# Design and Performance of a Planar Star Mixer

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*Abstract*—**This paper describes the realization of a hybrid star mixer as a planar circuit. The mixer has a minimum conversion loss of 5 dB and, for a conversion loss of less than 9 dB, spans over 2.2 GHz in IF bandwidth and 8 GHz in RF/LO bandwidth. The mixer employs a novel, planar balun structure, similar to conductor-backed CPW, that is suitable for realization as a monolithic circuit.**

## I. Introduction

The star mixer is one of the most commonly used doubly balanced configurations. The advantage of this mixer over other doubly balanced types is that its IF parasitic inductance is very low, and as a result the IF bandwidth is very broad. Furthermore, the IF is dc coupled, allowing this type of mixer to be used as a phase detector or for direct conversion of signals to baseband.

The structure of a traditional star mixer is nonplanar [1]. Such structures have a very serious disadvantage: it is difficult to integrate them with planar circuits, and especially difficult to realize them as practical monolithic circuits. We have overcome this difficulty by realizing the conventional nonplanar star mixer balun as a planar circuit. The trade-off for this realization is a slight increase in IF inductance, and a concomitant decrease in IF bandwidth, because of the more complex IF connection. Even so, the IF bandwidth of this mixer compares favorably to other types of doubly balanced diode mixers.

## II. Star Mixer Design

The star mixer uses a form of the Marchand balun [1]–[4]. The modification of the balun for use in nonplanar star mixer has been described previously [4]. This conventional balun is a parallel plate configuration with coupling between the top conductor and a pair of bottom conductors, and the diodes are placed in the center of the structure. In our design, shown in Fig. 1, we use an edge-coupled-line configuration. The mixer using this prototype balun is shown in Fig. 2, and the diode pads are placed on the outside corners of the center junction.

In the design of star mixer baluns, we attempt to make the even-mode characteristic impedance $Z_{0e}$ as high as possible, ideally infinite (for now we view the pair of narrow lines on the outside of the larger conductor, in Fig. 1, as a single coupled line). Under these conditions the center line in Fig. 1 and the outer two lines operate as a single, parallel-strip transmission line having the impedance $Z_0 = 2Z_{0o}$, where $Z_{0o}$ is the odd-mode impedance.

In practice, infinite even-mode impedance is, of course, impossible to achieve. We have found that Marchand baluns are far more tolerant of low even-mode impedance than other types, especially the parallel-line balun often used in ring mixers. This greater tolerance results in better mixer balance, hence more complete realization of the most important benefits of balanced mixers: spurious-response rejection, LO-to-RF isolation, and LO noise rejection. Specifically, we have found that adequate Marchand baluns can be produced having a ratio of even- to odd-mode impedance of 3.0 to 4.0 (depending on bandwidth and load impedance). This ratio must be 6.0 to 10.0 for parallel-line baluns.

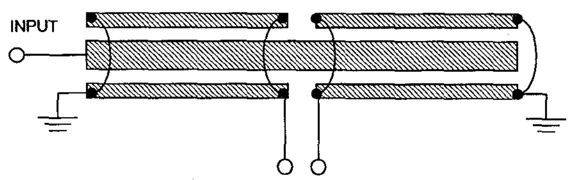


Fig. 1. Prototype Marchand balun for use in a planar star mixer.

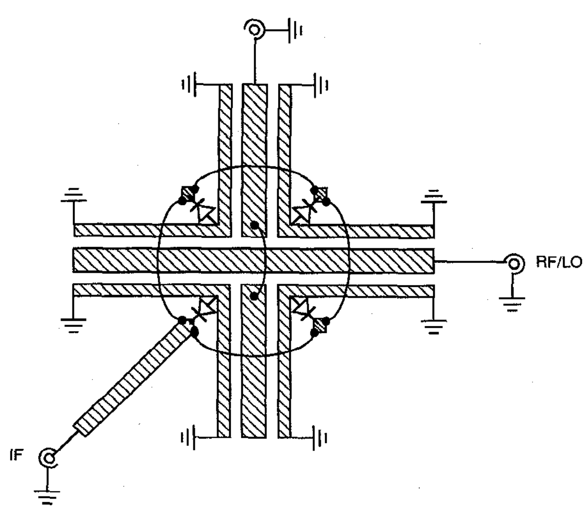


Fig. 2. Planar star mixer layout.

The design of the balun requires that the input impedance be close to 50 Ω in order to have minimal return loss at the input ports. An initial circuit analysis (using a harmonic-balance simulator) showed that the diodes' optimum input impedances should be close to 50 Ω. This convenient result is entirely fortuitous. The diode's RF input impedance below 10 GHz has a negligible reactive part; at higher frequencies, the junction capacitance becomes significant and its reactive contribution to the input impedance introduces a limitation to the mixer's bandwidth. The odd-mode impedance of the prototype balun is given [4] by

$$Z_{0o} = \frac{1}{2}\sqrt{Z_s Z_d} \tag{1}$$

where $Z_s$ is the source impedance and $Z_d$ is the impedance of an individual diode. This gives an odd-mode impedance of 25 Ω. The even-mode impedance must be as high as possible. Theoretically, if the ground plane did not exist, the even-mode impedance would be infinite, maximizing the balun's bandwidth. However, this approach is not practical since a ground plane is required to mount the circuit on a metal surface. Instead, our approach is to adjust the structure's dimensions to obtain as high an even-mode impedance as possible, while keeping the odd-mode impedance in the neighborhood of 25 Ω by varying such design parameters as the dielectric constant of the substrate, the height of the substrate, the separation of the adjacent lines from the signal line, and the width of the lines.

Analyzing the mixer on a commercial circuit simulator presents a difficulty: few circuit simulators include multiple nonhomogeneous coupled lines in their circuit-element catalogs. The three-conductor

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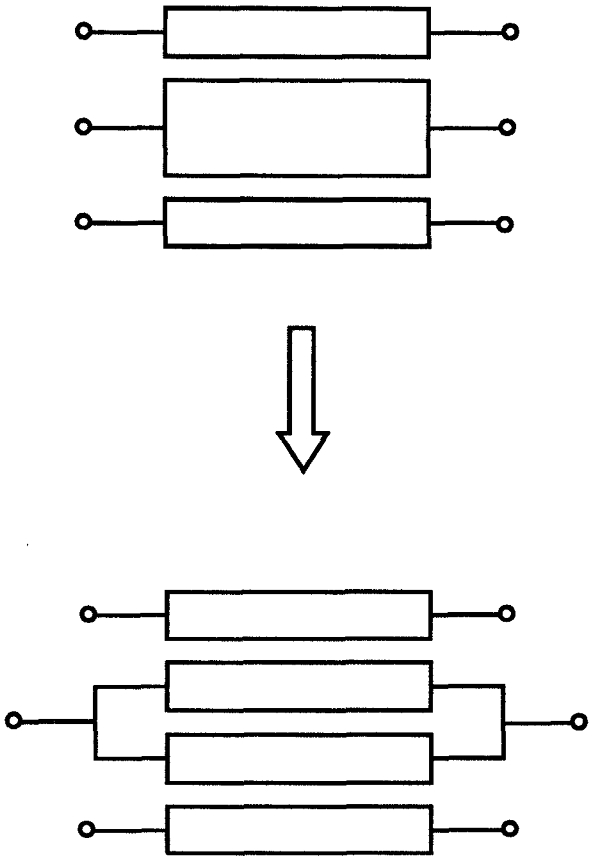

Fig. 3. The three-conductor balun approximated as a pair of two-conductor coupled lines. The impedances of each set of coupled lines is twice that of the prototype in Fig. 1.

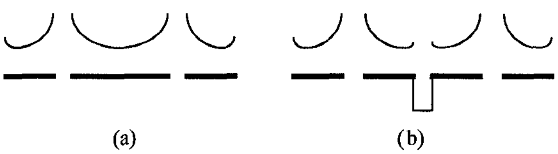

Fig. 4. Odd-mode charge distribution in the three-conductor line (a) and a pair of two-conductor lines (b). Because the charge distributions on both sets of lines are nearly identical, the pair of lines in (b) adequately models those in (a).

line can be approximated, for analysis on a nonlinear microwave network simulator, as a pair of coupled lines joined in parallel (Fig. 3); each pair has twice the even- and odd-mode impedances of the prototype in Fig. 1. This approximation can be justified if we consider the odd-mode charge distribution of the three-conductor strip and its two coupled-line model as depicted in Fig. 4. The charge distribution is slightly different at the center of the middle conductor due to fringing effects. This can be neglected for all practical purposes. This approximation was tested by means of appropriate software [5], and was found to be valid.

The dimensions and substrate of the circuit is designed to provide a high even-mode characteristic impedance $Z_{0e}$ while achieving the desired odd-mode impedance. A low dielectric constant substrate, duroid ($\varepsilon_r = 2.33$), was selected primarily to provide high $Z_{0e}$. The thickness of the substrate is 1.6 mm; this is a practical maximum. Although a thicker substrate would provide greater $Z_{0e}$, it would be difficult in practice to interface with other components. To achieve the desired odd-mode impedance, the separation between the center line and adjacent lines is made relatively small. The width is kept to a minimum since it lowers the even- and odd-mode impedances.

Linecalc [6] is used to determine the line width and separation that provides appropriate even- and odd-mode impedance ratios. Very low values of width and separation are discarded due to the limits of resolution of the fabrication facilities and the requirement that the odd-mode impedance of each pair of coupled lines be in the neighborhood of 50 Ω. Moreover, reducing the width of the strips causes the RF currents to encounter more resistance due to the reduction in cross-sectional area of the strip. The width of the outer strips is 0.13 mm and the separation is 0.50 mm. The inner strip is 0.26 mm wide.

A high-frequency silicon beam-lead diode is selected because of its low parasitics, small size, low cost, and easy installation. The values of the diode model parameters can be found through direct measurement of its $I/V$ and $C/V$ characteristics. For the beam lead diode, an Alpha Industries DMJ6777, the parameters are series resistance $R_s = 6$ Ω, breakdown voltage $V_b = 5$ V, saturation current $I_s = 5.0 \times 10^{-12}$ A, junction voltage $V_j = 0.7$ V, and junction capacitance $C_{jo} = 0.15$ pF, ideality factor $\eta = 1.19$. The beam-lead overlay capacitance plus the calculated microstrip open-end capacitance is 0.10 pF.

The mixer circuit is simulated on the HP Microwave Design System (MDS, [7]) to yield values for the lengths of the strips and to compensate for the effects of the inductance of the discontinuities present in the circuit (chief among these is the square loop used to form the IF connection). The optimum length of the balun is found to be 3.8 mm for a center frequency of 9 GHz; this length is chosen to center the balun's bandwidth. The square loop has the effect of reducing the bandwidth of the mixer due to its associated inductance and asymmetrical phase distribution. This loop was simulated using transmission-line models in MDS. Simulations show that the bandwidth would have been over 4.5 GHz in the absence of the loop. Improvements on bandwidth could be achieved using precision lithography to reduce the dimensions of the widths of the lines, to reduce the size of the loop. Using smaller diodes or monolithically fabricating the mixer would achieve the same function.

In the layout of the star mixer, the connection of the circuit to the RF, LO and the IF ports is done using a grounded coplanar waveguide in favor of better ground connection to the adjacent strips. It is necessary to implement jumpers across the three lines at all the ports to prevent ground currents from traversing long asymmetrical paths, and to prevent the generation of high-order modes and troublesome resonances.

## III. Performance

The measurements are performed with the power level of LO at 15 dBm and RF at −10 dBm. The best conversion loss, 5 dB, is achieved at 300 MHz IF and 7 GHz LO. Fig. 5 shows that the conversion loss increases as the IF increases. It also indicates that there is a good correlation between simulated and measured results. The mixer bandwidth reduction is due to two effects: (1) the inductance of the crossover bond wire in one of the center lines, and (2) the inductance and asymmetry of the square loop connecting the diodes to the IF port. The former limits the RF bandwidth, the latter the IF bandwidth.

The IF bandwidth of the mixer is 1.5 GHz for a conversion loss of less than 8 dB, and about 2.2 GHz for a conversion loss of less than 9 dB. To measure the RF/LO bandwidth of the mixer the RF and LO signals are varied, keeping the IF frequency constant. This has been done at two IF frequencies, 300 MHz and 1 GHz. The bandwidth for a conversion loss of less than 9 dB is 8 GHz at 300 MHz and 1 GHz IF frequency (Fig. 6).

Fig. 7 shows the LO-to-IF and RF-to-IF isolation; these are greater than 15 dB over 5 to 13 GHz range. The RF-to-LO and LO-to-RF

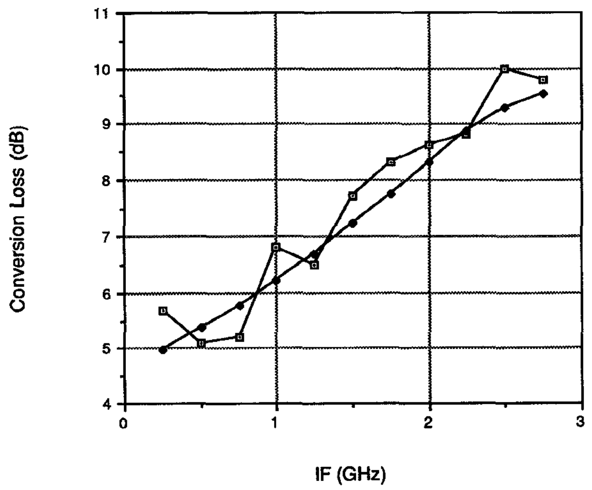


Fig. 5. Measured (open dots) and calculated (solid dots) conversion loss vs. IF frequency. $P_{LO} = 15$ dBm and $f_{LO} = 7$ GHz.

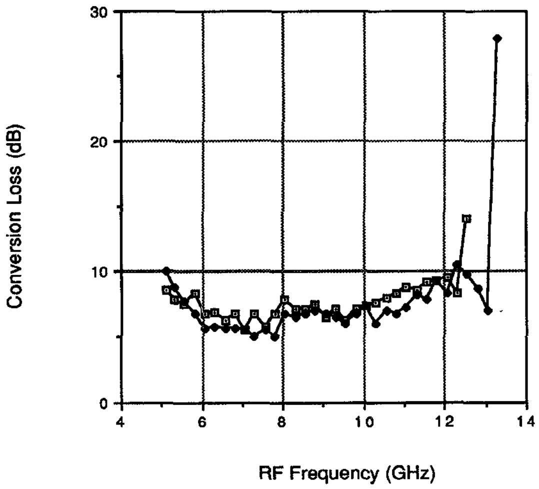


Fig. 6. Conversion loss vs. RF frequency. PLO = 15 dBm and $f_{IF}$ = 1 GHz (open dots) and 300 MHz (solid dots).

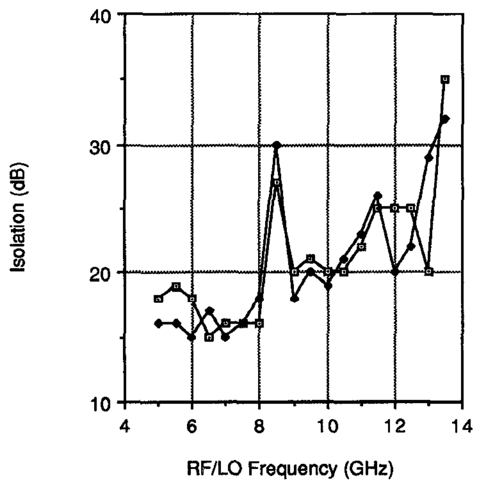


Fig. 7. LO-to-IF isolation (solid dots) and RF-to-IF isolation (open dots).

isolations are very similar and so only the LO-to-RF isolation is presented in Fig. 8. The isolation is greater than 20 dB over the 5 to 13 GHz range.

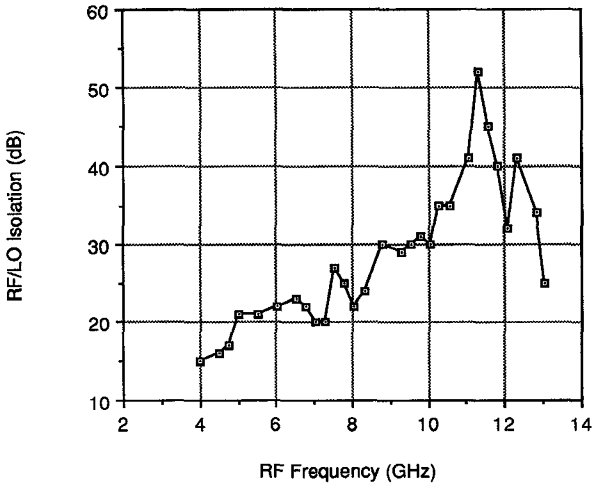


Fig. 8. LO-to-RF isolation.

TABLE I
SPURIOUS-RESPONSE LEVELS OF THE STAR MIXER
($P_{RF} = -10$ dBm; $P_{LO} = 15$ dBm)

| RF Harmonic no. | LO Harmonic no. | Output Level (dBm) |
|---|---|---|
| −1 | 2 | −48 |
| 2 | −2 | −62 |
| −1 | 3 | −47 |

The spurious responses are below −47.0 dBm. The measurement is done at 7.3 GHz RF and 7.0 GHz LO with power levels at −10 dBm and 15 dBm respectively. They are listed in Table I.

## IV. CONCLUSIONS

A novel planar star mixer has been designed and tested in a hybrid configuration to show its very broadband performance. The minimum conversion loss attained is 5 dB. For a conversion loss of less than 9 dB, the IF bandwidth is over 2.2 GHz and the RF and LO bandwidths are 8 GHz. The RF-to-LO isolation is over 20 dB in the 5 to 13 GHz range. And over the same range, the RF-to-IF and LO-to-IF isolation is over 15 dB. Better broadband performance with enhanced port-to-port isolation is anticipated in monolithic structures due to the reduction in the size of the square loop IF connection.

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