

## **A BROADBAND QUADRATURE HYBRID USING IMPROVED WIDEBAND SCHIFFMAN PHASE SHIFTER**

**E. Jafari, F. Hodjatkashani, and R. Rezaiesarlak**

Department of Electrical Engineering  
Iran University of Science and Technology (IUST)  
Tehran, Iran

**Abstract**—In this paper, a broadband quadrature hybrid is presented. The hybrid comprises a Wilkinson divider, followed by an improved Schiffman phase shifter. An improved wideband Schiffman phase shifter on a single layer printed circuit board is accompanied by a lumped capacitor between two coupled lines. Lumped capacitor is in parallel with the odd-mode capacitance of the two coupled lines, hence, the odd-mode capacitance is increased and consequently the odd-mode impedance is decreased. Therefore, by this method we can control the ratio of the even mode impedance to the odd mode impedance which is critical in Schiffman phase shifter design. Compared with the cascading Microstrip multisection coupled lines, our proposed single layer phase shifter is smaller in size. Also, the proposed phase shifter has the greater bandwidth compared to the patterned ground plane Schiffman phase shifter and its realization is simpler because of its single layer structure. As an example, a Schiffman phase shifter at frequency  $f_0 = 650$  MHz is designed and simulated. With the proposed phase shifter a  $90^\circ$  hybrid is designed, simulated, fabricated and measured. Experimental results show that the amplitude and phase imbalance between two paths at worst case are within 0.75 dB and  $5^\circ$ , respectively, over the frequency band from 362 MHz to 891 MHz, or around 84% bandwidth. The measured return loss is better than  $-10.8$  dB over the operating frequency band.

### **1. INTRODUCTION**

Quadrature hybrids are passive components which are very important for realizing balanced amplifiers, balanced mixers and antenna array feeds [1]. In particular, these hybrids are essential for image rejection

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Corresponding author: E. Jafari (e.jafari61@gmail.com).

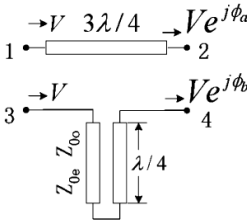
mixers, Doherty amplifiers, circularly polarized antennas and so on. The conventional branch line coupler offers very limited bandwidth (10%), which is suitable only for limited applications. Hence, for wideband communication systems broadband  $90^\circ$  hybrid is necessary. Various techniques for realizing broadband  $90^\circ$  hybrid have been reported [1, 2]. By cascading multisections of the couplers, the bandwidth can be improved [3]. However, it results in large circuit occupation and very high characteristics impedance line, which makes the fabrication difficult.

The  $90^\circ$  hybrid proposed herein uses a conventional Microstrip Wilkinson divider that provides equal power split, high output port isolation, and good return loss at all three ports, in combination with an improved wideband Schiffman phase shifter on a single layer printed circuit board. A Schiffman phase shifter [4] as shown in Figure 1 is a differential phase shifter that consists of two transmission lines, one of them folded (coupled section) to be dispersive. By the proper selection of the length of these lines and the degree of coupling, the phase difference between them can be adjusted to be almost constant over a broad bandwidth.

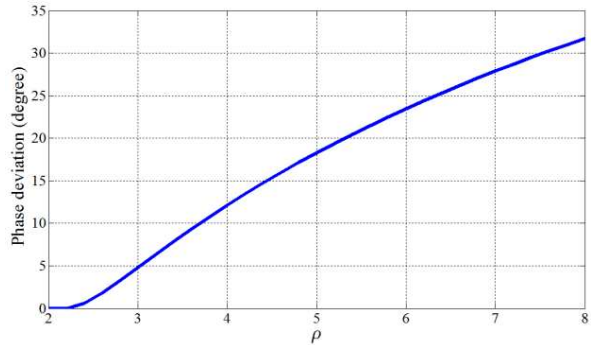
For Schiffman phase shifter, the maximum of differential phase shift  $\Delta\varphi_{\max}$  in terms of  $\rho$  was derived [5] as

$$\Delta\varphi_{\max} = K \cdot \tan^{-1} \left( \sqrt{\frac{K \cdot \rho - 2\sqrt{\rho}}{2\sqrt{\rho} - K}} \right) - \cos^{-1} \left( \frac{\rho + 1 - K \cdot \sqrt{\rho}}{\rho - 1} \right)$$

where  $K$  denotes the ratio of the length of uniform transmission line to the coupled lines, and  $\rho = \frac{Z_{0e}}{Z_{0o}}$ . So, the phase deviation is defined as  $\varepsilon = \Delta\varphi_{\max} - \Delta\varphi_0$  where  $\Delta\varphi_0$  is the desired phase shift. Phase deviation versus impedance ratio  $\rho$  for the standard  $90^\circ$  Schiffman



**Figure 1.** Standard  $90^\circ$  Schiffman phase-shifter structure.



**Figure 2.** Phase deviation versus impedance ratio  $\rho$  for the standard  $90^\circ$  Schiffman phase shifter.

phase shifter is shown in Figure 2. Also, it must be mentioned that for matching of the coupled lines to 50 ohm, the following relations should be considered

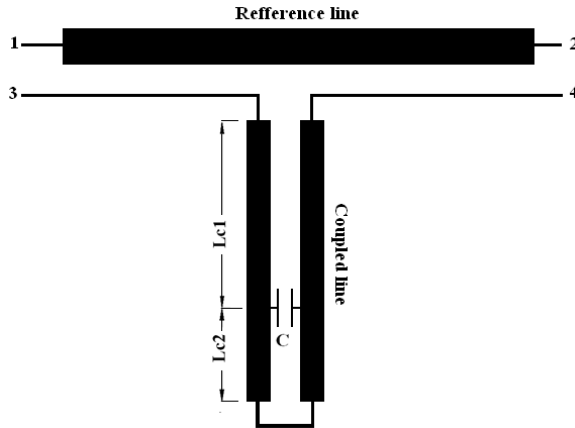
$$Z_{0e} = 50\sqrt{\rho} \quad Z_{0o} = \frac{50}{\sqrt{\rho}}$$

According to Figure 2, it is obvious that for achieving low phase deviation, low  $\rho$  is required. For achieving well designed phase shifter, the ratio of even to odd mode impedances must be low enough. Since, in the coupled lines even and odd mode impedances depend on even and odd mode capacitances, respectively, hence by changing these capacitances, the amount of  $\rho$  could be controlled [6, 7]. In [6] for desired  $\rho$ , ground plane underneath the coupled lines is defected which caused the amount of even mode impedance to be increased. Measured results show that the operational bandwidth (1.5 GHz–3.1 GHz) over 12 dB return loss is approximately 70%; amplitude and phase imbalance between the two paths are within 0.5 dB and 5° respectively. In this paper, by adding one lumped capacitor between two coupled lines the amount of odd mode impedance is decreased and by changing the amount of lumped capacitor, desired  $\rho$  could be obtained. Consequently, the operational bandwidth (362 MHz–891 MHz) over 10.8 dB return loss is approximately 84%; phase balance is 5°; amplitude balance is 0.75 dB. So the proposed structure in this paper compared to the structure presented in [6] has more bandwidth. Also, the proposed structure in [6] is on a double-sided printed circuit board that the radiation effects from the patterned ground plane should be considered and a minimum depth for the air cavity is necessary; otherwise practical values of  $Z_{0e}$  and  $Z_{0o}$  would be disturbed while the structure proposed in this paper is on a single layer printed circuit board that air cavity is not needed.

Paper is organized as follows: first theoretical issues related to structure under consideration are described in Section 2. In Section 3, design procedure is explained. Finally simulation and experimental results are discussed and compared in Section 4. The comparison confirms the validity and accuracy of the proposed design procedure.

## 2. THEORY OF OPERATION

The 90° hybrid proposed herein uses a conventional microstrip Wilkinson divider in combination with an improved wideband Schiffman phase shifter on a single layer printed circuit board. The main problem in realization of standard 90° Schiffman phase shifter on single layer Microstrip structure is that for achieving lower phase deviations, tight coupling is required. It means that in Microstrip



**Figure 3.** Circuit model of proposed improved Schiffman phase shifter.

edge coupled lines, spacing between coupled lines must be very low that is not practical because spacing is too small to be fabricated [6]. So, for realizing Schiffman phase shifter based on microstrip edge coupled lines, standard Schiffman phase shifter must be altered. The proposed architecture of the improved Schiffman phase shifter is shown in Figure 3 that consists of Microstrip edge coupled lines and one lumped capacitor. In the coupled lines, even and odd mode impedances are relevant to even and odd mode capacitances as follows

$$Z_{0e} = \sqrt{\frac{L_e}{C_e}} \quad Z_{0o} = \sqrt{\frac{L_o}{C_o}}$$

Since, even mode capacitance is the capacitance between strip conductor and the ground plane, and odd mod capacitance is the capacitance between the two coupled conductors, by adding parallel lumped capacitor to the coupled lines, the amount of the odd mode capacitance is increased and odd mode impedance is decreased. Consequently, by tuning the lumped capacitor value, the ratio of the even mode impedance to the odd mode impedance ( $\rho$ ) could be adjusted. It must be mentioned that by the loading capacitor the odd-mode impedance is decreased and the ratio of even-mode: odd-mode impedance is increased. For the Schiffman phase shifter, in the Ref. [5] is shown that  $\Delta\varphi$  has a maximum (where  $\Delta\varphi_{\max}$  is real) if  $2\sqrt{\rho} > K \rightarrow \rho > \frac{K^2}{4}$ . Thus, in this research which  $K = 3$ , the minimum value of the  $\rho$  is 2.25.

For instance, according to the design curve which is shown in Figure 2 for designing a  $90^\circ$  Schiffman phase shifter with  $\pm 3^\circ$  phase

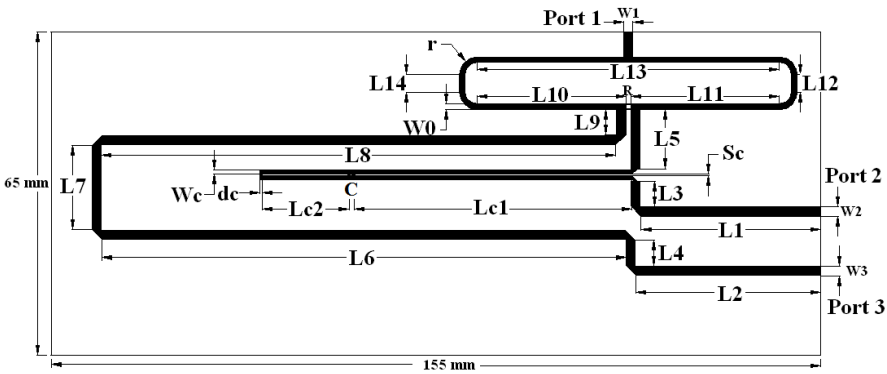
deviation, an impedance ratio  $\rho = 2.76$  must be chosen to ensure an optimal bandwidth. Accordingly, the even-mode and odd-mode impedances of the coupled lines could be determined as  $Z_{0e} = 50 \cdot \sqrt{\rho} = 83 \Omega$  and  $Z_{0o} = \frac{50}{\sqrt{\rho}} = 30.09 \Omega$ . For obtaining such even-mode and odd-mode impedances, the width of the coupled lines and the spacing between coupled lines could be determined as  $W = 1.23 \text{ mm}$  and  $S = 0.02 \text{ mm}$  on microwave substrate RO4003 having thickness  $0.8 \text{ mm}$  and dielectric constant  $\varepsilon_r = 3.38$ . In this case, spacing is too small to be fabricated. In this structure, the spacing between coupled lines is chosen so that it can be realized. In the next section, the design procedure is explained in detail.

### 3. DESIGN

The proposed  $90^\circ$  hybrid was implemented in Microstrip technology on a Rogers RO4003 substrate with  $\varepsilon_r = 3.38$  and height  $h = 0.8 \text{ mm}$  at a design frequency of  $f_0 = 650 \text{ MHz}$ . The Wilkinson divider was designed to provide equal power split between the two output branches and is used to achieve high output port isolation as well as good return loss characteristics at all three ports. The input feed line was designed with a characteristic impedance of  $Z_0 = 50 \Omega$ , while the two  $\frac{\lambda_g}{4}$  branches were designed with a characteristic impedance of  $\sqrt{2}Z_0 = 70.71 \Omega$ , resulting in a resistor value of  $R = 100 \Omega$ .

For designing the improved Schiffman phase shifter, at the first stage, the circuit model shown in Figure 3 is optimized in Agilent-ADS microwave circuit simulator. The initial values of coupled lines length and reference line length were selected as  $\frac{\lambda_g}{2}$  and  $3\frac{\lambda_g}{2}$  respectively, similar to standard  $90^\circ$  Schiffman phase shifter. In this research, the spacing between coupled lines is set  $S = 0.3 \text{ mm}$  and other parameters are optimized. After optimization the value of the loading capacitor, where to place it and the width of the coupled lines are obtained. Finally for the coupled lines,  $W = 0.8 \text{ mm}$  and  $S = 0.3 \text{ mm}$  and loading capacitor  $C = 2 \text{ pF}$  are obtained. Even and odd mode impedances of these coupled lines without lumped capacitor are  $99.7 \text{ ohm}$  and  $55.56 \text{ ohm}$  respectively. So, without lumped capacitor the value of  $\rho$  is  $1.79$ . Thus for achieving  $\rho = 2.76$  the ratio of even-mode: odd-mode impedance must be increased. By loading lumped capacitor the value of  $\rho$  could be increased.

At the second stage proposed  $90^\circ$  hybrid was simulated by method of moment in Agilent-ADS microwave circuit simulator. The proposed  $90^\circ$  hybrid is shown in Figure 4 and its optimized parameters are shown in Table 1.



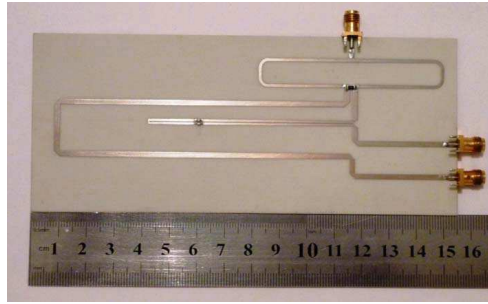
**Figure 4.** Proposed broadband 90° hybrid.

**Table 1.** Parameters of proposed 90° hybrid shown in Figure 4.

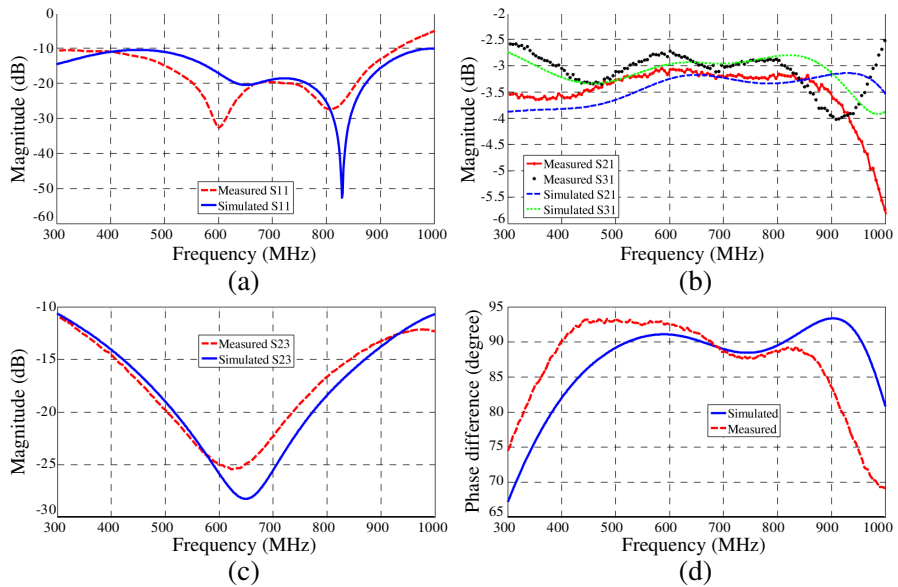
| Parameter  | Value     | Parameter        | Value        |
|------------|-----------|------------------|--------------|
| $W_1$      | 1.87 mm   | $L_{10}, L_{11}$ | 29.94 mm     |
| $W_2, W_3$ | 1.87 mm   | $L_{12}, L_{14}$ | 3.5 mm       |
| $W_0$      | 1.1 mm    | $L_{13}$         | 60.87 mm     |
| $L_1$      | 36.2 mm   | $L_{c1}$         | 56 mm        |
| $L_2$      | 37.2 mm   | $L_{c2}$         | 17.5 mm      |
| $L_3, L_4$ | 5.18 mm   | $W_c$            | 0.8 mm       |
| $L_5$      | 11.87 mm  | $S_c$            | 0.3 mm       |
| $L_6$      | 105.55 mm | $d_c$            | 0.5 mm       |
| $L_7$      | 16.8 mm   | $r$              | 3 mm         |
| $L_8$      | 103.68 mm | $R$              | 100 $\Omega$ |
| $L_9$      | 5.18 mm   | $C$              | 2 pF         |

#### 4. SIMULATION AND EXPERIMENTAL RESULTS

The above mentioned hybrid was designed and simulated in the Agilent-ADS microwave circuit simulator with momentum method and then it was implemented using Microstrip transmission lines. Figure 5 shows the fabricated 90° hybrid. The measurement was carried out on an HP8753D network analyzer. Figure 6(a) shows the measured versus the simulated return loss magnitude response for port 1, showing good agreement between the two. The measured return loss is below  $-10.6$  dB from less than 300 MHz to above 932 MHz, indicating that the device is well matched. Figure 6(b) shows that both the measured  $|S_{21}|$  and  $|S_{31}|$  remain above  $-4$  dB from 300 MHz to 933 MHz. Also



**Figure 5.** Photograph of the fabricated 90° hybrid.



**Figure 6.** Simulated and measured results of the proposed 90° hybrid. (a) Return loss magnitude response for port 1. (b) Through ( $S_{21}$  and  $S_{31}$ ) magnitude responses. (c) Isolation magnitude response ( $S_{23}$ ). (d) Phase difference response results.

Figure 6(c) shows the acceptable isolation between ports 2 and 3 that is below  $-10$  dB from less than 300 MHz to above 1 GHz. Measured result in Figure 6(d) shows that the phase deviation is within  $\pm 3^\circ$  covering a band from 375 MHz to 875 MHz, or 80% bandwidth. Also amplitude and phase imbalance between two paths at worst case are within 0.75 dB and  $\pm 5^\circ$ , respectively, over the frequency band from 362 MHz to 891 MHz, or around 84% bandwidth.

## 5. CONCLUSION

A wideband single layer  $90^\circ$  hybrid has been presented that offers a broadband phase difference of  $90^\circ$  between output signals as well as good return loss and through characteristics. The broadband nature of the  $90^\circ$  hybrid arises from the use of improved Schiffman phase shifter and wideband characteristics of the improved Schiffman phase shifter emanates from embedding of a lumped capacitor in parallel with Microstrip edge coupled lines. Since the two output ports can be spaced closely together, the proposed  $90^\circ$  hybrid is well-suited for designing broadband balanced low power amplifier such as DTV amplifiers (470 MHz to 860 MHz) and feeding planar devices that require broadband phase difference of  $90^\circ$  in input ports.

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