A High Directivity Microstrip Coupler Based on Reflective Resistors

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Abstract. *In this paper, a novel high-directivity microstrip coupler based on reflective resistors is presented. The proposed coupler consists of three pairs of coupled-line sections and one pair of resistors. Generally, the coupling degree can be controlled by the coupled lines, while the resistors are employed to adjust the amplitude of the reflected signal to cancel out the leakage signal. The mechanism of high directivity is derived and the S-parameters are presented. To verify the design concept, a 20 dB microstrip coupler operating at 2 GHz is processed and measured. The measured results indicate that the return loss of input and output ports is more than 28.5 dB with a typical insert loss of 0.3 dB, while that of coupled and isolated ports is more than 15 dB. And the directivity is more than 20 dB with a maximum 53.1 dB at 2.01 GHz in a fractional bandwidth of 22.5%.*

Keywords

High directivity, microstrip coupler, *S*-parameters

1. Introduction

Microstrip coupled-line couplers are widely used in microwave circuits such as balanced power amplifiers, mixers, modulators, power combiners, measurement systems, phase shifters, beam-forming array antennas, and so on [1]. Among several characteristics of a microstrip coupler, coupling degree and directivity are two most crucial parameters. The coupling degree is mainly limited by the minimum spacing between the coupled lines, which is about 0.1 mm in practical applications. The coupling degree of a traditional $\lambda/4$ microstrip coupled-line coupler can be exploited to 8–40 dB [1]. However, due to the difference between the phase velocities of even- and odd-modes on the microstrip coupled-line, the directivity is rather poor [1], [2], which is usually smaller than 20 dB in practical applications [2].

Directivity, defined by the difference between the coupled and isolated ports, plays a critical role in power measurement systems. Poor directivity can cause the uncertainty of the results, especially in high-power systems [3]. In order to solve the problem, various kinds of approaches have been investigated to compensate for the difference between the even-odd phase velocities, mainly including [1], [4]: 1) By adding capacitances [5], [6] or inductors [7], [8] at the ends or in the middle of the coupled lines. 2) By using a dielectric overlay on top of the coupled lines [9], [10]. 3) By using wiggly lines [11], [12]. Other effective methods, like additional output-port matching networks [13], [14], or additional passive component circuits on coupled-line [15] are also proposed. Although the mentioned means can enhance the directivity, they still have some disadvantages such as sensitivity of process [5], [11], [12], multilayer circuits [6], [9], [10], and low-power capability [6], [8].

In this paper, a novel microstrip coupler with high directivity based on reflective resistors is exploited. Initially, the mechanism of high directivity of the proposed microstrip coupler is described and the *S*-parameters are given. Then, ADS simulation and theoretical calculation are employed to verify the correctness of the design. Moreover, a 20-dB microstrip coupler operating at 2 GHz is presented. Finally, the proposed coupler is manufactured and measured to verify the design concept.

2. Analysis of the Proposed Coupler

2.1 Conventional $\lambda/4$ Microstrip Coupler

The topology of a traditional $\lambda/4$ microstrip coupler is shown in Fig. 1. Because of its completely symmetrical

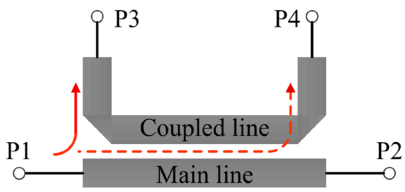

Fig. 1. The topology of a traditional $\lambda/4$ microstrip coupler.

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structure, even-odd modes theory can be used for analysis. The S-parameters of the traditional $\lambda/4$ microstrip coupler are described in the following:

$$\mathbf{S}=\begin{bmatrix} 0 & -\mathrm{j}\sqrt{1-k^2} & k & 0 \\ -\mathrm{j}\sqrt{1-k^2} & 0 & 0 & k \\ k & 0 & 0 & -\mathrm{j}\sqrt{1-k^2} \\ 0 & k & -\mathrm{j}\sqrt{1-k^2} & 0 \end{bmatrix} \quad (1)$$

where $$k=\frac{Z_{\mathrm{oe}}-Z_{\mathrm{oo}}}{Z_{\mathrm{oe}}+Z_{\mathrm{oo}}}.$$

Z_{oe}, Z_{oo} are the characteristic impedance of even- and odd-modes.

When the coupler is ideal, odd- and even-modes characteristic impedances and phase constants (β_{o}, β_{e}) satisfy with (2). The transmission coefficient can be negligible, as given by (3).

$$Z_{\mathrm{oo}}Z_{\mathrm{oe}}=Z_0^2,\quad \beta_{\mathrm{o}}=\beta_{\mathrm{e}}, \quad (2)$$

$$S_{41}=-\frac{\mathrm{j}Z_0}{2}\frac{\left(Z_{\mathrm{oo}}Z_{\mathrm{oe}}-Z_0^2\right)\left(Z_{\mathrm{oo}}-Z_{\mathrm{oe}}\right)}{\left(Z_{\mathrm{oe}}^2+Z_0^2\right)\left(Z_{\mathrm{oo}}^2+Z_0^2\right)}=0. \quad (3)$$

But the coupler is non-ideal in practical applications, then the phase constants in the odd- and even-modes are not equal [4]. Thus, the transmission coefficient can no longer be negligible [2], and (2) and (3) turn to

$$Z_{\mathrm{oo}}Z_{\mathrm{oe}}\neq Z_0^2,\quad \beta_{\mathrm{o}}\neq\beta_{\mathrm{e}}, \quad (4)$$

$$S_{41}=\frac{\left(1-\rho_{\mathrm{e}}^2\right)\mathrm{e}^{\mathrm{j}\beta_{\mathrm{e}}l}}{2\left(\mathrm{e}^{2\mathrm{j}\beta_{\mathrm{e}}l}-\rho_{\mathrm{e}}^2\right)}-\frac{\left(1-\rho_{\mathrm{o}}^2\right)\mathrm{e}^{\mathrm{j}\beta_{\mathrm{o}}l}}{2\left(\mathrm{e}^{2\mathrm{j}\beta_{\mathrm{o}}l}-\rho_{\mathrm{o}}^2\right)}\neq 0 \quad (5)$$

where $$\rho_{\mathrm{e}}=\frac{1-Z_{\mathrm{oe}}/Z_0}{1+Z_{\mathrm{oe}}/Z_0},\quad \rho_{\mathrm{o}}=\frac{1-Z_{\mathrm{oo}}/Z_0}{1+Z_{\mathrm{oo}}/Z_0}.$$

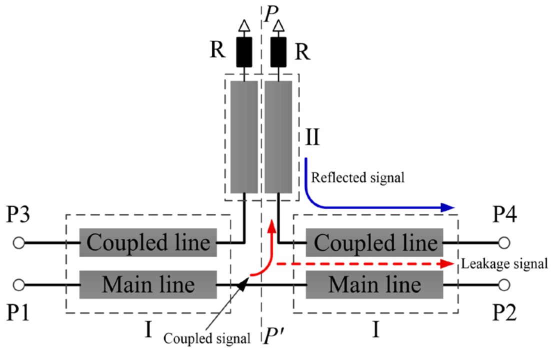

Fig. 2. The topology of the proposed microstrip coupler.

2.2 The Proposed Coupler

As known, the difference in the phase constants is the main factor that generates finite isolation in low directivity [4]. To solve this problem, a novel microstrip coupler is proposed as shown in Fig. 2. Compared to the conventional $\lambda/4$ microstrip coupler, the proposed coupler is improved in that a pair of coupled-line is inserted in the middle of the coupled-line, and two resistors are added as the loads. The deviation of directivity resulting from process, simulation, and so on, can be adjusted by changing the value of the resistors, which improves the design flexibility.

The mechanism of high directivity can be briefly explained as follows. Ports 1–4 are respectively labeled as the input, direct, coupled and isolated ports. Due to the finite isolation, a portion of the input signal appears at port 4, labeled as leakage signal (red dotted line). The coupled signal (red line), which can be exactly designed, translates to resistor R. Partial of it, as the reflected signal (blue line), is reflected by R, which is not a matched load. The amplitude of the reflected signal can accurately adjust to cancel out the leakage signal, via the inherent out-of-phase in between. The S-parameters of the proposed microstrip coupler can be inferred by the interconnected networks [1], [16], [17]. Finally, the S-parameters of the proposed coupler with equal odd- and even-mode phase constants are given by (6).

$$\mathbf{S}=\frac{1}{1-A_{\mathrm{I}}^2A_{\mathrm{II}}}\begin{bmatrix} \frac{A_{\mathrm{I}}^2B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} & B_{\mathrm{I}}^2-\frac{A_{\mathrm{I}}^2B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} & D-\frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} & \frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} \\ B_{\mathrm{I}}^2-\frac{A_{\mathrm{I}}^2B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} & \frac{A_{\mathrm{I}}^2B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} & \frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} & D-\frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} \\ D-\frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} & \frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} & \frac{B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} & A_{\mathrm{II}}B_{\mathrm{I}}^2-\frac{B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} \\ \frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} & D-\frac{A_{\mathrm{I}}B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} & A_{\mathrm{II}}B_{\mathrm{I}}^2-\frac{B_{\mathrm{I}}^2B_{\mathrm{II}}^2C\Gamma}{1-C^2} & \frac{B_{\mathrm{I}}^2B_{\mathrm{II}}^2\Gamma}{1-C^2} \end{bmatrix} \quad (6)$$

where $$A_{\mathrm{I}}=\frac{\mathrm{j}K_{\mathrm{I}}\sin\theta_{\mathrm{I}}}{\sqrt{1-K_{\mathrm{I}}^2}\cos\theta_{\mathrm{I}}+\mathrm{j}\sin\theta_{\mathrm{I}}},\qquad A_{\mathrm{II}}=\frac{\mathrm{j}K_{\mathrm{II}}\sin\theta_{\mathrm{II}}}{\sqrt{1-K_{\mathrm{II}}^2}\cos\theta_{\mathrm{II}}+\mathrm{j}\sin\theta_{\mathrm{II}}},$$

$$B_{\mathrm{I}}=\frac{\sqrt{1-K_{\mathrm{I}}^2}}{\sqrt{1-K_{\mathrm{I}}^2}\cos\theta_{\mathrm{I}}+\mathrm{j}\sin\theta_{\mathrm{I}}},\qquad B_{\mathrm{II}}=\frac{\sqrt{1-K_{\mathrm{II}}^2}}{\sqrt{1-K_{\mathrm{II}}^2}\cos\theta_{\mathrm{II}}+\mathrm{j}\sin\theta_{\mathrm{II}}},$$

$$C = -\frac{\Gamma(A_\mathrm{I} - A_\mathrm{I}^3 A_\mathrm{II} + A_\mathrm{I} A_\mathrm{II} B_\mathrm{I}^2)}{1 - A_\mathrm{I}^2 A_\mathrm{II}},$$

$$D = A_\mathrm{I} - A_\mathrm{I}^3 A_\mathrm{II} + A_\mathrm{I} A_\mathrm{II} B_\mathrm{I}^2,$$

$$K_\mathrm{I} = \frac{Z_\mathrm{oeI} - Z_\mathrm{ooI}}{Z_\mathrm{oeI} + Z_\mathrm{ooI}}, K_\mathrm{II} = \frac{Z_\mathrm{oeII} - Z_\mathrm{ooII}}{Z_\mathrm{oeII} + Z_\mathrm{ooII}}, \Gamma = \frac{R - Z_0}{R + Z_0}.$$

θ_I and θ_II are the electric lengths of the coupled-line I, II, respectively. Z_oeI and Z_ooI are the even-mode and odd-mode characteristic impedances of the coupled line I, respectively. Z_oeII and Z_ooII are that of the coupled line II, respectively.

As shown in (6), S_{ij} (i, j = 1 to 4) is a complicated function with many parameters. Return loss of each port is nonzero, indicating that all ports are not matched. The phase difference between P3 and P2 is $\Delta P = \pi/2 + \theta_\mathrm{I}$ [21], as the topology of the proposed microstrip coupler is not symmetric. In general, the coupling degree is controlled by coupled line I, and the reflected signal can be easily controlled to equal to the leakage signal with a proper value of R. As the resistors have conspicuous effects on the directivity, the effects of the parameters of R on the directivity are simulated and plotted in Fig. 3. It is demonstrated that the maximum directivity of 55.7 dB is achieved with $R = 23\ \Omega$ at 2 GHz. $R = 22\ \Omega$ and $24\ \Omega$ have the same effects on the directivity with worse maximum values.

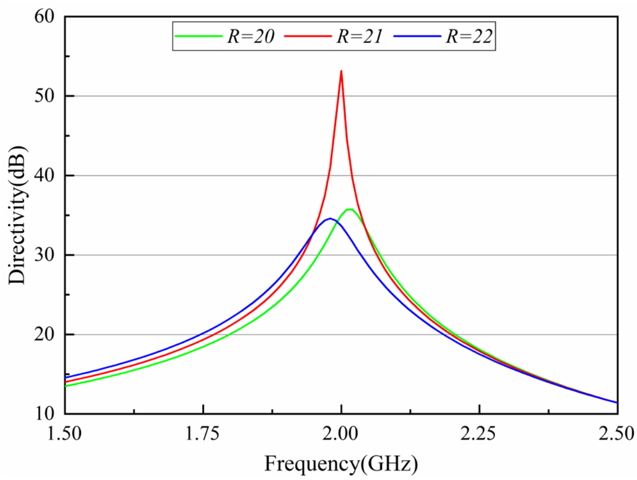

Fig. 3. Responses of directivity with different R with $\theta_\mathrm{I} = \theta_\mathrm{II}$ = 45° and $K_\mathrm{I} = K_\mathrm{II}$ = 0.139 (without matching network on P3 and P4).

	ADS Simulation	Theoretical Calculation	Traditional $\lambda/4$ Coupler
S_{11}/S_{22} (dB)	–49.949	–49.941	–31.880
S_{33}/S_{44} (dB)	–9.716	–9.725	–31.880
S_{31}/S_{42} (dB)	–19.582	–19.584	–19.950
S_{21}/S_{12} (dB)	–0.090	–0.090	–0.091
S_{41}/S_{32} (dB)	–29.851	–29.833	–24.512
S_{43}/S_{34} (dB)	–20.238	–20.214	–0.091

Tab. 1. Performance comparison between ADS simulation, theoretical calculation, and traditional quarter-wave coupler.

2.3 Analysis

To verify the accuracy of the S-parameters derived in the previous section, a comparison of results from ADS ideal model simulation (Keysight Technology) and theoretical calculation, as well as a traditional $\lambda/4$ microstrip coupler (microstrip model) with a 20-dB coupler working at 2 GHz is listed in Tab. 1 where $\theta_\mathrm{I} = \theta_\mathrm{II} = 45°$, $K_\mathrm{I} = K_\mathrm{II} = 0.139$ (according to Fig. 4), $\Gamma = -0.333$.

As shown in Tab. 1, it is evident that the results of ADS simulation and theoretical calculation have a good correspondence, which demonstrates the correctness of the S-parameters of the proposed coupler. The amplitude of reflected signal (S_{41} and S_{32} of ADS simulation) can be exactly controlled to cancel out the leakage signal of a practical coupler (S_{41} and S_{32} of traditional $\lambda/4$ coupler). The reflection coefficients of coupled ports (S_{33} and S_{44}) become worse, as the resistor R is not a matched load. It should be noticed that no attempt is offered to design exact coupling degree here, as the goal is to verify the correctness of the S-parameters.

3. Design of the Proposed Coupler

The design process of the proposed coupler is carried out as follows. The electrical length of coupled lines can be chosen anyone, but the sum of θ_I and θ_II must be equal to $\lambda/4$ to maximize the directivity. The values of K_I and K_II can be anyone, too. As the value of θ_I is not $\lambda/4$ anymore, therefore, compared to the traditional $\lambda/4$ coupler, the design parameter K_i should be adjusted, as

$$K_i = K_i' / \sin(\theta_i) \quad (7)$$

where K_i is the voltage coupling coefficient of the proposed microstrip coupler, K_i' is that of the traditional $\lambda/4$ coupler, θ_i is the electrical length of the coupler line, and i = I, II. When the parameters of the coupled lines are selected, it remains to determine the required value of the reflective resistors. For this, the amplitude of leakage signal is determined by simulation of circuit with $R = 50\ \Omega$, then the R is clarified by the minimizing of coefficient S_{41} of the coupler, at which the amplitude of the leakage signal will be equal to the amplitude of reflected signal. Since at the same time the return losses at ports P3 and P4 will be significant, as it can be seen from Tab. 1, so further it is necessary to provide the matching of the indicated ports.

A 20-dB microstrip coupler with $\theta_\mathrm{I} = \theta_\mathrm{II} = 45°$ operating at 2 GHz is designed to verify the design concept. In this example, $K_i' = 0.1$, $K_i = 0.139$ were chosen. Then, the even-mode and odd-mode characteristic impedances of the coupled line I, II are calculated. The amplitude of leakage signal can be simulated by ADS with $R = 50\ \Omega$, which is about –27.5 dBc. According to the S-parameters of the proposed microstrip coupler, the amplitudes of reflected signal under different R are calculated when $\theta_\mathrm{I} = \theta_\mathrm{II} = 45°$

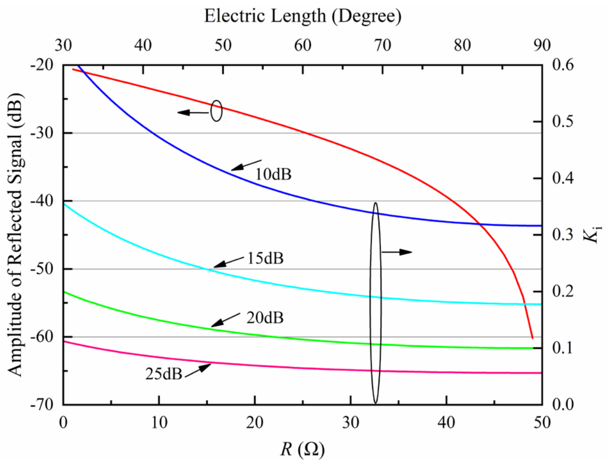

Fig. 4. Responses of K_i and θ_i with four typical coupling degrees, and the amplitudes of reflected signal under different R when $\theta_{\rm I} = \theta_{\rm II} = 45°$ and $K_{\rm I} = K_{\rm II} = 0.139$.

and $K_{\rm I} = K_{\rm II} = 0.139$, as displayed in Fig. 4. In detail, the amplitude of the reflected signal is –27.6 dBc with $R = 20\ \Omega$, which equals that of the leakage signal (–27.5 dBc). Two-section (≈ 34°) short-step Chebyshev impedance transformers [20] are used to match P3 and P4 to 50 Ω. Finally, the calculated, simulated (without matching network on P3 and P4) and fabricated parameters for the dielectric substrate specified below are presented in Tab. 2. Different R between them is acceptable, as the relative amplitudes of the reflected signal and the leakage signal are changed under different conditions. Based on the previous discussion, the corresponding relationship between K_i and θ_i with four typical coupling degrees is shown in Fig. 4.

4. Manufactures and Experiment

The manufactured prototype of the proposed coupler is fabricated on a dielectric substrate of Rogers 4350B with the relative permittivity of 3.66, the thickness of 0.508 mm, and the tangent loss of 0.0037, as shown in Fig. 5. With high-precision SMT resistor $R = 25\ \Omega$, the directivity of the proposed coupler is a bit different from the simulated one, as plotted in Fig. 6. Resorting to the previous analysis, the main factor affecting the directivity of the proposed coupler is the different amplitudes between the reflected and the leakage signals. Meanwhile, the measured results demonstrated that S_{11} and S_{22} are more than 28.5 dB with a typical insert loss of 0.3 dB, S_{33} and S_{44} is more than 15 dB.

	$w_{\rm I}$	$l_{\rm I}$	$s_{\rm I}$	$w_{\rm II}$	$l_{\rm II}$	$s_{\rm II}$	R	ΔP
CP	1.07	12.8	0.43	1.07	12.8	0.43	20	131°
SP	1.1	13	0.45	1.1	13	0.45	23	138°
FP	1.1	13	0.45	1.1	13	0.45	25	104°

Tab. 2. Parameters of the proposed coupler. (mm for length parameter, Ω for resistor, CP: calculated parameter, SP: simulated parameter (without matching network on P3 and P4). FP: fabricated parameters (with matching network on P3 and P4). ΔP: phase difference (∠P3–∠P2)).

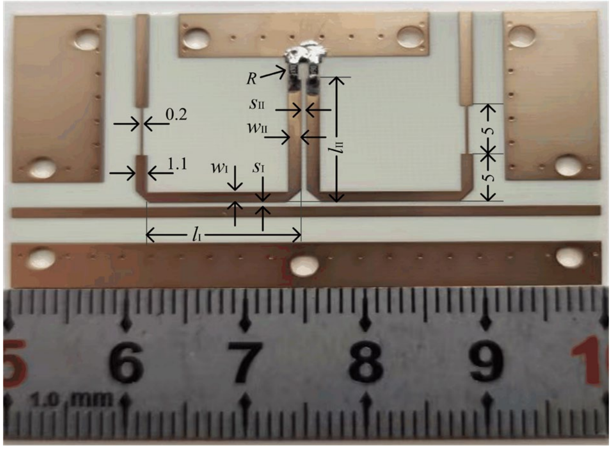

Fig. 5. Photograph of the proposed coupler (mm for length).

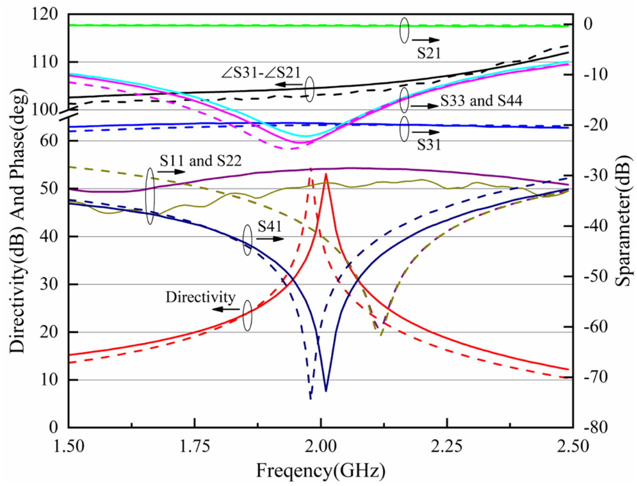

Fig. 6. Measurement (solid line) and EM simulation (dotted line) responses of the proposed coupler.

The directivity is more than 20 dB with the maximum directivity 53.1 dB at 2.01 GHz in a fractional bandwidth of 22.5% at 2 GHz. The fractional bandwidth is limited to 22.5%, due to the inherent response of the $\lambda/4$ microstrip line. The phase of P3 leads that of P2 by 104° at 2 GHz, as shown in Fig. 6.

A comparison of high directivity couplers is presented in Tab. 3. Compared with ref. [15], the proposed coupler exhibits a wider bandwidth and higher directivity. It should be noticed that the center frequencies of [15] are much lower than that of this work. In particular, a better normalized bandwidths and similar directivity have been achieved in [8] and [19], but regarding to power handling, they will present challenges for the structure.

5. Conclusion

A directivity enhancement method based on three pairs of coupled lines and two reflective resistors is demonstrated for microstrip coupler in this paper. The mechanism and the S-parameters are discussed. Compared with most of the previous methods, the deviation of directi-

	Design Method	Coupling Degree (dB)	Center Frequency (MHz)	Normalized Bandwidth (%)*	Directivity (dB)
This work	Microstrip with Reflected Resistor	20	2000	20	56.8
[15] at 7 T	Microstrip with Lumped Elements	25	298	8.8	48.2
[15] at 9.4 T		25	400	8	43.7
[15] at 9.4 T		25	440	7.8	41.2
[8]	Microstrip with Inductive-Loading	20	2000	42	59.9
[12]	Wiggly Microstrip Line	20	2250	20	35
[18]	Epsilon Negative Transmission Line	10	2000	8.7	40
[19], (structure1)	Microstrip with Fragment Structure	20	2000	45	48

*Bandwidth of 20 dB directivity

Tab. 3. Comparison of the proposed coupler and other published microstrip couplers.

vity resulting from process, simulation, and so on, can be adjusted, which improves the design flexibility. Moreover, a 20-dB coupler at 2 GHz is exploited to verify the effectiveness of the design. The excellent correspondence between the simulation and measured results is demonstrated. The proposed coupler is potential in the applications of high-power systems, precision measurement systems, and so on.

Acknowledgments

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References

[1] MONGIA, R., BAHL, I., BHARTIA, P. *RF and Microwave Coupled-Line Circuits*. 2nd ed. London (UK): Artech House, 2007. ISBN: 9780890068304

[2] CRIPPS, S. Coupler talk. *IEEE Microwave Magazine*, 2006, vol. 7, no. 5, p. 32–37. DOI: 10.1109/MW-M.2006.247908

[3] JORGESEN, D., MARKI, C. *Directivity and VSWR Measurements.* 8 pages. Morgan Hill (USA): Marki Microwave, Inc., 2010. [Online] Cited 2023-08-10. Available at: https://markimicrowave.com/technical-resources/white-papers/directivity-vswr-measurements/

[4] MARCH, S. L. Phase velocity compensation in parallel-coupled microstrip line. In *IEEE MTT-S International Microwave Symposium Digest.* Dallas (USA), 1982, p. 410–412. DOI: 10.1109/MWSYM.1982.1130739

[5] DYDYK, M. Microstrip directional couplers with ideal performance via single-element compensation. *IEEE Transactions on Microwave Theory and Techniques*, 1999, vol. 47, no. 6, p. 956 to 964. DOI: 10.1109/22.769332

[6] GRUSZCZYNSKI, S., WINCZA, K. Generalized methods for the design of quasi-ideal symmetric and asymmetric coupled-line sections and directional couplers. *IEEE Transactions on Microwave Theory and Techniques*, 2011, vol. 59, no. 7, p. 1709–1718. DOI: 10.1109/TMTT.2011.2138155

[7] LEE, S., LEE, Y. An inductor-loaded microstrip directional coupler for directivity enhancement. *IEEE Microwave and Wireless Components Letters*, 2009, vol. 19, no. 6, p. 362–364. DOI: 10.1109/LMWC.2009.2020014

[8] HA, J., SHIN, W., LEE, Y. An inductive-loading method for directivity enhancement of microstrip coupled-line couplers. *IEEE Microwave and Wireless Components Letters*, 2017, vol. 27, no. 4, p. 356–358. DOI: 10.1109/LMWC.2017.2678422

[9] SHELEG, B., SPIELMAN, B. E. Broad-band directional couplers using microstrip with dielectric overlays. *IEEE Transactions on Microwave Theory and Techniques*, 1974, vol. 22, no. 12, p. 1216–1220. DOI: 10.1109/TMTT.1974.1128466

[10] KLEIN, J. L., CHANG, K. Optimum dielectric overlay thickness for equal even- and odd-mode phase velocities in coupled microstrip circuits. *Electronics Letters*, 1990, vol. 26, no. 5, p. 274–276. DOI: 10.1049/el:19900182

[11] PODELL, A. A high directivity microstrip coupler technique. In *G-MTT 1970 International Microwave Symposium*. Newport Beach (USA), 1970, p. 33–36. DOI: 10.1109/GMTT.1970.1122761

[12] MULLER, J., JACOB, A. F. Advanced characterization and design of compensated high directivity quadrature coupler. In *IEEE MTT-S International Microwave Symposium Digest.* Anaheim (USA), 2010, p. 724–727. DOI: 10.1109/MWSYM.2010.5517872

[13] OHTA, I., KAWAI, T., FUJII, T., et al. Directivity improvement of microstrip coupled line couplers based on equivalent admittance approach. In *IEEE MTT-S International Microwave Symposium Digest.* Philadelphia (USA), 2003, vol. 1, p. 43–46. DOI: 10.1109/MWSYM.2003.1210879

[14] CHANG, S. F., CHEN, J. L., JENG, Y. H., et al. New high-directivity coupler design with coupled spurlines. *IEEE Microwave and Wireless Components Letters*, 2004, vol. 14, no. 2, p. 65–67. DOI: 10.1109/LMWC.2003.822565

[15] SOHN, S. M., GOPINATH, A., VAUGHAN, J. T. A compact, high power capable, and tunable high directivity microstrip coupler. *IEEE Transactions on Microwave Theory and Techniques*, 2016, vol. 64, no. 10, p. 3217–3223 DOI: 10.1109/TMTT.2016.2602835

[16] SAZANOV, D. M., GRIDIN, A. N., MISHUSTIN, B. A. *Microwave Circuits*. Moscow (Russia): Mir, 1982. ISBN: 0828523118

[17] ABELE, T.-A. Uber die Streumatrix Allgemein Zusammengeschalteter Mehrpole. (The scattering matrix of a general interconnection of multipoles). *Archive der Elektrischen Ubertragung,* 1960, vol. 14, p. 262–268.

[18] POURZADI, A., ATTARI, A. R., MAJEDI, M. S. A directivity-enhanced directional coupler using epsilon negative transmission line. *IEEE Transactions on Microwave Theory and Techniques*, 2012, vol. 60, no. 11, p. 3395–3402. DOI: 10.1109/TMTT.2012.2216283

[19] WANG, L., WANG, G., SIDEN, J. Design of high-directivity wideband microstrip directional coupler with fragment-type structure. *IEEE Transactions on Microwave Theory and Techniques*, 2015, vol. 63, no. 12, p. 3962–3970. DOI: 10.1109/TMTT.2015.2490671

[20] MATTHAEI, G. L. Short-step Chebyshev impedance transformers. *IEEE Transactions on Microwave Theory and Techniques*, 1966, vol. 14, no. 8, p. 372–383. DOI: 10.1109/TMTT.1966.1126277

[21] LIU, M., LIN, F. Two-section broadband couplers with wide-range phase differences and power-dividing ratios. *IEEE Microwave and Wireless Components Letters*, 2021, vol. 31, no. 2, p. 117–120. DOI: 10.1109/LMWC.2020.3041256

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