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A New Design Approach for Asymmetric Coupled-Section Marchand Balun

Ji An Park · Choon Sik Cho* · Jae Wook Lee

Abstract

A systematic design for asymmetric coupled-section Marchand baluns is presented. Asymmetrically coupled transmission lines in multilayer configuration are exploited for constructing Marchand baluns. Design equations for characteristic impedance and electrical length of asymmetrical coupled transmission lines are derived for establishing a systematic design procedure. Novel Marchand balun based on these design equations is composed of two identical asymmetrical coupled transmission lines. However, contrary to the general conventional design approach where ranges for characteristic impedances of coupled lines are ambiguously capitalized, values for characteristic impedance and length are explicitly expressed. Our approach is fundamentally different from the design method using coupling coefficients where solution for coupling coefficient is inherently restricted. To verify the proposed method, one design example is performed for wideband Marchand balun in multilayer configuration, and is fabricated for verifying the design procedure proposed. Maintaining the return loss more than 10 dB, the bandwidth is measured from 0.43 to 1.0 GHz, where S_{21} and S_{31} show better than -4 dB. The measured phase and amplitude imbalances illustrate 0.5 dB and $\pm 5^\circ$, respectively.

Key Words: Asymmetric Balun, Asymmetric Coupled Transmission Lines, Marchand Balun, Wideband.

I. INTRODUCTION

Due to compact configuration and ease of fabrication, the Marchand balun has been widely used since it was introduced [1–3]. As the operating frequencies for microwave and millimeter-wave systems increase, baluns composed of transmission lines have been integrated with amplifiers, mixers and frequency generators/converters since the balanced operation takes advantages over single-ended operation on various performances, such as noise reduction, power supply stability, and linearity, etc. [4–6]. MMICs are also now integrating this transmission line based baluns with active and passive circuits in single chip because transmission lines can be integrated conveniently for millimeter-wave frequencies. Therefore, more compact designs for baluns are continuously

required for modern microwave and millimeter-wave systems.

The Marchand balun has attracted substantial interest for performing this functionality because this balun can be constructed for very wideband and simple fabrication [7–10]. It is constituted generally using two identical symmetric coupled sections for simplifying the design. Since the symmetric coupled section is mainly characterized by the coupling factor, most of Marchand baluns composed of symmetric coupled sections are established using the design equation for the coupling factor according to design specifications [11–15]. In spite of its relatively easy implementation, Marchand baluns using symmetric coupled sections impose restriction on band extension and adjustability because very tight coupling is needed for wideband and not easy for fabrication. Asymmetric coupled-sections possibly using multilayer con-

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figuration may be employed for overcoming this restriction, however the design procedure will be more complicated compared with simple symmetric coupled section based Marchand baluns [16–18].

Not depending upon the coupling coefficient, Marchand balun can also be designed using the procedure presented in [8] where several sets of design equations are derived and capitalized for designing the asymmetric coupled line based Marchand balun. Although [4] and [19] do not use the coupling coefficient, explicit expression for obtaining the design equations are not shown, but just providing available ranges for characteristic impedances of transmission lines located over multilayers. Therefore, it seems to be quite difficult to obtain the exact design parameters, leading to possibility to distracted design since only ranges for design parameters are given. It is highly desired that the design equations for obtaining circuit configuration be explicitly characterized and the design procedure be clearly defined for asymmetric coupled line based Marchand balun.

In this work, a systematic design for achieving the characteristics of asymmetric coupled transmission lines over two layers is proposed for building the Marchand baluns. We do not use coupling coefficients for the asymmetric coupled lines, instead explicit expression for characteristic impedances is derived. Without using coupling coefficients, characteristic impedance of a transmission line on top layer over other wide transmission line located on bottom layer is derived using the balun requirements. The characteristic impedance of the transmission line on bottom layer can also be calculated assuming that this transmission line is so wide that this can be approximated to a single transmission line with ground layer located below this wide line. Other than characteristic impedances, electrical lengths for the coupled lines are also exploited for design parameters, which is not a general procedure for conventional design for Marchand baluns. In conventional design, electrical length is maintained to be 90° , however, electrical length can be varied for achieving the design specifications in this work, specially related to extending the bandwidth. Newly derived design equations are revealed in Section II, a Marchand balun is designed and evaluated according to the proposed procedure as explained in Section III, and finally conclusion is included in Section IV.

II. DESIGN PROCEDURE

The basic Marchand balun can be represented by using transmission lines as shown in Fig. 1(a) where unbalanced signal enters from A and balanced signal comes out between B and C. This type of balun can be equalized to the circuit as shown in Fig. 1(b) where two coupled sections are exploited for obtaining 3-dB insertion loss and coupling factor k determines the physical dimensions of the coupled sections.

For symmetric coupled sections, even- and odd-mode characteristic impedances are discovered, however, 3-dB cou-

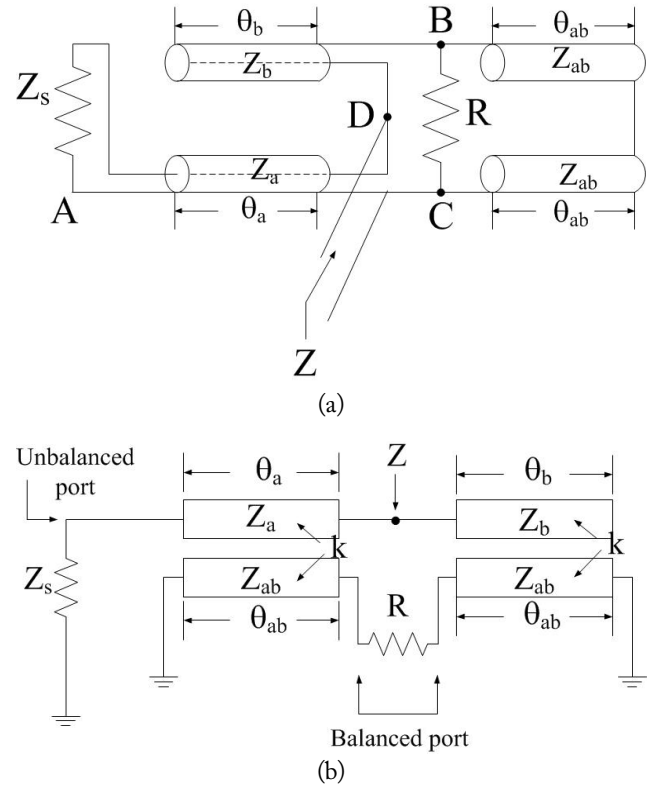


Fig. 1. The conventional Marchand baluns using (a) Transmission lines and (b) coupled line sections.

pling providing an overall 3-dB insertion loss for the coupled sections is so tight that this configuration shows a difficulty in obtaining acceptable insertion loss. Relative signal strengths coming into the unbalanced port and out of the balanced port are represented as in Eq. (1) where k is the coupling factor. As described in Eq. (1), only one solution is available for the coupling factor to achieve zero return loss and 3-dB insertion loss, and in some case unrealistic physical geometry is required.

$$\begin{aligned} \text{Unbalanced} &= \frac{1-3k^2}{1+k^2} \\ \text{Balanced}+ &= j \frac{2k\sqrt{1-k^2}}{1+k^2} \\ \text{Balanced}- &= -j \frac{2k\sqrt{1-k^2}}{1+k^2} \end{aligned} \quad (1)$$

$$Z_{ab} > 2Z_a \geq R > Z_b \quad (2)$$

Due to this restriction, asymmetric coupled-sections over two layers may replace the symmetric coupled sections for realistic implementation of 3-dB insertion loss. Ambiguous design equation expressed in Eq. (2) has been needed conventionally for obtaining physical geometry of asymmetric coupled-sections as derived in [10]. However, Eq. (2) does

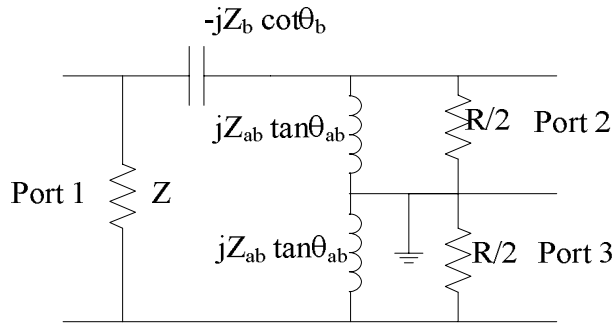


Fig. 2. Equivalent circuit for Marchand balun.

not have to be satisfied if the proposed design approach here in this paper is capitalized as explained later. Since no design equations manifest themselves in explicit expression up to now, it is highly desirable that more obvious representation be derived.

The equivalent circuit for Fig. 1 looking into Z may be redrawn as shown in Fig. 2 where the original unbalanced port can be thought to be propagated back by amount of θ_a from Z [3]. Since the characteristics of balun can be understood mainly in terms of reflection coefficient at the unbalanced port (port 1) and transmission coefficients from unbalanced port to balanced port, three-port $[S]$ -matrix is given as shown in Eq. (3),

$$[S]_{Balun} = \begin{bmatrix} 0 & e^{-j\theta} / \sqrt{2} & -e^{-j\theta} / \sqrt{2} \\ e^{-j\theta} / \sqrt{2} & e^{-j2\theta} / \sqrt{2} & e^{-j2\theta} / \sqrt{2} \\ -e^{-j\theta} / \sqrt{2} & e^{-j2\theta} / \sqrt{2} & e^{-j2\theta} / \sqrt{2} \end{bmatrix}. \quad (3)$$

To derive the explicit design equations for asymmetric coupled-line based Marchand balun, necessary S -parameters for the equivalent circuit as described in Fig. 2 are calculated for balun to work as represented in Eqs. (4)–(6) using $a = j2Z_{ab} \tan \theta_{ab} - jZ_b \cot \theta_b$ and $b = -jZ_b \cot \theta_b$,

$$S_{11} = \frac{(a - Z_0)(b^2 + 2bZ_0 + Z_0^2) - 2b(b^2 + bZ_0)}{\Delta} \quad (4)$$

$$S_{21} = S_{12} = \frac{b^3 + b(-b^2 + bZ_0 + ab + Z_0^2 + aZ_0 - (b^2 + bZ_0)(a - Z_0))}{\Delta} \quad (5)$$

$$S_{31} = S_{13} = \frac{-b^3 - b(-b^2 + bZ_0 + ab + Z_0^2 + aZ_0 + (b^2 + bZ_0)(a - Z_0))}{\Delta} \quad (6)$$

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

From Eq. (3), S_{11} should be zero for this equivalent circuit to work as a balun, therefore real and imaginary parts of S_{11} are zero as deduced in Eqs. (7) and (8). Solving Eqs. (7) and (8), two explicit solutions are derived as seen in Eqs. (9) and

(10).

$$\begin{aligned} \text{Re}(S_{11}) &= -4Z_{ab}^2 Z_0 \tan^2 \theta_{ab} + 2Z_b Z_{ab} Z_0 \tan \theta_{ab} \cot \theta_b \\ &\quad + 3Z_{ab}^2 Z_0 \tan^2 \theta_{ab} - Z_0^3 = 0 \end{aligned} \quad (7)$$

$$\text{Im}(S_{11}) = Z_{ab}^2 Z_b \tan^2 \theta_{ab} \cot \theta_b - Z_b Z_0^2 \cot \theta_b = 0 \quad (8)$$

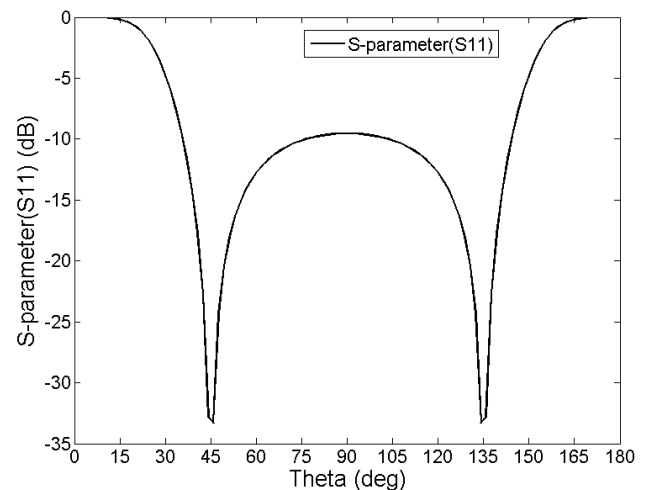
$$Z_0^2 = Z_{ab}^2 \tan^2 \theta_{ab} \quad (9)$$

$$Z_b \cot \theta_b = Z_{ab} \tan \theta_{ab}. \quad (10)$$

Substituting Eqs. (9) and (10) into Eqs. (5) and (6), we can confirm that this equivalent circuit satisfies the requirement for balun to work since $S_{21} = \frac{1}{\sqrt{2}} e^{-j225^\circ}$ and $S_{31} = \frac{1}{\sqrt{2}} e^{j45^\circ}$ leading to $|S_{21}| = |S_{31}| = 1/\sqrt{2}$ and $\angle S_{21} - \angle S_{31} = 180^\circ$. Once Z_b , Z_{ab} , θ_b , and θ_{ab} are determined satisfying Eqs. (9) and (10), physical geometry for balun can be obtained using electromagnetic (EM) simulation programs. Z_a and θ_a do not affect balun equation, so that they can be equalized to Z_b and θ_b , respectively. Since four parameters are to be determined (Z_b , Z_{ab} , θ_b , and θ_{ab}), two design freedoms for determining these parameters using Eqs. (9) and (10) are available. Rearranging Eqs. (9) and (10),

$$Z_0 = \pm Z_b \cot \theta_b = \pm Z_{ab} \tan \theta_{ab}. \quad (11)$$

where 90° for θ_b and θ_{ab} is excluded to determine Z_b and Z_{ab} . In case of 90° both for θ_b and θ_{ab} , the capacitance is shorted and inductances are open, resulting in S_{11} of $1/3$ ($= -9.5$ dB). For $Z_0 = Z_b = Z_{ab}$, the perfect match occurs when $\theta_b = \theta_{ab} = 45^\circ, 135^\circ, 225^\circ$, etc., as drawn in Fig. 3 where the fractional bandwidth based on S_{11} of under -10 dB goes up to 116%. But for Z_b or $Z_{ab} \neq Z_0$, θ_b and θ_{ab} do not need to be same any more, yielding smaller ba-


 Fig. 3. Calculated S_{11} ($\theta = \theta_b = \theta_{ab}$) using Fig. 2 with $Z_0 = Z_b = Z_{ab}$.

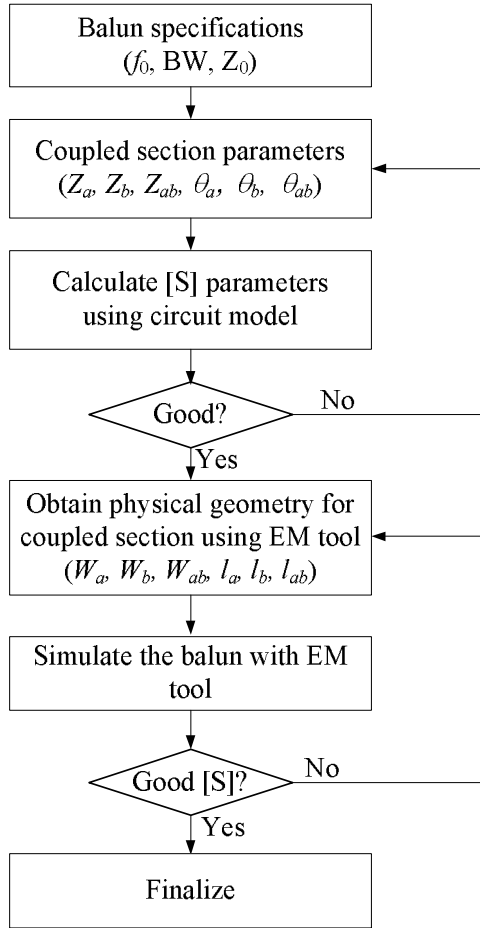


Fig. 4. A design approach for asymmetric coupled-section based Marchand balun.

ndwidth. For a maximum bandwidth, θ_b and θ_{ab} should be maintained close to 90° .

Once Z_b and Z_{ab} are determined initially by considering physical implementation, θ_b and θ_{ab} can be determined as close as possible to 90° by taking into account the desired bandwidth in terms of S_{11} .

A systematic procedure for designing asymmetric coupled-line based Marchand balun is summarized in the flow diagram of Fig. 4 where two steps are used for arriving at the final physical geometry. At the first step, coupled section parameters are decided using Eqs. (9) and (10) from the desired balun specifications. These parameters constitute an equivalent circuit model as in Fig. 2, and S -parameters are calculated for verifying the coupled section parameters. At the second step, the calculated coupled section parameters are exploited to obtain the physical widths and lengths (W_a , W_b , W_{ab} , l_a , l_b , and l_{ab}) as exhibited in Fig. 4. Usually, W_a is set equal to W_b , and $l_a = l_b$ is used for simplifying the design. Extended lines with 50Ω are added to line l_{ab} to connect ports 2 and 3 conveniently to this balun. $W_a (= W_b)$ is obtained by regarding the wide transmission line located on bottom layer of Z_{ab} used as the reference layer, and W_{ab} is obtained as a general transmission line located over a

ground layer where narrow transmission line located on top layer is used for synthesizing W_{ab} .

The characteristic impedance (Z_{ab}) of wide line on bottom layer can be thought to be little deviated from that of a general transmission line since a very narrow line is located on top layer. Therefore, this assumption does not affect the characteristic impedance of wide transmission line on bottom layer.

III. DESIGN OF THE ASYMMETRIC MARCHAND BALUNS

Based on the design procedure developed in Section II, a balun using asymmetric coupled-sections over two layers is designed varying characteristic impedances as illustrated in Fig. 5. Desired specifications are chosen as listed in Table 1. Design parameters and physical geometries for the design example are achieved as illustrated in Table 2 where the electrical lengths (θ_a and θ_b) are initially set to 90° at the center frequency of 0.9 GHz as a design freedom. Using Figs. 2 and 3, $\theta_b = 75^\circ$ and $\theta_{ab} = 105^\circ$ are then optimized with the pre-selected $Z_b = 75 \Omega$ and $Z_{ab} = 33 \Omega$. It is found

Table 1. Desired balun specifications

Center frequency (f_0)	Bandwidth	Z_0
0.9 GHz	> 50%	50 Ω

Table 2. Parameters for design example of asymmetric coupled-section based balun

Parameter	Value
Z_a	75 Ω
Z_b	75 Ω
Z_{ab}	33 Ω
W_a	4.6 mm
W_b	4.6 mm
W_{ab}	8.15 mm
l_a	65 mm (75° at f_0)
l_{ab}	85 mm (105° at f_0)

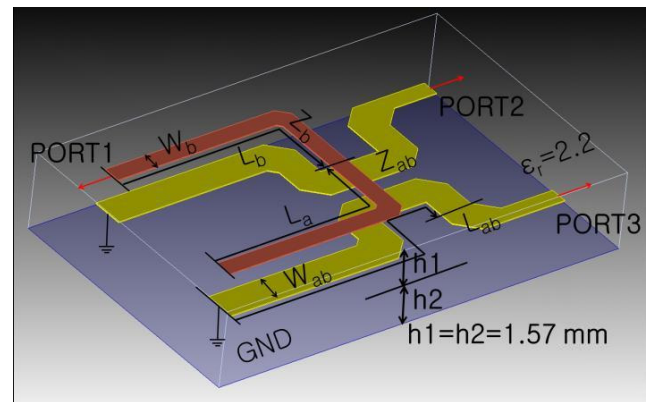


Fig. 5. The physical layout of asymmetric coupled-section based Marchand balun.

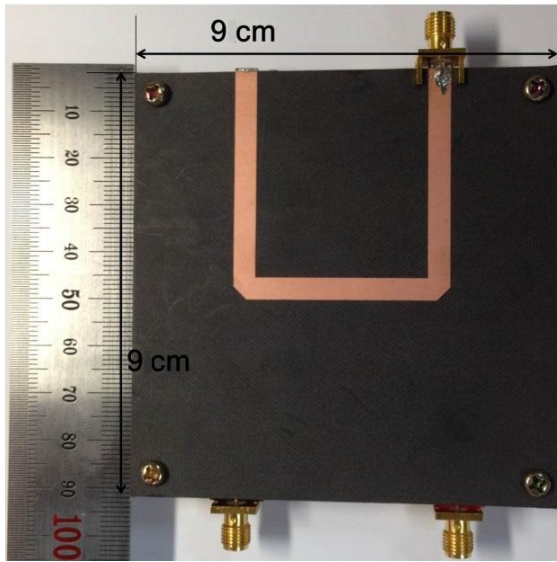


Fig. 6. The photograph of asymmetric coupled-section based Marchand balun.

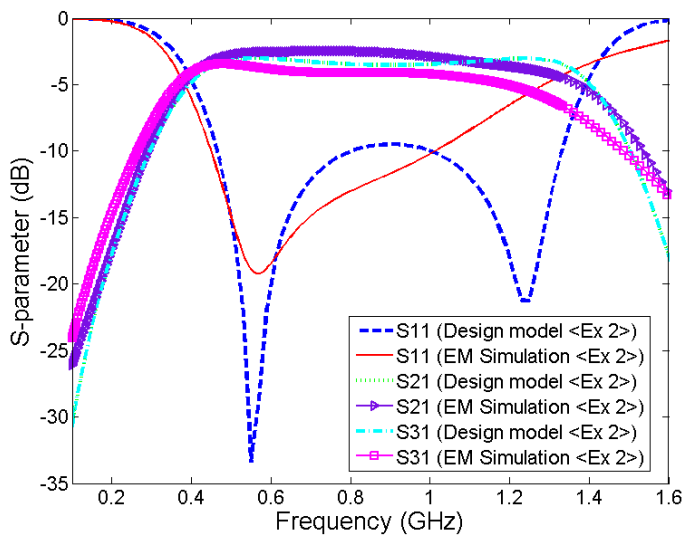


Fig. 7. S -parameters from the equivalent model compared with electromagnetic (EM) simulation for a design example.

that the relation between characteristic impedances is completely different from Eq. (2), therefore, a large number of freedoms in choosing design parameters are available.

Using the physical geometry obtained here, an asymmetric coupled-section based Marchand balun has been simulated on a full-wave EM simulator. S -parameters obtained from an EM simulator are displayed as shown in Fig. 6, and compared with those calculated from the equivalent circuit model as in Fig. 2. It is seen that the insertion loss is -3.2 to -2.5 dB, the amplitude imbalance is within 1.5 dB, and the phase imbalance is less than 5° over the frequency range of 0.5 to 1.0 GHz where $|S_{11}|$ is less than -10 dB. Although S_{11} obtained from an EM simulator shows disagreement in the higher frequency, S_{21} and S_{31} exhibit considerably outstanding result.

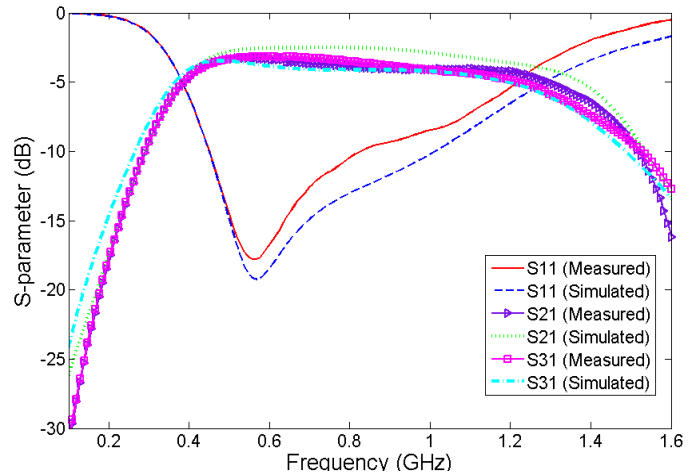


Fig. 8. The measured results of asymmetric coupled-section based Marchand balun.

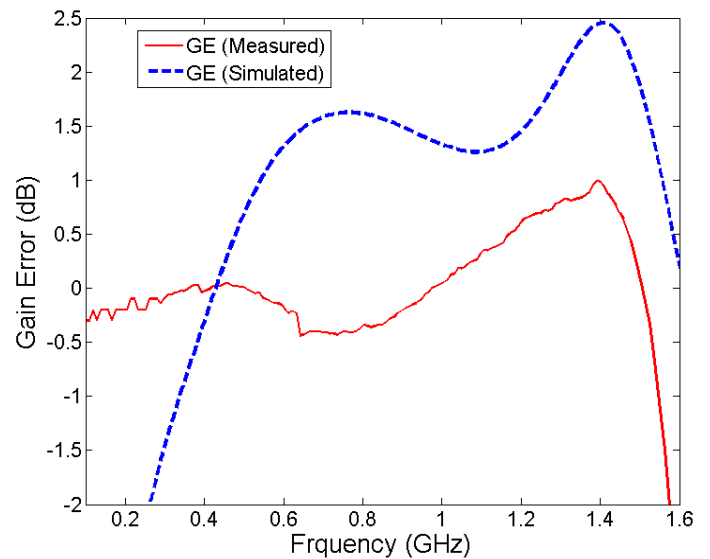


Fig. 9. Amplitude imbalance of asymmetric coupled-section based Marchand balun. GE = gain error.

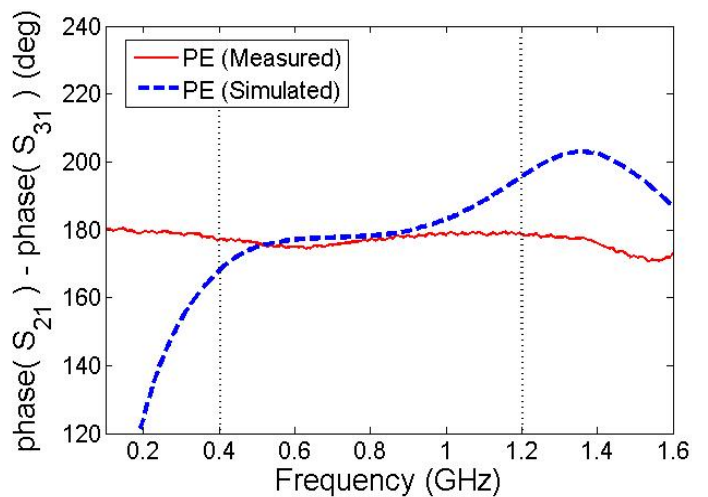


Fig. 10. Phase imbalance of asymmetric coupled-section based Marchand balun. PE = phase error.

The proposed balun using the layout depicted in Fig. 5 has been fabricated on Duroid 5880 substrate with dielectric constant of 2.2 and each layer thickness of 1.57 mm in two layer structure as shown in Fig. 6. Fig. 7 demonstrates S-parameter results from equivalent model and EM simulation. Deviation at the upper band is originated from the fact that Z_a and Z_b used 75 Ω , resulting in some reflection with 50 Ω input ($= Z_s$). Their S-parameters are measured and plotted in Fig. 8, $|S_{11}|$ is less than -10 dB over the frequency range of 0.43 to 1.0 GHz. The insertion losses are measured as -3.9 to -3.2 dB as in Fig. 8, the amplitude imbalances are measured less than 0.5 dB, and the phase imbalances are within 5° as shown in Figs. 9 and 10 (within vertically dashed lines), respectively. If 3-dB bandwidth is taken in terms of S_{21} and S_{31} , the bandwidth is extended to 0.38 to 1.4 GHz range which is around 1 GHz bandwidth. These measurement results are in fairly good agreement with EM simulation results. Two factors affected the frequency response of this balun: 1) since Z_a of 75 Ω is used, S_{11} seen at port 1 is 0.2 ($= -14$ dB) at 0.9 GHz when Z is matched to 75 Ω , and S_{11} deviates away from this value as frequency goes up; 2) since the difference of L_{ab} and L_a (or L_b) exists leading to significant effect at the high frequency, this yields degradation of S_{11} at higher frequency as shown in Figs. 8–10.

The air gap between top and bottom layers has been fabricated and assembled to be kept very little. We watched measured performance by changing the intensity of tightening screws at the corners, but not much difference has been come up with.

IV. SUMMARY

A design approach for the asymmetric coupled-section based Marchand balun has been presented along with design equations. An equivalent circuit model is exploited for evaluating the initial balun design before synthesizing the physical layout. The analytical procedure provides explicit relation between characteristic impedances of couples sections instead of using coupling factor which has been widely used conventionally. Physical geometry for coupled section is achieved by synthesizing the characteristic impedance of coupled line through an EM simulator.

This approach was validated by taking a design example for asymmetric coupled-section based Marchand balun. This balun was designed using two layers where unbalanced port is located on top layer, balanced port is located on bottom layer, and ground is underneath the bottom layer. One design was fabricated and measured to confirm the proposed design approach. Experimental results are compared with those from an EM simulator where both show good agreement as desired.

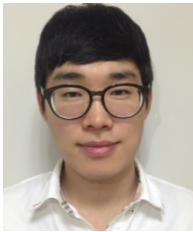
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REFERENCES

- [1] N. Marchand, "Transmission-line conversion transformers," *Electronics*, vol. 17, no. 12, pp. 142–145, Dec. 1944.
- [2] D. A. Dunn, J. W. Mclaughlin, and R. W. Grow, "A wide-band balun," *IRE Transactions on Microwave Theory and Techniques*, vol. 6, no. 3, pp. 314–316, Jul. 1958.
- [3] G. Oltman, "The compensated balun," *IEEE Transactions on Microwave Theory and Techniques*, vol. 14, no. 3, pp. 112–119, Mar. 1966.
- [4] H. K. Chiou and T. Y. Yang, "Low-loss and broadband asymmetric broadside-coupled balun for mixer design in 0.18 μm CMOS technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 4, pp. 835–848, Apr. 2008.
- [5] D. A. A. Mat, R. K. Pokharel, R. Sapawi, H. Kanaya, and K. Yoshida, "60 GHz-band on-chip Marchand balun designed on flat and patterned ground shields for millimeter-wave 0.18 μm CMOS technology," in *Proceedings of the Asia-Pacific Microwave Conference*, Melbourne, Australia, 2011, pp. 884–887.
- [6] P. H. Tsai, Y. H. Lin, J. L. Kuo, Z. M. Tsai, and H. Wang, "Broadband balanced frequency doublers with fundamental rejection enhancement using a novel compensated marchand balun," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 1913–1923, May 2013.
- [7] X. Lan, F. Fong, M. Kintis, K. Kono, D. Yamauchi, W. B. Luo, and D. Farkas, "An ultra-wideband balun using multi-metal GaAs MMIC technology," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 8, pp. 474–476, Aug. 2010.
- [8] J. X. Liu, C. Y. Hsu, H. R. Chuang, and C. Y. Chen, "A 60-GHz millimeter-wave CMOS Marchand balun," in *Proceedings of the IEEE Radio Frequency Integrated Circuits Symposium*, Honolulu, HI, 2007, pp. 445–448.
- [9] M. J. Chiang, H. S. Wu, and C. K. C. Tzuang, "A compact CMOS Marchand balun incorporating meandered multilayer edge-coupled transmission lines," in *Proceedings of the IEEE MTT-S International Microwave Symposium*, Boston, MA, 2009, pp. 125–128.
- [10] V. Govind, W. Yun, V. Sundaram, M. Swaminathan, S. Dalmia, and G. White, "Analysis and design of compact wideband baluns on multilayer liquid crystal-line polymer (LCP) based substrates," in *Proceedings of the IEEE MTT-S International Microwave Symposium*, Long Beach, CA, 2005, pp. 543–546.
- [11] C. Y. Ng, M. Chongcheawchamnan, and I. D. Robertson, "Analysis and design of a high-performance planar Marchand balun," in *Proceedings of the IEEE MTT-S International Microwave Symposium*, Seattle, WA, 2002, pp. 113–116.

- [12] K. S. Ang and I. D. Robertson, "Analysis and design of impedance-transforming planar Marchand baluns," *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 2, pp. 402–406, Feb. 2001.
- [13] C. S. Lin, P. S. Wu, M. C. Yeh, J. S. Fu, H. Y. Chang, K. Y. Lin, and H. Wang, "Analysis of multi-conductor coupled-line Marchand baluns for miniature MMIC design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 55, no. 6, pp. 1190–1199, Jun. 2007.
- [14] C. W. Tang, W. D. Cheng, J. W. Wu, and Y. C. Lin, "Design of a compact balun with three octant-wavelength coupled lines," in *Proceedings of the IEEE MTT-S International Microwave Symposium*, Anaheim, CA, 2010, pp. 109–112.
- [15] H. R. Ahn and S. Nam, "New design formulas for impedance-transforming 3-dB Marchand baluns," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 11, pp. 2816–2823, Nov. 2011.
- [16] R. Schwindt and C. Nguyen, "Computer-aided analysis and design of a planar multilayer Marchand balun," *IEEE Transactions on Microwave Theory and Techniques*, vol. 42, no. 7, pp. 1429–1434, Jul. 1994.
- [17] R. Michaelsen, T. Johansen, K. Tamborg, and V. Zhurbenko, "A modified Marchand balun configuration with tunable phase balance," *IEEE Microwave and Wireless Components Letters*, vol. 23, no. 2, pp. 66–68, Feb. 2013.
- [18] C. H. Tseng and Y. C. Hsiao, "A new broadband Marchand balun using slot-coupled microstrip lines," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 3, pp. 157–159, Mar. 2010.
- [19] T. G. Ma and Y. T. Cheng, "A miniaturized multilayered Marchand balun using coupled artificial transmission lines," *IEEE Microwave and Wireless Components Letters*, vol. 19, no. 7, pp. 446–448, Jul. 2009.

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