A Flexible Wideband Microstrip Antenna on TPU Substrate using Inset Slot Feed and Partial Ground Plane

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***Abstract*—This paper aims to present a flexible and wideband microstrip antenna on a Thermoplastic Polyurethane (TPU) substrate. TPU is used as the substrate in designing the flexible antenna due to its high flexibility, elasticity, and strength properties. The characteristic of the antenna is further enhanced by inserting inset slot feed and using a partial ground plane to improve the resonant frequency and realize a wide bandwidth, respectively. The performance of the proposed antenna is analyzed and compared with a common antenna design method which typically produces a narrower bandwidth. The antenna shows promising results resonating from 7.5 to 10.2 GHz with a percentage increase of 17.4% in terms of bandwidth, and greater return loss along the operating frequency range.**

Keywords— flexible microstrip antenna, wideband, inset slot feed, partial ground plane, Thermoplastic Polyurethane (TPU).

I. INTRODUCTION

The integration and technological advancement in modern communication networks have shown tremendous progression to the system in current civilization. Antenna is one of the most reliable mediums in communication technology. However, conventional antennas are stiff and rigid which is not suitable for certain situations as it does not have the resilient characteristic to withstand the adaptation [1,2]. Flexible antenna performs as an essential component in the practicality of modern communication networks, where the flexibility and effectiveness of the antenna depend on the substrate material used. Several materials have been investigated, analyzed, and used to form a bendable antenna such as rubber [3], polydimethylsiloxane (PDMS) [4], polyethylene terephthalate (PET), and Thermoplastic Polyurethane and Elastomers (TPU and TPE) [5,6]. In comparison with common antennas on rigid and hard substrates, these bendable antennas are shown to have the advantages of being lightweight and low profile, apart from having high elasticity and stable electrical properties.

Apart from being flexible, an antenna with a wide bandwidth would be beneficial in communication and wireless applications [7,8]. A wider bandwidth makes it more convenient for wireless networking due to its dominance in the allocated frequency band. Wideband technology has made an immense impact over the last decade due to its numerous advantages such as high-speed data rate characteristics, power efficiency, non-interfering signal, efficient use of spectrum, secure communication system, and simple circuitry for implementation.

Building a wideband microstrip antenna has been approached in several ways, including the use of inset slot feed and partial ground plane. In related works, the proposed antenna by [9] used rectangular slots to improve the antenna's resonant frequency and return loss. Authors in [10] used slots and inset slot feed to improve the impedance match, gain and return loss of their antenna for WBAN applications. Apart from this technique, the authors in [11] and [12] used the partial ground plane method to reduce mutual coupling and enhance the bandwidth of the antenna. These works demonstrate that adding slots and inset slot feed to the antenna design can improve resonant frequency and return loss, while the use of a partial ground plane can provide broader bandwidths.

In this paper, we promote and aim to demonstrate some ways to improve the bandwidth and performance of a flexible microstrip antenna within the X-Band region [13-18]. The antenna has been designed with a coplanar waveguide (CPW) technique, inset slots for the patch feedline, and a partial ground plane as the backing structure. The inset slots are expected to enhance resonant frequency and return loss, where surface current paths of the resonant modes can be lengthened, resulting in the decrease of corresponding resonant frequencies. On top of that, the partial ground plane technique is applied to achieve acceptable impedance matching characteristics and magnify the bandwidth. The overall antenna design methodology and computations using fundamental equations are explained in Section II. Section III analyzed the simulation results and discussed further the performances of the antenna in terms of S_{11}, bandwidth, realized gain, directivity, and radiation pattern. It is observed that the optimized antenna with TPU material has managed to provide a wide bandwidth of 2700 MHz from 7.5 to 10.2 GHz, and a better S_{11} of less than -10 dB throughout the working frequency range.

II. METHODOLOGY

A rectangular patch antenna is designed by performing several calculations referring to the fundamental formula in [19]. There are three fundamental factors that need to be considered to compute the patch dimensions and to ensure proper impedance matching between the radiating patch and transmission line. These factors are the resonant frequency, the dielectric thickness, and the dielectric constant (relative to vacuum) of the material chosen. For this work, the TPU substrate used for the proposed antenna has a dielectric constant of 3.0 [5,6] and a thickness of 2.5 mm. The specified values of the operating frequency (f_o), the substrate thickness (h), and the substrate relative permittivity of the dielectric constant (ε_r) are applied accordingly to define the computation of the patch width (W) and patch length (L). The patch width (W) is calculated as in equation (1).

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \quad (1)$$

Where c is the speed of light, 3 x 10^8 m/s. The effective dielectric constant ε_{eff} is calculated using equation (2) which is based on the substrate height h, dielectric constant ε_r and the calculated patch width in (1).

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

The patch length (L) is calculated using equation (3) which involved the difference between the effective length (L_{eff}) and length extension (ΔL), calculated using equations in (4) and (5) respectively.

$$L = L_{eff} - 2\Delta L \quad (3)$$

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \quad (4)$$

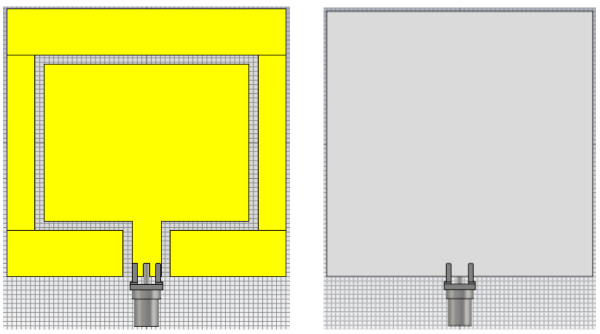
$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)} \quad (5)$$

After all calculation for the patch dimensions has been made, the antenna is designed on a 60 × 60 mm^2 TPU material and simulated using CST MWS software. The layout of the rectangular patch antenna before and after optimization are shown in Fig. 1 and Fig. 2, respectively. After optimization refers to (i) insertion of inset slot feed on top to enhance S_{11} and (ii) applying partial ground plane at the back to realize a wider bandwidth and better matching.

The finalized dimensions of the proposed antenna can be observed in Table I with the following parameters: width of patch (W), length of patch (L), slot width (W_s), slot length (L_s), and feedline width (W_f).

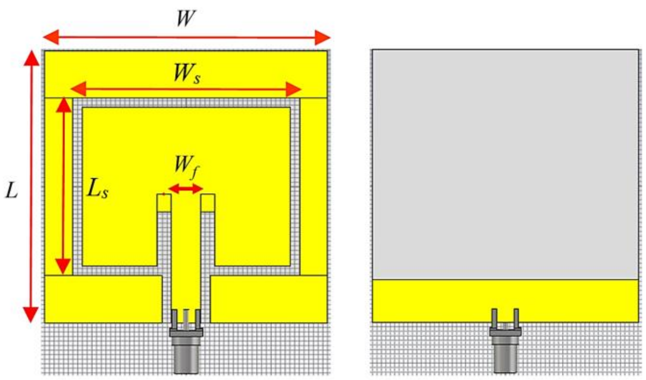
TABLE I FINALIZED DIMENSIONS OF THE PROPOSED ANTENNA AS IN FIG. 2

Parameters	W	L	W_s	L_s	W_f
Dimensions (mm)	60	60	44.19	35.11	6.26



(a) (b)

Fig. 1. The antenna before optimization (a) top view and (b) bottom view.



(a) (b)

Fig. 2. The antenna after optimization with inset slot feed at the top patch and partial ground plane at the bottom (a) top view and (b) bottom view.

The feedline width (W_f) is obtained using the CST features called macros where it calculates the analytical line impedance for the suitable width to achieve good impedance matching of 50Ω between the feedline and the antenna radiating patch. However, the feedline width can also be calculated using the fundamental equations in (6) referring to authors in [20], where Z_o is the input impedance. The reason for securing impedance matching is to ensure that power can be supplied without having losses which results in a better accuracy of the antenna performances.

$$W_f = \frac{7.48 \times h}{e^{\left(z_o\frac{\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25 \times t \quad (6)$$

The feedline is designed to have CPW characteristics to eliminate the narrow bandwidth produced by a typical rectangular patch. To increase the reflection coefficient performance, the inset slot feed is added to the patch (Fig. 2a) which may allow maximum full potential in the antenna performances. The authors of [9,10] demonstrated how antennas with slot feeds can increase resonant frequency and return loss. This is because they can stretch the surface current courses of the resonant modes, which lowers the corresponding resonant frequencies.

Next, the conventional method of a full ground plane at the bottom layer was brought up to the top layer corresponding to the CPW technique creating a gap with the patch. The gap has been defined as 2 mm between the rectangular radiating patch and the feedline with the ground plane surrounding it. Moreover, a partial amount of copper with the same thickness of 0.035 mm as the patch and ground plane has been set at the lower side of the bottom layer (Fig. 2b). This partial ground plane technique is to ensure that the antenna resonates at the targeted frequency band, amplify the bandwidth [11] and achieve good impedance matching characteristics [12].

III. RESULTS AND DISCUSSIONS

The performance of the antenna is analyzed based on the S_{11}, bandwidth, realized gain, directivity, and radiation pattern. Table II shows the comparison between the rectangular patch antenna before and after optimization in terms of S_{11} and bandwidth at targeted frequencies within the operating frequency range 7.5 to 10.2 GHz.

TABLE II REFLECTION COEFFICIENT AT SELECTED FREQUENCIES OF 8 GHZ TO 10 GHZ, AND OPERATING BANDWIDTH OF THE PROPOSED ANTENNA (WHICH CAN BE OBSERVED FROM FIG. 3).

Parameters	Freq (GHz)	Before optimization	After optimization	% increase
S_{11} (dB)	8	-16.73	-20.14	20.38%
	8.5	-12.43	-31.22	151.17%
	9	-13.06	-22.42	71.67%
	9.5	-15.14	-20.08	32.63%
	10	-4.49	-21.50	378.8%
Bandwidth (MHz)		2300	2700	17.4%

The simulated S_{11} of the antenna before and after optimization is shown in Fig. 3. The dotted green line indicates the patch antenna before optimization, while the solid red line signal shows the patch antenna after optimization with inset slot feed and partial ground plane. The result shows that the antenna produced better S_{11} in all corresponding frequencies after optimization. It can be observed from Table II that there is a tremendous increase of 3.41 dB (20.38%) at 8 GHz, 18.79 dB (151.17%) at 8.5 GHz, 9.36 dB (71.67%) at 9 GHz, 4.94 dB (32.63%) at 9.5 GHz, and 17.01 dB (378.84%) at 10 GHz. In addition, the optimized antenna also produced a broader bandwidth of 2700 MHz as compared to 2300 MHz by antenna without optimization. This indicates a 17.4% or 400 MHz increase in terms of bandwidth.

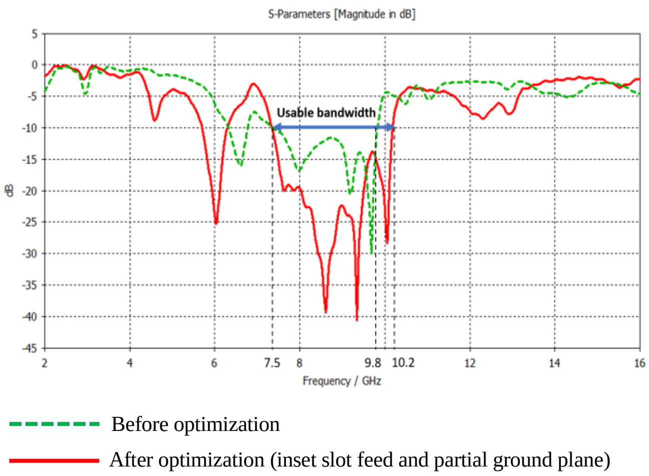


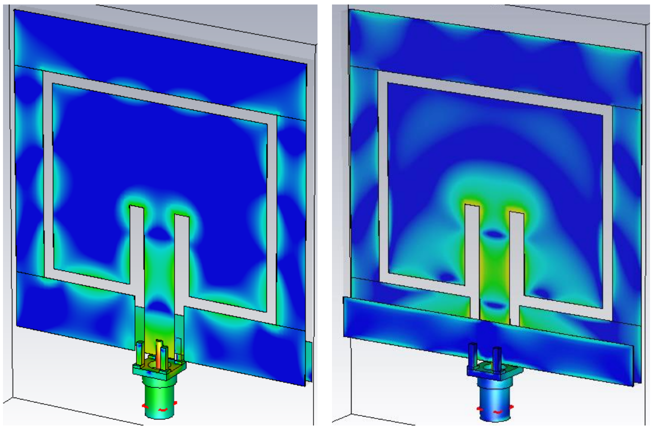
Fig. 3. S_{11} (dB) of the proposed antenna before optimization as in Fig. 1 (dotted green line) and after optimization as in Fig. 2 (solid red line).

This proved that the inset slot feed method does improve the S_{11} at the targeted frequencies [9,10]. In addition, the partial ground plane technique produces a wider bandwidth that would be usable in various applications [11,12]. The desired outcome is achievable with the proper action of modifying in terms of the variable's value.

TABLE III REALIZED GAIN AND DIRECTIVITY AT SELECTED FREQUENCIES OF 8 GHZ TO 10 GHZ OF THE PROPOSED ANTENNA

Frequency (GHz)	Realized gain (dBi)	Directivity (dBi)
8	4.194	4.265
8.5	4.567	4.591
9	5.828	5.875
9.5	5.283	5.354
10	5.533	5.524

The gain and directivity of the simulated antenna at 8 GHz to 10 GHz are also recorded in Table III. The antenna shows an average realized gain of more than 4 dBi with the lowest 4.194 dBi at 8 GHz and highest 5.828 dBi at 9 GHz. In terms of directivity, the antenna exhibits an average directivity of more than 4 dBi too, with the lowest 4.265 dBi at 8 GHz and highest 5.875 dBi at 9 GHz. The current distribution of the proposed antenna is shown in Fig. 4. The illustrated surface current for 9 GHz is observed as reference through the resonating bandwidth. The accumulated current density on the radiating patch before and after optimization are 35.2 A/m and 33.9 A/m, respectively. It is considered that a good amount of current has been accumulated on the radiating patch antenna for both designs.



(a) (b)

Fig. 4. Surface current distribution of the proposed antenna after optimization (with inset slot feed and partial ground plane) at 9 GHz (a) top view and (b) bottom view.

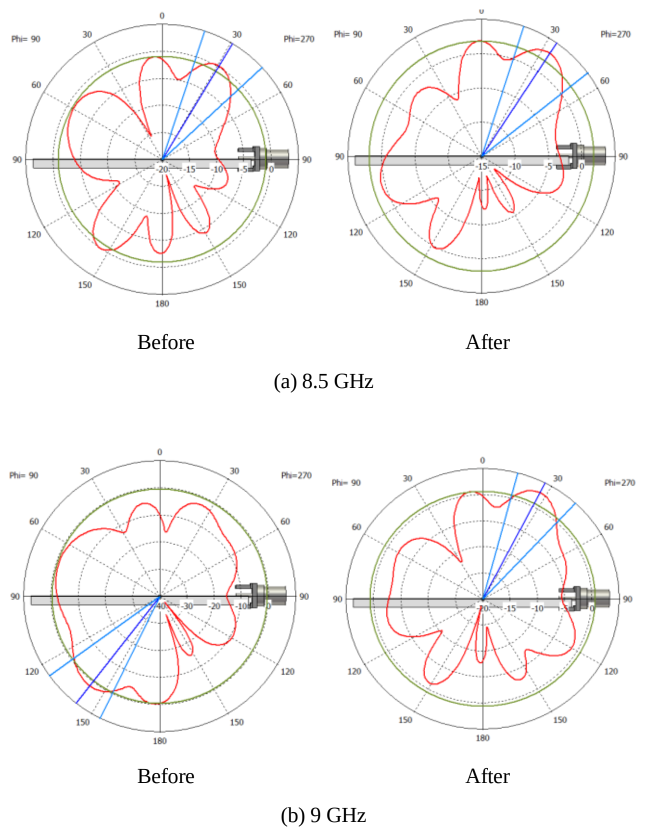


Fig. 5. The polar pattern of the proposed antenna in two frequencies of (a) 8.5 GHz and (b) 9 GHz, before and after optimization (with inset slot feed at the top patch and partial ground plane at the bottom).

The polar patterns of the proposed antenna are shown in Fig. 5. The illustrated patterns are presented in selected two frequencies of 8.5 GHz and 9 GHz. The polar pattern of the initial antenna design at 8.5 GHz displays that the main lobe direction is radiating upwards from the patch at 31º with only ~0.1 dBi gain, but improved tremendously to 4.567 dBi at 34º after modifications were made. On the other hand, the polar pattern at 9 GHz shows that the main lobe is moving downwards at 142º before the optimization. However, with the insertion of slot feed and partial ground plane, the main lobe direction shifted upwards at an angle of around 28º with a more refined front-to-back ratio and a higher gain of 5.828 dBi.

Table IV shows a comparison of the proposed antenna with other X-band antennas available in the literature. It is observed that our antenna works well in the X-band region from 7.5 to 10.2 GHz with an overall return loss of less than -10 dB along the operating frequency range, bandwidth of 2700 MHz, and having a flexible structure. These findings suggest that our proposed antenna may be a viable choice for a range of X-band applications that call for a broad bandwidth and a bendable structure.

TABLE IV COMPARISON OF THE PROPOSED ANTENNA WITH OTHER X-BAND ANTENNA AVAILABLE IN LITERATURE, IN TERMS OF SUBSTRATE USED, FREQUENCY, FLEXIBILITY, S_{11}, AND BANDWIDTH.

	Substrate	Freq (GHz)	Flexibility	S_{11} (dB)	BW (MHz)
[13]	FR-4	9.49	Non-bendable	-23.87	700
[14]	RT5880	7.5	Non-bendable	-42.09	399
[15]	RT5880	9.5	Non-bendable	-39.11	NR
[16]	FR-4	10.25 11.54	Non-bendable	-17.14 -14.29	1590
[17]	FR-4	10.3	Non-bendable	-29.21	NR
[18]	FR-4	8.74	Bendable	-27.33	NR
This work	**TPU**	**8 8.5 9 9.5 10**	**Bendable**	**-20.14 -31.22 -22.42 -20.08 -21.50**	**2700**

*NR = not reported, BW = bandwidth.

IV. CONCLUSION

A flexible microstrip patch antenna based on a Thermoplastic Polyurethane (TPU) substrate with a CPW has been proposed correlating to a wide bandwidth from 7.5 GHz to 10.2 GHz. The proposed patch antenna has been designed on a 2.5 mm TPU material with a dimension of 60 × 60 mm^2 and simulated by the CST MWS software. It is seen that the reformation and modification in the presence of an inset slot for the patch feedline and also a partial ground plane at the back of the antenna, has increased the bandwidth by 400 MHz, which equals to 17.4%. Furthermore, the performance of the antenna in terms of S_{11} has also improved significantly, with acceptable realized gain and directivity, when compared to a conventional method in designing a rectangular patch antenna. The proposed wideband antenna can be applied to many applications in the X-Band region for faster and better transmission. For future work, more investigation on observing the antenna performance in bending situations will be carried out, followed by fabrication and measurement of the antenna design for validation purposes.

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