New Design Formulas for Asymmetric Coupled-Section Marchand Balun

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***Abstract*—Design formulas for the asymmetric coupled-section Marchand balun are derived. The characteristic impedance, port impedance and electrical length of asymmetrical coupled transmission lines across two layers comprise the design formulas for designing the Marchand balun. A Marchand balun is realized based on the deduced design formulas using two identical asymmetrical coupled transmission lines fabricated across two layers. The conventional approach for designing the Marchand balun exploits the coupling coefficients of coupled transmission lines, and then provides ranges for their characteristic impedances which may but lead to inaccurate design. More accurate design method is established using the design formulas derived without using the coupling coefficients of coupled transmission lines. One example to verify the derived design formulas is taken and fabricated, showing measurement results of bandwidth from 0.62 to 1.44 GHz with the return loss of more than 10 dB, where S_{21} and S_{31} show better than -4 dB. Over these frequencies the measurement results show the phase and amplitude imbalances of $\pm 2^\circ$ and 0.2 dB, respectively.**

***Index Terms*—Asymmetric coupled-line based Marchand balun, design formulas, design method, equivalent circuit.**

I. INTRODUCTION

THE Marchand balun introduced in [1], [2] is now integrated into MMICs as the operating frequencies for RF subsystems approach millimeter-wave frequencies [3]. Thanks to design flexibility, asymmetric coupled transmission lines even across two layers have been adopted for providing tight couplings over coupled sections, leading to bandwidth extension for Marchand balun design. However, explicit design equations are not clear [4], [5]. With coupling coefficient, Marchand balun can be designed based on the procedure presented in [6]. Although [7] and [8] do not use the coupling coefficient, explicit expressions for the design equations are not shown, but just providing available ranges for characteristic impedances of transmission lines. Meanwhile, our previous work failed to build up the equivalent model, leading to inaccurate results [9].

In this letter, explicit design formulas are derived for building Marchand baluns. Without coupling coefficients, characteristic impedance of a transmission line in upper layer over other wide transmission line located in lower layer is derived. The transmission line in lower layer can also be approximated to a single line over the ground layer located under this transmission line where the effect of narrow transmission line in upper layer can be neglected.

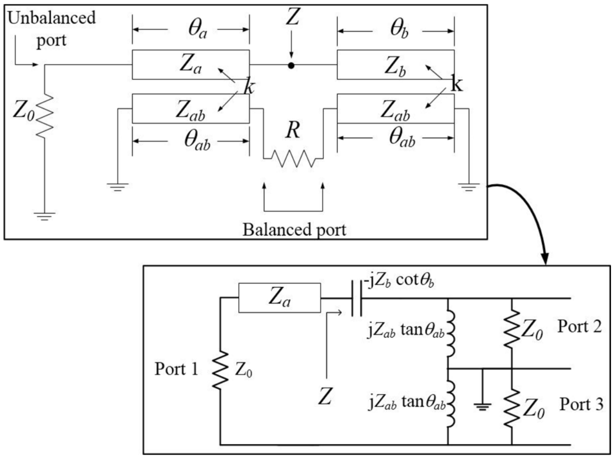

Fig. 1. The conventional Marchand baluns using coupled line sections with equivalent circuit looking into the unbalanced port.

II. DESIGN FORMULAS

The Marchand balun can be represented as shown in Fig. 1 where two coupled sections are exploited for obtaining 3 dB insertion loss and coupling factor *k* determines the physical dimension of the coupled sections. For symmetric coupled section, 3 dB coupling is so tight that this configuration shows a difficulty in obtaining acceptable insertion loss.

Due to this restriction, asymmetric coupled sections crossing two layers may replace the symmetric coupled sections for realistic implementation of 3 dB insertion loss as drawn in Fig. 2 which was designed for this work. The design equation as expressed in (1) has been derived for obtaining physical geometry of asymmetric coupled sections, but leading to inaccurate design [10]

$$Z_{ab} > 2Z_a \geq R = 2Z_0 > Z_b. \tag{1}$$

The equivalent circuit for Fig. 1 looking into the unbalanced port may be drawn as shown where θ_a and θ_{ab} are from 0 to 90° or from 180° to 270°, and the original unbalanced port is propagated back by amount of θ_a from Z [11]. For θ_a and θ_{ab} from 90° to 180° or from 270° to 360°, inductor is transformed to capacitor and capacitor is transformed to inductor.

To derive the explicit design formulas for asymmetric coupled-line based Marchand balun, S-parameters for the equiv-

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alent circuit as in Fig. 1 are calculated as represented in (2), (3) and (4) using $a = j2Z_{ab}\tan\theta_{ab} - jZ_b\cot\theta_b$ and $b = -jZ_b\cot\theta_b$

$$S_{11} = \frac{(a-Z_0)(b^2+2bZ_0+Z_0^2) - 2b(b^2+bZ_0)}{\Delta} \tag{2}$$

$$S_{21} = S_{12} = \frac{b^3 + b(-b^2 + bZ_0 + ab + Z_0^2 + aZ_0 - (b^2+bZ_0)(a-Z_0)}{\Delta} \tag{3}$$

$$S_{31} = S_{13} = \frac{-b^3 - b(-b^2 + bZ_0 + ab + Z_0^2 + aZ_0 + (b^2+bZ_0)(a-Z_0)}{\Delta} \tag{4}$$

where $\Delta = -2b^3 - b^2Z_0 + ab^2 + 2bZ_0^2 + 2abZ_0 + Z_0^3 + aZ_0^2$.

For $S_{11} = 0$,

$$\begin{aligned} Re(S_{11}) = &-4Z_{ab}^2 Z_0 \tan^2\theta_{ab} + 2Z_b Z_{ab} Z_0 \tan\theta_{ab}\cot\theta_b \\ &+ 3Z_{ab}^2 Z_0 \tan^2\theta_{ab} - Z_0^3 = 0 \\ Im(S_{11}) = &\ Z_{ab}^2 Z_b \tan^2\theta_{ab}\cot\theta_b - Z_b Z_0^2 \cot\theta_b = 0. \end{aligned}$$

Therefore,

$$Z_0^2 = Z_{ab}^2 \tan^2\theta_{ab} \tag{5}$$

$$Z_b\cot\theta_b = Z_{ab}\tan\theta_{ab}. \tag{6}$$

Substituting (5) and (6) into (3) and (4), this equivalent circuit satisfies the requirement for balun to work since $S_{21} = 1/\sqrt{2}e^{j225^\circ}$ and $S_{31} = 1/\sqrt{2}e^{j45^\circ}$ leading to $|S_{21}| = |S_{31}| = 1/\sqrt{2}$ and $\angle S_{21} - \angle S_{31} = 180^\circ$. Since Z_a and θ_a can be set not to affect balun performance, they are usually picked equally to Z_b and θ_b, respectively. Also for simplicity, θ_b can be equal to θ_{ab}. Since three parameters are at least to be determined (Z_b, Z_{ab} and θ_b) with a given Z_0, one design freedom for determining these parameters using (5) and (6) is possible. Rearranging (5) and (6),

$$Z_0 = \pm Z_b\cot\theta_b = \pm Z_{ab}\tan\theta_{ab} \tag{7}$$

where '$-$' sign is used when $\cot(\cdot)$ and $\tan(\cdot)$ provide negative values.

From an arbitrary Z_0, the relation between Z_b and Z_{ab} is obtained with appropriately selected θ_b and θ_{ab}. Using (5), Z_{ab} is calculated and Z_b is then calculated dependently using the relation obtained. For these Z_b, Z_{ab}, θ_b and θ_{ab}, an EM simulator is used to produce the physical geometry by taking into account the bandwidth in terms of S_{11}. For bandwidth, S-parameters are computed as illustrated in Fig. 3 using the equivalent circuit in Fig. 1 where θ_b and θ_{ab} can be chosen around 90° for fractional bandwidth of 80%, and Z_b and Z_{ab} are set to values oppositely apart from Z_0.

Using the aforementioned design equation, the physical widths and lengths exhibited in Fig. 4 are synthesized using an EM simulator. W_a is set to W_b, and $l_a = l_b = l_{ab}$ is used for simplifying the design. As shown in Fig. 2, W_a can be obtained by synthesizing the characteristic impedance of Z_a line regarding the wide transmission line located on bottom layer (Z_{ab} line) as the reference layer. W_{ab} can also be obtained by synthesizing the characteristic impedance of Z_{ab} line taking infinitely wide ground layer located at the lowest bottom.

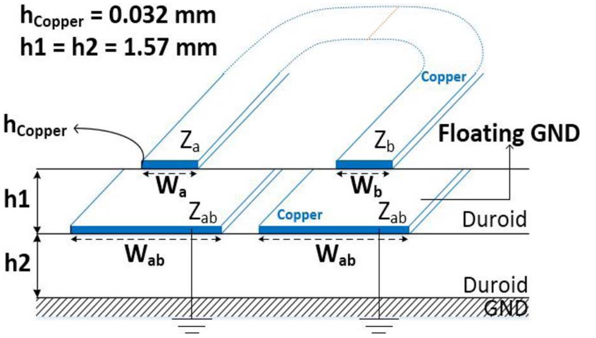

Fig. 2. The physical structure for this work using two-wire transmission lines.

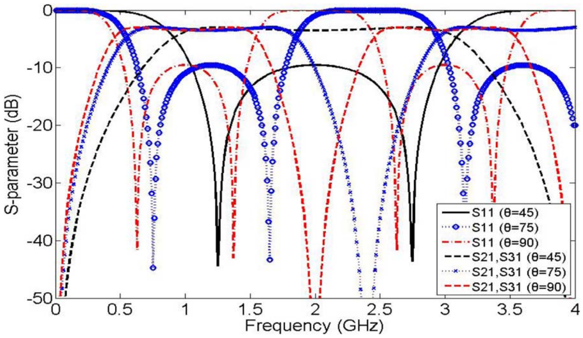

Fig. 3. Calculated S_{11}, S_{21}, and S_{31} varying electrical lengths ($\theta = \theta_a = \theta_b = \theta_{ab}$).

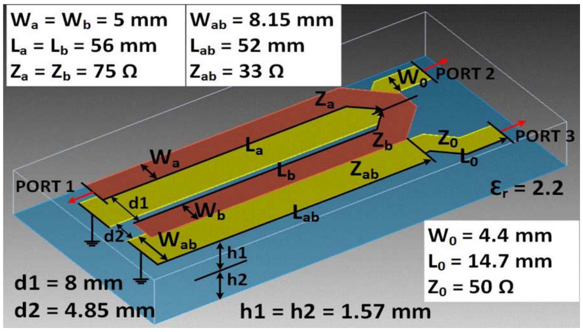

Fig. 4. Physical layout of the designed Marchand balun.

TABLE I
PARAMETERS FOR THE DESIGNED MARCHAND BALUN

Z_a	Z_b	Z_{ab}	W_a	W_b	W_{ab}	l_a	l_{ab}
75 Ω	75 Ω	33 Ω	5 mm	5 mm	8.15 mm	56 mm	52 mm

III. DESIGN OF AN ASYMMETRIC MARCHAND BALUN

Based on the design formulas developed so far, a balun using asymmetric coupled sections crossing two layers is designed as illustrated in Fig. 4. Desired specifications are chosen for center frequency of 1 GHz and bandwidth of about 80%. Physical geometries are achieved as illustrated in Table I where the electrical lengths are set to around 90°, precisely speaking l_a is set a bit longer than l_{ab} due to easy fabrication.

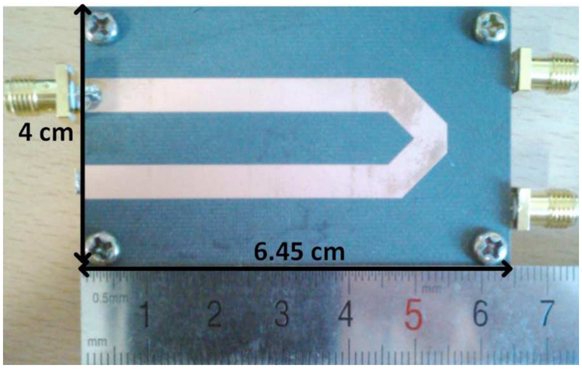

Fig. 5. The photograph of asymmetric coupled-section Marchand balun.

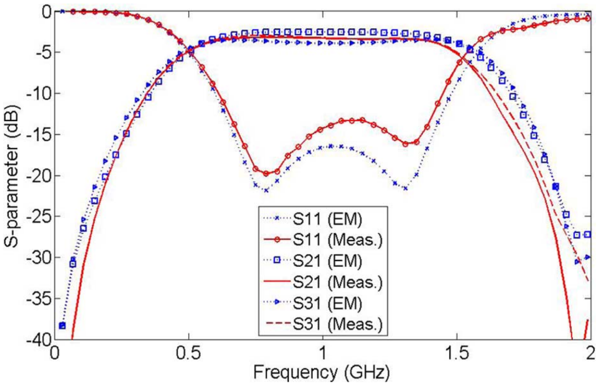

Fig. 6. The measured results of asymmetric coupled-section Marchand balun.

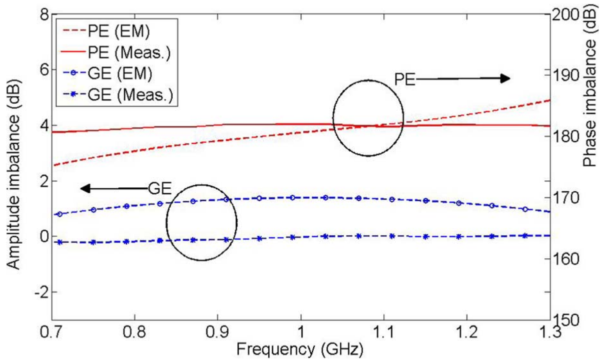

Fig. 7. Amplitude and phase imbalances of asymmetric Marchand balun.

Using the physical geometry obtained here, the asymmetric coupled-section based Marchand balun has been simulated with a full-wave EM simulator. It is found that the insertion loss is 2.4 to 3.1 dB, the amplitude imbalance is within 1.3 dB, and the phase imbalance is less than 5° over the frequency range of 0.7–1.3 GHz where S_{11} is less than -10 dB. The designed balun using the layout depicted in Fig. 4 has been fabricated on Duroid 5880 substrate with ε_r of 2.2, each layer thickness of 1.57 *mm* in 2-layer structure as appeared in Fig. 5. Their S-parameters are measured and plotted in Fig. 6 where S_{11} is less than -10 dB over the frequency range of 0.62–1.44 GHz. The insertion loss is 3 to 4 dB, the amplitude imbalance is less than 0.2 dB, and the phase imbalance is within 2° as shown in Fig. 7. If 3 dB bandwidth is taken in terms of S_{21} and S_{31}, this bandwidth is extended to 0.45–1.53 GHz range which is around 1.1 GHz bandwidth. These measurement results are in fairly good agreement with simulation results.

IV. CONCLUSION

Design formulas for the asymmetric coupled-section based Marchand balun have been presented. The conventional equivalent circuit model is modified for obtaining accurate design equations. The equivalent circuits used in conventional modeling and our previous work have been corrected accurately in this work. The design method shown here using the derived design formulas exploits the characteristic impedances and electrical lengths of coupled sections along with the port impedances. It has been validated by fabricating a design example in two-layer configuration where measurement results are in good agreement with those from an EM simulation and theoretical calculation.

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