TELKOMNIKA, Vol.17, No.5, October 2019, pp.2218~2225
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i5.12801

A wideband dielectric resonator antenna with a cross slot aperture for 5G communications

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Abstract

This paper represents design of a wideband Rectangular Dielectric Resonator antenna fed by an aperture coupled technique. A bandwidth of 2.2 GHz has been achieved using a cross slot aperture in a ground plane for Dielectric Resonator Antenna (DRA). The simulated gain value achieved is 6.5 dBi. The Rectangular Dielectric Resonator which has been designed in this paper can be used in 5G application frequency band of 24.25-27.5 GHz. The calculated percentage bandwidth is 15.38%. An optimization of slot dimensions has also mentioned which can help to select a desired impedance match. The measured gain and bandwidth are efficient to use this design for various 5G applications. This unit cell wideband DRA can be used for millimeter wave frequencies of 5G.

Keywords: *5G, 26 GHz, aperture coupling, cross slot aperture, DRA*

1. Introduction

The mm wave communication needs non-metallic radiators to act as antennas. The metallic losses as are very high so dielectric resonators are preferred at higher frequency bands. Dielectric resonators provide a high Q value with large value of permittivity. The rectangular Dielectric Resonators have practical advantages over other shapes. The mode degeneracy can be manipulated over the different dimensions of a rectangular Dielectric Resonator Antenna [1]. The Dielectric Resonators has several advantages like Higher Radiation efficiency (>90%) because of absence of Metallic conductors. For mm wave communications Dielectric Resonators play a key role to achieve higher data rates and bandwidth. At a desigred resonant frequency the aspect ratios of a rectangular DRA as height/length and width/length can be chosen independently to achieve a desigred impedance match and the bandwidth of a DRA depends on its aspect ratios, a rectangular-shaped DRA has more flexibility in terms of bandwidth control [2]. The size of Dielectric Resonators are function of relative permittivity of the material, so for the actual dimensions of a DRA can be controlled to minimal with larger Permittivity values from 10 to 100. The resonant mode used depends on the geometry of the resonator and the required radiation pattern. The radiated fields are not strongly confined which can be easily controlled to achieve maximum radiation efficiency. The main reason that mmWave spectrum lies idle is that,until recently, it had been deemed unsuitable for mobile communications because of rather hostile propagation qualities, including strong pathloss, atmospheric and rain absorption, low diffraction around obstacles and penetration through objects, and, further, because of strong phase noise and exorbitant equipment costs [3, 4]. To fullfill the demands of 5G networks as larger capacity, higher data rate, better connectivity, more advanced reliability,concepts and new design approaches to make antennas are in high necessity.One of the commonly declared 5G frequency band is 24.25-27.5 GHz. Therefore it is also essential to design antennas that can provide higher gain to overcome the path loss caused by the atmospheric absorption of electromagnetic waves at mm wave communications [5]. Dielectric antennas are one solution which can be used at mm wave frequency bands for better performance. In this paper a Dielectric Resonator has been designed to achieve a large value of bandwidth.

A dielectric resonator can be excited through a strip line, Aperture, Coaxial or substrate integrated waveguide techniques. In this paper an Aperture coupled technique has been used

Received October 20, 2018; Revised March 15, 2019; Accepted April 19, 2019

through a cross slot [6, 7]. By choosing proper dimensions of the rectangular DRA, the mode degeneracy problem can be avoided and, in addition, the bandwidth can be optimized [8].

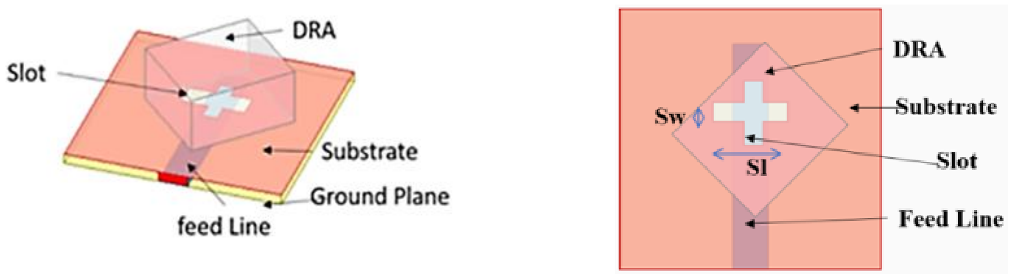
The impedance bandwidth of a Dielectric Resonator is the function of materials permittivity and Length to Height ratio. Because of Advantages like low loss, small size, wide bandwidth and easy of excitation the dielectric resonators are used at mm wave transmissions. This improvement in bandwidth is primarily a result of the additional degrees of freedom offered by the stub length and coupling aperture size.Dielectric Resonator antennas (DRA) [9, 10] are purely made of dielectric materials with no conductor loss and are more suitable for millimeter-wave systems. Unlike many other resonant antennas, the aspect ratio of most shapes of dielectric resonator antennas can be altered while maintaining the same resonant frequency, for a given dielectric constant [11]. A tall, thin dielectric resonator antenna can thus have the same resonant frequency (but not necessarily the same bandwidth) as a low, wide dielectric resonator antenna [12]. This allows for a certain degree of flexibility in shaping the dielectric resonator antenna to suit specific requirements [13]. The size of the DRA is proportional to $\lambda 0/\sqrt{\epsilon r}$ with $\lambda_0=c/f_0$ being the free-space wavelength at the resonant frequency $f0$ and where ϵr denotes the relative permittivity of the material forming the radiating structure. As compared to traditional metallic antennas whose size is proportional to $\lambda 0$, DRAs are characterized by a smaller form factor especially when a material with high dielectric constant (ϵr) is selected for the design [14].

2. Research Method

This section represents the basic design approach of a Rectangular DRA using a cross slot Aperture in the ground plane. This technique exposes the DRA with maximum coupling energy from the feed. Antenna Design and simulation work has been carried out using HFSS.

2.1. Design of Rectangular DRA resonating at 26 GHz

A rectangular Dielectric Resonator has been designed with dimensions a=2.9 mm, b=2.6 mm, and d=1.4 mm. A dielectric material Roger 5880 with permittivity of 2 is used as a substrate of dimensions W=5.74 mm, L=5.74 mm, and H=0.254 mm. A micro strip transmission line of 50 ohm impedance is used to feed the DRA through an aperture made in the ground plane. The ground plane is placed above to the substrate and the micro strip feed line is placed just below the dielectric substrate. A cross slot type aperture of dimensions SW=0.62 mm, SL=1.67 mm has been made fed the DRA through the ground plane. The amount of coupling depends upon the Electric field distribution over the transmission line and its impedance match. The appropriate slot dimensions can match with the 50 ohm transmission line for perfect impedance match [15]. An optimization of slot dimensions has been carried out to get a proper impedance match and return loss. The DRA is excited over TEx11 mode and the achieved gain is 6.5 dBi. Figure 1 represents a rectangular DRA excited by a cross slot aperture. The DRA is optimized and rotated by 45 degree to obtain the required resonance.



(a) (b)

Figure 1. DRA fed by cross slot (a) 3D view of rectangular DRA (b) top view of DRA

The electric field distribution over the rectangular DRA depends on the slot dimensions and the orientation of the DRA. Figure 2 shows the elctic field and current distribution over the DRA. The current and electric field distrinution can be controlled using the microstrip feed line dimensions. The resonating frequency for a rectangular dieletric resonator can be calculated from (1):

$$k_x \times \tan(k_x d/2) = \sqrt{(\varepsilon_r - 1)k_0^2 - k_x^2} \quad (1)$$

where

$$k_0 = \frac{2\pi}{\lambda 0} = \frac{2\pi f0}{c}$$

$$k_y = \frac{\pi}{w},\ k_z = \frac{\pi}{b} \quad \text{and} \quad k_x^2 + k_y^2 + k_z^2 = \varepsilon_r \times k_0^2 \quad (2)$$

here k_0 is free space wave number and Kx, Ky and Kz are the wave numbers along x, y and z directions. The aperture consists of the slot cut in a ground plane, having dimensions SL (length) and SW (width). The slot length is located along the x axis and the slot width along y axis, centered to microstrip line. The orientation of the slot will excite the TEx11 mode of the DRA [16]. The slot length ls is chosen to achieve strong coupling between DRA [17] and the feed line, and also so that, it resonate within the band of operation. Furthermore, different modes of the DRA can be used to obtain different radiation characteristics [18]. Besides controlling the characteristic impedance of the feed line, the width of the feed line affects the coupling through the slot. To a certain degree, thinner feed lines couple more strongly to the slot. For maximum coupling, the feed line should be positioned at right angles to the center of the slot [1]. Although DRAs received attention originally for millimeter-wave applications, they are also widely investigated at microwave frequency or even radio frequency (RF). It is because DRAs are volume devices that offer designers more degrees of freedom than 2-D-type antennas (e.g., microstrip antennas) or 1-D-type antennas (e.g., monopole antennas). Other advantages of DRAs include their small size, light weight, low cost, ease of excitation, and relative wide bandwidth (BW) as compared with microstrip antennas [10, 19].

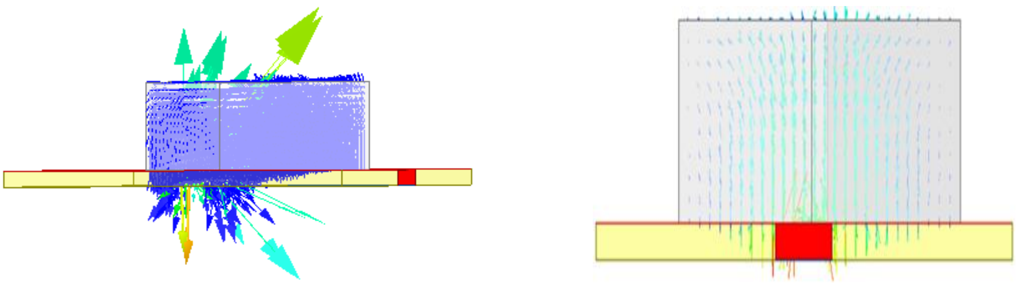

(a) (b)

Figure 2. Electric field distribution over DRA
(a) electric field over DRA (b) current distribution over DRA

3. Parameter Calculation and Analysis

The aperture consists of the slot cut in a ground plane, having dimensions SL (length) and SW (width). The slot length is located along the x axis and the slot width along y axis, centered to microstrip line. The orientation of the slot will excite the TEx11 mode of the DRA.The slot length ls is chosen to achieve strong coupling between DRA and the feed line, and also so that, it resonate within the band of operation. Furthermore, different modes of the DRA can be used to obtain different radiation characteristics [7]. Besides controlling the characteristic impedance of the feed line, the width of the feed line affects the coupling through the slot. To a certain degree, thinner feed lines couple more strongly to the slot. For maximum coupling, the feed line should be positioned at right angles to the center of the slot [1, 20]. The slot length (SL) and width (SW)are calculated as mentioned in equations.

$S_L = 0.4 * \lambda 0 / \sqrt{\mathcal{E}_{eff}} = 0.4 * 11.53/\sqrt{6.1} = 1.867$ mm and
$S_W = 0.2 * SL = 0.373$ mm

The slot imensions are considered over the ground plane and a cut has been made over the ground plane. The slot is located at the center of the microstrip line. A narrow slot width is preferred in general to avoid generation of back lobe radiation component [21]. The stub extension is S is calculated as:

$S=\lambda g / 4 = 1.72$ mm

here λg is called as guided wavelength of the substrate and can be calculated as

$\lambda g = \lambda / \sqrt{(\epsilon eff)}$

where εeff can be calculated as:

ε_eff=((ε_r+1))/2+((ε_r-1))/2 √((1+12h)⁄w)

The coupling factor depends upon the current distribution over the microstrip line. Here an offset type strip line feeding has been chosen where the aperture is placed just above to the half dimension of the Dielectric Resonator [22]. It helps in maximizing coupling between the strip line and the DRA through the aperture. So, the slot dimensions are chosen to be perfectly matched with the impedance. Table 1 represents the dimensions of rectangular antenna, microstrip feed line length and width.

Table 1. Antenna Dimensions

Parameters	Dimensions (mm)
a	2.9
b	2.6
d	1.4
fw	0.78
fl	4.2

The exact positioning of the aperture helps to achieve a large bandwidth in DRA. The amount of coupling depends upon the dimension of the both slot and the strip line. As the coupling depends upon the total Electric field distribution over the transmission line [23]. The coupling factor can be expressed as:

$C=\int_v [(E_{DRA} . Js)dV]$

where E DRA represents the Electric field distributed over the transmission line and Js represents a current source.

4. Results and Discussion

The simulated return loss achieved is -52 db with a bandwidth of 2.2 GHz. The calculated percentage bandwidth is 15.38%. Figure 3 and Figure 4 represents the simulated return loss and optimized return loss results. The simulation and parametric study were carried out using HFSS. The rectangular slot dimensions generate a distributed electric feld pattern over the DRA, As a narrow aperture dimension is able to couple maximum radiated energy to the DRA. The lowest order mode TEx11 has get excited here. The DRA has been tilted to an angle of 45 degree to resonate at the desigred frequency An optimization study has been done with different slot dimensions for proper impedance matching [15, 24]. Figure 5 shows the impedance match at required frequencies. The slot length and width were varied to get a minimum return loss and for high impedance bandwidth. Figures 6 and 7 represent the return loss with different slot length and width. Figures 4, 6, and 7 shows the return loss data at different slot dimensions which are optimized to get a desigred impedance bandwidth.

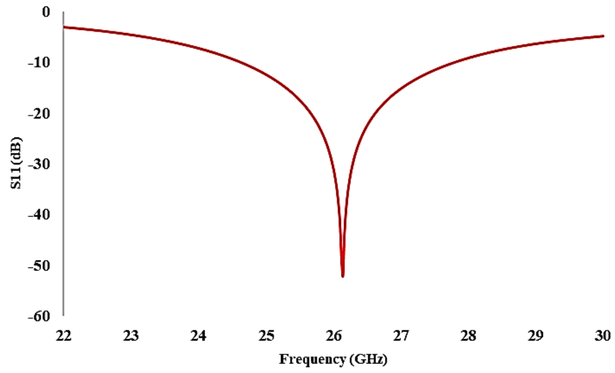


Figure 3. S11 (dB) Vs Frequency (GHz)

The slot position over a strip line has been optimized at different locations. As the voltage over a strip line is maximum at the near end, maximum current will flow towards the end of the feed line and minimum current will appear at the centre of feed. So to attain an impedance of 50 ohm is difficult as impedance is very high. Using HFSS the slot position is optimized to attain minimum impedance match. Figure 7 represents the slot location optimization in HFSS with respect to its respective return loss [25].

Table 2 represents the return loss in dB at different slot length and width which is achieved through slot dimension optimization in HFSS. The proper matching of the measured impedance bandwidth is achieved at slot length of 1.67 mm and slot width of 0.62 mm. The measured gain for both E and H plane is shown in Figure 8 for both phi at 0 and phi at 90 respectively. The simulated gain is 6.5 dBi. The 3D ratiarion pattern is shown in Figure 9. A gain of 6.5 dBi represents with a minimum back radiation lobe.

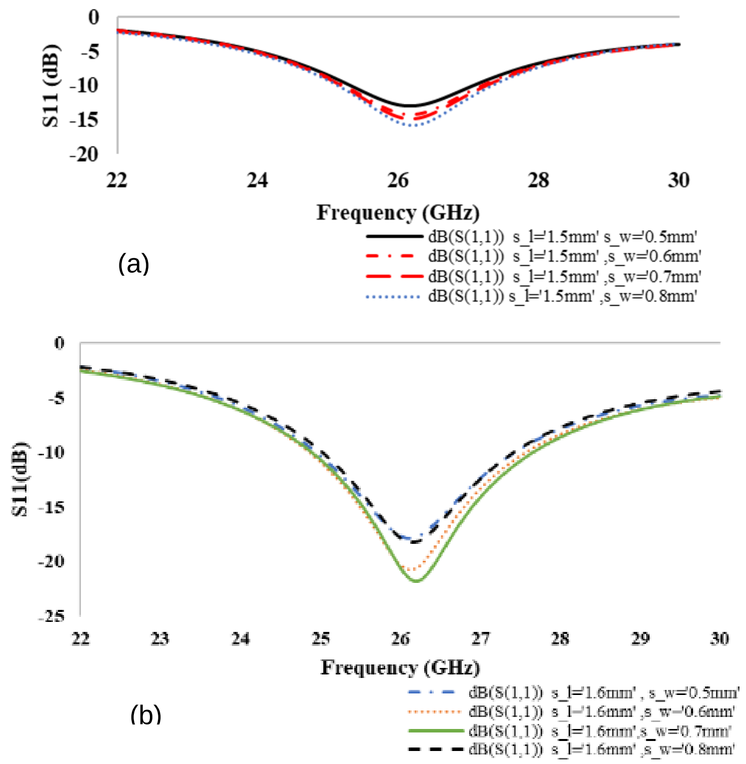


Figure 4. Return loss optimization
(a) return loss (db) at different slot width dimensions (mm) (b) varying slot length

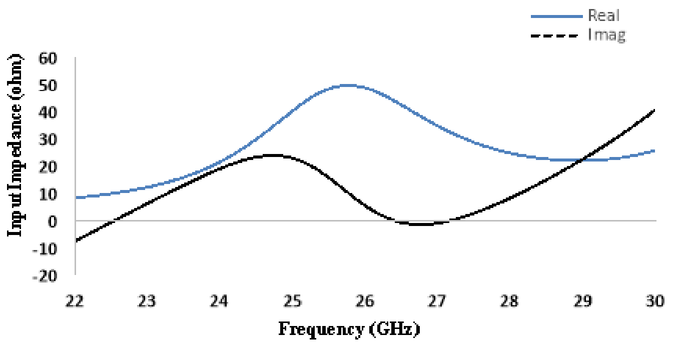


Figure 5. Input impedance (ohm) vs frequency

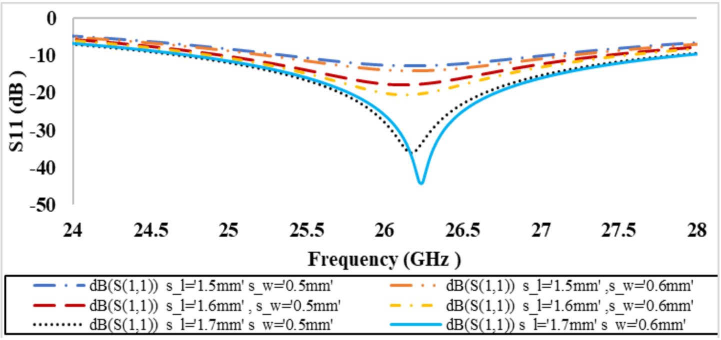


Figure 6. Return loss optimization

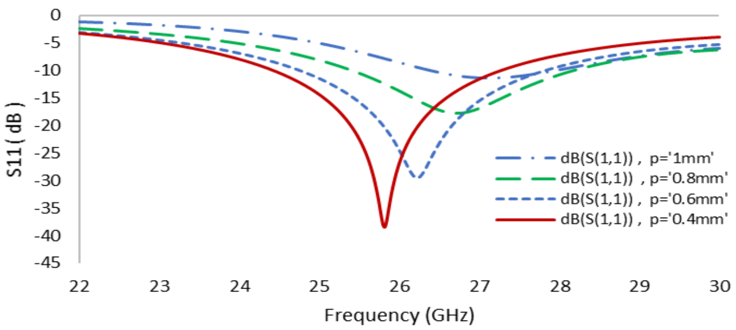


Figure 7. Return loss optimization with DRA position

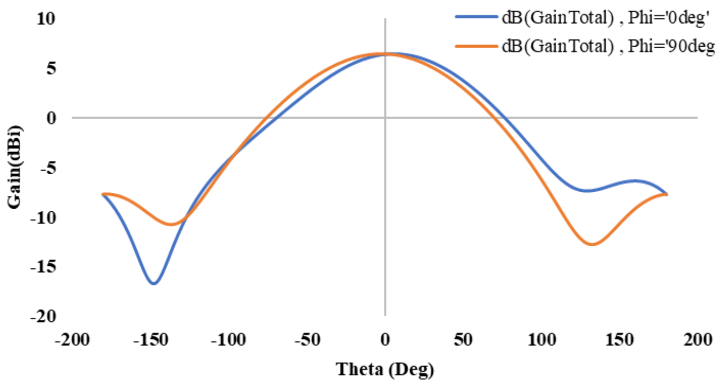


Figure 8. Gain (dBi) at phi=0 deg and phi=90 deg

Table 2. The Optimization Data for Different Slot Dimensions

Slot Length SL (mm)	Slot Width SW (mm)	S11 (dB)
1.67	0.62	-52
1.5	0.5	-15
1.5	0.6	-14
1.5	0.7	-13
1.5	0.8	-12
1.6	0.5	-22
1.6	0.6	-20
1.6	0.7	-17
1.6	0.8	-16
1.5	0.5	-42
1.6	0.5	-38
1.7	0.5	-18
1.5	0.6	-17
1.6	0.6	-16
1.7	0.6	-11

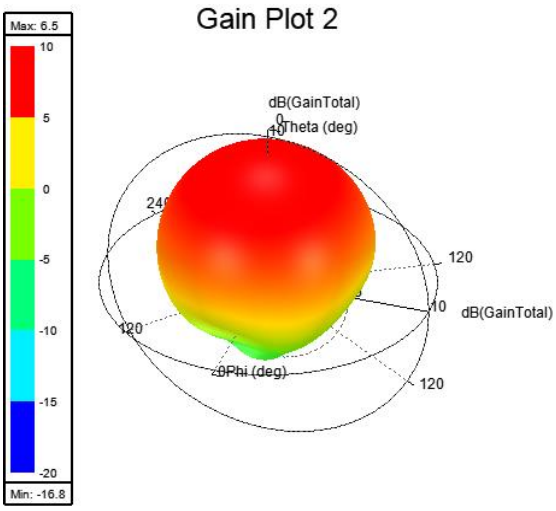


Figure 9. 3D radiation pattern

5. Conclusion

A bandwidth of 2.2 GHz has been achieved at resonating frequency of 26 GHz. This DRA design can be used for wideband applications in the 5G frequency band of 24.25–27.5 GHz. The calculated percentage bandwidth is 15.38%. The coupling factor can further be improved with variations in the slot dimensions with proper impedance matching.

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