

Novel 3-dB Tandem Coupler with Wide Bandwidth by Using 4 Short Stubs

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Abstract—A new wideband 3-dB tandem coupler is presented that has wide bandwidth using four 90° short stubs. The proposed tandem coupler does not require a higher transmission line impedance or a narrower coupling gap than conventional couplers. Measurements of the fabricated tandem coupler operated at a center frequency of $f_0 = 1$ GHz are presented as verification of the design concept. The fractional bandwidth (FBW) at which the return loss was suppressed to a level better than 15 dB was 71%. Theoretical calculations and measurements of the tandem coupler were in good agreement.

1. INTRODUCTION

3 dB couplers have been investigated due to their small size, wide bandwidth, high performance, and easy circuit fabrication. Branch line couplers [1, 2], ring hybrids [3], and Wilkinson power dividers [4] are well known and widely used in the design of amplifiers, balanced mixers, and modulators. These couplers can be easily implemented; however, they require large spaces to achieve a wide bandwidth. Furthermore, wideband 3 dB couplers require long coupled lines and tight coupling. In particular, Lange couplers [5, 6], broadside-coupled structures [7], tandem couplers [8, 9], and re-entrant [10] type couplers are used to realize tight coupling. However, these coupled structures require complex multilayer structures due to their narrow line widths and narrow gaps.

Tandem coupler has high coupling performance, even if there is no narrow gap between the coupling lines. In [9], a tandem coupler with a wide fractional bandwidth (FBW) was developed, as shown in Fig. 1(a). A wide bandwidth can be obtained using an asymmetrically fed short-circuit coupled line; however, it has a disadvantage that wire bonding is still required.

We propose a wideband tandem coupler, where four 90° short stubs are added to a conventional tandem coupler. The number of poles was increased, and a wider bandwidth was realized by the use of these four short stubs. Fig. 1(b) shows the four 90° short stubs added; however, the circuit size is not changed compared to Fig. 1(a). In addition, the use of a 4-layer FR-4 substrate and an inner layer crossover eliminates the labor of wire bonding. Circuit simulations show that the theoretically derived equations are in good agreement with the proposed coupler.

2. THEORETICAL ANALYSIS

Even- and odd-mode analysis was applied to the tandem coupler. The characteristic impedance of each transmission line is given by Z_A , Z_{0e} , Z_{0o} , Z_{0ex} , Z_{0ox} , and Z_1 . The length of all transmission lines is a quarter-wavelength. For $Z_{0ex} = Z_{0e}$, $Z_{0ox} = Z_{0o}$, and $S_{11} = 0$, the impedance Z_A and the imbalance (IB) between $|S_{21}|$ and $|S_{31}|$ can be expressed as [9]:

$$Z_A = \sqrt{\frac{8Z_{0e}Z_{0o}(Z_{0e}Z_{0o} - Z_0^2)}{4Z_0^2 + (Z_{0e} - Z_{0o})^2}}, \quad (1)$$

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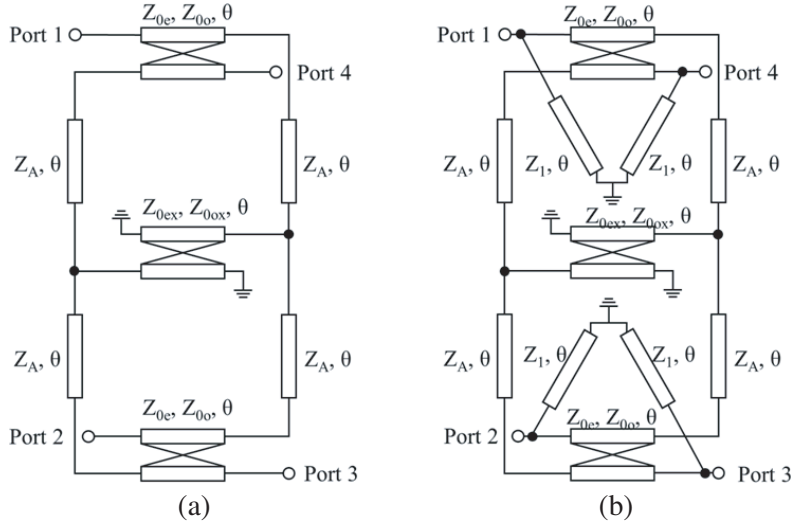


Figure 1. Schematic diagrams of (a) a conventional tandem coupler [9], and (b) the proposed tandem coupler.

$$\frac{|S_{21}|}{|S_{31}|} = \frac{4Z_0^2 - (Z_{0e} - Z_{0o})^2}{4Z_0(Z_{0e} - Z_{0o})} = 10^{-\frac{IB(dB)}{20}}. \quad (2)$$

With the assumption of $Z_{0o} < Z_A < Z_{0e}$, the impedance Z_{0e} can be expressed as:

$$Z_{0e} = Z_{0o} + 2 \left(\sqrt{10^{-\frac{IB}{10}} + 1} - 10^{-\frac{IB}{20}} \right) Z_0. \quad (3)$$

When $IB = 0$ dB, the relationship between the FBW with $S_{11} < -20$ dB and impedance Z_{0o} is as shown in Fig. 2(a). Fig. 2(a) shows that the Z_{0o} at which the FBW becomes wider is within the range of 42Ω to 47Ω . Furthermore, the relationship of the FBW when several Z_1 are selected in the range of those Z_{0o} is shown in Fig. 2(b). Here, the FBW is wide when Z_{0o} is 45Ω or 46Ω . To obtain the fine-tuned Z_1 in which the FBW with $S_{11} < -20$ dB becomes wide, Z_1 at $Z_{0o} = 45 \Omega$ and 46Ω is then optimized using the optimizer of the Microwave Office simulation software. The optimized impedances of Z_1 are then 84.6Ω when $Z_{0o} = 45 \Omega$, and 74.2Ω when $Z_{0o} = 46 \Omega$. The FBW calculated in each case is 64.0% when $Z_{0o} = 45 \Omega$ and $Z_1 = 84.6 \Omega$, and 64.7% when $Z_{0o} = 46 \Omega$ and $Z_1 = 74.2 \Omega$. $Z_{0o} = 46 \Omega$ and $Z_1 = 74.2 \Omega$ were selected because of the wider FBW. The Z_A and Z_{0e} impedances can be obtained from Eqs. (1) and (3) as 64.63Ω and 87.42Ω , respectively.

The validity of the proposed tandem coupler was confirmed by the simulation results. In the simulation, the center frequency (f_0) is assumed to be 1 GHz and the input/output impedance (Z_0)

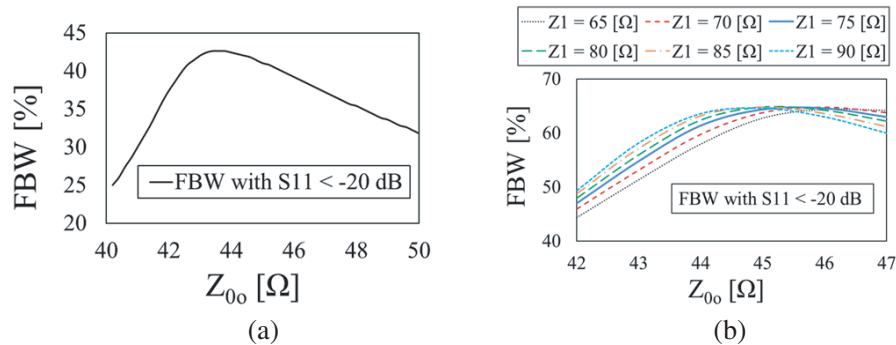


Figure 2. (a) Relationship between the FBW and Z_{0o} for $S_{11} < -20$ dB. (b) Relationship between the FBW and Z_{0o} with respect to Z_1 , for $S_{11} < -20$ dB.

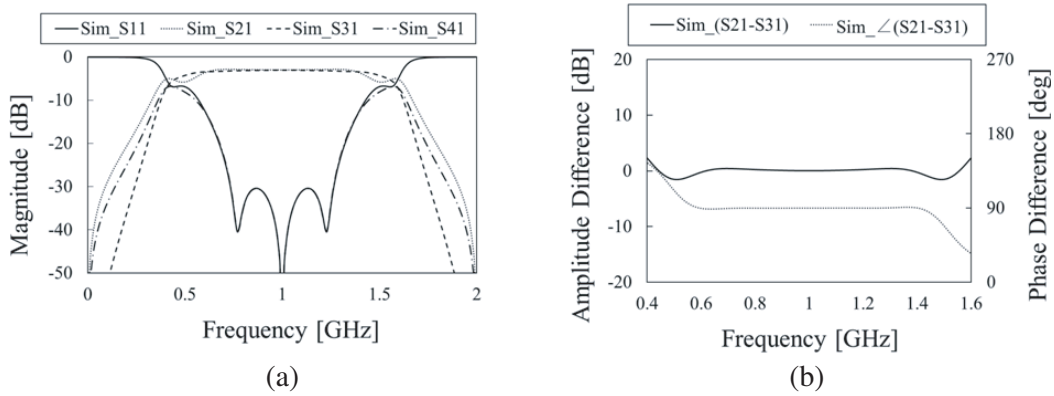


Figure 3. Simulated frequency responses of the proposed tandem coupler. (a) Magnitudes of S_{11} , S_{21} , S_{31} , and S_{41} . (b) Amplitude and phase differences between ports 2 and 3.

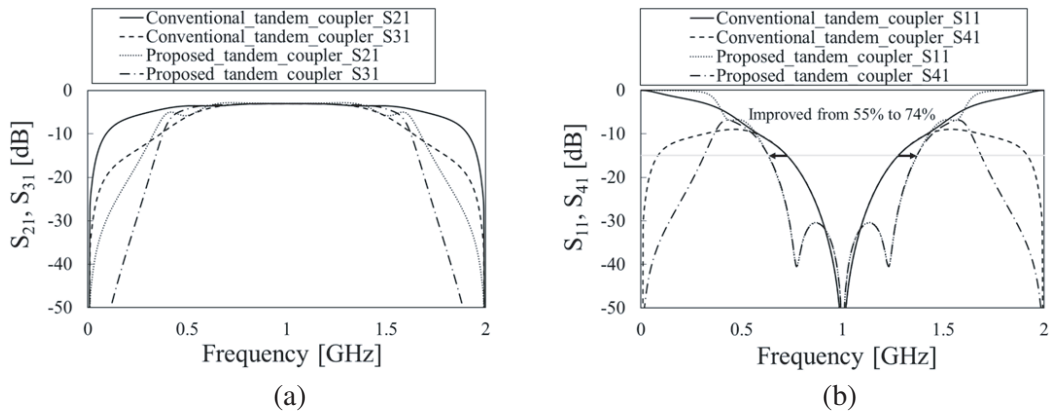


Figure 4. Comparison of a conventional tandem coupler and the proposed tandem coupler. (a) Magnitudes of S_{21} and S_{31} , and (b) magnitudes of S_{11} and S_{41} .

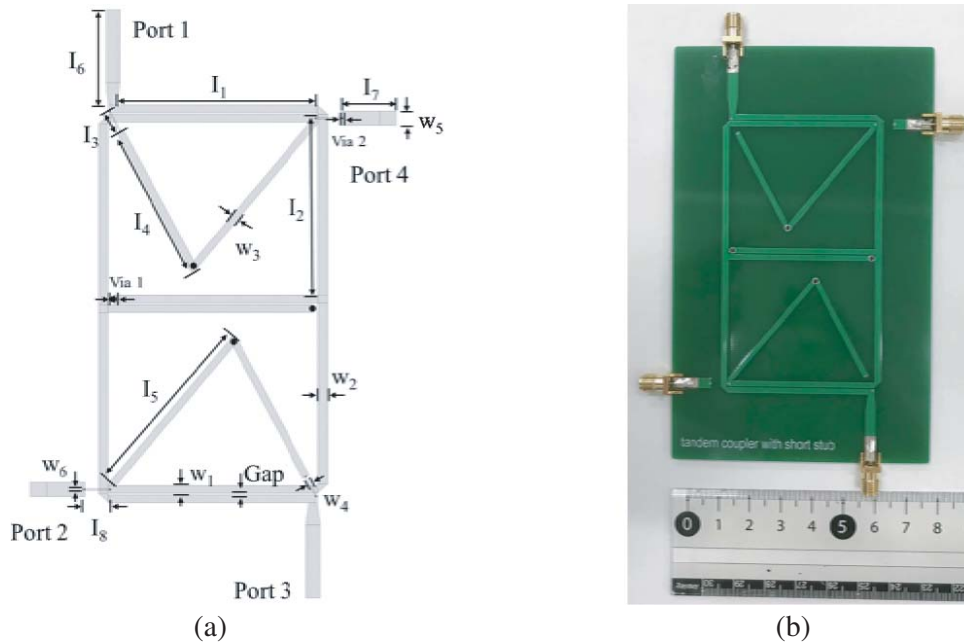
assumed to be 50Ω . Fig. 3 shows the simulation results. By placing the four stubs between ports and coupled lines, the number of poles was increased at frequencies of approximately 0.5 GHz, 0.75 GHz, 1.25 GHz, and 1.5 GHz, and a wider bandwidth was realized by improving the reflection characteristics. A newly proposed tandem coupler with a wide passband (S_{21} and S_{31}), return loss (RL) (S_{11}), and isolation (S_{41}) at the center frequency was thus determined. Fig. 4 compares a conventional tandem coupler with the proposed tandem coupler. The bandwidth of the proposed coupler was confirmed to be improved over that of the conventional coupler. The bandwidth where the RL is suppressed to a level better than 15 dB is 0.63 GHz to 1.37 GHz. The number of poles was increased with the four short stubs, and the FBW was improved from 55% to 74%. Table 1 compares the proposed tandem coupler with other designs.

3. EXPERIMENTAL RESULTS

A newly proposed tandem coupler was fabricated to test the design concept. The tandem coupler was fabricated on an FR-4 substrate with a center frequency (f_0) of 1 GHz and an input/output impedance (Z_0) of 50Ω . This substrate has a dielectric constant of 4.3, thickness of 1.6 mm, and $\tan \delta = 0.016$. Fig. 5(a) shows the structure of the fabricated tandem coupler. In this structure, a 4-layer FR-4 substrate was used to eliminate the labor of wire bonding. The crossover is realized by transition of port 2, port 4, and the 90° short stubs to the third layer. Table 2 shows the optimized dimensions of the proposed tandem coupler.

Table 1. Simulated bandwidths of proposed tandem coupler compared with other designs.

Ref.	Structure	Simulated FBW [%]			
		f_0 [GHz]	Return Loss < -15 [dB]	Amp. Imb. < ± 0.5 [dB]	Phase Imb. < ± 5 [deg]
[1]	Branch-line coupler	1	18	18	33
[3]	Ring hybrid	1	40	22	16
[6]	Lange coupler	10	-	> 40	-
[7]	Broadside-coupled	2.4	65	54	92
[9]	Tandem coupler	1	55	77	62
This work	Proposed tandem coupler	1	74	82	88

**Figure 5.** (a) Structure of the proposed tandem coupler. (b) Photograph of the fabricated tandem coupler.**Table 2.** Dimensions of the proposed tandem coupler.

l_1	l_2	l_3	l_4	l_5	l_6
46	40	4.8	35	41.4	21
l_7	l_8	w_1	w_2	w_3	w_4
12	6	1.7	2	1.5	0.18
w_5	w_6	Gap	Via 1 Diameter	Via 2 Diameter	Unit: mm
3.1	0.37	0.34	1.4	0.3	

Figure 5(b) shows a photograph of the fabricated proposed tandem coupler. Fig. 6 compares the measured responses with the simulated responses; Fig. 6(a) shows the coupling (S_{21} and S_{31}), RL (S_{11}) and isolation (S_{41}), and Fig. 6(b) shows the difference in the amplitude and phase between the output ports. The proposed tandem coupler was confirmed to have a wide bandwidth, an RL of -15 dB or less

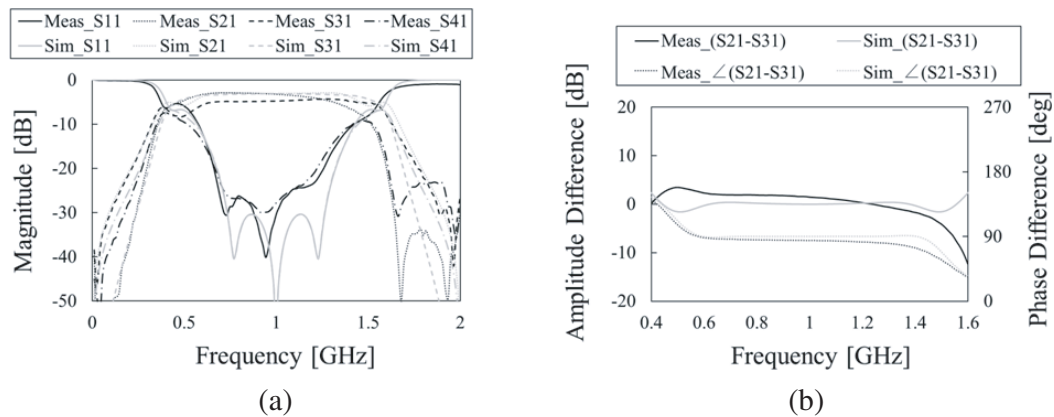


Figure 6. Comparison of the simulated and measured responses for the proposed tandem coupler. (a) Magnitudes of S_{11} , S_{21} , S_{31} , and S_{41} . (b) Amplitude and phase differences between ports 2 and 3.

at 0.63–1.32 GHz, and an FBW of 71%. The measured FBW of the tandem coupler with $S_{11} < -15$ proposed in [9] was approximately 53%, and the FBW of the proposed tandem coupler was improved by 18%. There is a slight difference between the measured responses and simulated responses due to the insertion loss of the FR-4 substrate.

4. CONCLUSION

We have presented a new wideband 3-dB tandem coupler. Theoretical analysis and experimental verification of the proposed tandem coupler were performed. A wideband coupler was realized without high impedance lines and tight coupling gaps. In addition, the use of four 90° short stubs enabled the use of the same circuit size as a conventional tandem coupler, and a wider bandwidth was realized. The measured and simulation responses of the proposed tandem coupler were in good agreement.

REFERENCES

1. Levy, R. and L. F. Lind, "Synthesis of symmetrical branch-guide directional couplers," *IEEE Trans. Microw. Theory Tech.*, Vol. 16, No. 2, 80–89, Feb. 1968.
2. Yoon, H.-J. and B.-W. Min, "Two section wideband 90° hybrid coupler using parallel-coupled three-line," *IEEE Microw. Wireless Compon. Lett.*, Vol. 27, No. 6, 548–550, Jun. 2017.
3. Pon, C. Y., "Hybrid-ring directional coupler for arbitrary power divisions," *IRE Trans. Microw. Theory Tech.*, Vol. 9, No. 6, 529–535, Nov. 1961.
4. Wilkinson, E. J., "An N -way hybrid power divider," *IRE Trans. Microw. Theory Tech.*, Vol. 8, No. 1, 116–118, Jan. 1960.
5. Lange, J., "Interdigitated strip-line quadrature hybrid," *IEEE Trans. Microw. Theory Tech.*, Vol. 17, 1150–1151, Dec. 1969.
6. Han, L., K. Wu, and X. Chen, "Accurate synthesis of four-line interdigitated coupler," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 10, 2444–2455, Oct. 2009.
7. Chang, C., J. Chiu, H. Chiu, and Y. Wang, "A 3-dB quadrature coupler using broadside-coupled coplanar waveguides," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, No. 3, 191–193, Mar. 2008.
8. Cho, J.-H., H.-Y. Hwang, and S.-W. Yun, "A design of wideband 3-dB coupler with N -section microstrip tandem structure," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, No. 2, 113–115, Feb. 2005.
9. Tang, C., C. Tseng, and K. Hsu, "Design of the modified planar tandem couplers with a wide passband," *IEEE Trans. Microw. Theory Tech.*, Vol. 61, No. 1, 48–54, Jan. 2013.

10. Hayes, R. E., J. W. Gipprich, and M. G. Hershfeld, "A stripline re-entrant coupler network for cofired multilayer microwave circuits," *IEEE S Int. Microw. Symp. Dig.*, 801–804, 1996.