

A Design of Wideband 3-dB Coupler With N -Section Microstrip Tandem Structure

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Abstract—New design equations and a 3-dB microstrip coupler example for N -section tandem connected structure with wide bandwidth are presented. The proposed four-port S -parameters and equations are obtained from a port reduction method. The designed microstrip 3-dB coupler not only does not need high impedance lines, but also uses tight coupling gaps differently from conventional couplers such as Lange couplers, parallel coupled line couplers, etc. The measured data agrees well with the expected data, which show a wide bandwidth of 42%, an amplitude imbalance of ± 0.5 -dB, a phase unbalance of 1.0° , and isolation characteristics of 15 dB at the band of 3.6 to 5.5 GHz.

Index Terms— N -section tandem connection, parallel coupled lines, 3-dB microstrip coupler, wideband coupler.

I. INTRODUCTION

THE 3-dB coupler has been continuously studied for smaller size, wider bandwidth, and easier circuit fabrication. Parallel coupled-line couplers, branch-line couplers, ring hybrids, and Wilkinson hybrids [1]–[3] are, especially, well known and widely used for the designs of balanced amplifiers, balanced mixers, and modulators, etc. Even though they can be implemented easily, these couplers occupy much more space for achieving tight coupling and wide bandwidth required at those application systems. To design and implement a wideband 3-dB coupler, long coupling length, or a narrow coupling gap, several tens of μm are required, depending on coupling structures. It is difficult to implement such a tight coupling by common printed circuit board (PCB) technologies. For this reason, many studies on implementation of the wideband directional coupler have been carried out by using broadside-coupled structure, kemp-type, tandem type, and re-entrant type [4]–[7]. Those researches give some methods to achieve tight coupling, though there still remained disadvantages such as much larger substrate areas and/or the need for multilayer circuitry [8]. The Lange coupler [9]–[13], which has been fabricated in a small size on the single layer PCB, has been suggested. Although it has wide band characteristics in a small size, it still has drawbacks

that narrow line widths, narrow gaps between coupled lines for the tight coupling, and low power capability depending on substrates, and multiple wire-bonding are required.

At this point, we tried to design an easily achievable wideband 3-dB coupler with minimum sections of parallel-coupled microstrip lines on a single layered PCB, after deriving new design equations for N -section tandem connected structure.

II. ANALYSIS OF N -SECTION COUPLER

In terms of network S -parameters, an ideal directional coupler can be expressed as a four-port S -matrix. It is well known that the coupling and through scattering parameters of a single section directional coupler are (1) and (2), respectively, where k is the coupling coefficient of a directional coupler

$$S_{13} = \alpha = \frac{jk \sin \theta}{\sqrt{1 - k^2 \cos \theta + j \sin \theta}} \quad (1)$$

$$S_{14} = \beta = \frac{\sqrt{1 - k^2}}{\sqrt{1 - k \cos \theta + j \sin \theta}}. \quad (2)$$

It is possible to achieve a large coupling factor by cascading N -section directional couplers with small k factor as shown in Fig. 1. The relation of coupling factor and the number of sections is verified by deriving four-port S -parameters composed of N -section parallel-coupled lines. An all port matched ideal coupler must satisfy the following conditions (center frequency):

$$\begin{aligned} S_{m,m} &= 0, \quad m = 1, 2, 3, \dots, 4N \\ S_{m,m+1} &= S_{m+1,m} = 0, \quad m = 1, 3, 5, \dots, 4N - 1. \end{aligned} \quad (3)$$

Here, we also assumed that each of the parallel-coupled lines is completely isolated from other coupled lines. The reflected waves at an n -port network that is connected with m -port load can be expressed in terms of S -parameters and incident waves as indicated in (4). If $[S_L]$ denotes the m -port network, the n -port network are reduced to $(n - m)$ -port network form

$$b_{n-m} = S_{11} + S_{12} (S_L^{-1} - S_{22})^{-1} S_{21} a_{n-m}, \quad (S_{11} = 0, S_{22} \neq 0) \quad (4)$$

where a_m and b_m are incident and reflected waves at m -port loads. Also, a_{n-m} and b_{n-m} are incident and reflected waves at $(n - m)$ -port network.

However, when arbitrary N ($N > 1$)-section parallel-coupled lines are selected, four-port matrix is not easily derived from (4) because S_{22} is not to be zero. Therefore, we separate N -section parallel-coupled lines into two parts. One is composed of $(N-1)$ -section parallel-coupled lines and the other is a single section. The $(N-1)$ -section parallel-coupled lines can be expressed as a four-port matrix in terms of α_{N-1} and β_{N-1} .

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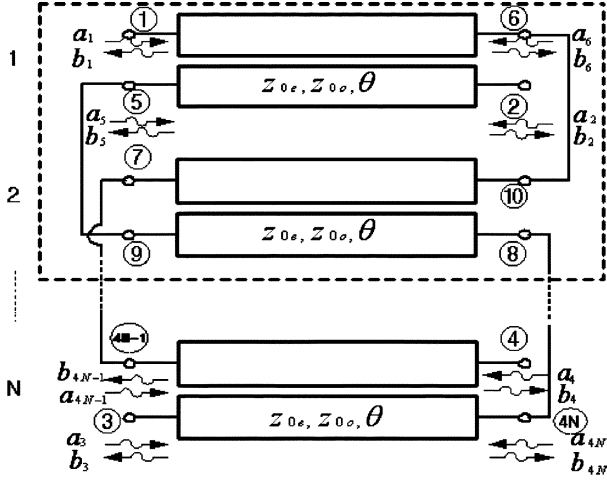


Fig. 1. Coupler composed of N -section parallel-coupled lines.

Here, α_{N-1} and β_{N-1} denote the S -parameters of the coupler, which is composed of $(N-1)$ -sections, at through and coupling ports, respectively. N -section parallel-coupled lines are analyzed by deriving relationships between the N th-section and the $(N-1)$ -sections, and similar to combining two parallel-coupled lines

$$[S_{N,N-1}] = \begin{bmatrix} [S_{11}] & [S_{12}] \\ [S_{21}] & [S_{22}] \end{bmatrix} \quad (5)$$

where

$$[S_{11}] = [S_{22}] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[S_{12}] = [S_{21}] = \begin{bmatrix} \alpha_{N-1} & \beta_{N-1} & 0 & 0 \\ \beta_{N-1} & \alpha_{N-1} & 0 & 0 \\ 0 & 0 & \alpha_1 & \beta_1 \\ 0 & 0 & \beta_1 & \alpha_1 \end{bmatrix}.$$

The network composed of $(N-1)$ -section and a single section can be expressed as 8×8 matrix form. The matrix in (5) must now be partitioned into four four-port networks. $[S_{11}] = [S_{22}] = [0]$ is satisfied because of the ideal directional coupler assumption. Therefore, (4) is simplified to

$$[b_{n-m}] = [S_{12}][S_L][S_{21}][a_{n-m}] \quad (6)$$

where

$$[S_L] = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (7)$$

The eight-port can then be reduced to an equivalent four-port by applying each partitioned matrix into (6). On the other hand, the directional coupler using N -section parallel-coupled lines can be put in the form

$$[S_N] = \begin{bmatrix} 0 & 0 & \alpha_N & \beta_N \\ 0 & 0 & \beta_N & \alpha_N \\ \alpha_N & \beta_N & 0 & 0 \\ \beta_N & \alpha_N & 0 & 0 \end{bmatrix}. \quad (8)$$

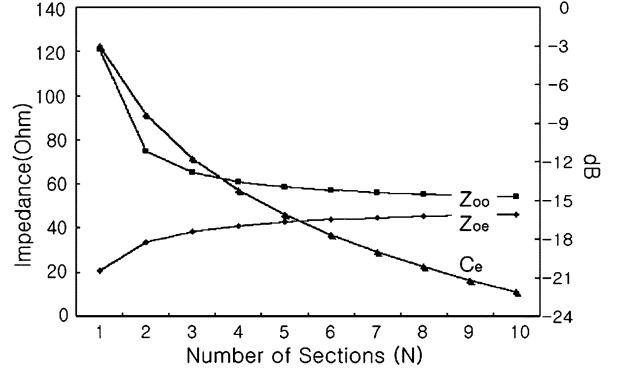


Fig. 2. Even/odd mode impedances and coupling values depend on a number of sections.

Consequently, since the four-port S -matrix derived from (6) is the same as (8), N -section parallel-coupled lines and $(N-1)$ -sections are related to each other as

$$\alpha_N = \alpha_{N-1}\alpha_1 + \beta_{N-1}\beta_1 \quad (9)$$

$$\beta_N = \beta_{N-1}\alpha_1 + \alpha_{N-1}\beta_1. \quad (10)$$

If we substitute coupling coefficient k into $\sin \phi$ and apply $\theta = 90^\circ$ into (1) and (2), respectively, α_1 and β_1 are expressed as $\sin \phi$ and $-j \cos \phi$. By using these conditions, the four-port S -matrix can be simplified to (11) and (12), depending on the case of the section number N

$$[S_{N \text{ odd}}] = (-j)^{N-1} \begin{bmatrix} 0 & 0 & \alpha_N & \beta_N \\ 0 & 0 & \beta_N & \alpha_N \\ \alpha_N & \beta_N & 0 & 0 \\ \beta_N & \alpha_N & 0 & 0 \end{bmatrix} \quad (11)$$

$$[S_{N \text{ even}}] = (-j)^{N-1} \begin{bmatrix} 0 & 0 & \beta_N & \alpha_N \\ 0 & 0 & \alpha_N & \beta_N \\ \beta_N & \alpha_N & 0 & 0 \\ \alpha_N & \beta_N & 0 & 0 \end{bmatrix} \quad (12)$$

where α_N and β_N are $\sin N\phi$ and $-j \cos N\phi$, respectively.

For the 3-dB coupler, $\sin N\phi$ term is equal to $10^{-3.01/20}$ or $1/\sqrt{2}$. From this condition, the electrical length and the coupling coefficient of each section can be rewritten by

$$\phi = \frac{\pi}{4N} \quad (13)$$

$$k = \sin\left(\frac{\pi}{4N}\right), \quad C_e(\text{dB}) = 20 \log k. \quad (14)$$

If the number of sections is increased, the coupling coefficient k is decreased. That is, the 3-dB coupler can be implemented by cascading N -section directional couplers with a small coupling coefficient k . We can decide the number of sections from some design purposes and/or the limitations of realizable coupling gap or line width depending on available physical substrate and etching technology. From (14), the even and odd mode impedances and coupling value of each parallel-coupled line sections for 3-dB couplers ($C_t = 3$ dB) are calculated as

$$Z_{0e} = Z_0 \frac{1 + \sin(\phi)}{\cos(\phi)}, \quad Z_{0o} = Z_0 \frac{1 - \sin(\phi)}{\cos(\phi)}. \quad (15)$$

Based on the above results, the even and odd mode impedances depending on the number of sections are shown in Fig. 2.

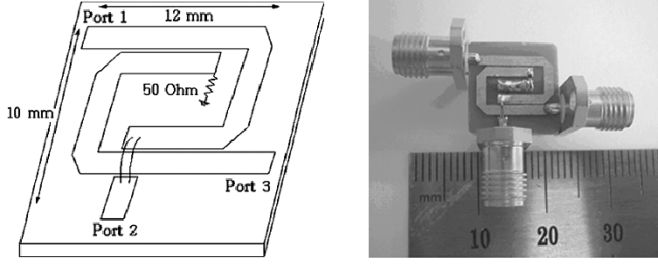


Fig. 3. Layout of the 3-dB coupler with two-section tandem connection.

TABLE I
MINIMUM NUMBER OF SECTIONS FOR 3-dB COUPLER DEPENDING ON SUBSTRATES

Substrate	A	B	C	D
Relative dielectric constant (ϵ_r)	6.15	2.6	3.48	3.48
Substrate thickness(H mm)	1.225	0.508	0.762	0.254
Impedance: Odd mode (Max. Ohm)	30	36	34	39
Limitation: Even mode (Min. Ohm)	82	67	72	65
Minimum # of sections	2	3	3	4

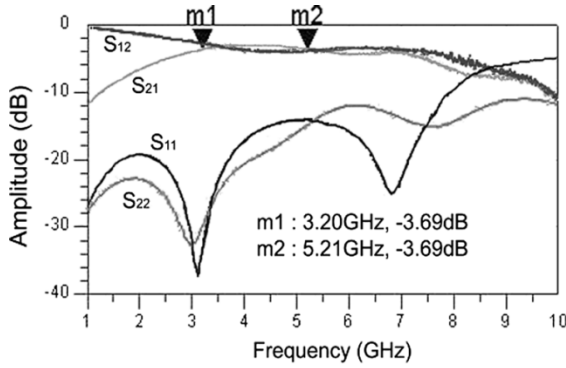
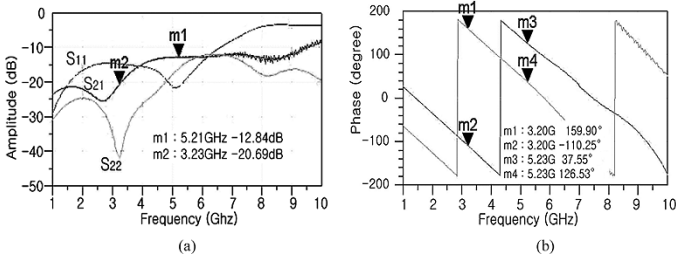
Fig. 4. Measured S -parameters of the 3-dB coupler with two-section tandem connection in Fig. 3.

Fig. 5. (a) Measured isolation and (b) phase characteristics for the 3-dB coupler with two-section tandem connection in Fig. 3.

In the case of a single section, it is difficult to realize the even and odd mode impedances. At least two or three section parallel-coupled lines are required to fabricate the 3-dB coupler with microstrip lines on a PCB.

III. EXPERIMENTAL PERFORMANCE

If we take $s \geq 0.1$ mm as a realizable physical limitation for the gap etching, the realizable odd mode impedance of each

directional coupler section for substrate “A” on table is above 30Ω . From (13) and (15), $N \geq 2$ is also decided. To make a 3-dB coupler with the substrate “A,” we can, therefore, choose two section parallel-coupled lines with 8.34-dB coupling value (C_e) and structure as shown in Fig. 3. The designed dimensions of each directional coupler section are $w = 1.37$ mm (line width), $s = 0.2$ mm (coupling gap), and length = 7.3 mm at 5.0 GHz.

The minimum number of sections and impedance limitations for 3-dB microstrip couplers are calculated about some typical available substrates. They are summarized in Table I. To obtain a maximum coupling value with a minimum number of sections, a thicker substrate with a higher dielectric constant is better.

The measured results of the 3-dB microstrip coupler are shown in Figs. 4 and 5. They show that the coupler has wide bandwidth, from 3.6 to 5.5 GHz within ± 0.5 -dB amplitude unbalance and has return losses below -15 dB. The isolation characteristics, of about 15 dB, and the phase difference, within one degree, are obtained as shown in Fig. 5.

IV. CONCLUSION

A new four-port S -parameter and design equations for an N -section parallel-coupled line coupler was presented. Using proposed equations, on a single layer (microstrip), a wideband 3-dB coupler was easily designed and realized without high impedance lines or tight coupling gaps. Measured data of the 3-dB microstrip coupler matches the expected data. Proposed design equations could be also useful to save layers on designing couplers with multilayered PCB, LTCC, MIC, etc.

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