Effect of Variation of Water Column Height in a Water DRA

1Naveeta Kant, 2Abhigyan Kaustubh, 3Ramesh Kulkarni
1Associate Professor, 2Independent Researcher, 3Professor
1,2Vivekanand Education Society Institute of Technology

***Abstract* - This paper discusses the on-site flexibility afforded in modifying the radiation parameters of a water Dielectric Resonator Antenna (DRA) by varying the height of its water column. These radiation parameters are Main Lobe Magnitude (MLM), Main Lobe Direction (MLD), Angular Width (AW), and Side Lobe Level (SLL), observed in the frequency range of 0.5 GHz to 8 GHz. Upon varying the height of the water column of the antenna under test (AUT) with FR-4 (Lossy) as the dielectric layer material, we find that different heights of the water column provide different flexibilities along the antenna parameters of MLM, MLD, AW, and SLL, and hence makes such an antenna adaptably suited for C-Band applications.**

***keywords* - DRA, VSWR, bandwidth, gain, main lobe magnitude (MLM), main lobe direction (MLD), angular width (AW), side lobe level (SLL), Q-factor**

I. Introduction

The demand and difficulties of the rapidly increasing scope of communication in the world has significantly increased the attention towards research and development of wireless communication technology [1]. Especially pandemics of the past, and the present Covid-19 pandemic, have posed a new challenge for engineers and scientists to enhance contactless, wireless communications even in ways that most humans had never dreamt off operating in before. Thus, the migration to a higher-frequency band is essential to support the required high data rate for catering to numerous applications. However, the main problem associated with a higher-frequency band is high path loss in short distance communication due to short wavelengths [2,3]. To overcome these issues, high-gain antennas are used to solve the problems of high path loss and increase the transmission range related to the high-frequency band [2,3]. A microstrip patch antenna (MSA) [4-8] has a compact size; however, at higher frequencies, it suffers from low radiation efficiency because of the inherent metallic losses [9-12]. Moreover, it offers low gain and narrow bandwidth. In contrast, DRAs exhibit higher radiation efficiency even at higher frequencies due to the absence of intrinsic conductor loss and surface wave loss [13]. Further, because of their (DRA's) numerous advantages and attractive features like light weight, low cost, and relatively wide impedance bandwidth [14-18], they have also gained increased attention from antenna designers in the field of 5G wireless communication. Additionally, they offer flexible excitation schemes such as coaxial feed probes, microstrip feed lines, aperture coupling, and co-planar waveguides [19-22]. Further, liquid filled DRAs offer additional on-site flexibility of configuring the radiation parameters by varying the height of the liquid column within the frequency range of up to 2 GHz [25].

In this paper, several liquids with high dielectric constant (ε_r), along with their availability, safety, and cost are considered for the liquid in the glass tube (dielectric resonator cavity) of the AUT. High dielectric constant aids in effective reduction of the size of the antenna by $\lambda_0 / \sqrt{\varepsilon_r}$, where λ_0 is the free space wavelength.

Table 1. Selection of a suitable liquid for the dielectric resonator cavity of AUT

Sr. No.	Liquid	(ε_r)	Properties
1	Water	80.1	non-reactive, high boiling point of 100°C, safe, easily available, cheap
2	Acetamide	67.6	may react with azo and diazo compounds to generate toxic gases. Exposure to this compound may cause irritation to the eyes, skin and mucous membranes
3	Cyanoacetylene	72.3	acutely toxic and flammable; very low boiling point of 42.5°C, hence it cannot be used in reconfigurable antennas which may be subjected to higher temperatures
4	Formamide	111	can be harmful when inhaled (can be absorbed by the skin also); can cause reproductive damage; contact with it can cause irritation and burn to eyes, skin (rash), nose, throat
5	Hydrogen cyanide	114.9	colorless, extremely poisonous, flammable, boils slightly above room temperature at 25.6 °C
6	Hydrogen fluoride	83.6	very low boiling point of 19.5°C; Hydrogen fluoride gas, even at low levels, can irritate the eyes, nose, and respiratory tract. Breathing in at high levels or in combination with skin contact can cause death from an irregular heartbeat or from fluid buildup in the lungs
7	Hydrogen peroxide	74.6	slightly more viscous than water; more expensive than water; due to contact with water or humidity, can quickly decompose

Hence, because of water's advantages compared to the other alternatives considered above, water has been selected as the dielectric material (liquid) in the glass tube of AUT.

Systematic design procedures including statistical analysis and CST were used to design optimum dimensions of various components of the simulated antenna [26, 27]. Its radiation parameters – MLM, MLD, AW, and SLL, were then observed for varying heights of water in its water column, the results of which are presented in this paper.

II. Water Antenna Under Test (Water AUT)

Water antennas are a special type of DRAs. High dielectric constant of water aids in considerable reduction of its size.

The advantages of water antennas are ease of fabrication, low frequency drift due to change in temperature, high gain, high bandwidth, high power handling capacity, simple coupling schemes, variable bandwidth by choosing variable dielectric constant (by changing the salinity of water), and high Q-factor [23,24]. They are further advantageous in terms of reduced weight and 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. They can be 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 in our water AUT.

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. [25] have analyzed 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 variation of height of the water column in the glass tube in the broad frequency range of 0.5 GHz to 8 GHz, which is the focus in this paper: the effect of variation in the height of the water column in the glass tube (henceforth referred to as the water column height) on the operational frequency, radiation parameters, and bandwidth of the water AUT, thereby understanding the aspect of the AUT's reconfigurability/ on-site flexibility, in the frequency range of 0.5 GHz to 8 GHz.

Water AUT used in this work consists of five parts: a ground plane, a dielectric layer, an SMA connector (discrete port in simulation), a glass tube, and a water column in the 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**.

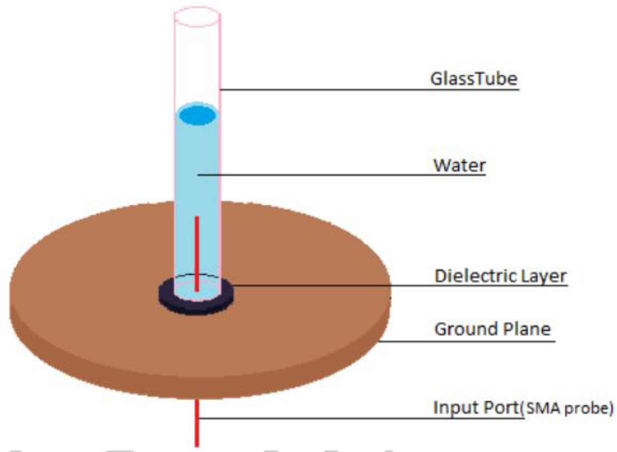

Figure 1. Structure of Simulated Water AUT

For our analysis, a water AUT with the following materials and their optimum values is selected [26, 27], as shown in Table 2.

Table 2. Optimal dimensions selected for the water AUT

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
Water Column	Distilled Water	-	3.5

The optimally selected dimensions were then used to construct and test a simulated water AUT for varying heights of water column in the frequency range from 0.5 GHz to 8 GHz. Their corresponding radiation parameters of MLM, MLD, AW, and SLL were observed via CST software, and statistical analysis was used to arrive at the results as shown in the subsequent tables.

Finally, a practical water antenna was also fabricated for the these dimensions as shown in **Fig. 2** and **Fig. 3** below, which also gave minimum variance in the radiation parameters in the frequency range of 0.5 GHz to 8 GHz, along with S_{11} less than 10 dB and VSWR less than 2 [26, 27].

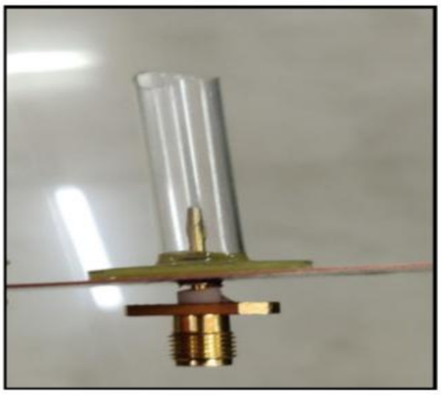

Figure 2. Side view of the fabricated antenna for the optimally selected dimensions [26, 27]

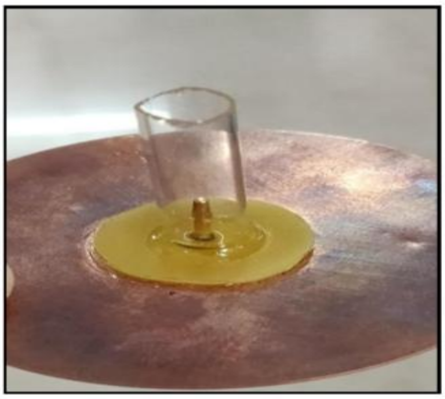

Figure 3. Top view of the fabricated antenna for the optimally selected dimensions [26, 27]

III. Observation

Antenna radiation parameters as the height of water column varies

Tables 3, 4, 5 and 6 summarize the radiation parameters of AUT for various heights of water column in the frequency range of 0.5 GHz to 8 GHz and the statistical parameters related to them.

Main Lobe Magnitude (MLM)

Table 3. Main Lobe Magnitude (MLM) at various heights of water column

Sr. 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 1	Variance 2
1	4 mm	-1.22	1.59	1.67	1.7	2.03	3.75	4.1	1.94	1.95	2.27
2	6 mm	-13.2	1.95	1.8	2.1	3.58	3.15	3.58	4.59	0.94	29.40
3	8 mm	-4.14	1.79	1.8	2.49	4.07	3.17	4.02	5.55	2.34	7.43
4	10 mm	-0.0031	1.76	1.822	3	4.04	2.01	3.18	2.44	2.28	1.28
5	12 mm	-7.13	1.65	1.85	3.58	3.87	2.48	2.9	2.68	1.49	11.11
6	14 mm	-18	1.5	1.88	3.87	3.7	3.89	4.24	3.62	0.59	50.24
	Mean 2	-7.28	1.71	1.80	2.79	3.55	3.08	3.67	3.47		
	Variance 2	49.90	0.03	0.01	0.72	0.59	0.52	0.29	1.93		

- Resonant frequency, for a particular height of water column, is the frequency at which the gain is maximum.
- Except for 0.5 GHz, MLM is appreciably high especially in 4.0 GHz to 8.0 GHz band (C- band region).
- As the respective variances at these frequencies are very less, the AUT will be immune to changing water column height at a given frequency.

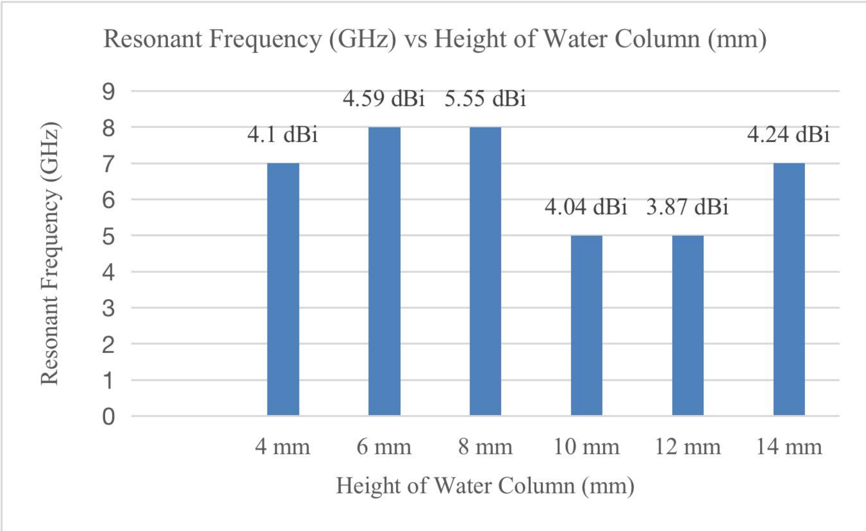

Figure 4. Resonant frequency versus height of water column with value of MLM indicated at the top of the bars.

Main Lobe Direction (MLD)

Table 4. Main Lobe Direction (MLD) at various heights of water column

Sr. 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 mm	89	90	89	85	73	45	143	34	81	954.75
2	6 mm	91	90	88	77	51	142	47	152	92.25	1256.44
3	8 mm	91	90	88	66	45	138	146	24	86	1534.25
4	10 mm	90	90	87	57	43	119	133	124	92.88	885.86
5	12 mm	91	89	87	51	42	143	92	66	82.63	848.73
6	14 mm	79	91	85	49	42	40	146	141	84.13	1511.61
	Mean N2	88.5	90	87.33	64.17	49.33	104.50	117.83	90.17		
	Variance N2	22.3	0.4	1.87	211.37	145.87	2384.30	1626.97	3133.77		

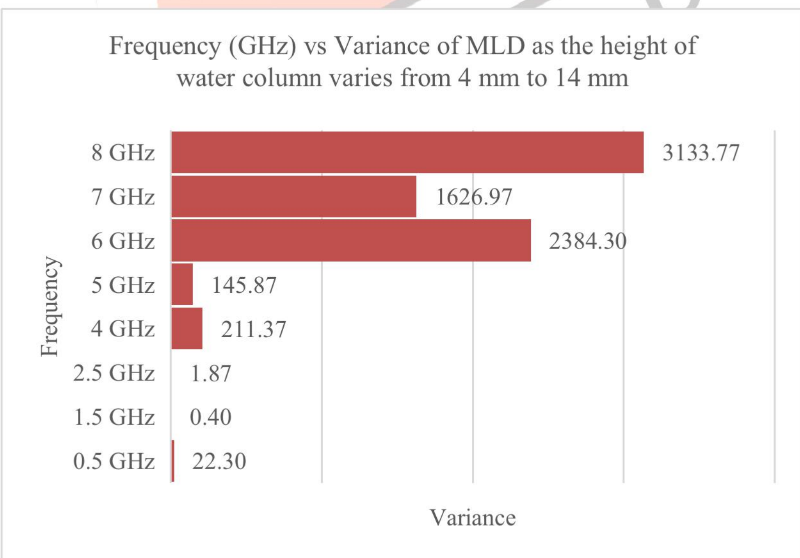

Figure 5. Main Lobe Direction (MLD) versus frequency at various heights of water column. Figures to the right of each bar indicates variance at a given frequency.

- At a given water column height, the greater variance in the MLD points to more directionally spread-out emitted signals.
- At lower frequencies, the signal is very directional irrespective of the changing water column, as variance is less. As the frequency increases and enters C-band range, the variance increases, which suggests that the antenna becomes sensitive to changing height of the water column in C-band region.

Angular Width (AW)

Table 5. Angular Width at various heights of water column

Sr. 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 (AW)**	**Variance**
1	4 mm	90	90.7	91.8	92.3	92.3	63.8	54	105.9	85.10	257.19
2	6 mm	90	90.2	89.9	82.1	63.4	49.1	63	41.3	71.13	336.67
3	8 mm	89.8	89.8	88.5	76.6	54.4	63	45.5	25.7	66.66	491.99
4	10 mm	90.1	89	87.9	67.9	51.2	75.6	71.2	84.7	77.20	159.68
5	12 mm	89.8	89.1	87.3	59	49.8	51.2	60.1	49.9	67.03	296.23
6	14 mm	88.5	89.9	86.7	55	49.2	56.6	46.3	60.6	66.60	301.49
	Mean O2	89.70	89.78	88.68	72.15	60.05	59.88	56.68	61.35		
	Variance O2	0.36	0.42	3.54	201.99	276.86	94.91	100.48	866.90		

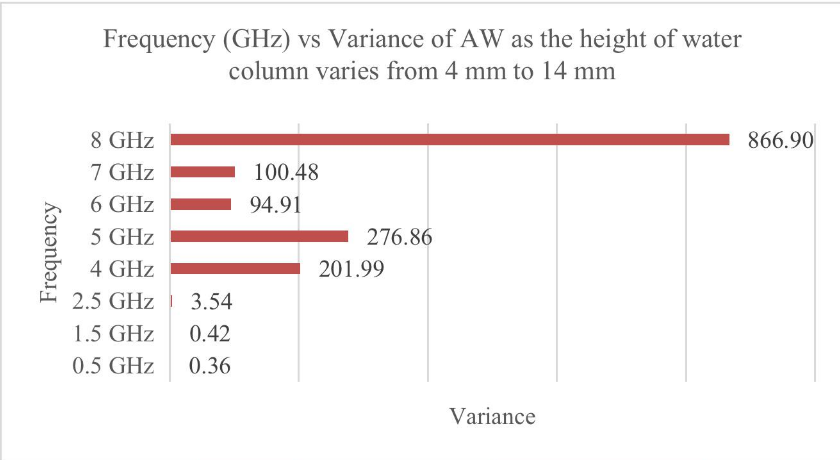

Figure 6. Frequency (GHz) versus Variance of AW as the height of water column varies from 4 mm to 14 mm.

- Angular Width (AW) is measured on the major lobe of an antenna radiation pattern at half power points which are the points at which signal power is half of its peak value.
- As can be seen, the frequency at which MLM is high, respective angular width is less, and vice versa. Lesser the angular width, more directive the antenna for those frequencies at a given height of water column.
- As the height of water column increases in the c-band region of frequencies, the angular width decreases leading to increased directivity. Hence, water column's height can be used to adjust directivity of the antenna.

Side Lobe Level (SLL)

Table 6. Side Lobe Level at various heights of water column

Sr. 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 mm	-	-	-	-	-	-9.2	-2.8	-0.9	-1.61	9.06
2	6 mm	-	-	-	-	-11.9	-0.8	-4	-2.1	-2.35	14.81
3	8 mm	-	-	-	-	-5.7	-	-3.4	-1.2	-1.28	4.03
4	10 mm	-	-	-	-	-3.8	-2.9	-7.7	-12.1	-3.31	17.60
5	12 mm	-	-	-	-7.5	-2.6	-1.6	-	-1.2	-1.61	5.78
6	14 mm	-	-	-	-6.2	-2	-3.8	-3.3	-5.7	-2.62	5.64
	Mean P2	-	-	-	-6.85	-5.20	-3.66	-4.24	-3.87		
	Variance P2	-	-	-	0.85	16.03	10.93	3.92	19.46		

- No Side lobes were observed at lower frequencies for any water column height (at least up to 2.5 GHz).
- At higher frequencies, side lobes were observed at certain water column heights.
- As seen by the **Variance 2** values, the AUT's SLL is most sensitive to the water column height at 5 GHz, 6 GHz, and 8 GHz. This implies that water column height can play a significant role in controlling the wasted power in C- band region.

- For higher C-band region, i.e., 7 GHz to 8 GHz, the power wastage/ SLL is minimal when water column height is 10 mm.

Antenna radiation patterns at resonant frequencies for different heights of water column from Table 3

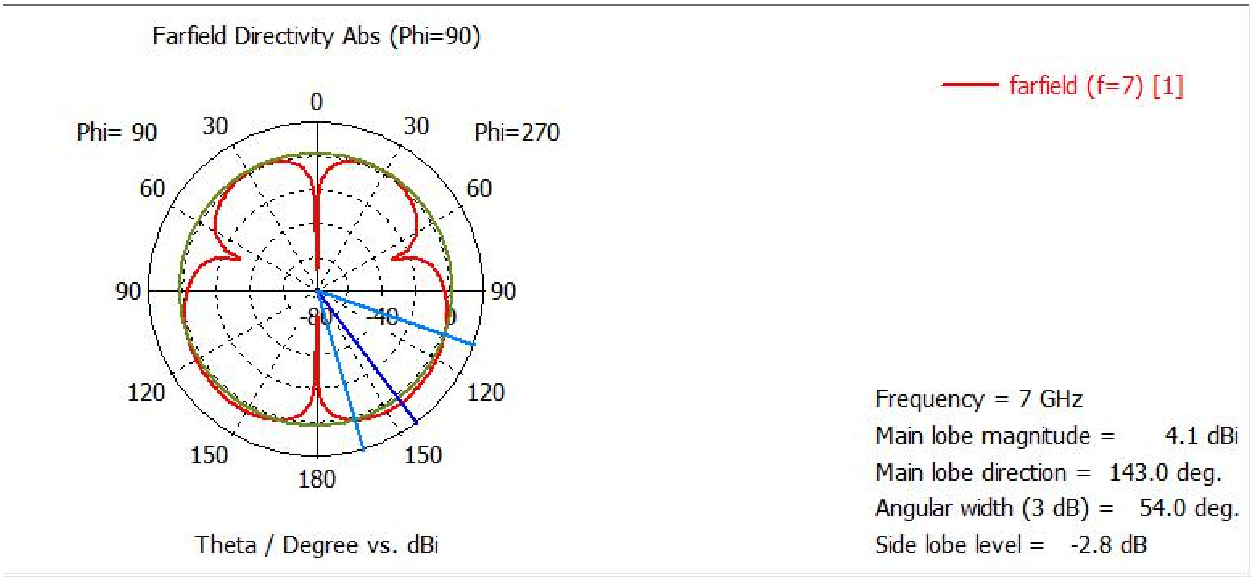

Figure 7. Radiation pattern at water column height of 4 mm and resonant frequency of 7 GHz

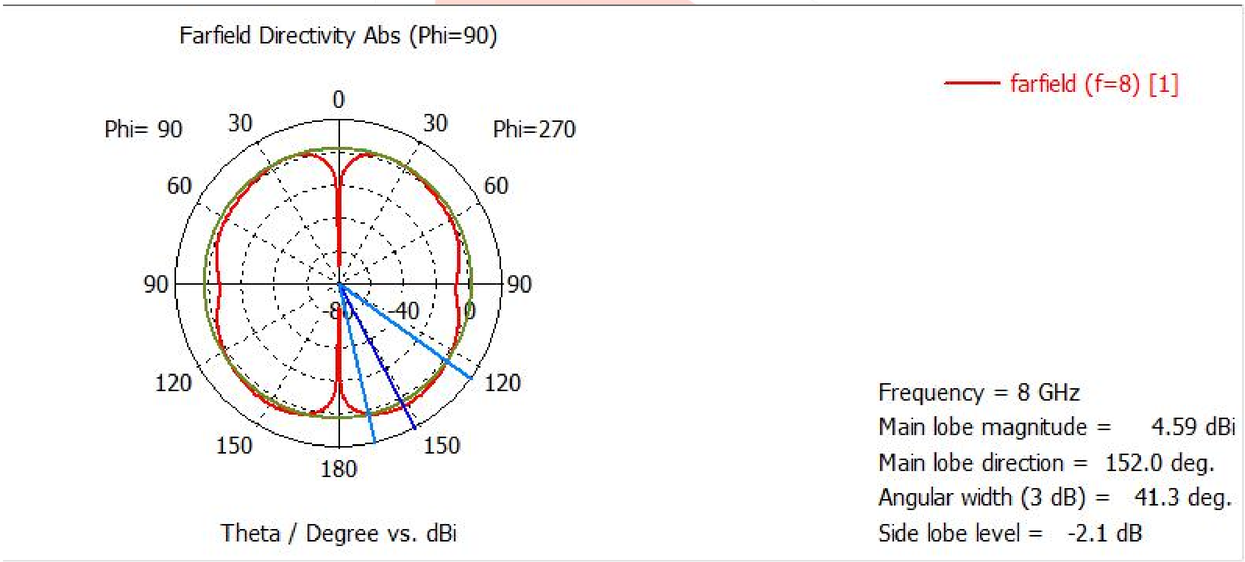

Figure 8. Radiation pattern at water column height of 6 mm and resonant frequency of 8 GHz

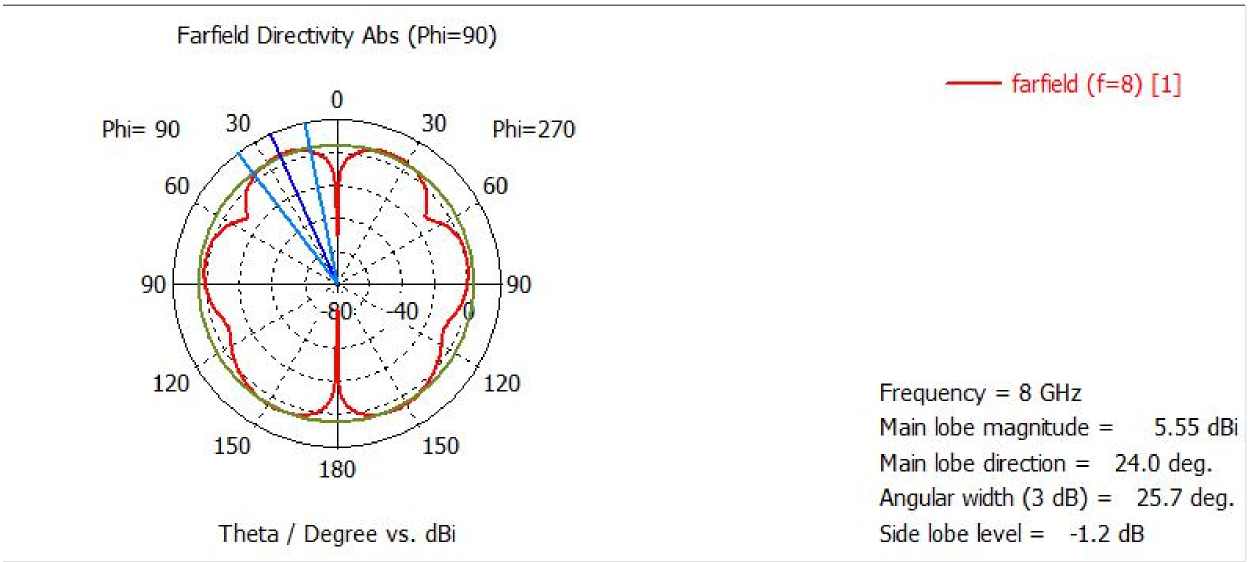

Figure 9. Radiation pattern at water column height of 8 mm and resonant frequency of 8 GHz

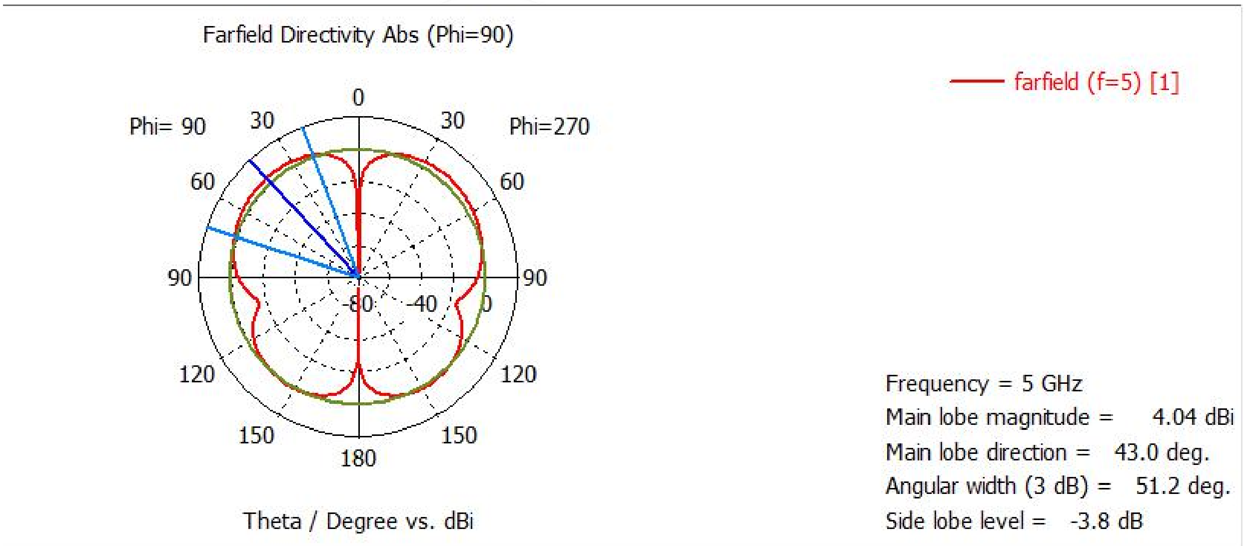

Figure 10. Radiation pattern at water column height of 10 mm and resonant frequency of 5 GHz

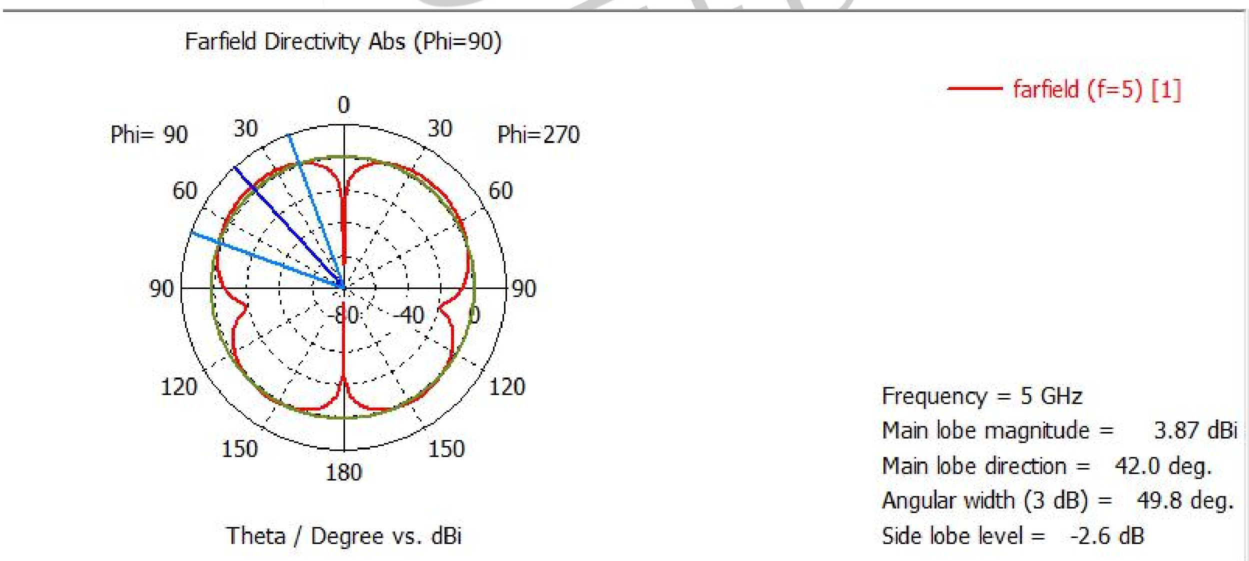

Figure 11. Radiation pattern at water column height of 12 mm and resonant frequency of 5 GHz

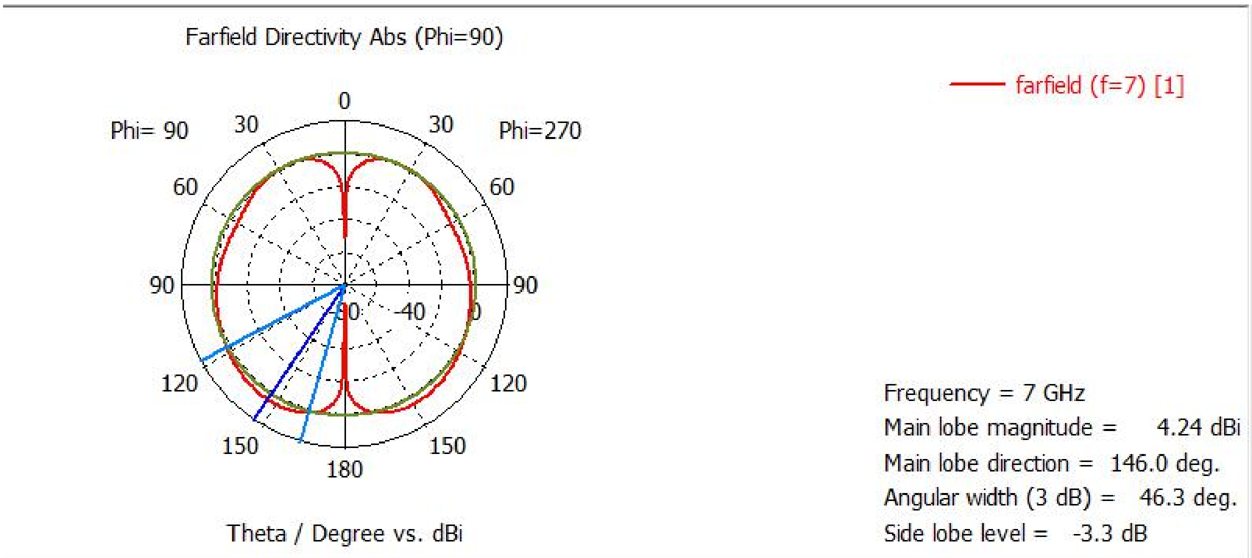

Figure 12. Radiation pattern at water column height of 14 mm and resonant frequency is 7 GHz

IV. RESULT ANALYSIS AND CONCLUSION

The designed water AUT's performance parameters have been statistically analyzed for various heights of water column. The significant results are:

Main Lobe Magnitude (MLM)

a. Resonant frequency is different at different heights of water column.
b. The AUT has excellent gain in the frequency range from 4.0 GHz to 8.0 GHz as the MLM is remarkably high (from 3.87 dBi to 5.55 dBi) in this range for various heights of water column.
c. However, as the variances at these frequencies are very less, the AUT is immune to changing water column height for a given frequency. This means that the gain of the antenna will not change appreciably as the water column height changes over a period of time due to environmental fluctuations, or if it is intentionally varied for attempting reconfiguration.

Main Lobe Direction (MLD)

d. At a given water column height, the greater variance in the MLD points to more directionally spread-out emitted signals from the AUT. This means that as the AUT radiates over a bandwidth, all the constituent signals of different frequencies will be radiated in different directions, causing the receiver in a particular direction to miss out a lot of the signals.
e. The MLD shows high variance at the C-band frequencies as the water column height changes, pointing to AUT's sensitivity to the water column height. This points to the significance of maintaining a steady water column height for a stable MLD.
f. At lower frequencies, as variance is less, the signal is very directional irrespective of the changing water column height.

Angular Width (AW)

g. Similarly, in the C-band region of frequencies, as the water column height increases, the AW appreciably decreases as seen by the higher variance values, leading to increased directivity. Hence, water column's height can be used to adjust directivity of the antenna. And, if the water evaporates due to environmental fluctuations like heat or if the water column height is intentionally reduced, the antenna's directivity reduces, particularly in the C-band region.

Side Lobe Level (SLL)

h. At various water column heights, no side lobes were observed at lower frequencies in the simulated radiation patterns. At higher C-band frequencies, water column height can play a significant role in controlling the SLL/ power wastage of AUT.

The values of MLM ranges from -0.0031 dBi to 5.55 dBi for various heights of water column in the frequency range of 0.5 GHz to 8 GHz. The range of values of other parameters can also be seen in their corresponding tables. As the gain is maximum in the C-Band, this proposed water antenna can be used as a broadband antenna for multiple C-Band applications with various resonant frequencies, directivity, and angular width being controlled by the water column height. Further, being broad band, light weight, and extremely cheap, this AUT can be used flexibly for various heights of water column - due to the sensitivity afforded by the height of the water column - in a wide range of applications such as satellite communication, surveillance, weather radar systems, some Wi-Fi devices, etc.

V. FUTURE SCOPE

As the height of water column is the only structural parameter that can be easily changed after the antenna is fabricated, future work can be done in exploring this aspect deeper to design a more flexible and versatile system. Specifically, given the sensitivity of the water column height on the antenna radiation parameters as seen in this paper, further research can be conducted in exploring efficient ways of maintaining a steady water column height without making the system bulky, or compromising its main advantages like utility, portability, cost, size, and safety. In addition, tools and processes can be designed as part of this antenna system to effectively regulate the water column height as needed on a manual and automatic basis, in a stand-alone or an antenna array configuration, ensuring that the aforesaid advantages are maintained, or further improved on.

ACKNOWLEDGMENT

Sincere gratitude to VES Management and the staff for their constant support and encouragement for the research work.

REFERENCES

[1] W. Feng, Y. Li,; D. Jin,. L. Su, S. Chen, "Millimetre-wave backhaul for 5G networks: Challenges and solutions", Sensors, vol. 16, no.6, p 892, June 2016.
[2] I. Ali, M.H. Jamaluddin, M.R. Kamarudin, A. Gaya,; M.H. Dahri, "Gain enhancement of dielectric resonator antenna for millimeter wave applications", TELKOMNIKA Telecommun. Comput. Electron. Control vol. 17, pp 1670–1673, 2019.[Google Scholar]
[3] A. Perron,; T.A. Denidni,; A.R Sebak, "High-Gain Hybrid Dielectric Resonator Antenna for Millimeter-Wave Applications:Design and Implementation", IEEE Trans. Antennas Propag. Vol. 57, pp 2882–2892, 2009. [Google Scholar]
[4] K. M. Luk, C. L. Mak, Y. L. Chow and K. F. Lee, "Broadband microstrip patch antenna", Electron. Lett., vol. 34, no. 15, pp. 1442-1443, 1998.
[5] P. Bhartia, K. V. S. Rao and R. S. Tomar, Millimeter-Wave Microstrip and Printed Circuit Antennas, Boston, MA, USA: Artech House, 1991.
[6] C. L. Mak, K. M. Luk, K. F. Lee and Y. L. Chow, "Experimental study of a microstrip patch antenna with an L-shaped probe", IEEE Trans. Antennas Propag., vol. 48, no. 5, pp. 777-783, May 2000.
[7] G. Clasen and R. Langley, "Meshed patch antennas", IEEE Trans. Antennas Propag., vol. 52, no. 6, pp. 1412-1416, Jun. 2004.
[8] J. Sun and K. M. Luk, "Design of a 2 × 2 water dielectric patch antenna array for Wi-Fi application", Proc. IEEE 4th Asia-Pacific Conf. Antennas Propag., pp. 237-238, 2015.
[9] R. Garg, P. Bhartia, A. Ittipiboon, Microstrip Antenna Design Handbook; Arteck House: Boston, MA, USA, 2001. [Google Scholar]
[10] J.R.James and P.S Hajj, Handbook of Microstrip Antennas; peter peregrinus Ltd. London United Kingdom: Oxford, UK, 1989. [Google Scholar]
[11] T. Itoh, "Overview of Quasi-Planar Transmission Lines", IEEE Trans. Microwave Theory Tec., vol. 37, pp 275–280, 1989. [Google Scholar]
[12] T.A. Denldni, Q. Rao, A.R. Sebak, Two-ring slot-fed dielectric resonator antenna for dual-frequency operation. Microwave Opt. Technol. Lett., vol. 44, no.5, pp 448–451, Mar 2005. https://doi.org/10.1002/mop.20663 [Google Scholar]
[13] J. Nasir, M.H. Jamaluddin, K.A. Ahmad, M. Kamarudin, Y.B. Chee, O. Owais, Throughput measurement of a dual-band MIMO rectangular dielectric resonator antenna for LTE applications. Sensors 2017, vol. 17, p148. Jan. 2017. https://doi.org/10.3390/s17010148
[14] K. M. Luk, K. W. Leung, Eds., "Dielectric Resonator Antennas", Research Studies Press, 2003.
[15] S.A. Long, M.W. McAllister, L.C. Shen, "The Resonant Cylindrical Dielectric Cavity Antenna", IEEE Trans. Antennas Propag. vol. no. 31, pp 406–412, 1983,.[Google Scholar]
[16] A. Petosa, Dielectric Resonator Antenna Handbook; Artech House Publishers: London, UK, 2007. [Google Scholar]
[17] Shahadan, N.H.; Jamaluddin, M.H. Steerable Higher Order Mode Dielectric Resonator Antenna with Parasitic Elements for 5G Applications. IEEE Access 2017, 5, 22234–22243. [Google Scholar]
[18] Altaf, A.; Munkyo, S. Triple-Band Dual-Sense Circularly Polarized Hybrid Dielectric Resonator Antenna. Sensors 2018, 18, 3899, 2018. [Google Scholar]
[19] T.A. Denidni; Z. Weng, "Rectangular dielectric resonator antenna for ultrawideband applications", IEEE Trans. Antennas Propag. Vol. 58, pp 4059–4062, 2010. [Google Scholar]
[20] K. W. Leung, W. C. Wong and H. K. Ng, "Circularly polarized slot-coupled dielectric resonator antenna with a parasitic patch", in *IEEE Antennas and Wireless Propagation Letters*, vol. 1, pp. 57-59, 2002, doi: 10.1109/LAWP.2002.805124.
[21] K. S. Ryu and A. A. Kishk, "UWB Dielectric Resonator Antenna Having Consistent Omnidirectional Pattern and Low Cross-Polarization Characteristics", in IEEE Transactions on Antennas and Propagation, vol. 59, no. 4, pp. 1403-1408, April 2011, doi: 10.1109/TAP.2011.2109676.
[22] Chair, R.; Kishk, A.A.; Lee, K.F. Wideband stair-shaped dielectric resonator antennas. IET Microwaves Antennas Propag. 2007, 1, 299–305. [Google Scholar]
[23] Q. Rao, T. A. Denidni, and R.H. Johnston, "A novel feed for a multi-frequency hybrid resonator antenna", IEEE Microwave and Wireless Components Letters,vol.15, no.4, pp238-240, 2005.
[24] B. Zheng and Z. Shen, "A nonuniform array of slots in the broad-walls of rectangular waveguides partially filled with dielectric slabs", International Journal of RF and Microwave Computer-Aided Engineering, CAE, 18(3): pp 278-285, 2008.

[25] L. Xing, Y.Huang, Y. Shen, S. Aljaafreh, Q. Xu and R. Alrawashdeh, "Further investigation on water antennas", IET Microwaves Antennas & Propagation, vol. 9, no. 8, pp 735-741, June 2015.
[26] Naveeta Kant, Ramesh Kulkarni, "Design and Performance Analysis of C-Band Water Antenna", International Journal on Emerging Technologies, vol. 10, issue. 4, pp 90-101, November 2019.
[27] Naveeta Kant, Abhigyan Kaustubh, Ramesh Kulkarni, "Performance Analysis of C-Band Water Antenna", 2019 Global Conference for Advancement in Technology (GCAT 2019), Paper ID 92, Bangalore, India, October 18-20, 2019