
(doi: 10.1109/ICMAC54080.2021.9678300)

This is the Author Accepted Manuscript.

© 2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

There may be differences between this version and the published version. You are advised to consult the publisher’s version if you wish to cite from it.

http://eprints.gla.ac.uk/257561/

Deposited on: 22 October 2021
Flexible Ultra-Wideband Antenna for 5G and Beyond Wearable Applications

Bowen Lyu*, Ghazanfar A. Safdar†, Muhammad Ali Jamshed*, and Masood Ur-Rehman*

* James Watt School of Engineering, University of Glasgow, Glasgow, UK
†School of Computer Science and Technology, University of Bedfordshire, Luton, UK
Email: muhammadali.jamshed@glasgow.ac.uk

Abstract—Millimeter wave frequencies are front running contenders for 5G wireless communications. A wideband antenna that can provide coverage in whole of these frequencies is a well sought off challenge. This paper presents design of a quasi-Yagi antenna consisting of three driven arms and three pairs of spiral directors that efficiently meets this requirement. To satisfy the flexibility demand of wearable applications, the antenna employs liquid crystal polymer LCP as the substrate. The antenna has a small size of $5 \times 8 \times 0.202$ mm$^3$ while covering 24-71 GHz band. The proposed antenna achieves peak gain of 2.85, 6.33 and 8.52 dBi, respectively, and an efficiency of more than 70% in the desired frequency bands. The symmetric structure of the antenna also makes the fabrication easier. The ultra-wideband, radiation characteristics and flexibility of usage makes it a promising candidate for 5G and Beyond wearable applications.

Index Terms—Quasi-Yagi antenna, millimeter wave, wearable applications, Liquid Crystal Polymer, 5G, ultrawideband.

I. INTRODUCTION

With the advent of fifth-generation (5G) communication and internet of things (IoT), wearable wireless devices, including portable healthcare equipment, smartwatch, and other smart devices have occurred a tremendous development [1]. The market size of the wearable application is expected to exceed £44000 million by the end of 2025, with a compound annual growth rate of 16.2% [2]. Antenna is an essential component of the wireless enabled wearable devices. Its operation is crucial and usually defining for the performance of these devices. Wearability brings its own challenges in the antenna design on top of the typical free space requirements and flexibility to conform with the body shape, underneath, is one of them [1]. The attraction for 5G system lies in its inherent features of wider availability, high data rate, increased reliability, low latency, smaller and lightweight components and reduced interference [3] [4]. An antenna design fulfilling all these criteria is a knotty problem. While, modalities for 5G networks are in proposition, the Federal Communication Commission (FCC) has identified millimeter wave (mm-wave) frequencies of 28 GHz, 38 GHz and 60 GHz as a favorite pick for 5G wireless communications [3] [4]. In addition, the Wireless Gigabit (WiGig) Alliance is committed to develop and promote wireless communications technology in the unlicensed 60 GHz frequency band. The WiGig standard requires a fractional bandwidth of more than 22% [5].

Coverage of these different frequency bands in a small wearable device is a labyrinth task. Having multiple antennas in a tiny space makes it bulkier, use of a single antenna covering multiple bands is an efficient alternative [4] [6]. Numerous antenna designs are proposed to meet the vivid demands of 5G wearable wireless applications at mm-wave frequencies [6]-[7]. Patch antennas have emerged as a popular choice for these devices because they offer ease of design, simple integration and low cost. A sector-disk radiator and an elliptical radiator are presented in [8] [9], respectively. Both of them exploit a $\pi$-shaped slot to couple with the feed line giving rise to a notched band.

A dual-feed square loop antenna is presented in [10]. Antenna resonates at 38.5 and 73.5 GHz with exhibiting gain values of 2.9 and 3 dBi, respectively. A dual-band microstrip patch antenna has been discussed in [11]. This antenna can achieve the gain of 5.5 dBi and 6 dBi, that corresponds to the resonant frequency of 37 GHz (bandwidth of 14.8%) and 54 GHz (bandwidth of 16%), respectively. Another microstrip patch antenna exploiting the H and E slots to radiate is presented in [12]. The antenna resonates at 26.9 GHz, 35.1 GHz, and 54.7 GHz with bandwidths of 2.92 GHz, 3.13 GHz and 7.62 GHz, respectively. Moreover, the gain of each operating frequency is 5.86 dBi, 4.63 dBi, 6.36 dBi, respectively. Chen et al. have presented a triband quasi-Yagi antenna covering 23–31 GHz, 36–41 GHz and 54–67 GHz frequencies for mm-wave operation at 28 GHz, 38 GHz and 60 GHz bands [13]. The antenna offers gain values of 6.2 dBi, 7.6 dBi, and 9.4 dBi at the three resonant frequencies. Though, these multiband antennas fulfill the basic requirements, the resonant structures constrain the maximum resonant frequency or bandwidth, which limit them to balance the wide bandwidth and extremely high frequency, for example, in the case of WiGig standard. Moreover, flexibility and conformity to the shape of the human user is also not achievable due to rigidity of the substrates used.

This limitation can effectively be eliminated by using antennas with ultra-wide bandwidths (UWB) and flexible substrate. Planar dipoles and bowtie structures offer wideband operation, but they need baluns for efficient performance [14] [15]. Moghaddam et al. have presented a bowtie antenna integrated with a multilayer substrate feeding network [16]. The antenna covers the frequencies of 20-50 GHz with a
reflection coefficient better than -8 dB requiring differential excitation in a way similar to magneto-electric dipoles and marchand baluns. Zeng et al. have come up with a microstrip-fed end-fire magneto-electric dipole antenna design having a -10 dB bandwidth ranging from 22.1 to 41.7 GHz with a peak gain of 6.7 dBi [17]. The antenna utilizes an integrated balun covering the whole operating. Wu et al. have proposed an array antenna covering the frequencies of 55-68 GHz [18]. The elemental design consists of a microstrip radiation element and the feeding planar hollow waveguide. Through the use of vias, substrate integrated cavity is formed. Sehrai et al. have proposed a quad element MIMO antenna where the radiating element consists of four arcs to cover mm-wave frequencies of 23 GHz to 40 GHz [7]. These structures are complex, inflexible and do not cover the three bands of interest in mm-wave frequency range.

In this paper, we have proposed a quasi-Yagi antenna to cover the 5G mm-wave bands from 24 to 70 GHz. To ensure flexibility and conformity, liquid crystal polymer (LCP) consisting of polyimide/polyethene terephthalate (PET) is chosen as a substrate. LCP is considered an excellent material to improve the conformal and flexible characteristics enhancing the adaptability of the wearable antennas [19]. Following the introduction, the rest of the paper is organized in three sections. Section II describes the antenna design. Section III presents the numerical results and analysis of the antenna performance. Section IV summarizes the findings and concludes the discussion.

II. ANTENNA DESIGN

Yagi antenna is conventionally being used for television signal reception for many years. It consists of several pairs of dipoles as driven modules and possess broad bandwidth, straightforward construction, and relatively high gain [13] [20]. We have chosen printed Yagi structure as the basis of our ultrawideband mm-wave antenna design. In the proposed structure, three pairs of drivers and spiral directors are laid on top and bottom sides of the flexible substrate (i.e., Rogers 3850 LCP with dielectric constant of 2.9, loss tangent of 0.0025 and thickness of 0.2 mm). To obtain an overall compact size of $5 \times 8 \times 0.202$ mm$^3$ while having an ultrawideband mm-wave operation, a detailed optimization process is carried out to have optimal dimensions of the driven arms (A1, A2 and A3 in Fig. 1), truncated ground (by adjusting the lengths of S1, S2 and S3), the size of rectangular ground patches, and the dimension of the small open stub.

For 28 GHz operation, the truncated ground is not only for receiving return current but also acts as the reflector of A1 whereas A2 and A3 perform as directors for A1. At 38 GHz, A1, A2 and A3 act as a reflector, driver and director, respectively. For 60 GHz operation, A2 works as a reflector while A3 is the driver element. The directors are realized in the form of spirals as they are more effective than other possible structures (such as L-shaped, L-shaped and U-shaped) for obtaining larger bandwidth and higher gain [21]. The driven arms resonate at 28, 38 and 60 GHz corresponding to A1, A2 and A3, respectively. In the design process, length of A2 is approximated first, then, S1, S2, and S3 are determined to match the impedance of A3. Subsequently, A1 and A2 are structured applying similar method. In addition, other elements are utilized for fine-tuning the antenna functionality.

The antenna is fed through a 50 Ω coaxial line. The coaxial line not only acts as a feedline but also provides signal transmission for the dipoles on top and bottom layers. The reference ground is extended to the radiating plane to reduce the power loss of the transmission line (Fig. 3) because the coaxial line encounters serious mismatch when passing through the substrate. There are several ways to achieve the broadband impedance matching including use of ladder networks, multiple stubs, multiple line sections and tapered lines [21]. A combination of the tapered transmission line and multiple stubs is employed to broaden the bandwidth in the proposed design. Especially, the main transmission line is elaborately designed as a tapered line, which can provide impedance matching for A1, A2 and A3 along with the coaxial feedline.

The length of the truncated ground is significant for the current distribution in the proposed antenna because the ground plane acts as a reflector and affects the performance of resonant dipoles. Only when A1 is resonating at 28 GHz, the truncated ground needs to be used as a reflector to enhance directivity. Thereby, the length of the ground plane should be less than S1 but greater than diameter of coaxial feedline. The triangular ground patches can change routes of return current of A1 at 28 GHz, which strengthens the impedance matching of 28 GHz band without affecting that of 38 and 60 GHz. The fine-tuning elements consisting of the open stub, cut angle of bending structure and bending structure (see Fig. 1), are important to adjust and improve the impedance matching.
TABLE I

OPTIMIZED GEOMETRICAL PARAMETERS OF PROPOSED QUASI-YAGI ANTENNA.

<table>
<thead>
<tr>
<th>A1 (mm)</th>
<th>A2 (mm)</th>
<th>A3 (mm)</th>
<th>Other (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA1</td>
<td>4.517</td>
<td>LA2</td>
<td>2.504</td>
</tr>
<tr>
<td>W1</td>
<td>0.259</td>
<td>W2</td>
<td>0.305</td>
</tr>
<tr>
<td>a1</td>
<td>0.691</td>
<td>a4</td>
<td>0.709</td>
</tr>
<tr>
<td>a2</td>
<td>1.119</td>
<td>a5</td>
<td>0.184</td>
</tr>
<tr>
<td>a3</td>
<td>0.305</td>
<td>a6</td>
<td>0.144</td>
</tr>
<tr>
<td>S1</td>
<td>1.289</td>
<td>S2</td>
<td>1.268</td>
</tr>
<tr>
<td>D1</td>
<td>0.396</td>
<td>D2</td>
<td>0.296</td>
</tr>
</tbody>
</table>

The bowtie shaped edges of A1 arms effectively widen the bandwidth at 28 GHz, that is essential to reach the entire coverage of 5G frequency bands.

Following the matching order of 28 GHz, 38 GHz and 60 GHz, the bending structure contributes to the impedance matching adjustment of A3 while the bending structure with cut angle serves the same purpose for A2 driver. However, it is hard to enhance the impedance matching at 28 GHz. Thereby, the triangular ground patches and open stub are designed to reinforce the impedance matching at 28 GHz. Through numerous calculations, iterations and simulations, the optimal values of different structural parameters for the antenna geometry shown in Fig. 1 are summarized in Table 1.

III. RESULTS AND ANALYSIS

The proposed quasi-Yagi antenna is modelled and analyzed numerically using CST Studio Suite. The antenna performance is studied in terms of reflection coefficient, bandwidth, gain, efficiency, and radiation pattern in the mm-wave frequency range.

A. Reflection Coefficient ($S_{11}$) Response

The reflection coefficient response of the proposed antenna is shown in Fig. 4. It is evident from the plot that the proposed antenna possesses a very good impedance matching in the entire band of interest. The bandwidth covers the whole spectrum from 24 GHz to 70 GHz with strong resonances at 27 GHz, 42 GHz, and 63 GHz frequencies.

B. Antenna Efficiency

Figure 5 illustrates the radiation and total efficiency of the proposed quasi-Yagi antenna. The proposed design exhibits an efficiency of more than 70% in the entire mm-wave band of interest supporting the operation at 28 GHz, 38 GHz and 60 GHz frequency with minimum losses.

C. Antenna Gain

The antenna peak gain performance is shown in Fig. 6. The antenna realizes good gain values of 2.9 dBi, 6.3 dBi and 8.5 dBi, respectively, at the three frequencies of 28 GHz, 38 GHz and 60 GHz. Though slightly less at the lower frequencies, in most of the operating bandwidth the gain value is above 6 dBi (ranging from 37 GHz to 70 GHz). Nevertheless, the antenna offers a good peak gain for the ultra-wideband mm-wave operation for 5G and beyond networks.

D. Radiation Pattern

The radiation patterns of the proposed quasi-Yagi antenna at 28 GHz, 38 GHz and 60 GHz are presented in Fig. 7.
A quasi-Yagi antenna for ultra-wideband mm-wave operation has been designed and analyzed numerically in this paper. The proposed antenna makes use of a relatively simple structure and small size to offer a huge -10 dB bandwidth ranging from 24-70 GHz. The antenna employs a flexible LCP substrate to ensure human body conformity while achieving good radiation coverage, high gain (greater than 6 dBi in most of the operating bandwidth) and greater than 70% of efficiency. These features make the proposed antenna a good candidate solution for ultra-wideband operation for 5G and beyond systems working at mm-wave frequencies.

IV. CONCLUSION

A quasi-Yagi antenna for ultra-wideband mm-wave operation has been designed and analyzed numerically in this paper. The proposed antenna makes use of a relatively simple structure and small size to offer a huge -10 dB bandwidth ranging from 24-70 GHz. The antenna employs a flexible LCP substrate to ensure human body conformity while achieving good radiation coverage, high gain (greater than 6 dBi in most of the operating bandwidth) and greater than 70% of efficiency. These features make the proposed antenna a good candidate solution for ultra-wideband operation for 5G and beyond systems working at mm-wave frequencies.

ACKNOWLEDGEMENT

This work was supported by Innovative and Collaborative Research Grant under Pakistan UK Education Gateway (ICRG-2020) Project No. 310366 - Deforestation in Pakistan: Combating through Wireless Sensor Networks (DePWiSeN)).

REFERENCES


