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RESEARCH ARTICLE

Undesirable Higher Order Modes Suppression Using Compact Hybrid Liquid Antenna for Wi-Fi Applications

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ABSTRACT In this paper, a multi-band multi-mode hybrid antenna using a liquid Dielectric Resonator Antenna (DRA) and patch configuration working for Wi-Fi applications at 2.4 GHz and 5 GHz bands is designed. This work proposes a way to suppress and replace undesirable higher-order modes of the DRA with desirable modes using a hybrid design keeping the compactness of the antenna still intact. The result is a compact multi-mode antenna with dimensions $\leq 1/2\ \lambda_0$ (*length & width*) and a *height* $\leq 1/4\ \lambda_0$, overall $0.42\lambda_0 \times 0.42\lambda_0 \times 0.18\lambda_0$, ('$\lambda_0$' is the wavelength at 2.4 GHz) with decent radiation efficiency, total efficiency, and realized gain for both lower and higher order modes.

INDEX TERMS DRA, patch antenna design, ME dipole, liquid dielectric antenna, hybrid antenna.

I. INTRODUCTION

Owing to the variety of advantages they offer, Dielectric Resonator Antennas (DRAs) are one of the extensively studied research areas. Some of them are relatively small in size (depending on the material properties such as permittivity), have low losses, decent radiation efficiencies, and comparatively improved bandwidth than conventional antennas. Due to the rapid expansion in the design and implementation of new-age wireless systems, there is a necessity for wide dual-band and multi-band features within the DRA [1], [2], [3], [4]. A wide dual-band DRA is presented in [5] with circular polarization (CP). Techniques were used such as truncation to achieve the CP. The disadvantage of this design is that the overall dimension of the antenna is $1\lambda_0 \times 1\lambda_0 \times 0.16\lambda_0$ which has a large ground plane. Therefore, there is no compactness. Similar works were seen in [6], [7], [8], and [9] where a souvenir DRA, a cylindrical DRA with twin aperture, a high-gain waveguide-fed DRA, and an equilateral triangular DRA are presented. All are dual-band DRAs with decent realized gains in both lower and higher bands. The basic disadvantages of all these works are that they have a relatively large ground plane close to $1\lambda_0$. In [8] the ground plane was around $2.5\lambda_0$. Therefore, all these dual-band DRA works lack compactness. Few works focused on this problem of large antenna sizes (including ground plane size) and came up with interesting ideas with reduced overall antenna dimensions. A hybrid aperture-based cylindrical DRA with dual-band and dual polarization is discussed in [10] for wireless applications. The overall antenna dimensions were $0.43\lambda_0 \times 0.43\lambda_0 \times 0.11\lambda_0$. But the problem in this work is the huge back radiation. Similar work was reported in [11] where a dual-band circularly polarized hybrid antenna is presented for WLAN / WiMAX applications. The overall antenna dimensions were also $0.43\lambda_0 \times 0.43\lambda_0 \times 0.11\lambda_0$ making it a compact design as the previous one. But as seen in the previous case, huge amounts of back radiation were seen in this work. Also, the realized gain even though is decent in the lower band, but poor ($\leq$ 2 dBi) in the higher band. A gravitational liquid antenna that employs passive beam-steering is presented in [12]. This antenna has dual-band characteristics. The overall dimensions were $0.52\lambda_0 \times 0.52\lambda_0 \times 0.12\lambda_0$ proving to be a compact design. But this work suffers from low radiation efficiency and poor total efficiency in the higher band. On an overall note, it can be seen that to have decent dual-band

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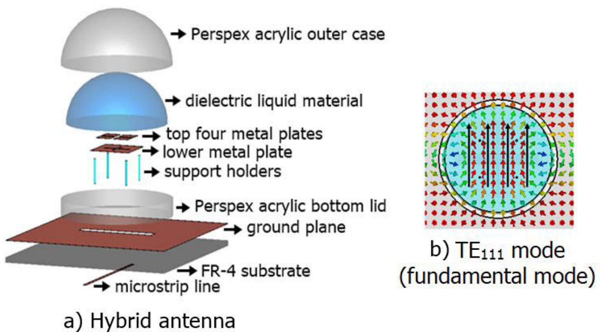

FIGURE 1. 3D view of the proposed hybrid antenna.

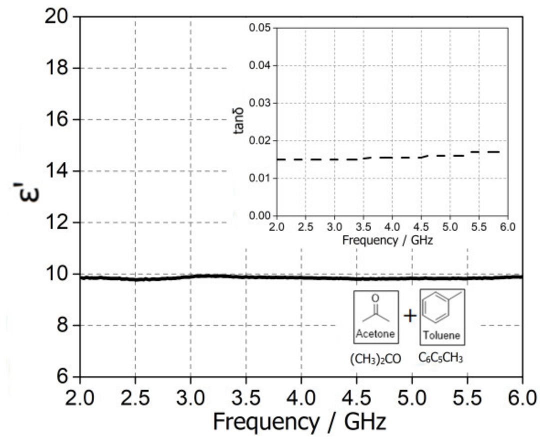

FIGURE 2. Material properties of the considered dielectric liquid mixture.

performance with properly realized lower-order and higher-order modes, and good antenna far-field characteristics the ground plane dimensions should be at least close to $1\lambda_0$. But this makes the antenna large. If the ground dimensions are restricted to close to $1/2\lambda_0$ there are issues concerning undesirable modes (characterized by either low gain, poor efficiencies, or back radiations, etc.,). This work overcomes this problem and proposes a new hybrid wide multi-band antenna design with multi-mode features to suppress these undesirable modes and replace them with desirable modes, at the same time keeping the antenna's overall dimensions close to around $1/2\ \lambda_0$ and the height profile to less than $1/4\ \lambda_0$ making the proposed design an extremely compact and an efficient antenna with good far-field properties.

II. PROPOSED HYBRID ANTENNA DESIGN

A hemispherical DRA (HDRA) as shown in Fig. 1a is considered to work in the wireless region around the 2.4 GHz and 5 GHz. For the liquid material characterization, in recent years liquid dielectrics turned out to be an alternate approach for enhancing the antenna performances in terms of improved bandwidth, design flexibility and reconfigurability.

The ability to realize miniature antennas using high permittivity liquid dielectrics and the ease of availability when compared to most costly liquid metals also make liquid dielectrics a prime candidate for interesting antenna designs [13]. Some of the works on antenna designs using liquid dielectrics can be found in [14], [15], [16], [17], and [18]. For this design, the dielectric liquid permittivity was chosen as 10. So, a suitable liquid material was tested and experimented. Finally, a mixture of 48% of Acetone – $(CH_3)_2CO$, and 52% of Toluene – $C_6C_5CH_3$ is taken which brings the combined permittivity to about 10 with a loss tangent (tanδ) of less than 0.02 as seen in Fig. 2. A microstrip-line feed mechanism is used to excite the fundamental TE_{111} mode of the HDRA as seen in Fig 1b. The radiation pattern for this mode is similar to that of a short horizontal magnetic dipole giving a broadside radiation pattern. The liquid HDRA is supported by an outer container and a solid base both made of Perplex acrylic material which has a relative permittivity of around 2.5. The container radius is $r_p = 16.5$ mm with a thickness of around 1.5 mm and the base thickness is around $h_{pb} = 5$ mm. The liquid material is confined inside this container with a liquid radius inside the container around $r_L = 15$ mm. This entire setup is placed on a ground plane with dimensions $(w_g\ x\ l_g) = 50 \times 50$ (in mm) supported by an FR – 4 substrate with a height $h_s = 1.6$ mm and permittivity around 4.3. To excite the antenna, a horizontal slot is realized on the ground plane with dimensions $(w_{gs}\ x\ \ l_{gs}) = 22 \times 3$ (in mm).

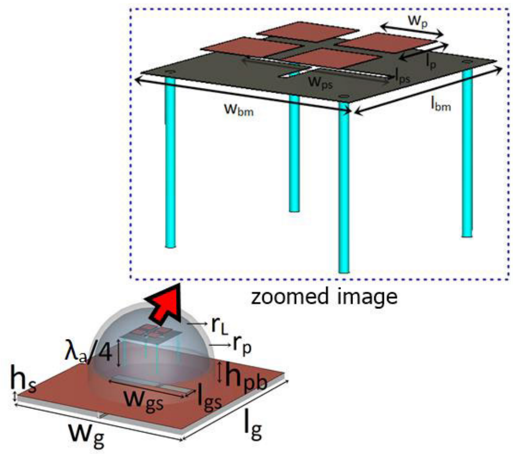

FIGURE 3. Overall view of the proposed hybrid antenna.

Liquids offer several advantages to improve antenna performance. One such advantage is to incorporate additional components within itself. In this work, this natural feature of the liquid is considered. A patch-like configuration containing two metal plates was realized inside the liquid HDRA at a distance of $\lambda_a/4$ ('λ_a' being the wavelength at 5 GHz) from the HDRA feeding source. Later, the top metal plate is made into four smaller individual patches with dimensions $(w_p\ x\ l_p) = 5 \times 4$ (in mm) each connected to the lower metal plate using individual metal vias. For the lower metal plate, horizontal and vertical slots were realized $(w_{ps}\ x\ l_{ps}) = 8 \times 0.5$ (in mm). The top four patches form the electric dipoles configuration and the lower metal plate with slot acts as a magnetic dipole, giving rise to a ME-dipole type configuration within the liquid HDRA. This is shown in Figs. 3 & 4.

III. WORKING SCENARIO OF THE DESIGN

Coming to the working scenario of the proposed design, the microstrip line beneath the ground aperture couples sufficient energy inside the DRA giving rise to the fundamental TE_{111} mode of the HDRA. This is shown in Fig. 1b. The resonant frequency for the TE_{111} mode can be calculated using the formula [19],

$$f_{GHz} = \frac{4.7713\text{Re}(k_o a)}{a_{cm}} \tag{1}$$

where,

$$\text{Re}(k_o a) = 2.8316\varepsilon_r^{-0.47829} \tag{2}$$

In addition to the fundamental DRA mode, which is realized around 2.60 GHz, the aperture feeding of the horizontal slot gives rise to a slot mode. The slot dimensions when carefully optimized can be combined with the TE_{111} mode of the DRA to realize additional bandwidth. This slot mode is realized around 2.45 GHz. The ME-dipole configuration is responsible for two modes. One corresponds to the electric dipole which is realized around 2.8 GHz corresponding to the half-working wavelengths of the incorporated electric dipoles. The other resonance corresponding to the magnetic dipole is realized around 4.2 GHz. In addition to this, the top and lower plates as a whole are responsible for realizing the fundamental TM_{10} mode and the higher-order TM_{21} mode similar to as seen in the working of a rectangular patch antenna configuration. For the rectangular patch antenna, the resonant frequency for the TM_{mn} modes can be calculated using the following formulas,

$$\begin{aligned} f_{mn} &= k_{mn}c/(2\pi\sqrt{\varepsilon_r}) \\ k_{mn}^2 &= (m\pi/W_{eff})^2 + (n\pi/L_{eff})^2 \end{aligned} \tag{3}$$

where 'c' is the speed of light, 'ε_r' is the effective permittivity 'W_{eff}' and 'L_{eff}' are the effective width and length of the patch, and 'm' and 'n' are the order of the modes. The parameters can be calculated using the method in [20].

One of the main advantages of this work is that no additional port terminals are required to excite or drive the ME-dipole. The liquid inside the HDRA acts as a source to drive the ME-dipole. The fields generated inside the HDRA as a result of the aperture feeding mechanism through the microstrip line will excite the ME-dipole. The top four patches and the lower metal plate with dielectric liquid separating them also act as a simple patch antenna as a whole which when driven by the fields generated within the HDRA produces additional modes, *viz.,* the fundamental TM_{10} mode, and the higher order TM_{21} mode around the 5 GHz and 5.5 GHz frequency range. The TM_{10} is a broadside mode. TM_{21} is usually a dual-beam mode with a single main lobe in broadside direction and an additional side lobe on both sides. But, in this work, because the patch is placed inside the HDRA with high permittivity liquid material, these sidelobes are restricted by the liquid material and are directed in the direction of propagation combining with the main lobe giving the TM_{21} mode more broadside radiation. The result is a hybrid antenna (mode combinations: hemispherical DRA + ME-dipole + patch configuration) covering both the Wi-Fi bands at 2.4 GHz and 5 GHz frequency ranges. This is shown in Fig. 5.

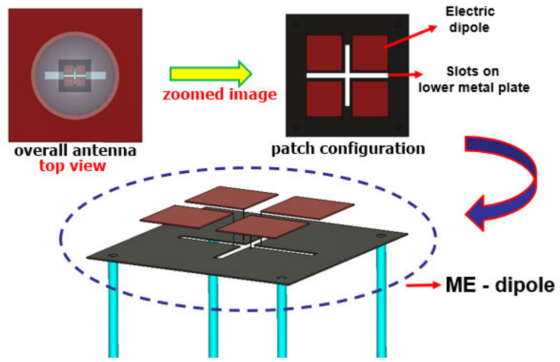

FIGURE 4. ME – dipole configuration incorporated inside proposed antenna.

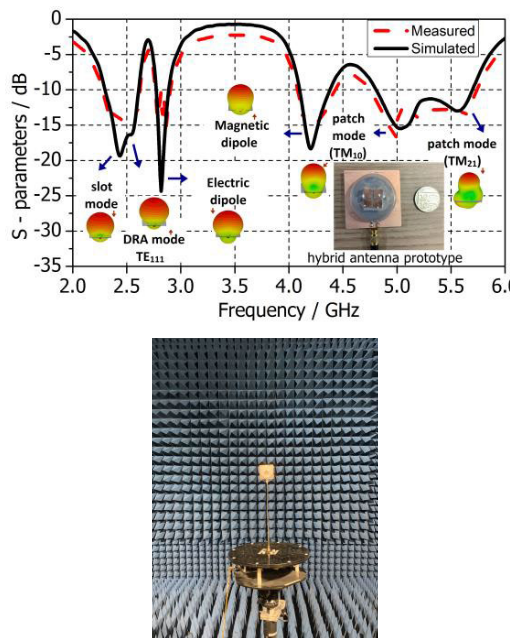

FIGURE 5. Reflection coefficient parameters of the fabricated hybrid antenna prototype.

The E-field distribution for the realized four modes is shown in Fig. 6. It can be seen in Figs. 6a and 6b, the modes generated are indeed from the slot and the hemispherical DRA. Very weak electric field concentration between the metal plates proves there is no significant effect due to the patches. But, when it comes to Figs. 6c and 6d, it can be seen, stronger electric fields are realized between the metal plates which escape into the free space through the edges. This action is similar to the working as seen in patch antennas. Therefore, from Figs. 6c and 6d, it is evident that the modes are indeed due to the metal patch which is excited due to fields generated within the liquid DRA. The field distribution for the TM_{10} and TM_{21} modes is shown in Fig. 7.

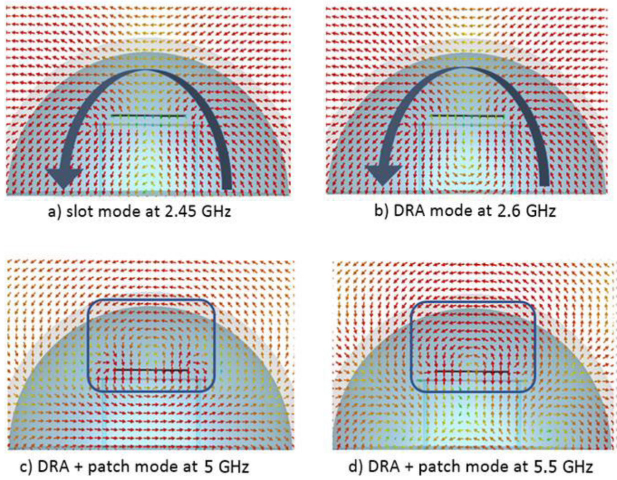

FIGURE 6. Electric field concentration for the realized modes at the lower band and higher band.

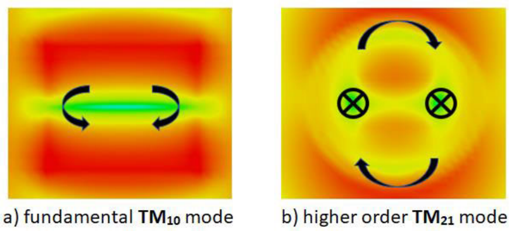

FIGURE 7. Electric field distribution for the realized patch modes at (a) 2.8 GHz and (b) 4.2 GHz.

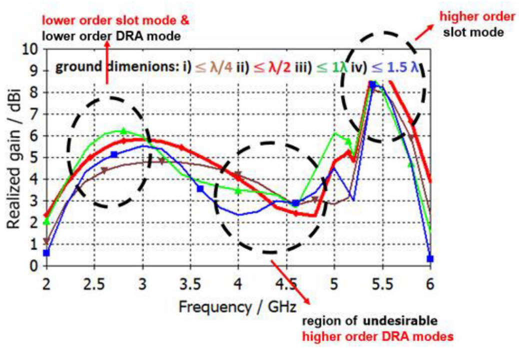

FIGURE 8. Realized gain for the conventional hemispherical DRA.

IV. BACKGROUND WORK—PROBLEMS WITH CONVENTIONAL DUAL—BAND DRA DESIGN

At first, a conventional hemispherical DRA is considered *(without top patches and lower metal plate and support holders)*. Once the HDRA is realized using the fundamental DRA mode the slot mode, steps were taken to realize the dual-band design using the higher-order modes. The idea behind the dual-band design is that the overall antenna should be as compact as possible. The height of the hemispherical DRA is found to be around $0.18\lambda_0$. Since the height is less than a quarter-wavelength, the focus was laid on the overall dimensions of the antenna. In this scenario, the ground plane dimension and its effects on the antenna far-field parameters are studied (not shown here). For the ground plane

TABLE 1. Analysis for dual-band performance using conventional DRA.

S.No	Ground size - wavelength in (λ_0)	Lower-order modes		Higher-order modes	
		Slot mode	DRA modes	Slot mode	DRA modes
1.	$\leq \lambda_0/4$	Back radiation	decent	Impedance mismatch	Undesirable modes
2.	$\leq \lambda_0/2$	Improved forward radiation	decent	Impedance improved	Undesirable modes
3.	$\leq 1\ \lambda_0$	destroyed	Back lobes + side lobes	destroyed	Back lobes + side lobes
4.	$\leq 1.5\ \lambda_0$	destroyed	Back lobes + side lobes + spurious radiation	destroyed	Back lobes + side lobes + spurious radiation

Undesirable modes - modes with either low gain, back radiation, improper radiation patterns, or low efficiencies.

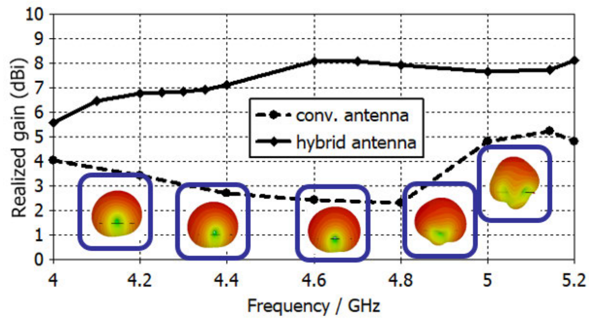

FIGURE 9. Realized gain comparison in the higher-band with proposed hybrid antenna after undesirable higher order modes are replaced with desirable modes.

dimensions $\leq 1\lambda_0$ and $\leq 1.5\lambda_0$, the lower-order and higher-order slot modes were completely destroyed. For the lower-order and higher-order DRA modes, high-side lobes and back lobe radiation were seen. In particular, spurious radiation was seen for the ground plane dimensions of $\leq 1.5\lambda_0$. The radiation efficiency was low, and the total efficiency was poor due to the mismatch losses and the radiation losses. For the ground plane dimensions $\leq 1/4\lambda_0$, the lower-order slot mode suffered from back radiation due to the small ground size. The higher-order slot mode suffered an impedance mismatch. The lower-order DRA mode was properly realized but the higher-order modes were realized to be undesirable modes. The results suggest that, for the ground plane dimensions $\leq 1/2\ \lambda_0$, the lower and higher-order slot modes were properly realized with the latter's improvement in impedance. The lower-order DRA mode was properly realized, and the higher-order DRA modes were still undesirable modes. The realized gain plot shown in Fig. 8 also depicts the region of undesirable higher-order DRA modes characterized by low gain.

Therefore, for the overall antenna dimensions $\leq 1/2\ \lambda_0$ case, which has all three requirements good with properly realized lower and higher-order slot modes, and lower-order DRA mode, only needs decent higher-order DRA modes to

TABLE 2. Comparison with the previously published works.

[Ref] & year	Dual-band DRA	Radiation/Total efficiency	Realized gain (dBi)		Overall antenna Profile (λ_0)	Comments
			lower band	upper band		
[5] 2016	Yes	NA	NA	NA	$1\lambda_0$ x $1\lambda_0$ x $0.16\lambda_0$	large ground plane. No compactness
[6] 2019	Yes	NA	≥ 6 dBi	≥ 6 dBi	$1\lambda_0$ x $1\lambda_0$ x $0.16\lambda_0$	large ground plane. No compactness
[7] 2021	Yes	NA	≥ 6 dBi	≥ 8 dBi	$0.8\lambda_0$ x $0.8\lambda_0$ x $0.13\lambda_0$	large ground plane. No compactness
[8] 2022	Yes	99% (No evidence)	≥ 10 dBi	≥ 10 dBi	$2.5\lambda_0$ x $2.5\lambda_0$ x $0.35\lambda_0$	large ground plane. No compactness. Lack of evidence to radiation efficiency
[9] 2021	Yes	NA	≥ 6 dBi	≥ 6 dBi	NA x NA x $0.14\lambda_0$	Huge ground plane (at least 5 times the size of DRA)
[10] 2017	Yes	NA	≥ 5 dBi	≥ 6 dBi	$0.43\lambda_0$ x $0.43\lambda_0$ x $0.11\lambda_0$	Compact. But huge back radiation. Lack of evidence for radiation efficiency
[11] 2017	Yes	NA	≥ 5 dBi	Poor ≤ 2 dBi	$0.43\lambda_0$ x $0.43\lambda_0$ x $0.11\lambda_0$	Compact. But huge back radiation. Poor gain in the higher band
[12] 2020	Yes	low RE & poor TE in higher band	≥ 5 dBi	≥ 4 dBi	$0.52\lambda_0$ x $0.52\lambda_0$ x $0.12\lambda_0$	Compact. Low RE & poor TE in the HB
This work	Yes	good RE ≥ 85% & TE ≥ 80%	≥ 5.5 dBi	≥ 7 dBi	$0.41\lambda_0$ x $0.41\lambda_0$ x $0.18\lambda_0$	decent gain, RE & TE. (*length & width*) ≤ 1/2 λ_0; *height* ≤ 1/4 λ_0 - very compact

λ_0 – operating wavelength; RE-radiation efficiency; TE-total efficiency

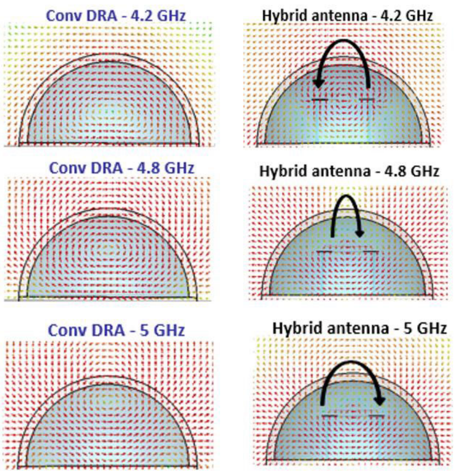

FIGURE 10. Mode transformation from omnidirectional-like mode to broadside modes in the higher band due to the incorporation of metal patches into the liquid HDRA.

achieve good bandwidth and gain. Therefore, the existing region of undesirable higher modes characterized by low realized gain needs to be suppressed and replaced with desirable higher-order modes. The analysis is tabulated in Table 1.

This is where the proposed hybrid antenna proves to be useful. The top four patches and lower metal plates incorporated inside the liquid HDRA act as ME-dipole and also as a patch configuration as a whole. The undesirable higher-order DRA modes are replaced by the new modes realized due to ME-dipole and TM_{10} and TM_{21} modes realized as a result of the patch configuration. The higher-order slot mode is replaced by the TM_{21} mode of the patch

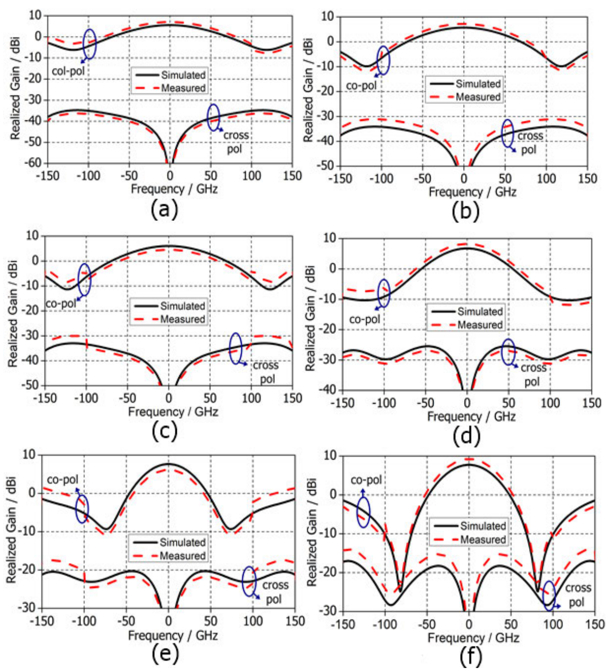

FIGURE 11. Realized gain of the proposed hybrid antenna at different frequencies concerning to the modes realized. (a) 2.45 GHz (b) 2.6 GHz (c) 2.8 GHz (d) 4.2 GHz (e) 5 GHz and (f) 5.5 GHz.

configuration. Thus, the region between 4 to 5.2 GHz which once served undesirable modes with a low gain is now transformed into a useful region with desirable modes having a high realized gain of above 6 dBi. The gain comparison is shown in Fig. 9.

The suppression and replacement of the undesirable modes in the region between 4 to 5.2 GHz (higher band)

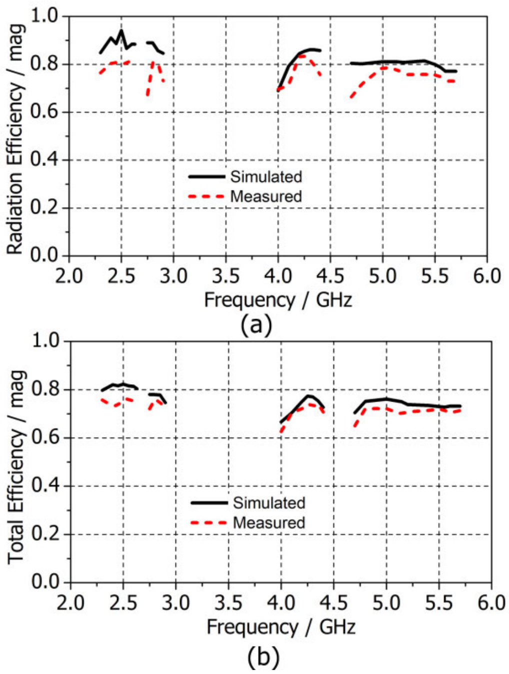

FIGURE 12. Overall simulated and measured radiation efficiency and the total efficiency.

are illustrated in Fig. 10. The fields in the conventional HDRA are responsible for an omnidirectional-like radiation pattern as shown in Fig. 9 giving rise to low forward gain modes (in the higher band) as a result of improper half-sine variations due to the short ground plane. This is overcome in the proposed hybrid antenna design due to the presence of the ME-dipole incorporated inside the liquid HDRA. Undesirable higher-order half-sinewave field variations generated within the HDRA on interaction with the top four patches and lower metal plate actuate or drive the ME-dipole and the additional TM_{10} and TM_{21} modes thus transforming from omnidirectional-like modes to useful broadside modes. In this way, the undesirable higher-order DRA modes are suppressed and replaced with the help of a hybrid antenna design. The transformation is shown in Fig. 10. Decent radiation characteristics were seen in both the lower and higher bands with an overall realized gain of above 5.5 dBi. The cross-polarization levels were seen to be below -20 dB and the radiation and total efficiency were over 70% making the hybrid antenna capable of achieving decent far-field characteristics. This is seen in Figs. 11 & 12.

V. CONCLUSION

A hybrid multi-mode wideband antenna is designed and presented targeting wireless applications in the region between 2 to 5 GHz, in particular the Wi-Fi bands at 2.4 GHz and 5 GHz. The proposed antenna overcomes the problems associated with the undesirable higher-order modes in conventional DRAs when designing compact antennas with dimensions $\leq 1/2\ \lambda_0$ (*length & width*) and a *height* $\leq 1/4\ \lambda_0$. The antenna has a decent realized gain of over 5.5 dBi across all the realized bands with good far-field characteristics, radiation efficiency and total efficiency being over 70%. A working prototype is designed and tested with good agreement between the simulations and the measured results.

REFERENCES

[1] A. A. Abdulmajid, Y. Khalil, and S. Khamas, "Higher-order-mode circularly polarized two-layer rectangular dielectric resonator antenna," *IEEE Antenna Wireless Propag. Lett.*, vol. 17, no. 6, pp. 1114–1117, Jun. 2018.

[2] H. I. Kremer, K. W. Leung, and M. W. K. Lee, "Compact wideband low-profile single- and dual-polarized dielectric resonator antennas using dielectric and air vias," *IEEE Trans. Antennas Propag.*, vol. 69, no. 12, pp. 8182–8193, Dec. 2021.

[3] R. E. Jacobsen, A. V. Lavrinenko, and S. Arslanagic, "A water-based Huygens dielectric resonator antenna," *IEEE Open J. Antennas Propag.*, vol. 1, pp. 493–499, 2020.

[4] A. Sharma, G. Das, S. Gupta, and R. K. Gangwar, "Quad-band quad-sense circularly polarized dielectric resonator antenna for GPS/CNSS/WLAN/WiMAX applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 3, pp. 403–407, Mar. 2020.

[5] Y. D. Zhou, Y. C. Jiao, Z. Bin Weng, and T. Ni, "A novel single-fed wide dual-band circularly polarized dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 930–933, 2016.

[6] X. S. Fang and S. M. Chen, "Design of the wide dual-band rectangular souvenir dielectric resonator antenna," *IEEE Access*, vol. 7, pp. 161621–161629, 2019.

[7] P. Gupta, D. Guha, and C. Kumar, "Dual-mode cylindrical DRA: Simplified design with improved radiation and bandwidth," *IEEE Antennas Wireless Propag. Lett.*, vol. 20, no. 12, pp. 2359–2362, Dec. 2021.

[8] S. Varghese, P. Abdulla, A. M. Baby, and P. M. Jasmine, "High-gain dual-band waveguide-fed dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 21, no. 2, pp. 232–236, Feb. 2022.

[9] P. Anoop and R. Bhattacharjee, "Investigation on dual-band equilateral triangular shaped dielectric resonator antennas for WLAN applications," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 31, no. 7, pp. 1–15, Apr. 2021.

[10] A. Sharma, G. Das, and R. K. Gangwar, "Dual-band dual-polarized hybrid aperture-cylindrical dielectric resonator antenna for wireless applications," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 27, no. 5, Feb. 2017, Art. no. e21092.

[11] A. Sharma, G. Das, and R. K. Gangwar, "Dual-band circularly polarized hybrid antenna for WLAN/WiMAX applications," *Microw. Opt. Technol. Lett.*, vol. 59, no. 10, pp. 2450–2457, Jul. 2017.

[12] C. Song, E. L. Bennett, J. Xiao, T. Jia, R. Pei, K.-M. Luk, and Y. Huang, "Passive beam-steering gravitational liquid antennas," *IEEE Trans. Antennas Propag.*, vol. 68, no. 4, pp. 3207–3212, Apr. 2020.

[13] E. Motovilova and S. Y. Huang, "A review on reconfigurable liquid dielectric antennas," *Materials*, vol. 13, no. 8, p. 1863, Apr. 2020.

[14] X. Yan, L. Li, H. C. Zhang, and J. Y. Han, "Broadband polarization-reconfigurable liquid dielectric resonator antenna controlled by gravity," *IEEE Antennas Wireless Propag. Lett.*, vol. 21, no. 10, pp. 2105–2109, Oct. 2022.

[15] C. Song, E. L. Bennett, J. Xiao, Q. Hua, L. Xing, and Y. Huang, "Compact ultra-wideband monopole antennas using novel liquid loading materials," *IEEE Access*, vol. 7, pp. 49039–49047, 2019.

[16] Z. Chen and H. Wong, "Wideband glass and liquid cylindrical dielectric resonator antenna for pattern reconfigurable design," *IEEE Trans. Antennas Propag.*, vol. 65, no. 5, pp. 2157–2164, May 2017.

[17] J. Ren, "Radiation pattern and polarization reconfigurable antenna using dielectric liquid," *IEEE Trans. Antennas Propag.*, vol. 68, no. 12, pp. 8174–8179, Dec. 2020.

[18] Z. Chen, H.-Z. Li, H. Wong, X. Zhang, and T. Yuan, "A circularly-polarized-reconfigurable patch antenna with liquid dielectric," *IEEE Open J. Antennas Propag.*, vol. 2, pp. 396–401, 2021.

[19] S. Gupta, V. Killamsetty, M. Chauhan, and B. Mukherjee, "Compact and circularly polarized hemispherical DRA for C-band applications," *Frequenz*, vol. 73, nos. 7–8, pp. 227–234, Jul. 2019.

[20] Z. Wang, X. Li, S. Fang, and Y. Liu, "An accurate edge extension formula for calculating resonant frequency of electrically thin and thick rectangular patch antennas with and without air gaps," *IEEE Access*, vol. 4, pp. 2388–2397, 2016.

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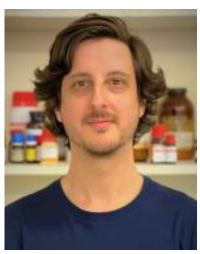

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