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Design of compact and broadband Wilkinson baluns using metamaterial phase shifting transmission lines

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Abstract: A compact and broadband Wilkinson balun design incorporating three metamaterial phase shifting transmission lines (MTM-PSTLs) is proposed in this study. The two quarter wavelength lines generally used in a Wilkinson divider are replaced by −90° and +90° MTM-PSTLs for the broadband balun (balun #1) and by +90° and +270° MTM-PSTLs for the compact balun (balun #2). The characteristic impedance of the MTM-PSTLs is 70.7 Ω. To improve isolation characteristics at output ports, a +180° MTM-PSTL with a characteristic impedance of 50 Ω is connected in series with two 50 Ω resistors between the two output ports. The designed baluns have the same size. The measured differential output phase bandwidths (180° ± 10°) are 340 MHz (55%) (445 − 785 MHz) for balun #1 and 62 MHz (30%) (174 − 236 MHz) for balun #2.

Keywords: balun, metamaterials, Wilkinson divider
Classification: Microwave and millimeter wave devices, circuits, and systems

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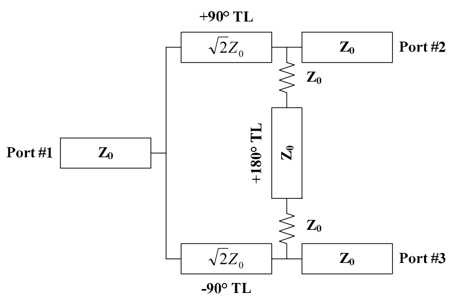
1 Introduction

Recently, various structures such as zeroth order antennas, dual band branch line couplers, compact ring hybrids, and broadband baluns, have been introduced by incorporating metamaterial transmission lines composed of composite right/left handed (CRLH) or LC loaded lines [1, 2]. In general, most of passive circuits in RF/microwave systems are designed by using $-90°$ or $-180°$ phase shifting lines. The use of phase shifters incorporating metamaterial transmission lines (MTM-PSTLs) as introduced in Ref. [3] allows these circuits to achieve size reduction and/or bandwidth extension [4, 5]. The broadband balun introduced in Ref. [4] consists of a Wilkinson divider, followed by $+90°$ and $-90°$ MTM-PSTLs along two output ports, respectively. Although the balun suggested in [4] has a broadband differential output phase bandwidth of 77%, the size of the balun must be increased for lower frequency applications.

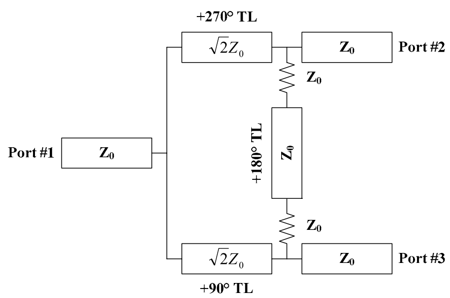
In this paper, we propose a novel design for compact and broadband baluns that corporate three MTM-PSTLs. Even though balun #1 is for UHF band and balun #2 is for VHF band, they have the same size of 70 mm $\times$ 15 mm excluding port areas.

2 Balun design

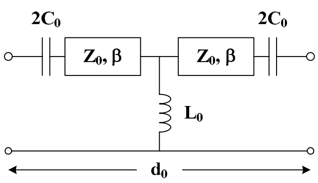
Fig. 1 shows the structures of the proposed baluns using MTM-PSTLs. The quarter wavelength lines generally used in Wilkinson dividers are replaced by $-90°$ and $+90°$ MTM-PSTLs in balun #1 (Fig. 1 (a)), and $+90°$ and $+270°$ MTM-PSTLs in balun #2 (Fig. 1 (b)). The characteristic impedance of the MTM-PSTLs is $\sqrt{2}Z_0 = 70.7\,\Omega$ to achieve differential output phase performance at output ports of designed baluns. The isolation between the two output ports is improved by adding a $+180°$ MTM-PSTL with two series re-



(a) Balun #1



(b) Balun #2



(c) Unit cell of the MTM TL phase shifter

Fig. 1. The proposed baluns structures and unit cell of the MTM TL

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sistances of $Z_0 = 50\,\Omega$ between the two output ports. Three MTM-PSTLs are designed by using the MTM-PSTL unit cell shown in Fig. 1 (c) and applying Eq. (1) [3, 4].

$$\phi = n\left(\omega\sqrt{LC}d_0 + \frac{-1}{\omega\sqrt{L_0C_0}}\right) \tag{1}$$

Here, L and C are the distributed inductance and capacitance of the host TL with propagation constant $\beta = \omega\sqrt{LC}$ and d_0 is its length, while L_0 and C_0 are loading element values. In addition, n is the number of unit cells and ω is the operating frequency. In Eq. (1), the following impedance matching condition must be satisfied: $Z_0 = \sqrt{L_0/C_0} = \sqrt{L/C}$.

Each MTM-PSTL in balun #1 has the following design parameter values;

$$\begin{cases} L_0 = 42\,\text{nH} & C_0 = 8.4\,\text{pF} & d_0 = 6\,\text{mm} & \text{for} + 90^\circ \\ L_0 = 470\,\text{nH} & C_0 = 94\,\text{pF} & d_0 = 16\,\text{mm} & \text{for} - 90^\circ \\ L_0 = 18\,\text{nH} & C_0 = 7.2\,\text{pF} & d_0 = 5\,\text{mm} & \text{for} + 180^\circ \end{cases}$$

For balun #2, each MTM-PSTL has the following design parameter values;

$$\begin{cases} L_0 = 66\text{ nH} & C_0 = 12\text{ pF} & d_0 = 6\text{ mm} & \text{for} + 270^\circ \\ L_0 = 150\text{ nH} & C_0 = 27\text{ pF} & d_0 = 16\text{ mm} & \text{for} + 90^\circ \\ L_0 = 68\text{ nH} & C_0 = 27\text{ pF} & d_0 = 5\text{ mm} & \text{for} + 180^\circ \end{cases}$$

In addition, each MTM-PSTL in the two baluns has 5 unit cells.

3 Experimental results

The designed baluns are implemented on a FR-4 substrate with $\varepsilon_r = 4.4$ and the thickness of 0.8 mm as shown in Figs. 2 (a) and 3 (a). The baluns have the same size in spite of different operating frequencies. Fig. 2 shows the characteristics of the designed balun #1. The 10 dB return loss bandwidths of the balun #1 are 275 MHz (425 − 700 MHz) at port #1, 370 MHz (390 − 760 MHz) at port #2, and 415 MHz (370 − 785 MHz) at port #3 as shown in Fig. 2 (b). Fig. 2 (c) shows the insertion losses (S_{21} and S_{31}) and the isolation (S_{32}). The maximum value of S_{21} and S_{31} are measured to be −3.817 dB and −3.171 dB, respectively. 1 dB bandwidths at each port are 225 MHz (470 − 695 MHz) at port #2 and 185 MHz (465 − 650 MHz) at port #3. The isolation (S_{32}) remains below −10 dB from 380 to 905 MHz. Fig. 2 (d) shows the measured phase responses of two outputs and the differential output phase of the balun #1. It can be observed that the phase slopes of S_{21} and S_{31} are very similar. The differential output phase remains nearly flat over the wide frequency band. The measured differential output phase bandwidth ($180^\circ \pm 10^\circ$) of balun #1 is 340 MHz (55%) from 445 to 785 MHz.

The characteristics of the designed balun #2 are shown in Fig. 3. Balun #2 has 10 dB return loss bandwidths of 86 MHz (134 − 220 MHz) at port #1, 122 MHz (119 − 241 MHz) at port #2, and 87 MHz (149 − 236 MHz) at port #3 as shown in Fig.3 (b). The insertion losses (S_{21} and S_{31}) and the isolation (S_{32}) of balun #2 are shown in Fig. 3 (c). The measured S_{21} and S_{31} values are −3.492 dB and −4.133 dB at the design frequency of 190 MHz, respectively.

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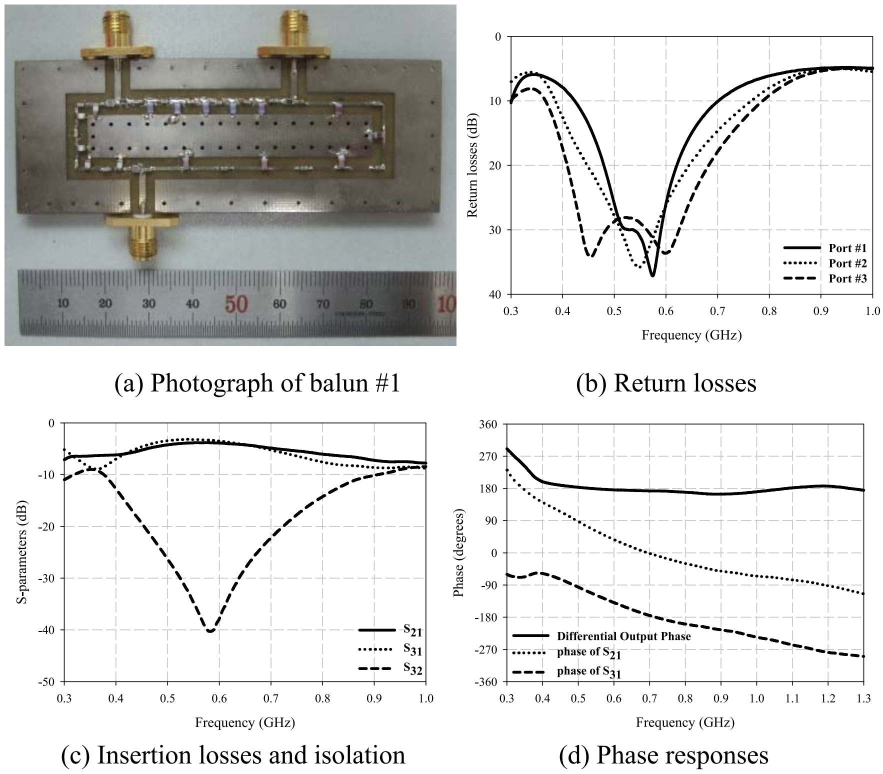
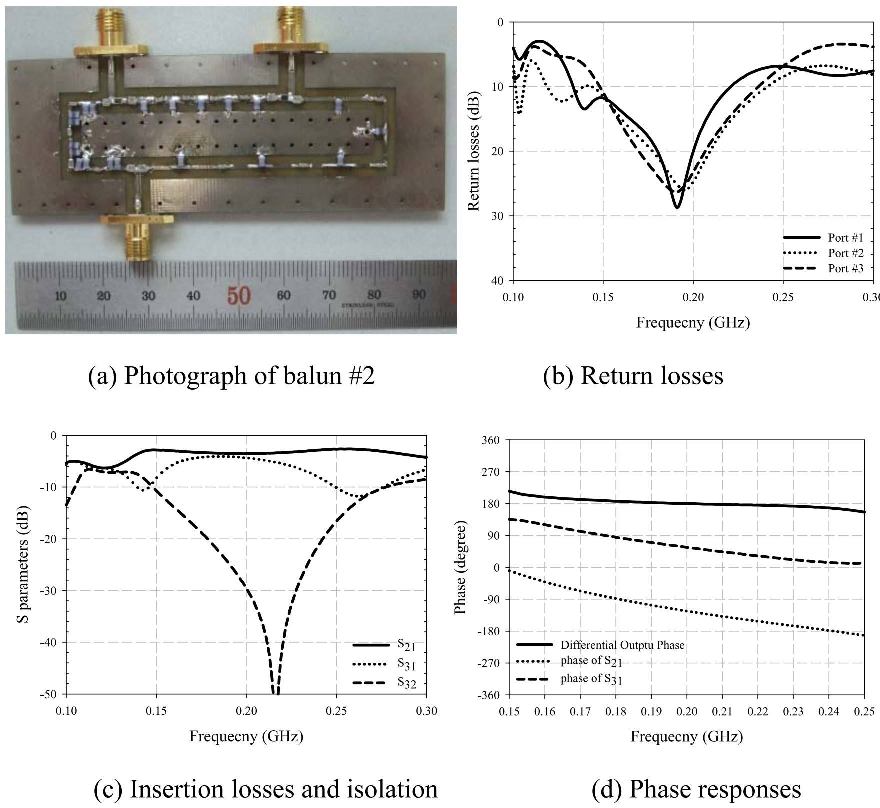


(a) Photograph of balun #1 (b) Return losses

(c) Insertion losses and isolation (d) Phase responses

Fig. 2. The characteristics of balun #1



(a) Photograph of balun #2 (b) Return losses

(c) Insertion losses and isolation (d) Phase responses

Fig. 3. The characteristics of balun #2

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The 1 dB bandwidths at each port are 146 MHz (140 − 286 MHz) at port #2 and 56 MHz (163 − 215 MHz) at port #3. The isolation (S_{32}) remains below −10 dB from 149 to 277 MHz. Fig. 3 (d) shows the measured phase responses of two outputs and the differential output phase of the designed balun #2. It can be observed that the phase slopes of S_{21} and S_{31} are very similar. The differential output phase remains nearly flat over the wide frequency band. The measured differential output phase bandwidth (180° ± 10°) of balun #2 is 62 MHz (30%) from 174 to 236 MHz.

4 Conclusion

In this paper, we introduced a novel design for compact and broadband Wilkinson baluns that incorporated three MTM-PSTLs. Two quarter wavelength lines generally used in Wilkinson divider were replaced by −90° and +90° MTM-PSTLs for balun #1, and +90° and +270° MTM-PSTLs for balun #2. The characteristic impedance of the MTM-PSTLs is 70.7 Ω. To improve the isolation characteristic at the output ports, +180° MTM-PSTL with the characteristic impedance of 50 Ω is connected in series with two 50 Ω resistors between two output ports. The designed baluns have the same size and the measured differential output phase bandwidths (180° ± 10°) of 340 MHz (55%) from 445 to 785 MHz for balun #1and 62 MHz (30%) from 174 to 236 MHz for balun #2, respectively. Although the designed baluns have higher insertion loss than a general balun, they have the same size in spite of different operating frequencies. Furthermore, they have broadband differential output phase bandwidth. Thus, the proposed balun structure can be used for various feeding networks that require a broadband differential input signal including broadband dipole antennas, spiral antennas, and so on.

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