IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received March 18, 2021, accepted April 5, 2021, date of publication April 8, 2021, date of current version April 19, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3071758

A Systematic Design of a Compact Wideband Hybrid Directional Coupler Based on Printed RGW Technology

MOHAMED MAMDOUH M. ALI[1], (Member, IEEE), MOHAMED S. EL-GENDY[2],
MUATH AL-HASAN[3], (Senior Member, IEEE),
ISMAIL BEN MABROUK[4], (Senior Member, IEEE),
ABDELRAZIK SEBAK[5], (Life Fellow, IEEE),
AND TAYEB A. DENIDNI[1], (Fellow, IEEE)
[1]Institut National de la Recherche Scientifique (INRS), Université du Québec, Montréal, QC H5A 1K6, Canada
[2]Electronics Research Institute, Cairo 12622, Egypt
[3]Department of Electrical Engineering, Al Ain University of Science and Technology, Abu Dhabi, United Arab Emirates
[4]Department of Electrical Engineering, Durham University, Durham DH1 3LE, U.K.
[5]Department of Electrical and Computer Engineering, Concordia University, Montréal, QC H3G 1M8, Canada

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

ABSTRACT Printed ridge gap waveguide (PRGW) is considered among the state of art guiding technologies due to its low signal distortion and low loss at Millimeter Wave (mmWave) spectrum, which motivates the research community to use this guiding structure as a host technology for various passive microwave and mmWave components. One of the most important passive components used in antenna beam-switching networks is the quadrature hybrid directional coupler providing signal power division with 90° phase shift. A featured design of a broadband and compact PRGW hybrid coupler is propose in this paper. A novel design methodology, based on mode analysis, is introduced to design the objective coupler. The proposed design is suitable for mmWave applications with small electrical dimensions ($1.2\ \lambda_o \times 1.2\ \lambda_o$), low loss, and wide bandwidth. The proposed hybrid coupler is fabricated on Roger/RT 6002 substrate material of thickness 0.762 mm. The measured results highlight that the coupler can provide a good return loss with a bandwidth of 26.5% at 30 GHz and isolation beyond 15 dB. The measured phase difference between the coupler output ports is equal $90^\circ \pm 5^\circ$ through the interested operating bandwidth. A clear agreement between the simulated and the measured results over the assigned operating bandwidth has been illustrated.

INDEX TERMS 5G communications, millimeter-wave components, hybrid coupler, ridge gap waveguide.

I. INTRODUCTION

With the incredible growth of mobile communication technologies and its broad applications, the wide spectrum associated with the mmWave frequency bands have recently been attracted significant attention. Communication in mm-Wave frequency bands is a potentially viable solution for high-data rate applications with a massive number of connected devices compared to current 4G cellular networks [1], [2]. Such enhancements in the characteristics of the wireless telecommunication system stimulate the development of various technological methods. One direction is utilizing a very large number of antennas that can simultaneously accommodate many users and are controlled by smart systems that incorporate beam-scanning techniques [3], [4].

For the 5G applications, beam-switching subsystems and the associated components should meet the various technical requirements such as low loss, small size, and low cost. The traditional couplers can be designed by classical guiding configurations such as waveguides, microstrip lines, and striplines [5]–[12]. On the other hand, these guiding structures suffer from significant losses at mmWave. To overcome this issue, modern guiding structures such as substrate integrated waveguide (SIW) and a ridge gap waveguide (RGW) have been introduced as promising candidates for high-frequency band applications [13]–[17]. The comparison between both technologies were visited many times over the past decade, and yet no clear superiority for one

The associate editor coordinating the review of this manuscript and approving it for publication was Young Jin Chun.

technology over the other [18]. On the other hand, different hybrid coupler components have been implemented by SIW technology, which have a compact size [19], [20]. However, many of these designs suffer from a narrow bandwidth, lack of isolation, and significant dispersion. Therefore, utilizing the state of the art guiding structures, especially PRGW, is recommended for mmWave applications [21], [22]. PRGW is considered as a featured solution to overcome the aforementioned defects of the traditional technologies. PRGW technology introduces a small signal distortion since it supports a Q-TEM propagating mode [23]–[25]. In addition, it has a low loss at high frequencies so it is suitable for mmWave applications where the wave mostly propagates inside an air gap [18], [26], [27]. Few trails have been reported in the literature regarding the design of quadrature hybrid coupler using PRGW technology [28], [31]–[33]. However, these reported designs suffer from a limited bandwidth, large size, poor phase imbalance, and high loss.

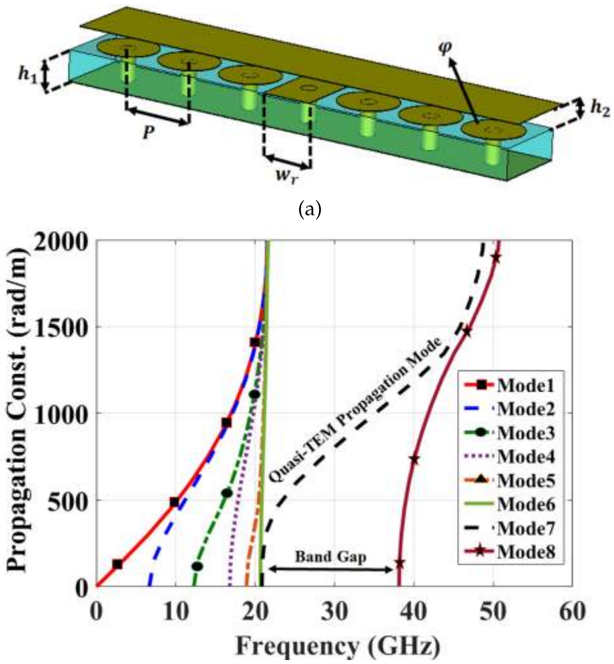
In this paper, a wide band hybrid coupler is proposed, driven by three objectives. First, it is implemented by PRGW technology to inherit the technology advantages needed for mmWave applications. Second, the wide impedance and isolation bandwidth is a major objective at 30 GHz. Last, the proposed design aims to provide the electrical characteristics in small size, which results in a compact beam-switching systems as an ultimate goal. These goals have been satisfied through a novel design methodology based on modal analysis for the coupler center patch. The organization of the paper is as follows. Sec.II illustrates the design concept for the proposed PRGW coupler. Afterwards, the fabricated circuit and the measured results of the coupler are shown in Sec. III. Moreover, Section IV highlights the evaluation of the proposed design among the similar published designs in terms of all electrical specifications. Finally, the outcomes of the proposed design are given in Sec. V.

II. PRGW HYBRID COUPLER

In this section, the systematic design procedure and a realization of the proposed coupler using PRGW technology is presented. First, the proposed PRGW structure is designed to cover more than the required operating frequency band using the Eigenmode Solver. Then, a full wave analysis is performed to ensure the confinements of the electric field within the PRGW structure. Afterward, a systemic design procedure for calculating the initial coupling section dimensions based on a novel modal analysis is proposed and discussed. Finally, the optimum performance is achieved through a fine tuning process over the whole operating frequency band.

A. PRGW STRUCTURE DESIGN

The design of the microwave passive components based on PRGW is considered as a significant research area due to the recently reported advantages [15], [28]. The design of this guiding structure mainly depends on the design of Electromagnetic Band Gap (EBG) structures based on mushroom shape as shown in Fig. 1(a). The EBG unit cell design is a straightforward procedure visited in many articles and textbooks [29], [30]. Here, a Roger RT 6002 substrate material with dielectric constant of 2.94 and a loss tangent of 0.0012 is selected to design the EBG unit cells. These EBG unit cells are the building block of the PRGW structure, where they are responsible for eliminating the wave propagation in the transverse direction and ensure the fields confinement above the ridge. The period P of EBG unit cell is 0.18 λ with air gap $h_2 = 0.508\lambda$, where λ is the free space wavelength at 30 GHz. In order to validate the operation of the PRGW structure shown in Fig. 1(a), an Eigenmode solver in CST Microwave studio Suite is used. The band-gap within the operating frequency from 22 to 38 GHz is shown in the dispersion diagram plotted in Fig. 1(b). In this band-gap, the fields will be confined within the ridge having a quasi- TEM field distribution result in a dominant mode with minimal dispersion. To emphasize on the operation of the designed PRGW structure, a straight PRGW line shown in Fig. 2(a) is simulated using the CST Transient Solver, where the electric field within the line is depicted in Fig. 6. It is clear that most of the fields are bounded within the ridge and a large exponential decaying for the fields in the transverse directions prevent any leakage of the wave outside the structure.



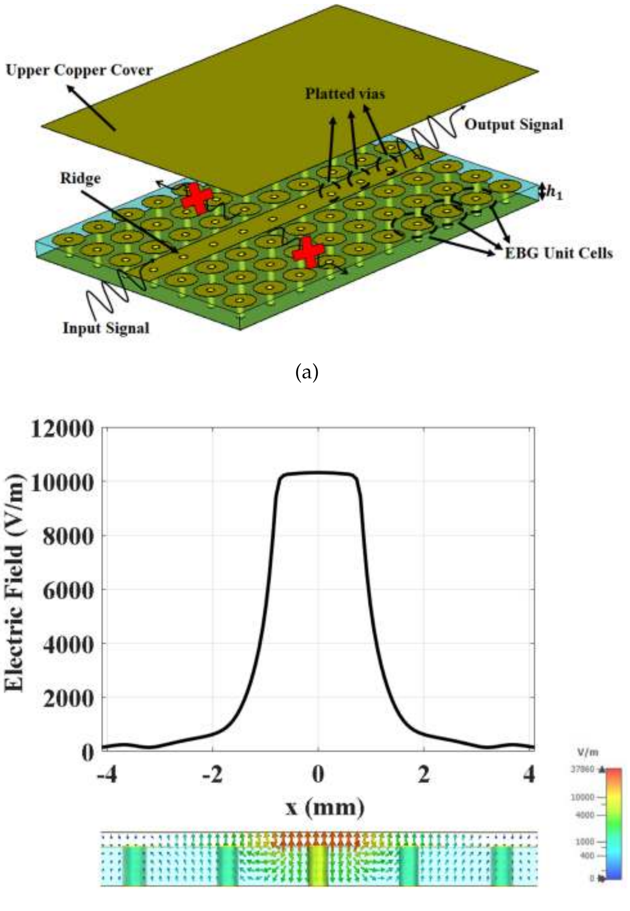
(a)

(b)

FIGURE 1. PRGW structure design. (a) Section of PRGW guiding structure. (b) Dispersion diagram of the PRGW line.

B. PRGW COUPLER DESIGN

The 3-D geometrical configuration of the proposed coupler is shown in Figs. 3(a) and 3(b). The proposed coupler consists of two PRGW lines crossing each other at right angles connected by a square junction surrounded by EBG unit cells as shown in Fig. 3(c). For exciting the proposed PRGW coupler,



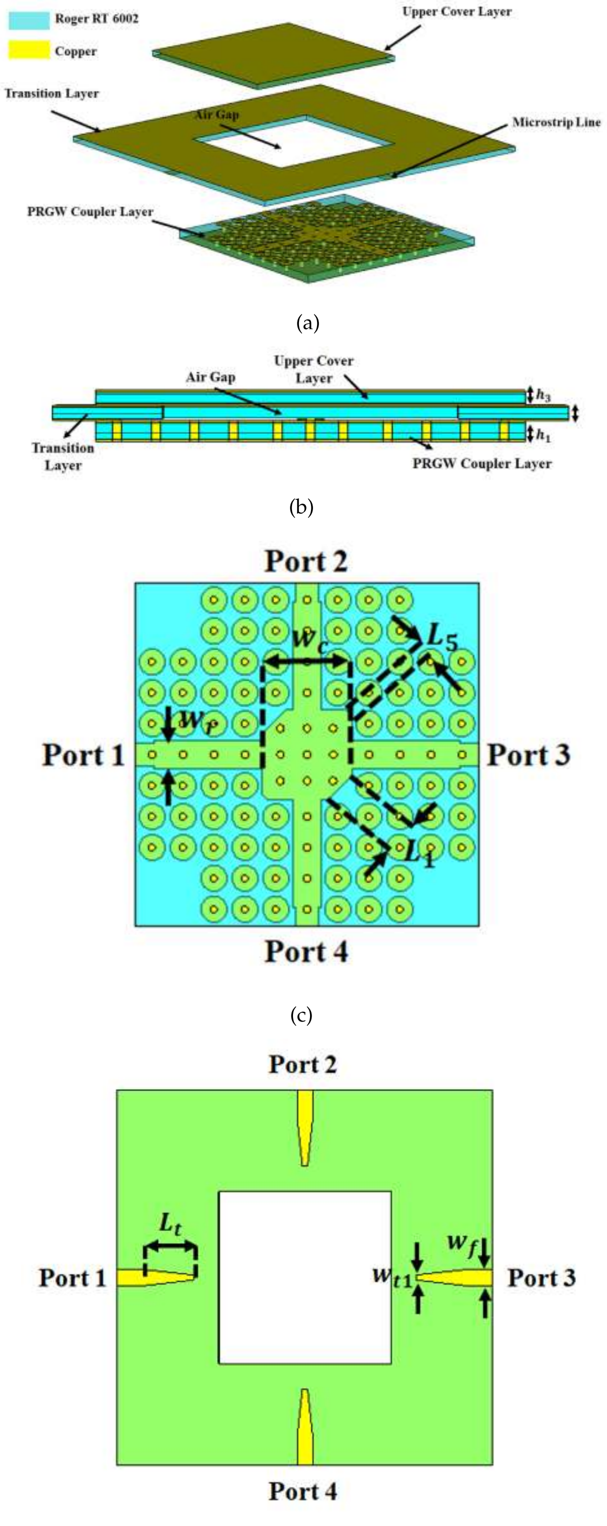
(a)

(b)

FIGURE 2. **Wave propgation in PRGW structure. (a) PRGW line. (b) E-field distribution.**

a microstrip transmission line to PRGW transition that shown in Fig. 3(d) was designed in the transition layer on a Roger RT 6002 substrate with a dielectric constant of 2.94, a loss tangent of 0.0012, and a substrate height $h_2 = 0.508$ mm. It is worth mentioning that the transition layer allows testing the proposed coupler and acts as a spacer between the upper ground layer and the mushroom surface as well.

The initial dimensions of the proposed coupler are obtained through performing mode analysis for the coupling section using the CST Eigenmode solver by considering a cavity resonator with boundaries assigned as shown in Fig. 4. A Perfect Boundary Condition (PMC) is considered for the sidewalls and bottom of the cavity that represents the EBG mushroom unit cells around the coupling section in the proposed coupler, while the top wall is considered a Perfect Electric Conductor (PEC) due to the presence of the ground plane. There are only three parameters used to control the operation of the proposed hybrid coupler, which are the size of the coupling section W_c as well as the length of the cuts L_1 and L_2 as indicated in Fig. 4.



(a)

(b)

(c)

(d)

FIGURE 3. **(a) 3-D geometrical configuration of proposed coupler. (b) Side-view. (c) Coupler layer. (d) Transition layer.**

Parametric studies were carried out to investigate the effect of the coupling section design parameters on the frequency response of the proposed PRGW coupler. From the mode analysis, it can be observed that there are two resonance frequencies within the bandgap, where the locations of these frequencies can be controlled by L_1, L_2 and W_c. The effect of

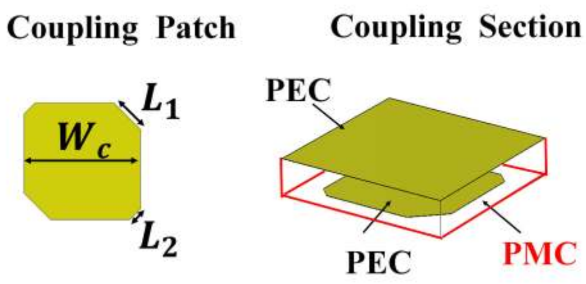
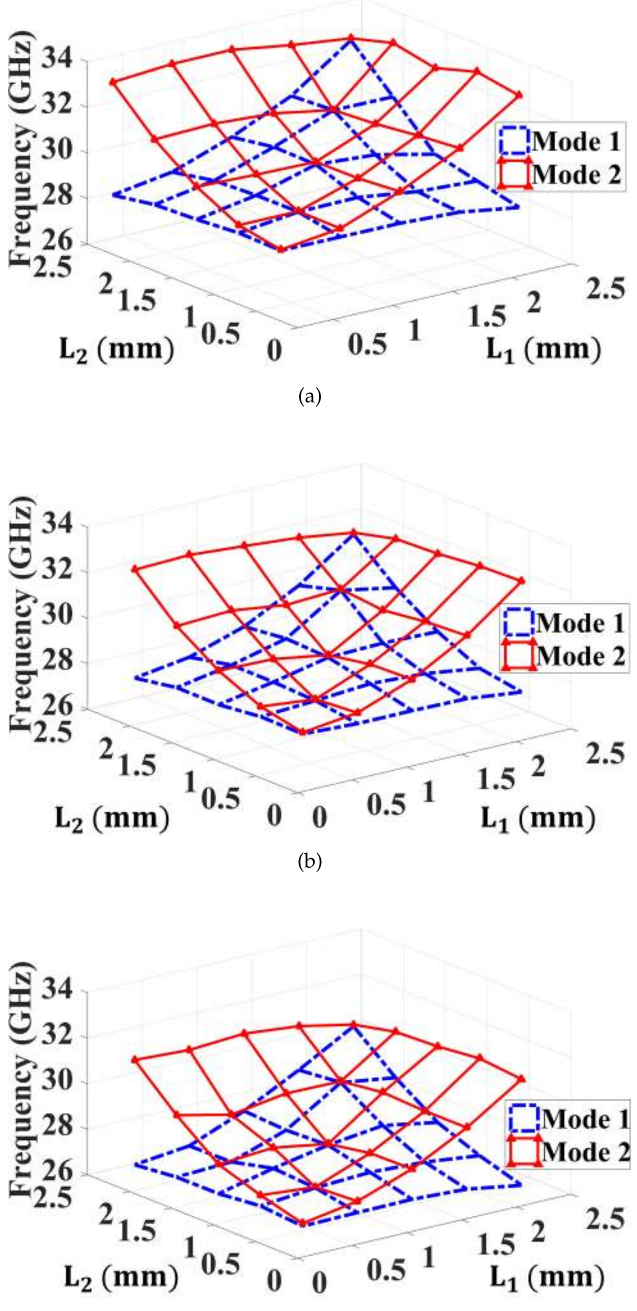


FIGURE 4. The proposed cavity resonator coupler model.

L_1 and L_2 on the two resonance frequencies is presented in a 3-D plot as shown in Fig. 5 for different values of W_c. It can be seen from these figures that symmetrical cuts result in two modes with equal resonance frequencies, while asymmetrical cuts with different sizes make the two resonance frequencies far from each other. Therefore, for a wide bandwidth of operation, the two cuts must be asymmetrical with different sizes to make the difference between the lower and higher resonance frequencies enough to cover the desired frequency bandwidth without deteriorating the mid-band matching level. In addition, the center operating frequency can be controlled by W_c, where the effect of this critical parameter is shown in Figs. 5(a), 5(b), and 5(c). Hence, the initial values of the coupling circuit are taken to be $W_c = 5$ mm, $L_1 = 1.9$ mm, and $L_5 = 0.4$ mm. These dimensions result in two resonance frequencies approximately at 27 GHz and 33 GHz, where the integration between these two resonances can cover the desired bandwidth without affecting the mid-band matching level. The center band is 30 GHz, while the objective bandwidth is from 26-34 GHz. This prediction is confirmed from the simulated and measured S-parameters that are shown in the simulation and experimental validation section, where we can observe that there are two resonance frequencies through the operating bandwidth. Besides, at these two resonance frequencies, the proposed configuration acts as a coupler, where deep matching and isolation levels are satisfied. This can be illustrated in Fig. 6, where the electric field distribution depicted the isolated port.

To understand the operation of the proposed coupler, it can be classified as branch line coupler. This classification is packed by three obvious remarks shown in the field distribution figures. The First remark is that the electric field intensity is significantly decreased at the center of the patch and the high intensity is allocated on the outer ring of the patch as shown in Fig. 6. The second remark is that the distances between the center points of the four feeding lines are approximately equal to a quarter wavelength at the center frequency. The third remark is that changing the coupler dimensions L_1 and L_2 does not only controls the locations of the resonances, but also control the coupling levels as shown in Fig. 7. This figure shows the effect of varying L_2 on the coupling value (S_{31}), while keeping L_1 at the optimized value. This explanation gives a brief physical insight of the proposed coupler operation mechanism. In addition, it can be used to evaluate the dimension selection of the coupler based on the Eigin mode solver deployed in this article.



(a)

(b)

(c)

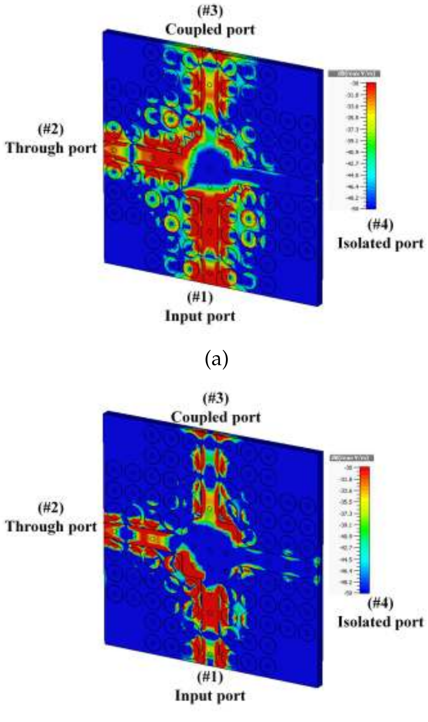
FIGURE 5. The effect of the cuts size on the resonance frequencies for different values of the coupling section width W_c. (a) $W_c = 4.8$ mm. (b) $W_c = 5$ mm. (c) $W_c = 5.2$ mm.

III. SIMULATION AND EXPERIMENTAL VALIDATION

The proposed PRGW coupler was fabricated using a standard PCB process, where the fabricated layers are shown in Fig. 8(a). The coupler is assembled using plastic screws as shown in Fig. 8(b), where a plastic holder is designed to mechanically support the fabricated coupler while measuring

TABLE 1. Comparison between milimeter wave coupler configurations.

Technology	Bandwidth S_{11}< -15 dB	Amplitude balance, dB	Phase balance	Size ($\lambda_o \times \lambda_o$)
Ridge gap waveguide [15]	14% at 15 GHz	3.5±0.75 BW = 7%	N.A	1.6 × 1.6
Substrate integrated waveguide [19]	18% at 24 GHz	4.7±0.5 BW = 10%	92° ±2 BW = 18%	1.4 × 1.5
Microstrip [5]	11% at 30 GHz	4±1 BW = 11%	90° ±1 BW = 11%	1.3 × 1.1
Printed RGW [28]	6% at 30 GHz	3.6±1 BW = 6%	90° ±5 BW = 6%	1.1 × 1.1
Printed RGW [32]	13% at 30 GHz	3.6±0.5 BW = 6.7%	90° ±10 BW = 14%	1.2 × 1.2
Printed RGW [31]	11% at 60 GHz	3.7±0.5 BW = 11%	90° ±5 BW = 11%	1.9 × 1.1
Printed RGW [33]	16% at 30 GHz	3.7±0.75 BW = 13%	90° ±5 BW = 16%	1.3 × 1.3
Proposed work Printed RGW	26.5% at 30 GHz	3.6±0.75 BW = 13%	90° ±5 BW = 26.5%	1.2 × 1.2



(a)

(b)

FIGURE 6. The E-field distribution of the proposed PRGW coupler at different frequencies. (a) F = 27 GHz. (b) F = 33 GHz.

it using the N52271A PNA network analyzer. The Thru-Reflect-Line (TRL) calibration was taken into consideration in order to avoid the transition losses.

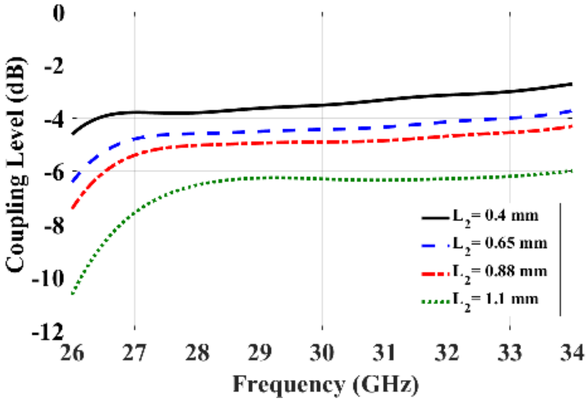


FIGURE 7. The effect of L_2 on the coupling value.

The S-parameters were sequentially measured using the PNA Model: N52271A through port 1 and port 2 of the coupler, while the other two ports are connected to 50 Ω matched loads as shown in Fig. 8(b). Fig. 8(c) shows the measured S-parameters compared to the simulated ones of the proposed hybrid coupler. Accordingly, it demonstrates that the fabricated coupler provides the bandwidth from 26 to 34 GHz with a return loss and isolation beyond 15 dB over the operating frequency band.

Fig. 8(d) shows the measured phase difference compared to the simulated one. It can be depicted from this figure that a 90° phase is achieved between the output ports with ± 5° over the whole operating bandwidth. The amplitude balance between both output ports is measured, where a ± 0.75 dB is

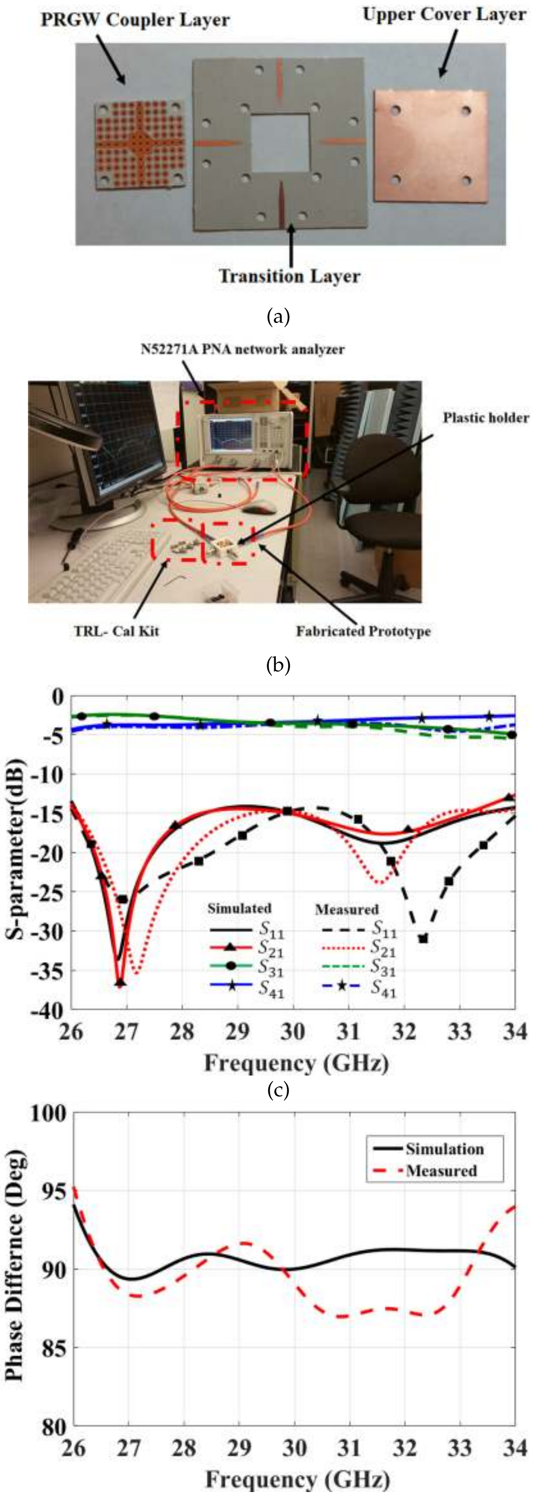


FIGURE 8. Fabrication and measurement of the proposed coupler. (a) The fabricated layers of the proposed coupler. (b) Measurement setup. (c) The proposed coupler response. (d) Simulated and measured output ports phase difference.

observed from 28 to 32 GHz with a measured loss of 0.7 dB at the center frequency of the desired bandwidth. There is a good agreement between the measured and the simulated results, where the discrepancies between the aforementioned results are due to the fabrication tolerances and the layer alignment of the proposed circuit.

IV. DESIGN EVALUATION

Finally, a design evaluation has been taken place through a comparison among other reported couplers implemented with different guiding technologies. This comparison is summarized in Table 1. The proposed PRGW coupler has a compact size and low insertion loss compared to the SIW couplers. The microstrip technology, can provide a smaller size on the expense of the bandwidth with higher insertion loss. Regarding the PRGW coupler presented in [28], it has a narrow band performance, which achieves only 6 % relative bandwidth at 30 GHz. In addition, the design concept in [28] is based on selecting the coupling section width, where the even and odd characteristic impedances are intersecting each other at single frequency, which results in a narrow band performance. On the other hand, the presented work focuses on improving performance based on different design criteria as described above. Another PRGW coupler at 30 GHz has been presented in [32], which has a narrow bandwidth with a large amplitude imbalance over the operating bandwidth. A PRGW multi-layer configuration has been introduced in [31], which provides a narrow bandwidth and has a large size, which limits their utilization in practical applications. Compared with the coupler presented in [33], which has smaller bandwidth of 16 %, the proposed coupler achieves a matching level of −15 dB over wider operating bandwidth. In addition, it has larger size which results in large losses. As a result, a remarkable improvement in the performance is achieved, where the proposed coupler has a 26.5% relative bandwidth with a stable phase balance over the whole operating bandwidth. Therefore, the proposed PRGW coupler circuit introduces a miniaturized size as well as a featured performance.

V. CONCLUSION

A hybrid directional coupler implemented by PRGW technology at 30 GHz has been proposed. The design procedure of the proposed PRGW coupler has been illustrated based on the mode analysis of the center coupling patch. The proposed coupler has been fabricated and measured, where a wide band performance of 26 % has been achieved at 30 GHz. In addition, a nearly 90° phase difference has been obtained over the interesting operating bandwidth. The measured results have been shown a good agreement with the simulated ones. This coupler can be considered an excellent candidate for future wideband mmWave beam switching networks.

REFERENCES

[1] D. Liu, L. Wang, Y. Chen, M. Elkashlan, K.-K. Wong, R. Schober, and L. Hanzo, “User association in 5G networks: A survey and an outlook,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1018–1044, 2nd Quart., 2016.

[2] F. C. Commission, “FCC takes steps to facilitate next generation wireless technologies in spectrum above 24 GHz,” Wireless Telecommun., Int., Eng. Technol., Washington, DC, USA, Tech. Rep. 20554, Jul. 2016.

[3] M. S. Islam, T. Jessy, M. S. Hassan, K. Mondal, and T. Rahman, "Suitable beamforming technique for 5G wireless communications," in *Proc. Int. Conf. Comput., Commun. Autom. (ICCCA)*, Apr. 2016, pp. 1554–1559.

[4] 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, doi: 10.1109/TAP.2018.2869228.

[5] X. F. Ye, S. Y. Zheng, and Y. M. Pan, "A compact millimeter-wave patch quadrature coupler with a wide range of coupling coefficients," *IEEE Microw. Wireless Compon. Lett.*, vol. 26, no. 3, pp. 165–167, Mar. 2016.

[6] 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.

[7] L. Wang, G. Wang, and J. Siden, "Design of high-directivity wideband microstrip directional coupler with fragment-type structure," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 3962–3970, Dec. 2015.

[8] J. E. Dalley, "A strip-line directional coupler utilizing a non-homogeneous dielectric medium," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-17, no. 9, pp. 706–712, Sep. 1969.

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

[10] K. Kuroiwa, A. Gonzalez, M. Koyano, T. Kojima, Y. Fujii, Y. Uzawa, and H. Ogawa, "Short-slot hybrid coupler using linear taper in W-band," *J. Infr., Millim., THz Waves*, vol. 34, no. 12, pp. 815–823, Dec. 2013.

[11] S. I. Shams, M. Elsaadany, G. Saad, and A. A. Kishk, "Compact wideband dual loop coupler with high power handling capability for radar applications," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 10, pp. 900–902, Oct. 2017.

[12] M. M. M. Ali, S. I. Shams, and A.-R. Sebak, "Low loss and ultra flat rectangular waveguide harmonic coupler," *IEEE Access*, vol. 6, pp. 38736–38744, 2018.

[13] K. Murai, H. Ikeuchi, T. Kawai, M. Kishihara, and I. Ohta, "Broadband design method of SIW directional couplers," in *Proc. China-Japan Joint Microw. Conf.*, Hangzhou, China, Apr. 2011, pp. 1–4.

[14] A. Doghri, T. Djerafi, A. Ghiotto, and K. Wu, "Substrate integrated waveguide directional couplers for compact three-dimensional integrated circuits," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 1, pp. 209–221, Jan. 2015.

[15] 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.

[16] M. Y. Soliman, M. M. M. Ali, S. I. Shams, M. F. A. Sree, D. E. Fawzy, and A. M. M. A. Allam, "Ridge gap waveguide wideband hybrid directional coupler for Ka-band applications," in *Proc. 7th Int. Conf. Electr. Electron. Eng. (ICEEE)*, Apr. 2020, pp. 211–214.

[17] M. M. M. Ali, I. Afifi, and A. R. Sebak, "Design of printed RGW crossover for millimeter wave beam switching network," in *Proc. USNC-URSI Radio Sci. Meeting (Joint AP-S Symp.)*, Jul. 2019, pp. 63–64.

[18] H. Raza, J. Yang, P.-S. Kildal, and E. Alfonso Alos, "Microstrip-ridge gap waveguide–study of losses, bends, and transition to WR-15," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 9, pp. 1943–1952, Sep. 2014.

[19] 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.

[20] T. Djerafi, K. Wu, and S. O. Tatu, "3 db 90° hybrid quasi-optical coupler with air field slab in SIW technology," *IEEE Microw. Compon. Lett.*, vol. 24, no. 4, pp. 221–223, Apr. 2014.

[21] E. Baghernia, M. M. M. Ali, and A. R. Sebak, "2 × 2 slot spiral cavity-backed antenna array fed by printed gap waveguide," *IEEE Access*, vol. 8, pp. 170609–170617, 2020.

[22] I. Afifi, M. M. M. Ali, and A.-R. Sebak, "Analysis and design of a wideband coaxial transition to metal and printed ridge gap waveguide," *IEEE Access*, vol. 6, pp. 70698–70706, 2018.

[23] M. S. Sorkherizi and A. A. Kishk, "Transition from microstrip to printed ridge gap waveguide for millimeter-wave application," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 1588–1589.

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] C. Balanis, *Advanced Engineering Electromagnetics*, 2nd ed. Hoboken, NJ, USA: Wiley, 2012.

[30] 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.

[31] 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.

[32] 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.

[33] 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.

MOHAMED MAMDOUH M. ALI (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, Québec, 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. He is currently a Research Associate with the Institut National de la Recherche Scientifique (INRS), University of Québec, Montréal. His current research interests include microwave reciprocal/nonreciprocal and antenna design.

MOHAMED S. EL-GENDY received the B.Sc. degree in electronics and communication engineering from the University of Menoufia, Egypt, in 2003, and the M.Sc. and Ph.D. degrees from Ain Shams University, Egypt, in 2011 and 2017, respectively. He is currently a Researcher with the Electronics Research Institute (ERI), Cairo, Egypt. His main research interests include microwave and millimeter wave circuit designs and planar antenna systems.

MUATH AL-HASAN (Senior Member, IEEE) received the B.A.Sc. degree in electrical engineering from the Jordan University of Science and Technology, Jordan, in 2005, the M.A.Sc. degree in wireless communications from Yarmouk University, Jordan, in 2008, and the Ph.D. degree in telecommunication engineering from the Institut National de la Recherche Scientifique (INRS), Université du Québec, Canada, in 2015. From 2013 to 2014, he was with Planets Inc., California, USA. In May 2015, he joined the Concordia University, Canada, as Postdoctoral Fellowship. He is currently an Assistant Professor with Al Ain University, United Arab Emirates. His current research interests include antenna design at millimeter-wave and terahertz bands, channel measurements in multiple-input and multiple-output (MIMO) systems, CAD and modeling of microwave and antenna structures, and numerical analysis.

ISMAIL BEN MABROUK (Senior Member, IEEE) received the B.A.Sc. and M.A.Sc. degrees in electrical engineering from the University of Lille, Lille, France, in 2006 and 2007, respectively, and the Ph.D. degree in electrical engineering from the University of Quebec, Canada, in 2012. From 2007 to 2009, he was with Huawei Technologies, Paris, France. In 2012, he joined the Wireless Devices and Systems (WiDeS) Group, University of Southern California, Los Angeles, USA. He is currently an Assistant Professor with Durham University, Durham, U.K. His research interests include antenna design at the millimiter-wave and THz frequencies, propagation studies for multiple-input and multiple-output (MIMO) systems, deep learning, and wireless body area network for medical applications. He was a recipient of the Abu Dhabi Award for Research Excellence (AARE).

ABDELRAZIK 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 involving 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 bio electromagnetics. He is a member of the Canadian National Committee of 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 as the Technical Program Chair for the 2002 IEEE CCECE Conference and the 2006 URSIANTEM Symposium. He is 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 Department of Engineering, Université du Québec à 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-Énergie, Materiaux et Telecommunications (INRS-EMT), Montréal. He has extensive experience in antenna design. He served as a Principal Investigator on 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.

• • •