

DESIGN OF FABRY-PERROT RESONATOR CAVITY WITH BOW-TIE FED-PROBE AND EBG FOR 2×4 ELEMENT ORDINARY MSA

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Abstract

Radiation characteristics of the ordinary 2×4 element rectangular microstrip array (MSA) excited by a Fabry-Perot resonator Cavity (FPC) are compared to those of an MSA fed by conventional phasing lines. The performance of the bandwidth of the antenna is significantly improved compared to that of a traditional MSA without modifying the shape of rectangular patches. This paper presents the design of an alternative feeder by using the technique of Fabry-Perot resonator cavity cooperated with the mushroom-like Electromagnetic Bandgap (EBG) placed on the reflector surface and isolated with the FR-4 substrate dielectric. The improved performance of 2×4 element MSA with FPR cavity designed for 10 GHz is described. Simulated and measurement characteristics are presented and compared. The -10 dB impedance matching bandwidth of the fabricated antenna is 20.7% covering from 9.07 GHz to 11.14 GHz. This alternative feeder is particularly suitable for improving the performance of the ordinary MSA.

Keywords: Microstrip array, bandwidth improvement, bowtie antenna, mushroom-like EBG, planar beam

Introduction

Phased array antenna, especially the microstrip array antennas (MSA) have developed for utilizing in many applications of the communication systems, which required generation of high directional beam patterns in the particular direction. The MSA is not only the compact and low-profile structure, but its gain and bandwidth also could be improved by modifying at the radiating patch (Shambavi *et al.*, 2009). In a part of the feeding system for MSA, nowadays, the proper feeder for MSA have been investigated and designed, relentlessly. Many researchers have developed techniques to reduce feed loss and improve gain and bandwidth of MSA. From works of literature, we can separate the

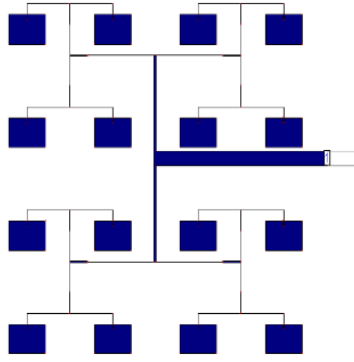
feeding methods for MSAs about four ways that were used to be feeding systems such as stripline feed, probe feed, aperture-coupling feed and proximity-coupling feed (Singh and Gupta, 2013).

From reviewing the literature, the classification of power feeding for MSA divided into two methods. Firstly, the conventional power divider method is an old system by feeding the power through the transmission line or stripline that are pasted on PCB and directly connected to the radiating patches, which are placed on the same surface, as shown in Figure 1(a). Such corporate feed network provided the gain and beamwidth for the 2×2 element was 10.78 dBi and 40.48 degrees

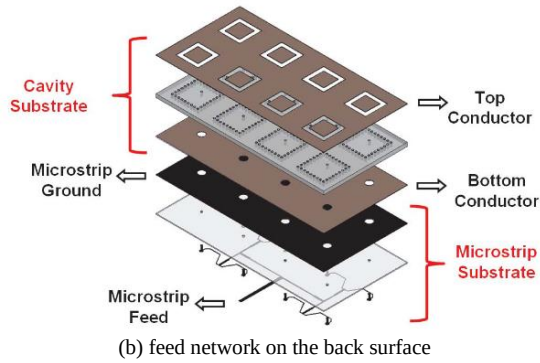
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and improved the gain and beamwidth for the 4×4 element of MSA around 14.81 dBi and 23.111 degrees, respectively (Shambavi *et al.*, 2009), (Kushwaha and Kumar, 2016) Furthermore, Singh and Gupta found that when replaced the rectangular patches of MSA to be the circular shape. At the same



(a) Corporate feed network on the top surface



(b) feed network on the back surface

Figure 1. The feeding network by using striplines feed to rectangular patches array

time, the corporate feed was used to transmit the power to patches array. The gain of MSA still yielded a higher gain and able to reduce the side lobe when compared to the radiation patterns of the square patches array (Singh and Gupta, 2013). Secondly, the microstrip feed network was placed in the back surface of the PCB while patches array was placed on the opposite side, as shown in Figure 1(b). This method could reduce the mutual coupling between the feed network and the patches (Mohamed *et al.*, 2010). However, the power loss in the feed lines will be appeared in term of the thermal, causing the radiation efficiency was degraded. Furthermore, bandwidth improvement also was limited by such a feeding system. Therefore, the current researchers have attempted to overcome such the weakness by investigating new feeder for MSA by using the dual 1-D EBG resonators (Weily *et al.*, 2006) the parasitic patch and capacitive feeding technique (Raut and Talandage, 2015) and modified microstrip array feed. (Kumar and Chaudhary, 2016).

Besides, in the past, the researchers also proposed other methods to excite the MSA by using the conventional waveguides and probes made from the various shapes of the microstrip patches, as illustrated with diagram in Figure 2. However, such ways were very hard to reduce the thermal loss in the feeding system, whereas some methods have the difficulty for fabrication. Currently, we found that the Febry Perot resonator Cavity (FPC) is attracted to be a choice of processes for MSA excitation. With the reason, the FPC can storage the electromagnetic energy inside the structure based on the cavity resonator (Lu *et al.*, 2012) due to reflection of waves between the top and button walls of the cavity. The ordinary Febry Perot antenna (FPA) consists of a

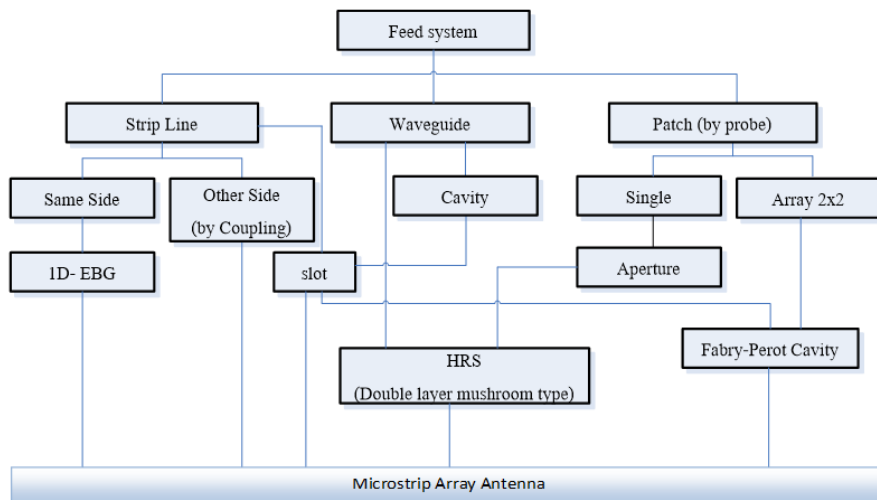


Figure 2. Various methods to improve the performance of MSA

printed microstrip radiator and resonant cavity, which was excited with any kind of antenna (Liu *et al.*, 2009; Liu *et al.*, 2013; Darshanand and Anil, 2017). The principle concept of FPC is how to generate the appropriate power pattern exciting to the MSA. The main idea is to calculate and design the desired power pattern inside the cavity for exciting to the MSA for achieving the desired performance.

The 10 GHz frequency band according to the federal communication commission (FCC) is designated for the fixed-mobile communication, amateur satellite, the amateur radio communication, maritime, and private land mobile (<https://transition.fcc.gov/oet/spectrum/table/fcc-table.pdf>). Additionally, for the future 5G at 10 GHz, the measurement and modelling technique was presented to consider about many devices connected to 5G will be used in the indoor environment (Eras *et al.*, 2015). Therefore, in this paper, we propose the 2×4 elements of microstrip planar array exciting with the main beam of the radiation pattern, which is generated from the FPC at the operating frequency of 10 GHz to support the applications as aforementioned. The essential idea is the shape of the radiation pattern creating from the FPC must have the appropriate excitation phase and amplitude incidents to each patch of MSA for achieving gain and bandwidth improvements in the desired direction of the main beam. However, the proposed antenna is neglected about the flatness of its structure since it is focused for use in fixed-mobile communication system on land. To achieve the original MSA operated in the wideband frequency; therefore, a bowtie dipole antenna is selected for exciting the MSA due to their simple, and planar structure as well as ease of design and fabrication, and they can provide much larger impedance bandwidth than thin wire dipoles (Qu *et al.*, 2008).

Furthermore, we use the mushroom-like Electromagnetic Band Gap (EBG) work together with a bowtie dipole to control the beam shape including the bandwidth of exciting power, appropriately, incident to the surface of each microstrip patch (Li *et al.*, 2012). The mushroom-like EBG is one type of metamaterial structures has been used in many applications of antenna technology and applied to the design of the low profile antenna, which needs to improve the performance (Yang and Rahmat-Samii, 2003; Li and Esselle, 2007; Neo and Lee, 2013). The mushroom-like EBG structure is formed by periodic arrays of conducting patches, which are connected to the ground plane with vertical vias.

In this paper, we propose the uniform phased array of ordinary rectangular MSA, which each patch is excited with the proposed feed system,

which consists of a bowtie dipole and mushroom-like EBG structure. Both essential parts of the FPC were designed to function as the bottom layer of Farby-Perot resonator to control the beamforming that radiates from a bowtie dipole, which is placed above the unit cells of mushroom-like EBG placed on FR-4 substrate and ground plane, respectively. Thereby the second function of mushroom-like EBG is also a reflector of MSA by itself. To achieve the uniform phase for MSA, and support the MSA to provide the bandwidth at least ten times of the bandwidth ever obtained from MSA, which excited by the cooperate stripline feed network. The arrangement of EBG unit cells is investigated to meet the proper position when collaborating with a bowtie dipole, while the number of EBG unit cells also are optimized. In Section 2, the theory of uniform phased array and the conceptual design of the proposed excitation by using a bowtie dipole operated together with the mushroom-like EBG structure and supplied to the MSA will be mentioned. Section 3 illustrated the simulated results of the radiation characteristics of the proposed FPC and compared to the radiation performance of the MSA with phasing lines by using CST simulation software. In Section 4, we validated and discussed the measured results by comparing to the simulation results. Lastly, in Section 5, the conclusion will be given.

Antenna Design

The structure of the FPC in this paper consists of two layers. Firstly, the bottom layer is a reflective surface formed by mushroom-like EBG on the top surface of PCB, which the back cover is conducting ground plane. Secondly, the top layer is superstrate created by the rectangular microstrip patches array of 2×4 element, which excited the power by bowtie dipole installed at the centre of the bottom layer, as shown in Figure 3. The substrate and superstrate are FR4-PCB ($\epsilon_r = 4.5$) of thickness 0.8 mm. The dimension of the top and bottom layers (W and L) equals 81 and 110 mm, respectively. Whereas, the spacing (H) between the two layers is initial given with one wavelength (~ 30 mm) at 10 GHz of the design frequency.

The dimension of a bowtie antenna is optimized by using CST simulation software, as displayed in Figure 4. We found that length (l_b) is around 0.15875λ , the width of broad end and narrow ends (w_{b1} and w_{b2}) are around 0.25λ and 0.03λ , respectively. While the spacing of feed gap (w_g) equals to 0.0033λ , and the thickness of bowtie dipole (t_b) is around 0.0033λ . The simulation results show the reflection coefficient (s_{11}) at the 10 GHz is

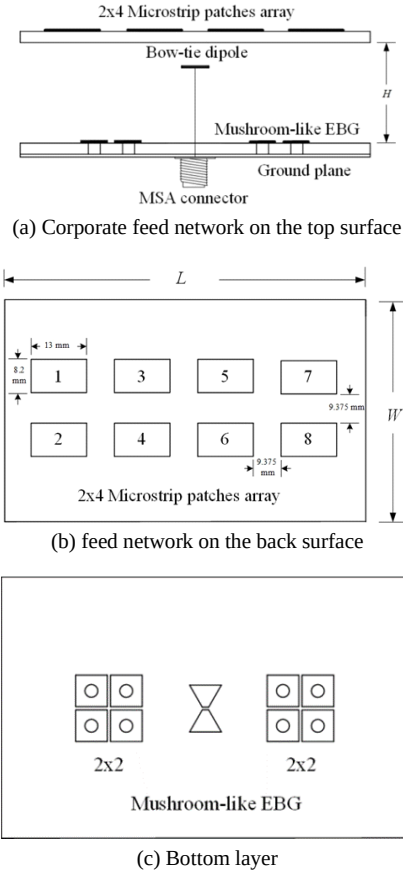


Figure 3. Structure of 2x4 MSA feed with FPC based on bowtie fed-probe and mushroom-like EBG

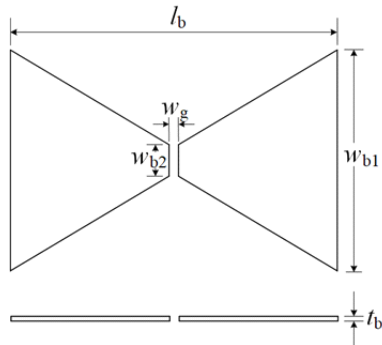


Figure 4. Configuration of bowtie dipole

about -41.963 dB with frequency bandwidth around 2,686 MHz for $|S_{11}| \leq -10$ dB and the gain is 2.257 dBi, as shown in Figures 5 and 6 respectively.

After that, the dimension of mushroom-like EBG is calculated analytically. The parameters of the EBG structure are patch width (W_p), gap width (g), substrate thickness (t), dielectric constant (ϵ_r), and vias radius (r), as labelled in Figures 7(a) and 7(b). Since the periodicity ($W+g$) is small compared

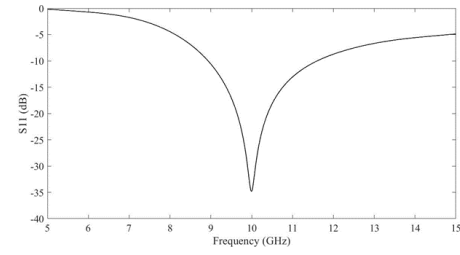


Figure 5. Simulated reflection coefficient (S_{11}) of bowtie dipole

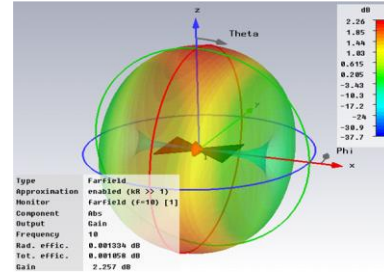


Figure 6. Simulated radiation pattern, efficiency and gain of bowtie dipole

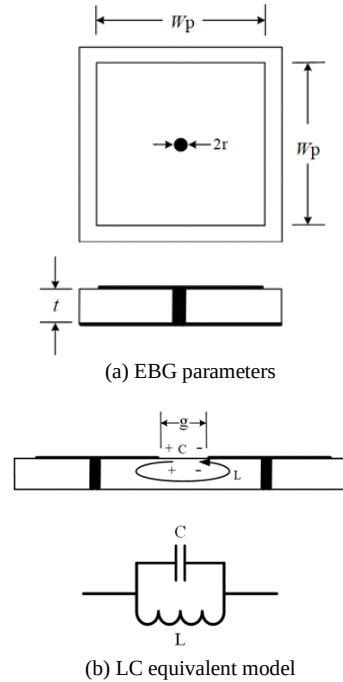


Figure 7. Configuration of the mushroom-like EBG structure

to the operating wavelength, such EBG structure can be explained with equivalent lumped LC elements, as illustrated in Figure 7(c) (Yang and Rahmat-Samii, 2009)

With the mushroom-like EBG structure, capacitance result by the gap between the adjacent

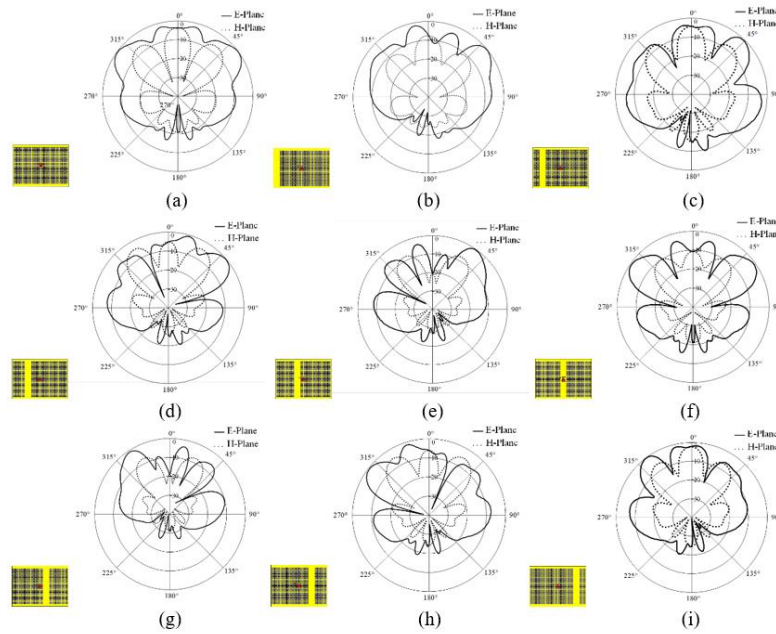


Figure 8. Variation of number and arrangement of EBG unit cells affect the shape of the radiation pattern

patches and inductance result from the current along with the adjacent patches. Therefore, the impedance and the resonant frequency of a parallel resonant LC circuit is expressed by (1) and (2), respectively.

$$Z = \frac{j\omega L}{1 - \omega^2 LC} \quad (1)$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (2)$$

Since the desired resonant frequency is specified at 10 GHz, the patch width is derived analytically by using the constitutive relations relates the capacitance to the permittivity of substrate and air including the gap width by the following equation

$$C = \frac{W\epsilon_0(1+\epsilon_r)}{\pi} \cosh^{-1} \left(\frac{W+g}{g} \right) \quad (3)$$

The substrate thickness is calculated by using the relation of inductance and the permeability of air by the equation:

$$L = \mu_0 t \quad (4)$$

where the permittivity and permeability of the air are $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ and $\mu_0 = 4 \times 10^{-7} \text{ H/m}$, respectively. Since the selected substrate of the EBG structure is FR-4 type and the analytical calculation by using (1)–(4), we found that the square patch width, vias radius, and gap width are about 0.167,

0.0167 λ , and 0.033 λ , respectively. After the optimized dimension of the bowtie dipole and mushroom-like EBG are obtained. The 12 $\times$ 18 cells of EBG are arrayed on the FR-4 PCB and backed with the ground plane, while the bowtie dipole is located at the centre of EBG array by giving the initial height of the bowtie dipole is around 0.75 λ (22.5 mm).

To investigate the proper shape of the radiation pattern that according to the concept of uniform phase and amplitude for exciting to 2 $\times$ 4 element of MSA, the number and arrangement of the EBG unit cells are considered, as illustrated in Figure 8. We found that removing the row of 1 $\times$ 6 EBG unit cells out of FR-4 PCB and varying the placement of remaining EBG unit cells can influence the shape of the radiation pattern. However, the balance and uniform distribution (planar beam) of a radiation pattern is significant variation and attractive. But the nine conditions, as shown in Figure 8, could not wholly response to our requirement unless the arrangement in Figure 8(f). As a consequence, the decrement of the number of EBG unit cells is tested and simulated repeatedly to find the appropriate quantity. In Figure 9, to retain the balance of the radiation pattern according to the configuration in Figure 8(f), therefore, the arrangement of the EBG unit cells are symmetry separated into twice (two groups of 10 $\times$ 6, 8 $\times$ 4, 4 $\times$ 4, and 2 $\times$ 2 element, respectively) on the substrate, while a bowtie dipole is at the centre. In this figure, we also show the simulated results of the radiation pattern of each

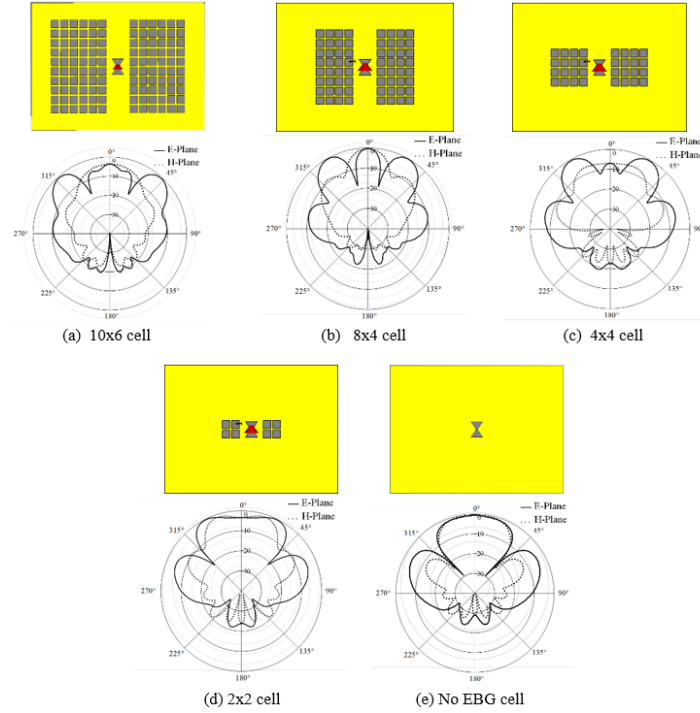


Figure 9. Configurations and radiation patterns of the proposed FPC with a different number of EBG unit cells

case for considering the most proper one. Finally, we found that two groups of 2×2 element of mushroom-like EBG can provide the radiation pattern both in E-plane and H plane similar to the planar beam when compared to the profile of single bowtie dipole without EBG, as shown in Figure 9(e).

Since the proposed structure is integrated with a bowtie dipole, mushroom-like EBG, and MSA, therefore, the combined structure must be optimized again by adjusting the height of bowtie from the EBG surface from 22.5 mm (0.75λ) to 20 mm (0.66λ). From the simulation results in Figures 10 and 11, we found that the gain (0.811 dBi) and S_{11} (< -10 dB) are in our requirement. Whereas, the frequency bandwidth is about 2.718 GHz, which is slightly increased when compared to the bandwidth of single bowtie dipole. After that, the most proper spacing (H) between two layers is investigated again by CST simulation to consider the results of S_{11} and gain by comparing from the different spacing of 22.75, 30.00, 33.75, and 37.50 mm. From the simulated results, as illustrated in Figure 12. We found that the most appropriate spacing between the two layers is 30 mm because the resonant frequency closes to 10 GHz, $S_{11} < -10$ dB, and gain is around 14.75 dBi.

However, the dimension of each patch of 2×4 element MSA, as shown in Figure 3(b), is designed and calculated by using the fundamental theory of

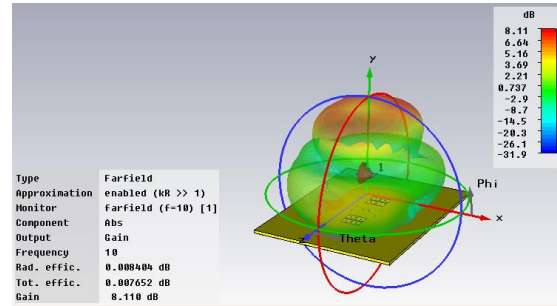


Figure 10. Simulated 3-D Radiation Pattern of the FPC with spacing between the bowtie probe and EBG surface equals to 0.66λ .

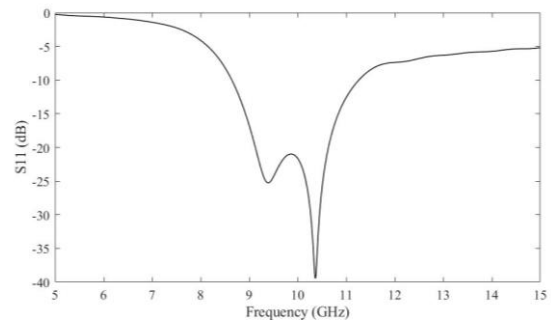


Figure 11. Simulated S_{11} of the FPC with the optimized dimension

the rectangular microstrip antenna. The width and length of each patch at the operating frequency of 10 GHz are 8.2 mm and 13 mm, respectively. The

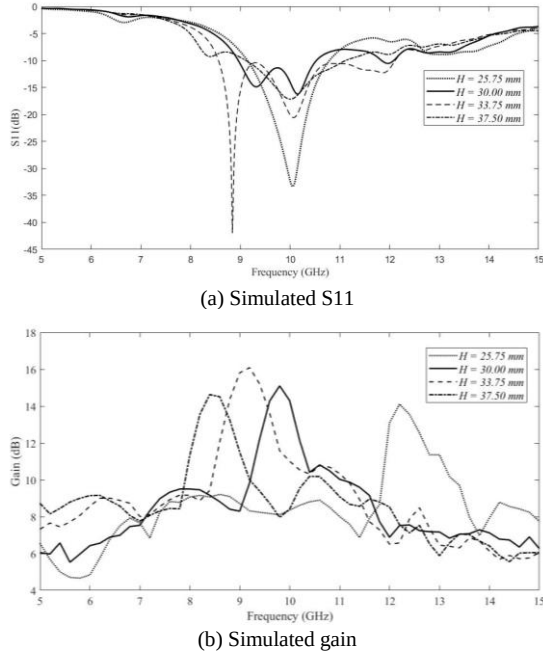


Figure 12. Simulated results of the MSA and FPC with the different spacing (H)

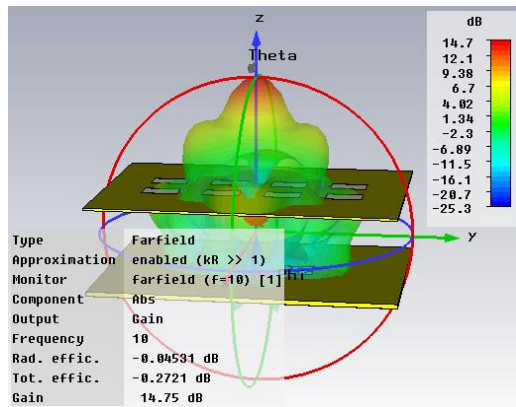


Figure 13. Simulated 3-D pattern of 2x4 element MSA excited with FPC

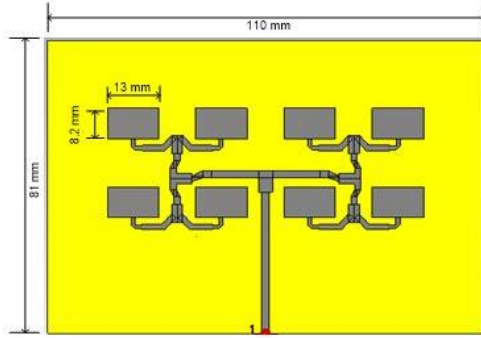
spacing between the adjacent pieces is around 9.375 mm. With such the dimension and placement, the magnitude and reflection phase of each ray of EM wave from bowtie dipole incident to each patch centre are calculated by using S_{21} mode of CST software, as summarized in Table 1. We found that at the centre of patches No. 3, 4, 5, and 6 have the same magnitudes of S_{21} equal to -28.81 dB. Meanwhile, while those of pieces No. 1, 2, 7, and 8 are -56.52 dB, equally. Besides, It can be noted that the phase difference between the rows (odd and even numbers: 1-2, 3-4, 5-6, and 7-8) and patch pairs No. 3-5 and 4-6 is 180 degrees, equally. However, we found that the phase difference of patch pairs No. 2-4 and 5-7 are 204.13 degrees, but those of patch pairs No. 1-3 and 6-8 are 155.85 degrees. Show that this MSA structure can be excited with the exact uniform magnitude and phase at the vertical patch pairs in E-plane (No. 1-2, 3-4, 5-6, and 7-8). Whereas the phase differences of patches No.1, 2, 7, and 8 differ from 180 degrees around 24.14 degrees, similarly.

Simulation Results

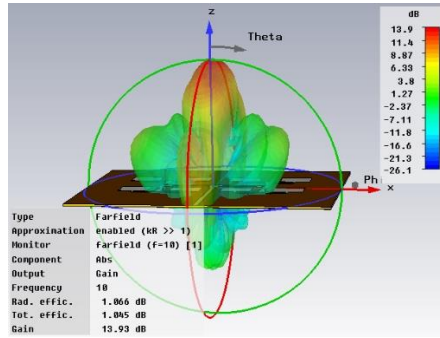
In Figure 13, the MSA with the proposed FPC is simulated to verify the results. It is found that this antenna yields the maximum gain and radiation efficiency around 14.75 dBi and -0.045 dB, respectively. To compare the radiation performance between the MSA with the proposed FPC and phasing line techniques, we also simulated the gain and efficiency of the MSA with the corporate feed network by using stripline as phasing line, as displayed in Figure 14. It is shown that MSA with phasing lines can provide the gain around 13.93 dBi, slightly lower than the gain obtained from MSA with FPC. Meanwhile, it gives radiation efficiency around 1.066 dB. However, even it provides higher efficiency, but the MSA with FPC yields the more extensive bandwidth, as shown in Figure 15. It is seen that the obtained bandwidth for $|S_{11}| \leq -10$ dB of SMA with FPC and phasing lines are about 1,670.60 MHz and 101.12 MHz or 17.14 % and 1.01 % of the centre frequency 10 GHz, respectively.

Table 1. Magnitude and reflection phase excited to each patch of MSA

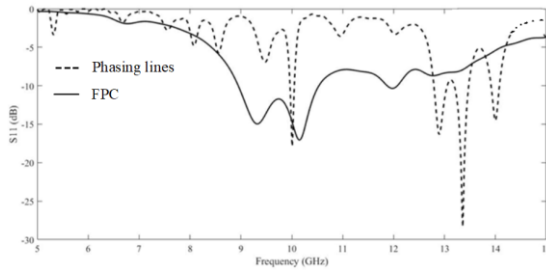
Patch No.	Magnitude (dB)	Phase (Degree)
1	-56.52	61.38
2	-56.52	-118.61
3	-26.81	-94.47
4	-26.81	85.52
5	-26.81	85.52
6	-26.81	-94.47
7	-56.52	-118.52
8	-56.52	61.38



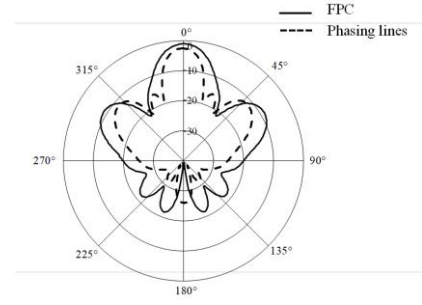
(a) MSA with phasing lines configuration



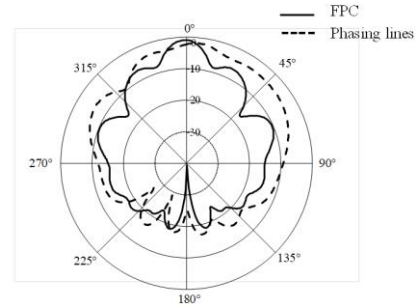
(b) Simulated result

Figure 14. Simulated 3-D pattern of 2×4 element MSA excited with corporate feed network**Figure 15. Comparison results of S11 between MSA with FPC and phasing lines**

The radiation patterns that obtained from simulation both of in E- planes and H-planes of 2×4 element MSA with different feeding are compared, as displayed in Figure 16. It is noted that the beamwidth of patterns generated by MSA with FPR and phasing lines are around 22.8/17.9 and 16.6/98.8 degrees (E-plane/H-plane), respectively. It is shown that the MSA with the proposed FPC provided the larger beamwidth in E-plane, while the beamwidth in H-plane is narrower. As a sequence, this antenna can afford the more extensive coverage area with the horizontal polarization. In contrast, when this antenna is utilized with the vertical



(a) E-Plane



(b) H-Plane

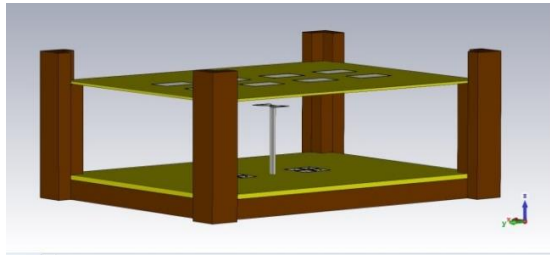
Figure 16. Comparison results of radiation patterns for 2×4 element MSA with (a) FPC and (b) phasing lines

polarization, it can extend the altitude in the vertical angle of the radio link.

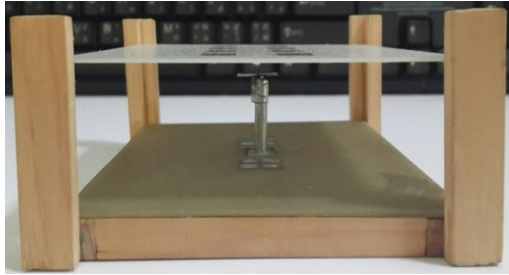
Experimental Results

The prototype of 2×4 element MSA with FPC is fabricated for measuring the radiation performance and then verified to the simulation results as illustrated in Section 3. Since the structure of the antenna for simulation, as displayed in Figures 1(a) and 13, could not be fabricated for practical measurement. Therefore, we used four wood poles locking at four corners of the top and bottom layers, as shown in Figure 17.

To observe the impact of four wood poles affecting the radiation characteristic of the antenna, we also simulated the antenna structure in Figure 17(a). The obtained patterns from simulation (antenna prototypes without/with wood poles) and measurement are superimposed and displayed in the same graph, as illustrated in Figure 18. It shows that the simulated patterns in E-plane/H-plane at 10 GHz of the operating frequency of 2×4 element MSA with FPC with and without wood poles are somewhat identical around 22.8/17.9 degrees and 22.2/17.6 degrees, respectively. However, the measured patterns of the fabricated antenna radiated



(a) Structure for simulation



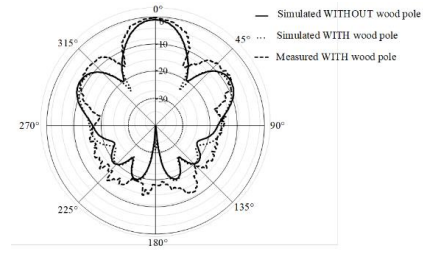
(b) prototype structure for measurement

Figure 17. Photos of the fabricated antenna for simulation and measurement

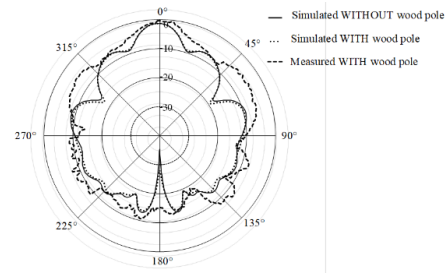
the more power in the direction of $\pm 45^\circ$ than those of the simulated results and provided the larger beamwidth, slightly.

To verify the antenna bandwidth; a vector network analyzer performed measurements the S_{11} of antenna prototype in an anechoic chamber. The simulated and measured S_{11} of the 2×4 MSA with FPC are shown in Figure 19. The measured bandwidth for $|S_{11}| < -10$ dB is around 2,070 MHz or 20.48 % of the centre frequency 10 GHz. The differences between the measured and simulated results are because of the fabricated antenna was fine tune the input impedance of FPC very close to 50 ohms causing the measured S_{11} is somewhat perfect. Besides, we found that the reflection coefficient of the antenna is not significantly affected by the additional wood poles for locking between two layers.

Table 2 shows that the 2×4 element ordinary rectangular MSA with FPC and conventional phasing lines have the same resonant frequency of 10 GHz. The simulated gain in the boresight direction of the MSA with the FPC (without the



(a) E-Plane



(b) H-plane

Figure 18. Simulated and measured radiation patterns of 2×4 element MSA excited with FPC

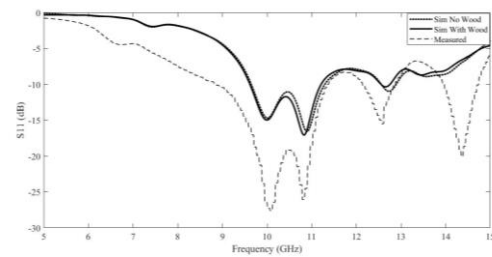


Figure 19. Comparison between the radiation patterns from simulation and measurements

wood poles) is 14.75 dBi, which is 1.87 dBi higher than that of the MSA with the phasing lines. Even though four wood poles are added to the structure, but the gain, bandwidth, and beamwidth are not significantly affected by them. The simulated gain is reduced around 0.58 dBi when compared to that of the MSA without wood poles. That is not significant, because of the advantage of this proposed antenna is the obtained bandwidth of around 17.14 % (without wood poles) and 20.70 % (with wood poles), which are 16.30 % and 19.86 %

Table 2. Performance comparison between 2×4 MSA excited by FPC without and with four wood poles

Performance	2x4 element of rectangular microstrip array (MSA)		
	FPC (Simulation) *without wood poles	FPC (Simulation) *with wood poles	FPC (Measurement) with wood poles
Gain (dBi)	14.75	14.17	14.71
Bandwidth (MHz)	1,676.60	15,875	2,070.00
Beamwidth	17.14%	16.03%	20.70%
in E-/H-planes (Degree)	22.8/17.9	22.2/17.6	24.2/18.5

larger than that of the MSA with phasing lines, respectively. However, the measured gain (14.71 dBi) of the fabricated antenna is higher than 0.54 dBi when compare to the simulated result (14.17 dBi). Besides, in Table 2, it is seen that the beamwidths for H-plane patterns of 2×4 MSA with FPC, both simulation and measurement are rather narrow. However, when we back to observe the radiation patterns in Figure 18(b), we found that its patterns are not smooth like as the H-plane pattern obtained from MSA with phasing lines. This discrepancy can result from the practical adjustment the input impedance of a bowtie probe closed to 50 ohms and partially from the deviation of the dielectric and metallic losses in simulation and the measurement setup and also the tolerance of the fabricated antenna.

Conclusions

The radiation characteristics of the 2×4 element ordinary rectangular MSA fed by FPC and fed by phasing lines are simulated and compared. The results showed that the performance of the ordinary MSA with the proposed FPC is significantly improved, especially the bandwidth, whereas the antenna gain is slightly increased. However, when the input impedance of the fabricated antenna was fine-tuned closed to 50 ohms, the obtained bandwidth and gain were recovered to 20.75% and 14.71 dBi, respectively. Finally, we found that 2×4 element ordinary rectangular MSA with the proposed FPC can improve the bandwidth and slightly increase the gain without any modifying the shape of the rectangular patch. As a sequence, the alternative feed system is particularly suitable for enhancing the performance of the ordinary MSA.

Acknowledgments

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