Highly Efficient and Wideband Millimeter-Wave Slotted-Array Antenna Technology for 5G Communications

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***Abstract*—The 5G, 6G of future wireless technology has brought a growing demand for different types of electrically small or large antennas, which are highly efficient, directive, and provide wideband coverage. We have presented here a compact and highly efficient slotted-array antenna technology operating at a millimeter-wave frequency range to be used for the emerging applications of 5G wireless backhauling and mobile radio services. The antenna consists of two conducting plates, with the upper plate having a slotted array in the form of a spiral. A waveguide forms between these plates and supports outward traveling TEM waves generated from a single coaxial connector at the center of the antenna. The slots are arrayed to generate circularly polarized electric fields. The antenna was simulated using CST Microwave Studio to validate the design mechanism. With a compact dimension of 0.1 m diameter, the proposed antenna achieved an extremely high gain of 27.2 dBic. The antenna has shown a wide 3dB gain bandwidth of 4.6 GHz, ranging from 33.2 GHz to 37.8 GHz, and an overall wide bandwidth of 13%. The antenna has demonstrated an aperture efficiency of 43%, and the total efficiency is varied between (87 - 93)% over the operating frequency range.**

***Index Terms*—5G, Millimetre-wave, radial line slot array, RLSA, circular polarisation, high gain, high efficiency, wideband, bandwidth, satellite, beamforming, IoT**

I. INTRODUCTION

Recent years have witnessed a significant interest in developing Fifth Generation (5G) wireless communications systems. 5G technology provides the characteristics of high data rate, faster connectivity, ultra-low latency, and high reliability through the communication channel [1]–[3]. Such characteristics of the 5G system require implementing a heterogeneous network in the millimeter-wave (mmWave) frequency range, which has unlimited bandwidth to be utilized and higher data throughputs. In mmWave spectrum, 28 GHz - 38 GHz bands have been assigned as the candidate for future 5G standards to support emerging applications in high-capacity wireless backhauling and mobile radio services. A low-profile, highly directive, and wideband antenna technology for such systems is imperative to overcome challenges, such as multipath fading, interference, eavesdroppers, and atmospheric pressures. In this work, we have presented a low-cost, compact, highly efficient radial line slotted-array (RLSA) antenna technology operating in the mmWave band to be implemented for 5G networks.

RLSA antennas are highly directive and slotted flat antennas first proposed by Ando in Japan for direct broadcast satellite (DBS) applications [4], [5]. These antennas have single or double-layered radial waveguides and produce inward or outward traveling TEM waves inside the waveguide. The thickness of RLSA is also low and does not suffer from feed losses as compared to the other directive array antennas. Both linearly polarized (LP) RLSA and circularly polarized (CP) RLSA antennas were investigated [4], [6]–[15]. CP RLSA provides better return loss performance than LP RLSAs. In the late 1990s, Paul Davis modified the design mechanism of LP RLSA antennas for DBS TV reception in Australia [7], [8]. Reflection canceling slots and tilting-beam techniques were used to improve the antenna performance of LP-RLSAs. Most of the RLSA designs reported in earlier publications were designed at a lower frequency range ($<$20 GHz) and have a large aperture and limited gain bandwidth, making the antenna technology very challenging and expensive for such applications of 5G networks.

This paper investigates a small aperture, directive, and wideband CP RLSA antenna design for 5G communication system. A recently developed bandwidth enhancement method using non-uniform waveguide permittivity was utilized here to increase the limited gain bandwidth of RLSAs. The antenna has a radius of 6 λ_0 and generates a fixed broadside narrow beam with acceptable pattern quality. This paper is arranged such that the configuration of the proposed antenna is explained in Section II. Near-field and far-field results that are predicted from simulations are presented in Section III, and the paper is concluded at the end.

II. CONFIGURATION OF THE ANTENNA

The CP RLSA antenna design methodology can be divided into two steps. In the first step, the slots are arranged on the top radiating plate of the antenna. The second step includes designing the non-uniform TEM waveguide and feed structure. Details of these design mechanisms are given below.

A. Slot Arrangement

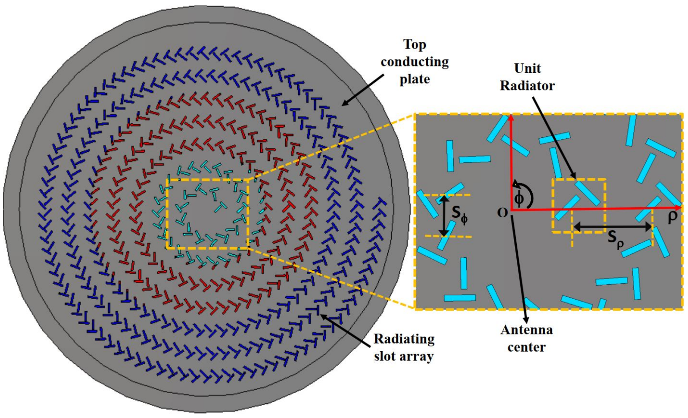

Fig. 1: Radiating slot distribution on the aperture of the CP RLSA antenna.

The slot configuration on the aperture is shown in Fig. 1. The antenna is designed to operate in the frequency range from 33 GHz to 38 GHz, having an aperture of $12\lambda_\circ$ (=100 mm), where $\lambda_\circ$ is the free-space wavelength. The aperture of the antenna consists of hundreds of unit radiators, as shown in the figure. Two slots make a unit radiator and have the same length and width. These slots are placed orthogonally to each other and inclined to an angle of $45°$ with the current-flowing line. The unit radiators produce circularly polarized electric fields. Details of the slot design can also be found in previous publications [6], [9], [13], [14] and some of the steps are not repeated here for brevity.

The unit radiators are arranged in a spiral to add the radiation in the broadside direction. The spacing between adjacent unit radiators in the radial direction is given by S_ρ and kept equal to one guided wavelength (λ_g). The spacing in azimuth direction is given by S_ϕ and kept equal to $\lambda_g/2$. Each unit radiator's length was increased gradually from the antenna's center towards the edges to make a uniform aperture distribution.

B. Waveguide and Feed Structures

Configuration of the non-uniform TEM waveguide and feed structure are shown in Fig. 2. The waveguide is often partially filled with dielectric material and air. The purpose of the dielectric material is to create slow waves to avoid grating lobes in radiation patterns. In the proposed antenna, the waveguide is divided into three sections following the design principle explained in [6], where each section is designed to radiate at a different frequency. The three sections named as S_1, S_2, S_3 as shown in the figure and have permittivity value of ϵ_1, ϵ_2, ϵ_3, respectively. The effective permittivity of the waveguide is the weighted sum of dielectric constants and air. The sections close to the center of the antenna are designed to radiate at higher frequency (e.g. 36 GHz - 38 GHz), and the sections close to the edge operate at lower frequency (e.g. 33 GHz - 35 GHz).

A single 50Ω coaxial cable feeds the power at the center of the antenna, as shown in Fig. 2. A cylinder-shaped disk is attached on top of the coaxial inner pin. The edge of the antenna is left empty. The ground plane's radius was increased slightly than the top plate to avoid propagation of the waves in the backward direction.

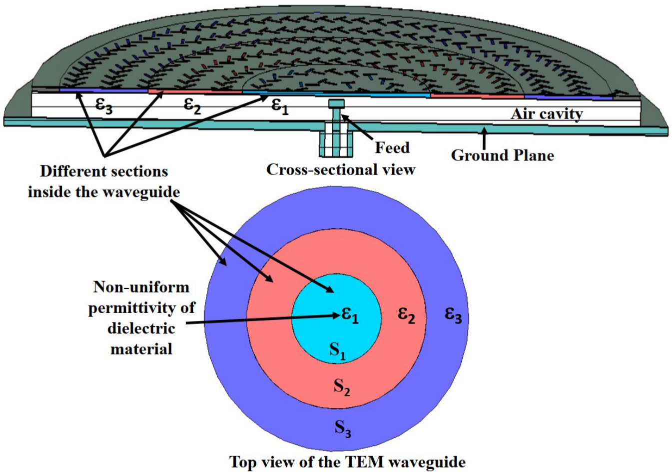

Fig. 2: Non-uniform TEM waveguide and feed structures of the CP-RLSA antenna.

III. RESULTS

The antenna was simulated in CST Microwave Studio using a transient solver. Fig. 3 shows the reflection coefficient ($|S_{11}|$) of the proposed antenna. The antenna has demonstrated acceptable impedance matching over the frequency range from 32 GHz to 39 GHz. The antenna has shown an impedance bandwidth of more than 20%. The electric near-field distribution of E_x close to the antenna aperture for six different frequencies is shown in Fig. 4. The field distributions were taken at a height of $2\lambda_0$ above the top plate and in parallel to the XY plane. It can be seen from the figure that as the frequency increases, the magnitude strength shifts towards the center of the antenna.

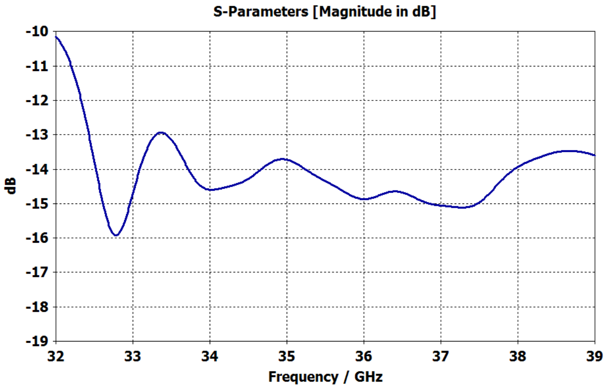

Fig. 3: Reflection coefficient ($|S_{11}|$) of the antenna.

The broadside directivity, realized gain, and the axial ratio of the CP-RLSA antenna are shown in Figure 5. The antenna has achieved a maximum directivity of 27.5 dBic with a realized gain of 27 dBic and an axial ratio of 0.3 dB at 34.4 GHz. The antenna has shown a wide 3dB gain bandwidth of 13% (4.6

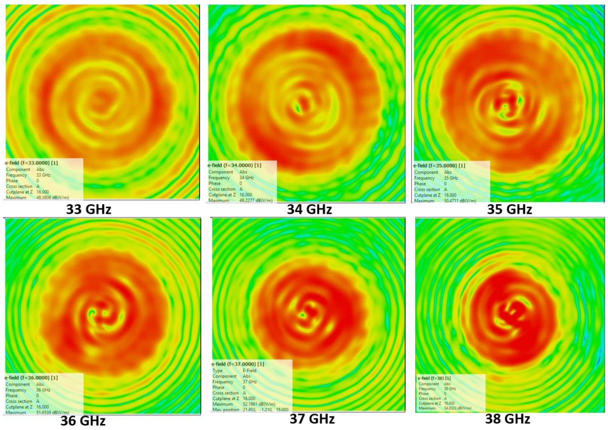

Fig. 4: Electric near-field distribution of E_x in XY plane at different frequencies.

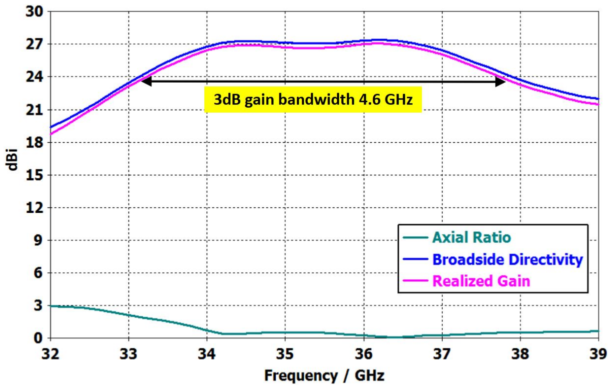

Fig. 5: Broadside directivity, realized gain and axial ratio of the antenna.

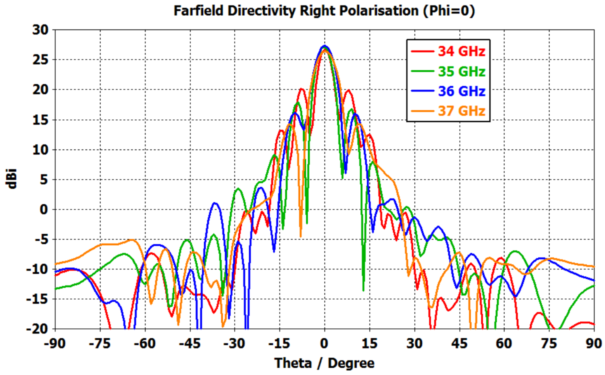

Fig. 6: Far-field radiation pattern taken at $\phi = 0°$ plane at four different frequencies.

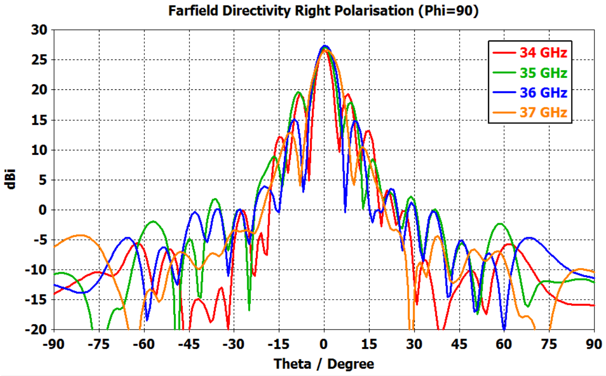

Fig. 7: Far-field radiation pattern at $\phi = 90°$ plane.

GHz), from 33.2 GHz to 37.8 GHz. The axial ratio is below the 3 dB over the operating frequency band, satisfying good circular polarisation. The proposed antenna has achieved an aperture efficiency of 43%. The radiation efficiency is varied between (94 - 96)% and the total efficiency between (87 - 93)% over the operating frequency range.

The far-field radiation pattern cuts taken at $\phi = 0°$ plane and $\phi = 90°$ plane at four different frequencies are plotted in Fig. 6 and Fig. 7, respectively. The radiation patterns show sidelobes less than -8 dB levels in both planes. The pattern quality can be further improved by optimizing the slot distributions on the top radiating plate and making a tapered amplitude distribution in its near-field.

IV. CONCLUSION

A compact, highly directive, and wideband CP-RLSA antenna design methodology operating at the mm-Wave band is presented in this paper. The antenna has provided good performance in terms of directivity, realized gain, axial ratio and efficiency. The thickness of the antenna is very low and provides a narrow 3dB beamwidth of less than 5°. The proposed design mechanism has also significantly enhanced the total operational bandwidth (includes gain, impedance, and axial ratio bandwidth) compared to the conventional RLSAs. Smaller aperture size, wide bandwidth, high efficiency, and gain make the antenna a suitable candidate for wireless backhauling network or mobile radio services for 5G communication systems.

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