1. Introduction

The tremendous growth and advancement of wireless communication networks have increased the demand for high quality and capacity networks for wireless users and applications. The 4G mobile communication system has largely two limitations: time and location. These limitations can be overcome by the new 5G technology [1]. Fifth-generation telecommunication systems are operating from 30–300 GHz frequency band of mm-wave whose wavelength is low, i.e. 1–100 mm so; antenna with highly directional and steerable characteristics could be used in different aspects [2,3]. For 5G systems, researchers are quite inclined to the band of frequencies 73, 60, 38, and 28 GHz. Most of the researchers focus on the frequency bands of 28 and 38 GHz because, at these bands, atmospheric absorption, rain attenuation, and losses are low compared to higher frequency bands [4,5]. A dual-band mm-wave antenna is preferred as the most important component of the millimeter-wave system which can transmit and receive simultaneously. To adjust the path losses because of the absorption of oxygen particles, the high gain antenna is primarily recommended in the mm-wave band [6,7]. It requires designing an antenna array at mm wave frequencies to resolve the issue of path losses and to achieve high gain.

There are many practical problems, such as high manufacturing cost, heavy weight, and increased size, while designing an antenna. Micro-strip antennas are popular for the merits such easy integration, low cost, and low profile with active circuits, but the main problems with micro-strip antennas are surface wave loss, severe dielectric and conductor losses, narrow bandwidth, and improper radiation [8]. Nowadays, new promising technology, substrate integrated waveguide (SIW), is introduced to overcome shortcomings of the antenna designs such as the gain, bandwidth, and radiation efficiency. The SIW, developed by K. Wu [9], is good at integrating the millimeter-wave circuits with high density. The SIW technique is grounded on the theory of substrate integrated circuits (SICs), i.e. the non-planar structure converted into the planar structure [10]. The SIW is similar to the structure in which the integration of a waveguide into planar form with two lines of metallic holes or vias inserted in the dielectric substrate [11]. During the fabrication of SIW design, metalized holes are drilled on the substrate by mechanical and laser drill, and this process requires low production cost.

Different SIW antennas at mm-wave are discussed and compared in [12,13]. Slotted SIW antennas are used to achieve better results in context of the radiation pattern, high gain, bandwidth, efficiency, etc. In paper [14], for 5G communication a slotted SIW antenna array is presented with two transverse slots. By inserting slots in the presented design there is an improvement in the return loss and a good radiation pattern is achieved. A single- and two-slot millimeterwave antenna using the SIW technique is presented in the paper [15]. From the simulation results, it is observed that by increasing the number of slots the antenna gain is improved. Recently, plenty of SIW antennas were proposed at bands 28 and 38 GHz frequency [16–21].
This article introduced a SIW antenna operating at dual-band frequencies of 28 and 38 GHz. The SIW technique is used to design a single element and to improve the operation of the antenna two longitudinal slots are inscribed in the plane. To acquire high gain, a (1 × 4) array of an antenna with four elements is configured. A feeding network based upon micro-strip line feed is utilized to agitate the SIW array elements. The architecture of the proposed work is as follows. In Section 2 a design of single-element and four-element array antenna using the SIW technique is introduced. The simulation results of both the designs are presented and discussed in 3 section followed by Section 4 that concludes the paper.

2. Design of SIW antenna

2.1. Single-element design

The design method of the developed SIW antenna is introduced and discussed with their simulation results in this section. Figure 1 indicates the single-element SIW antenna design. The SIW design is integrated with two lines of metallic via or holes on a substrate and it supports only $TE_{10}$ modes. The TM mode does not propagate from the SIW because the current flow, along with conducting vias, is discontinued [22]. In the proposed design, there are two slots engraved on the conducting plane to excite dual-band characteristics at 28 and 38 GHz frequency bands. To excite the proposed antenna, a conventional micro-strip line has been used as a feed network [23]. Micro-strip line and SIW are integrated on the same substrate with the gap near the transition section for impedance matching. It is called micro-strip to SIW transition [24]. In this design a modified feeding network is developed to improve the impedance matching so that a round gap is created near the feeding part, as shown in Figure 1(a).

The SIW width is denoted by $W_{SIW}$, $d$ represents the vias diameter and two vias are set apart by a longitudinal distance $D$. To calculate the equivalent width of the SIW empirical equation is shown as follows [22]:

$$a_{SIW} = w_{SIW} - 1.08 \frac{d^2}{D} + 0.1 \frac{d^2}{w_{SIW}}$$  \hspace{1cm} (1)

To select vias diameter and distance between vias the following condition should be considered to minimize the losses:

$$D < 2d, \frac{\lambda_g}{5} < d$$  \hspace{1cm} (2)

For the proposed antenna design, the vias diameter ($d$) is 0.5 mm, also the space among the two nearby vias ($D$) is 1.0 mm, complying with $D/d < 2.5$ [22]. The said structure is formulated using Rogers RT/duroid substrate material whose loss tangent $\tan \delta$ is 0.003, dielectric constant $\varepsilon_r$ is 2.2, and width is 0.254 mm.

Table 1. Dimensions of the single-element SIW design.

| Parameters | Dimension (mm) | Description |
|------------|----------------|-------------|
| $L$        | 30.00          | Substrate length |
| $W$        | 7.50           | Substrate width |
| $L_1$      | 6.54           | Length of the first Slot |
| $W_1$      | 0.70           | Width of the first Slot |
| $L_2$      | 4.22           | Length of the second Slot |
| $W_2$      | 0.17           | Width of the second Slot |
| $L_t$      | 6.10           | Transition section length |
| $W_t$      | 3.00           | Transition section width |
| $L_f$      | 3.50           | Feed line length |
| $W_f$      | 0.75           | Feed line width |

Table 2. Dimensions of the SIW array antenna.

| Parameters | Dimension (mm) | Description |
|------------|----------------|-------------|
| $L_a$      | 45.56          | Substrate length |
| $W_a$      | 30.00          | Substrate width |
| $L_f$      | 9.00           | Centre Feed line length |
| $W_f$      | 0.75           | Centre Feed line width |

Figure 1. Structure of the dual-band slotted SIW single-element antenna (a) view from the top and (b) view from the bottom.

Figure 2. Four-component SIW antenna array at 38 and 28 GHz frequency.
shunt conductance in a transmission line can be utilized directly to present the long slot inside the planar surface of an air-filled rectangular waveguide [25]. For a filled rectangular waveguide, the single slot normalized resistance is calculated by [26]

\[
R = \frac{8\pi w L}{\lambda_0^3 \lambda_g} \times \left[ 1 - \left( \frac{2L_1}{\lambda_g} \right)^2 \right]^2 \left[ \frac{1}{\sin^2 \left( \frac{\pi x}{w} \right)} \right. \\
\left. \cos^2 \left( \frac{\pi L_1}{\lambda_g} \right) \right]
\] (3)

where free space is represented by \( \lambda \), the guided wavelength is \( \lambda_g \), \( x \) is the slot offset from the centreline of a rectangular waveguide, and \( L_1 \) is the slot length. This design consists of two slots and each slot is working on different frequency. The length of slots is selected according to the operating frequency. Slot \( L_1 \) is working for the frequency of 28 GHz and slot \( L_2 \) is working for the frequency of 38 GHz. In the design, for slot \( L_2 \) the gap between the closing face and the last slot is taken as \( \lambda_g / 4 \) because at this distance the forwarded and reflected signals from ending phase are superimposed with the phase shift of 360° at the centre of slot; this provides good radiation and gain. Similarly, for slot \( L_1 \) the distance between the centres of two slots is half of the guided wavelength i.e. \( \lambda_g / 2 \). The dimension of all the parameters of the proposed design is depicted in Table 1.

### 2.2. Antenna array (1 \times 4) design

Figure 2 depicts the four-component dual-band slotted SIW linear array antenna. Table 2 summarizes the dimensions of all the parameters in an array structure. By using the proposed array structures and feeding technique, we can improve the parameters such as gain, efficiency, and directivity that might not be easy with a single-element antenna.

In this paper, a feeding network, using corporate feed with a two-stage power divider, is devised to excite the array elements. The corporate feed network gives a power division of \( 2^k \) (where \( k = 2, 4, 8, 16 \ldots \)). It provides equal power distribution to all the elements of the array [8]. In this corporate feed network, a quarter-wave transformer is used to avoid impedance mismatch. The input impedance for the proposed power divider is 50 Ω.

Figure 3 shows the prototype of fabricated antenna array with four elements and power divider network.

**Figure 3.** Fabrication prototype of four-component dual-band SIW antenna array at 38 and 28 GHz frequency.

**Figure 4.** Return loss (S11) for the single-element antenna.
Figure 5. At 28 and 38 GHz single-element radiation efficiency.

Figure 6. Radiation pattern for the single-element antenna at the frequency band of 38 and 28 GHz (a) E-plane and (b) H-plane.
The proposed design is tested by measuring parameters, such as return loss and antenna efficiency. The measured and simulated results for the proposed array are presented in the next section.

3. Results and discussion

The results for both single-element and antenna array structures are discussed in this section. For simulation and numerical analysis of the proposed antenna structure, the CST Microwave Studio (2018) software is used.

3.1. Results of single element

Figure 4 represents the reflection coefficient (S11) graph for a single-antenna element for 38 and 28 GHz. The return loss for the 28 GHz frequency band is $-19.00$ dB, and impedance bandwidth is 0.99 GHz. For the 38 GHz band, the return loss and impedance bandwidth
Figure 9. Far-field directivity polar plot at (a) 28 GHz (b) 38 GHz.

Figure 10. Antenna array radiation pattern at (a) E-plane (b) H-plane.
are −20.753 dB and 0.41 GHz, respectively. Figure 5 shows the radiation efficiency of the said design for the dual band. The efficiency of the single-element antenna achieved at 28 GHz is 94.90% and at 38 GHz is 89.16%.

Figure 6 represents the radiation diagram for the E and the H planes for the design comprising a single-element SIW antenna. The degrees of cross-polarization with the E plane and the H plane are below −25 dB. The developed design of a single element achieves a directive gain of 11.2 dBi at 38 GHz and at 28 GHz band, the directive gain is 7.2 dBi.

### 3.2. Results of SIW antenna array

For the antenna array the simulated and measured results in terms of return loss and efficiency are presented to validate simulation results and to verify the antenna design specification. The measured and simulated results for the proposed antenna are approximately matched and there are some deviations in results due to fabrication and measurement discrepancies.

Figure 7 shows the return loss or S11 parameter at both 28 and 38 GHz for an array. It is observed that the achieved simulated return loss is below −10 dB for both the upper and lower bands of frequency. The achieved impedance bandwidth at 28 GHz is 0.5 GHz (27.6 GHz to 28.1 GHz) and at 38 GHz it is 0.79 GHz (37.9 GHz to 38.69 GHz). The measured return loss shows −10 dB impedance bandwidth ranging (27.9–28.0 GHz) and (38.0–38.5 GHz) for 28 and 38 GHz bands, respectively.

Figure 8 represents the simulated performance efficiency of the array antenna which is 90.48% and 83.78% at 28 and 38 GHz, respectively. The measured efficiency for 28 GHz is 87.51% and for 38 GHz it is 87.01%.

Figure 9 shows the far-field directivity plot at both 28 and 38 GHz bands of frequency. Figure 10 shows the E and H plane radiation diagrams of radiating elements of the SIW array antenna. From the far-field diagram, it is observed that the accomplished gain at 38 GHz is 15.5 dBi and 12.7 dBi at 28 GHz.

Figure 11 demonstrates the distribution of the electric field of the SIW slotted antenna at both 38 and 28 GHz bands of frequency. From the electric field distribution, we can analyse power distribution in power divider lines which are equally divided into four ports with perfect phase matching so that there is no time-delay and power reaches each input at the same time from the main port and excites the 28 and 38 GHz band. Figure 11(a) represents the variation of the electric field for the designed array antenna at 28 GHz with 180° phase. In the array structure, the electric field distribution is maximum for the longer slots and negligible at shorter slots. Similarly, in Figure 11(b) the shorter slots excite the 38 GHz band. Therefore, maximum electric field distribution is at shorter slots and minimum at longer slots.

| Ref. | Frequency (GHz) | Gain (dBi) | Efficiency (%) | Substrate |
|------|----------------|-----------|----------------|-----------|
| [14] | 28             | 10        | –              | Rogers RT5880 |
| [19] | 28, 38         | 10, 10.2  | 75.75, 70.65   | RT/duroid 5880 |
| [21] | 28, 38         | 11.8, 14.3| 66, 72         | RT/duroid 5880 |
| [27] | 28, 38         | 11.9, 11.2| –              | RT/duroid 5880 |
| [28] | 28             | 10        | –              | FR408HR |
| This work | 28, 38     | 12.7, 15.5| 90.48, 83.78   | Rogers RT5880 |

The comparison of various SIW array antennas is represented in Table 3 with the developed structure. The main concern with the cited research is the design complexity with low efficiency and low gain. The proposed design maintains the performance in terms of gain and efficiency for both single element and array design at the lower and upper bands. Moreover, in this work the E-field distribution for both 28 and 38 GHz shows that the power distribution is equal at each port of the antenna array.

### 4. Conclusion

A dual-band slotted SIW single-element antenna and (1 × 4) antenna array with micro-strip to SIW transition has been presented in this paper. A four-element antenna array is designed to improve antenna performances such as gain, side-lobe levels, and efficiency. For
impedance matching the gap is created near the transition section. This antenna array includes the frequency bands of 28 GHz with a bandwidth of (27.6–28.1 GHz) as well as 38 GHz with a bandwidth of (37.9–38.69 GHz). For both frequency bands, cross-polarization levels are less than −25 dB. Taking all these into consideration, the proposed design has been fabricated and tested for the validation of simulation results. The high gain and dual-band antenna array has great potential and could be widely used in 5G communication in the coming years.

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