A Novel Multi-permittivity Cylindrical Dielectric Resonator Antenna for Wideband Applications

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Abstract. *In this paper, a novel multi-permittivity cylindrical dielectric resonator antenna for wideband application is presented. The multi-permittivity cylinder is formed by combining two different permittivity material sectors in such a way that each sector (with constant permittivity) is 90 degree apart. A direct microstrip line coupling terminated with T-stub at the open end is used to excite the multi-permittivity cylindrical dielectric resonator. The angular position of the multi sector dielectric resonator with respect to the longitudinal axis of the microstrip line and length of the additional strip at the open end of the feeding circuit is key parameters for wideband operation of the antenna. By optimizing all parameters of the proposed antenna, wideband impedance bandwidth of 56 % (12.1 GHz to 21.65 GHz) is achieved. The average gain of the antenna throughout the bandwidth is 5.9 dB with good radiation properties in both E-plane and H-plane. A well matched simulation and experimental results show that the antenna is suitable for wideband applications.*

Keywords

Dielectric resonator antenna (DRA), multi-permittivity dielectric resonator, wideband antenna.

1. Introduction

There is fast growing demand for modern day communication systems for wireless and radar applications to be employed in a wider range of frequency, which signifies the importance of wideband antenna. In the recent past abundant amount of research is carried out in the field of wideband antenna and tremendous development is made [1-5]. Since the emergence of dielectric resonator antennas (DRAs) back in 1983, it has been studied extensively by different researchers and vast numbers of articles are published covering different aspects of DRA i.e. low profile structures, excitation of DRA using different feeding schemes, compactness, polarization, theoretical and mathematical analysis, wideband operation and array DRAs. It has been proven that DRA offers high radiation efficiency, small size, wide band operation, flexible excitation mechanism and ease of fabrication. A very well written review on DRA can be noted in [6] which comprehensively address almost all features of DRA. In this paper, the attention of the readers is drawn towards wideband DRA. Bandwidth of DRA is mainly controlled by the dielectric constant of the material. The relation between DRA and dielectric constant is inverse, which means DRA with low permittivity will have wider bandwidth and hence lower radiation efficiency. Several wideband DRAs are reported in the literature, in which wideband performance of the DRA is achieved by manipulating different shapes of the dielectric resonators, using various feeding schemes, multiple dielectric resonators, modified DRA structures, hybrid designs, and by exciting DRA in multiple modes [7-10]. A comparison is done between previously published works in terms of antenna maximum dimension, type of feeder employed and impedance bandwidth, summary is given in Tab. 1.

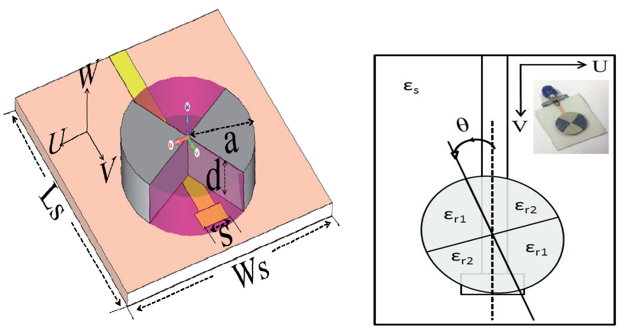
In this paper, a multi-permittivity cylindrical dielectric resonator antenna (MCDRA) consists of four sectors, excited by a modified 50 Ω microstrip line on top of the small conducting ground plane is presented. The cylindrical dielectric resonator is formed by placing four 90° pie shape sectors in such a way that, two similar permittivity sectors are positioned in non-adjacent quadrant. With this setup, more than 50% impedance bandwidth is achieved with a single element DRA. The proposed design is simulated using computer simulation technology (CST 2014) and verified using high frequency structure simulator (HFSS). To validate the design in a real world the antenna prototype is fabricated and characterized. A close agreement between simulation and experimental results is obtained. In the following section configuration of the proposed antenna is described, followed by a parametric study and subsequently simulated and measured results are presented.

DRA Type	Dimensions (mm)	Feed type	Resonant frequency (GHz)	Impedance bandwidth (%)	Refrences
Rectangular	50 x 50	Aperture	5.8	20	[1]
Rectangular	50 x 50	Slot	2.4	28.6	[11]
Cylindrical	115 x 115	Microstrip fed	2.35	14.65	[12]
Rectangular	150 x 150	Differently feed	2.4	10.4	[13]
Bowtie	60 x 60	Coaxial probe	5.5	49.4	[14]
Rectangular	30 x 30	Coaxial probe	3.4	25	[15]
Half Cylinder	140 x 110	Microstrip Line	2.4	7.45	[16]

Tab. 1. Summary of some of the selected dielectric resonator antennas.

2. Antenna Geometry and Design Configuration

Configuration and prototype of the proposed MCDRA are shown in Fig. 1. The corresponding dimensions of the geometry shown in Fig. 1 are defined as: a = radius of the multi-permittivity cylinder, d = depth of cylinder, L_m = length of microstrip line, W_m = width of microstrip line, s = length of microstrip line stub, Ls = length of substrate, Ws = width of substrate, ε_s = permittivity of substrate, ε_{r1} = high permittivity sectors, ε_{r2} = low permittivity sectors and θ is the angle of the position of MCDRA with respect to the longitudinal axis of the microstrip feed line. As shown in Fig. 1. A multi-permittivity cylindrical dielectric resonator is loaded over a modified microstrip line, placed on top of a small conducting ground plane. The antenna is designed and analyzed in CST® which utilizes finite integration technique in the time domain. Subsequently the design is verified in HFSS® which employs finite element method in the frequency domain. It is observed that the impedance matching of the proposed antenna is vastly dependent on the angular position 'θ' of the multi-permittivity cylinder with respect to the longitudinal axis (V-axis) of the microstrip feed line as shown in Fig. 1(b).



(a) (b)

Fig. 1. Illustration of the proposed wideband ECDRA: (a) perspective view, (b) top view.

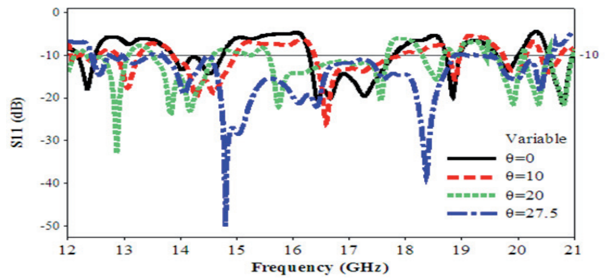
Further improvement in the impedance bandwidth is attributed to the addition of stub at the open end of the microstrip line, adjusting length 's' of the stub and the position of the stub along the U-axis of the feed line. Assortment of an appropriate combination of different permittivity sectors also plays a vital role in achieving wideband operation of the MCDRA. In the next section, a parametric study is done to evaluate the effect of varying the aforementioned parameters on the impedance bandwidth of the antenna.

3. Parametric Study of MCDRA

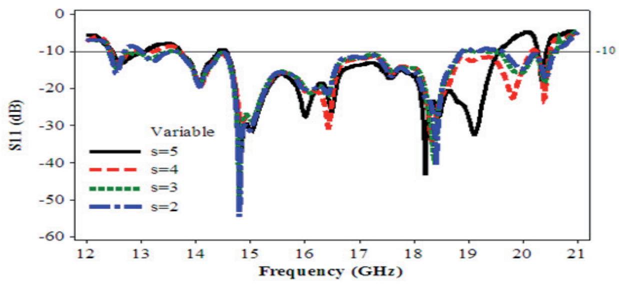
Parametric study of the proposed MCDRA is carried out in CST to achieve optimum values of all the parameters for practical design of the antenna. As mentioned in the preceding section the angular position 'θ' illustrated in Fig. 1(b) of the multi-permittivity DRA with respect to the longitudinal axis of the microstrip feed line plays an important role in accomplishing wideband MCDRA. Initially the multi-permittivity cylindrical resonator is rotated in an anticlockwise direction with 10° angle step size and the resulted S_{11} is evaluated. Afterwards the step size is further reduced to fine tune the impedance bandwidth of the antenna. Figure 2 shows variations in impedance bandwidth of the antenna relative to the change in angle theta 'θ' and length 's' of the additional stub of the microstrip line. Strength of electric field and magnetic field inside MCDRA is evaluated with each transformation of angle and length of the stub. As high permittivity material has a high quality factor and therefore can store more of the electrometric energy inside, this helps in achieving a strong coupling to the feeding structure. While low permittivity resonator has the tendency to operate in wider bandwidth, hence it is important to position the resonator in such a way that maximum field strength is achieved in all sectors of the MCDRA. By placing the multi-permittivity cylinder at the position where $\theta = 27.5°$ the resonator is excited in an asymmetric manner and maximum bandwidth is achieved. The optimum values of all the parameters for which the optimum performance of the antenna in terms of impedance bandwidth is achieved are listed in Tab. 2.

Parameter	Value	Parameter	Value
a	7 mm	W_m	1.898 mm
d	2.5 mm	ε_s	3.35
s	3 mm	ε_{r1}	15
Ls, Ws	25, 24 mm	ε_{r2}	10.2
L_m	20 mm	θ	27.5

Tab. 2. Optimized value for multi-permittivity cylindrical DRA.



(a)



(b)

Fig. 2. Illustration of impedance bandwidth and VSWR of the antenna: (a) S_{11} for different values of angle (theta), (b) S_{11} for various values of length of strip 's'.

4. Results and Discussion

The proposed antenna is simulated using two commercially used electromagnetic simulation software's to confirm the wide band operation of the antenna in both time domain and frequency domain. To further validate the simulation results a prototype of the antenna shown in Fig. 1(b) is fabricated and measured. As mentioned earlier, two different permittivity pie shape sectors are placed adjacent to form a cylinder. The high permittivity sector is of magnesium titanium oxide doped with cobalt ($MgTiO_3$ + Co) to achieve epsilon of 15. For lower permittivity sector, Rogers RT6010 substrate is used with epsilon of 10.2. Comparison of simulated and measured impedance bandwidth of the antenna is illustrated in Fig. 3. The simulated impedance bandwidth ranges from 12.3 GHz to 20.7 GHz which is almost 51 %. The measured impedance bandwidth increases considerably to 56 % (12.1 GHz - 21.65 GHz), which is possibly because of the small air gaps that remain in the fabricated multi-permittivity cylindrical dielectric resonator.

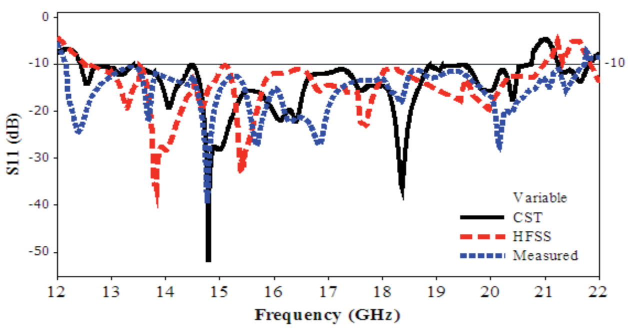
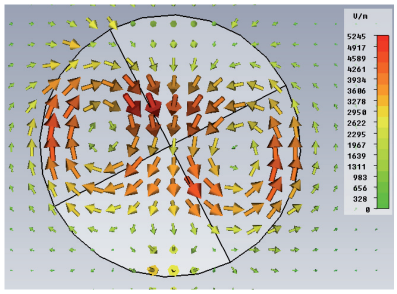
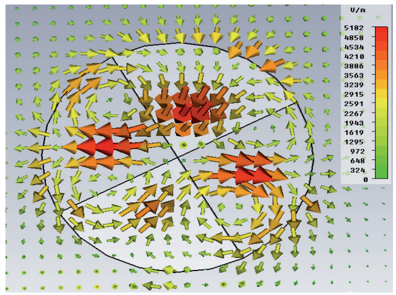


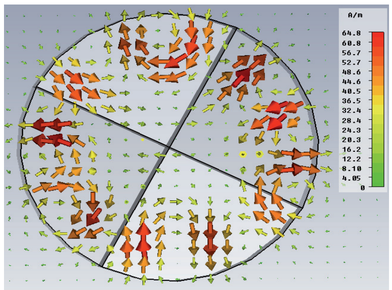
Fig. 3. Optimized impedance bandwidth of the MCDRA.



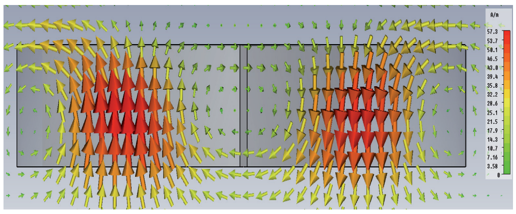
(a) E-Field 12.5 GHz



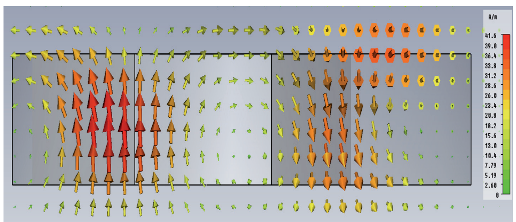
(b) E-Field 17.0 GHz



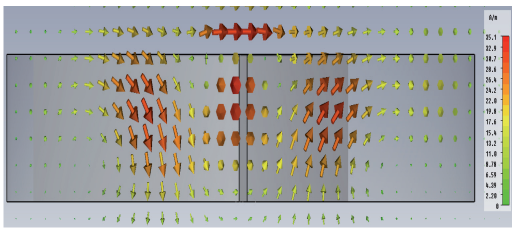
(c) E-Field 21.5 GHz



(d) H-Field 12.5 GHz



(e) H-Field 17.0 GHz



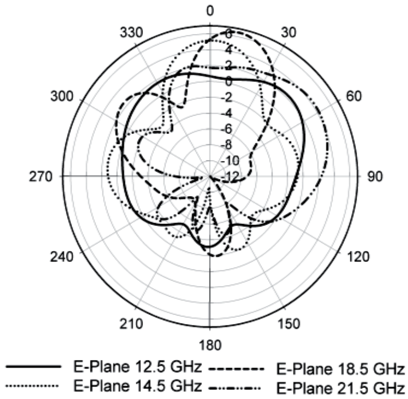
(f) H-Field 21.5 GHz

Fig. 4. Illustration of electric and magnetic field distribution in the proposed multi-permittivity cylindrical DRA at different frequencies.

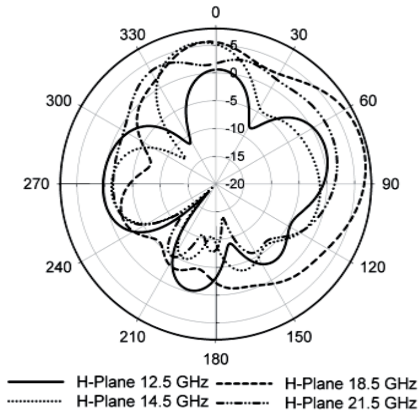
To study wideband response of the MCDRA mode analysis is performed in simulation. It was found that more than one mode was excited in MCDRA which helped in the increase in impedance bandwidth. When the cylindrical dielectric resonator is energized using direct microstrip line coupling it excites mode of a transverse magnetic (TM) type or hybrid mode in which both the electric field and magnetic field components are present [17]. To provide an approximation of the field inside the proposed multi permittivity cylinder eigenmode analysis is performed. The field patterns for our proposed multi permittivity cylinder at the lower cut-off frequency, centre frequency and the upper cut-off frequency are presented here.

The E field and H field distribution in the proposed DRA are illustrated in the equatorial plane and the meridian plane respectively. E field is shown from the top view of the resonator in equatorial plane cuts while the H field is shown from the side view and the resonator cross section appears as a rectangle. As the operating impedance bandwidth of the proposed antenna is from 12.1 GHz to 21.65 GHz, so the lower cut-off frequency is 12.1 GHz, centre frequency is approximately 17.0 GHz and upper cut-off frequency is 21.65 GHz. Figure 4 (a) and (d) shows the electric (E) and magnetic (H) fields distribution, respectively in the DRA at 12.5 GHz, which is on the brink of the lower cut-off frequency of our proposed antenna. As there is a direct relation between permittivity and operating frequency of the DRA, so the dielectric resonator with high permittivity will resonate at a lower frequency and vice versa. The field distribution analysis in Fig. 4 (a) and (d) exhibited that the E field components in the equatorial plane and H field components in the meridian plane existed mostly in the high permittivity sectors of the DRA at the lower cut-off of frequency. The field components near the centre frequency shown in Fig. 4(b) and (e) and upper cut-off frequency shown in Fig. 4(c) and (f) illustrate more variation in E fields in equatorial plane and presence of hybrid components in the H field shown from side view in the meridian plane. As can be seen clearly in the equatorial plane the number of variations in the E field increases with the increase in frequency which confirms the presence of high order modes excited in the proposed multi-permittivity cylindrical DRA. The color of the arrows indicates the intensity of the field in the DRA while the direction of the arrows shows the orientation of the fields. The orientation of magnetic field components especially at the centre frequency and the upper cut-off frequency confirms the presence of intricate hybrid modes, which helps the antenna to operate in wideband.

For efficient coupling of the cylindrical DRA the microstrip line is terminated with a T-stub at the open end which helped in exciting the antenna with high order mode and improves its performance in terms of impedance bandwidth. The drawback of high order modes is it enhances the level of cross polarization but still this antenna can be used for many applications where cross polarization level is not a concern and low profile structures are required. Further, as stated in the previous section that, the rotation angle ‘θ’ have a vital role in improving the electromagnetic energy coupling from the microstrip line to the resonator. As the dielectric resonator is of inhomogeneous nature due to sectors of different permittivity, proper positioning of the DR on top of microstrip line for efficient energy transfer is important. The parametric study exhibited that the angular position of the resonator with respect to the feed line can improve the reflection coefficient of the antenna and optimum value for maximum power transformation is achieved.



(a)



(b)

Fig. 5. Radiation pattern of the MCDRA at different frequencies: (a) E- plane, (b) H-plane.

The E-plane and H-plane radiation pattern of the antenna is shown in Fig. 5 at different frequencies. It is observed that the maximum radiation of the antenna is towards the boresight in the axis of symmetry of the antenna with a small back lobe. A slight beam tilt is observed in the H-plane main beam of the antenna at 18.5 GHz and also a shift in the side lobe towards the axis of symmetry with the increase in the frequency. Figure 6 shows the simulated and measured gain of the antenna. The gain is evaluated using gain absolute methods compared to a standard horn antenna. The average gain of the antenna throughout the bandwidth is 5.9 dB with maximum and minimum gain of approximately 9 dB and 3.5 dB at 13.1 GHz and 12.5 GHz respectively.

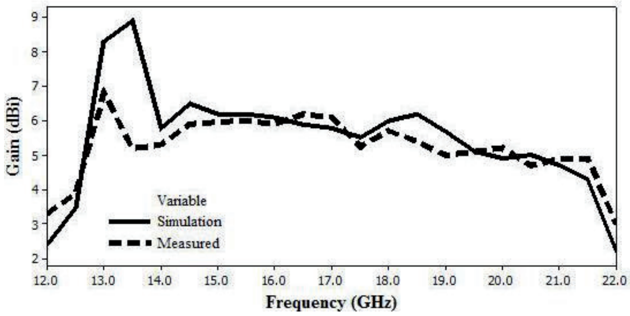


Fig. 6. Simulation and measure gain of the proposed antenna.

5. Conclusion

A novel multi-permittivity cylindrical dielectric resonator antenna for wideband applications has been designed and studied theoretically and experimentally. A parametric study of the antenna has been performed, so as to achieve optimum dimension and wideband operation of the antenna. It has been found that more than 50% impedance bandwidth can be realized with a relatively simple and low profile structure of the antenna.

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