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A Low-Profile Dual-Band Hybrid Coupler with Flexible Frequency Band Ratio

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Abstract—In this paper, a new method is introduced to design a simple-profile hybrid coupler in two arbitrary frequency bands. The structure is achieved by means of dual-band quarter-wavelength transformers as the arms of a traditional branch line coupler. A prototype of the coupler operating at 0.9 GHz and 2.45 GHz is designed and fabricated to validate the robustness of the method. Comparing simulated with measured results, a good agreement is observed. Moreover, the performance of the coupler in terms of impedance bandwidth and isolation level between the input ports is compared with existing works. Further, the suggested coupler has the simplest profile resulting from the most flexible design process.

1. INTRODUCTION

Directional couplers are among the most indispensable passive circuits when feeding networks are designed such as Butler Matrices (BM) and Nolen Matrices for both microwave and millimeterwave applications [1–3]. In the previous years, many works regarding the design of single-band couplers have been published [4–6]. Concerning the design of dual-band couplers, one can divide the methods proposed in literature into three categories: (1) using a circuit equivalent, (2) using an even-odd modes analysis technique, and (3) using optimization algorithms.

In general, the first method uses more sophisticated arms in a traditional singleband coupler, yielding a dual-band coupler. In [7], such a coupler is designed by means of a transmission line with two stubs. In [8], a shunt stub is tapped to the center of the conventional transmission line, yielding the equivalent dual-band circuit. The authors in [9] utilize a π-shaped circuit to create the coupler. In general, however, this method typically delivers designs suffering from narrow band width, low frequency band ratio or delivers sophisticated structures with many stubs.

The even-odd mode analysis technique is used in [10–12]. This coupler design technique typically includes coupled lines which makes the couplers less flexible in terms of operating frequency bands, since the distance between the lines limits the frequency band ratio [10, 11]. In [12], no coupled lines are present, but the design process is very complex in nature.

The third mostly used procedure is based on optimization algorithms resulting in a fast design [13–15]. These techniques require a thorough and detailed knowledge about optimization technology.

In this paper, a simple and solid technique is used, based on dual-band quarter-wavelength transformers to engender dual-band couplers with an arbitrary frequency ratio. Besides having a simple profile and flexible design process, the suggested coupler provides an acceptable impedance bandwidth of 33 and 14 percent at the center frequencies of 0.9 and 2.45 GHz, respectively. Also, the suggested structure does not have any limitations regarding the frequency band ratio. It should also be mentioned

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that the mentioned technique is not from any of the methods discussed in Introduction section since it does not need any optimization algorithm, even-odd mode analysis, or a sophisticated equivalent arm which requires solving complex matrixes.

2. DESIGN THEORY AND RESULTS

In this section, the mentioned technique is illustrated, and subsequently the coupler sample is designed by means of this method. Then, the simulated and measured results are compared to each other, and in the end a comparison between the performance and characteristics of the suggested coupler and previous structures is added.

2.1. Design of the Coupler with Quarter-Wavelength Transformer

Quarter-wavelength transformer is widely used in impedance matching between an arbitrary real load and the arbitrary real input [16]. As in the conventional branch line coupler shown in Figure 1, all the four arms are quarter wavelength. It would be a simple and solid way to make the coupler dual-band only by replacing the lines with dual-band transformers. To that end, the transformer introduced in [17] can be a suitable choice. Figure 2 depicts the transformer consisting of two cascaded transmission lines with different characteristic impedances, Z_1 and Z_2. Also, R_L and Z_0 are the real load and real source impedance, respectively. More specifically, if Z_0 and R_L are considered as arbitrary values, a quarter-wavelength transformer which can match theses two to each other in two frequency bands can be utilized in designing a dual-band coupler. Such a transformer is the mentioned cascaded lines owing different characteristic impedances.

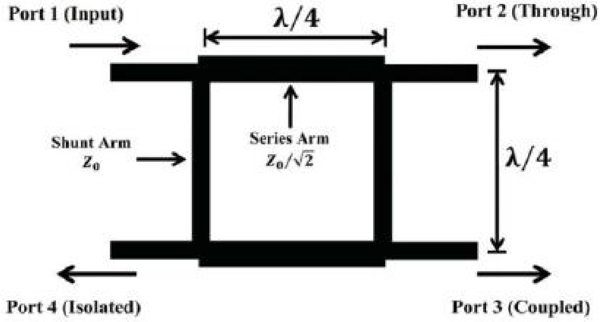


Figure 1. The schematic of branch line coupler.

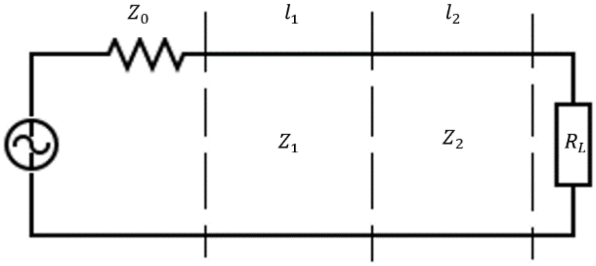


Figure 2. The quarter-wavelength transformer schematic.

With regard to the mentioned reference, the necessary line lengths for creating dual-band quadrature wavelength are obtained as follows [17]

$$l_1 = l_2 = \frac{\pi}{\beta_1 + \beta_2}. \tag{1}$$

l_1 and l_2 are lengths shown in Figure 2, and β_1 and β_2, associated with operation frequencies of f_1 and f_2, are propagation constants. As it is obvious the parameters are dependent on the operation frequencies and can be easily calculated knowing the traits of the substrate. The remaining variables are the characteristic impedance of the lines which is determined by Equations (2)–(4), [17].

$$Z_1 = \sqrt{\frac{Z_0}{2\alpha}(R_L - Z_0) + \sqrt{\left[\frac{Z_0}{2\alpha}(R_L - Z_0)\right]^2 + Z_0^3 R_L}}. \tag{2}$$

$$Z_2 = \frac{Z_0}{Z_1} R_L \tag{3}$$

in which:

$$\alpha = (\tan(\beta_1 l_1))^2 \tag{4}$$

The above-mentioned simple equations are sufficient to design a simple-profile dual-band coupler. The values of the load and source impedances, R_L and Z_0, can be any reasonable real number as long as their geometric median becomes 50 or 35.3 ohm according to the characteristic impedance of the conventional branch line coupler arms.

2.2. Design of the Coupler Sample by Mentioned Method

We choose the operation frequencies of 0.9 GHz and 2.45 GHz. Referring to Equation (1), the line lengths are calculated easily. The substrate used here is Rogers TMM 4 with 1.52 mm thickness and 4.5 dielectric constant. As for the 50-ohm characteristic impedance 100 and 25 ohms can be assigned to the load and source, respectively, we proceed with this assumption. It should be taken into consideration that the ratio of load impedance to source impedance is 4. The remaining parameters are achieved using Equations (2)–(4). For the horizontal arms of the branch line coupler, 71.5 and 17.5 ohm are selected to give the ratio of 4 as well. Having calculated the variables of the transformer, it is time to put them in place of the branches of the conventional hybrid coupler. Final optimization is done to complete the design of the dual-band coupler.

A summary of the design process is as follows:

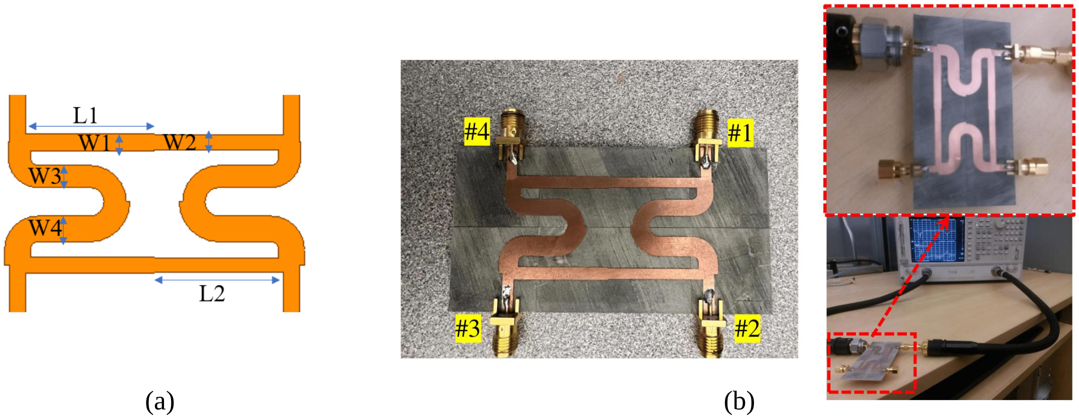
a — select two arbitrary values for Z_0 and R_L mentioned in Figure 2 in a way that 50-ohm and 35.5-ohm become the quarter-wavelength values.

b — calculate the parameters regarding the dual-band transmission line. Equations (1)–(4) are used during calculation.

c — replace the designed transmission lines (50 and 35.5 ohm) with the arms of traditional branch line coupler and do final optimization.

3. FABRICATION AND RESULTS

Figure 3 shows the fabricated dual-band 90° hybrid coupler. We used the smooth bends in horizontal arms to make the structure more compact. In case we consider the lower frequency band, 0.9 GHz, and put aside the transmission lines connected to the output and input ports, the size of the structure is $0.3\lambda \times 0.14\lambda$. Furthermore, it is evident that the structure has simple profile and is easy to be integrated in antenna feeding networks. As we consider the results, our expectation is to have a low reflection coefficient in both frequency bands. Moreover, the isolation between the two input ports, ports 1 and 4, should be in a minimum level. When it comes to talking about the output ports, it should be taken



(a)

(b)

Figure 3. (a) Layout and (b) prototype of the dual-band coupler. ($L1$ & $L2 = 25$, $W1 = 3.3$, $W2 = 2.9$, $W3 = 4.3$, and $W4 = 5\,\text{mm}$).

into account that the achieved signals through them must be equal to +90° or −90° phase difference according to the selected input port. However, an acceptable imbalance level in output amplitudes and phase differences is defined; this amount is ±1 dB and ±5° for our purpose. Figure 4 depicts the reflection coefficients, the isolation between ports 1 and 5, and the transmission coefficients. At the operating frequencies, the reflection coefficients as well as isolations are below −20 dB. The impedance matching bandwidth is roughly 33% for the lower frequency band and 14% for the higher one. The output amplitudes when port 1 and port 4 are excited are shown in Figure 4 as well. Considering amplitude imbalance below −1 dB, the operating bandwidth is more than 33% and 14% for the lower and higher bands, respectively.

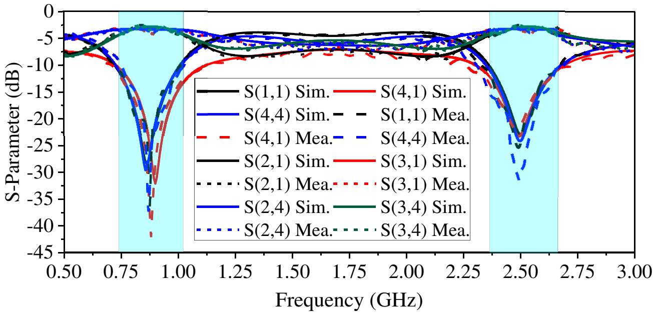


Figure 4. Reflection coefficients, isolation, and transmission coefficients between ports in simulated and measured cases.

Figure 5 depicts the phase difference between the signals received from output ports in both input excitation states. It was observed that from frequency of 0.73 GHz to 1.03 GHz the phase difference imbalance is within ±5° as it holds true for the frequency range from 2.35 GHz to 2.65 GHz.

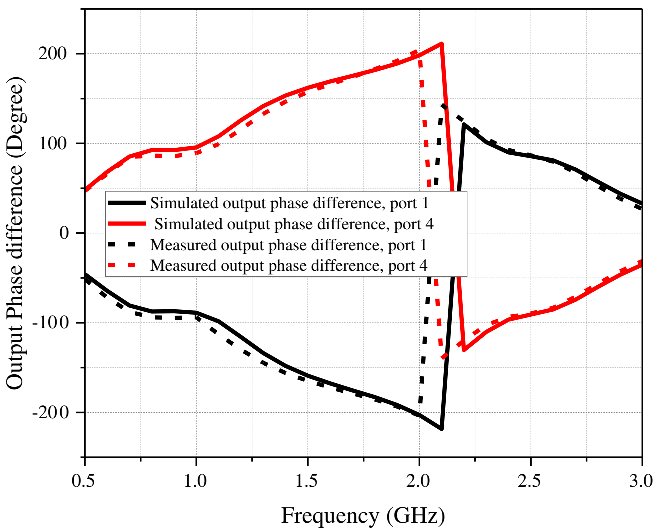


Figure 5. Output phase differences as port 1 or port 4 is excited.

The comparison between this and previous works is performed and presented in Table 1. Everything confirms the fact that the suggested technique brings about a dual-band coupler which has the simplest profile and design procedure among the existing works. It should also be mentioned that as we talk about the low profile, we mean that the suggested coupler has a reduced size and simple profile; other works provide big structures with complicated coupler shapes.

The operating bandwidth is closed to the best one achieved from [12]. Also, the flexibility

Table 1. Comparison between this work and three recently published papers.

Ref.	[11]	[12]	[15]	[18]	[19]	This work
Frequencies (GHz)	1/2	1/2.7	2.45/5.4	0.9/1.8	2.4/5.8	0.9/2.45
BW (%)	12.8/13.1	35/15	14/10.7	16/6	30/12.8	33/14
Size ($\lambda_L \times \lambda_L$)	0.59×0.024	0.56×0.28	0.3×0.2	0.38×0.18	0.6×0.6	0.3×0.14
Coupled (dB)	$-3.6/-3.63$	$-3.61/-3.76$	Not mentioned	$-3.5/-3.5$	Not mentioned	$-3.42/-3.53$
Through (dB)	$-3.76/-3.87$	$-3.84/-4.75$	Not mentioned	$-3.4/-3.6$	Not mentioned	$-3.66/-3.72$
design complexity	medium	high	high	high	high	low
profile complexity	low	medium	high	high	medium	low
design flexibility	low	low	low	low	low	high

in changing the operation frequency bands is unique relative to other couplers. Furthermore, the performance of the structure is indicative of its reliability as it is going to be utilized in a microwave system for beam switching applications. It is worth mentioning that the introduced method does not require any optimization algorithm, solving the sophisticated matrixes or even-odd mode analysis. This helps ease the design process.

4. CONCLUSION

In this letter, a simple technique has been presented to design a dual-band hybrid coupler. The method is based on the replacement of the arms of a traditional branch line coupler with a small two-section quadrature-wavelength operating at two arbitrary frequencies. The fabricated structure provides the results which are in a good agreement with the simulated outcomes. Furthermore, it is observed that the coupler has the simplest profile with a great flexibility in changing the operation frequency bands among the existing dual-band couplers.

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