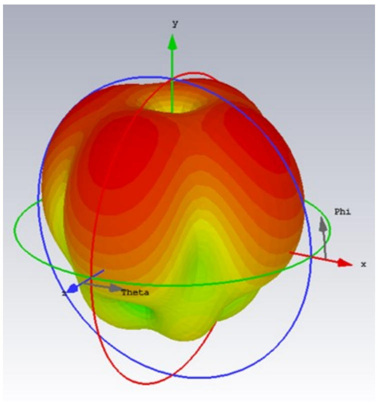


Fig.12. Radiation pattern of the slot antenna with EBG structure.

Switched beam slot antenna with mushroom-like EBG structures

The radiation pattern can be devided to two cases, case A and case B, providing two different directions. Case A, the beam pattern can be switched by a shorted circuit at the left and right edges of the antenna as shown in Fig. 13. At each edge, eight points are shorted circuit which the distance of each shorting point is e and the distance between corner and shorting point is j as shown in Fig. 14. The values of all parameters are concluded in Table 1. Also, case B the beam pattern can be turned by a shorted circuit at the top and bottom edges of the antenna as shown in Fig. 15. S_{11} of case A and case B are shown in Fig. 16 and Fig. 17, respectively. Bandwidth of the proposed antenna is 179 MHz, increased by 43.2% compared with the slot antenna without EBG structures. The radiation pattern of case A is shown in Fig. 18. Also, the radiation pattern of case B is shown in Fig. 19. As we can see, when the edges, which are a shorted circuit, the beam pattern is switched in the same directions of shorted positions. In addition, radiation patterns of case A and case B are similar. This is due to the configuration of the antenna being symmetrical. However, the main beam directions are different because of the different positions of the shorted circuit. Therefore, beam pattern of the proposed antenna can be switched in two different directions, the directions of case A are 90°/270° while the directions of case B are 0° /180°. The maximum gain of the proposed switched beam antenna is 6.73 dBi, increased by 34.06%.

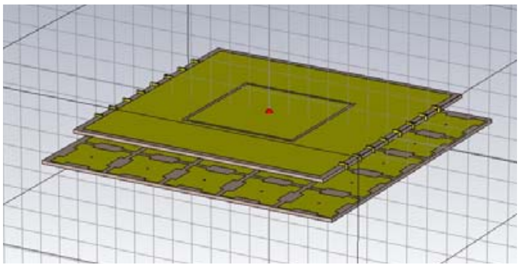


Fig.13. The slot antenna with EBG structures of case A.

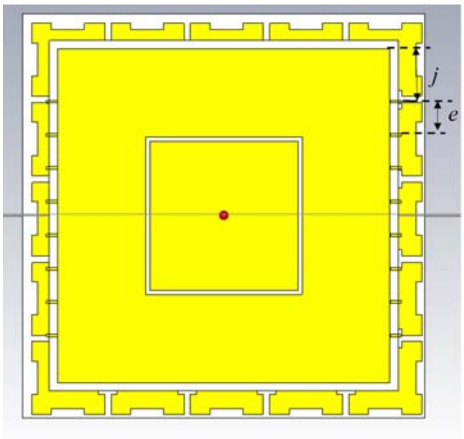


Fig.14. Structure of shorted circuit antenna.

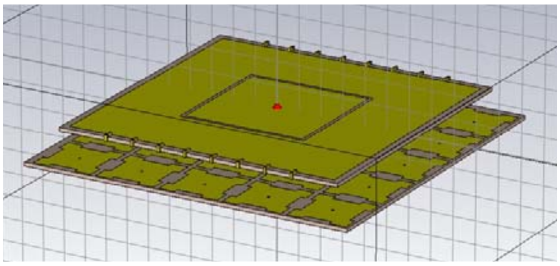


Fig.15. Structure of notched EBG.

Table 1. The dimensions of the antenna.

Parameters	Descriptions	Values
f	the width of patch	60.00 mm
a_1	the width from center of patch to slot	28.50 mm
a	the width of slot	1.50 mm
w	the width of band gap	26.45 mm
g	the gap of band gap	1.15 mm
ε_r	the dielectric constant of substrate	4.7
h	substrate thickness	1.60 mm
t	Patch and ground plane thickness	0.03 mm
b	the length of musgroom EBG	2.20 mm
c	the widgth of musgroom EBG	5.00 mm
i	the distance between the slot antenna and EBG	11.50 mm
j	the distance between corner and shorted point	16.50 mm
e	the distance of each shorting point	22.50 mm
-	the thickness of pins	1.00 mm

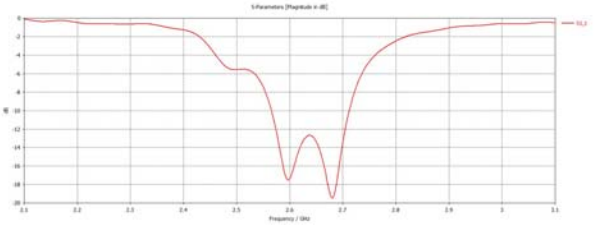


Fig.16. Configuration of the slot antenna with EBG structure.

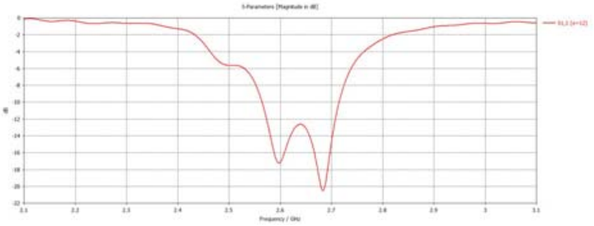


Fig.17. S_{11} of the slot antenna with EBG structure.

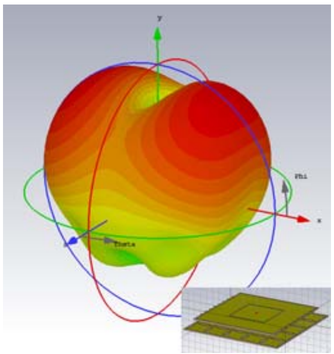


Fig.18. Radiation pattern of the slot antenna with EBG structure.

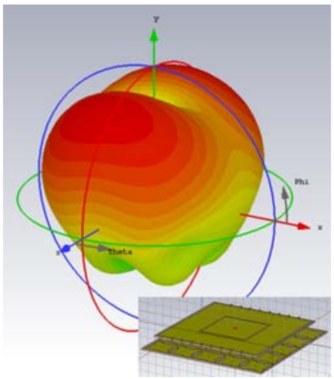


Fig.19. The slot antenna with EBG structures of case A.

Conclusion

This article proposes the single element switched beam antenna for 5G applications. The beam pattern can be steered by shorted circuit at terminal edges. The antenna is placed on mushroom-like EBG structures to suppress surface wave. The switched beam technique is applied to increase signal in desired direction and reduce interference in undesired directions. There are two cases of beam switching, case A which main beam directions are 90°/270° and case B which main beam directions are 0°/180°. The results confirm that when the proposed switched beam antenna is placed on mushroom-like EBG structures the bandwidth and gain can be enhanced to 43.2% and 34.6%, respectively.

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