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BEAM BROADENED RADIAL LINE SLOT ARRAY ANTENNA FOR FIFTH GENERATION (5G) MOBILE BROADBAND COMMUNICATION

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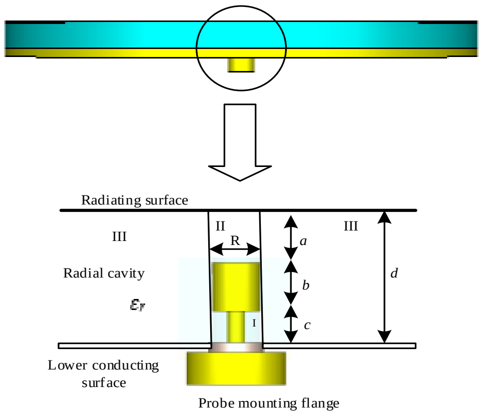
Graphical abstract



Abstract

Radial line slot array antenna with broad beam is easily realized at frequencies in the lower part of super high frequency band. But emerging broadband mobile communication systems like the fifth generation target frequencies in the upper part of the band and beyond. Therefore, this paper presents the design of beam broadened radial line slot array antenna at 28 GHz for fifth generation broadband mobile communication system. Surface slot distribution synthesis was carried on beam squinted standard single layer radial line slot array design to achieve the broad beam. Using computer simulation technology microwave studio 2014 software, 85 mm radius antenna having polypropylene (ε_r = 2.33) as cavity material was realized. Simulated results shows a gain of 15.8 dB, impedance bandwidth of 1.6 GHz, radiation efficiency of 96 % and 3 dB half power beamwidth of up to 32.3°.

Keywords: Linear polarization; slot array antenna; broad beam; 5G; 28 GHz; beamwidth

1.0 INTRODUCTION

Spectrum search to support bandwidth allocation for broadband mobile communication systems like the fifth generation (5G) is ongoing. This informed the need for researchers to look at the possibilities of using the millimeter wave band [1]. In light of this, frequencies including 28 GHz have been identified as potential candidates [2]. However, signal transmission and reception in millimeter wave band requires the use of high gain and narrow beam antennas. This makes radial line slot array antenna (RLSA) attractive.

RLSA has high gain, efficiency [3] and ease of manufacture. It was hitherto studied for applications like wireless local area network [4], [5], direct broadcast system [6], [7] local multiport distribution system [8], mobile satellite [9] and applications in extremely high frequency band [10], [11].

The antenna in its standard form consists of two circular conducting surfaces usually made of copper and a dielectric material of thickness *d* separating them. The top conductor (radiating surface) carries the radiating slots that are arrayed in concentric circles and may be oriented to produce circular [6], linear [12], or elliptically [13] polarized radiation pattern at boresight. An empty region is created at the center of the radiating surface for stabilization of the radiating or received energy. The lower conductor does not carry any slot. Excitation of the antenna is done via coaxial to waveguide transition feed from bottom center of the lower conductor. A simple perspective diagram of the antenna is shown in Figure 1.

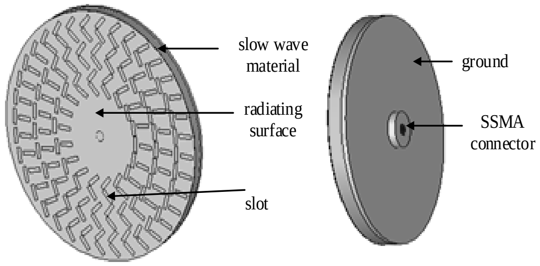


Figure 1 Perspective of RLSA

Typically, when the antenna is in transmit mode, a transverse electromagnetic (TEM) wave from the coaxial to waveguide transition feed probe is launched into the radial cavity as TEM radial mode. This wave travels radially into the cavity and subsequently couples the slots to produce the desired radiation pattern. Residual power not radiated, on reaching the end of the antenna is lost out into open space with some reflected back. A detailed operation of single layer RLSA with linear polarization can be found in [14].

Also in the standard design, the slots distributions on the radiating surface are arrayed to couple a greater percentage of the energy in the cavity into a radiated pencil beam [14]. That is why RLSA has inherent narrow 3 dB half power beamwidth. These can be seen from references [7], [10], [13], [15] and [16]. Where 8.2° was the largest angular width obtained among. Additionally, most of the publications on RLSA especially those for applications in the upper super high frequency and extremely high frequency bands were silent on the achieved angular width since it is not an issue for the applications being studied.

But a broadened beam may sometimes be desired. For example, when used for point to point application, with broad beam, the effect of small shift from line of sight will never be noticed. In the same vain, in applications like wireless local area network, cellular or mobile systems, broader beam may be desirable in order to satisfy a specified coverage area.

Beam broadened RLSA was demonstrated by Imran, et al. [17] at 5.8 GHz. In their study, they varied the diameter of a standard RLSA with polypropylene as cavity material from 600 mm to 300 mm. The 3 dB angular width was increased from 8.0° and 6.6° to 13.0° and 14.0° on E- and H- planes respectively. In another work, Muhamad et al. [18] used a combination of polypropylene and FR4 as cavity material in a compact size RLSA with only 8 slots on the radiating surface. An angular width of up to 44.7° was achieved. Similarly a multilayer FR4 cavity material antenna was designed by Islam and Abd Rahman [19]. With two rings of 94 slots, angular width of up to 60° was realised. Also a broad beam was obtained for a compact size design having 25 slots with hybrid of air/FR4 cavity material [20]. The air gap was varied between 12 mm and 7mm and a broad beam was obtained with the 7 mm gap.

These studies were all carried at the frequency of 5.8 GHz for wireless local area network application. It can be seen that the beam broadening was primarily accomplished by reducing the size of the antenna, modifying the cavity material and using fewer (longer) slots on the radiating surface. The same technique when applied at higher frequencies failed. Instead, a scattered radiation pattern and poor return loss were observed.

RLSA having gain and impedance bandwidth greater than 12 dB and 1 GHz suitable for 5G mobile communication [22] was demonstrated at the frequency of 28 GHz [23]. In the paper, the observed 3 dB angular widths stand at 7.5° on both planes. Now, harnessing the work of Davis and Bialkowski [21] on beam synthesis of llinearly polarized RLSA for beam broadening at 12 GHz, an attempt to broaden the beam of RLSA at 28 GHz suitable for 5G broadband mobile communication was carried out in this paper. Aggressive surface slot distribution synthesis and feed transition matching were carried in order to achieve the broad beam.

The remaining paper is organized as follows: In section 2, the surface slot synthesis for the beamwidth enhancement was explained. The obtained results were discussed in section 3 and the conclusion given in section 4.

2.0 SURFACE SLOT SYNTHESIS FOR BEAMWIDTH ENHANCEMENT

Previous studies on beam broadened RLSA were carried out mostly at frequencies in the lower part of super high frequency band. The technique used which implored the use of longer and fewer slots on the radiating surface performed poorly at frequencies in the upper part of the band such as 28 GHz. The broadening at these upper frequencies then has to deal with the natural number of slots distributed on the radiating surface.

To carry out the broadening, further study utilizing the work of Davis and Bialkowski [21] was persued. Davis and Bialkowski [21] showed that a radiating slot can be substituted by an equivalent magnetic dipole as shown in Figure 2. The electric field distribution is then expressed as

$$\vec{E}\left(\xi,\vartheta,\zeta,t\right) = x\frac{V_m}{w}\sin\left[k\left(l-|\vartheta|\right)\right]e^{j\omega t} \qquad (1)$$

Using Schelkunoff equivalence theorem, the free space magnetic field was found to be

$$\vec{M}\left(\xi,\vartheta,\zeta,t\right) = -y\frac{2V_m}{w}\sin\left[k\left(l-|\vartheta|\right)\right]e^{j\omega t} \qquad (2)$$

Applying the theory of magnetic dipole, the resultant far field for a slot became

$$E_{\theta}(\theta,\phi) = j\cos\phi\,\frac{\cos\left(kl\sin\theta\sin\phi\right)-\cos\left(kl\right)}{\left(1-\sin^{2}\theta\sin^{2}\phi\right)}\,IM \qquad (3)$$

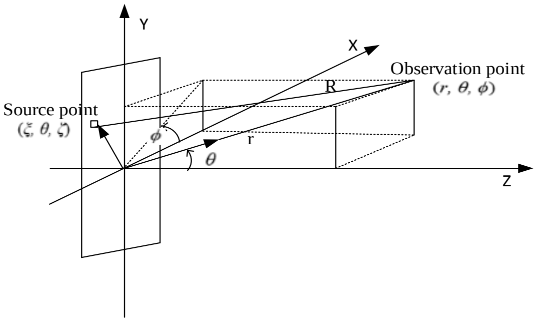


Figure 2 Slot radiated fields' evaluation geometry

$$E_{\phi}(\theta,\phi) = -j\cos\theta\sin\phi\,\frac{\cos\left(kl\sin\theta\sin\phi\right)-\cos\left(kl\right)}{\left(1-\sin^{2}\theta\sin^{2}\phi\right)}\,IM \qquad (4)$$

where

$$IM = \frac{V_m}{\pi}\,\frac{\sin\chi}{\chi}\,\frac{e^{j(\omega t-kr)}}{r}$$

$$\chi = \frac{ks_w\sin\theta\cos\phi}{2}$$

V_m	slot excitation coefficients
k	free space wave number
l	length of slot
(θ,ϕ)	far field region angular coordinate
s_w	slot width

By evaluating V_m, the array far field can be obtained using superposition principle. But V_m depend on a number of parameters that make knowing its exact expression difficult. These parameters comprises of the slot size, position, orientation, interaction between slots and excitation field in the radial guide.

When a particular polarization is desired, position and slot orientation are fixed with only slot size varying. Davis and Bialkowski [21] therefore set the slot length to achieve uniform amplitude taper and using surface slot design software they developed for the purpose of RLSA manufacture, the slot position and size became readily available thereby facilitating the design.

For this paper, computer simulation technology microwave studio 2014 (CST MWS 2014) software was used to implement the design and carry out the synthesis. In order to achieve good result, beam squinted surface slot distribution [15] design was adapted. The design allow for easy slot distribution manipulation with good return loss performance. With linear polarization desired, initial antenna diameter, slot width and length are intuitively assigned for the start of the simulation. These parameters are successively manipulated while the slot position, orientation and the remaining evaluation are automatically executed by the software until the best result is reached.

At the same time, the feed transition is also matched. Figure 3 shows an amplified diagram of the transition made of 50 Ω dielectric coated disc ended feed probe [7], [24]. The probe post is buried in the center of the cavity material (region III) with a vacuum in regions I and II created below and above its disc head respectively.

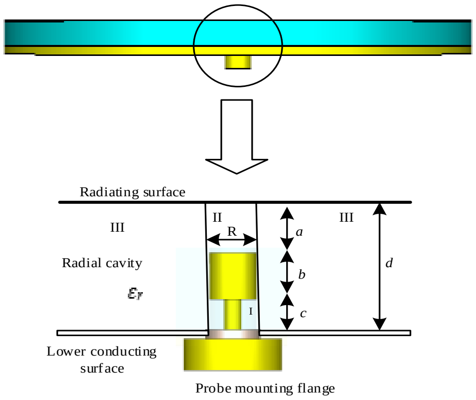


Figure 3 Disk ended coaxial to waveguide transition

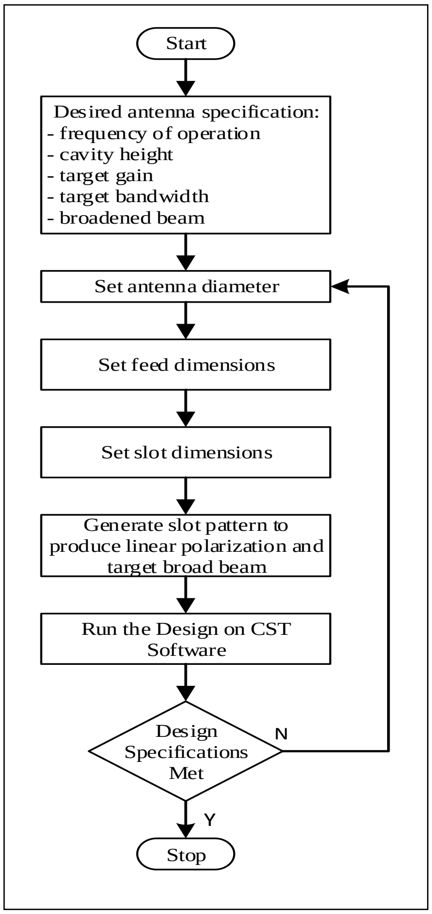


Figure 4 Simulation flow chart

The spacing *d* is defined by

$$d < \frac{\lambda_g}{2} \tag{5}$$

where $\lambda_g = c / f_o \sqrt{\mu_r \varepsilon_r}$ and

λ_g	wavelength in the guide
c	speed of light
f_o	center frequency
μ_r	relative permeability

To avoid grating lobes, ε_r was chosen to be greater than 1.0 [7]. The matching is then achieved by finding the appropriate values of the parameters R, *a*, *b* and c.

The overall simulation is implemented as outlined in Figure 4. The final simulation output a structure that can be implemented for practical testing.

3.0 RESULTS AND DISCUSSION

The approach adapted was demonstrated by using polypropylene polymer (ε_r = 2.33) of thickness 3.0 mm as the cavity material; copper conducting surfaces: 0.1 mm (for the radiating surface) and 1.0 mm. Starting with small antenna diameter, $\lambda_g/2$ initial slot length, rough values of R, *a*, *b*, *c* as can be deduced from [7] and a more practical slot width, the design was iteratively run on the simulation software until an acceptable result is achieved. The optimized values of the antennas' parameters reached are given in Table I while the obtained results in Figures 5 to 10.

Table I The antennas' optimized parameter values

Parameter	Value
Radius of antenna	85 mm
Slot width	1.0 mm
Diameter of disk head (R)	2.4 mm
Height of upper air gap (*a*)	0.3 mm
Height of disk head (*b*)	1.7 mm
Height of lower air gap (c)	1.0 mm

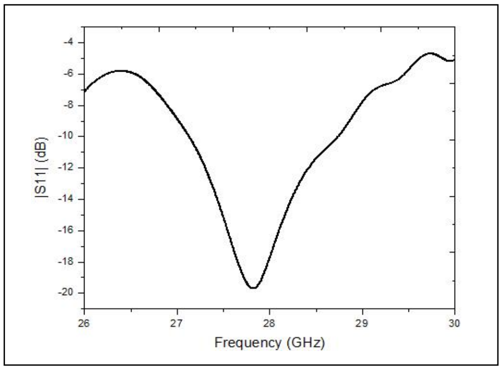
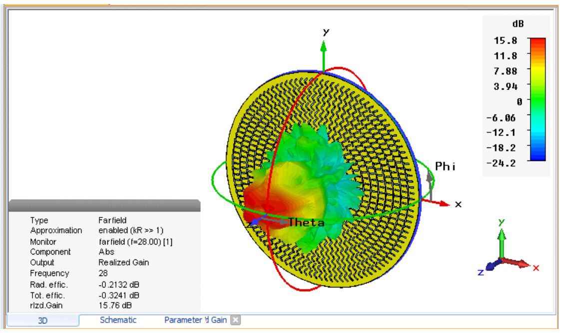


Figure 5 Simulated S-parameter

Figures 5 show the simulated S-parameter result of the final design reached. It can be observed that the antenna achieved an impedance bandwidth of 1.6 GHz and return loss of -17.7 dB at 28 GHz. A gain of 15.8 dB was realized as displayed in Figure 6. Additionally, the gain over the frequency range for the simulation is shown in Figure 7. A value greater than 15 dB was observed for the entire simulation frequency range.



Type Farfield
Approximation enabled (kR >> 1)
Monitor farfield (f=28.00) [1]
Component Abs
Output Realized Gain
Frequency 28
Rad. effic. -0.2132 dB
Tot. effic. -0.3241 dB
rlzd.Gain 15.76 dB

Figure 6 Antenna simulation model

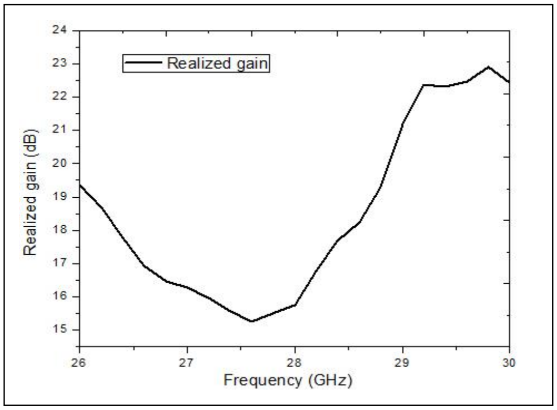


Figure 7 Simulated realized gain

The radiation pattern of the synthesized antenna is contained in Figures 8 and 9. A 3 dB half power beamwidth of 21.8°, 32.3° on E- and H- planes were recorded respectively. This is a significant improvement compared with what was obtained with similar attempt for a frequency in the upper super high frequency band [21]

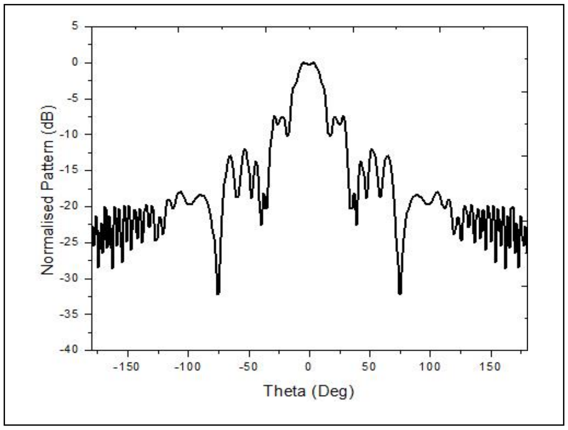


Figure 8 Radiation pattern on E- plane

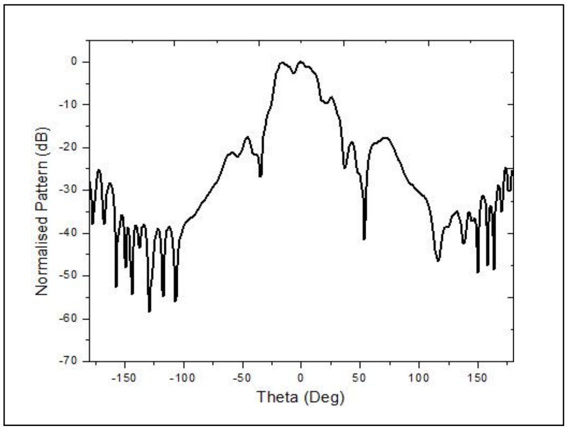
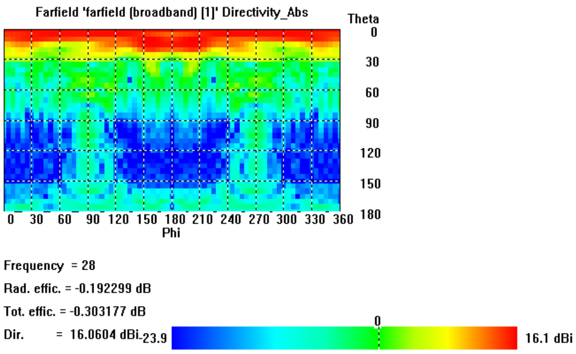


Figure 9 Radiation pattern on H- plane



Frequency = 28
Rad. effic. = -0.192299 dB
Tot. effic. = -0.303177 dB
Dir. = 16.0604 dBi

Figure 10 2D farfield plot

Furthermore, from the 2D farfield plot in Figure 10, the antenna has a directivity of 16.1 dBi and a radiation efficiency of -0.192 dB which translates to efficiency of 96% [25].

4.0 CONCLUSION

A standard form RLSA with polypropylene ($\varepsilon_r = 2.33$) as the radial guide material and employing beam squint technique was simulated at 28 GHz using CST MWS 2014 software for beam broadening. By iteratively running the design and manipulating the slot distribution and key parameters of the antennas, the broad beam is achieved. An antenna with a gain of 15.8 dB, directivity of 16.1 dBi and impedance bandwidth of 1.6 GHz was achieved. The 3 dB half power beamwidth on E- and H- planes stand at 21.8° and 32.3° respectively.

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