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Coupling-Compensated 180° Phase Shift Coupled-Line Filters Terminated in Arbitrary Impedances

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***Abstract* — Coupled-line filters (CLFs) with a 180° phase shift are analyzed and coupling compensated design equations are derived. They can be applied for arbitrary termination impedances and arbitrary coupling coefficients. To verify the design equations reasonable, a microstrip CLF with a coupling coefficient of -7 dB is fabricated on a substrate ($\varepsilon_r = 3.5$, $H = 30mil$, tan δ = 0.04) and tested for 100 Ω and 70 Ω termination impedances. The measured results show good agreement with the simulated ones.**

***Index Terms* — Arbitrary termination impedances, Coupled-line filters, Impedance transformers with a 180° phase shift, Ring hybrids, Baluns.**

I. INTRODUCTION

The coupled line filters (CLFs) with a 180° phase shift have been applied for various microwave components: wideband ring hybrids [1]-[2], filters, baluns are several. A CLF with a 180° phase shift can be obtained by terminating two of four ports of a directional coupler in short. Therefore, for the analyses of the CLFs terminated in arbitrary impedances, any background of directional couplers for impedance transforming is needed. Since first directional coupler was reported in 1922 [3], numerous papers [4]-[11] described the theory and applications. However, they can be applied only for equal termination impedances. Very recently, design equations of the directional couplers for impedance transforming were first derived [12], [13] and will be used to derive the scattering parameters of the CLFs terminated in arbitrary impedances.

When the power is fed into a port of the CLF, a part of the excited power is transmitted and the remaining power coupled, and the transmitted power is again coupled into the other port by the short boundary condition adjacent the other port. The resulting power delivered to the other port is sum of the coupled and transmitted ones. Therefore, only when the coupled power is half, all the excited power at a port is transmitted into the other port. However, any CLF with a -3 dB coupling coefficient can not be realized with any microstip technology [1].

In this paper, to realize the CLFs terminated in arbitrary impedances without any coupling problem, coupling compensated design equations of the CLFs are derived. Since they can choose the termination impedances arbitrarily, there are big advantages like other asymmetric passive components [14]-[17]. To verify the design equations reasonable, a microstrip CLF with a -7 dB coupling coefficient is fabricated and tested at a design center frequency of 2 GHz. The measured results show good agreement with the predicted ones.

II. ANALYSES

A CLF with a 180° phase shift and its equivalent circuit are depicted in Fig. 1 where Z_L and Z_r are arbitrary termination impedances and Z_{in} is an input impedance looking into the coupled transmission lines terminated in Z_L .

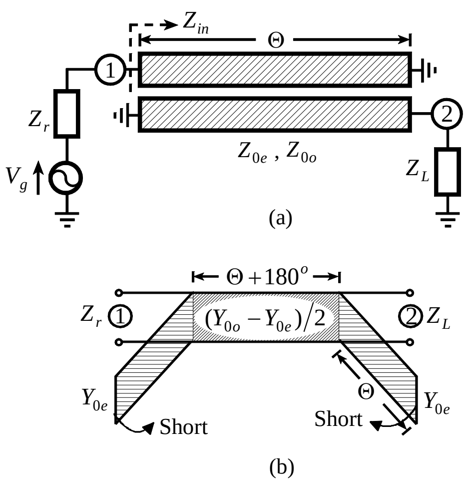


Fig. 1. A CLF with a180° phase shift (a) A CLF with a180° phase shift with power fed into port ①. (b) Its equivalent circuit.

The admittance matrix of the CLF is derived by using boundary conditions from a directional coupler for impedance transforming [18] and it gives

$$[Y]=\begin{bmatrix} -j\dfrac{Y_{0e}+Y_{0o}}{2}\cot\Theta & -j\dfrac{Y_{0o}-Y_{0e}}{2}\csc\Theta \\ -j\dfrac{Y_{0o}-Y_{0e}}{2}\csc\Theta & -j\dfrac{Y_{0e}+Y_{0o}}{2}\cot\Theta \end{bmatrix} \quad (1)$$

where

$$Y_{0e}=\sqrt{\frac{(1-C)}{(1+C)}Y_L Y_r}\ , \quad (2a)$$

$$Y_{0o}=\sqrt{\frac{(1+C)}{(1-C)}Y_L Y_r} \quad (2b)$$

where $Y_{0e}=1/Z_{0e}$, $Y_{0o}=1/Z_{0o}$, $Y_L=1/Z_L$ and $Y_r=1/Z_r$ and which are presented in [12], [13]. From the admittance parameters in (1), normalized scattering parameters are calculated as

$$S_{11}=-\frac{(Y_{0e}+Y_{0o})^2\cos^2\Theta-(Y_{0o}-Y_{0e})^2+4Y_LY_r\sin^2\Theta+j(Y_L-Y_r)(Y_{0e}+Y_{0o})\sin 2\Theta}{(Y_{0e}+Y_{0o})^2\cos^2\Theta+(Y_{0o}-Y_{0e})^2-4Y_LY_r\sin^2\Theta+j(Y_r+Y_L)(Y_{0e}+Y_{0o})\sin 2\Theta}\ , \quad (3a)$$

$$S_{22}=-\frac{(Y_{0e}+Y_{0o})^2\cos^2\Theta-(Y_{0o}-Y_{0e})^2+4Y_LY_r\sin^2\Theta-j(Y_L-Y_r)(Y_{0e}+Y_{0o})\sin 2\Theta}{(Y_{0e}+Y_{0o})^2\cos^2\Theta+(Y_{0o}-Y_{0e})^2-4Y_LY_r\sin^2\Theta+j(Y_r+Y_L)(Y_{0e}+Y_{0o})\sin 2\Theta}\ , \quad (3b)$$

$$S_{12}=\frac{-j4(Y_{0o}-Y_{0e})\sqrt{Y_LY_L}\sin\Theta}{(Y_{0e}+Y_{0o})^2\cos^2\Theta+(Y_{0o}-Y_{0e})^2-4Y_LY_r\sin^2\Theta+j(Y_r+Y_L)(Y_{0e}+Y_{0o})\sin 2\Theta} \quad (3c)$$

If the termination admittances Y_L and Y_r are equal to each other, S_{11} is identical to S_{22} . However, if Y_L and Y_r are different, S_{11} and S_{22} are equal in magnitudes but 180^o out of phase. Based on the derived scattering parameters, frequency responses have been calculated as the coupling coefficients are varied. The calculation has been carried out by use of Matlab. Version 6 . The calculation results are plotted in Fig. 2 where f/f_0 are the frequencies normalized to a center frequency f_0 , and return and insertion losses with the impedance transformation ratio $IR=1.5$ are in Fig. 2(a) and (b), respectively. Depending on the coupling coefficients, coupling characteristics are classified as critical coupling ($C=-3dB$), under coupling ($C<-3dB$) and over coupling ($C>-3dB$). Figure 2 shows that perfect matching appears only with the critical coupling, and that ripples with no perfect matching exist in the over-coupling case. The excited power at port ① is transmitted into port ② in Fig. 1(a) and the amount of the transmitted power is dependent on the coupling structure. Therefore, the equivalent circuit can be suggested as a series resonant circuit [19] and the input impedance with $\Theta=90^o$ in Fig. 1(a) is calculated as

$$Z_{in}=R=Z_r\left(\frac{1-C^2}{C^2}\right) \quad (4)$$

which also demonstrates that the value of R is Z_r only with $C=1/\sqrt{2}$ and agrees with the simulation results shown in Fig. 2. For the CLF with any coupling coefficient to be perfectly matched, the even- and odd-mode impedances should be compensated in a way that the R is always Z_r regardless of the coupling coefficients. The Z_r in (4) comes from the even- and odd-mode impedances in (2) and can be compensated to have a constant R value, regardless the coupling coefficients. The compensated even- and odd-mode impedances are

$$Z_{0e-CF}=\sqrt{Z_rZ_L\frac{C^2}{1-C^2}}\sqrt{\frac{1+C}{1-C}}\ , \quad (5a)$$

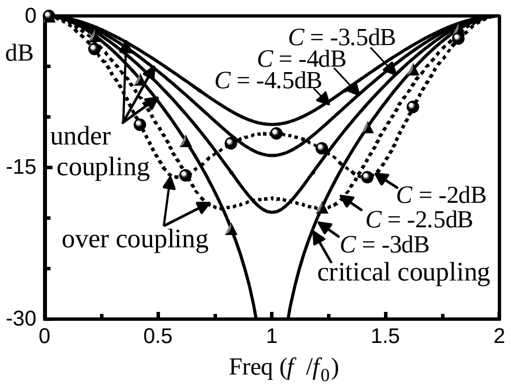
$$Z_{0o-CF}=\sqrt{Z_rZ_L\frac{C^2}{1-C^2}}\sqrt{\frac{1-C}{1+C}}\ . \quad (5b)$$

Based on the design equations in (5), the even- and odd-mode impedances are calculated depending on the different coupling coefficients and written in Table I for $Z_L=100\ \Omega$, $Z_r=70\ \Omega$. In the case of C = -3 dB, the even- and odd-mode impedances are 202.8 Ω and 34.68 Ω and the even-mode impedance of 202.8 Ω can not be realized with microstrip transmission lines.

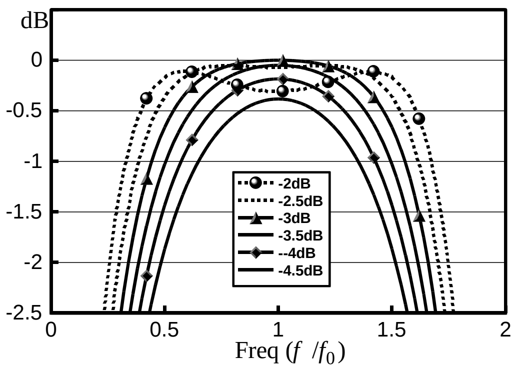
With the data given in Table I, three CLFs with each 180^o phase shift have been simulated as the coupling coefficients are varied. The simulation results are plotted in Fig. 4 where all the CLFs are perfectly matched; regardless of the coupling coefficients and show that more coupling powers result in more bandwidths.

Table I. Z_{0e-CF} and Z_{0o-CF} with $Z_L = 100\ \Omega$, $Z_r = 70\ \Omega$.

dB \ Ω	C = -3	C = -5	C = -7	C = -8
Z_{0e-CF}	202.8	107.5	67.5	46.0
Z_{0o-CF}	34.68	30.1	23.8	21.9



(a)



(b)

Fig 2. Calculation results of scattering parameters with (2). (a) Return losses. (b) Insertion losses.

III. Measurements

To verify the derived design equations in (5) reasonable, a microstrip CLF terminated in 100 Ω and 70 Ω has been fabricated on a substrate ($H = 30\,mil$ and $\varepsilon_r = 3.4$) and measured at a center frequency of 2 GHz. Figure 5 shows the microstrip CLF with $C = -7$ dB and the impedance transformers "Ipt 1" and "Ipt 2" to transform 100 Ω and 70 Ω into 50 Ωs. In this case, $Z_{0e} = 67.5\,\Omega$ and $Z_{0o} = 23.8\,\Omega$ as written in Table I. The even-mode impedance can be realized without any problem but the odd-mode impedance is somewhat difficult because the substrate given has a low dielectric constant. Therefore, three-dimensional structure or three coupled transmission lines is needed to get the wanted odd-mode impedance. This work made use of the three-dimensional structure as shown in Fig. 5(b). Figure 6 compares the measured results with the calculated ones and they are in good agreement.

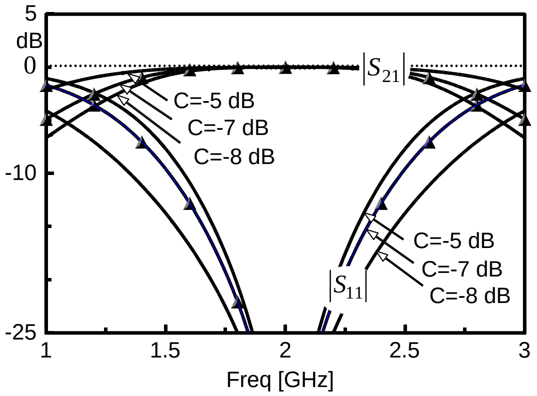


Fig. 4. Simulation results of three CLFs with 180° phase shift.

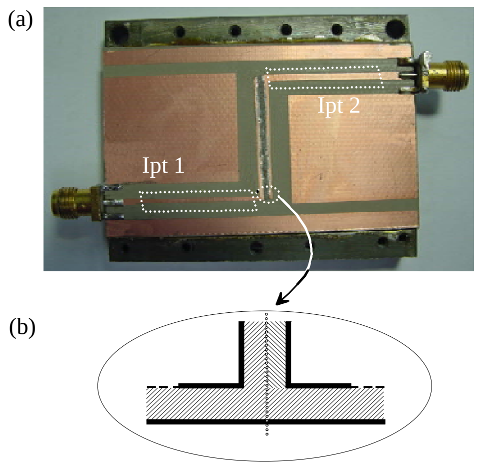


Fig. 5. (a) A microstrip CLF terminated in 100 Ω and 70 Ω and (b) its three dimensional structure.

IV. Conclusions

Coupled line filters (CLFs) with a 180° phase shift were analyzed and coupling compensated design equations derived. The design equations derived can be applied to both arbitrary termination impedances and arbitrary coupling coefficients. By using the CLFs, wideband ring hybrids and baluns can be designed and any advantage to reduce total size of microwave integrated circuits can be gained like asymmetric branch-line hybrids, power dividers, impedance transformers, phase shifters and attenuators.

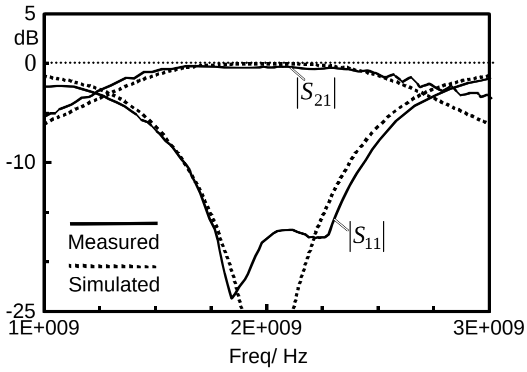


Fig. 6. Results measured and simulated are compared.

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