Ultra-Wideband Slot-Loaded Planar Antenna for Future 5G Millimeter Wave Applications

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An ultra-wideband, compact planar antenna with defected ground structure (DGS) has been presented in this article for future 5G millimeter-wave applications. The proposed antenna overcomes the limitation of bandwidth of the conventional microstrip patch antenna (typically < 5%). The antenna exhibits an ultra-wideband characteristic covering frequency band from 21.3 GHz to 40.6 GHz which makes the fractional bandwidth of 62.36%. The antenna performance is enhanced by etching slots on the patch and incorporating defect on the ground plane. The antenna achieves gain greater than 4.01 dBi and radiation efficiency greater than 95% throughout the operating band. In the given band it also exhibits very low cross-polarization level as well as stable radiation performance. This antenna is designed to operate in n257, n258, n260 and n261 5G millimeter-wave spectrum.

Key words: 5G communication systems, ultra-wideband (UWB), slot antenna, defected ground structure (DGS), millimeter wave

1. INTRODUCTION

In recent years, efficient wireless communication systems are more demanding due to explosion of mobile subscribers, which results in huge communication traffic and this requires large bandwidth and high data rate communication systems [1]. To meet these requirements, 5G communication systems come into picture, 5G offers huge bandwidth, high data rates, ultra-low latency as compare to existing 4G communication systems.

5G offers huge chunk of spectrum, classified as sub-6 GHz and millimeter-wave. The Federal Communication Commission (FCC) classified millimeter-wave ranges from 30 GHz – 300 GHz. According to World Radio communication Conference (WRC-15), millimeter spectrum is classified as 24.25 GHz - 27.5 GHz, 26.5 GHz - 29.5 GHz, 27.5 GHz – 28.35 GHz, 31.8 GHz – 33.4 GHz, 37 GHz – 40.5 GHz, 40.5 GHz – 42.5 GHz, 42.5 GHz – 43.5 GHz, 45.5 GHz – 47 GHz, 47 GHz – 47.2 GHz, 47.2 GHz

– 50.2 GHz, 50.4 GHz – 52.6 GHz, 66 GHz – 76 GHz and 81 GHz – 86 GHz. These millimeter frequency bands are considered as most favorable spectrum for future 5G communication systems [2], [3].

Antenna that poses characteristics such as low profile, light weight, offer large bandwidth and high gain are most desirable for the future 5G communication systems. Various techniques are reported to enhanced the impedance bandwidth and reduce the physical size of the antennas, hence microstrip patch antenna (MPA) is the best choice for modern communication system. In addition, MPA is conformal with both planar and non-planar structure and are relatively cheap and easy to fabricate [4], [5]. Nevertheless, the conventional MPAs offer very narrow impedance bandwidth (typically < 5%) and low radiation efficiency.

Since, high data-rate requires high impedance bandwidth, thus ultra-wideband antennas are well suited for providing large bandwidth which results high data rates. Future high-speed communication networks will require broadband antennas for both indoor and outdoor applications. Several UWB antennas are reported with more than 10 GHz of operating frequency band [6]-[14]. In [6], authors designed octagonal fractal geometry to achieve ultra-wideband. High bandwidth is achieved using different

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sectional blocks, reported in [7]. To achieve high bandwidth several fractal geometries, such as hexagon, octagonal, tapered tree shape, Sierpinski, slotted patch, defected ground structures are reported in [8]-[14].

In this paper, a novel structure is proposed to overcome the main demerit of the conventional microstrip patch antenna and thereby designed a compact ultra-wideband planar antenna with high radiation efficiency. The designed antenna is loaded with slots and stub to improve the performance without increasing the size of the antenna. The proposed antenna is designed to cover n257 (26.5 GHz – 29.5 GHz), n258 (24.5 GHz – 27.5 GHz), n261 (27.5 GHz – 28.35 GHz) and n260 (37 GHz – 40.5 GHz) 5G millimeter-wave spectrum. Furthermore, it exhibits a stable radiation pattern with high radiation efficiency and gain. Thus, this antenna is well suited for future 5G millimeter-wave communication systems.

The content of this paper is organized as follows: in Section 2, antenna design with its parametric analysis is described. Results and discussions are presented in Section 3. The work is concluded in Section 4.

2. ANTENNA DESIGN

2.1. Antenna Description

The top, bottom and cross-sectional view of the proposed antenna are shown in Figure 1. The overall size of antenna structure is $4.2 \times 4.2 \times 0.127 \text{ mm}^3$. The antenna is designed on Rogers RT/duroid 5880 as a substrate, which has dielectric constant 2.2, loss tangent of 0.0009 and thickness of 0.127 mm. The structure is designed, simulated and analyzed using three-dimensional (3D) full-wave electromagnetic solver (ANSYS HFSS v.15). Detailed dimension of the proposed antenna is listed in Table 1.

Figure 1 - Design geometry of proposed 5G antenna: (a) top view, (b) bottom view and (c) cross-sectional view

Antenna is loaded with rectangular and triangular slots along with a rectangular stub. This combination

enabled the antenna to cover 21.3 GHz – 40.6 GHz frequency band with improved performance. Additionally, on the ground plane a rectangular ring defect is incorporated to enhance the performance of the antenna.

Table 1. The value of the geometrical parameters of the proposed antenna

Parameter	Value (mm)	Parameter	Value (mm)
L_g	4.20	W_3	1.00
W_g	4.20	W_4	0.25
L_1	1.50	W_5	0.25
L_2	1.00	d_1	1.23
L_f	1.00	d_2	1.20
W_1	0.65	d_3	2.80
W_2	0.60	h	0.127

Antenna is excited with 50Ω microstrip probe feed. Initially, a rectangular patch is designed to achieve ultra-wideband, but due to limitation of conventional patch antenna, narrow bandwidth is achieved. To improve the performance, a rectangular slot is deployed on the patch and analyzed its characteristics. But still satisfactory results are not achieved. Further, two more vertical slots are incorporated on the patch so that higher frequencies also covered. Thereafter, a rectangular notch along with a triangular notch on the inner patch is incorporated to improve the performance of the antenna. Better impedance matching is achieved with an additional rectangular stub which is deployed on the top of the patch. Moreover, ultra-wideband is achieved because of the defected ground structure (DGS). On the ground plane a $d_3 \times d_3$ and $d_2 \times d_2$ rectangular ring slot is incorporated, having slot gap d_1 .

Parametric Analysis

Antenna parameters have been optimized with the help of parametric analysis using Ansys HFSS.

Figure 2 – Scattering parameter S_{11} of the proposed antenna with variable L_2

Based on the analysis, parametric analysis is performed on four crucial parameters of the antenna including length and width of the stub, width of the outer patch, and length of the inner patch. These parameters are analyzed to get optimized values for better antenna performance. Parametric analysis of the inner patch length (L_2) is illustrated in Figure 2. It is obvious that, for shorter length of the inner patch, antenna is unable to operate in the desired band. As the length increases, the antenna is getting closer to the desired range of the operating spectrum. For $L_2 = 0.4$ mm, 0.5 mm and 0.6 mm, the antenna is radiated very less power within the band. For $L_2 = 1$ mm, antenna is well resonated and cover frequency range from 21.3 GHz – 40.6 GHz, with impedance bandwidth of 19.3 GHz and fractional bandwidth of 62.36% .

Figure 3 - Scattering parameter S_{11} of the proposed antenna with variable W_2

Figure 3 presents tuning of the stub width (W_2). It is observed that operating frequency range is controlled by the variation of stub width. As the width increases, better operating frequency range is achieved. For $W_2 = 0.2$ mm, antenna is trying to get the operating range, but as width increase such as $W_2 = 0.3$ mm, smaller impedance bandwidth is achieved. Antenna covers frequency range from 22.5 GHz – 29.1 GHz with impedance bandwidth of 6.6 GHz and fractional bandwidth of 25.58% . For $W_2 = 0.4$ mm, antenna operates at a 9.2 GHz larger bandwidth, and it covers frequency range from 21.4 GHz – 37.2 GHz with impedance bandwidth of 15.8 GHz and fractional bandwidth of 53.92% . For $W_2 = 0.5$ mm, antenna gets small increment in bandwidth of order 2.3 GHz, and it ranges from 21.4 GHz – 39.5 GHz with impedance bandwidth of 18.1 GHz and fractional bandwidth of 59.44% . Further tuning the parameter gets the optimized performance at $W_2 = 0.6$ mm.

Tuning of the width of outer patch (W_4) is presented in Figure 4. It is clear that operating bandwidth is control with the variation of parameter W_4 . As the width decreases better operating bandwidth is achieved. For $W_4 = 0.85$ mm, smaller impedance bandwidth

is achieved of order 12.9 GHz and fractional bandwidth of 45.82% and its operating frequency is ranges 21.7 GHz – 34.6 GHz. Further decreasing in the width ($W_4 = 0.65$ mm) get better impedance bandwidth of 15.3 GHz. For $W_4 = 0.45$ mm, antenna gets small increment in bandwidth of order 2.3 GHz, it ranges from 21.4 GHz – 39 GHz with impedance bandwidth of 17.6 GHz and fractional bandwidth of 58.27% . Further tuning width of the outer patch gets the better performance when $W_4 = 0.25$ mm.

Figure 4 - Scattering parameter S_{11} of the proposed antenna with variable W_4

For the better performance, precise selection of length of the stub (W_5) is performed with the help of parametric analysis. As the length is shorten, better operating frequency range is obtained as shown in Figure 5.

Figure 5 - Scattering parameter S_{11} of the proposed antenna with variable W_5

From Figure 5, it is observed that operating frequency range is control with the variation of parameter W_5 . As the length decreases better operating bandwidth is achieved. For $W_5 = 0.85$ mm, dual frequency bands are obtained with smaller impedance bandwidth of order 4.8 GHz and 8.7 GHz with fractional bandwidth of 20.86% and 26.56% respectively. At $W_5 = 0.75$ mm,

wide bandwidth is achieved ranges from 20.8 GHz – 38.5 GHz. Further tuning of parameter (at $W_5 = 0.65$ mm), antenna gets small increment in bandwidth of order 0.7 GHz, it ranges from 20.9 GHz – 39.3 GHz with impedance bandwidth of 18.4 GHz and fractional bandwidth of 61.12%. Precise tuning of the length of patch enables wide impedance bandwidth of order 19.3 GHz at $W_5 = 0.25$ mm with fractional bandwidth of 62.36%.

Figure 6 - Scattering parameter S_{11} of the proposed antenna

3. RESULTS AND DISCUSSIONS

3.1. Scattering Parameter

The reflection coefficient plot of the proposed 5G antenna is depicted in Figure 6. Proposed antenna is efficiently cover wide frequency band ranges from 21.3 GHz – 40.6 GHz with impedance bandwidth ($|S_{11}|_{dB} < -10$ dB) of 19.3 GHz and fractional bandwidth of 62.36%. Designed antenna is well suited to operate in n257, n258, n260 and n261 5G millimeter-wave communication systems. For performance verification, antenna is analyzed on 24.5 GHz, 28 GHz, 32 GHz and 38 GHz. From scattering parameter analysis obtained return losses at 24.5 GHz, 28 GHz, 32 GHz and 38 GHz are -18.21 dB, -16.84 dB, -19.43 dB and -23.77 dB respectively.

3.2. Surface Current Distribution

The surface current distribution of the proposed 5G antenna at different frequencies is shown in Figure 7. At lower frequency such as 24.5 GHz, current is mainly concentrated around the inner patch along with lower portion of rectangular ring on ground plane as shown in Figure 7(a). Whereas, Figure 7(b) represents surface current distribution at 28 GHz and maximum current is residing around the inner patch and outer patch along with corner of the rectangular slot on the ground plane. Figures 7(c) and 7(d) depict the current distribution at 32 GHz and 38 GHz respectively. Higher frequency band is obtained because the current is mainly concentrated around the inner as well as

outer patch of the proposed antenna. Moreover, defected ground contributes to get the ultra-wideband characteristic of the proposed antenna as shown in Figure 7.

Figure 7 - Surface current distribution of the proposed antenna at (a) 24.5 GHz, (b) 28 GHz, (c) 32 GHz and (d) 38 GHz

3.3. Antenna Gain and Radiation Efficiency

Antenna gain and radiation efficiency with respect to 5G millimeter frequency of the proposed antenna are shown in Figure 8.

Proposed antenna exhibits antenna gain greater than 4.01 dBi which is stable throughout the operating frequency bands. Obtained antenna gain at frequencies 24.5 GHz, 28 GHz, 32 GHz and 38 GHz are 4.01 dBi, 4.09 dBi, 4.14 dBi and 4.35 dBi, respectively. The radiation efficiency of the proposed antenna is greater than 95% throughout the operating frequency band.

Figure 8 - Antenna gain and radiation efficiency of the proposed antenna

3.4. Radiation Pattern

Two-dimensional Co-Polarization (Co-pol) and Cross-Polarization (X-pol) radiation patterns in terms

of gain of the proposed antenna at 24.5 GHz, 28 GHz, 32 GHz and 38 GHz are illustrated in Figure 9.

It can be observed that antenna has omnidirectional radiation pattern in the H -plane and a dumbbell shaped one in the E -plane. Antenna exhibits low cross-polarization level, less than -15 dB in the E -plane, whereas in the H -plane, it shows cross-polarization level below -24 dB. Proposed antenna shows very low cross-polarization level as well as stable radiation performance throughout the operating frequency band. Therefore, antenna is suitable for future 5G millimeter-wave communication systems.

4. CONCLUSION

In this article, an ultra-wideband slot-loaded microstrip patch antenna for future 5G communication systems is presented.

Figure 9 - Co-Polarization (Co-pol) and Cross-Polarization (X-pol) radiation pattern in terms of gain at 24.5 GHz (a) E-plane, (b) H-plane; at 28 GHz (c) E-plane, (d) H-plane; at 32 GHz (e) E-plane, (f) H-plane; at 38 GHz (g) E-plane, (h) H-plane

Antenna is designed to operate in the n257, n258, n260 and n261 5G millimeter-wave spectrum. Multiple slots and a stub on the radiating patch along with the defected ground structure make the antenna to exhibit ultra-wideband characteristic and offers fractional bandwidth of 62.36%. Moreover, proposed antenna exhibits antenna gain greater than 4.01 dBi which is almost stable and radiation efficiency greater than 95% throughout the operating frequency bands. Also, it exhibits very low cross-polarization level as well as stable radiation performance throughout the operating frequency band. Therefore, proposed antenna is found suitable for future 5G millimeter-wave applications.

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REZIME

ULTRA-ŠIROKOPOJASNA PLANARNA ANTENA SA PROREZOM ZA BUDUĆE 5G PRIMENE NA MILIMETARSKIM TALASIMA

U ovom radu prikazana je ultra-širokopojasna kompaktna planarna antena, sa prorezom u zajedničkoj masi, namenjena za buduće 5G primene u opsegu milimetarskih talasa. Predložena antena prevazilazi problem ograničene širine propusnog opsega konvencionalne mikrotrakaste antene (tipično < 5%). Antena ima ultra širokopojasne karakteristike i pokriva opseg učestanosti od 21.3 GHz do 40.6 GHz, što čini relativni propusni opseg od 62.36%. Karakteristike antene mogu se poboljšati uvođenjem proreza na pločici i u ravni zajedničke mase. Antena ima zadovoljavajuće pojačanje, veće od 4.01 dBi, i efikasnost zračenja veću od 95% u celom radnom opsegu. Antena u datom opsegu pokazuje vrlo nizak nivo unakrsne polarizacije, kao i stabilne karakteristike zračenja. Ova antena je projektovana da radi u opsezima n257, n258, n260 i n261 5G milimetarskih talasa.

Ključne reči: 5G telekomunikacioni sistemi, ultra širokopojasni, antenna sa prorezom, struktura sa otvorom u zajedničkoj masi, milimetarski talasi