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SPECIAL SECTION ON ANTENNA AND PROPAGATION FOR 5G AND BEYOND

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A High Gain and Wideband Narrow-Beam Antenna for 5G Millimeter-Wave Applications

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ABSTRACT A wideband antenna with a high gain and narrow beam-width for future 5G communication systems is presented in this research. The antenna operates in 28 GHz 5G band with a large 35.53% bandwidth ranging from 23.41-33.92 GHz. The array has 4-elements arranged in a linear fashion to attain a high gain of 10.7 dBi. It radiates along its end-fire direction and provides a very narrow beam-width of 14.6° in its H-plane. A corporate feed network specifically designed for thin substrates was used in order to excite the array elements. It is built upon thin 0.254 mm Rogers substrate to minimize transmission losses and attain high radiation efficiencies of more than 90% throughout its operating frequency range. It has a compact structure bearing low cost and is easy to fabricate. This antenna fulfills necessary requirements of 5G communication and is therefore a good candidate to be used in the millimeter-wave range.

INDEX TERMS 5G, millimeter-wave, 28 GHz, wideband, future mobiles, antenna arrays.

I. INTRODUCTION

The future of mobile communication is now entering into its fifth generation (5G) with a clear aim of communication at an extremely high bit-rate in excess of Gbps. In order to be practical in achieving such an outstanding data communication rates, large bandwidth is needed. This bandwidth is nowhere found in the currently used spectrum below 6 GHz by International Mobile Telecommunications (IMT). Therefore, an upgraded spectrum utilization will be required, which is only available at high frequencies in the millimeter-wave range [1]. The world radio-communication conference (WRC) has proposed the use of 24 GHz and beyond spectrum and requested ITU-R to come up with recommendations of proposed frequency bands [2]. Until now, the widely reported number of frequency bands are in the range of 24 to 86 GHz out of which 28 and 38 GHz bands are the most favorable bands for future 5G network technologies [3], [4].

Recently, the scientific research community has been focusing on the design of RF-frontend for future 5G related systems including antennas. Various 5G antennas have been reported [5]–[20] that fulfill some of the key requirement of 5G systems such as high gain, large bandwidth, narrow beam-width and compact size. The antenna structures specifically published to target 5G requirements can be divided into three categories: 1) Cavity-backed multi-layered slot 2) SIW based and 3) Simple planar antennas.

For example, Park [5] proposes an array antenna that is based on a cavity-backed multi-layered elements in 28 GHz band. This antenna has a gain of 13.97 dBi by virtue of its very low side-lobe-levels, however by doing so the antenna has become complex in design. Another cavity-backed antenna by Choubey [6] has similar gains but with lesser number of elements in a smaller size of 23.5 × 22.4 mm^2. This antenna has a large bandwidth of 16.67% at 28 GHz and 22% at 45 GHz. A multi-layered antenna [7] with a broadband response in 26.5-38.2 GHz range has also been reported. This complex antenna has a high gain of 15 dBi.

SIW-fed antenna has characteristics of low transmission losses, for example, the antenna array presented in [8] produces a very large gain of 26.7 dBi in a small size of 28.8 × 28.8 mm^2. This antenna however operates at a higher frequency ISM band of 57-71 GHz. The antenna is also difficult to assemble and complex in nature due to the use of multiple substrate layers, bonding films and a waveguide-to-SIW feed network.

Planar antennas on the other hand are simple structures that are easy to fabricate and integrate with modern small size electronic devices. Planar antenna arrays have relatively high

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TABLE 1. Optimized parameters of the antenna.

Parameter	Value (mm)
Ls	5
Ws	9
Lg	2
Wf	0.78
Lf	2
a	1.8
b	1.5
h	1
w_1	0.2

transmission losses however, they can achieve equally good radiation characteristics if designed intelligently. Thus, they are a good compromise between cost and performance. For example, the antenna by Khalily [9] is a simple 3 × 3 planar microstrip phased array antenna operating at 28 GHz. It has a high gain of 15.6 dBi and 1.7 GHz bandwidth with a small 20 × 20 mm^2 size. Similarly, [10], [11] are small sized simple and planar broadband antennas for unlicensed 60 GHz band. Recently, a planar 5G antenna [12] with printed-dipole array with integrated baluns was published which has 36.2% bandwidth in 26.5-38.2 GHz range. Similarly, a printed log-periodic dipole array [13] bearing a quasi-Yagi structure and parasitic bow-tie patches has been reported. This antenna operates in 40-50 GHz band and has gain of 12.5 dBi.

In order to minimize path loss and attenuation due to environmental effects, which is incurred more profoundly in millimeter-wave spectrum, it is necessary to have an antenna that radiates with a very high gain [1], [14]. Such high gains are attainable with directional beam patterns having narrow beam-beam-widths. Furthermore, giga-bit-per-second (Gbps) communication is only possible with antenna having a very large bandwidth. Achieving both high and large bandwidth simultaneously in a small compact form factor becomes quite a challenging task. Therefore a compromise between bandwidth and gain is usually made, if the antenna has to be of small compact size.

Keeping in view the above discussion, it is clear that planar structures will be preferred if they have a reliable performance since planar structures are easy to fabricate and have low cost. In this paper, we have propose a uniquely designed planar antenna array that gives an end-fire radiation pattern with a very narrow-beam of 14.6° in one of its planes. This ensures high directivity and hence our resulting antenna has a gain of 10.7 dBi. Our proposed antenna provides both the key requirements of high gain and large bandwidth simultaneously in a small form factor, which will prove to be excellent choice for high speed future 5G communications.

II. ANTENNA DESIGN

A. SINGLE ELEMENT

The proposed antenna is modelled upon Rogers RT Duroid 5880 substrate with a thickness of 0.254 mm, dielectric constant of 2.2 and loss tangent of 0.0009. The optimized parameters of the single element antenna are given in Table 1.

The antenna structure consists of a planar dipole resembling a bowtie shape fed by a microstrip line of width Wf, as shown in Fig. 1. The top layer consists of rectangle of width 'w_1', height 'b' which is connected to the feed line through a curved surface at a distance 'a'. The bottom side consists of a horizontally flipped structure of the same shape. The curved surface is formed by making use of Bezier curves [15]. Bezier curves c_1 and c_2 are placed between points p_1, p_2 and p_3, p_4 respectively as shown in Fig. 1(b). The resulting structure thus formed is a modified bowtie shape. This new and modified structure is different from a standard bowtie shape in two ways: 1) A standard bowtie has a triangular shaped arms having straight lines connected to its feed line whereas the proposed antenna has curved arms 2) The proposed modified shape has a larger 'length-to-span' ratio thus provides better compactness. The length-to-span ratio is defined as the overall length starting from point p_2 to p_1, whereas 'span' is the width 'a'. Thus by structuring the proposed antenna in a curved fashion, a far better and controlled compactness has been achieved. Bezier curves are parametric curves that are useful in 2D/3D structure modelling [15].

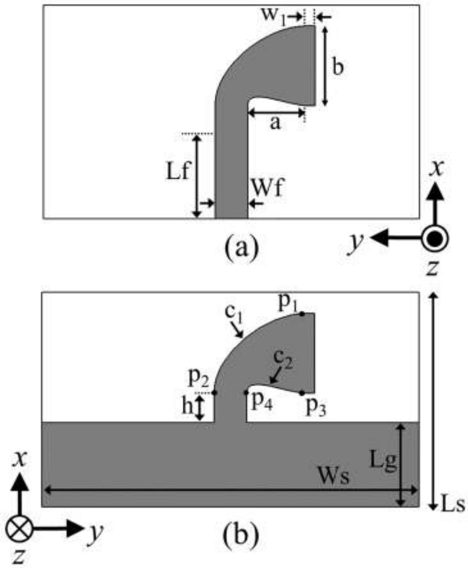

FIGURE 1. Geometry of single element antenna. (a) front side (b) back side.

The back side also consist of a truncated ground of length Lg, which is connected to the bottom bowtie arm through an extension of length 'h'.

To attain resonance at 28 GHz, two parameters are varied to see their effect on the antenna's reflection coefficient. The first parameter is 'a' which relates directly to the overall length of the bowtie. The parametric sweep over frequency is shown in Fig. 2. It can be observed that variation in dimension 'a' affects the resonant point of our antenna. The optimum length of 'a' is 1.8 mm which makes the antenna resonate exactly at 28 GHz.

The second parameter is width 'b' of the bowtie arm and its effects on the reflection coefficient is depicted graphically

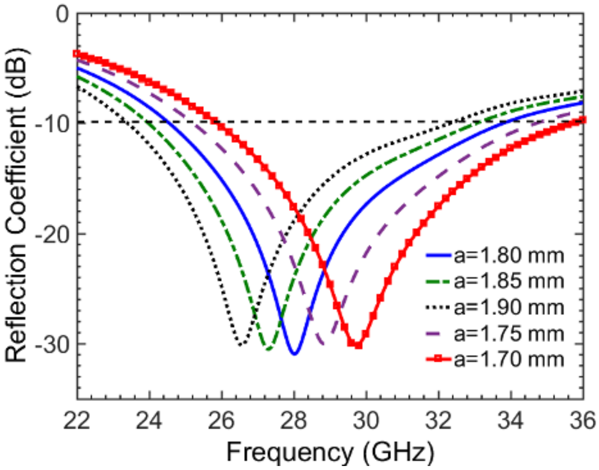

FIGURE 2. Effect of distance 'a' on refection coefficient of the antenna.

in Fig. 3. This parameter helps in improving impedance bandwidth and matching of the antenna. The optimal value of 'b' is chosen to be 1.5 mm for larger bandwidth as well as keeping resonance at 28 GHz. The parameter 'h' also affects impedance matching but its analysis will not be provided here for brevity. Once these parameters are finalized, the proposed single element antenna has a bandwidth in the range of 24.56-33.80 GHz (i.e. 9.24 GHz).

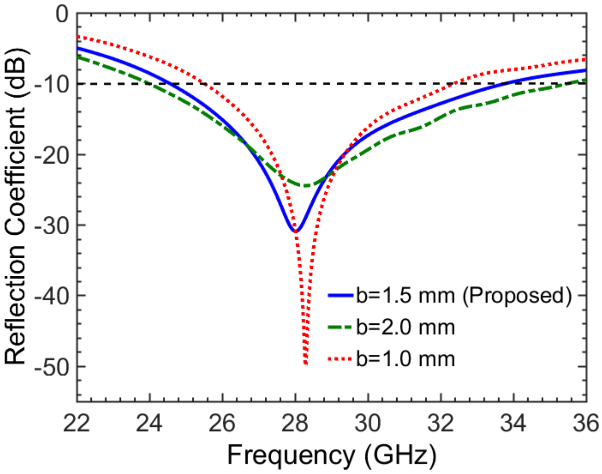

FIGURE 3. Effect of width 'b' on refection coefficient of the antenna.

Vector current distribution of the single element antenna is shown in Fig. 4(a). The current indicates that there is a concentration in middle portion of the antenna and nulls at the ends. This current distribution will result in maxima along x-axis giving high gain. The fact is seen in Fig. 4(b) where we can clearly see that the radiation is along the end-fire direction because back lobe in both planes is less than −10 dB. The antenna has a half-power-beam-width of 69° in xy-plane and has a maximum simulated 3D gain of 5.16 dBi.

B. ANTENNA FEED NETWORK AND ARRAY

Gain of the antenna is enhanced by arranging four single elements in linear formation and fed by a custom microstrip based feeding network. The 4-way feed network has low substrate as well as radiation losses having less than −15 db simulated reflection coefficient throughOUT its operating range. the feed network provides equal magnitude and in-phase signals to each element. Reflection coefficient of this feed network is shown in Fig. 5. The overall antenna array has dimensions Wsub = 37.6 MM, Lsub = 14.3 mm and is shown in Fig. 6.

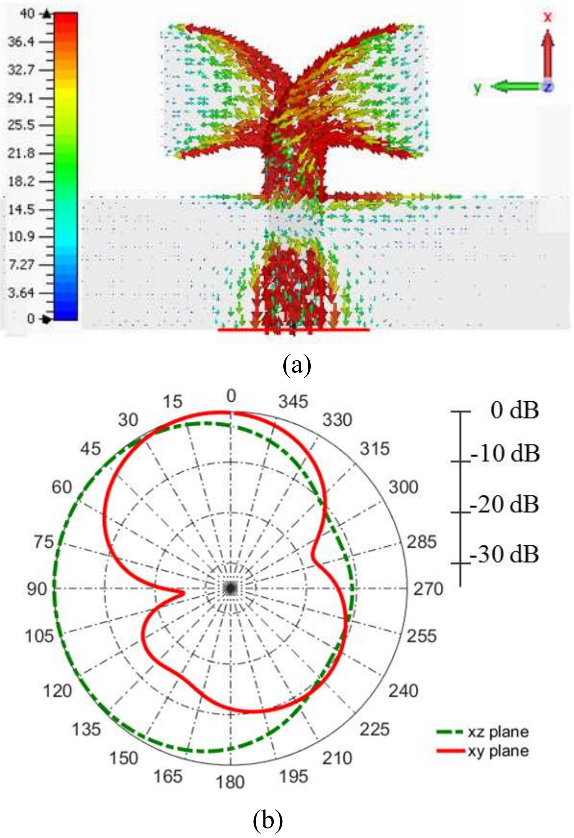

FIGURE 4. (a) Vector current distribution and (b) normalized radiation pattern of the single element antenna.

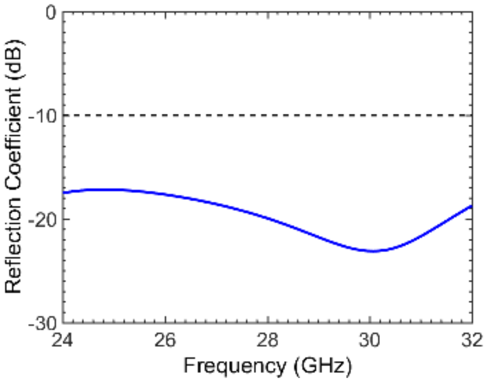

FIGURE 5. Simulated reflection coefficient (S11) magnitude of the proposed feed network.

III. MEASUREMENT RESULTS

The fabricated antenna array reflection coefficient (S11) is measured with a vector network analyzer and radiation patterns inside an anechoic chamber. A Southwest RF connector

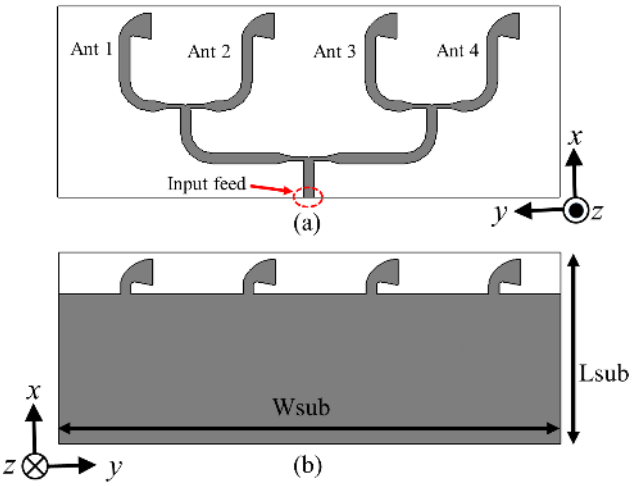

FIGURE 6. Structure of the proposed array antenna (a) front side (b) backside.

is used to feed the antenna array. Photograph of the fabricated antenna array along with its reflection coefficient is shown in Fig. 7.

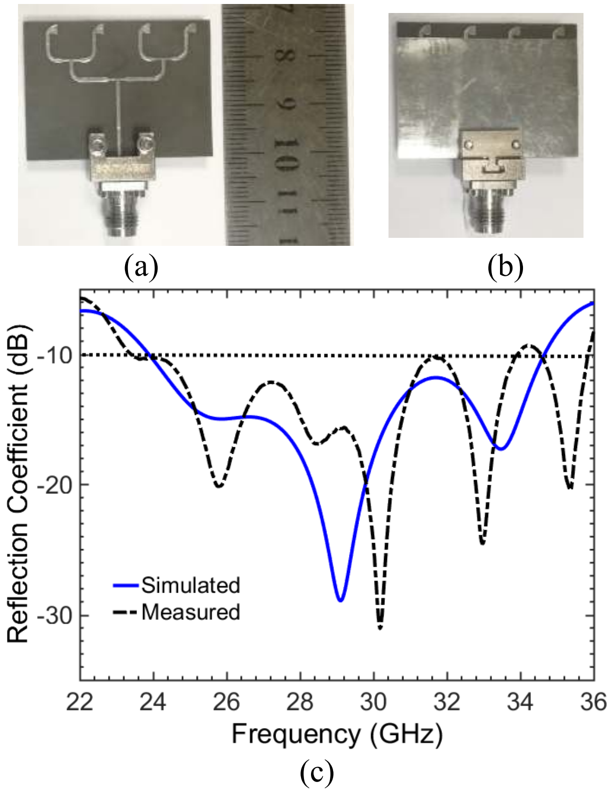

FIGURE 7. Final fabricated antenna array (a) front side (b) back side (c) simulated and measured reflection coefficients.

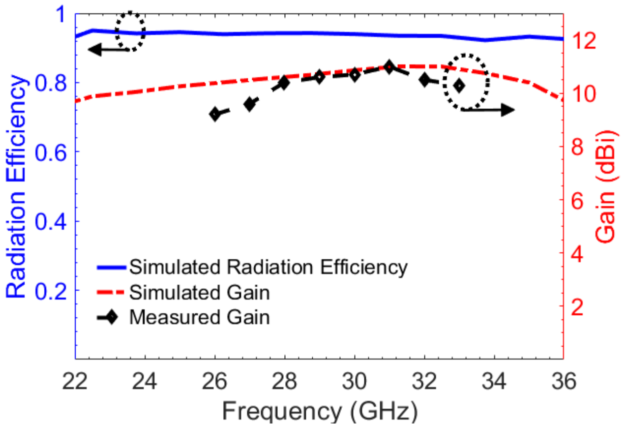

FIGURE 8. Antenna array simulated radiation efficiency, simulated and measured gain.

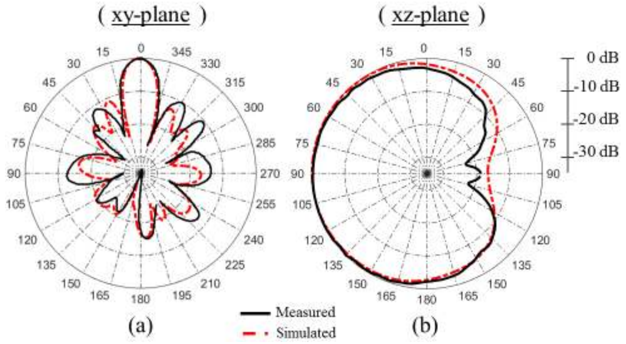

FIGURE 9. Antenna array simulated and measured radiation patterns at 28 GHz. (a) xy-plane (b) xz-plane.

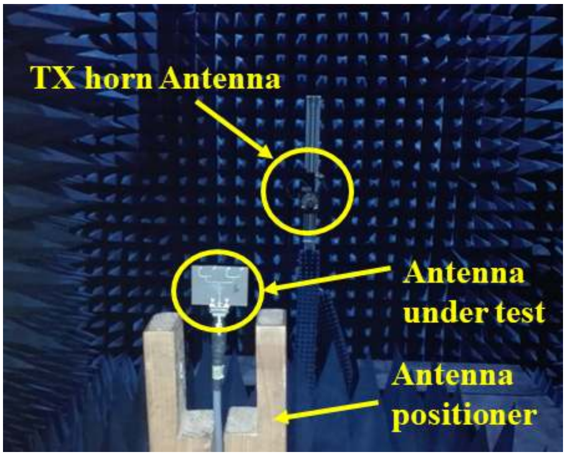

FIGURE 10. Photograph of proposed antenna array during measurement inside an anechoic chamber.

Measured results show that the antenna has an impedance bandwidth in the range 23.41-33.92 GHz which is 35.53% at 28 GHz (i.e. 10.51 GHz). This is a large bandwidth which will be suitable for communication systems operating in millimeter-wave spectrum. Its radiation efficiency and gain plots are shown in Fig. 8. The antenna radiates with more than 90% efficiency and has a peak measured gain of 10.7 dBi.

Radiation patterns of the antenna in xy and xz planes are shown in Fig. 9. The simulated and measured results are in good agreement. We can see that the antenna has a very narrow beam-width of 14.6° in xy-plane. In xz-plane, the antenna radiates in one hemisphere (i.e. in x-axis direction). Its radiations in the direction opposite are very low and low side lobe levels of −10.9 dB (as indicated by simulated as well measured results). Photograph of the antenna under test is shown in Fig. 10.

IV. CONCLUSION

The paper presented a planar millimeter-wave antenna that provided a high gain of 10.7 dBi along with a very wide bandwidth of 10.51 GHz in 23.41-33.92 GHz frequency range. The antenna's characteristics include its end-fire radiation pattern which fulfills a key requirements for 5G antennas i.e. narrow beam-width and high gain. Not only that it has a high gain, but it also has a wide bandwidth which is another key requirement for Gbps 5G communications. A low transmission loss 4-way feed network has been used to excite each antenna element arranged in linear configuration. The antenna was fabricated on thin Rogers substrate, tested for performance using specialized high frequency RF connectors and was found to conform very well to simulated results. The antenna array proposed is deemed fit for use in future 5G communication in millimeter-wave range due to its robust and excellent performance in a small compact size.

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