Compact CPW-Fed Slot Antenna with Harmonic Suppression

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ABSTRACT: A compact coplanar waveguide (CPW)-fed uniplanar antenna with harmonic suppression characteristics is presented. The above characteristics are achieved by properly modifying the ground plane and adjusting the signal strip of an open-ended CPW-fed transmission line. The simulated and experimental characteristics of the antenna are presented, compared, and discussed. Int J RF and Microwave CAE 21:543–550, 2011.

Keywords: compact antenna; coplanar waveguide fed antenna; CPW-fed transmission line; uniplanar antenna; harmonic suppression; harmonic suppressed antenna; planar antenna; slot antenna

I. INTRODUCTION

Coplanar waveguide (CPW) structures have gained great attention in microwave and millimeter wave applications due to uniplanar structure and are commonly used in monolithic microwave integrated circuits. The users can get more flexibility because the characteristic impedance of CPW is virtually independent of substrate height and depends only on the top planar dimensions.

Tsuji et al. [1] presented a detailed study on the power leakage from CPW. They concluded that the width of the lateral strip also plays an important role in the radiation properties in addition to the width of signal strip and gaps. Rohith et al. [2] modified the lateral ground plane, signal strip dimensions, and the feed point of a CPW to develop a dual band antenna for WLAN application.

Scientists have explored various modifications on the signal strip of a CPW-fed transmission line. Chen et al. [3] presented a dual-frequency monopole antenna by modifying the signal strip into two unequal lengths, in which the longer monopole works for the first resonant mode and the shorter monopole for the second. A CPW-meandered feed line [4] is used to obtain broadband dual frequency operation on a planar monopole antenna.

Researchers have tried the modification of the ground plane also to obtain the required radiation characteristics. Zhong et al. [5] modified the ground plane of an elliptical monopole antenna in to a trapezoidal shape to achieve an impedance bandwidth in excess of 21:1. Further modification of ground plane led to the birth of slot antennas that became a favorite among antenna designers due to the easy attainment of impedance match. Several impedance tuning techniques based on slot and signal strip dimensions have been reported in the literature. A CPW-fed slot antenna with an E-like feeding structure and a matching stub at the slot edge together with the four floating patches on the bottom plane of the substrate to attain dual frequency operation is also proposed [6]. Lin and Hung [7] used a pair of T-match stub to generate dual resonance in a CPW-fed slot antenna on a substrate of dielectric constant 4.3 with an overall dimension of 31×35 mm^2. However, most of the recently published CPW-fed antennas are either complex in structure or large in size for practical application.

The other recently emerged interesting modification in CPW-fed antennas are the inductively or capacitively [8] coupled antennas. Yu and Lin [9] investigated on CPW-fed inductor-loaded inductive slot antenna. By properly modifying the slot and trimming the inductor, he succeeded in attaining required frequency band. By the other end, Lin et al. [10] proposed a capacitive H-shaped narrow slot antenna in which the input impedance and radiation pattern could be varied by controlling the electric field around the slot. Combining the inductive and capacitive couplings, Bhobe et al. [11] and Sierra-Garcia and Laurin [12] proposed hybrid antennas with normal and log periodic slotted structures to attain wideband characteristics. A compact CPW fed H-shaped antenna [13] and

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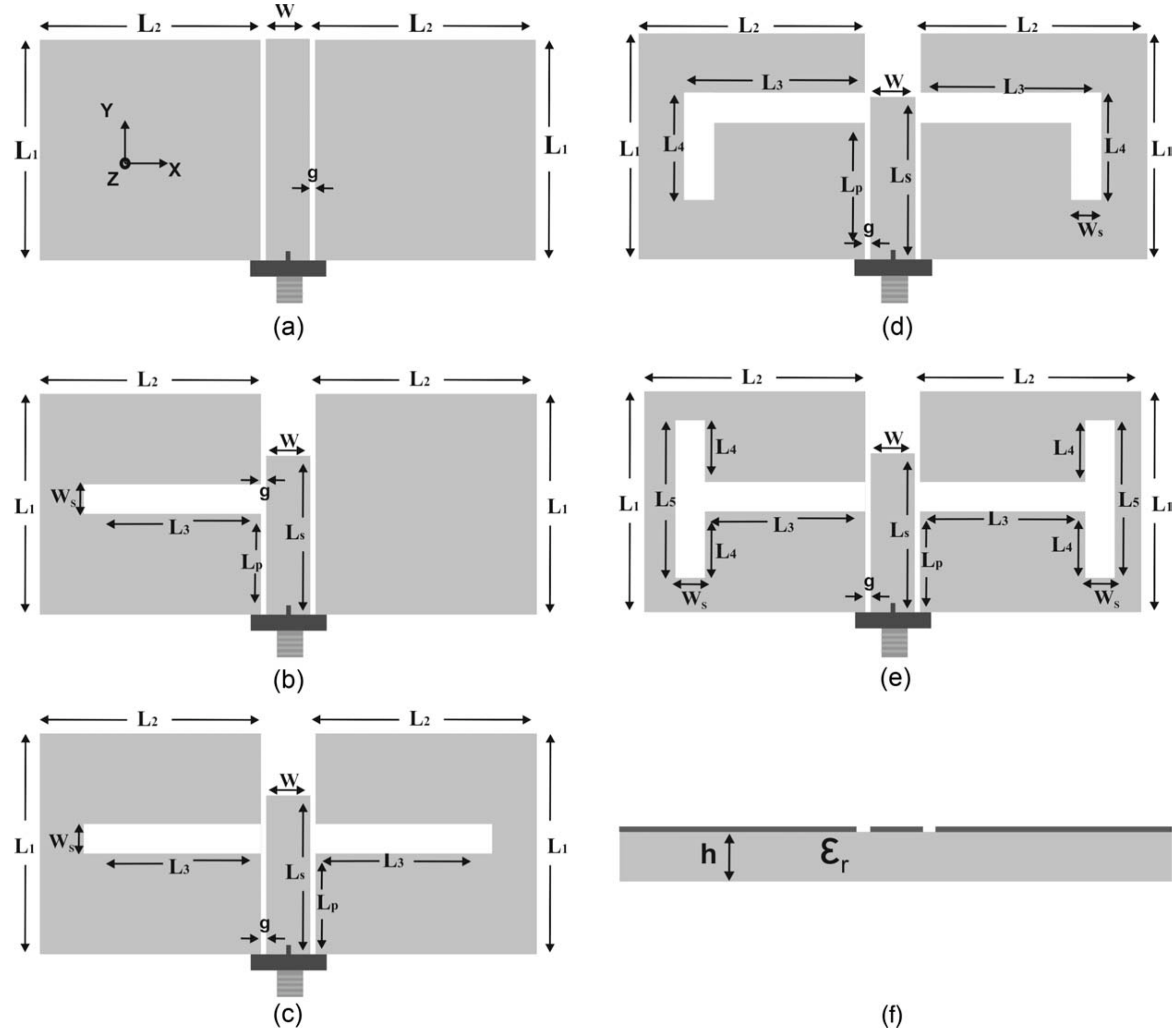


Figure 1 (a) Open Circuited CPW fed Transmission line, (b) Antenna 1, (c) Antenna 2 (L_1 = 15 mm, L_2 = 15 mm, L_3 = 10 mm, L_s = 11 mm, L_p = 5 mm, W = 3 mm, W_s = 2 mm, g = 0.35 mm, h = 1.6 mm, ε_r = 4.4), (d) Antenna 3 (L_3 = 12 mm, L_4 = 7 mm, L_p = 9 mm), (e) Antenna 4 (L_2 = 11.25 mm, L_3 = 7.5 mm, L_4 = 4.5 mm, L_5 = 10.5 mm, L_p = 6.25 mm, L_s = 9.375 mm, W_s = 1.5 mm), and (f) Side view.

H-shaped active integrated antenna [14] for harmonic suppression is also reported. This article deals with the elaborate study of the above work and narrates the evolution of the antenna from CPW transmission line.

Realization of required impedance bandwidth, radiation performances, conformal structure, compact size, reduction of cable current, and suppression of higher harmonics are the main task for modern antenna designers. In this article, a novel approach to effectively convert a CPW transmission line into an antenna is presented. The radiation behavior of the antenna is brought about by inserting slots in the ground plane thereby creating discontinuities in the CPW transmission line. The chronological investigation of the developed novel antenna, depicted here, clearly explains the conversion of high-impedance open-ended CPW-fed transmission line into a matched efficient radiator. This article deals with open-ended CPW-fed transmission line, unsymmetrically slotted antenna (Antenna 1), symmetrically slotted antenna (Antenna 2), unsymmetrically slotted dual band antenna (Antenna 3), and H-shaped slot antenna with harmonic suppression (Antenna 4).

II. EVOLUTION AND GEOMETRY OF PROPOSED ANTENNA

The geometry of the proposed CPW structures are printed on a substrate of dielectric constant 4.4 and height 1.6 mm. The signal strip width (W) and gap (g) is chosen for 50-Ω impedance. The antenna evolves from an open-circuited CPW-fed transmission line as shown in Figure 1a with signal strip width, W, and lateral ground planes of dimension $L_1 \times L_2$ mm^2. A slot of dimension $L_3 \times W_s$ mm^2 is etched on one of the lateral ground planes resulting in Antenna 1 as shown in Figure 1b. An identical slot etched on the other lateral ground plane makes the antenna symmetric (Antenna 2) as shown in Figure 1c. More compactness is achieved with L-shaped slots etched

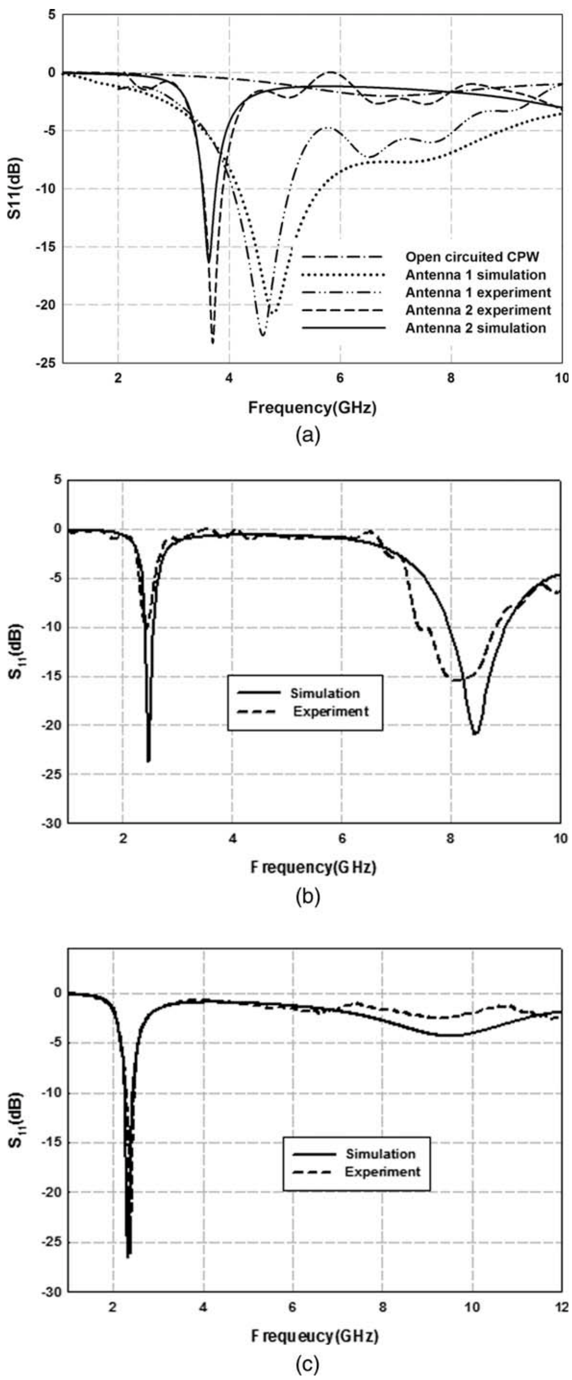


Figure 2 Refelection characteristics of (a) open-ended CPW, Antenna 1, and Antenna 2, (b) Antenna 3, and (c) Antenna 4.

symmetrically on both the ground planes ($L_1 \times L_2 = 0.12\lambda_0 \times 0.12\lambda_0$) of a CPW-fed transmission line as shown in Figure 1d, where λ_0 is the free space wavelength corresponding to the resonant frequency. Antenna 3 has an overall dimension of $0.27\lambda_0 \times 0.12\lambda_0$, which is much smaller than that reported earlier [2–10]. The width of the slot (W_s) is constant for both the slots. To make this slot antenna more compact, an H-shaped slot is inserted resulting in a symmetrical antenna with good radiation characteristics as in Figure 1e (Antenna 4). The side view of all these antennas are shown in Figure 1f.

TABLE I Antenna Parameters

Antenna Parameters (mm)	Ant. 1	Ant. 2	Ant. 3	Ant. 4
L_1	15	15	15	15
L_2	15	15	15	11.25
L_3	10	10	12	7.5
L_4	–	–	7	4.5
L_5	–	–	--	10.5
L_p	5	5	9	6.25
L_s	11	11	11	9.37
W	3	3	3	3
W_s	2	2	2	1.5

III. RESULTS AND DISCUSSIONS

The simulation and measurement of the antenna have been done using Ansoft HFSS and HP8510C Vector Network Analyzer, respectively.

In open-circuited 50-Ω CPW-fed transmission line, the reflection coefficient is 0 dB, indicating high reflection from the input port due to the open circuit at the other end as shown in Figure 2a. There is no resonance with the ground plane dimension, signal strip width, and dielectric constant variations. This confirms that the system is not radiating.

Four different antennas were fabricated on the same substrate, and their dimensional parameters are given in Table I.

Creating a slot on any one of the lateral ground plane and modifying the strip dimension as shown in Figure 1b, the system offers a resonance at 4.8 GHz resulting in Antenna 1, and its reflection characteristics is also shown in Figure 2a. This resonance occurs when the slot dimension is nearly quarter wave. For a particular slot position as the slot length increases the resonant frequency decreases. Hence, it is possible to control the resonance primarily with slot length.

The resonant frequency and return loss variation with slot position (L_p) and signal strip length (L_s; for constant slot length) are shown in Table II. From the table, it is clear that the signal strip length and slot position are important in determining resonant frequency and attaining good impedance match. As the slot is asymmetrical about the signal strip, the radiation pattern is found to be tilted with respect to the slot position on any of the lateral ground planes.

The tilt in radiation pattern of antenna 1 can be overcome by inserting symmetrical slot as in Figure 1c, resulting in Antenna 2. The reflection characteristics of Antenna 2 are shown in Figure 2a. As the overall slot dimension is increased, the antenna resonates at a lower frequency.

The variation in resonant frequency and return loss of antenna for a constant slot length is shown in Table III. By comparing Tables II and III, it is clearly apparent that

TABLE II Variation in Resonant Frequency and Reflection Characteristics of Antenna 1 with Slot Position and Signal Strip (Slot Length L_3 = 10 mm)

Slot position (L_p) Signal Strip Length (L_s)	[Frequency (GHz), Reflection Coefficient (dB)]					
	1 mm	3 mm	5 mm	7 mm	9 mm	11 mm
3 mm	5.47, −4.45	5.65, −1.4	–	–	–	–
5 mm	5.25, −12.56	5.47, −5.1	5.47, −1.46	–	–	–
7 mm	**5.29, −37.7**	5.29, −14.79	5.27, −5.04	4.87, −1.32	–	–
9 mm	7.03, −14.64	**5.16, −19.32**	5.05, −15.01	4.73, −4.55	4.46, −1.32	–
11 mm	7.32, −14.89	4.64, −10.61	**4.80, −20.74**	4.53, −12.98	4.28, −4.61	4.15, −1.43
13 mm	6.85, −8.86	7.21, −8.75	4.19, −13.24	**4.15, −23.7**	4.015, −13.71	4.01, −5.63
15 mm	–	–	3.85, −8.7	3.83, −13.27	**3.72, −31.51**	**3.65, −18.80**

the symmetrical slotted antenna (Antenna 2) has more dependence on signal strip length. Better matching is observed for this antenna when open end of the signal strip (L_s) is about 11 mm.

The polarization in the X-directed slot is along Y direction and, hence, is purely Y-polarized. The radiation pattern of Antenna 2 is shown in Figure 3. The radiation pattern is symmetric like a center-fed slot antenna with good polarization purity along the bore sight in the entire operating band.

The symmetrical slot on the ground plane excites resonance corresponding to the slot dimension with almost symmetrical radiation pattern with good cross polar isolation as in the figure. Meandering this symmetrical slot into L-shaped slot improves the compactness of antenna (Antenna 3). The simulated and measured return loss characteristics of Antenna 3 resonating at 2.4 GHz are shown in Figure 2b. The antenna exhibits a 2:1 VSWR bandwidth from 2.39–2.51 GHz covering the 2.4-GHz WLAN band.

The total perimeter of the L-shaped slot is about one wavelength in the substrate at the resonant frequency. The electric field distribution of the antenna in the X-directed slot is along Y-direction and that of the Y-directed slot is along X-direction. This is responsible for an effective tilt of 45° in the polarization of the antenna. The antenna has a cross polarization level of about 10 dB in both the planes. The measured peak gain in the 2.4-GHz band is about 1 dBi with small gain variation across the band. However, this antenna exhibits second resonance at 8.5 GHz as observed in Figure 2b.

Meandering the slots improves the compactness but generates higher harmonics, which should be removed for better antenna performance. The first mode is matched (59 Ω – j3 Ω), whereas the second mode is suppressed due to high-capacitive reactance (55 Ω – j240 Ω), but the third mode is excited (79 Ω + j56 Ω). So, meandering should be done in such a way that along with the compactness, the radiation characteristics should also improve. The third harmonics of Antenna 3 is suppressed by making a H-slot (Antenna 4) to provide very low impedance (8 Ω + j3 Ω) at that harmonics. The slots (L_4) will act as two parallel LCR circuits with equal inductance (L) and capacitance (C) in each slot. The effective resistance decreases drastically, and the resonance is suppressed.

The current distribution of the antenna at resonant frequency (2.4 GHz) is shown in Figure 4. The transmission line guides the wave toward the slot and then launches the wave into the slot as in the figure. A full wavelength variation along the perimeter of the slot is observed. The slot insertion is not making any change in the fundamental mode distribution of the CPW transmission line. The

TABLE III Variation in Resonant Frequency and Reflection Characteristics of Antenna 2 with Slot Position and Signal Strip (Slot Length L_3 = 10 mm)

Slot Position (L_p) Signal Strip Length (L_s)	[Frequency(GHz), Reflection Coefficient (dB)]					
	1 mm	3 mm	5 mm	7 mm	9 mm	11 mm
2 mm	3.83, −5.6	–	–	–	–	–
3 mm	3.56, −14.99	3.94, −1.9	–	–	–	–
4 mm	**3.27, −16.32**	3.79, −4.18	–	–	–	–
5 mm	3.02, −8.68	3.58, −8.89	3.94, −1.92	–	–	–
6 mm	2.82, −5.98	**3.34, −23.52**	3.76, −3.73	–	–	–
7 mm	2.64, −4.4	3.11, −15.98	3.56, −7.44	–	–	–
8 mm	2.44, −3.2	2.91, −9.74	3.31, −16.31	3.76, −3.6	–	–
9 mm	2.32, −2.63	2.78, −6.89	**3.11, −29.35**	3.56, −7.18	3.94, −2.04	–
10 mm	–	2.59, −5.00	2.93, −12.63	3.34, −14.05	3.83, −3.89	3.97, −1.32
11mm	–	2.50, −3.99	2.75, −8.77	**3.11, −30.85**	3.61, −7.74	3.99, −2.41
12 mm	–	2.39, −3.27	2.62, −5.94	2.91, −13.26	3.36, −17.62	3.88, −4.64
13 mm	–	–	–	2.77, −8.54	**3.11, −21.4**	3.67, −9.62
14 mm	–	–	–	2.64, −6.24	2.89, −15.3	**3.4, −18.47**

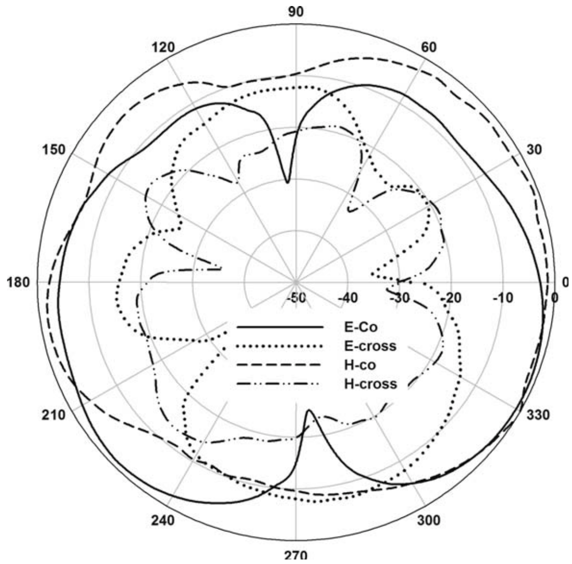


Figure 3 Measured far field radiation pattern of Antenna 2 ($L_1 = 15$ mm, $L_2 = 15$ mm, $L_3 = 10$ mm, $L_p = 5$ mm, $L_s = 11$ mm, $W = 3$ mm, $W_s = 2$ mm).

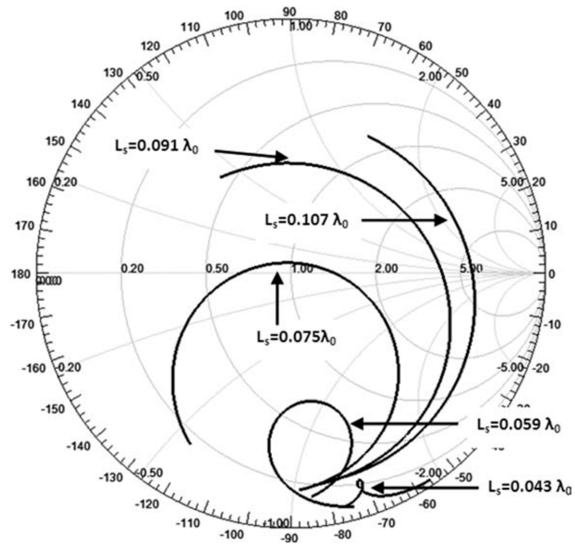


Figure 5 Input impedance on Smith chart for various strip length L_s.

X-directed electric field gets cancelled at the far field resulting in an effective polarization along the Y-direction.

The variation of input impedance with signal strip (L_s) is shown in Figure 5. The reactive part of impedance varies cyclically from highly capacitive to less capacitive as L_s increases. For a given slot, the impedance is highly capacitive for small signal strip length. By increasing the strip length, the inductance increases and the imaginary part of impedance reaches zero for an optimized length. So, it is very interesting to note that the capacitance can be easily tuned by trimming the slot dimension (L_3 and L_4). Similarly the inductance and real part of impedance can be adjusted by trimming the strip length (L_s). At the optimized length, the impedance locus is around 50 Ω with affordable reactance at the resonant frequency. For all other frequencies, the structure acts as an open-ended CPW-fed transmission line.

The design equations for the optimized antenna are given below

$$L_1 = 0.2\lambda_g \tag{1}$$
$$\lambda g = \lambda/\varepsilon_{\mathrm{reff}},$$

where λ is the wavelength corresponding to resonant frequency (F_r) and $\varepsilon_{\mathrm{reff}} = (\varepsilon_r + 1)/2$ is the effective dielectric constant of the substrate.

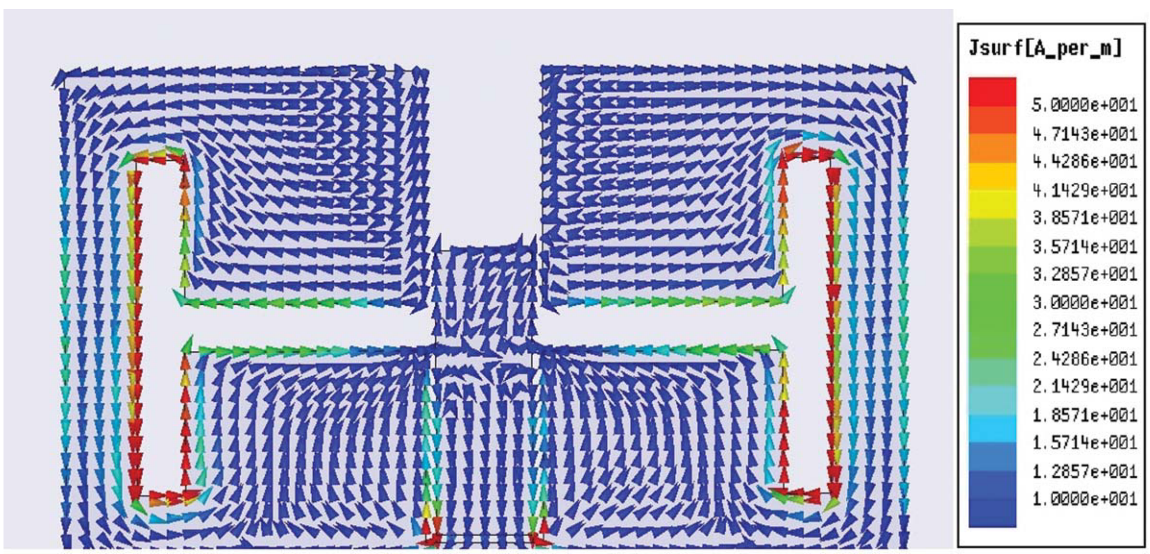


Figure 4 Simulated Current distribution of the antenna at resonant frequency. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

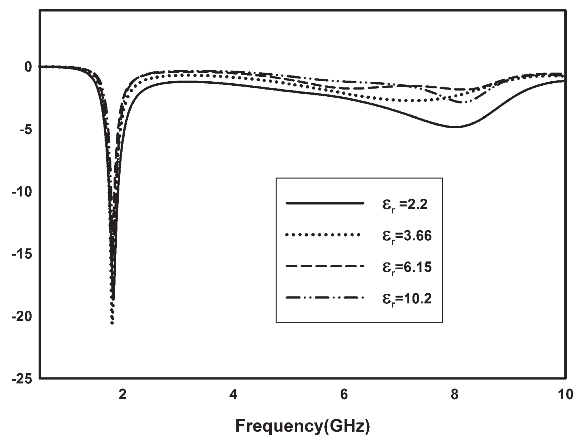


Figure 6 Reflection characteristics of antennas designed for different dielectric substrates.

$$L_2 = 0.15\lambda_g \tag{2}$$

$$L_3 = 0.1\lambda_g + K_1 \tag{3}$$

$$L_4 = 0.06\lambda_g + K_2, \tag{4}$$

where

$$K_1 = 0$$

For $\varepsilon_r > 5$,

$$K_1 = 10^*(\varepsilon_{\text{reff}} - 1.64)/F_r$$

For $\varepsilon_r \leq 5$,

$$K_2 = 0$$

For $\varepsilon_r > 5$,

$$K_2 = 5^*(\varepsilon_{\text{reff}} - 1.64)/F_r$$

For $\varepsilon_r \leq 5$,

$$L_p = 0.08\lambda_g \tag{5}$$

$$L_s = 0.125\lambda_g \tag{6}$$

$$W = 0.04\lambda_g \tag{7}$$

$$W_s = 0.02\lambda_g \tag{8}$$

These design equations are then validated for different dielectric substrates of dielectric constant 2.2, 3.66, 6.15, and 10.2 for the antenna resonating at 1.8 GHz. The reflection characteristics of the antennas for the designed parameters shown in Figure 6 validate the design equation.

The H-shaped slot can be considered as a center-fed slot dipole with each arm of length $\lambda_g/4$, where λ_g is the guided wavelength in the resonant frequency. Top loading the dipole arm (L_3) with L_4 will increase the effective

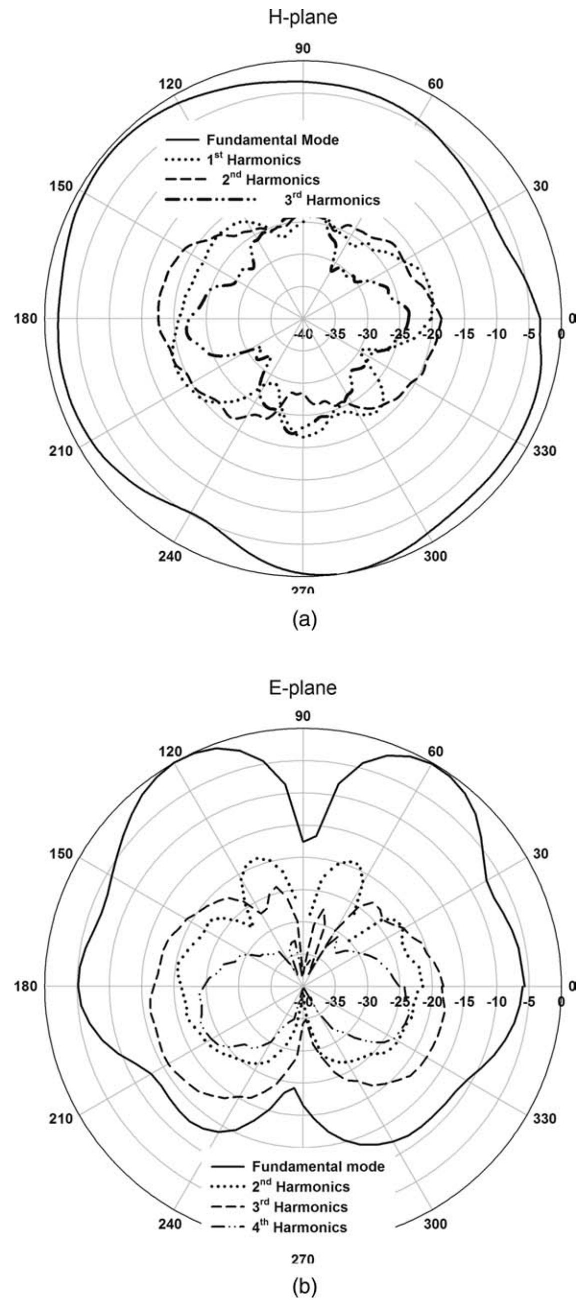
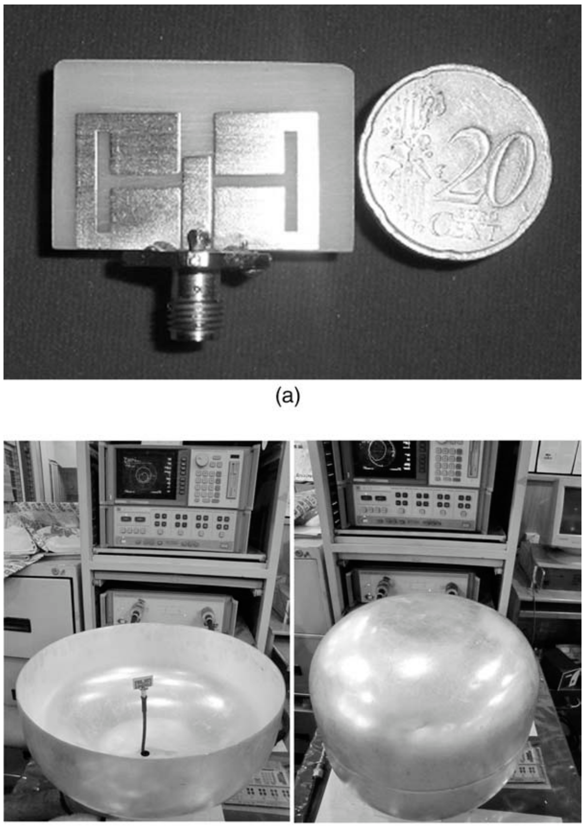


Figure 7 Radiation pattern of the antenna at resonance and higher harmonics (a) *H*-Plane and (b) *E*-Plane.

electrical length like a top-loaded monopole. The measured radiation patterns of Antenna 4 at resonant frequency and higher harmonics are shown in Figure 7. The pattern is uniform in the *H*-plane and bidirectional in *E*-Plane as a center-fed slot antenna. From the figure, it is clear that the radiations from the higher harmonics are negligible. Without any additional filters and external circuits, the antenna successfully suppresses radiation from higher harmonics up to 12 GHz. The measured peak gain in the 2.4-GHz band is about 1 dBi with small gain variation in the band. The gain of the antenna is small compared with a



(a) (b)

Figure 8 Photograph of (a) proposed antenna (b) Wheeler cap method with and without cap.

conventional dipole, because the antenna is electrically very small. The efficiency of the antenna measured using wheeler cap method is 79%. The photograph of the proposed compact antenna (Antenna 4) is shown in Figure 8.

IV. CONCLUSIONS

Compact CPW fed antenna with excellent radiation characteristics is presented. The slot position, slot length, and signal strip length appears as critical parameters allowing flexibility in the tuning of antenna characteristics. Without any additional filters and external circuits the antenna successfully suppresses radiation from higher harmonics with an efficiency of 79%. In comparison with the conventional uniform slot antenna, the proposed antenna is compact and free from higher harmonics.

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