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A MINIATURE CPW BALUN CONSTRUCTED WITH LENGTH-REDUCED 3 dB COUPLES AND A SHORT REDUNDANT TRANSMISSION LINE

Z.-Y. Yeh and Y.-C. Chiang *

Institute of Electronics Engineering, Chang Gung University, No. 259 Wen-Hwa 1st Road, Kwei-Shan, Tao-Yuan 333, Taiwan, R.O.C.

Abstract—This work presents a new type of CPW balun consisting of 3 dB coupled-line sections, which are one eighth wavelength long, and a short redundant transmission line for the applications of the modern wireless communication systems. A set of design equations that can determine the values of the elements of balun is proposed. A new type of coupler constructed with a structure similar to the conventional step impedance resonator is developed to further reduce the size of the balun. An experimental prototype operated at 1.0 GHz was designed and fabricated to verify the proposed design method. The measurement results show quite good correspondences with the theoretical predictions and the EM simulations.

1. INTRODUCTION

Various planar slot antennas, which adopt CPW feeding structures, have been proposed to show their superior performances in multi-band or wideband applications [1–12]. Due to the requirement of lowering common mode noise in the modern wireless communication systems that adopt the receiver chips fabricated with CMOS technology, a RF circuit, namely balun, is needed to transfer the RF signal received from CPW antenna into balanced signals for entering the inputs of the CMOS receiver [13]. The commonly used type of balun is the Marchand balun that is composed of two couplers with quarter wavelength long and the coupling coefficients of 4.8 dB [14–16]. Therefore, the size of the conventional balun is quite large and needs to be realized by using some specially structure for achieving the required

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* Corresponding author: Yi-Chyun Chiang (ycchiang@mail.cgu.edu.tw).

tight coupling. In this paper, a new structure of CPW balun that consists of two 3 dB couplers, which are only one eighth wavelengths long, and a short redundant line is proposed. The total length of the proposed balun is about 60% of the length of the conventional Marchand balun. A set of equations that can calculate the required electric length and the impedance of redundant line of the proposed balun will be derived and described in the next section.

Recently, three types of structures, i.e., step impedance resonators (SIR), floating plate overlay, and both of SIR and floating plates, have been reported for the realizations of the dual-band or the wide-band filters with very compact size [17–26]. Further reducing the size of the coupler, the structure of coupler realized by using three short coupled line sections with different characteristics, which is similar to the conventional step impedances resonator reported in [27] and covered with floating plate overlay, is proposed for constructing the proposed CPW balun with single-layer PCB technology and very compact size. With adopting the length reduction technique and the floating plate overlay structure, the physical size of the proposed balun not only is about one half of the conventional Marchand balun, but also can be easily applied in a modern communication system that uses CPW antenna and CMOS receiver.

To prove the validity of the proposed structure of balun, an experimental prototype operated at 1.0 GHz was designed and fabricated on the FR4 substrate. The size of the experimental prototype is only $34 \times 20\,\text{mm}^2$ that is very compact as compared with the conventional balun fabricated on PCB. The measurements of the experimental prototype show the input return loss is better than 15 dB associated with less than 0.6 dB amplitude imbalance of the balanced ports and the phase difference of $180 \pm 2^\circ$ over the frequency range of 1.0 GHz to 1.36 GHz. The measurements show the validity of the structure of the new type balun and the proposed design equations.

2. DESIGN OF THE MINIATURIZED CPW BALUN WITH $\lambda/8$ 3 dB COUPLERS

Figure 1 depicts the structure of the balun which is composed of two 3 dB CPW couplers with electrical length of one eighth wavelengths and a redundant CPW line with a characteristic impedance of Z_a and an electrical length of θ.

Obtaining the equations to synthesize the circuit shown in Fig. 1, one can cascade the transmission matrices of the components as follows. It is known that the scattering matrix of an ideal 3 dB coupled line

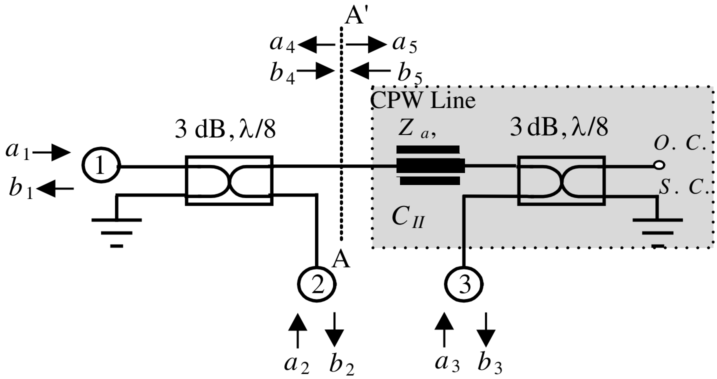

Figure 1. Schematic of the proposed miniature balun with incident and reflected wave variables.

section with one eighth wavelength long is given by

$$S_{coupler} = \begin{bmatrix} 0 & C & 0 & C_T \\ C & 0 & C_T & 0 \\ 0 & C_T & 0 & C \\ C_T & 0 & C & 0 \end{bmatrix}, \tag{1}$$

where C and C_T indicate the transmitted wave ratios at the coupled and through ports and equal to

$$C = \frac{1}{\sqrt{3}} e^{j35.3^\circ} \quad \text{and} \quad C_T = \sqrt{\frac{2}{3}} e^{-j54.7^\circ}, \tag{2}$$

respectively. With applying open- and short-circuited boundary conditions at the proper ends of the coupled line enclosed by the dotted square in Fig. 1, one can reduce the scatting matrix of Eq. (1) into a two port network by terminating through and coupled ports of the coupler with open- and shorted circuit, respectively, and the transmission matrix of such a two-port network is given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_I = \begin{bmatrix} \sqrt{2} & -jZ_0 \\ -jY_0 & 0 \end{bmatrix} \tag{3}$$

Multiplying the matrix of Eq. (3) with the transmission matrix of the transmission line, one can obtain the transmission matrix of the circuit over the right side of the line A-A', which is depicted as C_{II} in Fig. 1, to be

$$\begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}_{II}$$

$$= \begin{bmatrix} A & B \\ C & D \end{bmatrix}_I \cdot \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{CPW}$$
$$= \begin{bmatrix} \sqrt{2} & -jZ_0 \\ -jY_0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & jZ_a \sin\theta \\ jY_a \sin\theta & \cos\theta \end{bmatrix}$$
$$= \begin{bmatrix} \sqrt{2}\cos\theta + Y_a Z_0 \sin\theta & j(\sqrt{2} Z_a \sin\theta - Z_0 \cos\theta) \\ -jY_0 \cos\theta & Z_a Y_0 \sin\theta \end{bmatrix} \tag{4}$$

For calculating the composite matrix of overall balun, it is convenient to transfer the transmission matrix of circuit of C_{II} into the S-parameter matrix as $[S]_{II}$ first. Then the scattering matrix of the circuit over left side of the line A-A' in Fig. 1 with terminating the short-circuited condition at one port of the coupler is obtained as

$$[S]_{III} = \begin{bmatrix} 0 & C & C_T \\ C & -C_T^2 & -CC_T \\ C_T & -CC_T & -C^2 \end{bmatrix} \tag{5}$$

Substituting the boundary conditions of $a_4 = b_5$ and $a_5 = b_4$ at the interface of the line A-A', one can yield

$$\begin{bmatrix} b_1 \\ b_4 \\ b_2 \end{bmatrix} = [S]_{III} \begin{bmatrix} a_1 \\ a_4 \\ a_2 \end{bmatrix}; \quad \begin{bmatrix} b_3 \\ b_5 \end{bmatrix} = [S]_{II} \begin{bmatrix} a_3 \\ a_5 \end{bmatrix} \tag{6}$$

and finally obtain the scattering matrix of the balun as

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = [S]_{balun} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \tag{7}$$

where

$$[S]_{Balun} = \begin{bmatrix} \left[\left(\frac{-A_2+B_2Y_0-C_2Z_0+D_2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) C_T C_T - CC\right] & CC_T\left(\frac{-2A_2-2C_2Z_0}{A_2+B_2Y_0+C_2Z_0+D_2}\right) & C_T\left(\frac{2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) \\ CC_T\left(\frac{-2A_2-2C_2Z_0}{A_2+B_2Y_0+C_2Z_0+D_2}\right) & \left[\left(\frac{-A_2+B_2Y_0-C_2Z_0+D_2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) CC - C_T C_T\right] & C\left(\frac{2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) \\ C_T\left(\frac{2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) & C\left(\frac{2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) & \left(\frac{A_2+B_2Y_0-C_2Z_0-D_2}{A_2+B_2Y_0+C_2Z_0+D_2}\right) \end{bmatrix} \tag{8}$$

and A_2, B_2, C_2 and D_2 in Eq. (8) are the elements of the transmission matrix of the circuit given in Eq. (4), and C and C_T are shown in

Eq. (2). By setting $S_{balun,21} = -S_{balun,31}$ and $S_{balun,11} = 0$, we can obtain one set of equations to find the appropriate characteristics of the CPW line to realize the proposed balun. From the requirement of $S_{balun,21} = -S_{balun,31}$, the equation of $C(A_2 + C_2Z_0) = 1$ is obtained and leads to two equations as follows

$$3\cos\theta + \sqrt{2}Z_a \sin\theta/Z_0 = 3 \tag{9}$$

$$Z_0 \sin\theta/Z_a = 0 \tag{10}$$

Equation (10) implies that shorter electric length and higher characteristic impedance of the CPW line can achieve better amplitude and phase balances between the signals delivered from balanced ports. Then another equation of $S_{balun,11} = 0$ may be applied to determine the characteristics of CPW line for implementing the balun with prefect matching in port 1 as

$$\begin{aligned} &S_{Balun,11} \\ &= C\cdot C\cdot \frac{-A_2 + 3B_2Y_0 - C_2Z_0 + 3D_2}{A_2 + B_2Y_0 + C_2Z_0 + D_2} \\ &= \frac{1}{3}e^{j70.6^\circ}\frac{\left[-\sqrt{2}\cos\theta + \left(\frac{3Z_a}{Z_0} - \frac{Z_0}{Z_a}\right)\sin\theta\right] + j\left(\frac{3\sqrt{2}Z_a}{Z_0}\sin\theta - 2\cos\theta\right)}{\left(\sqrt{2}\cos\theta + \frac{Z_a}{Z_0}\sin\theta\right) + j\left(\frac{\sqrt{2}Z_a}{Z_0}\sin\theta - 2\cos\theta\right)} \\ &= 0 \end{aligned} \tag{11}$$

Unfortunately, no exact solutions of Z_a and θ can be found from the previous equation. However, the previous equation might be changed to find the values of Z_a and θ that can achieve the minimum amplitude of $S_{Balun,11}$ for being able to satisfy the requirements of the communication system as

$$Min\left\{\frac{\left[-\sqrt{2}\cos\theta + \left(\frac{3Z_a}{Z_0} - \frac{Z_0}{Z_a}\right)\sin\theta\right]^2 + \left(\frac{3\sqrt{2}Z_a}{Z_0}\sin\theta - 2\cos\theta\right)^2}{\left[-\sqrt{2}\cos\theta + \left(\frac{3Z_a}{Z_0} - \frac{Z_0}{Z_a}\right)\sin\theta\right]^2 + \left(\frac{\sqrt{2}Z_a}{Z_0}\sin\theta - 2\cos\theta\right)^2}\right\} \tag{12}$$

Assume $Z_a = \alpha Z_0$. The required electric length of CPW line might be determined from Eq. (12) and equal to

$$\tan\theta = \frac{9\sqrt{2}\alpha^3 - \sqrt{2}\alpha}{27\alpha^4 - 6\alpha^2 + 1} \tag{13}$$

According to Eq. (13), the appropriate electric lengths of CPW lines with various characteristic impedances for constructing the balun are depicted in Fig. 2. Because the solution obtained from Eq. (12) is just for minimizing the magnitude of S_{11}, it is necessary to check the achievable return losses of the baluns consisting of $\lambda/8$ 3 dB

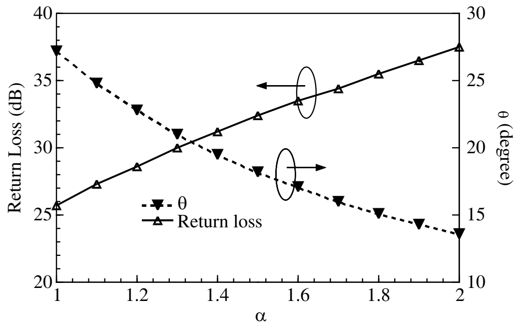

Figure 2. The required electric lengths of CPW lines and the associated return losses the proposed baluns that consist of $\lambda/8$ 3 dB couplers and various characteristic impedances of CPW lines.

couplers and the redundant lines obtained in (13). Bring the results obtained in Eq. (13) into Eq. (8), the return losses of the baluns constructed with various structures are obtained and depicted in Fig. 2 for demonstrating the effectiveness of Eq. (13). As shown, the return losses are greater than 30 dB while a 70 Ω transmission line with 18° electrical length is adopted in the realization of the balun. Such return losses can satisfy most of requirements of the commercial wireless communication systems. Then one can use Eq. (8) and the previously obtained components' values to evaluate other characteristics of the baluns. The amplitude and phase balances of the baluns composed of different elements are illustrated in Fig. 3 for proving the correctness of the proposed design method. It is shown that the higher impedance CPW line of the balun is, the better return loss, amplitude and phase balance of the balun are obtained. However, the balun constructed by using two $\lambda/8$, 3 dB couplers and 70 Ω redundant line can achieve about 0.4 dB amplitude imbalance and smaller than 3° phase imbalance in the assigned operation frequency. The size of the proposed balun is about 60% of the conventional one.

Because a certain separation must be kept in the region between two couplers of the balun to place the redundant line, a new feature of coupler constructed by step impedance coupled-line sections might be adapted to further decrease the overall length of the balun. According to the analysis method proposed in [27], one section of the transmission line having characteristic impedance Z_0 can be replaced by using three sectional microstrips consisting of high and low characteristics of Z_1 and Z_2, respectively, and the required electrical lengths of two kinds of microstrips to approximate the microstrip with characteristic

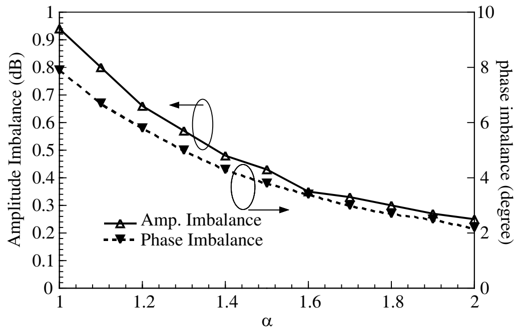

Figure 3. The amplitude and phase balances of the proposed baluns constructed with $\lambda/8$ 3 dB couplers and various characteristic impedances of CPW lines having the electric length obtained from Eq. (13).

impedance of Z_0 are given by

$$\theta_1 = \tan^{-1}\sqrt{\frac{K^2 - M^2}{K^2M^2 - 1}} \tag{14}$$

$$\theta_2 = \cos^{-1}\frac{\sqrt{(K^2M^2 - 1)(K^2 - M^2)}}{M(K^2 - 1)}, \tag{15}$$

where θ_1 and θ_2 represent electrical lengths of the transmission line sections, respectively; K represents the impedance ratio of Z_1 to Z_2; M represents the impedance ratio of Z_1 to Z_0. It is shown that the higher is the value of K, the shorter is the length of stepped-impedance microstrip, i.e., $2\theta_1 + \theta_2$ is obtained. Applying a similar design concept, one can realize a new type of coupler having length-reduced feature, and the top and cross sectional views of such a new coupler are shown in Fig. 4.

In Fig. 4, Z_{e1} and Z_{o1} represent the even and odd mode impedances of the high impedance coupled line sections, and Z_{e2} and Z_{o2} represent the even and odd mode impedances of the coupler with lower characteristic impedance. With assuming C is the desired coupling coefficient of the coupler and kept same in each section, the even and odd mode impedances of coupled line sections with a certain coupling factor are given by

$$Z_{e1} = Z_0 \cdot \sqrt{\frac{1 + C}{1 - C}} \cdot M \tag{16}$$

$$Z_{o1} = Z_0 \cdot \sqrt{\frac{1 - C}{1 + C}} \cdot M \tag{17}$$

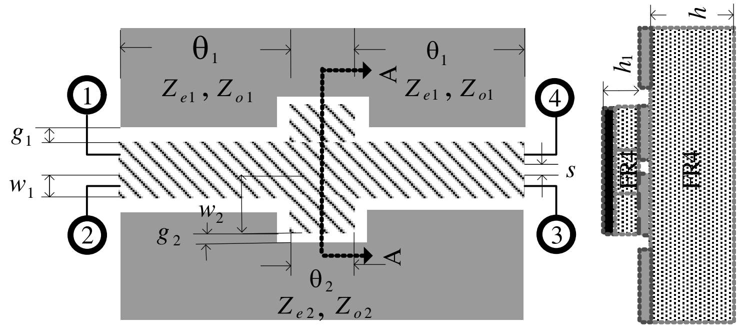

Figure 4. Structure of the CPW coupler realized by using step impedance coupled line sections and floating-plat overlay.

$$Z_{e2} = Z_0 \cdot \sqrt{\frac{1+C}{1-C}} \cdot M/K \tag{18}$$

$$Z_{o2} = Z_0 \cdot \sqrt{\frac{1-C}{1+C}} \cdot M/K \tag{19}$$

The electrical lengths of the coupled lines are determined according to Eqs. (14) and (15). It was shown in [28] that both even and odd mode impedances of a re-entrant coupler vary in almost the same ratio of the widths of the coupled lines, while the coupler adopts a thin dielectric support (h_1) over the coupled line. Therefore, the required even and odd mode impedances of the coupled lines calculated from (16)–(19) can be simply realized by just varying widths of coupling line sections, i.e., W_1 and W_2 in Fig. 4.

3. IMPLEMENTATION OF CPW BALUN WITH LENGTH-REDUCED RE-ENTRANT COUPLERS

The validity of the design method was fulfilled by constructing an experimental prototype of balun operated at about 1 GHz. Based on the proposed design equations and a similar analyzing method proposed in [28], a length-reduced 3 dB CPW coupler was designed and simulated by EM simulator. The experimental coupler was fabricated on a FR4 substrate with a thickness (h) of 1.6 mm and a height (h_1) of the dielectric support of 0.14 mm. The values of K and M are chosen to be 1.7 and 1.2, respectively. The other physical dimensions of the coupler corresponding to Fig. 4 are $W_1 = 0.5$ mm, $W_2 = 1.8$ mm and $S = 0.6$ mm. Fig. 5 depicts the EM simulation results of the CPW coupler operated at second harmonic of the operation frequency of

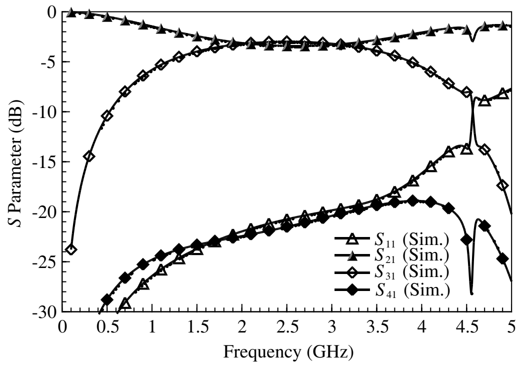

Figure 5. Simulation results of a CPW coupler consisting of three step-impedance coupled line sections.

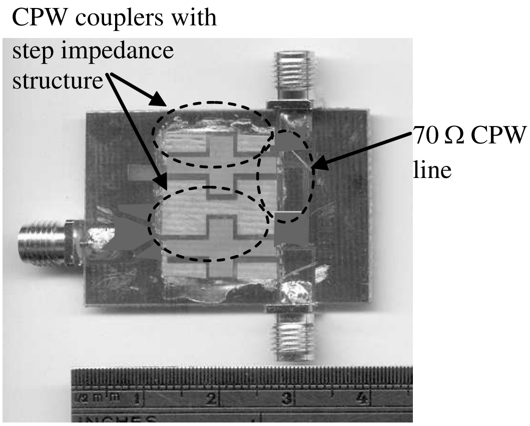

Figure 6. Photograph of the CPW balun constructed by length-reduced couplers on FR4 PCB.

the balun. The simulation results reveal that the coupler has the operation bandwidth of about 50% for achieving the desired 3 dB coupling coefficient and keeping the phase difference of through and coupled ports within $90 \pm 2°$. The length of the coupler can be reduced to 80% of the conventional coupler.

Then an experimental prototype is realized by using two length-reduced coupled line sections constructed with the previously mentioned structures and a short 70 Ω CPW line. Fig. 6 illustrates the photograph of the prototype of the balun constructed on a FR4 substrate. Some parts of the couplers of the balun are invisible because

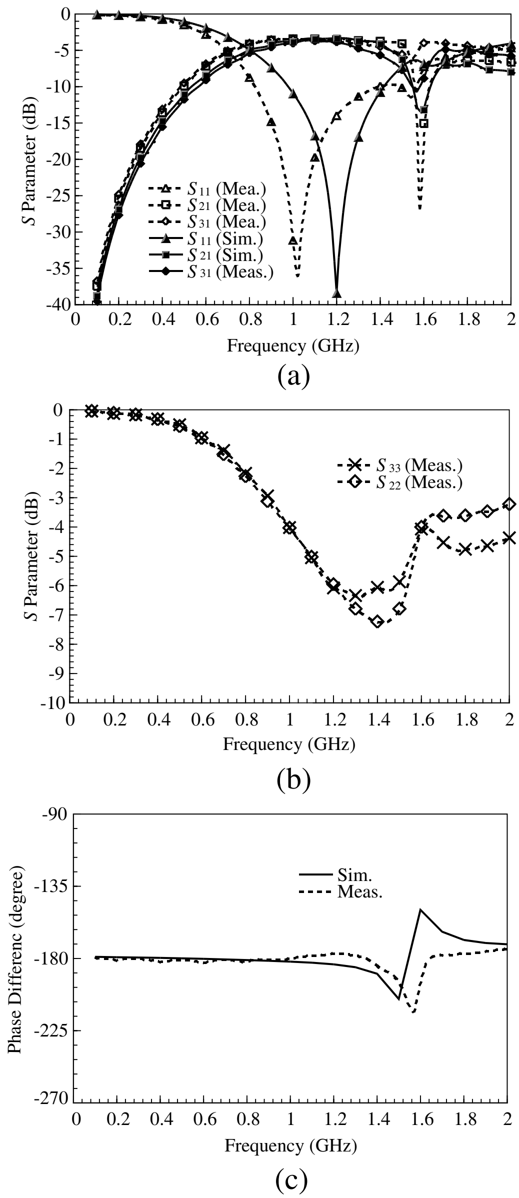

Figure 7. Simulated and measured S-parameters of the balun shown in Fig. 6. (a) S_{11}, S_{21} and S_{31}, and (b) S_{22} and S_{33}. (c) Phase difference between S_{21} and S_{31}.

of being covered by floating plate overlays, which is an up-side-down FR4 substrate with only back side metal and directly adhesive to the lower FR4 substrate. The sizes of floating plates are just larger enough to cover the area of parallel-coupled CPW lines fabricated on the lower substrate. It is shown that one output port of each coupler is connected to the nearest ground for the realization of short-circuit, and the other outputs of the couplers located at the same sides of short-circuited connections are kept in open-circuit and connected to the input launcher, respectively, to implement the practical circuit of the prototype. It is also shown in Fig. 6 that a $70\,\Omega$ CPW line having electric length of $18.0°$ is inserted between two $\lambda/8$ CPW couplers. The overall dimension of the balun prototype is about $34 \times 20\,\text{mm}^2$, which is responding to $0.25\lambda_g \times 0.15\lambda_g$, where λ_g represents the wavelength of $50\,\Omega$ CPW line fabricated on same substrate. The prototype was connected with HP 8753D network analyzer for the S parameters measurement. The measured S parameters are superimposed in Fig. 7, of which the measured insertion losses of balanced ports have less than 0.6 dB magnitude difference and the relative phase difference of less than $3°$ over the frequency range from 1.0 to 1.32 GHz. The measured input return losses are greater than 15 dB over the designed bandwidth. The simulation and measurement results also show quite good correspondences.

4. CONCLUSIONS

The design of a new type of CPW balun constructed with length-reduced re-entrant $\lambda/8$, 3 dB CPW couplers and a redundant line was described. With adopting two kinds of size reduction mechanisms, i.e., the coupled line constructed with the configuration of step-impedance sections and that consisting of two $\lambda/8$ couplers conjugating with a redundant line, the proposed CPW balun is very compact in size and easily fabricated by using commercial single-layer PCB technology. An experimental prototype operated at 1 GHz was fabricated to verify the proposed design concepts. The measurement results are also very close to the theoretical predictions and show that the amplitude imbalance of the output ports can be kept less than 0.2 dB associated with the phase difference of $180 \pm 3°$ over 26% fractional bandwidth.

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