Investigation of substrate materials laminated CPW-Fed patch antennas: Opportunities and challenges

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Abstract: This article investigates the design of antennas fed by coplanar waveguide (CPW) utilizing different substrate materials and techniques. The article illustrates the impact of several materials such as FR-4, Rogers, Arlon, etc on electrical properties such as impedance bandwidth (IBW), reflection coefficient (|S11|), and gain. The article also examines the effects of design approaches such as including stubs, slots, arrays, etc on antenna |S11| parameters. The resonance frequencies (fr) of the suggested antennas may be modified by manipulating the electrical dimension, the dielectric constant of the substrate materials, and their respective thicknesses. The structure of the Flame-Retardant fiberglass epoxy (FR-4) proposed antenna covers an operating frequency range of 3.3 to 10.1 GHz. It can operate at six distinct frequency bands, making it appropriate for applications including C-band (4-8 GHz), X-band (8-12 GHz), 5G (3.5-6.0 GHz), and 6G (7-20 GHz). The antenna designed and simulated using computer simulation software (CST) electromagnetic simulator.

Keywords: Substrate Material, FR-4, Rogers RT5880, Arlon AD600, CPW-fed

1. Introduction: Antennas are essential for wireless communication systems. Demand for affordable, flexible, low-profile, and small broadband antennas has grown rapidly in the past two decades. Multiple antennas are required for transceiver services, but it's challenging to incorporate them into a single mobile device due to size constraints. Communication technologies must be carefully kept apart. A multi-band circularly polarized (CP) antenna is needed to overcome this limitation. It is used to make independent data transmission and reception, remove fading or multipath shortcomings, tolerate adverse weather conditions, achieve accurate polarization between antennas, and has proven to be highly robust in varied electromagnetic environments. The advantage of this approach is its simplicity, which allows it to be easily redesigned for multiple frequency bands. The redesign technique is simple, requiring simply a recalculation of the chosen physical dimensions followed by electromagnetic-based parameter modification. The slot antennas with a coplanar waveguide feed increase bandwidth and reduce antenna size. CPW feed offers wideband, high impedance bandwidth, reduced radiation loss, and ease of integration with active elements. To cover radio frequency identification (RFID), global navigation satellite system (GNSS), wireless local area network (WLAN), and worldwide interoperability for microwave access (WiMAX) frequency ranges of interest, a wideband compact CPW-fed circularly polarized antenna is provided [1-6].

A large axial ratio bandwidth (ARBW) is achieved by coupling three CP modes together with an asymmetric CPW structure [7]. The modified coplanar ground plane to accomplish dual operating bands that include S-Band, C-Band, WiMAX, WLAN, 4th generation mobile network (4G), 5th generation mobile network (5G), ultra-wideband (UWB), and X-band communications. A CPW-fed UWB flexible composite antenna is used for wireless personal area network (WPAN) applications. The CPW-fed antennas on high-permittivity substrates are designed to achieve high gain for industrial, scientific, and medical (ISM) applications. The antenna array showed good impedance matching when tested in conformal conditions and has the potential for wearable applications [8-10].

CPW-fed antennas are suitable for various wireless applications, including 5G, and can be optimized for 6G by achieving the desired gain, directivity, efficiency, and bandwidth. Design techniques like defected ground structure (DGS), frequency selective surface (FSS), Metamaterials, arrays, and multiple-input-multiple-output (MIMO), can further improve these characteristics. This article will explore parametric studies using different design techniques with various substrate materials and appropriate thicknesses to optimize the antennas for several radio frequency (RF) and wireless application. A dielectric material is very important for the operating frequency range. The thicker substrate with lower dielectric constants carries more efficiency and a wider impedance bandwidth but results in a larger antenna. Hence, high-dielectric constant substrate techniques to allow appropriately small antenna sizes have been analyzed for RF and microwave applications. The different types of substrate materials and their properties are tabulated in Table 1. The resonance frequencies are dependent on the substrate area, thickness, and dielectric constant. Fundamental resonance frequencies are moved towards the low-frequency band at a higher dielectric constant with low substrate thickness. Thus, substrates with the high dielectric constants ensure the antenna miniaturization [11-14].

This article reviews various design techniques for CPW-fed antennas, focusing on substrate materials and their thickness. The article is presented in four sections. In section 2, comparative studies and design techniques have been discussed. In section 3, the proposed work and in section 4, comparative outcomes are given.

Table 1: Properties of substrate materials

Material	Dielectric Constant (ε_r)	Loss Tangent ($\tan\delta$)	Specific Heat (J/g. K)	Thermal Conductivity (W/mK)	Moisture Absorption (%)	Surface Resistivity (MΩ)
Silicon	11.9	0.0010	1.01	100-150	0.02	-
Polyethylene Tere -phthalate (PET)	1.80	0.0005	1.17	0.256	-	-
Taconic CER-10	10.0	0.0035	-	0.63	0.02	1.1×10^9
Arlon	3.20	0.0038	0.90	0.24	0.06	1.6×10^9
Rogers RT/Duroid 5880	2.20	0.0009	0.96	0.71	-	3×10^7
Rogers RT/Duroid RO3006	6.15	0.0020	0.86	0.61	0.02	1×10^5
Rogers RT/Duroid RO4003	3.38	0.0027	0.93	0.64	0.04	4.2×10^9
FR-4	4.2 - 4.6	0.0200	0.95	0.16	0.25	4×10^6

2. Comparative Study and Design Techniques: The selection of design techniques and selecting a suitable antenna is crucial for RF system performance, including bandwidth and communication range. Researchers have proposed various techniques [1-14] to increase antenna bandwidth and gain, and reduce the size of the antenna. These methods modify parameters like bandwidth, gain, directivity, efficiency, and impedance bandwidth, allowing antennas to work in various applications like RFID, WLAN, Wi-Fi, Wi-Max, WPAN, ISM, IMT bands, GNSS, S-band, C-band, X-band, Ku, Ka-band, 5G, high-performance radio local area network (HiperLAN), unlicensed national information infrastructure (U-NII), and work in multiple bands simultaneously. It also shows the applicability of antennas to work in multiple bands at the same time. This paper introduces mathematical modeling for antenna design, focusing on determining dimensions and optimizing performance. Geometries enhance parameters like return loss, bandwidth, gain, and radiation pattern. The antenna's size is crucial for wideband purposes, with resonant frequency, radiation pattern, and input impedance controlled by patch length and width. Basic calculations for antenna dimensions are provided using formulae [3]. The L and W of the patch antenna can be calculated by using the equations (1–5).

2.1. Calculation of the width (W)

$$W = \frac{1}{2fr\sqrt{\mu 0 \varepsilon 0}}\sqrt{\frac{2}{1+\varepsilon r}} \quad (1)$$

$$W = \frac{c}{2fr}\sqrt{\frac{2}{1+\varepsilon r}} \quad (2)$$

where, $c = \frac{1}{\sqrt{\mu 0 \varepsilon 0}}$ is the velocity of light in the free space, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, ε_r is the relative permittivity of the substrate, and f_r is the resonant frequency.

2.2. Actual length of the patch (L)

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

$$L = \frac{1}{2fr\sqrt{\mu 0 \varepsilon 0}\sqrt{\varepsilon reff}} - 2\Delta L \quad (4)$$

$$L = \frac{c}{2fr\sqrt{\varepsilon reff}} - 2\Delta L \quad (5)$$

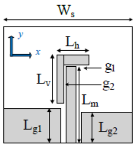
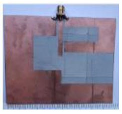
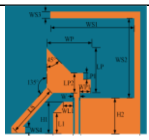
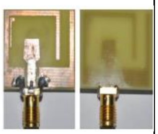
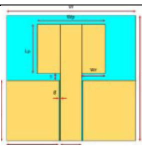
where, ΔL is the incremental length due to Fringing field, and ε_{reff} is the relative effective dielectric constant. The effective dielectric constant can be calculated by using the equation (6), and the effective length (L_{eff}) can be calculated using equation (7).

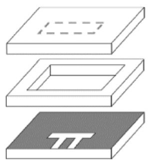
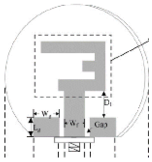
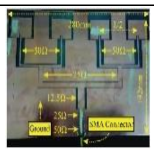
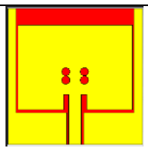
$$\varepsilon r_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1+\frac{12h}{w}}}\right) \quad (6)$$

$$Leff = \frac{c}{2fr\sqrt{\varepsilon reff}} \quad (7)$$

2.3. Effects of adding stubs, slots, strips, cutting corners, and arrays: Recent ultra-wideband antenna structure designs have used various techniques to achieve CP radiation on a microstrip antenna, as seen in Table 2. These approaches include cutting corners, slot-loading, branch line loading, adding slits, arcs, asymmetrical feeding, arrays, spiral stubs, and so on. These approaches permit CP radiation, efficient impedance matching, and effective gain across a wider frequency range, with potential biomedical, wearable, and industrial applications.

Table 2. Summary of comparative performance of referred CPW-Fed antennas with various substrate materials

Antenna Design Techniques	Antenna Structure	Antenna Area (mm^2)	Substrate Material (ε_0)	IBW (%) (at > -10dB)	Peak Gain (dBi)	Applications	Ref.
Annular Ring Slot, Cutting corner, Slot loading		25 ×24	FR4 (4.4)	56.27%	3.7-4.6	UWB	[1]
L-shaped Strip		35×22.5	Rogers RO4003C (3.38)	89%	3.3	Wideband (3.2-8.4 GHz)	[2]
Square Ring slits, Cross shaped tuning stub		50×50	FR4 (4.4)	91.12%	5.7	WLAN, WiMAX, IMT	[3]
Inverted L-shaped strip, square slot		26×26	Rogers Duroid RT5880 (2.2)	104%	3.4-4.4	C-Band	[4]
Square slot, spiral stub		20×30	FR4 (4.4)	38.89%	3.5	5G Network	[5]
Asymmetrical rectangle slots		88×89.9	Rogers RO3006 (6.5)	129.5%	5.0	RFID, WLAN, Wi-MAX, GNSS	[6]
L-shaped strip		60×80	FR4(4.4)	100%	3.7	Sub-6 band	[7]
Inverted L-shaped strip		24.5×20	FR4(4.6)	-	4.33-4.80	Wi-MAX, WLAN, 4G/5G, X-band	[8]
L -shaped Stubs		50×50	Rogers (2.2)	95%	10.2	IMT, GSM	[9]
Rectangular patches		27.2×26.4	Jute (2.36)	101.3%	2.0	WPAN	[10]

Top layer: Inverted Patch, Bottom layer: CPW-fed and ground plane		4×2.83/ 4.4×2.6	Taconic CER (10)/ Silicon (11.9)	-	6	ISM 24-GHz band	[11]
Inverted E-shaped monopole		490	Ceramic (8.5)	60.45%	4.4	ISM, HIPERLAN, UNII and WiMAX	[12]
Arrays		280×192	Polyethylene Terephthalate (PET) (1.8)	-	10	ISM	[13]
Split-ring resonator (NB-SRR), MIMO antenna		47.4 × 31.7	FR4(4.4)	30.10%, 8.83%	5	Sub-6 GHz 5G	[14]
Rectangular patch with circular slits		32×32	FR4(4.3)	5.73%, 4%, 17.9%,18.2% ,9.2%,6.3%	2.8	5G, C-Band, X-Band	Proposed Antenna

3. Antenna Design: In this section, the work examines the characteristics of three antennas: Antenna-1 focuses on the impact of dielectric substrate materials on patch antenna design based on three materials (Rogers RT5880, FR-4, and Arlon AD600) with permittivity values of 2.2, 4.3, and 6.15 and substrate thickness of 1.6 mm as shown in Figure 1(b). Antenna-2 shown in Figure 1(c) is based on FR-4 substrate material with a permittivity value of 4.3 and substrate thickness values of 1.30 mm, 1.60 mm, and 2 mm, respectively, for analyzing the |S11| parameter. The CPW-Fed antenna is shown in figure 1(d). The antenna dimensions for antenna-1, 2, and antenna-3 is 32×32mm^2. The structural design parameters of patch are shown in figure 1(a). The proposed work aims to understand the effects of these substrate materials and thicknesses on antenna performance metrics, particularly resonant frequencies, which are essential for optimal antenna operation. The antennas are designed for the efficient transmission and reception of high-frequency electromagnetic waves.

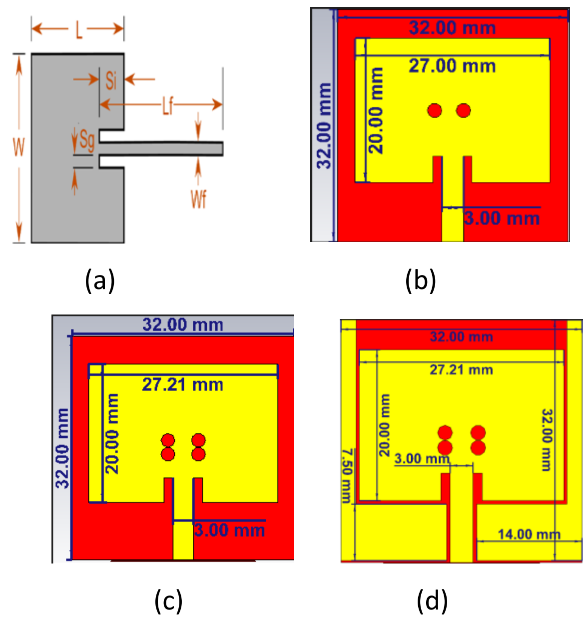


Fig.1: Structure of antennas: (a) Structural design parameter of patch, (b) Antenna-1 (with 2-slits), (c)

Antenna-2 (with 4-slits), and (d) Antenna-3 (4-slits with CPW-Fed)

Table 3. Optimal structural design parameter list of proposed Antenna-3

Design Parameter	Values (mm)	Description
h	2.00	Substrate Thickness
W	27.21	Radiating Stub Width
L	20.00	Radiating Stub Length
Si	3.61	Insert Length of Feed Line
Sg	1.20	Insert Feed Gap
Lf	8.24	Feed Line Length
Wf	3.00	Feed Line Width
R	1.00	Circular slit radius

3.1. Performance of Antenna-1 with various substrate materials: The performance of the proposed antennas utilizing various materials is comprehensively analyzed. The simulation results for Antenna-1 laminated with RT/Duroid, FR-4, and Arlon (see Figure 2) are depicted in Table 4. The simulation results for Antenna-1, as depicted in Figure 2, reveal resonant frequencies (fr) for Roger RT5880, 6.75 GHz at −20 dB and 9.80 GHz at −20 dB for dual band application. For FR-4 laminated Antenna-1, the resonance frequencies are 4.95 GHz at −45 dB, 7.20 GHz at −12 dB, 8.85 GHz at −26 dB, and 9.90 GHz at -31 dB obtained for quad-band applications. Similarly, in the case of Arlon laminated Antenna-1, the resonance frequencies (fr) are 4.15 GHz at -28 dB and 7.25 GHz at -21 dB for dual-band applications. Here, the FR-4 based substrate (Antenna-1) provides quad bands in comparison to other substrates. For this structure, the FR-4 dielectric material is appropriate with proper impedance matching, as illustrated in Figure 2.

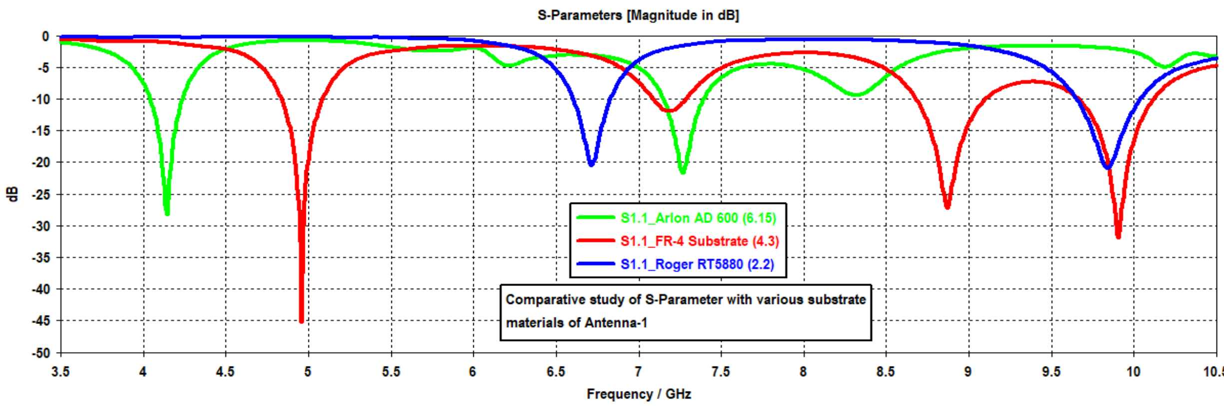


Fig. 2: Optimized reflection coefficient |S11| Parameter: Antenna-1 based on different substrate materials.

Table 4. Performance comparison of proposed Antenna-1 with various substrate materials

Antenna Design Technique	Substrate Material (ε_r)	Substrate Thickness (h, mm)	Resonating Frequencies (f_N), GHz				
			f_{N1} (−dB)	f_{N2} (−dB)	f_{N3} (−dB)	f_{N4} (−dB)	Frequency Bands (|S11| ≤−10 dB)
Two circular strips on the radiating stub	Roger RT5880 (2.2)	1.6	6.75 (20)	9.80 (20)	-	-	2
	FR-4 Glass/Epoxy	1.6	4.95 (45)	7.20 (12)	8.85 (26)	9.90 (31)	4

	(4.3)						
	Arlon AD600 (6.15)	1.6	4.15 (28)	7.25 (21)	-	-	2

3.2. Performance of Antenna-3 (proposed) with various substrate thicknesses: The impact of substrate material (FR4) and their respective thicknesses on antenna performance, specifically |S11| parameters, is thoroughly examined in this section. The selection of FR-4 in antenna-2 is based on the highest number of bands it provides in comparison to Rogers RT5800 and Arlon AD600 given in Table 4. The findings for antenna-3 are illustrated in Figure 3, providing valuable insights into how resonance frequencies are influenced by substrate thickness and dielectric constant. By analyzing the |S11| parameters across different substrate materials and thicknesses, a comprehensive understanding of their effects on antenna performance is gained. The simulation result revealing resonant frequencies (fr) at thicknesses of substrate 1.30, 1.60, and 2 mm is shown in Table 5. This proposed work (Antenna-3) offers multi-operating resonance frequencies (fr) for substrate thickness 1.30 mm at 3.51 GHz (3.46-3.60 GHz), 5.20 GHz (5.10-5.24 GHz), 6.60 GHz (6.51-6.81), 9.10 GHz (8.70-9.20), and 9.85 GHz (9.65-10.05). For substrate thickness 1.60 mm, at 3.50 GHz (3.44-3.58 GHz), 5.10 GHz (5.04-5.17 GHz), 6.55 GHz (6.48-6.77), 8.70 GHz (8.60-9.20), and 9.65 GHz (9.50-9.90). Similarly for substrate thickness 2 mm, at 3.49 GHz (3.38-3.59 GHz), 4.95 GHz (4.89-5.10 GHz), 6.36 GHz (5.84-6.99), 7.70 GHz (7.01-8.43), 9 GHz (8.49-9.28), and 9.95 GHz (9.50-10.13). Optimized results for antenna-2 (without CPW-Fed) and antenna-3(with CPW-Fed) at the thickness h=2 mm, is shown in figure 4. The results for antenna-2 at 3.48 GHz (3.37-3.56 GHz), 5.20 GHz (5.03-5.19 GHz), 6.65 GHz (6.22-7.01), 7.35 GHz (7.15-7.55), and 9.55 GHz (9.39-9.79). The result for antenna-3 (with CPW-Fed) on substrate thickness 2 mm, at 3.49 GHz (3.39-3.59 GHz), 4.99 GHz (4.89-5.09 GHz), 6.42 GHz (5.85-7.00), 7.73 GHz (7.03-8.44), 8.88 GHz (8.47-9.29), and 9.81 GHz (9.50-10.12). Here the advantage of using CPW-Fed (antenna-3) is that there is a considerable increase in the bandwidth (B.W) as compared to the antenna-2 (without CPW-Fed) with an increase in number of bands from five to six as shown in Table 6. The gain of antenna-2 and antenna-3 are shown in figure 5. The antenna-2 has the peak gain of 4.8 dBi and for antenna-3 is 2.8 dBi. The value of gain is reduced in antenna-3 as compared to antenna-2.

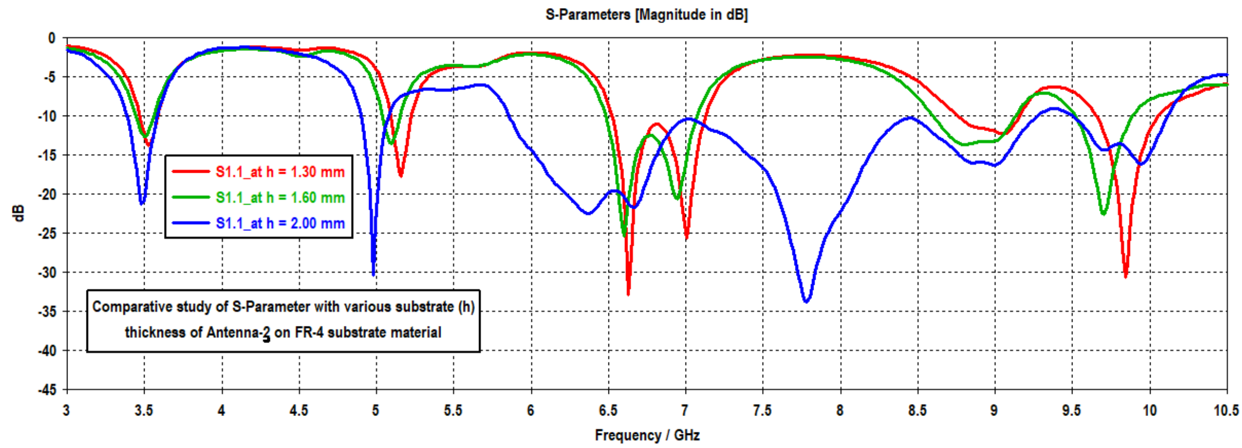


Fig. 3: Optimized |S11| Parameter: CPW-Fed antenna-3 based on different substrate thickness.

Table 5. Performance comparison of proposed antenna-3 on FR-4 material on 4-slits CPW-Fed antenna with different substrate thicknesses

Antenna Design Technique/ Substrate Material (ε_r)	Substrate Thickness (mm)	Resonating Frequencies (f_N), GHz						Frequency Bands (|S11| ≤−10 dB)
		f_{N1} (−dB)	f_{N2} (−dB)	f_{N3} (−dB)	f_{N4} (−dB)	f_{N5} (−dB)	f_{N6} (−dB)	
CPW-Fed with four circular strips/ FR-4 Glass/Epoxy (4.3)	1.30	3.51 (14)	5.20 (17)	6.60 (33)	-	9.10 (12)	9.85 (30)	5
	1.60	3.50 (13)	5.10 (14)	6.55 (25)	-	8.70 (14)	9.65 (23)	5
	2.00	3.49 (21)	4.95 (30)	6.36 (22)	7.70 (34)	9.00 (16)	9.95 (16)	6

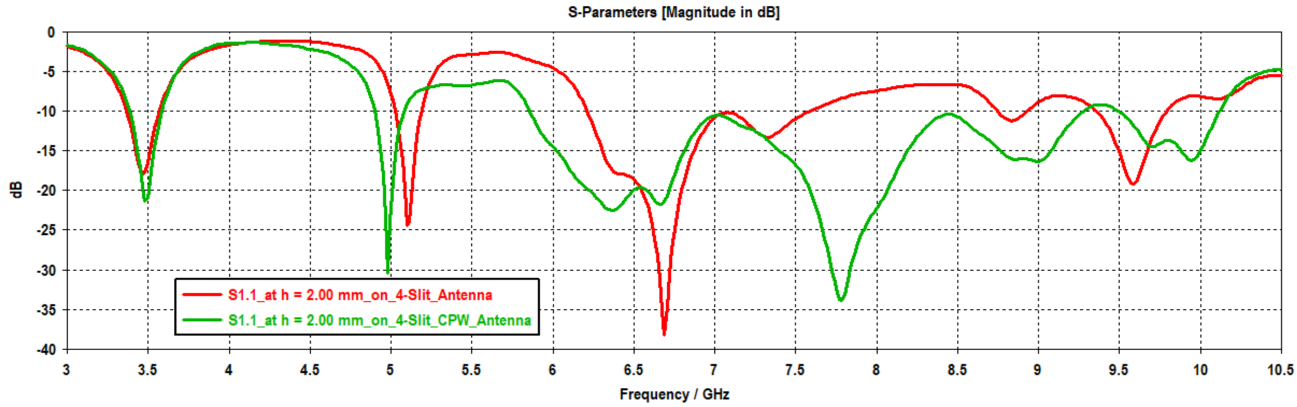


Fig. 4: Optimized |S11| Parameter: Antenna-2 (without CPW) and antenna-3(with CPW-Feed) at thickness, h=2 mm on FR-4 taken on 4-slits.

Table 6. Performance comparison of proposed Antenna-2 and Antenna-3 using FR-4 with same thickness, h=2mm.

Antenna Design Technique/ Substrate Material (ε_r)	Substrate Thickness (2 mm)	Resonating Frequencies (f_N), GHz and IBW, (GHz)						Frequency Bands (|S11| ≤−10 dB)
		f_{N1} (IBW)	f_{N2} (IBW)	f_{N3} (IBW)	f_{N4} (IBW)	f_{N5} (IBW)	f_{N6} (IBW)	
CPW-Fed with four circular strips/ FR-4 Glass/Epoxy (4.3)	Without CPW	3.48 (0.19)	5.20 (0.16)	6.65 (0.79)	7.35 (0.40)	-	9.55 (0.40)	5
	With CPW	3.49 (0.20)	4.95 (0.20)	6.36 (1.15)	7.70 (1.41)	9.00 (0.82)	9.95 (0.62)	6

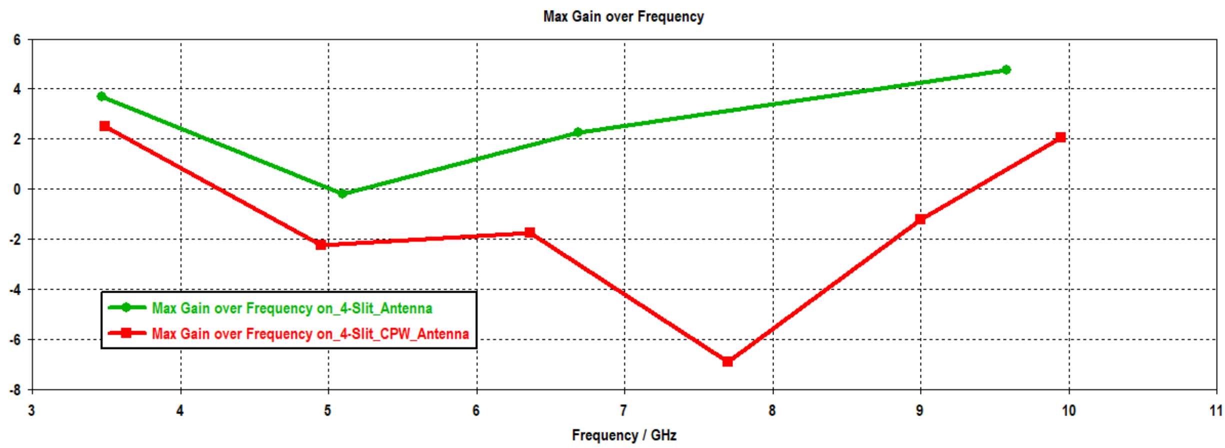


Figure 5. Gain of antenna-2 and antenna-3 at different frequencies.

4. Comparative Outcomes: This article reviews various design techniques for CPW-fed antennas, focusing on substrate materials. Thicker substrates offer more efficiency and wider IBW for a lower dielectric constant. High dielectric constant substrates favor small antenna sizes. The antennas' low profile, simple structure, and broadband impedance characteristics make them suitable for wideband RF communication applications. An Antenna-2 and 3, using two circular slits and four circular slits are used for improving the impedance bandwidth as shown in Table 4 and Table 5. The achieved |S11| results for Antenna-1 and Antenna-2, shows a shift of fundamental resonance frequencies towards the low-frequency band especially in case of increasing in the value of dielectric constant, as shown in Table 4 enabling effective miniaturization of around 60% in between using the substrate material of dielectric constant 2.2 to 6.15. The proposed 4-slit CPW-Fed antenna-3 offers six frequency bands promising potential for enhancing advancements in next-generation wireless technologies in terms of efficiency, bandwidth, and versatility.

5. Conclusions: This article explores the design of coplanar waveguide (CPW)-fed antennas using different substrate materials, thicknesses, and techniques. It investigates how materials like FR4, Rogers, and Arlon affect electrical parameters like as impedance bandwidth, |S11|, and gain. The research also investigates how design techniques such as stubs, slots, strips, arrays, etc affect antenna parameters. The FR-4 suggested antenna has a frequency range of 3.3 to 10.1 GHz and can operate at six frequencies. The proposed antenna has a peak gain of 2.8 dBi. The antennas' low profile, simple construction, and broadband impedance make them ideal for wideband RF and wireless communication applications. The proposed antenna has the potential to increase efficiency, bandwidth with the challenges to achieve the significant gain in next-generation wireless technology applications.

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Conflict of Interest: Authors declare No conflicts of interest.

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