Broadband Monolithic Passive Baluns and Monolithic Double-Balanced Mixer

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***Abstract*—This paper presents the design and fabrication of four broadband monolithic passive baluns including CPW Marchand, multilayer MS Marchand, planar-transformer and broadside-coupled line baluns. Operational frequencies range from 1.5 GHz to 24 GHz. Maximum relative bandwidths in excess of 3:1 are achieved. Simulated performances using full wave electromagnetic (EM) analysis are in good agreement with the measured results. Also, two accurate equivalent circuit models constructed from either EM simulated or measured s-parameters are developed for the MS Marchand and transformer baluns making the optimization of baluns and circuit design using the baluns much more efficient. Additionally, the design of a monolithic double-balanced diode mixer using two planar-transformer baluns is also presented. Without dc bias, the mixer shows a minimum conversion loss of 6 dB with the RF at 5 GHz and a LO drive of 15 dBm at 4 GHz. The measured input IP_3 of this mixer is better than 15 dBm over the 4 to 5.75 GHz frequency band.**

Introduction

BALUNS are required in a variety of important microwave components such as balanced mixers, push-pull amplifiers, multipliers, and phase shifters. As monolithic microwave integrated circuit technology advances, the need for broadband monolithic baluns that can be fabricated with the same technology becomes evident. Although multi-octave distributed active baluns [1] have been reported, they not only consume dc power but suffer from high noise figure, high spurious responses, low power handling capability, and low 3rd order intermodulation intercept point. Therefore a broadband monolithic passive balun is an indispensable element in realizing high performance and low risk MMIC's. This paper reports four different monolithic passive baluns designed with a full-wave EM analysis [2]. We also report a monolithic double-balanced diode mixer which incorporates two of the planar-transformer baluns and two accurate models for the Marchand balun and transformer balun, respectively.

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IEEE Log Number 9103929.

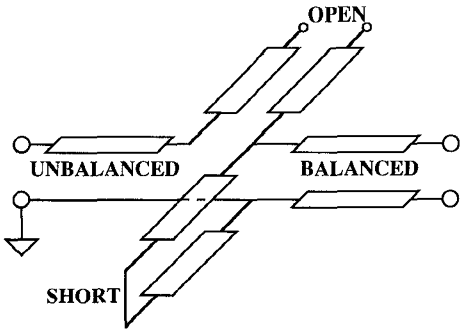


Fig. 1. Simplified equivalent circuit of a fourth-order Marchand balun.

Balun Designs

Marchand Compensated Baluns: The fourth-order Marchand compensated balun [3], [4] consists of an unbalanced, balanced, compensation open-circuited, and two compensation short-circuited transmission lines. Each transmission line is a quarter wavelength at the center frequency of the operating band. Fig. 1 shows the simplified equivalent circuit of the fourth-order Marchand balun. The two short-circuited transmission lines are shunted across the balanced load and thus their characteristic impedances are made as large as possible. These impedances along with the remaining transmission lines' impedances determine the bandwidth and the impedance transformation between the unbalanced and the balanced ports. However, the bandwidth is primarily limited by the highest achievable impedance ratio between the short-circuited and open-circuited lines. In this design, the Marchand baluns are realized in two different structures: the uniplanar CPW/slot-line Marchand balun and multilayer Marchand balun [5] structures.

The uniplanar CPW Marchand balun utilizes CPWs as unbalanced and open-circuited lines and slot-lines as balanced and short-circuited lines. The slot-line to CPW transitions are provided for the balanced lines so that the balun can be on-wafer tested. The uniplanar CPW Marchand balun is designed to transform a 50 Ω unbalanced impedance to a 100 Ω balanced impedance. The line impedances of this balun are 25 Ω for the open-circuited line, 65 Ω for the unbalanced line, 76 Ω for the balanced

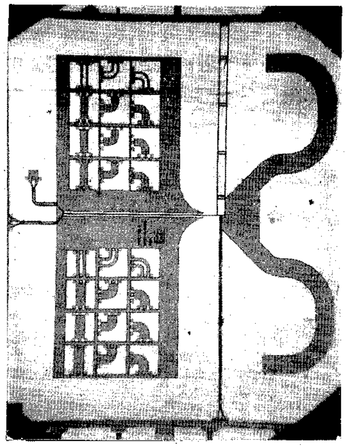


Fig. 2. Photograph of a uniplanar CPW Marchand balun (two sets of CPW on-wafer calibration impedance standards were also included on the balun chip)

lines and 200 Ω for the short-circuited lines. The characteristic impedances of the open-circuited and short-circuited lines are different from their optimal impedances of 20 Ω and 250 Ω, respectively, due to their realizable physical dimensions. Fig. 2 shows a photograph of the uniplanar CPW Marchand balun. The chip size is 5×4.8 mm^2.

In the multilayer MS Marchand balun, the two balanced lines are omitted from the physical circuit making it a third-order Marchand balun. To realize the other three transmission lines, a three-layer conductor structure is used. The structure consists of a backside, first interconnect, and air-bridge metallizations with the first interconnect and the air-bridge metallizations separated by a 3 μm thick SiO_2. The two short-circuited lines are realized by using the first interconnect metal lines between the SiO_2 layer and GaAs substrate. Their short terminations are provided with the through-substrate via holes. As to the unbalanced line and open-circuited line, they are constructed using the air-bridge metal lines landed on top of the SiO_2 layer. Air-bridges are used for these two lines to provide a smooth landing from top of the SiO_2 layer to top of the substrate. Fig. 3 shows a SEM photograph of the air-bridges spanning the 3 μm step from top of the SiO_2 layer to top of the substrate. The line impedances of the multilayer MS Marchand balun are designed to be 23 Ω for the open-circuited line, 63 Ω for the unbalanced line and 67 Ω for the short-circuited lines. The low characteristic impedance of the short-circuited line which is limited by the realizable line width is the major performance-limiting factor of the balun. Our simulations show that the bandwidth can be slightly increased by using a 10 mil instead of 3 mil thick substrate. Fig. 4 shows a photograph of the multilayer MS Marchand baluns, where all transmission lines are meandered to save space. The balun along with the RF probe pads measures 2.9×1.5 mm^2.

Planar-Transformer Baluns: The planar-transformer balun consists of two oppositely wrapped twin-coil transformers connected in series. One of the two outer nodes in the primary coils and the inner common node in the secondary colis are grounded. Fig. 5 shows a simplified circuit diagram and a photograph of a rectangular spiral transformer. The chip measures 1.4×1.1 mm^2 which is very small compared to other types of broadband baluns. The resonant frequency of the spiral coil divides the operating frequencies of the transformer balun into two regions: the magnetic coupling region (frequencies below the resonant frequency) and the magnetic/electric coupling region (frequencies above the resonant frequency) [6]. The former region is usually more useful because of its wider relative bandwidth. In this region, the inductance and the resonant frequency of the spiral coil are the two bandwidth-limiting factors. The coil inductance sets the lower limit of the frequency band while the resonant frequency sets the upper limit. Therefore, the bandwidth

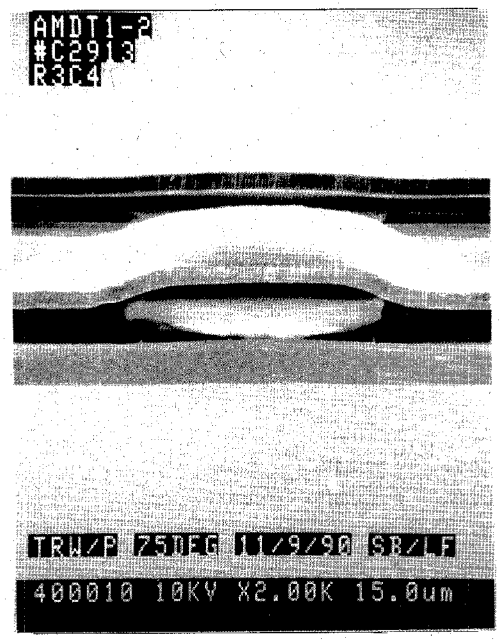


Fig. 3. SEM photograph of the air-bridges spanning the 3μm step from top of the SiO2 layer to top of the GaAs substrate.

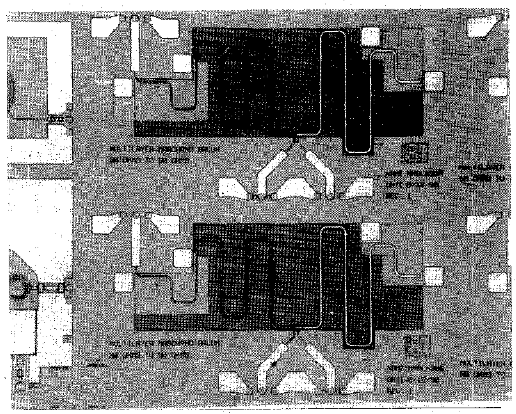
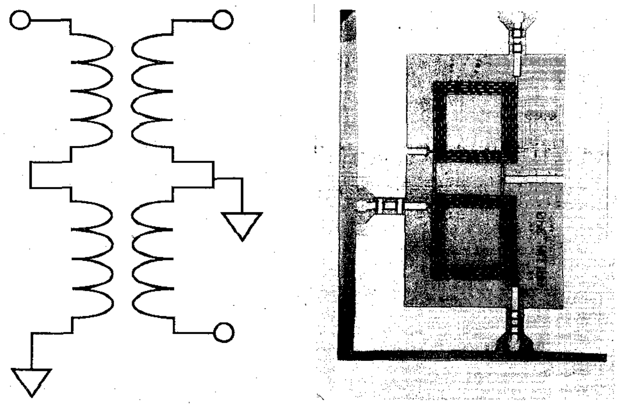


Fig. 4. Photograph of two identical multilayer MS Marchand baluns which have different output ports terminated with on-chip resistors.



(a) (b)

Fig. 5. (a) Simplified circuit diagram. (b) Photograph of a rectangular spiral transformer.

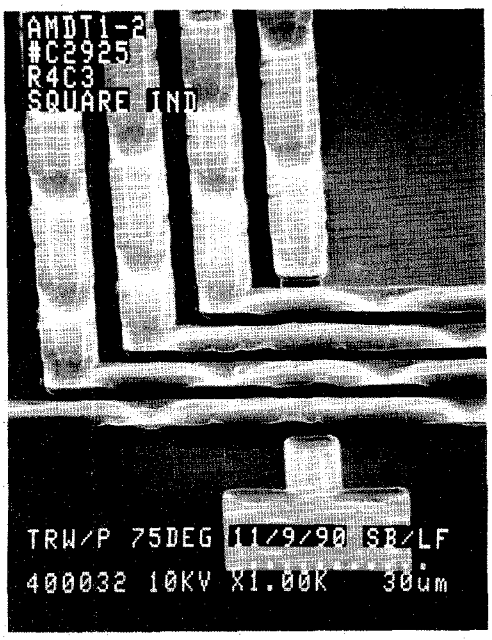


Fig. 6. SEM photograph of a rectangular spiral coil constructed with air-bridged lines.

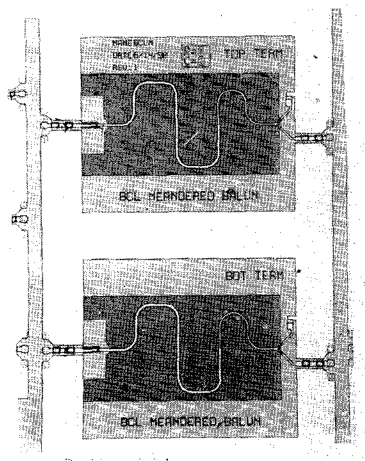


Fig. 7. Photograph of two identical broadside-coupled line (BCL) baluns which have different output ports terminated with on-chip resistors.

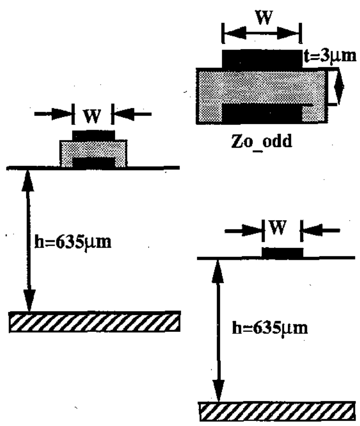


Fig. 8. Illustration for the realization of a typical BCL line.

can be increased either by increasing the resonant frequency while maintaining the same inductance or by increasing the inductance of the coil while maintaining the same resonant frequency. To increase the resonant frequency without lowering the inductance, one can reduce the electrical length of the spiral coil at high frequencies and/or coupling capacitance between the primary and secondary coils while maintaining the same physical length of the coil. In the present design, we reduce the electrical length of the spiral coil by using air-bridged metallizations to lower line capacitance and the coupling capacitance between coils by using thinner substrate and increase the coil inductance by maximizing the spiral area-to-length ratio. The transformer baluns are constructed with both landed and air-bridged lines and are surrounded by ground metal so that they can be on-wafer tested for both the thick without backside metallization and thin substrate with backside metallization. Fig. 6 shows a SEM photograph of a rectangular spiral coil constructed with air-bridged lines.

Broadside-Coupled Line Balun: The broadside-coupled line (BCL) balun shown in Fig. 7 is a monolithic version of the hybrid double-sided microstrip/strip-line balun. It comprises a dielectric sheet with metallizations of equal width on both sides. This sandwiched structure realized with the first interconnection and air-bridge metallizations and a 3 μm thick SiO_2 sits on top of a 25 mil thick GaAs substrate. Fig. 8 illustrates the realization of a typical BCL line. Because of the large thickness ratio of the GaAs substrate to the SiO_2 layer, the BCL structure has a large even-mode impedance which is essential for good balun performance. The BCL balun is designed using two cascaded BCL sections with different impedances to improve the performance at higher frequencies in addition to a 1:1 impedance transformation between the unbalanced and balanced ports.

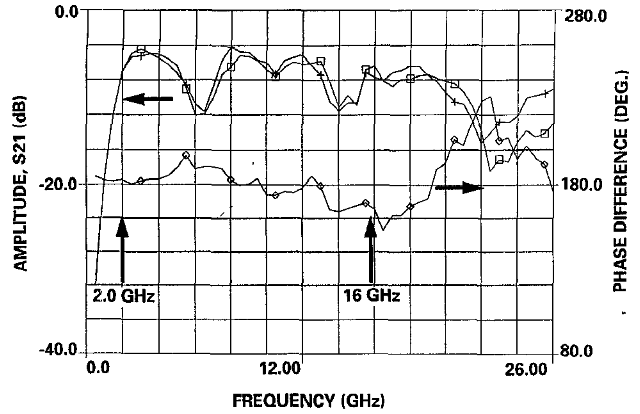


Fig. 9. Measured performances of an uniplanar CPW Marchand balun.

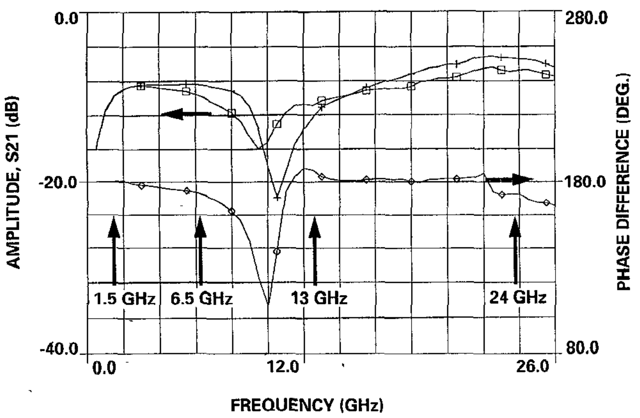


Fig. 10. Measured performances of a planar-transformer balun using air-bridged lines on a 25 mil thick substrate.

Balun Performances

Fig. 9 shows the measured performances of the uniplanar CPW Marchand balun. The amplitude and phase unbalances between the two balanced ports are less than 1.5 dB and 15°, respectively, over the 2 to 16 GHz frequency band. The poor flatness of the insertion loss, especially the two dips around 7 GHz and 14 GHz, could be due to the self resonance of the balun circuit whose chip area is large. Fig. 10 shows the measured performances of a planar-transformer balun constructed with air-bridged lines on a 25 mil thick substrate. The amplitude and phase unbalances between the two balanced ports are less than 1.5 dB and 10°, respectively, over the 1.5 to 6.5 GHz and 13 to 24 GHz frequency bands. Fig. 11 compares simulated results using EM analysis with measured data for a transformer balun constructed with landed lines on a 4 mil thick substrate. The agreement is reasonably good. In addition, measured results show that a 30% bandwidth improvement is obtained by using air-bridged lines instead of landed lines and a 25% improvement is obtained by using a 4 mil instead of a 25 mil thick substrate. Figs. 12 and 13 illustrate these bandwidth improvements by using air-bridged lines and a 4 mil thick substrate, respectively.

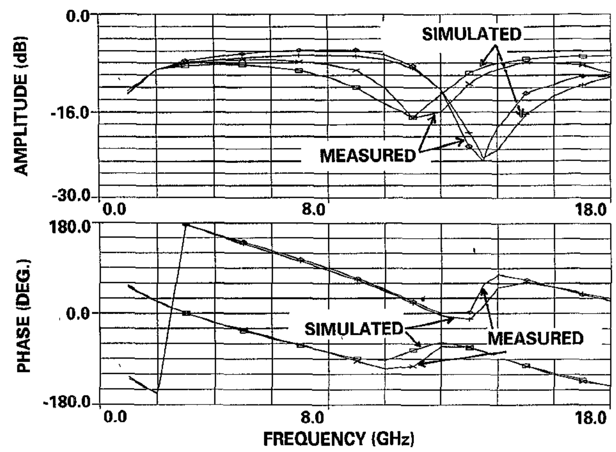


Fig. 11. Comparison of EM simulated and measured performances for a transformer balun.

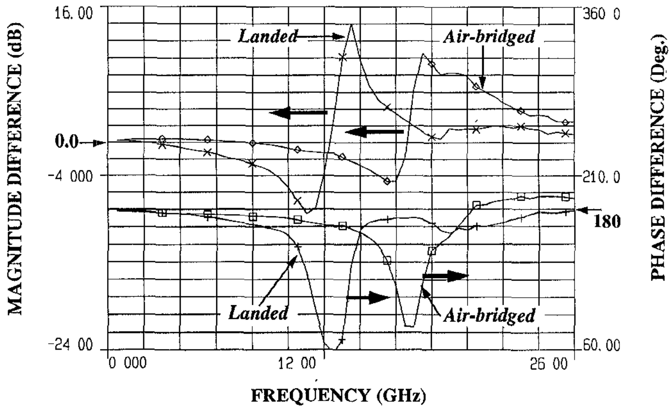


Fig. 12. Measured performance comparison of a transformer balun using landed lines and a transformer balun using air-bridged lines.

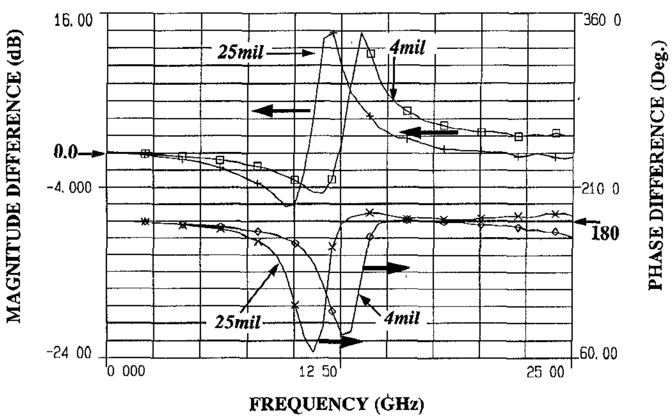


Fig. 13. Measured performance comparison of a transformer balun on a 4 mil thick substrate and a transformer balun on a 25 mil thick substrate.

Fig. 14 compares the measured and simulated performances of a multilayer MS Marchand balun. The EM simulated results are in good agreement with the measured data. The amplitude and phase trackings between two balanced ports are excellent and the insertion loss is between 2 and 4 dB over the 2 to 16 GHz frequency band.

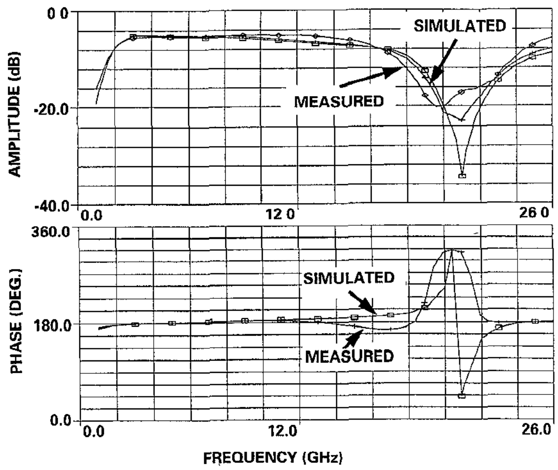


Fig. 14. Comparison of EM simulated and measured performances for a multilayer MS Marchand balun.

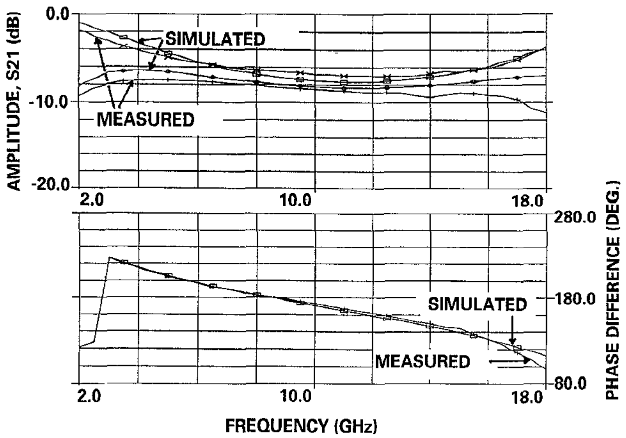


Fig. 15. Comparison of EM simulated and measured performances for a BCL balun.

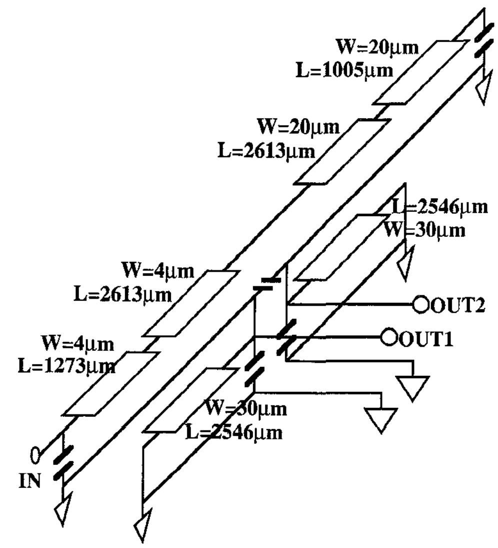


Fig. 16. An equivalent circuit of the multilayer MS Marchand balun.

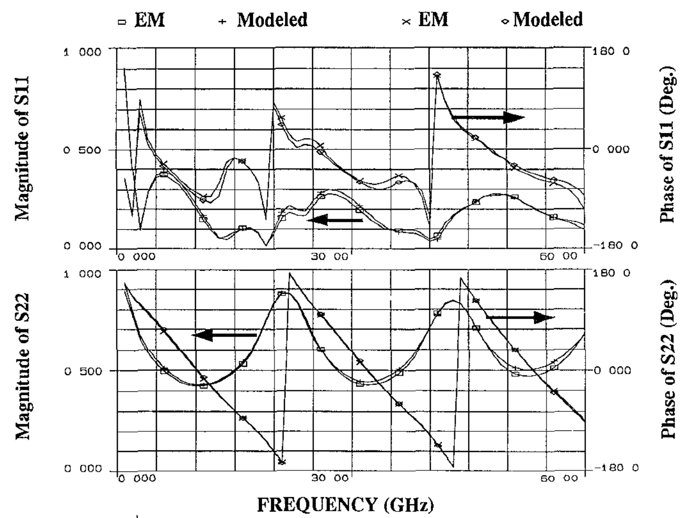


Fig. 17. Comparison of EM simulated and modeled input/output reflection coefficients for a multilayer MS Marchand balun.

Fig. 15 compares the simulated and measured performances of a BCL balun. The agreement is generally good, however the bandwidth is relatively narrow compared to other types of baluns.

Balun Modeling

Using a balun equivalent circuit is much more efficient and convenient than using a set of S-parameters to design a circuit including baluns because the balun performance can be easily adjusted to meet the specific circuit requirements. This is especially true for a mixer or multiplier circuit whose simulation involves many higher-order harmonics. Moreover, although the full wave EM simulation can accurately predict the performances of a specific balun structure, it is not practical to use the EM simulation for the design work due to its CPU intensive nature. Therefore, an equivalent circuit which can precisely represent the balun performances is an inevitable tool for the optimization of the balun itself and the design of a circuit including baluns. The balun equivalent circuit can be constructed from the computed S-parameters using EM simulation or measured S-parameters of a balun structure. Then this equivalent circuit model can be used easily to synthesize the balun performances with various parameter values for the optimal performance. Once the optimal set of the parameter values is obtained, its corresponding balun structure can be verified by and followed on EM simulation. By doing so, the balun design time can be significantly reduced.

Among all baluns presented above, the multilayer MS Marchand balun is the most promising due to its compact size and high performance. Fig. 16 shows an equivalent circuit along with the physical dimensions of the multilayer MS Marchand balun. This equivalent circuit can accurately model the measured S-parameters for frequencies up to 26 GHz and computed S-parameters using EM simulation for frequencies up to 60 GHz. Figs. 17 and 18 illustrate the excellent agreement between the modeled and EM simulated results. The planar-transformer balun is another promising balun due to its miniature size and

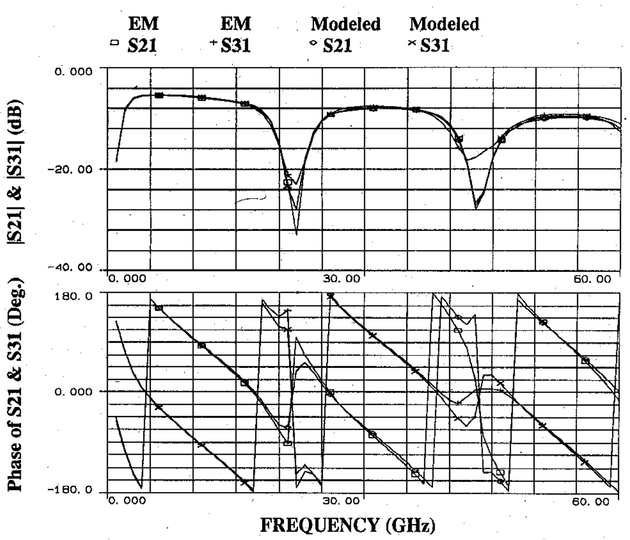


Fig. 18. Comparison of EM simulated and modeled forward transmissions for a multilayer MS Marchand balun.

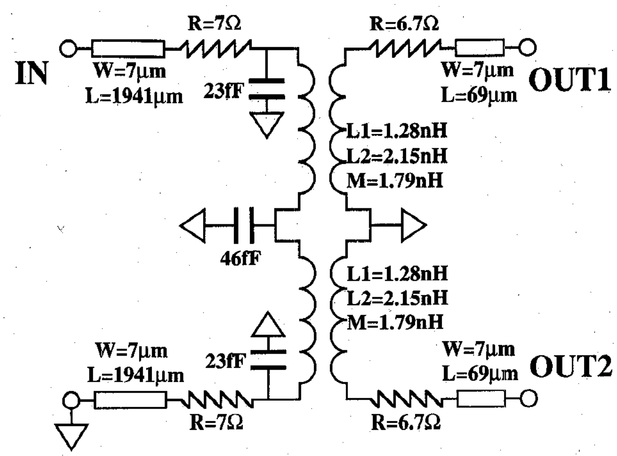


Fig. 19. Equivalent circuit of the planar-transformer balun.

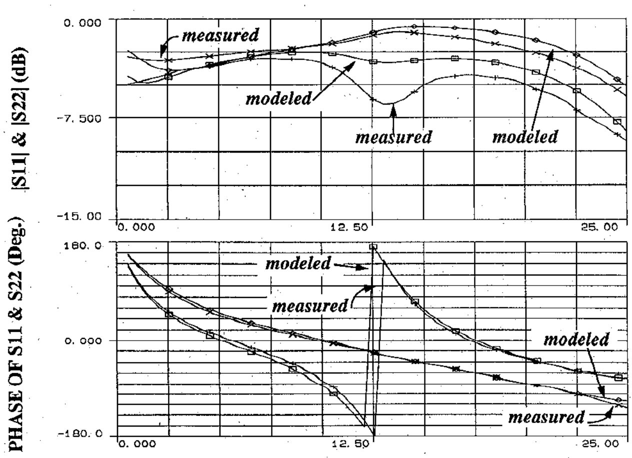


Fig. 20. Comparison of EM simulated and modeled input/output reflection coefficients for a rectangular spiral transformer balun.

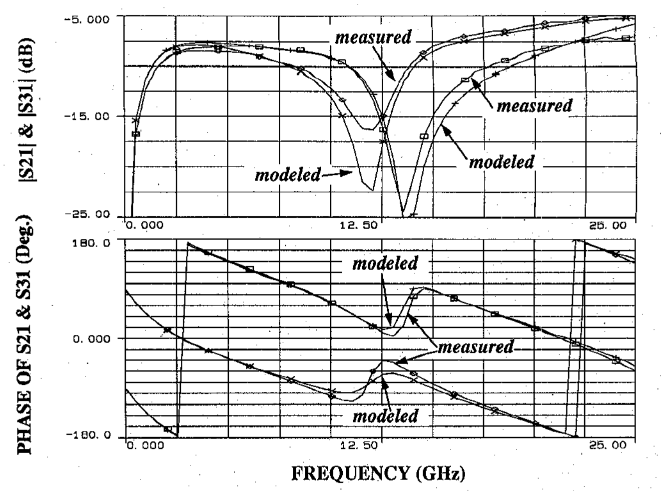


Fig. 21. Comparison of EM simulated and modeled forward transmissions for a rectangular spiral transformer balun.

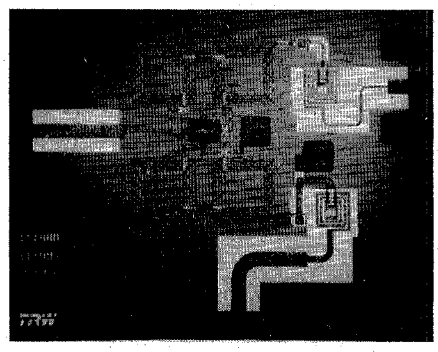


Fig. 22. Photograph of a double-balanced diode mixer chip.

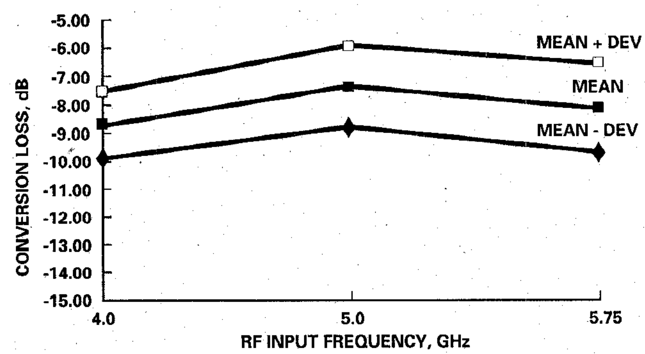


Fig. 23. Measured conversion loss of a diode mixer as a function of the RF frequency.

broad bandwidth. Its equivalent circuit along with the parameter values are shown in Fig. 19. Note that the series resistances shown in the figure are dc values, while their RF resistance values are given by

$$R_{\mathrm{RF}} = R_{\mathrm{dc}}\{1+[f(\mathrm{GHz})/35]^2\}^{1/4}.$$

Figs. 20 and 21 compare the measured and modeled results for a rectangular spiral transformer balun using air-bridged lines on a 4 mil thick substrate. The agreement is generally good over the measured frequency range from 0.5 to 25 GHz.

Mixer Design and Performances

A double-balanced diode mixer configuration is used in the design of a 4–6 GHz monolithic mixer. Fig. 22 shows a photograph of the mixer chip which measures 2.25×1.75 mm^2. The mixer circuit consists of a diode quad, two planar-transformer baluns, and several MIM capacitors and spiral inductors for impedance matching. The Schottky diode is a two finger 0.5×60 μm^2 MESFET with its drain and source connected together. The cutoff frequency of the diode is near 130 GHz at zero bias. Two transformer baluns are used for the LO and RF ports with RF balun's center tap serving as the IF output. The LO balun's center tap is grounded. These transformer baluns are constructed with air-bridged lines on a 4 mil thick substrate to extend the bandwidth. No dc bias is required for the mixer circuit.

The measured conversion loss of a double-balanced diode mixer as a function of the RF frequency is shown in Fig. 23. A fixed IF frequency of 1 GHz and a LO drive of 15 dBm were used. The best conversion loss is about 6 dB at RF of 5 GHz while the average loss varies from 7.5 to 8.5 dB. Two-tone intermodulation measurement shows that the input IP_3 is better than 15 dBm over the 4 to 5.75 GHz frequency band.

Conclusion

Four different monolithic passive baluns have been designed and fabricated. The uniplanar CPW Marchand balun and the BCL balun have been tested on the 25 mil thick GaAs substrate, the multilayer MS Marchand balun has been tested on the 4 mil thick substrate and the planar-transformer balun has been tested on both 4 mil and 25 mil thick substrates. Both the Marchand compensated and transformer baluns achieve maximum relative bandwidths in excess of 3:1. Although the multilayer MS Marchand balun requires one additional thick SiO_2 layer, it is the most promising passive balun due to its compact size and high performance. The miniature planar-transformer balun using air-bridged lines on a 4 mil substrate also shows very promising performance for frequencies below 10 GHz. Additionally, good agreements between the measured and EM simulated results as well as the accurate equivalent circuits for the Marchand and transformer baluns have also been achieved. Finally, the planar-transformer baluns have been utilized in a double-balanced diode mixer design and good measured performance has been achieved.

Acknowledgment

The authors would like to thank S. Pak for his help in testing, J. Yonaki, T. N. Ton and J. Coakley for their help in circuit layout and L. Klamecki, E. Matthews, D. Streit, A. C. Han, and P. H. Liu for their supporting in wafer fabrication.

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Tzu-hung Chen (S'83–M'84), for a photograph and biography, see this issue, p. 1979.

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Huei Wang (S'83–M'83–S'84–M'86–S'87–M'87), for a photograph and biography, see this issue, p. 1978.

Gee Samuel Dow (S'78–M'82), for a photograph and biography, see this issue, p. 1979.

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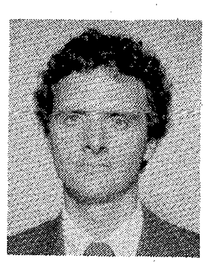

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Mr. Titus is the author of a number of technical papers and holds several U.S. patents related to mixer and balun design. He is a member of the American Physical Society and Tau Beta Pi.