Progress In Electromagnetics Research Letters, Vol. 76, 27–32, 2018

Design of Terahertz Short-slot Coupler with Curved Waveguide

Wu Pan, Hao Cheng*, Xia Yin, and Xuan Li

Abstract—The design of a terahertz short-slot coupler with curved waveguide is proposed. A traditional short-slot coupler uses a step-like structure in order to suppress higher order modes and improve bandwidth. It becomes difficult to control the fabrication of tiny steps with the incensement of frequency especially in terahertz band. The designed coupler is composed of two curved waveguides overlapping in the middle to realize a specific coupling coefficient. Then the step-like structure can be replaced with a curved structure which is much easier to fabricate. The coupling coefficient of the coupler is 3 dB, and the variation is less than 1 dB around the center frequency. The phase difference between two output ports is 90°. The isolation is greater than 10 dB in the whole working band. Measured results show high agreement with simulation predictions. The designed coupler can be widely used as feed networks of horn antenna array.

1. INTRODUCTION

Directional coupler is an important passive component widely used in microwave and millimeter systems and is fundamental for the realization of power splitting, combining and detecting networks [1–3]. With the rapid development of terahertz technology, directional couplers operating in terahertz regime have been proposed [4]. In 2012, Fang and Yan [5] proposed a narrow-wall short-slot 3 dB directional coupler for 3 mm-wave frequency band. It has achieved a coupling variation of less than 1 dB, and the isolation is greater than 7 dB. In 2013, Kuroiwa et al. [6] proposed a short-slot hybrid coupler in W band using linear taper. The measured results show that the coupling variation is less than 2 dB and the isolation greater than 10 dB. In 2014, Castellano et al. [7] proposed a SIW short-slot directional coupler. A standard PCB process was employed to fabricate the coupler. The results show that the coupling variation is less than 2 dB and the isolation greater than 10 dB. In 2015, Liu et al. [8] proposed a waveguide 10 dB short-slot directional coupler operating from 325 GHz to 400 GHz. It adopted an coupler aperture structure in the coupling area to adjust the coupling coefficient. The measured results show that the coupling variation is less than 2 dB and the isolation greater than 10 dB.

Terahertz directional couplers are usually formed with metal rectangular waveguide due to its advantages of high power handling capability, low loss and high Q factor [9]. Riblet short-slot coupler is a frequently used structure which is formed with a slot on the H face of waveguides. The specific coupling coefficient is realized by adjusting the length and width of the slot. However, there are some differences between a traditional microwave coupler and terahertz coupler due to the small size of terahertz components. It brings some difficulties to the design of terahertz components. For instance, manufacturing will be extremely difficult because high accuracy is needed. Thus, it should be considered in the design procedure.

Accordingly, we design a curved waveguide short-slot coupler which is composed of two curved waveguides overlapping in the middle to realize a specific coupling coefficient. The operating frequency

Received 30 March 2018, Accepted 29 April 2018, Scheduled 21 May 2018
* Corresponding author: Hao Cheng (chenghao_0803@163.com).
The authors are with the College of Photoelectric Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China.

range of the designed coupler is $340 \sim 400$ GHz. The results show that the coupling coefficient is 3 dB which means that half energy imported into the input port is transmitted to the coupled port. A broad bandwidth of 60 GHz is realized. The return loss is below -10 dB in the whole working frequency range, and it is below -15 dB from $370 \sim 395$ GHz. Configuration and measurement results of the proposed coupler are discussed in later sections.

2. CONFIGURATION AND DESIGN CONSIDERATION

The Riblet short-slot coupler has a full-height slot in the common narrow-wall between two adjacent rectangular waveguides, and it usually has a step-like structure on the bilateral wall at the coupling region, as shown in Figure 1. The reason for this structure is that we only want the dominant mode (TE_{10} mode) to transmit in the waveguide. Because the TE_{10} mode has the lowest attenuation of all modes in a rectangular waveguide and its electric field is definitely polarized in one direction everywhere, it is of particular practical importance. The cutoff frequency of TE_{mn} $(m, n = 0, 1, 2, \ldots)$ in rectangular waveguide is:

$$f_c = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \tag{1}$$

where ε is the dielectric constant; μ is the magnetic permeability; a and b are the width and height of the waveguide. To realize single mode transmission, a should meet: $\lambda/2 < a < \lambda$, where λ is the wavelength. However, in the coupling region, the width of the waveguide is $2a$. In order to suppress higher order modes, H-plane steps are employed. Only TE_{10} and TE_{20} modes are transmitted in the waveguide. The bandwidth performance of the coupler is improved with the incensement of number of steps [10]. Based on the thinking of limits, when there are enough steps, the step-like structure will infinitely approach a curved structure as shown in Figure 2. In terahertz regime, it becomes extremely difficult to fabricate a tiny step-like structure with high accuracy. The curved structure is much easier to fabricate.

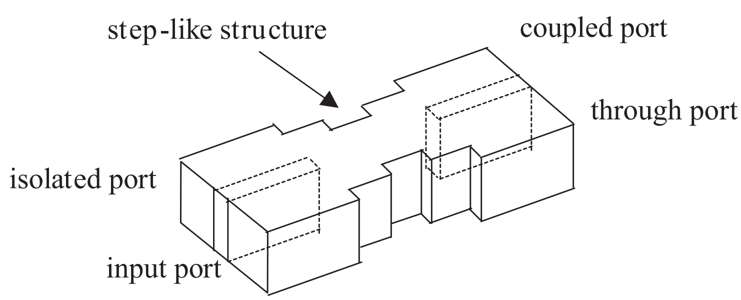

Figure 1. Prototype of Riblet short-slot coupler with step-like structure.

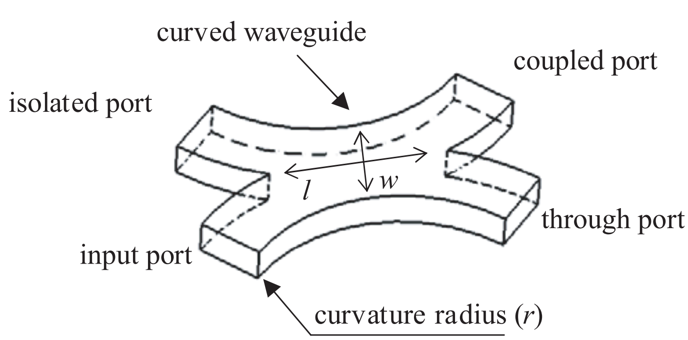

Figure 2. Prototype of the designed coupler with curved waveguides.

The designed coupler has two adjacent routing bent waveguides overlapping in the middle. A full-height slot is placed as shown in Figure 2. The length of the slot can be derived from formula:

$$l = \frac{\arctan(E_2/E_3)}{\beta_{10} - \beta_{20}} \tag{2}$$

where E_2 and E_3 are the electric field intensities at through port and coupling port, respectively. β_{10} and β_{20} are phase shift constants of TE_{10} mode and TE_{20} mode, respectively. The coupling coefficient of the designed coupler is 3 dB which means $E_2/E_3 = 1$. Considering its working frequency ($340 \sim 400$ GHz) and coupling coefficient (3 dB), the length of the slot l is 0.860 mm. We choose the standard waveguide WR-2.2 with a width of 0.56 mm and height of 0.28 mm. The working frequency range of WR-2.2 is $330 \sim 500$ GHz which meets the design requirement. There are two important dimensions of coupler in this design which are the length of the slot l and the middle width of the coupling region w. The length of the slot which has been determined will largely influence the coupling coefficient. The middle width of the coupling region, as aforementioned, will largely influence the suppression of higher order modes. Then we have to determine the middle width of the coupling region. As shown in Figure 2, with the length of the slot settled, we can only change the curvature radius of the curved waveguide to change the middle width of the coupling region. It is easy to find that the middle width w will decrease when the curvature radius decreases which will be helpful to suppress higher order modes. However, the return loss of the waveguide will obviously increase when the curvature radius decreases. Thus, we have to make a reasonable balance between these two factors. We use the electromagnetic simulator CST Microwave Studio to accurately model the coupler and optimize the performance. Figure 3 shows the sectional view of the fabricated coupler. The coupler was fabricated of copper with conductivity of 5.96×10^7 S/m. The routing waveguides are connected to ports of the curved waveguides to connect the test equipment. The lengths of three straight waveguides are $d_1 = 2.51$ mm, $d_1 = 2.51$ mm, and $d_2 = 1.00$ mm, respectively. The side length of the copper block is $s = 20$ mm. The inner curvature radius of curved waveguide is $r_i = 6.44$ mm. The outer curvature radius is $r_o = 7.00$ mm. The length of coupling slot is $l = 0.86$ mm. The width of the center coupling region is $w = 1.1$ mm. The fixed holes on each corner are set to compact the coupler.

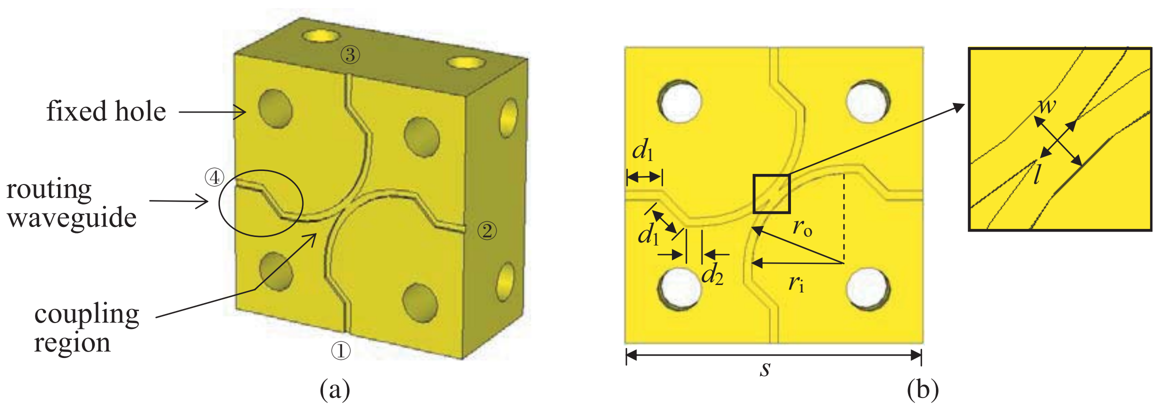

Figure 3. Sectional view of the fabricated coupler: (a) structure, (b) schematic diagram.

3. SIMULATION AND MEASUREMENT RESULTS

The proposed coupler was simulated using CST Microwave Studio and measured with Angilent vector network analyser. As shown in Figure 3, the four input and output ports are located on the center of four sides. There are four cylindrical holes on the sides to connect the standard flange. The ports $1 \sim 4$ refer to input port, through port, coupling port and isolated port, respectively. Photographs of the fabricated coupler are shown in Figure 4. When measuring S parameter of one output port, other two output ports should be filled with wave-absorbing material (Polyurethane foam).

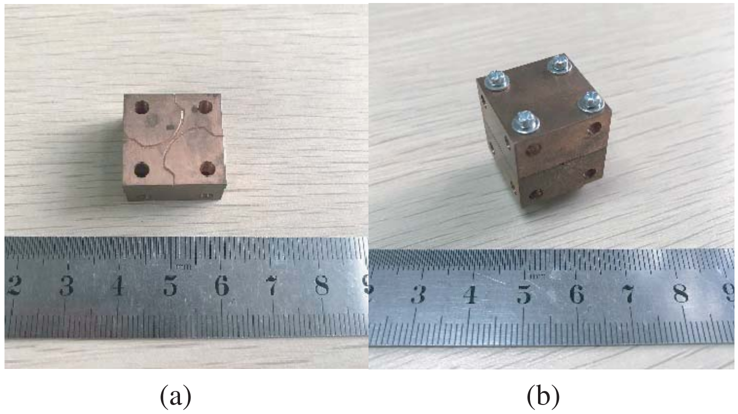

Figure 4. Photographs of the designed coupler: (a) sectional view, (b) assembly view.

Figure 5 shows the phase difference between through port and coupling port. It can be seen that it remains 90° in the whole working band. As shown in Figure 6(c), the coupling coefficient is 3 dB. The variation of coupling amplitude is less than 2 dB in the working band and less than 1 dB from 370 ∼ 400 GHz. The return loss in Figure 6(a) is less than −10 dB. The isolation in Figure 6(d) has the same trend as return loss and is greater than 20 dB at the center frequency of 370 GHz. The measured results agree well with the simulated ones. However, a relatively big variation of S_{21} can be found at around 355 GHz. This is caused by the fabrication error of 5 µm.

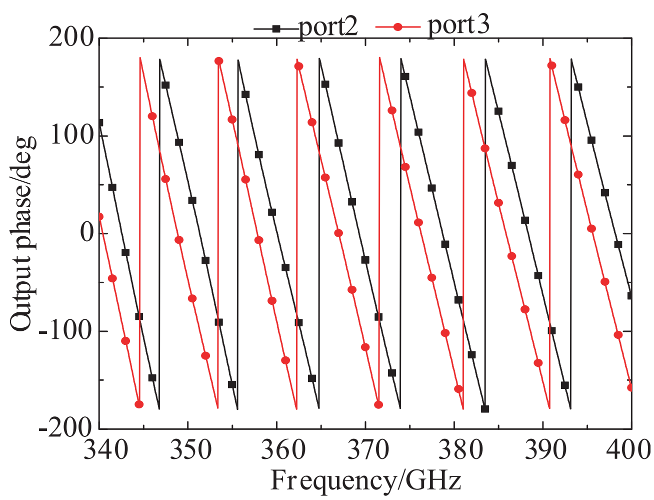

Figure 5. Output phase. Port2 and Port3 are through and coupled port.

Table 1. Comparison with some other reported short-slot couplers.

coupler	working frequency	coupling coefficient	coupling variation	isolation
Fang et al. [5]	80 ∼ 100 GHz	3 dB	$<$ 1 dB	$>$ 7 dB
Kuroiwa et al. [6]	80 ∼ 120 GHz	3 dB	$<$ 2 dB	$>$ 10 dB
Castellano et al. [7]	10 ∼ 13 GHz	3 dB	$<$ 2 dB	$>$ 10 dB
Liu et al. [8]	325 ∼ 400 GHz	10 dB	$<$ 2 dB	$>$ 10 dB
proposed coupler	340 ∼ 400 GHz	3 dB	$<$ 1 dB	$>$ 10 dB

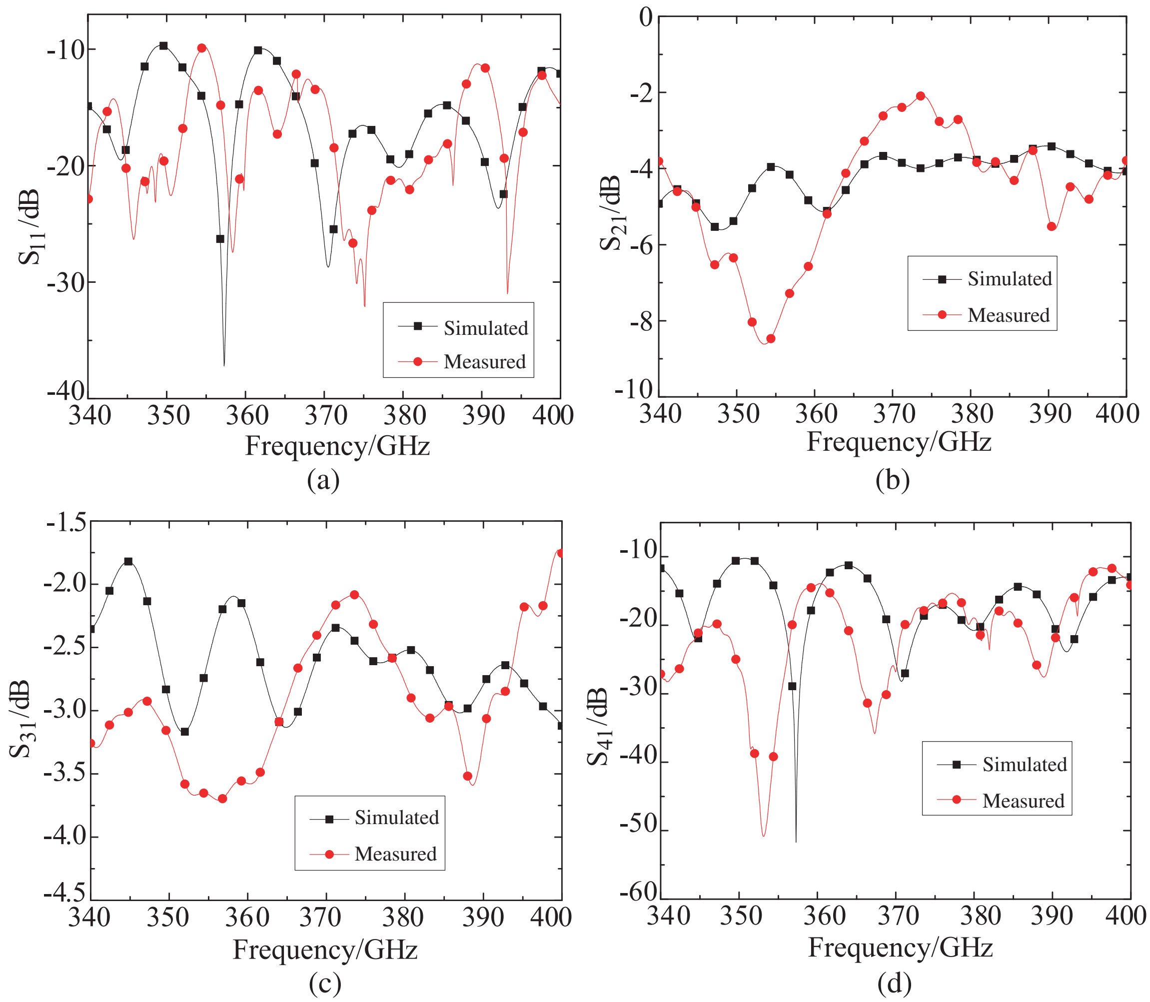

Figure 6. Simulated and measured S parameter results of the designed coupler: (a) S_{11}, (b) S_{21}, (c) S_{31}, (d) S_{41}.

4. CONCLUSION

We have proposed a new design of terahertz bent waveguide short-slot coupler. We use two bent waveguides overlapping in the middle to realize a short-slot on the common wall. Then the traditional step-like structure which is hard to fabricate in terahertz regime can be replaced. The standard WR-2.2 waveguide is used. The coupling coefficient of the designed coupler is 3 dB, and the variation is less than 1 dB at the center frequency. Isolation is greater than 10 dB in the whole working band. The measured results agree well with the simulation predictions, showing a low variation in return loss and isolation. The performance of the designed coupler is compared with some other reported short-slot couplers in Table 1. It can be seen that the proposed coupler reaches a high isolation with a relatively low coupling variation. An important application of this design is the feeding of horn antenna array, to provide equal power to all antenna pixels with the rectangular waveguide port.

ACKNOWLEDGMENT

This work was supported by New Direction Cultivation Project of Chongqing University of Posts and Telecommunications (A2014-116). This work was supported by the Key Research Program of Chongqing University of Posts and Telecommunications on Interdisciplinary and emerging field (A2018-01).

REFERENCES

1. Sun, D. and J. Xu, "Rectangular waveguide coupler with adjustable coupling coefficient using gap waveguide technology," *Electronics Letters*, Vol. 53, No. 3, 167–169, 2017.
2. Tan, B. K. and Y. G. Planar, "Microstrip coupler with enhanced power coupling," *Electronics Letters*, Vol. 53, No. 1, 34–36, 2016.
3. Sharma, R. Y., T. Chakravarty, S. Bhooshan, et al., "Design of a novel 3 dB microstrip backward wave coupler using defected ground structure," *Progress In Electromagnetics Research*, Vol. 65, No. 65, 261–273, 2006.
4. Reck, T. J., C. Jung-Kubiak, J. Gill, et al., "Measurement of silicon micromachined waveguide components at 500–750 GHz," *IEEE Transactions on Terahertz Science & Technology*, Vol. 4, No. 1, 33–38, 2017.
5. Fang, Y. and X. Yan, "Design of waveguide narrow-wall 3 dB coupler for 3 mm-wave frequency band," *2012 5th Global Symposium on Millimeter Waves (GSMM)*, 166–169, IEEE, 2012.
6. Kuroiwa, K., A. Gonzalez, M. Koyano, et al., "Short-slot hybrid coupler using linear taper in W-band," *Journal of Infrared, Millimeter, and Terahertz Waves*, Vol. 34, No. 12, 815–823, 2013.
7. Castellano, T., O. Losito, L. Mescia, et al., "Feasibility investigation of low cost substrate integrated waveguide (SIW) directional couplers," *Progress In Electromagnetics Research*, Vol. 59, No. 59, 31–44, 2014.
8. Liu, S., J. Hu, Y. Zhang, et al., "Sub-millimeter-wave 10 dB directional coupler based on micromachining technique," *International Journal of Antennas and Propagation*, Vol. 10, No. 5, 1–9, 2015.
9. Kang, X., P. Chen, X. Deng, Z. Chen, J. Jiang, L. Miao, and B. Cheng, "Design method about 0.14 THz power divider based on 3 dB directional coupler," *Inf. Las. Engineer*, Vol. 43, No. 9, 2907–2911, 2014.
10. Hildebrand, L. T., "Results for a simple compact narrow-wall directional coupler" *IEEE Microwave & Guided Wave Letters*, Vol. 10, No. 6, 231–232, 2000.