Received October 24, 2016, accepted November 16, 2016, date of publication November 29, 2016, date of current version January 27, 2017.

Digital Object Identifier 10.1109/ACCESS.2016.2633361

Novel Feeding Mechanism to Stimulate Triple Radiating Modes in Cylindrical Dielectric Resonator Antenna

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ABSTRACT This paper examines a triple band cylindrical dielectric resonator antenna (CDRA) with three different radiating modes, i.e., $\mathbf{HEM_{11}}_\delta$, $\mathbf{TM_{01}}_\delta$, and $\mathbf{HEM_{12}}_\delta$. Excitation of all these radiating modes simultaneously, in CDRA, is the most challenging task, which have been accomplished by using composite feeding structure [combination of vertical strip and psi-shaped (ψ) microstrip line]. Out of three radiating mode, two hybrid modes (i.e., $\mathbf{HEM_{11}}_\delta$ and $\mathbf{HEM_{12}}_\delta$) radiate in broadside direction, while remaining one ($\mathbf{TM_{01}}_\delta$) creates monopole like radiation pattern. Diversified radiation patterns make the proposed CDRA suitable for different wireless applications. Simulated outcomes of the proposed antenna design have been practically confirmed with the help of archetype of proposed antenna. The proposed CDRA is working in three different frequency bands: 2.5–3.02, 3.76–3.86, and 4.38–4.72 GHz. The proposed radiator is quite suitable for WiMAX (2.5 GHz) and vehicular applications.

INDEX TERMS Cylindrical dielectric resonator antenna, triple band antenna, radiating mode, microstrip line fed antenna.

I. INTRODUCTION

Dielectric Resonator as a radiator is the most reveling antenna at microwave frequencies due to its natural abilities like low loss, high gain, compactness and supportive nature of different radiating modes [1]. Three basic shapes of dielectric resonator antenna (DRA) are hemispherical, cylindrical and rectangular. All these shapes have their own benefits and problems. Out of which, cylindrical shape DRA are easily available in commercial market and it can support three different modes i.e. TE_{mnp}, TM_{mnp} and HEM_{mnp} [2].

Dominant hybrid mode i.e. $HEM_{11\delta}$ mode (for radiating purpose) in CDRA was first proposed by S.A. Long, M. W. McAllister, and L. C. Shen in 1983. They also proved that $HEM_{11\delta}$ mode radiates in broadside direction in both the principal planes [3]. Similarly, $TM_{01\delta}$ mode is another important mode in CDRA which has monopole like radiation pattern [4]. Recently, D. Guha and his research team have done the intense study on the creation of another higher order hybrid mode in CDRA i.e. $HEM_{12\delta}$ mode because of its high gain and broadside radiation characteristics. Different types of feeding mechanism have been utilized to generate $HEM_{12\delta}$ mode in CDRA like non-resonant patch, probe fed CDRA along with air cavity in ground plane as well as composite aperture feeding mechanism [5]–[7].

In recent era of wireless communication, multiband antenna is widely required due to its capability of operating in different frequency bands simultaneously. Multiband characteristics can be obtained in DRA by using three different techniques i.e. hybrid DRA [8], loading of parasitic resonating element with DRA [9] and higher order mode generation in DRA [10]. Out of all these methods, higher order mode generation technique is quite effective but it is quite difficult to generate higher order radiating modes in CDRA simultaneously.

In this article, we have presented a novel composite feeding mechanism (vertical strip along with psi-shaped microstrip line) in order to excite three different radiating modal patterns in CDRA. Two significant features of realized CDRA are (i) three different radiating modes i.e. $HEM_{11\delta}$, $TM_{01\delta}$ and $HEM_{12\delta}$ are created in CDRA simultaneously. It helps in achieving the multiband characteristics in realized CDRA. The beauty of the proposed feeding mechanism is that it can behave like both electric dipole (oriented as both horizontal and vertical) and magnetic dipole. (ii) Diversified radiation pattern is obtained in different operating frequency bands due to different mode generation i.e. broadside pattern due to $HEM_{11\delta}$, $HEM_{12\delta}$ and monopole like radiation pattern due to $TM_{01\delta}$ mode. The advantages of proposed radiator as compared to other published structure (mention in previous paragraph) are: (i) fabrication complexity is lesser as compared to [5], [6], [8], and [10]; (ii) proposed radiator's gain is higher as compared to other hybrid antennas [8]; (iii) the feature of diversified radiation patterns is not available in previously published articles.

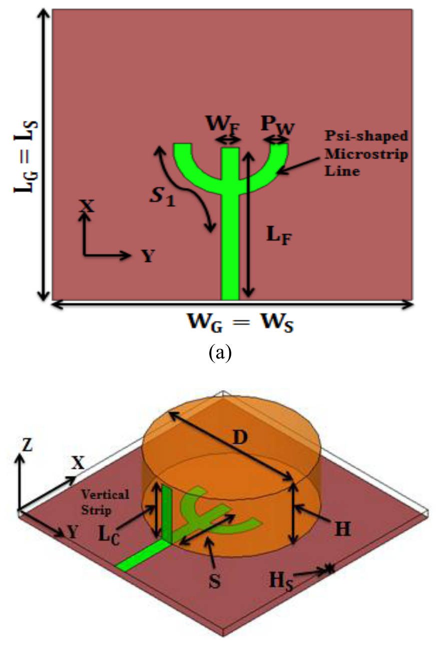

FIGURE 1. Schematic Diagram of Proposed CDRA (a) Psi-Shaped Microstrip Line (b) Isometric View of Realized CDRA: $L_S = L_G = 50$ mm; $W_S = W_G = 50$ mm; $L_F = 26.25$ mm; S=14 mm; S_1 =29.38 mm $W_F = P_W = 2.5$ mm; $L_C = 2.5$ mm; D = 31 mm; H = 12 mm; $H_S = 1.6$ mm.

II. DESIGN AND ANALYSIS OF PROPOSED CDRA

Fig. 1 shows configuration of realized multiband cylindrical dielectric resonator antenna. The proposed antenna design is excited with the combination of vertical strip and psi-shaped (ψ) microstrip line. Cylindrical shaped DRA is made up of alumina material $\left(\varepsilon_{r,CDRA} = 9.8, \tan\delta = 0.002\right)$ with a radius of R = 15.5 mm and height of H = 12 mm. Psi-shaped microstrip line has been etched on FR4 substrate$\left(\varepsilon_{r,sub} = 4.4, \tan\delta = 0.02\right)$ with length of $L_G = 50$ mm and width of $W_G = 50$ mm. Conventional ground plane, vertical strip and psi-shaped microstrip line have been made up of copper.

In order to understand the concept behind generation of different radiating modes with the help of composite feeding structure, we have divided the complete analysis of proposed antenna into four different antennas. The designs of these antennas have been shown in Fig. 2

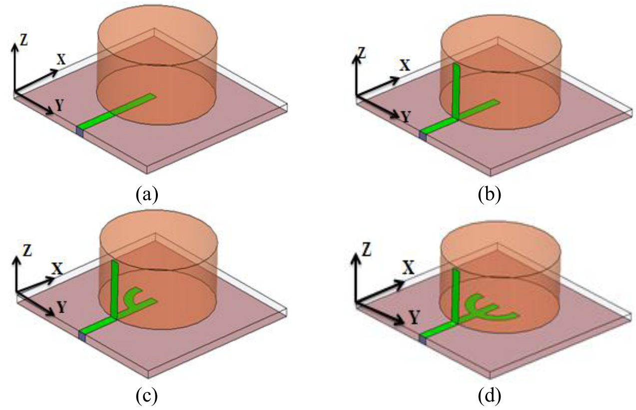

FIGURE 2. Schematic Diagram of Different Antenna Design (a) Antenna-1 (b) Antenna-2 (c) Antenna-3 (d) Proposed Antenna/Antenna-4.

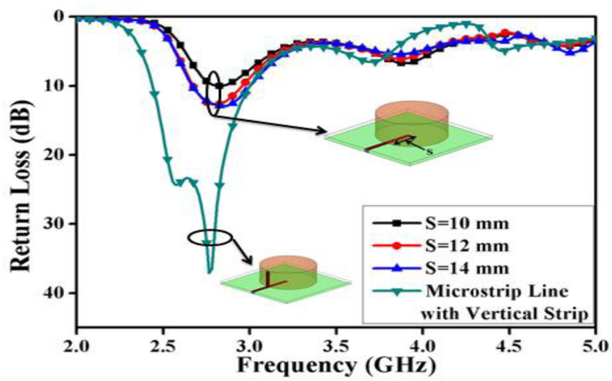

FIGURE 3. Return Loss variation of Antenna-1 (with different value of S) and Antenna-2.

A. EXCITATION OF $HEM_{11\delta}$ MODE IN CDRA AND MATHEMATICAL VERIFICATION

Fig. 3 shows return loss variation of antenna-1 (i.e. microstrip line fed CDRA) and antenna-2 (i.e. microstrip line along with conformal fed CDRA). It is clearly observed from Fig. 3 that impedance matching at 2.77 GHz is slightly being improved with increase in stub length (S) but it is being greatly improved after applying vertical strip on edge of CDRA (Antenna-2). Fig. 4 shows near field distribution of CDRA at 2.77 GHz. From Fig. 4, it is clear that $HEM_{11\delta}$ mode is generated in CDRA at 2.77 GHz [11].

In order to create $HEM_{11\delta}$ mode in CDRA, feeding structure must behave like a horizontally placed magnetic dipole. Simple microstrip line acts like magnetic dipole (horizontally placed) and generates $HEM_{11\delta}$ mode in CDRA [1], [12]. But, in case of low permittivity DRA, there is a problem of weak coupling occurs with simple microstrip line. It can be overcome with the help of vertical strip placed at the edge of CDRA. Vertical strip at the edge of CDRA also behaves a magnetic dipole and provides strong coupling to CDRA (due to vertical source of electric current) [13]. In order to verify the resonance due to $HEM_{11\delta}$ mode mathematically, resonant frequency of $HEM_{11\delta}$ mode is calculated as

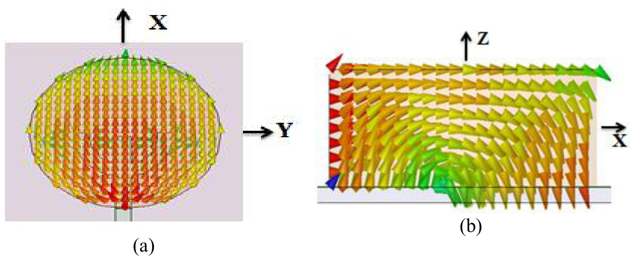

FIGURE 4. Near Field Distribution on Antenna-2 at 2.77 GHz (a) Top View (b) Isometric View.

follow [12]:

$$f_r = \frac{6.321c}{2\pi R\sqrt{\varepsilon_{r,eff}+2}} \times \left[0.27 + 0.36\left(\frac{R}{2H_{eff}}\right) + 0.02\left(\frac{R}{2H_{eff}}\right)^2\right] \quad \text{(A)}$$

Where, $\varepsilon_{r,eff}$ is the effective dielectric constant of proposed CDRA, R is the radius of CDRA, H_{eff} is the total height of proposed antenna design and c is the speed of light. The value of $\varepsilon_{r,eff}$ and H_{eff} can be determined as follow [1]:

$$\varepsilon_{r,eff} = \frac{H_{eff}}{\frac{H}{\varepsilon_{r,CDRA}} + \frac{H_S}{\varepsilon_{r,sub}}} \quad \text{(B)}$$

And

$$H_{eff} = H + H_S \quad \text{(C)}$$

From eqn. (A), (B) and (C), resonant frequency of $HEM_{11\delta}$ mode is found to be 2.81 GHz. Theoretically calculated resonant frequency of $HEM_{11\delta}$ mode is quite close to simulated one.

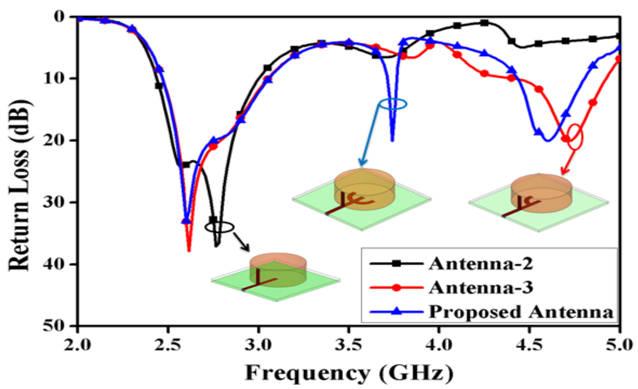

FIGURE 5. Return Loss variation of Antenna-2 and Antenna-3 Configuration.

B. EXCITATION OF $HEM_{12\delta}$ AND $TM_{01\delta}$ MODE IN CDRA AND MATHEMATICAL VERIFICATION

Fig. 5 shows comparison among the return loss of antenna-2, antenna-3 and proposed antenna. It is clear from Fig. 5 that two additional resonances have been generated at 4.7 GHz and 3.81 GHz with antenna-3 and antenna-4 (proposed antenna). Fig. 6 and Fig. 7 show the near field distribution in CDRA at 4.7 GHz and 3.81 GHz respectively. It is clearly observed from Fig. 6 and Fig.7 that $HE_{12\delta}$ and $TM_{01\delta}$ mode are created at 4.7 GHz and 3.81 GHz respectively [11].

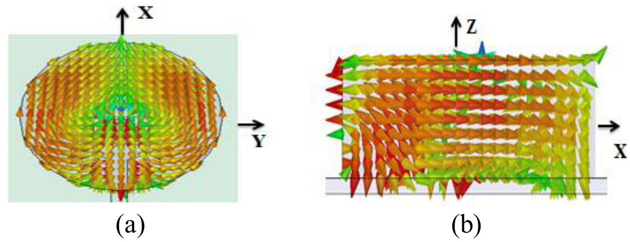

FIGURE 6. Near Field Distribution on Antenna-3 (a) Top View at 4.7 GHz (b) Isometric View at 4.7 GHz.

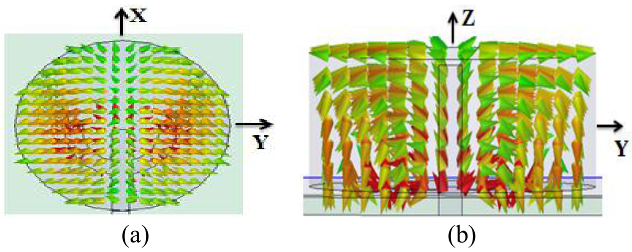

FIGURE 7. Near Field Distribution on proposed antenna at 3.81 GHz (a) Top View (b) Isometric View.

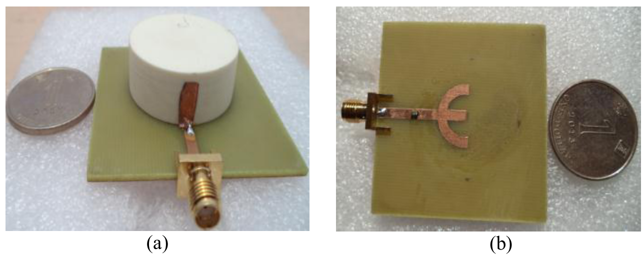

FIGURE 8. Archetype of Realized Antenna (a) Isometric View (b) Feeding Structure.

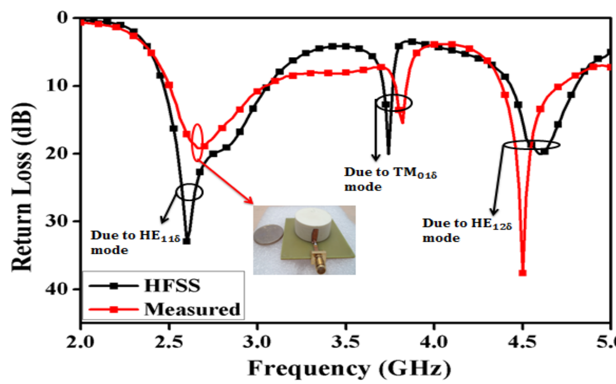

FIGURE 9. Measured and Simulated Return Loss variation of Proposed Antenna.

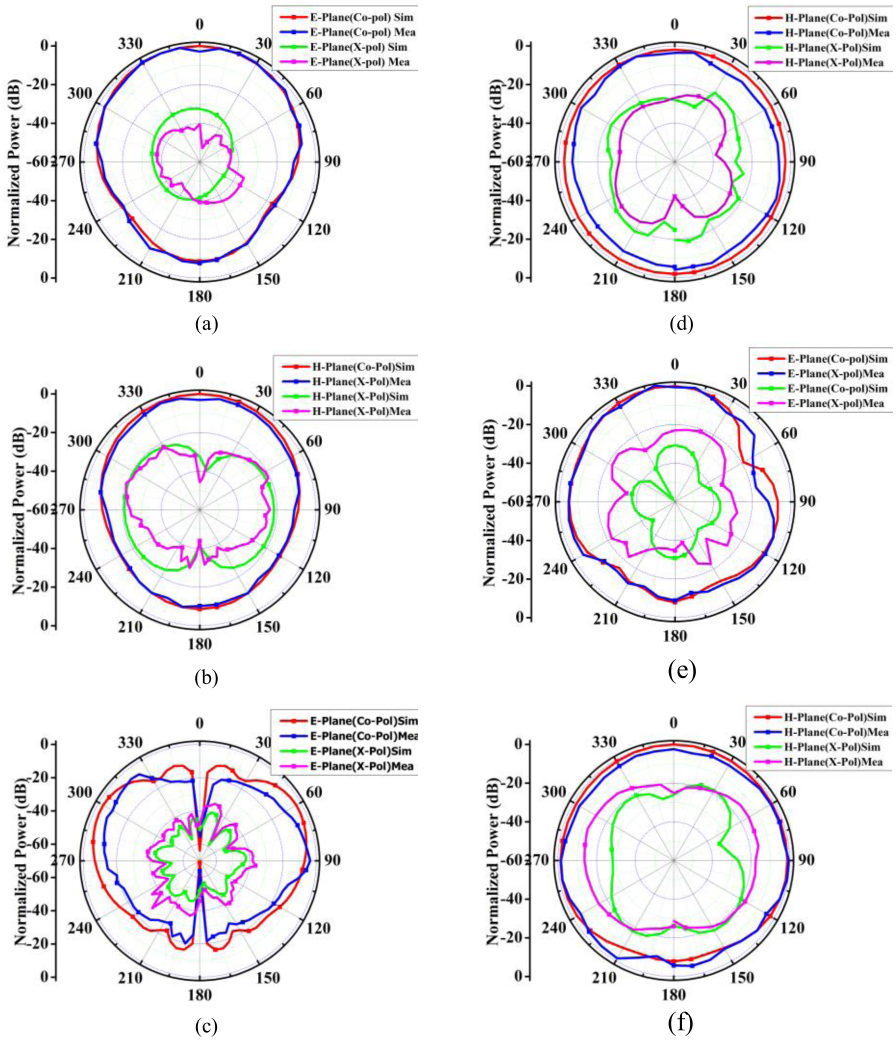

FIGURE 10. Far Field Pattern of Proposed Antenna (a) E-Plane 2.6 GHz (b) H-Plane 2.6 GHz (c) E-Plane 3.8 GHz (d) H-Plane 3.8 GHz (e) E-Plane 4.6 GHz (f) H-Plane 4.6 GHz.

In order to generate $HEM_{12\delta}$ and $TM_{01\delta}$ mode in CDRA, the feeding structure must behave as a horizontally and vertically placed electric dipole respectively [12]. In antenna-3 configuration, the quarter annular shaped stub (S_1) is added to straight microstrip line (S). This quarter annular shaped stub loaded microstrip line ($S_1 = 0.46\lambda$) creates additional $\lambda/4$ path delay in comparison to straight microstrip line ($S = 0.21\lambda$) at 4.7 GHz. This path delay creates $\pi/2$ phase shift in field lines at 4.7 GHz and behaves as an electric dipole (horizontally placed) [7]. There is no empirical formula available for calculating the resonant frequency of $HEM_{12\delta}$ mode. But it can be forecast with the help of resonant frequency of $HEM_{11\delta}$ mode as follow (from Fig. 9(a) [7]):

$$f_{HE_{12\delta}} \geq 1.65 f_{HE_{11\delta}} \tag{D}$$

Therefore; the resonant frequency of $HEM_{12\delta}$ mode is found to be 4.65 GHz. The factor 1.65 is totally depending on aspect ratio (R/H). As the aspect ratio of CDRA changes, the resonant frequency will be changed accordingly.

Vertical electric dipole can be created by parallel placing of two-symmetric horizontal electric dipole. (from Ch. 4, pp. 186 [14]). Psi-shaped (ψ) microstrip line behaves as a vertically oriented electric dipole due to the presence of parallel placed two quarter annular stub and generates $TM_{01\delta}$ mode in CDRA at 3.81 GHz. For mathematical verification, the resonant frequency of $TM_{01\delta}$ mode can be calculated as follow [12]:

$$f_r = \frac{c\sqrt{3.83^2 + \left(\frac{\pi R}{2H_{eff}}\right)^2}}{2\pi R\sqrt{\varepsilon_{r,eff} + 2}} \tag{E}$$

The resonant frequency of $TM_{01\delta}$ mode is found to be 4.01 GHz which is quite close to simulated result. There is small difference in the simulated and theoretical resonance frequency. It is due to the fact that mathematical formula has been obtained by assuming isolated dielectric resonator. It is important to note here that Eqn. (A)-(E) are used to calculate the resonant frequency of $HE_{11\delta}$ and $TM_{01\delta}$ mode in CDRA but the tuning of resonant frequency with the help of these equations are quite difficult. It is due to the fact that these equations do not include any information regarding coupling factor as well as quality factor of CDRA and also change with the aspect ratio (R/H) [12]. Therefore, the parametric analysis is the only way to tune the resonant frequency of different modes. These empirical formulas are only used to mathematical verification of resonant frequencies of different radiating modes.

III. ANTENNA ARCHETYPE AND MEASUREMENTS

Fig. 8 shows isometric view and feeding structure of the fabricated antenna structure. Fig.9 displays the comparison of measured and simulated return loss variation of realized antenna structure. The return loss characteristic of proposed antenna has been measured with the help of Rhode & Schwarz (Model No. ZVH 8, 100 KHz - 8 GHz) vector network analyzer. From Fig. 9, it can be observed that there is minor difference between simulated and measured outcomes. It is due to the use of the glue material (Fevi-Quick) to fix the CDRA with substrate. The proposed CDRA is working in three different frequency bands 2.5-3.02 GHz, 3.76-3.86 GHz and 4.38-4.72 GHz respectively.

The impedance bandwidth of the frequency band originated due to $TM_{01\delta}$ mode is lower as compare to the frequency band generated due to $HEM_{11\delta}$ and $HEM_{12\delta}$ mode. It is due to the fact that the quality factor of $TM_{01\delta}$ mode ($Q = 77$ [11]) is higher as compare to $HEM_{11\delta}$ ($Q= 31$ [11]) and $HEM_{12\delta}$ ($Q= 52$ [11]) mode.

Fig. 10 shows far-field patterns of proposed CDRA at 2.6 GHz, 3.8 GHz and 4.6 GHz respectively. These patterns are measured in anechoic chamber with the help of Agilent Technologies E8275D PSG Analog Signal Generator (250 KHz- 20 GHz) and ROHDE & SCHWARZ FSL Spectrum Analyzer (9 KHz- 18 GHz). There is good co-pol to cross-pol difference in both the principal planes (approximately 25 dB). From Fig. 10, it is observed that there is the minute difference between measured and experimental far-field patterns. It is due to the misalignment between reference antenna (horn antenna) and antenna under test (proposed antenna) during the movement of positioner. $HE_{11\delta}$ and $HE_{12\delta}$ mode radiates in broadside direction in both the principal planes which is clearly shown in Fig. 10 (a), Fig. 10 (b), Fig. 10 (e) and Fig. 10 (f). It is due to the fact that for both the hybrid mode Z-component of electric field (E_Z) and magnetic field (H_Z) are directly related to $\cos\theta$. If $\theta = 0^0$, then the value of radiated field is maximum and generates maximum radiation in broadside direction [12]. From Fig. 10 (c) and Fig. 10 (d), it is clear that $TM_{01\delta}$ mode is originated in CDRA at 3.8 GHz (due to monopole like radiation pattern [4]).

Fig. 11 shows measured and simulated gain variation of proposed antenna (gain is measured in only shadowed region) in broadside direction. It is clearly observed from Fig.11 that the value of gain is higher in the frequency range 4.38-4.72 GHz. It is very obvious because this

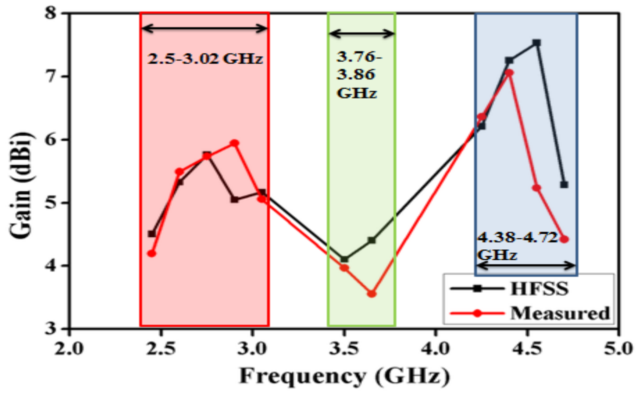

FIGURE 11. Measured and Simulated Gain variation of Proposed Antenna ($\theta = 0^0, \emptyset = 0^0$).

frequency band is generated due to the higher order mode i.e. $HEM_{12\delta}$ mode (higher order mode occurs at higher frequency and $G \propto f^2$) [14]. Similarly, the value of gain is lower in the frequency range 3.76-3.86 GHz ($TM_{01\delta}$ mode). It is due to the fact that the radiation Q-factor of $TM_{01\delta}$ is quite high as compare to other radiating modes which in turn reduce the antenna gain ($\eta \propto {}^1/_{Q_{rad}} \Rightarrow G \propto \eta$) [14].

IV. CONCLUSION

This paper presents a novel feeding mechanism in order to excite triple radiating modes in CDRA. Two important features of proposed antenna are (i) three different mode patterns are generated in CDRA simultaneously with the help of composite feeding structure i.e. combination of vertical strip and psi-shaped (ψ) microstrip line. (ii) Diversified radiation patterns are obtained due to generation of three different mode patterns i.e. $HEM_{11\delta}$, $HEM_{12\delta}$ and $TM_{01\delta}$. The proposed concept of multiband generation (with the help of dominant and higher order mode) in the area of dielectric resonator antenna has large number of possibilities for future research. Such as psi-shaped microstrip may be changed with other innovative shapes of microstrip line and create other radiating mode in CDRA like $TE_{01\delta}$, $HEM_{11\delta+1}$, $HEM_{12\delta+1}$.

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