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3D Printed Slotted Waveguide Antenna Array for Millimeter-wave Communication Systems

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***Abstract*—This paper introduces a 3D printed slotted waveguide linear antenna array at 28 GHz. The proposed antenna offers the advantages of low fabrication cost and reduced weight compared to the metallic slotted waveguide antenna array. The proposed design can achieve a high gain, low losses, and simplicity of fabrication. The proposed antenna geometry suggests an operating bandwidth of 15.8% (26.45 GHz – 31 GHz) suitable to fulfil 5G demands with a high gain performance of 12.0 dBi over the operating bandwidth. The proposed antenna structure is a suitable candidate for a variety of applications in the domain of 5G and beyond featuring cost-effectiveness, high gain, and very good performance overall.**

***Index Terms*—antenna, millimetre-wave, 3D printed antenna, slotted waveguide antenna, slots linear array.**

I. INTRODUCTION

Device to device (D2D) communication is considered one of the essential and emerging technologies to support the promise of 5G in connecting more devices with high data rate, reduced latency and reliable networks. [1-2]. As the front-end of wireless communication, the antenna plays a key role in this device-centric communication. Efforts are made to design an antenna for the D2D communication having higher gain with a unidirectional pattern to compensate for the high propagation losses at the mm-Wave band, reduce the losses, and simplifying the fabrication process [3-5].

Slotted waveguide antenna array (SWAA) can be used in the D2D communication scenarios (like vehicular transportation networks) due to its attractive features such as high gain, low feeding loss, wide bandwidth, high power capacity, easy fabrication process and low cross-polarization [6-7]. Traditional metallic slotted waveguide antenna array always suffers from apparent disadvantages such as bulky size, heavyweight, high cost and complex integration with the planar components. Due to these reasons, its use is limited to just a few specific radar and communication systems applications.

In this paper, linear slotted waveguide antenna arrays have been presented. The proposed antennas are 3D printed and metallized using a very low-cost technique. The proposed antenna arrays are lightweight due to their 3D printed nature and can be integrated easily with the end-user products for many applications. Design and fabrication procedures for a linear array having four radiating slots have been discussed and investigated for simulated and measured results.

II. ANTENNA DESIGN AND CONFIGURATION

A linear slotted waveguide antenna array is designed having four radiating slots, as shown in Figure 1. The WR 28 standard waveguide dimensions (7.112 mm × 3.556 mm) are used for the proposed linear array. Four longitudinal radiating slots are cut on the broad wall of the waveguide. These longitudinal slots interrupt the transverse current flow and get excited. The waveguide is fed at one end and terminated at the other end with short-circuit to produce standing waves inside the guide. All four radiating slots are fed in series by the waveguide feed and are placed in the standing wave-based waveguide to get radiation patterns in the broadside direction. Also, efforts are made to place the slots' center at the maxima of the standing waves for maximum efficiency and radiation. For this and broadside radiation patterns, the center of the last slot (i.e. nearest slot to the short end) is placed at a quarter guided wavelength from the short end. To place other slots, a half-guided wavelength distance is maintained between two consecutive slots and keep at an alternate offset distance from the center of the broad wall of the waveguide. This half-guided wavelength distance between the slots and the alternate position from the center line provide a 180^o phase difference for the peak maxima in the broadside direction. The slots' length controls the resonating frequency of the designed antenna, while slots' offset distance controls each slot's feeding power level. In the proposed linear antenna array, all the slots are kept at the same offset distance from the centre of the waveguide resulting in a uniform fed linear array and theoretical slide lobes level of -13 dB are expected in the direction of the array. i.e. in the H-plane.

The antenna is modelled and numerically evaluated using the CST Studio software [8]. The dimension of the proposed linear array is provided in Table 1.

Table I. Parameters and values of the proposed array

Parameter	*mm*	*Parameter*	*mm*
Antenna Length, $L_{antenna}$	38.5	***Waveguide Dimensions, $W_{guide} \times H_{guide}$***	*7.112 × 3.556*
Antenna Width, $W_{antenna}$	*10.71*	***Slot Length, L_S***	*5.4*
Slot Width, W_S	*1.8*	***Slot offset position from Centre axis, X_{offset}***	1.1
Thickness	*1.8*	***Guided Wavelength, λ/g***	16.29

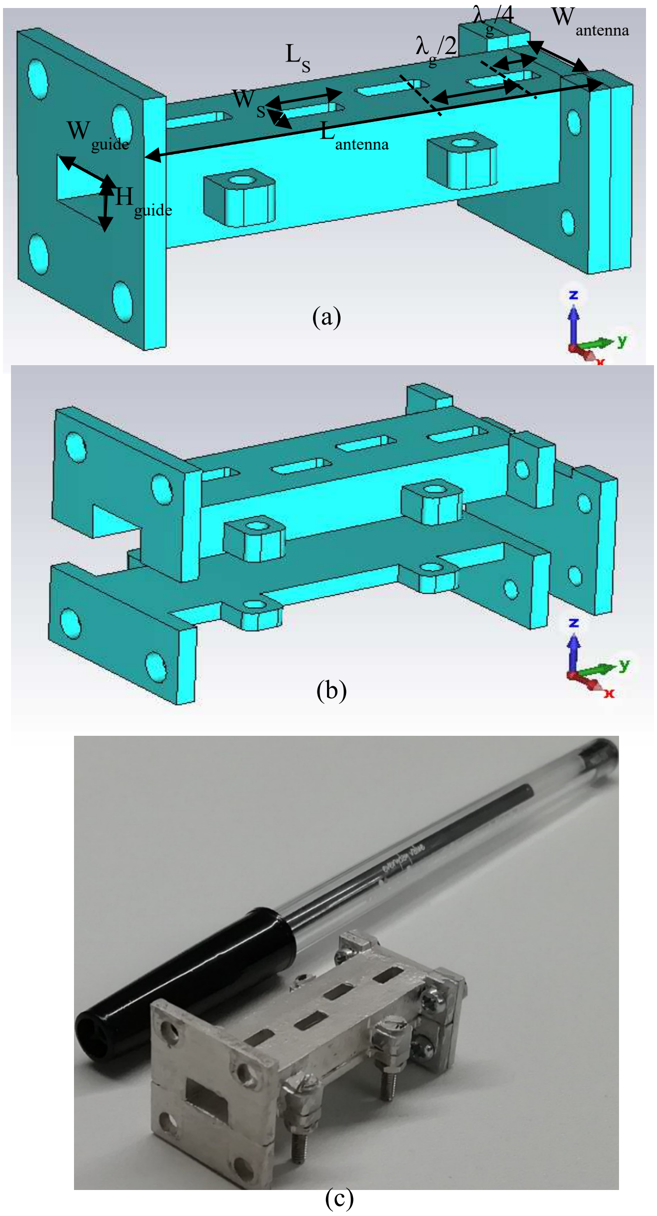

Figure 6.1 Propose 3D printed slotted waveguide linear array (a) perspective view (b) exploded view (c) 3D printed prototype

III. FABRICATION METHOD

The proposed 3D printed linear slotted waveguide antenna array was 3D printed using the in the house available 'Object 30' 3D printer. The Object 30 3D printer works based on the PolyJet technology using VeroWhite material for the model and SUP705 gel-like photopolymer as a support material. The support material can be removed easily through wash using water and a toothbrush once the printing is done [8]. The proposed slotted waveguide antenna array is printed in three parts as clear from Figure 1(b). Two parts are formed by cutting the waveguide in the x –y plane such that these can be joined together using the 2 mm metallic screws mounted on the side support for them. This way, it avoids using any support material inside the wave propagated guide and smooth surface finishing inside the guide can also be guaranteed. The third part is the endplate used to terminate the waveguide to be shorted circuit to generate standing waves inside the guide. The endplate is screwed to the waveguide via screws once the first two parts are combined.

The slotted waveguide linear antenna array is metallized using a Silver Conductive Paint (SCP) from the Electrolube Company [9]. SCP provides a thin, smooth, adherent, flexible film having a high electrical conductivity. The metallization process used in this work simply involves manually painting each antenna part using an excellent paintbrush. Each part is painted with two coats to guarantee full paint coverage. The painted parts were left to dry for 10 minutes at room temperature after each coat. The proposed antenna's parts were then assembled using the metallic screws mentioned earlier. A very small gap was observed between the upper and lower parts of the assembly. Nevertheless, this gap is covered using two additional coats of paint. Applying the paint after assembling to shield the gap is highly essential to guarantee high performance and will be discussed in the result section

IV. RESULTS AND ANALYSIS

The proposed linear antenna array is investigated for the simulated and measured results in terms of S-parameters (S11), radiation patterns, realized gain and total efficiency. It is observed that the measured results of the proposed linear array agree well with the simulated results.

The reflection coefficients (S11) of the 3D printed linear antenna array is experimentally measured using R&S ZNA vector network analyzer for the band 26 GHz to 32 GHz. The measured results for S11 of the proposed linear array is given in Figure 2 along with the simulated results. The simulated bandwidth for $|S11| < -10$ dB is from 26.3 GHz – 29.687 GHz (12.1%) while that for measured results is 15.8 % (i.e. from 26.45 to 31 GHz). The simulated and measured results for S11 show a good match from 26.5 to 29.5 GHz and follow almost the same profile trend. The slightly extended bandwidth for the measured results is probably due to the imperfection in the metallization and fabrication tolerances particularly due to the roughness and conductivity losses of the conductive paint surface.

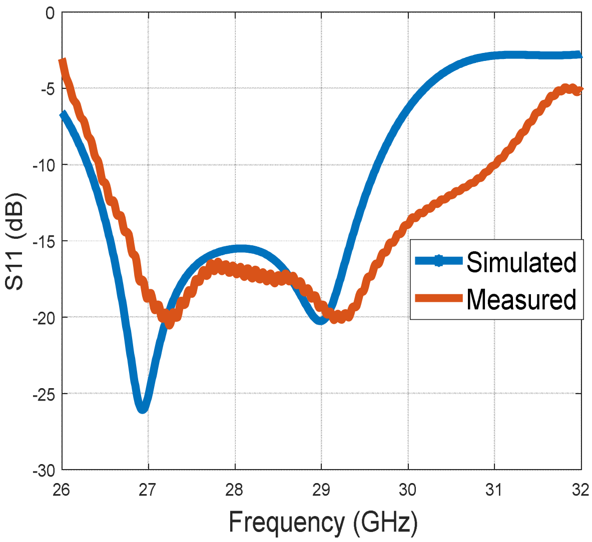

Figure 6.2 Reflection Coefficient of the Proposed Linear Array

The radiation pattern of the proposed linear antenna array is measured using the NSI-MI spherical near-field scanner. The simulated and measured E- and H-plane normalized radiation pattern of the proposed antenna array at 27, 28 and 29 GHz are shown in Figure 3 and having good agreement between them. As the proposed antenna is linear array in the H-plane of the radiating slots, that's why it is demonstrating a fan shape radiation pattern having a wider beam width in the E-plane and a narrow beamwidth (direction of array) in the H-plane. In addition, symmetric main lobes in the E- and H-plane directed along the broadside direction can be observed at all three frequencies with the acceptable sidelobes level.

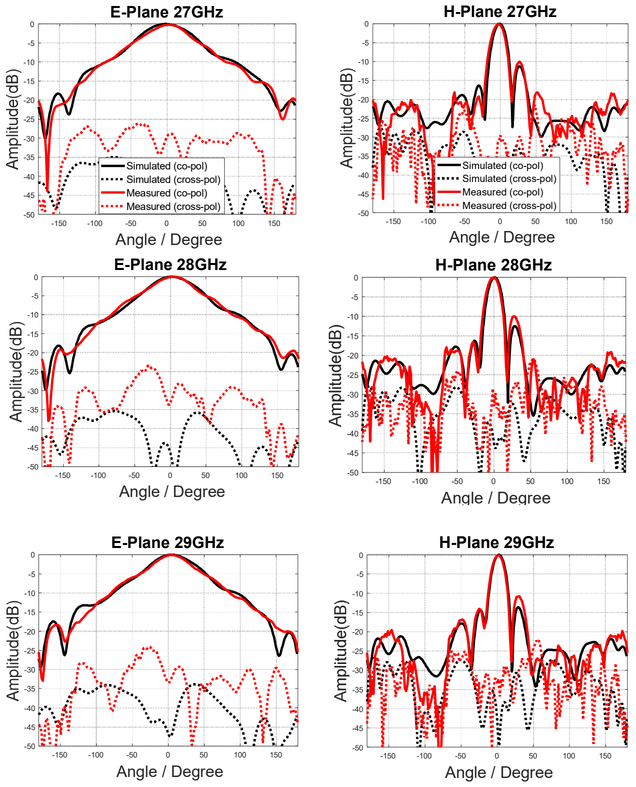

Figure 6.3: Radiation pattern of the proposed antenna array at 27 GHz, 28 GHz and 29 GHz in the E- (phi= 0º) and H-plane (phi = 90º).

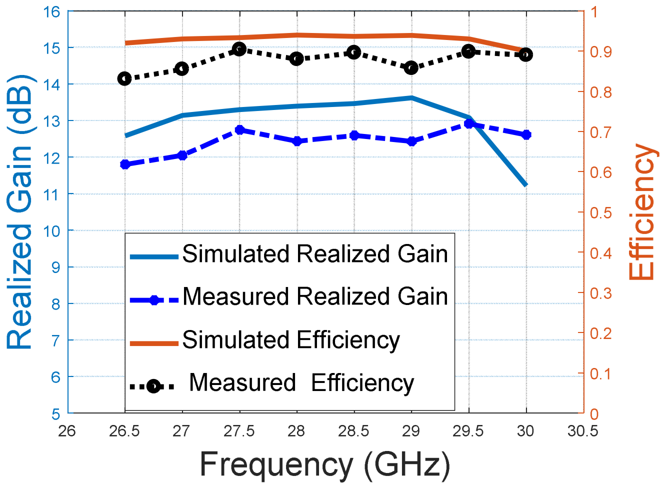

Figure 4. Realized gain and Total efficiency vs Frequency

The simulated and measured realized gain plot for the proposed linear antenna array against the frequencies from 26.0 GHz to 30.0 GHz has been reported in Figure 4. The measured realized gain is calculated by the gain comparison method [10]. The proposed 3D printed linear array's measured gain has the same trend as that of the simulated realized gain but with a maximum variation of about 1 dB. The reason for this variation is the non-ideal and non-uniform behavior of the used metallization technique as well as the roughness of the metallized surface. The value of conductivity of the SCP used in the simulation is 1.0×10^6 s/m while practically it varies ranges from 0.82×10^6 and 2.6×10^6 s/m as discussed in detail in chapter 5. The measured realized gain of the proposed antenna is higher than the simulated gain at 30 GHz due to the good match with the 3D printed prototype. Moreover, the measured and simulated total efficiency of the proposed linear array is also given in Figure 4, indicating that the proposed linear antenna array is highly efficient all over the operating band

CONCLUSION

A linear slotted waveguide antenna arrays has been presented. The proposed antennas are 3D printed and metallized using a very low-cost technique. Very good agreement between the simulated and measured results is observed for the proposed linear arrays. The linear 3D printed slotted waveguide antenna array has a measured impedance bandwidth of 15.8% (26.45 GHz – 31 GHz) and peak measured realized gain of 12.0 dBi. Based on these features the antenna is recommended as potential candidate to be incorporated in future millimeter-wave communication whether for 5G application or beyond.

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