Design and Analysis of flexible patch antenna on transparent PVC material substrate

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Abstract. Flexible substrates play a vital role in the design of wearable antennas. Analysis and fabrication of rectangular microstrip patch antenna have been demonstrated in this paper on a least explored flexible PVC-based transparent sheet. The substrate's dielectric constant and loss tangent have been calculated by conducting a standard ring resonator test. The effect of bending on an antenna with different bending diameters along the x-axis and y-axis has been observed on Vector Network Analyzer (VNA) to verify the flexibility of substrate material for wearable applications.

1 Introduction

Flexible antennas have become the center of attraction as they can be used in wearable applications, flexible electronics, WBAN applications, medical applications, and military applications. Flexible substrates such as polyethylene terephthalate (PET), Kapton, Paper, Textile, Rubber, etc., have been used by different researchers for the fabrication of flexible antennas [1]– [4]. Along with flexibility, transparency of substrate is required for various wireless applications. Transparent antennas can be located on transparent glasses and windows and integrated into watches, mirrors, and solar cells [5]. Microstrip patch antennas must be fabricated on flexible substrates for ISM band and other applications [6].

In literature, various antennas on different flexible substrates have been designed, such as a simple dipole antenna for UHF band applications has been reported on flexible Kapton polyimide [7]. A flexible rubber substrate is presented for wearable antenna application in [2]. An array antenna on four flexible substrates (i.e., cotton, polyimide, polyester, and Teflon) are reported for biomedical applications with DGS for enhancement in bandwidth [8], a circular patch antenna on a wax-coated paper and polyester substrate for wireless energy harvesting applications[9], a flexible patch antenna is designed on a paper substrate, and patch dimensions are reduced by introducing air gap [10], a PDMS substrate is explored in the design of patch antenna to attain the flexibility, and the wide band is achieved using DGS [11], paper-based antenna for ISM band is reported in [12], and a graphite monopole antenna has been reported for 2.4 GHz wireless system where the paper substrate is utilized to attain the flexibility [13].

This paper uses a polyvinyl Chloride (PVC) flexible sheet to design a rectangular microstrip patch antenna (MPA) with coaxial feed for ISM band applications. In this approach, the transparent sheet is purchased from the local market, which is flexible, low-cost, and readily available. In the literature, the only paper based on PVC material substrate is a hexagonal-shaped substrate of PVC material with a flag-shaped slot on the circular patch and slotted ground for defense and Radio-determination applications [14]. A copper sheet of 0.08mm thickness for conductive patch and ground is used with coaxial feed type. The coaxial feeding technique is used as it is simple and compatible with coaxial cables, and it is easy to obtain input matches by adjusting the feed position [15]. The correct feed point is obtained by using the optometric feature in HFSS.

PVC sheets' characteristics reported in the literature emphasize flexibility and low cost. PVC sheets are also less rigid, have less chemical resistance, have high impact strength, and are more accessible to mold. It is a thermoplastic non-crystalline polymer best used for structural applications, good outdoor weathering characteristics, and increased clarity[16].

To offer correct dielectric characteristics of PVC sheet substrate in ISM band frequencies, a thorough analysis has been carried out in this paper. Using the microstrip ring resonator approach, the RF characterization of the PVC sheet was carried out in Section II. In Section III, a microstrip rectangular patch antenna for ISM band frequencies is analyzed and designed utilizing copper tape over a PVC sheet substrate. Results from simulations and measurements are contrasted in Section IV. The impact of bending on the PVC substrate antenna along the x and y axes is examined and contrasted in Section V.

2 RF Characterization of PVC Sheet

For determining RF characteristics, the microstrip ring resonator method is popular among all resonator-based methods as it provides dielectric information at periodic peaks for higher frequencies [17]. A file sheet of thickness 0.15 mm has been selected to fulfill the requirement of cheap and flexible material. Seven layers of 70 mm x 70 mm x 0.15 mm are pasted using adhesive to get the 1 mm thickness of the substrate. So, there is a need to find the dielectric properties, i.e., permittivity and loss tangent, for designing the patch antenna on this multilayer PVC substrate. A thinner substrate can result in higher efficiency for the antenna and also helps to reduce the size and weight of the antenna, for this reason, a 1mm thin substrate has been used.

The basic structure of the ring resonator used for characterization is shown in Fig. 1. Reference for calculating the parameters required for dielectric constant and loss tangent in the ring resonator test is given in [18]. Simulation of ring resonator is performed on HFSS (High-frequency structure simulator). After fabrication, it was tested on VNA for the S_{21} parameter to get the required peak for the dielectric and loss tangent calculation. The ring resonator, feed lines, and transmission lines all have a chosen 50 Ω characteristic impedance. To distinguish the resonant behavior of the ring from the feed network, a thin gap Δ that is between 0.1 and 1.0 times the width of the feed microstrip is inserted between each feed line and the ring. The equations for standard design from [17] - [19] have been used to calculate the physical dimension of the ring resonator method, which is presented in Table I.

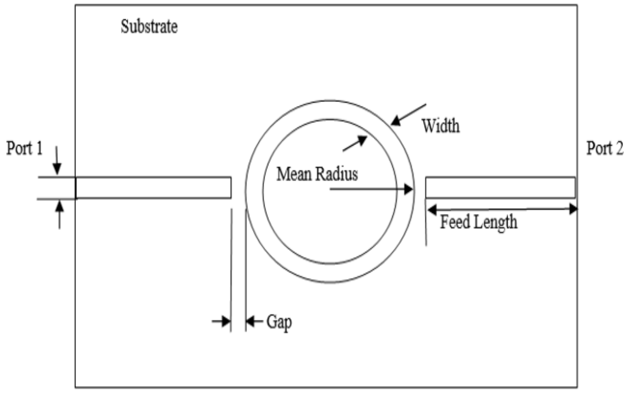

Fig. 1. Ring Resonator for RF characterization [18].

Table 1. Dimensions required for ring resonator method

Parameters	**Values(mm)**
Mean Radius	11.40
Width of the feed line	2.23
Length of feedline	20.36
Coupling gap	0.2
Length of substrate	70
Width of substrate	70
The outer radius of the ring	12.51
The inner radius of the ring	10.26
Substrate used	PVC film sheet

Copper tape of thickness 0.08mm has been used for conductive parts. The ring made of copper tape is designed by the screen-printing method and pasted on the substrate; the SMA connector is soldered on both sides as the ring resonator has two ports.

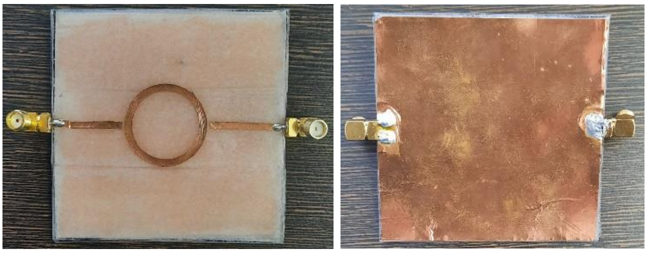

Fig. 2. Fabricated ring resonator – Top and bottom view

Fig. 2 presents the ring resonator which is fabricated on the PVC file sheet. Fig. 3 presents a comparison of the measured and simulated results of the ring resonator. The Simulated results show that the ring has a peak at 2.89 GHz with an S_{21} parameter - 39.124 dB, which is a desirable range to find a dielectric constant. The S_{21} parameter obtained on VNA (Anritsu MS46322A) after fabrication is - 70.37 dB, where the peak frequency obtained is 2.83 GHz and the highest peak is taken for calculation of ε_r and tan δ (dielectric constant and loss tangent). A little deviation is there in terms of peak frequency. Further, the calculation is done using simulated and measured results to obtain the values of ε_r and tan δ (dielectric constant and loss tangent). The obtained values of ε_r and tan δ are 2.72 and 0.0042, respectively. These parameters are further used for designing the rectangular patch antenna.

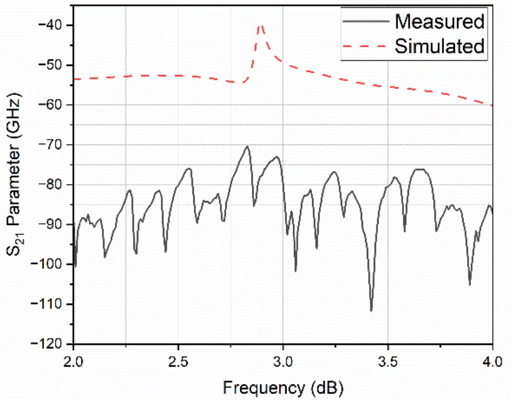

Fig. 3. Result of S_{21} parameter of PVC file sheet-based ring resonator

3 Design and analysis of Microstrip Rectangular patch antenna

On the PVC substrate defined in the preceding part, the design and analysis of a microstrip rectangular patch antenna are presented in this section. To design, simulate and fabricate an antenna for the 2.45 GHz ISM band frequency, measured values of the ε_r and tan δ (dielectric constant and loss tangent) were employed. The standard design equations from [20] have been used for the calculation of the physical dimensions of the antenna, and the same is presented in Table 2.

Table 2. Parameters for simulating antenna on HFSS

Parameter	Value (mm)
Length of patch	36
Width of patch	43.56
Length of substrate	70
Width of substrate	70
Feed position (x, y)	(7, 0)

As presented in Fig. 4, simulated results show that the designed antenna has a resonating frequency of 2.45 GHz, an S_{11} parameter of -26.37 dB, a gain of 6.28 dB, and a bandwidth of 30 MHz. The return loss i.e., S_{11} parameter should be less than -10 dB for wireless applications. This level of return loss is considered to be relatively good. After simulation, the designed antenna is fabricated and tested using VNA for verification. A PVC sheet of thickness 0.15 mm, length and width of 70 x 70 mm^2 is used, and seven layers of this sheet are pasted one over one to obtain a thickness of 1 mm with the help of adhesive. Then manually, the copper tape of 70 x 70 mm^2 for the ground is pasted in the substrate's bottom part, and the copper tape patch of size 43.56 x 36 mm^2 on the top side is pasted. The fabricated antenna is shown in Fig. 5.

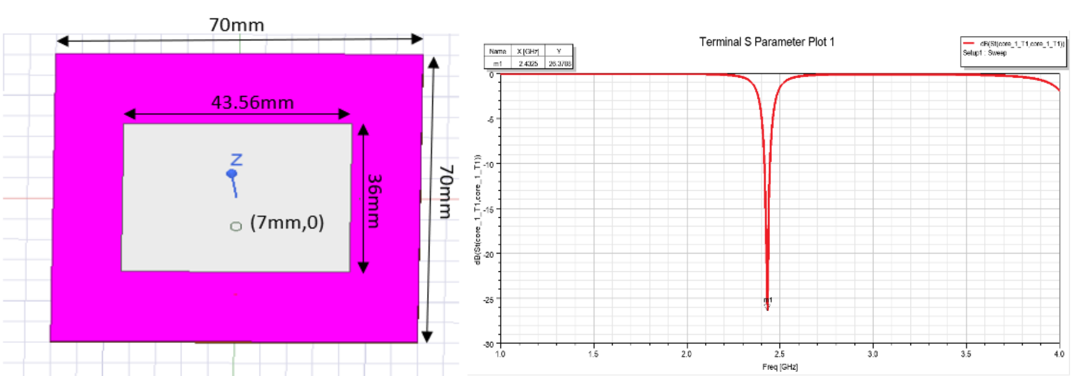

Fig. 4. Design of MPA and its simulated results

After fabrication, the prototype was tested on VNA by connecting the antenna through port 1. Measured results show that the antenna resonates at 2.65 GHz with S_{11} – 25.97 dB. There is a slight difference in frequency, as shown in Fig. 6, mainly due to manufacturing errors.

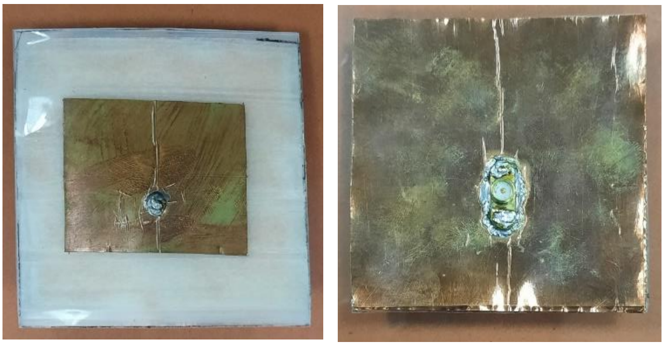

Fig. 5. Fabricated patch antenna- Top and bottom view

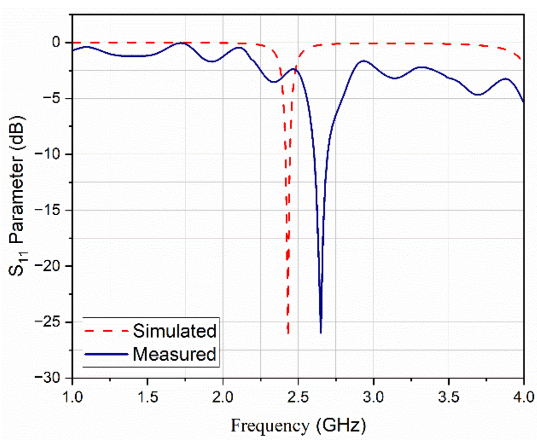

Fig. 6. Comparison of Simulated and Measured results

The return loss obtained after fabrication i.e. - 25.97 dB, achieving this level of return loss is important for maintaining system performance and minimizing signal loss.

Table 3. Comparison with existing flexible antennas

Antenna parameters	Antenna-1 (Circular microstrip patch antenna)[21]	Antenna-2 (Microstrip patch antenna)[22]	Antenna-3 (Hexagonal Microstrip antenna)[23]	Fabricated Antenna (Microstrip patch antenna)
Substrate used	PDMS (polydimethylsiloxane)	felt	foam	PVC (Polyvinylchloride)
Dielectric Constant and Loss tangent	2.65; 0.02	1.3; (-)	1.07; 0.0025	2.72;0.0042
Resonating frequency (GHz)	5, 5.8, 6.6	6.32	3.5,5.8,9.6	2.65
Return loss (dB)	-24.9, -20.2, -19.4	-22.83	-21.25, -25.58, -18.05	-25.97

Bandwidth (MHz)	820, 640, 520	680	8700	30
Gain (dB)	6.2,4.2,2.3	5.66	5.24	6.28
Height of substrate (mm)	1	0.5	1.7	1
Area (mm^2)	50 X 40	65X65	38X30	70X70

The comparison Table 3 shows the comparison of fabricated PVC-based substrate antenna with existing flexible antennas in literature, it has been observed that the gain of PVC substrate antenna is comparatively more than PDMS, felt, and foam-based substrate antennas. Even the return loss obtained is better than existing antennas. PVC sheet is cheap and easily available, which makes the antenna cost-effective and user-friendly.

4 Bending analysis of Fabricated antenna

The flexible antenna is subjected to bending along different directions during practical applications. The bending may affect the antenna performance, and bending analysis is a must to analyze the bending effects. Bending is done with a 40 mm and 60 mm radius along the x-axis and y-axis of the designed antenna. A comparison between the results of the antenna without a bend and with a bend along different radii is shown in Table 4. It has been observed that frequency is constant along the x-axis; there is a slight frequency shift while bending along the y-axis. Frequency shifts to the lower end with decreasing radius (i.e., 40 mm). The best results are obtained along the x-axis bending with a radius of 60 mm.

Table 4. Measured resonant frequency and s_{11} parameters of the antenna with bending along the x and y axis

Antenna Parameters	**Antenna bending conditions**				
	Flat	**Radius along the x-axis (mm)**		**Radius along the y-axis (mm)**	
		40	60	40	60
S_{11} Parameter (dB)	-25.97	-7.28	-19.60	-13.19	-18.04
Resonant Frequency (GHz)	2.65	2.65	2.65	2.57	2.61

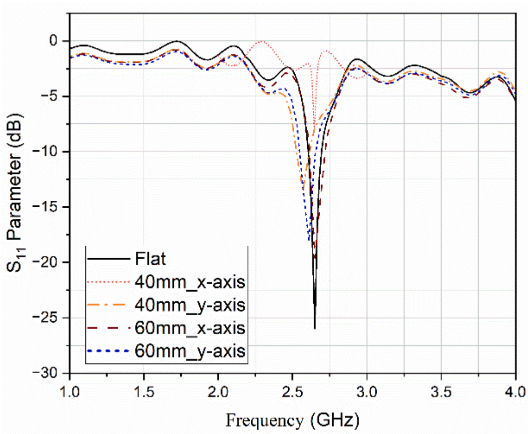

Fig. 7. Frequency versus S_{11} parameter graph with different bending radii along the x and y axis

5 Conclusion

A flexible, transparent antenna is designed, fabricated, and tested for the 2.45 GHz operating frequency range. The designed antenna has a 2.65 GHz frequency with an S_{11} parameter equal to - 25.97 dB, it indicates that only 1.8 % of the incident power is reflected back from the system while 98.2% of power is transmitted through the system. The 2.65 GHz frequency range is used in radar systems, cordless phones, wireless security systems, and Industrial heating applications, some devices and routers also support this frequency range to improve network performance. A low-cost approach using screen printing has been utilized to expose the structure of the ring on copper tape, and the actual performance of the patch antenna has been analyzed. RF characterization has been used to obtain the ε_r and tan δ for calculating the dimensions of the patch antenna to be printed on a PVC substrate. This antenna is suitable for wearable applications as it is bendable and flexible. Bending analysis has been done along the x and y axis with different radius values. This study concludes that ordinary file sheets available at local market shops are also suitable for antenna designing.

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