A Broadband, Planar, Doubly Balanced Monolithic Ka-Band Diode Mixer

Stephen A. Maas, *Fellow, IEEE,* and Kwo Wei Chang

***Abstract*—This paper describes a new type of planar, monolithic diode mixer achieving 5-10 dB conversion loss and very low distortion and spurious responses over a 26- to 40-GHz RF and LO bandwidth and dc-12 GHz IF. The mixer has exhibited low loss and low distortion operating as both a downconverter and upconverter. Two types of diodes have been used: the first used the gate-to-channel junctions of 0.2 × 80 μm InGaAs HEMT's; and the second used Schottky diodes realized in HBT technology. The baluns are Marchand-like coplanar structures.**

I. Introduction

ONE of the more frustrating problems in monolithic (MMIC) microwave mixer design is the realization of planar, doubly balanced mixers. Most types of baluns for doubly balanced mixers require metallizations on both sides of a suspended substrate, or have some other type on nonplanar structure; thus, they are not amenable to monolithic integration.

In most mixers, the balun serves as a return path for IF currents; consequently, the balun introduces an inductive discontinuity in series with the IF. This inductance limits the IF bandwidth. Many types of baluns also introduce IF resonances that further limit bandwidth; this is especially true of the parallel-strip baluns frequently used in ring-diode mixer designs [1]-[5].

We have developed a mixer that solves many of these problems. Its star structure has inherently wider IF bandwidth than ring structures, and its planar baluns provide much better balance than other types of coplanar structures. These unique baluns are the key to the mixer's exceptional performance, especially its good port-to-port isolation and rejection of even-order spurious responses.

II. Design and Measurements

A. Star-Mixer Structure

Virtually all doubly balanced diode mixers use diodes in either a star [4] or ring configurations [1]-[3] (the latter being far more common). These basic structures are used alone or as building blocks for more complex mixers. One of the most common realizations, shown in Fig. 1, is a ring mixer using parallel-line baluns at the RF and LO ports (many mixers that may not appear to have this structure, e.g., [3], do, in fact, use such baluns). This mixer requires a fairly complex IF decoupling circuit; this circuit usually has limited bandwidth, and the blocking capacitors and IF bypass inductors often introduce troublesome resonances into the IF passband.

A conventional star mixer is shown in Fig. 2. Although less commonly used than the ring mixer, the star mixer has significant advantages in comparison to the ring. An important advantage of the star mixer is its use of the balun's lower strips—and only those strips—as an IF return. Unlike the ring mixer, it has no IF-return inductors. This results in lower inductance in series with the IF port, and broader IF bandwidth.

Another advantage of the star mixer is its symmetrical balun structure. The obvious asymmetries in the ring mixer's baluns degrade, to some degree, its balance and thus limit the amount of LO-noise and even-order spurious-response rejection of the mixer. The very neat symmetry of the star mixer enhances the mixer's balance and provides a high degree of LO noise and spurious rejection.

The main disadvantage of the conventional star-mixer structure is that it will not accommodate overlapping RF/LO and IF bands. This limitation results from the fact that the IF currents excite the baluns in an even mode, and the baluns present open circuits to even-mode excitation within their passbands. Thus, the IF must be comfortably outside the baluns' passbands. Although the ring mixer theoretically allows overlapping RF/LO and IF bands, the resonances introduced by the IF-return inductors and blocking capacitors often prevent such operation in practice.

B. Mixer Baluns

Most coupled-line baluns used in balanced diode mixers require high even-mode impedance and closely matched even- and odd-mode phase velocities. To maximize even-mode impedance, the mixer is usually realized on a suspended, low-dielectric-constant substrate. This minimizes the capacitance between the strips and ground, thus maximizing the even-mode impedance. However, it also results in an even-mode phase velocity that is close to v_c, the velocity of light. The odd-mode fields, however, are retained primarily in the substrate, so unless the

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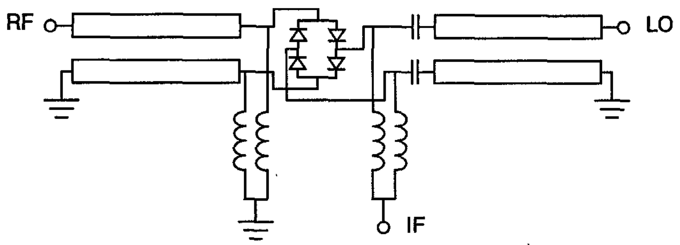

Fig. 1. Ring-diode mixer. The parallel-line baluns at the RF and LO ports each consists of a pair of coupled transmission lines. For satisfactory operation, the even-mode characteristic impedance of these lines must be nearly ten times the odd-mode impedance.

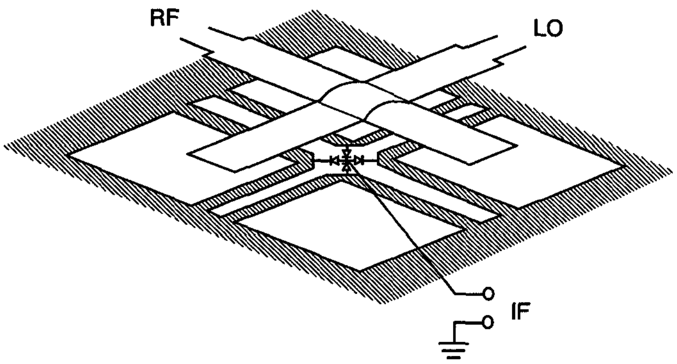

Fig. 2. Conventional star mixer, realized as a hybrid. The shaded area are metallizations on the top side of the substrate; the cross-hatched areas are on the bottom (ground-plane) side. This structure must be realized as a suspended-substrate component.

substrate's dielectric constant is very low, the odd-mode phase velocity is much lower than the even-mode. Usually, composite materials having dielectric constants of approximately 2.3 are used for the substrate, giving an odd-mode phase velocity of approximately $0.7 v_c$. The practical result of this difference in phase velocity is degraded balance and port-to-port isolation.

Marchand baluns are more tolerant of low even-mode impedances than parallel-line baluns. Because of this tolerance, it is possible to realize successful star-mixer baluns as planar structures; we do this by locating the lower strips in Fig. 2 on the upper surface of the substrate, on either side of the existing strip. The resulting balun is shown, connected as a single-output balun, in Fig. 3. Such baluns have a significant advantage over the conventional, nonplanar baluns shown in Fig. 2: when realized on high-dielectric-constant substrates such as alumina or GaAs, their even- and odd-mode phase velocities are much more closely matched. Furthermore, the coupling between the outer strips is much lower than in the conventional star mixer; this results in better LO-to-RF isolation. Unfortunately, unless the designer exercises care, the even-mode impedance may not be high enough.

In order to achieve adequate even-mode impedance on the high-ϵ_r GaAs substrate, it was necessary to use a thick substrate—635 μm instead of the usual ~ 100 μm. The resulting even- and odd-mode impedances and effective

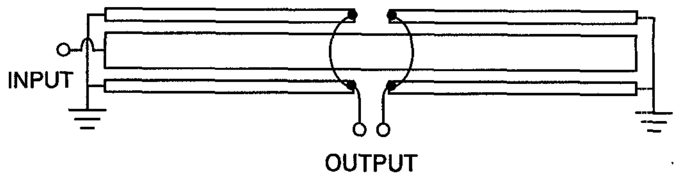

Fig. 3. Planar star-mixer balun connected to form a coupled-line Marchand balun having a single output.

dielectric constants, with the balun connected as shown in Fig. 3, were as follows:

$$Z_{0e} = 112\ \Omega \qquad \epsilon_{\text{eff},e} = 7.543$$

$$Z_{0o} = 31\ \Omega \qquad \epsilon_{\text{eff},o} = 6.950.$$

These were calculated by means of commercial coupled-line software [6].

The use of a three-strip balun in a star mixer introduces another problem: most microwave circuit simulators do not include a three-strip coupled-line section in their element catalogs. We have found that the balun can be modeled adequately by treating it as two two-strip couplers in parallel. This model ignores the capacitance between the outer strips; however, because these strips are separated by significant distance, the results of this approximation are adequate. Fig. 4 compares the coupling of the balun shown in Fig. 3, calculated with this model, to calculations that include the coupling between the outer strips (the software of [7] was used for this purpose). The results are more than adequate for practical design.

C. Diodes

Two different types of diodes are used in our mixers. In the earlier mixers, the gate-to-channel junction of a 0.2 × 80 μm InGaAs HEMT was used as a diode; compatibility with other devices on the same wafer dictated the choice of this structure. This diode (which we shall call the *HEMT diode*) has 0.030 pF zero-voltage junction capacitance. Because the current t passes laterally through a long region of lightly doped semiconductor before reaching the ohmic contacts, these diodes have a relatively high series resistance of 21 Ω. The resulting cutoff frequency is only 253 GHz; this is a distressingly low cutoff frequency for a diode used in a 40-GHz mixer. Subsequent designs used a Schottky-barrier diode, realized in HBT technology, having a considerably higher cutoff frequency. To realize this diode, the base and emitter regions of an HBT are not grown, leaving only the collector and its n^+ ohmic contact. The anode is deposited directly on top of the collector mesa, resulting in a true Schottky diode. Unlike the HEMT diodes, the cathode ohmic contact is directly underneath the anode, so lateral current components in the lightly doped collector region are minimized. This results in a lower series resistance of 8.1 Ω. The diode has 0.025 pF zero-bias junction capacitance, giving it a 786-GHz cutoff frequency. Because the doping density and thickness of the collector region are not op-

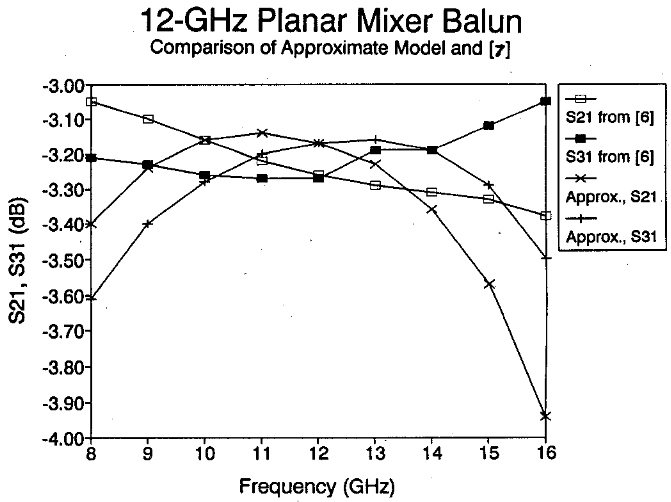

Fig. 4. Comparison of balun performance calculated by approximating the balun as two sets of coupled lines in parallel and the complete (quasistatic) analysis of [6]. These results confirm the adequacy of the former model, which is necessary for use in commercial circuit simulators.

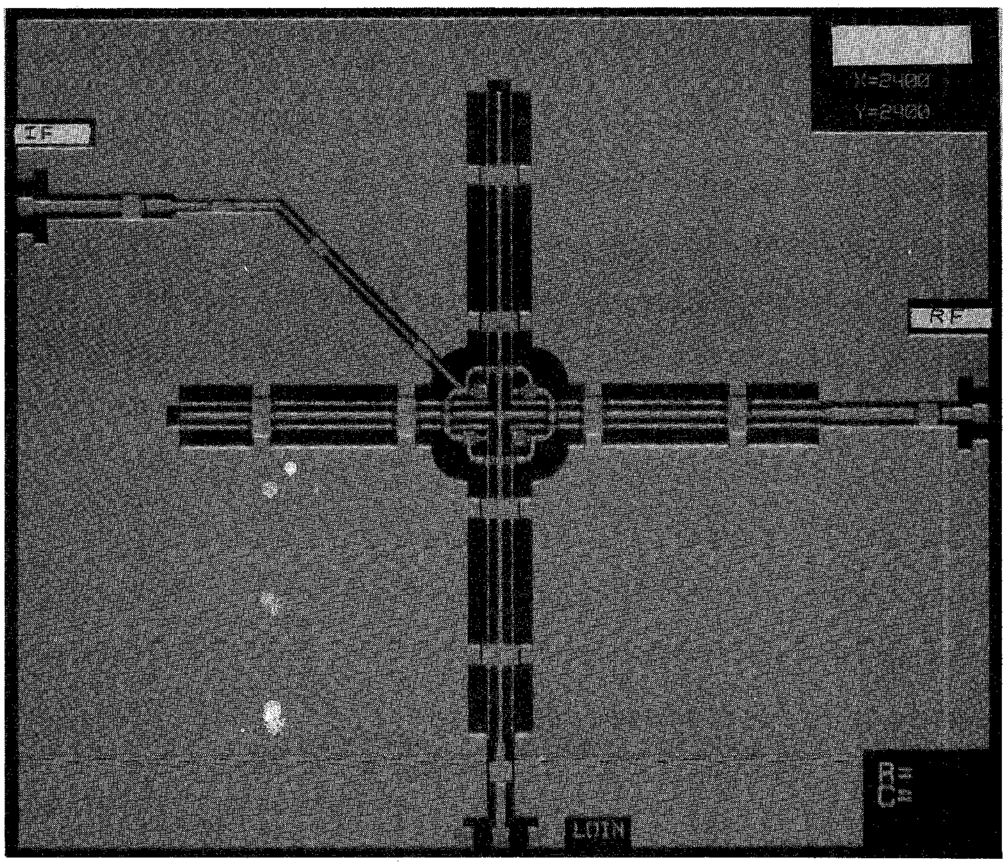

Fig. 5. Top view of the mixer chip. The IF output is at the top left; the RF and LO ports are interchangeable. Chip dimensions are 2.4 × 2.8 mm.

timum for Schottky diodes, this cutoff frequency is still lower than can be achieved in discrete devices or in monolithic devices where the diode process can be optimized. However, it is adequate for these mixers.

D. Mixer Structure

We have fabricated and tested a number of mixers using the planar-balun topology. Fig. 5 shows a microphotograph of one of our mixers. (The differences between the types of mixers, consisting of experiments with balun dimensions, lengths, and of course different diode types, are almost indistinguishable at this scale.) The structure is that of a classical star mixer using Marchand-like baluns. However, unlike the conventional star mixer, the baluns of Fig. 3 are used. The odd-mode impedances of these baluns were chosen to match the 50-Ω RF and LO sources to the real parts of the diodes' input impedances. The baluns' lengths were slightly shorter than one-quarter wavelength, so their inductive output impedances compensated the diodes' capacitive reactance. All three ports—RF, LO, and IF—are coplanar-waveguide interfaces. The balun length was optimized by means of a harmonic-balance circuit simulator.

A disadvantage of this structure, compared to the conventional star mixer, is that the diodes are not connected at a common point, but instead are connected to a narrow strip that encircles the center of the structure. This reduces, to some degree, the symmetry of the circuit and its inductance limits the IF bandwidth. However, in a monolithic realization of this mixer, the ring is very small and its effects are minimal.

III. Performance

We measured several mixers as both upconverters and downconverters. These circuits showed good uniformity between individual mixers.

Figs. 6–8 show the performance of a mixer using HEMT diodes operated as a conventional downconverter. Fig. 6 shows the conversion loss and output third-order intercept point of the mixer at a fixed RF frequency of 28 GHz. This indicates that the IF bandwidth is at least 10 GHz. Fig. 7 shows the conversion loss and (2,-2) spurious-response level at a fixed IF frequency of 1 GHz; the RF and LO bandwidths cover 28–40 GHz. LO-to-RF and RF-to-IF isolations are shown in Fig. 8.

Figs. 9 and 10 show the performance of the HEMT-diode mixer operated as an upconverter (this is the same type of mixer as in Fig. 5, but not the same individual mixer). The output frequency was kept constant at 28 GHz, and the LO frequency was varied from 28 to 40 GHz, with a resulting input frequency range of 0–12 GHz. The conversion loss varied smoothly from 5 dB at the lower end of the band to approximately 8 dB at 12 GHz. The output third-order IM intercept point (IP_3), shown in Fig. 10, was 17 dB at the low end of the band; it degraded considerably at the high end. We believe that this was caused by the rolloff of the LO balun combined with reduced available LO power at this frequency. The $(-2, 1)$ spurious response was below 60 dBC over most of the band, the $(-3, 1)$ was below -65 dBC. These quantities were measured with -10 dBm input power. RF-to-LO isolation was better than 40 dB over the entire band. All the above measurements were made on-wafer.

Figs. 11 and 12 show the performance of a upconverting mixer using HBT diodes. Fig. 11 shows the conversion loss of the mixer, measured in a test fixture, with an output frequency of 22 GHz. This mixer operated over a lower RF/LO frequency range of 22–34 GHz. The conversion loss was somewhat better at 5–7 dB, but the output IP_3 still exhibited the troublesome rolloff at the high end of the band. The latter is shown in Fig. 12, with a 28-GHz output frequency, measured on-wafer.

There are two possible reasons for the rolloff in the IP_3 evident when the RF and IF frequencies are more than a few GHz apart. One is the threshold effect in diodes having high series resistances. We have observed a threshold effect in both calculations real circuits: the IP_3 is often quite high at high LO levels, but drops suddenly when the LO level drops below a threshold value [5]. When the LO level is marginal, and the LO frequency approaches the edge of the balun's passband, the LO losses increase, and less power reaches the diodes. The diodes' IM perfor-

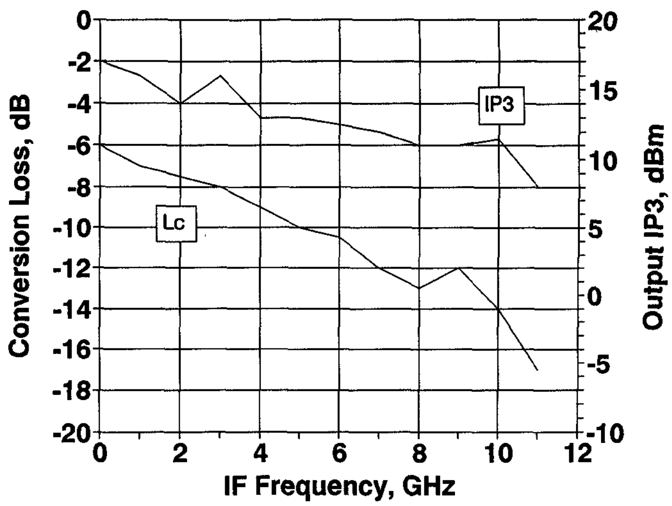

Fig. 6. Conversion loss and third-order output intercept point of the HEMT-diode mixer, as a function of IF frequency, with the mixer operated as a conventional dowconverter. The input frequency is fixed at 28 GHz and the LO is frequency varied from 26 to 40 GHz. The LO level is +16 dBm.

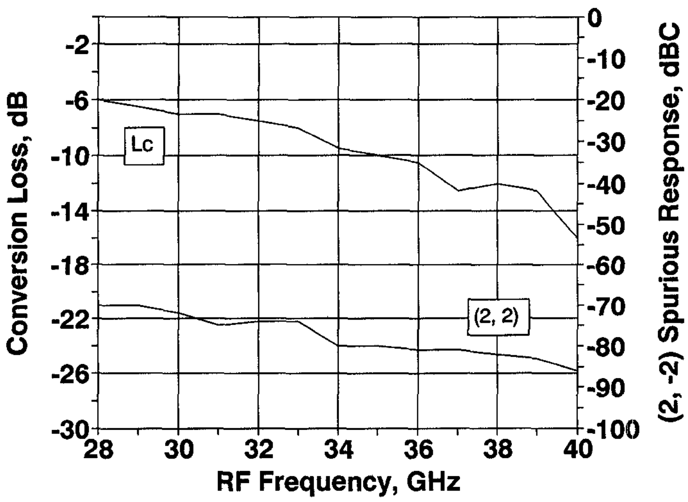

Fig. 7. Conversion loss and (2,2) spurious-response output level; $P_{RF} = -10$ dBm, P_{LO} +16 dBm. Here the IF is fixed at 1 GHz and the LO and RF are swept in tandem from 27 to 39 GHz and 28 to 40 GHz, respectively.

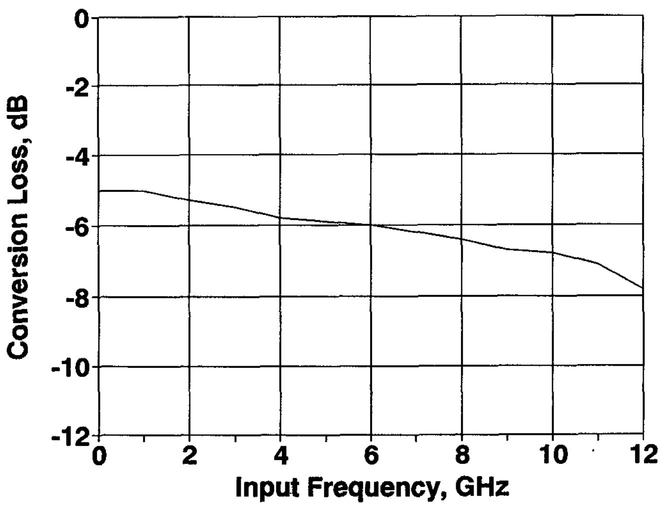

Fig. 8. LO-to-RF and RF-to-IF isolations of the downconverting HEMT-diode mixer.

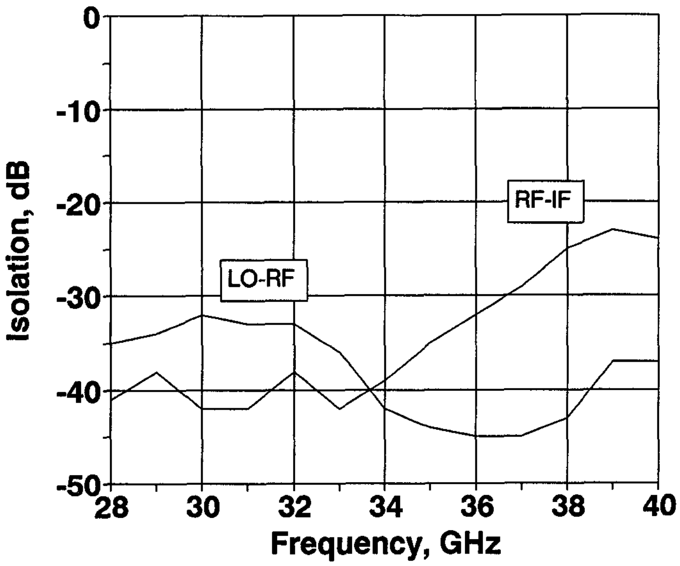

Fig. 9. Conversion loss of the HEMT-diode mixer operated as an upconverter. The RF output is fixed at 28 GHz and the LO is swept 28–40 GHz. The LO power is +13 dBm.

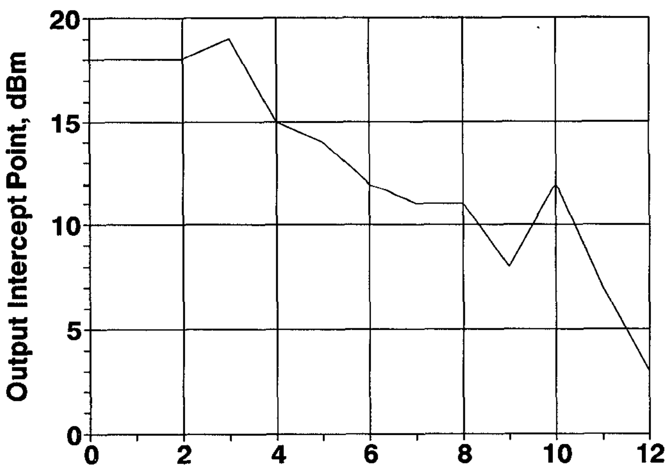

Fig. 10. Third-order intercept point of the HEMT-diode mixer operated as an upconverter. Conditions are the same as in Fig. 9.

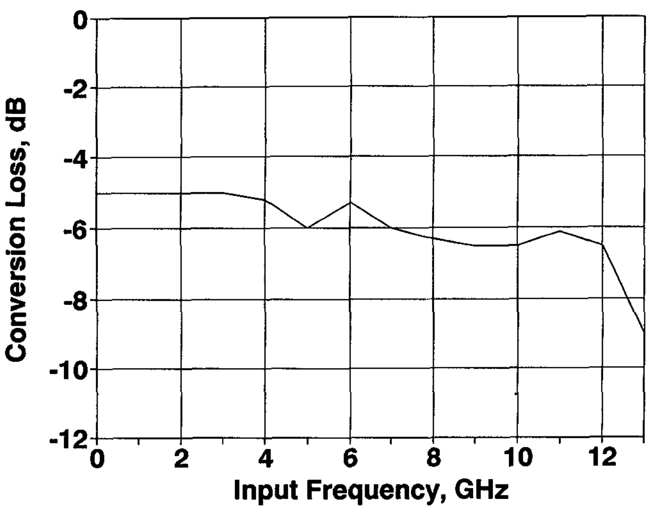

Fig. 11. Conversion loss of an upconverting mixer using HBT-compatible Schottky diodes. The LO level is +13 dBm, the output frequency is 22 GHz, and the LO frequency varies from 22 to 34 GHz. The frequency range for this mixer is different from that of the HEMT-diode mixer, because a mask error caused its baluns' passbands to be lower than intended.

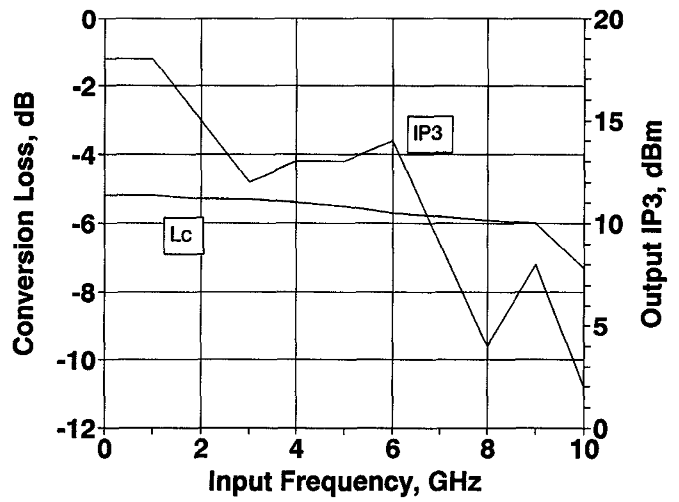

Fig. 12. IP_3 of the HBT-diode mixer as a function of IF frequency. The output is fixed at 28 GHz and the high-side LO is varied.

mance degrades more gradually with LO level as series resistance decreases. A second possibility is that, in an upconverting mixer, the sum and image frequencies are well outside of the baluns' passbands, and thus may be terminated suboptimally. We are investigating ways to circumvent these difficulties.

IV. Conclusions

We have described a Ka-band monolithic diode mixer having broad bandwidth and, in virtually all respects, high performance. It achieves this performance by employing a star structure and unique, Marchand-like baluns.

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