A Wideband 90 Phase Shifting Element Applied in Quadrature Phase Filtering Power Divider

Citation for published version:

Digital Object Identifier (DOI):
10.1109/LMWT.2023.3340720

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
IEEE Microwave and Wireless Technology Letters

Publisher Rights Statement:
© 2023 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

General rights
Copyright for the publications made accessible via Heriot-Watt Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
Heriot-Watt University has made every reasonable effort to ensure that the content in Heriot-Watt Research Portal complies with UK legislation. If you believe that the public display of this file breaches copyright please contact open.access@hw.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 09. Mar. 2024
A Wideband 90° Phase Shifting Element Applied in Quadrature Phase Filtering Power Divider

Zhipeng Xia®, Jianpeng Wang®, Qing-Yuan Lu®, Wen Wu®, Senior Member, IEEE, and Jiasheng Hong®, Fellow, IEEE

Abstract—A wideband 90° phase shifting element for application in the quadrature phase filtering power divider (QFPD) is presented in this letter. Instead of the complex calculation procedure of phase information between reference and main branch in traditional phase shifter design, this letter initially reveals the inherent property of 90° phase difference between terminal open- and short-circuited transmission lines (TLs) by investigating their respective electric field distributions. Following this concept and conventional filtering design method, a new topology of QFPD is constructed. For demonstration, a design example of wideband QFPD is implemented and measured. Results show that the proposed wideband QFPD exhibits phase bandwidths of 69.24%, impedance bandwidths of 58.68%, and magnitude imbalances of less than 0.7 dB, together with better than 20 dB isolation performances.

Index Terms—Electric field distribution, filtering power divider, wideband quadrature phase difference.

I. INTRODUCTION

WITH the rapid development of modern wireless communication systems, the demands for miniaturization and integration are highly urgent. To satisfy these increasing requirements, function-integrated devices are drawing more and more attention. On the other hand, the quadrature-phase signal has wide application in mixers, balanced amplifiers, and various antenna feeding networks [1] [2], [3], [4], [5]. As indicated in Fig. 1(a), the conventional feeding scheme utilized in a circularly polarized antenna system consists of a power divider, bandpass filter, and 90° phase shifter. Obviously, the construction of a quadrature phase filtering power divider (QFPD), which integrates the functions of power division, frequency selectivity, and 90° phase shift, will be beneficial a lot to the integration and miniaturization of the antenna system as Fig. 1(b) shows.

In general, the way of designing a power divider with phase shift can be classified into two categories. The first type is to cascade a phase shifter with the filtering power divider [6], [7], [8]. This method commonly introduces filtering characteristics in divider and loads phase shifting structures such as extension line [9], [10], Schiffman phase shifter [11], stub-loaded phase shifter [12], or self-coupled transmission lines (TLs) [13], on the output ports of the divider. Obviously, the advantages of this method are that it is straightforward, and an arbitrary value of phase shift can be synthesized since the filtering power divider and phase shifter are designed individually [10]. However, it usually results in complex circuit structures and large circuit footprints. The other method is developed based on the concept of electric field distribution. In this method, the relationship between field distribution and phase information is revealed to design a power divider with phase shift such as λ/2 open-ended TL [14] [15], double-sided parallel-strip lines [16], [17], [18], and slot lines [19], [20], [21]. However, almost all the examples are focused on developing filtering power dividers with 180° phase differences, and very few reported on filtering power dividers with arbitrary phase differences. Specifically, the relationship between electric field distribution and 90° phase difference has not been revealed and is involved in the design of an orthogonal-phase filtering power divider.

The motivation of this letter is to present a convenient and effective scheme to realize wideband 90° phase difference by investigating the electrical field distributions of open-terminated and short-terminated TLs. According to the proposed concept, a wideband QFPD is developed. Both
the voltage distribution can be expressed as follows:

$$V_{\text{open}}(z) = V_0^+ \left( e^{-j\beta z} + e^{j\beta z} \right) = 2V_0^+ \cos \beta z \quad (1)$$

and its normalized voltage distribution is shown in Fig. 2(a). While referring to Fig. 2(b) for the short-circuited termination, the voltage distribution can be expressed as follows:

$$V_{\text{short}}(z) = V_0^+ \left( e^{-j\beta z} - e^{j\beta z} \right) = -2jV_0^+ \sin \beta z. \quad (2)$$

To discuss the phase information, the ratio of $$V_{\text{open}}$$ and $$V_{\text{short}}$$ is considered as follows:

$$\phi = \angle \left( \frac{V_{\text{open}}}{V_{\text{short}}} \right) = \angle \left( \frac{2V_0^+ \cos \beta z}{-2jV_0^+ \sin \beta z} \right) = 90^\circ. \quad (3)$$

Noting that $$\cos \beta z$$ and $$\sin \beta z$$ actually represent the normalized amplitude distributions of the open-terminated and shorting-terminated TLs, respectively. $$j$$ in the ratio clearly reveals that their voltages have stable 90° phase differences with respect to $$z$$.

### B. Implementation of QFPD

Based on the above analysis, the inherent property of the 90° phase difference between open-circuited and short-circuited TLs has been revealed. Obviously, this property is very meaningful for constructing quadrature phase filtering power division topology. As Fig. 2(c) shows, to achieve flexible filtering characteristics and wideband quadrature phase difference, the input signal can be deployed to equally coupled to open- and short-circuited TLs through resonating elements which can be realized in forms of multimode resonators or multiororder cascading coupled resonators, and so on.

To verify the feasibility of the proposed topology in realizing wide impedance bandwidth and phase bandwidth, one QFPD demonstrator centered at 2.5 GHz with main specifications of 60% impedance and phase bandwidths, better than 15 dB return loss, and more than 20 dB isolation within the working frequency is explored. Considering resonators with multiple resonant modes utilized in the developed topology can result in wide impedance bandwidth and phase bandwidth, herein, a triple-mode resonator is adopted. As indicated in Fig. 3, when the signal is fed to the $$\lambda/4$$ open-circuited TL, it will equally couple to two identical triple-mode resonators. Afterward, the two identical triple-mode resonators will respectively couple to open- and short-circuited TLs so as to result in a 90° phase difference between port 2 and port 3 and the phase shifting bandwidth can be tuned by varying the impedances of coupling lines.

The resonator utilized in this design is a typical triple-mode resonator with a center loading stub which can generate two even-modes, one odd-mode inside the passband, and two transmission zeros outside the passband. The position of two even modes can be controlled by impedance ratio $$Z_1/Z_2$$ to adjust the bandwidth of response and the two transmission zeros can be controlled by the electrical length of the open stub. According to the design specifications, the frequency of three resonant poles is set as 0.76 $$f_0$$, 0.98 $$f_0$$, and 1.29 $$f_0$$.

Moreover, to determine the position of the implemented isolation resistor, the three coupled line model [23], [24], [25] in Fig. 3(b) is analyzed where the terminated impedance of port 1, port m and n is $$Z_0$$. To determine the position of the
isolation resistor, the calculated $S_{mm}$ at center frequency with respect to different positions of the isolation resistor is plotted in Fig. 4(a). The result exhibits that when $\theta_2/(\theta_3 + \theta_4) = 0$, i.e., the isolation resistor is deployed at the top end, well isolation level on center frequency can be achieved by the adjustment of $R_{iso}$. However, as $\theta_2/(\theta_3 + \theta_4)$ increases, i.e., the isolation resistor moves toward the bottom end, the isolation level will be degraded. Moreover, when $\theta_2/(\theta_3 + \theta_4) = 1$, which means the isolation resistor is deployed at the bottom end, the isolation level has no relationship with the value of $R_{iso}$. Therefore, to achieve good isolation performance, we choose the top end as the position of the isolation resistor. Besides, to explore the relationship between isolation level and $R_{iso}$, theoretical isolation levels versus the changing of $R_{iso}$ are indicated in Fig. 4(b). These results show that different isolation levels and isolation bandwidth can be achieved by selecting proper values of isolation resistor. As such, in consideration of the design specification, the implemented isolation resistor is ultimately determined as 261 $\Omega$ in this design.

Finally, simulation and measurement are carried out for demonstration. The structure parameters of developed QFPD are indicated in Fig. 5(a). Fig. 5(b) shows that the simulated and measured impedance bandwidths are separately 58.11% (1.77–3.22 GHz) and 58.68% (1.71–3.13 GHz) with 1.68 dB measured insertion loss, during which the return loss is better than 15 dB and the resonant frequencies of three poles are 1.94, 2.55, and 3.13 GHz. Outside the passband, two transmission zeros mainly caused by the resonances of the centrally loaded stub in the triple-mode resonator are observed at about 1.25 and 3.7 GHz, thus ensuring the QFPD a good selectivity. Moreover, the isolation is also verified more than 20 dB within the working frequency. Besides, the characteristics of magnitude imbalance and phase difference are also considered. As Fig. 5(c) indicated, the simulated and measured results manifest that the phase difference is within 90° ± 5° from 1.52 to 3.13 GHz (69.24%) and the magnitude imbalance is less than 0.7 dB.

C. Comparison and Discussion

Table I shows the performance of the developed wideband quadrature phase power divider in comparison with reported counterparts. It can be found that even the cascaded designs such as [9], [10], and tunable design [26] can also realize a 90° phase difference, they suffer from larger circuit sizes compared with our work. Specifically, benefitting from the new 90° phase shifting element, the developed QFPD has achieved wider impedance and phase bandwidths as well as better selectivity in comparison with others.

### III. Conclusion

Having revealed the inherent wideband 90° phase difference between the electric field distributions of open- and short-terminated TLs, a new quadrature phase filtering power division topology has been developed. Both simulation and measurement results are provided for validation. As expected, the design concepts are well confirmed by the experiment, thus indicating that the presented wideband QFPD successfully integrated the function of power division, frequency selectivity, and 90° phase shifting. Attributing to these distinctive features, the developed wideband QFPD is prospective to have good applications in modern high-integrated wireless communication systems.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PERFORMANCE COMPARISON WITH PREVIOUS COUNTERPARTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>[9]</td>
</tr>
<tr>
<td>Tunability</td>
<td>No</td>
</tr>
<tr>
<td>Implementation method</td>
<td>Cascaded</td>
</tr>
<tr>
<td>Center frequency (GHz)</td>
<td>10</td>
</tr>
<tr>
<td>Insertion loss (dB)</td>
<td>0.85</td>
</tr>
<tr>
<td>Footprint ($\lambda^2$)</td>
<td>3.84</td>
</tr>
<tr>
<td>FBW (%)</td>
<td>(3.53 dB)</td>
</tr>
<tr>
<td>Filtering function</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnitude imbalance (dB)</td>
<td>$\leq 1.11$</td>
</tr>
<tr>
<td>Phase bandwidth (%)</td>
<td>10.8</td>
</tr>
<tr>
<td>QTZs</td>
<td>0</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\geq 25$ dB</td>
</tr>
</tbody>
</table>

$\lambda$: guide wavelength in microstrip line, FBW: fractional bandwidth, QTZ: quantity of transmission zero, N.P: Not provided.
REFERENCES


