Research Article

Analysis and Design of Ultra-Wideband 3-Way Bagley Power Divider Using Tapered Lines Transformers

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An ultra-wideband (UWB) modified 3-way Bagley polygon power divider (BPD) that operates over a frequency range of 2–16 GHz is presented. To achieve the UWB operation, the conventional quarter-wave transformers in the BPD are substituted by two tapered line transformers. For verification purposes, the proposed divider is simulated, fabricated, and measured. The agreement between the full-wave simulation results and the measurement ones validates the design procedure.

1. Introduction

Recently, the need for microwave components that have the capability of operating over a wide range of frequencies has motivated many researchers. Thus, many papers that investigate the ultra-wide operation for different microwave devices such as the Wilkinson power dividers (WPDs), branch line couplers (BLCs), and antennas were proposed. In [1], an UWB directional coupler that operates over a frequency range of 3.1–10.6 GHz was presented. To realize such an UWB coupler, two elliptically shaped microstrip lines, which are broadside coupled through an elliptically shaped slot, were used. In [2], a similar approach was used to design a slot-coupled multisection quadrature hybrid coupler for UWB applications. A novel approach for the design of UWB 3 dB couplers, out-of-phase equal-split power dividers, omnidirectional monopole antennas, and directional tapered slot antennas was proposed in [3]. In [4], a novel UWB WPD with modifications on the traditional divider by adding an extra open stub on each branch was proposed. In [5], an UWB WPD that consists of two branches of impedance transformers, each one consisting

of two sections of transmission lines with different characteristic impedances and different lengths, was proposed. A modified UWB WPD formed by implementing one delta stub on each branch was proposed in [6]. In [7], and based on the theory presented in [8], a WPD that operates over a frequency range of 2–10.2 GHz was designed by substituting its conventional quarter-wave arms by tapered lines. Three resistors were added along the tapered lines to achieve an acceptable isolation between the output ports.

One of the power dividers, which has been a new area of research, is the Bagley polygon power divider (BPD) [9–17]. Compared to other power dividers, such as the Wilkinson power divider, Bagley polygon power divider does not use lumped elements, such as resistors, and can be easily extended to any number of output ports. However, the output ports for such dividers are not matched, and the isolation between them is not as good as that of the Wilkinson power divider. In [9], reduced size 3-way and 5-way Bagley power dividers (BPDs), using open stubs, were presented. In [10], an optimum design of a modified 3-way Bagley rectangular power divider was investigated. In [11, 12], a general design of compact multiway dividers based

FIGURE 1: The obtained input return loss (in dB) versus B for $Z_s = 100 \Omega$ and $Z_l = 33.333 \Omega$.

FIGURE 2: Schematic diagram of the 3-way BPD and its equivalent circuit.

FIGURE 3: The tapered impedance variation for different values of B .

FIGURE 4: The tapered line width variation for different values of B .

on BPDs was introduced. In [13], a compact dual-frequency 3-way BPD using composite right-/left-handed (CRLH)

FIGURE 5: (a) The designed UWB tapered line transformer (dimensions are in mm). (b) The input port matching parameter S_{11} and the transmission loss parameter S_{21} .

FIGURE 6: The layout of the proposed UWB 3-way BPD (dimensions are in mm).

transmission lines was implemented. Recently, and based on the generalized 3-way Bagley polygon power divider, dual-passband filter section was presented in [14]. Moreover, compact 5-way BPD for dual-band (or wide-band) operation was proposed in [15]. Dual-band modified 3-way BPDs based on substituting the quarter-wave sections of the conventional design by their equivalent dual-band matching networks were presented in [16]. Very recently, multiband miniaturized 3-way and 5-way BPDs were proposed in [17]. It should be mentioned here that all of the BPDs investigated in [9–17] have an odd number of output ports. In [18], a novel approach for the design of modified BPDs with even number of output ports was proposed.

In this paper, an UWB modified 3-way BPD that operates over the frequency range of 2–16 GHz is presented. To have such a divider, the quarter-wave sections are substituted by their equivalent UWB tapered lines. The designed UWB divider is simulated using two full-wave EM simulators. Moreover, the divider is fabricated and measured, and the

simulation and measurement results are in a good agreement.

2. Tapered Line Design

According to [7, 8], the maximum input return loss (in dB) for a given tapered line that is used in order to match a source impedance Z_s to a load impedance Z_l is given by the following equation:

$$|RL_{\text{input}}|_{\text{max}} = -20 \log \left[\tanh \left(\frac{B}{\sinh B} (0.21723) \ln \left(\sqrt{\frac{Z_l}{Z_s}} \right) \right) \right], \quad (1)$$

where B is a predefined design parameter used to determine the tapered line curve. Figure 1 shows the effect of increasing B on the obtained input return loss.

As seen from Figure 1, larger values of B result in lower reflection at the input port. However, increasing B will demand wider tapered line width and longer length.

After choosing the value of B in order to achieve a desired input return loss, the exponential tapered line characteristic impedance is calculated using the following equations [7, 8]:

$$\ln \left(\frac{Z(z)}{Z_s} \right) = 0.5 \ln \left(\frac{Z_l}{Z_s} \right) \left[1 + G \left(B, 2 \left(\frac{z}{d} - 0.5 \right) \right) \right], \quad (2a)$$

where

$$G(B, \xi) = \frac{B}{\sinh B} \int_0^\xi I_0 \left(B \sqrt{1 - \xi'^2} \right) d\xi'. \quad (2b)$$

It should be mentioned here that $Z(z)$ in (2a) represents the characteristic impedance of the tapered line at point z , and $I_0(x)$ represents the modified zero-order Bessel function. The tapered line length d is a predefined variable chosen appropriately to achieve the desired maximum return loss.

FIGURE 7: Simulated scattering parameters for the designed UWB BPD.

3. UWB 3-Way BPD Design

In this section, the design of a modified UWB 3-way BPD is presented. Figure 2(a) shows the schematic diagram of the 3-way modified BPD [11]. Noting that this divider is symmetric around its center line, an equivalent circuit (looking from port 1 to the right or left side) can be drawn as shown in Figure 2(b).

Referring to the equivalent circuit, it can be easily realized that choosing $Z_h = 2Z_0$ makes the design of this BPD independent of the length l_h . In this case, the characteristic impedance (Z_m) of the quarter wave section is $Z_m = \sqrt{(2Z_0)Z_l}$, where $Z_l = 2Z_0/3$. This gives

$$Z_m = \frac{(2Z_0)}{\sqrt{3}}. \quad (2)$$

Thus, each quarter-wave section matches a load impedance of $Z_l = 2Z_0/3$ to a source impedance of $Z_s = 2Z_0$, resulting in a perfect match at port 1 (the input port) and equal split power division to the three output ports. As noted in the Introduction, the BPD does not contain any lumped

elements, and it can be easily extended to any number of output ports.

Now, considering a characteristic impedance of 50Ω , the values of Z_s and Z_l are 100Ω and 33.333Ω , respectively. These values will be incorporated in the tapered line design equations given in (1) and (2a). Then, the resulting tapered line will replace each conventional quarter-wave transmission line transformers in the BPD presented in Figure 2 in order to obtain an UWB operation. Figure 3 shows the variation of the tapered impedance for different values of B , which can be translated into microstrip width variation as shown in Figure 4. It is worth mentioning here that the substrate used in order to obtain the tapered line width for all cases is Duroid RT5870 with a relative permittivity $\epsilon_r = 2.33$, a thickness of 0.508 mm , and a loss tangent of 0.0012 .

It can be seen from Figures 3 and 4 that larger values of B result in a wider microstrip line width. In our design, B is chosen to be 5.5 , which corresponds to a maximum input return loss of 56.44 dB . The length of the designed tapered line is set to 40 mm , which is about 1.48 times the length of the conventional transmission line transformer at the lower

FIGURE 8: The photograph of the fabricated divider.

FIGURE 9: Measured scattering parameters of the divider shown in Figure 8.

frequency (2 GHz). However, such slight increase in the circuitry size leads to obtaining the desired electrical performance, especially the input port matching and transmission parameters performances, not only at a single frequency, but also over a considerable wide range of 2–16 GHz. Figure 5(a) shows the designed tapered transformer that matches a source impedance of $100\ \Omega$ to a load impedance of $33.333\ \Omega$ along with its obtained input port matching parameter (S_{11}) and transmission loss parameter (S_{21}) shown in Figure 5(b). An input return loss better than 10 dB is obtained over a frequency range of 2–16 GHz for the designed transformer. Moreover, the transmission coefficient S_{21} equals to $-0.2\ \text{dB}$ over the entire frequency range. It is worth to point out here that these results were obtained using the full-wave simulator IE3D [19].

4. Simulation Results

Figure 6 shows the layout of the designed UWB modified 3-way BPD. This proposed divider is simulated using two different full-wave electromagnetics simulators: IE3D [19]; which solves Maxwell's equations using the method of

moments (MoM), and HFSS [20]; which solves the same equations using the finite element method. Figure 7 shows the obtained scattering parameters.

Figure 7(a) shows that an input return loss better than 10 dB is achieved over the frequency range of 2–16 GHz. Moreover, the resulting transmission parameter S_{21} (which is equals to S_{41} because of the symmetry of the structure) is close to its theoretical value of $-4.7\ \text{dB} \pm 1\ \text{dB}$ over the same frequency range except for the increase in the losses at higher frequencies. Such losses can be decreased through the use of low-loss tangent substrates. The transmission parameter S_{31} is also close to its theoretical value ($-4.7\ \text{dB} \pm 0.8\ \text{dB}$) over the frequency band 2–16 GHz. The discrepancies between the results of the two simulators are thought to be due the different technique each simulator follows to solve Maxwell's equations, and the way the structure was divided in the meshing process during the simulations.

5. Measurement Results

The circuit layout shown in Figure 6 is implemented on the same substrate mentioned in Section 3 (Duroid RT5870 with a relative permittivity $\epsilon_r = 2.33$ and a thickness of 0.508 mm). The extended ports in the circuit layout have been chosen to allow accurate S-parameter measurements using universal test fixture (GigaLane) without soldering. A photograph of the fabricated circuit is shown in Figure 8. The measurements have been performed using Anritsu 37369C network analyzer. The measured results are shown in Figure 9. The measured return loss is better than 10 dB from 2 to 16 GHz. The measured S_{31} is almost flat, around $-5\ \text{dB}$, in the entire band. It changes at a few bands to $-6\ \text{dB}$ and some others to $-4.5\ \text{dB}$. On the other hand, the measured S_{21} is approximately $-5.6 \pm 0.7\ \text{dB}$ from 2 GHz to 12 GHz except at 4.8 GHz and 7 GHz, where it reaches $-7.2\ \text{dB}$. From 12.5 GHz to 16 GHz, S_{21} changes from $-6\ \text{dB}$ to $-7\ \text{dB}$; except for a small notch at about 15 GHz at which S_{21} is about $-7.7\ \text{dB}$.

6. Conclusions

In this paper, an UWB 3-way BPD using tapered line transformers was designed, simulated, fabricated, and measured. Simulation results show a very good performance of the designed divider over a frequency range of 2–16 GHz. Measurement results show an acceptable performance with little discrepancies from the simulation ones. These differences could be mainly due to the fabrication process, as well as, measurement errors.

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