A Differential-Fed Dual-Polarized High-Gain Filtering Antenna Based on SIW Technology for 5G Applications

Yasir I. A. Al-Yasir[1,*], Naser Ojaroudi Parchin[1], Mohammad N. Fares[2], Ahmed Abdulkhaleq[1], Mustafa S. Bakr[3], Mohammed Al-Sadoon[1], Jamal Kosha[1], Raed Abd-Alhameed[1]
[1] Faculty of Engineering and Informatics, University of Bradford, Bradford, UK, Y.I.A.Al-Yasir@bradford.ac.uk*
[2] Department of Chemical Engineering, College of Engineering, University of Basra, Basra, Iraq
[3] Institute of Pollard, University of Leeds, Leeds, UK

***Abstract*—A new differential-fed wideband dual-polarized microstrip filtering antenna exhibiting high gain, and high common-mode rejection is presented in this paper. The presented antenna is composed of a square patch radiator mounted on a substrate integrated waveguide (SIW) cavity. The structure is excited by two differential pairs of feeding probes providing differentially exciting signals. The filtering response is achieved by introducing symmetrical defected ground structures (DGS) in the ground layer surrounding the four excitation ports for dual-polarized antenna. The DGS is optimized to introduce nulls at the high and low edges of the passband transmission maintaining high gain and wide bandwidth. Because of the symmetric geometry of the proposed antenna, the design is studied and analyzed in one polarization mode, while the performance for the second mode will be identical. The filtering antenna is simulated and optimized using finite element solver software (CST & HFSS). Good performance is obtained with wide bandwidth of 11%, realized gain of 8 dBi at the resonant frequency (3.5 GHz) and low cross-polarization level due to the differentially driven ports, and complete symmetry using SIW technology. Also, the antenna has a single layer substrate with a height of 0.035 of the free space wavelength and operating at the sub-6 GHz 5G spectrum.**

***Index Terms*—microstrip antennas, radiation nulls, filtering, dual-polarizatio, differentially-fed antenna, SIW.**

I. Introduction

The introduction of the fifth-generation (5G) of wireless communications requires new solutions for miniature and multi-functionality RF components such as antennas and filters [1-4]. The integration of the filtering performance in the antenna radiation pattern while maintaining high gain, high isolation, high front-to-back ratio (FTBR), stable radiation pattern, good common-mode (CM) rejection level and unidirectional radiation pattern is considered as a potential solution for 5G applications [5-10]. Recently, dual-polarized, SIW, and differential-fed techniques have been introduced to improve the performance of the microwave and RF systems [11-13]. Different differential-fed antennas have been reported, such as planar antennas [14-17], magneto-electric dipole antennas [18, 19], 3D-backed antennas [20], and so on. In [14] a differential planar antenna presented that is fed by 0^0 and 180^0 signals. The antenna exhibits a low cross-polarization, wide bandwidths, and high gain. The presented design operates at a resonant frequency of 13.2 GHz with a fractional bandwidth of 5%. Unlike conventional differentially fed microstrip antennas, the design proposed in [15] and [16] employ a folded plate pair as the differential feeding approach. The proposed antennas have stable realized gains of 8 dB within the operating bandwidth, featuring the high stability of the radiation patterns with the symmetrical performance for the two resonating modes. A differential-fed planar antenna with a realized gain of 8.2 dBi and a 130 MHz bandwidth is presented in [17]. The designed antenna can serve different applications such as energy harvesting, Radio-frequency identification (RFID) tags and differential/balanced circuits.

The above-mentioned differential-fed microstrip antennas show a single polarization radiation pattern. Dual-polarized antennas provide polarization diversities to decrease the side effect of multipath fading and improve channel capacity are presented in [21]. They find prospective application in many wireless communications, especially in base stations of cellular mobile phones. Nevertheless, there are few researchers proposed differential-fed dual-polarized microstrip antennas [22, 23]. In [22], a dual-polarized cavity-backed planar antenna with differentially-driven coaxial feeds is introduced. In this antenna, both polarizations can be tuned from 0.65 GHz to 1.2 GHz using (1.2–5.4 pF) varactor diodes. Besides, the fractional bandwidth differs from 1% to 2% over that range.

On top of that, SIW technology finds an emerging and very promising application in recent years, especially for 5G wireless communication systems [12]. SIW technologies have attracted high attention and have been extensively applied in recent wireless applications due to their lightweight, low profile, high quality factor, and easy integration to microstrip antennas [24]. The cavity-backed microstrip antennas use the SIW configuration and provide improved performance, including high gain and unidirectional far-field pattern using a single-layer transmission line [25].

In this paper, we propose a differentially driven, dual-polarized, and high gain filtering antenna using SIW technology. The differential-fed microstrip antenna with square SIW generates two resonant modes, that is, the patch mode (TM_{10}) and the cavity mode (TM_{21}), and therefore, a wide fractional bandwidth is achieved [26-28]. Half wavelength open-ring slots are introduced in the ground layer to provide the filtering characteristics. The filtering antenna is designed on a Rogers RT5870 substrate with a relative dielectric constant of 2.33, loss tangent = 0.0012 and thickness h = 3.2 mm, and is simulated and optimized using CST and HFSS simulators. Because of the differentially-driven and strict symmetrical geometry, very good performance including high stability of the radiation pattern characteristics, high isolation, good CM rejection, low-cross polarization level with filtering characteristics are obtained. All of these merits make this presented microstrip antenna suitable for the sub-6GHz 5G communications.

II. CONFIGURATION AND ANALYSIS OF THE DESIGNED FILTER/ANTENNA

Fig. 1 shows the geometry of the proposed dual-polarized differentially driven SIW filtering antenna. The antenna is designed on a Rogers RT5870 substrate with a relative dielectric constant of 2.33, loss tangent = 0.0012, and thickness h = 3.2 mm. The proposed filtering antenna consists of a square microstrip-radiating element, one square SIW resonator, DGS resonators, and two pairs of differential feeding probes. The square SIW resonator is formed by using a series of copper pins representing the four sidewalls of the structure. The initial dimensions of the square SIW resonator can be predicted using the following closed-form equation [28]

$$f_{mn} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m}{w_{eff}}\right)^2 + \left(\frac{n}{w_{eff}}\right)^2} \quad (1)$$

Where μ_r and ε_r represent the permeability and permittivity of the substrate, respectively, and w_{eff} is the width of the square cavity and can be determined using (2)

$$w_{eff} = w - \frac{d^2}{0.95S} \quad (2)$$

Where w is the real width/length of the square SIW cavity resonator. The diameter (d) of the copper pins and the distance (S) between adjacent pins are selected in such a manner that there are minimal energy leakages during the sidewalls [29]. The defected ground structure (DGS) can be achieved by loading slots with different shapes on the ground surface and can be exploited to vary surface current densities for exciting specific frequency modes, minimizing antenna size, or improving design performance. In this paper, DGS is loaded on the antennas to provide a broadside radiation-pattern nulls at lower and higher edges of the in-band antenna performance to improve the stopband rejection. The defected ground structure consists of eight open-loop ring slots, which are loaded on the ground layer of the square SIW cavity resonator. The total length of each slot is about half the wavelength of the resonant frequency. The differentially fed port 1 is composed of port 1^+ and port 1^-, whereas the differential-fed port 2 is composed of port 2^+ and port 2^-.

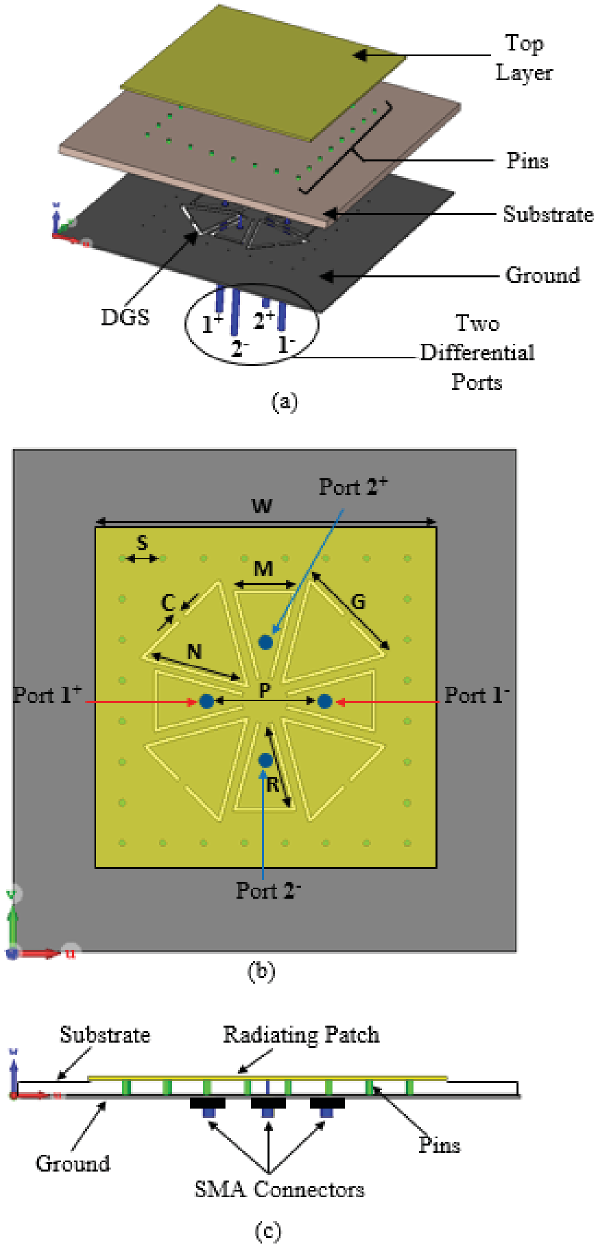

Fig. 1. The geometry of the proposed differential-fed SIW antenna. (a) 3D view (b) Top view. (c) Side view.

In this paper, CST and HFSS software are used for analyses and simulations to obtain optimal design configurations. Table I summarizes the final optimized dimensions of the proposed high-gain differential-fed dual-polarized filtering antenna. The simulated current distributions of the proposed antenna at two resonant modes 3.35 GHz and 3.55 GHz are illustrated in Fig. 2. At the lower mode resonance (f_{D1} = 3.37 GHz), and due to exciting the TM_{10} mode, the current density is concentrated on the radiating microstrip layer, whereas at the higher mode resonance (f_{D2} = 3.57 GHz), and due to exciting the TM_{21} mode, the current density is concentrated on the SIW cavity.

TABLE I. DIMENSIONS OF THE PROPOSED DIFFERENTIAL-FED SIW FILTERING ANTENNA (IN MM)

Parameters	W	S	C	M	G	N	P	R
Values	73	7.8	2	13	18	19	23	18

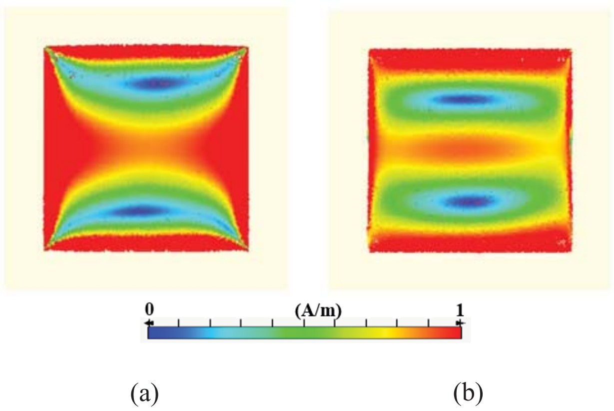

Fig. 2. The current distribution of the proposed antenna. (a) f_{D1}. (b) f_{D2}

III. RESULTS AND DISCUSSION

In this section, filtering antenna characteristics in terms of reflection coefficient, peak realized gain, efficiency, and radiation pattern are presented and discussed using CST and HFSS simulators. The following equations can be used to determine the differential- and common- modes s-parameters of the proposed design [30]

$$S_{11dd} = 0.5\ (S_{1+1+} - S_{1+1-} - S_{1-1+} + S_{1-1-}) \quad (3)$$

$$S_{22dd} = 0.5\ (S_{2+2+} - S_{2+2-} - S_{1-1+} + S_{2-2-}) \quad (4)$$

$$S_{21dd} = 0.5\ (S_{2+1+} - S_{2+1-} - S_{2-1+} + S_{2-1-}) \quad (5)$$

$$S_{11cc} = 0.5\ (S_{1+1+} - S_{1+1-} - S_{1-1+} + S_{1-1-}) \quad (6)$$

As long as the proposed patch antenna has a strict symmetry configuration, therefore the characteristics in only one polarization scenario (port 1^+ and port 1^-) are studied to show the filtering performance of the antenna, while the performance will be identical on the second state. The proposed differential-fed SIW microstrip antenna is designed, optimized and simulated using CST and HFSS microwave simulators. Figs. 3 and 4 show the differential reflection coefficients of the presented SIW patch filter/antenna. The obtained performance illustrates that the filter/antenna resonances at 3.5 GHz with dual resonant modes, namely, the radiator patch mode (f_{D1}) and the SIW cavity mode (f_{D2}). The two resonant modes are employed to obtain a wide bandwidth (about 12%) at the resonant frequency with a return loss of more than 16.5 dB (see Fig. 3). Besides, and under exciting the two differential ports, the isolation between the two ports is plotted in Fig. 4. Good polarization isolation, greater than 30 dB, is obtained between the two differential ports.

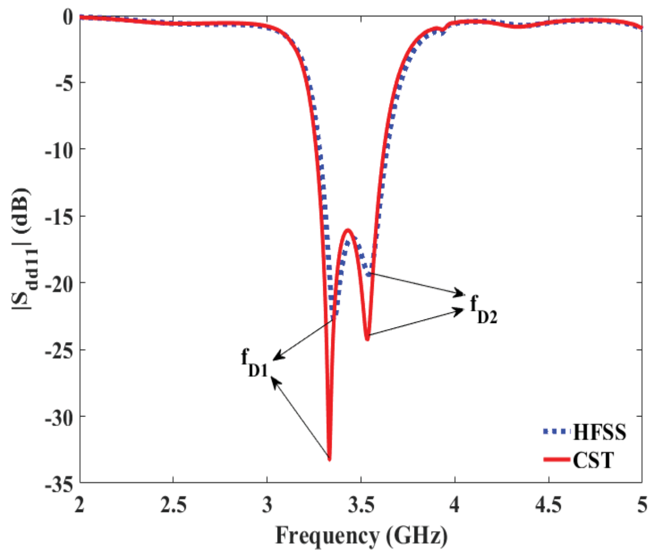

Fig. 3. Simulated (HFSS and CST) $|S_{dd11}|$ results of the proposed differential-fed SIW microstrip antenna.

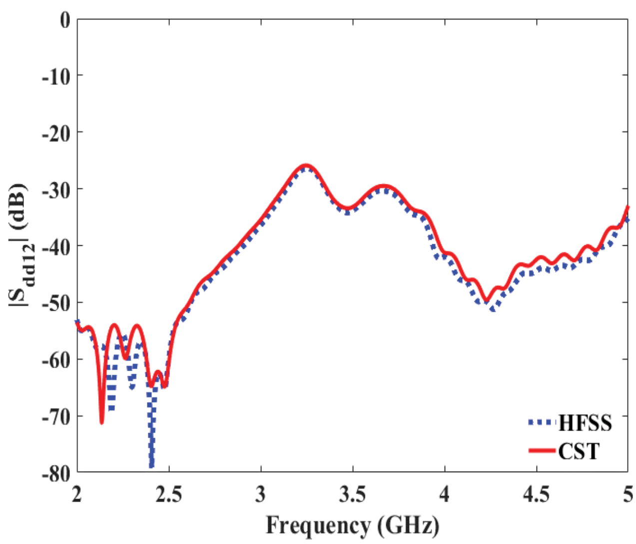

Fig. 4. Simulated (HFSS and CST) $|S_{dd12}|$ results of the proposed differential-fed SIW microstrip antenna.

Fig. 5 shows the peak realized gain versus frequency of the proposed antenna. High gain goes up to 8.5 dBi is observed during the operating band with a relatively flat performance. Moreover, the achieved |Sdd11| result is less than 1 dB to obtain a high stopband rejection of over 10 dB, with high isolation is also observed through the entire spectrum. The total simulated efficiency for the presented dual-polarized antenna is illustrated in Fig. 6, it can be shown that the total efficiency is greater than 95% through the operating bandwidth, whereas it is less than 20% through the stopband spectrum.

Next, the far-field normalized radiation patterns are simulated and presented under the excitation of the differential-fed port 1 (port 1^+ and port 1^-). The radiation patterns are simulated in the xz- and yz- planes at the resonant frequency (see Fig. 7). In the xz-plane, the achieved cross-polarization (x-pol) level is calculated to be 28 dB lower than the corresponding value of the achieved copolarization (Co-pol) level. On the other hand, in the yz-plane, the achieved cross-polarization (x-pol) level is calculated to be 30 dB lower than the corresponding value of the achieved copolarization (Co-pol) level.

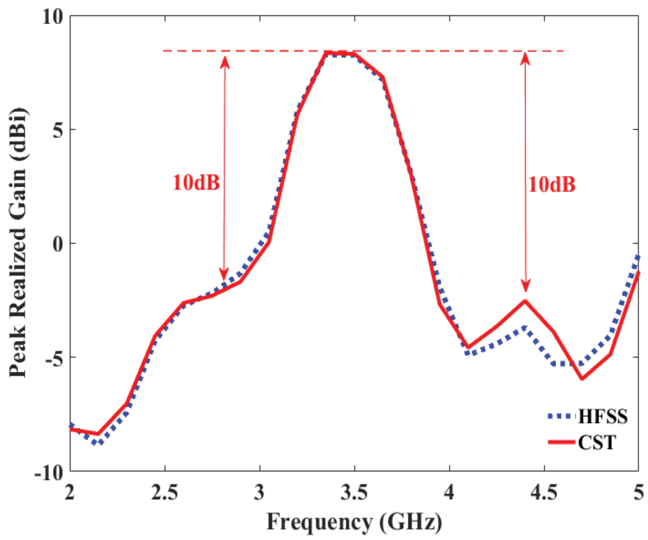

Fig. 5. Simulated (HFSS and CST) realized gain of the proposed differential -fed SIW microstrip antenna.

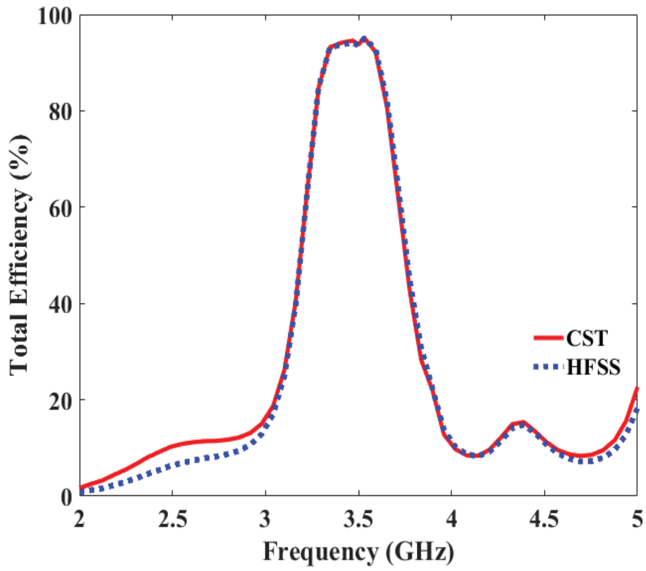

Fig. 6. The total efficiency of the proposed differential -fed SIW microstrip antenna.

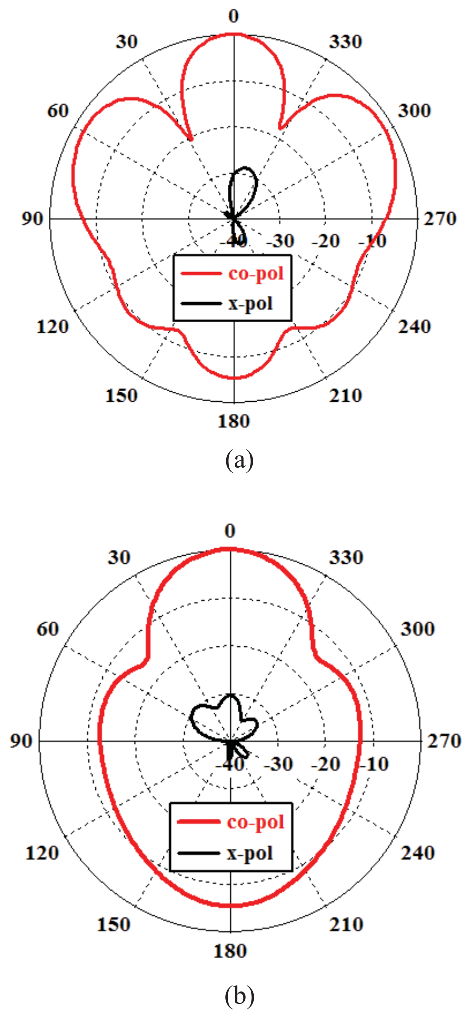

Fig. 7. Far-field radiation patterns at the resonant frequency for differential port 1 excitation of the proposed antenna. (a) xz-plane. (b) yz-plane.

IV. Conclusion

In this paper, a new differential-fed wideband dual-polarized microstrip filtering antenna with high gain, and high common-mode rejection is presented for 5G communication systems. To achieve good performance, the microstrip antenna is integrated with the SIW cavity. Filtering performance is achieved by etching a symmetrical DGS to the ground plane using open-loop ring resonators. The designed antenna is simulated and optimized using CST and HFSS simulators. Good performance is achieved with a wide bandwidth of about 11% at the resonant frequency 3.5 GHz and a realized gain more than 8 dBi around the passband. Furthermore, the performance has exhibited a few attractive features of our presented filter/antenna, that is, high gain, high efficiency, as well as much lower cross-polarization level due to the differentially-driven ports, and complete symmetry based on SIW technology. The antenna is dual polarized with a height of 0.035 λ_g and operating at the sub-6 GHz 5G spectrum.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement H2020-MSCA-ITN-2016 SECRET-722424.

REFERENCES

[1] Y. Liu, S. Wang, N. Li, J. Wang and J. Zhao, "A compact dual-band dual-polarized antenna with filtering structures for sub-6 GHz base station applications," IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 10, pp. 1764-1768, Oct. 2018.

[2] X. Gu, S. Nikhil N, L. Guo, S. Hemour and K. Wu, "Diplexer-based fully passive harmonic transponder for sub-6-GHZ 5G-compatible iot applications," IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 5, pp. 1675-1687, May 2019.

[3] Y. Al-Yasir, N. Ojaroudi Parchin, R. Abd-Alhameed, A. Abdulkhaleq and J. Noras, "Recent Progress in the Design of 4G/5G Reconfigurable Filters" Electronics", vol. 8, no. 1, Jan. 2019.

[4] Y. Al-Yasir, A. S. Abdullah, N. Ojaroudi Parchin, R. A. Abd-Alhameed, and J. M. Noras, "A New Polarization-Reconfigurable Antenna for 5G Applications," Electronics, vol. 7, no. 11, p. 293, 2018.

[5] C. Wang, J. Bian, J. Sun, W. Zhang and M. Zhang, "A survey of 5G channel measurements and models," IEEE Communications Surveys & Tutorials, vol. 20, no. 4, pp. 3142-3168, Fourth quarter 2018.

[6] S. J. Yang, Y. M. Pan, Y. Zhang, Y. Gao and X. Y. Zhang, "Low-profile dual-polarized filtering magneto-electric dipole antenna for 5G applications," IEEE Transactions on Antennas and Propagation, vol. 67, no. 10, pp. 6235-6243, Oct. 2019.

[7] T. Alam, S. R. Thummaluru and R. K. Chaudhary, "Integration of MIMO and cognitive radio for sub-6 GHz 5G applications," IEEE Antennas and Wireless Propagation Letters, vol. 18, no. 10, pp. 2021-2025, Oct. 2019.

[8] M. E. Yassin, H. A. Mohamed, E. A. F. Abdallah and H. S. El-Hennawy, "Single-fed 4G/5G multiband 2.4/5.5/28 GHz antenna," IET Microwaves, Antennas & Propagation, vol. 13, no. 3, pp. 286-290, 27 Feb. 2019.

[9] Y. I. A. Al-Yasir et al., "Design of multi-standard single/tri/quint-wideband asymmetric stepped-impedance resonator filters with adjustable TZs," IET Microwaves, Antennas & Propagation, vol. 13, no. 10, pp. 1637-1645, 14 Aug. 2019.

[10] Al-Yasir, R. A. Abd-Alhameed, J. M. Noras, A. M. Abdulkhaleq and N. O. Parchin, "Design of very compact combline band-pass filter for 5G applications," The Loughborough Antennas & Propagation Conference (LAPC 2018), Loughborough, 2018, pp. 1-4.

[11] Z. Nie, H. Zhai, L. Liu, J. Li, D. Hu and J. Shi, "A dual-polarized frequency-reconfigurable low-profile antenna with harmonic suppression for 5G application," IEEE Antennas and Wireless Propagation Letters, vol. 18, no. 6, pp. 1228-1232, June 2019.

[12] T. Hong, Z. Zhao, W. Jiang, S. Xia, Y. Liu and S. Gong, "Dual-band SIW cavity-backed slot array using TM_{020} and TM_{120} modes for 5G applications," IEEE Transactions on Antennas and Propagation, vol. 67, no. 5, pp. 3490-3495, May 2019.

[13] Y. I. A. Al-Yasir et al, "Design, simulation and implementation of very compact dual-band microstrip bandpass filter for 4G and 5G applications," 2019 16th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD), Lausanne, Switzerland, 2019, pp. 41-44.

[14] H. Jin, K. Chin, W. Che, C. Chang, H. Li and Q. Xue, "Differential-fed patch antenna arrays with low cross-polarization and wide bandwidths," IEEE Antennas and Wireless Propagation Letters, vol. 13, pp. 1069-1072, 2014.

[15] C. K. Chin, Q. Xue and H. Wong, "Broadband patch antenna with a folded plate pair as a differential feeding scheme," IEEE Transactions on Antennas and Propagation, vol. 55, no. 9, pp. 2461-2467, Sept. 2007.

[16] C. h. k. Chin, Q. Xue, H. Wong and X. y. Zhang, "Broadband patch antenna with low cross-polarisation," Electronics Letters, vol. 43, no. 3, pp. 137-138, 1 Feb. 2007.

[17] M. Arrawatia, M. S. Baghini and G. Kumar, "Differential microstrip antenna for rf energy harvesting," IEEE Transactions on Antennas and Propagation, vol. 63, no. 4, pp. 1581-1588, April 2015.

[18] Q. Xue, S. W. Liao and J. H. Xu, "A Differentially-driven dual-polarized magneto-electric dipole antenna," IEEE Transactions on Antennas and Propagation, vol. 61, no. 1, pp. 425-430, Jan. 2013.

[19] Y. Luo and Q.-X. Chu, "Oriental crown-shaped differentially fed dualpolarized multidipole antenna," IEEE Trans. Antennas Propag., vol. 63, no. 11, pp. 4678–4685, Nov. 2015.

[20] C. R. White and G. M. Rebeiz, "A differential dual-polarized cavity backed microstrip patch antenna with independent frequency tuning," IEEE Trans. Antennas Propag., vol. 58, no. 11, pp. 3490–3498, Nov. 2010.

[21] K. L. Wong, Compact and Broadband Microstrip Antennas. New York: Wiley, 2002, p. 10.

[22] C. R. White and G. M. Rebeiz, "A differential dual-polarized cavity-backed microstrip patch antenna with independent frequency tuning," IEEE Trans. Antennas Propag., vol. 58, no. 11, pp. 3490–3498, Nov. 2010.

[23] G. Adamiuk, W. Wiesbeck, and T. Zwick, "Differential feeding as a concept for the realization of broadband dual-polarized antennas with very high polarization purity," in Proc. IEEE Antennas Propag. Soc. Int. Symp., Charleston, SC, Jun. 2009, pp. 1–4.

[24] M. Bozzi, A. Georgiadis, and K. Wu, "Review of substrate-integrated waveguide circuits and antennas," IET Microw., Antennas Propag., vol. 5, no. 8, pp. 909–920, Jun. 2011.

[25] 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.

[26] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, Microstrip Antenna Design Handbook. Boston, MA, USA: Artech House, 2001.

[27] Q. Liu, L. Zhu, J. Wang and W. Wu, "Wideband low-profile differential-fed patch antennas with an embedded cavity under dual-mode," IEEE Transactions on Antennas and Propagation, vol. 67, no. 6, pp. 4235-4240, June 2019.

[28] D. M. Pozar, Microwave Engineering, 4th ed. New York, NY, USA: Wiley, 2011.

[29] C. R. White and G. M. Rebeiz, "A differential dual-polarized cavity backed microstrip patch antenna with independent frequency tuning," IEEE Trans. Antennas Propag., vol. 58, no. 11, pp. 3490–3498, Nov. 2010.

[30] Y. P. Zhang and Z. Chen, "The wheeler method for the measurement of the efficiency of differentially-driven microstrip antennas," IEEE Trans. Antennas Propag., vol. 62, no. 6, pp. 3436–3439, Jun. 2014.