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A Wideband Microstrip Patch Antenna for 60 GHz Wireless Applications

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***Abstract*—In this paper a compact microstrip patch antenna designed for the unlicensed 60 GHz millimeter-wave band applications is presented and discussed in details. The proposed antenna consists of a rectangular radiating patch with an embedded U-shape slot inside, and excited by the coaxial probe feeding technique. A wide range of parametric studies has been performed on the patch size, feeding positions and U-slot dimensions and the antenna is optimized for the best possible results. The proposed antenna configuration achieved a wide bandwidth of 15.4 GHz (25.69 %) covering the frequency range from 52.20 to 67.70 GHz. The lowest return loss of the antenna is –41.2 dB and the maximum gain obtained is 9.52 dB at the 60 GHz resonance frequency. Considering the size, bandwidth, and gain, this microstrip antenna can be a suitable candidate for the 60 GHz wireless applications for short range high speed communications.**

***Index Terms*—Microstrip patch antenna, 60 GHz, wideband, millimeter wave, coaxial probe feed, WPAN.**

I. INTRODUCTION

In the recent years, the rapid development and changing of wireless communications technology increased the interest to design a compact and wideband antenna, which is an important part of any wireless system [1]–[5]. Also, development of target oriented microstrip antenna is a thrilling research interest nowadays and many techniques have been proposed to improve their performances [6]–[9]. In 2001, Federal Communications Commission (FCC) released the unlicensed millimeter-wave band around the 60 GHz frequency [10], [11]. This band is of immense interest due to the availability of universal unlicensed spectrum around 60 GHz for short-range communication systems such as indoor and underground communication and high speed wireless applications [12] like Gigabit-Ethernet bridges, Intelligent Transport Systems (ITS) and so on [13].

The European RACE mobile broadband system (MBS) project has paid particular attention on this band to extend the broadband integrated services digital network (B-ISDN) to mobile users for achieving high-data-rate exchange to 100 Mbps [14]. Also, the 60 GHz frequency band is considered for Wireless Personal Area Networks (WPANs) in IEEE 802.15 standard body [15]. WPAN can achieve high data rate at the rate of gigabits per second (Gbps) in the short transmitting distance in various applications such as high speed internet access, un-compressed high definition media transfer, video conferencing, streaming content download, data file transfer in fraction of seconds etc. [12], [16]. Antennas for communication systems at 60 GHz are expected to be broadband to achieve high data rate [15], [17] and should have a high gain due to the high path loss at these frequencies [13]. Moreover, high gain antenna provides a wide area coverage for data exchange.

Generally, a horn antenna is used at millimeter-wave frequency due to its high performances but it is heavy, bulky and expensive too. It also requires comparatively high power and have additional losses [18]. Therefore, for 60 GHz wireless applications, microstrip patch antenna has been chosen due to their small size, light weight, low cost and ease of fabrication and integration with complex circuitry. However, the conventional microstrip patch antenna inherently has a narrow bandwidth and low gain [19], [20]. Many broadband patch antennas can be found in the literature that proposed various techniques for bandwidth improvement. Some of the designs include patch with Substrate Integrated Waveguide (SIW), multi-layer and multi-patch designs, different shape with multi slotted patch and so on [21]–[24]. However, various shapes of slotted antenna are frequently used to enhance the antenna performances because of their structural simplicity.

Authors in [14] presented a 60 GHz active patch antenna using a Gunn diode as an oscillator in a reflection amplifier module where the patch acts as the resonant and radiating element as well as the stabilizing component for the oscillator. The tuning bandwidth obtained by varying the DC bias voltage is 62.277 GHz to 63.316 GHz and it is equivalent to a 1.6 % (1.039 GHz) bandwidth. An antenna is built on a silicon membrane with an upper BCB (Benzo-Cyclo-Buten dielectric material) thin film deposited and excited with U-shape and T-shape microstrip feeder via a dielectric gap achieved a bandwidth of 13.3 % [25]. A 60 GHz coplanar waveguide (CPW) fed patch antenna

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implemented on a high dielectric constant substrate (ε_r = 9.9, which is close to the dielectric constant of commercial GaAs and CMOS process). This antenna covers from 58.3 GHz to 63 GHz having an operational bandwidth of 4.7 GHz or 7.75 % [18]. The hybrid dielectric resonator antenna proposed in [26] obtained 14.36 % bandwidth using stacking and superstrate schemes and aperture coupled feeding. In [27] a balanced-fed aperture-coupled patch antenna with an air cavity embedded in the PCB stack is developed which has about 7 dBi gain, with at least 12 GHz impedance bandwidth.

In this paper, a 60 GHz microstrip patch antenna with wide bandwidth and high gain is presented. The bandwidth is enhanced by inserting U-slot into the patch. Several parametric studies have been conducted on the coaxial probe fed microstrip antenna and the most optimized results are discussed in the following sections.

II. Antenna Design Geometry

The geometry of the proposed antenna is shown in the Fig. 1. The proposed antenna comprises of a rectangular patch with an embedded U-shape slot inside the patch. The basic rectangular patch antenna has the dimension of width (*W*) and length (*L*) and placed at a distance of *h* mm (substrate thickness) away from the ground plane. The chosen substrate material is 1.575 mm thick Rogers RT/duroid 5880 dielectric board with a dielectric constant of 2.2 and a loss tangent of 0.0009. This printed circuit board (PCB) material has some advantages such as low dielectric torelance and loss, stable electric property against frequency and thus it is a better choice for high frequency operation. The width (*W*) and length (*L*) of the antenna can be approximated by using the equations from (1) to (4) [28].

$$W = \frac{c}{2 f_0 \sqrt{\frac{\varepsilon_r + 1}{2}}}. \quad (1)$$

The effective dielectric constant (ε_{eff}) need to be calculated to find the additional length (ΔL) on reach end due to the fringing field along the width:

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

$$\Delta L = 0.412h \frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}, \quad (3)$$

$$L = \frac{c}{2 f_0 \sqrt{\varepsilon_{eff}}} - 2\Delta L. \quad (4)$$

Based on the above formulas, theoretically calculated width and length of the top radiating patch for 60 GHz resonance are found to be 2 mm and 0.5 mm, respectively. However, the dimensions have been adjusted and optimized to meet the requirement of the resonant frequency and other characteristics. The design parameters are obtained from several parametric studies and suitable patch and slot size are selected for a high gain, wideband 60 GHz antenna. The primary design parameters are listed Table I.

TABLE I. INITIAL DESIGN PARAMETERS.

Substrate	RT / Duroid 5880
Thickness (*h*)	1.575 mm
Dielectric Constant (ε_r)	2.20
Loss Tangent	0.0009
Patch Size (*W* x *L*)	2 x 1.5 mm²
Ground Plane (W_g x L_g)	5 x 4 mm²
Total Antenna Profile	5 x 4 x 1.575 mm³

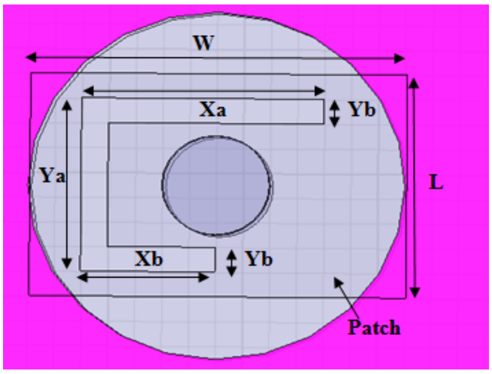


Fig. 1. Geometry of the proposed antenna.

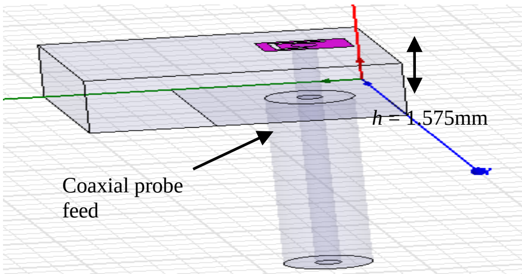


Fig. 2. Coaxial probe feed of the proposed antenna.

The patch of the proposed antenna is placed on 1.575 mm above the ground plane and the coaxial probe feed method is used to excite the antenna. The outer side of the coaxial connector is connected to the ground plane and the center of the conductor is extended up to the top patch antenna as shown in Fig. 2. The whole structure is designed, optimized and analyzed by the finite element method (FEM) based 3D full-wave electromagnetic solver HFSS.

III. Study of The Antenna Performances

The study of the antenna characteristics starts with a conventional rectangular patch which is gradually optimized for better performances at 60 GHz. Then, an equal arm U-slot is introduced for further enhancement of the antenna performances. Later on, the slot length and width are optimized and better results are obtained with an unequal arm U-slot. As mentioned in the introduction section, the incorporation of different slots inside a conventional patch gives a wider bandwidth and the U-slot is found better for antenna than the other slot types. The arms of a U-slot act like separate and compactly coupled resonators, and their mutual coupling moves the resonances toward higher and lower end frequencies, thus increasing the impedance bandwidth. A wide range of parametric study has been performed on the proposed antenna to investigate the effect of the probe feed position, the dimensions of the patch, and the embedded U slot.

The selection of excitation point is an important part of an antenna design. So, first of all, the feeding position is chosen by exciting the optimized patch through a coax-probe at different feeding point. Figure 3 compares the resulted return loss curves for different feed positions along the *x* and *y* axes. Since the radiating patch is very compact and the feeding point is inside the U-slot, the displacement is considered within a narrow area. The best result found with a feed point at (1.1, 1.55); 11.3 GHz bandwidth with –41 dB return loss value at 59.84 GHz. The obtained results are summarized in Table II for ease of comparison. Though, feed at (1.2, 1.55) gives a wider bandwidth but the feed at (1.1, 1.55) shows deeper return loss.

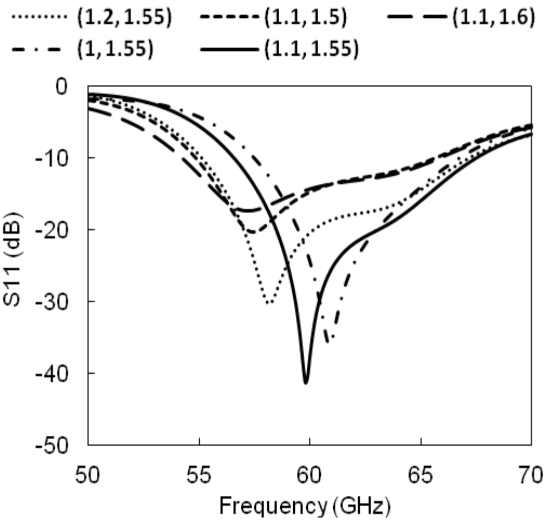


Fig. 3. Comparison of bandwidth for different probe feed position.

TABLE II. COMPARISON OF BANDWIDTH, RETURN LOSS AND RESONANT FREQUENCY FOR DIFFERENT PROBE POSITIONS.

Feed Position (x, y)	Return Loss (dB)	Resonant Frequency (GHz)	BW (%)
(1, 1.55)	-36.13	60.94	14.97
(1.1, 1.5)	-20.47	57.48	17.60
(1.1, 1.55)	-41.23	59.84	18.20
(1.1, 1.6)	-17.33	57.14	19.30
(1.2, 1.55)	-30.52	58.16	20.65

Secondly, the patch size is adjusted again with excitation at (1.1, 1.55). Figure 4 shows the graph of return loss versus frequency for different dimension of the patch in width (*W*) and length (*L*). The resulted wide band around 60 GHz can be noticed for different combinations. The variation in the resonant nature of the antenna along with these two vital parameters is obvious from the figure. Since the target frequency is 60 GHz, so parameter values are chosen to meet the targets and wideband as well. The simulated results for different sizes of the patch have been compared in Table III.

Comparing the bandwidth, lowest return loss (dB) value and nearest resonance around 60 GHz, top radiating patch of 1.4 x 0.9 mm^2 is finalized. The maximum bandwidth obtained at –10 dB return loss level (VSWR 2:1) is 11 GHz (18.2 %) and the minimum return loss value is –41.23 dB at 59.84 GHz.

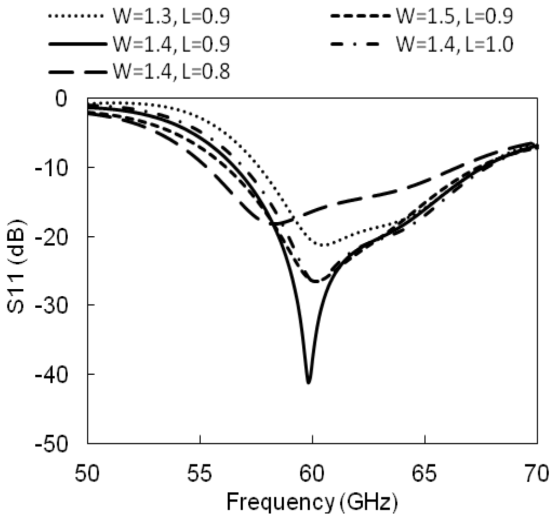


Fig. 4. Comparison of return loss and resonant frequency for different dimension of *W* and *L*.

TABLE III. COMPARISON OF BANDWIDTH, RETURN LOSS AND RESONANT FREQUENCY FOR DIFFERENT DIMENSIONS OF PATCH.

W (mm)	*L* (mm)	Return Loss (dB)	Resonant Frequency (GHz)	BW (%)
1.3	0.9	-21.90	60.53	15.7
1.4	0.8	-18.12	58.30	17.3
1.4	0.9	-41.23	59.84	18.2
1.4	1.0	-26.84	60.19	17.6
1.5	0.9	-26.50	60.13	18.2

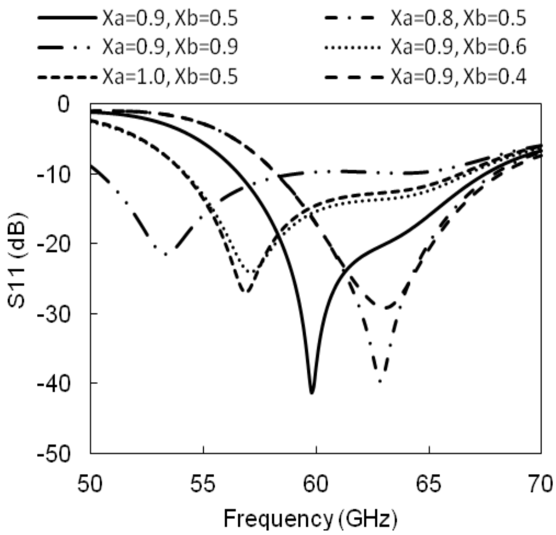


Fig. 5. Comparison of return loss and resonant frequency for different dimension of *Xa* and *Xb*.

Similarly, the length and width of the U-slot are also optimized by the separate parametric study and suitable dimensions are preferred. An unequal arm U-slot is used as it gives wider bandwidth and minimum return loss than an equal arm U-slot. Figure 5 depicts the return loss characteristics for various combinations of the slot dimensions *Xa* and *Xb*. From the comparative studies, the most suitable dimensions are selected and shown in Table IV. Although some other combination gives a wider bandwidth but does not give a minimum return loss and resonant frequency nearer 60 GHz and vice-versa. Hence a trade-off is done by selecting the parameter values.

TABLE IV. COMPARISON OF BANDWIDTH, RETURN LOSS AND RESONANT FREQUENCY FOR DIFFERENT DIMENSIONS OF XA AND XB.

***Xa* (mm)**	***Xb* (mm)**	**Return Loss (dB)**	**Resonant frequency (GHz)**	**BW (%)**
0.9	0.5	-41.23	59.84	18.2
0.8	0.5	-39.93	62.88	14.3
0.9	0.9	-21.55	53.28	16.1
0.9	0.6	-24.05	57.08	21.1
1.0	0.5	-27.01	56.87	21.4
0.9	0.4	-29.12	63.12	15.7

After that, another study is performed to find out the suitable width of the unequal arm U-slot. The slot dimensions *Ya* and *Yb* are adjusted to 0.7 mm and 0.1 mm respectively, which gives 18.2 % bandwidth at 59.84 GHz covering the frequency band from 56.3 GHz to 67.6 GHz. Figure 6 shows the effect of U-slot dimensions on the antenna return loss characteristics and Table V summarizes the antenna performances.

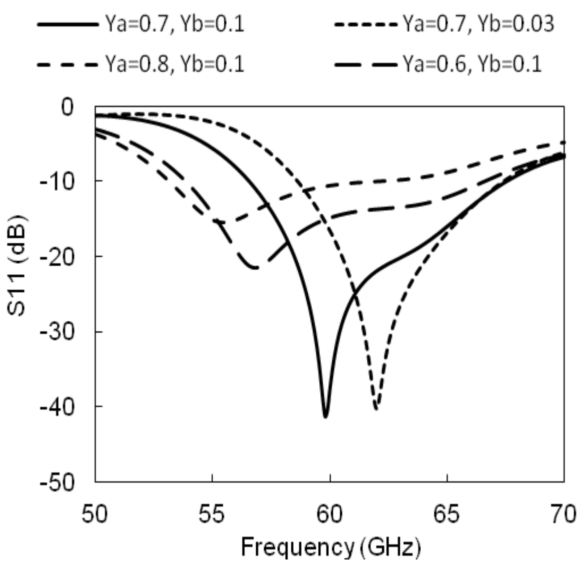


Fig. 6. Comparison of return loss and resonant frequency for different dimension of *Ya* and *Yb*.

It is clear from the Fig. 5 and Fig. 6 that the resonant frequency is very sensitive to the U-slot dimensions. The resonance is varied within 52 GHz to 64 GHz frequency range for various combinations investigated. The minimum return loss value is also varied with respect to the slot length and width.

In accordance with the parametric analysis (Table V), the feeding location, patch size and slot dimensions are chosen as tabulated in Table VI. With the selected design parameters, the antenna is further simulated and the return loss curve is shown in Fig. 7.

TABLE V. COMARISON OF BANDWIDTH, RETURN LOSS AND RESONANT FREQUENCY FOR DIFFERENT DIMENSIONS OF YA AND YB.

***Ya* (mm)**	***Yb* (mm)**	**Return Loss (dB)**	**Resonant Frequency (GHz)**	**BW (%)**
0.6	0.1	-38.36	64	15.6
0.7	0.15	-21.67	56.9	21.4
0.7	0.3	-40.11	62	13.78
0.7	0.1	-41.23	59.84	18.2
0.8	0.1	-15.50	55.43	15.31

TABLE VI. SELECTED DESIGN PARAMETERS.

Attributes	**Values (mm)**
W	1.4
L	1.0
Xa	0.9
Xb	0.5
Ya	0.7
Yb	0.1
Feed position (*x*, *y*)	(1.1, 1.55)

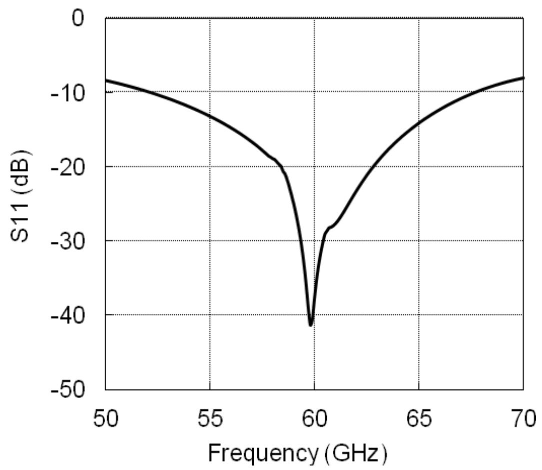


Fig. 7. Return loss curve with optimized parameters.

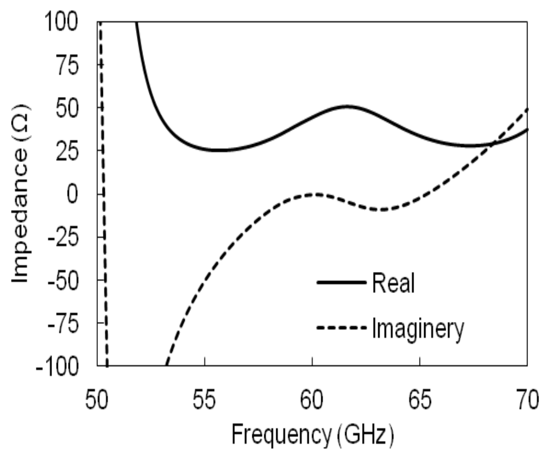


Fig. 8. Impedance characteristics of the proposed antenna.

The combination gives better results in terms of bandwidth and minimum return loss value. The antenna resonates very nearly at 60 GHz and the bandwidth obtained is 15.4 GHz that covers from 52.3 GHz to 67.7 GHz, with minimum return loss is –41.23 dB. Figure 8 shows the impedance characteristics of the proposed antenna. In the operating frequency range, the real part of the impedance is matched very well to 50 Ω whereas the imaginary part is almost zero.

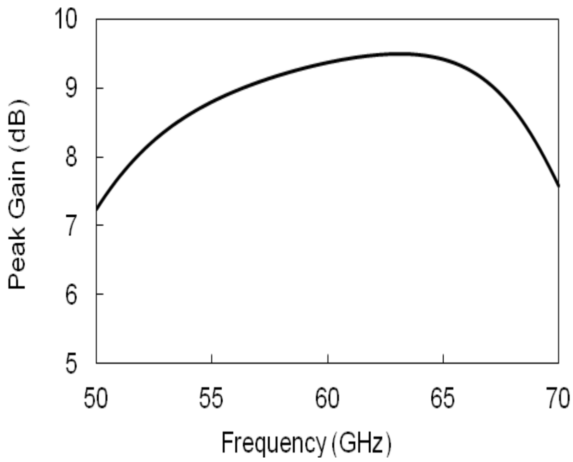


Fig. 9. Comparison gain between slotted and rectangular antenna.

The resulted peak gain of the proposed configuration over the frequency range of 50 GHz – 70 GHz is shown in Fig. 9. The maximum gain obtained is approximately 9.52 dB around 60 GHz and it is stable over the operating band. However, the gain can be further enhanced by making a compact array of this small antenna configuration. The combination of the optimized design parameters along with the embedded U-slot and the coaxial probe feed improved the antenna performances.

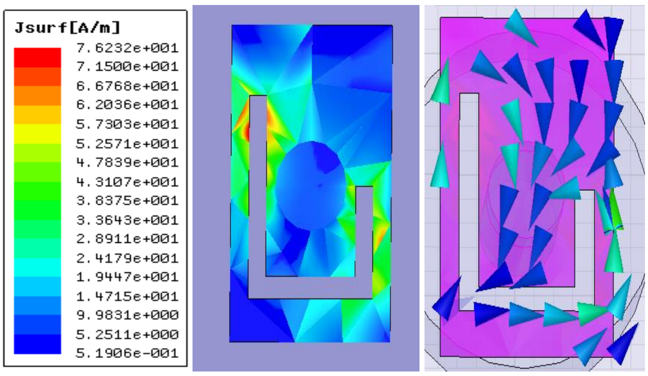
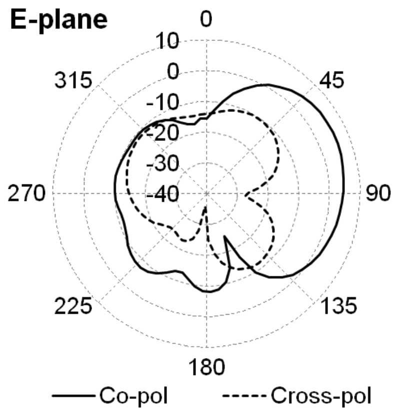


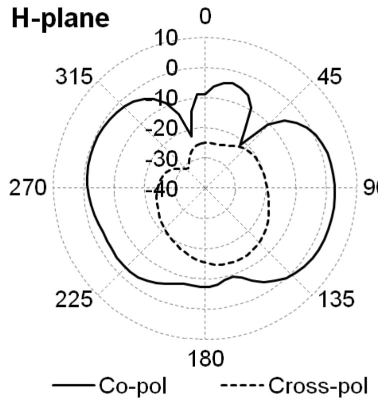
Fig. 10. Surface current distributions and current flow direction at 60 GHz resonance.

The surface current distribution in scalar and vector forms at 60 GHz are shown in Fig. 10. At the edges of the U-slot, high concentration of current is observed whereas the current is almost uniformly distributed in other areas.

Figure 11 shows the 2D polar plot of the radiation characteristics at 60 GHz in E-plane and H-plane, respectively. The pure line represents the co-polarization whereas the dashed line represents the cross-polarization pattern. In the H-plane, the co-polarization level is higher than the cross-polarization while in the E-plane cross-polar component slightly higher but below –15 dB. As the antenna operates at a millimeter wave band, it is not surprising to have big cross components. At the frequency of resonance, the patterns are likely to be omnidirectional in both E- and H-planes.



(a)



(b)

Fig. 11. 2D radiation pattern for (a) E-plane and (b) H-plane at 60 GHz.

TABLE VII. PERFORMANCES OF THE FINAL ANTENNA CONFIGURATION.

Return Loss (dB)	Frequency range (GHz)			BW		Gain (dB)
	f_l	f_h	f_r	GHz	(%)	
-41	52.20	67.70	60	15.4	25.69	9.52

Table VII summarizes the final antenna performances. The performance of the proposed antenna such as return loss, bandwidth and gain is highly sensitive to the change of the U-slot, probe feed position and the patch size. Thus, the dimensions of U-slot, patch size and probe feed position are adjusted to get the optimized results as high bandwidth and high gain of the antenna.

IV. CONCLUSIONS

In this paper, the design of a wideband microstrip patch antenna has been proposed for short range high-speed wireless applications at 60 GHz. The antenna configuration is designed and analyzed by using the HFSS simulator based on the finite element method. Several parametric studies have been performed to obtain a better combination of design parameters. By inserting an unequal arm U-shape slot into the rectangular patch bandwidth is enhanced up to 25.69 % and peak gain obtained is 9.52 dB at the resonance. This low profile structure is very simple and easy to fabricate but required some highly precise fabrication facilities for such a small antenna. Moreover, as we may aware that the HFSS EM simulator which we used here to obtain the provided results is a very strong and efficient solver thereby lead to the highest-fidelity solution possible. Therefore this antenna can be considered as a good candidate for indoor and short distant speedy communications at 60 GHz.

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