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Design and Performance Analysis of C-Band Water Antenna

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ABSTRACT: This paper proposes a dielectric water antenna which is compact, flexible, has low weight, high gain, directivity, and a wide bandwidth. The proposed design has been optimized for the structural values over a frequency range from 0.5 to 8.0 GHz. Distilled water has been used in the glass tube resulting in its significant size reduction. The simulated results have been analysed for statistical parameters (mean & variance). The results have been compared for three different materials used as dielectric layers such as RT-Duroid (6002-lossy), alumina and FR-4. Radiation patterns have been generated using CST 2019 to observe Main Lobe Magnitude, Side Lobe Magnitude, Angular Width and Angular Direction over a frequency range from 0.5 GHz to 8.0GHz. It was observed that dimensional variations of the proposed antenna play an important role in controlling its radiation parameters such as Gain, Main Lobe Direction, Angular Width and Side Lobe Levels. The simulated results for all the three materials used as dielectric layer exhibit a resonant frequency at 5 GHz for the selected dimensions. VSWR for fabricated antenna < 2 and S_{11} < –10 in 3.5 to 8.0 GHz frequency range. This antenna is much cheaper than those using the dielectric materials like mercury, eutectic gallium indium and liquid crystal. It has a much simpler design as compared to Dense Dielectric Patch Antenna (DDPA) which also uses water as a dielectric material.

Keywords: antenna performance, dielectric antenna, water antenna.

Abbreviations: CST, computer simulation technology; DRA, Dielectric Resonator Antenna; SMA, Sub Miniature Version A; VSWR, Voltage standing wave ratio; VNA, Vector Network Analyser; DDPA, Dense Dielectric Patch Antenna.

I. INTRODUCTION

An antenna serves as one of the most important components of any wireless communication system. Since its invention by Henrich Hertz in 1886, antennas have been constantly modified to meet the challenges of the era. Liquid antennas are becoming popular as they are flexible and reconfigurable [1, 2]. To harness these features of liquid antennas Monopole seawater antenna, half-loop water antenna with pump and water-loaded antenna were developed [3-5]. Various liquid materials, such as mercury [6, 7], eutectic gallium indium Hayes *et al.,* [8], liquid crystal [9, 10] and water [11, 12] have been used for implementation of antennas due to their properties such as liquidity, transparency etc. Among these materials, water has become the most popular one because of low cost, easy access, and safety. Water, when used for designing antennas can be of two types, salt water and pure water. The salt water is usually used as a conductor to support the current flow. Different water monopoles have been designed based on this idea [13, 14]. On the other hand, the pure water is commonly applied as a dielectric to construct dielectric resonator (DR) antennas [2, 15-16]. In Dense Dielectric Patch Antenna (DDPA), due to the transparency of the water dielectric patch, it was integrated with solar cells [17]. However the materials used in the above mentioned monopole antennas are much more expensive than the water antenna as described here.

Further the design of DDPA is much more complex than our fabricated water antenna. Madhav *et al.,* [21] designed and implemented a compact antenna on FR-4 substrate material, working in the range of for LTE bands at 1.95–2.04 and 5.92–7.2 GHz, and WiM87AX band 2.87-3.76 GHz. Xu *et al.,* (2013) [22] designed and implemented compact multiple frequencies monopole antennas by loading a set of complementary metamaterial transmission lines with impedance matching better than -10 dB. The metal parts of the antenna become lossy at high frequencies, thus dissipating energy [18]. The DRAs have lower losses as they have lesser metal parts. They are thus more efficient than metal antennas at high microwave and millimetre wave frequencies [19, 20].

Water antennas are a special type of DRAs. The antenna's size is given by $\lambda_0 / \sqrt{\varepsilon_r}$ where λ_0 is the free-space wavelength and ε_r is the dielectric constant of the resonator material. Water has a high dielectric constant, especially dielectric constant of pure water is 81. Thus the antenna's size gets considerably reduced. They are advantageous as they have reduced weight, exhibit excellent conformability as it is easy to make antenna of the desired shape which is difficult to achieve using other dielectric materials or metals. It is reconfigurable as the operational frequency and bandwidth can be controlled by altering height and radius of the liquid column. It can be turned off or drained when not in use. Even large water antennas are easily transportable.

The probe can be inserted well inside the water column, ensuring excellent electromagnetic coupling which was not possible in the antennas discussed earlier and thus the electromagnetic coupling was not as good as our fabricated water antenna.

By altering structural parameters and the material used for constructing the antenna, the operating bandwidth of the DRAs can be varied over a wide range. Xing *et al.*, (2015) [20] have analysed the performance of water antenna by considering the effect of (a) variation of outer radius of ground plane, dielectric layer, and glass tube; (b) variation of height of dielectric layer, and glass tube; (c) variation of temperature and salinity of water column. However, they have not considered the effects of inner radius of the ground plane and dielectric layer through which the SMA probe is inserted into the glass tube on the radiation pattern of the antenna.

In our investigation, inner radii of the ground plane and the dielectric layer have been considered while observing the proposed antenna's radiation pattern.

The antenna performance can be varied by altering various parameters such as diameter of the glass tube, height of the water column, inner and outer radii of the dielectric layer, inner and outer radii of the ground plane, permittivity of the water used (saline, distilled or tap water), and the position of the feed into the glass tube.

II. GEOMETRY OF WATER ANTENNA

Water antenna consists of five parts: a ground plane, a dielectric layer, an SMA connector (discrete port in simulation), a water column, and a glass tube. Dielectric layer is used for isolating the water in the glass tube from the ground plane. CST simulated water antenna is shown in Fig. 1.

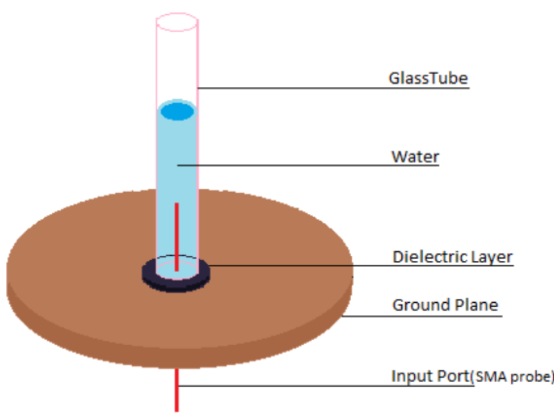

Fig. 1. Structure of Water Antenna.

III. ANTENNA IMPLEMENTATION METHODOLOGY

CST (2019) simulation has been used to design the antenna and observe its performance parameters such as the radiation pattern, VSWR, S_{11}, efficiency, etc. At a time, only one of the structural dimensions has been varied while maintaining the other dimensions as constant. The effect of variation of these parameters has been observed on the antenna's radiation pattern. For this analysis, the optimum values of the dimensions of the ground plane, the dielectric layer, inner and outer radii of the glass tube, height of the glass tube and height of the water column have been selected sequentially.

This antenna was tested in the frequency range from 0.5 GHz to 8 GHz. The statistical parameters such as mean and variance, have been used for selecting the optimum values of the antenna geometry.

Table 1 shows the material used for constructing various parts of the antenna:

Table 1: Material used for various parts of antenna.

Parts of Antenna	Material Used
Ground Plane	PEC
Dielectric Layer	FR-4 (lossy)
Glass Tube	(Pyrex) (loss free)
Water Column	Distilled Water

Effect of variation of radius of ground plane:
As the first step, radius of ground plane was varied while keeping the dimensions of other parts of antenna as given below.

Ground Plane:
– Height = 0.45 mm,
– Inner Radius = 0.6 mm
– Outer Radius = (26 - 30) mm.

Dielectric Layer:
– Material = FR-4,
– Height = 1.5 mm,
– Inner Radius = 0.6 mm,
– Outer Radius = 10 mm.

Glass Tube:
– Height = 20 mm,
– Outer Radius = 4 mm,
– Inner Radius = 3.5 mm.

Water column: (Distilled Water)
– Height = 10 mm,
– Outer Radius = 3.5 mm.

Port length:
– Length = –4 to 5 along z-axis (9 mm).

The observations are as summarized in Tables 2, 3, 4 and 5.

Table 2: Effect of variation of outer radius of the ground plane on Main Lobe Magnitude in the range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of Ground Plane (mm)	Main Lobe Magnitude (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	26	–3.93	2.05	1.81	2.4	3.8	2.32	3.52	2.81	1.84	5.926
2.	28	–0.192	1.78	1.82	3.0	4.06	2.02	3.22	2.43	2.26	1.403
3.	30	4.79	1.78	1.83	2.45	3.81	2.32	3.4	2.81	2.89	0.949

Table 3: Effect of variation of outer radius of the ground plane on Main Lobe Direction in the range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of Ground Plane (mm)	Main Lobe Direction (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	26	90	90	88	64	45	116	133	132	94.75	851.687
2.	28	90	90	87	57	43	119	134	124	93.00	896
3.	30	90	90	88	63	45	116	132	132	94.50	850

Table 4: Effect of variation of outer radius of the ground plane on Angular Width in range of 0.5 GHz to 8 GHz.

S.No.	Outer radius of Ground Plane(mm)	Angular Width (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	26	90.1	89	88.1	77.1	51.6	72.3	66.7	80.6	76.93	153.137
2.	28	90.1	89	88	67.9	51.3	75.3	70.5	84.7	77.10	160.532
3.	30	90	89.2	88	76.3	51.4	72.5	68.6	80.3	77.03	149.547

Table 5: Effect of variation of outer radius of the ground plane on Side Lobe Level in the range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of Ground Plane(mm)	Side Lobe Level (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	26	0	0	0	0	–3.9	–5.9	–10.9	–14.4	–4.38	27.773
2.	28	0	0	0	0	–3.9	–2.9	–7.3	–11.5	–3.20	15.905
3.	30	0	0	0	0	–3.8	–5.1	–11.7	–14.1	–4.33	28.204

The frequency response of the antenna for outer radius of the ground plane with 30 mm radius gives higher positive values and less variance of Main Lobe Magnitude. Hence outer radius of the ground plane has been selected as 30 mm.

In the second step, after fixing the outer radius of the ground plane; the outer radius of the dielectric layer has been varied from 8.5 mm to 25 mm, while maintaining dimensions of glass tube, water column and port length as constant, as mentioned in the first step. The results are tabulated as follows:

Table 6: Effect of variation of outer radius of the dielectric layer on Main Lobe Magnitude over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of dielectric layer (mm)	Main Lobe Magnitude (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	8.5	–3.11	1.9	1.81	2.95	4.08	2.04	3.29	2.32	1.91	4.136
2.	10	–10.1	3.92	1.67	3.44	4.02	1.66	2.75	2.39	1.21	19.038
3.	13	–0.003	1.76	1.82	3.0	4.04	2.01	3.18	2.44	2.28	1.277
4.	15	–1.66	1.81	1.82	2.99	4.05	1.89	3.15	2.37	2.05	2.512
5.	18	–1.43	1.79	1.82	2.99	4.02	1.98	3.13	2.36	2.08	2.281
6.	20	–2.07	1.82	1.82	2.97	3.99	2.0	3.2	2.35	2.01	2.886

Table 7: Effect of variation of outer radius of the dielectric layer on Main Lobe Direction over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of dielectric layer (mm)	Main Lobe Direction (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	8.5	90	90	87	57	43	120	136	125	93.50	931.250
2.	10	91	88	87	53	42	119	124	111	89.37	765.234
3.	13	90	90	87	57	43	119	133	124	92.87	885.859
4.	15	90	90	87	57	43	119	133	124	92.87	885.859
5.	18	90	90	87	57	43	118	133	123	92.62	871.734
6.	20	90	90	87	57	43	118	133	124	92.75	879.437

Table 8: Effect of variation of outer radius of the dielectric layer on Angular Width over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of dielectric layer(mm)	Angular Width (Degrees)									
		0.5 GHZ	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	8.5	90.2	88.9	88	68.5	51.3	74.9	69.3	87.7	77.35	168.350
2.	10	89.6	90.2	87.9	62.5	50.3	80.8	76.4	47.6	73.16	267.037
3.	13	90.1	89	87.9	67.9	51.2	75.6	71.2	84.7	77.20	159.680
4.	15	90.2	89	87.9	68	51.2	76.1	71.6	86.6	77.57	162.896
5.	18	90.2	88.9	87.9	68	51.2	76.4	72	86.7	77.66	162.154
6.	20	90.2	88.9	87.9	68.2	51.3	76.3	71	86.7	77.56	162.579

Table 9: Effect of variation of outer radius of the dielectric layer on Side Lobe Level over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Outer radius of dielectric layer (mm)	Side Lobe Level (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	8.5	0	0	0	0	–4	–2.8	–6.7	–11.5	–3.12	15.356
2.	10	0	0	0	–10.3	–3.3	–2	–8.4	0	–3.00	14.942
3.	13	0	0	0	0	–3.8	–2.9	–7.7	–12.1	–3.31	17.596
4.	15	0	0	0	0	–3.8	–2.9	–7.9	–12.5	–3.38	18.713
5.	18	0	0	0	0	–3.6	–3	–8.1	–12.7	–3.42	19.376
6.	20	0	0	0	0	–3.6	-3.2	–8.1	–13	–3.48	20.063

It can be observed that with the variation of the radius of dielectric layer, there is not much difference in the antenna's radiation pattern values at resonant frequency (5 GHz). Hence, the outer radius of the dielectric layer was selected as 10 mm. In the third step, the outer radius of ground plane and dielectric layer are fixed as 30 mm and 10 mm respectively; only the height of glass tube is varied while the other parameters are maintained as the same, as in the second step. The results are summarized in Tables 10, 11,12 and 13, as given below:

Table 10: Effect of variation of glass tube height on Main Lobe Magnitude over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Height of Glass tube (mm)	Main Lobe Magnitude (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	20.45	-0.003	1.76	1.82	3.0	4.04	2.01	3.18	2.44	2.28	1.277
2.	24.45	1.31	1.8	1.83	3.08	4.04	2.11	3.35	2.4	2.49	0.743
3.	28.45	0.823	1.78	1.83	3.08	4.05	1.95	3.29	2.49	2.41	0.922
4.	30.45	–5.12	1.56	1.68	1.72	2.06	3.88	4.41	1.83	1.50	7.307

Table 11: Effect of variation of glass tube height on Main Lobe Direction over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Height of Glass tube (mm)	Main Lobe Direction (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	20	90	90	87	57	43	119	133	124	92.87	885.859
2.	24	90	90	87	56	43	116	134	123	92.37	878.734
3.	28	90	90	87	56	43	117	135	122	92.50	887.750
4.	30	91	90	88	83	72	44	145	130	92.87	881.609

Table 12: Effect of variation of glass tube height on Angular Width over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Height of Glass tube (mm)	Angular Width (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	20	90.1	89.0	87.9	67.9	51.2	75.6	71.2	84.7	77.20	159.680
2.	24	90.1	89.0	87.6	66.7	51.2	75.1	70.8	84.3	76.85	161.857
3.	28	90.2	88.9	87.5	66.8	51.2	77.9	70.1	81.9	76.81	158.491
4.	30	90.1	91.0	91.6	91.6	81.6	62.8	51.8	109.7	83.77	294.231

The highest value of Main Lobe Magnitude was observed while using 20 mm as the height of glass tube. Also variance of Main Lobe Magnitude and Side Lobe Levels is less at 20 mm. Hence the height of glass tube has been chosen as 20 mm.

In the fourth step, height of water column has been varied while other structural dimensions have been retained as given in the previous step. The observations are tabulated in Tables 14, 15, 16 and 17.

Table 13: Effect of variation of glass tube height on Side Lobe Level over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Height of Glass tube (mm)	Side Lobe Level (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	20	0	0	0	0	–3.8	–2.9	–7.7	–12.1	–3.31	17.596
2.	24	0	0	0	0	–3.8	–3.4	–7.6	–12.4	–3.40	18.13
3.	28	0	0	0	0	–4	–2.9	–7.6	–12.2	–3.33	17.737
4.	30	0	0	0	0	0	–9.8	–2.9	–0.9	–1.70	10.267

Table 14: Effect of variation of water column on Main Lobe Magnitude over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Water column height (mm)	Main Lobe Magnitude (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	4	–1.22	1.59	1.67	1.7	2.03	3.75	4.1	1.94	1.945	2.274
2.	6	–13.2	1.95	1.8	2.1	3.58	3.15	3.58	4.59	0.944	29.399
3.	8	–4.14	1.79	1.8	2.49	4.07	3.17	4.02	5.55	2.344	7.427
4.	10	–0.0031	1.76	1.822	3	4.04	2.01	3.18	2.44	2.281	1.277
5.	12	–7.13	1.65	1.85	3.58	3.87	2.48	2.9	2.68	1.485	11.110
6.	14	–18	1.5	1.88	3.87	3.7	3.89	4.24	3.62	0.588	50.238

Table 15: Effect of variation of water column on Main Lobe Direction over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Height of Water column (mm)	Main Lobe Direction (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	4	89	90	89	85	73	45	143	34	81	954.750
2.	6	91	90	88	77	51	142	47	152	92.25	1256.438
3.	8	91	90	88	66	45	138	146	24	86	1534.250
4.	10	90	90	87	57	43	119	133	124	92.875	885.859
5.	12	91	89	87	51	42	143	92	66	82.625	848.7345
6.	14	79	91	85	49	42	40	146	141	84.125	1511.609

Table 16: Effect of variation of water column on Angular Width over a frequency range of 0.5 GHz to 8 GHz.

S. No.	Height of Water column (mm)	Angular Width (degrees)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	4	90	90.7	91.8	92.3	92.3	63.8	54	105.9	85.1	257.185
2.	6	90	90.2	89.9	82.1	63.4	49.1	63	41.3	71.125	336.674
3.	8	89.8	89.8	88.5	76.6	54.4	63	45.5	25.7	66.6625	491.985
4.	10	90.1	89	87.9	67.9	51.2	75.6	71.2	84.7	77.2	159.68
5.	12	89.8	89.1	87.3	59	49.8	51.2	60.1	49.9	67.025	296.2295
6.	14	88.5	89.9	86.7	55	49.2	56.6	46.3	60.6	66.6	301.49

Table 17: Effect of variation of water column on Side Lobe Level over a frequency range of 0.5 GHz to 8 GHz.

S. No	Height of Water column (mm)	Side Lobe Level (dBi)									
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz	Mean	Variance
1.	4	0	0	0	0	0	–9.2	–2.8	–0.9	–1.61	9.061
2.	6	0	0	0	0	–11.9	–0.8	–4	–2.1	–2.35	14.81
3.	8	0	0	0	0	–5.7	0	–3.4	–1.2	–1.28	4.029
4.	10	0	0	0	0	–3.8	–2.9	–7.7	–12.1	–3.31	17.596
5.	12	0	0	0	–7.5	–2.6	–1.6	0	–1.2	–1.61	5.776
6.	14	0	0	0	–6.2	–2	–3.8	–3.3	–5.7	–2.62	5.642

The variances of Main Lobe Magnitude and Angular Width of the Water Antenna are minimum while using 10 mm as the height of water column. Hence height of water column has been selected as 10 mm.
After step by step designing of antenna parts, the optimal dimensions are given as below:

Ground Plane:
– Height = 0.45 mm,
– Inner Radius = 0.6 mm,
– Outer radius = 30 mm.

Dielectric Layer:
–Height = 1.5 mm,
– Inner Radius = 0.6mm,
– Outer radius = 10mm.

Glass Tube:
– Height = 20 mm,
– Outer Radius = 4 mm,
– Inner Radius = 3.5 mm.

Water Column:
– Outer Radius = 3.5 mm
– Height = 10 mm.

Port length:
– Length = -4 to 5 along z-axis (9 mm).

Table 18: Antenna specifications for the optimally selected dimensions of the water antenna with FR-4 as the dielectric layer.

Parts of Antenna	Material Used	Dimensions	
		Inner Radius (mm)	Outer Radius (mm)
Ground Plane	PEC	0.6	30
Dielectric Layer	FR-4 (lossy)	0.6	10
Glass Tube	(Pyrex)(loss free)	3.5	4.0
Water Column	Distilled Water	—	3.5

Table 19: Antenna parameters for the optimally selected dimensions of the water antenna with FR-4 (lossy) as the dielectric layer.

S. No.	Antenna Parameters for the optimally selected dimensions	Values for FR-4 (lossy) at							
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz
1.	Main Lobe Magnitude (dBi)	–0.003	1.76	1.822	3	4.04	2.01	3.18	2.44
2.	Main Lobe Direction (degrees)	90	90	87	57	43	119	133	124
3.	Angular Width (degrees)	90.1	89	87.9	67.9	51.2	75.6	71.2	84.7
4.	Side Lobe Level (dB)	0	0	0	0	–3.8	–2.9	–7.7	–12.1

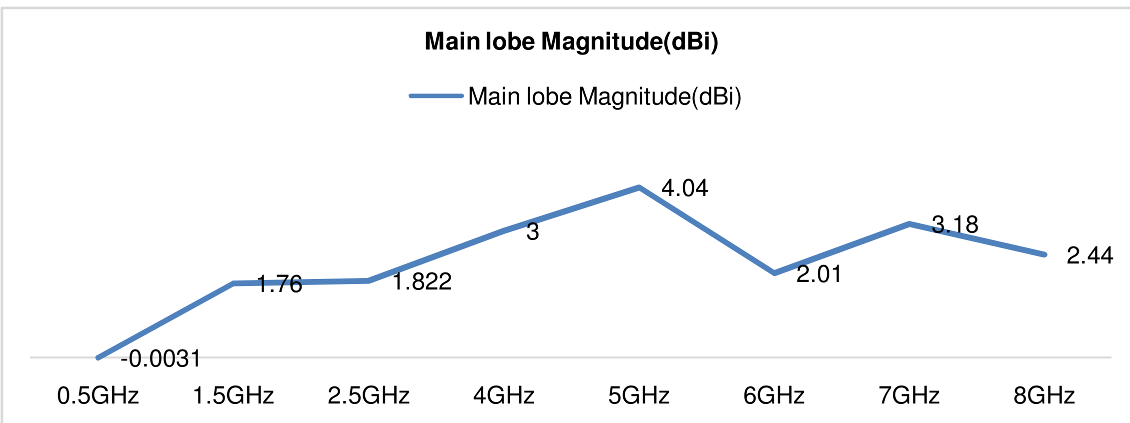

Fig. 2. Plot of Main Lobe Magnitude versus frequency with FR-4 lossy as the dielectric layer of the optimally selected dimensions.

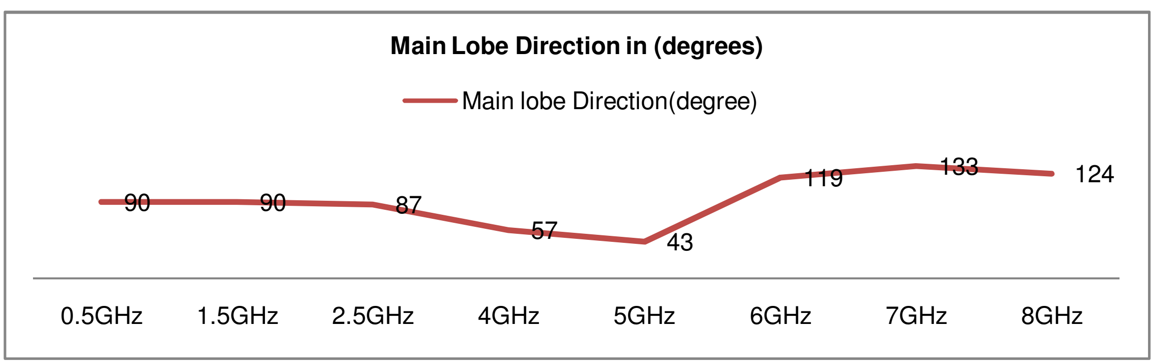

Fig. 3. Plot of Main Lobe Direction versus frequency for FR-4 lossy for the optimally selected dimensions.

The experiment was repeated with other dielectric layer materials such as RT-Duroid (6002-lossy) and then alumina. The tables of antenna specifications, performance parameters and graphs are as follows:

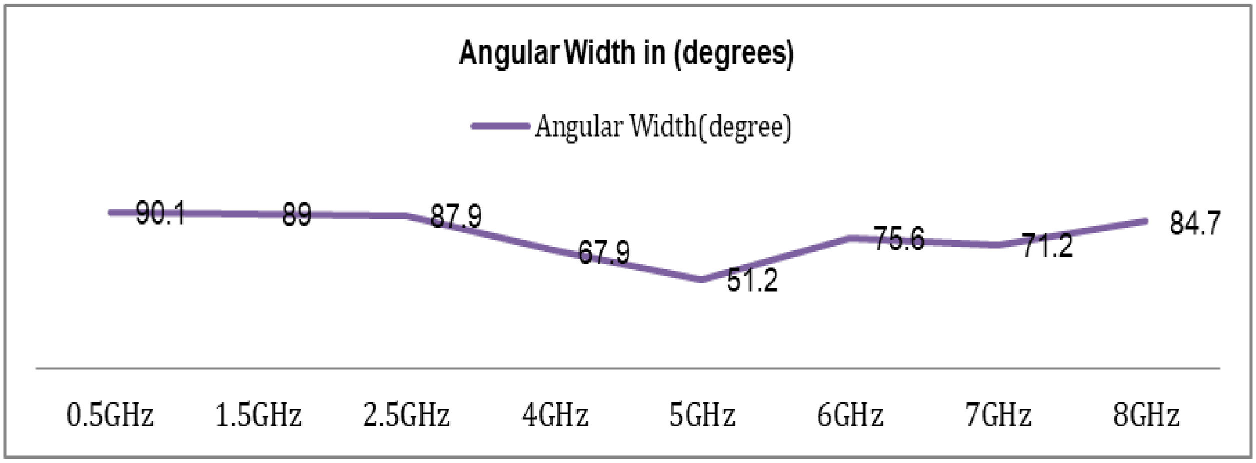

Fig. 4. Plot of Angular Width versus frequency for FR-4 lossy for the finally selected dimensions.

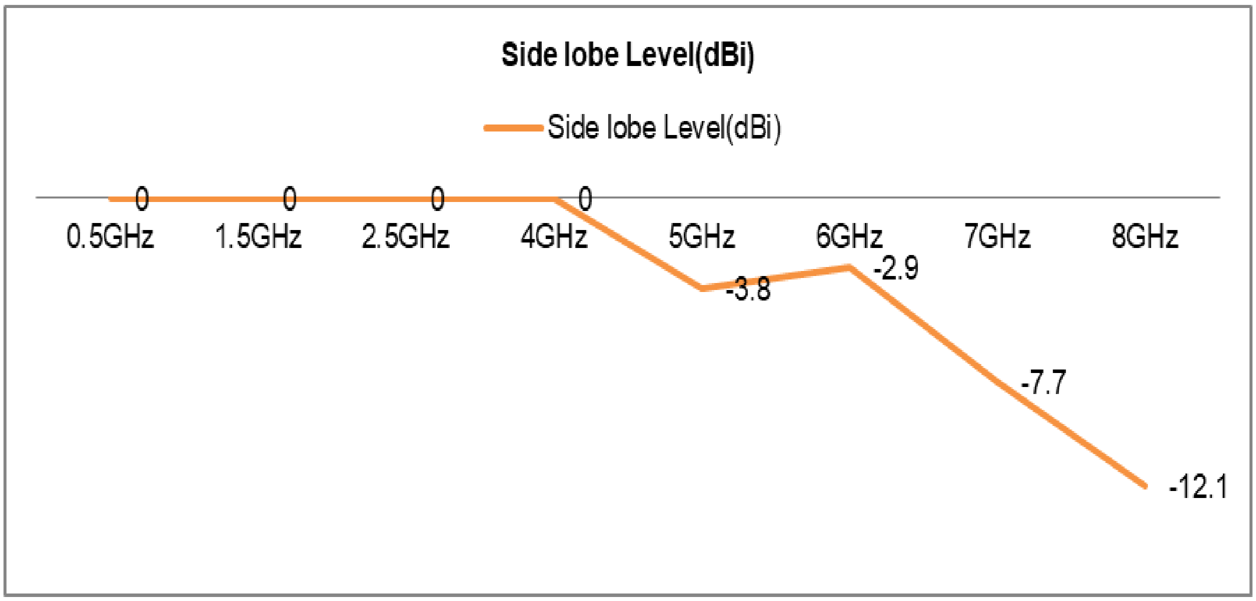

Fig. 5. Plot of Side Lobe Level versus frequency for (FR-4 lossy) for the optimally selected dimensions.

Table 20: Antenna specifications with dielectric layer as RT-Duroid (6002 lossy).

Parts of Antenna	Material Used	Dimensions	
		Inner Radius (mm)	Outer Radius (mm)
Ground Plane	PEC	0.6	30
Dielectric Layer	RT-Duroid (6002 lossy)	0.6	10
Glass Tube	(Pyrex) (loss free)	3.5	4.0
Water Column	Distilled Water	—	3.5

Table 21: Antenna parameters for the optimally selected dimensions using RT-Duroid (6002 lossy) as the dielectric layer.

S. No.	Antenna Parameters for the optimally selected dimensions	Final Values for RT-Duroid (6002 lossy) at							
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz
1.	Main Lobe Magnitude (dBi)	-4.86	2.16	1.79	2.72	4.05	2.34	3.44	2.27
2.	Main Lobe Direction in (degrees)	90	90	88	59	44	123	136	125
3.	Angular Width in (degrees)	90.1	89	88	71.8	51.9	71.9	68.1	89
4.	Side Lobe Level in (dB)	0	0	0	0	-4.2	-3.1	-7.5	-10.9

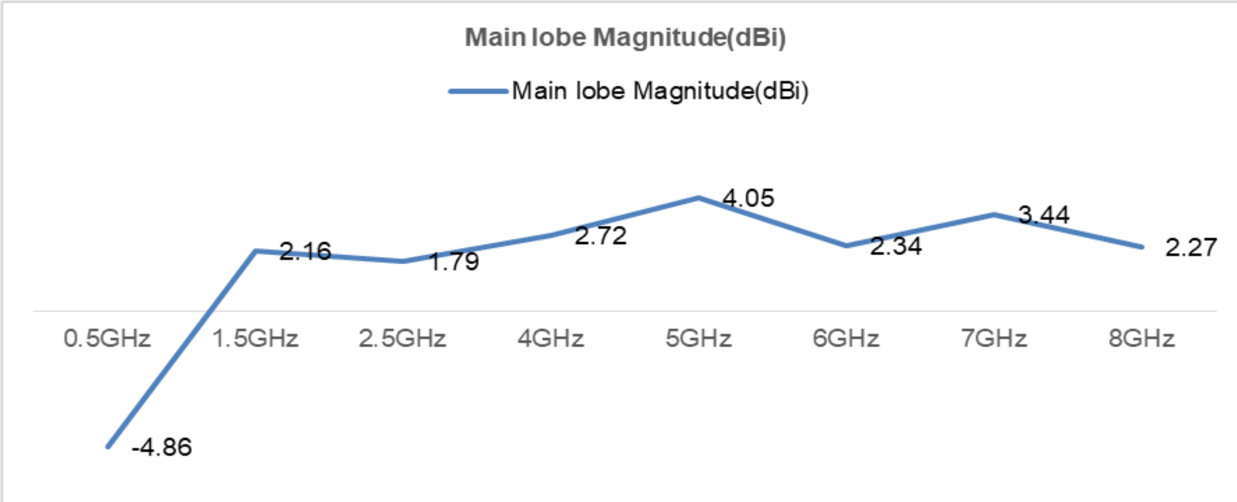

Fig. 6. Plot of Main Lobe Magnitude versus frequency for RT-Duroid (6002-lossy) for the optimally selected dimensions.

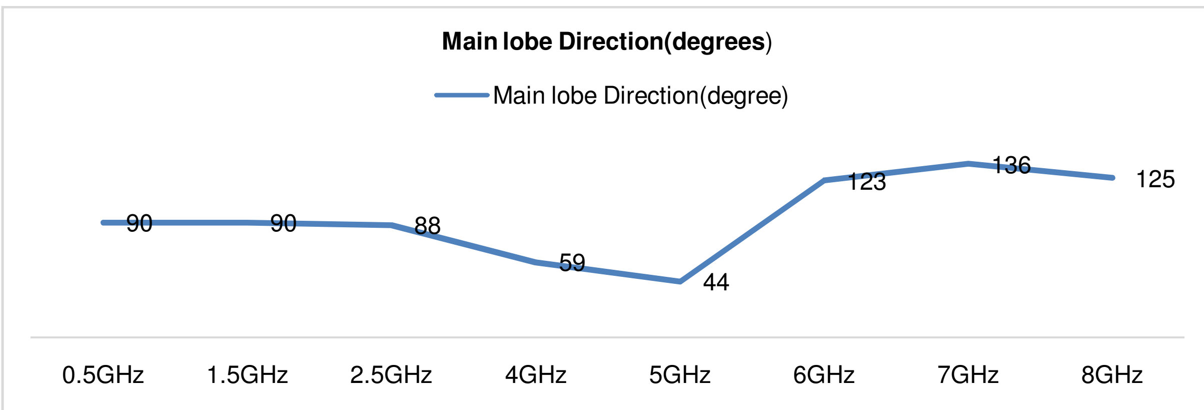

Fig. 7. Plot of Main Lobe Direction versus frequency for RT-Duroid (6002-lossy) for the optimally selected dimensions.

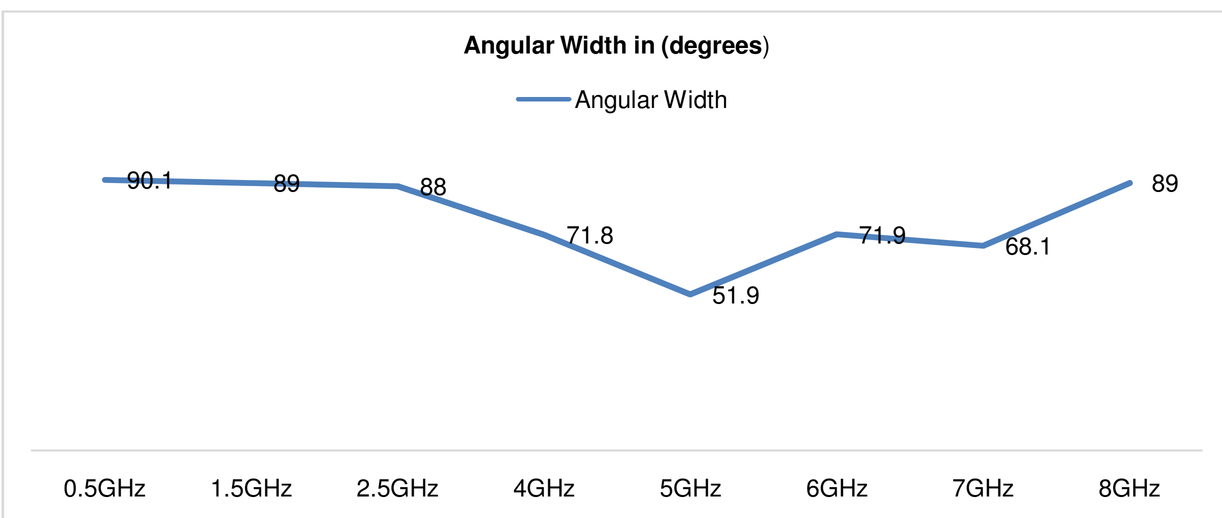

Fig. 8. Plot of Angular Width versus frequency with RT-Duroid (6002-lossy) as the dielectric layer for the optimally selected dimensions.

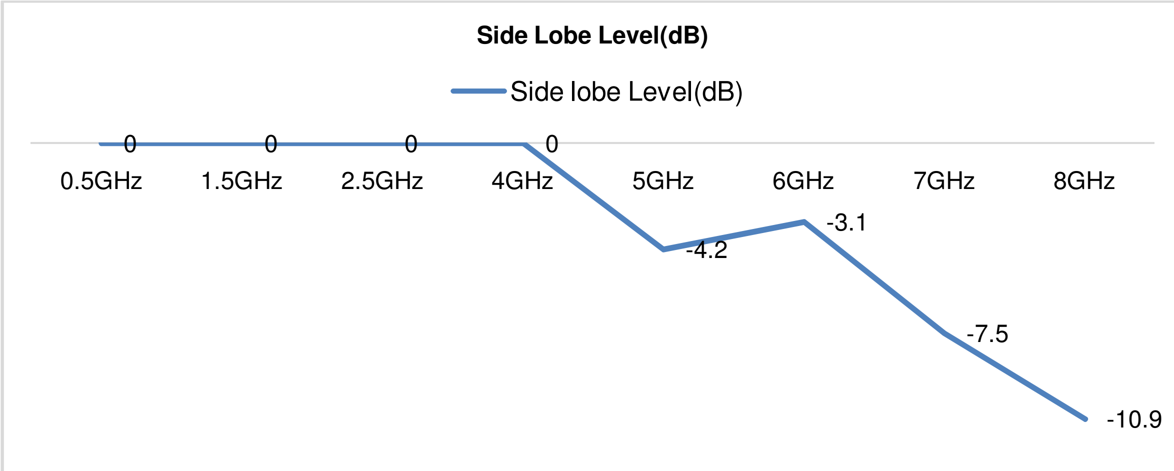

Fig. 9. Plot of Side Lobe Level versus frequency with RT-Duroid (6002-lossy) as the dielectric layer for the optimally selected dimensions.

Table 22: Antenna specifications with alumina (96% Loss free) as the dielectric layer

Parts of Antenna	Material Used	Dimensions	
		Inner Radius (mm)	Outer Radius (mm)
Ground Plane	PEC	0.6	30
Dielectric Layer	Alumina (96% loss free)	0.6	10
Glass Tube	(Pyrex)(loss free)	3.5	4.0
Water Column	Distilled Water	—	3.5

Table 23: Antenna parameters for the optimally selected dimensions of proposed antenna with alumina (96% loss free) as the dielectric layer.

S. No	Antenna Parameters for the optimally selected dimensions	Values for Alumina (96% loss free) at							
		0.5 GHz	1.5 GHz	2.5 GHz	4 GHz	5 GHz	6 GHz	7 GHz	8 GHz
1.	Main Lobe Magnitude (dBi)	–5.73	2.11	1.78	3.44	4.05	1.71	2.79	2.4
2.	Main Lobe Direction (degrees)	91	88	87	53	43	120	126	112
3.	Angular Width (degrees)	89.8	90	88.1	62.5	50.3	79	75.7	48.1
4.	Side Lobe Level (dB)	0	0	0	-10.4	-3.4	-2.1	-7.5	-0.5

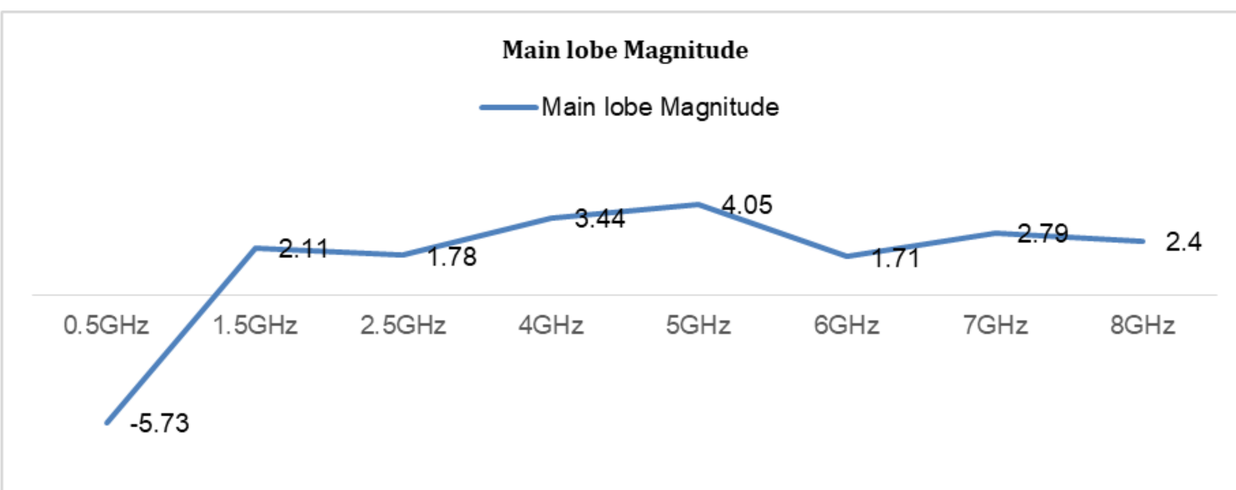

Fig. 10. Plot of Main Lobe Magnitude versus frequency with alumina (96% loss free) as the dielectric layer for the optimally selected dimensions.

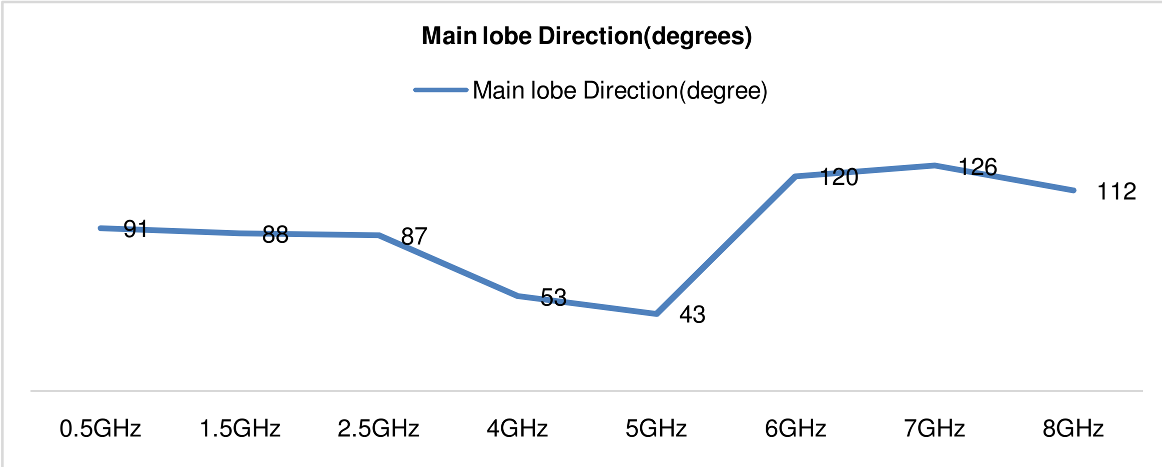

Fig. 11. Plot of Main Lobe Direction versus frequency with alumina (96% loss free) as the dielectric layer for the optimally selected dimensions.

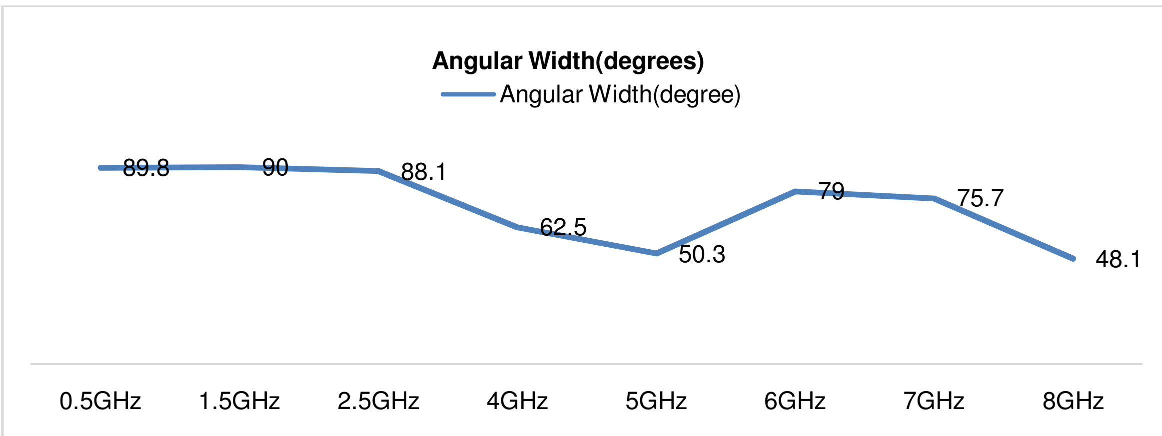

Fig. 12. Plot of Angular Width versus frequency for alumina (96% loss free) as the dielectric layer for the optimally selected dimensions.

The resonant frequency, at which the gain is maximum, is 5GHz for all the three selected materials, i.e., FR-4, RT-Duroid and alumina. Hence, any of the above dielectric material can be chosen for constructing the dielectric layer of the proposed antenna. The plots and figures given below are that of the fabricated antenna, constructed using FR-4, and dimensions selected through statistical analyses of the simulated results.

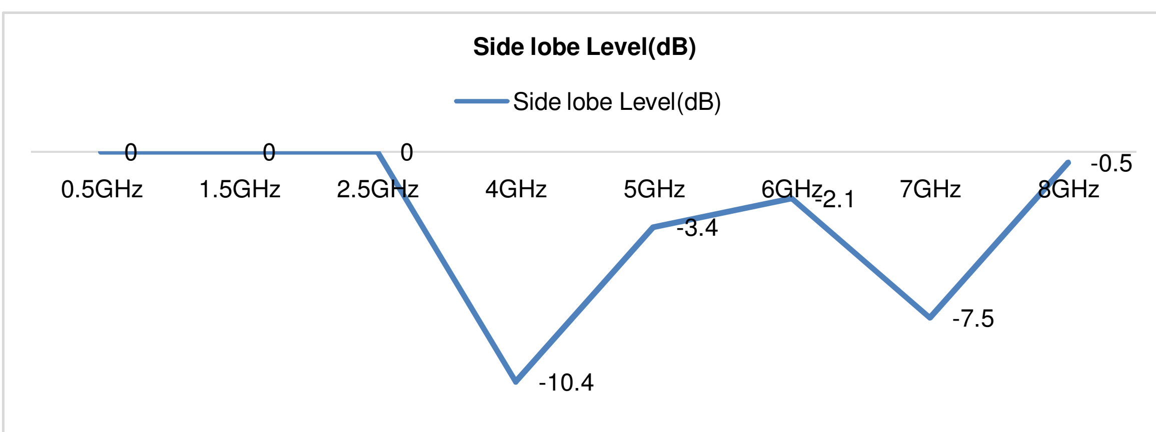

Fig. 13. Plot of Side Lobe Level versus frequency for alumina (96% loss free) as the dielectric layer for the optimally selected dimensions.

Table 24: Radiation parameters for the optimally selected dimensions of proposed antenna with three different materials of the dielectric layer.

S. No.	Antenna Parameters	Range of values when dielectric layer is constructed using		
		RT DUROID	FR-4	ALUMINA
1	Main Lobe Magnitude (dBi)	–4.86 to 4.05	–0.0031 to 4.04	–5.01 to 4.05
2.	Main Lobe Direction (degrees)	44 to 136	43 to 133	43 to 126
3.	Angular Width (degrees)	50.9 to 90.1	51.2 to 90.1	48.1 to 90
4.	Side Lobe Level (dB)	–10.9 to 0	–12.1 to 0	–10.4 to 0
5.	Resonant Frequency (GHz)	5.0	5.0	5.0

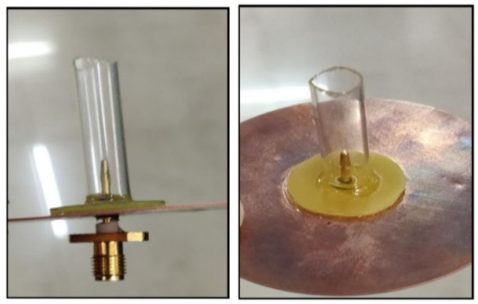

Fig. 14. Images of the Fabricated Antenna for the optimally selected dimensions.

Fig. 15. Graph of s11 on VNA for the optimally selected dimensions.

Fig. 16. Graph of VSWR for the optimally selected dimensions.

IV. RESULTS AND CONCLUSION

The designed water antenna's performance parameters have been statistically analysed, and the optimal dimensions for various parts of the antenna were arrived at, to construct the same. The main observations are: (i) It has excellent performance in the frequency range from 0.5 GHz to 8.0 GHz; (ii) The fabricated antenna was found to have VSWR less than 2; (iii) The resonant frequency is 5 GHz irrespective of the dielectric material used for the dielectric layer of the proposed antenna; (iv) The values of antenna parameters such as Main Lobe Magnitude in (dBi) ranges from -4.86 to 4.05 for RT-Duroid, -0.0031 to 4.04 for FR-4 and -5.01 to 4.05 for alumina. The range of values of other parameters is also tabulated in Table 24. As the gain is maximum in the C-Band, this proposed water antenna can be used as a broadband antenna for the C-Band applications. This proposed water antenna can be tested for various other materials in the glass tube, and also with varying salinity of the water column.

V. FUTURE SCOPE

This proposed antenna can be tested for various materials in the glass tube and also with varying salinity of the water column. The methodology for sensing and automatic monitoring of the water level in the glass tube needs to be designed.

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