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A Miniaturized High Fractional Bandwidth Microstrip Antenna for Wide-Band Application

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Abstract
This scholarly work presents the design of a compact microstrip antenna for transmitting and receiving signals. The antenna is optimized using parametric analysis and simulated using HFSS 15 on a 1.6-mm FR4 substrate with a dielectric constant 4.4 and a tangent angle of 0.02. It offers a wide impedance bandwidth of 8.5 GHz to 19.6 GHz, with a fractional bandwidth of 79%. The reflection coefficient of the antenna is remarkable, with values of -66.61 and -46.20 dB, and it has a gain of 3.42 dB. Its radiation patterns, both in the E- and H-plane, are observed, and it is suitable for wireless communication. The proposed antenna is ideal for various applications, including mobile communication devices, wireless networks, and satellite communication systems.

1. Introduction

Wireless communications are increasingly using microstrip patch antennas due to their small size and wide frequency range [1]. Wide frequency ranges and bandwidths make wide bands useful for wireless networking, radar, and satellite communication applications [2]. Wireless connectivity is making it vital to combine mobile devices with varied standards and multi-functionality thus, integrated wireless systems must be smaller and more reliable. In this scenario, future wireless systems merge the antenna fabrication onto one substrate [3]. Wireless technology now includes broader channels for higher speed, decreased latency for improved responsiveness, and increased bandwidth to accommodate more devices simultaneously [4]. Recent years have seen a rise in the demand for printed antennas, which has drawn researchers from all over the world to work on microstrip antennas and contribute significantly to the expanding market. Microstrip antennas are being utilized in wearable technology and other internet of things (IoT) applications in addition to their traditional employment in LAN and satellite connectivity [5], [6]. Conventional microstrip antennas may have limited applicability in compact or space-restricted scenarios because of their size, recent research has concentrated on addressing this limitation through the introduction of new designs and tactics. The reflection coefficient of the Patch antenna demonstrates superior impedance-matching properties [7], [8] and the fractional bandwidth (FBW) is defined as the ratio of a signal's frequency deviation from its center frequency, expressed as a percentage, signal with a big bandwidth has a high fractional bandwidth, while a signal with a small bandwidth has a low fractional bandwidth [9]. The microstrip patch antenna design operates in wideband and ultra-wideband, achieving high fractional bandwidths of 42%, 60.7%, and 61%, as well as high reflection coefficients of -29.462 dB, -14.085 dB, and -27.07 dB, respectively these antennas are commonly utilized in wireless communication and 5G networks [10]-[12]. The antenna's reported dimensions are large, with a reflection coefficient ranging from -20 dB to -40 dB and a fractional bandwidth between 15% and 31%. Despite achieving moderate gain, these antennas are utilized in Ultra-Wideband (UWB) applications, wideband radar applications, and S-Band telemetry applications [13]-[16]. Additional research has been conducted in the area of microstrip antenna design to enhance gain performance with a compact size of 11 x 8 x 0.5 mm3, achieving a gain of 7.486 dB however, the acquired fractional bandwidth is moderate and the reflection coefficient is lower at -18.117 dB [17]. The antenna's performance in S-band applications has been assessed in terms of return loss, bandwidth, VSWR, and efficiency. The antenna has a fractional bandwidth of approximately 65.7% and a reflection coefficient of -43.52 dB, gain of 2.646 dBi, which is a significantly positive result for analysis [18]. The latest design of a wideband Circularly Polarized (CP) antenna array operating at Ku-band demonstrates significant gain, with modest values for size and reflection coefficient [19]. The Microstrip Patch antenna is used in wide bands for various wireless applications, 5G wireless communication, satellite communication, wireless computer Networks, and mobile communication [20]-[23]. In most of the above cited literature it is found that though the electrical dimensions of the antenna was comparatively low, but the FBW was not obtained up to the mark. This motivated us to work on a high FBW antenna design with miniaturized dimension as well as good impedance matching in the desired frequency range. So in this paper we presented a very compact microstrip antenna with modified ground plane. The wide-band antenna has an excellent reflection coefficient (S11) of -66.61 dB at 10.1 GHz and -46.20 dB at 18.4 GHz. Design evolution gave us the best design structure by modifying the patch, ground, and feed. For best impedance matching and performance, we also studied patch-cut shapes. The proposed antenna was tested for stepped feed, tapered feed, and varied feed widths. The result section discusses these findings and performance coefficients. The major contribution of this proposed work includes

- Simple and compact design approach
- High fractional bandwidth as compared to the other reported literature.
- Good impedance matching at operating frequencies

The whole content of the paper is divided into three subsections. In Section I we discussed the antenna design and parametric analysis to reach the optimum dimension, Section II discussed the result of the antenna like reflection coefficient, gain, and radiation pattern, Section III discussed the conclusion and future scope of proposed work.

2. Antenna Design

The antenna's resonance displaces its radiation modes, which may be verified using the formula

$$(f_r)_{010} = \frac{c}{2L\cdot\sqrt{\varepsilon_r}} \quad \text{--------(1)}$$

Where L = L1 + Lf, L_1 is the Patch length and L_f is the feed length

$$(f_r)_{110} = \frac{1.8412c}{2\pi R_e\cdot\sqrt{\varepsilon_r}} \quad \text{-------(2)}$$

Re = effective radius of the half-disk patch

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad \text{--------(3)}$$

The resonance frequency and width of the patch are calculated with the help of the above equations [24]. The calculated values of resonance frequencies using Equation (1), and (2) are found to be 10.1 GHz and 18.4 GHz, respectively. The width at the port is calculated with the equation (3).To create the antenna, an FR4 substrate with a thickness of 1.6 mm and a dielectric constant of 4.4 was used, the antenna radiator is made up of a rectangular patch that has a half-disc patch (with a radius of "a = 2.4 mm") placed on top of it, the area of the copper patch is equal to pathwidth multiplied by pathlength, and there is an additional copper patch that removes a quarter of the area of an ellipse whose major radius is equal to s=2 mm and whose ratio of major radius to minor radius is equal to 1.1 these patches are located at the two lower corners of the rectangular patch. The ground plane is modified by a partial cut in the sides and it is also cut through by a circular copper patch with a radius of a2 that is at the upper side of the ground plane. The purpose of these modifications in the ground plane for improve performance, gain, and bandwidth [25].Various feed lines are utilized with microstrip antennas to achieve impedance matching, minimize cross-polarization, and enhance symmetry. We simulated a simple microstrip feed, a stepped feed, and a tapered feed, we found that the tapered feed line system had the best impedance matching. Parametric analysis is a design study where several model parameters are adjusted and the system conducts analyses for each parameter combination automatically. We analyse different design modifications as shown in figure 1 with six step by step design approach. By performing rigorous investigation using HFSS (High Frequency Structure Simulator) software, we reached to the final proposed antenna as mentioned in figure 2 and the optimized dimension as depicted in Table 1.

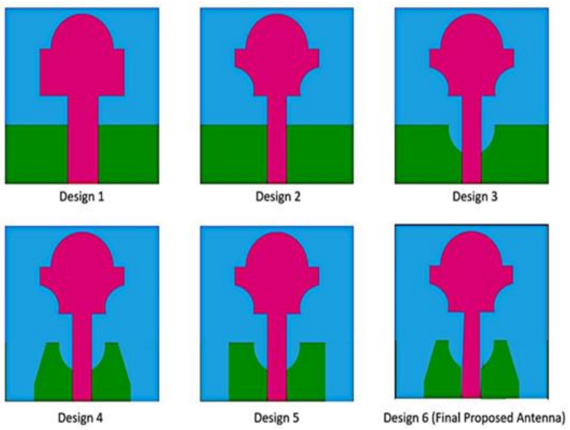

Figure 1 Design evolution from Design 1 to 6

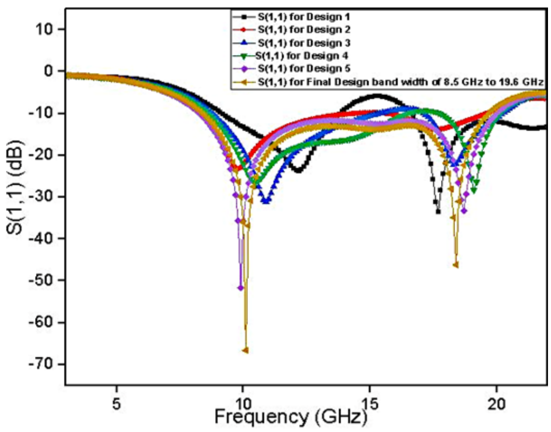

Figure 2 Reflection Coefficient for Design 1 To Final Proposed Antenna

After performing rigorous investigation using HFSS simulation software we reached to the final proposed design approach as in iteration 6 of antenna design evolution. All these steps 1 to step 6 iterations are depicted in Figure 5. It is found that in iteration 6 the impedance matching is quite improved as -66.61 dB and -46.20 dB at 10.1 GHz and 18.4 GHz respectively from the last 5 iterations. Moreover, the optimized antenna (iteration 6) demonstrates a wide frequency range from 8.5 to 19.6 GHz, with an excellent fractional bandwidth of 79% which is the key objective of the design approach Shown in Figure 3 and 4.

Table 1 Optimized parameter of the proposed antenna

Parameter	**W**	**L**	**h**	**w**	**l**	**a**	**a2**	**Pw**	**Pl**
Unit (mm)	12	12	1.6	2	5.5	2.4	1.7	8.3	5
Parameter	**X1**	**X2**	**X3**	**X4**	**Y1**	**Y2**	**K1**	**K2**	**S**
Unit (mm)	1.5	3.5	10.5	9	0.6	4.4	0.1	2	0.2

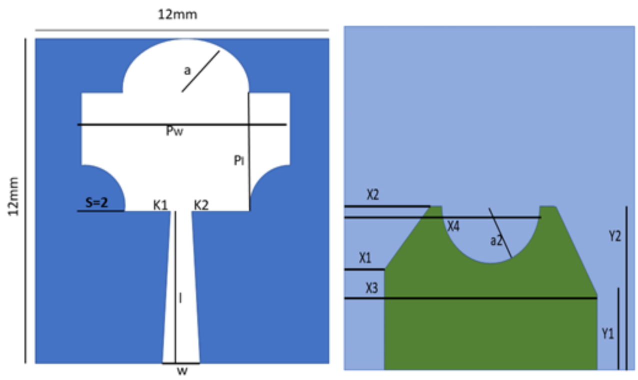

Figure 3 Antenna Front and Ground Plane Dimension

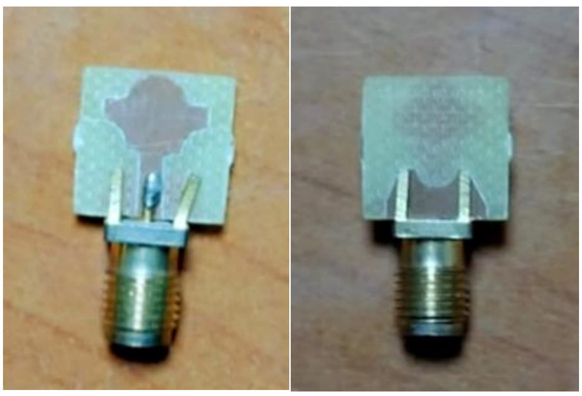

Figure 4 Antenna Front and Ground Plane

Figures 5 and 6 depict a patch antenna with a variety of cuts made in it to evaluate its performance. This was done with and without a stepped feed line. Based on our examination of the results, we have discovered that the impedance matching in the operational bandwidth is improved by using an elliptical cut in the patch in conjunction with a microstrip line feed (i.e., without a stepped feed).

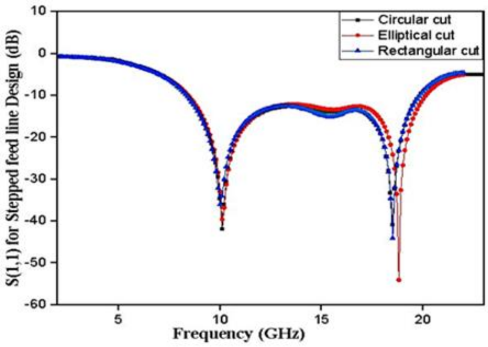

Figure 5 Reflection Coefficient for Stepped Feed

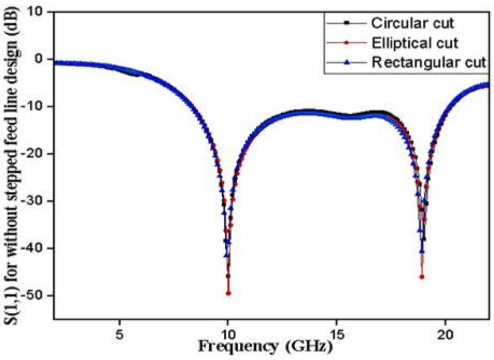

Figure 6 Reflection Coefficient for Without Stepped Feed

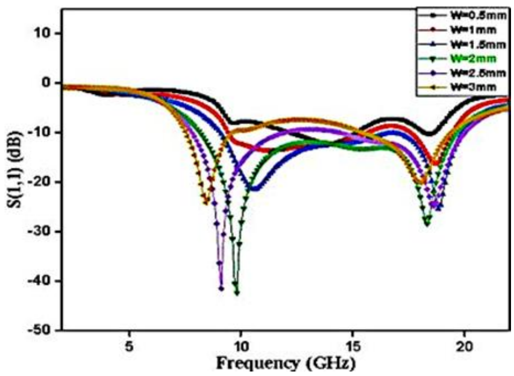

Figure 7 Microstrip Antenna at Feed Line of Different Width

The width of the antenna feed line is determined by the parametric study, and the result that yields the best performance (9.8 GHz, -42.30 dB) is illustrated in Figure 7. with w equal to 2 mm, results of the microstrip feed line, stepped feed line, and tapered feed line depicted in Figure 8. are compared, and we find that tapered feed line has the best impedance matching with the proposed design

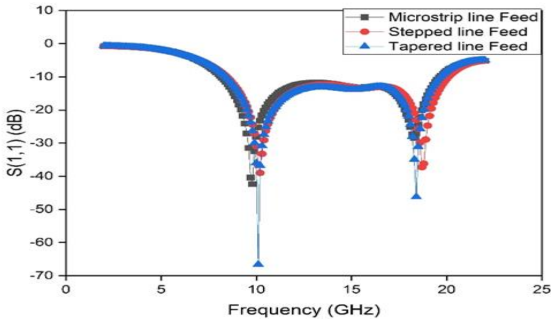

Figure 8 Microstrip Antenna at Different Feed Line

3. Results and Discussion

The Results should include the rationale or design of the S11 parameter reflects antenna port matching, with lower values indicating improved performance. It offers a wide impedance bandwidth of 8.5 GHz to 19.6 GHz, with a fractional bandwidth of 79% The simulated bandwidth is 11.1 GHz, whereas the measured bandwidth is 10.3 GHz, based on the –10 dB return loss criterion from figure 9. Discrepancies are attributed to fabrication tolerances that alter resonance due to minor dimensional variations. Changes in dielectric characteristics also affect the effective wavelength and impedance. Environmental variables and real-world testing conditions deviate from ideal simulation parameters. Finally, HFSS and similar electromagnetic solvers employ approximations that may lead to inconsistencies [26].

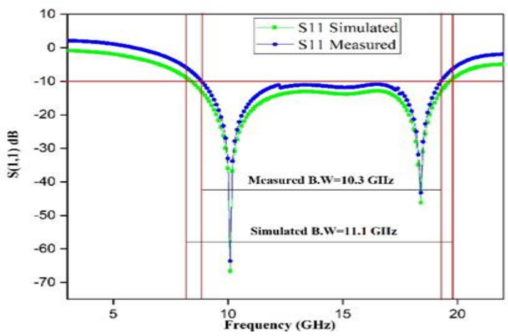

Figure 9 Reflection Coefficient of Designed Microstrip Antenna

The gain vs frequency plot is shown in Figure 10. and a maximum gain of 3.42 dB is achieved in the operating frequency range. The gain plot displays a slow rise from about 0 dB to a peak at about 16.5 GHz, after which there is a drop. Whereas the measured peak is about 3.2 dB, the simulated peak is about 3.42 dB. Due to real substrate losses, measurement losses, radiation inefficiencies, and flawed ground plane and fringing effect models, the measured gain is still marginally lower than the calculated gain across the band [27].

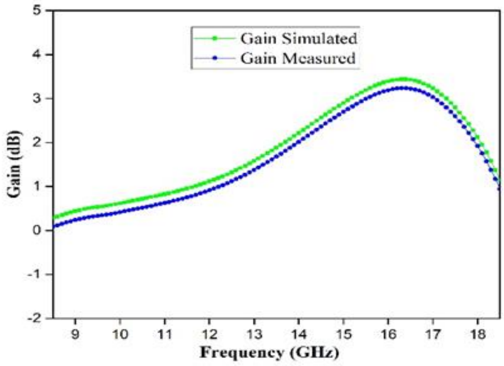

Figure 10 Gain Vs Frequency Plot

In figure 11. The detailed analysis as bellow E-Plane at 10.1 GHz: Simulated patterns are broad, directed, and symmetrical with minimal rear lobes. Measured patterns show good agreement, with only minor distortions due to practical issues. E-Plane at 18.4 GHz: Simulated patterns are more complex and multi-lobed due to the higher frequency, yet still directional. Measured patterns show greater differences, with variations in lobe shape and orientation, indicating increased distortion. H-Plane at 10.1 GHz: Both simulated and measured patterns display strong bidirectional lobes at 90° and 270°.

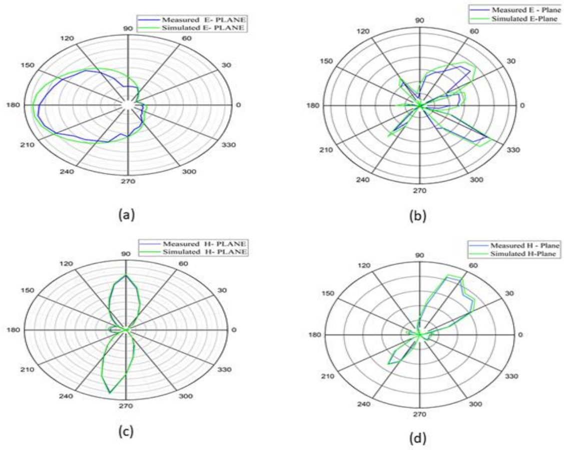

Figure 11 Radiation Pattern (a) and (c) at 10.1 GHz, (b) and (d) at 18.4 GHz

The measured pattern has slight asymmetry and smaller lobes, but generally matches well with minor amplitude variations. H-Plane at 18.4 GHz: There is a larger mismatch between simulated and measured patterns, mainly due to challenges in high-frequency measurement accuracy and susceptibility to fabrication issues. General Causes of Differences: Discrepancies can arise from fabrication flaws, variations in material properties, problems with the measurement setup, and assumptions made during simulation Shown in Table 2.

Table 2 Comparison of the proposed antenna with recently reported Literature

Ref.		**Size (unit in mm^3)**	**Reflection coefficient in dB**	**BW GHz**	**FBW**	**Gain in dB or dBi**
[10]		13 x 13 x 1.52	-29.462	26.1-40.0	42	7.0
[11]		4.20 x 4.20 x 0.127	-14.085	23.60 - 44.20	60.77	4.703
[12]		25x 21x2.1	-27.07	6.63 -10.93	61	-
[13]		40 x 48 x 1.59	-37.50 (approx.)	12.8-15.8	18.87	3.6
[14]		100 × 100 × 1.6	-39.21	0.245	26.6	3.325
[15]		60 x 60 x 2.34	-25	4.81- 6.01	24.5	5 to 7.6
[16]		30 x30x 1.52	-37 (approx.)	2.7 – 3.8	31	1.43
[17]		11 x 8 x 0.5	-18.117	45.04-66.04	38.63	7.486

[18]		16.36 x 49.2 x 1.5	-43.52	2.6 - 4.9	65.7	2.646
[19]		38 × 34 × 2.38	-30	12-17.65	40	11.02
Proposed		12 x 12 x 1.6	-66.61 dB	8.5-19.6 GHz	79	3.42

From the comparison table, it is deduced that the electrical dimension of our proposed work is comparatively small concerning the other antennas reported recently in the literature. Additionally, our work achieved a better impedance matching at the desired frequency which is -66.61dB along with a very good fractional bandwidth of 79% highest among other reported literature. With all these finding the proposed design found to be a potential candidate for modern wireless applications, other antennas under consideration have single-band characteristics having some reflection coefficient value however in Our Proposed antenna, we obtained single-band from 8.5 GHz to 19.6 GHz with a very compact size of 12 x 12 x 1.6 mm3, highest reflection coefficient, and the overall band-width is 11.1 GHz

Conclusion Future Scope

An extremely compact patch antenna is designed for the use in wide-band applications has been simulated with great success. Here, excellent return loss with considerable gain and very good impedance matching is obtained. The proposed design is being simulated by a tool called High-Frequency Structural Simulator with excellent fractional bandwidth of 79% which is remarkable for wideband application. The radiation patterns observed are also quite impressible both in E plane H plane. The designed antenna can be used in indoor and outdoor multi-service wireless communications system. The further scope of work is to extend this proposed antenna design in MIMO antenna of 2 x 2 and 4 x 4 for wideband communication applications such as data communication, radar, and sensing broad band surveillance

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