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Multilayered Cavity Material Radial Line Slot Array Antenna with Improved Bandwidth for 5G Communication Application

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Abstract

Mobile broadband communication systems like the fifth generation (5G) will require large bandwidth allocation. Currently, the sweet spot is congested with no enough spectrum to support higher bandwidth allocation. The millimeter wave band is being explored to provide the needed spectrum with 28 GHz so far identified as a potential carrier frequency. Development of complimentary antennas for transmission and reception on the band therefore become necessary. This paper present the design of linearly polarized radial line slot array antenna at 28 GHz for mobile broadband communication system application. The antenna consists of radiating surface with radius ρ sitting on squared cavity and ground of side 2ρ. It is excited via a rear center mounted modified straight dielectric coated 50 Ω SSMA connector. The cavity is filled with layers of air space, low dielectric constant syntactic foam and high frequency laminate RT/duroid 5880. With ρ = 50 mm and a maximum total cavity height of 3.0 mm, the antenna was simulated using Computer Simulation Technology Microwave Studio 2014 software. A gain of 18.13 dB, directivity of 18.4 dBi, efficiency of 96 % and impedance bandwidth of up to 2.34 GHz were realized.

Keywords: bandwidth improvement, millimeter wave, RLSA antenna, 28 GHz, 5G

1. Introduction

Next generation mobile communication systems like the fifth generation (5G) is being developed and is expected to accommodate the fast growing data intensive and multimedia based applications. It is also expected to utilize the millimeter wave spectrum, support high speed data rates, use energy friendly devices and network infrastructure.

Antenna is one of the core components of any wireless communications system. Its development for any emerging technology usually attracts research attention. As such, research activity into antennas for next generation mobile communication systems has since commenced. It was in that respect (Khan et al., 2012) suggested that any antenna for 5G application must have an impedance bandwidth of at least 1.0 GHz and gain of 12 dB. Microstrip antennas have been a popular choice for applications on the current licensed bands for mobile communication. But with no much space on the current band to provide for larger bandwidth allocation, many options including the use of 3-300 GHz band (sometimes referred as millimeter wave band (Zhouyue & Khan, 2011)) are being considered. At millimeter wave band, microstrip antenna design becomes challenging and to date little is known about antenna design at millimeter wave for cellular or mobile communication (Chen & Zhang, 2013). Radial Line Slot Array (RLSA) antenna with its starling characteristic of high gain, low cost, ease of manufacture, attractive radiation characteristics and high efficiency (Ando et al., 1988; Takahashi et al., 1992) becomes a good candidate.

RLSA antenna was first developed by Kelly towards the end of the year 1950 (Kelly, 1957). It is viewed as a slotted waveguide planar array which utilizes waveguide as a feed circuit. It is therefore free of conductor loss. More so, from theoretical point of view it is supposed to have high efficiency independent of its aperture diameter. It has been used in applications like direct broadcast system satellite TV reception (Ando et al., 1985), (Goto & Yamamoto, 1980), local multiport distribution system (Akiyama et al., 2000), wireless local area networks, mobile satellite and for applications in the extremely high frequency band (T. Purnamirza et al., 2012). Furthermore, the antenna can be designed for linear (Ando et al., 1988), circular (Ando et al., 1985; Goto &Yamamoto, 1980) or elliptical (Tung et al., 2012) polarization. But it suffers from bandwidth limitation which is inherent with traveling wave antennas. So, in this paper a simplified technique for boosting the bandwidth of a linearly polarized RLSA at 28 GHz for mobile broadband communication systems is presented. The design employed a multilayered cavity material consisting of air gap and 2 layers of dielectric materials with different dielectric constants.

The remaining paper is thus organized as follows: standard or conventional design of RLSA antenna and the making of the proposed antenna were highlighted in section 2. Section 3 contains the discussion of the realized results whereas the concluding remarks were stated in section 4.

2. Method

2.1 The Standard RLSA Antenna

The basic structure of single layer cavity RLSA antenna is shown in Figure 1. The power is launched into the guide via the rear mounted coaxial to waveguide transition feed. The transition feed which is modified with disc end head ensures proper matching of the radial waveguide to the coaxial transmission line and efficiently convert the power from transverse electromagnetic (TEM) transmission line mode to TEM cavity mode. The energy radiated from the feed travel radially outward into the cavity. The dielectric material filling the cavity creates a slow wave and minimizes reflection towards the coaxial transmission line. An area of radius ρ_{min} at the center on the radiating surface is left unslotted for stability of the wave before the slots are encountered. The slots are arrayed on the radiating surface in a specified distribution so that a greater percentage of the energy in the cavity forms a pencil beam with a specific polarization (Davis & Bialkowski, 1999).

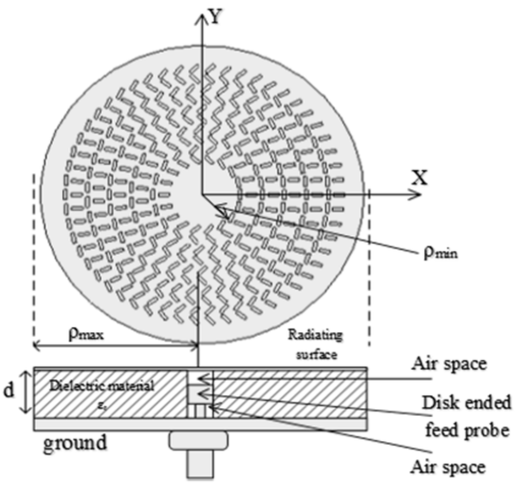


Figure 1. The Basic Single Layer RLSA Antenna

Energy not radiated on reaching the circumference of the antenna is either reflected back or lost to the space outside the cavity. In this case, the lost energy escapes via an open edge. To achieve uniform illumination over the radiating surface, the slot length is varied with respect to the maximum radius ρ_{max} according to (Davis & Bialkowski, 1999)

$$l_{rad} = \left(5.8678 + 6.415\times10^{-3}\rho\right)\frac{12\times10^{9}}{f_o} \tag{1}$$

Where f_o is the center frequency.

The height of the radial guide (d) is dictated by the expression

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

λ_g is the wavelength of the slow wave in the guide caused by the dielectric material of relative permittivity ε_r filling the cavity. For grating lobes free radiation pattern, it was shown by (Davis & Bialkowski, 1997) that $\varepsilon_r$must be greater than 1.0. More on the theory and design of RLSA antenna with linear polarization utilizing disk ended feed probe can be found in (Davis & Bialkowski, 1997; Takada et al., 1992).

However in realizing the antenna, $\varepsilon_r$is selected in line with the frequency of operation. The desired slot pattern is then made. The design is finalized when the appropriate values of height of air space above the disk head (*h_above*), height of the disk head (*h_head)*, height of air space below the disk head (*h_below*), and diameter of the disk head (*D_disk*) are found.

2.2 The Proposed Antenna Structure

Design of RLSA antenna with the cavity filled by 2 layers of materials of different dielectric constant at 5.8 GHz was achieved by (Purnamirza & Rahman, 2012). In their design, good results were obtained as compared to the single material filled cavity design. Building on that and using the idea demonstrated by (Chen & Chia, 2006; Ibrahim et al., 2014) for using air cavity to boost bandwidth in broadband planar antennas, we proposed three layered cavity filling material linearly polarized RLSA antenna at 28 GHz to improve the bandwidth. The proposed antenna is shown in Figure 2.

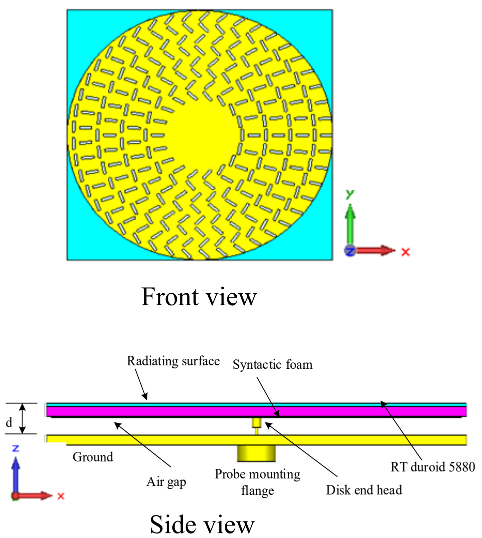


Figure 2. CST perspective of proposed antenna

As in the single material filled cavity, it consists of two parallel plates made of copper separated by space *d*. The upper plate with circular dimension of radius ρ carries the radiating slots and the lower plate with dimension 2ρ x 2ρ has at its bottom center the coaxial to waveguide transition feed. The space *d* is in turn filled with, starting from top: 2ρ x 2ρ layer of Rogers RT/duroid 5880 high frequency laminate of height *d_RT*& permittivity ε_{rRT} = 2.2, 2ρ x 2ρ layer of low dielectric constant syntactic foam of height *d_foam*& permittivity ε_{rfoam} = 1.2 and air layer of height *d_air*. Thus giving *d* to be

$$d = d\_RT + d\_foam + d\_air \tag{3}$$

The square shaped layers and lower plate are to ease manufacturing process and result in a well aligned structure.

In the theory for the double layered cavity filling material design presented by (Ibrahim et al., 2014) which is applicable for any number of layers in the cavity, the reflected waves from the slots will travel back through the layers towards the feed probe. The waves may add up or cancel out causing poor or good return loss respectively. But to achieve a good return loss, the waves must be made to add up destructively at any point. That means, the phase difference between the interfering waves must be out of phase or π radians always. To achieve that, the parameters that influence the signal characteristics were examined. These include ε_{rRT}, ε_{rfoam}, *d_RT*, *d_foam* and *d_air.*

Additionally since ε_{rAir} is constant, the material (ε_r) for the remaining two layerswere determined based on the frequency range they can handle and the ability to be tuned in line with the cavity height limit to yield low effective cavity dielectric constant. For this case, RT/duroid 5880 high frequency laminate (ε_{rRT} = 2.2) and low dielectric constant syntactic foam (ε_{rfoam} = 1.2) were found suitable. The effective cavity dielectric constant is calculated from (Ali & Khairuddin, 2003)

$$\varepsilon_{reff} = \left[\sum_{n=1}^{N} \frac{d_{xxn}}{\varepsilon_{rn}}\right]^{-1} \left[\sum_{n=1}^{N} d_{xxn}\right] \tag{4}$$

Where in the equation, d_{xxn}, N,ε_{rn} are the height of the layer n, number of layers and relative permittivity of layer n respectively.Furthermore, the design in this paper utilise the diskended feed probe with disk of height *h_disk*and diameter *D_disk*. This is in variance to the design of (Ibrahim, et al., 2014) which did not incorporate a disc head.

It can now be seen that the parameters of interest for the design are: *d_RT*, *d_foam*, *d_air*, *D_disk* and *h_disk*. It would have sufficed to mathematically render these parameters. But as shown in (Purnamirza & Rahman, 2012), that does not easily work as it lead to complex mathematical equation that is laborious to solve and only give a guess value. Therefore by running the design with beam squinted (Davis & Bialkowski, 1999) slot distribution pattern (effective in combating poor return performance) on Computer Simulation Technology Microwave Studio (CST MWS) 2014 software, the complex computation was avoided and the desired parameters were rendered easily.

3. Results

The proposed antenna and the established RLSA antenna designs referred were simulated for the frequency of 28 GHz. These designs include:

1. The conventional design (Davis & Bialkowski, 1999).
2. 2 layered (RT/duroid laminate and air gap) with disk ended probe post (Maina, et al., 2015).
3. 3 layered as in the proposed without disk ended feed probe post.

The design specification parameters for these designs are listed in Table I, while the obtained results are shown in Figures 3 to Figure 8.

Table 1. The Design specifications used for simulation

Centre frequency = 28 GHz Radius of antenna = 50 mm Thickness of ground = 1.0 mm Thickness of radiating surface = 0.1 mm		
Proposed	Conventional	2 layered with disk ended head
Cavity material height and thickness		
RT/duroid 5880 *d_RT* = 0.254 mm ε_{rRT} = 2.2	Polypropylene *d* = 3.0 mm ε_{rPp} = 2.33	RT/duroid 5880 *d_RT* = 0.254 mm ε_{rRT} = 2.2
Syntactic foam *d_foam* = 1.0 mm ε_{rfoam} = 1.2		Air gap *d_air* = 2.5 mm ε_{rAir} =1.0
Air gap *d_air* = 1.8 mm ε_{rAir} =1.0		

For the proposed and its variants, two or three layers of material of appropriate height and having different dielectric constants are used to fill the space *d* as shown in Figure 2. A dielectric constant gradient is thus created in the cavity. This in turn modulates the effective dielectric constant in the cavity. The value of this effective dielectric constant from equation (4) was calculated to be 1.11 for the proposed antenna and its version without the disk ended feed probe. Whereas that for the 2 layered cavity filling material design with disk ended feed probe is 1.05. The disk end of the feed makes direct contact with the slow wave material at the air slow wave material boundary with the whole post now residing in the air gap layer. For the conventional design as usual, the disk ended feed post is buried in a tight empty cavity between the ground and radiating surface at the center of the material filling the cavity.

Hence the design is completed by finding the optimum values of *h_above*, *h_head*, *h_below*, and *D_disk* in the case of the conventional design. *h_head* and *D_disk* for the proposed and the 2 layered cases. With the transition feed made by modifying straight dielectric coated 50 Ω SSMA coaxial to waveguide connector with disk head, the designs were simulated using CST MWS 2014 software.

The simulated return loss performance for the proposed with *D_disk* fixed and *h_head* varied are shown in Figure 3. It can be observed that *D_disk* = 2.0 mm with *h_head* = 1.2 mm can be adjudged the best in terms of the obtained impedance bandwidth with a value of 2.34 GHz and return loss of -15.04 dB at 28 GHz. Though other values of *h_head* gave lower return loss, the bandwidth obtained is less than that of the selected. The values of *D_disk* is then varied while keeping *h_head* = 1.2 mm. The result is as in Figure 4. In this case too, other values of *D_disk* gave lower return loss than the one with *D_disk* = 2.0 mm, but it still provided the largest impedance bandwidth among.

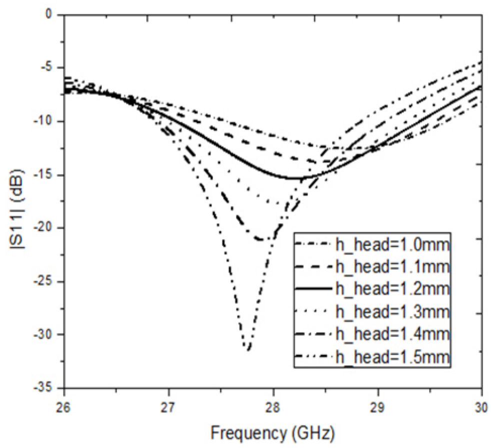


Figure 3. Simulated return loss of the proposed Antenna . D_disk = 2.0 mm and variable h_head

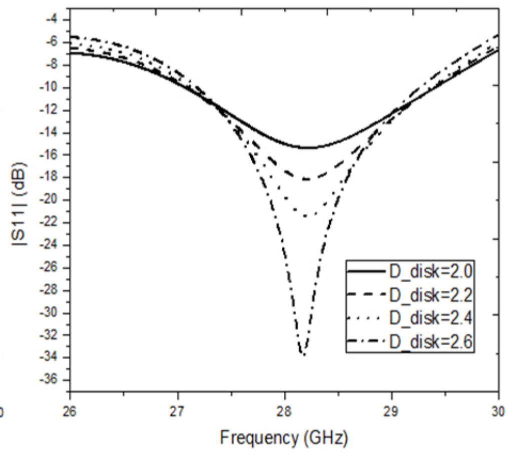


Figure 4. Simulated return loss of the proposed antenna . h_head = 1.2 mm and variable D_disk

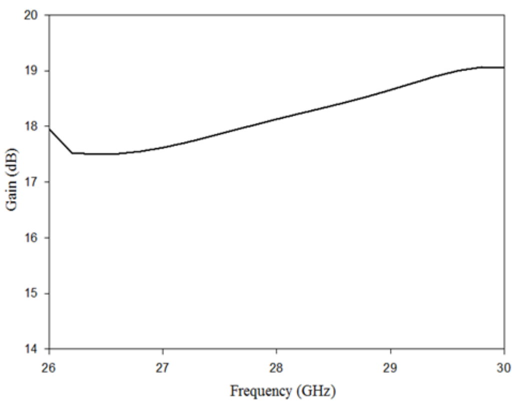


Figure 5. Simulated realized gain of the proposed antenna

Additionally, Figure 5 shows that a realized gain of 18.13 dB was observed at 28 GHz with the observed realized gain over the range of simulation being above 17.4 dB. The antenna's directivity is 18.4 dBi as revealed in Figure 6. With a radiation efficiency of -0.16655 dB from the CST 2D farfield snap shot in Figure 6, the efficiency can be calculated to be (http://www.edaboard.com/thread 309645.html)

$$\text{Efficiency} = 100 * 10^{(-0.1662/10)} = 96\ \%$$

The E - and H - plane polar radiation pattern plots are shown in Figure 7. A 3 dB angular beam width of8.5°and 9.0° were observed respectively.

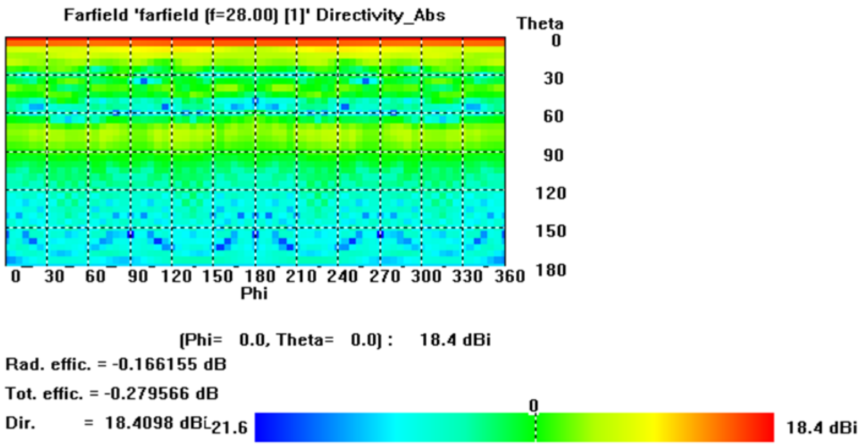
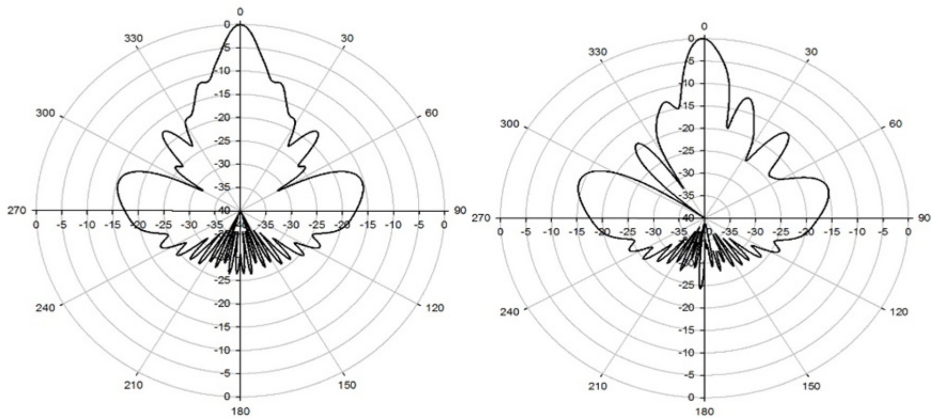


Figure6. 2D farfield plot



E – planeH – Plane

Figure7. Polar radiation pattern plot

The result for the comparison of the proposed design with the referred design mentioned above is shown in Figure 8. These included the conventional design with d = 3.0 mm [h_above = 0.3 mm, h_head = 1.5 mm,h_below = 1.2 mm], and D_disk= 2.6 mm; 2 layered design with disk head (2L_DH), 3 layered with no disk head (3L_NDH). It is evident from the plot that the proposed antenna outperformed the rest in terms of impedance bandwidth.

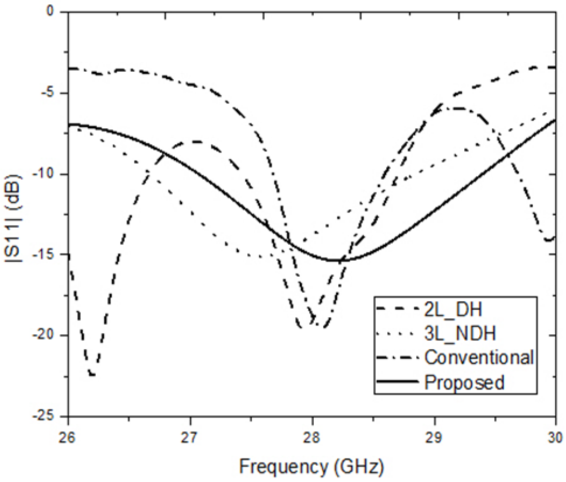


Figure 8. Simulated return loss of the proposed antenna with other designs

4. Conclusion

A multilayered cavity material low profile linearly polarized RLSA antenna with disk ended probe was designed and simulated for mobile broadband communication at 28 GHz. CST MWS 2014 software was used as the simulation platform. The antenna achieved has a diameter cum length of 100.0 mm. The multi layered cavity material structure comprised of RT/duroid 5880, low dielectric constant syntactic foam and air gap. The arrangement which created a dielectric constant gradient in the radial cavity minimizes the effect of reflection due to the small size of the antenna and from adjacent slots pairs on the radiating surface. This resulted in the impedance bandwidth enhancement.

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