Dual $HE_{11\delta}$ Mode CDRA for Polarization Diversity Applications in K Band Point-to-Point Communications

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Submitted November 26, 2019 / Accepted May 11, 2020

Abstract. *A dual port Cylindrical Dielectric Resonator Antenna (CDRA) has been demonstrated for point-to-point communication link in K band (22 GHz) applications in this work. The antenna offers polarization diversity which is introduced by degenerating $HE_{11\delta}$ modes in a single CDRA. Orthogonal feed lines produce two modes which are perpendicular so they do not interfere with each other and offer excellent linear polarization diversity in orthogonal planes. Since the CDRA size is compact, the feed lines have been modified to ensure the generation of desired modes. A detailed investigation into the generation of resonant modes along with parametric analysis is presented. Measured results show fractional bandwidth of 9.5% and 18.18% for port 1 and port 2 respectively. Isolation of better than 32 dB has been measured between the two ports through transmission coefficient. Difference of about 20 dB between co-polarization and cross polarization powers in both planes for broadside direction has been measured which endorses the polarization diversity performance of the antenna. Different MIMO performance parameters including envelope correlation coefficient, total active reflection coefficient, channel capacity loss and mean effective gain have been measured to assess the performance of the design.*

Keywords

Cylindrical Dielectric Resonator Antenna (CDRA), degenerated modes, hybrid modes, polarization diversity

1. Introduction

Modern wireless standards are focused on throughput and reliability as far as the physical layer design of a transceiver is concerned. The proliferation of user data in existing frequency bands has exacerbated the quality of communication link. One of the practical solutions to this challenge is to use higher frequency bands for establishing the RF link. This will not only help in reducing the load on existing infrastructure but the device size will also reduce significantly. Antenna, being one of the core components of an RF front-end, requires special attention. Diversity antennas are extremely popular to either enhance the throughput or improve the signal-to-noise ratio [1, 2, 3]. Spatial diversity, pattern diversity and polarization diversity are commonly deployed techniques [4, 5]. Since we require miniaturization in consumer products, the antenna size plays a significant role in overall compactness of an RF-front end. This limitation has restricted the use of spatial diversity techniques for consumer products thus leaving with pattern and polarization diversity.

Dielectric Resonator Antenna (DRA) is an excellent choice for high frequency applications since they are immune to ohmic losses and tolerant to thermal variations [6]. The size of a DRA is compact and more practical for K-band or beyond applications. Cylindrical DRA (CDRA) is commonly used profile of a DRA that has additional benefit of its symmetry thus allowing excitation of various modes especially degenerated ones. Although the fundamental mode of a CDRA is $TE_{01\delta}$ hybrid modes such as $HE_{11\delta}$ are suitable for polarization diversity applications. Ever since the first article was reported on CDRA [7] a number of research papers have been published which investigate various aspects of CDRA [8–15]. Like in [8] a dual polarization CDRA is proposed which operates on $TE_{01\delta}$ and $TM_{01\delta}$ modes for pattern diversity applications. Each of these modes generates linearly polarized waves which are orthogonal to each other. Similarly in another research study a dual band CDRA is presented which exploits HEM_{111} mode and higher order HEM_{113} mode for producing two resonant frequencies at 1.8 GHz and 2.4 GHz [9]. Recently a circularly polarized diversity antenna is reported which is based on a CDRA fed with planar shorted cross microstrip design. The customized feed topology is capable of exciting $TM_{01\delta}$ mode, without probe feeding, and $TE_{011+\delta}$ mode simultaneously at 2.45 GHz [10]. In another design a CDRA has been investigated that produces polarization diversity. Hybrid modes $HE_{11\delta}^x$ and $HE_{11\delta}^y$ are launched in the CDRA from their respective ports. The design offers impedance bandwidth of 11.7% and 11.4% [11]. A very recent design of CDRA is reported in [12], the design is based on pattern diversity and the

CDRA operates on 2.4 GHz band and two ports are used to excite $TM_{01\delta}$ and $HEM_{11\delta}$ modes in the DRA. The antenna offers 6.1% and 9.1% of impedance bandwidths for the two modes respectively. Three port polarization diversity antenna has been proposed in [13] which generates $TM_{01\delta}$ and $HEM_{12\delta+1}$ modes, the antenna operates at 2.45 GHz where one port generates $TM_{01\delta}$ while the other two ports excite balanced slots to generate $HEM_{12\delta+1}$. In [14] an omnidirectional circularly polarized design is proposed that offers pattern diversity. The antenna generates a fundamental $TM_{01\delta}$ mode and a hybrid $HEM_{12\delta+1}$ mode for omnidirectional and broadside radiation pattern respectively. The design is demonstrated at 2.4 GHz. Pattern diversity has been achieved in another recent study where even and odd modes of CPW feed have been used to generate end-fire and broadside radiation patterns from the CDRA respectively [15]. Most of the work available in literature is based on either pattern diversity or polarization diversity using two different modes with limitation on antenna gain or impedance bandwidth.

In this research work a CDRA with polarization diversity features is presented that operates on two $HE_{11\delta}$ modes generated orthogonally inside the CDRA with the help of two orthogonal microstrip feeds. The resonant frequency of 22 GHz has been chosen for the design demonstration and this high frequency allows the usage of thin CDRA which is cut off a commercially available high frequency laminate. High isolation is achieved between the two feeding ports and sufficient difference between the powers of co-polarized and cross polarized signal is observed.

2. Antenna Configuration

CDRA offers a wide range of design options which is principally steered by the requirements of desired mode. Since polarization diversity is intended to be introduced in this design thus the first two modes $TE_{01\delta}$ and $TM_{01\delta}$ are not suitable since none of them can be degenerated orthogonally in a single CDRA. $HE_{11\delta}$ mode however can be excited simultaneously from two feed lines orthogonally placed. This technique excites two $HE_{11\delta}$ modes that are perpendicular to each other and also have low mutual coupling. The most common technique to excite $HE_{11\delta}$ mode is through aperture coupling with the help of a microstrip feed. Since the plane of symmetry for this mode, at $z = 0$ plane, is perfect E thus the ground plane of microstrip feed acts as a perfect E plane for CDRA as well as it has an aperture through which the fields are coupled to the CDRA. This hybrid mode radiates in the broad side and the far field radiations resembles to that of a magnetic dipole. The optimized geometry of the CDRA and the direction of magnetic field vector generated by respective feeding lines are shown in Fig. 1a and Fig. 1b.

$HE_{11\delta}$ mode is excited through a rectangular aperture etched in the middle of CDRA in the ground plane along with a slightly extended feed line beneath it. However, the

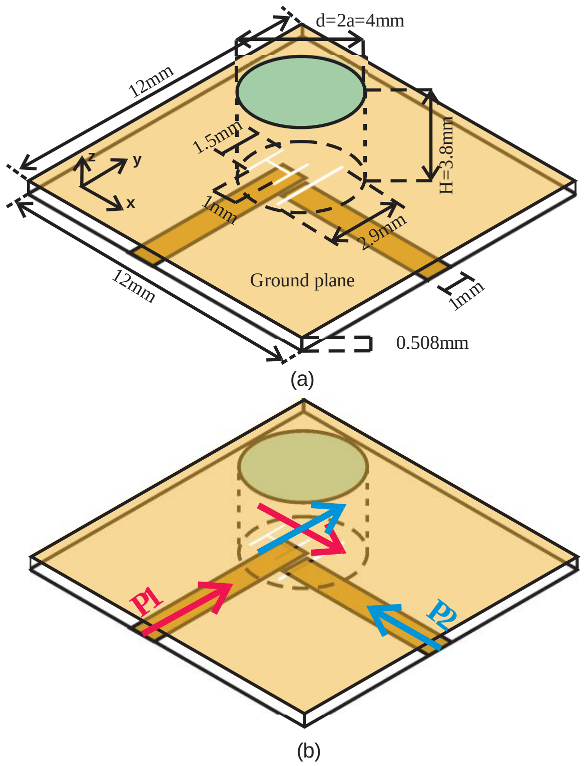

Fig. 1. Layout of CDRA: (a) Optimized geometry, (b) direction of magnetic vector.

additional orthogonal feed line and rectangular aperture for another port is not possible thus a modified H shape slot has been used to couple the desired mode in the CDRA from the other port [16]. Alongside, the feed line from port 1 is slightly displaced towards negative x axis to ensure better isolation. Neltec NH9338 substrate has been used in this study that has thickness of 0.5 mm and dielectric constant of 3.38. CDRA has been cut from another substrate (Ro TMM6) which has thickness of 3.8 mm and radius of 2 mm. The dielectric constant of this material is 6. The design dimensions of the CDRA have been estimated by the relation (1) [17].

$$f_{\mathrm{TM}npm} = \frac{c}{2\pi a\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(X'_{np}\right)^2 + \left((2m+1)a\pi/2H\right)^2} \quad (1)$$

where $n = 1$, $p = 1$ and $m = 0$.

Bessel function of the first kind has root of X_{np} whereas X'_{np} used in (1) is the first order derivative of this root. Its value depends on n and p and in this case the first order derivate has value of 1.841. The above theoretical relation gives a good estimate for starting values of CDRA. In [18] R. K. Moniga has reported the empirical relation for $HE_{11\delta}$ mode of CDRA; the relation is given in (2).

$$f_{\mathrm{HE}11\delta} = \frac{6.324 \cdot c}{2\pi a\sqrt{\varepsilon_r + 2}} \left[0.27 + 0.36(a/2H) + 0.02(a/2H)^2\right]. \quad (2)$$

The empirical relation (2) is valid for $0.4 \le a/H \le 6$.

The radiated quality factor of the DRA is another important parameter which describes the bandwidth of the antenna. Higher values of quality factor restrict the bandwidth and for low values of radiation quality factor larger bandwidth can be achieved. The empirical relation for calculating radiation quality factor for $HE_{11\delta}$ mode is given in (3) [18]

$$Q_{\mathrm{rad}} = 0.01007\varepsilon_{\mathrm{r}}^{1.3}\frac{a}{H}\cdot \left\{1+100\exp\left[-2.05\left(0.5\left(\frac{a}{H}\right)-0.0125\left(\frac{a}{H}\right)^{2}\right)\right]\right\}. \quad (3)$$

The radiation quality factor relation is also valid for $0.4 \le a/H \le 6$.

Normalized free space wave number k_{0a} has been calculated and plotted from the relations (1) and (2). The quality factor is also presented for different ratios of *a/H* in Fig. 2.

It can be observed that the quality factor peaks for *a/H* ratio of 1. Here it is important to note that the above plot is only valid for CDRA placed on a perfect E plane. In this work *a/H* ratio of 0.526 has been chosen for a suitable bandwidth however this ratio can be adjusted as per the requirement of the bandwidth. The plot of normalized free space wave number is also helpful in calculating the resonant frequency of the $HE_{11\delta}$ mode in any ratio from 0.4 to 5 with dielectric constant of 6.

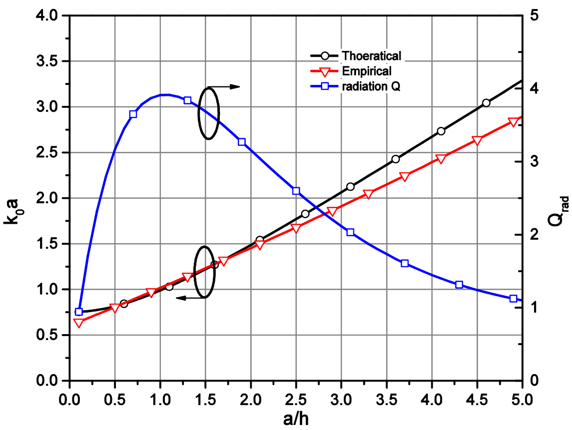

Fig. 2. Normalized free space wave number and radiation quality factor $HE_{11\delta}$ mode with ε_r of 6.

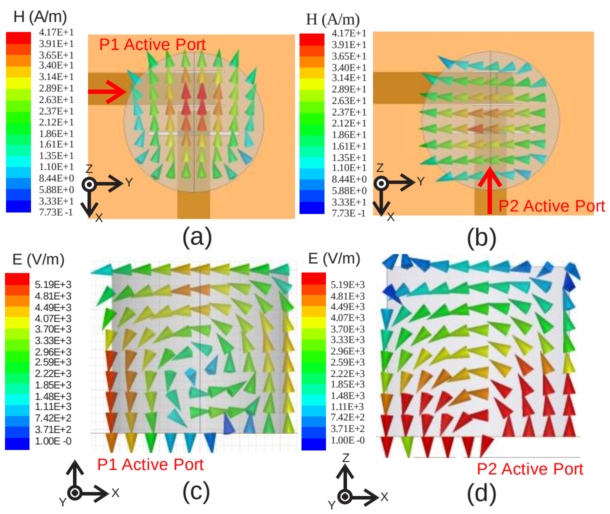

Fig. 3. $HE_{11\delta}$ mode plot in the CDRA at resonant frequency: (a) H field vector plot for port 1; (b) H field vector plot for port 2; (c) E field vector plot for port 1; (d) E field vector plot for port 2.

The microstrip feed line from port 1 has been offset slightly from the center to accommodate the second microstrip feed from port 2. However, it is assured that $HE_{11\delta}$ mode is being generated from both ports and they do not couple strongly within the CDRA. The E field and H field plots from both ports are presented in Fig. 3. The mode plot confirms that despite of variation in ideal feeding mechanism the desired $HE_{11\delta}$ mode is excited from both ports.

3. Parametric Analysis

Since the fundamental design parameters have been finalized which comprise of the CDRA size and the mode it is operating up on. The H shape slot dimensions for port 1 and rectangular slot dimensions for port 2 also require optimization. The parametric analysis of the center slot length, arm length and the width of the H shape slot, that couples energy to CDRA from port 1, are presented in Fig. 4. The simulations were carried out in a commercially available full wave 3D electromagnetic simulator that works on Finite Element Method based algorithm (Ansys HFSS). The center slot length and the extended arm length of the H shape slot mainly direct the resonant frequency by optimizing the coupled energy. Slot width fine tunes the reflection coefficient. Likewise the parametric analysis of the rectangular slot length and width for port 2 has been

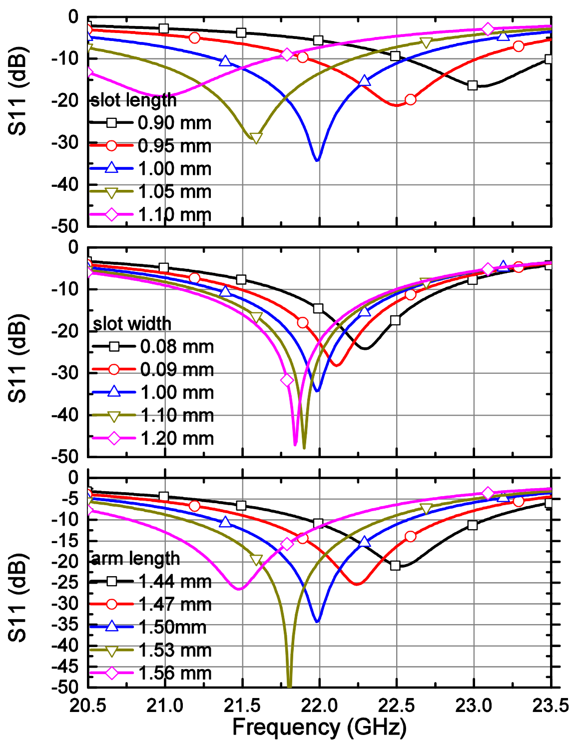

Fig. 4. Parametric analysis of H shape coupling slot for port 1.

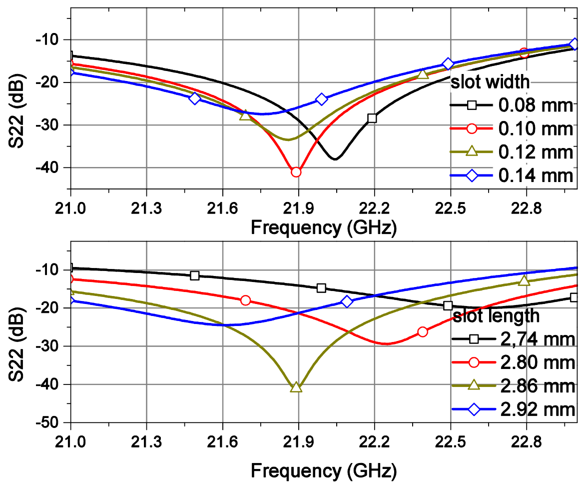

Fig. 5. Parametric analysis of the rectangular coupling slot for port 2.

presented in Fig. 5. Here it can be observed that the slot length significantly affects the resonant frequency and the slot width changes the return loss by varying the impedance.

The optimized dimensions shown in Fig. 1a have been used for fabrication. The design has been realized on 0.5 mm thick Neltec NH9338, and the CDRA was made from Rogers TMM 6 substrate with thickness of 3.8 mm.

4. Measured Results

The measured and simulated results of the CDRA are compared in Fig. 6. The simulated fractional bandwidth of the CDRA is 4.54% when port 1 is excited and it increases to 15% when port 2 is excited. The bandwidth can be changed by varying *a/H* ratio as shown in Fig. 2. The port isolation simulated through transmission coefficient came out to be 33 dB.

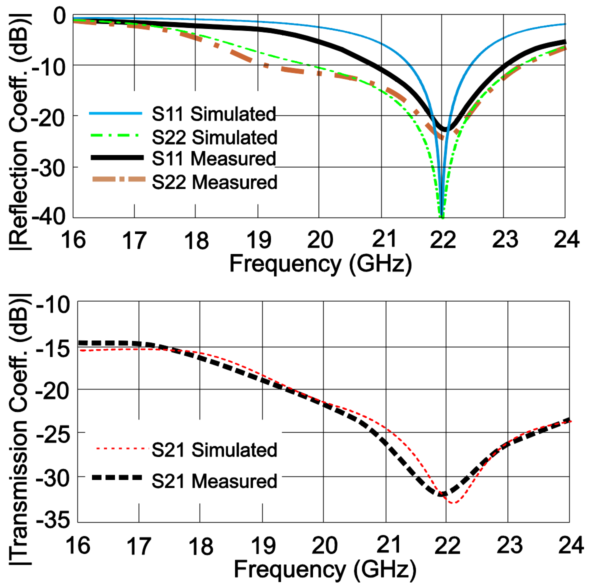

Fig. 6. Simulated and measured scattering parameter response of CDRA.

The measured and simulated results are in good agreement, whereas the measured results offer enhanced fractional bandwidth. When port 1 is excited the fractional bandwidth is measured to be 9.5% and when measured for port 2 it came out to be 18.8%. The measured isolation between the two ports is 32.5 dB which shows that the two degenerated modes are properly decoupled.

4.1 MIMO Performance Parameters

The CDRA design offers polarization diversity therefore in order to assess its performance for diversity applications various parameters have been investigated. Envelope Correlation Coefficient (*ECC*) is a basic parameter which reports on the radiation pattern independence of antenna elements used in the design. For ideal response the correlation among the MIMO element should be zero however, for practical purposes the values smaller than –3 dB or 0.5 are considered fair. The ECC can be approximated through scattering parameters for an isotropic environment as proposed by Blanch et al. (4) [19]. Likewise Diversity Gain (*DG*) is another parameter which shows the improvement in the signal to noise ratio performance of a particular device by employing the diversity antenna. DG is related to ECC as shown in (5). Measured ECC and DG of the CDRA is shown in Fig. 7. It can be observed that the CDRA has high diversity gain close to 10 dB and correlation of less than –55 dB at the resonant frequency.

$$ECC = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^2}{\left(1-\left|S_{22}\right|^2-\left|S_{12}\right|^2\right)\left(1-\left|S_{11}\right|^2-\left|S_{21}\right|^2\right)}, \tag{4}$$

$$DG = 10\sqrt{1-\left|ECC\right|^2}\ . \tag{5}$$

For conventional antennas the reflection coefficient shows the basic insight into the device performance however, in the presence of mutual coupling active reflection coefficient is necessary that shows the performance of a multi element antenna in the presence of mutual coupling when all elements are excited. This reflection coefficient is referred to as Total Active Reflection Coefficient (*TARC*)

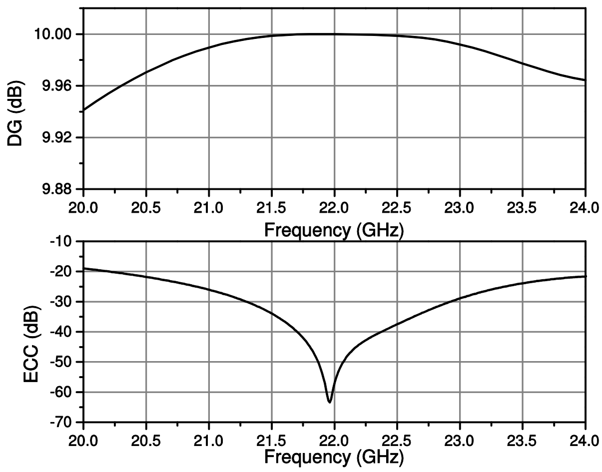

Fig. 7. Measured ECC and DG.

and is given in (6). Measured TARC is presented in Fig. 8. For an optimum diversity antenna system TARC should be less than 0 dB; here at resonant frequency TARC is less than –15 dB. Likewise for MIMO antennas it is imperative to estimate the Channel Capacity Loss (*CCL*), which tells the upper limit of the data rate that can be achieved through this antenna system without any loss to the information. CCL has been calculated from the measured data by taking log of the correlation matrix through (7) as shown in Fig. 8. For a good MIMO antenna system CCL is desired to be less than 0.5 bits/s/Hz; here at the resonant frequency the CCL is much smaller than the minimum requirements as shown in Fig. 8.

$$TARC = \sqrt{\frac{\left|S_{11}+S_{12}\right|^2+\left|S_{21}+S_{22}\right|^2}{2}}, \tag{6}$$

$$CCL = -\log_2\begin{vmatrix} P_{11} & P_{12} \\ P_{21} & P_{22}\end{vmatrix} \tag{7}$$

where
$$P_{ii} = 1-\left|S_{ii}\right|^2-\left|S_{ij}\right|^2, \tag{8}$$

$$P_{ij} = -\left(S_{ii}^{*}S_{ij}+S_{ji}S_{jj}^{*}\right), \tag{9}$$

i and *j* represent the antenna elements, or modes in this case, for an $N \times N$ MIMO system.

Mean Effective Gain (*MEG*) of a diversity antenna is another very important performance parameter of a MIMO antenna. For a multipath fading environment MEG represents the ratio of the power received by the MIMO antenna to the power received by an isotropic antenna. It is calculated through (10). A maximum of –3 dB MEG can be achieved for an antenna. It is also desired that the ratio of the MEG of both elements (modes in this case) should be close to 0 dB. The MEGs and ratio of MEGs have been determined and plotted in Fig. 9. It can be observed that the antenna has excellent MEG values for both modes and they are also close to each other around the resonant frequency and the MEG ratio is about –1 dB. These values represent excellent MIMO performance for any antenna.

$$MEG_i = 0.5\eta_{i,\,\mathrm{rad}}\left(1-\sum_{j=1}^{N}\left|S_{ij}\right|^2\right). \tag{10}$$

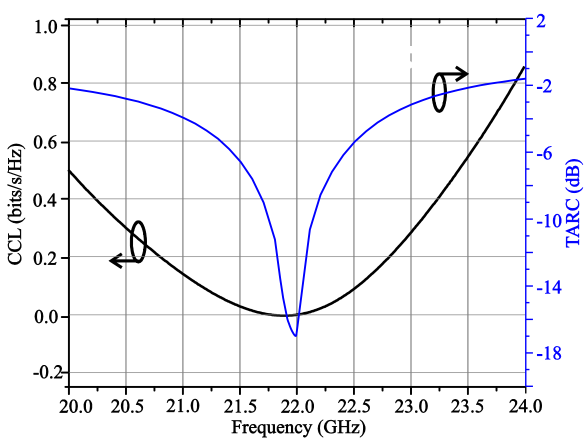

Fig. 8. Measured CCL and TARC.

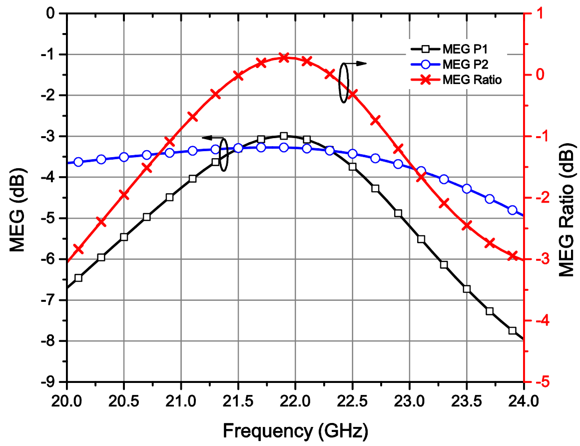

Fig. 9. MEG of the proposed CDRA and MEG ratio of the two degenerated modes.

4.2 Radiation Performance

The radiation efficiency of the two degenerated modes in the CDRA has been computed and shown in Fig. 10. Both modes have high radiation efficiency of above 90% around the resonant frequency. The normalized radiation patterns of the proposed CDRA were measured in an anechoic chamber; the patterns of co-polarization and cross-polarization have been measured for both E and H planes. The measured radiation patterns are shown in Figs. 11–14. The ideal radiation pattern for $HE_{11\delta}$ mode resembles to that of a magnetic dipole thus the broadside has maximum radiation which can be seen from the measured patterns. For infinite ground plane the back radiation will be negligible however since finite ground plane is used for practical purpose the back radiation can be seen in the radiation patterns. In all measurements the co-polarization is dominant and at least 20 dB stronger in the broadside direction as compared to that of cross-polarization in the same plane. This difference assures that a high degree of polarization diversity has been achieved. Measured boresight gain of the CDRA was 5.89 dBi for port 1 and 6.39 dBi for port 2.

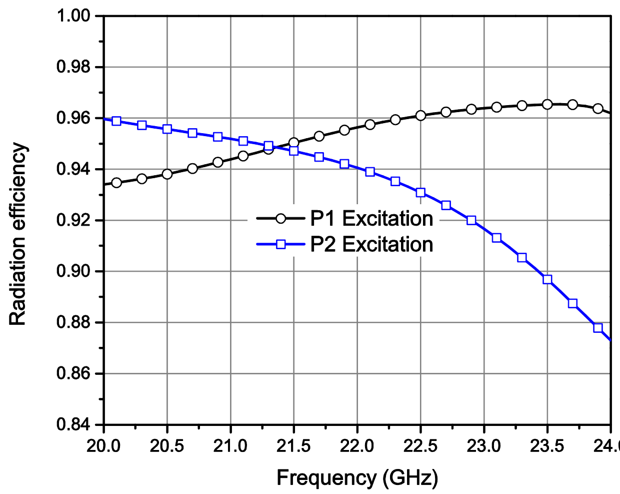

Fig. 10. Radiation efficiency of the two degenerated modes in the CDRA.

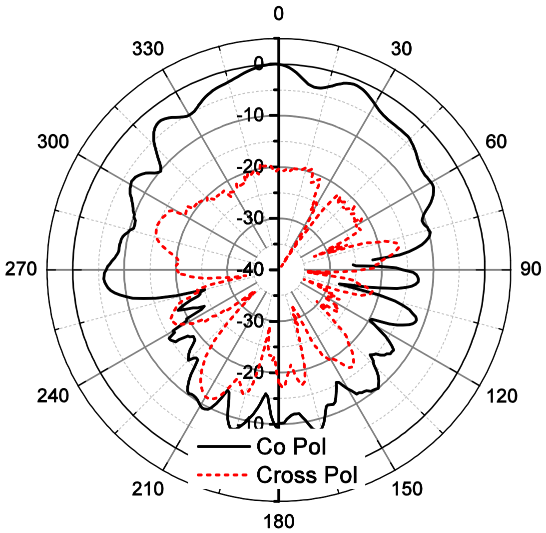

Fig. 11. E plane measured response for co- and cross-polarization for port 1.

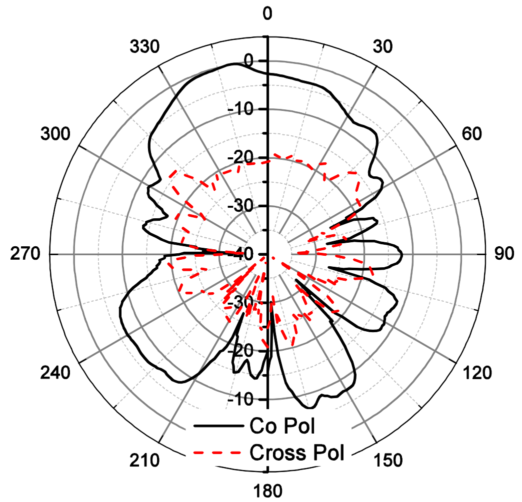

Fig. 12. H plane measured response for co- and cross-polarization for port 1.

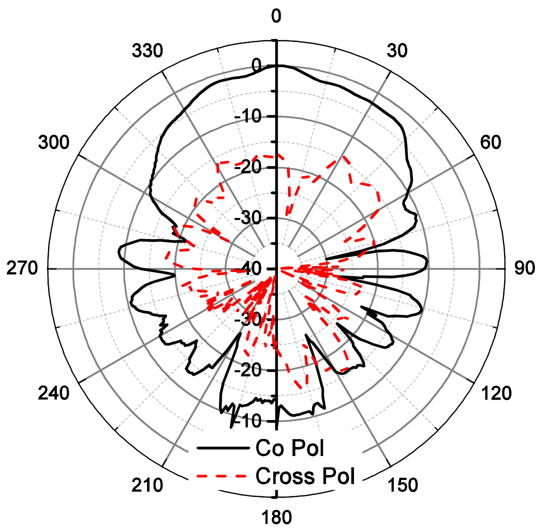

Fig. 13. E plane measured response for co- and cross-polarization for port 2.

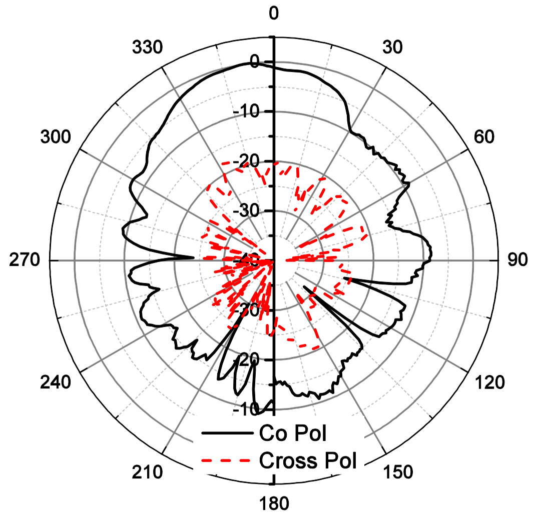

Fig. 14. H plane measured response for co- and cross-polarization for port 2.

Ref.	**Freq. (GHz)**	**Band-wwidth (%) P_1, P_2**	**Volume (λ_d^3)**	**Gain (dBi) P_1, P_2**	**Diversity type**
8	4.1	7.4, 19.1	0.794	5.30, 2.10	Polarization
9	1.8	18.38, 7.01	0.297	6.45, 8.02	Polarization
10	2.4	10.4, 10.8	0.671	1.41, 1.03	Polarization
11	3.4	11.7, 11.4	0.222	5.50, 5.50	Polarization
12	2.4	6.1, 9.1	0.299	0.60, 6.10	Pattern
13	2.5	18.75, 4.5	1.05	2.26, 2.51	Polarization
14	2.4	10.08, 14.9	0.671	1.12, 1.38	Pattern
This work	22	9.50, 18.18	0.276	5.89, 6.39	Polarization

Tab. 1. Comparison between the proposed CDRA and relevant designs.

A detailed comparison of the proposed CDRA has been carried out with most relevant designs reported in literature. Since the CDRAs reported in literature operate on different resonant frequencies and are made of different materials therefore the volumes are computed in terms of dielectric wavelength, additionally impedance bandwidths and diversity mechanism is also listed in Tab. 1.

5. Conclusion

A detailed analysis of a dual port cylindrical dielectric resonator antenna is presented. The antenna is intended to be used for point-to-point communication link in K band. The proposed antenna is excited with two orthogonally placed microstrip feed lines which degenerates two $HE_{11\delta}$ modes. Both of these modes are well isolated and the mutual coupling measured through transmission coefficient is less than –32 dB. Antenna radiates in the broadside direction with linear polarization thus both ports generate their own linearly polarized wave through $HE_{11\delta}$ mode. The simulated and measured results are in good agreement with sufficient measured fractional bandwidth of 9.5% and

18.18% for port 1 and port 2 respectively. The radiation patterns confirm the polarization diversity through a difference of 20 dB between co- and cross-polarization gain levels in both E and H plane patterns. The MIMO performance parameters including ECC, TARC, MEG, CCL also ascertain the performance of the antenna system. The antenna finds excellent applications in consumer electronics and harsh environment sensor applications due to low losses and compact size.

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