Directivity Improvement of Microsrip Coupled Line Couplers Based on Equivalent Admittance Approach

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ABSTRACT The present paper suggests a simple and effective technique for remarkably improving the directivity of inhomogeneous coupled line couplers such as a microstrip coupler. The technique is based upon the equivalent admittance approach, and requires only properly designed matching networks. In this paper, we treat a 1/4-wave parallel-coupled microstrip coupler of 15.8 dB, and obtain the directivity improvement of 20 or more dB over a bandwidth of about 1.2 GHz at a center frequency of 3.5 GHz. Finally, the design results are confirmed by an em-simulator.

Introduction

Microstrip directional couplers are widely used because of their easy incorporation in microwave integrated circuits. In general, however, their directivity is poor due to slightly different velocities and, thus, different wavelengths between odd and even modes on coupled microstrip lines. Nevertheless, the convenience of integrating microstip couplers with other microwave circuitry makes them attractive, especially if it is possible to improve their directivity property by simple and effective means.

For this reason, several techniques have been proposed as follows:

(a) Wiggly-line couplers [1].
(b) Anisotropic substrate couplers [2].
(c) Dielectric overlay couplers [3].
(d) Couplers with velocities-compensation capacitors [4].
(e) Pseudo-suspended-substrate couplers [5].

In these techniques, complicated structures and substrates with specified physical constants are required, and/or design procedure is based on approximate analysis.

In this paper, we apply the equivalent admittance approach [6], [7] to improvement in the directivity of a quarter-wave microstrip coupler. This approach is marked by a logical design of matching networks for an equivalent admittance, and hence requires only microstrip matching networks for the improvement not like the other techniques requesting various ingenious devices.

First, we try to improve the directivity by inserting impedance steps at each output port. Next, in order to realize a broader bandwidth, 1/2-wave open-circuited stubs are loaded at an appropriate position of each matching network. While the fractional bandwidth of the former is about 10 percents for directivity and return loss better than 20 dB, that of the latter is widened up to about 37 percents.

Finally, the validity of the theoretical results is confirmed by comparing with simulation results of an em-simulator (S.NAP-Field).

Basic Theory

Fig. 1 shows a circuit to be considered, which is a lossless four-port circuit symmetrical with regard to the two planes AA' and BB' and possesses four external matching networks (M.N.) added at each port. Generally, the twofold symmetric coupler has a 90-degree output phase difference, and is classified into three types according to a port isolated from an input port; codirectional (S_{21}= 0), transdirectional (S_{31}= 0), and contradirectional (S_{41}= 0) couplers [8]

As well known, a quarter-wave coupled line coupler belongs to contradirectional couplers. In the following, therefore, we will discuss only in case of S_{41}= 0.

We can analyze the circuit by an even-odd analysis regarding to both the symmetry planes AA' and BB' from its symmetry. Now let's consider a one-port circuit including port # 1 quartered along the two planes as in Fig. 2. Each symmetry plane is replaced by an open-circuited or short-circuited boundary according as an even or odd excitation about each symmetry plane. Here, we define the normalized input admittances (eigenadmittances) of the one-port circuit for the four kinds of characteristic excitations as

(a) jy_1': AA' is open-circuited and BB' open-circuited,

(b) jy_2' : AA' is short-circuited, and BB' open-circuited,
(c) jy_3' : AA' is open-circuited, and BB' short-circuited,
(d) jy_4' : AA' is short-circuited, and BB' short-circuited.

In the case of contradirectional couplers (S_{41}= 0), matching conditions require

$$y_1' = -1/y_4', \quad y_2' = -1/y_3' \qquad \text{(1a,b)}$$

Then, the power-split ratio, $R = |S_{31}/S_{21}|^2$, is given as

$$R = (y_1' - y_3')^2/(1 + y_1'y_3')^2 = (y_4' - y_2')^2/(1 + y_2'y_4')^2 \quad (2)$$

If M.N. has transfer matrix elements A, jB, jC, D, then we have

$$y_i' = (C + y_i D)/(A - y_i B), \quad i = 1 \sim 4 \quad (3)$$

where jy_i represents a normalized eigenadmittance of the original circuit as shown in Fig. 2.

Substitution of Eq. (3) into Eq. (1), and comparing the resulting expressions with the matching conditions of a one-port admittance $Y_{eq} = G_e + jY_e$ through the same M.N., we can derive an equivalent admittance,

$$G_e^2 = -(y_1 - y_2)(y_1 - y_3)(y_4 - y_2)(y_4 - y_3)/(y_1 - y_2 - y_3 + y_4)^2 \quad (4a)$$

$$Y_e = (y_1 y_4 - y_2 y_3)/(y_1 - y_2 - y_3 + y_4) \quad (4b)$$

on condition that the right side of Eq. (4a) is positive. Consequently, we can consider this four-port matching problem as a one-port matching one for the equivalent admittance given by Eq. (4).

Similarly to the above procedure, substituting Eq. (3) into Eqs. (1) and (2), and examining the two sets of the resultant equations, we have

$$R = |S_{31}/S_{21}|^2 = -(y_1 - y_2)(y_4 - y_3)/(y_4 - y_2)(y_1 - y_3) \quad (5)$$

This equation implies that a power-split ratio after matched is expressed in terms of the eigenadmittances of the original circuit before matching.

Eq. (5) is invariable for exchanging y_i for y_i' if M.N. is reciprocal, i.e., $AD + BC = 1$. In other words, R corresponds to an invariable expression of a power-split ratio transformed from Araki's invariant[9]. Moreover, if R is a finite positive value, $y_1 - y_2 - y_3 + y_4 \neq 0$, and the right side of Eq. (4a) is always positive; G_e can be defined [10].

The above discussion enables us to state that when R given by Eq. (5) takes positive value, we can determine the equivalent admittance Y_{eq} necessarily, and consequently construct a directional coupler having a high directivity and a power-split ratio of R by adding the same M.N. as that for matching a one-port admittance of Y_{eq} at each port. Here, we should note that a completely matched 1/4-wave coupler with two-fold symmetry, which satisfies Eq. (1), exhibits the ideal contradirectional isolation property (S_{41}= 0).

Design method and property

In this section, we deal with a 15.8 dB coupler on an alumina substrate after the reference [5] as an example. The characteristic impedances of the even and odd modes must be chosen 59.79 ohms and 43.13 ohms for an input/output impedance of 50 ohms, respectively. If the dielectric constant and the thickness of the substrate are 9.9 and 0.2 mils, respectively, we can calculate the following parameters: strip width of 22.21 mils, conductor separation of 21.09, and effective permitivity of even and odd modes 7.185 and 5.832 for spacing between substrate and upper shield of 500 mils. The physical length of coupling is chosen 332 mils as an average value of quarter-wavelengths of the even and odd modes for 3.5 GHz .

Fig. 3 shows the S-parameters of the original coupler. The directivity (S_{21}/S_{41}) degrades and its value is equal to or less than 8 dB. In Fig. 3, the line drawn along dots exhibits the coupling coefficient C (= $|S_{21}|$) transformed from the invariable R, thar is, if a matched state is achieved at a frequency the coupling coefficient of this coupler necessarily becomes the value on the curves of C at the corresponding frequency.

a) Impedance step matching network

The equivalent admittances of the original coupler vs. frequencies are shown in Fig. 4. Here, if we desire to match the equivalent admittance to 50 ohms line at the center frequency of 3.5 GHz using an impedance step (Fig. 5) as a matching network, then the characteristic admittance and the electrical length of the impedance step are determined with the aid of Smith chart as shown in Fig. 4.

Fig. 6 exhibits the S-parameters of the improved coupler. We can see a high directivity near the center frequency. The fractional bandwidth for directivity and return loss better than 20 dB is about 10 percents.

b) Combined technique of impedance step and stub

As shown in Fig. 7, for the purpose of broader performance a half-wave open-circuited stub is utilized along with an impedance step. The locus of equivalent admittances seen looking toward the load of Y_{eq} at various reference planes are drawn in Fig. 8. In this case a remarkably band-widened characteristics is obtained and its fractional bandwidth is about 37 percents as shown in Fig. 9.

Simulation results

In order to verify the above design technique, we calculated the scattering parameters for the circuit pattern on the above-mentioned alumina substrate in Fig. 10 corresponding to Fig. 10 by a commercial em-simulator (S.NAP-Field). Fig. 11 exhibits the simulation results in case of considering a conductor loss of gold. The results verify the above improvement technique.

Conclusions

We have suggested simple and effective means of directivity improvement for microstrip 1/4-wave couplers and successfully realized high directivity. A fractional bandwidth of about 10 percents for directivity and return loss better than 20 dB has been obtained for a very simple structure with impedance steps. Moreover, the bandwidth has been broadened up to about 37 percents by loading 1/2-wave open-circuited stubs, though the circuit pattern was large-sized. The design results also were confirmed by em-simulation results.

An experimental confirmation would be an important subject to do shortly.

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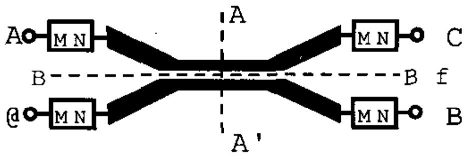

Fig.1 Circuit configuration of microstrip coupled line coupler with external matching networks.

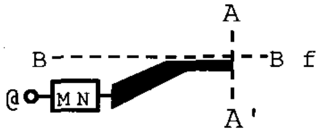

Fig.2 A quarter one-port circuit.

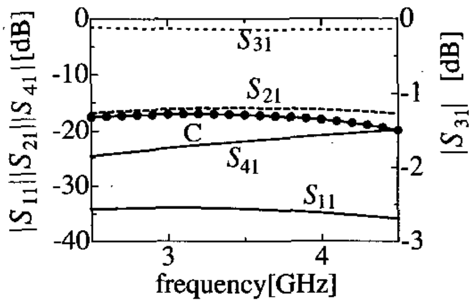

Fig.3 Theoretical frequency characteristics of S-parameters for the original coupled line coupler.

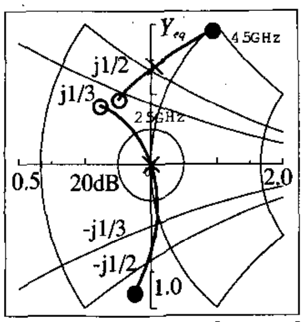

Fig.4 Frequency dependence of equivalent admittances on a Smith admittance chart.

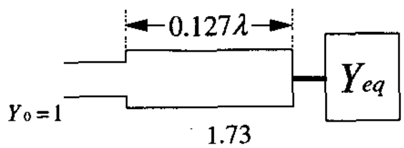

Fig.5 Matching network composed of impedance step.

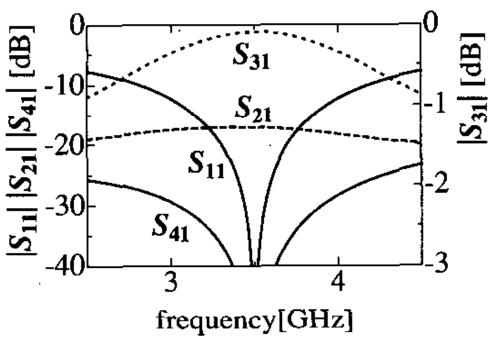

Fig.6 Frequency characteristics of S-parameters for the coupled line coupler with impedance step.

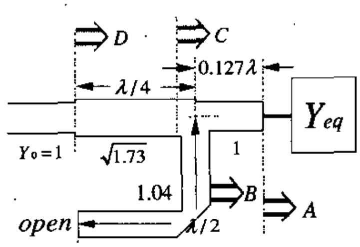

Fig.7 Matching network composed of impedance steps and open-circuited 1/2-wavelength stub.

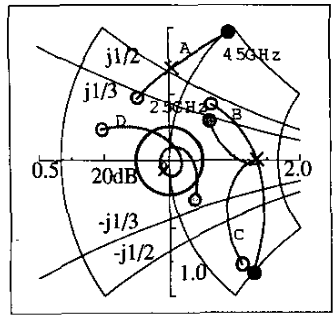

Fig.8 Equivalent admittances at various reference planes.

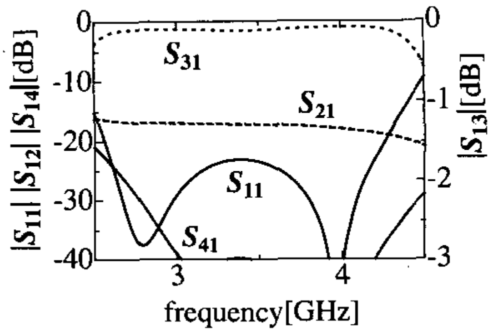

Fig.9 Frequency characteristics of S-parameters for bandbroadened coupler.

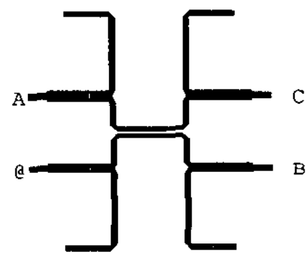

Fig.10 Circuit pattern for simulation.

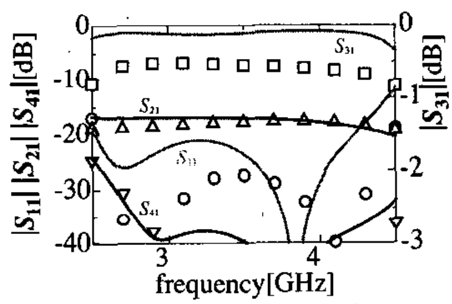

Fig.11 Simulation results.