Ka-Band Monolithic GaAs Balanced Mixers

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***Abstract*—Monolithic integrated circuits have been developed on semi-insulating GaAs substrates for millimeter-wave balanced mixers. The GaAs chip is used as a suspended stripline in a cross-bar mixer circuit. A double sideband noise figure of 4.5 dB has been achieved with a monolithic GaAs balanced mixer filter chip over a 30- to 32-GHz frequency range. A monolithic GaAs balanced mixer chip has also been optimized and combined with a hybrid MIC IF preamplifier in a planar package with significant improvement in RF bandwidth and reduction in chip size. A double sideband noise figure of less than 6 dB has been achieved over a 31- to 39-GHz frequency range with a GaAs chip size of only 0.5×0.43 in. This includes the contribution of a 1.5-dB noise figure due to IF preamplifier (5–500 MHz).**

I. Introduction

The performance of GaAs devices has been steadily improved with recent advances in material, process, and device technology. Monolithic integration of passive elements and active devices on GaAs substrates becomes increasingly attractive for use at millimeter-wave frequencies as opposed to the more conventional MIC hybrid approach where the effects of parasitics are difficult to control. Considerable attention has been given to the development of millimeter-wave monolithic balanced mixers which serve as an important building block for a number of potential systems. Recently, a monolithic mixer IF preamplifier using a microstrip circuit approach has been demonstrated with good performance at millimeter-wave frequencies. [1] The circuit requires an on-chip coupler to combine the local oscillator and signal frequencies increasing the chip size, but has the advantage of simple interfaces. The present paper describes a monolithic balanced mixer using a suspended stripline circuit approach in a cross-bar mixer circuit [2] which does not require an on-chip coupler. The monolithic mixer has also been integrated with a hybrid MIC IF amplifier in a wafer-type waveguide package. In this approach the only passive elements on the monolithic GaAs chip are the coupling circuits for millimeter-wave frequencies. The low-pass filter is incorporated with the bipolar IF preamplifier on a hybrid MIC.

II. Circuit Design

The basic configuration of the monolithic balanced mixer is illustrated in Fig. 1. The GaAs chip is used as a suspended stripline and is coupled to local oscillator power and RF signal via two full-height waveguide ports. It consists of two planar mixer diodes and matching circuits for RF waveguide, LO coupling, and IF filter. There are several unique features of the mixer that significantly reduce the complexity and take advantage of the monolithic circuit technique. The diodes are electrically in series with respect to the RF signal. The RF impedance of a single mixer is usually much lower than that of waveguide. With two diodes in series, the RF input impedance of the chip at the signal port can be matched easily with straight full-height waveguide. Furthermore, if a reduced height or ridged waveguide is used to match the impedances of circuit and chip over the desired frequency range, then the RF bandwidth of this mixer could be increased to nearly full waveguide bandwidth.

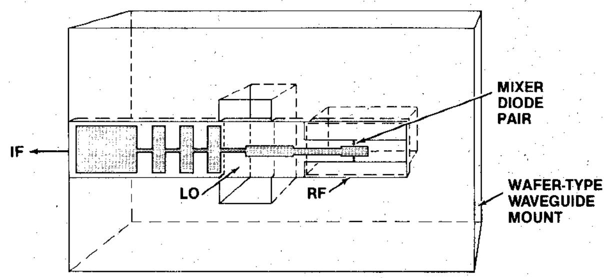

Fig. 1. Millimeter-wave integrated mixer chip design containing two planar mixer diodes and matching circuits for RF waveguide, LO coupling, and IF filter.

The diodes are electrically in parallel with respect to the local oscillator and are in a direction such that the induced LO currents in the diodes are out of phase. This eliminates the need for a magic tee to cancel the noise contributed by the local oscillator. The conventional waveguide magic tee is inherently a narrow-band component and is very expensive to make, particularly at millimeter-wave frequencies. Furthermore, the two diodes are physically close to each other and can have nearly identical parameters because they are monolithically fabricated. Such a well-matched diode pair gives excellent LO noise suppression.

The isolation between the local oscillator and signal ports can be very high over a wide range of frequencies since the dominant TE_{10} mode in the RF waveguide is orthogonal to the quasi-TEM LO input.

III. Chip Layout and Fabrication

The monolithic mixer described above has been fabricated with advanced semiconductor technology available in our laboratory. The monolithic chip design and the key

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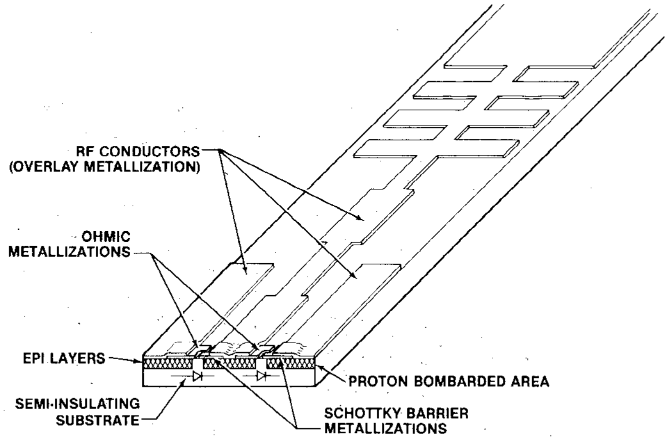

Fig. 2. Monolithic mixer chip shown with two planar Schottky-barrier mixer diodes isolated parasitically by a proton ion-implantation technique and RF matched by overlay metallization patterns.

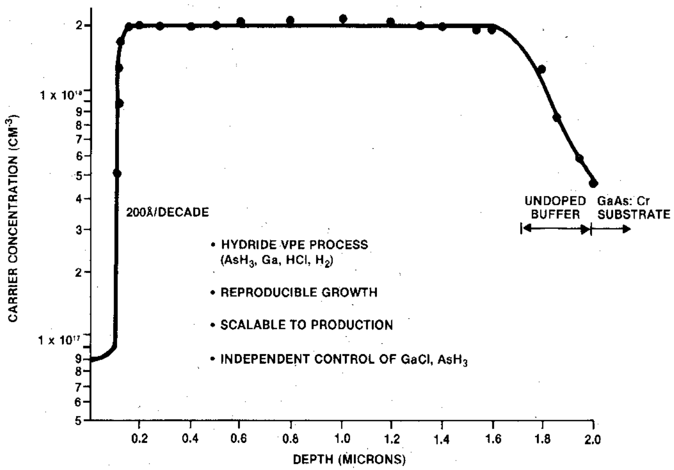

Fig. 3. Doping profile.

technology needed for its fabrication are illustrated in Fig. 2. The diodes are fabricated with VPE-grown n-n$^+$ layers on a semi-insulating substrate isolated by proton bombardment [3]. High-quality n-n$^+$ layers are grown on 10-mil semi-insulating GaAs:Cr substrates which have been qualified by our established qualification test procedure. The n$^+$ layer has a doping density of 2×10^{18} cm^{-3} and is 2 μm thick and the n layer which is on top of n$^+$ layer has a doping density of 9×10^{16} cm^{-3} and is 0.1 μm thick. These layers have been grown by our vapor-phase epitaxial reactor with the hydride process (AsH_3, HCl, Ga, H_2). Carrier concentration as a function of depth from the surface of the n-n$^+$ epi-layer is shown in Fig. 3. Schottky-barrier (TiW/Au) and contact (AuGe/Ni/TiW/Au) metallizations are then deposited for the planar mixer diodes. The chip is bombarded by high energy protons everywhere except at the diodes which are protected by a thick layer of photoresist and gold metal. This proton bombardment process isolates the diodes from the circuit parasitics. After the protective layers are removed, overlay metallization is deposited for the RF matching circuits. Individual chips are cut from the large wafer and mounted in the wafer-type waveguide package as shown in Fig. 4.

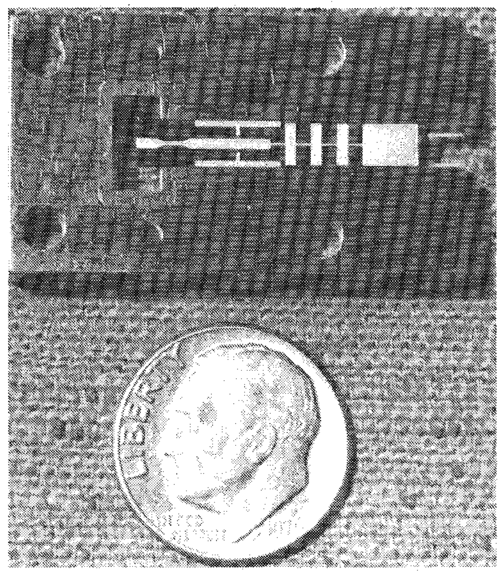

Fig. 4. Monolithic mixer chip in a wafer-type mount.

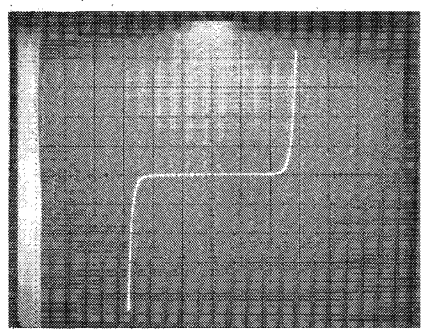

Fig. 5. $I-V$ characteristics of the monolithic diode pair. Horizontal: 0.2 V/div; Vertical: 1 μA/div.

Diodes with a zero biased cutoff frequency of better than 600 GHz have been achieved. Fig. 5 shows the $I-V$ characteristics of a monolithic diode pair.

IV. Monolithic Balanced Mixer-Filter

Fig. 6 shows the double sideband noise figure of the mixer filter chip as a function of the local oscillator power for the three different LO frequencies. A double sideband noise figure of 4.5 dB has been achieved with the monolithic GaAs balanced mixer chip over a 30- to 32-GHz frequency range at a LO power of approximately 10 mW. This includes the contribution of a 1.5-dB noise figure due to an IF preamplifier which has a bandwidth of 5–500 MHz.

This performance is quite competitive with the best conventional mixers at this frequency. Measurements of noise figure as a function of LO frequency for three different mechanical tuning positions are also plotted in Fig. 7. This indicates that some tuning is possible with the monolithic balanced mixer but the current chip configuration works best around 31 GHz with a low noise IF bandwidth of about 500 MHz.

The isolation between the local oscillator and signal

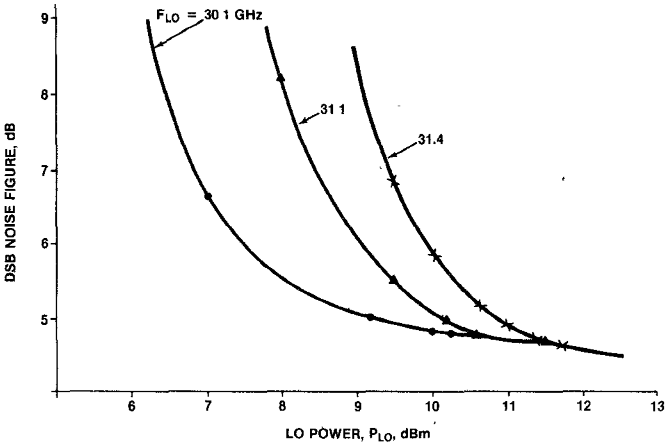

Fig. 6. Noise figure versus P_{LO} of the monolithic mixer.

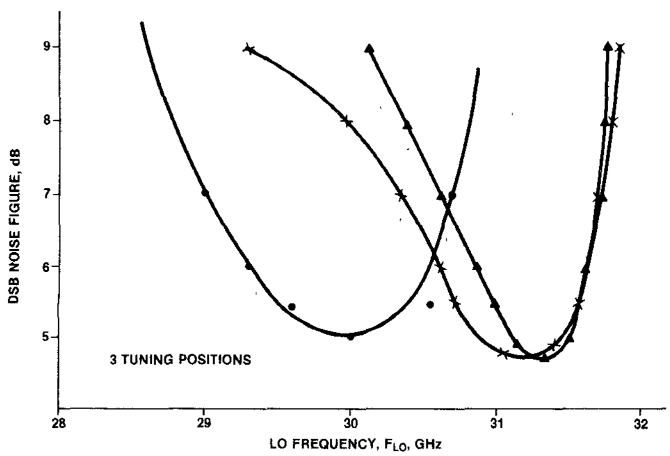

Fig. 7. Noise figure versus F_{LO} of the monolithic mixer.

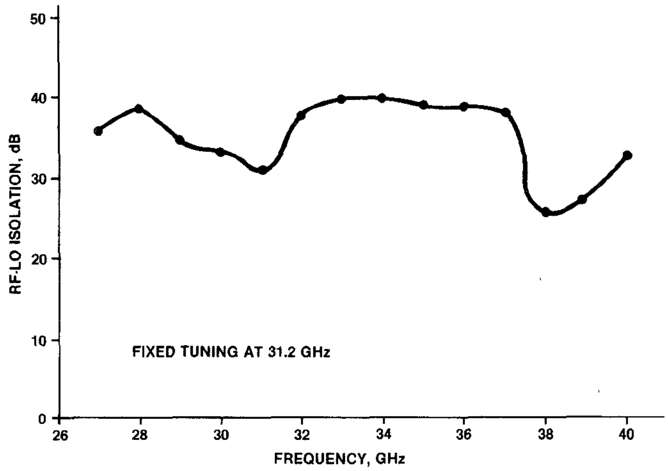

Fig. 8. Isolation versus frequency of the monolithic mixer.

ports of the mixer is excellent as indicated in Fig. 8. An isolation of better than 30 dB has been achieved over a frequency range of 27–37 GHz when the mixer is tuned at 31 GHz. This excellent isolation property is a direct consequence of the mixer circuit design approach, i.e., the LO and RF ports are decoupled because the E-fields of the dominant modes are orthogonal to each other.

The single-sideband conversion loss of the mixer is about

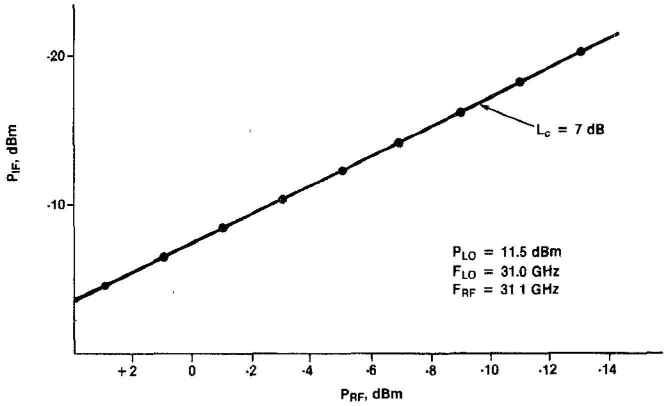

Fig. 9. Single sideband conversion loss of the monolithic mixer.

7 dB as shown in Fig. 9. The corresponding single sideband noise figure is 7.6 dB. This means that the noise due to the diode is very low and the diodes are well matched. This confirmed our belief that the monolithic diode pair fabricated in close proximity to each other would have nearly identical parameters and therefore the LO noise suppression property of the mixer is excellent.

Excellent correlation between the experimental data and theoretically calculated results was obtained for the monolithic mixer filter chip. The theoretical model has also been used to aid the optimization of the monolithic mixer. Theoretical performance of the mixer was determined with the aid of a very complete mixer analysis program [4] which was obtained from Kerr and Siegel at NASA Goddard Space Flight Center. This program has been significantly modified to increase its speed and convenience for mixer design without degrading its accuracy. An extensive series of calculations with the program indicates that the order of importance of the parameters affecting the performance of a mixer diode are the series resistance, capacitances, and then the series inductance. The optimum inductance value is a function of the circuit impedance level and other factors.

Using realistic parameters for the various diode characteristics, the performance of the monolithic mixer indicated in Fig. 10(a) was obtained. The equivalent circuit is given in Fig. 10(b). The performance predicted for the series inductance estimated from the diode lead geometry for the monolithic mixer is indicated. The measured performance is essentially identical. It is clear that a slight adjustment of the circuit could give considerably better noise performance by improved impedance matching between the diode and waveguide.

V. Integration of Monolithic Mixer and Hybrid IF Preamplifier

A monolithic GaAs balanced mixer has been combined with a hybrid IF preamplifier in a planar waveguide package. Fig. 11 is a schematic of the circuit configuration and Fig. 12 is a photograph of the package. The size of the monolithic balanced mixer has been minimized by incorporating only those circuit elements which are critical for matching of devices at millimeter-wave frequencies on the

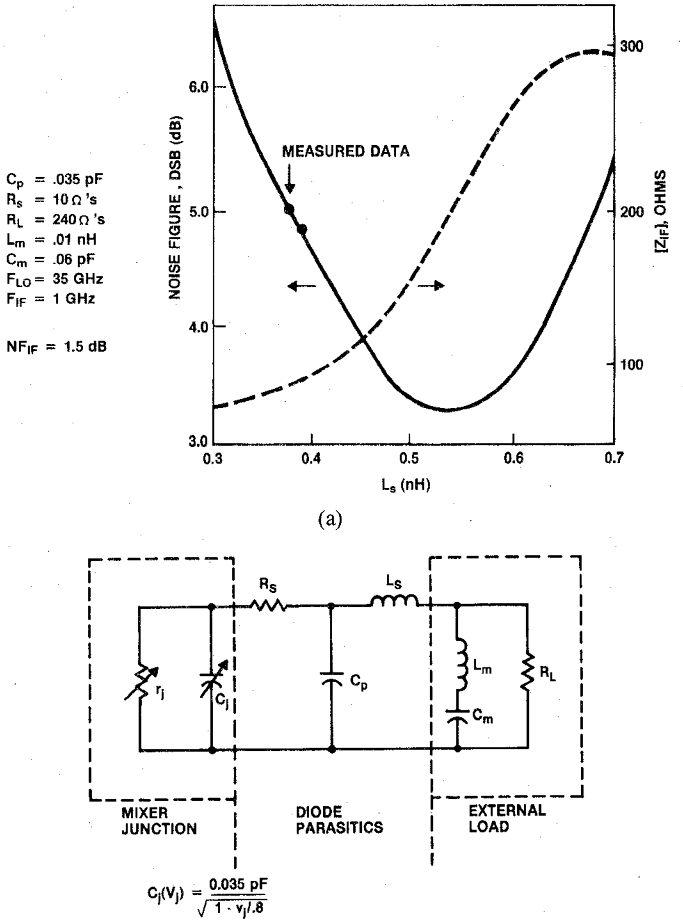

Fig. 10. (a) Comparison of measured data and calculated performance of the monolithic mixer filter chip. (b) Equivalent circuit used for mixer junction embedding impedance calculation.

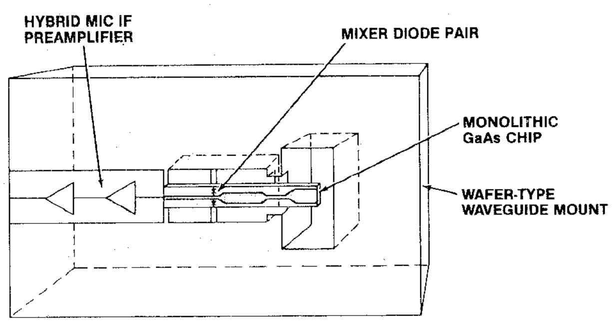

Fig. 11. Packaging technique for combining a monolithic balanced mixer and a hybrid IF preamplifier.

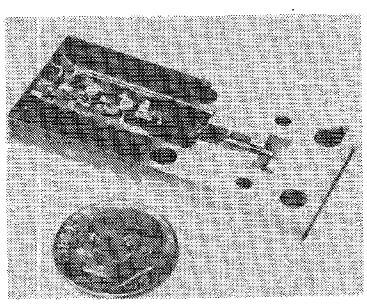

Fig. 12. *Ka*-band monolithic GaAs balanced mixer chip integrated with a hybrid MIC IF preamplifier on a planar package.

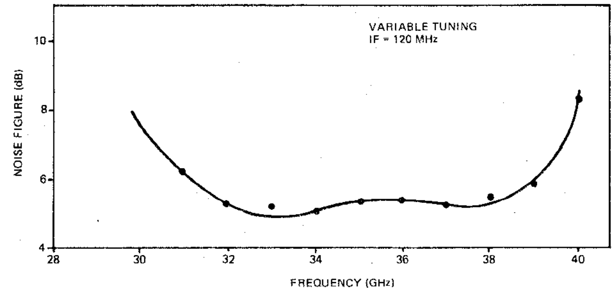

Fig. 13. Monolithic mixer noise figure versus frequency demonstrates wide tunable operating frequency range for flexible system applications (includes 1.5-dB IF preamplifier noise).

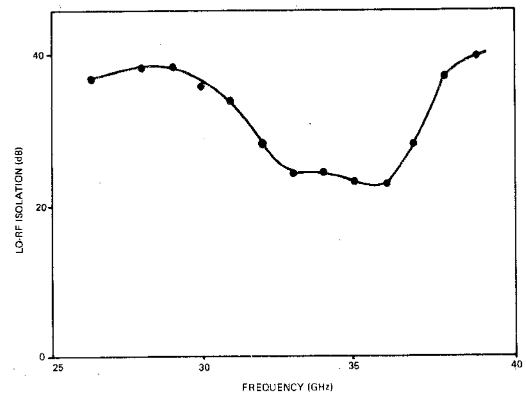

Fig. 14. Monolithic mixer LO-RF isolation versus frequency.

GaAs substrate. Significant reduction in chip size and improvement in RF bandwidth have been achieved.

Fig. 13 shows noise figure versus frequency of a monolithic chip from 30 to 40 GHz. A double sideband noise figure of less than 6 dB has been achieved over an 8-GHz bandwidth with a GaAs chip size of only 0.05×0.43 in. This includes the contribution of a 1.5-dB noise figure from IF preamplifier which has a bandwidth of 5–500 MHz. This performance gives an improvement of RF bandwidth by a factor of 4 and a reduction of chip size by a factor of 5 with respect to a result reported previously [2]. The isolation between the local oscillator and signal ports of the mixer is very good as indicated in Fig. 14. An isolation better than 20 dB over 26–40 GHz has been achieved.

VI. Conclusions

A monolithic GaAs balanced mixer chip with a minimum chip size can be combined with a hybrid MIC IF preamplifier in a unique circuit configuration to achieve high-performance and potentially cost-effective components for millimeter-wave receiver applications.

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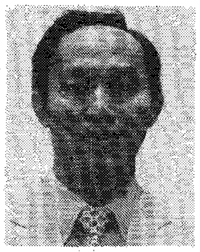

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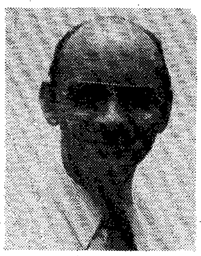

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