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

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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° ± 5° 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 There 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
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 ($\lambda_s \times \lambda_d$) |
|----------------|------------|----|-----------------------------|------------------|----------------|-------------------|
| [23] / Metal RGW | 11         | 13% | 11%                         | 13%              | 0.35 dB        | 4 $\times$ 2.7    |
| [24] / Metal RGW | 15         | 14% | 7%                          | N.A              | 0.7 dB         | 1.6 $\times$ 1.6  |
| [25] / Groove GW | 14         | 14.3% | 12.5%                      | 14.3%            | N.A            | 4.7 $\times$ 2.9  |
| [26] / PRGW     | 30         | 6%  | 3%                          | 3%               | 0.8 dB         | 1.1 $\times$ 1.1  |
| [27] / PRGW     | 30         | 26.5% | 13%                        | 23%              | 0.7 dB         | 1.3 $\times$ 1.3  |
| [29] / PRGW     | 30         | 13%  | 6.7%                       | 7%               | 1 dB           | 1.12 $\times$ 1.12 |
| [30] / PRGW     | 60         | 11%  | 11%                        | 11%              | N.A            | 1.9 $\times$ 1.1  |
| The proposed work / PRGW | 30 | 38% | 26.5%                       | 38%              | 0.55 dB        | 1.1 $\times$ 0.97 |

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
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FIGURE 1. Geometry of the proposed PRGW directional coupler.

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.

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 \( H_s = 0.762 \text{ mm} \), 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 \( H_a = 0.254 \text{ mm} \), while the dimensions of the mushroom inclusions are the following: the period between unit cells \( d = 1.62 \text{ mm} \), the lateral dimension \( W = 1.42 \text{ mm} \), and via radius \( R_v = 0.19 \text{ mm} \). 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 is achieved by cutting an elliptical slot in both ground planes of a thin RT6002 substrate with \( H_a = 0.13 \text{ mm} \). 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 \( W_R = 1.5 \text{ mm} \) 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 \( H_t = 0.254 \text{ mm} \) 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
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 \( Z_{\text{odd}} \) 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 characteristic impedance \( Z_{\text{even}} \), 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 \( Z_{\text{odd}} \) and \( Z_{\text{even}} \) 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:

\[
Z_0 = \sqrt{Z_{\text{even}} Z_{\text{odd}}} \tag{1}
\]

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]:

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

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...
can be described as shown in Fig. 8. In this work, the line impedance $Z_o$ is selected to be larger than 50 $\Omega$ in order to allow deploying impedance transformers to match $Z_o$ to a 50 $\Omega$ 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 $\sim -15$ 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 $\pm 0.5$ 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
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 ± 5° 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° ± 5°) have been achieved over the operating bandwidth. The proposed directional coupler can be considered a good candidate for the implementation of millimeter ultra-wideband beam switching networks for 5G applications.

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