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Research Article

Design and Analysis of a Slotted Patch Antenna for Dualband Millimeter-Wave Applications

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Abstract: In this article a low cost, efficient and high flexible dual band slotted patch antenna has been designed for point to point and broadband high-speed wireless communication. For high data rate transmission and wideband spectrum, a low resistivity silicon substrate has been used having relative permittivity of 11.9, thickness of 0.275 mm and tangent loss of 0.002. The proposed slotted patch antenna has been designed for millimeter wave band operating at 57.52 GHz (V-Band) and 70.64 GHz (E-Band) applications. Two inverted U-shaped slots have been introduced on both sides of the patch to get the dual band operation. The Jerusalem-shape slot is used for achieving good impedance matching and better bandwidth. The antenna achieved a wide bandwidth of 1.82 GHz and 1.06 GHz with a maximum gain of 4.546 dB and 2.770 dB at 57.52 GHz and 70.64 GHz, respectively. The antenna achieves a radiation efficiency of 89.68% and 93.21% at 57.52 GHz and 70.64 GHz frequency bands respectively. The overall size of the antenna is 2.36x2.63 mm^2 and can be used in portable gigabit speed applications.

Keywords: Millimeter wave, Patch antenna, Dual band.

1. INTRODUCTION

The rapid development in modern mobile and wireless communication system (GSM, 2G, 2.5G, and 3G) have made a tremendous growth in the last decade. According to demand and scope the researcher's focus is encouraged towards a design of compact and portable devices having multi-band capability that fulfill the users need. In addition to these desirable characteristics of a device a high data transmission rate along with a wide bandwidth is required for a long-distance communication. In the recent years, a wide spread research has been proposed to increase the bandwidth and to improve the transmission quality for a reliable communication over a long distance [1-5]. To meet the demands of modern communication system in terms of wide bandwidth, high transmission rate, higher resolution and compact size, millimeter wave frequencies (f >30 GHz) [6] are the optimum choice. Millimeter wave is the band of spectrum between 30 GHz to 300 GHz. Antenna experts and researchers are testing 5G broadband wireless technologies on millimeter wave spectrum. Millimeter waves are extremely high frequency waves that have short wavelengths ranging from 10 mm to 1 mm. In telecommunication, millimeter wave is used for a variety of services and wireless networks, point-to-point, and broadband access as it allows for higher data rates up to 10 Gbps. At present, there is a shortage of bandwidth in conventional cellular systems [7]. Millimeter waves have a significant role in a variety of wireless communication and satellite applications that aim to achieve high data rate to provide services simultaneously. Microstrip patch antenna is the key candidate that has a numerous application in wide spread wireless systems [8], including millimeter-wave systems. The microstrip antenna technology is very feasible in millimeter-wave regime due to its desirable features such as small size, low cost, easy in fabrication, robust, low profile and light weight [9-11]. In [12], various feeding techniques are used to increase the antenna bandwidth to enhance transmission data rate [12].

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A 40 GHz coplanar waveguide fed antenna backed by FR4 Epoxy substrate is proposed for radar communications [13]. A 4x4 array antenna has been developed at 35.7 GHz for millimeter wave energy harvesting services. Another planer array antenna operating at 79 GHz and 80 GHz has been proposed for Ultra-Wideband (UWB) applications, such as Short-Range Radar (SSR) for vehicles [14]. A Coplanar Waveguide (CPW) feed patch antenna covering a huge chunk of the 60 GHz band (58.3 -63 GHz) is proposed in [15]. Antennas for wireless communication systems are expected to be broadband to achieve high data rate at 60 GHz [16]. Other multiband approaches are discussed in [16, 17]. In [18, 19] antennas for high data rate (Gbps) applications, such as video conferencing and live internet streaming, are proposed. Previously millimeter-wave antennas have been designed using different substrate materials like FR 4, germanium, RT-Duriod, Teflon R03010, Arlon and Silicon. One of the most efficient and conformable silicon materials with low loss characteristics has been reported in [20-23]. A slotted 60 GHz wideband patch antenna incorporating an air cavity has been reported in [24]. Cavity technique increases the immunity of an antenna from its environment, reduces surface waves and improves antenna bandwidth. A cavity based broadband antenna has been proposed for V-band applications [25]. Alternative approaches have been utilized in [26, 27] for improving the efficiency and bandwidth of the conventional patch.

In this paper, a novel-shape dual-band slotted patch antenna for 57.52 GHz (V-Band) and 70.64 GHz (E-Band) millimeter wave applications is presented. A highly conformable substrate such as silicon with a low loss characteristic is selected for designing the proposed antenna. The rest of the paper is organized as follows: the geometry and configuration model of proposed antenna is described in section 2. Section 3 presents the antenna performance and discussion. The conclusion and future work is discussed in section 4.

2. DESIGN METHODOLOGY OF CONVENTIONAL WEARABLE PATCH ANTENNA

The layout of proposed antenna geometry along with parameters is depicted in Fig 1. The patch antenna is designed using a silicon substrate having a relative permittivity of 11.9, thickness of 0.275 mm and tangent loss of 0.002. The slotted portion in proposed structure of patch is responsible for dual mm wave band operation. The antenna is properly matched with a microstrip feed via waveguide port. The effective dielectric constant (ε_{reff}), width (W), length (L) of the proposed patch antenna and position of feedline (y_0), are calculated from the following transmission line theory equations [27], i.e.

$$W = \frac{c}{2\, f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$L = \frac{c}{2 f_r \sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{2}$$

where, c is the speed of light in vacuum, εreff, is the effective relative permittivity of the substrate of thickness (h) and ΔL the differential increase in resonant length due to fringing.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W_p}\right]^{-1/2} \tag{3}$$

$$\frac{\Delta L}{h} = 0.412\ \frac{(\varepsilon_r+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_r-0.258)\left(\frac{W}{h}+0.8\right)} \tag{4}$$

The position of the feed (y_0) is found using the relationship between the input resistances at 50 Ω feed point (R_{in} ($y=y_0$)) and edge of the patch (R_{in} ($y=0$)). The later varies in the range of 200-300 Ω and depends on the conductance (G_l) of the patch. It can be found using the transmission line model of patch antennas, i.e.

$$R_{in}(y=yo) = R_{in}(y=0)Cos^2\left(\frac{\pi}{L}yo\right) \tag{5}$$

$$R_{in}(y=0) \approx \frac{1}{2G_1} \tag{6}$$

$$G_1 = \frac{1}{90}\left(\frac{W}{\lambda_0}\right)^2 \tag{7}$$

The width of the feed line (W_0) is found using [4]

$$W_0 = \left(\frac{377}{Z_c\sqrt{\varepsilon_r}} - 2\right)h \tag{8}$$

where, Z_c is the characteristic impedance of the feed line. The calculated dimensions were optimized for the desired radiation characteristics are given in Table 1.

Table 1. Parameters and their values

Parameters	values (mm)	Parameters	values (mm)
W	0.9843	yo	0.261
L	0.62	Lf	0.571
Lg	2.36	a	0.7
Wg	2.63	b	0.03
h	0.275	c	0.02
mt	0.05	d	0.104
ff	0.10	e	0.08
Wo	0.051	g	0.238

3. MATERIALS AND METHODS

This section is mainly focused on the analysis of the proposed antenna in terms of return loss, directivity, gain and surface currents. Return loss is the significant and desirable characteristics of an antenna. The main objective of the U-shaped slots embedded at bottom in both sides of the patch is to achieve a dual band frequency operation. However slight changes in the dimensions of U-shaped slots result a slight variation in selected frequency bands. The proposed antenna shows an optimum return loss of -17.57 dB at 57.52 GHz and -15.87 dB at 70.64 GHz as depicted in Fig. 2. The -10 dB, driving point impedance bandwidth of the antenna is 1.82 GHz and 1.06 GHz in the lower

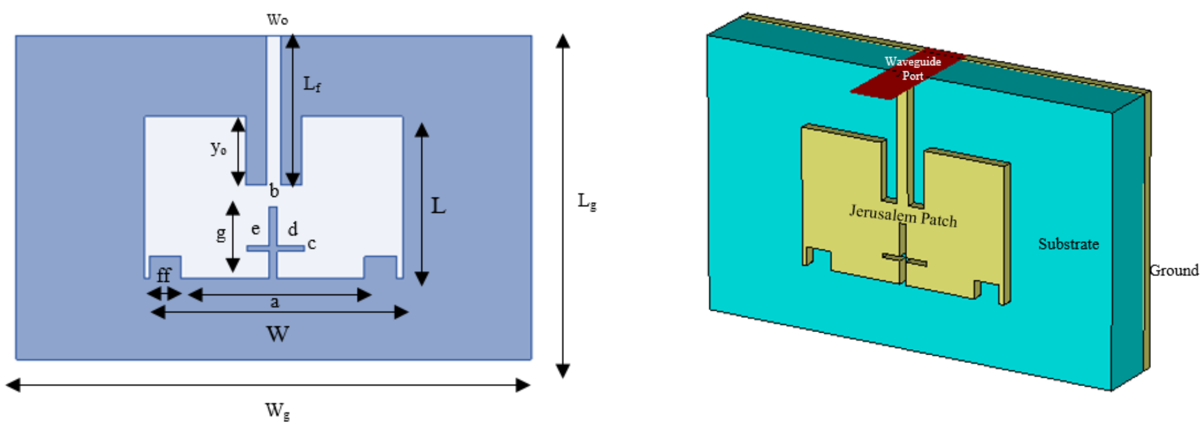

Fig. 1. Geometry of proposed slotted patch antenna (a) front view (b) perspective view

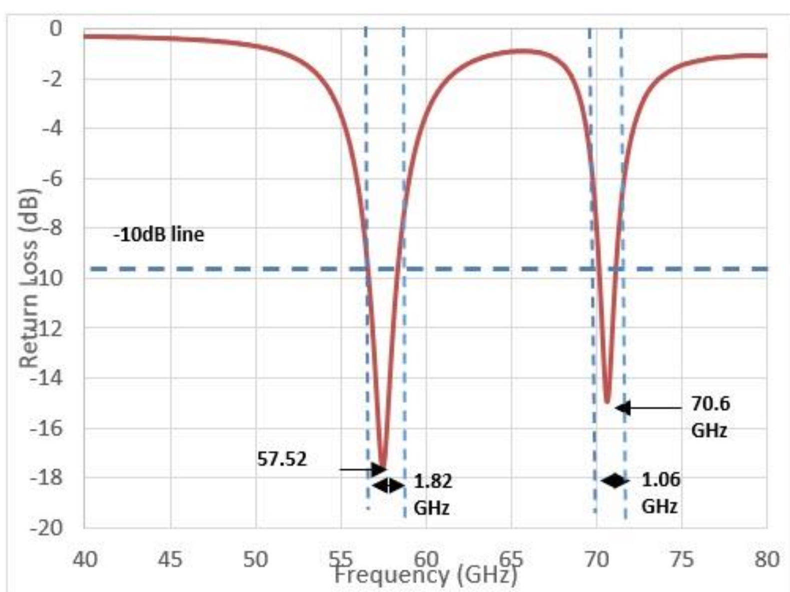

Fig. 2. Return loss of proposed patch antenna on silicon substrate.

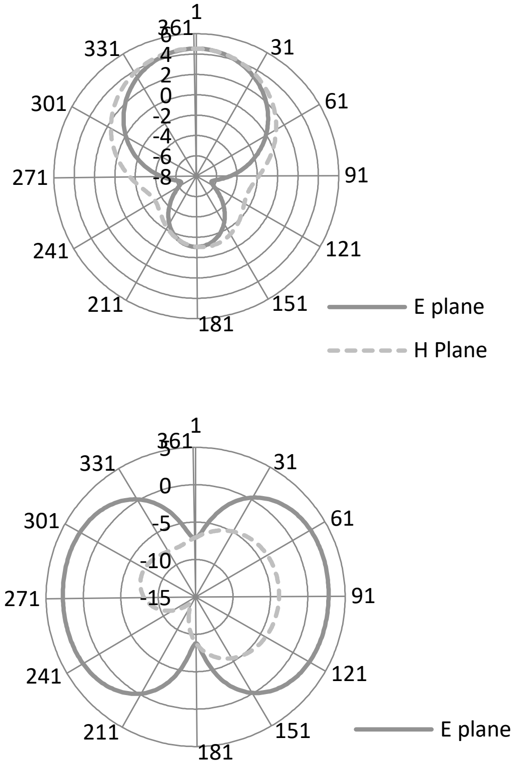

Fig. 3. Gain of the proposed antenna in both principal planes (a) 57.52 and (b) 70.64 GHz.

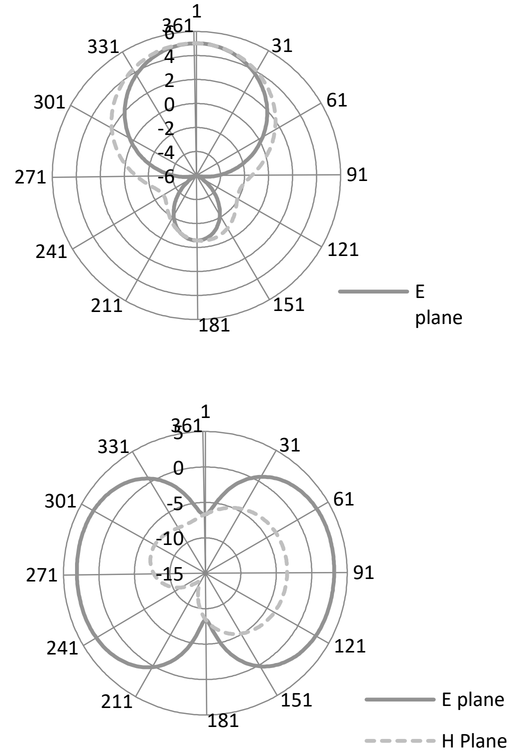

Fig. 4. Directivity of the proposed antenna in both principal planes (a) 57.52 and (b) 70.64 GHz

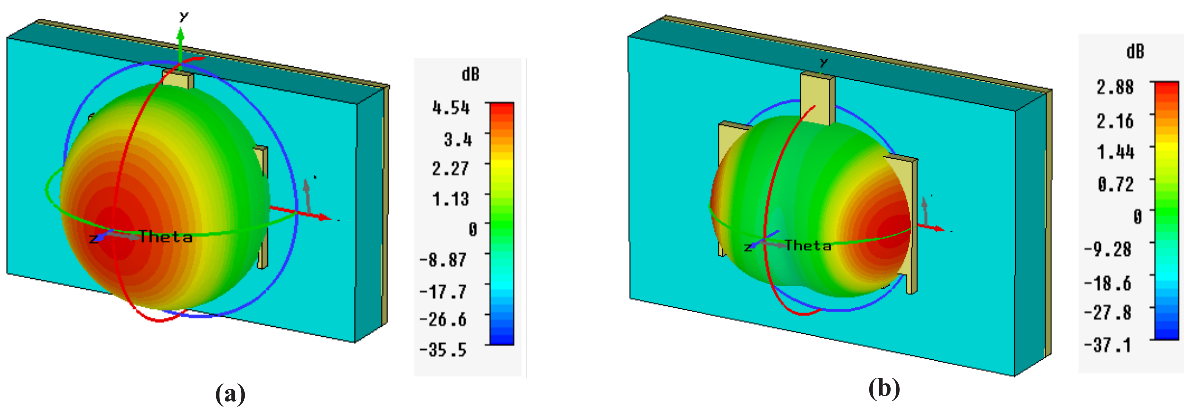

Fig. 5. 3D Gain plots of the proposed antenna at (a) 57.52 GHz and (b) 70.64 GHz.

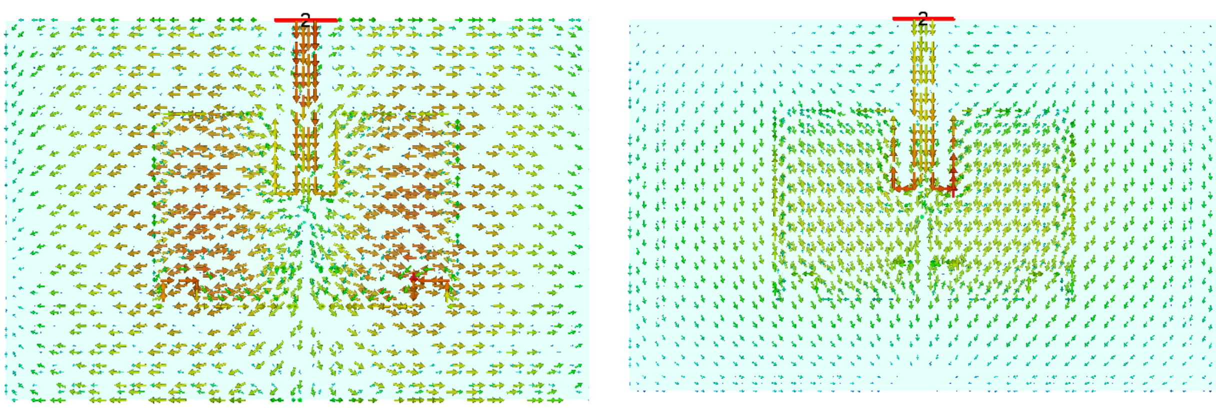

Fig. 6. Surface current patterns of proposed antenna at (a) 57.52 GHz and (b) 70.64 GHz.

Table 2. Performance summary of characteristics parameters

Parameters	57 GHz Band	70 GHz Band
Frequency (GHz)	57.52	70.6
Return loss (dB)	-17.57	-14.91
Bandwidth (%)	3.17	1.50
Beamwidth φ=00	94.8	94.8
(Degrees) φ=900	116	116
Gain (dBi)	4.546	2.770
Directivity(dB)	5.019	3.075
Radiation Efficiency (%)	89.68	93.21

and upper resonant frequency band, respectively. The proposed dual band slotted patch antenna has a maximum gain of 4.546 dBi and 2.770 dBi and a directivity of 5.019 dB and 3.075 dB at 57 GHz and 70 GHz, respectively. The E-field ($\phi=0^0$) and H-field ($\phi=90^0$) gain and directivity radiation patterns of a proposed antenna is shown in Fig. 3 and Fig. 4. The Half Power Beamwidth (HPBW) of the antenna is 94.8^o and 124.7^o at 57.52 GHz and 70.64 GHz, respectively.

For further clarification of the boresight gain, side and back lobe radiation, the perspective of the three-dimensional gain patterns of the proposed patch antenna at 57 GHz and 70 GHz are illustrated in Fig. 5. The Fig. 6 represents the surface current patterns of designed antenna for both the frequencies. It is evident that the surface current density is maximum through the entire patch which generates the lower frequency band (57.52 GHz), whereas at higher frequency (70.64 GHz) the current density is maximum in the central part of the rectangular patch. The performance matrices of the antenna are outlined in Table 2.

4. CONCLUSIONS

In this research, a dual-band inverted U-shaped slotted patch antenna has been designed for millimeter wave applications operating at 57.52 GHz (V-Band) and 70.64 GHz (E-Band). The proposed antenna is compact, low cost and very efficient that can be used for numerous mm wave applications such as video conferencing, streaming contents downloading, and high speed internet. The two inverted U-shaped slots of same dimensions have been embedded in the both sides of the patch that are responsible for dual band frequency operation of proposed antenna, while a Jerusalem-shaped slot has been introduced at the center of the patch to achieve better performance of characteristic parameters like gain, return loss, and directivity. A flexible and high conformable material such as silicon with a low loss characteristic has been used as a dielectric substrate. It is observed that the proposed antenna achieved bandwidth of 3.17% and 1.50% with a maximum gain of 4.546 dB and 2.770 dB at resonance frequency bands of 57.52 GHz and 70.64 GHz respectively. It is also noted that the designed antenna has maximum radiation efficiency of 89.68% and 93.21% at 57.52 GHz and 70.64 GHz, respectively. A prototype of this antenna will be fabricated to validate the results.

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