# A Low-Loss Planar Microwave Balun with an Integrated Bias Scheme for Push-Pull Amplifiers

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*Abstract*— **We report a new planar low loss microstrip balun with radial stub RF grounding. This structure achieves a good RF ground for a Marchand-type balun and facilitates microstrip balun characterization. Moreover, a simplified biasing scheme for a push-pull amplifier was designed using this concept and this approach has been used successfully in a push-pull amplifier. The measured balun insertion loss was less than 0.5 dB over a 5-11 GHz band.**

## I. Introduction

The linearity of push-pull amplifiers while achieving high efficiency makes them attractive for many applications. The major impediment to their widespread use at microwave frequencies has been the difficulty of achieving easily-fabricated, low-loss baluns presenting the correct impedance at both the input and output of a push-pull pair of transistors. Recently, particularly good performance has been achieved with a multi-layer balun which had an insertion loss of 0.7 dB over 6 GHz to 21 GHz [1], and a planar three coupled-line balun with air-bridges achieved loss of 0.5 dB over K/Ka-band [2]. These broadband results used the compensated concept of Marchand [3] with shorted resonators achieved through via holes.

The Marchand balun DC-isolates the active devices. Hence, bias cannot be supplied externally through the RF ports. Therefore, introduction of gate and drain bias to the FETs requires four bias voltages with appropriate RF decoupling, which can occupy significant semiconductor real estate. With good symmetry in the push-pull design, the bias can be injected at the virtual ground points [4]. Bias has also been injected through a more narrow-band 180° hybrid ring balun, which does not have DC isolation [5]. Another approach is self-biasing through a source resistor, but this is unsuitable for high power operation.

In this paper we demonstrate a planar low-loss and broadband balun structure with an integrated biasing scheme that significantly simplifies circuit design and thus leads to lower loss. A push-pull amplifier was built based on this new balun, providing proof-of-concept.

## II. Planar Coupled Line Balun

The stripline implementation of the Marchand balun has two coupled resonators and provides an unbalanced line to balanced line transformation, or vice-versa. While multilayer coupled-line structures have the advantage of smaller size and tight coupling through a thin intervening dielectric layer, planar coupled-lines are simpler to fabricate. Realizing the required coupling and input impedances results

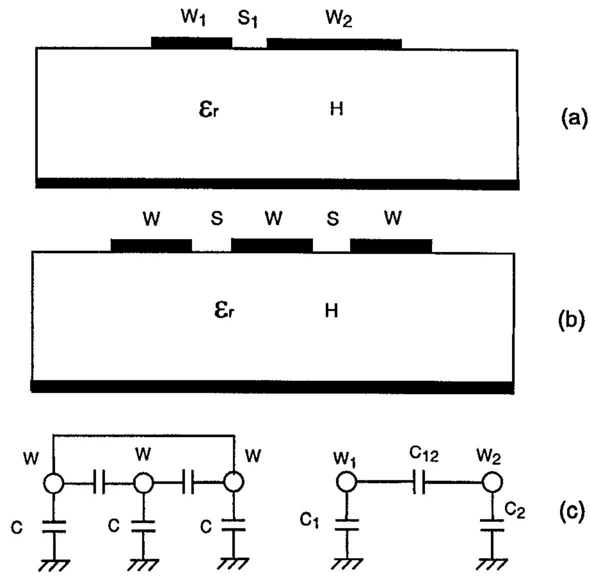


Fig. 1. Cross-sectional view of the (a) asymmetric two coupled-line and (b) symmetric three-coupled-line balun. (c) Simplified equivalent capacitance model of the three symmetric-coupled-line system with air-bridges and the equivalent asymmetric coupled-line system.

in the asymmetric planar structure of Figure 1(a). To allow increased inter-line spacing, we use the symmetric three-line system of Figure 1(b), with air-bridge connections between the outer lines and where all three lines have the same width. The air-bridges eliminate the odd current mode in the three-line system, realizing increased coupling over a two-line system for fixed inter-line spacing. Our analysis of the symmetric three-line system also shows less inter-line spacing sensitivity. The equivalent capacitance model of the air-bridge-connected three coupled-line structure is shown in Figure 1(c), together with an equivalent asymmetric coupled line model.

The Marchand coupled-line balun requires shorted resonators, which we achieved using radial stubs [6]. This alleviates the need for vias, further simplifying fabrication. More importantly, the use of the radial stub allows simplified active device biasing.

## III. Balun Design Procedure

Various Marchand-type baluns have been analyzed [7], [8], [9]. We provide a convenient synthesis approach for a planar microstrip Marchand-type balun. We directly optimize the balun dimensions using a network model. This model is represented as a $3 \times 3$ matrix derived from asymmetric coupled-line normal mode parameters, which can be applied to the symmetric three-coupled-line balun. As there are only three design variables for the cross-sectional structure, $W$, $S$, and $H$ in Figure 1, for a given substrate material, reasonable values for these parameters can be found in a few iterations. The approximate network model reduces design time compared to using electromagnetic field simulation during synthesis. Final verification is achieved through a 3-D field simulation.

For the inhomogeneous microstrip problem, where the phase velocities of the propagating modes are not equal, the multi-line [L] and [C] matrices are evaluated numerically for the 2-D cross-sectional geometry, i.e., for particular $W$, $S$, and $H$ values, where

$$C = \begin{bmatrix} C_1 & -C_m \\ -C_m & C_2 \end{bmatrix}, L = \begin{bmatrix} L_1 & L_m \\ L_m & L_2 \end{bmatrix}. \qquad (1)$$

Using [L] and [C], a $4 \times 4$ Z-matrix of the coupled-line system is obtained in terms of the asymmetric coupled-line normal mode parameters $Z_{c1}$, $Z_{\pi1}$, $Z_{c2}$, $Z_{\pi2}$, $\beta_c$, $\beta_\pi$, $R_c$, and $R_\pi$ [10], [11]. The balun can be modeled as a connection of two 4-port coupled lines with appropriate terminations, which can be transformed to an equivalent $3 \times 3$ balun Z-matrix. From the balun Z-matrix, the S-parameter matrix is obtained by incorporating a termination impedance matrix, $[Z_t]$, as

$$[S] = ([Z] - [Z_t])([Z] + [Z_t])^{-1}. \qquad (2)$$

A 4-port element in Agilent EEsof ADS [12] was used for each coupled line section. The S-parameters were calculated as a function of frequency. Satisfactory $S_{21}$, $S_{31}$, and $S_{11}$ was obtained in a few iterations.

For acceptable line spacings and widths, a relatively thick substrate was used (380 $\mu$m AlN). The wider conductors also can result in low conductor loss for a microstrip line [13], as well as higher (bias) current handling. However, ground vias involve additional processing, and for thick substrates significant parasitic inductance may result, hence degrading the balun performance. We use a wide-bandwidth radial stub to ground the resonators, allowing a simple planar process which is convenient for dielectric substrates such as alumina and AlN. The radial stub length is given approximately by [6]

$$L_{rad} = \lambda_0 \left(2\pi\sqrt{\epsilon_{eff}}\right)^{-1}. \qquad (3)$$

The effective dielectric constant, $\epsilon_{eff}$, was calculated for the microstrip line width of $r_i + r_o \sin(\frac{\theta}{2})$, where $r_i$, $r_o$, and $\theta$ are the inner radius, outer radius, and sectoral angle, respectively [14]. The sectoral angle was chosen to provide sufficient balun bandwidth. The coupled line length, $L_{line}$, was determined as a quarter wavelength at 10 GHz using the average of the modal phase constants. In an amplifier application, large periphery devices usually have small input impedance. Therefore, a balun was designed to transform a 50 Ω unbalanced input to a 25 Ω (each line to ground) balanced output. The optimized dimensions are given in Table I.

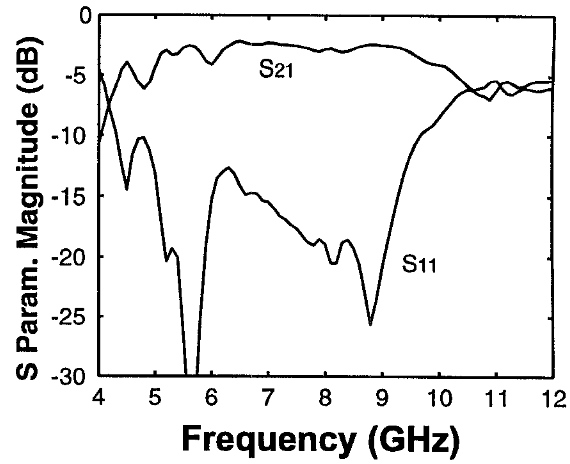


Fig. 2. Measured back to back response of the asymmetric coupled-line balun

TABLE I

OPTIMIZED BALUN DIMENSIONS FOR 4-12 GHz BANDWIDTH.

| Dim.($\mu$m) | $W_1$ | $W_2$ | $S$ | $L_{line}$ | $L_{rad}$ | $\theta(°)$ |
|---|---|---|---|---|---|---|
| Asymmetric | 30 | 80 | 5 | 3000 | - | - |
| Symmetric | 80 | - | 20 | 3500 | 2500 | 60 |

Full electromagnetic simulations of the balun designs were performed using Agilent EEsof Momentum to verify the results. The approximate synthesis yielded results that were close to the full numerical simulation. The simulated insertion loss for this balun with 50 Ω input and 25 Ω output was less than 0.5 dB, with good amplitude/phase balance.

## IV. Fabrication and Measured Results

An AlN substrate ($\epsilon_r = 8.5$) was chosen to provide high thermal conductivity for a hybrid amplifier, with 2.5 $\mu$m thick gold (three skin depths at 10 GHz). Gold bond wires were used for the balun air-bridges. Both asymmetric two-coupled-line and symmetric three-coupled-line baluns were fabricated and tested. Figure 2 shows the measured back-to-back balun response for two cascaded asymmetric coupled-line baluns. Figure 3 shows the measured back-to-back balun response of the symmetric coupled-line balun. Good reflection loss was maintained over the design bandwidth, reaching -27 dB at 6 GHz. The insertion loss performance was excellent, being better than 0.5 dB over the 5-11 GHz band, as shown in the inset. For a balun with an additional microstrip to CPW transition at the balanced end, the insertion loss increased slightly to a typical value of 0.7 dB for each balun. Figure 4 shows the simulated (using the

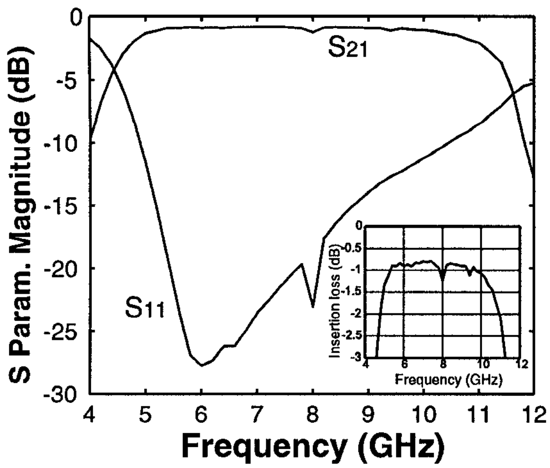


Fig. 3. Measured back to back response of two cascaded symmetric three-coupled-line baluns

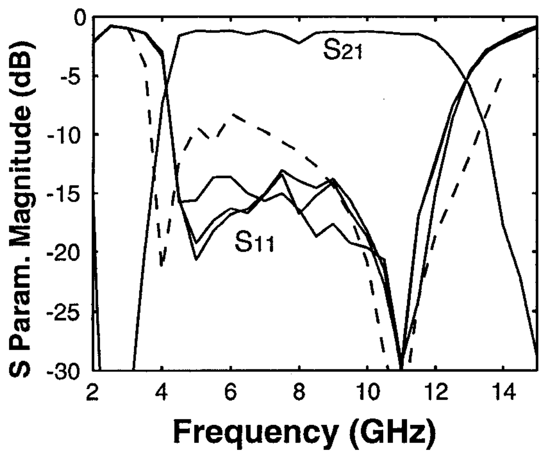


Fig. 4. Three measured results (solid lines) and a simulated result (dashed line) for the symmetric three coupled-line balun with an additional microstrip to CPW transition at the balanced output.

simplified network design model) and three measured back to back balun responses, with good agreement.

## V. Biasing Scheme, Stability and Layout

Based on successful balun loss performance, a balun circuit suitable for a push-pull amplifier was achieved by adding biasing elements, and the schematic is shown in Figure 5. The simplified biasing exploited the coupled line balun structure, which eliminates the need for a DC blocking capacitor. The radial stub, used for balun RF grounding, is used as the DC bias feed-point. A high impedance line connecting the two radial stubs makes it possible to provide DC bias to two devices with only one bias injection.

Resistive loading was used to suppress instabilities [15]. A 100 Ω resistor was fabricated in the middle of the shunt line connection using a TiW layer of sheet resistance 10 Ω per square (input balun only), the adhesive layer under the Au. For RF bypassing, a 100 pF chip capacitor was used.

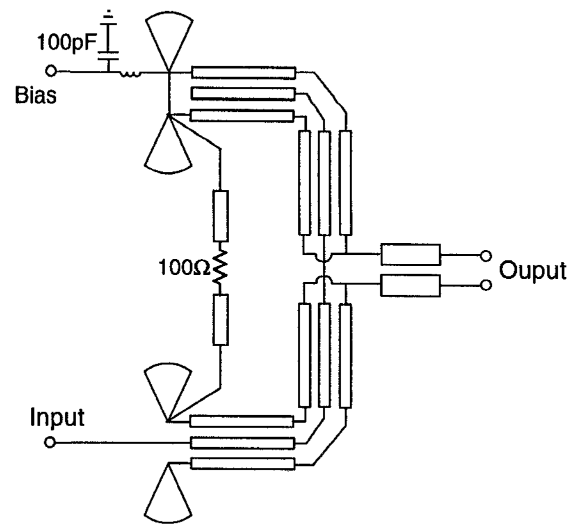


Fig. 5. Schematics of balun circuit with an integrated biasing scheme. The 100 Ω resistor was used only in the input balun.

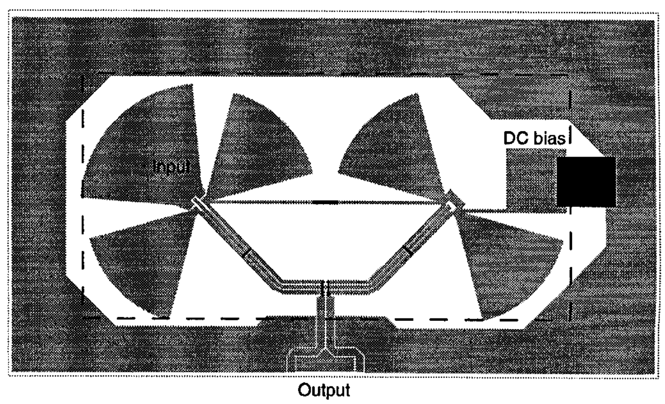


Fig. 6. The layout of the three symmetric coupled-line balun. The microstrip balun is enclosed with a dotted line. An additional microstrip to CPW transition is located at the balanced output.

An additional microstrip to CPW transition was designed at the balanced output to interface with CPW-based components. The transition consists of coupled microstrip line, coupled CPW line, and single CPW line sections. The resulting layout of the balun is shown in Figure 6. The region enclosed with the dotted line is the microstrip balun.

## VI. Push-Pull Amplifier Results

Using the new balun with integrated biasing, a push-pull amplifier was constructed by adding matching networks to each balanced line. Two 1.5mm FETs were connected to the balun using 1-mil bond wires. The new scheme resulted in a significantly simplified circuit and assembly. The measured small-signal S-parameters are shown in Figure 7, indicating 7.5 dB gain at 5 GHz with a 3-dB bandwidth of 3-10.5 GHz.

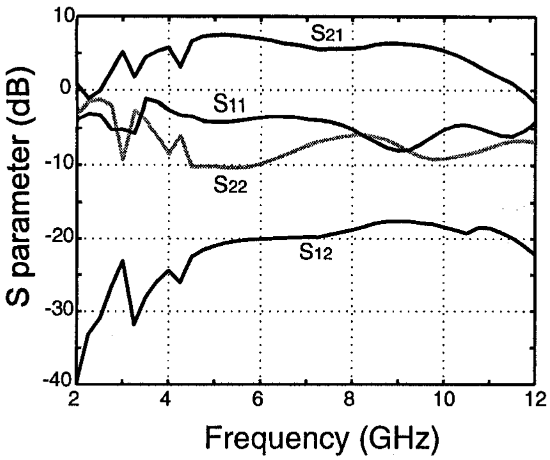


Fig. 7. Measured small-signal performance of the push-pull amplifier using integrated biasing scheme

## VII. Conclusion

A new balun using a symmetric three-coupled-line system was designed on an AlN substrate. These baluns were synthesized from an equivalent network model constructed from asymmetric coupled line theory. A radial stub was used for balun RF grounding, enabling good balun performance without physical vias, thereby providing a simplified bias opportunity for push-pull amplifiers. Excellent insertion loss, less than 0.5 dB, was achieved in the 5-11 GHz band. This demonstration of a three-coupled-line balun with integrated biasing in a push-pull amplifier suggests a simple high-performance approach for broadband applications.

## VIII. Acknowledgments

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