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Two-Layer Sapphire Rectangular Dielectric Resonator Antenna for Rugged Communications

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Abstract—This paper presents a stacked rectangular dielectric resonator antenna design. In this structure, two sapphires having the same dielectric constant and different dimensions piled over each other have been used for designing the proposed antenna. The designed antenna exhibits two frequency bands from 7.41 GHz to 8.21 GHz and 9.11 GHz to 12.65 GHz and impedance matching of 50 ohms. The proposed antenna design is a fine choice for subterranean and rugged communication, in addition, owing to sapphires unique features viz. durability, endurance, and aversion to physical change. The antenna structure is aperture coupled. Due to the advantage of aperture coupled feed mechanism such as good isolation between antennas and feed networks it has been employed. The antenna prototype has been fabricated, measured, and tested using Vector Network Analyzer and Anechoic Chamber to validate the proposed antenna design. The simulation results obtained indicate close proximity of tested result.

1. INTRODUCTION

Since its inception, wireless technology has undergone many stages of development. There has been revolutionary growth in the world of wireless communications systems. Antennas form the most integral part of any wireless communication systems. In order to keep pace with fast changing requirements of the wireless communication market, fast and efficient antennas are in great demand. Besides, it is desired that antennas should be of that type which can be scaled up in frequency. There are two types of antennas which have been able to match up these needs namely microstrip antenna and dielectric resonator antenna. Initially, microstrip patch antennas were best suited, but from last few decades dielectric resonator antennas have totally replaced them [1–3], since dielectric resonator antennas (DRAs) have an edge over microstrip antennas because of its many attributes namely ease of fabrication, flexibility infeed mechanism, low profile, high radiation efficiency, and wide frequency range to name a few. Moreover, DRA is a 3-D structure whereas microstrip antenna is a 2-D structure. In addition, DRAs are well suited for low-loss applications for the reason that there is no conductor loss in them.

In 1939, Richtmyer proved that dielectric resonator antenna radiates energy [4]. However, the investigation done by the author was theoretical. Thus practical applications did not occur till the 1960s. It was Long et al. [5] who for the first time conducted a proper study and experimentally investigated properties. Long et al. also measured the radiation pattern, the input impedance for structures of many geometrical aspect ratios, and the permittivity and sizes of co-axial fed probes. Their study on the dielectric resonator antenna gave a suitable substitute over traditionally used low gain antenna elements. After carrying out an investigation of cylindrical DRA, Long and colleagues carried out research on other DRA shapes such as rectangle and hemisphere [6–9]. Design flexibility in terms of shape and feeding mechanisms makes DRA the first choice of antenna designers. DRA

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has given the base worldwide for many research activities which have resulted in the design of many efficient and novel DRAs. However, there are many unexplored areas too, such as using new material for designing DRA. Therefore, because of sapphire's lot of merits namely robustness, light transmission, thermal insulation, sapphire can be used to design an antenna [10]. The literature review [11–22] shows that materials used for DRAs so far are thermoset microwave material which is a ceramic thermoset polymer. In the microwave region, the losses in the ceramic material increase because of interaction among the applied field and phonons which leads to the damping of the optical lattice vibrations, in turn, causing a dielectric loss. Thus, there is a need for a material to replace the ceramic material. Dielectric resonator antenna with sapphire material overcomes drawbacks of ceramic material and thus outweighs dielectric resonator antenna with ceramic material in terms of better performance. It is a potential prospect for future smartphones and mobile communication. Hence this paper presents a sapphire stacked rectangular dielectric resonator antenna design. The stacked structure gives one of the effective ways of enhancing the impedance bandwidth as well as generating multiple modes of an antenna instead of a single structure design [23–25]. A number of shapes of DRAs are available, but the rectangle-shaped DRA has been put in use as it is the only shape that gives more fabrication flexibility than other geometries, also because this shape achieves better radiation as well as impedance in the design [26]. There are multiple ways or methods to excite an antenna such as microstrip transmission line, coaxial probe feed, coplanar waveguide line, and aperture coupled feed to name a few. Out of all, aperture coupled feed mechanism is mostly employed. The objective behind using aperture coupled feed is that it avoids spurious modes because it keeps feeding networks below the ground plane [27–29]. The five sections of the paper are organized as follows. Section 1 covers the introduction. Section 2 shows antenna design calculation. Section 3 gives antenna configuration and design. Section 4 demonstrates various results and their discussion whereas Section 5 is the conclusion and future scope.

2. ANTENNA DESIGN CALCULATION

Dielectric waveguide model has been utilized for finding the resonant frequency and initial dimensions of rectangular dielectric resonator antenna. By the magnetic wall boundary condition and solving the following transcendental equation the resonator frequencies for dominant modes (TE to Z mode) are obtained [30]:

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \tag{1}$$

$$f_o = \frac{c}{2\pi\sqrt{\varepsilon}_r}\sqrt{k_x^2 + k_y^2 + k_z^2} \tag{2}$$

$$k_x = \frac{\pi}{a}; \quad k_y = \frac{\pi}{b} \tag{3}$$

$$k_z\left(\tan\frac{k_z d}{2}\right) = \sqrt{(\varepsilon_r - 1)k_0^2 - k_z^2} \tag{4}$$

where ε_r denotes dielectric constant of dielectric resonator antenna; a and b are width and height, respectively, c is the velocity of light; and k_0, k_x, k_y and k_z are the wave numbers along x, y, and z directions.

As shown in Fig. 1, aperture coupling is used as a method of excitation. Equations (5), (7), (8) are utilized as the initial point for designing slot dimensions [31].

Slot length,

$$L_S = \frac{0.4\lambda_o}{\sqrt{\varepsilon}_e} \tag{5}$$

where λ_o is the wavelength, and effective permittivity is defined as:

$$\varepsilon_e = \frac{\varepsilon_r + \varepsilon_s}{2} \tag{6}$$

where ε_r and ε_s are the relative dielectric constants of the rectangular dielectric resonator and substrate, respectively.

Slot width,

$$W_s = 0.2L_s \tag{7}$$

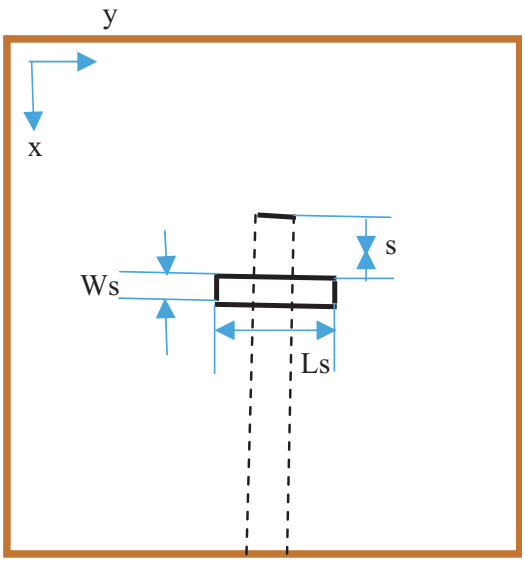

Figure 1. Aperture coupled Feed.

Stub length,

$$s = \frac{\lambda_g}{4} \tag{8}$$

where λ_g is the guided wave in the substrate.

3. ANTENNA CONFIGURATION AND DESIGN

Both the design structures have been created on an FR4 substrate possessing dielectric constant 4.4 and dimensions $50 \times 50\,\text{mm}^2$ with loss tangent 0.002. The antenna design consists of two sapphires of the same permittivity = 10 and same height = 2.5 mm but different dimensions piled over each other as shown in Fig. 2.

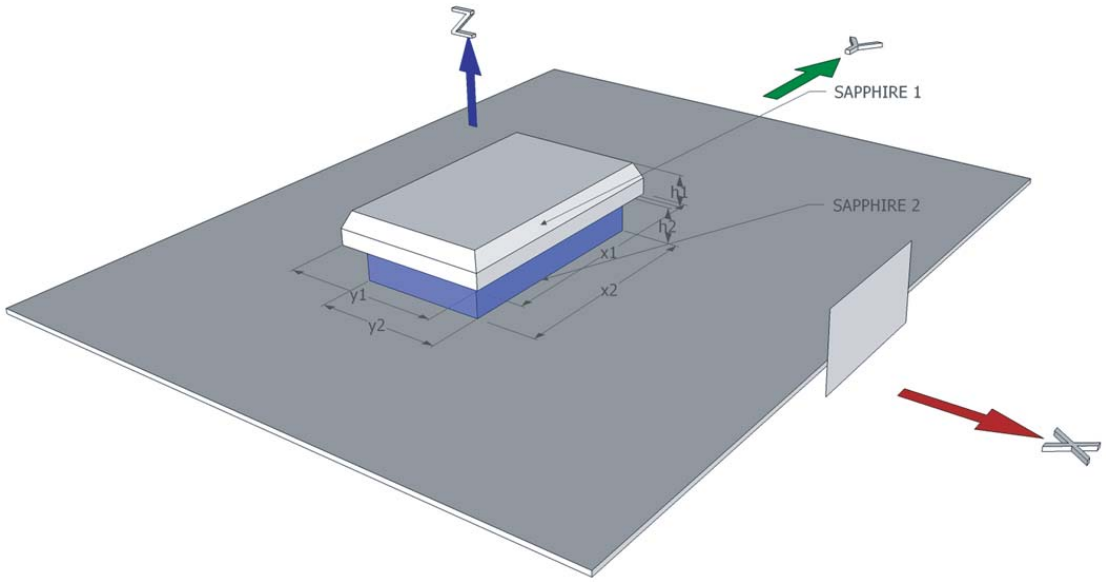

Figure 2. Geometry of the Sapphire Stacked Antenna $x_1 = 13\,\text{mm}$, $y_1 = 10\,\text{mm}$, $h_1 = 2.5\,\text{mm}$, $x_2 = 12\,\text{mm}$, $y_2 = 8\,\text{mm}$ and $h_2 = 2.5\,\text{mm}$.

In order to provide feeding mechanism through aperture coupled method, a feed line of $L = 30.5\,\text{mm}$ and $W = 1.2\,\text{mm}$ and a slot of dimension $Ls = 9\,\text{mm}$ and $Ws = 1.5\,\text{mm}$ are etched from the ground plane to create the aperture coupling excitation mechanism shown in Fig. 3.

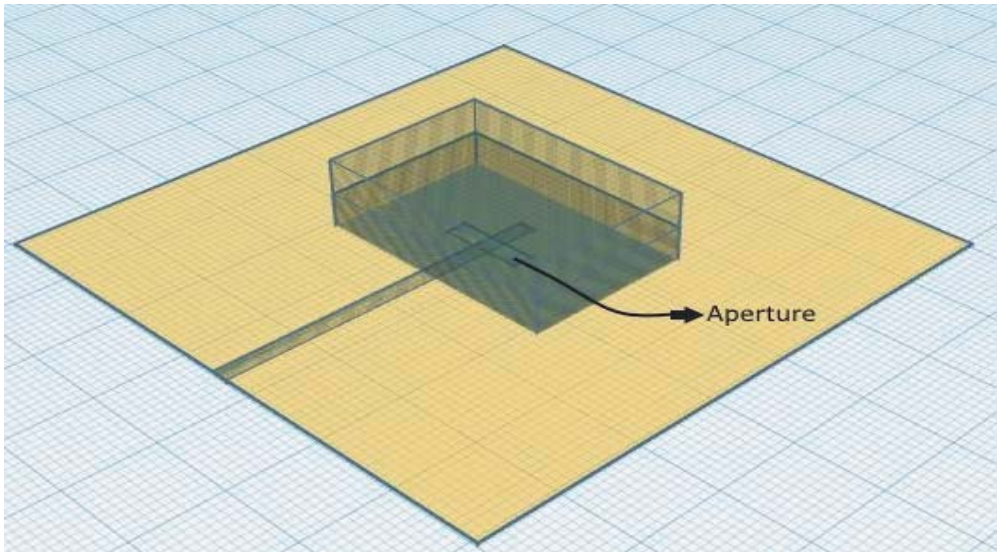

Figure 3. Aperture coupled Feed.

All the design dimensions are summarized in Table 1.

Table 1. Design parameters of stacked antenna.

Object	Material	Dielectric Constant (ε_r)	Dimension Specifications in mm		
			Length	Breadth	Height
Ground Plane	FR4	4.4	50	50	0.8
Dielectric Layer 1	Sapphire	10	13	10	2.5
Dielectric Layer 2	Sapphire	10	12	8	2.5

4. RESULTS AND DISCUSSION

4.1. Simulated Result

Using Ana Soft HFSS the designed antenna is simulated. Fig. 4 exhibits that the proposed antenna design shows reflection over two frequency bands from 7.41 GHz to 8.21 GHz and 9.11 GHz to 12.65 GHz. Hence antenna match is considered positive.

4.2. Fabrication and Measured Result

Fabrication of antenna prototype is shown in Fig. 5. Several tested results on VNA (Vector Network Analyzer) and Anechoic Chamber are given and discussed.

Measurement setup used for measurements is as follows:

(a) Star lab with 18 GHz anechoic is used for radiation pattern measurements.

(b) The standard antenna of 5 dBi, 18 GHz Horn antenna, linear is used.

(c) Size or External dimensions of Star Lab are $1.82 \times 1.08 \times 2.00\,\text{m}$ ($L \times W \times H$) with rail length 6 meters.

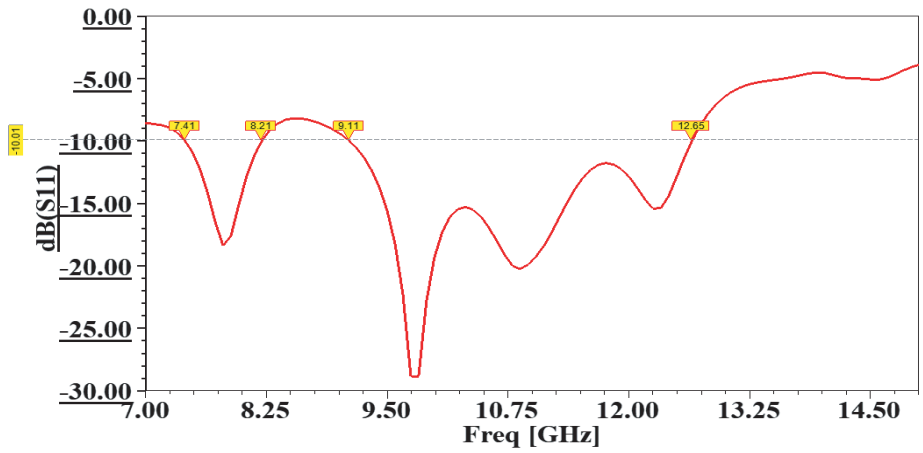

Figure 4. Simulated result of $|S_{11}|$.

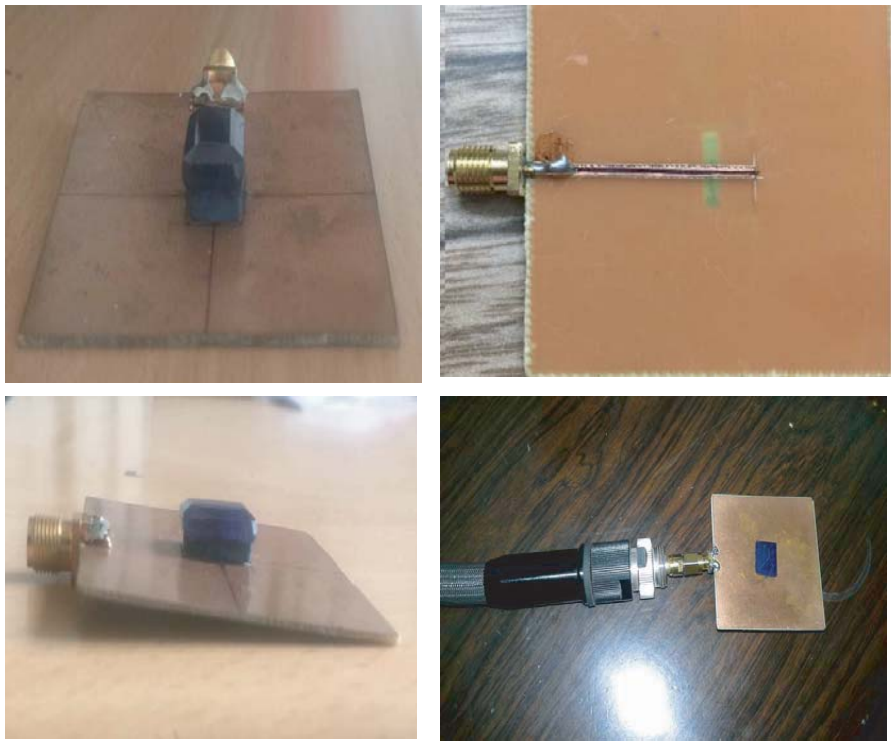

Figure 5. Photographs of the fabricated stacked antenna top view/back view/side views.

Simulated and measured results of the designed antenna, namely gain and radiation pattern (xz plane) are shown in Fig. 6–Fig. 7. From Fig. 6 two peak measured gains of 2.5 dB and 5.5 dB at 5.5 GHz and 6.8 GHz respectively can be observed. It is also evident from Fig. 7 that the radiation pattern of the antenna is broadside. Fig. 8 indicates measured S_{11} plot. The experimental results are in close proximity of simulated results.

Table 2 gives the comparisons in terms of dielectric constant, frequency achieved, and return loss of the proposed DRA with existing DRAs.

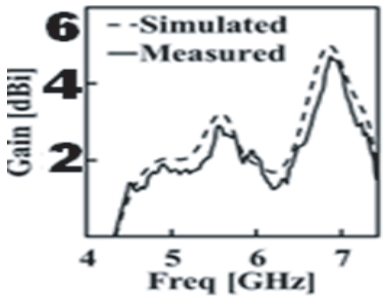

Figure 6. Gain vs frequency plot.

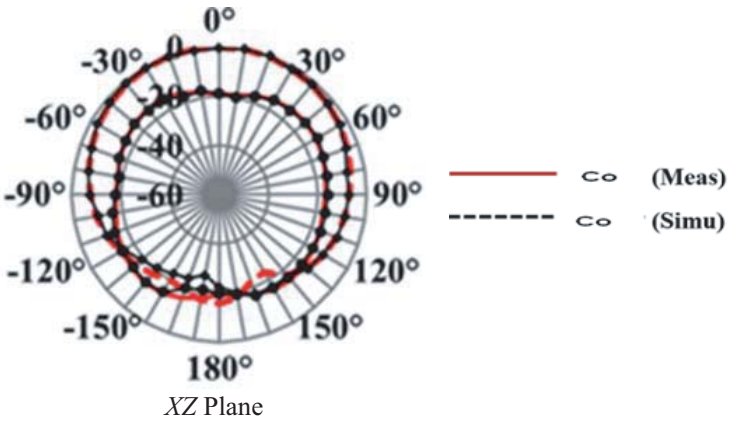

Figure 7. Simulated and measured result of radiation pattern.

Figure 8. Measured result of S_{11} at 7.2 GHz.

Table 2. Comparison of the proposed DRA with existing DRAs.

Reference	Material	Dielectric Constant (ε_r)	Frequency achieved (GHz)	Return Loss
[32]	Roger TMM10i	9.8	5.14–6.51	18
[33]	Rogers RT5880LZ	2	5.21–6.84	18
Proposed Design	Sapphire	10	7.41–8.21 & 9.11–12.65	26

5. CONCLUSION AND FUTURE SCOPE

A two-layer sapphire antenna has been designed and fabricated. The simulated and measured bandwidths achieve two usable frequency bands along with impedance matching of 50 ohms. The antenna design achieves desirable radiation pattern with gains of 2.5 dB and 5.5 dB. The designed antenna is best suited for underground and rugged communication due to the natural property of sapphire which is hardness. Thus, this two-layer antenna structure is proven to be a good choice for designing antennas in the future.

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