CHIN. PHYS. LETT. Vol. 33, No. 8 (2016) 088401

Design of a Broadband E-Plane Power Combiner Based on Quarter-Arc Bent Rectangular Waveguides for Sub-THz and THz Wave *

Xiao-Pin Tang(唐效频)**, Zi-Qiang Yang(杨梓强), Zong-Jun Shi(史宗君), Feng Lan(兰峰)

Terahertz Research Center, School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054

(Received 11 March 2016)

A method of designing an E-plane power combiner composed of two quarter-arc bent rectangular waveguides is proposed for sub-THz and THz waves. The quarter-arc bent-waveguide power combiner has a simple geometry which is easy to design and fabricate. By HFSS codes, the physical mechanism and performance of the power combiner are analyzed, and the relationship between the output characteristics and the structure/operating parameters is given. Simulation results show that our power combiner is suitable for the combining of two equal-power and reversed-phase signals, the bandwidth of the combiner is wide and can be adjusted by the radius of the quarter-arc, and the isolation performance of the combiner can be improved by adding thin film resistive septa at the junction of two quarter-arc bent waveguides. Meanwhile, an approximate method based on the analytic geometrical analysis is given to design this power combiner for different frequency bands.

PACS: 84.32.−y, 07.50.−e, 84.40.Az DOI: 10.1088/0256-307X/33/8/088401

A high-power radiation source is absolutely necessary in the applications of the sub-THz and THz technology.[1−4] However, the output capacity of the existing high-frequency source is very limited, thus there is great interest in the development of the power combining techniques at sub-THz and THz frequencies.[5−9] Since the waveguide corporate combiner has low loss, high combining efficiency and wide bandwidth, it plays an important role in the power combining in high frequency bands.[10] In 2005, Epp *et al.* reported a waveguide corporate combiner composed of an E-plane T-junction and a resistive card. This combiner has about −0.06 dB insertion loss, −27 dB return loss, and −33 dB isolation from 31 GHz to 36 GHz.[11−13] The optimization of the geometry and the septum will extend the bandwidth and will improve the isolation between two input ports.[14,15] According to these works, we can conclude that the isolation is mainly provided by the resistive card and the stepped-impedance transformer is used to reduce the return loss of the device. However, with the increase of the operating frequency, the structure will be much smaller. It makes the design and fabrication of the stepped-impedance transformer more difficult. To simplify the geometry of the combiner operating in higher frequency range, in this study, we present an E-plane structure based on the quarter-arc bent rectangular waveguides. We will show the physical mechanism as well as the performance of our power combiner, and will summarize an approximate method to design this combiner at sub-THz and THz frequencies.

The model of our E-plane power combiner is shown in Fig. 1. Unlike the T-junction structure in Refs. [11–14], this power combiner has two symmetrical quarter-arc bent rectangular waveguides with radius r instead of the stepped-impedance transformer to avoid the micro-geometry. It is beneficial for the design of the combiner operating in higher frequency range. The constant height of the waveguide can also reduce the fabrication difficulty.

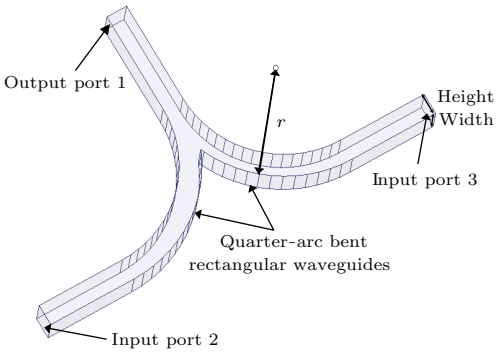

Fig. 1. The E-plane power combiner based on the quarter-arc bent rectangular waveguides.

To analyze the physical mechanism, we observe the vector electric field distribution in the power combiner. As displayed in Fig. 2, after transmitting through two symmetrical quarter-arc bent rectangular waveguides, two input signals (TE_{10} modes) with reversed phases and equal amplitude will almost have consistent phase, and then will combine with each other in the output waveguide. The key process of the power combining can be owed to the phase modulation of two symmetrical quarter-arc bent waveguides.

The standard rectangular waveguide WR-7 (1.651 mm × 0.8255 mm) is employed to design our E-plane power combiner. According to the reciprocity principle, a power combiner can be analyzed as a power divider. Therefore, we only need to analyze the return loss at port 1, the transmission rate from port 1 to port 2/port 3, the isolation between port 2 and port 3, and the insertion loss of the device. The power combiner/divider is simulated and optimized by HFSS software. The material is assigned to be

*Supported by the National Natural Science Foundation of China under Grant No 11075032, and the Fundamental Research Funds for the Central Universities under Grant No ZYGX2014J033.

**Corresponding author. Email: xiaopintang@gmail.com

© 2016 Chinese Physical Society and IOP Publishing Ltd

a perfect electric conductor (PEC). Figure 3 gives the simulation results under the condition that the radius r is 5 mm. As shown in Figs. 3(a) and 3(b), this quarter-arc bent-waveguides power combiner has a broad bandwidth, which locates from 119 GHz to 203.6 GHz. In this frequency range, the return loss is very low ($S_{11} < -20$ dB), and the transmission rate from port 1 to each branch is about 50% (S_{21} and S_{31} are around -3.03 dB). The minimum value of isolation S_{23} in Fig. 3(c) is about -6.6 dB in the operating frequency band. In addition, we can calculate the insertion loss, as shown in Fig. 3(d), it is better than -0.1 dB in the operating frequency band.

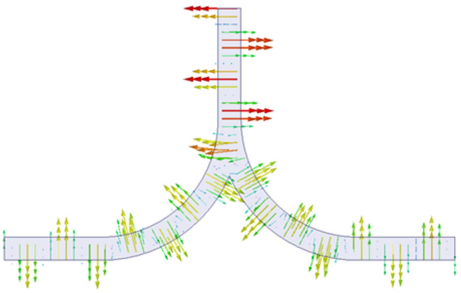

Fig. 2. The vector graph of the electric field in the power combiner.

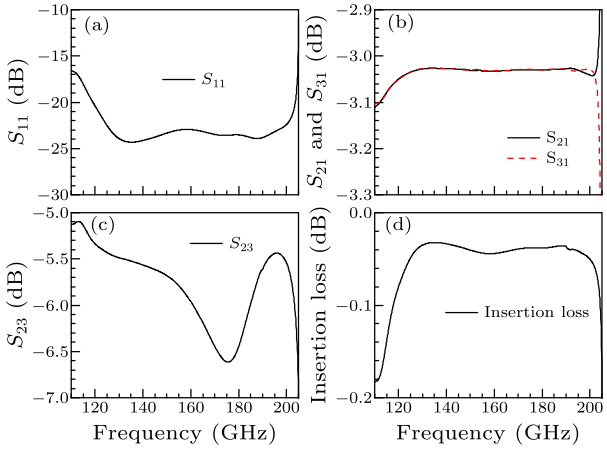

Fig. 3. The S-parameters and insertion loss of the power combiner based on the quarter-arc bent rectangular waveguides: (a) S_{11}, (b) S_{21} and S_{31}, (c) S_{23}, and (d) insertion loss.

The influence of the structure parameters on the output has been analyzed. As mentioned above, the rectangular waveguide is WR-7, thus the radius r of the quarter-arc is the only variable that needs to be discussed. Table 1 lists the operating frequency band and the relative bandwidth varying with the radius r. The relative bandwidth is defined as $2 \times (f_{\rm H} - f_{\rm L})/(f_{\rm H} + f_{\rm L})$, where $f_{\rm H}$ and $f_{\rm L}$ are the upper limit and the lower limit of the frequency range, respectively. The frequency band broadens with the increase of r, and the relative bandwidth exceeds 50% when $r \geq 5$ mm. The vector graphs of the electric field in Fig. 4 show that the angle ϕ between two electric fields in the starting combining region decreases when the radius of the quarter-arc increases, i.e., the phase consistency is better when the radius is larger. This is why the larger radius corresponds to the better combining performance. However in the practical application, the energy attenuation in the metal material could not be ignored. The total length of the circuit increases with the radius r, which will lead to greater energy attenuation. Thus we need to choose an appropriate radius according to the practical requirement.

Table 1. Operating frequency band and relative bandwidth varying with radius r.

r (mm)	Frequency band (GHz)	Relative bandwidth (%)
3	143–180	22.9
4	128–200	43.9
5	119–203.6	52.4
6	112.8–206.5	58.7
7	107.6–207.5	63.4

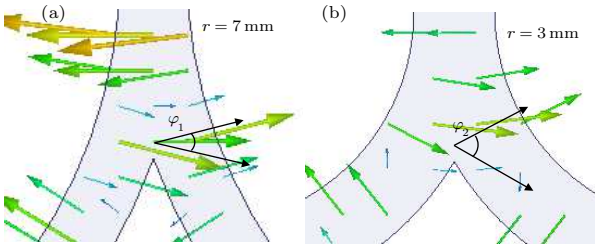

Fig. 4. The vector graphs of the electric field in the starting combining region: (a) $r = 7$ mm, and (b) $r = 3$ mm.

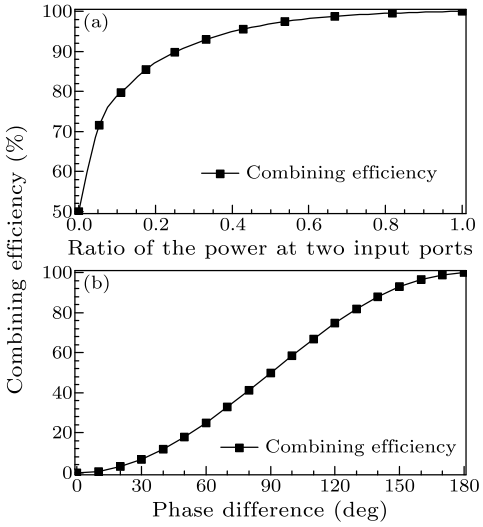

Fig. 5. The combining efficiency as functions of the operating parameters: (a) power-difference, and (b) phase-difference.

The combining efficiency in the operating frequency band varying with the operating parameters is given in Fig. 5. Figure 5(a) shows the combining efficiency results for the input signals of reversed phases and different powers. The efficiency increases with the rise of the ratio of the power at two input ports and reaches maximum when the ratio is 1. Figure 5(b) is the efficiency as a function of the phase-difference of two input signals with equal power. As the phase-difference increases, the efficiency shows a rapid rise and runs up to the maximum value when the difference equals 180°. The results indicate that our power combiner is suitable for the combining of two signals with equal power and reversed phases. The mismatch

of two input signals will definitely worsen the combining efficiency. In addition, we can find that, to make sure the efficiency exceeds 90%, the power ratio of two input signals should be larger than 0.3, while the phase-difference must be larger than 140°. Obviously, the combining efficiency is more sensitive to the phase-difference.

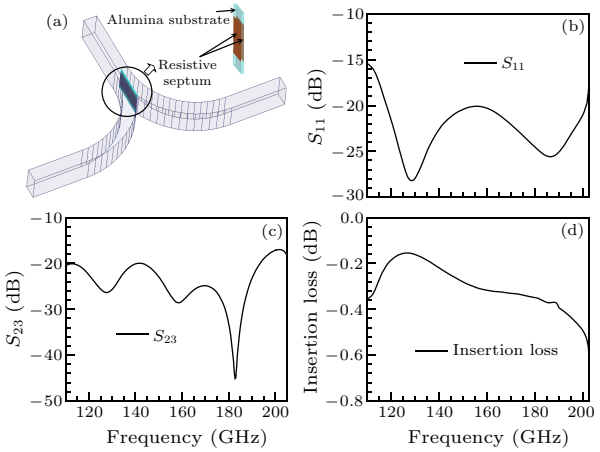

Fig. 6. The model and results of the resistive septum combiner: (a) the combiner model, (b) S_{11}, (c) S_{23}, and (d) insertion loss.

The poor isolation between two input ports in Fig. 3(c) may cause instability. To solve this problem, we can add thin film resistive septa[11] at the junction of two symmetrical quarter-arc bent waveguides, as shown in Fig. 6(a). The thickness, length and width of the alumina substrate are 0.05 mm, 2 mm and 1.651 mm, respectively. The width of the resistive septa on both sides of the substrate is 1 mm. The resistance of the septum is 300 Ω/sq. Figures 6(b), 6(c) and 6(d) indicate that in the operating frequency band, S_{11} keeps below −20 dB, S_{23} is below −20 dB, and the insertion loss is better than −0.6 dB. Due to the introduction of the thin film resistive septum, our combiner shows good isolation performance.

Based on the above results, we try to summarize an approximate method to design this E-plane quarter-arc bent-waveguide power combiner at sub-THz and THz frequencies. To simplify the analysis, we still only consider the power combiner based on the standard rectangular waveguide.

As a rule of thumb, there is a one-to-one correspondence between the relative bandwidth and the determinate structure parameters. The analytic geometrical analysis is given to seek the numerical relations between the relative bandwidth and the structure parameters. To make the analysis clearer, we introduce an intermediate variable $\tan\theta$. As shown in Fig. 7, we can calculate

$$\tan\theta = \frac{h}{2r - \sqrt{4rh - h^2}}, \tag{1}$$

where h is the height of the rectangular waveguide, and r is the radius of the quarter-arc. It is obvious that $\tan\theta$ is determined by the structure parameters h and r. Thus we assert that the value of $\tan\theta$ can determine the relative bandwidth of the power combiner. Combining Eq. (1) and Table 1, we obtain Table 2, which shows the relationship between $\tan\theta$ and the relative bandwidth. It is demonstrated that the relative bandwidth decreases with the increase of $\tan\theta$.

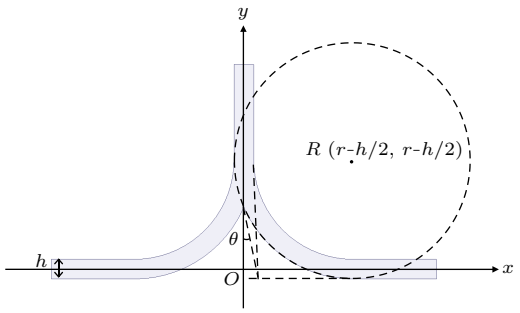

Fig. 7. The geometry of the E-plane power combiner.

Table 2. Relationship between $\tan\theta$ and the relative bandwidth.

$\tan\theta$	0.2771	0.1841	0.1364	0.1077	0.0887
Relative bandwidth (%)	22.9	43.9	52.4	58.7	63.4

Table 3. E-plane power combiners for different operating frequency bands.

Waveguide	Height (mm)	Radius (mm)	Frequency band (GHz)	Relative bandwidth (%)
		3.71	115.4–147.1	24.15
WR-8	1.016	6.17	96.8–165.5	52.4
		8.65	89.4–171.6	62.99
		2.36	181.2–230	23.74
WR-5	0.648	3.93	153.2–259.5	51.5
		5.515	144.6–275	62.15
		1.99	214.9–271.8	23.38
WR-4	0.546	3.31	179–307	52.6
		4.65	167.3–316.5	61.68
		1.576	271.5–345.5	23.99
WR-3	0.432	2.62	229–390	52
		3.677	209.6–413.5	65.45

We utilize the relationship between $\tan\theta$ and the relative bandwidth to design the quarter-arc bent-waveguide power combiner at other frequency bands. Firstly, we can choose an appropriate standard rectangular waveguide according to the demand of operating frequency band, i.e., the height h can be determined by the frequency band. Secondly, on the basis of Table 2, we can obtain $\tan\theta$ corresponding to

the required relative bandwidth. Finally, by putting the value of h and $\tan\theta$ into Eq. (1), the radius r of the quarter-arc can be calculated. Table 3 lists the results of the power combiners operating in different frequency bands and can prove the validity of our approximate method. The quarter-arc bent-waveguide power combiner is easy to scale to other sub-THz and THz frequencies.

In summary, we have presented the design of a simple, scalable E-plane power combiner. This power combiner is composed of two symmetrical quarter-arc bent rectangular waveguides, and it is easily designed and fabricated due to the fact that it avoids the micro-geometry in the traditional T-junction combiner. As an E-plane power combiner, the quarter-arc bent-waveguide combiner is suitable for the combining of two equal-power and reversed-phase signals, and its physical mechanism can be described such that the phase modulation of the quarter-arc bent waveguide plays a major role in the power combining process. The HFSS results show that the quarter-arc bent-waveguide power combiner has a wide operating frequency band which can be broadened by increasing the radius of the quarter-arc, and the thin film resistive septum can help to improve the isolation performance between two input ports. In addition, an approximate method based on the analytic geometrical analysis, which is verified by results of combiners for different operating frequency bands, is given to simplify the design of the power combiner. Using this method, the power combiner based on the quarter-arc bent rectangular waveguides is easy to scale to other frequency bands.

References

[1] Linfield E 2007 *Nat. Photon.* **1** 257
[2] Li Z Y, Yao J Q, Lü D, Xu D G, Wang J L and Bing P B 2011 *Chin. Phys. Lett.* **28** 064209
[3] Zhang X B and Shi W 2008 *Acta Phys. Sin.* **57** 4984 (in Chinese)
[4] Xu D G, Zhang H, Jiang H, Wang Y Y, Liu C M, Yu H, Li Z Y, Shi W and Yao J Q 2013 *Chin. Phys. Lett.* **30** 024212
[5] Russell K J 1979 *IEEE Trans. Microwave Theory Tech.* **27** 472
[6] Chang K and Sun C 1983 *IEEE Trans. Microwave Theory Tech.* **31** 91
[7] Zhan C H, Li T M, Meng L, Li Z H, Wu Y and Shao J B 2014 *Acta Phys. Sin.* **63** 238405 (in Chinese)
[8] Li W, Liu Y G and Yang J H 2012 *Acta Phys. Sin.* **61** 038401 (in Chinese)
[9] Chen Q J, Jiang Q X, Zeng F L and Song C B 2015 *Acta Phys. Sin.* **61** 204101 (in Chinese)
[10] Wang L, Xu J, Zhao L, Ran D and Wang M Y 2010 *Proc. Int. Symp. Signals Syst. Electron.* (Nanjing 17–20 September 2010) p 1
[11] Khan P, Epp L and Silva A 2005 *InterPlanet. Network Prog. Report* (Pasadena CA US, 15 August 2005) p 1
[12] Epp L, Khan P and Silva A 2005 *InterPlanet. Network Prog. Report* (Pasadena CA US, 15 November 2005) p 1
[13] Epp L, Hoppe J, Khan P and Stride L 2008 *IEEE Trans. Microwave Theory Tech.* **56** 1899
[14] Ye T and Xu J 2011 *Cross Strait Quad-Regional Radio Sci. Wireless Technol. Conf.* (Harbin, 26–30 July 2011) p 579
[15] Xie X Q, Zhou Q and Li D W 2014 *Electron. Lett.* **50** 1714