Progress In Electromagnetics Research C, Vol. 45, 113–123, 2013

DIRECTIONAL COUPLER USING MULTI-STAGE COUPLED STRUCTURE THEORY

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Abstract—This paper presents a new directional coupler design, which can increase power capacity working with S band. The design concept is based on multi-stage coupled structure. Aim is to increase the size of coupling aperture by reducing the coupling degree of each stage structure. In view of this, multi-stage coupled structure theory is utilized to improve the directivity of directional coupler, coupling flatness and power capacity. According to the derivation of theory, it can be deduced that the sum of the coupling degree of single stage coupling structure is equal to the coupling degree of two-stage coupling directional coupler (TSCDC), and the directivity of TSCDC depends on the directivity of the first stage coupling structure. Then, rectangular waveguide two-stage coupled directional coupler is designed and fabricated. The measured results demonstrate full-band from 1.72 to 2.61 GHz with coupling flatness < 0.65 dB and the directivity > 26 dB.

1. INTRODUCTION

Directional coupler is a fundamental component especially in microwave measurement system [1, 2]. References [3–5] reported that because of the relative stable structure and properties of rectangular waveguide directional coupler, it was extensively used in microwave engineering to monitor, measure and separate incident power, etc. However, most of devices cannot directly measure the power source because they work in small power environment. In [6, 7], with the development of industry, directional couplers have different forms and can be widely used in the field of coaxial, strip-line, micro-strip structure because of their high directivity in [8–10], but there are only

Received 1 May 2013, Accepted 28 October 2013, Scheduled 4 November 2013

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a few studies about waveguide coupler. References [11, 12] proposed a new approach to improve the directivity of directional coupler based on Chebyshev coupling aperture. Now, with the development of power source, higher requirement has been proposed in the power measurement system in [13, 14].

This paper reports the design of two-stage coupled directional coupler (TSCDC) by using multi-stage coupled structure theory. We need to design a new type of TSCDC applied directly to microwave power measurement system that can achieve indicators of high directivity and best coupling flatness.

The main content is as follows. Section 1 introduces the current development of high-power directional coupler. Section 2 gives a guide at the theoretical level by using multi-stage coupling structure theory. Design and simulation of high power two-stage directional coupler are presented in Section 3. Measurement results are given in Section 4. This paper is concluded by Section 5.

2. ANALYSIS OF MULTI-STAGE COUPLED STRUCTURE THEORY

Generally, the total coupling degree of directional coupler is an assumed value. When rectangular waveguide directional coupler using multi-stage coupled structure, with increase of stages, the coupling degree of each stage coupled structure will become small; the size of the coupling aperture of each stage coupling structure will increase; the power capacity can increase ten times as multi-stage coupled directional couplers.

Suppose that the coupling degrees of stage coupled structures C_1, C_2, C_2, …, C_N are known and that P_1 is the input power from input port, P_2 the input power from output port, P_3 the power of coupling port received from the first-stage coupling structure, P_5 the power of coupling port received from the second-stage coupling structure, so P_{2N+1} is the power of coupling port received from the N-stage coupling structure.

$$C_1 = 10\lg\frac{P_3}{P_1} \tag{1}$$

$$C_2 = 10\lg\frac{P_5}{P_3} \tag{2}$$

$$\cdots$$

$$C_{N-1} = 10\lg\frac{P_{2N-1}}{P_{2N-3}} \tag{3}$$

$$C_N = 10\lg\frac{P_{2N+1}}{P_{2N-1}} \tag{4}$$

$$C = 10\lg\frac{P_{2N+1}}{P_1} = C_1 + C_2 + C_3 + \ldots + C_{N-1} + C_N = \sum_{i=1}^{N} C_i \quad (5)$$

We can then obtain C which is the coupling degree of multi-stage coupled rectangular waveguide directional coupler.

Where D is the directivity of multi-stage coupled rectangular waveguide directional coupler, I the isolation of it, I_1 the isolation of the first-stage coupled structure, and D_1 the directivity of first-stage coupled structure.

$$I_1 = 10\lg\frac{P_3}{P_2} \quad (6)$$

$$I = 10\lg\frac{P_{2N+1}}{P_2} = I_1 + C_2 + C_3 + \ldots + C_{N-1} + C_N = I_1 + \sum_{i=1}^{N} C_i \quad (7)$$

$$D = I - C = I_1 + \sum_{i=2}^{N} C_i - \sum_{i=1}^{N} C_i = I_1 - C_1 = D_1 \quad (8)$$

From Equations (1)–(5), we can see that the sum of the coupling degrees of single stage coupling structure is equal to the coupling degree of multi-stage coupling directional coupler. When you choose different coupling degrees of single-stage coupling structure, the multi-stage coupled directional coupler can measure the different sizes of microwave power.

It can be seen from Equations (6)–(8) that directivity of multi-stage coupled directional coupler depends on the first stage coupling structure's directivity. In order to improve the directivity of multi-stage coupled rectangular waveguide directional coupler, we just need to increase the first stage coupling structure's directivity.

3. DESIGN AND SIMULATION

Because the size of multi-stage coupled structure is usually big in low frequency, considering the practical application, multi-stage coupled directional couplers are generally designed with two-stage structure.

3.1. The Coupling Degree of Two-stage Rectangular Waveguide Directional Coupler

In Section 2, in the theoretical derivation it is known that the sum of the coupling degree of each stage coupled structure is equal to the coupling degree of multi-stage coupled rectangular waveguide directional coupler. However, the coupling flatness is present in each coupling structure, typically ±0.5 dB∼±1 dB. If the coupling flatness of first-stage coupling structure and second coupling structure is ±1 dB, then, the coupling flatness of TSCDC will become ±2 dB.

The two-stage coupled directional coupler cannot obtain the best indicators about the simple concatenation of two-single-stage coupling structure, thus, in order to achieve optimal coupling flatness, two methods have been proposed, which are based on the superposition of the same direction and the superposition of the opposite direction for coupling degree.

(1) The coupling superposition of same direction.

The coupling flatness of first-stage coupled structure ±1.5 dB is shown in Figure 1(a). The coupling flatness of second-stage coupling

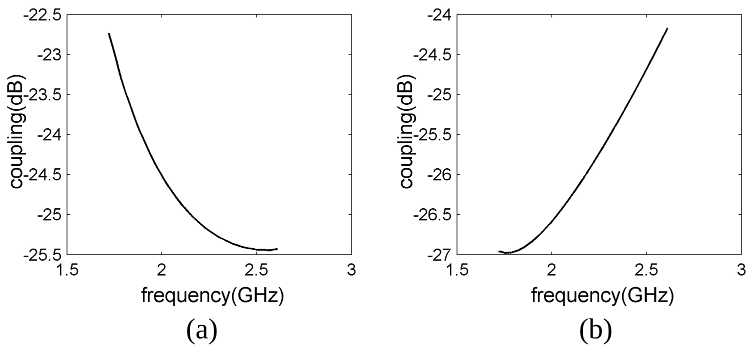


Figure 1. The coupling degree of first-stage coupled structure and the coupling degree of second stage coupled structure. (a) First stage. (b) Second stage.

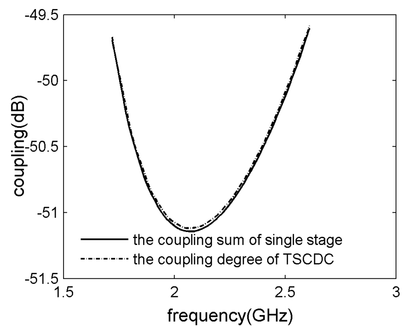


Figure 2. Contrast of single-stage and two-stage structure's coupling degree.

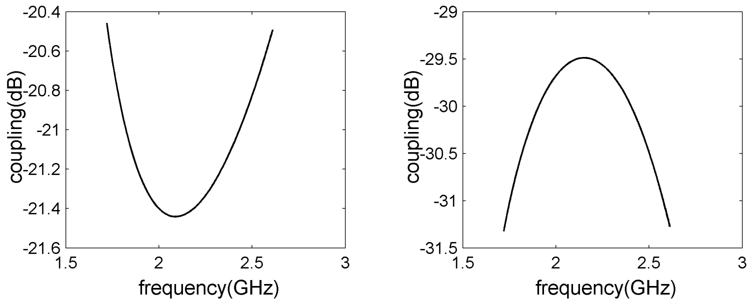
structure ±1.5 dB is shown in Figure 1(b).

The coupling of two-stage coupled rectangular waveguide directional coupler is equal to 50 dB, and coupling flatness of it ±0.75 dB is shown in Figure 2. Using the superposition of the same direction, the coupling flatness decreases 4.4 dB in the full frequency band of two-stage coupled rectangular waveguide directional coupler.

(2) The coupling superposition of opposite direction.

The coupling flatness of first-stage coupling structure ±0.5 dB is shown in Figure 3(a). The coupling flatness of second-stage coupling structure ±1 dB is shown in Figure 3(b).

In Figure 4, the coupling of TSCDC is equal to 51 dB, and coupling flatness ±0.5 dB is shown in Figure 4. Using the superposition



(a) (b)

Figure 3. The coupling degree of first-stage coupling structure and the coupling degree of second stage coupling structure. (a) First stage. (b) Second stage.

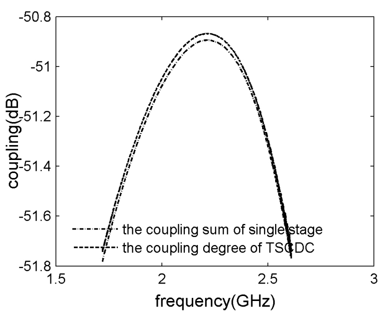


Figure 4. Contrast of single-stage and two-stage structure's coupling degree.

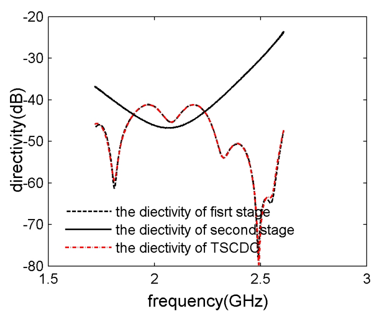


Figure 5. Contrast of single-stage and two-stage structure's directivity.

of opposite direction, which achieves better coupling flatness in full frequency band of two-stage coupled rectangular waveguide directional coupler, ideal coupling flatness is within 0 dB.

When you choose a different model structure and methods, trend and size of coupling flatness are different. The superposition of the opposite direction's method is noticeably better than the same direction. As long as the coupling flatness is equal to the single-stage coupling structure, we can get optimal coupling flatness by using method with the superposition of the opposite direction.

3.2. The Directivity of Two-stage Rectangular Waveguide Directional Coupler

In Figure 5, the total directivity of TSCDC depends on the directivity of the first stage coupling structure. The directivity of second coupling structure does not affect the directivity of two-stage coupling structure, which is shown in Figure 5. In order to improve the directivity of two-stage coupled rectangular waveguide, we just need to improve the directivity of the first stage coupling structure.

3.3. Miniaturization of the Two-stage Coupled Rectangular Waveguide Directional Coupler

Although two-stage coupling structure of this form can achieve high power, the size of two-stage coupling structure is usually cumbersome, and we need to select different structures to meet the demands of different occasions without changing the coupling degree and directivity. The smaller the structure is, the easier the processing and manufacturing are. Smaller structure, easier processing and manufacturing, low cost and portability, make its application to power measurement system more convenient. Therefore, the miniaturization of multi-stage coupling structure has also become an important factor.

In short, using the above method, a rectangular waveguide two-stage directional coupler working over a wide frequency band (1.72 to 2.61 GHz) is presented. The proposed directional coupler consists of a two-stage coupling structure, each of which uses the Chebyshev distribution of multi-holes structure as the first stage structure, in addition second stage coupling structure based on double cross-aperture.

4. IMPLEMENT AND MEASUREMENT

According to analysis, most of the devices cannot directly measure the power source because they work in a small power environment. A new type of two-stage coupled rectangular-waveguide directional coupler is designed, from which we can get the indicators of weak coupling, high directivity, small coupling flatness and high peak power. The project technical indicators:

Frequency bandwidth: 1.72 GHz∼2.61 GHz,

Coupling: -50 ± 1 dB,

Directivity: > 20 dB.

the coupling degree of first-stage coupling structure is 21 dB, and the coupling degree of second-stage coupling structure is 31 dB in the design of two-stage coupled rectangular waveguide directional coupler. The size of this structure and ordinary rectangular waveguide directional coupler is very close. The proposed directional coupler has been fabricated on a standard rectangular waveguide using copper material which is shown in Figure 6.

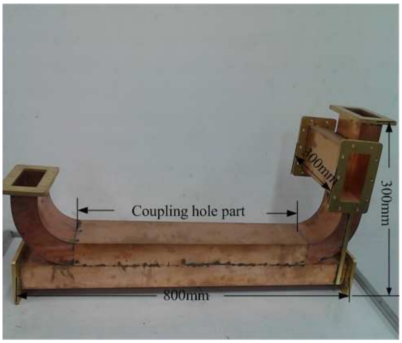


Figure 6. The photograph of the fabricated of TSCDC.

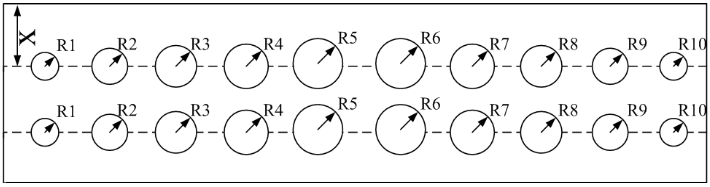


Figure 7. The photograph of TSCDC's coupling hole part.

Table 1. The size of main-stage structure's aperture.

Rectangular waveguide (mm)	$a = 109.22$	$b = 54.61$	$t = 2$
TSCDC (mm)	$L = 800$	$W = 300$	$H = 300$

Table 2. The size of second-stage structure's cross hole.

Name	Angle	The distance between center of common wall	Length (mm)	Width
Cross-aperture 1	45	$X_1 = Y_2 = 27.42$ (mm)	38.2	4.4
Cross-aperture 2	45	$X_2 = Y_2 = 28$ (mm)	38.2	4.4

The operating frequency band is from 1.72 GHz to 2.61 GHz, and the geometrical dimensions of high power two-stage directional coupler are listed below: the radius of single row coupling aperture of the main-stage coupling structure: $R_1 = 6.02$ mm, $R_2 = 8.98$ mm, $R_3 = 11.50$ mm, $R_4 = 13.33$ mm, $R_5 = 14.28$ mm, $R_6 = 14.28$ mm, $R_7 = 13.33$ mm, $R_8 = 11.50$ mm, $R_9 = 8.98$ mm, $R_{10} = 6.02$ mm, coupling aperture position: $x = 0.235 * a$ is shown in Figure 7, the other sizes as in Table 1 and Table 2.

Figure 8 shows a photograph of the measurement of high power two-stage directional coupler. From the measured data, using mutual coupling compensation principle in Section 3, it can be found that the coupling degree: 50.4 ± 0.35 dB, the coupling flatness within ± 0.35 dB and reduced 1.3 dB compared with the project technical indicators in full band. We can get the best coupling flatness by using the method with superposition of the opposite direction, which is shown in Figure 9(a). The isolation is greater than 76 dB in Figure 9(b). The directivity is greater than 26 dB by improving the directivity of the first stage coupling structure in the full frequency band in Figure 9(c). The VSWR is below 1.07 in Figure 9(d), which decreases the reflection of input port.

Figure 8. The measurement photo of the coupling degree of TSCDC.

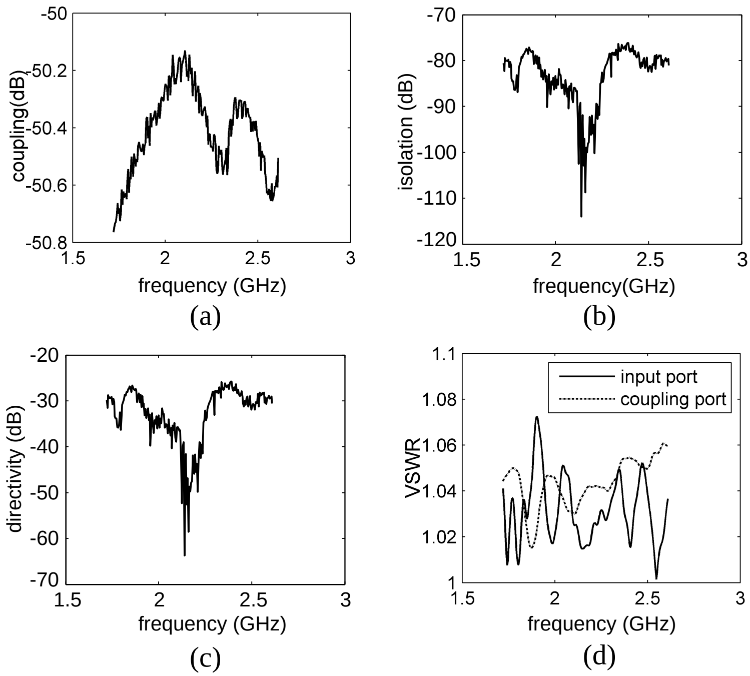


Figure 9. The measurement results of two-stage rectangular waveguide directional coupler. (a) Coupling. (b) Isolation. (c) Directivity. (d) VSWR.

5. SUMMARY

A new type of rectangular waveguide two-stage coupled directional coupler is designed through the theoretical analysis of the multi-stage coupling structure. It can withstand different power values by adjusting the coupling degree of single-stage coupling structure. We can achieve optimal coupling flatness by using those methods with the coupling superposition of the same direction and the coupling superposition of the opposite direction. In order to improve the directivity of two-stage coupled rectangular waveguide, we merely need to improve the directivity of the first stage coupling structure. So if you want to make the best indicators of TSCDC, in addition to the theoretical derivation, we must have a precise calculation, simulation, optimization and excellent mechanical processing.

ACKNOWLEDGMENT

This work is supported by University of Electronic Science and Technology of China. The authors would like to thank Ling Tong, Yu Tian and Bo Gao, School of Automation Engineering, UESTC, for their helpful advice and discussion.

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