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A Miniaturized Filtering 3-dB Branch-Line Hybrid Coupler with Wide Suppression Band

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Abstract—A 3-dB branch-line hybrid coupler with wide stopband responses is presented in this letter. An equivalent K-inverter with bandpass function is used instead of one quarter-wavelength transmission line, which will realize size reduction and wide stopband characteristic of the coupler. Prototype of a branch-line hybrid coupler, which divides the power equally with 90° phase difference between the output ports, is also fabricated and tested. Both the simulation and measurement results show that such a hybrid coupler exhibits an 83.2% size reduction and has transmission suppression of $-20\,\mathrm{dB}$ or less within five-fold bandwidth.

1. INTRODUCTION

Branch-line hybrid coupler is widely implemented in modern wireless communication systems such as power synthesis, phase shifters, balanced mixers and amplifiers, thanks to their intrinsic capability to divide the power equally with 90° phase difference between the output ports. The traditional branch line hybrid coupler may be bulky, especially in low-frequency region. Moreover, because of the periodicity of the transmission line, it may exhibit higher order harmonics that may adversely affect system performance.

To date, various methods have been reported so as to realize the miniaturization of branch-line hybrid couplers, such as using distributed capacitors [1], interdigitated shunt capacitors [2], transmission line with triple-stubs [3], metrical T-structures [4], polar curves [5] and substrate integrated suspended line technology [6]. Furthermore, some methods were also reported to accomplish wide stopband operation. In [2], the coupler can suppress the second harmonic, and its size is reduced by 73.2% compared to the conventional couple due to the utilization of interdigitated shunt capacitors. In [3], a branch-line coupler based on a unit of transmission-line section with triple-stubs occupies 56% size of a conventional one and achieves sixth harmonics suppression. Apart from branch-line hybrid couplers, bandpass filters also attract more and more attention. Thus, it is beneficial to integrate them for size reduction [7–10].

A novel modified filtering 3-dB branch-line hybrid coupler with wide stopband responses is presented in this letter. An equivalent K-inverter with bandpass function is used instead of one quarter-wavelength transmission line, which will realize size reduction and wide stopband characteristic of the coupler. Section 2 describes the theoretical analysis about the configuration of the proposed coupler. In Section 3, a branch-line hybrid coupler using the proposed technology is fabricated. In Section 4, the measurement and simulation results are presented in order to validate the theoretical analysis.

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2. TECHNIQUE

The conventional branch-line coupler consists of a pair of vertical Z_0 transmission lines and a pair of horizontal $Z_0/\sqrt{2}$ transmission lines, where Z_0 represents the characteristic impedance of the transmission line. At the center frequency, the length of each transmission line is a quarter of the wavelength, which may be impractical at low frequencies. In [11], one or three quarter-wavelength transmission lines are replaced by four $\pm K$-inverters in order to achieve a miniaturized rat-race hybrid. The branch-line coupler using this technology results in miniaturization and high-order harmonics suppression.

In Fig. 1, the configuration of the proposed branch-line directional coupler is shown. It consists of a pair of K_1-inverters and a pair of K_2-inverters, which can be used to replace Z_0 microstrip lines and $Z_0/\sqrt{2}$ microstrip lines of the conventional branch-line coupler, respectively. The structures of the two K-inverters are exactly the same (as seen in Fig. 2), which consist of four transmission lines and six capacitors, and the only difference exists in the parameter selection.

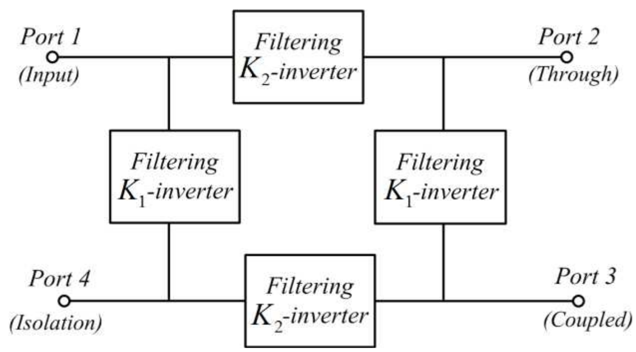


Figure 1. Proposed branch-line directional coupler with wide stopband responses.

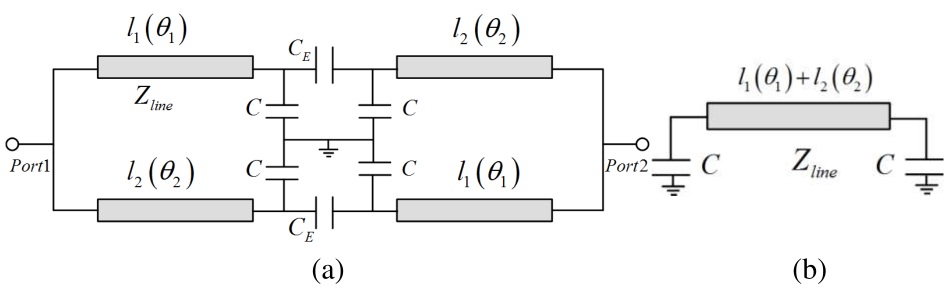


Figure 2. The circuit of (a) K-inverter and (b) equivalent resonator.

With the aid of the transmission line theory, we can see that a quarter-wavelength transmission line has an impedance inverse transform function, so it can be used as a K-inverter. In [11], the analysis is carried out to indicate that the structure represented in Fig. 2(a) can be functioned as a K-inverter. From another point of view, a pair of transmission lines l_1 and l_2 and two capacitors C compose an equivalent resonator shown in Fig. 2(b), two equivalent resonators coupled with each other by using two capacitors C_E. The fundamental resonant frequency and the second harmonic of the resonator can be calculated from [11]. Fig. 3 shows the simulated frequency responses of the K_1-inverter and the K_2-inverter, and we can see that the structure can be used as a network with wide stopband and filtering characteristic. In addition, there is nominal value tolerance of capacitor due to their dispersion. Fig. 3(a) and Fig. 3(c) show that when the tolerance of C_E's nominal value is less than 0.1 pF in K_1-inverter and K_2-inverter, the circuit sensitivity is acceptable; Fig. 3(b) and Fig. 3(d) show that when the tolerance of C's nominal value is less than 0.25 pF in K_1-inverter and K_2-inverter, the circuit sensitivity is acceptable. The simulation results indicate that if the capacitors within the specified tolerance, the circuit sensitivity is permissible.

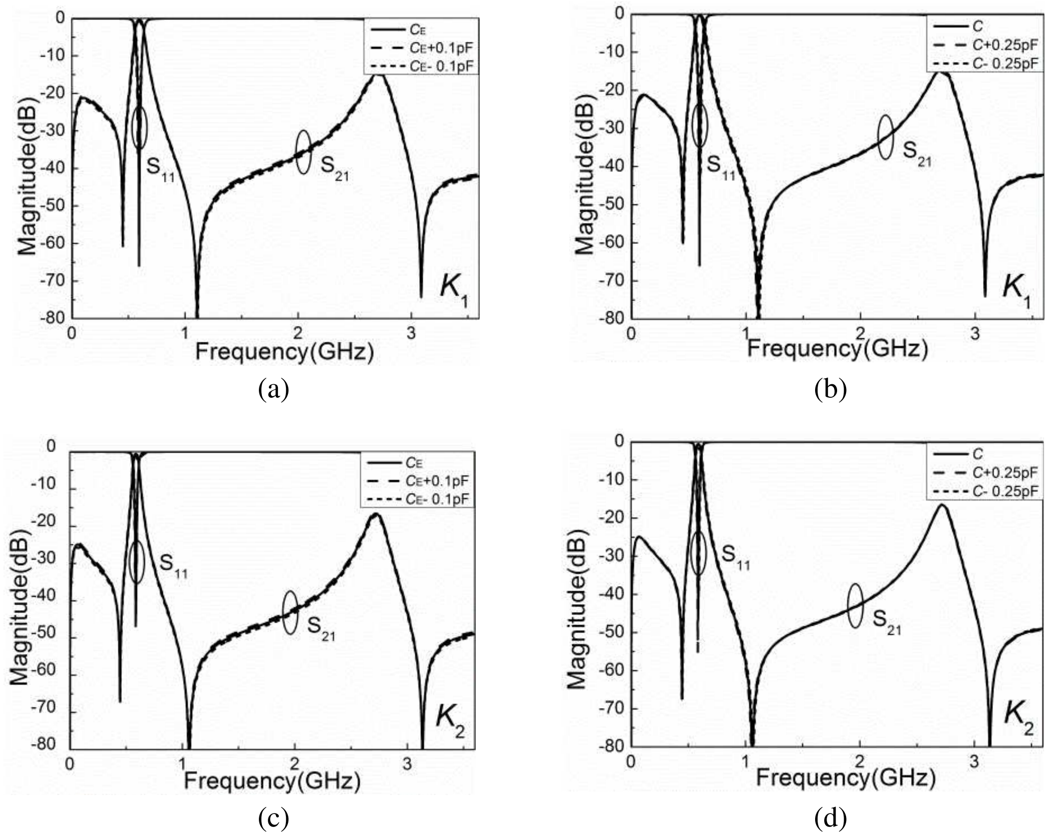


Figure 3. Simulation results of the (a) K_1-inverter against the C_E's nominal value tolerance, (b) K_1-inverter against the C's nominal value tolerance, (c) K_2-inverter against the C_E's nominal value tolerance, (d) K_2-inverter against the C's nominal value tolerance.

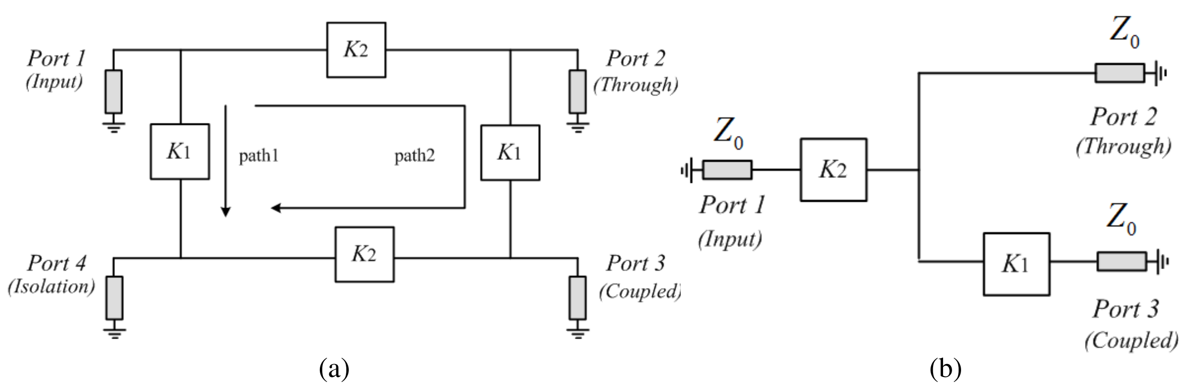


Figure 4. (a) Configuration with path 1 and path 2 from input port to isolation port. (b) Equivalent circuit when port 1 is an input port.

According to the requirements of branch-line hybrid coupler, assuming that the port 1 is excited, the port should be matched exactly. Port 1 has no power reflection, and no current flows to port 4. These requirements can be written as:

$$S_{11} = S_{41} = 0 \tag{1}$$

As shown in Fig. 4(a), when port 1 is an input port, the power can go through two paths from the input port to isolation port. The transmission matrices of path 1 and path 2 are written as Eqs. (2)

and (3) as follows:

$$\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} = \begin{bmatrix} 0 & jK_1 \\ \dfrac{K_1}{j} & 0 \end{bmatrix} \tag{2}$$

$$\begin{aligned} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} &= \begin{bmatrix} 0 & jK_2 \\ \dfrac{K_2}{j} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_0 & 1 \end{bmatrix} \begin{bmatrix} 0 & jK_1 \\ \dfrac{K_1}{j} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_0 & 1 \end{bmatrix} \begin{bmatrix} 0 & jK_2 \\ \dfrac{K_2}{j} & 0 \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{K_1}{jZ_0} & -j\left(\dfrac{K_2^2}{K_1} + \dfrac{K_1 K_2^2}{Z_0^2}\right) \\ \dfrac{K_1}{jK_2^2} & \dfrac{K_1}{jZ_0} \end{bmatrix} \end{aligned} \tag{3}$$

Under the transformation between the S-parameter matrix and the admittance matrix [12], S_{41} is obtained according to the following formula:

$$S_{41} = \frac{-2Y_{41}Y_0}{(Y_{11}+Y_0)(Y_{44}+Y_0) - Y_{41}Y_{14}} \tag{4}$$

By observing Eq. (4), $Y_{41} = 0$ should be satisfied to make $S_{41} = 0$. We can get the admittance parameter as follows through the transformation between the admittance matrix and transmission matrix:

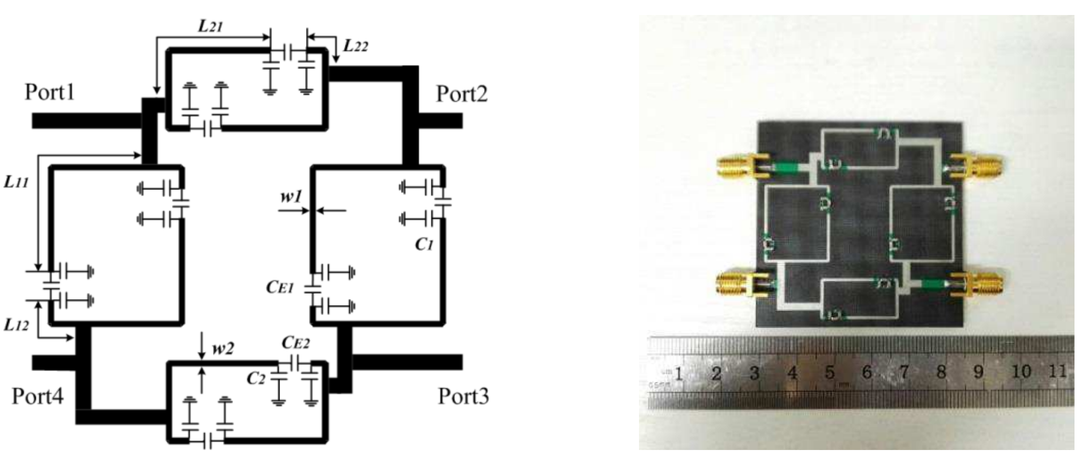
$$Y_{41} = -\frac{1}{B} = \frac{1}{B_1} - \frac{1}{B_2} = j\left(\frac{K_2^2\left(Z_0^2 + K_1^2\right) - K_1^2 Z_0^2}{K_1 K_2^2\left(Z_0^2 + K_1^2\right)}\right) \tag{5}$$

With the condition of $Y_{41} = 0$, we can obtain:

$$K_2 = \frac{1}{\sqrt{2}}K_1 = \frac{1}{\sqrt{2}}Z_0 \tag{6}$$

Condition in Eq. (1) can be fulfilled when formulas (6) is satisfied, and it can be found that port 4 is isolated.

From Eq. (6), we can get $K_1 = Z_0$. It can be observed from Fig. 4(b) that the power flowing from port 1 to port 2 passes through the K_2-inverter, but this power is guided to port 3 through a K_2-inverter and a K_1-inverter. Due to the characteristic of the K_1-inverter, the power is equally divided to ports 2 and 3 with 90° phase difference at the center frequency. The responses of S_{21} and S_{31} are similar to the K_2-inverter, including the filtering responses.



(a) (b)

Figure 5. (a) Configuration of proposed filtering coupler. (b) Photograph of the fabricated miniaturized 3-dB branch-line hybrid coupler.

Thanks to the compact size of this structure, the corresponding miniaturization of the total branch-line hybrid coupler can be realized. Moreover, the wideband isolation and filtering responses are realized synchronously due to the characteristic of this structure.

3. DESIGN OF COUPLER

In order to verify the structure presented in Section 2, a 3-dB branch-line hybrid coupler operating at 559 MHz is designed with the HFSS. The configuration of the proposed coupler is shown in Fig. 5(a). It consists of two K_1-inverters and two K_2-inverters, which replace two vertical Z_0 microstrip lines and two horizontal $Z_0/\sqrt{2}$ microstrip lines, respectively. The dimensions in Fig. 5(a) are obtained as follows: $L_{11} = 27.5\,\text{mm}$, $L_{12} = 8.1\,\text{mm}$, $L_{21} = 23\,\text{mm}$, $L_{22} = 6\,\text{mm}$, $C_1 = 10\,\text{pF}$, $C_2 = 10\,\text{pF}$, $C_{E1} = 1\,\text{pF}$ and $C_{E2} = 2\,\text{pF}$. All of the capacitors utilize 0603 capacitor package, and the tolerance of the capacitor nominal value is 0.1 pF.

In this design, the proposed structure is implemented with the substrate, and the relative dielectric constant, loss tangent and thickness are 3.5, 0.0015 and 1 mm, respectively. In Fig. 5(b), a photograph of the miniaturized 3-dB branch-line hybrid coupler is shown. The occupied area of the proposed coupler is $55 \times 55\,\text{mm}^2$ or $0.1\lambda_g \times 0.1\lambda_g$, where λ_g represents the guided wavelength at the center frequency. Compared with the conventional implementation, the proposed technology achieves 83.2% reduction in size. It is observed that the dimensions are greatly reduced.

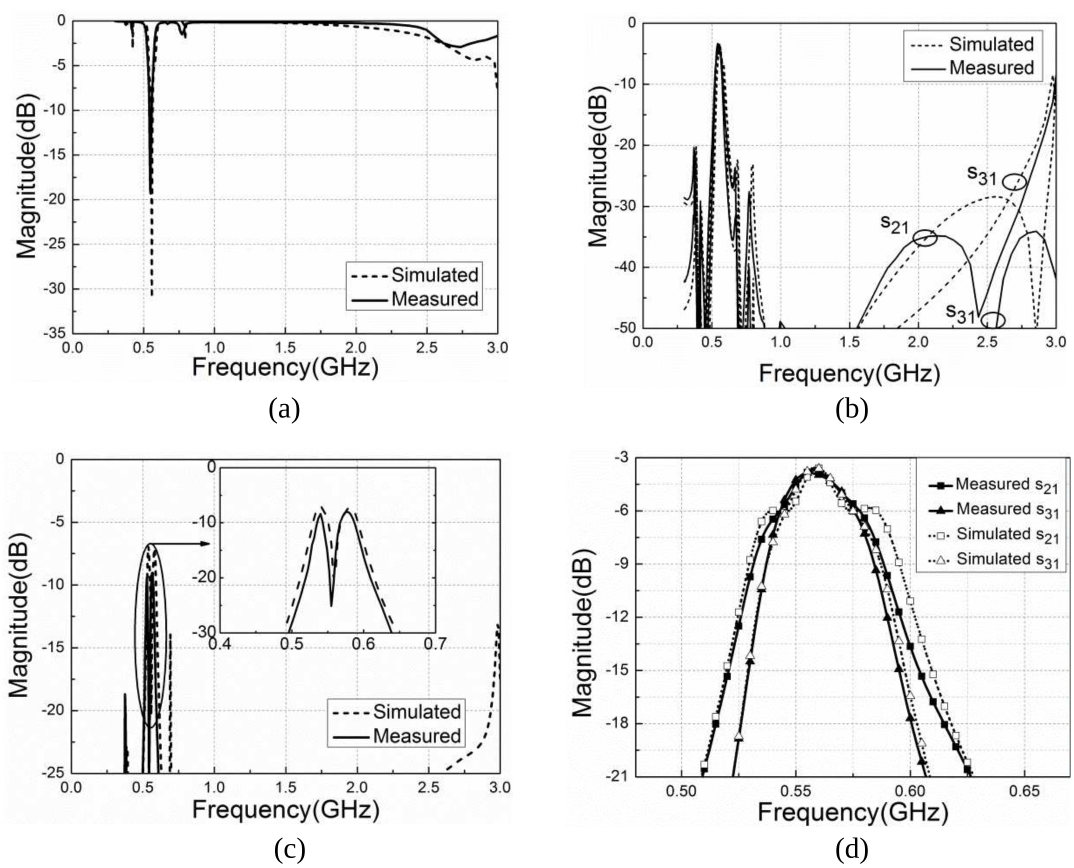


Figure 6. Simulated and measured (a) S_{11}, (b) S_{21} and S_{31}, (c) S_{41}, (d) detail of S_{21} and S_{31} in the passband.

4. MEASUREMENT RESULTS

Figure 6 shows the simulated and measured scattering parameters of the proposed branch-line hybrid coupler. The simulation and measurement results of return loss and insertion loss at port 2 and port 3 are shown in Fig. 6(a) and Fig. 6(b), respectively. From the plot, the proposed branch-line hybrid coupler operates at 559 MHz, and it is observed that the unwanted harmonics are suppressed by at least 20 dB up to 2.85 GHz (the suppressed harmonic response is up to fifth harmonic). The isolation between ports 1 and 4 shown in Fig. 6(c) is 26.1 dB at a center frequency of 559 MHz. In Fig. 6(d), the power is equally split with S_{21} and S_{31} of $-(3 + 0.56)$ dB and $-(3 + 0.57)$ dB, respectively at the center frequency.

Figure 7 shows the simulation and measurement phase difference between port 2 and port 3. The phase difference between the output ports is 92° at the center frequency. The measurement results are consistent with the simulation ones.

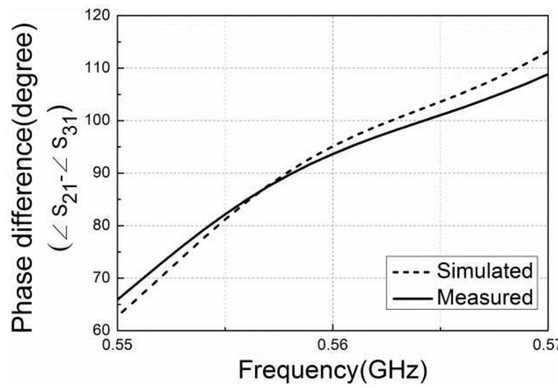


Figure 7. Phase difference between port 2 and port 3.

Table 1 summarizes some of the previous works with the proposed work in this letter in terms of percentage size reduction, harmonic suppression capability and filtering function. There are differences between the design technology of this work and other prior works. In the works mentioned, several techniques such as interdigitated shunt capacitors [2], coupled line section [13] and MTSTL [14] are used to achieve a branch-line hybrid coupler with size reduction and wide stopband. In [4], the dimensions of the proposed coupler are compressed to 12.2% without harmonic suppression capability. However, in these approaches, there are no additional filtering function. In [14], the harmonic suppression capability is better than the proposed work, but the occupied area is larger than the proposed work. In [8], the branch-line hybrid coupler is realized with bandpass responses by using a new feeding network, and the stopband is enhanced to $3f_0$.

Table 1. Comparison with previous works.

Ref.	**Technology**	**% size reduction**	**Harmonic suppression**	**Filtering function**
[2]	interdigitated shunt capacitors	73.2	up to 2nd	No
[4]	metrical T-structures	87.8	− − −−	No
[8]	new feeding network	− − −−	up to 3rd	Yes
[13]	coupled line section	80.2	up to 5th	No
[14]	MTSTL	74	up to 8th	No
This work	filtering K-inverters	83.2	up to 5th	Yes

5. CONCLUSIONS

The technique of replacing one quarter-wavelength transmission lines with an equivalent K-inverter to realize effectively miniaturizing and filtering responses simultaneously is implemented in this paper to obtain a 3-dB branch-line hybrid coupler. The proposed hybrid coupler achieves a size reduction of 83.2% compared to the conventional hybrid with no significant degradation in performance. Additionally, the fabricated hybrid coupler achieves transmission suppression up to $5f_0$.

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