Progress In Electromagnetics Research C, Vol. 16, 233–239, 2010

COMPACT BRANCH-LINE COUPLER FOR HARMONIC SUPPRESSION

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Abstract—This paper presents the modified design that can reject harmonic components in the branch-line coupler. After adding open stubs at the center of branch lines of the traditional design, their new network parameters can be found in order to maintain the conventional function at an operating frequency and suppress its harmonic terms chosen. Experimental results show the second and third harmonic suppressions to be -28.3 and -39.6 dBs, while maintaining its traditional performance at the fundamental frequency.

1. INTRODUCTION

The branch-line coupler as a four-port power divider in microwave circuits has been redesigned for new requirements, such as compact size, wide bandwidth, and multi-band operations. Recently, the removal of harmonic signals, which generate spurious responses at out-of-band regions and lead to high intermodulation distortion (IMD), has become a new requirement at the design of power dividers, such as Wilkinson power divider, branch-line coupler and rat-race hybrid coupler. There have principally been two methods used to solve the harmonic problem in microwave power dividers: by the use of stubs or (electromagnetic bandgap) EBG structures.

Received 30 August 2010, Accepted 17 September 2010, Scheduled 23 October 2010
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A Wilkinson power divider for nth harmonic suppression using two open stubs located at the center of the quarter-wave branches was proposed in [1], where the third harmonic component was suppressed to less than -40 dB. Power dividers using transmission lines incorporating EBG structures have been popularly investigated in all kinds of power dividers, since they exhibit band-stop and slow-wave characteristics simultaneously, which can be utilized to suppress unwanted harmonics and reduce the circuit dimensions. For instance, power dividers with EBG cells effectively reduced the third and fifth order levels to about 32.5 and 12 dBs in [2] and the second and third ones to -26 and -25 dBs in [3], respectively. As defected ground structure (DGS) can provide the same properties as EBG, a Wilkinson power divider using DGS was obtained with size reduction of 90% of the conventional divider and suppression levels of 18 and 16 dBs for the second and third harmonics in [4]. Furthermore, the compact 180° ring hybrid coupler with EBG perforated on the microstrip transmission line can be found in [5–7].

However, the use of open stubs on each quarter-wave branch results to increase of its circuit size and addition of an inductor in parallel with isolation resistor. The use of EBG cells has difficulties of finding their inherent structures according to the design frequency and the desired suppression terms. In this letter, a new structure of the branch-line coupler with harmonic rejection will be proposed by virtue of open stubs tapped to the center of each branch line, similar to [1]. Moreover, the physical dimension of the proposed coupler can be reduced in terms of a slow wave by employing the shunt open stubs and new designing the series section, similar to slow wave effect of EBG cells. The main concept of our design is the use of open stubs for harmonic rejection and slow wave feature for compact design. To verify the design concept, a microstrip coupler exhibiting harmonic suppression by the tapped stubs is demonstrated on an FR4 circuit board.

2. THE PROPOSED DESIGN

Figure 1 shows the center-tapped branch section with which all quarter-wave branches of the branch-line coupler can be replaced. Two open shunt stubs with their characteristic impedance and electrical lengths of Z_b, θ_{b1} and θ_{b2} are tapped to the center of a series line with its designated parameters of Z_a and θ_a.

By cascading the matrices of the three different sections in Fig. 1, its ABCD-matrix can be written as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_a & jZ_a \sin\theta_a \\ jY_a \sin\theta_a & \cos\theta_a \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_b(\tan\theta_{b1} + \tan\theta_{b2}) & 1 \end{bmatrix}$$
$$\cdot \begin{bmatrix} \cos\theta_a & jZ_a \sin\theta_a \\ jY_a \sin\theta_a & \cos\theta_a \end{bmatrix}$$
$$= \begin{bmatrix} \cos 2\theta_a - b\sin 2\theta_a & jZ_a(\sin 2\theta_a - b(1-\cos 2\theta_a)) \\ jY_a(\sin 2\theta_a + b(1+\cos 2\theta_a)) & \cos 2\theta_a - b\sin 2\theta_a \end{bmatrix} \quad (1)$$

where $b = \frac{Z_a}{2Z_b}(\tan\theta_{b1} + \tan\theta_{b2})$. Since the proposed structure is intended to be equivalent to a quarter-wavelength transmission line, (1) should be equal to the ABCD-matrix of a quarter-wave line, so yielding

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & jZ_c \\ jY_c & 0 \end{bmatrix} \quad (2)$$

where Z_c is the characteristic impedance of a branch line, i.e., either Z_0 or $Z_0/\sqrt{2}$. By setting $A = D = 0$ in (1), we obtain

$$b = \cot 2\theta_a. \quad (3)$$

Substituting (3) into (1) produces the following simple form,

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & jZ_a \tan\theta_a \\ jY_a \cot\theta_a & 0 \end{bmatrix}. \quad (4)$$

We can obtain the following relation for the series line by network equivalence between two matrices, (2) and (4).

$$Z_a \tan\theta_a = Z_c. \quad (5)$$

The characteristic impedance of open stubs can be determined by modifying (3) as follows,

$$Z_b = \frac{Z_a}{2}\tan 2\theta_a \cdot (\tan\theta_{b1} + \tan\theta_{b2}). \quad (6)$$

The electrical length of $\theta_a = \pi/4$ in (5) and (6) is the case of the conventional one, i.e., $Z_a = Z_c$ and $Z_b = \infty$. The circuit of Fig. 1 contains five unknowns of Z_a, Z_b, θ_a, θ_{b1} and θ_{b2}. Among them, the electrical lengths of the shunt stubs can be fixed to $\theta_b = \pi/(2n)$ by the desired term to be rejected. The remaining three variables can be chosen from Equations (5) and (6). The normalized characteristic impedances of series and shunt lines are calculated using (5) and (6) for the series electrical length of $15 \sim 35°$, which is the realizable range of characteristic impedances obtained. The calculation results for the simultaneous suppression of the second and third terms harmonic suppression are plotted in Fig. 2 for the $Z_0/\sqrt{2}$ line. The normalized

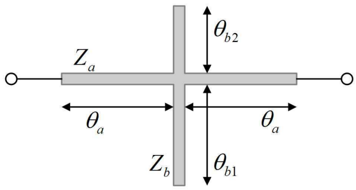


Figure 1. The equivalent branch line.

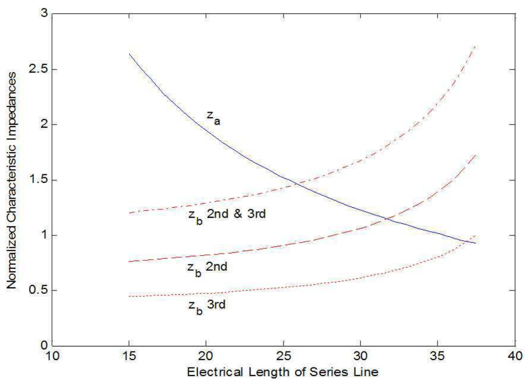


Figure 2. Normalized characteristic impedance versus electrical length of series line.

characteristic impedance of the series line decreases for increasing its electrical length. Meanwhile, those of the shunt lines increase for the same horizontal variations. Two impedance values of series and shunt sections can be obtained after choosing the electrical length of the series section. Some of the line impedance values become impractical and limit the usefulness of the proposed approach, especially at either the (less than 15°) or higher (greater than 35°) end of the series electrical angle in Fig. 2. The choice of only one harmonic term to be suppressed can be done by adding one open stub in Fig. 1 and $\tan\theta_{b1}+\tan\theta_{b2}$ in (6) should be reduced into $\tan\theta_b$. In Fig. 2, two cases of one term harmonic suppression, the second and third orders, are plotted together. Note that the series line is independent of the choice of harmonic terms as implied in (5). If the circuit design in [1] takes Equations (5) and (6), its circuit dimension will be more compact and an isolation inductor will be unnecessary.

3. RESULTS AND DISCUSSION

We implement the modified branch-line for the second and third order harmonic suppressions by adding two open stubs of $\theta_{b1} = 45°$ and

$\theta_{b2} = 30°$ as a verification case. We choose the electrical length θ_a of the series line as 20° considering its implementation limitation of the obtained impedance values. The characteristic impedances, Z_a and Z_b, of the horizontal branch line are 97.0 and 64.3 Ω for the chosen θ_a condition. The vertical branch line has $Z_a = 137.4\,\Omega$ and $Z_b = 90.9\,\Omega$ for the same angles. The proposed divider at $f = 1.0$ GHz and $Z_0 = 50\,\Omega$ is made on a 0.8 mm-thick FR4 substrate, which has a relative permittivity of 4.4 and a conductor thickness of 35 μm in Fig. 3. The conventional coupler, as shown in Fig. 3, was implemented as a reference example. All open stubs for the second and harmonic suppression are outward directed and all those for the third one are inward directed, respectively. All stubs are folded for economic use of circuit dimensions. It was simulated using the ADS Momentum, the electromagnetic simulator based on the method of moment from Agilent Technologies, Inc., for comparison. It is shown from S_{21} and S_{31} data of Fig. 4 that it passes its fundamental signal, but reflects its second and third-order harmonic components. The measured S_{21} at the design frequency of 1.0 GHz shows a power division of −3.3 dB and those at 2.0 and 3.0 GHz show suppression levels of −28.3 and −39.6 dBs. It provides the measured return loss (S_{11}) and isolation (S_{41}) of −24.0 and −32.0 dB at 1.0 GHz in Fig. 4(a) and Fig. 4(d). The bandwidth of 15 dB return loss has 12.5%, narrower than 18% of the conventional one by mathematical comparison of S_{11}. The bandwidth of the proposed coupler becomes narrower than that of the traditional one due to addition of open stubs in all branch lines. However, the bandwidth difference between two couplers is unnoticeable, as shown in Fig. 4(a), due to implementation tolerances. It is possible to suppress all integer multiple frequencies of the second and third harmonics in this fabricated design. In Fig. 3, the circuit area of the conventional coupler is 1890 mm^2 versus 700 mm^2 for the proposed one, about 63% smaller, which is due to reduction of the phase velocity by increased inductance and capacitance of the center-tapped branch

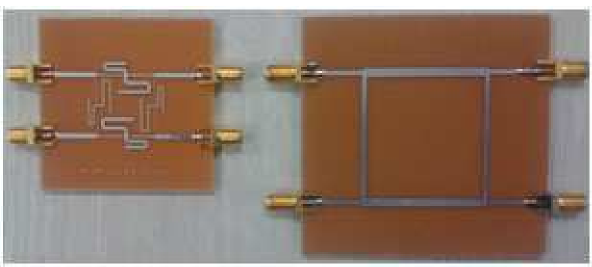
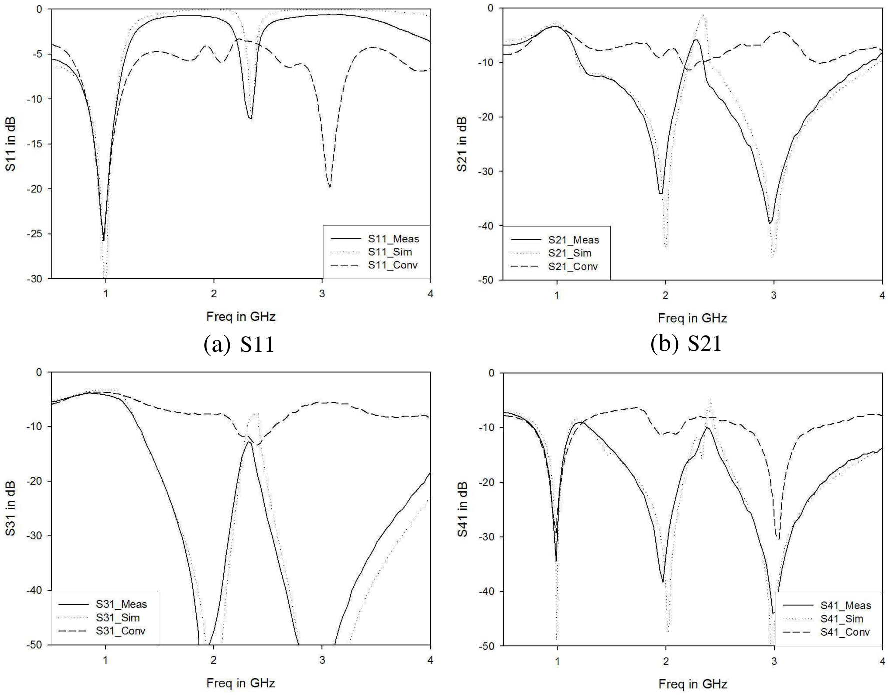


Figure 3. Photograph of the fabricated branch-line couplers.



(a) S11 (b) S21

(c) S31 (d) S41

Figure 4. Measured and simulated S-parameters of the proposed branch-line coupler and measured S-parameters of the conventional one as a reference.

lines, comparable reduction ratio in [8]. There are difficulties in directly comparing their sizes each other due to difference of the open stubs between two couplers. Of course, folding all branches of the conventional one can reduce its circuit size and replacing all stub lines with radial stubs in the proposed design can lead to size improvement. It can be meaningfully compared with the conventional one that length reduction of series lines results from slow wave of the proposed design.

4. CONCLUSION

The modified design of the branch-line coupler for suppressing the nth harmonic outputs is proposed by modifying its circuit parameters after adding shunt stubs at the center of all branch lines. For an experimental case of the second and third harmonic suppressions, the measured results of S_{11}, S_{21}, S_{31} and S_{41} at 1.0 GHz are -24.0, -3.3,

-3.7, and -32.0 dBs, respectively. Furthermore, suppression levels of 28.3 and 39.6 dBs can be obtained at 2.0 and 3.0 GHz, respectively. Its application in balanced amplifiers can reduce the intermodulation distortion, so leading to increasing available dynamic range.

ACKNOWLEDGMENT

This research was supported by Kyungsung University Research Grants in 2010.

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