AUT Journal of Electrical Engineering

AUT J. Elec. Eng., 56(2) (2024) 165-174
DOI: 10.22060/eej.2024.22597.5551

Design and Simulation of Bethe Hole Coupler Using Ridge Gap Waveguide Technology for Satellite Communication

K. Salehian, Gh. Moradi*

Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

ABSTRACT: In this research paper, an innovative approach is employed to design and simulate a Bethe hole coupler utilizing ridge gap waveguide (RGW) technology. The RGW structure includes two parallel metal plates, a ridge, and strategically placed pins. To achieve the coupler structure, we place two waveguides facing each other, and between these two waveguides, there is a perforated metal plate. Initially, four holes are set in the plate between the waveguides to enhance the coupling coefficient's bandwidth. The radius of the holes is initially calculated and designed to achieve a 20 dB coupling. The validity of the design is confirmed using CST software. RGW transition design is usually more difficult than other gap waveguide structures. For this reason, in this paper, a technique called Step Ridge Waveguide Excitation (SRWE) is introduced for efficient excitation of the designed coupler. The proposed methodology is implemented in the Ku band, which is suitable for satellite communication with high bandwidth. The dimensions of our structure are 50mm × 30mm × 17mm. Additionally, a 20±2 dB coupling coefficient is obtained for a fractional bandwidth (FBW) of approximately 29%. It demonstrates a directivity range of 6-16 dB, and the isolation is lower than 23 dB, surpassing the performance of similar previous works.

Review History:

Received: Aug. 04, 2023
Revised: Oct. 05, 2023
Accepted: Jan. 11, 2024
Available Online: Mar. 01, 2024

Keywords:

Bethe hole coupler
Ridge gap waveguide
SRWE
Step Ridge Waveguide Excitation

1- Introduction

Couplers are one of the building blocks of many microwave and millimeter wave components. Waveguide and microstrip couplers are known as the most common types of these components. Implementing couplers in different technologies such as microstrips [1,2], waveguides [3], and SIWs [4] can create design limitations for us, resulting in trade-offs between different structures in different technologies. Waveguides are big structures against microstrips, so they can carry more microwave power but they cannot simply integrate with electronic circuits. SIW's in this sense is between waveguides and microstrips. gap waveguide technology was developed in [5], is a new technology with some advantages due to classical waveguides. Recently, manufacturing problems in mm-wave and THz designs motivated consideration of the gap waveguide technology [6-9]. They use soft and hard surfaces. These surfaces act as periodic strips of the perfect electric conductor (PEC) and perfect magnetic conductor (PMC) surfaces. For hard surfaces, the corrugation must be filled with a dielectric material that has a dielectric constant larger than the permittivity of the medium above the surface. The direction of the wave propagation relative to the direction of corrugation determines whether it enables or prevents wave propagation at the surface. Because of passing waves through an air gap, this technology has a low loss against some types of waveguides. Three common types of gap waveguide technology are groove gap waveguide (GGW) [10-12], microstrip gap waveguide (MGW) [13], and ridge gap waveguide (RGW) [14,15]. RGW is used for the designed coupler in this paper. In Section 2, we discuss the RGW structure. The design and simulation of the Bethe hole coupler are presented in section 3. In section 4, the transition method that runs in *Ku* band for having a 20 dB coupling coefficient is proposed. Finally, in section 5, we express the conclusion.

2- Ridge gap waveguide structure

The geometry of the RGW is shown in Figure 1. In this structure, the field propagates through a gap between the top plane and metal pins. Unlike common waveguides such as rectangular or circular waveguides, the RGW does not require electrical contact between planes. To achieve desired parameters in *Ku* band, full-wave simulation is performed to obtain the cutoff frequency of the structure. This frequency must be lower than 12 GHz and the band gap must continue at least until 18 GHz. Dimensions were chosen to achieve a stop band from 12 to 18 GHz, and the desired parameters are depicted in Table 1. The band gap is also illustrated in Figure 2. As can be seen in Figure 2, the first bandgap of the dispersion curve spans 7.5 GHz to 21 GHz. it should be noted

*Corresponding author's email: ghmoradi@aut.ac.ir

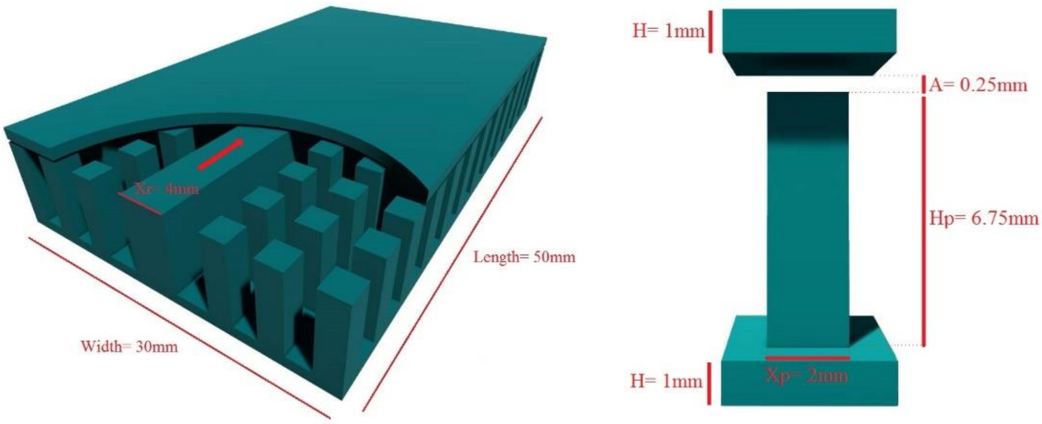

Fig. 1. RGW structure. (a)The side view of the designed waveguide in the Ku band. (b) Enlarged view of the pins.

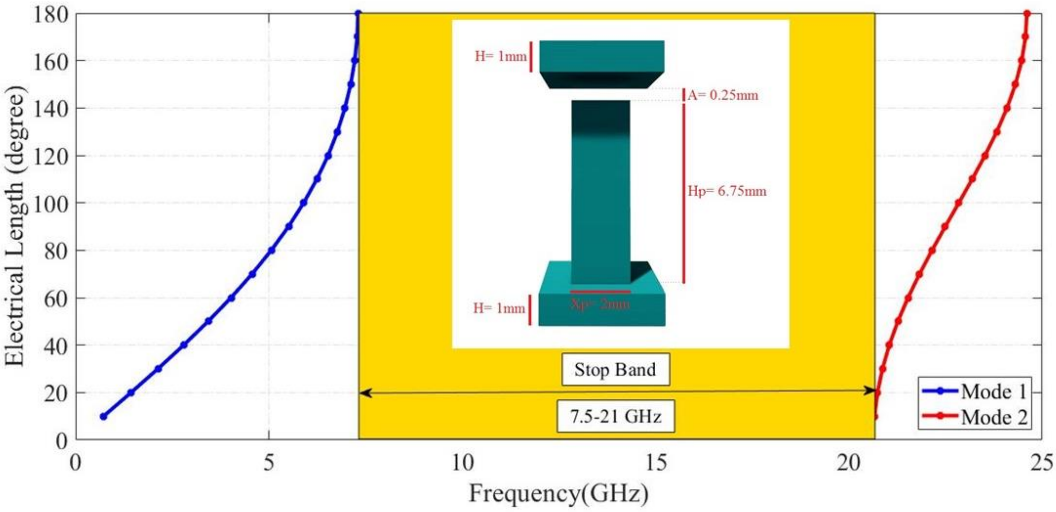

Fig. 2. The band gap between the first and second modes of propagation.

Table 1. Parameters for the designed ridge gap waveguide.

Parameters	Value (mm)
Width (Width of structure)	30
Length (Length of structure)	50
X_p (Width and length of Pins)	2
H_p (Height of pins)	6.75
X_r(Width of ridge)	4
H (Total height of structure)	17

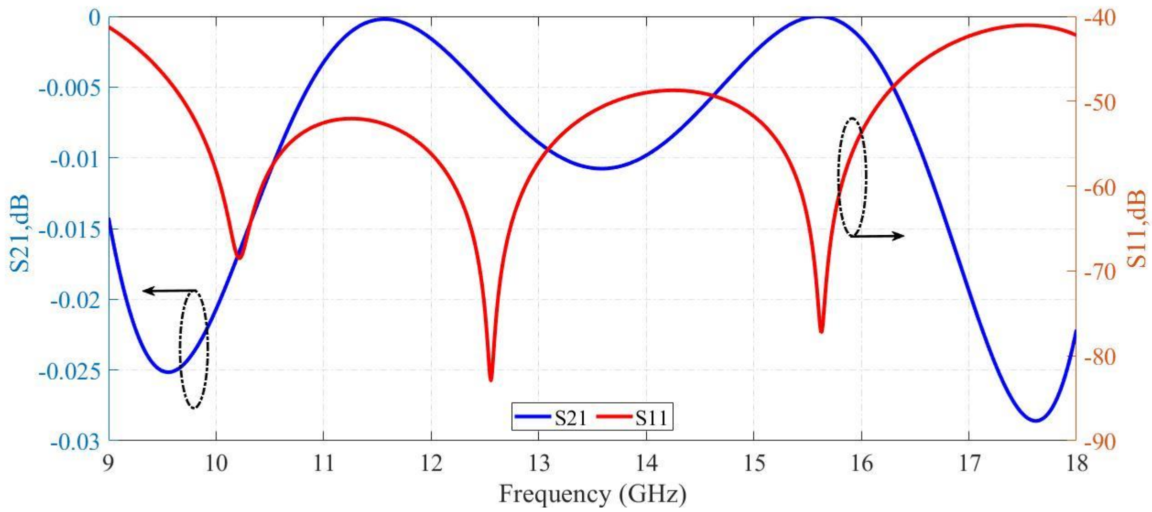

Fig. 3. Return loss and transmission coefficient of the designed ridge gap waveguide.

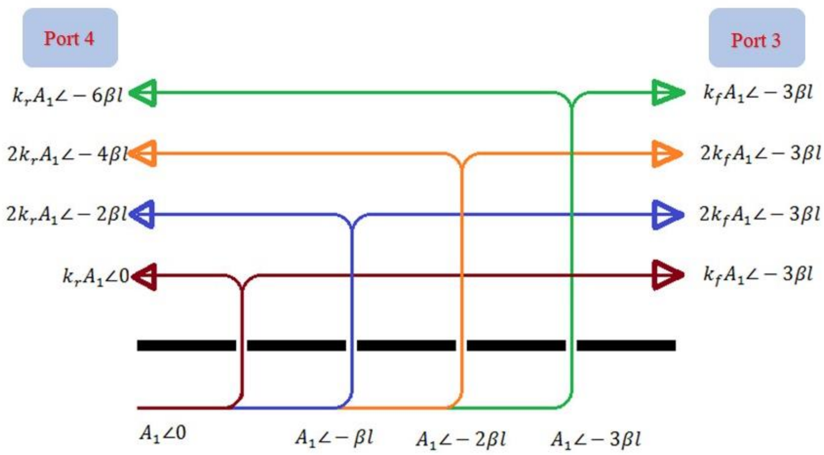

Fig. 4. The third and fourth ports of the four-hole directional coupler.

that using the small air gap (compared to λ/4) is crucial for preventing stop-band effects. The detailed analysis of these structures is found in [5], [16,17].

3- Design and simulation of *Ku* Band Bethe hole coupler

3- 1- Design Bethe hole coupler

To design the Bethe hole coupler, first, we assume that the coupling coefficients of holes are 1,2,2,1, then we define the coupling coefficient as $C = 10\log\frac{P_1}{P_3}$, for an incident wave at port 1, the phasor sum of four waves at ports 3 and 4 is given by:

$$B_4 = k_r A_1 (1\angle 0 + 2\angle -2\beta l + 2\angle -4\beta l + 1\angle -6\beta l) \quad (1)$$

$$B_3 = 6 k_f A_1 \angle -3\beta l \quad (2)$$

where k_f and k_r are the forward and reverse aperture coupling coefficients.

To obtain a 20 dB coupling coefficient we have

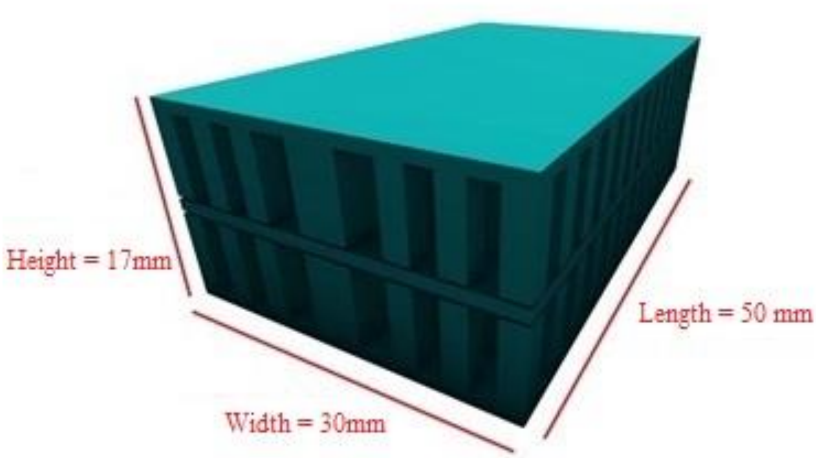

Fig. 5. The side view of full structure.

Table 2. Parameters for designed Bethe hole coupler.

Parameters	Value (mm)
R (Radius of holes)	1.1 (1.64 for middle hole)
Q (Thickness of holes)	1

$$C = 10\log\frac{P_1}{P_3} = 10\log\left(\frac{1}{36{k_f}^2}\right) = -20$$
$$\frac{1}{36{k_f}^2} = 0.01;\ k_f = 1.6667 \quad (3)$$

$$C = -20\log\left|k_f\right| - 20\log\sum_{n=0}^{N} C_n \quad (4)$$

where C_n's are the coupling coefficients and N is the number of holes.

For circular holes leads to [18,19]:

$$ {r_n}^3 = k_f C_n:\ r_1 = r_4 = 1.186\text{mm},\ r_2 = r_3 = 1.494mm \quad (5)$$

3- 2- Simulation of Bethe hole coupler

The configuration of the coupler is shown in Figure 5. Four holes are used for designing the coupler. Using more holes can increase the bandwidth of the structure. The radius of each hole is calculated in the previous section. They were applied as initial values and optimization is used to achieve the desired parameters. Additionally, the distance between the holes should be less than λ/4. The final parameters of the coupler are shown in Table 2.

As seen, the calculated parameters in section 3.a. and the desired parameters for the radius of holes that are achieved with optimization in section 3.b. are very close. The scattering parameters of the designed coupler are shown in Figure 6. The simulation results of the designed coupler show a flat coupling coefficient is about 20 ± 3 dB from 10-18 GHz. The return loss is lower than 10 dB over the entire bandwidth and shows that the impedance matching of the designed coupler is proper enough for use in microwave-integrated circuits. The isolation of the coupler is lower than 22 dB and the transmission coefficient is about -0.4 dB throughout the band. The designed coupler is excited by four ideal ports

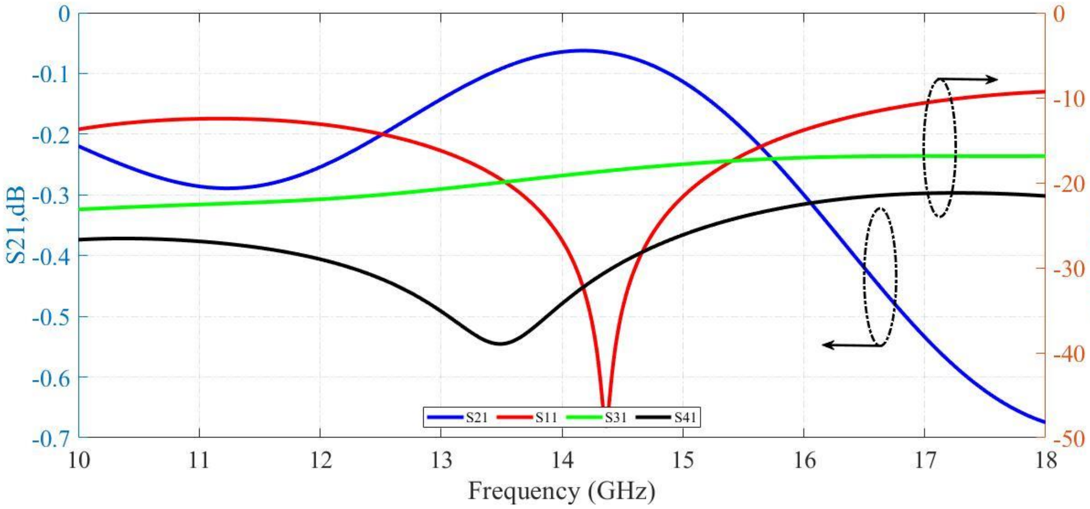

Fig. 6. Return loss and transmission coefficient, coupling coefficient and isolation of designed Bethe hole coupler. In this case, the FBW is 57%.

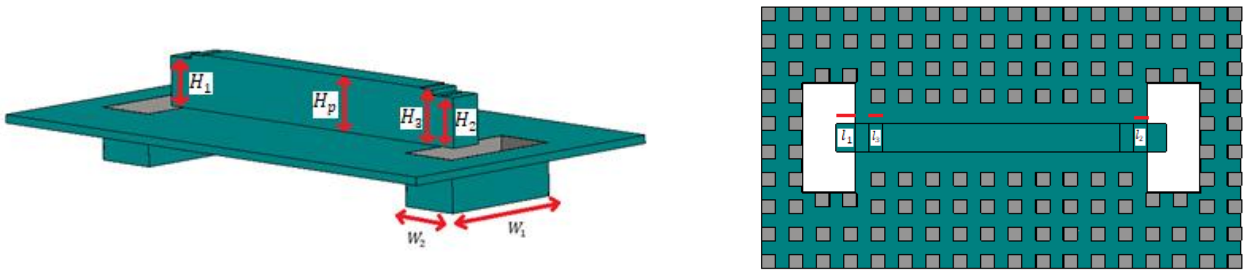

Fig. 7. Excitation structure. (a) The side view of our excitation. (b) The top view of the designed excitation.

as can be seen in Figure 5. It is noticeable that increasing the thickness of the holes decreases the coupling coefficient while increasing the radius of the holes increases it. Using more holes can improve the directivity and bandwidth of the coupler.

4- Excitation

[20-22], propose various methods, such as using a coaxial cable [20], ridge gap to groove gap waveguide transition [21], or microstrip lines [22] for excitation of the structure. However, due to the small gap in the structure, it may not be feasible to use traditional coaxial cables. However, [14] used a coaxial cable with a new method for the excitation of the coupler. In this paper, the Step Ridge Waveguide Excitation (SRWE) technique is used for exciting the designed coupler, as depicted in Figure 7. The WR62 waveguide is used to excite the structure, which can create wider bandwidths. The structure and scattering parameters of the coupler are shown in Figure 7 and Figure 8, respectively. Table 3 provides the parameters used in the excitation process.

After all, we use this excitation for our coupler. The final structure and scattering parameter are shown in Figure 9 and Figure 10, respectively. As we can see the coupling coefficient of the final design is 20±2 dB through the frequency range 11.7-15.6 GHz. Also, return loss of structure is less than 9 dB through the whole band. Isolation is lower than 23 dB and directivity is about 6-16 dB for the frequency range of 11.7-15.6 GHz.

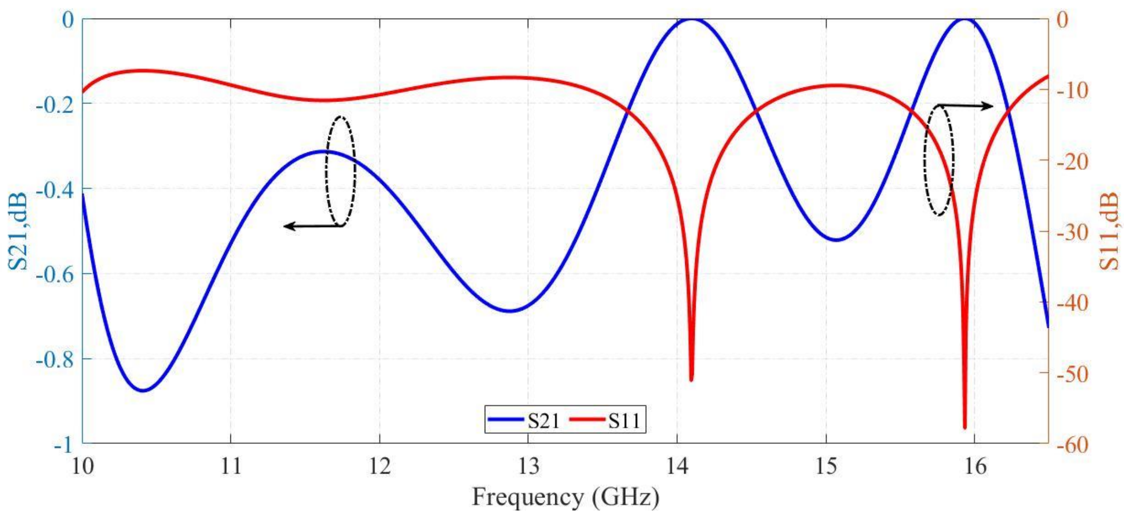

Fig. 8. Return loss and transmission coefficient of the waveguide excitation.

Table 3. Parameters for excitation of coupler.

Parameters	Value (mm)
W_1	15.7
W_2	7.84
H_1	5.9
H_2	6
H_3	6.6
l_1	2.13
l_2	1.41
l_3	1.99

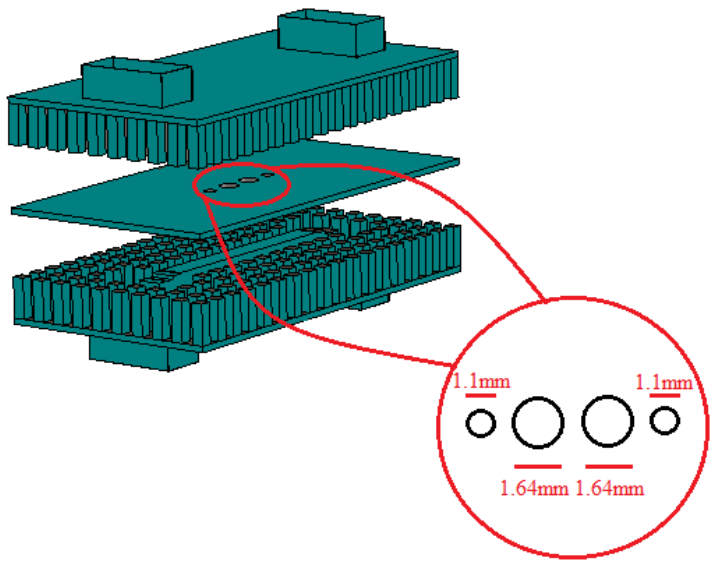

Fig. 9. Side view of the final structure.

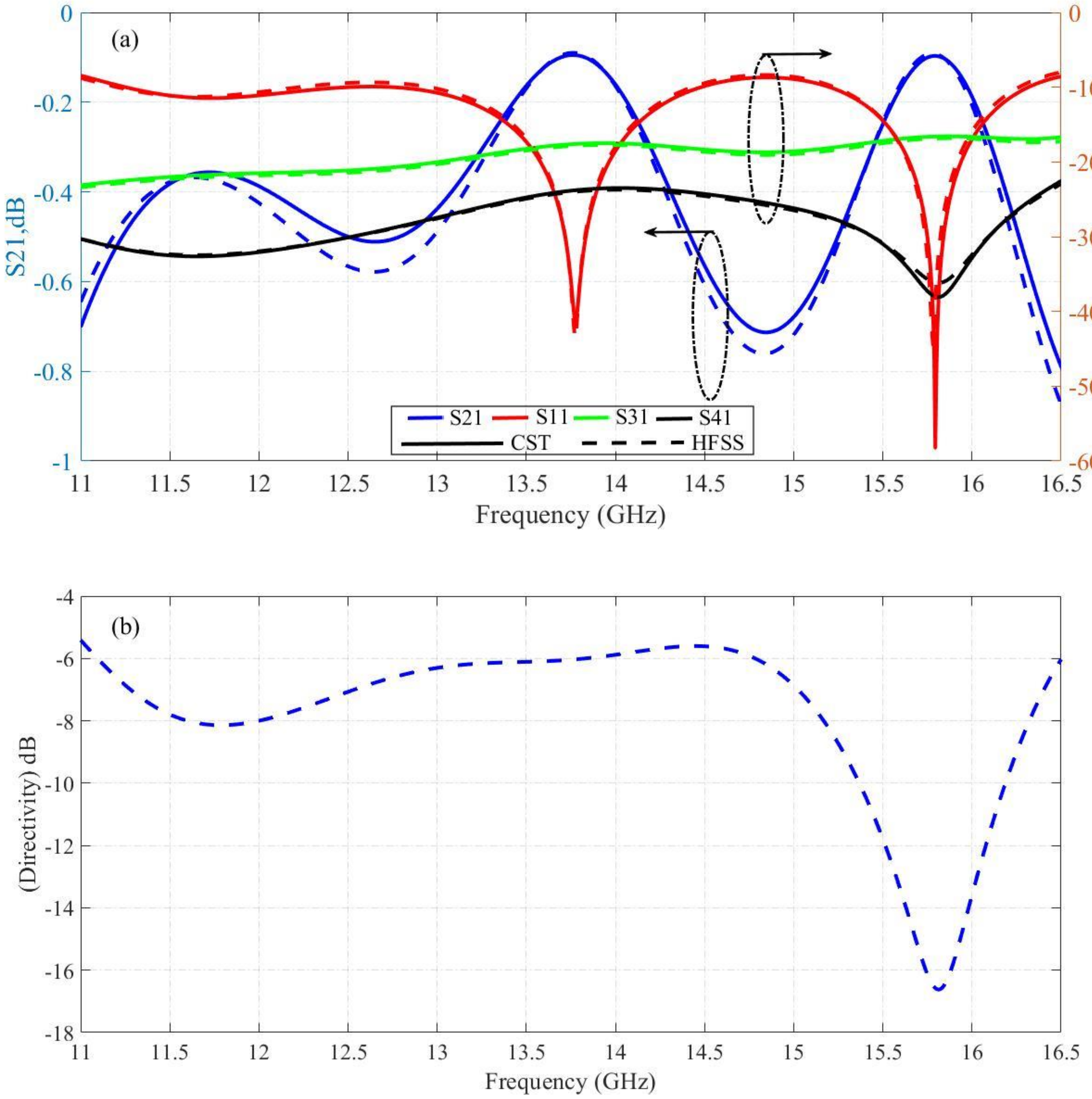

Fig. 10. Bethe hole coupler results with proposed excitation method. In this case the FBW is 29% (a) Return loss, transmission coefficient, coupling coefficient and isolation of coupler. The solid lines represent simulations with CST and the dashed lines represent simulations with HFSS. (b) Directivity of coupler.

Table 4. Comparing the proposed structure performance with other counterparts.

Reference	Technology	Frequency (GHz)	FBW	Coupling (dB)	Return loss (dB)	Transition
[14]	RGW	12.8-16.5	25%	20±2	Min(10), Max(45)	Coaxial
[23]	SIW	9.4-10.6	13%	15±1	Min(15), Max(50)	Microstrip
[24]	GGW	12-17	34.5%	20±2	Min(15), Max(60)	Not proposed
[25]	SIW	9.4-9.8	4.1%	25±1	22	Microstrip
This paper	RGW	11.7-15.6	29%	20±2	Min(9), Max(58)	Waveguide

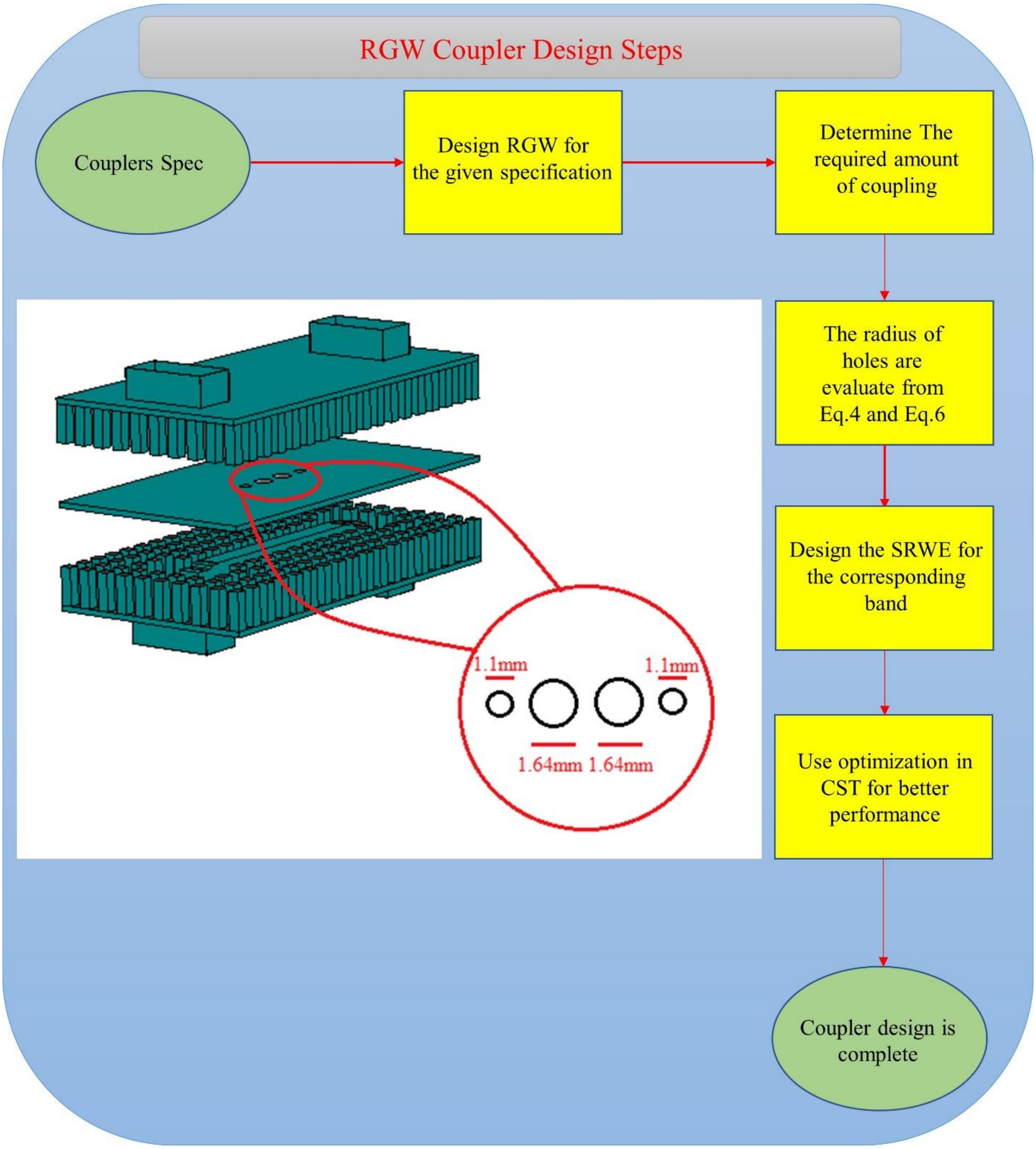

Fig. 11. RGW coupler design steps

Also, we should mention that the directivity of the designed coupler is between 6-16 dB, whereas the directivity of [14] is between 4-13 dB.

The flowchart of RGW coupler design steps is shown in Figure 11.

5- Conclusion

In this research, the design and simulation of a ridge gap waveguide in the Ku band have been completed. Subsequently, the design and simulation of a 4-hole Bethe coupler using this technology have been achieved. The performance of the designed circuit has been verified using CST. The coupling coefficient of our design remains consistently flat at approximately 20 dB. The return loss exceeds 9 dB, while the coupler's isolation surpasses 23 dB. The structure exhibits negligible loss, with a transmission coefficient of about -0.4 dB. By incorporating 4 holes into our design, we achieved a fractional bandwidth (FBW) of 29%. Additionally, the directivity ranges from 6 to 16 dB across the entire band. A comparison of the specifications of our designed circuit with those mentioned in recent references reveals better FBW and directivity, making it well-suited for modern microwave couplers.

References

[1] M. Y. İmeci, B. Tütüncü, and Ş. T. İmeci, "A 3-dB 90 degrees microstrip hybrid directional coupler at 2.27 GHz," AEU-International J. Electron. Commun., vol. 163, p. 154606, 2023.

[2] L. Nouri, S. I. Yahya, A. Rezaei, M. A. Chaudhary, and B. N. Nhu, "A novel configuration of microstrip coupler with low loss and suppressed harmonics," AEU-International J. Electron. Commun., vol. 165, p. 154653, 2023.

[3] B. Dai, B. Zhang, Z. Niu, Y. Feng, Y. Liu, and Y. Fan, "A novel ultrawideband branch waveguide coupler with low amplitude imbalance," IEEE Trans. Microw. Theory Tech., vol. 70, no. 8, pp. 3838–3846, 2022.

[4] N. Sun, Y. Zhao, X. Yang, and H. Deng, "A simple SIW balanced directional coupler with high common-mode suppression," Microw. Opt. Technol. Lett., vol. 65, no. 2, pp. 434–440, 2023.

[5] P.-S. Kildal, E. Alfonso, A. Valero-Nogueira, and E. Rajo-Iglesias, "Local metamaterial-based waveguides in gaps between parallel metal plates," IEEE Antennas Wirel. Propag. Lett., vol. 8, pp. 84–87, 2008.

[6] N. Kiani, F. T. Hamedani, and P. Rezaei, "Implementation of a Graphene-Based RGW Coupler for THz Applications," 2023.

[7] M. M. M. Ali, S. I. Shams, M. Elsaadany, G. Gagnon, and K. Wu, "Graphene-based terahertz reconfigurable printed ridge gap waveguide structure," Sci. Rep., vol. 12, no. 1, p. 21111, 2022.

[8] S. Farjana, E. Alfonso, P. Lundgren, V. Vassilev, P. Enoksson, and A. U. Zaman, "Multilayer Dry Film Photoresist Fabrication of a Robust> 100 GHz Gap Waveguide Slot Array Antenna," IEEE Access, 2023.

[9] W. Y. Yong, A. Vosoogh, A. Bagheri, C. Van de Ven, A. Haddadi, and A. Alayon Glazunov, "An Overview of Recent Development of the Gap-Waveguide Technology for mmWave and sub-THz Applications," 2023.

[10] [10] D. Zarifi and M. Nasri, "Design of a Ku-band filter based on groove gap waveguide technology," Prog. Electromagn. Res. Lett., vol. 76, pp. 71–76, 2018.

[11] C. Máximo-Gutiérrez, J. Hinojosa, and A. Alvarez-Melcon, "Design of evanescent mode band-pass filters based on groove gap waveguide technology," AEU-International J. Electron. Commun., vol. 164, p. 154628, 2023.

[12] A. H. Haghparast and P. Rezaei, "High performance H-plane horn antenna using groove gap waveguide technology," AEU-International J. Electron. Commun., vol. 163, p. 154620, 2023.

[13] U. Nandi, A. U. Zaman, A. Vosoogh, and J. Yang, "Millimeter wave contactless microstrip-gap waveguide transition suitable for integration of RF MMIC with gap waveguide array antenna," in 2017 11th European Conference on Antennas and Propagation (EUCAP), IEEE, 2017, pp. 1682–1684.

[14] E. Nematpour, M. H. Ostovarzadeh, and S. A. Razavi, "Development of a wide band TEM-based Bethe Hole coupler using ridge gap waveguide technology," AEU-International J. Electron. Commun., vol. 111, p. 152933, 2019.

[15] P. Mahdavi, S. E. Hosseini, and P. Shojaadini, "Broadband Three-Section Branch-Line Coupler Realized by Ridge Gap Waveguide Technology from 12 to 20 GHz," IEEE Access, 2023.

[16] A. Polemi, S. Maci, and P.-S. Kildal, "Dispersion characteristics of a metamaterial-based parallel-plate ridge gap waveguide realized by bed of nails," IEEE Trans. Antennas Propag., vol. 59, no. 3, pp. 904–913, 2010.

[17] E. Rajo-Iglesias and P.-S. Kildal, "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 microwaves, antennas Propag., vol. 5, no. 3, pp. 282–289, 2011.

[18] R. Levy, "Directional couplers," Adv. microwaves, vol. 1, pp. 115–209, 1966.

[19] P. A. Rizzi, Microwave engineering: passive circuits, vol. 449. Prentice Hall New Jersey, 1988.

[20] A. U. Zaman, E. Rajo-Iglesias, E. Alfonso, and P.-S. Kildal, "Design of transition from coaxial line to ridge gap waveguide," in 2009 IEEE Antennas and Propagation Society International Symposium, IEEE, 2009, pp. 1–4.

[21] R. Huang, Y. Wu, and W. Wang, "A Low Insertion Loss Wideband mm-Wave Crossover with Three-Section Branch-Line Structure Based on Ridge Gap Waveguide Technology," AEU-International J. Electron. Communication., p. 154720, 2023.

[22] J. Liu, A. Vosoogh, A. U. Zaman, and P.-S. Kildal, "Design of a cavity-backed slot array unit cell on inverted microstrip gap waveguide," in 2015 International Symposium on Antennas and Propagation (ISAP), IEEE, 2015, pp. 1–4.

[23] M. Mbaye, L. Talbi, K. Hettak, and A. Kabiri, "Design of 15 dB directional coupler using substrate-integrated waveguide technology," Microw. Opt. Technol. Lett., vol. 54, no. 4, pp. 970–973, 2012.

[24] E. Nematpour, M. H. Ostovarzadeh, and S. A. Razavi,

"Ku Band Bethe Hole Coupler Using Gap Waveguide Technology," J. Telecommun. Inf. Technol., no. 3, pp. 70–74, 2019.

[25] A. Amine, L. Talbi, and K. Sellal, "Design of a Bethe-hole directional coupler using substrate integrated waveguide technique," Microw. Opt. Technol. Lett., vol. 53, no. 8, pp. 1730–1734, 2011.

HOW TO CITE THIS ARTICLE

K. Salehian, Gh. Moradi. Design and Simulation of Bethe Hole Coupler Using Ridge Gap Waveguide Technology for Satellite Communication. AUT J. Elec. Eng., 56(2) (2024) 165-174.

DOI: 10.22060/eej.2024.22597.5551