Modified Wilkinson Power Divider for nth Harmonic Suppression

Kun-Hui Yi and Bongkoo Kang, *Member, IEEE*

***Abstract*—This paper presents a structure of the Wilkinson power divider that can suppress the nth harmonic output. The power divider consists of two $\lambda/4n$ open stubs, which are located at the center of $\lambda/4$ branches and a parallel connection of a resistor and an inductor, which shunts the output ports. Experimental results show that this power divider suppresses the third harmonic component to less than -40 dB, while maintaining the characteristics of a conventional Wilkinson power divider; featuring an equal power split, a simultaneous impedance matching at all ports and a good isolation between output ports. These results agree quite well with the simulation results.**

***Index Terms*—Harmonic suppression, power combiners, power dividers, power splitter, Wilkinson power combiner.**

I. Introduction

THE Wilkinson power divider and combiner are being used widely for microwave power amplifiers [1], [2]. Both have the same structure, which consists of two $\lambda/4$ branches of transmission line and a termination resistor, where λ is the wavelength of the transmission line. They match all input and output ports simultaneously and provide a good isolation between the input ports for the power combiner and between the output ports for the power divider. Also, they can handle arbitrary power levels from input to output ports. If the harmonics are suppressed in the power divider or combiner structure, we can eliminate separate harmonic rejection filters from the circuit and design an area-effective power amplifier.

In this paper, we present a modified Wilkinson power divider that suppresses the nth harmonic component using two $\lambda/4n$ open stubs, where n is the harmonic number that is to be suppressed. By placing a $\lambda/4n$ open stub at the center of each $\lambda/4$ branch of the power divider and shunting the output ports with a parallel connection of a resistor and an inductor, the nth harmonic component and its odd multiples are suppressed without sacrificing the characteristics of the conventional Wilkinson power divider at the operating frequency. In Section II, we propose a structure of the Wilkinson power divider for nth harmonic suppression. The simulation and experiment results of the Wilkinson power divider for third harmonic suppression are given in Section III and a conclusion is given in Section IV.

Manuscript received August 9, 2002; revised October 29, 2002. This work was supported by Korea Agency for Defense Development and by Korea Ministry of Education under the BK21 Program. The review of this letter was arranged by Associate Editor Dr. Arvind Sharma.

The authors are with the Department of Electrical Engineering, Pohang University of Science and Technology, Kyungpook, 790-784, Korea.

Digital Object Identifier 10.1109/LMWC.2003.811670

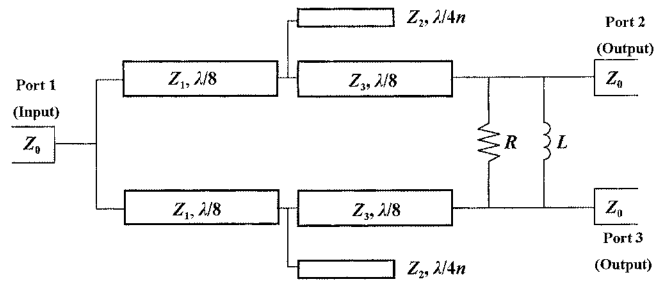

Fig. 1. Schematic diagram of the Wilkinson power divider for nth harmonic suppression.

II. Wilkinson Power Divider for nth Order Harmonic Suppression

A schematic diagram of the proposed Wilkinson power divider, which suppresses the nth harmonic component using two $\lambda/4n$ open stubs, is shown in Fig. 1. The $\lambda/4$ branch of the original Wilkinson power divider, which has two identical $\lambda/4$ branches and an output termination resistor, is divided into two $\lambda/8$ sections. The characteristic impedance of the $\lambda/8$ section connected to the input port is Z_1 and that connected to the output port is Z_3, while the input and output impedances are Z_0. One $\lambda/4n$ open stub with a characteristic impedance of Z_2 is connected to the junction of the $\lambda/8$ sections. The output ports are shunted with a parallel connection of a resistor R and an inductor $L = X/\omega$. This power divider is symmetric and we can use the even- and odd-mode analyses to determine the circuit parameters for nth harmonic suppression [2], [3].

A. Even-Mode Analysis

In the case where two signals of the same magnitude and phase (even-mode signals) are applied to ports 2 and 3 of the circuit shown in Fig. 1, no current flows through the plane of symmetry. The circuit is bisected at the plane of symmetry for the even-mode analysis. Because no current flows through the plane of symmetry, the circuit elements R and L, which shunt the ports 2 and 3, can be eliminated. The impedance Z_0 at port 1 is doubled on the bisected circuit. For $Z_1 = 2Z_0$, the impedance for the even mode at port 2, Z_{out}^E, is calculated using the transmission line impedance equation [2], resulting in

$$Z_{out}^E = Z_3 \frac{4Z_0Z_2^2Z_3}{(Z_2Z_3)^2 + 4Z_0^2\left(Z_2 + Z_3\tan\left(\frac{\pi}{2n}\right)\right)^2} + jZ_3\frac{(Z_2Z_3)^2 - 4Z_0^2\left(Z_2^2 - Z_3^2\tan^2\left(\frac{\pi}{2n}\right)\right)}{(Z_2Z_3)^2 + 4Z_0^2\left(Z_2 + Z_3\tan\left(\frac{\pi}{2n}\right)\right)^2}. \quad (1)$$

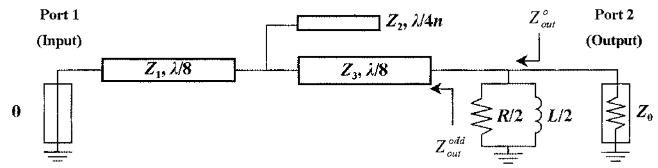

Fig. 2. Circuit of Wilkinson power divider for the odd-mode analysis.

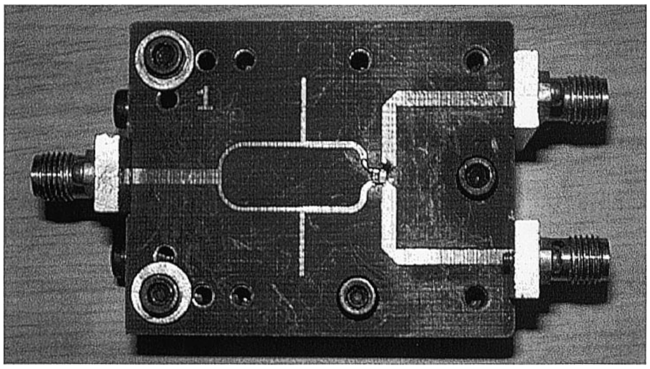

Fig. 3. Photograph of fabricated 2 GHz Wilkinson power divider for third harmonic suppression.

For impedance matching to Z_0, the imaginary part must be zero, which results in

$$(Z_2Z_3)^2 - 4Z_0^2\left(Z_2^2 - Z_3^2\tan^2\left(\frac{\pi}{2n}\right)\right) = 0.$$

After defining a positive parameter $t \equiv Z_3/Z_2$ $(t > 0)$, the above equation is solved for Z_2, resulting in

$$Z_2 = \frac{2Z_0\sqrt{1 - t^2\tan^2\left(\frac{\pi}{2n}\right)}}{t}. \qquad (2)$$

Accordingly, the characteristic impedance Z_3 should be

$$Z_3 = 2Z_0\sqrt{1 - t^2\tan^2\left(\frac{\pi}{2n}\right)}. \qquad (3)$$

When we insert (2) and (3) into the real part of (1) and enforce the condition for impedance matching $Z_{out}^E = Z_0$, the parameter t satisfies the following equation:

$$2t^2\tan^2\left(\frac{\pi}{2n}\right) + t\tan\left(\frac{\pi}{2n}\right) - 1 = 0.$$

The solutions of the above equation are $t\tan(\pi/2n) = 1/2$ and -1. Because $0 < \pi/2\pi < \pi/2$ and $t > 0$, a valid solution is

$$t\tan\left(\frac{\pi}{2n}\right) = \frac{1}{2}.$$

This solution results in

$$Z_2 = 2\sqrt{3}\tan\left(\frac{\pi}{2n}\right)Z_0 \qquad (4)$$

$$Z_3 = \sqrt{3}Z_0. \qquad (5)$$

For the characteristic impedances $Z_1 = 2Z_0$, $Z_2 = 2\sqrt{3}\tan(\pi/2n)Z_0$ and $Z_3 = \sqrt{3}Z_0$, the impedance for the even mode at port 1 is

$$Z_{in}^E = \frac{Z_2}{j\tan\left(\frac{\pi}{2n}\right)} \parallel Z_3\frac{Z_0 + Z_3 j\tan\left(\frac{\pi}{4}\right)}{Z_3 + Z_0 j\tan\left(\frac{\pi}{4}\right)} = 2Z_0$$

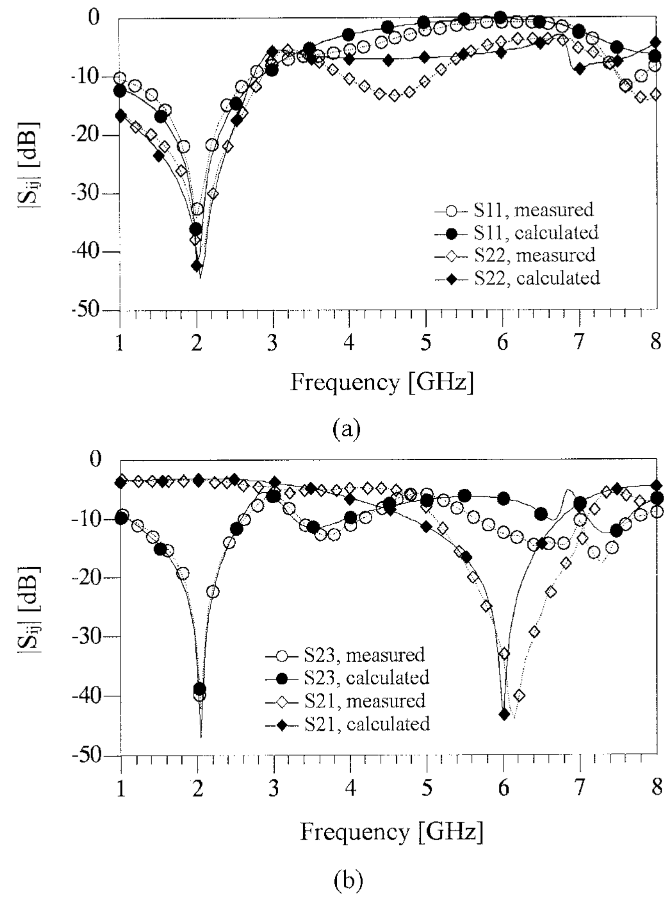

Fig. 4. Measured and calculated S-parameters of the 2.05 GHz Wilkinson power divider for third harmonic suppression: (a) S_{11} and S_{22}. (b) S_{23} and S_{21}.

where the symbol $\parallel$ denotes a parallel connection of circuits. For the circuit shown in Fig. 1, this result gives the input impedance $Z_{in} = Z_0$, which is independent of n. We use this fact to suppress the nth harmonic component without degrading the properties of the Wilkinson power divider at the fundamental frequency f_0. At the nth harmonic frequency nf_0, the $\lambda/4n$ open stub shorts the junction of $\lambda/8$ sections and no transmission from the input to output ports, or vice versa, is possible.

B. Odd-Mode Analysis

The resistance R and the inductance L are determined from the output matching condition. In the case where two signals, which are applied to port 2 and 3 of the circuit shown in Fig. 1, have the same magnitude but 180° out of phase (odd-mode signals), the voltage at the symmetry plane is fixed at 0 V. Accordingly, the circuit can be bisected into the one shown in Fig. 2 for odd-mode analysis. The impedance Z_{out}^{odd} at the fundamental frequency f_0, which is the output impedance without R and L, is

$$Z_{out}^{odd} = jZ_3\frac{(Z_1 + Z_3)Z_2 - Z_1Z_3\tan\left(\frac{\pi}{4n}\right)}{(Z_3 - Z_1)Z_2 - Z_1Z_3\tan\left(\frac{\pi}{4n}\right)} = -j(2+\sqrt{3})Z_0.$$

Because the port 2 is shunted with a parallel connection of $R/2$ and $L/2$, the output impedance Z_{out}^o at port 2 becomes

$$Z_{out}^o = \left(j\frac{1}{(2+\sqrt{3})Z_0} + \frac{2}{R} - j\frac{2}{X}\right)^{-1}$$

where $X \equiv \omega_0 L$ and $\omega_0 = 2\pi f_0$. For impedance matching to Z_0 at port 2, we choose

$$R = 2Z_0 \tag{6}$$

and

$$X = 2(2+\sqrt{3})Z_0. \tag{7}$$

The resistance R given in (6) is the same as the one for the conventional Wilkinson power divider. For $Z_0 = 50\ \Omega$ and $f_0 = 2$ GHz, the required L and R are 29.7 nH and 100 Ω, respectively.

III. Simulation and Experiment

A Wilkinson power divider for $f_0 = 2$ GHz and $Z_0 = 50\ \Omega$ is fabricated on a 0.78 mm-thick TLC32 substrate from Taconic Ltd., which has a relative permittivity of 3.2 and a conductor thickness of 35 μm. For third harmonic suppression, the power divider has the characteristic impedances of $Z_1 = 100\ \Omega$, $Z_2 = 100\ \Omega$ and $Z_3 = 87\ \Omega$. The resistance R and inductance L required for the odd-mode impedance matching are 100 Ω and 29.7 nH. However, the fabricated power divider has an inductance of 27.0 nH due to fabrication error. A photograph of the fabricated Wilkinson power divider is shown in Fig. 3. This power divider has an area of $\sim 3 \times 3$ cm^2. The S-parameters are measured using an HP8510C network analyzer and are calculated using the ADS software from Agilent Technologies, Inc.

The measured and calculated S-parameters are shown in Fig. 4. One observes from Fig. 4 that the measured S-parameters agree quite well with the calculated ones. The measured S-parameters are shifted from the design goal of $f_0 = 2$ GHz to 2.05 GHz and $3f_0 = 6$ GHz to 6.15 GHz. The sources of this discrepancy include the T-junction effects, the representation errors for simulation and the fabrication errors on L and $\lambda/4n$ open stubs. In Fig. 4(a), which shows S_{11} ($\circ$ and $\bullet$) and S_{22} ($\diamondsuit$ and ♦), it is shown that the power divider passes the 2.05 GHz fundamental signal, but reflects the 6.15GHz third-order harmonic component. At 2.05 GHz, the measured S_{11} and S_{22} are -34 dB and -39 dB, respectively. In Fig. 4(b), which shows S_{23} ($\circ$ and $\bullet$) and S_{21} ($\diamondsuit$ and ♦), it is shown that the 2.05 GHz signal at port 1 is equally divided and transmitted to the output ports 2 and 3, but the 6.15 GHz third harmonic signal is not transmitted. The measured S_{23} at 2.05 GHz shows that the isolation between ports 2 and 3 is $\sim$ 42 dB. The reflected power at 2.05 GHz from one output port has little effect on the operation of the other output port. The measured S_{21} at 2.05 GHz shows a power split of $\sim$ 3.3 dB and that at 6.15 GHz shows a third harmonic suppression of $\sim$ 44 dB. These results show that the proposed power divider operates well as a conventional Wilkinson power divider at the operating frequency, while suppressing the third harmonic component.

IV. Conclusion

A structure of the Wilkinson power divider, which can suppress the nth harmonic output, is proposed. A power divider for 2.05 GHz operation has been fabricated and its S-parameters are measured. At 2.05 GHz, the measured S_{11}, S_{21}, S_{22} and S_{23} are -34 dB, -3.3 dB, -39 dB and -42 dB, respectively. At the third harmonic frequency of 6.15 GHz, the measured S_{11}, S_{21}, S_{22} and S_{23} are -0.8 dB, -44 dB, -4 dB and -13 dB, respectively. The results at 2.05 GHz show that the power divider has an equal power split to the output ports, good isolation between the output ports and simultaneous impedance matching at all ports. The measured S_{21} at 6.15 GHz shows a third harmonic suppression of $\sim$ 44 dB. These results indicate that the proposed Wilkinson power divider operates well as a conventional Wilkinson power divider at the operating frequency of 2.05 GHz, while suppressing the 6.15 GHz third harmonic component.

References

[1] E. Wilkinson, "An N-way hybrid power divider," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 116–118, Jan. 1960.
[2] D. M. Pozar, *Microwave Eng.*: Addison-Wesley, 1990, pp. 395–399.
[3] J. Reed and G. J. Wheeler, "A method of analysis of symmetrical four-port networks," *IRE Trans. Microwave Theory Tech.*, vol. MTT-4, pp. 246–252, Oct. 1956.