A Dielectric-Loaded Waveguide Aperture Antenna Based on Waveguide-Fed Cavity-Backed in the 60-GHz Band

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***Abstract*—In this paper, a 4×4-element waveguide-aperture array antenna is designed for applications in the 60 GHz band. To simplify the design process of the feed network, instead of using a conventional waveguide power divider, an efficient approach is proposed where the antenna is fed with two layers of back cavities to distribute power uniformly among the array aperture. The connection between cavities is obtained by a set of coupling slots. A standard WR-15 rectangular waveguide is designed to excite the antenna at the input port over the operating frequency. Furthermore, to improve the antenna gain characteristics and reduce size, array aperture is loaded with a dielectric plate. The most significant advantage of using this design is its efficient radiation patterns and the ability to decrease complexity of feeding network. Simulated results demonstrate that the antenna gain is larger than 25 dB over the frequency range from 58 to 64 GHz. This high gain antenna combined with the simplicity of feeding network is greatly advantageous to millimeter wave applications.**

***Index Terms*—Cavity-backed, waveguide aperture, high-gain, millimeter-wave.**

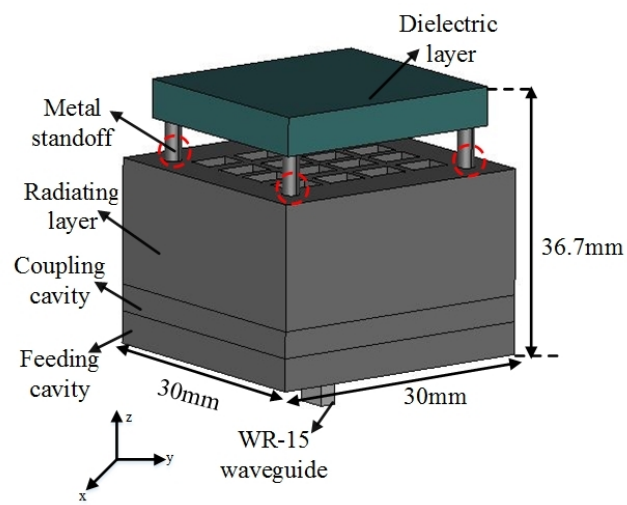


Fig. 1: 3-D view of the proposed antenna.

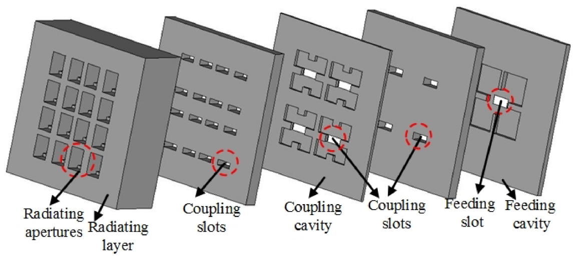
I. Introduction

In recent years, millimeter wave (mm-wave) wireless technology is considered as an attractive field for the next generation of wireless communication systems. With the growing demand for mm-wave wireless systems, there has been significant interest in designing RF components and antennas in mm-wave spectrum. However, mm-wave frequencies suffer from high path loss, which creates the needs for a new class of antenns for this band to overcome this loss [1]. Design requirements for such antennas include highly directional pattern with high radiation efficiency. Antennas with high gain property produce very directive narrow beam that can overcome severe path loss at mm-wave frequencies. Based on this demand, planar array antennas such as microstrip and substrate integrated waveguide (SIW) antennas are among the most common low-profile and low-cost choice for high gain applications. However, their excessive losses, due to a large feed network, and limited bandwidth limits their application at mm-wave frequencies [2]–[6]. Antennas based on metallic hollow waveguides on the other hand, have larger bandwidth and lower losses at mm-wave frequencies. Recently, high gain multi-layer cavity-backed waveguide-based antennas have been a subject of extensive research at mm-wave frequencies [7]–[10]. Multi-layer structures enhance the freedom within the design process which in turn improves antenna performance in terms of bandwidth and radiation characteristics. The key challenge of using multi-layer structures is assembly process of the layers which requires a high level of precision at mm-wave frequencies. Apart from the assembly complications, high gain array antenna with a large number of elements requires a big distribution network leading to a complex layout for the feed network [11]. To overcome this issue we need to employ some techniques to reduce the number of array elements.

This letter presents a new cavity-backed array antenna that supports high gain and wide impedance bandwidth for the 60 GHz band. The antenna consists of a multi-layer structure where the layers are electrically connected together. In order to reduce the number of array elements and simplify the design process of the feed-network, the antenna is loaded with a dielectric plate to increase antenna gain. The present work result in a much simpler layout of the corporate-feed network. Simulations show that the antenna can achieve a gain of larger than 25 dB over the frequency range of 58 to 64 GHz.

II. Design and Configuration

Fig. 1 shows the configuration of the proposed cavity-backed 4×4- element array antenna. The antenna consists of four main layers: the feeding-cavity, the coupling cavity,



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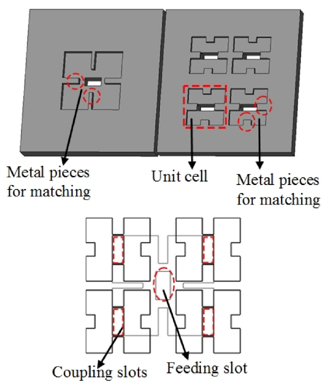

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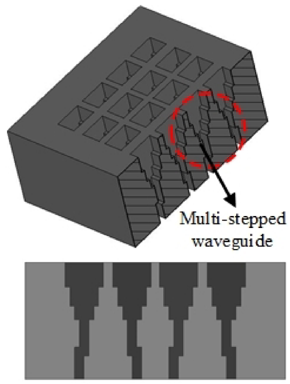


(c)

Fig. 2: Schematic of the (a) Exploded view (b) Feeding layers. (c) radiating layer

the radiating layer and the dielectric layer. All the layers are connected together. Fig. 2 shows the geometry of the proposed antenna layers in more detail. The radiating layer is composed of an array of 16 waveguide apertures. The height of the radiating layer is modeled by multi-stepped waveguide structure to enhance the aperture efficiency and antenna frequency bandwidth. The dimension of each step including its depth and width is optimized carefully to minimize the input reflection coefficient at the operating frequency. To increase antenna gain and reduce the number of array elements, the overall aperture of the antenna is loaded with the dielectric plate positioned at a distance over the aperture of the antenna. Adjustment of the air gap between antenna aperture and the dielectric plate and the thickness of the dielectric plate result in additional parameters to control the input return loss and gain characteristics of the antenna. For this purpose, we used a low cost polystyrene material (Rexolite, $\epsilon_r = 2.54$, $tan\delta = 0.00066$ at 10 GHZ) which exhibits low dielectric loss at millimeter wave frequencies. As shown in Fig. 2, the antenna is fed by the feeding and the coupling cavities. The feeding cavity is excited through a feeding slot located at the center of its bottom surface. In this case, the feeding slot have the same size as the standard WR-15 waveguide.

The input feeding power through the standard WR-15 is divided equally through the feeding slot to four coupling slots in the coupling cavity. The coupling cavity is designed to be symmetrical with respect to the center of the feeding cavity. Hence, this arrangement operates as a compact and simple feeding network to excite each unit cell of the antenna. To

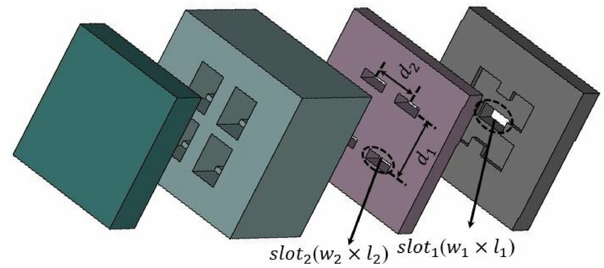
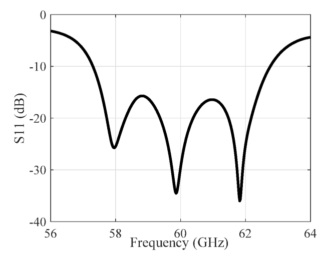


Fig. 3: Perspective view of the 2×2-element subarray: $w_1 \times l_1 = 1.5$ mm $\times$ 3.7 mm, $w_2 \times\ l_2 = 1.2$ mm $\times$ 3.3 mm , $d_1 = 7.2$ mm, $d_2 = 5.1$ mm



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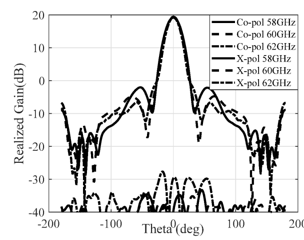

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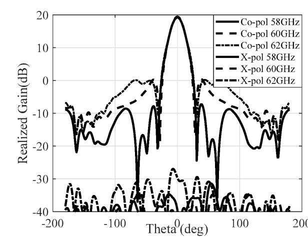


(c)

Fig. 4: Simulated performance of the 2×2-element subarray: (a) Reflection coefficient (b) Radiation pattern at E-plane. (c) Radiation pattern at H-plane

improve working impedance matching between two cavities several metallic steps are incorporated in wall of the cavities. The length and width of the steps are optimized to minimize antenna return loss. This type of cavity-backed feeding structure provide an efficient and compact design of the feeding network without any need to use typical T-junction power dividers to excite each unit cell. Therefore, this 4×4-element array can be used as a subarray in a larger array to achieve higher gains without the need for a complex feed network.

III. Simulation Results

The designed array is analyzed using commercial electromagnetic (EM) simulator Ansys-HFSS. As shown in Fig. 2, a 2×2-element subarray is a design unit cell of the proposed antenna. Fig. 3 shows the exploded model of the 2×2-element subarray. The design frequency of the antenna is 60 GHz, and center to center slot spacing in the x (d_2) and y (d_1) directions are fixed to be 5.1 mm (1.05λ) and 7.2 mm (1.44λ) respectively. Design of the subarray antenna is optimized to achieve a broadband impedance matching with high-gain and high-efficiency performance. Simulated results of the 2×2-element subarray are shown in Fig. 4.

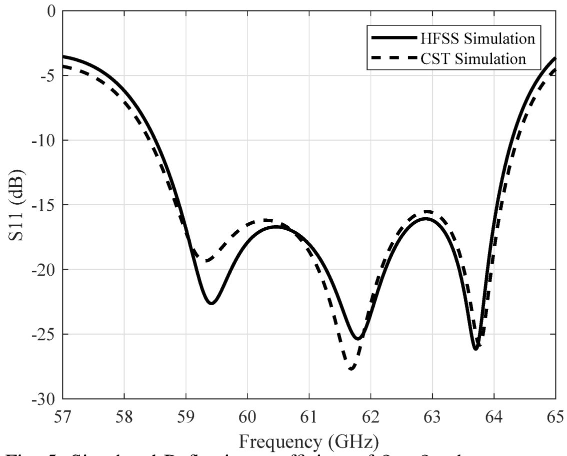
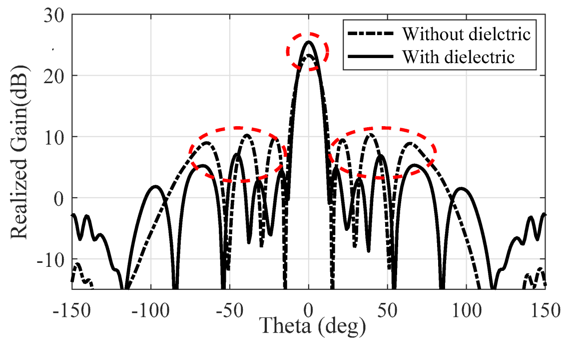


Fig. 5: Simulated Reflection coefficient of 2×2 subarray antenna.



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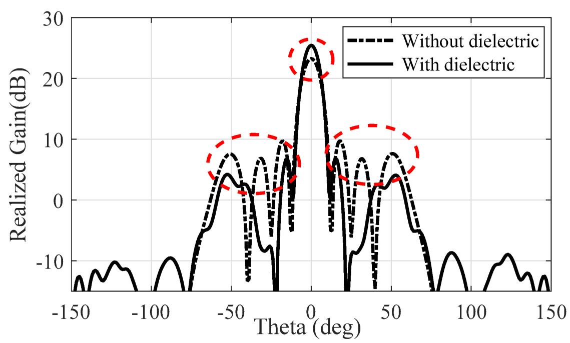

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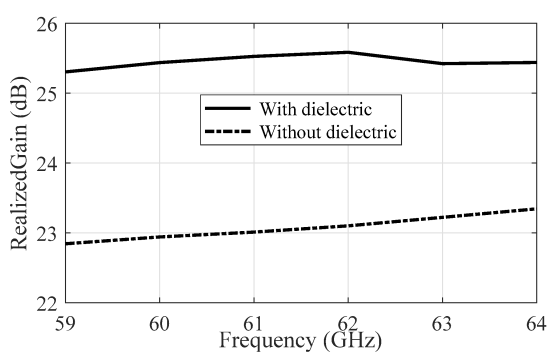

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Fig. 6: Simulated performance of the antenna array with/without the dielectric loading.: (a) Radiation pattern at E-plane (b) Radiation pattern at H-plane. (c) Gain

Then, the design is extended to a larger array antenna. A parametric study of the impedance matching and radiation characteristics of the antenna has been accomplished over the frequency range of 57-65 GHz. The design parameters of the layers are carefully optimized to maintain a broadband bandwidth with high-gain and high-efficiency performance over the operating frequency. This has been accomplished through careful analysis and optimization of the dimension of the stepped waveguide apertures, the metallic matching steps, and the dielectric plate. Ultimately, the overall antenna dimensions are 30 mm $\times$ 30 mm $\times$ 36.7 mm. The dielectric layer of 4.5 mm $(0.9\lambda_0)$ thickness is placed at a height of 4.8 mm $(0.98\lambda_0)$ above the radiating aperture of the array. Fig. 5 depicts the reflection coefficient performance of the antenna. It can be seen that the simulated -10.0 dB reflection coefficient of the antenna is 9.6% over 58.4-64.3 GHz rang. The result is verified using CST Microwave Studio and is found to be in good agreement with HFSS. To investigate the effects of the dielectric plate on antenna performance, an antenna array is simulated without the dielectric for comparison. Fig. 6 shows simulated antenna performance with/without the dielectric loading. Simulation results reveal that the dielectric loading improves antenna performance interms of the sidelobe level and gain. The dielectric boosts antenna gain more than 2 dB over the frequency range from 58 to 65 GHz. The antenna radiation pattern in the E- and H-planes at three different frequencies 59, 62, 64 GHz are shown in Fig. 7 and Fig. 8. We see that the cross-polarization values are lower than than -27 dB in the two planes. Moreover, the sidelobe level is found to be less than -15.5 dB in both E-and H-planes. Fig. 9 shows field distribution of the antenna simulated at 62 GHz. It depicts that uniform field distribution is obtained over the aperture by adopting the proposed feed network. The frequency characteristic of the gain of this antennna is shown in Fig. 10. The simulated result is displayed with CST and HFSS software. It can be observed that the realized gain is more than 25 dB over the frequency band of 59 to 64 GHz. Table I shows the pattern characteristics of the antenna as a function of the frequency.

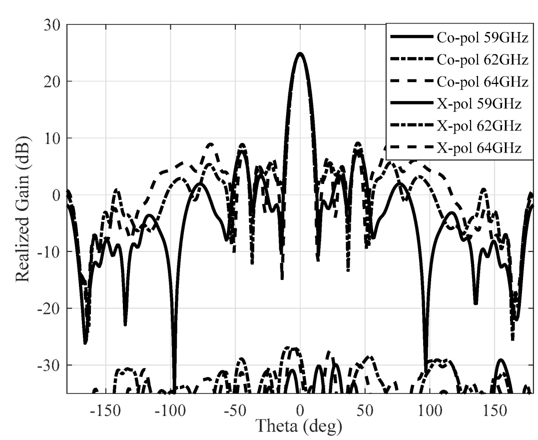


Fig. 7: Radiation patterns of the simulated 4×4-element antenna for different frequencies at E-plane.

TABLE I: Radiation characteristics of the antenna

Frequency [GHz]	E-plane 3 dB Beamwidth [deg.]	H-plane 3 dB Beamwidth [deg.]	E-plane First Sidelobe Level [dB]	H-plane First Sidelobe Level [dB]	Gain [dB]
59	10.8	9.5	-17.53	-17.6	25.3
62	10.3	9.3	-16	-16	25.1
64	10.2	8.9	-15.5	-17.3	25.3

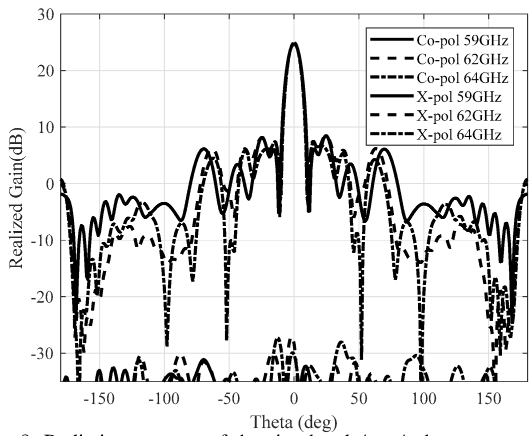
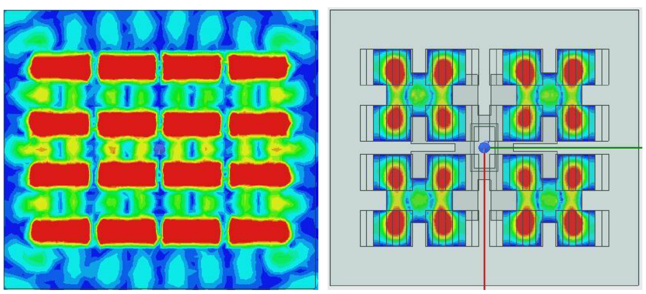


Fig. 8: Radiation patterns of the simulated 4×4-element antenna for different frequencies at H-plane.



(a) (b)

Fig. 9: (a) Electric field distribution in the cavity layer of the 4×4-element antenna. (b) Electric field distribution in the radiating layer.

IV. Conclusion

We have designed and studied a wideband structure of the waveguide aperture antenna array for 60 GHz applications. We propose a 4×4- element antenna array where the radiating aperture of the antenna is loaded with a dielectric plate to enhance antenna gain and reduce overall planar size of the antenna. Moreover,This antenna design can be used as a sub-array to achieve higher gain by designing a compact and less sophisticated feed-network. The simulated results of the proposed structure demonstrate a wide impedance bandwidth with greater than 25 dB gain over the entire operating bandwidth.

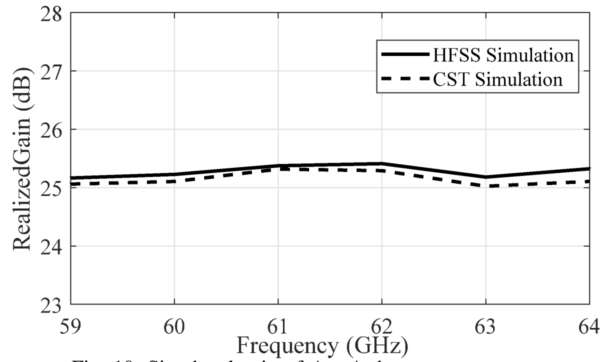


Fig. 10: Simulated gain of 4×4-element array antenna.

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