Hemispherical Dielectric Resonator Antenna loaded with a Photonic Band Gap Structure for Wideband and High Gain Applications

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Abstract

In this paper, a novel investigation of a Hemispherical Dielectric Resonator Antenna (HDRA) loaded with a Photonic Band Gap (PBG) structure is carried out. The HDRA is designed of material of permittivity ε_r=9.2 and is resonant at 1.816 GHz offering 10.4% impedance bandwidth and a peak gain of 6 dBi. The PBG designed from a dielectric of ε_r=9.8, is arranged in a square lattice and offers a band gap from 1.6 GHz to 1. 95 GHz. The effect of the PBG loaded on HDRA reveals that the bandwidth is increased for TE_{111} mode to 38% at 1.78 GHz offering a peak gain of 8.05 dBi. The efficiency is above 90% for the entire bandwidth of operation.

1. Introduction

The modern communication systems have witnessed an escalation in frequency of operation to achieve faster, safer and higher data rate transfers. The need for such systems has boosted the growth of MIC/MMIC based planar technology especially patch antennas. However, at extremely high frequencies, metal components suffer from high losses. DRAs, on the contrary, offers wide bandwidth, low overall losses and low cost when used at such high frequencies [1]. Several geometries of DRA like rectangular, cylindrical, etc. have been investigated, however, Hemispherical geometry offers wideband and the ease of modeling the air and dielectric interface [1,2].

Many wideband and high gain techniques have been investigated on the HDRA like air gap in HDRA, multilayer and multi element stacking of dielectric materials [1], etc. Also some novel variants of the Hemispherical Geometry like half HDRA [3,4], segmented HDRA [5], etc. have also been investigated. Though so, the modes excited in the novel variants are also modified despite offering broadband operation [3-5]. The excitation of the modes of a DRA is also dependent critically on the feeding mechanism. A probe fed at an offset to the HDRA is capable of exciting both TE and TM modes of an HDRA [2,6].

The preliminary inspection of PBG was carried out in [7], where Yablonovitch showed that a periodic array of holes drilled in a dielectric material prohibits the propagation of Electromagnetic Waves along a particular direction. This band of frequencies is called as Band Gap. This property of PBG has been well harnessed to enhance the characteristics of planar antennas like Gain, Bandwidth [8-10], etc.

In this paper, a novel investigation of a PBG loaded on an HDRA is carried out. The effect of PBG on HDRA shows a significant improvement in Bandwidth (S_{11}<-10 dB) of operation from 10.4% to 38% at 1.78 GHz and also improvement in peak gain from 6 dBi to 8.05 dBi at 1.95 GHz. The fundamental TE_{111} mode remains preserved. All simulations have been carried out on CST Microwave Studio.

2. Design Procedure

A dielectric material resting on a ground plane is capable of radiating when given an appropriate feed. The resonant frequency of the HDRA is governed by the following equation [1] :-

$$f_r = \frac{4.775\times10^7 Re(K_a)}{\sqrt{(\varepsilon_r)}r} \tag{1}$$

Where 'f_r' is the resonant frequency, 'ε_r' is the dielectric constant of the HDRA, 'r' is the radius of the hemisphere (in cms) and 'K_a' is the wave number in the dielectric. The dielectric material used for simulation and fabrication is TMM10, a ceramic thermoset polymer composite material of the Rogers high frequency laminates. The dielectric constant of the material is ε_r=9.2, the dissipation factor tanδ=0.0022 and the density is 2.8 gm/cm^3. An HDRA with a radius of r=2.54 cm (1") made up of the above mentioned dielectric material, when given an offset probe feed at x=1.74

cm, will resonate at 1.816 GHz with a bandwidth of 10.4%. The length of the arm of the square shaped ground plane is L=16 cm. The offset probe feed with length l=1.5 cm, excites the fundamental TE_{111} mode at this frequency [2,3,6]. The S_{11} plot of a simple HDRA is as shown in Fig. 4(a).

The design of a PBG depends on two critical constraints, the contrast between the dielectric materials used and the lattice size. The unit cell of the PBG structure can be seen in Fig. 1(a). In our proposed design, square lattice of holes of radius 'r_1' is drilled in a dielectric slab of ε_r=9.8. This maximizes the contrast between the dielectrics. In order to achieve a band gap which is centered around the resonant frequency of the HDRA, two parameters need to be optimized, the radius of the holes 'r_1' and the periodicity of the holes drilled 'p'. The dielectric material of the PBG is available as a standard slab of Rogers High frequency laminate TMM10i. The parametric analysis as shown in Fig. 1(b), yields that as 'r_1' is changed from 0.5 to 0.8 cm for p=2.5 cm, the band gap also shifts towards higher frequencies. The variation of 'p' from 2.5 cm to 3.5 cm reveals that the band gap shifts on the lower frequencies. After rigorous parametric variations study on CST MWS, the dielectric material of ε_r=9.8 of size 6''×6'' with 5×5 number of holes in a square lattice with r_1=0.8 cm and p=3 cm, shows a band gap from 1.6 GHz to 1.95 GHz. The simulator settings in CST include 25 mesh cells per unit wavelength, with hexahedral meshes using Transient Solver technique. The boundary condition is open along the direction of the ports and Electric wall i.e. E_t=0 along the top and bottom of the PBG. This offers a band gap for the TM modes. The band gap response for the simple PBG with drilled holes in dielectric slab is as shown in Fig. 1(c).

The proposed geometry is as shown in Fig. 2. Initially we choose, h=0 cm and vary the parameter 'r_2'. Thus, this basic structure is an HDRA embedded in the PBG. To initiate the parametric analysis, r_2=3 cm is chosen. As 'r_2' is increased from 3 cm, a wideband is observed. The maximum bandwidth (~18%) is offered for r_2=3.8 cm at 1.79 GHz. The parametric analysis is as shown in Fig. 3(a). The field lines of the HDRA in the near field region, gets coupled into the PBG which generates persistent reflections lowering down the Q factor and hence, increases the bandwidth. As an extension of the proposed structure, the height 'h' of the PBG is increased as shown in Fig. 3(b). It can be observed that as the height is increased a wider bandwidth of operation is observed. The maximum bandwidth is achieved for h=1.25 cm which is 30% at 1.9 GHz. Beyond h=1.25 cm, the bandwidth is reduced again. Further, the value of 'r_2' is now optimized for h=1.25 cm. As the value of 'r_2' is reduced from 3.8 cm, the bandwidth is increased further as shown in Fig. 3(c). The optimized value is reached at r_2=1.85 cm, where the bandwidth of operation is 38% at 1.78 GHz. It should be noted that even at r_2=1.85 cm, the HDRA does not touch the PBG physically; however, it is extremely close to it. At h=1.25 cm and r_3=3.8 cm, there is maximum coupling of the Electric and Magnetic Fields as the PBG is in the near field region. This coupling is even enhanced when r_3=1.25 cm and h=1.85 cm. Since, this is a TM mode PBG, hence the first resonant mode of the HDRA i.e. TE_{111} mode, gets coupled into the PBG and the continuous reflection of the EM waves in the PBG, decreases the overall Quality Factor (Q factor) of the HDRA, thus enhancing the bandwidth of operation. Interestingly, the bandwidth is enhanced for the TE_{111} mode only which is evident from the field lines as shown in Fig. 4(b), observed at 1.78 GHz. Also, the radiation pattern as measured in the bandwidth of operation show a broadside radiation pattern which confirms the TE_{111} mode of the HDRA [6].

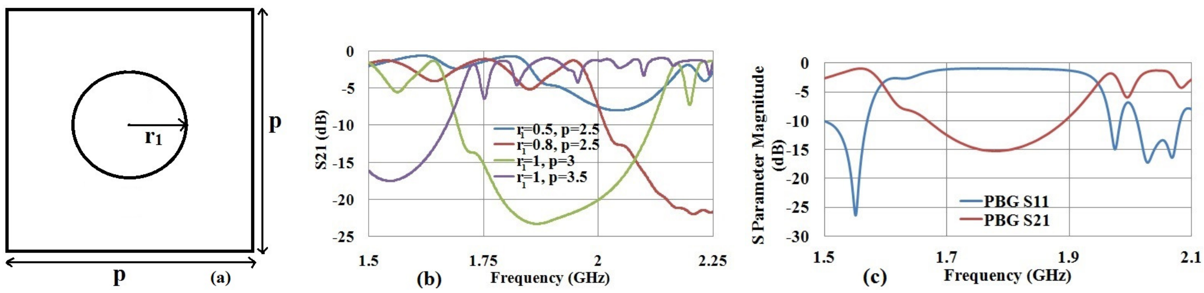

Fig. 1 The proposed PBG structure. (a) The unit cell of PBG. (b) Parametric analysis of 'r_1' and 'p'. (c) The response of the square lattice PBG.

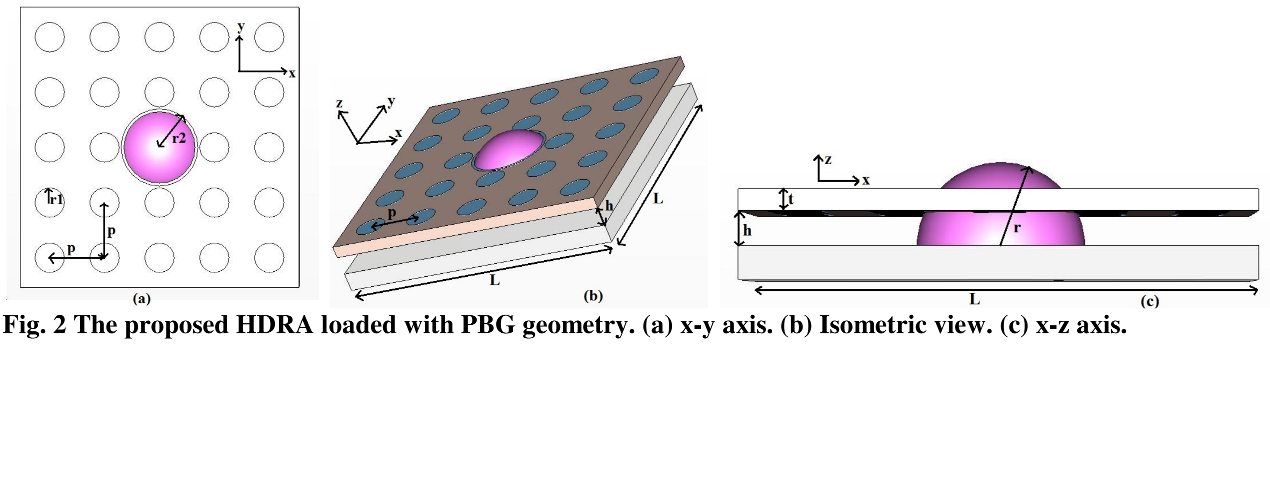

Fig. 2 The proposed HDRA loaded with PBG geometry. (a) x-y axis. (b) Isometric view. (c) x-z axis.

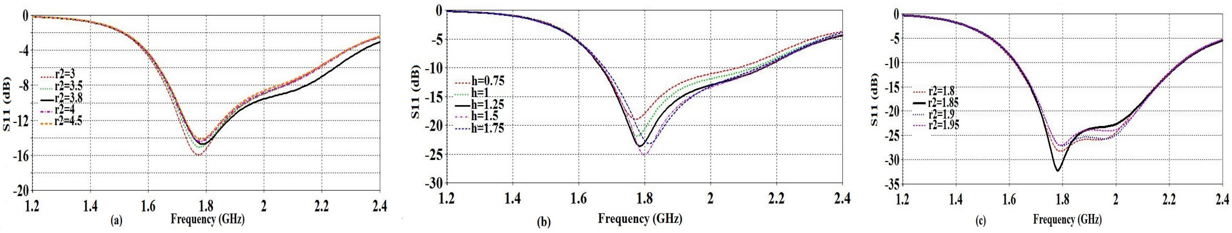

Fig. 3 The parametric analysis of various parameters. (a) h=0cm, r_2 is varied. (b) r_2=3.8 cm, h is varied. (c) h=1.25 cm, r_2 is varied.

3. Results and Discussions

The effect of loading the PBG on HDRA reduces the overall Q factor of the HDRA. The reduction in Q factor leads to a significant improvement in bandwidth of operation. The relationship between the Q factor and bandwidth is given as follows:-

$$BW = \frac{VSWR-1}{Q\sqrt{VSWR}} \tag{2}$$

A comparison of the plot of S_{11} for the proposed structure and the basic HDRA is as shown in Fig. 4(a). The increase in bandwidth can also be seen clearly. The impedance bandwidth (%) is measured by the following equation:-

$$\text{BW}= \frac{\Delta f}{f_0} \times 100 \tag{3}$$

and $$\Delta f = f_u - f_l \tag{4}$$

where BW is bandwidth, f_0 is the resonant frequency (GHz), Δf is the difference between the upper (f_u) and the lower frequency (f_l) along the -10 dB line on the S_{11} plot, measured in GHz.

The loading of the PBG on HDRA doesn't affect the mode of the HDRA. Instead the broadband is observed for the fundamental TE_{111} mode of the HDRA. The field lines in Fig. 4 (b), when compared with the ref. [6] suggest that our assumption is correct. Further justification is achieved by the fact that the radiation pattern in the bandwidth of operation is broadside in nature [6].

The radiation pattern of the proposed geometry is as shown in Fig. 5. The Fig. 5 (a) is for 1.78 GHz and Fig. 5 (b) for 2 GHz. It is clearly observed that the radiation is in the broadside direction justifying the assumption made regarding the TE_{111} mode of operation of the HDRA. The radiation patterns have been plotted for both $\Phi=0^0$ (y-z plane) and $\Phi=90^0$ (x-z plane) for both the frequencies. The cross-polar levels of the radiation patterns are high which is generally true for any DRA [1].

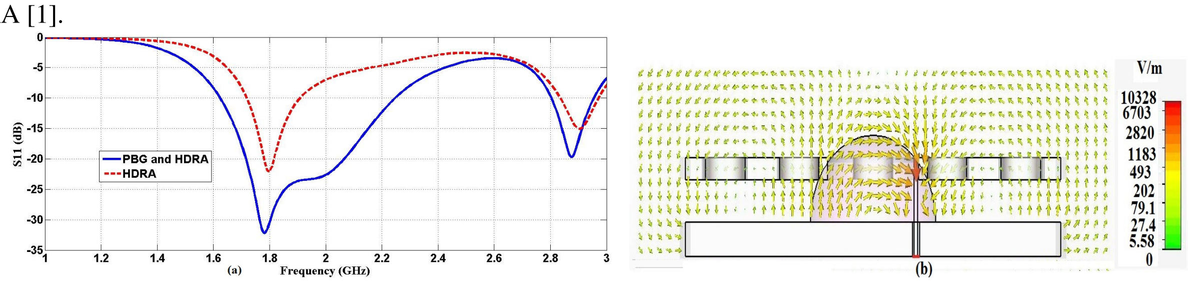

Fig. 4 Results of the proposed geometry. (a) Comparison of the S_{11} plot of the proposed geometry with the basic HDRA. (b) The Electric field line distribution at 1.78 GHz verifies the TE_{111} mode of operation.

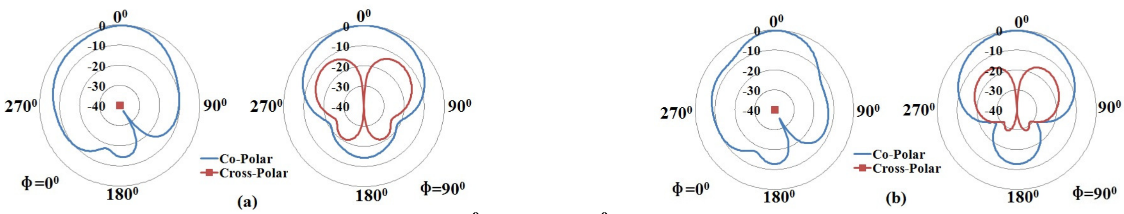

Fig. 5 Radiation Patterns plotted for $\Phi=0^0$ and $\Phi=90^0$. (a) 1.78 GHz (b) 2 GHz.

The plot of the gain versus frequency as shown in Fig. 6(a), suggests that the gain is almost constant in the frequency band of operation. The peak gain observed is at the resonant frequency which is around 8.05 dBi at 1.95 GHz. In the complete bandwidth, the gain is above 7 dBi, which is generally high when compared to the other DRAs. The reason for high gain is attributed to the reason that as the forbidden frequency band is formed in PBG, the EM waves in this frequency band will be suppressed or they cannot be transmitted in any direction. Since, the PBG is positioned at the optimized height h=1.25 cm, where maximum radiation takes place, the EM waves will be restrained, and therefore, energy reflected into the space is increased, thus, improving the Gain. The plot of the total efficiency versus the frequency is as shown in Fig. 6(b). The total efficiency is above 90% for the entire bandwidth. At 1.95 GHz, the peak efficiency observed is 97% as per simulations. Table I is a compilation of the comparison of the proposed structure with the references of various researches carried out on HDRA. It can be seen that the results of the HDRA with PBG offers the best combination of Gain and Bandwidth, which is rarely observed.

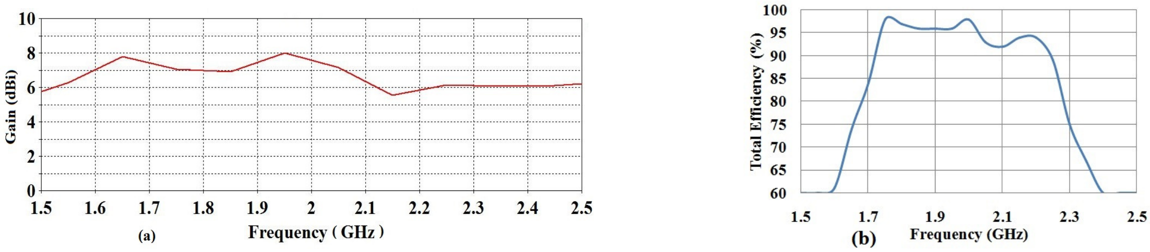

Fig. 6 Results of Simulation for the proposed structure. (a) Gain versus frequency plot. (b) Total Efficiency versus Frequency plot.

TABLE I COMPARISON OF THE PROPOSED STRUCTURE

Ref	ε_r	*Shape*	*Mode*	*V*	*BW*	f_r	*Gain*
2	8.9	Hem.	TE_{111}	34.3	10.5	1.9	6
3	9.2	Hem.	TM_{101}	12	29	4.55	7.2
4	10	Hem.	$HEM_{11\delta}$, TM_{101}	16.75	35	3.2	5
5	10	Hem.	$HEM_{11\delta}$, TM_{101}	16.75	30	3.5	2.5
PS	**9.2**	**Hem.**	$\mathbf{TE_{111}}$	**34.3**	**38**	**1.78**	**8.05**

ε_r= dielectric constant, Hem.= Hemispherical Geometry, f_r= resonant frequency (GHz), BW= Bandwidth (%), Gain= units in dBi, Mode= mode excited, Vol.= Volume of the dielectric material occupied, PS= Proposed Structure.

4 Conclusion

This paper presents a novel investigation of a PBG loaded HDRA. The effect of the PBG loading results in improvement in bandwidth from 10.4% to 38% at 1.78 GHz and the improvement in peak gain from 6 dBi to 8.05 dBi at 1.95 GHz. The fundamental TE_{111} mode of the HDRA remains preserved. The gain and total efficiency of the proposed geometry is above 7 dBi and 90% respectively. To the best of our knowledge, such an investigation has not been done so far. The results of the investigation are also extremely competitive when compared to other references.

5 References

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