A Terahertz 3dB Waveguide Power Divider with 90° Phase Shifter Integrated

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Abstract. A 3dB power divider is designed based on E-plane waveguide directional coupler and self-compensating waveguide phase shifter. This power divider was implemented with a center frequency at 110GHz. Simulation results show that amplitude balance within ±0.3dB and phase balance within +0.5/-1.2 degrees, and isolation is better than -15 dB from 100 to 120 GHz. It has good performance in-band flatness and bandwidth is 18%. It can be used in terahertz communication system.

1. Introduction
In recent years, terahertz communication has been widely used based on more and more research progress[1]. Power divider is an important functional component in terahertz radar and communication system[2]. Because the size of devices is small, processing technology and performance are both important factors when designing devices of terahertz band. The T-junction structure is easy to processing, while the isolation between ports is bad[3]. Waveguide directional coupler is widely used with excellent isolation between ports and simple structure[4-5]. However, the port output of the waveguide directional coupler has a phase difference of 90°, and compensating the phase by directly increasing the length of waveguide will decrease the bandwidth of power divider. Therefore, a power divider with better port balance is developed by combining the waveguide directional coupler with the self-compensating waveguide phase shift structure in this paper. This design compensates the phase difference in the frequency band and makes the bandwidth extended, and it can be used in the image rejection mixer , which is beneficial to improve the performance of the device.

2. Theory and structure
This part tells theory and waveguide structure used in this paper. Waveguide directional coupler

2.1. Waveguide directional coupler
E-plane waveguide directional coupler is a general componte in communication system. Each branch can be regarded as a four-port network, thus a branch line waveguide directional coupler can be regarded as a series of several four-port networks. According to theoretical research, increasing the number of branch can increase the bandwidth of the coupler. There have been a large number of research results in the submillimeter wave band using multi-branch line to expand the bandwidth (N >6), but increasing the branch line will also decrease the width of the branch and increase the processing difficulty. In this paper, after considering the bandwidth and processing size, we decide to
adopt the coupler structure of 6-arm branch. As shown in Figure. 1, the overall structure of the coupler is symmetrical about the center.

Figure 1. The structure of E-plane coupler

According to the branch coupler theory, the even-mode transmission matrix of the 6-arm branch coupler can be derived, as in

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
1 & ja_1 \tan \theta_1 / 2 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
0 & j \tan \theta_{b1} \\
j \tan \theta_{b1} & 0
\end{bmatrix} \begin{bmatrix}
1 & ja_2 \tan \theta_2 / 2 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
0 & j \tan \theta_{b2} \\
j \tan \theta_{b2} & 0
\end{bmatrix} \begin{bmatrix}
1 & ja_3 \tan \theta_3 / 2 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
0 & j \tan \theta_{b3} \\
j \tan \theta_{b3} & 0
\end{bmatrix} \begin{bmatrix}
1 & ja_4 \tan \theta_4 / 2 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
0 & j \tan \theta_{b4} \\
j \tan \theta_{b4} & 0
\end{bmatrix}
$$

Where $\theta$ is the electrical length of the corresponding waveguide. Through the transmission matrix, the reflection coefficient and transmission coefficient of the coupler can be obtained, and then the $S$ parameters of the coupler can be obtained, too. As in

$$
S_{11} = \frac{1}{2}(r_e + r_w)
$$

$$
S_{21} = \frac{1}{2}(r_e + r_w)
$$

$$
S_{31} = \frac{1}{2}(r_e - r_w)
$$

$$
S_{41} = \frac{1}{2}(r_e - r_w)
$$

2.2. Waveguide phase shifter

the self-compensating waveguide phase shifter structure is referenced from[6]. As shown in Figure. 2, this structure combines a widened rectangular waveguide and periodic grooves structure to achieve better phase shift performance. The width of the rectangular waveguide decides the dominant mode cut-off frequency of the waveguide, and increasing the width of the waveguide will increase the cut-off frequency, thus reducing the phase velocity in the waveguide. The widened waveguide has the advantage of low insertion loss and easy to processing, however its bandwidth is hard to expand. So we adding delay lines on the waveguide to expand bandwidth. The periodic groove structure on the side of the waveguide is a kind of slow wave structure, which can reduce the phase velocity in the waveguide. Figure. 3 shows the phase difference of the three structures, which relative to the waveguide of the same length. It can be found that the self-compensating waveguide phase shift structure has excellent phase shifting characteristic with wider bandwidth.
Figure 2. The three structure of phase shift

Figure 3. Comparison result of three phase shift structures

3. Simulation and optimization

The coupling of the coupler designed in this paper is 3dB, and the standard waveguide is WR-08 waveguide standard with size of 2.03mm×1.01mm. Through the above theory, the initial values of the parameters of the 3dB waveguide coupler can be obtained, and the 3D-EM solver software HFSS from Ansoft is used to implementing the models. The calculated initial values are substituted into the model, and then the optimization is carried out to obtain the best performance.

In order to be close to the actual processing situation, the material of the cavity surface is set as gold, and the bulk conductivity is 4.1×10⁷S/m. In Table 1, we provide the value of main parameters of the coupler obtained by the optimization. Figure. 4 shows the model in HFSS of the waveguide directional coupler.

| parameters | a1 | a2 | a3 | b1 | b2 | b3 |
|------------|----|----|----|----|----|----|
| value(mm)  | 0.32 | 0.34 | 0.33 | 0.58 | 0.58 | 0.57 |
Figure 4. The model of directional coupler

Figure 5 shows the simulation results of the waveguide directional coupler. In the frequency range of 100GHz-120GHz, the imbalance between S12 and S13 is within 0.2dB, and the phase imbalance is within 0.5° compared with the 90° index.

Then the self-compensating phase shifter is directly connected to the coupling port of the waveguide directional coupler to generate a phase compensation of 90°. After combined, the parameters need to be adjusted to improve the performance. During the optimization process, the center frequency of the phase shifter is changed by adjusting the width of waveguide, because the cut-off frequency of this section of the widened waveguide can be changed by changing the width. Beyond that, the size of the groove can affect the phase shift, because the change of the structural parameters of the groove will generate the slow wave effect in the waveguide, so as to change the phase shift length of the waveguide. The power divider model finally established is presented in Figure 6. Periodic plots are placed on the outside of the waveguide to decrease the processing difficulty.
Figure 6. The structure of power divider

The simulation results of the power divider are presented in Figure 7. In the 100-120GHz frequency band, the amplitude imbalance within 0.3dB, and phase imbalance is +0.5°/-1.2°, and the relative bandwidth is about 18%.

Figure 7. simulation results of the power divider

In addition, we also make a sensitivity analysis to the design, when the parameter of periodic groove is varied by 10 um in the proposed divider, the amplitude and phase imbalances will only have a maximum change of 0.2dB and 1.5°. And when the width of branch is varied by 10 um, the amplitude and phase imbalance will only have a maximum change of 0.3dB and 0.5° over the operation frequency 100–120GHz. The results show that variations in the coupler branches had the larger impact on the amplitude imbalance, while variations in the groove structure of phase shifter seem to have the larger effect on the phase imbalance.

4. Appendices
Based on the waveguide directional coupler and the self-compensating phase shifter, a terahertz waveguide power divider is designed in this paper with 18% bandwidth. The power divider can work from 100GHz to 120GHz with a phase and amplitude imbalance of 1.2° and 0.3dB. The sensitivity analysis shows when the design has a machining tolerance of 10um, the phase and amplitude imbalance are less than 1.5°and 0.2dB. The phase shifter of power divider has wider bandwidth compared with waveguide. It can be used in terahertz image rejection mixer or other components to improve the performance.

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