Broadband Planar SIW Cavity-Backed Slot Antennas Aided by Unbalanced Shorting Vias

Qi Wu, *Student Member, IEEE*, Jiexi Yin, *Student Member, IEEE*, Chen Yu, *Member, IEEE*, Haiming Wang, *Member, IEEE*, and Wei Hong, *Fellow, IEEE*

***Abstract*—Two types of substrate integrated waveguide (SIW) cavity-backed slot (CBS) antennas are proposed for bandwidth enhancement. First, a quad-resonance SIW CBS antenna is proposed using a cross-shaped slot and loading unbalanced shorting vias. Additional half-TE$_{120}$ mode is successfully excited along with three other independent modes including half-TE$_{110}$ and odd and even TE$_{210}$ modes. Next, a penta-resonance SIW CBS antenna with a cross-shaped slot is proposed, in which two pairs of shorting vias are loaded. Two additional hybrid modes of half-TE$_{210}$ and half-TE$_{120}$ modes are introduced along with three other independent modes including half-TE$_{110}$ and odd and even TE$_{310}$ modes. Furthermore, the working mechanism of these two types of SIW CBS antennas is explained. Finally, prototypes of these two antennas are fabricated and measured at *X*-band. Their measured fractional bandwidths are 20.0% and 20.8%, respectively. Simulation and measurement results agree very well, which confirms the validity of the proposed designs.**

***Index Terms*—Broadband antennas, cavity-backed antennas, slot antennas, substrate integrated waveguide (SIW).**

I. Introduction

Substrate integrated waveguide (SIW)-like cavity-backed slot (CBS) antennas have been widely investigated for various applications including satellite communications and wireless communications recently because of their outstanding advantages of easy integration with planar circuits, low profile, and excellent directional radiation performance [1]–[17]. Various kinds of performance requirements, including broad bandwidth [8], [10], [15], dual-band operation [12], [17], circularly polarized radiation [9], [11]–[13], [18], [19], and miniaturization [9], [11], have been investigated for different applications.

Among the above-mentioned investigations, the SIW CBS antenna of bandwidth enhancement stands as an important research topic because of its application in broadband wireless communication systems [3]–[8], [10], [16]. The conventional SIW CBS antenna suffers from a narrow bandwidth of about 1.7% [14], in which only a single resonance exists. The strategies for forming a broadband SIW CBS antenna can be generally divided into three categories: 1) substrate removal [3]; 2) additional resonant patch [4], [5]; 3) additional resonant cavity modes [6]–[8], [10], [16]. Considering both fabrication ease and bandwidth enhancement performance, the antenna with additional resonant cavity modes excited by slots and shorting vias has become more popular for broadband SIW CBS antennas. Using a similar geometry in [14], the fractional impedance bandwidth of the antenna was improved up to 6.3% by simply utilizing two hybrid cavity modes in [16]. Using a bowtie-shaped slot, the SIW CBS antenna achieved a bandwidth of 9.4% in [7]. In [6], a triangular complementary split-ring slot is utilized to achieve a bandwidth of 16.7%. In [8], shorting vias were introduced in the SIW cavity to realize triple- and quad-resonance SIW CBS antennas, and achieved bandwidths of 15.2% and 17.5%, respectively. In [10], a coupled half-mode/quarter-mode SIW CBS antenna was proposed, and a measured fractional impedance bandwidth of 11.7% was achieved.

Many applications including, but not limited to, motion detection, terrestrial communications and networking, electron paramagnetic resonances, and amateur radio operation are using the frequencies at *X*-band [20]–[22]. The proposed prototypes are able to cover the required bandwidth of the above-mentioned applications. Moreover, the proposed design strategies can be easily generalized to other frequency bands.

In this letter, two types of SIW CBS antennas are proposed for broadband applications. First, using a cross-shaped slot and the load of unbalanced shorting vias, a quad-resonance SIW CBS antenna is proposed. Additional half-TE$_{120}$ mode is successfully excited along with three other independent modes to broaden the operating bandwidth. Second, based on a similar principle, a penta-resonance SIW CBS antenna is designed. Two additional hybrid modes made of half-TE$_{210}$ and half-TE$_{120}$ modes are introduced along with half-TE$_{110}$ and odd and even TE$_{310}$ modes. The antenna structures are designed and analyzed with the aid of the ANSYS High-Frequency Structure Simulator (HFSS) [23] at *X*-band, to allow for better comparison and explanation of the operating principle of the design. These two types of SIW CBS antennas are fabricated using a standard printed circuit board process, and their performances are evaluated. Simulation and measurement results agree very well.

II. Quad-Mode SIW CBS Antenna

In [11], the equivalence between the edge of the HMSIW cavity and the longitude slot curved on the surface of the SIW cavity is proposed to guide the miniaturization design process

Manuscript received October 29, 2018; revised November 30, 2018; accepted December 18, 2018. Date of publication January 7, 2019; date of current version February 1, 2019. This work was supported in part by the National Natural Science Foundation of China under Grant 61501111 and Grant 61671145, and in part by the Key R&D Program of Jiangsu Province of China under Grant BE2018121. *(Corresponding author: Haiming Wang.)*

The authors are with the State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China (e-mail: qiwu@seu.edu.cn; yinjiexi@seu.edu.cn; chenyu@seu.edu.cn; hmwang@seu.edu.cn; weihong@seu.edu.cn).

Digital Object Identifier 10.1109/LAWP.2019.2891108

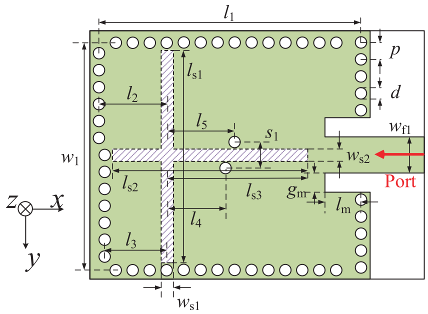


Fig. 1. Geometry of the proposed quad-mode SIW CBS antenna. $l_1 = 23.2, l_2 = 6.0, l_3 = 5.5, l_4 = 5.2, l_5 = 6.0, l_{s1} = 19.05, l_{s2} = 17.5, l_{s3} = 12.5, l_m = 3.2, w_1 = 20.15, w_{s1} = 1.1, w_{s2} = 1.1, w_{f1} = 3.1, s_1 = 2.3, g_m = 1.7, d = 1.0, p = 1.5$. Unit: mm.

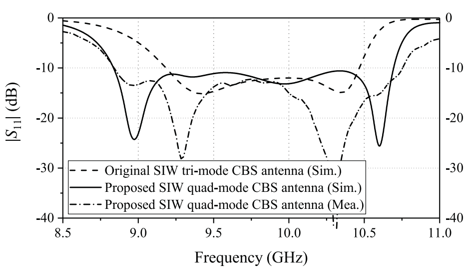


Fig. 2. Comparison of reflection coefficient $|S_{11}|$ for the proposed quad-mode SIW CBS antenna and the original tri-mode SIW CBS antenna in [8].

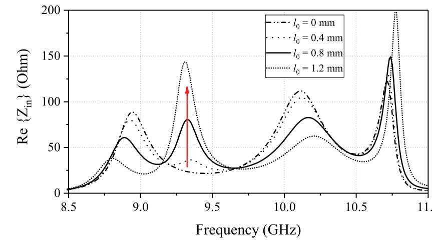


Fig. 3. Simulated input resistance of the quad-mode antenna with varying values of the offset l_0 between the two vias.

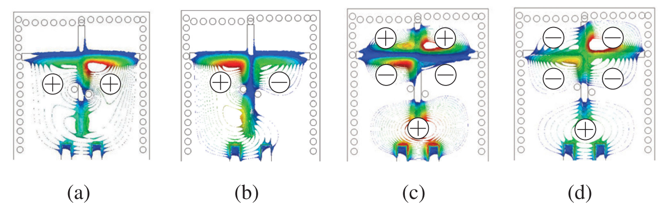


Fig. 4. Electric field distributions from the HFSS for the quad-mode SIW CBS antenna at (a) 8.9, (b) 9.3, (c) 10.2, and (d) 10.7 GHz.

of the antenna. A similar equivalence is utilized in [10] to help with the bandwidth enhancement of the SIW CBS antenna. A quad-mode SIW CBS antenna using unbalanced shorting vias and cross-shaped slot is presented here to realize the bandwidth enhancement. The geometry of the proposed antenna is depicted in Fig. 1. Rows of metallic vias with diameter d are uniformly arranged along the edges of the antenna to form an SIW cavity. A cross-shaped slot is etched on the ground plane of the cavity. Two shorting vias with the same diameter d are located at the two sides of the symmetry plane of the SIW cavity. The proposed quad-mode SIW CBS antenna can be seen as the combination of the two HMSIW CBS antennas with different cavity lengths and different shorting via locations. An additional mode is successfully excited with the help of the unbalanced shorting vias. Microstrip line of 50 Ω is utilized to feed the proposed antenna for measurement purpose. Different from the dual-fed geometry in [2], here, by applying the cross-shaped slot and the unbalanced shorting vias, four separated modes are introduced and, therefore, utilized to support the broadband radiation of the single-fed proposed antenna.

The reflection coefficients of the proposed quad-mode SIW CBS antenna and the original tri-mode SIW CBS antenna are given in Fig. 2. Starting with the original tri-mode antenna, by modulating the first resonance mode downwards, and the second and third mode upwards, the additional half-TE_{120} mode is then inserted between the original half-TE_{110} mode and the TE_{210} mode. The proposed quad-mode CBS antenna achieves a measured fractional bandwidth of 20.0% (8.77–10.72 GHz), with an increase of 5.1% when compared with the conventional tri-mode CBS antenna.

To determine the resonance frequencies of the additional half-TE_{120} mode and the three original modes, the following formula [15] can be employed based on the corresponding equivalent cavity size:

$$f_{mnp} = \frac{1}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{L_e}\right)^2 + \left(\frac{n}{W_e}\right)^2 + \left(\frac{p}{h}\right)^2} \tag{1}$$

where m, n, p are integers, μ_r and ε_r are the permeability and permittivity of the cavity substrate, respectively, and L_e and W_e are the equivalent length and width of the cavity, respectively. The following formula can be utilized to calculate the length of the longitude slot:

$$l_{s3} = \frac{1}{2 f_2 \sqrt{\mu_r \varepsilon_e}} \tag{2}$$

where $\varepsilon_e = (\varepsilon_r + 1)/2$ is the equivalent permittivity of the slot, and f_2 is the resonance frequency of the inserted half-TE_{120} mode. It should be noticed that l_{s3} instead of l_{s2} is utilized here because of the characteristic of the excited half-TE_{120} mode. Using (2), the initial length of l_{s3} is determined as 12.7 mm.

The two loaded unbalanced vias are introduced here to achieve multimode excitation. First, similar with the approach in [8], the two loaded vias are introduced to increase the resonant frequency of the half-TE_{110} mode. Second, by using the unbalanced placement, the half-TE_{120} mode is successfully excited at 9.3 GHz. Defining the offset between the two vias along the x-axis as $l_0 = l_5 - l_4$, the variation of the input resistance along with l_0 is shown in Fig. 3. It can be seen that the offset between the two vias along the x-axis introduces the excitation of the half-TE_{120} mode, while it does not dramatically affect the resonant of the other three modes.

The electric field distributions from the HFSS for the quad-mode SIW CBS antenna are shown in Fig. 4. Half-TE_{110} mode at 8.9 GHz, half-TE_{120} mode at 9.3 GHz, and odd TE_{210} mode at 10.2 GHz and even TE_{210} mode at 10.7 GHz are successfully excited. The resonance frequency of the first mode (half-TE_{110}) is tuned from 9.1 to 8.9 GHz by expanding the width of

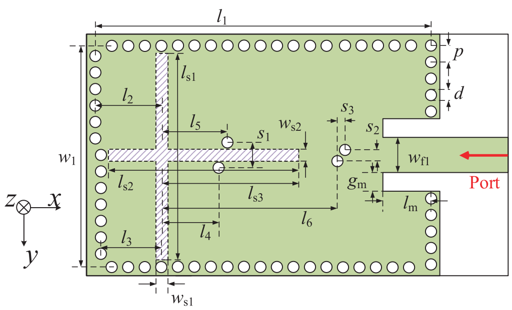


Fig. 5. Geometry of the proposed penta-mode SIW CBS antenna. $l_1 = 33.0$, $l_2 = 5.8$, $l_3 = 5.8$, $l_4 = 5.5$, $l_5 = 6.1$, $l_6 = 16.4$, $l_{s1} = 18.9$, $l_{s2} = 16.0$, $l_{s3} = 10.7$, $l_m = 3.5$, $w_1 = 19.9$, $w_{s1} = 1.5$, $w_{s2} = 1.5$, $w_{f1} = 3.1$, $s_1 = 3.0$, $s_2 = 1.2$, $s_3 = 0.2$, $g_m = 1.6$, $d = 1.0$, $p = 1.5$. Unit: mm.

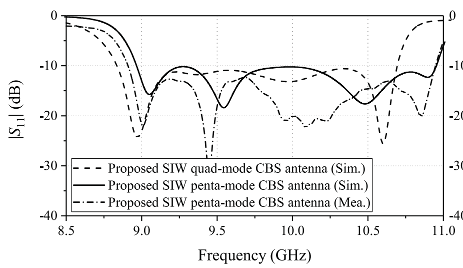


Fig. 6. Comparison of reflection coefficients for the proposed penta-mode and quad-mode SIW CBS antennas.

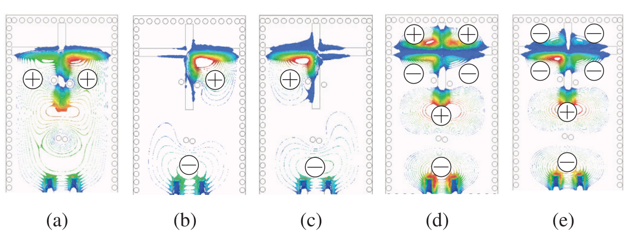


Fig. 7. Electric field distributions from the HFSS for the penta-mode SIW CBS antenna at (a) 8.9, (b) 9.4, (c) 9.8, (d) 10.6, and (e) 10.9 GHz.

the SIW cavity. By utilizing the unbalanced shorting vias and the longitude slot, the half-TE_{120} mode is excited at 9.3 GHz. The resonances of the two higher modes (odd TE_{210} mode and even TE_{210} mode) are also slightly tuned to expand the bandwidth while maintaining the resonance performance, by using the lengths from the cavity boundary to the transverse slot l_2 and l_3. In addition, the whole operating band can be modulated based on the width of the SIW cavity w_1.

III. Penta-Mode SIW CBS Antenna

To further enhance the operating bandwidth, a penta-mode antenna is developed in this section based on a similar strategy. The geometry of the proposed antenna is depicted in Fig. 5. Five cavity modes are excited by using two pairs of unbalanced shorting vias along with the cross-shaped slot.

The comparison of the reflection coefficients of the proposed penta-mode SIW CBS antenna and the quad-mode SIW CBS antenna is shown in Fig. 6. The five cavity modes are excited to enhance the -10 dB bandwidth of the proposed antenna to 20.8% (8.89–10.95 GHz), with an increase of 3.3% when compared with the conventional quad-mode antenna in [8]. The

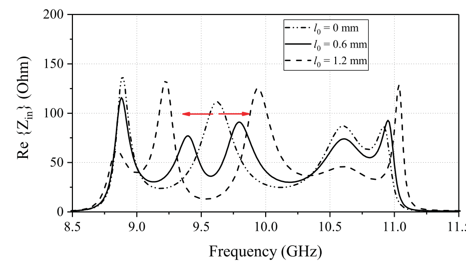


Fig. 8. Simulated input resistance of the penta-mode antenna with varying value of the offset l_0 between the two vias.

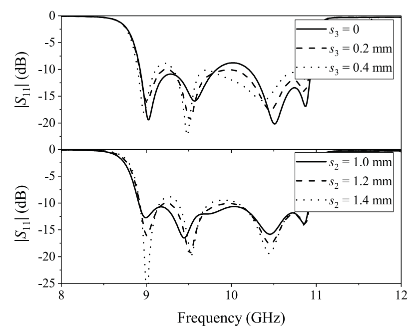
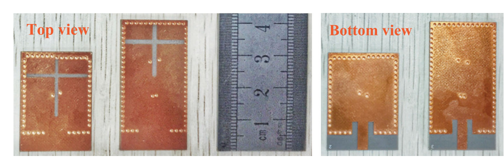


Fig. 9. Simulated reflection coefficient of the penta-mode antenna with varying values of s_2 and s_3.



(a) (b)

Fig. 10. Photographs of the two types of the proposed broadband SIW CBS antennas. (a) Top view. (b) Bottom view.

electric field distributions from the HFSS for the penta-mode SIW CBS antenna are shown in Fig. 7. With the half-TE_{110} mode excited at 8.9 GHz, and the odd TE_{310} mode at 10.6 GHz and even TE_{310} mode at 10.9 GHz, two hybrid modes are excited at 9.4 and 9.8 GHz because of the proposed longitude slot and the unbalanced vias. The two hybrid modes can be seen as the combination of the half-TE_{210} mode and the half-TE_{120} mode, which are separated by offsetting the placement of the two vias aside the longitude slot. As depicted in Fig. 8, by offsetting the mentioned two vias along x-axis with parameter $l_0 = l_5 - l_4$, the original half-TE_{210} mode will be replaced by two separated hybrid resonant modes. Then, $l_0 = 0.6$ mm is utilized to balance the tradeoff between the reflection performance and the bandwidth. The placement of the second pair of the vias is also modulated to achieve the best impedance performance, as depicted in Fig. 9.

IV. Results and Discussion

As shown in Fig. 10, these two types of proposed SIW CBS antennas are fabricated using the single-layer Taconic TLY substrate with thickness of $h = 1$ mm, dielectric constant of $\varepsilon_r = 2.2$, and loss tangent of 0.0009. Their measured impedance

TABLE I
COMPARISONS OF THE PROPOSED ANTENNAS WITH PREVIOUSLY REPORTED SIW CBS ANTENNAS

Reference	Antenna	Freq. (GHz)	Dimension (λ_0^3)	Impedance BW	Peak Gain (dBi)	Radiation Efficiency
This work	Quad-mode SIW CBS antenna	10	$0.63 \times 0.77 \times 0.03$	20.0%	4.9	$> 86\%$
	Penta-mode SIW CBS antenna	10	$0.63 \times 1.07 \times 0.03$	20.8%	5.7	$> 84\%$
[14]	Single-mode SIW CBS antenna	10	$0.59 \times 0.59 \times 0.02$	1.7%	5.4	$> 75\%^*$
[16]	Dual-mode SIW CBS antenna	10	$0.59 \times 0.41 \times 0.02$	6.3%	6.0	$> 81\%$
[6]	SIW CBS antenna using TCSRS	28	$0.58 \times 0.86 \times 0.05$	16.7%	10.0	$> 91\%^*$
[8]	Tri-mode SIW CBS antenna	10	$0.63 \times 0.77 \times 0.03$	15.2%	4.8	$> 83\%^*$
	Quad-mode SIW CBS antenna	10	$0.63 \times 1.07 \times 0.03$	17.5%	7.3	$> 84\%^*$

$*$: Simulated radiation efficiency.

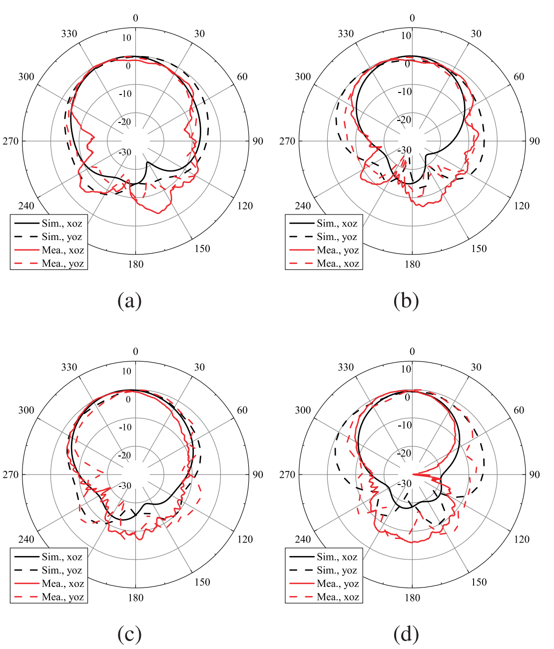


Fig. 11. Simulated and measured radiation patterns of the SIW quad-mode CBS antenna at (a) 9.3 and (b) 10.2 GHz, and the SIW penta-mode CBS antenna at (c) 9.6 and (d) 10.4 GHz.

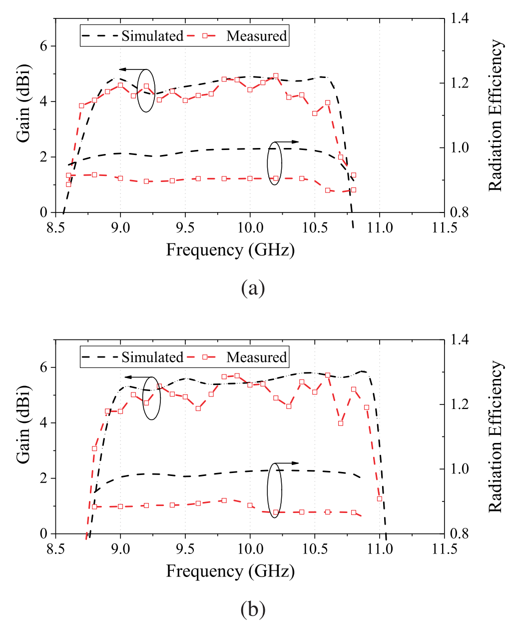


Fig. 12. Gains and efficiency of the SIW CBS antennas in the broadside. (a) Quad-mode antenna. (b) Penta-mode antenna.

bandwidth is 20.0% and 20.8%, respectively, as shown in Figs. 2 and 6.

The measured radiation performance of these two types of antennas is shown in Fig. 11. The radiation patterns of the two types of antennas show excellent similarity with the simulation results. The gain performance at the broadside is shown in Fig. 12(a) and (b), with peak gain of 4.93 and 5.72 dBi, 3 dB gain bandwidths of 20.6% (8.7–10.7 GHz) and 21.3% (8.8–10.9 GHz), and radiation efficiency larger than 86.3% and 84.7% within the operating bandwidth, respectively.

Comparisons between the proposed SIW CBS antennas and previously reported ones are given in Table I. These two types of proposed SIW CBS antennas achieve 5.1% and 3.3% bandwidth enhancement by using the additional half-TE_{120} mode when compared with those in [8], respectively, under the condition of same SIW cavity size. To summarize, the proposed SIW CBS antennas exhibit simple geometry, low profile of $0.03\lambda_0$, high radiation efficiency, broad impedance bandwidth, broad gain bandwidth, and stable radiation within the operating bandwidth. It is worth noticing that the proposed design is evaluated at *X*-band to allow for better comparison and explanation of its operating principle. Following the same design principle, the SIW CBS antennas operating at millimeter-wave band are expected to have similar performance, which will be addressed in future work.

V. CONCLUSION

For broadband applications, two types of planar slot antennas based on SIW cavities have been proposed. First, a quad-resonance SIW CBS antenna has been proposed by combining two coupled unbalanced via-loaded HMSIW CBS antennas to achieve the bandwidth of 20.0%. Second, a penta-resonance SIW CBS antenna has been designed with the bandwidth of 20.8%. Additional modes excited by the cross-shaped slots and the loading vias have been investigated, manipulated, and utilized to support the broad operating bandwidth of the proposed antennas. Prototypes of these SIW CBS antennas have been fabricated and measured for *X*-band applications. Simulation and measurement results show that the proposed SIW CBS antennas provide excellent features, including broad bandwidth, low profile, and fabrication ease.

References

[1] A. Kumar and S. Raghavan, "A design of miniaturized half-mode SIW cavity backed antenna," in *Proc. IEEE Indian Antenna Week*, 2016, pp. 4–7.

[2] S. Mukherjee and A. Biswas, "Substrate integrated waveguide (SIW) cavity backed slot antenna for polarization diversity application," in *Proc. IEEE Appl. Electromagn. Conf.*, 2015, pp. 1–2.

[3] S. Yun, D.-Y. Kim, and S. Nam, "Bandwidth and efficiency enhancement of cavity-backed slot antenna using a substrate removal," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1458–1461, 2012.

[4] T. Y. Yang, W. Hong, and Y. Zhang, "Wideband millimeter-wave substrate integrated waveguide cavity-backed rectangular patch antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 205–208, 2014.

[5] K.-S. Chin, W. Jiang, W. Che, C.-C. Chang, and H. Jin, "Wideband LTCC 60-GHz antenna array with a dual-resonant slot and patch structure," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 174–182, Jan. 2014.

[6] P. N. Choubey, W. Hong, Z.-C. Hao, P. Chen, T.-V. Duong, and J. Mei, "A wideband dual-mode SIW cavity-backed triangular-complementary-split-ring-slot (TCSRS) antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2541–2545, Jun. 2016.

[7] S. Mukherjee, A. Biswas, and K. V. Srivastava, "Broadband substrate integrated waveguide cavity-backed bow-tie slot antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1152–1155, 2014.

[8] Y. Shi, J. Liu, and Y. Long, "Wideband triple- and quad-resonance substrate integrated waveguide cavity-backed slot antennas with shorting vias," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 5768–5775, Nov. 2017.

[9] C. Jin, R. Li, A. Alphones, and X. Bao, "Quarter-mode substrate integrated waveguide and its application to antennas design," *IEEE Trans. Antennas Propag.*, vol. 61, no. 6, pp. 2921–2928, Jun. 2013.

[10] T. Deckmyn *et al.*, "A novel 60 GHz wideband coupled half-mode/quarter-mode substrate integrated waveguide antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6915–6926, Dec. 2017.

[11] Q. Wu, H. Wang, C. Yu, and W. Hong, "Low-profile circularly polarized cavity-backed antennas using SIW techniques," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2832–2839, Jul. 2016.

[12] Q. Wu, J. Yin, C. Yu, H. Wang, and W. Hong, "Low-profile millimeter-wave SIW cavity-backed dual-band circularly polarized antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 7310–7315, Dec. 2017.

[13] G. Q. Luo and L. L. Sun, "Circularly polarized antenna based on dual-mode circular SIW cavity," in *Proc. Int. Conf. Microw. Millimeter Wave Technol.*, 2008, vol. 3, pp. 1077–1079.

[14] G. Q. Luo, Z. F. Hu, L. X. Dong, and L. L. Sun, "Planar slot antenna backed by substrate integrated waveguide cavity," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 236–239, 2008.

[15] G. Q. Luo, Z. F. Hu, Y. Liang, L. Y. Yu, and L. L. Sun, "Development of low profile cavity backed crossed slot antennas for planar integration," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 2972–2979, Oct. 2009.

[16] G. Q. Luo, Z. F. Hu, W. J. Li, X. H. Zhang, L. L. Sun, and J. F. Zheng, "Bandwidth-enhanced low-profile cavity-backed slot antenna by using hybrid SIW cavity modes," *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1698–1704, Apr. 2012.

[17] T. Zhang, W. Hong, Y. Zhang, and K. Wu, "Design and analysis of SIW cavity backed dual-band antennas with a dual-mode triangular-ring slot," *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5007–5016, Oct. 2014.

[18] Q. Wu, J. Hirokawa, J. Yin, C. Yu, H. Wang, and W. Hong, "Millimeter-wave planar broadband circularly polarized antenna array using stacked curl elements," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 7052–7062, Dec. 2017.

[19] Q. Wu, J. Hirokawa, J. Yin, C. Yu, H. Wang, and W. Hong, "Millimeter-wave multi-beam end-fire dual circularly polarized antenna array for 5G wireless applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4930–4935, Sep. 2018.

[20] D. M. Pozar, *Microwave Engineering*. Hoboken, NJ, USA: Wiley, 2009.

[21] K. K. Sadasivuni, J.-J. Cabibihan, D. Ponnamma, M. A. S. Al-Maadeed, and J. Kim, *Biopolymer Composites in Electronics*. New York, NY, USA: Elsevier, 2016.

[22] Federal Communications Commission, "Part 97—Amateur radio service," Government Printing Office, Oct. 1988.

[23] *Ansoft HFSS. ver. 12*, Ansoft Corp., Pittsburgh, PA, USA, 2010.