Design and development of broadband gap waveguide-based 0-dB couplers for Ka-band applications

Citation for the original published paper (version of record):
Zarifi, D., Farahbakhsh, A., Uz Zaman, A. (2022). Design and development of broadband gap waveguide-based 0-dB couplers for Ka-band applications. IET Microwaves, Antennas and Propagation, 16 (11): 718-724. http://dx.doi.org/10.1049/mia2.12287

Received: 16 May 2022 | Revised: 22 July 2022 | Accepted: 27 July 2022
IET Microwaves, Antennas & Propagation
DOI: 10.1049/mia2.12287

ORIGINAL RESEARCH

Design and development of broadband gap waveguide-based 0-dB couplers for Ka-band applications

Davoud Zarifi[1] | Ali Farahbakhsh[2] | Ashraf Uz Zaman[3]

[1]School of Electrical Engineering, University of Kashan, Kashan, Iran

[2]School of Electrical Engineering, Graduate University of Advanced Technology, Kerman, Iran

[3]Department of Signals and Systems, Chalmers University of Technology, Goteborg, Sweden

Correspondence
Davoud Zarifi, School of Electrical Engineering, University of Kashan, Kashan, 8731753153, Iran.
Email: zarifi@kashanu.ac.ir

Abstract

The design and fabrication of a wideband millimetre-wave 0-dB coupler is proposed in this paper using gap waveguide technology for low-loss and high-power applications in 30-GHz frequency band. To overcome the fabrication challenges in millimetre-wave frequencies, the gap waveguide technique is utilised. Two gap waveguide-based coaxial- and waveguide-fed 0-dB couplers are designed with broadband performance, high return loss, acceptable coupling flatness and high isolation. For verifying the performance of the proposed structures, a prototype of the waveguide-fed 0-dB coupler is manufactured and measured. The measurement results show that the return and insertion losses and the isolation of the fabricated 0-dB coupler is better than 18 dB, 0.5 and 18 dB, respectively, in the specified frequency range from 26.2 to 34 GHz. Moreover, the breakdown power level of the proposed millimetre-wave structures is in kW orders to satisfy the high-power requirements.

KEYWORDS
0-dB coupler, Gap waveguide, ka-band, millimetre-wave components

1 | INTRODUCTION

In the microwave circuits and systems, it is important to find an effective solution for routing signals via a common microwave component while maintaining high isolation between two signals. Microwave 0-dB couplers or crossovers are known as two crossing transmission lines used in microwave systems and circuits, which achieve the above-mentioned functionality. 0-dB couplers are widely used in feed networks of antenna arrays, Butler matrix for beam-forming technique and high-density printed circuit boards. Low insertion loss, input matching, high isolation, appropriate power handling, wide operating bandwidth and compact structure are known important parameters for a 0-dB coupler.

A variety of structures and methods have been presented in the literature for microwave 0-dB couplers, such as multi-section couplers [1–4], intact and defected ground structures [5–11], and microstrip to coplanar waveguide transition [12–14]. For technologies of microstrip, substrate integrated waveguide and low-temperature co-firing ceramic in microwave and millimetre-wave bands, the main limiting factors are high dielectric loss, limited power handling and unwanted leakage via substrate modes, all deteriorating the performance of the printed 0-dB couplers.

At millimetre-wave frequencies and high power applications, waveguide 0-dB couplers are often used as the best candidates because of the high performance, great isolation and high power handling capabilities. Unfortunately, extremely accurate and high precision fabrication processes should be used to design and fabrication of this kind of structures by using costly and time-consuming manufacturing procedures such as diffusion bonding, metal brazing techniques etc. The aforementioned challenges can be overcome with gap waveguide technology (GWT). With the development of numerous new millimetre-wave applications in the recent years, GWT has gotten a lot of attention [15–17]. There is a clear need to develop GWT that not only maintains the advantages of other technologies but also addresses the above mentioned fabrication and assembly challenges, especially at millimetre-wave frequency range. According to the review of literature, GWT has been used to design a wide range of microwave and high-frequency components, such as planar array antenna [18–22], filter [23–26], coupler [27–30], phase shifter [31, 32] and switch [33, 34].

Recently, millimetre-wave microwave 0-dB couplers using printed ridge gap waveguide (RGW) are proposed and fabricated [35, 36]. Over a 13% operational bandwidth in 30 GHz frequency band, the measurement results indicate that the return loss of the proposed coupler is better than 15 dB, the insertion loss is about 0.5 dB, and the isolation level of the input port and the other two ports is higher than 15 dB. The printed 0-dB coupler's key disadvantages are its high loss, poor separation, and low power handling capability that prevent its usage in high power millimetre-wave applications. In addition, to the authors' knowledge, millimetre-wave hollow waveguide 0-dB couplers have been rarely reported in the literature. In this contribution, the aim of the present study is to utilise GWT to develop and fabricate waveguide 0-dB couplers which can be utilised in antenna beam forming networks.

The paper is organised as follows. Section 2 and Section 3 are devoted to design and simulation of RGW and groove gap waveguide (GGW)-based 0-dB couplers. The details of the manufacturing and measurement procedures are presented in Section 5. Finally, Section 4 presents the conclusions and summary.

2 | DESIGN OF RGW-BASED 0-DB COUPLER

As shown in Figure 1, in RGW and GGW structures, the frequency stop-band of a parallel plate waveguide with one perfect electric conductor and one perfect magnetic conductor plates is utilised to confine the propagation of the electromagnetic waves along desirable paths. The desired stop frequency band from 20 to 40 GHz is achieved by choosing $a = 1$ mm, $d = 3$ mm, $p = 1.8$ mm, and $g = 0.5$ mm.

At high operating frequency bands, the 0-dB couplers are placed in the planar structures to prevent the interference of electromagnetic waves at the line intersection. As shown in Figure 2, by cascading two 3-dB hybrid couplers, a conventional 0-dB coupler can be achieved. The feeding ports of 0-dB coupler are ports 1–4. When a wave is fed into port 1, it will not appear at ports 2 and 4. Also, the wave fed into port 4 will not emerge at ports 1 and 2. Low insertion loss and high return loss and isolation are the most important parameters of a 0-dB coupler.

Topology of the designed RGW-based 0-dB coupler formed with two cascaded hybrid 3-dB couplers is depicted in Figure 3. The width and length of the coupling section should be adjusted to achieve the desired power splitting ratio. After optimisation, the optimised design values are given as $w_0 = 1$ mm, $w_1 = 0.95$ mm, $w_2 = 1.12$ mm, $w_3 = 2.56$, $l_1 = 8.67$ mm and $l_2 = 6.49$ mm. The proposed 0-dB coupler S-parameters are simulated and illustrated in Figure 4. The results indicate the narrowband behaviour of the structure. The insertion loss and the return loss are better than −0.1 and

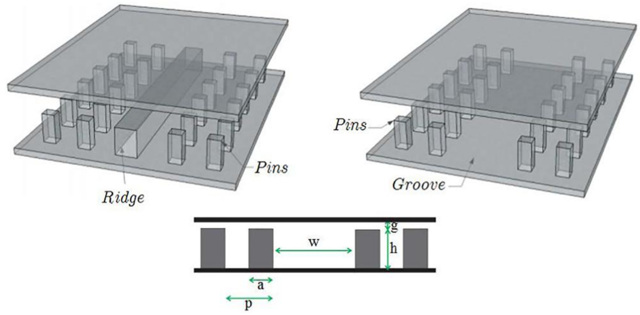

FIGURE 1 Topology of ridge and groove gap waveguide (GGW) structures

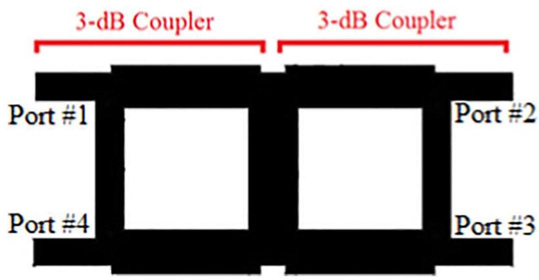

FIGURE 2 The configuration of a conventional 0-dB coupler

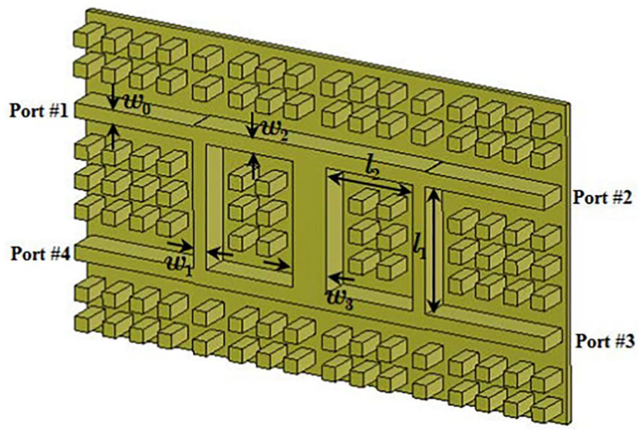

FIGURE 3 The configuration of RGW-based 0-dB coupler. Top metal plate is not shown

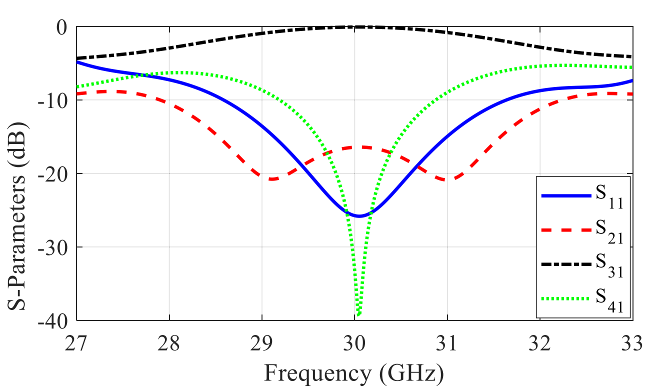

FIGURE 4 Simulated S-parameters of RGW-based 0-dB coupler

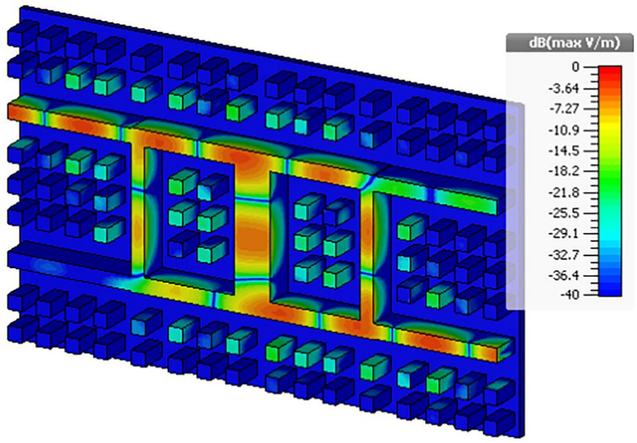

FIGURE 5 Electric field distribution of the RGW-based 0-dB coupler at 30 GHz

15 dB over the frequency band from 29 to 31 GHz, respectively. Moreover, the isolation level of port 1 and ports 2 and four is higher than 17 and 35 dB at 30 GHz, respectively. The electric field distribution of the RGW-based 0-dB coupler depicted in Figure 5 verifies the S-parameters results.

3 | DESIGN OF WIDEBAND GGW-BASED 0-DB COUPLER

The SIW-based and rectangular waveguide cruciform directional couplers are composed of two crossed waveguide sections in which some metal posts are employed to control the signal flow in the desired direction [37]. In this type of couplers, the coupling level between the output ports can effectively be adjusted in the range of 0.5–7 dB by tuning the position and dimension of metal posts. Here, in order to implement a wideband 0-dB coupler, we can use a combination of two 3-dB cruciform directional couplers.

The configurations of the proposed four-port GGW-based 0-dB couplers are illustrated in Figure 6. Observe that the coupler topology is composed of two GGW branches crossing each other at right angles. Port 1 is the input port, port 3 is through port, and ports 2 and 4 are isolated ports. In the coupling zone, some metallic pins (Pin 2, Pin 3 and Pin 4) are arranged to control the division of the input signal for achieving the required 0-dB coupling and isolation specifications. Also, one pin (Pin 1) is inserted at each GGW branch close to the coupling region to minimise the reflections.

To feed the 0-dB coupler with the standard connectors or waveguides, transitions from GGW to the SubMiniature A (SMA) connector and rectangular waveguide are required, as depicted in Figure 6. In the coaxial-fed case, each GGW branch of the 0-dB coupler is interconnected to a SMA connector. The electromagnetic fields from the TE_{10} mode of GGW mode is transformed to the transverse electro-magnetic mode of coaxial connector in this transition. To make an impedance matching over the required bandwidth, the length of probe and its distance to the end wall should be tuned. In the waveguide-fed case, the 0-dB coupler is excited with standard Ka-band rectangular waveguides (WR-28: 7.11 × 3.56 mm^2) from the bottom plate. Each branch of the 0-dB coupler is connected with a transition from GGW to WR-28. As shown in Figure 6b, to make an appropriate impedance matching, metal bricks with extensions to the waveguide ports are inserted in the ends of grooves on the bottom plate of the structure. To minimise the reflection, all the parameters of the transition section should be optimised.

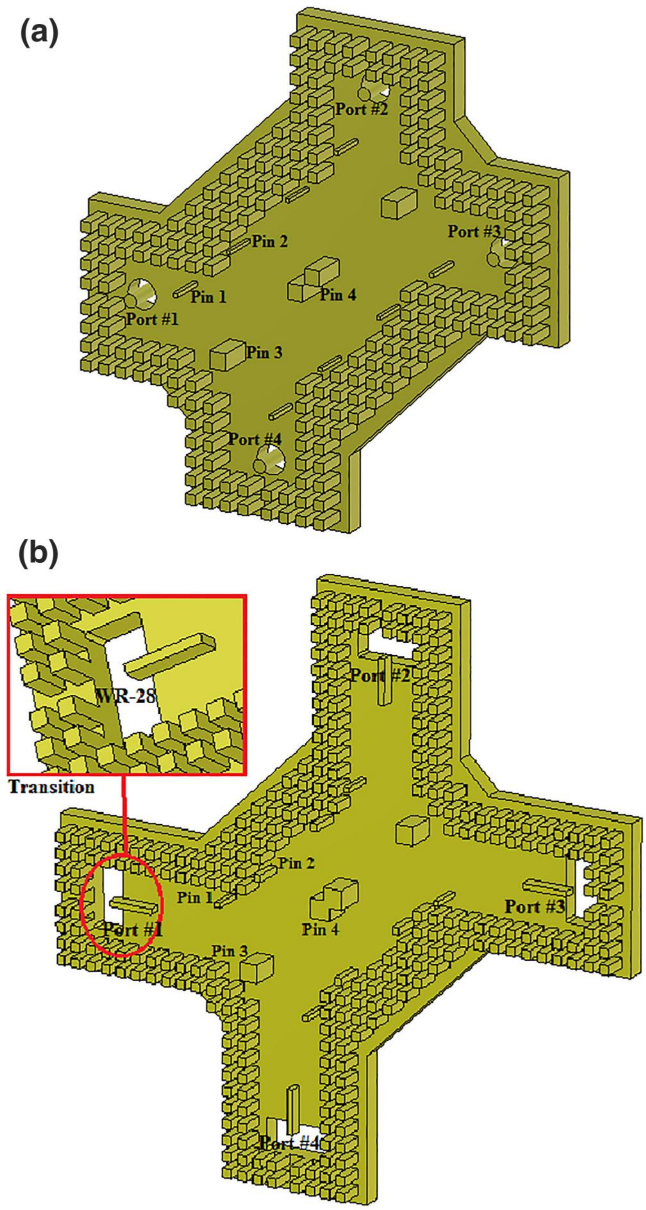

FIGURE 6 The configuration of wideband GGW-based 0-dB couplers. (a) Coaxial-fed case. (b) Waveguide-fed case. The top metal plates are not shown

The 0-dB coupler is intended to operate at 30 GHz frequency band with maximum bandwidth, reflection level below −20 dB, isolation level greater than 20 dB and insertion loss less than 0.5 dB. To achieve these specifications, by considering the error function as

TABLE 1 Design parameters of coaxial-fed (I) and waveguide-fed (II) GGW-Based 0-DB couplers

Component	Parameter	Value (I) (mm)	Value (II) (mm)
Pin 1	Dimension	0.43	0.56
	Distance to side wall	2.08	1.18
	Distance to coupling region	3.37	2.67
Pin 2	Dimension	0.4	0.77
	Distance to side wall	1.79	1.33
Pin 3	Dimension	1.71	1.96
	Distance to side wall	2.62	2.17
Pin 4	Dimension	1.54	2.13
Grooves	Width of side grooves	8.69	8.77
	Width of centre groove	14.87	14.92
WR-28 transition	Length of brick	-	4.95
	Height of brick	-	1.42
	Width of brick	-	0.60
SMA transition	Length of probe	2.12	-
	Distance to side wall	1.79	-
Bottom metal plate	Thickness	10	10
Top metal plate	Thickness	1	1
Feed waveguides	Length	-	7.11
	Width	-	3.56

Abbreviation: SMA, SubMiniature A.

$$\text{Fitness} = \sqrt{\frac{1}{M}\sum_{m=1}^{M}\left(|S_{11}(f_m)|^2 + |S_{21}(f_m)|^2 + |1-|S_{31}(f_m)||^2 + |S_{41}(f_m)|^2\right)} \quad (1)$$

The geometrical dimensions of proposed 0-dB coupler structure are optimised with the help of Computer Simulation Technology Microwave Studio software at M frequency samples (f_m) over the defined frequency range. The optimised values for the design parameters are tabulated in Table 1.

The simulated S-parameters of RGW-based 0-dB couplers are illustrated in Figure 7. In the simulations, the metallic structure is assumed to be aluminium with $\sigma = 3.6 \times 10^7$ S/m. The results reveal that for both coaxial-and waveguide-fed structures, the input reflection level is below −20 dB, while the isolation between input port and output ports 3 and 4 are better than 20 dB over the frequency range of 25.7–34.5 GHz. The simulated transmission coefficients of input port to output port 3 is larger than −0.2 dB from 26.3 to 34 GHz. Observe that at frequencies below 26 GHz, the near cut-off behaviour of the rectangular waveguide-fed structure leads to deteriorate the input reflection coefficient. Figure 8 shows the electric field distribution of the GGW-based 0-dB couplers at 30 GHz.

The size and location of matching pin (d_1: distance to side wall; s_1: distance to coupling region) will significantly have an

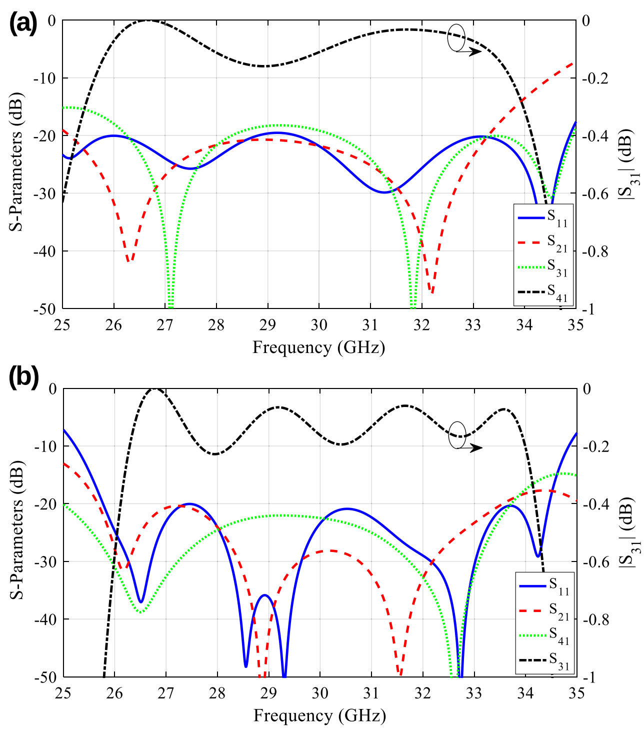

FIGURE 7 Simulated S-parameters of wideband GGW-based 0-dB couplers. (a) Coaxial-fed case. (b) Waveguide-fed case

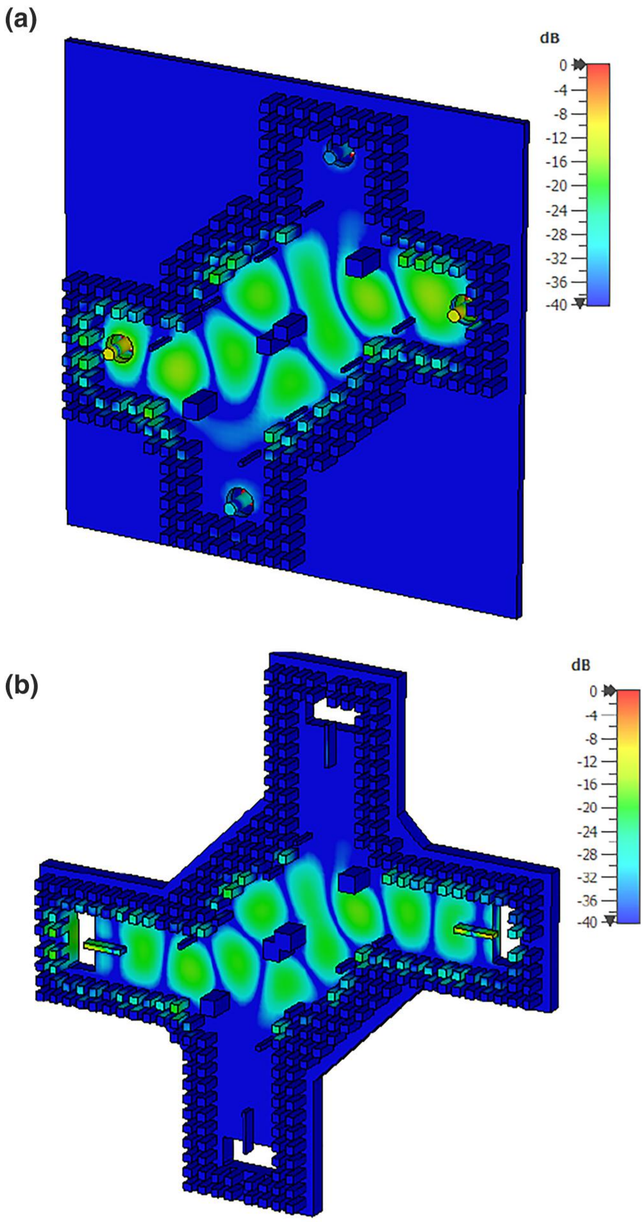

FIGURE 8 Electric field distribution of the GGW-based 0-dB couplers at 30 GHz. (a) Coaxial-fed case. (b) Waveguide-fed case

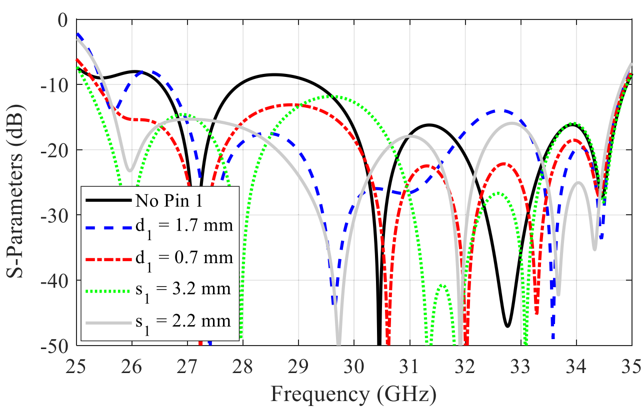

FIGURE 9 Simulated reflection coefficient of wideband waveguide-fed GGW-based 0-dB coupler by swiping Pin 1 position

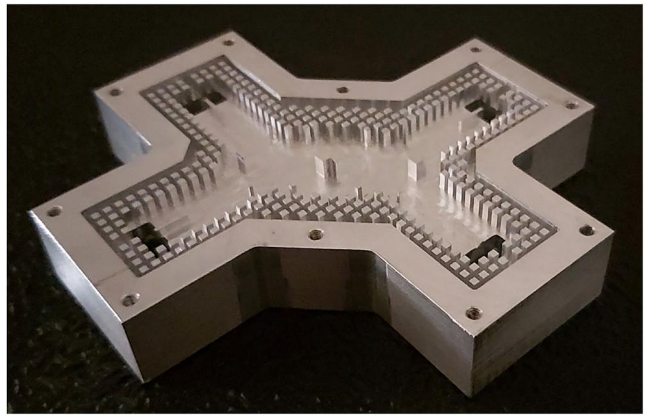

FIGURE 10 Photograph of the fabricated prototype of waveguide-fed GGW-based 0-dB coupler

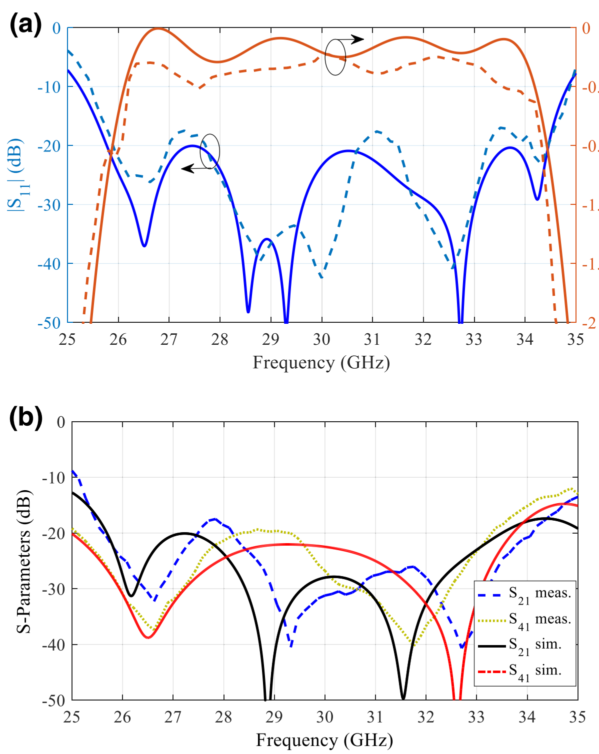

FIGURE 11 Measured S-parameters of manufactured wideband waveguide-fed GGW-based 0-dB coupler

effect on the amount of return loss at the input port. Also other pins control the division of the input signal to output ports. To investigate the role of these geometrical dimensions in the performance of 0-dB coupler, some parameter studies are performed and the results are drawn in Figure 9. Further studies shows that there is no serious challenge in the fabrication process, because available fabrication techniques ensure an accuracy of 0.05 mm.

To evaluate the power handling capacity of the proposed 0-dB coupler, the structure is excited by an electromagnetic wave with 1-W power. The simulated maximum electric field in the structure is 50,291 V/m. Since the air breakdown is 3 MV/m,

TABLE 2 Measurement results comparison of the proposed 0-dB couplers with other millimetre-wave structures

Ref.	Tech.	Freq. (GHz)	B. W (%)	R. L (dB)	I. L (dB)	Iso. (dB)
[3]	Microstrip	30	3	13	0.7	17
[6]	SIW	30	16.7	14	2	18
[7]	SIW	35	16.6	17	0.9	17
[9]	SIW	20	2.4	21	1.6	30
[11]	SIW	20	6.6	18.5	1.05	20
[35]	Printed RGW	30	13.3	15	0.5	15
[36]	Printed RGW	30	13	15	0.5	20
This work	GGW	30	25.9	18	0.5	18

the power handling capacity of the structure can reach up to 3.5 kW [34].

4 | FABRICATION AND EXPERIMENTAL RESULTS

For the proof of concept and to validate the simulation results, a prototype of proposed high-power waveguide-fed 0-dB coupler is fabricated in low-loss AA6061 aluminium by standard milling techniques. The photograph of the fabricated prototype is shown in Figure 10. The measurements are performed by using the Agilent 8722ES vector network analyser.

The simulated and measured results for S-parameters of 0-dB coupler against frequency for comparison are illustrated in Figure 11. The measured reflection and isolation levels are better than 18 dB, while the insertion loss of 0-dB coupler is less than 0.5 dB over the frequency range of 26.2–34 GHz. There is a reasonable agreement between the measurement and simulation results, and the software simulation is confirmed by the measurements. Some minor deviations between the experimental and simulation results may be attributed to the manufacturing tolerances and miss-alignment of the WR-28 feeding adaptors.

To evaluate the proposed design, the performance of the present work is compared with some similar previously reported 0-dB couplers in Table 2. The proposed coupler has a broad bandwidth of 25.9% with excellent return loss and insertion loss in comparison with the other similar structures. Although the SIW- and printed RGW-based 0-dB couplers have usually smaller size due to dielectric substrate, their power handling capacity and bandwidth are lower. In the future, it is expected to use this design to realise feed network of high gain dual-polarised slot antenna arrays.

5 | CONCLUSION

In this paper, two wideband coaxial- and waveguide-fed 0-dB couplers based on GWT have been proposed for 30 GHz applications. Gap waveguide technology has been used to remove fabrication and assembling challenges. The return loss and isolation levels of the manufactured 0-dB coupler are higher than 18 dB in the frequency range of 26.2–34 GHz. The proposed 0-dB coupler with high power handling and wide band operation is an appropriate candidate for Ka-band satellite telecommunication applications.

ACKNOWLEDGEMENT

None.

CONFLICT OF INTEREST

The authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licencing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

None.

DATA AVAILABILITY STATEMENT

Research data are not shared.

ORCID

Davoud Zarifi https://orcid.org/0000-0002-0703-6909

REFERENCES

1. Ohta, I., et al.: Cruciform directional couplers in H-plane rectangular waveguide. In: Proceeding Asia–Pacific Microwave Conference, vol. 2, pp. 1–4 (2005)
2. Yao, J., Lee, C., Yeo, S.P.: Microstrip branch-line couplers for crossover application. IEEE Trans. Microw. Theory Techn. 59(1), 87–92 (2011). https://doi.org/10.1109/tmtt.2010.2090695
3. Ye, X.F., Zheng, S.Y., Deng, J.H.: A compact patch crossover for millimeter-wave applications. In: 2015 International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), pp. 1–2 (2015)
4. Djerafi, T., Fonseca, N.J.G., Wu, K.: Design and implementation of a planar 4 × 4 butler matrix in SIW technology for wide band high power applications. Progress in Electromagn. Res. B 35, 29–51 (2011). https://doi.org/10.2528/pierb11062004

5. Tang, C.-W., Lin, K.-C., Chuang, W.-M.: Design of a microstrip dual-band crossover with asymmetrical π-shaped transmission lines. IEEE Microw. Wireless Compon. Lett. 25(9), 588–590 (2015). https://doi.org/10.1109/lmwc.2015.2451398
6. Zheng, S.Y., Ye, X.F.: Ultra-compact wideband millimeter-wave crossover using slotted SIW structure. In: Proc. IEEE iWEM, pp. 1–2 (2016)
7. Guntupalli, A.B., Djerafi, T., Wu, K.: Ultra-compact millimeter-wave substrate integrated waveguide crossover structure utilizing simultaneous electric and magnetic coupling. In: IEEE MTT-S International Microwave Symposium Digest, pp. 1–3 (2012)
8. Pang, Y.-H., Lin, E.D., Chen, Y.-Y.: A planar balanced crossover. IEEE Trans. Microw. Theory Techn. 64(6), 1812–1821 (2016). https://doi.org/10.1109/tmtt.2016.2551703
9. Han, S., et al.: Novel substrate integrated waveguide filtering crossover using Orthogonal degenerate modes. IEEE Microwave and Wireless Components Letters. 27(9), 803–805 (2017). https://doi.org/10.1109/lmwc.2017.2734842
10. Bayat, M., Shahi, H., Mazloum, J.: Dual-band balanced-to-single ended crossover based on composite right- and left-handed transmission lines. Electron. Lett. 56(8), 380–382 (2020). https://doi.org/10.1049/el.2019.3612
11. Zhou, Y., et al.: Substrate-integrated waveguide filtering crossovers with improved selectivity. Int J RF Microw Comput Aided Eng. 30(3) (2019). https://doi.org/10.1002/mmce.22067
12. Tajik, A., Fakharzadeh, M., Mehrany, K.: DC to 40-GHz compact single-layer crossover. IEEE Microw. Wireless Compon. Lett. 28(8), 642–644 (2018). https://doi.org/10.1109/lmwc.2018.2843134
13. Tajik, A., Alavijeh, A.S., Fakharzadeh, M.: Asymmetrical 4×4 Butler matrix and its application for single layer 8×8 Butler matrix. IEEE Trans. Antennas Propag. 67(8), 5372–5379 (2019)
14. Amini, A., Shahi, H., Mehri, M.: A single-layer balanced directional coupler design based on crossover structures. IEEE Transactions on Microwave Theory and Techniques. 68(8), 3298–3307 (2020). https://doi.org/10.1109/tmtt.2020.2995796
15. Kildal, P.-S., et al.: Local metamaterial-based waveguides in gaps between parallel metal plates. IEEE Antennas Wireless Propag. Lett. 8(4), 84–87 (2009). https://doi.org/10.1109/lawp.2008.2011147
16. Rajo-Iglesias, E., Kildal, P.-S.: Numerical studies of bandwidth of parallel-plate cut-off realised by a bed of nails, corrugations and mushroom-type electromagnetic bandgap for use in gap waveguides. IET Microw., Antennas Propag. 5(3), 282–289 (2011). https://doi.org/10.1049/iet-map.2010.0073
17. Kildal, P.-S., et al.: Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression. IET Microw., Antennas Propag. 5(3), 262–270 (2011). https://doi.org/10.1049/iet-map.2010.0089
18. Zaman, A.U., Kildal, P.-S.: Wide-band slot antenna arrays with single-layer corporate-feed network in ridge gap waveguide technology. IEEE Trans. Antennas Propag. 62(6), 2992–3001 (2014). https://doi.org/10.1109/tap.2014.2309970
19. Zarifi, D., et al.: Design and fabrication of a high-gain 60-GHz corrugated slot antenna array with ridge gap waveguide distribution layer. IEEE Trans. Antennas Propag. 64(7), 2905–2913 (2016). https://doi.org/10.1109/tap.2016.2565682
20. Ferrando-Rocher, M., et al.: Dual circularly polarized Aperture array antenna in gap waveguide for high-efficiency ka-band satellite communications. IEEE Open Journal of Antennas and Propagation. 1, 283–289 (2020). https://doi.org/10.1109/ojap.2020.3001087
21. Palomares-Caballero, A., et al.: Millimeter-wave 3-D-printed antenna array based on gap-waveguide technology and split E-plane waveguide. IEEE Transactions on Antennas and Propagation. 69(1), 164–172 (2021). https://doi.org/10.1109/tap.2020.3008620
22. Farjana, S., et al.: Realizing a 140 GHz gap waveguide–based array antenna by low-cost injection molding and micromachining. Journal of Infrared Milli Terahz Waves (2021)
23. Alós, E.A., Zaman, A.U., Kildal, P.-S.: Ka-band gap waveguide coupled-resonator filter for radio link diplexer application. IEEE Trans. Compon., Packag., Manuf. Technol. 3(5), 870–879 (2013). https://doi.org/10.1109/tcpmt.2012.2231140
24. Sun, D., Xu, J.: A novel Iris waveguide bandpass filter using air gapped waveguide technology. IEEE Microwave and Wireless Components Letters. 26(7), 475–477 (2016). https://doi.org/10.1109/lmwc.2016.2574822
25. Rezaee, M., Uz Zaman, A.: Groove gap waveguide filter based on horizontally polarized resonators for V-band Applications. IEEE Transactions on Microwave Theory and Techniques. 68(7), 2601–2609 (2020). https://doi.org/10.1109/tmtt.2020.2986111
26. Ahmadi, B., Banai, A.: Substrateless amplifier module realized by ridge gap waveguide technology for millimeter-wave applications. IEEE Trans. Microw. Theory Techn. 64(11), 3623–3630 (2016). https://doi.org/10.1109/tmtt.2016.2607177
27. Shams, S.I., Kishk, A.: Design of 3-dB hybrid coupler based on RGW technology. IEEE Trans. Microw. Theory Tech. 65(10), 3849–3855 (2017). https://doi.org/10.1109/tmtt.2017.2690298
28. Zarifi, D., Farahbakhsh, A., Zaman, A.U.: Design and fabrication of wideband millimeter-wave directional couplers with different coupling factors based on gap waveguide technology. IEEE Access. 7, 88822–-88829 (2019). https://doi.org/10.1109/access.2019.2926233
29. Zhao, Z., Denidni, T.A.: Millimeter-wave printed-RGW hybrid coupler with symmetrical square feed. IEEE Microwave and Wireless Components Letters. 30(2), 156–159 (2020). https://doi.org/10.1109/lmwc.2019.2960475
30. Nasri, M., Zarifi, D., Zaman, A.U.: A wideband 3-dB directional coupler in GGW for use in V-band communication systems. IEEE Access 8, pp. 17819–17823 (2020). https://doi.org/10.1109/access.2020.2968609
31. Escuderos, D.S., et al.: True-time-delay mechanical phase shifter in gap waveguide technology for slotted waveguide arrays in ka-band. IEEE Trans. Antenna Propag., Early Access (2020)
32. Abdollahy, H., Farahbakhsh, A., Ostovarzadeh, M.: Mechanical reconfigurable phase shifter based on gap waveguide technology. AEU-International Journal of Electronics and Communications. 132, 153655 (2021). https://doi.org/10.1016/j.aeue.2021.153655
33. Tayebpour, J., et al.: A waveguide switch based on contactless gap waveguide technology. IEEE Microwave and Wireless Components Letters. 29(12), 771–774 (2019). https://doi.org/10.1109/lmwc.2019.2950164
34. Alazemi, A., Farahbakhsh, A., Zarifi, D.: A 12-20 GHz wideband high-power SP2T switch based on gap waveguide technology. Sensors 21(16), 5396 (2021). https://doi.org/10.3390/s21165396
35. Ali, M.M.M., Sebak, A.: Compact printed ridge gap waveguide crossover for future 5G wireless communication system. IEEE Microwave and Wireless Components Letters. 28(7), 549–551 (2018). https://doi.org/10.1109/lmwc.2018.2835149
36. Ali, M.M.M., Afifi, I., Sebak, A.R.: Design of printed RGW crossover for millimeter wave beam switching network. In: 2019 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), pp. 63–64 (2019)
37. Djerafi, T., Wu, K.: Super-compact substrate integrated waveguide cruciform directional coupler. IEEE Microwave and Wireless Components Letters. 17(11), 757–759 (2007). https://doi.org/10.1109/lmwc.2007.908040

How to cite this article: Zarifi, D., Farahbakhsh, A., Zaman, A.U.: Design and development of broadband gap waveguide-based 0-dB couplers for Ka-band applications. IET Microw. Antennas Propag. 16(11), 718–724 (2022). https://doi.org/10.1049/mia2.12287