

Design of Filtering Power Dividers for Desired Filter Responses Using Parallel Coupled-Line Filters

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Abstract—This paper presents a design method for using two parallel coupled-line bandpass filters to realize a filtering power divider. For a specified filter response that involves the fractional bandwidth Δ and the element values g_1, g_2, \dots , and g_{n+1} , an n -pole filtering power divider can be readily designed using the design equations derived in this paper. As demonstrated by a proof-of-concept microstrip filtering power divider, the design method leads to an isolation network that needs only a resistor to achieve wideband isolation. The measured isolation is better than 15 dB from DC to $7.5f_c$, or is better than 12 dB from DC to $10f_c$, where f_c is the center frequency of the passband.

Keywords—Wilkinson; power divider; filtering power divider; isolation network.

I. INTRODUCTION

RF and microwave systems often require several bandpass filters and power dividers. In order to enhance the degree of integration and reduce losses in RF and microwave systems, many researchers have been proposing solutions to the joint design of bandpass filters and power dividers, i.e., filtering power dividers [1]–[8].

Nonetheless, unlike the design of bandpass filters with narrow fractional bandwidths [9], [10], there is still a lack of design methods that can be used for designing a filtering power divider for a specified filter response. As indicated by a survey of the literature [1]–[8], due to the design methodologies and topologies, the existing filtering power dividers lack the flexibility in adapting themselves to different filter responses other than the designed ones.

This paper presents a design method and derives the design equations for using two parallel coupled-line bandpass filters to realize a filtering power divider. For a specified filter response that involves the fractional bandwidth Δ and the element values g_1, g_2, \dots , and g_{n+1} , an n -pole filtering power divider can therefore be designed accordingly.

The concept is that a bandpass filter indeed has no problem to have a desired filter response [9], [10], and so may do a filtering power divider consisting of the bandpass filters. In practice, the point is how to isolate the bandpass filters. As demonstrated in Section III, the design method can effectively isolate two parallel coupled-line bandpass filters with only a resistor as the isolation network.

As a proof of concept, a two-pole filtering power divider having a fractional bandwidth of 10%, a passband ripple of 0.1 dB, and a center frequency of 2 GHz is implemented using

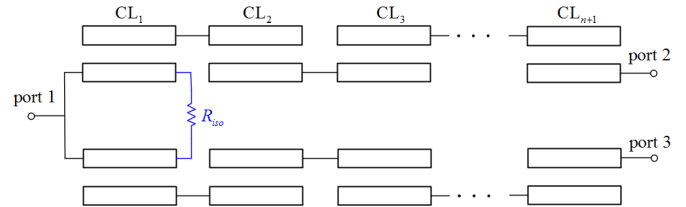


Fig. 1. Configuration of the coupled-line filtering power divider.

coupled microstrip lines on an RO4003C substrate. The filtering power divider with only a chip resistor as the isolation network exhibits wideband isolation, as indicated by the simulation and measured results in Sections III and IV.

II. CIRCUIT CONFIGURATION AND DESIGN EQUATIONS

Fig. 1 shows the configuration of the proposed coupled-line filtering power divider, which is composed of two identical n -pole parallel coupled-line bandpass filters (BPF) and a resistor as the isolation network. Note that a resistor is the minimum requirement for implementing the isolation networks [9].

Due to the symmetry, we can analyze the power divider using even-odd mode decomposition technique [9]. The S-parameters of the power divider can be expressed as

$$S_{11} = S_{11e}, \quad (1a)$$

$$S_{21} = S_{21e}/\sqrt{2}, \quad (1b)$$

$$S_{22} = (S_{22e} + S_{22o})/2, \quad (1c)$$

$$S_{32} = (S_{22e} - S_{22o})/2, \quad (1d)$$

where $S_{..e}$ and $S_{..o}$ are the generalized S-parameters of the even- and odd-mode circuits in Figs. 2(a) and 2(b). Note that the normalized reference impedances of the generalized S-parameters are 2 and 1.

The even-mode circuit in Fig. 2(a) is an n -pole parallel coupled-line bandpass filter with normalized reference impedances of 2 and 1. For a given set of the fractional bandwidth Δ and the element values g_1, g_2, \dots , and g_{n+1} , the even-mode circuit can be readily designed for a specified filter using the formula for parallel coupled-line bandpass filters [9], [10]. The filtering power divider is therefore able to be

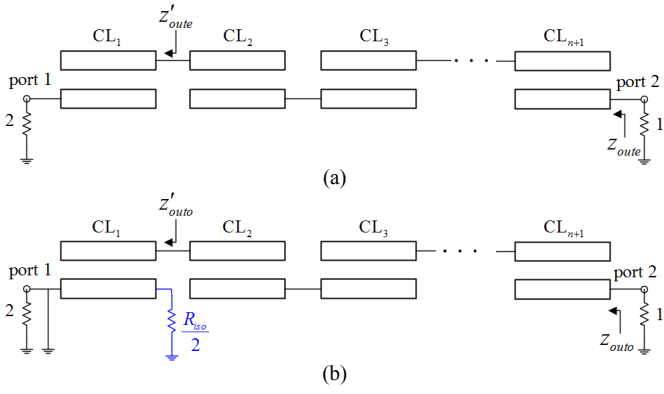


Fig. 2. Schematic circuits of the filtering power divider. (a) Even-mode circuit. (b) Odd-mode circuit.

designed for desired characteristics for S_{11} and S_{21} , as indicated by (1a) and (1b).

The problem now is how to design the isolation network for achieving matching and isolation at the output ports. According to (1b) and (1d), the isolation network can be designed by making the difference between S_{22e} and S_{22o} as small as possible. Accordingly, we need to equalize the output impedances of the even- and odd-mode circuits.

In order to equalize the output impedances, it is a logical choice to place the isolation network at the first pair of the coupled-line sections. By such a placement, the problem is simplified. We then need to equalize z'_{oute} and z'_{outo} rather than z_{oute} and z_{outo} , because the coupled-line sections CL_2 to CL_{n+1} are the same in the even- and odd-mode circuits as can be seen in Figs. 2(a) and 2(b).

Figs. 3(a) and 3(b) depict the equivalent circuits for isolation network design. At the center frequency, i.e., $\theta_l = \pi/2$, the output impedances can be computed as

$$z'_{oute} = \frac{(z_{e,1} - z_{o,1})^2}{8}, \quad (2a)$$

$$z'_{outo} = \frac{R_{iso} (z_{e,1} - z_{o,1})^2}{2(z_{e,1} + z_{o,1})^2}. \quad (2b)$$

The resistance of the isolation resistor can then be evaluated by letting $z'_{oute} = z'_{outo}$ to give

$$R_{iso} = \frac{(z_{e,1} + z_{o,1})^2}{4}. \quad (3)$$

Note that the expression for R_{iso} is a result evaluated at the center frequency. The frequency response of the isolation network is to be numerically studied in the Section III using the CAD simulation software.

Because the isolation network makes $S_{22e} \approx S_{22o}$, the S-parameters of the filtering power divider can be expressed as $S_{11} = S_{11e}$, $S_{21} = S_{21e}/\sqrt{2}$, $S_{22} \approx S_{22e}$ and $S_{32} \approx 0$. As a result, the

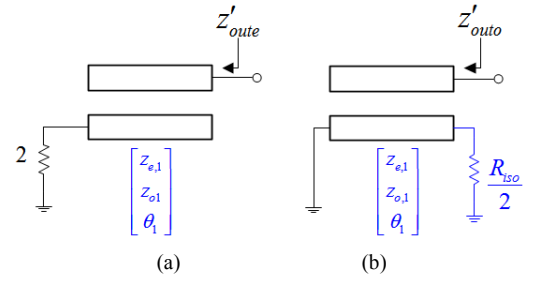


Fig. 3. Equivalent circuits for isolation network design. Coupled line parameters are labeled with the column vector. (a) Even-mode circuit. (b) Odd-mode circuit.

filtering power divider has the same filter response as that of the even-mode circuit. In other words, we can specify the filter response of a filtering power divider as we do for the design of bandpass filters with narrow fractional bandwidths [9], [10].

With the formula for parallel coupled-line bandpass filters [9], [10] and (3), the design equations for an n -pole filtering power divider having a specified filter response can be derived as

$$z_{e,1} = \frac{\Delta\pi}{g^1} + z_r \left(1 + \sqrt{\frac{\Delta\pi}{g^1 z_r}} \right), \quad (4a)$$

$$z_{o,1} = \frac{\Delta\pi}{g^1} + z_r \left(1 - \sqrt{\frac{\Delta\pi}{g^1 z_r}} \right), \quad (4b)$$

$$z_{e,k} = z_r \left(1 + \frac{\Delta\pi}{2\sqrt{g^k g^{k+1}}} + \frac{\Delta^2 \pi^2}{4g^k g^{k+1}} \right), \quad (4c)$$

$$z_{o,k} = z_r \left(1 - \frac{\Delta\pi}{2\sqrt{g^k g^{k+1}}} + \frac{\Delta^2 \pi^2}{4g^k g^{k+1}} \right), \quad (4d)$$

$$z_{e,n+1} = \frac{\Delta\pi}{2g^n g^{n+1}} + z_r \left(1 + \sqrt{\frac{\Delta\pi}{2g^n g^{n+1} z_r}} \right), \quad (4e)$$

$$z_{o,n+1} = \frac{\Delta\pi}{2g^n g^{n+1}} + z_r \left(1 - \sqrt{\frac{\Delta\pi}{2g^n g^{n+1} z_r}} \right), \quad (4f)$$

$$R_{iso} = \left(\frac{\Delta\pi + g^1 z_r}{g^1} \right)^2, \quad (4g)$$

where $k=2, 3, \dots, n$, and z_r is a free variable to which we can assign a value. Note that all the coupled lines are a quarter-wavelength long at the center frequency, and z_r is the normalized characteristic impedance that appears in the equivalent circuit of a coupled-line section [9, Fig. 8.44].

TABLE I

DESIGN PARAMETERS OF THE TWO-POLE FILTERING POWER DIVIDER

$Z_{e,1}$	$Z_{o,1}$	$Z_{e,2}$	$Z_{o,2}$	$Z_{e,3}$	$Z_{o,3}$	R_{iso}
2.513	1.061	1.788	1.174	2.114	1.087	3.193

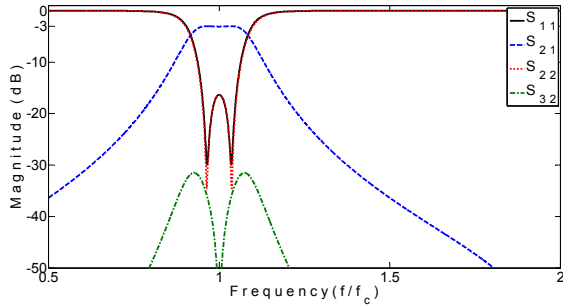


Fig. 4. Theoretical performance of the two-pole filtering power divider.

TABLE II

DESIGN PARAMETERS OF THE FOUR-POLE FILTERING POWER DIVIDER

$Z_{e,1}$	$Z_{o,1}$	$Z_{e,2}$	$Z_{o,2}$	$Z_{e,3}$	$Z_{o,3}$	$Z_{e,4}$	$Z_{o,4}$	$Z_{e,5}$	$Z_{o,5}$	R_{iso}
2.33	1.06	1.62	1.25	1.57	1.28	1.62	1.25	2	1.11	2.88

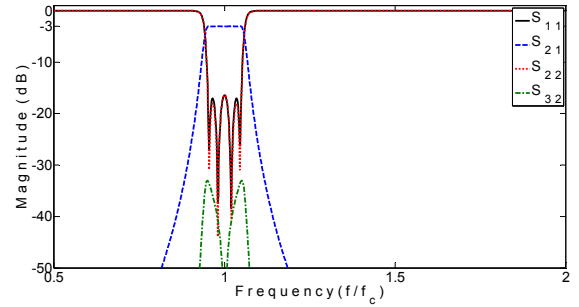


Fig. 5. Theoretical performance of the four-pole filtering power divider.

III. DESIGN EXAMPLES

As an example, a two-pole filtering power divider is presented in this section. The power divider is designed for a fractional bandwidth of 10% and a passband ripple of 0.1 dB, i.e., $\Delta=0.1$, $g_1=0.8431$, $g_2=0.6220$, and $g_3=1.3554$.

We assign $z_r=\sqrt{2}$ in this design. The normalized characteristic impedances of the coupled-line sections and the resistance of the isolation resistor are calculated with (4a)–(4g) and tabulated in TABLE I.

Fig. 4 shows the theoretical performance, which are simulation results based on the ideal transmission line models. The theoretical performance observed in Fig. 4 has two features that are worth pointing out. Firstly, the isolation or $1/|S_{32}|$ is theoretically better than 30 dB at all frequencies, because the response is periodic in frequency and repeats at $3f_c$, $5f_c$, and so on. Secondly, the responses of return loss at the output ports follow those of the constituent BPFs, because we make $S_{22e}\approx S_{22o}$ and therefore $S_{22}\approx S_{22e}$, as indicated by (1c). In other words, the filtering power divider has the same Chebyshev response as that of the constituent BPFs.

Furthermore, higher order filtering power dividers can also be readily designed with the derived design equations. As an example, TABLE II lists the design parameters for a four-pole filtering power divider having a fractional bandwidth of 10% and a passband ripple of 0.1 dB. The theoretical performance is shown in Fig. 5.

IV. MICROSTRIP REALIZATION

The two-pole design example is implemented in microstrip on a 20-mil thick RO4003C substrate that has a dielectric constant of 3.55 and a loss tangent of 0.003. The filtering power divider is designed for a center frequency of $f_c=2$ GHz.

With the design parameters listed in Table I, we conduct EM simulations using Keysight's Momentum to take into

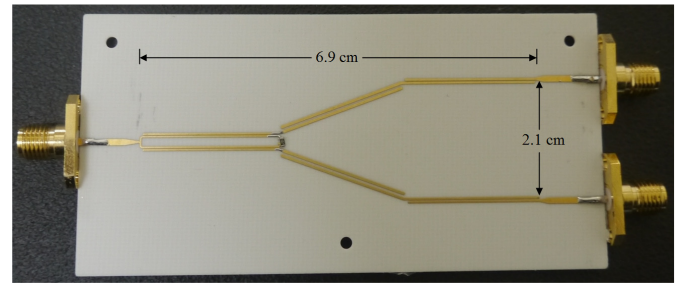
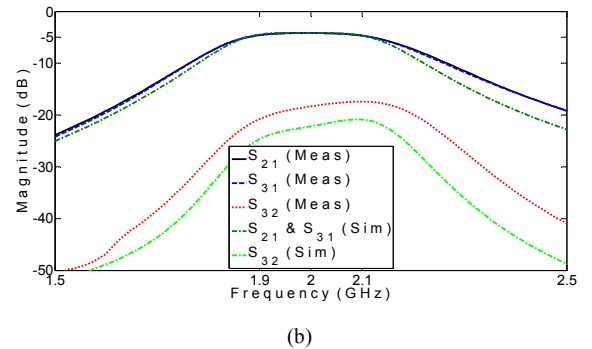
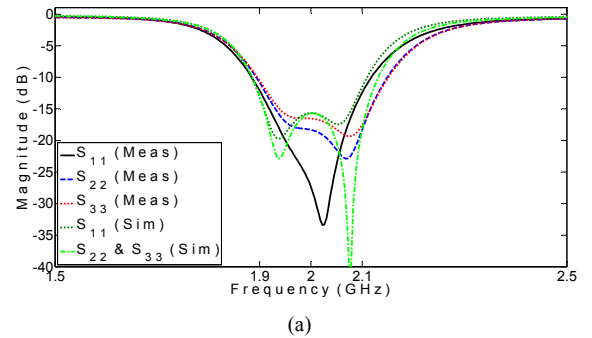


Fig. 6. Photograph of the fabricated two-pole filtering power divider.

Fig. 7. Frequency responses of the fabricated filtering power divider. (a) $|S_{11}|$, $|S_{22}|$ and $|S_{33}|$. (b) $|S_{21}|$, $|S_{31}|$ and $|S_{32}|$

account the parasitic and high-order effects. The photograph of the fabricated filtering power divider is shown in Fig. 6. A 160- Ω chip resistor is used for the isolation network. Note that the normalized resistance of the chip resistor is 3.2, which is a round number of the theoretical value 3.1928.

Figs. 7(a) and 7(b) show the frequency responses of the fabricated filtering power divider. In the passband, the isolation is better than 17.7 dB while the return loss and insertion loss are better than 16.6 dB and 4.3 dB, as indicated by the measured results. Note that, for a 0.1-dB passband ripple, the ideal Chebyshev response has a return loss of about 16.4 dB, as can be seen in Fig. 4.

Fig. 8 shows the measured wideband performance of the fabricated filtering power divider. The isolation is observed to be better than 15 dB from DC to 15 GHz, i.e, $7.5f_c$, or be better than 12 dB from DC to 20 GHz, i.e, $10f_c$.

In theory, the isolation of the filtering power divider is better than 30 dB in the passband and stopband, as can be seen in Fig. 4. The performance of the fabricated power divider is, however, affected by the inhomogeneous nature of the microstrip [10].

V. CONCLUSION

We developed a design method for using two parallel coupled-line bandpass filters to realize a filtering power divider. For a specified filter response that involves the fractional bandwidth Δ and the element values g_1, g_2, \dots , and g_{n+1} , an n -pole filtering power divider can be readily designed using the design equations (4a)–(4g). The filtering power divider can achieve wideband isolation, while uses only a resistor as the isolation network.

Moreover, the proposed method is quite general, being applicable to other types of coupled-line BPFs. For example, the circuit size and wideband performance of a filtering power divider is expected to be improved by using the parallel-coupled dual-mode resonator bandpass filters [11].

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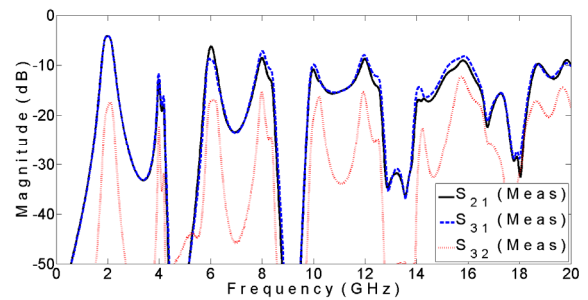


Fig. 8. Measured wideband performance of the fabricated filtering power divider.

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