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Gain Enhancement of SIW Cavity-Backed Antenna Using Dielectric Loading

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Abstract—This article presents the design and development of a low profile substrate integrated waveguide semi-circular cavity-backed antenna loaded with dielectric cylinders of glass-reinforced epoxy and Teflon. The substrate integrated waveguide semi-circular cavity-backed antenna without dielectric loading radiates at 5.8 GHz with 3.13 dB gain. The antenna is modified by putting dielectric cylinders of different materials and different sizes at the edge of a semi-circular cavity to enhance the gain of the antenna. The new antenna thus created has improved gain of 8.13 dB. All simulations are done using high frequency structure simulation software. The proposed design is fabricated on a glass-reinforced epoxy substrate with a semi-circular cavity having a size of $60\,\text{mm} \times 50\,\text{mm}$. The measured results are in good agreement with simulated ones.

1. INTRODUCTION

In recent years, the antennas having low-profile and large bandwidth, high gain, and good radiation are in high demand for advanced wireless communications. The rapid development of wireless communication systems needs antennas with a good radiation pattern and high-performance parameters including low profile, low cost, light weight, easy fabrication, and smooth integration with planar circuits [1–4]. Microstrip slots antennas are best suitable for above applications; however, they suffer from low forward gain and radiation efficiency due to conductor losses and bidirectional radiation. To overcome these disadvantages and improve gain and radiation efficiency, a metallic reflector or cavity backed antennas [5, 6] were introduced. However, metallic antennas and cavity-backed antennas are massively heavy, and high fabrication costs make them not suitable for some applications in satellite, aircraft, and high-density microwave communication systems [7]. The substrate integrated waveguide (SIW) technology was applied to cavity backed slot antennas to eradicate the above-mentioned drawbacks [8].

Recently, some solutions aimed at enhancing the gain of SIW cavity antennas have been investigated. In [9], to enhance antenna gain, high order of cavity resonance TE_{220} is used. In [10], three parallel transverse slots were created on back of the antenna, used higher resonance TE_{410} mode to enhance the gain parameters, and these slots acted as radiating elements.

In [11], a compact and light weight SIW antenna was reported. To improve gain a horn mounted cylindrical dielectric resonator was used. In [12], a dual-polarized SIW cavity backed slot antenna was reported, and the antenna gain was enhanced by using a higher order cavity resonance to generate arbitrary levels of inclined linear polarization having metal posts embedded in main cavity.

In this paper, a half-mode semicircular cavity backed antenna is presented. Further, to enhance the antenna gain, the design of a semicircular cavity backed antenna is modified using two parallel stacks of dielectric cylinders of different sizes and different materials. Teflon and FR4 are used as dielectric materials. The systematic design analysis of cavity backed antennas with dielectric cylinders is represented in Section 2 followed by the comparative analysis between simulated and measured parameters of the proposed antenna.

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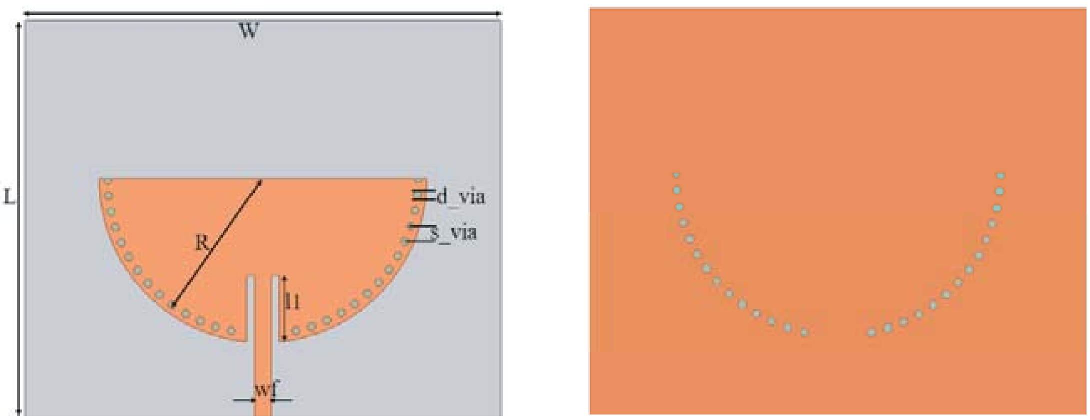
2. ANTENNA DESIGN

2.1. SIW Cavity Backed Half Mode Antenna (Design 1)

The top and bottom configurations of the proposed semicircular SIW cavity antenna design are shown in Figure 1(a) and Figure 1(b), respectively. The glass-reinforced epoxy (FR4) having the thickness of 1.6 mm, permittivity (ε_r) of 4.4, and loss tangent ($\tan\delta$) of 0.002 is used as dielectric substrate material. The SIW structure is created into the substrate by inserting vias in order to attach top and bottom airfields. The size of the cavity is calculated from theory of circular resonator cavity illustrated in [21].



(a) (b)

Figure 1. Layout of the proposed antenna; $W = 60$ mm, $L = 50$ mm, $R = 20.7$ mm, $wf = 2$ mm, $l1 = 8.5$ mm. (a) Top view. (b) Bottom view.

d_{via} (diameter of Vias) is 1 mm with S_{via} (center-to-center distance) of 1.5 mm selected in such a way to minimize radiation loss. The top layer and bottom layer of copper claddings are shielded with the vias of thickness 1.6 mm. To reduce the leakage of energy coming out from the PEC walls, guidelines for SIW cavity that are $d_{via}/S_{via} \geq 0.5$ and d_{via}/λ_o are strictly followed. To achieve 50 Ω characteristic, the width of feed line is optimized at 2 mm. The prototype of antenna is manufactured by PCB technique, and vias are drilled and coated with copper by PTH (plated through hole) technique.

Figure 2(a) presents the prototype of proposed antenna design 1. Figure 2(b) shows the return loss of simulated and measured results. The simulated gain of antenna design 1 is 3.13 dB as shown in Figure 2(c). Figure 2(d) presents the simulated radiation patterns for E-plane and H-plane. Figure 2(e) presents E-field for TM_{210} mode.

2.2. SIW Cavity Backed Half Mode Antenna with Teflon Cylinder (Design 2)

To improve the gain of antenna while keeping the same S_{11} characteristic of antenna, Teflon with dielectric constant 2.1 is used as dielectric material. Teflon cylinders are placed at the edge of the half circular cavity where E-field is maximum as shown in Figure 2(e). Figure 3 illustrates the antenna design 2 with Teflon cylinders.

Parametric analysis of radius and height of Teflon cylinders is carried out to find out optimum results of return loss and gain. The values of radius (R_{tef}) of Teflon cylinders are taken as 3.2 mm, 4.2 mm, 5.4 mm, 6.2 mm, 7.2 mm, and 8.2 mm. From Figure 4(a), it is observed that as the radius of the Teflon cylinder increases, the return loss decreases. Frequency shift is also observed for radius 7.2 mm and more. From Figure 4(b), it is observed that gain increases as radius decreases up to the radius 4.2 mm; however, gain decreases for 3.2 mm. From the above analysis, the optimum value of radius is chosen as 4.2 mm as at that value return loss characteristic is good with higher gain.

Similarly, the heights (H_{tef}) of Teflon cylinders are taken as 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm, and its return loss and gain are shown in Figure 5(a) and Figure 5(b), respectively. With increase

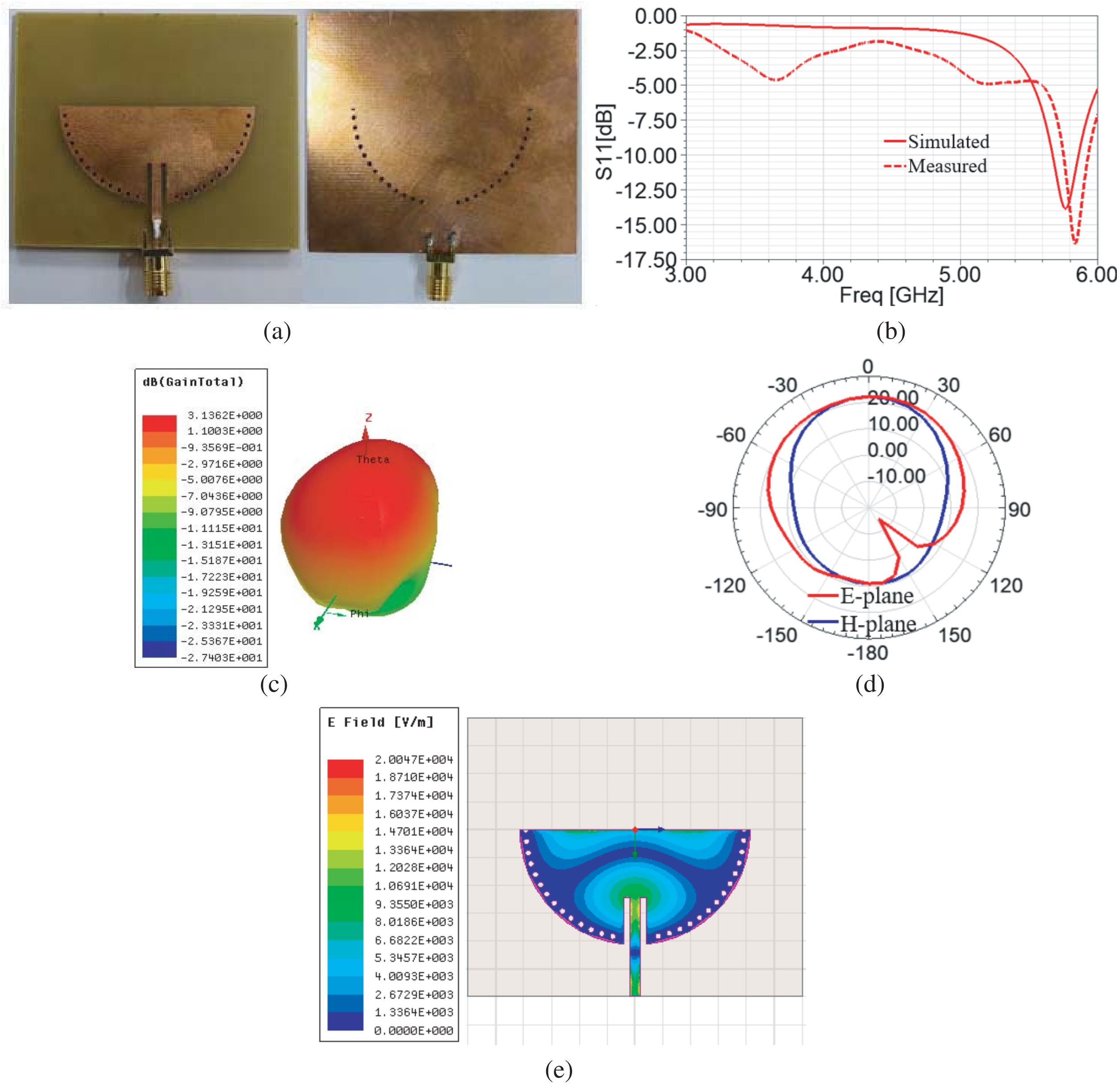


Figure 2. Fabricated Proposed antenna. (a) Front view and back view. (b) Return loss characteristic of antenna. (c) Simulated gain in 3D. (d) Simulated 2D radiation pattern. (e) E-field pattern.

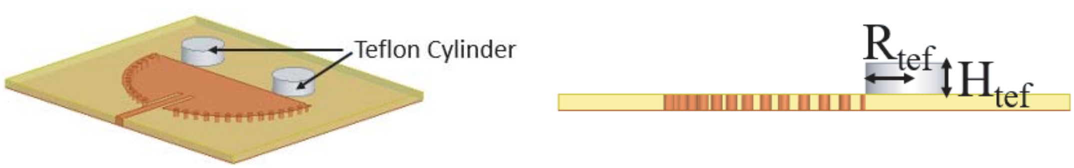
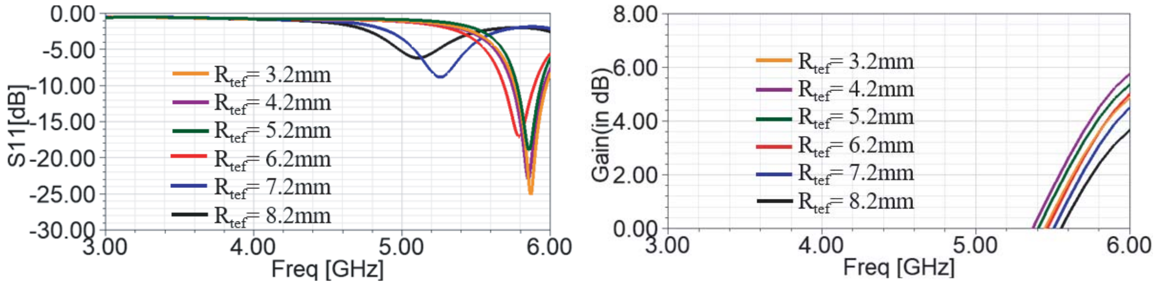


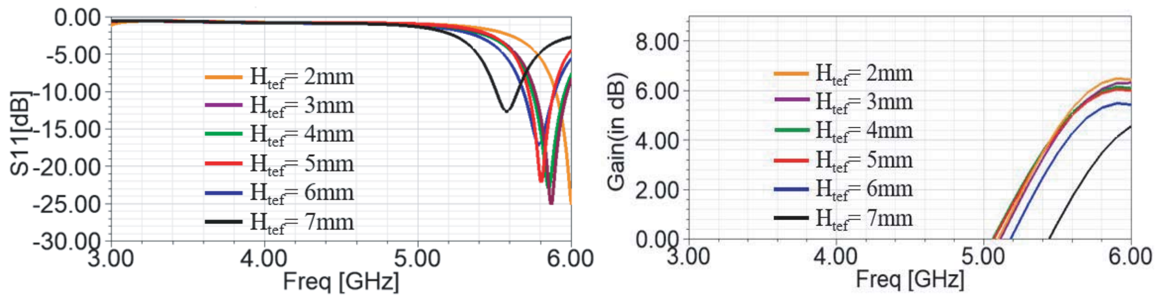
Figure 3. Schematic view of antenna design 2.

in height, return loss decreases. Similarly, the gain of antenna increases as height decreases. However, frequency shift observed at height 3 mm and less, which is not acceptable though gain is high. Thus, the optimum value of height is considered as 3 mm which provides better return loss and gain.



(a) (b)

Figure 4. Effect of different values of radius and height of Teflon cylinder on the performance of return loss and gain. (a) Return loss characteristic for values of R_{tef}. (b) Performance of gain for values of R_{tef}.



(a) (b)

Figure 5. Effect of different values of radius and height of Teflon cylinder on the performance of return loss and gain. (a) Return loss characteristic for values of H_{tef}. (b) Performance of gain for values of H_{tef}.

Thus, antenna is fabricated with Teflon cylinders as dielectric loader having the radius of 4.2 mm and height of 3 mm. The fabricated antenna design 2 prototype is shown in Figure 6(a). The return loss characteristic and gain of fabricated antenna are shown in Figure 6(b) and Figure 6(c), respectively. Figure 6(d) presents 2D simulated radiation pattern of the antenna. The simulated improved gain of antenna is 4.69 dB (compared to gain 3.13 dB with antenna design 1).

2.3. SIW Cavity Backed Half Mode Antenna with Teflon and FR4 Cylinders (Antenna Design 3)

To improve the gain of antenna without affecting S_{11} characteristic of antenna, another cylinder of dielectric material is placed on top of the Teflon cylinder. Here, FR4 with dielectric constant 4.4 is used along with Teflon as dielectric loader to enhanced gain. Figure 7 illustrates antenna design 3 with Teflon and FR4 as dielectric loader.

Parametric analysis of radius (R_{in}) and height (H_{in}) of FR4 cylinders is carried out to find out optimum results of return loss and gain. The values of radius of FR4 cylinders (R_{in}) are taken as 3.3 mm, 4.3 mm, 5.3 mm, 6.3 mm, 7.3 mm, and 8.3 mm. From Figure 8(a), it is observed that as the radius of the FR4 cylinder increases the return loss increases. From Figure 8(b), it is observed that the value of gain increases as radius increases up to 7.3 mm; however, for greater than 7.3 mm gain starts decreasing. From the above analysis, the optimum value of radius is chosen as 7.3 mm as at that value return loss characteristic is good with higher gain.

Similarly, the values of height (H_{in}) of FR4 cylinders are taken as 0.8 mm, 1.6 mm, 2.4 mm, 3.2 mm, 4.8 mm, and 5.6 mm. Its response of return loss and gain are shown in Figure 9(a) and Figure 9(b). With increase in height, the return loss increases. However, from Figure 9(b) it is observed that the gain of antenna increases up to the height 4.8 mm then starts decreasing again. Thus, the optimum value

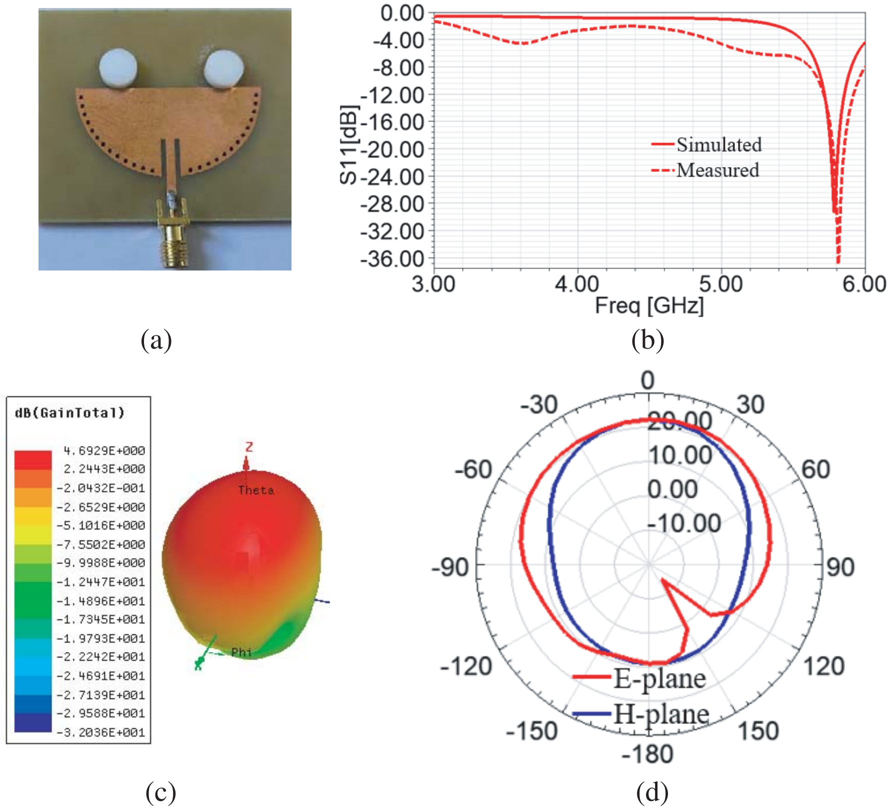


Figure 6. (a) Antenna with dielectric material (Teflon). (b) Return loss characteristic. (c) Simulated gain in 3D. (d) Simulated 2D radiation pattern.

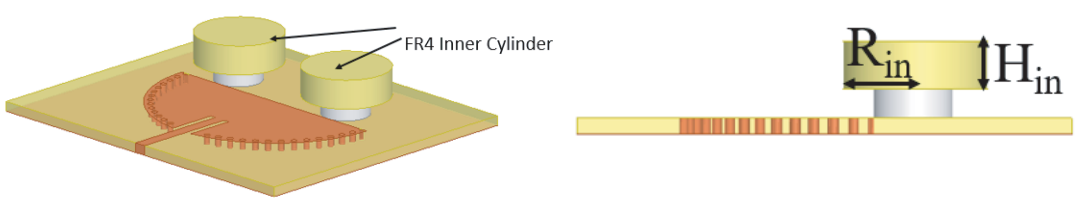


Figure 7. Schematic view of antenna design 3.

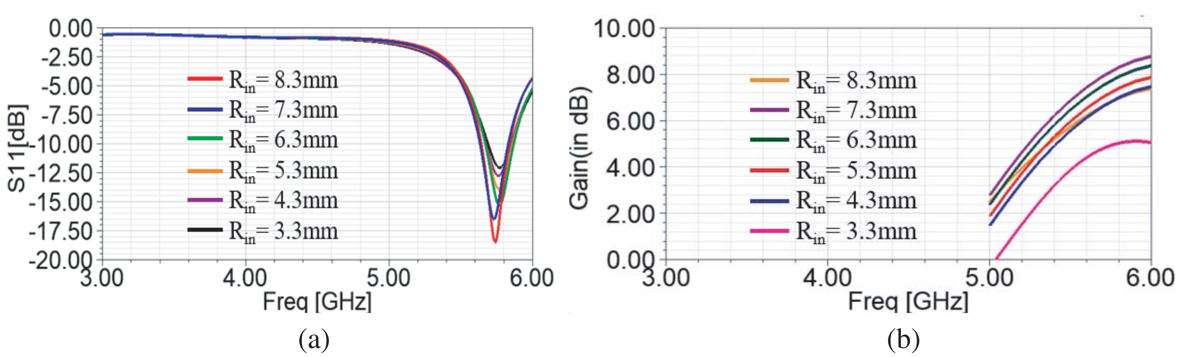


Figure 8. Effect of different values radius of FR4 inner cylinder on the performance of return loss and gain. (a) Return loss characteristic for values of R_{in}. (b) Performance of gain for values of R_{in}.

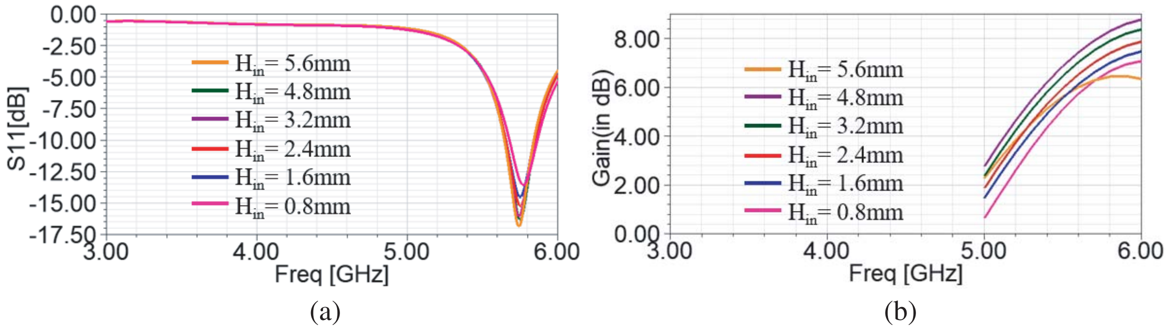


Figure 9. Effect of different values height of FR4 inner cylinder on the performance of return loss and gain. (a) Return loss characteristic for values of H_{in}. (b) Performance of gain for values of H_{in}.

of height is considered as 4.8 mm which provides better return loss and gain. The simulated improved gain of antenna is 6.23 dB (compared to gain 4.69 dB with antenna design 2).

Considering above parametric analysis, antenna is fabricated with Teflon and FR4 as dielectric loaders having the radius of FR4 cylinder 7.3 mm and height 4.8 mm. The fabricated antenna design 3 prototype is shown in Figure 10(a). The return loss characteristic and gain of fabricated antenna are shown in Figure 10(b) and Figure 10(c), respectively. Figure 10(d) resents 2D radiation pattern of the antenna.

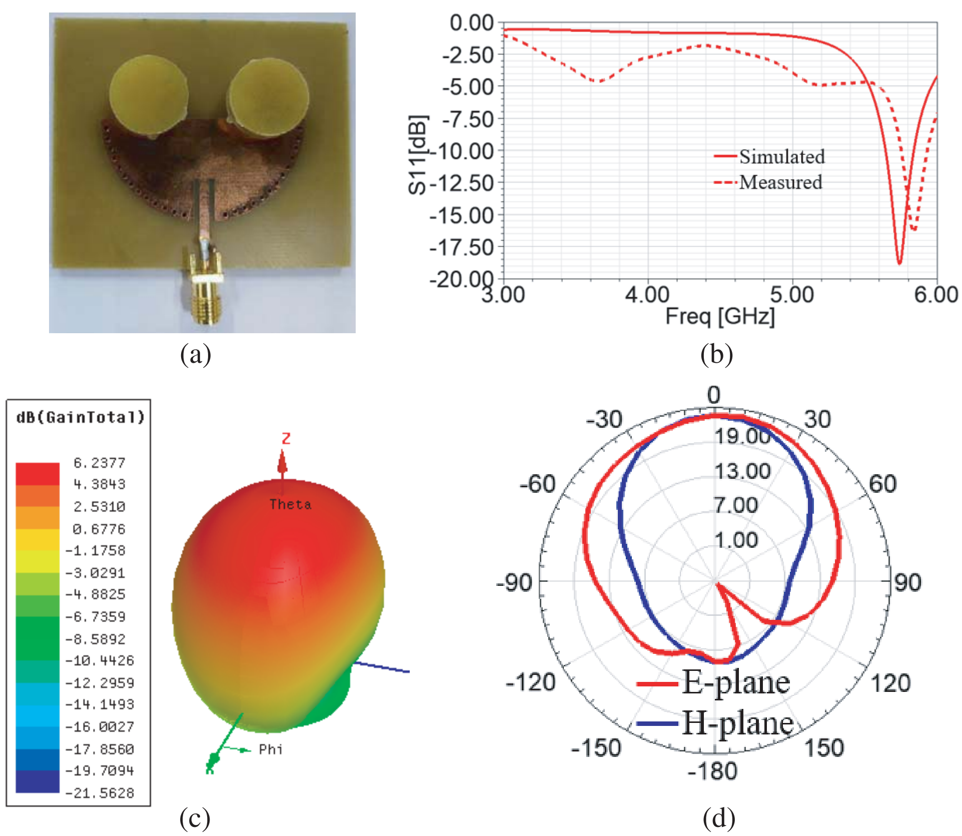


Figure 10. (a) Antenna with dielectric material (Teflon+Fr4). (b) Return loss characteristic. (c) Simulated gain in 3D. (d) Simulated 2D radiation pattern.

2.4. SIW Cavity Backed Half Mode Antenna with Teflon, FR4 and FR4 Cylinders (Antenna Design 4)

Figure 11 illustrates the antenna design 4 with Teflon and two layers of FR4 having different sizes as dielectric loader. In design antenna 3, good characteristic of return loss is maintained, and also the gain of antenna is improved to expectable range. However, when additional cylinder of FR4 having the radius 11 mm and height 2.4 mm is loaded on antenna, the gain is improved which is 8.27 dB while maintaining the same S_{11} characteristic of antenna.

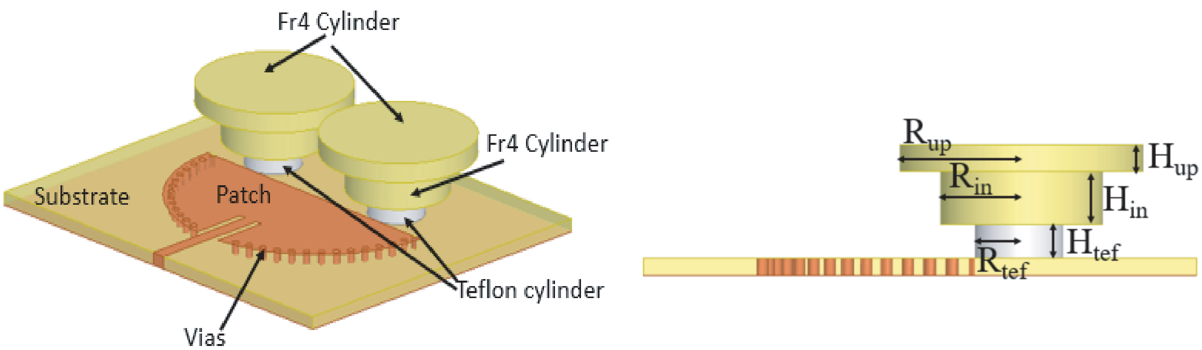
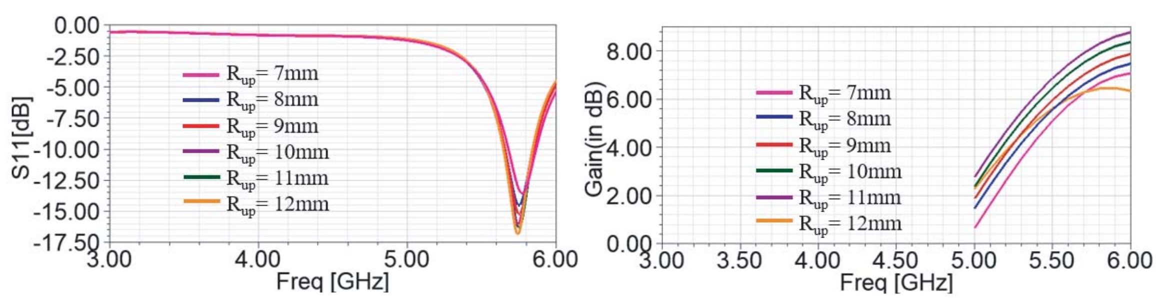


Figure 11. Schematic view of antenna design 4.

Parametric analysis of parameters of FR4 cylinders is carried out to find out optimum results of return loss and gain. The values of radius of FR4 cylinder (R_{up}) are taken as 7 mm, 8 mm, 9 mm, 10 mm, 11 mm, and 12 mm. From Figure 12(a), it is observed that as the radius of the FR4 cylinder increases, the return loss increases. From Figure 12(b), it is observed that the value of gain increases as radius increases up to radius 11 mm. From the above analysis, the optimum value of radius is chosen as 11 mm as at that value return loss characteristic is good with higher value of gain.

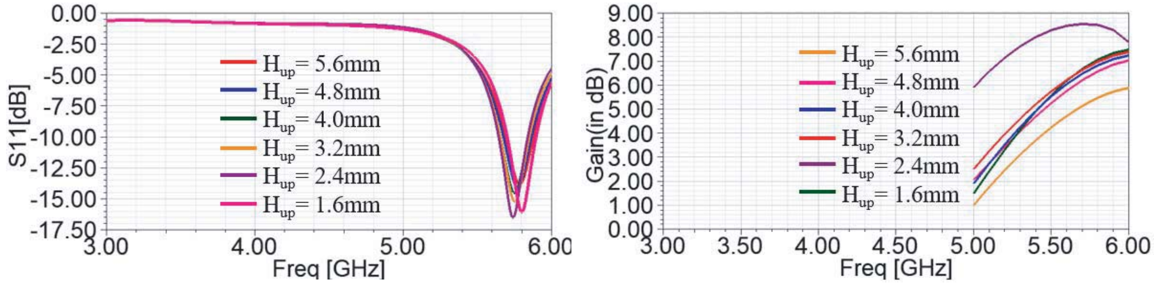


(a) (b)

Figure 12. Effect of different values of radius and height of FR4 upper cylinder on the performance of return loss and gain. (a) Return loss characteristic for values of R_{up}. (b) Performance of gain for values of R_{up}.

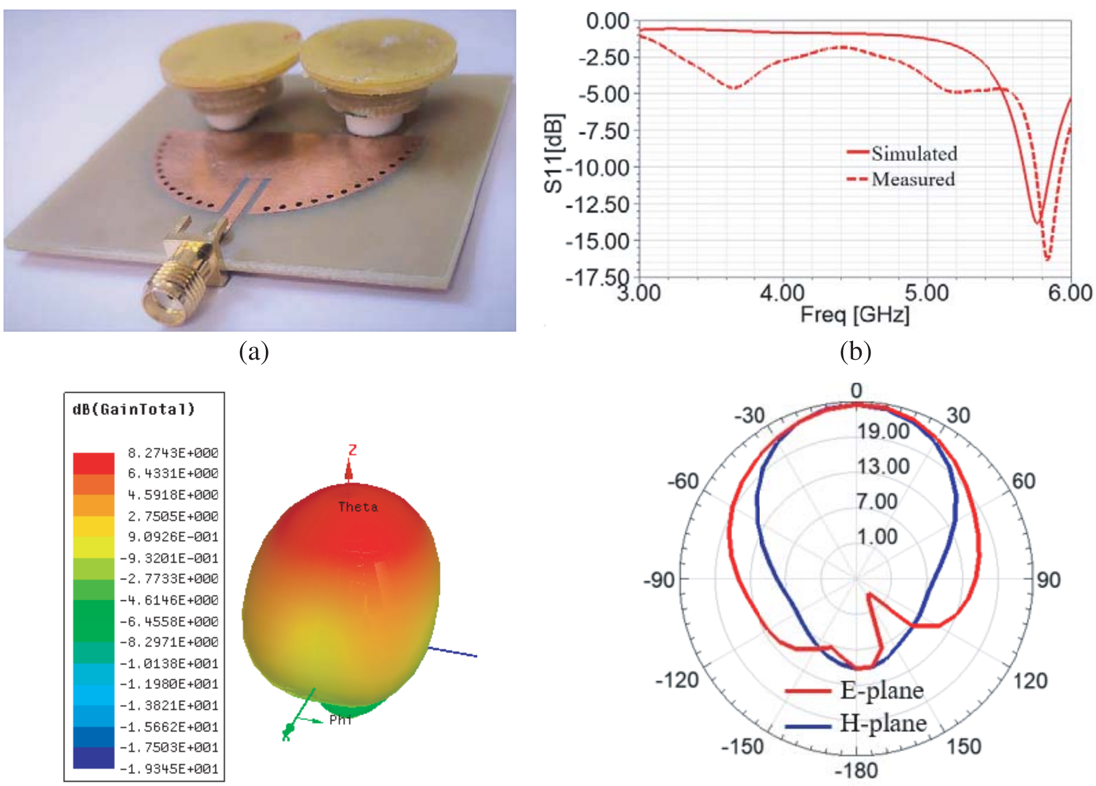
As for the height (H_{up}) of FR4 cylinder, the values are taken as 1.6 mm, 2.4 mm, 3.2 mm, 4.0 mm, 4.8 mm, and 5.6 mm. And its response of return loss and gain are shown in Figure 13(a) and Figure 13(b). With the increase in height, the return loss response and gain both decrease. Thus, the optimum value of height is considered as 2.4 mm which provides better return loss and gain. Finally, the simulated gain of antenna is 8.27 dB (compared to gain 6.23 dB with antenna design 3).

Considering above parametric analysis, the antenna is fabricated with Teflon, FR4 (inner), and FR4 (upper) as dielectric loaders having the radius of FR4 (upper) cylinder 11 mm and height 2.4 mm. The fabricated antenna design 4 prototype is shown in Figure 14(a). The return loss characteristic and gain of fabricated antenna are shown in Figure 14(b) and Figure 14(c), respectively. Figure 14(d) presents simulated and measured radiation patterns of the antenna.



(a) (b)

Figure 13. Effect of different values of radius and height of FR4 upper cylinder on the performance of return loss and gain. (a) Return loss characteristic for values of H_{up}. (b) Performance of gain for values of H_{up}.



(a) (b)

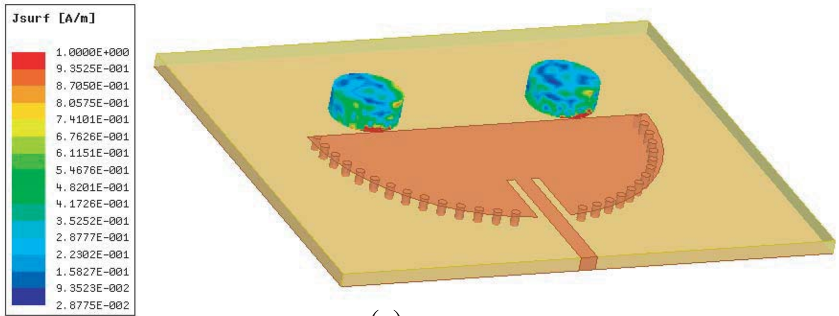
(c) (d)

Figure 14. (a) Antenna with dielectric cylinders (Teflon+FR4+FR4). (b) Return loss characteristic. (c) Simulated gain in 3D. (d) Simulated 2D radiation pattern.

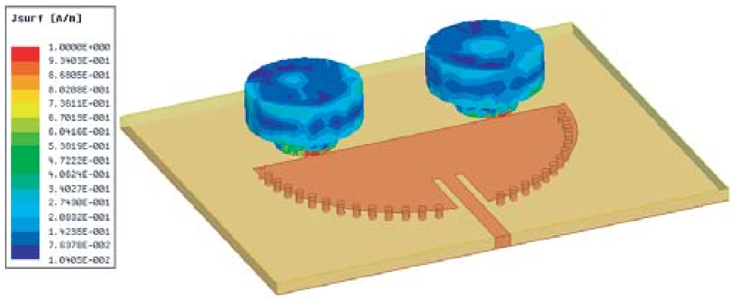
3. RESULTS AND DISCUSSION

The gain enhancement can be achieved by the use of stacked dielectric materials [17, 18], use of uniaxial anisotropic layers of different dielectric materials [17, 18], and use of dielectric layers of different volumes [19, 20]. These methods increase the boresight gain of the antenna [17–20]. The idea is to increase the radiation intensity from the side walls of the dielectrics compared to that of the top wall [17–20].

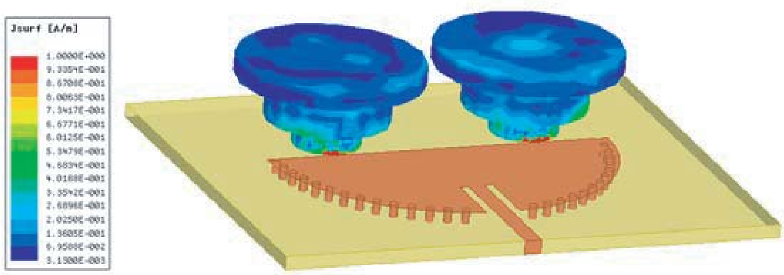
Figures 15(a), (b), (c) show current distribution along the surface of dielectrics. Figure 15(a) shows that the current is more at side wall of Teflon cylinders which are kept at the edge of half circular SIW



(a)

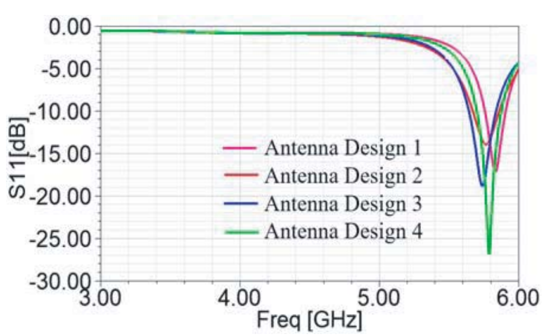


(b)

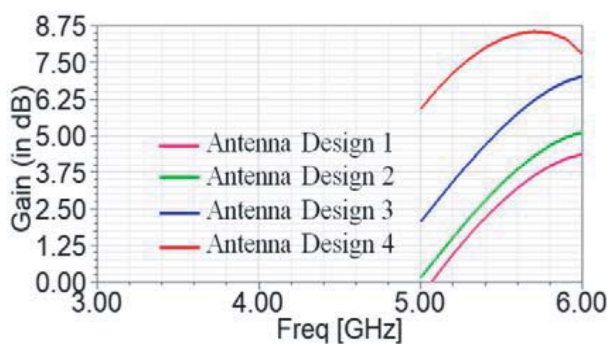


(c)

Figure 15. Current distribution at the surface of dielectric materials. (a) Current distribution at the surface of dielectric material for antenna design 2. (b) Current distribution at the surface of dielectric material for antenna design 2. (c) Current distribution at the surface of dielectric material for antenna design 2.



(a)



(b)

Figure 16. Comparison between antenna designs. (a) Return loss comparison. (b) Simulated gain.

cavity. In Figure 15(b), FR4 cylinders are kept above Teflon cylinders. The current is gathered more around side wall than top wall as shown in Figure 15(b). In Figure 15(c), another layer of FR4 cylinders is kept above Teflon and FR4. The current is gathered more around side wall than top wall as shown in Figure 15(c). The main reason for side wall radiation is the use of uniaxial, three different size anisotropic dielectric layers as discussed in [17–20].

All antennas are simulated in HFSS software. Figure 16(a) and Figure 16(b) present comparison in terms of the return loss characteristics and gains of all antenna designs. It is shown that antenna design 4 achieves the highest gain.

Figures 17(c) and (d) present the comparison between simulated and measured radiation patterns for antenna design 4. Figures 17(a) and (b) show radiation pattern measurement setups in an anechoic chamber for E-plane and H-plane, respectively. Figures 17(c) and (d) show the comparison between simulated and measured radiation patterns for E-plane and H-plane, respectively. Figure 18 presents

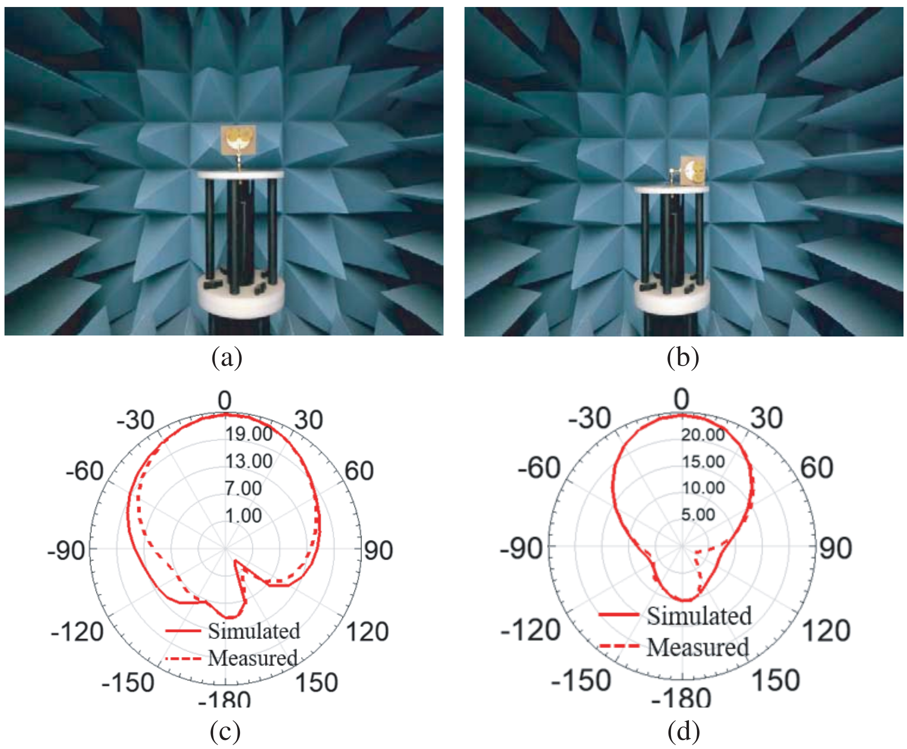


Figure 17. (a) Radiation pattern measurement setup in anechoic chamber for E-plane. (b) Radiation pattern measurement setup in anechoic chamber for H-plane. (c) Simulated and measured radiation pattern for E-plane of antenna design 4. (d) Simulated and measured radiation pattern for H-plane of antenna design 4.

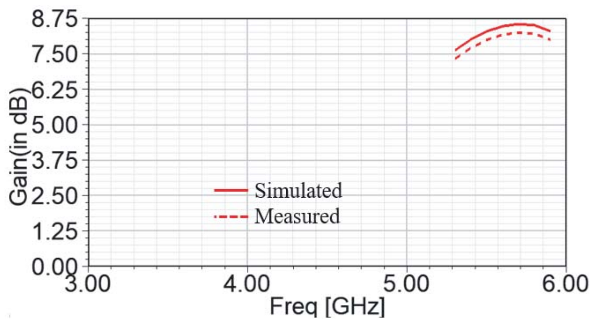


Figure 18. Simulated and measured gain for antenna design 4.

the comparison between simulated and measured gains for antenna design 4. Here, simulated gain is 8.27 dB while measured gain is 8.13 dB.

Table 1 shows the comparison of current research work and previously published work. From the comparison, the gain of the proposed design is higher than others. Therefore, it is a promising candidate for the wireless communication application.

Table 1. Comparative statistics of proposed antenna with previously published work.

Reference No.	Gain (in dB)	Resonant frequency (GHz)
[9]	8.1	12
[12]	6.9	10
[13]	4.5	5.3
[14]	4.3	3.55
[15]	4.3	3.35
[16]	4.4	10
Proposed Design	8.13	5.8

4. CONCLUSION

A gain enhancement technique of a low profile SIW based semi-circular cavity-backed slot antenna is presented in this paper. SIW based semi-circular cavity-backed antenna is initially chosen, and stacks of dielectric resonators are then introduced at the edge of semi-circular cavity. The proposed antenna resonates at 5.8 GHz with the measured gain of 8.13 dB which has application in wireless communications.

REFERENCES

1. Wu, K., Y. J. Cheng, T. Djerafi, et al., "Substrate-integrated millimeter-wave and terahertz antenna technology," *Proc. IEEE*, Vol. 100, No. 7, 2219–2232, 2012.
2. Xu, Z., Q. Zhou, Y. Ban, and S. Ang, "Hepta-band coupled-fed loop antenna for LTE/WWAN unbroken metal-rimmedsmartphone applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 2, 311–314, 2018.
3. Li, Y. S. and R. Mittra, "A three-dimensional circularly polarized antenna with a low profile and a wide 3-dB beamwidth," *Journal of Electromagnetic Waves and Applications*, Vol. 30, No. 1, 89–97, 2016.
4. Li, M. Y., Z. Q. Xu, Y. L. Ban, et al., "Eight-port dual-polarized MIMO antenna for 5G smartphone applications," *IET Microw. Antennas Propag.*, Vol. 11, No. 12, 1810–1816, 2017.
5. Nakano, H., M. Iwatsuki, M. Sakurai, et al., "A cavity-backed rectangular aperture antenna with application to a tilted fan beam array antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 4, 712–718, 2003.
6. Hong, W., N. Behdad, and K. Sarabandi, "Size reduction of cavity-backed slot antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 5, 1461–1466, 2006.
7. Kumar, A. and S. Raghavan, "Broadband SIW cavity-backed triangular-ring-slotted antenna for Ku-band applications," *AEU — Int. J. Electron. Commun. 2018*, Vol. 87, 60–64, 2018.
8. Bozzi, M., A. Georgiadis, and K. Wu, "Review of substrate-integrated waveguide circuits and antennas," *IET Microw. Antennas Propag.*, Vol. 5, No. 8, 909–920, 2011.
9. Luo, G. Q., X. H. Zhang, L. X. Dong, W. J. Li, and L. L. Sun, "A gain enhanced cavity backed slot antenna using high order cavity resonance," *Journal of Electromagnetic Waves and Applications*, Vol. 25, Nos. 8–9, 1273–1279, 2011.

10. Xu, Z., J. Liu, S. Huang, and Y. Li, "Gain-enhanced SIW cavity-backed slot antenna by using TE_{410} mode resonance," *International Journal of Electronics and Communications*, 2018.
11. Kumar, P., J. Kumar, S. Singh, Utkarsh, and S. Dwari, "SIW resonator fed horn mounted compact DRA with enhanced gain for multiband applications," *International Journal of Microwave and Wireless Technologies*, 1–8, 2019.
12. Bayderkhani, R., K. Forooraghi, and B. Abbasi-Arand, "Gain-enhanced SIW cavity-backed slot antenna with arbitrary levels of inclined polarization," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 931–934, 2015.
13. Banerjee, S. and S. K. Parui, "Bandwidth improvement of substrate integrated waveguide cavity-backed slot antenna with dielectric resonators," *Microsyst. Technol.*, Vol. 26, 1359–1368, 2020.
14. Niu, B. and J. Tan, "Bandwidth enhancement of low-profile SIW cavity antenna using fraction modes," *Electronics Letters*, Vol. 55, No. 5, 233–234, 2019.
15. Niu, B. and J.-H. Tan, "Bandwidth enhancement of low-profile SIW cavity antenna with bilateral slots," *Progress In Electromagnetics Research Letters*, Vol. 82, 25–32, 2019.
16. Huang, J.-Q., D. Lei, C. Jiang, Z. Tang, F. Qiu, M. Yao, and Q.-X. Chu, "Novel circularly polarized SIW cavity-backed antenna with wide CP beamwidth by using dual orthogonal slot split rings," *Progress In Electromagnetics Research C*, Vol. 73, 97–104, 2017.
17. Fakhte, S., H. Oraizi, and L. Matekovits, "High gain rectangular dielectric resonator antenna using uniaxial material at fundamental mode," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 1, 342–347, Jan. 2017.
18. Fakhte, S., H. Oraizi, L. Matekovits, and G. Dassano, "Cylindrical anisotropic dielectric resonator antenna with improved gain," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 3, 1404–1409, Mar. 2017.
19. Gupta, S., P. Kshirsagar, and B. Mukherjee, "Sierpinski fractal inspired inverted pyramidal DRA for wide band applications," *Electromagnetics*, 2018.
20. Fakhte, S., H. Oraizi, and L. Matekovits, "Gain improvement of rectangular dielectric resonator antenna by engraving grooves on its side walls," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 2167–2170, 2017.
21. Pozar, D. M., *Microwave Engineering*, 3rd Edition, Wiley, New York, USA, 2005.