A High Isolation, Low-Profile, Triple-Port SIW Based Annular Slot Antenna for Millimeter-Wave 5G MIMO Applications

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ABSTRACT This paper presents a compact, triple-port, millimeter-wave (mm-wave) substrate-integrated waveguide (SIW) based annular slot antenna. The presented antenna was fabricated on a single dielectric layer, 30 mil TLY-5 substrate with a standard PCB process. Measurement results show that, the proposed antenna can achieve better than 30 dB isolation between the ports at 28 GHz, thanks to carefully tuned distances between the ports and ∼90% radiation efficiency. Furthermore, it has 4.7 dBi and 8 dBi radiation gain at 28 GHz for single-port and double-port excitation cases respectively. Because of its easy integration and the high isolation between the ports, the presented antenna can be a promising candidate to be used as a monostatic simultaneous transmit and receive (STAR) antenna. In addition, depending on application, it can also be directly adopted to a 5G phased array system in either transmitter or receiver, without requiring physical modification.

INDEX TERMS 5G, high isolation, millimeter wave, MIMO, phased array, simultaneous transmit and receive (STAR), slot antenna, substrate integrated waveguide (SIW).

I. INTRODUCTION

To increase system capacity with higher spectrum efficiency, millimeter-wave (mm-wave) MIMO phased arrays will be deployed in the fifth generation (5G) wireless systems [1]. Designing mm-wave MIMO antennas has many challenges due to high gain and low mutual coupling requirements with a small size of the antenna structure. Recently, some works have focused on simultaneous transmit and receive (STAR) antennas. Among them, especially the monostatic STAR antennas can be strong candidates for MIMO systems due to their very small antenna size and high isolation properties. Different from bistatic architectures, in monostatic architectures, each antenna element is used for both transmit (TX) and receive (RX) [2], [3], [4]. Therefore, monostatic architectures are more spatially efficient than bistatic ones. In this context, [2] presents a wideband, co-horizontally polarized omnidirectional STAR antenna subsystem whereas [3] proposes a co-polarized STAR antenna with a thin single-layer substrate. Moreover, [4] discusses a STAR antenna based on a circular array of four half-wavelength dipole antennas. However, neither of the antennas presented in [2], [3], and [4] are at mm-wave frequencies.

Besides the STAR antennas, several multi-port antennas or antenna arrays have been proposed for 5G mm-wave MIMO systems [5], [6], [7], [8]. A tri-modal patch antenna is presented in [5]. However, this antenna requires additional fabrication steps for the multi-layer printed circuit board (PCB) process, which adds to the complexity of fabrication. Furthermore, the isolation between ports is not high enough compared to recently published ones. In [6], the authors proposed a substrate-integrated waveguide (SIW) based mm-wave antenna array for 5G base stations. This design requires a separate antenna element for each port,
increasing the overall size of the array. In [7], a compact dual-port SIW fed single element MIMO antenna is presented, but the proposed antenna has a limited bandwidth. In [8], a dual polarized broadband microstrip patch antenna was proposed, but parasitic patches are required to improve the bandwidth that increases the overall antenna size in this design.

In this paper, a triple-port, single element, mm-wave SIW based annular slot antenna is presented. The antenna structure is easy to fabricate compared to [2], [4], [5], and [6] since it has only a single dielectric layer. Furthermore, it has more compact size than [6], [7] due to its circular shape and adopting SIW as the transmission line type. The high isolation between the ports enables the proposed antenna to be compatible with 5G mm-wave in-band full-duplex (IBFD) systems as a monostatic STAR antenna. IBFD has attracted attention recently for its potential to theoretically double spectral density and system capacity of a wireless communications by allowing STAR to be on the same frequency at the same time [9]. The key challenge of IBFD systems is to achieve 90–120 dB isolation between the TX and RX signal paths [10]. Such high isolation cannot be attained with antenna design only. Additional self-interference cancellation (SIC) techniques should be deployed. Nevertheless, higher isolation attained in the antenna domain helps to ease the requirements of SIC in RF and digital domains [10], [11]. Different from the recent monostatic STAR antennas [2], [3], [4], the proposed antenna can operate at mm-wave frequencies. Moreover, any combinations of the three ports in this design can be assigned for TX and RX without requiring any physical modification. Additionally, the proposed antenna can also be applied in a 5G MIMO phased array system for TX-only or RX-only purposes. The presented antenna was fabricated on 30 mil TLY-5 substrate (\(\varepsilon_r = 2.2, \tan\delta = 0.0009 \) @10 GHz) with a standard PCB process. The maximum measured gain is 4.71 dBi and 8 dBi for single port and two ports excitation cases, respectively, with a radiation efficiency of 88.78%. Finally, the smallest 10 dB bandwidth is 0.55 GHz between 27.5–28.05 GHz where the envelope correlation coefficient is smaller than 0.002.

The rest of the paper is organized as follows. In Section II, the design procedure and considerations of the proposed antenna are discussed in detail. The measurement results and discussions are presented in Section III. Finally, conclusions are drawn in Section IV.

II. ANTENNA DESIGN

The proposed antenna structure consists of a circular SIW structure with periodic slots as shown in Figure 1. As the first task of the design procedure, the dimensions of the SIW should be determined.

A. SIW DESIGN

SIW is chosen as the transmission line because of its easy integration while the antenna can be highly isolated from the other circuits on the same substrate. SIW consists of two parallel metal plates connected by two rows of conducting cylinders whose width can be calculated with the equation given in (1) for TE\(_{10}\) mode excitation at 28 GHz [12].

\[
as_{SIW} = \frac{c}{2f_c \sqrt{\varepsilon_r}} + p \left( 0.766 e^{0.4482 d/p} - 1.176 e^{1.214 d/p} \right)\]

where \(d\) is the the diameter, \(p\) is the pitch of the via, \(c\) is the speed of light, \(f_c\) is the waveguide cut-off frequency for TE\(_{10}\) mode and \(\varepsilon_r\) is the relative dielectric permittivity. For the proposed antenna design, \(d\) and \(p\) are 1 mm and 1.5 mm, respectively. The initial value of the SIW width is set using (1) and after the optimizations made in Ansys HFSS, 6 mm is determined as the final dimension. Figure 2 indicates the field distribution within the resulting SIW and also points out that only TE\(_{10}\) mode is excited.

The next step after setting the width is to decide the length of the circular SIW. For this, all the ports must be placed first and then the distance between them should be adjusted accordingly. After locating the ports as shown in Figure 1, to achieve a high isolation between port 1 - port 2 and port 1 - port 3, the distance between each is set to \(m\lambda_{28}/4\),
B. SLOT ANTENNA DESIGN

In [13], how the slot dimensions and the offset from the center line affect the performance of a slot antenna operating at 9.375 GHz is analyzed thoroughly. Based on this analysis, the initial slot dimensions and offset from the center line in this design are adjusted by scaling the dimensions with the frequency. After the initial slot sizes and location are determined, several trials with different number of slots are carried on to find the optimum number of slots that meet the spacing requirement discussed in the previous section. First, 8 slots are tested. The optimum slot sizes, deviation from the center line and position of the first slot are set by Ansys HFSS simulations. According to the optimization results, to achieve both the best isolation between ports and the best impedance matching at 28 GHz simultaneously, the length of the circular SIW is consequently set to 59.2 mm where \( \lambda_e \) approximately equals to 9 mm at 28 GHz.

It is worth to mention that the location of the antenna slots is another design parameter. To find the optimum slot locations, two different coordinate systems are used as shown in Figure 3: x'- and y'-axes are used for placing the ports and x-axis and y-axis are adopted for locating the slots. As can be seen in the figure, Port 2-Port 3 are symmetric around y-axis, and the slots can be placed with a rotation angle of \( \phi \) between the two coordinate systems. The optimum \( \phi \) can be found with Ansys HFSS simulations. According to the optimization results, to achieve both the best isolation between ports and the best isolation performance. Through this high isolation between the ports, it confirms that all the cases can result in a good isolation between port 2 - port 3 with 8 slots is 17.77 dB, which is lower than that presented in the state-of-the-art publications. Therefore, the number of slots is increased to 12, and the optimization procedure is repeated. Based on the simulation results, the isolation between port 2 - port 3 can be made better than 40 dB by increasing the number of slots. Higher isolation can be attained with further increasing the number of slots. However, in order not to increase the size of the antenna further, the number of slots is set to 12. In this case, the optimum antenna slot width and length for the array are determined as 0.7 mm and 4.74 mm, respectively. Considering the above discussions, the length of the circular SIW is consequently set to 59.2 mm where \( \lambda_e \) approximately equals to 9 mm at 28 GHz.

C. PERFORMANCE ANALYSIS

To investigate the isolation performance of the antenna, the surface current distribution is evaluated for different port excitation cases, the results of which are shown in Figure 4. And it confirms that all the cases can result in a good isolation performance. Through this high isolation between the ports, the proposed design is suitable for application as a monostatic STAR antenna. Besides, any combinations of the three ports can be used for TX or RX without requiring any physical modification. However, note that feeding signal should have a...
suitable phase for higher gain and therefore, higher radiation efficiency. For instance, if port 2 and 3 are set for TX, out-of-phase signals should be provided to these ports as the physical difference between them is $m\lambda_g/2$, which corresponds to 180°.

To further investigate the proposed antenna performance, the equivalent circuit model depicted in Figure 5, is studied using the optimization toolbox of Keysight ADS. As can be seen in Figure 6 and Figure 7, a good agreement is obtained between the equivalent circuit model and the 3D simulations.

III. MEASUREMENT RESULTS AND DISCUSSION

The proposed antenna was fabricated on 30 mil TLY-5 substrate with a standard PCB process. Figure 8 shows the photos of the top and bottom layer of the fabricated antenna.

A. S-PARAMETER MEASUREMENT

S-parameters were measured with Agilent E8361A PNA. SOLT calibration was performed with Agilent 85056A calibration kit. Figure 9 presents the measured matching and isolation performance of the fabricated antenna with the Southwest connectors connected to each port. The comparison between measurement and simulation results that show
FIGURE 9. Measured (a) matching and (b) isolation performance of the fabricated antenna with the connectors included.

good agreement can also be found in Figure 9. According to the measurement results, the isolation between all the ports is better than 15 dB between 25 and 30 GHz and is better than 30 dB at 28 GHz. The largest bandwidth is obtained by the second port which provides return loss higher than 10 dB between 26.58 and 30.5 GHz. On the other hand, port 1 has the smallest bandwidth between 27.5 and 28.05 GHz with return loss better than 10 dB.

B. FAR-FIELD MEASUREMENT

Figure 10 illustrates the radiation pattern measurement setups used for only port 1 excitation and port 2–3 excitation with out-of-phase signals cases. For this measurement, a planar balun fabricated with a standard PCB process was used to provide out-of-phase signals to ports 2 and 3. At 28 GHz, the phase difference between the balun output ports is 179.2° which is very close to theoretically calculated required 180° phase difference for port 2 and 3 excitation. The normalized radiation patterns of the designed multiport antenna, measured and simulated in two different planes at 28 GHz, are shown in Figure 11. The difference in the radiation patterns between the single port and two-port excitation cases is due to the altered surface current distribution in these two cases, which can be seen in Figure 4(a) and Figure 4(d). In terms of antenna gain, the maximum measured gain is 4.71 dBi for single port excitation case while the expected antenna gain is 4.9 dBi. Furthermore, the maximum measured gain is 8 dBi for two port excitation case where the expected antenna gain is 8.2 dBi.

FIGURE 10. Radiation pattern measurement setups of the (a) port 1 only excitation and (b) port 2–3 excitation cases.

One of the methods that can be used for finding the antenna radiation efficiency is based on estimating the directivity of the antenna with the measured far-field patterns in the two principal planes. For planar arrays, directivity can be estimated with the following equation [19]

\[ D_0 \approx \frac{32 \times 400}{\Theta_{1d} \Theta_{2d}} \]  

where \( \Theta_{1d} \) and \( \Theta_{2d} \) are the half power beamwidths in the two principle planes. However, (3) is valid for a pattern that has only one major lobe and any minor lobes. Again in [19], it is suggested that the maximum directivity value for a pattern with two identical main lobes calculated using (3) will be twice the actual value. Based on this information, the directivity of the antenna was estimated. Then, using the calculated directivity and the measured gain values, the radiation efficiency was evaluated as 88.78% where as the simulated radiation efficiency is 96.1%.

C. MIMO PERFORMANCE

To examine the diversity performance of the proposed design, envelope correlation coefficient (ECC), which gives the correlation between received signals, was evaluated. In [20], it has been demonstrated that ECC calculated using S-parameters yields sufficiently accurate results even the radiation efficiency is as low as 80%. Therefore, the S-parameter approach was adopted for the calculation of ECC, as the estimated efficiency of the proposed antenna is
TABLE 1. Performance comparison with recent antennas in the literature.

| Reference       | Structure                    | Frequency (GHz) | Element Number | Number of Ports | BW (GHz) | Isolation (dB) | Gain (dBi) | ECC    | Size (mm^3) | Number of Dielectric Layers |
|-----------------|------------------------------|----------------|----------------|-----------------|----------|----------------|------------|--------|-------------|-----------------------------|
| [5] AWPL’22     | Tri-Modal Patch              | 27.2           | 1              | 3               | 1.44     | >15            | 4.5        | <0.011 | 5.3 x 5.3 x 1.3* | 5                           |
| [6] TAP’22      | SIW Based Slot-Coupled Strip | 28             | 12             | 8               | 4        | >20            | 14.3       | Not available | 97 x 141 x 1.239 | 3                           |
| Access’21       | Air-Filled Slot              | 28             | 1              | 2               | 0.4      | >20            | 6.9        | <0.05  | 33 x 27.5 x 0.76 | 1                           |
| [8] Access’21   | µstrip Patch                 | 28             | 4              | 2               | 6        | >30            | 11         | <0.017 | 29.8 x 4.4 x 1.07 | 1                           |
| [14] TAP’20     | Substrate Integrated Dielectric Resonator | 28   | 2              | 2               | 8.1      | Not available     | 8.15       | Not available | 26.4 x 13.2 x 1.524 | 2                           |
| [15] Access’20  | Patch + Metasurface          | 27.5           | 4              | 4               | 6.4      | >30            | 11         | 0.015  | 20.4 x 20.4 x 0.51 | 1                           |
| [16] Electronics’20 | 1 x 2 Patch with Defected Ground Array | 28 | 8              | 4               | 4.1      | >17            | 8.02       | <0.01  | 30 x 35 x 0.76  | 1                           |
| [17] AWPL’19    | Dielectric Resonator         | 28             | 2              | 2               | 0.85     | 24             | 9**        | 0.013  | 20 x 20 x 2.54  | 2                           |
| [18] Access’19  | Fabry-Perot                  | 28             | 4              | 4               | 7        | >25            | 14.1       | <0.008 | 19 x 19 x 7.608 | 2                           |
| This Work       | SIW Based Air-Filled Slot    | 28             | 1              | 3               | 0.55     | >30            | 4.71***    | <0.002 | 26 x 26 x 0.76  | 1                           |

* Only the size of the radiator. ** Estimated from plot. *** Excitation from only 1 port. For two port excitation, the measured gain is 8 dBi.

FIGURE 12. Measured envelope correlation coefficient.

88.78%. Ideally, ECC for an uncorrelated diversity antenna equals to zero but in practice, it should be less than 0.5. The measured ECC is presented in Figure 12, which confirms that it is very close to zero in the band of interest.

D. PERFORMANCE COMPARISON

Table 1 summarizes the performance of the proposed multi-port antenna and compares it with state-of-the-art publications. Among all, [5] and the proposed antenna have the maximum number of ports per unit element. However, the proposed antenna provides higher isolation between the ports which decreases the ECC and also makes it more convenient for STAR antenna implementation. Furthermore, the proposed design has only 1 dielectric layer while [5] has 5 dielectric layers. Therefore, this high number of dielectric layers in [5] inevitably results in a more challenging and costly fabrication.

In terms of the antenna gain, [7] has the highest gain per unit element. However, it should be emphasized that the gain for the proposed antenna can be increased up to 8 dBi with 2 ports excitation instead of 1 port. On the other hand, the proposed antenna can offer higher gain than [5], which has the closest port–unit element configuration, even with a single port excitation. Also, with the 2 port excitation, the proposed antenna can achieve a similar antenna gain as [14], [16]. But the antennas demonstrated in [6], [8], [15], [17], and [18] still have higher gain than the proposed antenna. At this point, it should be noted that these are antenna arrays, not a single antenna element. Likewise, the proposed antenna element can also be used in an array design, which may come with similar or higher gains. Furthermore, higher antenna gain can also be achieved by increasing the number of slots if required. Yet, this will also increase the antenna size.

IV. CONCLUSION

This paper proposes a compact, single-layer, triple-port, mm-wave SIW slot antenna suitable for standard PCB operation. The proposed antenna was fabricated on 30 mil TLY-5 substrate with a standard PCB process. At 28 GHz, the antenna gain is 4.71 dBi for single port excitation and 8 dBi for 2 port excitation. Furthermore, the measured isolation between the ports is higher than 30 dB. Thanks to this high isolation obtained, the proposed antenna becomes suitable for 5G mm-wave IBFD MIMO systems to be implemented as a monostatic STAR antenna. Moreover, the proposed antenna is applicable to a 5G phased array system for only TX or RX purposes. Therefore, depending on the application, it can be used as a STAR, only TX or only RX antenna.
within the same system without requiring any physical modification.

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