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Design of a Compact Narrowband Microstrip Patch Antenna using Multilateral Slots for Radar Applications

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Abstract: The fascinating features of microstrip patch antenna such as lightweight, low cost and low-profile planar configuration, which account for easy fabrication, led to its gaining popularity in the recent past. However, designers are struggling to overcome its major demerits such as low gain, low directivity and low efficiency. The most common option for the parameter improvement was the use of parasitic patches, increased substrate height or implementation of antenna array, all of which results in cumbersome design. This article presents a single element narrowband microstrip patch antenna, for radar applications. The radiating patch of the antenna was mounted on Flame Retardant Circuit Board (FR-4), and fed with 50Ω microstrip feedline, using edge-feeding technique. Multilateral slots were cut on the patch for better impedance matching and gain enhancement. The total dimension of the patch was 15.8x11.5mm^2. Simulation results using Finite Element Method shows that, the proposed antenna operates at a resonant frequency of 8.5GHz, with a bandwidth of 200MHz. The antenna exhibits a good reflection coefficient of -40.35dB, very low VSWR of 1.02. and a maximum gain of 6.4dB at the same resonant frequency. Efficiency of the antenna was also improved to 99%. Comparison of the proposed antenna with previously reported literature indicated that, the proposed antenna is the best candidate for specific Radar applications.

Keywords: Multilateral slot, Narrowband; FR-4 Substrate; Micro-strip, VSWR, Radar application.

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1. INTRODUCTION

The need for compact and miniaturized antennas has been on the exponential rise, due to the everchanging trends in wireless communications [1]. These include mobile communications, satellite and radar applications, military, medical imaging, as well as wearable and body-embedded wireless devices [2],[3]. To meet this end, microstrip patch antenna (MPA) has shown promising features in the last decades, such as low profile, low cost, light wight, easy fabrication and low power consumption during transmission and reception [4],[5]. However, MPA also exhibits some undesirable features, such as low gain, and less efficiency. In an effort to eliminate these limitations, various research activities proposed several techniques which prove to be effective. These techniques include decreasing dielectric constant, increasing the height of the substrate, and using parasitic patches [6]. Despite the prospects of these techniques, there are further limitations attached to each. Substrates with lower dielectric materials yield better bandwidth[7],[8], but often expensive and not readily available. Increased substrate height result in increased dimension of the design, which is undesirable feature. Gain and bandwidth were said to have improved with increased number of parasitic patches [9], yet result in cumbersome design and thereby compromising the desired miniature of the antenna. However, patch modification by inserting slots was effective [10],[11], since it can improve the desired parameters and drive down the effective size and weight of the antenna[12].

2. RELATED WORK

Various proposals of microstrip patch antennas for X-band frequency range were presented in the recent past, with an effort to improve performance parameters. In [13] a multiband fractal microstrip patch antenna was presented with a reflection coefficient of -18.36 dB, and peak gain of 5.6 dB. A compact triple band microstrip patch antenna was also proposed in [6]. Using I-shape slots, a return loss of -30.5dB and peak gain of 5.27 dB have been achieved at 8.5 GHz. By etching circular slot on the radiating patch in [14], a return loss of -16.87dB was achieved at X-band frequency. While high gain narrow band microstrip patch antenna [15] was achieved using 8 x 1 array of unit cells, a single antenna design [16] achieved a gain of 6.1dB with return loss of -30dB. In all the presented designs, there has been trade-offs between return loss, peak gain, bandwidth, and efficiency. In this paper, three multilateral slots were cut on the patch of the antenna which result in better compact design, light-weight MPA with improved performance parameter at X-band resonant frequency.

2.1 Theoretical Background of Multilateral Slots

Conventional microstrip patch antenna was constructed with dielectric substrate sandwiched between ground plane and radiating element. The radiating element, (rectangular patch) is connected to a microstrip feeding network, which uses a quarter-wavelength to ensure impedance matching between the rectangular patch and the feedline contact [17]. The equivalent circuit model of microstrip patch antenna comprise of the approximate *RLC* circuit of rectangular patch and inductance of connector prob *Lp* as shown in Figure 1. When the multilateral slots are etched on the surface of the radiating patch, each slot is modeled by a combination of a series L_sC_s connected to $L_{sp}C_{sp}$ shunt, which mimic a bandpass filter. The approximate multilateral slot model was then coupled to the radiating patch via the patch inductor, as depicted in Figure 2.

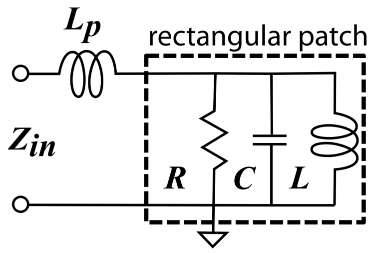

Figure 1. Equivalent circuit of standard microstrip patch antenna

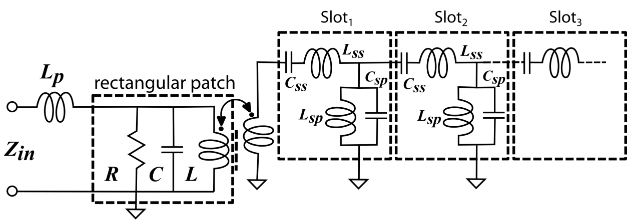

Figure 2. Equivalent circuit of multilateral slotted microstrip patch antenna

The resonant frequency of the conventional microstrip patch antenna is obtained from the equivalent circuit model as expressed in equation (1). When the slots are introduced on the radiating patch, the inductance changes and thereby alter the resonant frequency. If the slots are large, the impedance of the patch will increase which will consequently force the resonant frequency to drop[17]. However, the resonant frequency can be maintained using appropriate size and shape of the slots. The resistance of the patch (R) also regulates the bandwidth and quality factor of the antenna. Bandwidth and quality factor Q are related in equation (2), and from the equivalent circuit model of the standard patch without slots, the quality factor is expressed in equation (3). The quality factor results from losses in the patch conductor and dielectric substrate, as indicated in equation (4)[18]. Now, due to presence of slots, the quality factor in equation (3) decreases due to increase of the inductance. It should also be noted that the presence of slots reduces the effective area of the patch conductor, thereby reducing the losses due to patch conductor and substrate. This results in low value of quality factor, and hence higher bandwidth in equation (2).

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

$$BW = \frac{1}{Q\sqrt{2}} \quad (2)$$

$$Q = \frac{1}{W_0 L} \quad (3)$$

$$Q = \frac{1}{\frac{1}{Q_c}+\frac{1}{Q_d}} = \frac{1}{\frac{2\beta_{nm}^2}{\omega\varepsilon_0\varepsilon_r h_d \sigma_c \delta_c (\beta_0 Z_0)^2}+\frac{\sigma_d}{\omega\varepsilon_0\varepsilon_r}} \quad (4)$$

Where $Q_d\, \sigma_d$ ***and*** h_d are the dielectric substrate parameters (relative permittivity, conductivity and thickness), where by $\sigma_c\, \delta_c$ are patch conductivity and skin depth $\beta_0, \beta_{nm}, \omega,$ ***and*** Z_0 are propagation constant at resonant frequency, propagation constant for nm^{th} mode, working radiation frequency, and surface impedance of antenna.

3. PROPOSED ANTENNA DESIGN

The proposed antenna comprises a thin copper ground and radiating patch, with a flame-retardant woven glass reinforced epoxy (FR-4) sandwiched between the patch and ground. The FR-4 has a dielectric constant Ɛr = 4.3, with loss tangent of 0.025. Edge feeding technique was applied using 50Ω microstrip line. Substrate height was given by Hs = 1.5mm, length and width (Ls x Ws) = 20.9x24.8. The radiating patch has a dimension of (Lp x Wp) = 11.5x15.8, with three multilateral slots etched on the patch as depicted in Figure 1. A defected ground structure (DGS) was also applied to the ground plane. Table 1 presents the summary of the antenna design geometry, which was derived from transmission line theory [19]. The design equations used for efficient radiation of rectangular MPA [20] are presented below.

The width W, is given by:

$$w = \frac{c}{2f_0}\sqrt{\frac{2}{(\varepsilon_r+1)}} \quad (5)$$

Where f_o is frequency at which the antenna resonates, c constant light speed and ε_r is substrate dielectric constant.

The effective dielectric constant ε_{eff} is:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\left(\frac{h}{w}\right)\right]^{\frac{1}{2}} \quad (6)$$

Effective length L_{eff} is:

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (7)$$

Length extension (ΔL) is:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\left[\frac{w}{h} + 0.264\right]}{(\varepsilon_{eff} - 0.258)\left[\frac{w}{h} + 0.8\right]} \quad (8)$$

The actual length L is the given by:

$$L = L_{eff} - 2\Delta L \tag{9}$$

Table 1. Design dimensions

Name	Value	Unit
Ws	24.8	mm
Ls	20.9	mm
Hs	1.50	mm
Wp	15.8	mm
Lp	11.5	mm
Wg	24.8	mm
Lg	20.9	mm
Wf	2.0	mm
Lf	4.50	mm

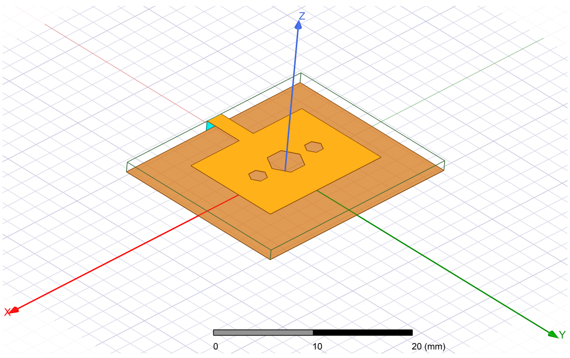

Figure 3. Proposed antenna design geometry

4. SIMULATION RESULTS AND COMPARISON OF STANDARD DESIGN MPA AND MULTILATERAL SLOT MPA

The proposed antenna was design and investigated using Finite Element Method based simulation software (ANSYS Electronics Desktop 2020R$_2$). The results for both standard microstrip patch antenna and multilateral slotted antenna were analyzed and evaluated. These results are further compared with previously reported literature, and the details of were presented in the following sections.

4.1 Return loss (S_{11})

The standard microstrip patch antenna achieved a return loss of -29.04 dB before etching the multilateral slots as depicted in Figure 4. The antenna return loss was improved to -40.35 dB after etching slots and defected ground as shown in Figure 5. The reflection coefficient for both antennas was attained at resonating frequency of 8.5GHz. This is the frequency at which the antenna radiates maximum power while attenuating minimum power.

4.1 Voltage Standing Wave Ration (VSWR)

The VSWR is the description of the impedance matching of the transmission line. Lower value indicates good impedance matching. The VSWR achieved in this design was 1.42 for the standard antenna design, while 1.02 was achieved for the multilateral slotted design. The achieved VSWR for both designs are much lower than the prescribe value 2.0, as shown in Figure 6 and 7. In general, a VSWR < 2 at resonant frequency is acceptable.

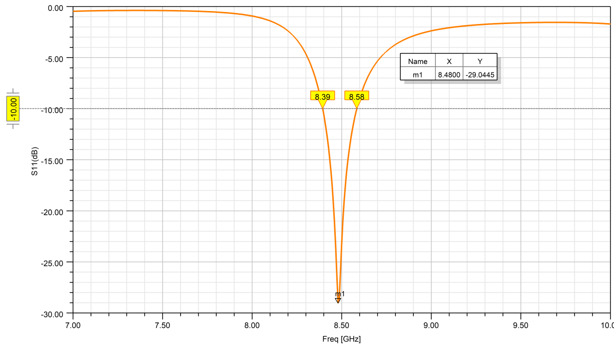

Figure 4. Return loss (S_{11}) for standard MPA design

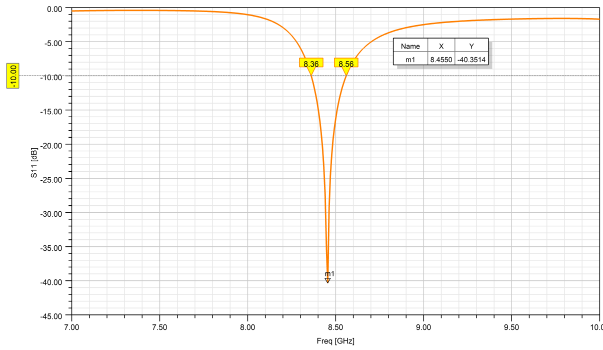

Figure 5. Return loss (S_{11}) for multilateral slot MPA design

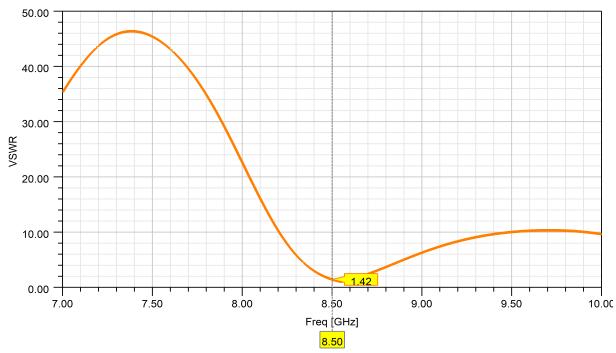

Figure 6. Minimum VSWR achieved for standard MPA

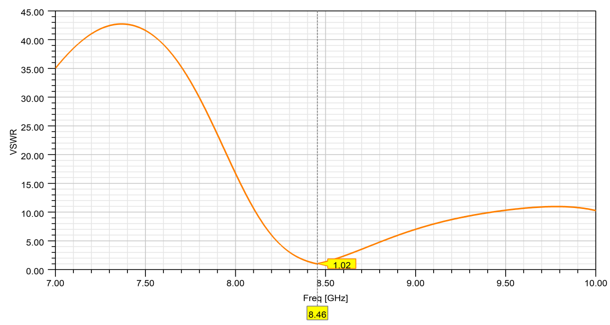

Figure 7. Minimum VSWR achieved for slotted design

4.2 *Gain plots*

The peak gain achieved for the slotted antenna design was 6.4 dB as shown in Figure 8. This is an improvement from 3.8 dB of gain achieved by the standard microstrip patch antenna (un-slotted design), as depicted in Figure 9. Summary of the characteristics of standard MPA and the proposed multilateral slotted microstrip patch antenna with respect to resonant frequency, return loss, VSWR, gain and efficiency are compared in Table 2.

4.3 Radiation pattern

The polar radiation pattern of the antenna is presented in Figure 10 and 11 for E and H plane, with main lobe direction at 0o degree. In both standard MPA and the proposed design, it can be observed from the radiation pattern that, the antenna produces a stable radiation throughout the operation band.

4.4 E-Field and Surface current distribution

At 8.5GHz, the E-Field is distributed around the center and corners of the patch. However, the E-Field is dense at the center, around the multilateral slots. The surface current is distributed around the microstrip feedline, the center and towards the edges of the radiating patch. The results of the antenna E-Field and Surface current distribution are given in Figure 12-15.

4.5 Comparison of the design with reported literature

The comparison of the performance parameters of this work and other previously reported literature is presented in Table 3. It can be observed that, the proposed design outperform earlier reported designs [6], [14], [16], [21], in terms of miniature, low reflection coefficient at resonant frequency, and gain, except [14], which shows higher gain than the proposed antenna. However, its dimension is twice the size of the proposed antenna, and thereby compromises the higher gain that was achieved in that design.

Table 2. Comparison of standard microstrip patch antenna

Design iteration	Resonant frequency (GHz)	Return loss S_{11} (dB)	Band width (MHz)	Peak Gain (dB)	Efficiency (%)
Standard MPA	8.5	-29.04	180	3.8	97
Multilateral slot design	8.5	-40.35	200	6.4	99

Table 3. Comparison with previous works

Reference	Dimension (mm)	Frequency (GHz)	Return loss – S_{11} (dB)	Gain (dB)
[6]	48x50x1.6	8.5	-18.50	5.27
[13]	38x38x2.2	8.5	-18.36	5.64
[14]	50x50x1.6	8.5	-16.87	9.74
[16]	39x47x0.2	8.5	-30.00	6.17
[19]	60x40x1.5	5.2	-18.00	2.70
This work	21x25x1.5	8.5	-40.35	6.4

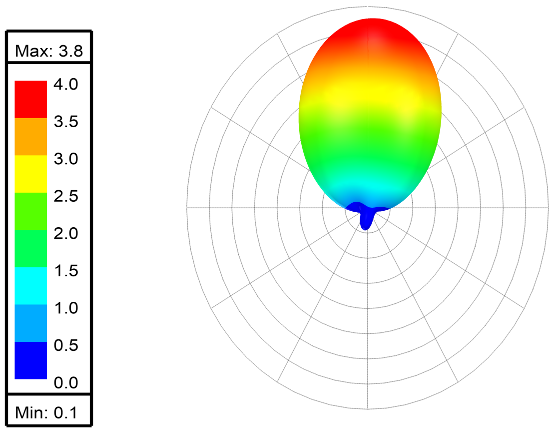

Figure 8. 3D gain plot for standard MPA design

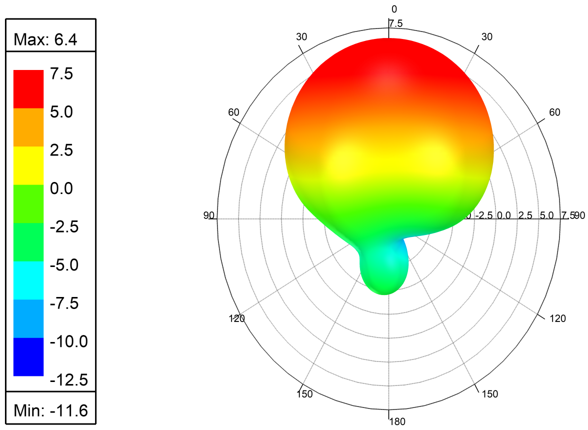

Figure 9. 3D gain plot for multilateral slots MPA design

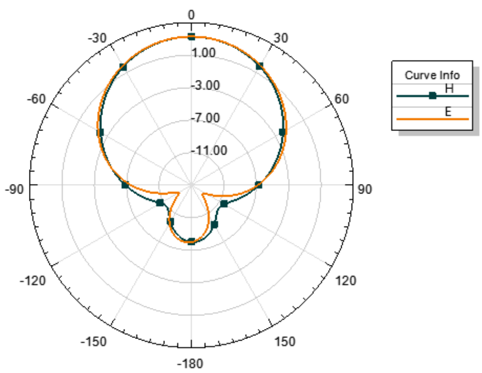

Figure 10. 2D radiation pattern for the standard MPA design

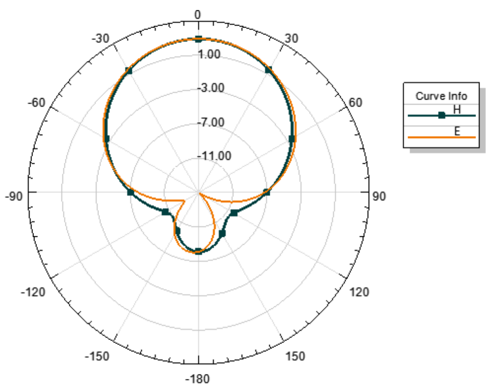

Figure 11. 2D radiation pattern for the multilateral slot MPA design

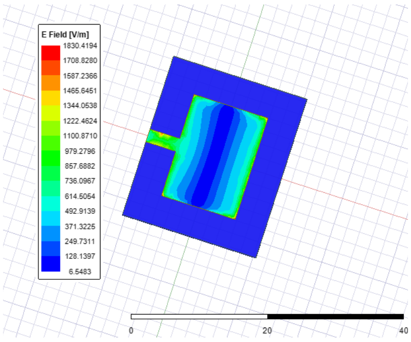

Figure 12. E-Field distribution for standard MPA design

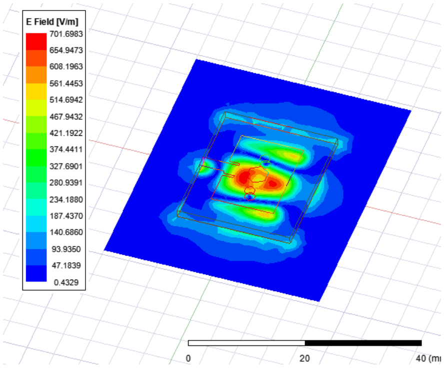

Figure 13. E-Field distribution for multilateral slot MPA design

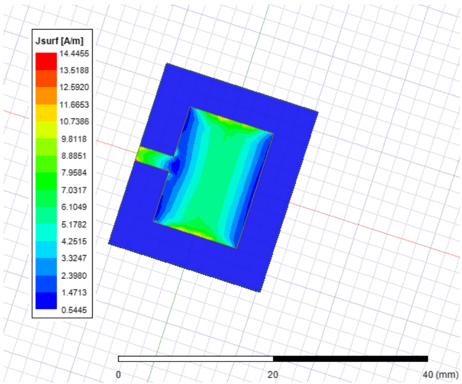

Figure 14. Surface current distribution for standard MPA design

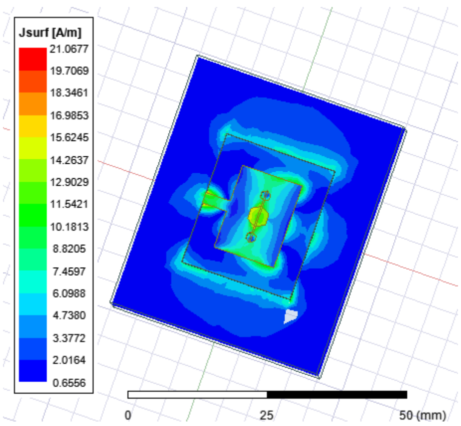

Figure 15. Surface current distribution for multilateral slot MPA deign

5. CONCLUSION

In this article, a single element narrowband microstrip patch antenna was proposed using multilateral slots. The antenna was design using Flame Retardant Circuit Board (FR-4), which is cheap and readily available. Simulation results from Finite Element Method indicates that the antenna resonates within the X-Band frequency range. Comparison with earlier reported literature shows that the antenna exhibits better performance parameters such as compactness, reflection coefficient and gain. The proposed antenna has the potential to serve as a good option for Radar applications within the x-band frequencies, such as short-range tracking, missile guidance, and airborne intercept.

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