Progress In Electromagnetics Research C, Vol. 36, 207–221, 2013

A NOVEL HALF HEMISPHERICAL DIELECTRIC RESONATOR ANTENNA WITH ARRAY OF SLOTS FOR WIDEBAND APPLICATIONS

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Abstract—A novel half Hemispherical Dielectric Resonator Antenna (HDRA) with an array of slots has been designed. The dielectric material used is Rogers TMM10, which is a ceramic thermoset polymer composite material having a dielectric constant of $\varepsilon_r = 9.2$. Periodic holes lower down the Q factor of the antenna and hence enhance the impedance bandwidth. The measured value of the 10 dB bandwidth is close to 1 GHz (∼17.74%). The mode investigated is a TM_{101} like mode. Further, the effect of increasing the probe length on the resonance and the radiation pattern is also studied. As the probe length is increased, a shift in the resonant frequency is observed and the Dielectric Resonator Antenna (DRA) behaves as a monopole antenna loaded with the DRA. The experimental results confirm that a wide bandwidth of 1.3 GHz (∼29%) with a high gain of 7.2 dBi can be obtained. The radiation pattern of such an antenna is directive in nature.

1. INTRODUCTION

In the recent years, DRAs have attracted significant interest. These antennas have the advantage of no metal inclusion, hence the ohmic losses, which are high at higher frequencies, are not present in them. This lowers the total losses at such frequencies significantly. A number of different structures have been well investigated over the years like rectangular, cylindrical, hemispherical, triangular, etc. [1–4]. Each of these shapes has its own advantages in terms of size and the characteristics it offers in radiating the Electromagnetic waves.

Received 20 December 2012, Accepted 17 January 2013, Scheduled 23 January 2013
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The hemispherical geometry has drawn attention since its inception [5] due to its wide bandwidth and the simplicity of analysis. The interface between the air and dielectric can be modeled with ease and we do not need any magnetic wall assumption [6] as needed in case of rectangular DRA. The HDRA can be excited by various feeding mechanisms like slot coupled [7–9], aperture coupled [10], microstrip feed [1], and waveguide feed [11], but when fed by a coaxial probe, it is capable of exciting the dominant TE_{111} mode and TM_{101} mode [5, 12].

A number of techniques have been employed for enhancing the performance characteristics of the HDRA. Wider bandwidth can be obtained, by modifying the shapes of the DRA using methods like increasing the surface area or by cutting slots and sections. Multilayer stacking of different dielectric materials [13] and air gap [14] in DRA for broad band applications have also been studied [1, 3].

Investigation carried out by introducing parasitic slots in the ground plane revealed that the dimensions of the slot can widen the bandwidth of operation and tune the frequency of the HDRA [7]. The aperture coupled HDRA with parasitic patch has been used to design circularly polarized HDRA [15]. The circular polarized frequency and axial ratio are governed by the patch location and dimensions respectively. Further it is also cited that parasitic patch can be used for enhancing the bandwidth of a linearly polarized HDRA. Pattern reconfigurable Hemispherical Dielectric Resonator Antennas and their linear phased arrays have also been studied [16], which show the capability of configuring the beam in four directions. It has also been shown that HDRA placed on a cylindrical ground plane is capable of producing high gain and omnidirectional radiation pattern [17].

An interesting research of placing the HDRA adjacent to a monopole, demonstrates the mutual coupling between the two antennas and how the radiation pattern gets affected by engineering the separation between the two [18]. Similarly, novel geometries like half and quarter of HDRA [6, 19], hollow hemisphere with conformal patch [20] have also been investigated for broadband applications. It is interesting to note that for these novel geometries the modes excited are not the dominant ones rather modified TM_{101} or $HEM_{11\delta}$ are excited. Further, effect of multiple probes on DRA [21] and loading monopole with dielectric material [22] for wideband applications have also been studied.

In this paper, a novel half HDRA with an array of slots has been discussed. The drilled holes decrease the effective dielectric permittivity of the material, thereby lowering the Q factor of the antenna which aids in increasing the bandwidth of operation. Further, the effect of increasing the probe length has also been studied. The novel geometry excites a TM_{101} like mode. On increasing the probe length, the DRA offers a bandwidth of 1.3 GHz (∼29%) with a gain of 7.2 dBi. Contrary to the research carried out in references [18, 21, 22], in our case, the effect of increasing the probe length is similar to a monopole antenna loaded with a half HDRA. The simulations have been done on CST Microwave Studio and its results have been validated experimentally. Both, the simulations and measured results, are in close agreement to each other.

2. HALF HDRA WITH PERIODIC SLOT

The geometry of the proposed antenna structure consists of a hemisphere of radius 2.54 cm (1″), which is cut exactly half of the radius, from the top. Thus, the height 'h' of the hemisphere is given by $h = radius/2$. The ground plane size is 10 cm × 10 cm. From the top surface of the DRA, a 5 × 5 array of holes is drilled, with each hole having a radius 'r' at a periodicity of distance 'p'. 5 × 5 is the maximum number of holes that can be symmetrically drilled in the proposed DRA, for the optimized values of 'r' and 'p'. The periodicity of the holes is measured from center to center distance. The dielectric material used for simulation and fabrication is TMM_{10}, a ceramic thermoset polymer composite material of the Rogers high frequency laminates. The dielectric constant of the material is $\varepsilon_r = 9.2$, the dissipation factor $\tan\delta = 0.0022$, thermal coefficient is -38 ppm/K, Volume resistivity is 2×10^8 Mohm-cm, surface resistivity is 4×10^7 Mohm and the density is 2.8 gm/cm^3.

A simple HDRA of radius 2.54 cm based on the above material specification will resonate at 1.8 GHz with TE_{111} being the dominant mode, when given an offset probe feed [2, 5, 12]. The design equation of a simple Hemispherical DRA geometry is given as below [5]:

$$f_r = \frac{4.775 \times 10^7 \mathrm{Re}(K_a)}{(\varepsilon_r) a} \tag{1}$$

where f_r is the resonant frequency, K_a is the wave number in the dielectric, ε_r is the dielectric constant, a is the radius of the hemisphere.

The proposed antenna is excited by a probe located at $x = 1.3$ cm and $y = -0.65$ cm from the central hole. The feed location is chosen so as to provide the best impedance matching and excite all the modes of the DRA.

Figure 1 explains the details of the antenna configuration. The radius of the holes 'r', periodicity 'p' and the height of the HDRA 'h' can be seen clearly. The effect of increasing the probe length 'L' is

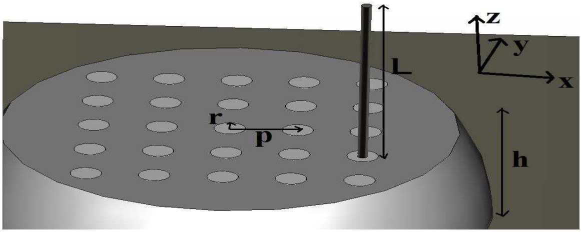

Figure 1. The proposed structure with radius 'r' and periodicity 'p' of the drilled holes. The probe is increased by length 'L' and 'h' is the height of the HDRA. For the above case, 'L' is zero.

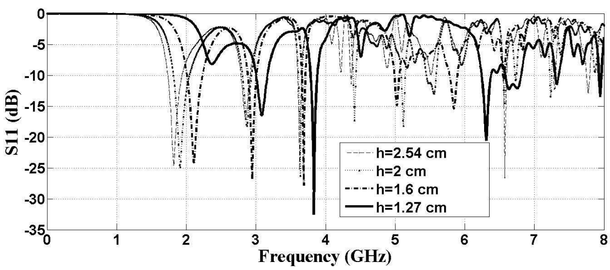

Figure 2. The parametric analysis of decreasing the height of the HDRA. A wideband is observed at a height of $h = 1.27$ cm at around 6.3 GHz.

discussed in the next section. For the current case, we have $L = 0$. The fabricated structure is shown in Figure 8.

For a Hemispherical Dielectric Resonator Antenna, the impedance offered [1], at the input port is given by the following equation:

$$Z_{in} = \frac{-1}{I^2} \iint_{S_0} E_z(r') J_z(z) dS \tag{2}$$

where E_z is the z directed electric field component due to the probe current J_z. The z directed probe current J_z is the surface current flowing on the imaged probe surface S_0. Also, $I_z(z) = 2\pi r_1 J_z(z)$. Now, as the surface area decreases by slashing the top of the DRA, the input impedance decreases. Thus the adjacent resonant modes are grouped closer to each other, thereby increasing the bandwidth of operation.

The above concept has been used to derive the height of the DRA to half of the radius. Figure 2 shows that when the height 'h' of the DRA is decreased, the lower order resonating modes are also lost subsequently. This is evident from the Figure 2, since for a hemispherical DRA, the resonance is observed at 1.8 GHz, 2.9 GHz and 3.8 GHz with narrow bandwidths. However, when the height is reduced to half of the radius, due to modified current distribution, the DRA resonates at 3.08 GHz, 3.83 GHz and 6.3 GHz with a wider bandwidth at 6.3 GHz. Hence the height $h = radius/2$, is the optimized value.

Through parametric analysis, the optimized results of the radius 'r' and periodicity 'p' of the drilled holes are obtained. This is shown in Figure 3. It can be seen that by keeping a fixed radius and increasing the periodicity, the magnitude of S_{11} increases. This is evident since, for $r = 0.1$ cm, when the periodicity is increased, S_{11} increases. However, as 'r' is also increased, the S_{11} decreases and optimized results are observed at $r = 0.15$ cm and $p = 0.65$ cm. For these values, through simulation, a wide bandwidth of 0.96 GHz (∼17%) is achieved as the effective dielectric constant of the material is reduced and hence the Q factor of the antenna also lowers. The relationship between the bandwidth, Q factor and the VSWR is given

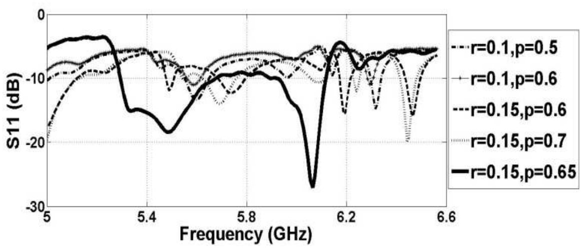

Figure 3. The parametric analysis to optimize the value of the drilled holes of radius 'r' and the periodicity 'p' of the repetition of the holes. All measurements of 'r' and 'p' are in cms.

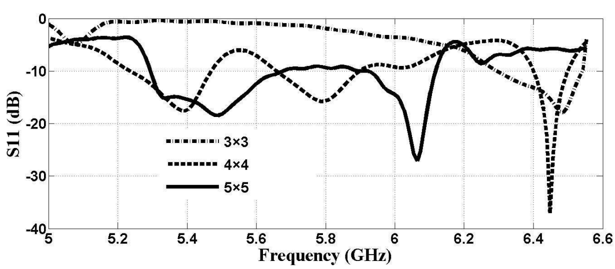

Figure 4. Array of holes drilled in the half HDRA. The optimum value is reached for the array size of 5×5.

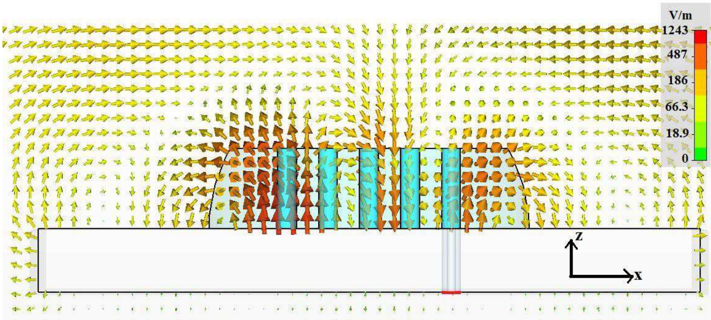

Figure 5. The Electric Field distribution of the half HDRA with periodic holes at 6.08 GHz. The Blue coloured cylinders are the holes drilled in the half HDRA. The arrows show the orientation of the electric field.

by:

$$BW = \frac{VSWR - 1}{Q\sqrt{VSWR}} \tag{3}$$

Once the radius and the periodicity of holes are determined, the number of holes to be drilled becomes crucial. In order to maintain the symmetry, an array of 3×3, 4×4 and 5×5 holes are drilled from the top surface of the half HDRA. The S parameter response shows that 5×5 is the optimum number of holes that can be drilled. Further, 5×5 is the maximum number of holes that can be drilled in the half HDRA. This is shown in Figure 4.

Also, the drilled holes suppress the lower frequencies (i.e., the lower frequencies of half HDRA without the drilled holes) and resonate at around 5.3 GHz. The shift in the resonant frequency, with holes present, can be attributed to lowering of the effective dielectric constant. The Electric Field pattern of the proposed antenna at 6.08 GHz is as shown in Figure 5. For the other resonant frequencies, the modes are mixed and so they are not clearly distinguishable. However, at 6.08 GHz, the Electric field pattern is TM_{101} like mode when compared with the result as cited by Guha et al. [6]. In the reference [6], the authors have used probe feed at the center of the HDRA which shows that the field lines emerge from the probe and terminate on the ground plane. Contrary to it, we have used a feed at an offset from the center. The radiation pattern as discussed in the next section suggests that the mode is TM_{101} like mode [12].

3. EFFECT OF INCREASING THE PROBE LENGTH

The probe length in the above antenna configuration is increased and its effects are also studied. The protruded length of the probe is denoted by length 'L'. Parametric analysis carried out, yields the optimized value of 'L' which offers widest bandwidth of operation. Figure 1 shows the configuration details. In this proposed structure, all other parameters are invariant except the length of the probe.

As the probe length 'L' is increased, the antenna starts acting like a monopole loaded with a dielectric resonator and consequently a frequency shift is also observed. The total length of the probe is now $L + h$ as can be seen in Figure 1. Figure 6 shows the parametric study to find out the optimized value of the increased probe length. At $L = 1.4\,\text{cm}$, two resonant points are observed centered at around 4 GHz and 4.75 GHz, but the bandwidth of operation is low due to

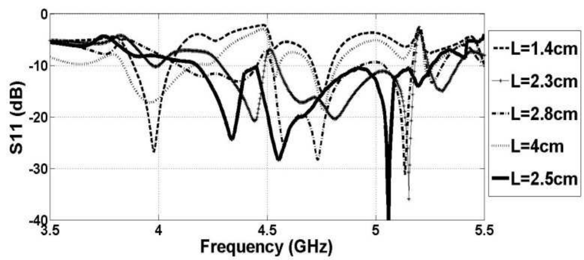

Figure 6. The effect of increasing the length 'L' of the probe. The optimized value of 'L' is 2.5 cms.

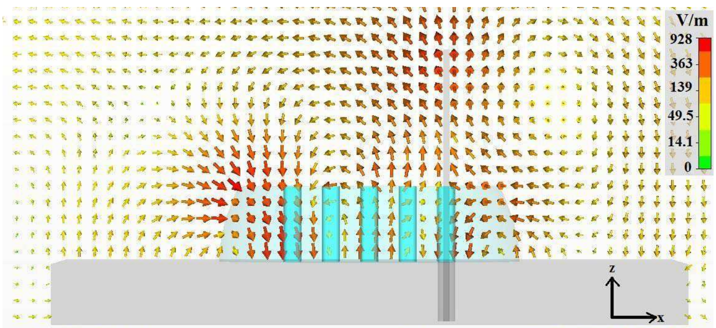

Figure 7. The electric field distribution of the antenna with probe length $L = 2.5\,\text{cm}$ at 4.55 GHz. It can be observed that there is no variation along the broadside of the probe.

impedance mismatch. As the length of the probe is further increased, the widest bandwidth of 1.3 GHz is observed at $L = 2.5$ cm. This can be attributed to matched impedance along the complete frequency range of operation.

A simple monopole of the above optimized length would resonate at 1.8 GHz and 5.3 GHz. However, the loaded half HDRA with periodic holes lowers the resonant frequency to 4.4 GHz and suppresses all other lower order resonant frequencies. Further, because of the effect of the loaded half HDRA, the field pattern gets modified. Figure 7 shows the Electric field pattern and it can be observed that there is a null in the broadside direction, and because of the offset probe feed, the electric field distributes more along the dielectric material which contributes in the radiation from the antenna. The field inside the dielectric region is quite similar to the field lines of the previous case. However, the null in the broadside suggests that there will be no radiation in the broadside direction and thus the pattern must be directive. This has been verified experimentally and the results are discussed in the next section.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The Rogers copper clad high frequency Laminates are available in thickness of 0.25″. Hence to fabricate the structure, two slabs were joined by applying glue from the edges under high pressure to form a slab of thickness of 1.27 cm (0.5″). The structure was then fabricated using a high precision lathe machine. Commercially available SMA connectors were used to provide coaxial feeding to the fabricated antenna. All measurements were taken on the Vector Network

Figure 8. The side view of the fabricated structure of half HDRA with probe feed. The inset picture shows the side view of the fabricated structure of half HDRA with extended probe feed of length $L = 2.5$ cms.

Analyzer of Agilent, model No.-8722ET. The fabricated structure of the half HDRA with array of slots is shown in Figure 8. The inset picture in Figure 8 shows the fabricated structure after increasing the probe length to 'L' cms. For measurements, $L = 2.5$ cms, the optimized value obtained through the parametric analysis.

The half HDRA with air holes when excited by probe, as discussed in the previous section, resonates at a frequency of 5.74 GHz when measured experimentally. The return loss measurement of the simulation and the measured data show a minor difference as shown in Figure 9. The resonance as predicted by the simulation is 6.08 GHz whereas the measured value shows a resonance at 5.74 GHz. The difference in the results are mainly due to the fabrication inconsistencies like small air gaps between the slabs of the DRA, air gaps between the DRA and the metal portions, i.e., Ground Plane, imperfections while drilling the holes, etc.. The 10 dB bandwidth measured experimentally is close to 1 GHz (~17.74%) which is approximately the same as that of the simulation results, which measures 17% bandwidth. The measured VSWR is 1.1 at the resonant frequency of 5.74 GHz. The VSWR plot versus the frequency as shown in Figure 10, shows that the VSWR is less than 2 for the complete bandwidth of operation.

The measured radiation pattern along the x-z ($\Phi = 0°$) plane and

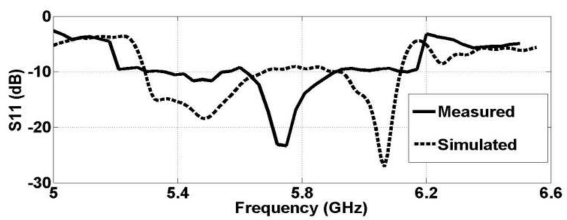

Figure 9. Plot of the measured and simulated return loss for the half HDRA with array of slots.

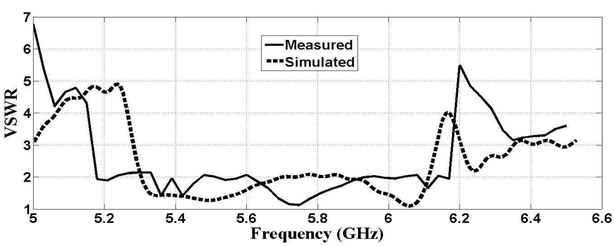

Figure 10. The plot of the VSWR vs. frequency for the half HDRA with array of slots.

y-z ($\Phi = 90°$) plane are shown in Figure 11. These are measured at 5.74 GHz and 6.02 GHz for both co and cross polarization. The cross polar pattern is generally higher [23] for DRA and it is verified from these results as well. Though, it is worth observing that in most of the angles of measurement the cross polar pattern is around 15 dB lower than the co-polar pattern values. The radiation pattern clearly resembles the pattern for TM_{101} like mode radiation pattern

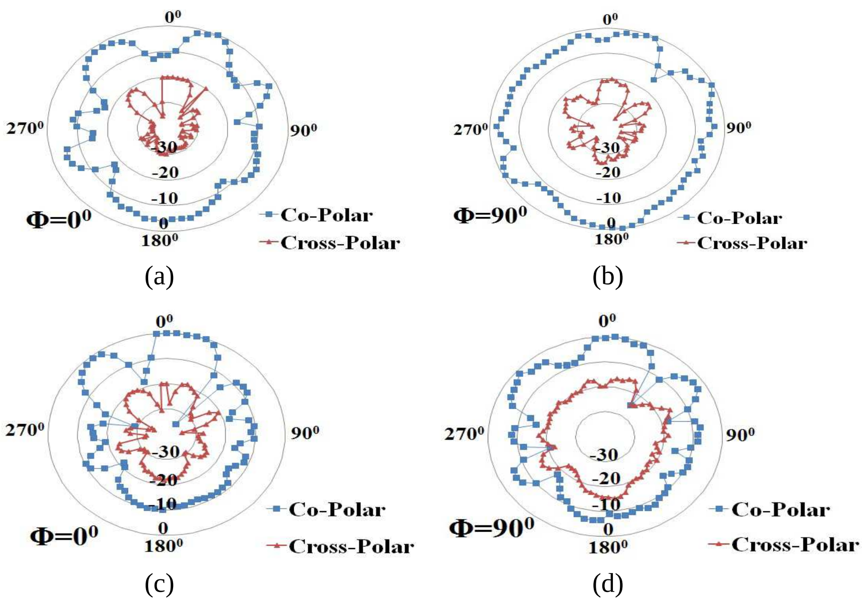

Figure 11. The radiation pattern as measured for the half HDRA with array of slots. The angles marked represent the 'θ' plane. (a) (c) x-z plane ($\Phi = 0°$). (b) (d) y-z plane ($\Phi = 90°$). (a) (b) 5.74 GHz. (c) (d) 6.02 GHz.

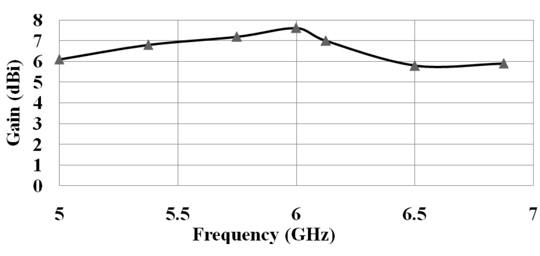

Figure 12. The gain vs. frequency plot for the half HDRA with periodic slots.

at 5.74 GHz when compared with the results cited by Leung et al. [12]. The measured gain of the antenna is 7.2 dBi and 7.618 dBi for 5.74 GHz and 6.02 GHz, respectively. The gain vs. frequency plot, as shown in Figure 12, confirms that the gain is almost constant for the entire bandwidth of operation and is higher than 6 dBi, which is considerably

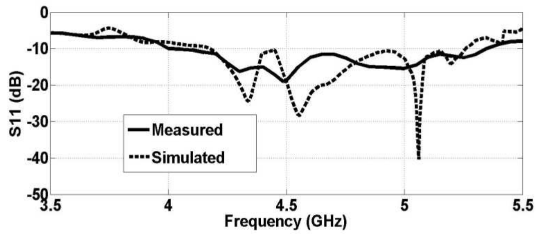

Figure 13. Plot of the measured and simulated return loss for the half HDRA with extended probe length of $L = 2.5$ cm. The 10 dB bandwidth measured is 1.3 GHz.

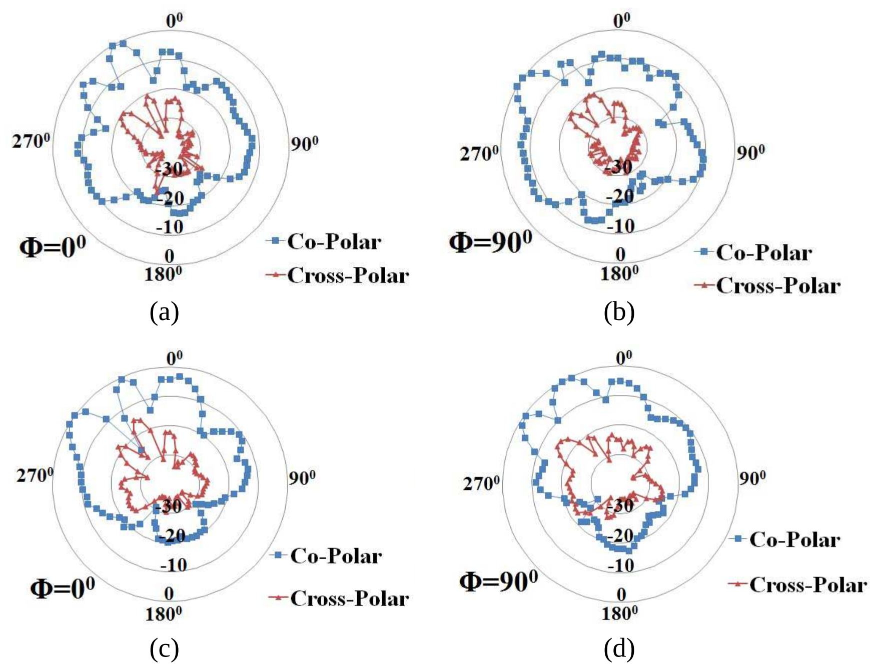

Figure 14. The radiation pattern as measured for the half HDRA with extended probe length of $L = 2.5$ cm. The angles marked represent the 'θ' plane. (a) (c) x-z plane (Φ=0°). (b) (d) y-z plane ($\Phi = 90°$). (a) (b) 4.5 GHz. (c) (d) 5 GHz.

high for a dielectric resonator antenna. Most of the references cite a gain of 5 to 6 dBi, hence our proposed structure is comparatively superior.

The effect of increasing the probe length on the HDRA characteristics has also been discussed. The analysis reveals that at $L = 2.5$ cm, the DRA offers the widest bandwidth of operation. The measured bandwidth is 1.3 GHz ($\sim$29%). Thus the total probe length from the ground plane level becomes $L + h = 2.5 + 1.27 = 3.77$ cm. The return loss measurement of simulation and experiment are well in agreement and are shown in Figure 13. The resonance is observed at around 4.5 GHz.

As has been discussed in the previous section, the Electric field pattern shows a null in the broadside of the probe. Thus, we can expect that the radiation pattern will not be broadside but directive, which is confirmed from the measured radiation pattern at 4.5 GHz, in Figures 14(a) and (b). The measured gain of the antenna is 7.2 dBi at 4.5 GHz and 7.05 dBi at 5 GHz. Figures 14(c) and (d) show the pattern at 5 GHz. The gain vs. Frequency plot for the antenna in the bandwidth of operation is consistent and almost constant. This can be seen in Figure 15. The efficiency of the antenna is also considerably high. The efficiency has been calculated by the solver. It shows that at 4.5 GHz, the efficiency is around 98%. Further, Figure 16 shows that

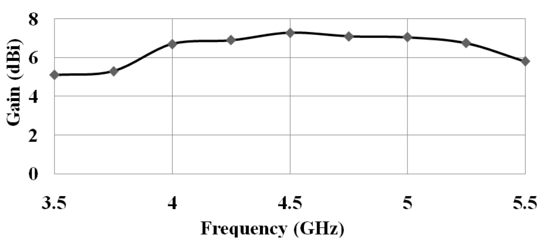

Figure 15. The gain vs. Frequency plot for the half HDRA with periodic slots and extended probe length of $L = 2.5$ cm.

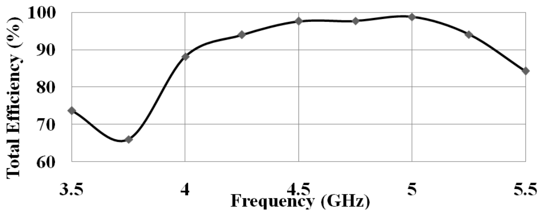

Figure 16. The plot of total efficiency vs. the frequency for the half HDRA with periodic slots and extended probe length of $L = 2.5$ cm.

Table 1. Comparison of the proposed antenna structure.

Reference	ε_r	f_r	**BW**	**Gain**	**Mode**	**Volume**
[3]	10,12	3.3	0.96	4	$HEM_{11\delta}$	13.1
[5]	8.9	1.9	0.22	6.4	TE_{111}	34.3
[6]	10	3.2	1.12	5	$HEM_{11\delta}$, TM_{101}	16.75
[7]	9.5	3.68	0.77	5	TE_{111}	515.2
[15]	9.5	3.5	0.74	5	TE_{111}	4.09
[19]	10	3.5	1.05	2.5	$HEM_{11\delta}$, TM_{101}	16.75
PS	**9.2**	**4.55**	**1.3**	**7.2**	**TM_{101} like**	**12**

ε_r = dielectric constant, f_r = resonant frequency (GHz), BW = bandwidth (GHz), Gain = measured in dBi, Volume = volume occupied by the antenna (cm^3), PS = Proposed Structure (case of half HDRA with increased probe length), The above is the comparison of the best cases from all references.

the antenna efficiency in the bandwidth of operation is above 90%.

The comparison of the best case of the proposed structure with other references is as tabulated in Table 1, which shows that our proposed antenna has the best results so far.

5. CONCLUSION

A half Hemispherical Dielectric Resonator Antenna with an array of slots has been proposed and investigated. The antenna is excited by a probe feed. The mode investigated reveals it to be TM_{101} like mode. The effect of drilling holes results in higher bandwidth of operation. Further, the effect of increasing the probe length on the antenna performance characteristics is also studied. A bandwidth of 1.3 GHz (~29%) and a high gain of 7.2 dBi has been achieved at the resonant frequency of 4.5 GHz, for the probe length of 2.5 cm. The new antenna is simple in configuration and can be excited by commercially available SMA connectors and probes. The antenna offers wide bandwidth, high gain and to the best of our knowledge, such geometry has not been explored yet. Further, on comparison, it is revealed that the Gain and Bandwidth of operation for such geometry is the best so far.

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