IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 30 July 2022, accepted 23 August 2022, date of publication 26 August 2022, date of current version 1 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3201865

RESEARCH ARTICLE

Ultra-Wideband Compact Millimeter-Wave Printed Ridge Gap Waveguide Directional Couplers for 5G Applications

MOHAMED MAMDOUH M. ALI[1], (Senior Member, IEEE), OSAMA M. HARAZ[1], (Senior Member, IEEE), ISLAM AFIFI[2], (Member, IEEE), ABDEL-RAZIK SEBAK[3], (Life Fellow, IEEE), AND TAYEB A. DENIDNI[4], (Fellow, IEEE)

[1]Department of Electrical Engineering, Faculty of Engineering, Assiut University, Assiut 71515, Egypt
[2]Department of Engineering Mathematics and Physics, Faculty of Engineering, Cairo University, Cairo 12613, Egypt
[3]Electrical and Computer Engineering, Concordia University, Montreal, QC H3G 1M8, Canada
[4]Institut National de la Recherche Scientifique (INRS), Université du Québec, Montreal, QC H5A 1K6, Canada

Corresponding author: Mohamed Mamdouh M. Ali (mohamed.ali@ieee.org)

ABSTRACT A compact ultra-wideband printed ridge gap waveguide directional couplers for millimeter-wave applications are presented in this paper. A multi-layer coupling technique between two resonant patches is adopted to achieve a wider operating bandwidth with better amplitude and phase balance compared to single-layer technology. For this purpose, a systematic design procedure is deployed to achieve several coupling values in the range of 3-10 dB over a wide frequency bandwidth centered at 30 GHz. A 3-dB hybrid coupler is fabricated and measured, where a bandwidth of 12 GHz (about 38 % fractional bandwidth) from 25 GHz to 37 GHz is achieved. In addition, the phase balance is $90^o \pm 5^o$ over 38% fractional bandwidth with an amplitude balance of 3.4 ± 0.5 dB over a 26.5% centered at 30 GHz. The proposed couplers with superior characteristics such as compactness, low loss, and low dispersion are considered a good candidate for millimeter-wave applications such as the fifth-generation (5G) wireless communications.

INDEX TERMS Hybrid coupler, printed ridge gap waveguide, multilayered structure, proximity coupling, resonating patches, millimeter waves, fifth-generation (5G) cellular.

I. INTRODUCTION

T here is a growing interest in the fifth-generation (5G) of wireless communication systems as it is considered one of the most promising technology in the near future. This new technology can accommodate a large number of subscribers with small latency time, high data rate, and reliable connectivity [1]. 5G will use spectrum in the current frequency range of Long-Term Evolution (LTE) (600 MHz to 6 GHz) and also in millimeter-wave (mm-wave) bands (24-86 GHz). However, the implementation of the 5G communication systems is limited due to the lack of high-performance components, especially in the millimeter-wave range. Furthermore, 5G systems will need smart subsystems like beam-switching to improve the reliability of communication links [2].

The Beam-switching network is realized through the integration of different components including transitions, crossovers, couplers, and phase shifters [3], [4]. Among all these components, a directional coupler is considered the essential passive microwave component of any millimeter-wave system for getting a sample of the input power. Directional couplers are commonly designed using multi-layer planar technology where the input signals are coupled between the lines through a non-resonant aperture or proximity coupling of resonant patches [5], [6]. They can be designed and implemented using either traditional technology such as microstrip line [7], [8] or modern guiding structures, such as substrate integrated waveguide (SIW) [9], [10], [11]. These guiding structure technologies have well-known limitations including large material and radiation losses, that limit their operation at mm-wave frequencies.

Recently, the ridge gap waveguide (RGW) technology has emerged as an alternative technology, which overcomes

The associate editor coordinating the review of this manuscript and approving it for publication was Masood Ur-Rehman.

TABLE 1. Performance comparison between hYBRID rgw coupler configurations.

Ref. / Technol.	Freq. (GHz)	BW	Ampl. balance BW (± 0.5 dB)	Phase balance BW	Insertion Loss	size ($\lambda_o \times \lambda_o$)
[23] / Metal RGW	11	13%	11%	13%	0.35 dB	4×2.7
[24] / Metal RGW	15	14%	7%	N.A	0.7 dB	1.6×1.6
[25] / Groove GW	14	14.3%	12.5%	14.3%	N.A	4.7×2.9
[26] / PRGW	30	6%	3%	3%	0.8 dB	1.1×1.1
[27] / PRGW	30	26.5%	13%	23%	0.7 dB	1.3×1.3
[29] / PRGW	30	13%	6.7%	7%	1 dB	1.12×1.12
[30] / PRGW	60	11%	11%	11%	N.A	1.9×1.1
The proposed work / PRGW	30	38%	26.5%	38%	0.55 dB	1.1×0.97

major flaws in excising technologies [12], [13], [14], [15], [16], [17], [18], [19]. The gap waveguide technology relies on using two parallel layers, where the upper plate is a perfect electric conductor (PEC), and the lower is designed as a regular periodic surface acting like an artificial magnetic conductor (AMC) [20]. Guiding structures in the gap waveguide technology is realized by inserting a ridge, groove, or microstrip line into the AMC layer [21], [22]. In this way, a propagating wave is confined in the air gap between the PEC layer and the provided guiding element in the AMC layer. Therefore, gap waveguide structures are realized without any contact between the two layers. Hence, they are considered a cost-effective manufacturing process and fully open structures to improve heat transfer. In addition, the dielectric losses are minimal as signals are propagating inside an air gap between PEC and a ridge introduced into the AMC. Due to these advantages, the ridge gap waveguide technology has been proven to be very promising for directional coupler design, as many well-functioning measured coupler configurations have been reported in [23], [24], [25], [26], [27], [28], [29], and [30].

Many hybrid directional coupler configurations implemented based on metal RGW have been presented in the literature [23], [24]. One featured type of hybrid coupler is based on the branch line configuration, which achieves a low loss for x-band applications [23]. However, a narrow bandwidth, large size, and high fabrication cost are the main disadvantages of this coupler. Another technique for metal RGW coupler is to deploy a rectangular junction with capacitive domes [24]. Although this technique achieves a compact size and low insertion loss, it has a narrow bandwidth. Groove gap waveguide (GW) is considered among the modern guiding structure that is used to implement a hybrid coupler, which is based on the continuous coupling between adjacent grooves [25]. Although this configuration exhibited a low insertion loss and high isolation, it has a moderate bandwidth, and large size, and its propagating mode is TE, which has more dispersion. It is worth mentioning that a complicated fabrication process is mandatory to realize the aforementioned couplers since a high precision Computer numerical control (CNC) machine is mandatory to realize them, which increases the overall cost of this type of directional couplers. Therefore, several hybrid coupler configurations have been presented based on printed ridge gap waveguide [26], [27], [28], [29], where a low-cost conventional printed circuit board (PCB) fabrication process is used to fabricate them. Single-layer technology has been deployed to implement PRGW coupler, where several configurations have been reported in the literature [26], [27], [29]. In [26], the first single-layer PRGW hybrid coupler has been proposed. Even though it has a compact size, a narrow bandwidth with a large amplitude imbalance is achieved. An improved design based on increasing the size of the rectangular coupling section has been presented to enhance the bandwidth [27]; however, the amplitude imbalanced bandwidth is narrow. Another single layer PRGW coupler formed by a square patch with one diagonal slot is proposed in [29]. Although this coupler has a compact size, a narrow bandwidth with a large amplitude balance is achieved. Most of the previously discussed articles are based on single-layer PRGW technology, where a narrow bandwidth and large amplitude imbalance are the common disadvantages of these configurations. To improve the amplitude imbalance, a multi-layer configuration has been introduced in [30]. Although this coupler provides a flat 3-dB coupling, it still has a narrow bandwidth and a large size, which limits its deployment in practical applications. Based on the authors' knowledge, the design of PRGW hybrid couplers having a wide bandwidth and compact size with small amplitude and phase imbalance has not been addressed yet in the literature.

This paper presents a compact ultra-wideband millimeter-wave quadrature hybrid coupler using a printed ridge gap waveguide for 5G communication applications centered at 30 GHz. The main contribution and novelty of this work is the introduction of a new coupling mechanism in PRGW technology that provides a flat 3-dB forward coupling with superior electrical characteristics in the mm-wave frequency range compared with the published ones in the literature, where their performances are discussed and summarized in Table 1. Furthermore, the analysis and systematic design procedure are provided, where a class of wideband directional couplers achieving different coupling levels in the range

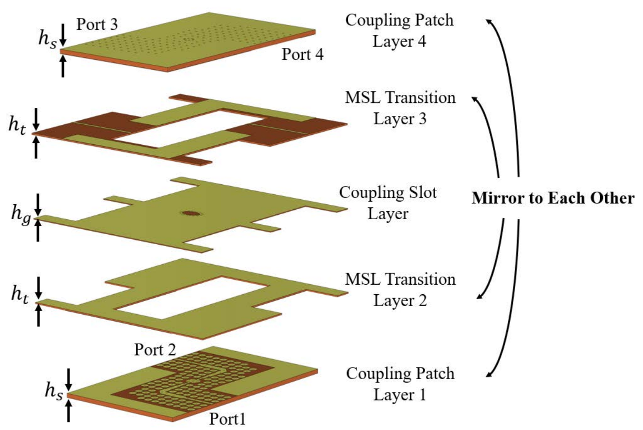


FIGURE 1. Geometry of the proposed PRGW directional coupler.

of 3-10 dB is proposed. The proposed couplers are characterized by their compact size allowing the integration with other components and reducing the total cost of the system. In addition, the proposed 3 dB coupler has a 38% fractional bandwidth with a low phase and amplitude imbalance capable of covering the operating bandwidth of 5G applications at 30 GHz.

This paper is organized as follows: Section II presents the directional coupler configuration. This is followed by a directional coupler analysis and design procedure in Section III. In Section IV, the measured and simulation results of the proposed coupler are presented. Finally, a summary of the paper's findings and conclusion is given in Section IV.

II. DIRECTIONAL COUPLER CONFIGURATION

The proposed coupler implementation based on the printed ridge gap waveguide (PRGW) technology is shown in Fig. 1. The proposed PRGW directional coupler design is based on multi-layer proximity coupling of resonant patches through a coupling slot, where more details on the coupling patch and slot are shown in Fig. 2(a). The propose structure is designed using a dielectric substrate Rogers RT6002 with thickness $H_s = 0.762$ mm, permittivity $\varepsilon_r = 2.94$, and dielectric loss tan $\delta = 0.0012$. The cell design and simulation process as well as the related realized bandwidth have been covered in numerous articles and theses [40], [41]. Periodic boundary conditions are used to model the whole EBG unit cell structure as shown in Fig. 3(a). The described design process makes getting the cell dimensions quite simple, where the geometrical parameters of the unit cell are designed to obtain a wide bandgap that covers the frequency range 22-40 GHz as shown in Fig. 3(b). In this case, the height of the air gap is $H_a = 0.254$ mm, while the dimensions of the mushroom inclusions are the following: the period between unit cells $d = 1.62$ mm, the lateral dimension $W = 1.42$ mm, and via radius $R_v = 0.19$ mm. The proposed coupler design simply consists of two elliptical patches facing each other on the top and bottom layers and connected to the input and output PRGW lines. The proximity coupling between these patches

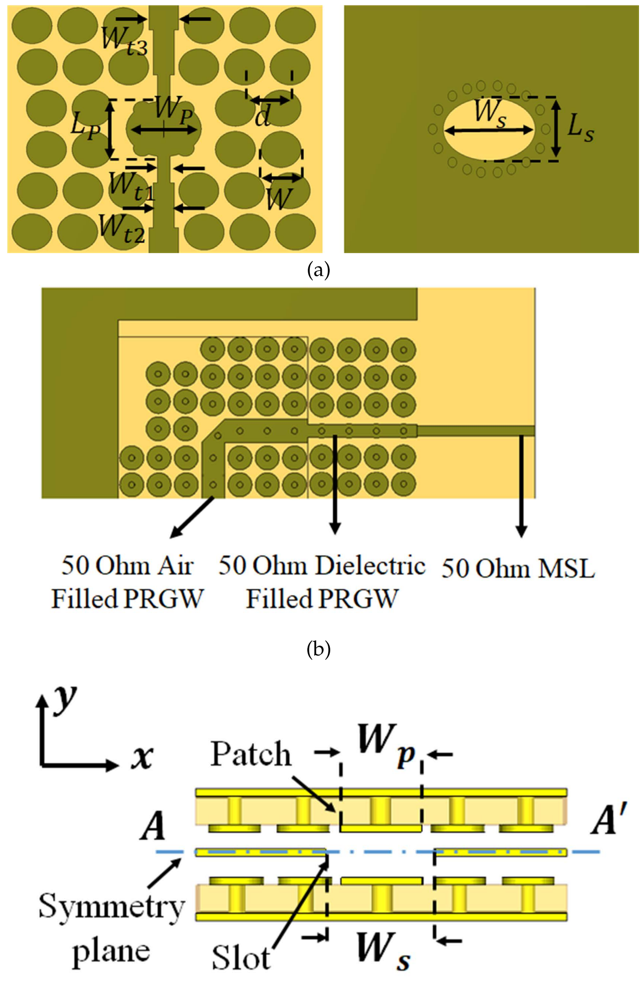


FIGURE 2. Geometry of the proposed PRGW directional coupler. (a) Top view of coupling patch and slot layers. (b) MSL to PRGW transition. (c) Cross-section view.

is achieved by cutting an elliptical slot in both ground planes of a thin RT6002 substrate with $H_g = 0.13$ mm. The coupling slot is surrounded by vias to confine the field on the slot. The geometric parameters of coupler elliptical patches are the width W_p and the length L_p, while the elliptical coupling aperture has a width and length of W_s and L_s, respectively. The width of the PRGW lines at the top and bottom layers $W_R = 1.5$ mm is chosen to give an input impedance of 50 Ω. To experimentally evaluate the directional coupler, a microstrip line (MSL) to PRGW transition is deployed and printed on Rogers RT6002 substrate with a thickness of $H_t = 0.254$ mm as shown in Fig. 2(b).

III. DIRECTIONAL COUPLER ANALYSIS AND DESIGN PROCEDURE

Due to the reciprocal and symmetrical nature of the proposed coupler, the even and odd mode analysis is deployed to calculate the even- and odd-mode characteristic impedances [31], [32], [33], [35]. The even and odd mode analysis of the

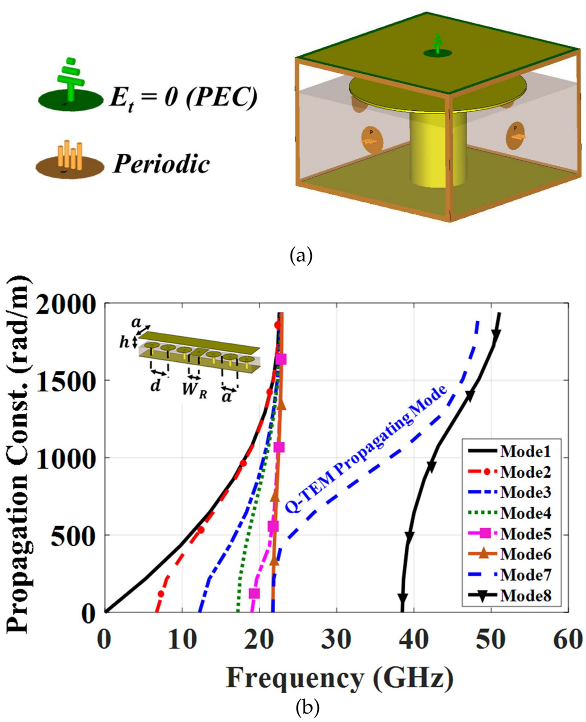


FIGURE 3. Unit cell design and simulation response. (a) Unit cell simulation setup. (b) Dispersion diagram of PRGW line.

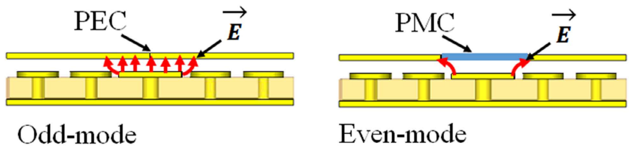
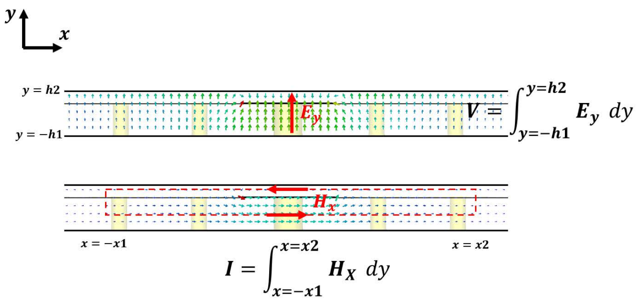


FIGURE 4. Electric field lines for odd- and even-mode excitation.

equivalent rectangular-shaped directional couplers implemented using traditional techniques such as microstrip lines have been discussed in the literature [36], while either the implementation or the analysis of such coupler realized using PRGW technology has not been addressed yet. As a result, in the following subsections, the even- and odd-mode characteristics in the coupling region will be evaluated. This gives the initial dimensions for a class of directional couplers capable of providing coupling between 3-10 dB with a reduction in the design time frame.

A. EVEN AND ODD MODE ANALYSIS

Fig. 2(c) shows the cross-sectional view for the proposed patch coupler, where AA' is the symmetry plane used for the even/odd mode analysis. For odd mode, a perfect electric conductor (PEC) boundary condition is applied at AA' as shown in Fig. 4. It can be observed that the existence of the slot in the common ground plane results in odd mode characteristic impedance Z_{odd} that depends only on the coupling patch width W_p. In addition, the odd mode operation and electric filed distributions are similar to those for the printed ridge gap waveguide. A perfect magnetic conductor (PMC) boundary condition is applied at AA' to calculate the even mode



$$V = \int_{y=-h1}^{y=h2} E_y \, dy \qquad I = \int_{x=-x1}^{x=x2} H_X \, dy$$

FIGURE 5. Electric and magnetic field illustration for the even mode impedance calculation.

characteristic impedance Z_{even}, which is affected by both coupling patch width W_p and coupling slot width W_s. Due to the difficulty to obtain closed-form formulas for even and odd characteristic impedances of the PRGW configurations shown in Fig. 4, the CST Microwave Studio simulator [36] is used to calculate both Z_{odd} and Z_{even} through applying a magnetic wall and electric wall as a boundary condition at the plane of symmetry AA'. Figure 5 demonstrate the electric and magnetic field distribution, where a $Z = V/I$ model to calculate the characteristics impedance is used, where $V = \int E_y dy$ and $I = \int H_x dx$ are the voltage and current in the transverse plane defined by $x - y$ plane. Several E and H-field probes at the center operating frequency are distributed along the PRGW coupling section, where the fields are integrated by using the CST post-processing yields to the desired impedances. Figs. 6(a) and 6(b) show the even and odd mode characteristic impedances for various coupling patch width W_p and slot width W_s. These main parameters W_p and W_s can be adjusted to guarantee a backward coupling behavior. This can be achieved for any value of the coupling patch and slot lengths when:

$$Z_o = \sqrt{Z_{even} Z_{odd}} \tag{1}$$

where, Z_o is the input line impedance, which is plotted for various coupling patch width W_p and slot width W_s in Fig. 6(c), where its calculations give an initial step to design the matching transformers.

For the maximum amount of coupling between port 1 and port 3, the lengths of both the coupling patch L_p and slot L_s are selected to equal the quarter free space wavelength at the center operating frequency 30 GHz [34], [35], [36], [37], [38]. Hence, the coupling value can be related to the even and odd impedance as follow [31]:

$$C_{dB} = -20log_{10} \frac{Z_{even} - Z_{odd}}{Z_{even} + Z_{odd}} \tag{2}$$

where, Fig. 7 shows the coupling value for various coupling patch width W_p and slot width W_s.

B. DESIGN PROCEDURE

Based on the even and odd analysis discussed in the previous subsection, the design procedure for the proposed coupler

TABLE 2. Final design values of the proposed PRGW directional couplers.

Coupling (dB)	Characteristics impedance (Ω)			Coupling Section Dimensions (mm)				Transformer Dimensions (mm)		
	even-mode	odd-mode	line	W_p	W_s	L_p	L_s	W_{t1}	W_{t2}	W_{t3}
3 dB	209	31	80.5	2.6	3.4	2.4	2.4	0.45	0.75	1.05
6 dB	105.9	31.95	58	2.75	2.5	2.2	2.2	0.7	0.7	1.07
10 dB	60	29	41	2.7	2	2	2	0.75	0.88	1.08

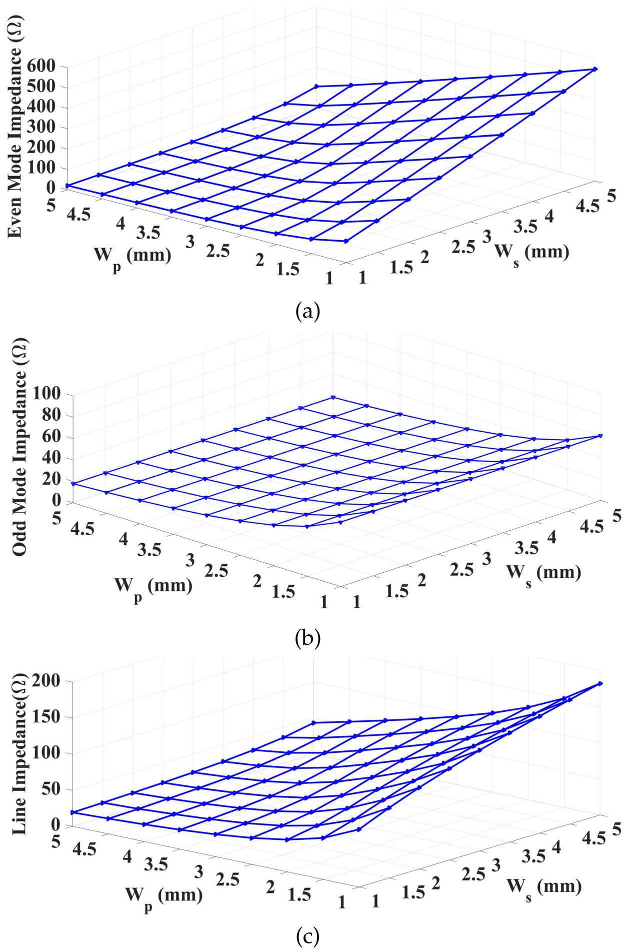


FIGURE 6. Results of even and odd analysis. (a) Even mode impedance. (b) Odd mode impedance. (c) Line impedance.

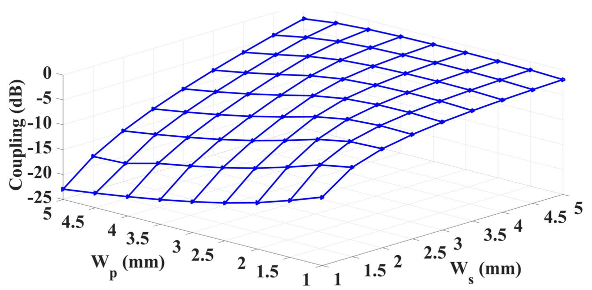


FIGURE 7. Coupling results of even and odd analysis.

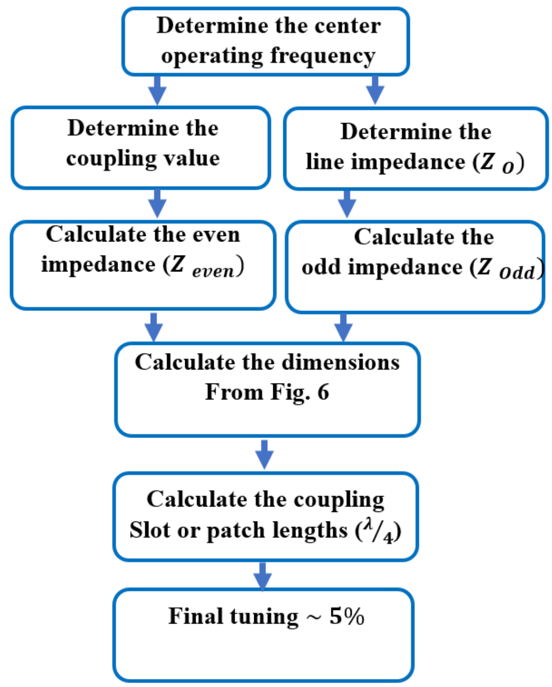
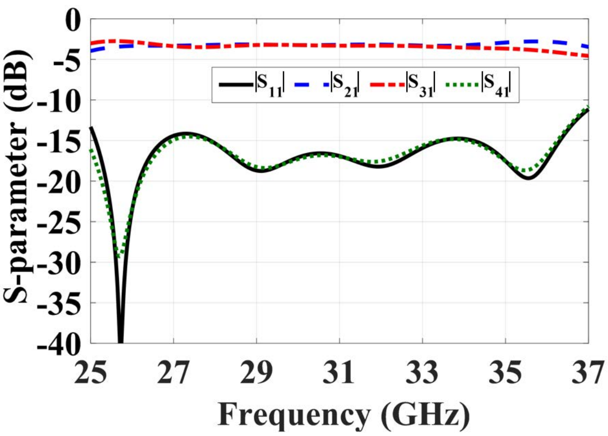


FIGURE 8. Proposed coupler design procedure.

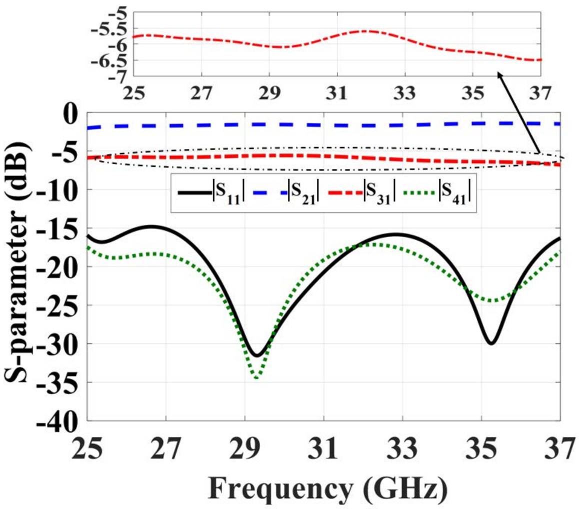
can be described s shown in Fig. 8. In this work, the line impedance Z_o is selected to be larger than 50 Ω in order to allow deploying impedance transformers to match Z_o to a 50 Ω input PRGW line, as shown in Fig.2. Although the transformer section increases the size of the design, it provides a degree of freedom to achieve deep matching and isolation levels. Table 2 shows the values of even- and odd-mode characteristic impedances and the coupling section dimensions of 3 dB, 6 dB, and 10 dB PRGW directional couplers, where the corresponding simulated S-parameters are plotted in Figs.9(a),9(b), and 9(c). The proposed couplers achieved a deep matching level and isolation below −15 dB, which can be improved by using more than two matching transformers that will increase the size correspondingly. On the other hand, the proposed 6 dB and 10 dB couplers achieved more than 10 dB directivity over the whole operating frequency band. In addition, the proposed couplers provide a flat coupling response with a variation of ± 0.5 dB over the operating frequency bandwidth. These results emphasize the validity of the proposed design procedure that achieved a class of PRGW directional couplers having a wide bandwidth, high isolation with small amplitude imbalance.

IV. EXPERIMENTAL VALIDATION

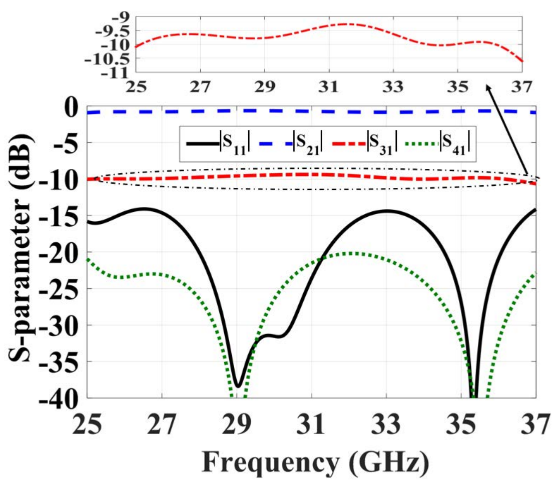
The performance of the proposed PRGW directional couplers is experimentally validated through the fabrication and



(a)



(b)



(c)

FIGURE 9. Simulated S-parameter for the proposed PRGW directional couplers. (a) 3-dB directional coupler. (b) 6-dB directional coupler. (c) 10-dB directional coupler.

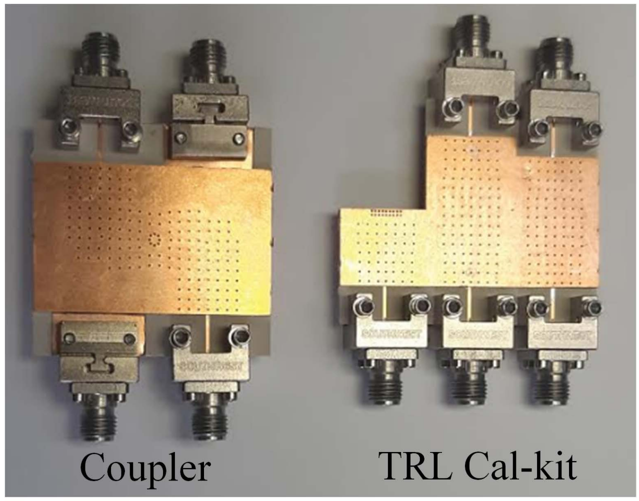
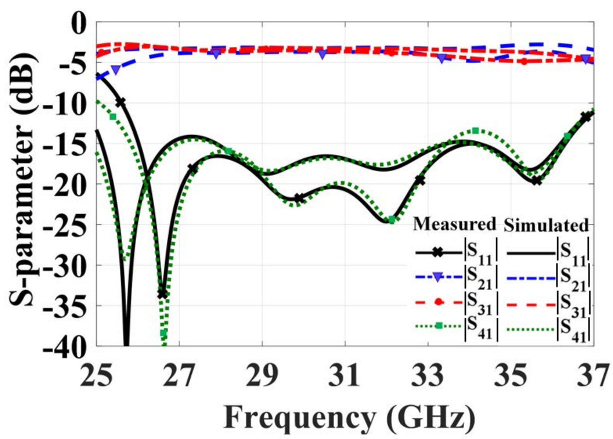
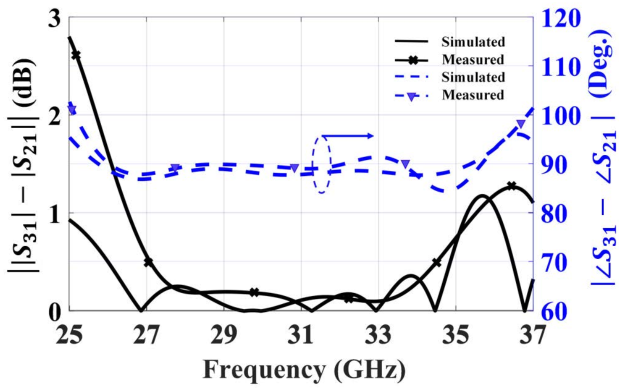


FIGURE 10. Photograph of fabricated coupler prototypes.



(a)



(b)

FIGURE 11. Comparison between simulated and measured results of the proposed 3dB PRGW quadrature hybrid coupler. (a) S-parameters. (b) Amplitude and phase imbalance.

measurement of a 3-dB PRGW hybrid coupler, where the prototype is shown in Fig. 10. The detailed dimensions of the proposed coupler are listed in Table 2. The fabricated parts of the proposed PRGW directional coupler are assembled using epoxy at high temperature and pressure [39]. A TRL calibration kit is deployed to eliminate the effect of the connectors and microstrip line transition for accurate performance evaluation of the proposed coupler. The S-parameters are measured using the (N52271A) PNA network, where the comparison between the measured and simulated results is shown in Fig. 11(a). A good agreement between the measured and simulated S-parameters can be observed, where a relative bandwidth of 38% is achieved at 30 GHz. However, it can be noticed that there is a mismatch in the measured results from 25 to 26 GHz, which is mainly related to the fabrication tolerance and the glue used to assemble the fabricated layers. Both amplitude and phase imbalance are calculated and presented in Fig. 11(b). It can be observed that the proposed coupler achieves a quadrature phase between the output ports with $\pm 5^o$ over the whole operating bandwidth. Furthermore, the through and the coupled port amplitudes are balanced within ±0.5 dB from 26 GHz to 34 GHz.

V. CONCLUSION

In this paper, a novel class of ultra-wideband printed ridge gap waveguide directional couplers for millimeter-wave applications has been proposed. A systematic design procedure has been deployed for the design of the proposed PRGW directional couplers with coupling values in the range of 3-10 dB over a wide frequency bandwidth centered at 30 GHz. The proposed couplers have been implemented based on a multi-layer technique between two resonant patches coupled through a slot in a common ground plane. It has been validated that the proposed multi-layer technique can achieve better performance in terms of bandwidth, phase, and amplitude balance compared with other couplers implemented with single-layer technology. A prototype of a 3-dB hybrid directional coupler has been fabricated and measured. The obtained results have shown that the proposed coupler design has achieved a compact size, low loss, and relative bandwidth of 38% at 30 GHz. In addition, a good amplitude (3.4 ± 0.5 dB) and phase balance ($90^o \pm 5^o$) have been achieved over the operating bandwidth. The proposed directional coupler can be considered a good candidate for the implementation of millimeter ultra-wide bandwidth beam switching networks for 5G applications.

REFERENCES

[1] Y. Wang, J. Li, L. Huang, Y. Jing, A. Georgakopoulos, and P. Demestichas, "5G mobile: Spectrum broadening to higher-frequency bands to support high data rates," *IEEE Veh. Technol. Mag.*, vol. 9, no. 3, pp. 39–46, Sep. 2014.

[2] O. M. Haraz, A.-R. Sebak, and S. A. Alshebeili, "Ultra-Wideband 4 × 4 Butler matrix employing trapezoidal-shaped microstrip-slot technique," *Wireless Pers. Commun.*, vol. 82, pp. 709–721, May 2015.

[3] M. M. M. Ali and A.-R. Sebak, "2-D scanning magnetoelectric dipole antenna array fed by RGW Butler matrix," *IEEE Trans. Antennas Propag.*, vol. 66, no. 11, pp. 6313–6321, Nov. 2018.

[4] I. Afifi and A.-R. Sebak, "Wideband 4 × 4 Butler matrix in the printed ridge gap waveguide technology for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 68, no. 11, pp. 7670–7675, Nov. 2020.

[5] O. M. Haraz and A. R. Sebak, "Two-layer butterfly-shaped microstrip 4×4 Butler matrix for ultra-wideband beam-forming applications," in *Proc. IEEE Int. Conf. Ultra-Wideband (ICUWB)*, Sydney, NSW, Australia, Sep. 2013, pp. 1–6.

[6] A. Alaqeel, H. Shaman, S. Almorqi, O. Haraz, S. Alshebeili, and A. R. Sebak, "Butterfly-shaped slot coupled microstrip 90° hybrid couplers for K- and Ka-band millimeter-wave radar applications," *Proc. Medit. Microw. Symp. (MMS)*, Marrakech, Morocco, 2014, pp. 1–3.

[7] O. M. H. Ahmed, A.-R. Sebak, and T. A. Denidni, "A novel butterfly-shaped multilayer backward microstrip hybrid coupler for ultrawideband applications," *Microw. Opt. Technol. Lett.*, vol. 54, no. 10, pp. 2231–2237, Oct. 2012.

[8] O. M. Haraz and A.-R. Sebak, "Novel UWB trapezoidal and butterfly shaped microstrip phase shifters using multilayered PCB technology," *Appl. Comput. Electromagn. Soc. J.*, vol. 31, no. 11, pp. 1309–1314, 2016.

[9] T. Djerafi and K. Wu, "Super-compact substrate integrated waveguide cruciform directional coupler," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 11, pp. 757–759, Nov. 2007.

[10] B. Liu, W. Hong, Y. Zhang, H. Jun Tang, X. Yin, and K. Wu, "Half mode substrate integrated waveguide 180° 3-dB directional couplers," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 12, pp. 2586–2592, Dec. 2007.

[11] D. Shen, K. Wang, and X. Zhang, "A substrate integrated gap waveguide based wideband 3-dB coupler for 5G applications," *IEEE Access*, vol. 6, pp. 66798–66806, 2018.

[12] P.-S. Kildal, A. U. Zaman, E. Rajo-Iglesias, E. Alfonso, and A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression," *IET Microw., Antennas Propag.*, vol. 5, no. 3, pp. 262–270, Mar. 2011.

[13] M. M. M. Ali and A. Sebak, "Printed RGW circularly polarized differential feeding antenna array for 5G communications," *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3151–3160, May 2019.

[14] S. I. Shams and A. A. Kishk, "Determining the stopband of a periodic bed of nails from the dispersion relation measurements prediction," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 7, no. 4, pp. 621–629, Apr. 2017.

[15] M. M. M. Ali and A. Sebak, "Compact printed ridge gap waveguide crossover for future 5G wireless communication system," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 7, pp. 549–551, Jul. 2018.

[16] S. I. Shams and A. A. Kishk, "Printed texture with triangle flat pins for bandwidth enhancement of the ridge gap waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 6, pp. 2093–2100, Jun. 2017.

[17] I. Afifi, M. M. M. Ali, and A. R. Sebak, "Analysis and design of a 30 GHz printed ridge gap ring-crossover," in *Proc. USNC-URSI Radio Sci. Meeting, Joint AP-S Symp.*, Atlanta, GA, USA, Jul. 2019, pp. 65–66.

[18] P.-S. Kildal, "Three metamaterial-based gap waveguides between parallel metal plates for mm/submm waves," *Proc. 3rd Eur. Antennas Propag. Conf.*, Mar. 2009, pp. 28–32.

[19] S. M. Sifat, M. M. M. Ali, S. I. Shams, and A.-R. Sebak, "High gain bow-tie slot antenna array loaded with grooves based on printed ridge gap waveguide technology," *IEEE Access*, vol. 7, pp. 36177–36185, 2019.

[20] M. G. Silveirinha, C. A. Fernandes, and J. R. Costa, "Electromagnetic characterization of textured surfaces formed by metallic pins," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 405–415, Feb. 2008.

[21] M. M. M. Ali, I. Afifi, and A.-R. Sebak, "A dual-polarized magneto-electric dipole antenna based on printed ridge gap waveguide technology," *IEEE Trans. Antennas Propag.*, vol. 68, no. 11, pp. 7589–7594, Nov. 2020.

[22] D. Sievenpiper, L. Zhang, R. F. J. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 11, pp. 2059–2074, Nov. 1999.

[23] M. Taraji and M. Naser-Moghaddasi, "Design of branch line coupler based on ridge gap waveguide technology for X-band application," *IETE J. Res.*, vol. 68, no. 2, pp. 917–923, 2022.

[24] S. I. Shams and A. A. Kishk, "Design of 3-dB hybrid coupler based on RGW technology," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 10, pp. 3849–3855, Oct. 2017.

[25] D. Zarifi and A. R. Shater, "DESIGN of a 3-DB directional coupler based on groove gap waveguide technology," *Microw. Opt. Technol. Lett.*, vol. 59, no. 7, pp. 1597–1600, Jul. 2017.

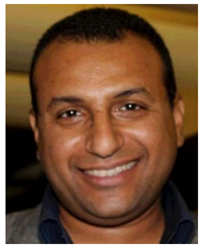
[26] M. M. M. Ali, S. I. Shams, and A. R. Sebak, "Printed ridge gap waveguide 3-dB coupler: Analysis and design procedure," *IEEE Access*, vol. 6, pp. 8501–8509, 2018.

[27] M. M. M. Ali, S. I. Shams, and A. Sebak, "Ultra-wideband printed ridge gap waveguide hybrid directional coupler for millimetre wave applications," *IET Microw., Antennas Propag.*, vol. 13, no. 8, pp. 1181–1187, Jul. 2019.

[28] M. Mamdouh M. Ali, M. S. El-Gendy, M. Al-Hasan, I. B. Mabrouk, A. Sebak, and T. A. Denidni, "A systematic design of a compact wideband hybrid directional coupler based on printed RGW technology," *IEEE Access*, vol. 9, pp. 56765–56772, 2021.
[29] Z. Zhao and T. A. Denidni, "Millimeter-wave printed-RGW hybrid coupler with symmetrical square feed," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 2, pp. 156–159, Feb. 2020.
[30] M. Farahani, M. Akbari, M. Nedil, T. A. Denidni, and A. R. Sebak, "A novel low-loss millimeter-wave 3-dB 90° ridge-gap coupler using large aperture progressive phase compensation," *IEEE Access*, vol. 5, pp. 9610–9618, 2017.
[31] R. Mongia, I. J. Bahl, P. Bhartia, and S. J. Hong, *RF and Microwave Coupled-line Circuits*. Norwood, MA, USA: Artech House, 2007.
[32] C. G. Montgomery, H. Robert, and M. Edward, *Principles of Microwave Circuits*. London, U.K.: IET, 1987.
[33] S. Y. Zheng, J. H. Deng, Y. M. Pan, and W. S. Chan, "Circular sector patch hybrid coupler with an arbitrary coupling coefficient and phase difference," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 5, pp. 1781–1792, May 2013.
[34] K. L. Chan, F. A. Alhargan, and S. R. Judah, "A quadrature-hybrid design using a four-port elliptic patch," *IEEE Trans. Microw. Theory Techn.*, vol. 45, no. 3, pp. 307–310, Feb. 1997.
[35] T. Kawai and I. Ohta, "Planar-circuit-type 3-dB quadrature hybrids," *IEEE Trans. Microw. Theory Techn.*, vol. 42, no. 12, pp. 2462–2467, Dec. 1994.
[36] M. F. Wong, V. F. Hanna, O. Picon, and H. Baudrand, "Analysis and design of slot-coupled directional couplers between double-sided substrate microstrip lines," in *IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 2, Boston, MA, USA, Jul. 1991, pp. 755–758.
[37] T. Tanaka, K. Tsunoda, and M. Aikawa, "Slot-coupled directional couplers between double-sided substrate microstrip lines and their applications," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-36, no. 12, pp. 1752–1757, Dec. 1988.
[38] A. M. Abbosh and M. E. Bialkowski, "Design of compact directional couplers for UWB applications," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 2, pp. 189–194, Feb. 2007.
[39] J. F. J. V. van Zanten, G. A. Schuerink, A. H. J. Tullemans, R. Legtenberg, and W. W. Wits, "Method to determine thermoelastic material properties of constituent and copper-patterned layers of multilayer printed circuit boards," *J. Mater. Sci., Mater. Electron.*, vol. 29, no. 6, pp. 4900–4914, Mar. 2018.
[40] S. A. Razavi, P. S. Kildal, L. Xiang, E. A. Alós, and H. Chen, "2-slot element for 60-GHz planar array antenna realized on two doubled sided PCBs using SIW cavity and EBG-type soft surface fed by microstripridge gap waveguide," *IEEE Trans. Antennas Propag.*, vol. 62, no. 9, pp. 4564–4573, Sep. 2014.
[41] M. M. M. Ali, "Millimeter-wave components and antennas for spatial and polarization diversity using PRGW technology," Ph.D. dissertation, Concordia Univ., Montreal, QC, Canada, 2020.

MOHAMED MAMDOUH M. ALI (Senior Member, IEEE) received the B.Sc. (Hons.) and M.Sc. degrees in electronics and communications engineering from Assiut University, Egypt, in 2010 and 2013, respectively, and the Ph.D. degree in electrical and computer engineering from Concordia University, Montréal, QC, Canada, in 2020. From 2010 to 2015, he was a Teaching and Research Assistant with the Department of Electronics and Communications Engineering, Assiut University. From 2015 to 2020, he was a Teaching and Research Assistant with the Department of Electrical and Computer Engineering (ECE), Concordia University. From 2020 to 2021, he was a Research Associate with the Institut National de la Recherche Scientifique (INRS), University of Quebec, Montreal. He is currently an Assistant Professor at the Department of Electrical Engineering, Faculty of Engineering, Assiut University. He is also a Research Associate with the Poly-Grames Research Center, Department of Electrical Engineering, Ecole Polytechnique de Montréal, Montreal University, Canada. His research interests include millimeter-wave antennas for 5G/6G applications, analog and hybrid beamforming networks, dielectric resonator antennas, microstrip antennas, multi-function antennas, microwave circuits, electromagnetic bandgap (EBG), artificial magnetic conductors, soft and hard surfaces, frequency selective surfaces, reflect/transmitarray, and non-reciprocal microwave devices.

He received the IEEE senior membership in December 2021. He received the Distinction with Honor from Assiut University, in 2010. He was a recipient of Egyptian Government Mission Scholarship, in 2015. He was a recipient of the Concordia University Recruitment Award, in 2016, and the Concordia University Accelerator Award, in 2019. He received the NSERC CREATE Training Program in Pervasive and Smart Wireless Applications for the Digital Economy (PERSWADE), in 2018. Recently, he received a recipient of Nature et Technologies (FRQNT) Postdoctoral Research Scholarship, in 2021.



OSAMA M. HARAZ (Senior Member, IEEE) was born in Aswan, Egypt, in October 23, 1976. He received the B.S. (Hons.) and M.S. degrees in electrical engineering from Assiut University, Egypt, in 1999 and 2004, respectively, and the Ph.D. degree from Concordia University, Montreal, QC, Canada, in 2011. From 1999 to 2000, he worked as an Electronic Engineer with Nuclear Material Authority, Cairo, Egypt. From 2000 to 2006, he was an Assistant Lecturer with the Electrical Engineering Department, Faculty of Engineering, Assiut University. He was a Postdoctoral Fellow with the KACST Technology Innovation Center in Radio Frequency and Photonics for the e-Society (RFTONICS), King Saud University, from September 2013 to September 2015. He has been an Antenna Research and Development Engineer with WAFER/E-Space, Beverly, MA, since 2019. He is also an Associate Professor of electrical engineering with the Electronics and Communication Section, Assiut University. His current research interests include small antennas, microwave circuits for MMW applications, phased array antennas, and the interaction of EM waves with new advanced materials. He received the 2010 Concordia Ph.D. Thesis Completion Award from Concordia University, Montreal, Canada. He also received the 2000 MobiNil Communication Company Excellence Award and the 6th October University Academic Distinction Award, Cairo, Egypt, from 1997 to 1998. He also received the Scholarship from the Egyptian Ministry of Higher Education, from 2006 to 2010.

ISLAM AFIFI (Member, IEEE) received the B.Sc. degree in electronics and communication engineering and the M.Sc. degree in engineering physics from Cairo University, Cairo, Egypt, in 2009 and 2014, respectively, and the Ph.D. degree in electrical and computer engineering from Concordia University, Montreal, QC, Canada, in 2020. He is currently a Lecturer and a Researcher with the Engineering Mathematics and Physics Department. His research interest includes millimeter-wave microwave components and antennas.

ABDEL-RAZIK SEBAK (Life Fellow, IEEE) received the B.Sc. degree (Hons.) in electrical engineering from Cairo University, Cairo, Egypt, in 1976, the B.Sc. degree in applied mathematics from Ain Shams University, Cairo, in 1978, and the M.Eng. and Ph.D. degrees in electrical engineering from the University of Manitoba, Winnipeg, MB, Canada, in 1982 and 1984, respectively. From 1984 to 1986, he was with Canadian Marconi Company, where he involved in the design of microstrip phased array antennas. From 1987 to 2002, he was a Professor with the Department of Electronics and Communication Engineering, University of Manitoba. He is currently a Professor with the Department of Electrical and Computer Engineering, Concordia University, Montréal, QC, Canada. His research interests include phased-array antennas, millimeter-wave antennas and imaging, computational electromagnetics, and interaction of EM waves with engineered materials and bioelectromagnetics. He is a member of the Canadian National Committee of the International Union of Radio Science Commission B. He was a recipient of the 2000 and 1992 University of Manitoba Merit Award for Outstanding Teaching and Research, the 1994 Rh Award for Outstanding Contributions to Scholarship and Research, and the 1996 Faculty of Engineering Superior. He has served as the Chair for the IEEE Canada Awards and Recognition Committee, from 2002 to 2004, and the Technical Program Chair for the 2002 IEEE CCECE Conference and the 2006 URSIANTEM Symposium. He was also the Technical Program Co-Chair of the 2015 IEEE ICUWB Conference.

TAYEB A. DENIDNI (Fellow, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from Laval University, Quebec City, QC, Canada, in 1990 and 1994, respectively. From 1994 to 2000, he was a Professor with the Engineering Department, University of Quebec at Rimouski (UQAR), Rimouski, QC, Canada, where he founded the Telecommunications Laboratory. Since 2000, he has been with the Institut National de la Recherche Scientifique (INRS), University of Quebec, Montreal, QC, Canada. He founded the RF Laboratory, INRS–Energie, Materiaux et Telecommunications (INRS-EMT), Montreal. He has extensive experience in antenna design. He served as a Principal Investigator for many research projects sponsored by NSERC, FCI, and numerous industries. His current research interests include reconfigurable antennas using electromagnetic bandgap and frequency-selective surface structures, dielectric resonator antennas, meta-material antennas, adaptive arrays, switched multi-beam antenna arrays, ultrawideband antennas, microwave, and development for wireless communications systems.