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Design of Slow Wave Microstrip Patch Antenna Array

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Abstract

This paper presents the design of a Slow wave Micro-Strip (SMS) patch antenna array with two different configurations. The main difference is presented in the radiation patterns of these two configurations. The first array is designed to radiate towards a single user, while the second radiates equally towards two distant users. The SMS technique is applied on the developed arrays in order to reduce their overall surface area. This technique is based on the slow wave effect created using a double layer Roger stack, with an artificially modified bottom layer. The artificial layer is hosting rows of metallic via holes having a cylindrical shape. The insertion of these metallic via holes increases the effective permittivity of the substrate layer, thus, a slower wave propagation is obtained. Consequently, a lower wavelength and smaller antenna size are achieved. The proposed SMS 2×2 antenna arrays resonate around the Industrial, Scientific and Medical (ISM) radio bands at 2.45 GHz and targeting the Wi-Fi and Bluetooth applications. A good agreement between the simulated and measured results is achieved with up to 57 % size reduction for both configurations.

Keywords: Microstrip patch antenna, antenna array, miniaturization, slow wave technique, return loss, gain.

I. INTRODUCTION

The continuous development in wireless communication systems raised the demand for compatible antenna systems having good performance and small size. Microstrip patch antenna (MPA) serves as an appropriate candidate for such enhancement due to its simple planar configuration and physical characteristics (light weight, small size with low profile), as well as its low fabrication cost [1].

Recently, many research papers have been conducted on MPAs using different miniaturization techniques such as introducing fractural slots on radiating element [2–4]. Defected Ground Structure (DGS) [5–6], Electromagnetic Band Gap structures (EBG) [7] and the use of high permittivity dielectric materials [8]. In [2], authors use slot etching on the surface of the radiating patch in order to decrease the antenna surface area up to 80% of its original size. The drawbacks observed when employing the slot etching technique were low gain level and broad radiation pattern [3]. Authors in [4] use Complementary Split Ring Resonators (CSRRs) to design a compact size two element antenna array operating at 5 GHz. The achieved surface area reduction is 47%, with an acceptable gain level of 8.9 dBi. Defected Ground Structure (DGS) technique is based on creating a non-uniform ground plane. The main purpose of DGS technique is to confine the electric field between the radiating element and dielectric surface while some part of the wave travels into air through DGS slots. The DGS assists in having smaller size and enhanced bandwidth [5–6]. The implementation of a 2×2 microstrip patch antenna array with Electromagnetic Band Gap (EBG) structures is studied in [7]. A 47% miniaturization is obtained with a total gain equals to 8.8 dBi. These results are achieved on the expense of antenna array design complexity.

Another method to reduce the size of the MPA, is presented by the use of periodic structure made of hollow copper cylinders embedded in the substrate layer. Such method is known as Substrate Integrated Artificial Dielectric (SIAD), it helps in creating relatively high paramagnetic media where the effective permeability is higher than the effective permittivity [8]. The achieved miniaturization percentage (around 34%) is considered low when compared to other techniques [9]. Other researchers used the Artificial Magnetic Conductor (AMC) material in the ground plane at the back of each array element [10–11]. This technique helped in obtaining moderate miniaturization and minimized back lobes at the expense of the gain level (4.2 dBi for four elements array).

In [12], the Slow wave Micro-Strip (SMS) miniaturization technique is applied to reduce the size of a MPA. This technique is based on using a two layer substrate stack, where rows of metallic via holes are inserted in the bottom layer. These via holes helped in confining the electric field lines in the lower substrate layer, hence, raising up the value of the effective relative permittivity (ε_{reff}). This raise is the main cause to slow down the signal propagating through the antenna, hence, lowering its wavelength which is in turn proportional to the overall antenna size. An overall surface area reduction of 32% is achieved. Based onthis concept (SMS), the design of the 2×2 patch antenna arrays is presented in this paper.

The organization of the paper is as follows. In section II, the SMS miniaturization technique is presented. Next in the related work section, the design of an SMS inset feed patch antenna element is presented along with that of the conventional (MS) and SMS antenna arrays. The section ends with the simulation and measurement results. A comparison between the designed SMS antenna arrays and those presented in the state of art is conducted in comparison section. The paper ends with a conclusion and future prospective.

II. THE CONCEPT OF THE SMS MINIATURIZATION TECHNIQUE

The miniaturization techniques that have been presented in the introduction are mainly based on the use of single substrate layer with varying degree of complexity. One of the efficient techniques in reducing the size of a patch antenna is proposed by the authors in [12]. Authors have developed the SMS technique on the basis of Metamaterials (MTMs), where a simple artificial substrate is created. This artificial substrate is achieved by the use of a double layer Roger stack having a total height of 1.103 mm. Table 1 includes the characteristics of the Roger stack used. The bottom substrate layer is modified by vertically inserting cylindrical metallic via holes inside it. These via holes are sandwiched between the top substrate layer and the ground plane.

In [13], a parametric study with respect to the diameter of these cylindrical shaped via holes is conducted. The optimum results were selected with respect to less attenuation losses introduced. The optimum diameter and height of the via holes are 0.4 mm and 0.813 mm, respectively. To reduce the degree of complexity in the fabrication process, an enhanced via holes shape is used. The pellet used on top end of the via holes [13] is removed. The final hollow cylindrical shape is easier to drill in the printed circuit board of the antenna arrays. Furthermore, the separation distance between the adjacent via holes (lateral and longitudinal) is optimum at 0.8 mm as obtained in [13].

Table 1. Characteristics of the used Roger stack

Substrate Type	RO4403	RO4003
Position in stack	Top layer	Bottom layer
Dielectric constant [ε_r]	3.4	3.55
Loss Tangent [$\tan\delta$]	0.005	0.0027
Height h [mm]	0.29	0.813
Copper thickness [mm]	0.05	0.05

The insertion of these via holes helps in shortening the distance travelled by the electric field from the radiating patch to the ground plane, thus, raising the effective relative permittivity and lowering the guided wavelength λ_g. Accordingly, a decrease in the fringing fields at the patch periphery is noticed. This is justified by calculating the new values of the effective relative permittivity and the extended length ΔL from Equ. (1) and Equ. (2), respectively. These new values (ε_{reff} , ΔL and h) are depicted in Table 2.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{(\varepsilon_r-1)}{2}\left(1+12\frac{h}{W}\right)^{-\frac{1}{2}} \qquad (1)$$

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)}{(\varepsilon_{reff}-0.258)}\frac{\left(\frac{W}{h}+0.264\right)}{\left(\frac{W}{h}+0.8\right)} \qquad (2)$$

Where W is the width of the patch antenna element, h is the height of the substrate. As a conclusion, a compact size antenna is achieved due to the reduced value of λ_g.

Table 2. Summary of the new values corresponding to: height of the substrate (h), effective relative permittivity (ε_{reff}) and extended length (ΔL)

	Old value	New value
Dielectric height h [mm]	1.103	0.29
Effective relative permittivity ε_{reff}	3.313	3.425
Extended length ΔL [mm]	0.531	0.141

III. RELATED WORK

III.I. Design of the SMS Patch Antenna Element

Herein, the design of a miniaturized SMS patch antenna element resonating at 2.45 GHz is presented. The proposed antenna element is designed using the Roger stack provided in Table 1. It is worth mentioning that this SMS antenna element is a modified version of the optimum case that have been presented by authors in [12]. The modification is seen by changing the feeding technique from λ/4 transmission line to the well known inset feed technique. The purpose behind this change is to acquire a more compact antenna element. As to where the via holes are inserted within the bottom substrate layer, a parametric study on the position and number of the via holes used has been conducted by authors in [12]. However, the results are strictly simulation results obtained using the Ansoft HFSS simulator and the concept was not verified practically.

The miniaturization percentage ($\%M$) of the antenna element is calculated from the frequency shift introduced by the insertion of the via holes. The frequency is re-optimized to 2.45 GHz, and the Slow Wave Factor (SWF) is calculated as the ratio of the area of the SMS patch to that of the conventional patch, as given in Equ. (3).

$$SWF = \frac{A_{SMS-patch}}{A_{Conventional-patch}} \qquad (3)$$

The resonance frequency of the SMS antenna element is shifted up to a higher value which corresponds to a decrease in the wavelength and antenna size. Hence the decrease in the overall antenna area can be calculated from Equ. (4).

$$\%M = |1 - SWF| \times 100 \qquad (4)$$

The fabricated SMS patch is shown in Fig.1(a) and (b). An optimized inset cut of 8.8 mm depth is obtained. The total surface area size reduction of the antenna obtained is increased by 8% with respect to [12]. The surface area reduction reaches, hence, 40% when compared to a conventional patch antenna realized using microstrip technique (MS) without via holes.

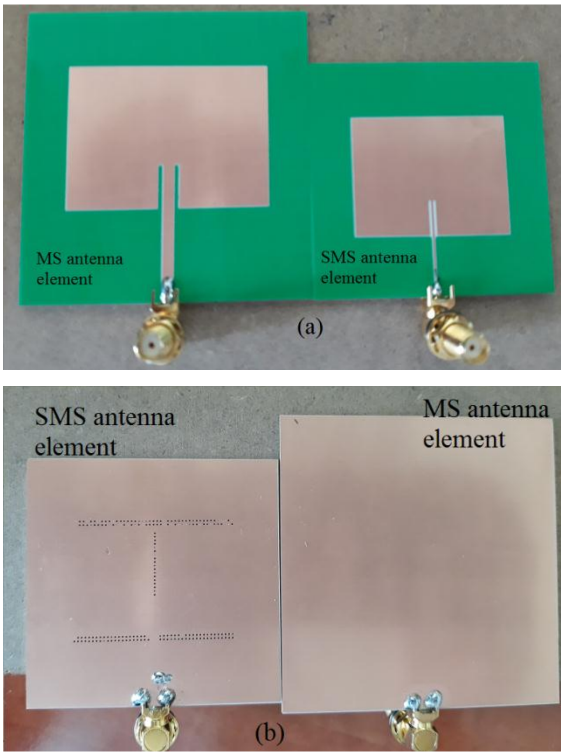
The surface area reduction is obtained at the expense of the antenna gain. The gain decreases from 5 dBi (MS case) to 3.23 dBi (SMS case). Measurement results of the SMS patch antenna are shown in Fig.1(c) and (d). Measurement results are in good agreement with the simulated ones. Fig.1(c) shows the return loss of the SMS patch between 2 GHz and 3 GHz. A frequency shift between simulation and measurement results of 150 MHz is obtained. The fabricated antenna has a resonance frequency at 2.30 GHz. The shift is due to the addition of an adhesive sheet (RO4450B) necessary to adhere the two substrate layers together. Fig.1(d) shows the antenna gain in E-plane (φ = 0º). Simulation and measurement results are in good agreement. It is worth noting that the measured gain is plotted for the shifted operating frequency (2.30 GHz). The half power beam width HPBW is increased from 60º (MS case) to 70º (SMS patch case). Table 3 summarizes the obtained results of the fabricated antenna elements (MS and SMS).

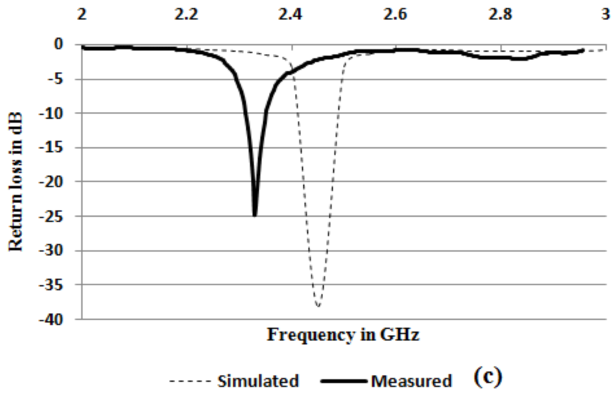
Table 3. Summary of the measurement results between the conventional and SMS patch antenna elements.

Results	Microstrip patch antenna element	
	Conventional (MS[1])	SMS
Return loss [dB]	-16	-24
Band width [MHz]	60	40
Gain [dBi]	5	3.23
HPBW	60º	70º
Area [$\lambda_0 \times \lambda_0$]	0.52×0.35	0.44×0.25
SWF	N.A.[2]	0.6
%M	N.A.	40%

[1]MS Micro Strip

[2]N.A. Not Allowed





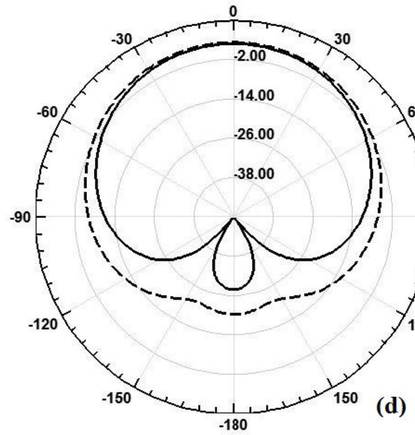


Fig. 1 Fabricated SMS microstrip patch antenna (a). Front view (b). Back view (c). Return loss S_{11} versus frequency (d). Radiation pattern of the gain in E plane (φ=0º)

In the next subsections, the SMS concept is used to design a (2x2) microstrip patch antenna array, where two different configurations are investigated.

III.II. Design of the Conventional (MS) and SMS (2x2) MPA Arrays

The design of the antenna array requires an appropriate feeding network. So, a T junction power divider network is firstly designed to be used in the proposed antenna array. The SMS technique is applied in the design of the T junction power divider network. The role of the three port T junction power divider network is to divide the input power equally at two output ports. So, the required power division ratio is half or 3dB. The power divider is designed to operate at 2.45GHz. The same substrate stack presented earlier in Table 1 is used to design the T junction MS (conventional) and SMS power divider. Fig. 2(a), presents a schematic diagram of the used network with and without vias. The conventional MS T junction power divider is simply composed of the main feeding 50 ohm transmission line followed by two bulky λ/4 long transmission lines that divide the input signal into two equal parts. In Fig. 2(b) via holes are inserted under the bulky transmission lines to reduce their length. For simplicity only a single row of metallic via holes is inserted. According to [13], the optimized via holes have a diameter equals to 0.4mm, and are placed at 0.8mm center-to-center from each other. After optimization, the designed SMS power divider is compared to its conventional version Fig. 2(a). The simulation results of the

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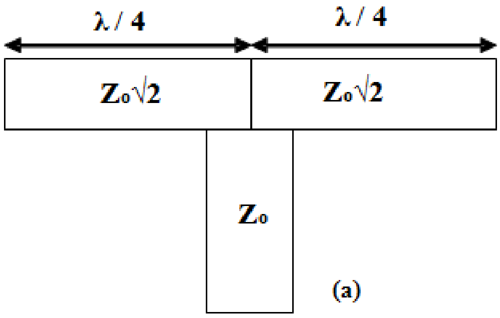
SMS version are presented in Fig.3. The obtained return loss of -22dB at the targeted operating frequency (2.45GHz) implies that the SMS feeding network is matched. The transmission coefficients (S_{21} and S_{31}) are equal to -3.27dB and -3.28dB, respectively. The insertion loss does not exceed 0.28dB. The magnitude imbalance between the output ports ($|S_{21}|$ - $|S_{31}|$) is very good since it does not exceed 0.01dB at the operating frequency. An overall surface area reduction of about 70% is achieved with respect to the conventional design (Fig. 2(a)). The surface reduction is obtained on the expense of a slight increase in the insertion loss that does not exceed 4% compared to that obtained in the conventional version of the divider (0.16dB). The addition of the metallic via holes is the reason for increasing the metallic losses, and hence the total losses of the divider.

The proposed T junction power dividers (MS and SMS) are employed to design an MS and SMS 2×2 MPA array operating at the same frequency, 2.45 GHz.



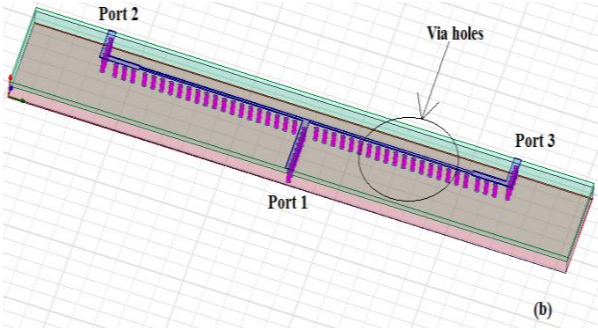


Fig. 2(a). Schematic diagram of the 3dB T junction conventional power divider (b). SMS T junction power divider

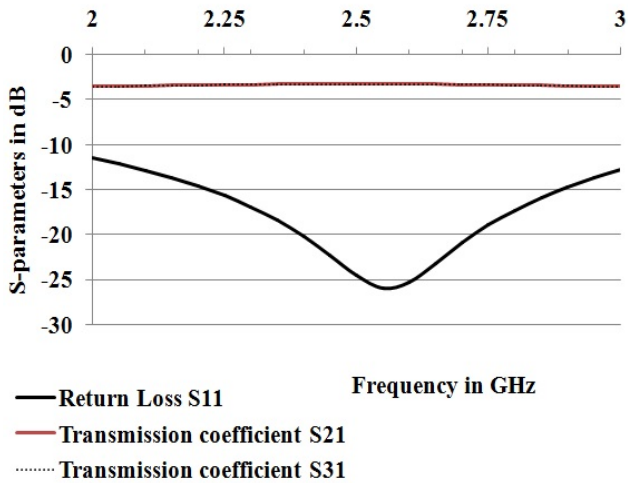


Fig. 3 Return loss S_{11} and transmission coefficients S_{21} and S_{31} for the SMS T junction power divider

III.II.I. Conventional (MS) MPA Arrays

The antenna array is required to operate at 2.45 GHz. A 2x2 MPA array is designed, simulated and fabricated. Two versions are investigated in this section; a conventional MS version without via holes (this subsection) and an SMS version in the next subsection. The SMS technique is used in the design of the array in order to reduce the surface area of the antenna array.

Starting with the conventional microstrip version, two antenna array configurations with different orientation are investigated and compared (Fig.4 and Fig.6). In the first configuration the four patches are oriented to the same side (Fig.4). In the second configuration the patches are arranged to radiate towards two different users as shown in Fig.6. In order to reduce mutual coupling, the center to center distance between the patches in the H-plane is chosen to be 0.5 λ_0 [1]. Moreover, the array elements are rotated by an angle α equals to 45°(Fig.4 and Fig.6).

Configuration 1 shown in Fig.4 is optimized for best electrical performance. The rotation angle α with respect to main vertical feeding line is found to be 45° ensuring both an appropriate separation distance between adjacent array elements and best performance. It is worth noting that for this configuration only a coaxial feeding is possible. Fig.5 shows the optimized results. Fig.5(a) represents the return loss in function of frequency between 2GHz and 3GHz. It is obvious that the antenna array is matched to better than 23dB at the target frequency 2.45GHz. The bandwidth of the antenna array is calculated from Fig.5(a) and is found to be equal to 60MHz. Fig.5(b) represents the polar plot of the conventional antenna array gain in the E-plane. The array has a maximum gain of 10 dBi at $\varphi = \theta = 0^o$. The half power beam width (HPBW) is found to be equal to 46°. Fig.5(c) represents a three dimensional plot of the gain at 2.45GHz.

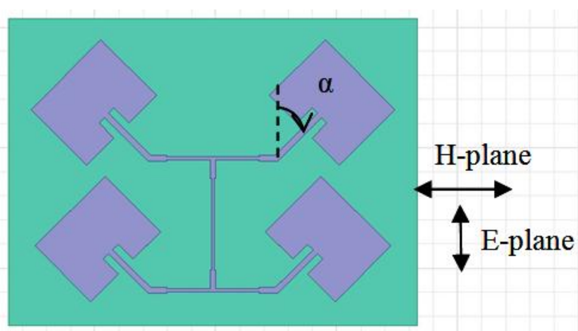


Fig. 4 Conventional MS 2×2 MPA array with all elements oriented in the same direction using coaxial feeding (configuration 1)

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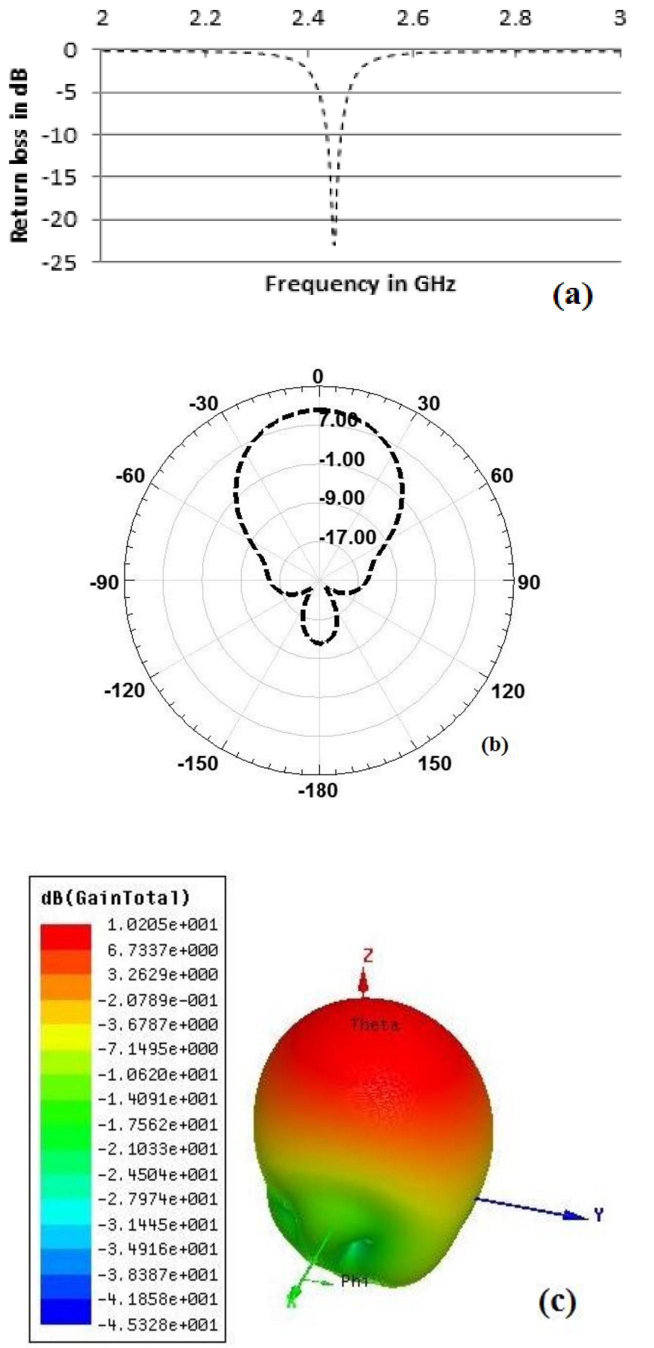


Fig. 5 Simulation results of the conventional MS 2×2 MPAA of configuration 1 (a). Return loss S_{11} versus frequency (b). Radiation pattern of the gain in E plane (φ=0°) (c). 3D polar plot of the antenna gain

It can be noted that the radiation pattern of this configuration consists of a single major lobe. The antenna configuration, hence, can be used to target users located at this position. The overall surface area of the MS array configuration of Fig.4 is equal to 150×108mm^2 (1.225λ_0×0.882λ_0).

In configuration 2 (Fig.6), the patch antenna elements are rearranged in such a way that each two elements radiate into a different direction. In such an arrangement, the array becomes a circular array with 45° angular distance between the array elements. The main idea behind using this configuration is to divide the array's main lobe into multiple secondary lobes targeting distant users.

In this case (configuration 2), microstrip transmission line signal feeding can be used. Transmission line feeding is tidier than coaxial feeding. Moreover, using this feeding type almost does not increase the surface area of this antenna array (configuration 2). For concept validation, this array configuration was considered for fabrication. The array is fabricated on the same substrate stack described previously but without including via holes. Fig.6 shows a photography of the fabricated antenna. The antenna array is measured and its response is shown in Fig.7. Fig.7(a) shows that the array measured resonance frequency is shifted by 120MHz with respect to simulation. A return loss better than -25dB at the shifted frequency (2.33GHz) is obtained. The frequency bandwidth calculated from Fig. 7(a) is found to be 40MHz which is less than the expected bandwidth (60 MHz). Fig.7(b) shows that the obtained overall gain of the array is equal to 7.6dBi at 2.33GHz which is in good agreement with the simulated gain (8.35dBi at 2.45GHz). The three dimensional radiation plot of the gain shows four lobes (Fig.7(c)). The overall obtained surface area of the conventional four elements MPAA shown in Figure.6 is equal to 153×159mm^2(1.25λ_0 ×1.3λ_0).

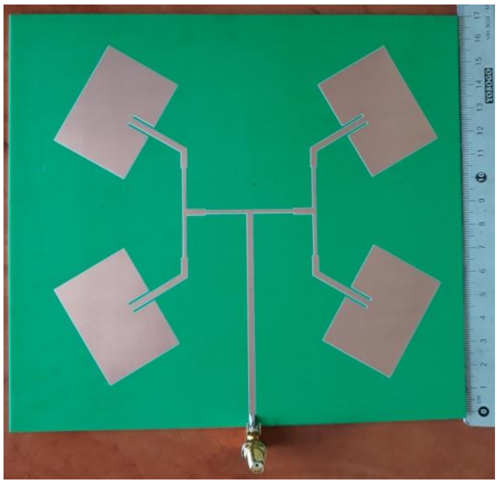
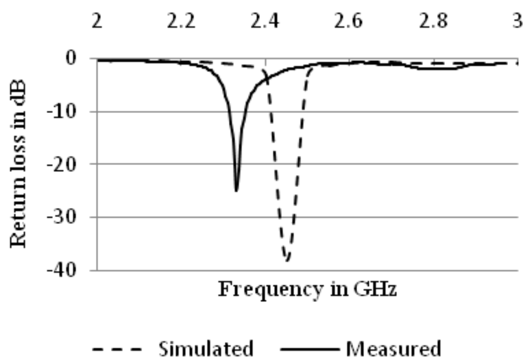
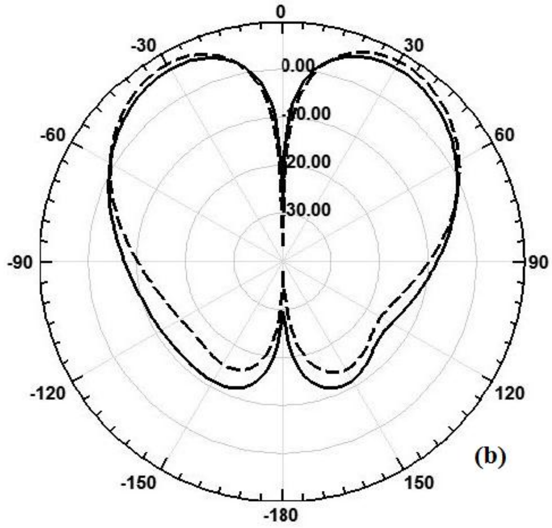


Fig. 6 Fabricated conventional MS 2x2 MPA array (configuration 2)



(a)



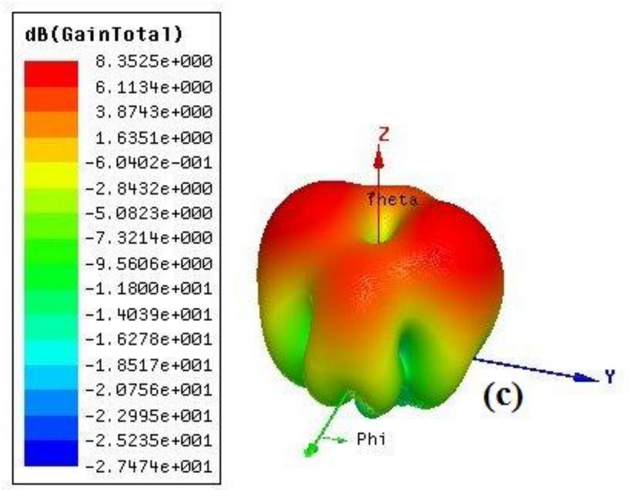


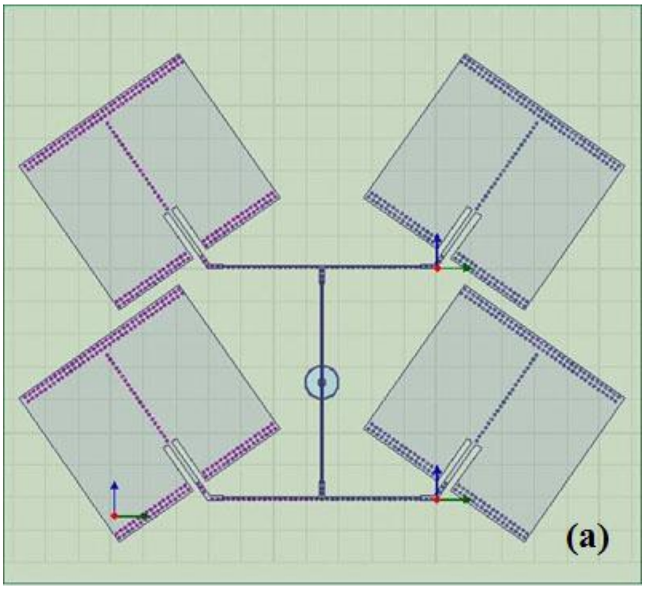
Fig. 7 Measured results of the fabrication 2×2 MS MPA array (configuration 2) (a). Return loss S_{11} versus frequency (b). Radiation pattern of the gain in E-plane (φ=0°) (c). 3D polar plot of the antenna gain

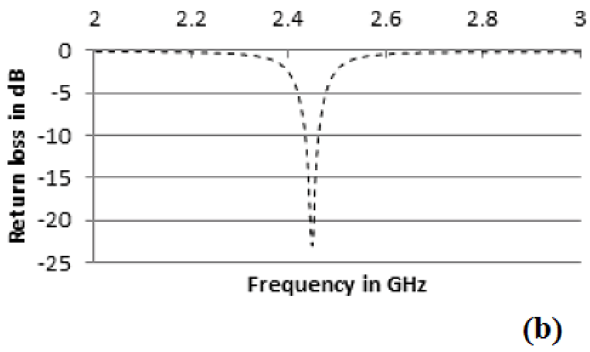
By comparing both conventional MS antenna array configurations, it is noticed that the second configuration offers a multi radiation lobes that could target distant users. Of course, this is achieved at the expense of lower gain and greater surface area. As it can be noticed, both configurations occupy large surface area. In order to decrease the surface area, both configurations are redesigned using the SMS technology in the next subsection.

III.II.II. SMS MPAArrays

In the design of the SMS patch antenna array the metallic via holes are located under the radiating slots of each patch (as done in Fig.3). The number and position of the via holes inserted under each patch are inspired from previous parametric study performed by the authors in [12].

Here again, as in the previous subsection, two array configurations are investigated. The SMS version of configuration 1 with its corresponding simulation results are presented in Fig.8. The insertion of the metallic via holes miniaturized the antenna feeding network, so the adjacent array elements in H plane were rotated by an optimized angle of 45° similar to the MS version to reduce the mutual coupling effect. The simulation results are depicted in Fig.8, where Fig.8(b) presents the return loss between 2GHz and 3GHz. It is found that the return loss is better than -23dB at the resonance frequency (2.45GHz). The bandwidth obtained around the resonance frequency is 40 MHz which is less than by 20 MHZ than that obtained in the MS version of configuration 1. The radiation pattern representing the total antenna gain in the E plane (φ = 0°) is shown in Fig.8(c). The total gain is reduced from 10dBi (MS case) to about 7dBi (SMS case). A 24° wider HPBW in comparison with the MS version is noticed (70°). The three dimensional polar plot of the array gain in Fig.8(d) confirms the one lobe radiation pattern. The SMS version of configuration 1 has a compact surfacearea that is equal to $93\times76mm^2 (0.76\lambda_0 \times 0.62\lambda_0)$. Hence, a miniaturization percentage of 57% is achieved in comparison to the MS version. Hence, a tradeoff between antenna size reduction and its gain is noticed.





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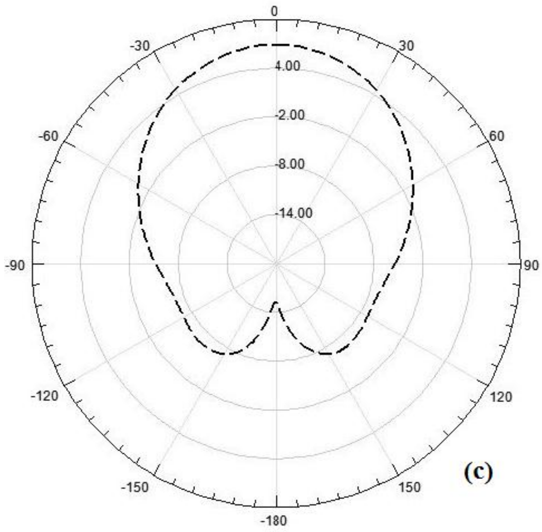


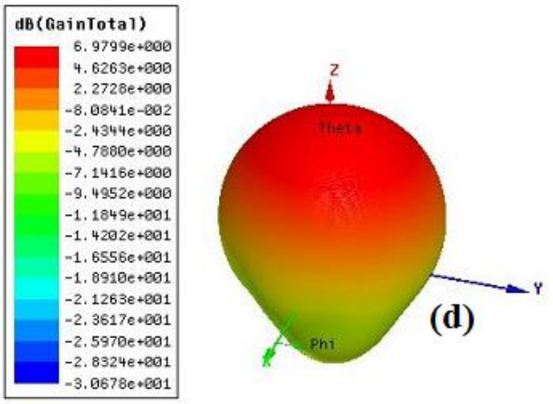
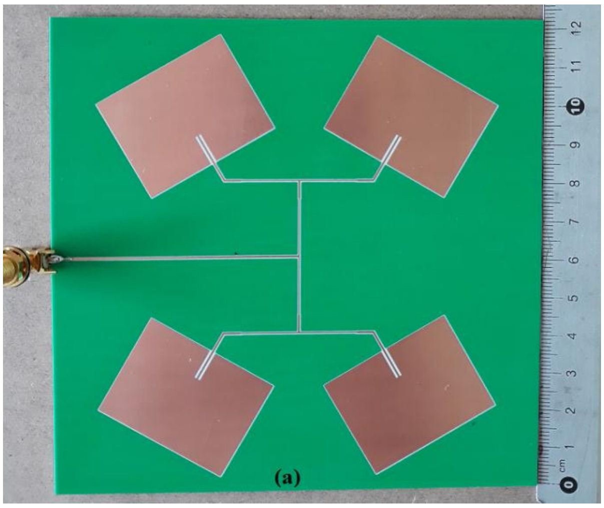


Fig. 8 Simulation results of SMS 2×2 MPA array (configuration 1) (a). Ansoft HFSS photograph of the SMS array (configuration 1) (b). Return loss S_{11} versus frequency (c). Radiation pattern of the gain in E plane (φ=0°) (d). 3D polar plot of the antenna gain

The fabricated SMS version of the configuration 2 (Fig. 6) is shown in Fig.9 and its corresponding results are presented in Fig.10. The results show a good agreement with that of the conventional version. Fig.10(a) shows that the array measured resonance frequency is shifted by 140MHz with respect to simulation. The frequency shift is again due to the added adhesive layer. A return loss better than -36dB at 2.32GHz is achieved. The measured frequency bandwidth is equal to 60MHz which is greater than the measured MS version of the design (40MHz). As for the measured E-plane antenna array gain (Fig.10(b)) it has a maximum value of 5.5dBi at $\varphi = \theta = 0^o$. This value is less than the obtained for the conventional MS version (Fig. 7(b)). As expected, this configuration offers a multi radiation lobes. The total surface area of the antenna array is 100×105mm^2 ($0.82\lambda_0 \times 0.85\lambda_0$). The reduction in the surface area with respect to the conventional array is about 57%. This size reduction is achieved, again, at the expense of gain reduction.



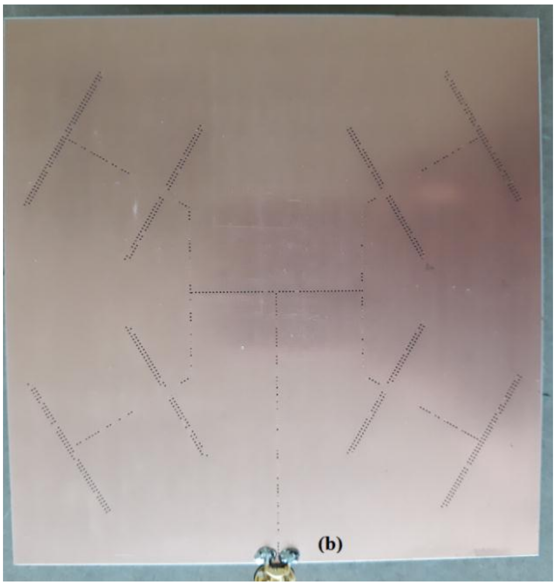
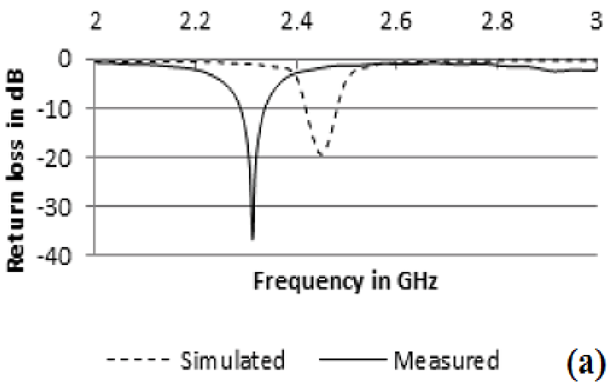


Fig. 9 Fabricated SMS 2x2 MPA array (configuration 2) (a). Front view (b) Back view



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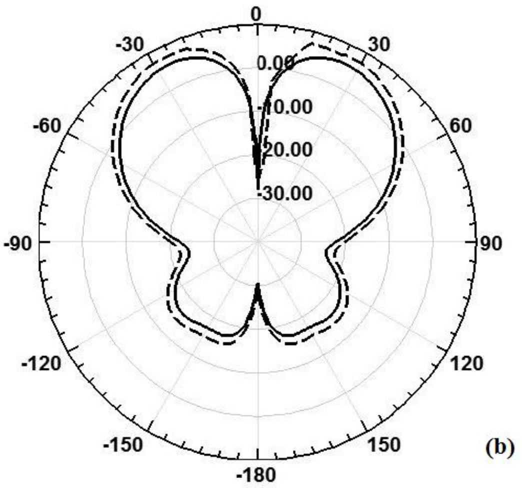

Fig. 10 Simulated and measured results of the fabricated MPA array (configuration 2) (a). Return loss S_{11} versus frequency (b). Radiation pattern of the gain in the E-plane (φ=0º)

In the next section a comparison with the state of art results is performed.

IV. COMPARISON WITH THE EXISTING MINIATURIZATION TECHNIQUES

Table 4 presents a comparison between this work and recent miniaturization techniques applied for microstrip patch antenna arrays. The used miniaturization techniques: Electromagnetic Band-Gap Structure (EBG) [7], Artificial Magnetic Conductor (AMC) [10], high ε_r with slit loaded antenna [11] and Substrate Integrated Waveguide (SIW) [14]. The comparison is performed in function of antenna gain, bandwidth, reduced antenna size and return loss . The slow wave technique showed promising results with respect to miniaturization percentage. This is achieved at the expense of gain reduction.

Table 4. Comparison between different miniaturization technique

Reference	Technique	Frequency [GHz]	Gain [dBi]	Band width	Size	Number of elements	Return loss [dB]
[7]	EBG	2.25	8.8	1.75 GHz	Reduced by 47 %	4	-22.5
[10]	AMC	2.59	4.2	NA	63×95 mm^2	4	-20.9
[11]	High ε_r and slits loading	1.268	1.4	NA	140×140 mm^2	4	-15
[14]	SIW slots	5	6.4	25 MHz	1.35 λ_0×0.61 λ_0	4	-20
Designed array	SMS Configuration 1	2.45	7	40MHz	93×76 mm^2 (0.76λ_0 ×0.62λ_0)	4	-23
	SMS Configuration 2		5.5 /user	60MHz	100× 105 mm^2 (0.82λ_0 ×0.85 λ_0)		-36

V. CONCLUSION

The effect of introducing the SMS technique into the 2×2 MPA array has been successfully investigated. The MPA array operates well at its corresponding resonance frequency and had a 60MHz bandwidth, which covers the operation frequency of Wi-Fi (802.11b/g) and Bluetooth. An overall surface area miniaturization of the MPA array of 57% is achieved along with the design of its feeding network.

The future prospective for this work is to use the metallic via holes as switches; to direct the radiation towards a single user by switching off array elements in one side. This will be done by shorting the via holes underneath the required array elements to ground. This will help in creating an AM modulated signal out of the antenna array. Moreover, these metallic via holes will be inserted under the non- radiated slots of the array elements to improve the mutual coupling between near array elements.

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