Wideband Cavity-Backed Slot Subarray Fed by Gap Ridge Waveguide for 5G mmWave Base Station

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Index Terms— Gap Waveguide, Slot Array, 5G, Millimeter Wave

1. Introduction

5G communication systems are envisioned to provide Gbps peak data rates to multiple users simultaneously. To realize this arduous vision, moving toward the millimeter-wave (mmWave) spectrum offering unprecedented unlicensed bandwidth has gained the support from governments, the industry and academia. High-gain beam antennas are required to compensate for the high propagation path loss in the mmWave bands. To this end, numerous antenna designs employing substrate integrated waveguide (SIW) technologies [1, 2] as well as the waveguide-fed slot arrays [3, 4] have been presented. However, in the case of SIW, the proposed antennas suffer from high losses due to the presence of a dielectric substrate. Moreover, the radiation efficiency can be deteriorated and leakage can occur since transmission line design at this frequencies is more sensitive to the proper design of via holes that are prone to providing deficient shielding [5]. While waveguide-fed slot arrays manage to resolve the problem with the SIW technology, the key challenge of these waveguide-fed antennas is that they require a good electrical contact between the feeding and the radiating layers [6]. Hence, a much more complex manufacturing process is required to ensure good electrical contact among the layers incurring in high fabrication costs.

A solution overcoming the problems of unsatisfactory electrical contacts as well as the problems due to the mechanical assembly of a waveguide-fed slot array can be found in the recently introduced gap waveguide technology [7]. Gap waveguide technology is designed using the periodic artificial magnetic conductor (AMC) to control the propagation of waves in the desired directions between two PEC plates, i.e., propagation is allowed in certain directions while it is suppressed in others [8, 9]. Indeed, by introducing an air gap with a size of...
smaller than $\lambda/4$ between the PEC-PMC plates, no waves can propagate in between the PEC-PMC parallel plate structure.[8]. Recently, several gap waveguide-fed array antennas have been developed at the mmWave band. However, these antennas usually support a bandwidth of around 15 – 20% [9, 10, 11]. One of the recently proposed techniques to enhance the bandwidth performance of the gap waveguide-fed array antenna is to increase the number of tuning pins in the cavity layer to provide more capacitive tuning on the cavity layer leading to a wider impedance bandwidth matching [12]. This technique has resulted in a bandwidth of around 30%. However, the main drawback of the proposed solution is that the dimensions and the positions of the additional tuning pins are fully determined through numerical simulations [12], which requires heavy computational burden. Furthermore, the additional pins also result in a higher fabrication costs which is unfavorable for the industrial fabrication of the antennas. In this paper, we propose an alternative solution for the bandwidth enhancement of the cavity backed slot array antenna fed by gap waveguide without the need of adding any additional tuning pins in the cavity layer.

2. Antenna Design

Fig. 1 illustrates a view of the proposed slot array unit cell in perspective. The proposed structure comprises 3 layers. The top, radiating layer is designed as a $2 \times 2$ configuration of radiating slots. These radiating slots are backed by an air-filled cavity in the middle layer. The bottom layer is the feeding layer, which design is based on the gap waveguide technology. The unit cell dimension of the proposed subarray is $18.3 \times 19 \text{ mm}^2$ in the E-plane and the H-plane, respectively. A single slot has the dimensions of $3.6 \times 6.4 \text{ mm}^2$. The distance between every two slots in x- and y-directions are $9.15 \text{ mm}$ and $9.5 \text{ mm}$, respectively. Both distances in x- and y-directions are less than one wavelength of the 31.25 GHz to avoid high grading lobes. In the conventional cavity-backed slot array antenna, a rectangular slot is used. The main function of this rectangular coupling slot is to maximize the energy coupled from the feed gap waveguide into the cavity layer [6]. Therefore, in this paper, we propose to modify the rectangular slots (RSL) into a ‘bow-tie’ shaped slot (BTSL) for bandwidth enhancement. By replacing the RSL with the BTSL, the coupling slot behaves like a double-ridge slot. This feature allows the cut-off frequency in the dominant modes to shift into a higher frequency and the resonant frequency of the next higher order modes is altered to a lower frequency. In addition, the T-shaped cavity tuning pin is used for impedance matching and suppressing higher order modes. Hence, by proper modification of the coupling slot and the cavity tuning pin, the bandwidth performance of the subarray antenna has been improved.

![Figure 2: Comparison of the simulated reflection coefficient $S_{11}$ of the conventional rectangular cavity slot (RSL) and modified bow-tie cavity slot (BTSL). $f$ is the frequency.](image-url)
Figure 3: Simulated radiation patterns of the proposed unit cell slot array antenna at (a) E-plane, and (b) H-plane at various frequencies $f$, where $G_0$ is the antenna gain in dBi, $\theta$ is the polar angle in degrees.
3. Simulation Results

The simulation and optimization of the proposed unit cell subarray has been performed using the Computer Simulation Technology (CST) software. The simulations have been performed assuming the infinite array model with periodic boundary conditions. The $2 \times 2$ slot subarray is excited by a waveguide port at the ridge gap waveguide in the bottom feeding layer. Fig. 2 illustrates the comparison of the simulated reflection coefficient of the proposed unit cell subarray with conventional RSL and the modified BTSL in the cavity layer. As can be seen, the conventional RSL has a $-10$ dB relative bandwidth of 20.6% ($24 - 29.5$ GHz), which has been considerably improved to the relative bandwidth of 27% ($24 - 31.5$ GHz) by using the modified BTSL in the cavity layer.

Fig. 3 illustrates the normalized far-field gain of the proposed unit cell slot array simulated over the operating bandwidth at $24 - 31.5$ GHz for the E-plane and the H-plane in subplots (a) and (b), respectively. The simulated gain of the proposed unit cell slot array is around 15.6 dBi at the center frequency of 27 GHz. The radiation patterns at the E- and H-plane of a $16 \times 16$ comprising $4 \times 2$ slot subarrays are computed and shown in Fig 4. As can be seen, the side-lobe-level of the $16 \times 16$ array is low which is below $-15$ dBi for both E- and H-planes.

Fig. 5 shows the computed directivity of the proposed slot array antenna with $16 \times 16$ elements array antenna over $24 - 31.5$ GHz. At center frequency of 27.5 GHz, the directivity is around 33.8 dBi.

4. Conclusion

A numerical design of a $2 \times 2$ unit cell slot subarray based on the ridge gap waveguide feeding operating over $24 - 31.5$ GHz is presented. The design covers the entire proposed mmWave spectrum for 5G communications. We proposed a modification to the conventional rectangular slot in the cavity layer using a bow-tie shaped coupling slot for the purpose of bandwidth enhancement. By modifying the coupling slot in the cavity layer, the $-10$ dB relative bandwidth of the proposed slot array antenna has been increased from 20.5% to 27%. The proposed unit cell slot array shows a high directivity of 15 dBi at the centre frequency of 27.5 GHz. The radiation pattern of the designed $16 \times 16$ slot array comprising eight $2 \times 2$ slot subarrays is also computed. The directivity at 27.5 GHz is approximately 33.8 dBi. Moreover, the side-lobe-level of the $16 \times 16$ slot array antenna is less than $-15$ dBi over the operating bandwidth. The proposed unit cell is a promising subarray element for a fixed beam array antenna. In future work, we will further investigate the bandwidth improvement by combining the addition of more tuning pins and our proposed modifying the cavity coupling slot solution.

Acknowledgment

This project has received funding from the European Unions Horizon 2020 research and innovation programm under the Marie Sklodowska-Curie grant agreement No. 766231 WAVECOMBE H2020-MSCA-ITN-2017.

References


Figure 4: Computed radiation patterns of the proposed 16 × 16 slot array antenna for (a) E-plane, and (b) H-plane at various frequencies. $D_0/D_{\text{max}}$ denotes the normalized antenna gain in dBi and $\theta$ is the polar angle in degrees.
Figure 5: Computed directivity $D_0$ of the designed $16 \times 16$ slot array antenna as a function of frequency $f$. 