A New Planar Marchand Balun

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Abstract — **In this paper, a novel planar Marchand balun using a patterned ground plane is presented. In the new design, with a slot under the coupled lines cut on the ground plane, the even-mode impedance can be increased substantially. Meanwhile, we propose that two additional separated rectangular conductors are placed under the coupled lines to act as two capacitors so that the odd-mode impedance is decreased. Design theory and procedure are presented to optimize the Marchand balun. As an example, one Marchand balun on a double-sided PCB is designed, simulated, fabricated and measured. The measured return loss is found to be better than −10 dB over the frequency band from 1.2 GHz to 3.3 GHz, or around 100% bandwidth. The measured amplitude and phase imbalance between the two balanced output ports are within 1 dB and 4^0, respectively, over the operating frequency band.**

Index Terms — **Baluns, coupled lines, wideband**

I. INTRODUCTION

Baluns are key components in many wireless communication systems for realizing components such as balanced mixer, push-pull amplifier, and antenna feed networks [1, 2]. Many analog circuits require balanced inputs and outputs in order to reduce noise and high order harmonics as well as improve the dynamic range of the circuits. Various types of baluns have been reported for applications in microwave integrated circuits (MICs) and monolithic microwave integrated circuits (MMICs) [1-8]. Among them, the planar version of the Marchand balun [3] is perhaps one of the most popular because of its ease of implementation and wide bandwidth. The planar Marchand balun consists of two sections of quarter-wave coupled lines, which may be realized using microstrip coupled lines [4], Lange coupler [5], or multilayer coupler structures [6-8].

A strong coupling is required for both the two coupled line sections to obtain a well designed Marchand balun [9]. Also, high even-mode impedances to reject even-mode excitations are required in Marchand baluns for broadband performance [10]. For the edge-coupling structure, the coupling factor is largely dependant on the gap between two coupled lines. For MMICs design, the gap between two coupled lines can be a few micrometers, thus such tight coupling is still achievable in the edge-coupled way [4, 5]. However, for MIC designs using the printed circuit board (PCB) fabrication technology,

Marchand Baluns usually tend to choose broadside coupling lines, or multilayer structures [6-8] to achieve tight coupling, which is high in cost or complex in structure. Therefore, it will be very beneficial if baluns can be implemented using simple microstrip couple lines. In [11], by cascading several of single-layer microstrip coupled-line sections, very high even-mode impedances can be obtained, yielding good balun amplitude and phase balance. Furthermore, the cascading microstrip coupled-lines with a slot cut in the ground plane beneath the coupled lines were proposed to increase the even-mode impedances, and hence improve the coupled-line balun performance in [11].

In this paper, a novel planar Marchand balun using a patterned ground plane is presented. In this new design, with the ground plane under the coupled lines removed similarly as in [11], the even-mode impedance will be increased substantially. Meanwhile, we propose that two additional separated rectangular conductors are placed under the coupled lines to act as two capacitors so that the odd-mode impedance is decreased. The new design is based on the concept that the even-mode impedance of a coupler is mainly relevant to the capacitance of the microstrip conductor to the ground plane, and the odd-mode impedance is relevant to the capacitance between the microstrip conductor and the ground plane as well as the capacitance between the two coupled conductors [12]. Simple design theory and design procedure are presented to optimize the designed Marchand balun. The proposed new design was simulated by the full-wave electromagnetic software Ansoft HFSS and validated by the measurement. Compared with the cascading microstrip multi-section coupled-line baluns with a slot cut in the ground plane [11], our newly proposed planar Marchand balun with a patterned ground plane is small in size and meanwhile has a good performance. As an example, one Marchand balun on a double-sided PCB is designed, simulated, fabricated and measured. The measured return loss is found to be better than −10 dB over the frequency band from 1.2 GHz to 3.3 GHz, or around 100% bandwidth. The measured amplitude and phase imbalance between balanced output ports are within 1 dB and 4°, respectively, over the operating frequency band.

II. THEORETICAL ANALYSIS

The conventional Marchand consists of two symmetrical $\lambda/4$ coupled lines. Fig. 1(a) shows the equivalent circuit of a Marchand Balun when the coupled-line sections are replaced by their admittance matrix. The corresponding Y parameters expressed in terms of the even- and odd-mode characteristic admittances Y_{0e} and Y_{0o} are given as in [13]:

$$Y = \begin{bmatrix} -j\frac{1}{2}(Y_{0e}+Y_{0o})\cot\theta & -j\frac{1}{2}(Y_{0e}-Y_{0o})\cot\theta & j\frac{1}{2}(Y_{0e}-Y_{0o})\csc\theta & j\frac{1}{2}(Y_{0e}+Y_{0o})\csc\theta \\ -j\frac{1}{2}(Y_{0e}-Y_{0o})\cot\theta & -j\frac{1}{2}(Y_{0e}+Y_{0o})\cot\theta & j\frac{1}{2}(Y_{0e}+Y_{0o})\csc\theta & j\frac{1}{2}(Y_{0e}-Y_{0o})\csc\theta \\ j\frac{1}{2}(Y_{0e}-Y_{0o})\csc\theta & j\frac{1}{2}(Y_{0e}+Y_{0o})\csc\theta & -j\frac{1}{2}(Y_{0e}+Y_{0o})\cot\theta & -j\frac{1}{2}(Y_{0e}-Y_{0o})\cot\theta \\ j\frac{1}{2}(Y_{0e}+Y_{0o})\csc\theta & j\frac{1}{2}(Y_{0e}-Y_{0o})\csc\theta & -j\frac{1}{2}(Y_{0e}-Y_{0o})\cot\theta & -j\frac{1}{2}(Y_{0e}+Y_{0o})\cot\theta \end{bmatrix} \quad (1)$$

The coupled-line network enclosed by a dashed line in Fig. 1(a) can be regarded as a three-port one with an admittance matrix Y_{Balun} shown in Fig. 1(b).
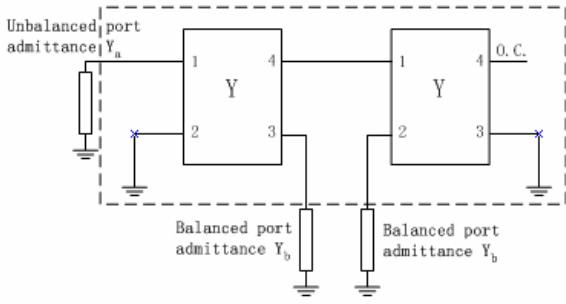
(a) original network
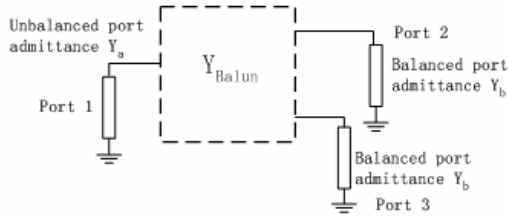
(b) transformed network
Fig. 1 Equivalent circuit of the Marchand balun

With the port assignments defined in Fig. 1, the S-parameters characterizing the Marchand Balun is given by:

$$S_{11} = 0;$$
$$S_{21} = -S_{31} \quad (2)$$

Substitute the obtained S parameters into the equations above, the desired design equation for Marchand Baluns is

$$((Y_{0e} - Y_{0o})\cdot\csc\theta)^4 - 2\cdot(Y_{0e}-Y_{0o})^2\cdot Y_a\cdot Y_b\cdot\csc^2\theta = 0 \quad (3)$$

As the coupled transmission line is $\lambda/4$ ($\theta = 90^0$) in length, the above equation can be simplified as:

$$Y_{0o} - Y_{0e} = \sqrt{2Y_a Y_b} \quad (4)$$

Referring to the equation (4), the desired relationship between Z_{0e} and Z_{0o} for different combinations of the input and output port impedances Z_a and Z_b is plotted in Fig .2(a). Note that for a given set of balun impedances at the input and output port impedances Z_a and Z_b, the even- and odd-mode impedances Z_{0e} and Z_{0o} of the coupled line parameters are not unique.
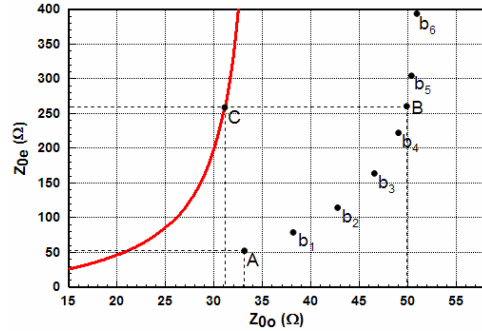
On the other hand, the imbalance of the Marchand balun as in Fig. 1 can be quantified by the ratio of S_{21}/S_{31} as follows [10].

$$\frac{S_{31}}{S_{21}} = -\frac{Z_{0e}-Z_{0o}}{Z_{0e}-Z_{0o}} \quad (5)$$

Equation (5) shows that the ratio of the even- and odd-mode impedances is more crucial for achieving a well designed Marchand balun.
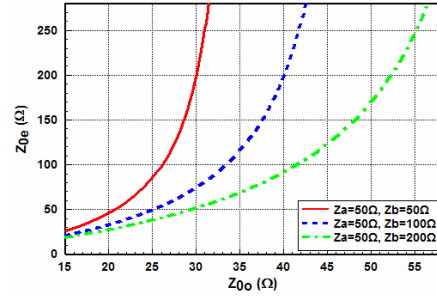
(a) Design curves for different combinations of unbalanced and balanced port impedances

(b) Design procedure for the Marchand balun in Fig. 3, $Z_a = Z_b = 50\Omega$

Fig. 2 Even- and odd-mode impedances Z_{0e} and Z_{0o}

III. DESIGN AND STRUCTURE DESCRIPTION

From the above analysis, a large impedance ratio between the even- and odd- mode impedances of the coupled-line sections is required. For the Marchand balun design on one single-layer and single-side PCB, such a high impedance ratio is hard to be achieved. On the other hand, as we know, the even-mode impedance of a coupler is mainly relevant to the capacitance of the microstrip conductor to the ground plane, and the odd-mode impedance is relevant to the capacitance between the microstrip conductor and the ground plane as well as the capacitance between the two coupled conductors. Therefore, it is easy to know that the major challenge in the edge-coupled Marchand balun designs is about how to

decrease the even-mode capacitance and increase the odd-mode capacitance.

A. Structure

In our new design, we demonstrate the even-mode impedance is not only increased, meanwhile the odd-mode impedance is also decreased. Fig. 3 shows the new Marchand balun. The gray area stands for the metallization on the front side of the PCB, and the dashed line area stands for the metallization on the bottom side of the PCB. In this improved Marchand balun structure, a patterned ground plane is used. With a slot under the coupled lines cut on the ground plane, both the even-mode capacitance and the odd-mode capacitance of the coupled lines will be decreased substantially. However, the decreasing of the even-mode capacitance is much faster that that of the odd-mode capacitance. Meanwhile, two additional separated rectangular conductors are placed under the coupled lines to act as two capacitors so that the odd-mode capacitance is increased. Therefore, a large impedance ratio between the even- and odd-mode impedances can be attained.
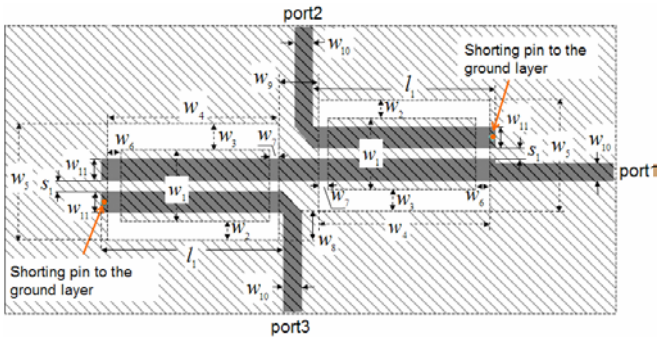

Fig. 3 New planar Marchand balun using a patterned ground plane $w_1 = 4.65$ mm, $w_2 = 4$ mm, $w_3 = 4$ mm, $w_4 = 17.4$ mm, $w_5 = 12.65$ mm, $w_6 = 0.9$ mm, $w_7 = 0.5$ mm, $w_8 = 2$ mm, $w_9 = 4$ mm, $w_{10} = 1.86$ mm, $w_{11} = 2.2$ mm, $l_1 = 18.5$ mm, and $s_1 = 0.15$ mm

B. Design procedure

The physical sizes of the proposed Marchand balun are determined through an optimization procedure. The optimization was carried out with the aid of theoretically calculated values of Z_{0e} and Z_{0o} as in Fig. 2(a). There are four key parameters which are relevant to the values of Z_{0e} and Z_{0o}. These parameters are the width W_{11} of the coupled lines, the line spacing S_1 between the coupled lines, the width W_5 of the slots beneath the coupled lines and the width W_1 of the conductors located under the coupled lines. For convenience, the width and line spacing of the coupled lines are fixed.

The balun was designed on the microwave substrate RO4003 having thickness 0.8 mm and dielectric constant $\varepsilon_r = 3.38$. For the measurement convenience, all the balanced and unbalanced ports impedances are assumed to be 50Ω. In Fig. 2(b), a design procedure is illustrated for this Marchand balun design. The solid line stands for the desired relationship between Z_{0e} and Z_{0o} for a well matched Marchand balun for Z_a

$= Z_b = 50$ Ω. Firstly the coupled lines are set 2.2 mm in width; and according to the PCB fabrication capability, the gap between the coupled lines is set as 0.15 mm. At this stage, with a perfect ground plane under the coupled lines, the even- and odd-mode impedances of the coupled lines can be determined as $Z_{0e} = 52.5$ Ω and $Z_{0o} = 33.1$ Ω, which locate at point A in Fig. 2(b). Then a slot is cut on the ground plane beneath the coupled lines to increase the value of Z_{0e}. The dots (b_1, b_2, b_3, b_4, B, b_5, b_6) denote the trace of Z_{0e} and Z_{0o} with the varying of the width W_5 of the slot. Regarding this movement from b_1 to b_6 as in Fig. 2(b), it is observed that a larger slot width will produce a higher even-mode impedance. However, a wider slot in the ground plane may need a large PCB in size. In this demonstrated design example, point B is chosen with W_5 being 12.65 mm where $Z_{0e} = 260$ Ω and $Z_{0o} = 49.9$ Ω. From Fig. 2(b), Z_{0o} is too big to meet the requirement of a matched Marchand balun. Then two additional conductors are placed under the coupled lines to decrease Z_{0o}. This treatment will not affect the value of Z_{0e} much. The dots c_1 and c_2 between point B and C denote the trace of Z_{0e} and Z_{0o} with the varying of the width of the additional conductors W_1. One well-matched Marchand balun can be achieved with the dimensions at the point C which locates on the solid line of Fig. 2(b) with $Z_{0e} = 260$ Ω and $Z_{0o} = 31.1$ Ω. Table I exhibits the relationship between the even- and odd-mode impedances Z_{0e} and Z_{0o} and the physical dimensions of the coupled lines with a patterned ground plane during the above process from point A to C. Moreover, considering the changing of the even-mode and odd-mode capacitances and the fringing effects of the coupled lines, the length of the coupled line is a little less than one quarter wavelength. For this design, the length of the coupled lines with the center operating frequency being at 2.2 GHz is 18.5 mm. The short circuit is attained through the via holes connected to the ground. More dimensions for the balun are displayed at the figure caption of Fig. 3.

TABLE I

Relationship between the even- and odd-mode impedances Z_{0e} and Z_{0o} and the physical dimensions of the coupled lines with a patterned ground plane as in Fig. 3.

Trace point	W_5(mm)	W_1(mm)	$Z_{0e}(\Omega)$	$Z_{0o}(\Omega)$
A	--	--	52.5	33.1
b_1	2.75	--	81.3	38.2
b_2	4.65	--	115	42.8
b_3	6.65	--	164	46.7
b_4	9.65	--	223	49.1
B	12.65	--	260	49.9
b5	14.65	--	305	50.3
b6	18.65	--	395	51
c_1	12.65	2.35	260	43.1
c_2	12.65	3.35	260	37.2
C	12.65	4.65	260	31.1

IV. RESULTS AND DISCUSSIONS

Figs. 4(a) and (b) show the simulated and measured results for the amplitude response and phase balance of the proposed Marchand balun. The new balun was simulated using Ansoft HFSS v9.0. The measurement was carried out on an HP8510C vector network analyzer. It is observed that good agreement is achieved between measurement and simulation. The measured return loss is found to be around –18 dB from 1.7 GHz to 2.8 GHz and better than –10 dB over the frequency band from 1.2 GHz to 3.3 GHz, or around 100% bandwidth. The measured amplitude and phase imbalance between the two balanced output ports are within 1dB and 4^0, respectively, over the 100% operating frequency band.
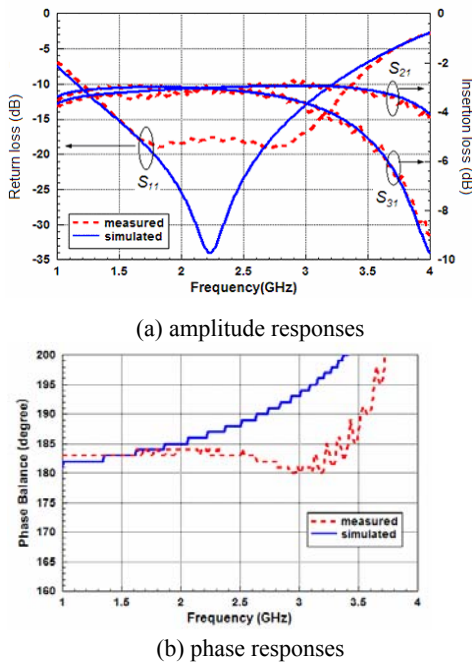

(a) amplitude responses

(b) phase responses

Fig. 4 S-parameters of the proposed Marchand balun

To further demonstrate the merits of the proposed design, two contrast design cases were simulated and compared. Case 1 is that the ground plane under the coupled lines is kept perfect without any removed, i.e. point A in Fig. 2(b), and Case 2 is that the ground plane under the coupled line is removed, but two extra separated conductors under the coupled lines are not added, i.e. point B in Fig. 2(b). From the simulation not shown for brevity, it is observed that, for Case 1, the matching at the unbalanced port S_{11} is very bad over the band and, for Case 2, the matching at the unbalanced port can be improved but the imbalance between the two balanced ports become worse. By the comparison, it is very clear to see the advantages of the proposed design to achieve an improved planar Marchand balun using a patterned ground plane.

Moreover, the radiation effects from the patterned ground plane are investigated by placing one additional ground plane as a virtual system box surface. From the simulation not shown, it can be seen that in our design the interference can be ignored when the distance is larger than 3mm. When the distance is less than 3mm, the smaller the depth of the air cavity is, the stronger the interference is. A value of the cavity depth less than 0.5 mm is not recommended in order to maintain a good performance.

V. CONCLUSION

A new Marchand balun using a patterned ground plane has been presented in this paper. In our new design, we have demonstrated the even-mode impedance has not only increased, meanwhile the odd-mode impedance has also decreased. The proposed structure provides a planar configuration which greatly eases its use in many applications. Design theory and procedure have been presented to optimize the Marchand balun. The novel Marchand balun has been simulated and verified by measurement. The measured results exhibit that the proposed Marchand balun has a bandwidth of around 100%. The measured amplitude and phase imbalances between two balanced ports are within 1dB and 4^0, respectively, over the operating frequency band.

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