

A directivity enhancement for directional couplers using additional coupled lines

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Abstract: A novel method for enhancing the directivity of coupled-line directional couplers is presented. In a coupled-line directional coupler formed on thin multi-layered substrates, it is difficult to match the coupled-line characteristic impedance with the load impedance. This impedance mismatch causes forward coupling in the directional coupler, thus degrading the directivity. This method utilizes reverse-phase forward coupling with an additional coupled line to cancel the undesired forward coupling due to the primary coupled line. It has been experimentally verified that the directivity of the proposed 20-dB coupler is increased by 13 dB at 840 MHz in comparison with the conventional coupler.

Keywords: directional couplers, directivity, forward couplings, multi-layered substrates

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Coupled-line directional couplers are used as a power detector in a power amplifier module. In a coupled-line directional coupler formed on thin multi-layered substrates, there are manufacturing constraints, such as the relatively narrow space between signal conductors and ground conductors. This constraint often prevents the matching of a coupled-line characteristic impedance Z_C [1, 2, 3, 4, 5] with a load impedance Z_L . This impedance mismatch causes undesired forward coupling in the directional coupler, thus degrading the directivity [6].

In this case, the directivity of the coupled-line directional coupler is improved by adjusting the coupled line width. However, it is often difficult to reduce the coupled line width because of manufacturing constraints such as line/space.

In addition, the directivity of the coupled-line directional coupler is improved by adjusting the spacing of the signal conductors [7, 8, 9, 10]. However, the directional coupler then exhibits loose coupling. Because it is necessary to obtain the desired backward coupling by extending the coupled line length, the space occupied by the directional coupler increases significantly. It is often difficult to package the directional coupler in the small module on the relationship of the layout.

In other words, it is difficult to improve the degraded directivity of coupled-line directional couplers formed on thin multi-layered substrates [11].

In this study, we propose a new method to improve the directivity of coupled-line directional couplers formed on thin multi-layered substrates with an impedance mismatch. The method utilizes reverse-phase forward coupling by an additional coupled line to cancel the undesired forward coupling. The 20-dB microstrip coupled-line directional couplers operating in the 800-MHz band are simulated and measurements are taken to verify the proposed enhancement method.

2 Configuration

Fig. 1 shows the circuit configuration of a directional coupler to which the proposed directivity enhancement method is applied. In this method, a primary coupled line with an impedance mismatch is connected to an additional coupled

line. The additional coupled line generates an equal-amplitude and reverse-phase forward coupling against the primary coupled line.

The forward couplings of the coupled line are out of phase owing to the relationship between the coupled-line characteristic impedance Z_C and the load impedance Z_L . Therefore, in the case of the primary coupled line, where the coupled-line characteristic impedance is lower than the load impedance ($Z_C^{Prim} < Z_L$), an additional coupled line is chosen such that the coupled-line characteristic impedance is higher than the load impedance ($Z_C^{Add} > Z_L$). Then the forward couplings of the primary and additional coupled lines can have approximately equal amplitudes and reverse phases by adjusting the additional coupled line length. Thus, in the directional coupler to which this improvement method is applied, the forward couplings of the primary and additional coupled lines are canceled, and its directivity is improved.

Further, because the directional coupler is small enough for a wavelength, the phase shift due to the transmission line is not considered.

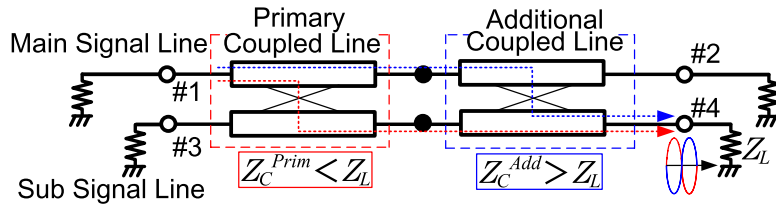


Fig. 1. Circuit configuration of a directional coupler to which directivity enhancement is applied.

3 Principle

Fig. 2 shows the schematic of a symmetric coupled-line directional coupler. As shown in Fig. 3, a symmetry plane of this symmetric directional coupler is assumed to be an electric or a magnetic wall in the even and odd modes, respectively.

The forward coupling of this symmetric directional coupler is given by

$$S_{41} = (T_e - T_o)/2 \quad (1)$$

where T_e and T_o are the transmission characteristics, and the subscripts e and o denote the even and odd modes, respectively [1].

In this case, the transmission characteristics of the even and odd modes are expressed by the following equation through F parameter representation (ABCD matrix):

$$T_i = \frac{2}{[\{2 \cos \beta_i \ell_i\}^2 + \{(Z_{Ci} Y_L + Y_{Ci} Z_L) \sin \beta_i \ell_i\}^2]^{1/2}} e^{j\theta_i} \quad (2)$$

where

$$\theta_i = -\tan^{-1} \left\{ \frac{(Z_{Ci} Y_L + Y_{Ci} Z_L)}{2} \tan \beta_i \ell_i \right\}. \quad (3)$$

($i = e, o$)

Note that in a two-port transmission line of even and odd modes, Z_{Ci} are the characteristic impedances, Y_{Ci} are the characteristic admittances, β_i are the phase constants, and ℓ_i are the transmission line lengths (the coupled line lengths in a directional coupler).

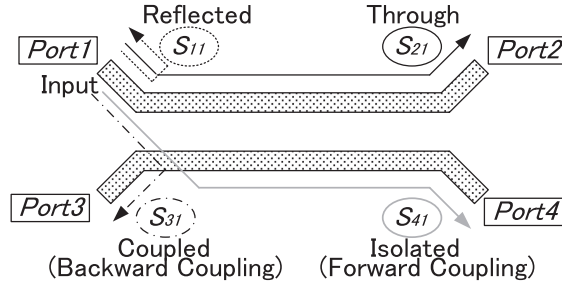


Fig. 2. Schematic of the symmetric coupled-line directional coupler.

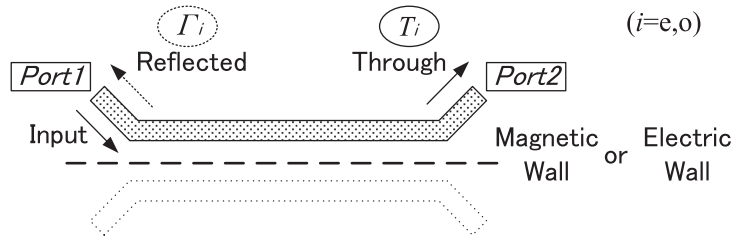


Fig. 3. Schematic of the symmetric coupled-line directional coupler in the even/odd modes

3.1 Forward couplings

In a homogeneous medium, because the phase constants β_i and the coupled line lengths ℓ_i given in (2) are equal independent of whether the modes are even or odd, they are denoted β and ℓ . Further, because the loosely coupling directional coupler, which is small enough for the wavelength is considered, the coupled line length ℓ is very short. In addition, the effect of the difference between the values of the impedance Z_{Ci} is very small. Hence, the transmission phases of even–odd modes are given by

$$\theta_e \approx \theta_o \approx \theta. \quad (4)$$

Therefore, the forward-coupling characteristic S_{41} is represented in the following equation by (1), (2), and (4):

$$S_{41} = \left[\frac{1}{[\{2 \cos \beta \ell\}^2 + \{(Z_{Ce} Y_L + Y_{Ce} Z_L) \sin \beta \ell\}^2]^{1/2}} - \frac{1}{[\{2 \cos \beta \ell\}^2 + \{(Z_{Co} Y_L + Y_{Co} Z_L) \sin \beta \ell\}^2]^{1/2}} \right] e^{j\theta}. \quad (5)$$

Note that the coupled-line characteristic impedance Z_C is defined by the following equation [1]:

$$Z_C = \sqrt{Z_{Ce} Z_{Co}}. \quad (6)$$

3.2 Relationships between forward coupling and impedance

In the amplitude portion of (5), in view of the denominator of the first and second terms, the relationships between the forward couplings and the impedances can be described as shown in Table I. Thus, the phase of the forward coupling in the low-impedance coupled line and the phase of the forward coupling characteristic in the high-impedance coupled line become out of phase. Therefore, a coupled line with the impedance condition $Z_C < Z_L$ is connected to another coupled line with the impedance condition $Z_C > Z_L$, whose length is adjusted. Hence, the directional coupler to which the proposed method is applied obtains good directivity, which enables it to cancel the forward couplings of both coupled lines.

Table I. Relationships of forward coupling and impedance

Impedance	$ S_{41} $	$\angle S_{41}$	Directivity
$Z_C < Z_L$	finite	θ	finite
$Z_C = Z_L$	0	none	infinite
$Z_C > Z_L$	finite	$\theta + \pi$	finite

4 Designs

In this study, a 20-dB microstrip coupled-line directional coupler in the 800-MHz band is studied. In this design, there are constructed on a bismaleimide-triazine resins (BT resins) multi-layered substrates with a thickness of 0.36 mm, relative permittivity ϵ_r of 4.5, and loss tangent $\tan \delta$ of 0.014. The designed coupled lines and directional coupler are illustrated in Fig. 4.

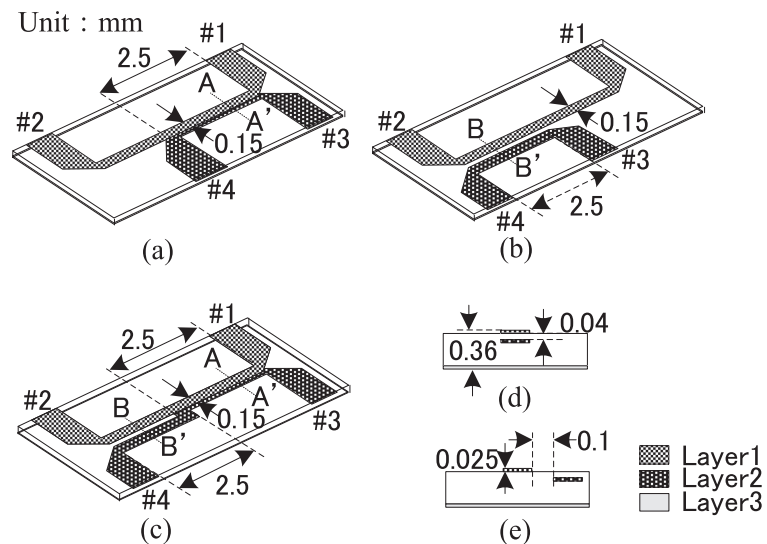


Fig. 4. Layout of (a) primary coupled line (without additional coupled line), (b) additional coupled line, (c) proposed directional coupler (primary coupled line with additional coupled line), (d) A-A' cross-sectional view, and (e) B-B' cross-sectional view.

The primary coupled line consists of a broadside coupled line. The coupled-line characteristic impedance Z_C^{Prim} of the primary coupled line is designed to be approximately $44\ \Omega$, which is lower than the load impedance $Z_L (= 50\ \Omega)$. Further, the additional coupled line consists of an offset-broadside coupled line. The coupled-line characteristic impedance Z_C^{Add} of the additional coupled line is designed to be approximately $70\ \Omega$, which is higher than the load impedance $Z_L (= 50\ \Omega)$. Moreover, the proposed directional coupler is constructed by connecting the primary coupled line and the additional coupled line with a connection line.

5 Experimental results

The designed coupled lines and directional coupler are manufactured and measurements are conducted. Fig. 5 shows photographs of the manufactured coupled lines and directional coupler. Note that GSG probe pads are utilized in the design result because GSG probes are used in this measurement. The measurements were performed using the Keysight (Agilent) E8364B vector network analyzer. The simulations employed an electro-magnetic simulator known as Ansoft HFSS. Fig. 6 plots the measured and simulated forward couplings of the primary and additional coupled lines. The manufactured primary and additional coupled lines have approximately equal amplitudes and reverse phases, that is, an amplitude difference of 0.5 dB and a phase difference of 152.9° at 840 MHz. Fig. 7 illustrates the simulated and measured directivities of the primary coupled line (the conventional directional coupler) and the proposed directional coupler. The directivity is 18.0 dB before connecting the additional coupled line, and it increases to 31.0 dB after connecting ones at 840 MHz. Hence, in a directional coupler composed of inhomogeneous media, this method can reduce the forward coupling and thus obtain good directivity.

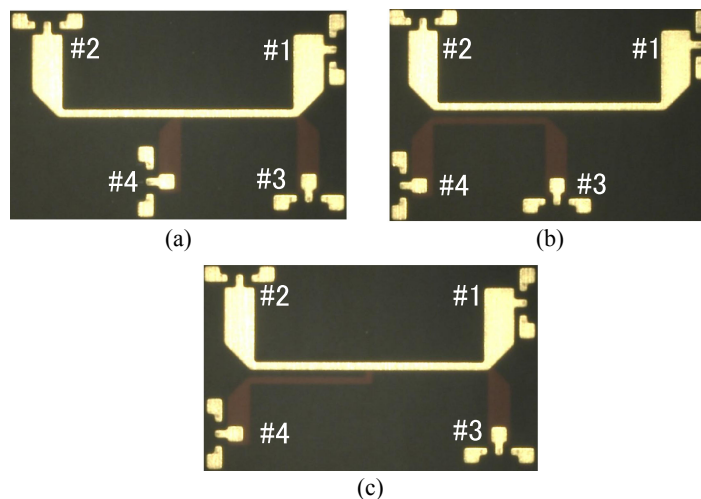


Fig. 5. Photographs of manufactured (a) primary coupled line (without additional coupled line), (b) additional coupled line, and (c) proposed directional coupler (primary coupled line with additional coupled line).

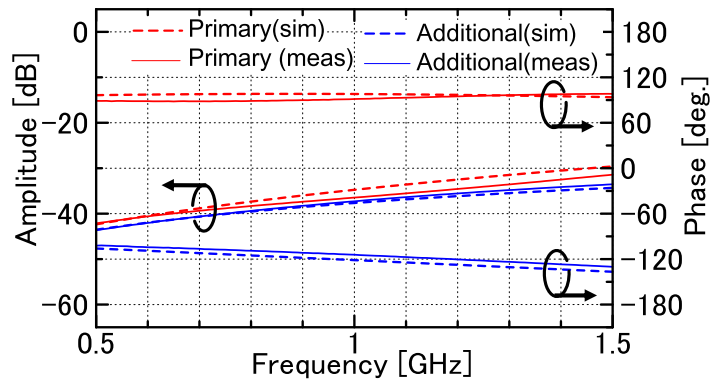


Fig. 6. Measured and simulated forward couplings (S_{41}^{Prim} , S_{41}^{Add}) of primary/additional coupled lines.

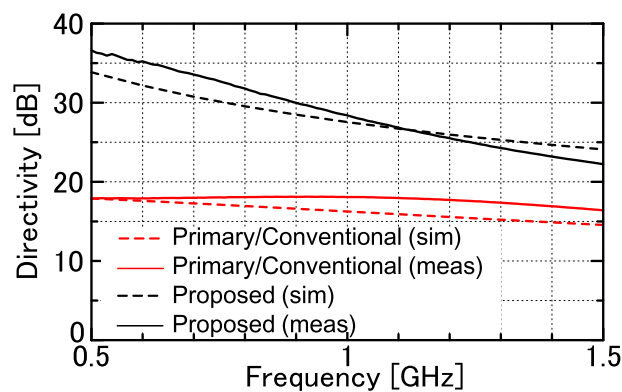


Fig. 7. Measured and simulated directivities of the primary coupled line (conventional directional coupler) and the proposed directional coupler.

6 Conclusion

In this paper, a method for enhancing the directivity of coupled-line directional couplers has been presented. It has been experimentally verified that the directivity of the proposed 20-dB directional coupler is increased by 13 dB at 840 MHz in comparison with the conventional directional coupler.