

Miniaturized Broadband Quadrature Hybrid Coupler with Phase Shifter

Soheyl Soodmand*, Mark A. Beach, and Kevin A. Morris

Abstract—A 3-dB compact hybrid coupler is presented in this paper in an ultra-wideband frequency range from 1.5 GHz to 3.2 GHz with 90° phase deference between the two output ports. The proposed coupler is formed by two notched elliptically shaped microstrip lines and four phase shifters, which are broadside coupled through an elliptically shaped slot. A combination of impedance matching technique and structural modification then has been employed to increase coupler efficiency. The design is demonstrated assuming a 0.51-mm-thick Rogers RO4350B substrate. Results of simulation and measurements show that the designed device exhibits a coupling of 3 ± 1 dB across the aimed bandwidth. This ultra-wideband coupling is accompanied by smooth isolation in the order of better than 25 dB and return loss in the order of better than 17 dB. The manufactured device including microstrip ports and phase shifters occupy an area of $35 \text{ mm} \times 30 \text{ mm} \times 1.1 \text{ mm}$ ($0.27\lambda \times 0.23\lambda \times 0.009\lambda$) which makes it a compact suitable device for UHF applications and measurements, specifically measuring and determining isolation in in-band full duplex transceivers, because of its smooth isolation versus frequency and ultra-wideband bandwidth.

1. INTRODUCTION

Radio Frequency (RF) broadband quadrature hybrid couplers are important passive elements which are used to divide or combine signals with phase of 90 degrees. They are generally used in RF front-end blocks such as modulators, duplexers, antenna beamforming networks, and mixers [1]. Also, they are very important for developing commercial measurement devices [2, 3]. The specific interest of us in these devices is with respect to developing an ultra-wideband (UWB) electrical balance duplexer (EBD) to be used in in-band full duplex (IBFD) transceiver [4–6] where a UWB smooth isolation versus frequency is needed in the coupler and the antenna for a suitable transmitter-receiver gain.

Mostly, the used couplers nowadays are often required to be accomplished in planar (microstrip or stripline) technology. To obtain these couplers' broadband operation, the approach of coupled transmission lines can be utilized. The intrinsic features of this method are suitable directivity and matching, which are almost frequency independent, while getting tight UWB 3-dB coupling is a challenge. Tight broadband coupling can be fulfilled using Tandem [7, 8] or Lange couplers [9] (2.4–3.6 GHz range) utilizing coupled microstrip lines, but they require wire crossovers and sometimes narrow strips, which are not easy to fabricate. On the other side, when being realized in microstrip technology, the tandem coupler generally requires serpentine or wiggles [7, 10].

To eliminate the above issues, the slot-coupling method implicating double-sided substrate [11, 12] can be used to realize a tight coupling where the coupler is implemented by two microstrip lines separated by a rectangular slot in the common planar ground. A microstrip-slotline method is given in [10] as an alternative to design a 3-dB coupler. The method in [10] keeps the one-layer microstrip structure but etching in both sides of substrate in contrast to [11]. On one side of the coupler in [10] there are two

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parallel connected lines, and the other side has a slotline with two circular terminating slots. There is also a capacitive disc below the slotline in [10] to increase bandwidth (Multioctave operation) in a militarized structure.

An alternative approach to [10] is given in [13] to design a multioctave 4 : 1 compact 3-dB coupler with some modifications while a bigger slot below substrate is used, and also, both terminating slots and circular disc are eliminated to obtain UWB operation. Some 3-dB microstrip slot couplers are also suggested in [14] and [15] at 4–8 GHz range with simpler structures, but their bandwidth is narrower than [10] and [13]. A 3–10 dB coupler formed by two elliptically shaped microstrip lines is also suggested in [16] with selectable dimensions to achieve UWB performance in 3.1 to 10.6 GHz range. Some other couplers have also been presented on single layer substrate at 2.1–2.7 GHz range [17] and two-layer substrate at range 4–12 GHz [18], dual-band branch line coupler [19, 20]. Characteristics of the composite right/left-handed transmission lines are also given in [21].

While most of the above couplers are working above UHF band or they have narrow bandwidth, in this paper, we describe a compact planar 3-dB coupler over a UWB frequency range from 1.5 GHz to 3.2 GHz suitable for UHF applications. In addition, there was a specific interest here to achieve a smooth UWB isolation versus frequency in the coupler, suitable for EBD stage of IBFD system. Firstly, the initial form of the proposed miniaturized coupler capable of providing tight coupling over an UWB band is given in Section 2. Then, four 0.4λ phase shifters are added to the structure to achieve 90° phase deference in the coupler in Section 3. A combination of impedance matching technique and structural modification has been employed then in Section 4 to optimize the coupler results while final dimensions are obtained with the use of full-wave electromagnetic analysis of finite integration technique (FIT) with high meshing in CST MICROWAVE STUDIO [22] software package. The validity and performance of the presented coupler are confirmed with measurements. At the end, a conclusion is given in Section 5.

2. INITIAL COUPLER

The initial form of the proposed miniaturized coupler, capable of providing tight coupling over a UWB, is shown in Figure 1 where its coupling mechanism is similar to [11] and [16]. The differences for the initial model concern the shaping factor of the broadside coupled strips, the slot, electrical size, and most importantly the operation frequency which is in the UHF band. The coupler consists of three conductor

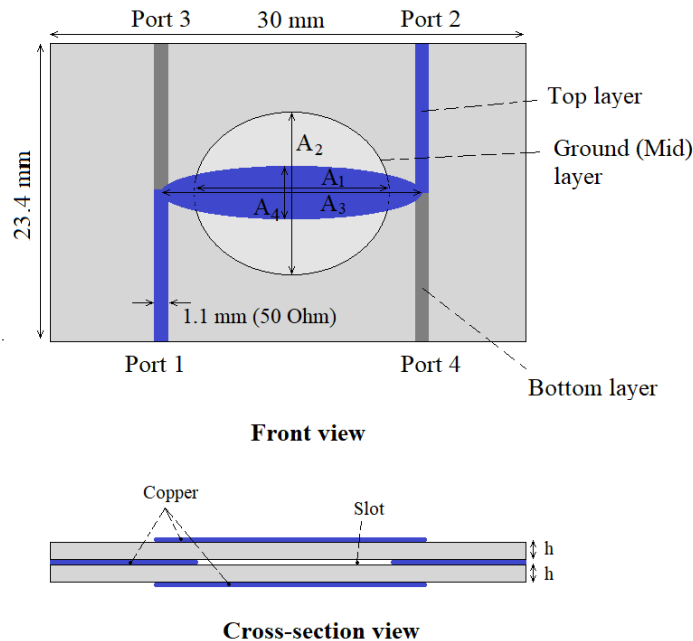


Figure 1. Initial coupler layout, Section 2.

copper layers which are interleaved by two dielectric substrates. The top copper layer includes ports 1 and 2. The bottom copper layer is similar to the top layer, but the ports here are ports 3 and 4. Ports 3 and 4 are on opposite sides of the substrate compared to ports 1 and 2. The two layers are coupled via a slot, which is made in the copper layer supporting the top and bottom dielectrics. As seen in Figure 1, the two microstrip conductors and the slot are of an elliptical shape. The 50 Ω microstrip lines are included to make connections to SMA ports. The structure features double symmetry with respect to both horizontal and vertical plans while an even-odd mode approach with respect to ports 1 and 3 can be applied to analyse this coupler [1].

Analysis starts in a similar way to the ones described in [12] for the equivalent rectangularly shaped microstrips. Assuming that the coupler is required to have C_{dB} coupling, the even Z_{ev} and odd Z_{od} mode characteristic impedances are calculated using Eqs. (1) and (2) as follows:

$$Z_{ev} = Z_0 \sqrt{\frac{1 + 10^{-C/20}}{1 - 10^{-C/20}}} \tag{1}$$

$$Z_{od} = Z_0 \sqrt{\frac{1 - 10^{-C/20}}{1 + 10^{-C/20}}} \tag{2}$$

where Z_0 is the characteristic impedance of the microstrip ports of the coupler. Assuming that $Z_0 = 50 \Omega$ and the coupling factor C_{dB} is 3 dB, the values of Z_{ev} and Z_{od} can be calculated from Eqs. (1) and (2) as 175.5 Ω and 14.2 Ω for $C_{dB} = 3$ dB.

The validity of the presented design method is tested for a 3-dB directional coupler aimed for operation in the 1.5–3.2 GHz frequency band. For this band, the centre frequency of operation is 2.35 GHz. A Rogers RO4350B substrate with a dielectric constant of 3.48, a loss tangent of 0.0037, $h = 0.51$ mm thickness, plus 35-μm-thick conductive copper is used for the coupler development. The coupler length is chosen as $A_3 = 20.5$ mm $\sim \lambda/6 \sim \lambda_e/4$ where λ_e is the effective wavelength, and λ is the free space wavelength at the central frequency of 2.35 GHz. The return loss, coupling, and isolation of the designed coupler are first verified by running the high mesh FIT in the CST software, and the final dimensions of $A_1 = 15.4$ mm, $A_2 = 12.7$ mm and $A_4 = 4.2$ mm are adjusted. Figure 2 shows the simulated amplitudes of the scattering parameters for the designed 3-dB coupler. These are followed by results of the phase difference between the two output ports, Figure 3. It is seen that the achieved phase difference above 2 GHz is around 270° at the aimed frequency range of 1.5–3.2 GHz while 90° phase difference is needed to realize a hybrid coupler. The preferred 90° phase difference will be achieved by adding phase shifters in the next section, Section 3.

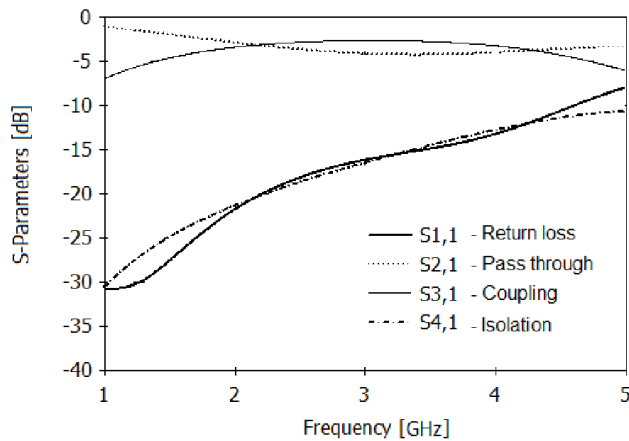


Figure 2. Simulated characteristics of the initial 3-dB coupler in Figure 1, Section 2.

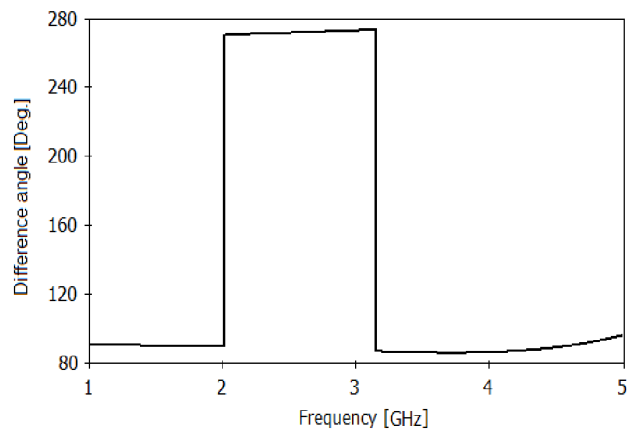


Figure 3. Simulated phase characteristic of the initial 3-dB coupler in Figure 1, Section 2.

3. COUPLER WITH PHASE SHIFTERS

To overcome the phase difference issue in Section 2, four phase shifters, each having length of $LL = 33 \text{ mm} = 0.4\lambda_e$, are added to terminals of elliptical bodies as shown in the new coupler in Figure 4. To form phase shifters curved microstrip lines are used to maintain a contact size. Simulations do not show considerable differences in results when the curves angles are not smaller than 75 degrees. Figure 5 shows the simulated amplitudes of the scattering parameters for the coupler with phase shifters. These are followed by results of the phase difference between the two output ports, as shown in Figure 6. It is seen that the designed coupler features coupling of 4.3 dB for the 1.5–3.2 GHz band. The isolation and return loss are better than 16 dB for the aimed frequency bandwidth. In Figure 6, it is observed that the phase difference between ports 2 and 3 is $89^\circ \pm 1^\circ$, near 90° over the bandwidth. This result together

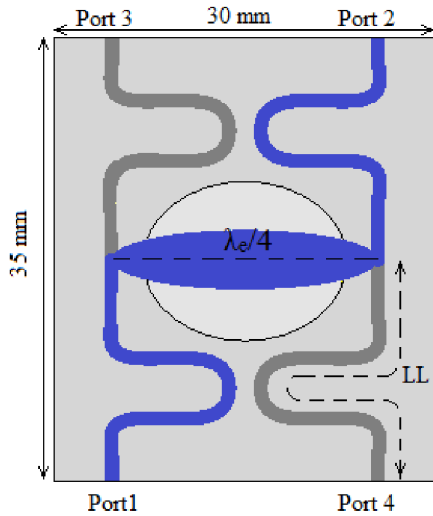


Figure 4. Coupler with phase shifters layout, Section 3. (All other dimensions are same with Figure 1).

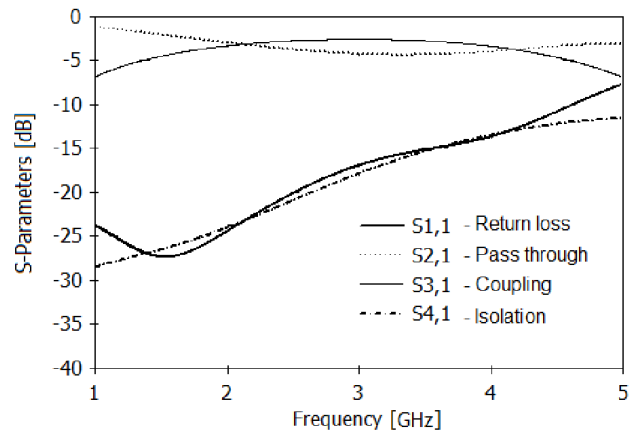


Figure 5. Simulated characteristics of the 3-dB coupler with phase shifters in Figure 4, Section 3.

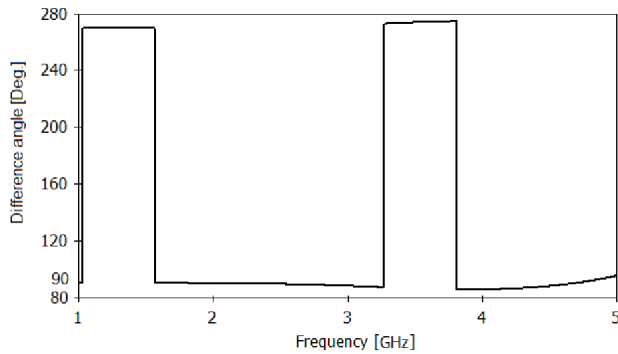


Figure 6. Simulated phase characteristic of the 3-dB coupler with phase shifters in Figure 4, Section 3.

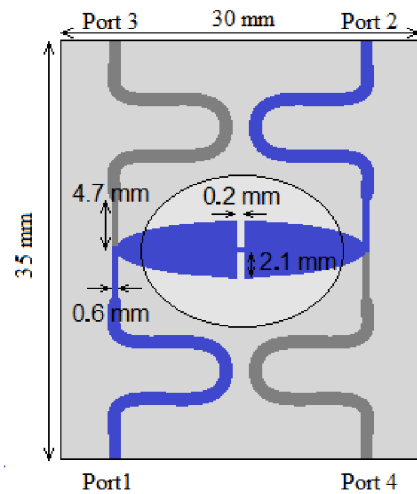


Figure 7. Modified coupler with phase shifters layout, Section 4 (All other dimensions are same with Figure 4).

with the magnitude results shown in Figure 5 indicates that the coupler operates as a backward wave quadrature coupler, but some modifications are carried out in the next section, Section 4, to increase efficiency.

4. FINAL COUPLER: MODIFIED COUPLER WITH PHASE SHIFTERS

A combination of impedance matching technique and structural modifications has been employed here to optimize the coupler results. The impedance matching is carried out in a similar way for all four ports by narrowing the width of tracks which connect the ports to the elliptical body as shown in Figure 7. Also, two narrow slots have been etched on each elliptical body as shown in the same figure. Simulation results are given in Figure 8 and Figure 9, and also measurement results by Vector Network Analyzer (VNA) are given in Figure 10 and Figure 11. The final coupler features measured UWB characteristics as coupling of 3 ± 1 dB at the aimed 1.5–3.2 GHz band is achieved. Also, smooth isolation in the order of better than 25 dB and return loss in the order of better than 17 dB are achieved. In Figure 11, it is observed that the measured phase difference between ports 2 and 3 is about 90° over the target band. Figure 12 shows the fabricated coupler. These results indicate that this compact coupler with $35 \text{ mm} \times 30 \text{ mm} \times 1.1 \text{ mm}$ ($0.27\lambda \times 23\lambda \times 0.009\lambda$) dimension operates as a backward wave quadrature coupler suitable for UHF applications. A comparison between the literature and this work is also given in Table 1.

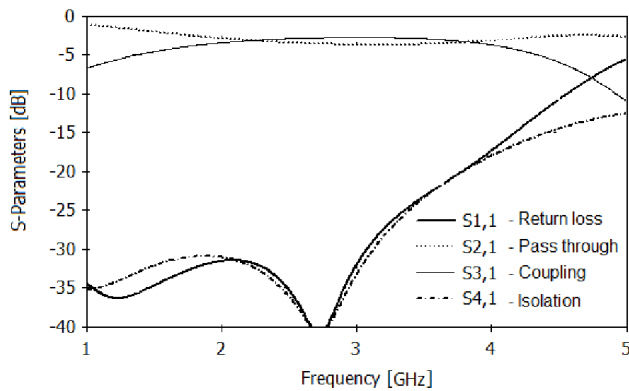


Figure 8. Simulated characteristics of the 3-dB modified coupler with phase shifters in Figure 7, Section 4.

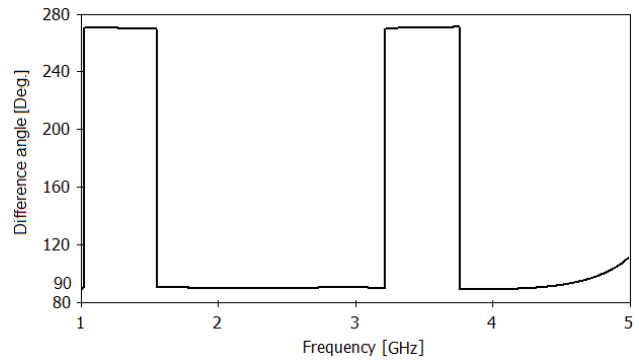


Figure 9. Simulated phase characteristic of the 3-dB modified coupler with phase shifters in Figure 7, Section 4.

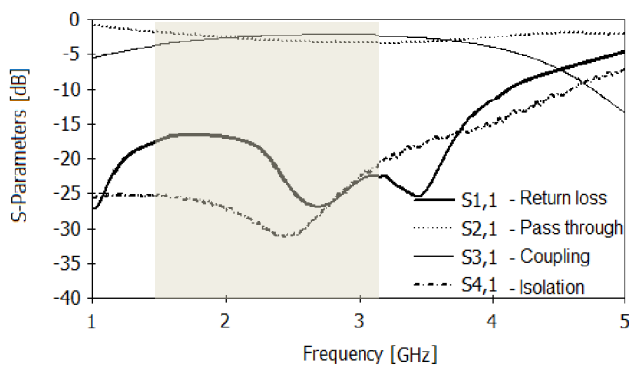


Figure 10. Measured characteristics of the 3-dB modified coupler with phase shifters in Figure 7, Section 4.

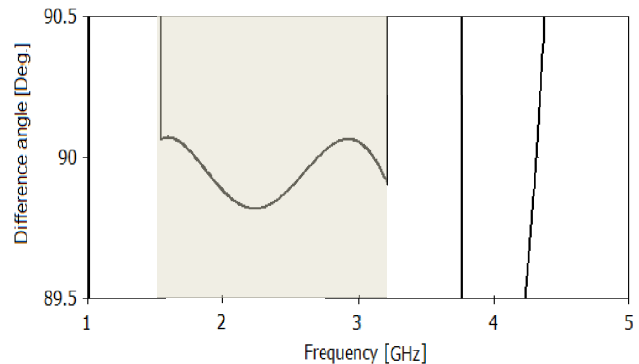


Figure 11. Measured phase characteristic of the 3-dB modified coupler with phase shifters in Figure 7, Section 4. (Zoomed view).

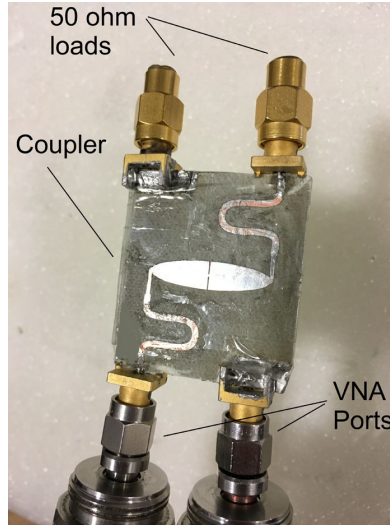


Figure 12. Manufactured 3- dB modified coupler with phase shifters (Figure 7) under test by VNA, Section 4.

Table 1. Comparison with referenced (3-dB) hybrid couplers.

	Frequency (GHz)	Max. Isol. (dB)	Max. S_{11} (dB)
[8]	3.6–5.5	–15	–15
[9]	2.5–3.5	–24	–20
[11]	1.2–1.8	–26	–24
[13]	4.5–7.5	–18	–19
[16]	3.1–10.6	–25	–23
[17]	2.1–2.7	–19	–19
[18]	4–12	–20	–19
This work	1.5–3.2	–25	–17

5. CONCLUSION

A method has been proposed for the design of a compact UWB directional 3-dB coupler for UHF applications and measurements. The proposed device has been formed by a multilayer microstrip structure with broadside slot coupling, and then phase shifters have been added to obtain suitable phase difference. A combination of impedance matching technique and structural modification has been employed also to increase efficiency. The coupler has been manufactured and experimentally tested, showing UWB behaviour across the band from 1.5 to 3.2 GHz. Our aim has been to use this coupler in the electrical balance duplexer to be used in in-band full duplex transceiver. Due to smooth isolation, compact size, and suitable electrical performance, there should be of considerable interest to the designers of UWB systems for UHF applications.

REFERENCES

1. Pozar, D. M., *Microwave Engineering*, 4th Edition, 2012.
2. Bialkowski, M. E. and A. P. Dimitrios, "A step-frequency six-port network analyser with a real-time display," *AEU Int. J. Electron. Commun.*, Vol. 47, No. 3, 193–197, 1993.
3. Choi, M. K., M. Zhao, S. C. Hagness, and D. W. van Der Weide, "Compact mixer-based 1–12 GHz reflectometer," *IEEE Microwave and Wireless Components Letters*, Vol. 15, No. 11, 781–783, 2005.

4. Laughlin, L., et al., "Tunable frequency-division duplex RF front end using electrical balance and active cancellation," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 66, No. 12, 5812–5824, 2018.
5. Laughlin, L., M. A. Beach, K. A. Morris, and J. L. Haine, "Electrical balance duplexing for small form factor realization of in-band full duplex," *IEEE Communications Magazine*, Vol. 53, No. 5, 102–110, 2015.
6. Laughlin, L., M. A. Beach, K. A. Morris, and J. L. Haine, "Optimum single antenna full duplex using hybrid junctions," *IEEE Journal on Selected Areas in Communications*, Vol. 32, No. 9, 1653–1661, 2014.
7. Uysal, S. and A. H. Aghvami, "Synthesis and design of wideband symmetrical nonuniform couplers for MIC applications," *IEEE MTT-S Int. Microw. Symp. Dig.*, 587–590, 1988.
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 Microwave and Wireless Components Letters*, Vol. 15, No. 2, 113–115, 2005.
9. Lange, J., "Interdigitated stripline quadrature hybrid," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 17, No. 12, 1150–1151, 1969.
10. De Ronde, F. C., "A new class of microstrip directional couplers," *IEEE MTT-S Int. Microw. Symp. Dig.*, 184–189, 1970.
11. Tanaka, T., K. Tsunoda, and M. Aikawa, "Slot-coupled directional couplers on a both-sided substrate MIC and their applications," *Electronics and Communications in Japan (Part II: Electronics)*, Vol. 72, No. 3, 1989.
12. Wong, M. F., V. Fouad Hanna, O. Picon, and H. Baudrand, "Analysis and design of slot-coupled directional couplers between double-sided substrate microstrip lines," *IEEE MTT-S Int. Microw. Symp. Dig.*, 2123–2129, 1991.
13. Garcia, J. A., "A wideband quadrature hybrid coupler," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 19, No. 7, 660–661, 1971.
14. Schiek, B., "Hybrid branchline couplers — A useful new class of directional couplers," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 22, No. 10, 804–869, 1974.
15. Hoffmann, R. K. and J. Siegl, "Microstrip-slot coupler design — Part II: Practical design aspects," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 30, No. 8, 1205–1216, 1982.
16. Abbosh, A. M. and M. E. Bialkowski, "Design of compact directional couplers for UWB applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 25, No. 22, 189–194, 2007.
17. Chang, C. P., J. C. Chiu, H. Y. Chiu, and Y. H. Wang, "A 3-dB quadrature coupler using broadside-coupled coplanar waveguides," *IEEE Microwave and Wireless Components Letters*, Vol. 18, No. 3, 191–193, 2008.
18. Malo-Gómez, I., J. D. Gallego-Puyol, C. Diez-González, I. López-Fernández, and C. Briso-Rodríguez, "Cryogenic hybrid coupler for ultra-low-noise radio astronomy balanced amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 12, 3239–3245, 2009.
19. Hayati, M. and M. Nosrati, "Loaded coupled transmission line approach of left-handed (LH) structures and realization of a highly compact dual-band branch-line coupler," *Progress In Electromagnetics Research C*, Vol. 10, 75–86, 2009.
20. Nosrati, M., M. Daneshmand, and B. Virdee, "Novel compact dual-narrow/wideband branch-line couplers using T-Shaped stepped-impedance-stub lines," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 21, No. 6, 642–649, 2011.
21. Sanada, A., C. Caloz, and T. Itoh, "Characteristics of the composite right/left-handed transmission lines," *IEEE Microwave and Wireless Components Letters*, Vol. 14, No. 2, 2004.
22. "CST studio suite electromagnetic field simulation software (2020)," DASSAULT SYSTÈMES, [Online]. Available: <https://www.3ds.com/products-services/simulia/products/cst-studio-suite/>.