Analysis and design of an unequal termination impedance power divider with bandpass filtering response

P. Kim, G. Chaudhary and Y. Jeong✉

The design of an unequal termination power divider (PD) with a bandpass filtering response and wide out-of-band suppression characteristics is presented. The two-cascaded coupled lines can be designed with a low impedance transforming ratio. For the validation, a 50-to-5 Ω termination impedance PD was implemented at a centre frequency (f_0) of 2.6 GHz. The measured results are in good agreement with the simulations, showing input and output return losses that are better than 19 dB over a passband bandwidth of 190 MHz (2.51–2.7 GHz), and an out-of-band suppression that is better than 19.6 dB from DC to 2.25 and 2.9 to 7.2 GHz. The isolation between the output ports is 39.2 dB at f_0, and it is better than 19 dB with a broadband frequency (DC to 7.2 GHz).

Introduction: Power dividers (PDs) are widely used in communication systems to split/combine the RF powers. Recently, PDs have been studied for various design issues such as size reduction and the filtering response. A PD with a wide stopband characteristic was presented in [1]. A wide stopband attenuation was obtained by adding two open TLs stubs. Alternatively, a bandpass-response PD/combiner was presented in [2], where the two stub-loaded resonators were used between the input and output ports to obtain a bandpass response; moreover, the open stub-loaded resonators were meandered to reduce the circuit size. In [3], the PD was designed using multimode resonators, and it provided a wide stopband characteristic. In [4], an unequal termination impedance PD with a filtering response was designed using a single-coupled line with open-stub TLs. The shunt open-stub TL can be used to provide four transmission zeros at the stopband. However, it is difficult to design with low impedance transforming ratio (r).

In this Letter, the general design formula of an unequal termination impedance PD with the bandpass response is presented using two cascaded parallel coupled lines. The proposed circuit can be designed with a low r. To verify the proposed PD, a 50-to-5 Ω termination PD was designed, simulated, and fabricated at a centre frequency (f_0) of 2.6 GHz.

Filtering PD design equations: Fig. 1*a* shows the proposed structure of the bandpass filtering PD with unequal termination impedances. The proposed circuit consists of two pairs of coupled lines and an isolation resistor (R) that is connected at the junction of the coupled lines. The resistor R is used to obtain a high isolation between the two output ports and to provide a good output return loss.

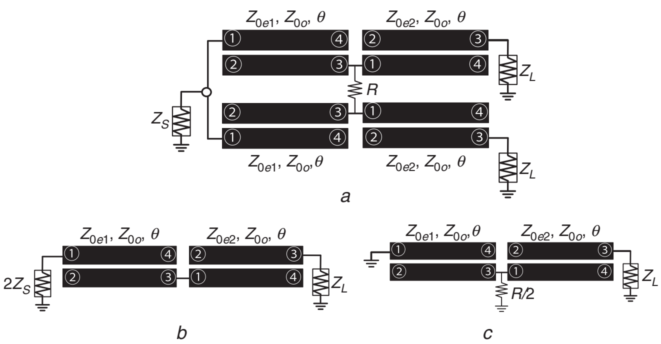

Fig. 1 *Proposed filtering PD*

a Schematic
b Even-mode equivalent circuit
c Odd-mode equivalent circuit

The even- and odd-mode equivalent circuits are illustrated in Figs. 1*b* and *c*, respectively. At the even-mode, resistor R does not affect the connected circuit; moreover, Z_S is transformed to $2Z_S$ for the equal power dividing. The S-parameters of this mode are derived [5] from the *ABCD* parameters of the cascaded coupled lines 1 and 2, as given in (1) and (2), as follows:

$$S_{11e} = \frac{A_e Z_L + B_e - C_e r Z_L^2 - D_e r Z_L}{A_e Z_L + B_e + C_e r Z_L^2 + D_e r Z_L} \tag{1a}$$

$$S_{22e} = \frac{-A_e Z_L + B_e - C_e r Z_L^2 + D_e r Z_L}{A_e Z_L + B_e + C_e r Z_L^2 + D_e r Z_L} \tag{1b}$$

where

$$A_e = \frac{(Z_{p1} + Z_{p2}) Z_{p1} \cos^2\theta - Z_{m1}^2}{Z_{m1} Z_{m2}} \tag{2a}$$

$$B_e = j \cot\theta \left[\frac{Z_{p1} Z_{m2}^2 + Z_{m1}^2 Z_{p2} - (Z_{p1} + Z_{p2}) Z_{p1} Z_{p2} \cos^2\theta}{2 Z_{m1} Z_{m2} \sin\theta} \right] \tag{2b}$$

$$C_e = j \frac{2 \sin\theta \cos\theta}{Z_{m1} Z_{m2}} (Z_{p1} + Z_{p2}) \tag{2c}$$

$$D_e = \frac{(Z_{p1} + Z_{p2}) Z_{p2} \cos^2\theta - Z_{m2}^2}{Z_{m1} Z_{m2}}, \tag{2d}$$

$$r = \frac{Z_L}{2 Z_S} \tag{2e}$$

$$Z_{mi} = Z_{0ei} - Z_{0o}, \tag{2f}$$

$$Z_{pi} = Z_{0ei} + Z_{0o}, \quad i = 1, 2. \tag{2g}$$

From (1a), the Z_{0e2} can be derived as (3) with a predefined S_{11e} at f_0 [5]

$$Z_{0e2} = Z_{0e1} N + Z_{0o}(1 - N) \tag{3}$$

where

$$N = \sqrt{\frac{r\left(1 + S_{11e}|_{f=f_0}\right)}{1 - S_{11e}|_{f=f_0}}}. \tag{4}$$

From (1a) and (3), the Z_{0e1} can be derived as follows:

$$Z_{0e1}^3 Y_1 + Z_{0e1}^2 Y_2 + Z_{0e1} Y_3 + Y_4 = 0 \tag{5}$$

where

$$Y_1 = rN(1 + N) \tag{6a}$$

$$Y_2 = r Z_{0o} (2 - N^2 - 3N) \tag{6b}$$

$$Y_3 = Z_{0o}^2 (3rN - rN^2 - 4r) - 4 Z_L^2 (N + 1) \tag{6c}$$

$$Y_4 = r Z_{0o}^3 (N^2 - N + 2) + 4 Z_L^2 Z_{0o} (N - 3) \tag{6d}$$

At the odd-mode, the Z_S become short-circuited and the resistor R is divided into halves. The output reflection coefficient S_{22o} can therefore be derived from the *ABCD* parameters of the cascaded coupled TLs and the shunt resistor R, which is given by (7) as follows:

$$S_{22o} = \frac{-A_o Z_L + B_o}{A_o Z_L + B_o} \tag{7}$$

where

$$A_o = \frac{Z_{p1} Z_{p2} \cos^2\theta - Z_{m1}^2 + Z_{p1}^2 \cos^2\theta}{Z_{m1} Z_{m2}} + j \frac{Z_{m1}^2 - Z_{p1}^2 \cos^2\theta}{R Z_{m1} Z_{m2} \sin\theta} Z_{p2} \cos\theta \tag{8a}$$

$$B_o = -\frac{\left(Z_{m1}^2 - Z_{p1}^2 \cos^2\theta\right)\left(Z_{m2}^2 - Z_{p2}^2 \cos^2\theta\right)}{2 R Z_{m1} Z_{m2} \sin^2\theta} + j \frac{\cos\theta}{2 Z_{m1} Z_{m2} \sin\theta} \left[\left(Z_{m2}^2 - Z_{p2}^2 \cos^2\theta\right) Z_{p1} + \left(Z_{m1}^2 - Z_{p1}^2 \cos^2\theta\right) Z_{p2} \right]. \tag{8b}$$

From (1b) and (7), the resistance R can be derived as

$$R = \frac{r Z_{m1}^2}{2 Z_L}. \tag{9}$$

The calculated resistor can provide a perfect isolation between the two output ports. To validated the analysis, the equal PDs with the $Z_S = 50\ \Omega$, $Z_L = 5\ \Omega$ ($r = 0.05$) and the 20 dB return loss at f_0 were designed. Fig. 2 shows the S-parameter characteristics of the PD. The PD provides an equal power division with the bandpass response; furthermore, the return loss is 20 dB at f_0 with two poles in the passband. The resistor provides good output return losses and high isolation characteristics. The bandwidth of the proposed PD was enhanced by the two poles in the passband.

The normalised frequency locations of transmission poles can be found in (10) from the real part of (1a), as follows:

$$f_{p1,p2}/f_0 = 1 \mp \left[1 - \frac{2}{\pi} \cos^{-1} \sqrt{\frac{r Z_{m1}^2 - Z_{m2}^2}{(Z_{p1} + Z_{p2})(r Z_{p1} - Z_{p2})}} \right] \tag{10}$$

where f_{p1} and f_{p2} are the lower and upper of the transmission poles frequencies.

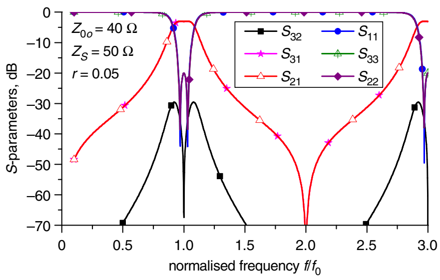

Fig. 2 *S-parameter characteristics of PD with r = 0.05 (Z_{0o} = 40 Ω, Z_{0e1} = 108.01 Ω, Z_{0e2} = 56.81 Ω, R = 23.13 Ω, f_{p1} = 0.969, f_{p2} = 1.031)*

Fig. 3 shows the variation of Z_{0ei} and transmission pole locations according to Z_{0o}. Z_{0e1} and Z_{0e2} are increased as Z_{0o} increases. Moreover, the transmission poles are moved close to f_0 as Z_{0o} increases. Hence, high Z_{0o} causes the narrow bandwidth of the PD. However, low Z_{0o} is faced the realisation of coupled line. Therefore, a trade-off between bandwidth and Z_{0o} should be considered. The calculation was done by specifying $Z_L = 5$ Ω, $r = 0.05$ and $S_{11} = -20$ dB.

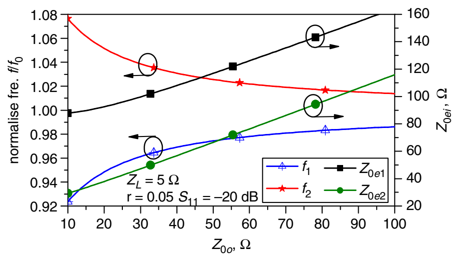

Fig. 3 *Variation of Z_{0ei} and transmission poles location according to Z_{0o}*

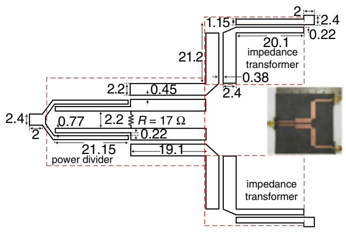

Fig. 4 *Photograph and layout of the proposed PD (unit: mm)*

Experimental results: For validation of the proposed PD, 50-to-5 Ω transformer ($r = 0.05$) had been designed at f_0 of 2.6 GHz. S_{11} is chosen −20 dB at f_0. The circuit was fabricated on a substrate RT/Duroid 5880 with a dielectric constant (ε_r) of 2.2 and thickness (h) of 31 mils. Fig. 4 shows the photograph and the EM simulation layout of the fabricated PD. Port 1 is terminated with 50 Ω, while ports 2 and 3 are terminated with 5 Ω; therefore, the impedance transformers are attached to the output ports 2 and 3 for the measurements. The circuit size of the PD is 43.48mm × 15 mm. Fig. 5*a* shows the simulated and measured *S*-parameter characteristics and the amplitude imbalance between the two output ports of the PD. The proposed unequal terminated PD provides the bandpass filtering response. From the measurements, the magnitudes of S_{21} and S_{31} at f_0 are determined to be −3.7 and −3.67 dB, respectively. The amplitude division is better than −3.8 dB within the bandwidth of 0.19 GHz (2.51–2.7 GHz). These values include the insertion losses of the output impedance transformers for the measurement. A spurious response was produced due to the difference between the even- and odd-mode phase velocities of coupled microstrip [6]. The out-of-band suppression characteristics are higher than 19.6 dB from DC to 2.25 GHz and from 2.9 to 7.2 GHz. The measured amplitude imbalance is ± 0.2 dB within the passband. The input and output return losses are 19 dB at f_0 and higher than 19 dB over a bandwidth of 0.19 GHz. The two transmission poles are observed at 2.55 and 2.67 GHz providing the *FBW* of 4.6%. The simulated and measured isolation and phase differences between the two output ports are shown in Fig. 5*b*. The isolation is 39.2 dB at f_0 and higher than 19 dB extending from DC to 7.2 GHz is achieved. Similarly, the measured phase difference varies from ± 3° in the range of 2–3.8 GHz.

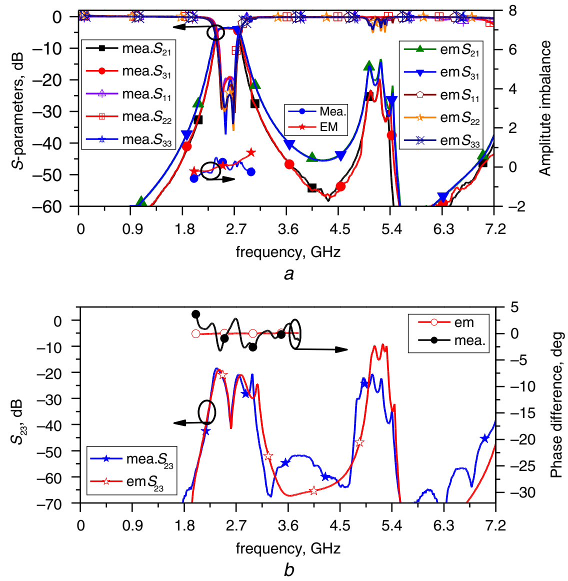

Fig. 5 *Simulation and measured results*

a Insertion/return loss and amplitude imbalance
b Isolation and phase difference

Conclusion: This Letter presents the design of an unequal termination-impedance filtering PD with wide out-of-band suppression characteristics. The PD can be designed with a low impedance transforming ratio. The general design equations were derived and explained in detail with a simulation and measurement validation.

Acknowledgments: This research was supported by the Basic Science Research Program through the NRF of Korea, funded by Ministry of Education, Science and Technology (2016R1D1A1B03931400).

Submitted: *26 May 2017* E-first: *14 August 2017*
doi: 10.1049/el.2017.2032
One or more of the Figures in this Letter are available in colour online.

P. Kim, G. Chaudhary and Y. Jeong (*Division of Electronic and Information Engineering, Chonbuk National University, Jeonju-Si, Republic of Korea*)

✉ E-mail: ycjeong@jbnu.ac.kr

References

1 Gao, S., Sun, S., and Xiao, S.: ‘A novel wideband bandpass power divider with harmonic-suppressed ring resonator’, *Microw. Wirel. Compon. Lett.*, 2013, **23**, (3), pp. 119–121
2 Song, K., Hu, S., Mo, Y., *et al.*: ‘Novel bandpass-response power divider with high frequency selective using centrally stub-loaded resonators’, *Microw. Opt. Technol. Lett.*, 2013, **55**, (7), pp. 1560–1562
3 Wang, X., Wang, J., and Zhang, G.: ‘Design of wideband filtering power divider with high selectivity and good isolation’, *Electron. Lett.*, 2016, **52**, (16), pp. 1389–1391
4 Kim, P., Jeong, J., Chaudhary, G., *et al.*: ‘A design of unequal termination impedance power divider with filtering and out-of-band suppression characteristic’. Proc. of 45th European Microwave Conf., Paris, France, September 2015, pp. 123–126
5 Kim, P., Chaudhary, G., and Jeong, Y.: ‘Ultra-high transforming ratio coupled line impedance transformer with bandpass response’, *Microw. Wirel. Compon. Lett.*, 2015, **25**, (7), pp. 445–447
6 Gilb, J.P., and Balanis, C.A.: ‘Pulse distortion on multilayer coupled microstrip lines’, *Trans. Microw. Theory Tech.*, 1989, **37**, (10), pp. 1620–1628