23-40 GHz InP HEMT MMIC Distributed Mixer

Reza Majidi-Ahy, Cliff Nishimoto, Jeff Russell*
Weiming Ou*, Steve Bandy, George Zdasiuk

Varian Research Center
3075 Hansen Way, Palo Alto, California 94304-1025

**Litton Solid-State*
3251 Olcott St., Santa Clara, California, 95050

Abstract

We report the development of an active millimeter-wave InP HEMT MMIC distributed mixer operating over 23-40 GHz RF bandwidth, with IF frequencies in the range of 2-13 GHz, and fixed LO frequencies of 20 and 28 GHz. The devices were InGaAs-InAlAs-InP HEMTs with a gatelength of 0.25μm. The mixer had an average conversion gain of 0 dB when biased for maximum bandwidth, and an average conversion gain of 5 dB when biased for maximum gain. The overall chip dimensions for this MMIC, were 500 by 1000 μm.

Introduction

Advanced microwave and millimeter-wave instruments, ECM and ESM systems critically depend on the performance of broadband, small size, and low cost mixers. Traditionally diode mixers have been used for broadband applications. FET mixers however, have the primary advantage of conversion gain instead of conversion loss in the case of diode mixers [1]. HEMTs for mixers, are fundamentally similar to FETs, with potential for stronger nonlinearities in the transconductance.

FET mixers based on a distributed design approach, make broadband active mixers possible [2]. Distributed hybrid and MMIC, single-gate and dual-gate, GaAs MESFET mixers with good broadband performance have already been reported up to 26 GHz [3], [4], [5], [6], [7]. Also dual-gate GaAs-AlGaAs HEMT mixers have been reported to 18 GHz [8]. However, although ultrabroadband distributed amplifiers have been demonstrated up to 100 GHz [9], [10], millimeter-wave broadband mixers have primarily been based on using Schottky diodes as the nonlinear element, and millimeter-wave broadband FET or HEMT mixers have not been reported.

We report in this paper, the development of a 23-40 GHz distributed mixer using HEMTs as the nonlinear elements. This MMIC mixer was fabricted using InGaAs-InAlAs HEMT technology on an InP substrate, and is compatible with other MMIC components such as broadband active combiners [11], and amplifiers. The measured performance of this MMIC, represents highest frequency distributed mixer reported to date.

Device Characteristics

The active device in the MMIC was a lattice-matched $In_{0.53}Ga_{0.47}As - In_{0.52}Al_{0.48}As$ HEMT, also lattice-matched to its semi-insulating InP substrate. The cross section of this device is shown in Figure 1, (where mole fractions are the same as indicated). The large conduction band discontinuity between InAlAs and InGaAs [12], and larger $\Gamma - L$ valley separation (0.55 eV) of InGaAs [13] compared to AlGaAs-GaAs makes InGaAs-InAlAs more attractive for high speed device applications. For HEMTs this material structure has the advantages of a higher sheet carrier (two-dimensional electron gas) density, higher low-field electron mobility, higher electron saturated velocity, and higher electron peak velocity. These advantages result in a higher frequency, lower noise HEMT particularly suited for millimeter-wave MMIC applications. The material structure was grown by molecular beam epitaxy (MBE) on an iron-doped semi-insulating InP substrate. The undoped InGaAs layer at the top surface improved the breakdown characteristics of the device [14].

The nonlinear elements in this MMIC distributed mixer were two 0.25μm by 150μm, lattice-matched InAlAs-InGaAs-InP HEMT's on a semi-insulating InP substrate. The device fabrication uses our standard InGaAs-InAlAs HEMT process. A triangular gate defined by E-beam lithography was used for simlpifying the fabrication process and yield enhancement. By using a mushroom gate process, it is expected that the conversion gain of the mixer will be improved by more than 1.0 dB. The devices had a typical pinch-off voltage of approximately -2.5 volts, and a maximum channel current of 500 mA per millimeter. The DC transonductance was typically 533 millisiemens per millimeter of gate width, with peak g_m typically near -0.4 volts.

Circuit Design

The concept of distributed mixing is an extension of that of distributed amplification. In single-gate common-source distributed FET mixers, LO and RF signals are combined using an active or passive combiner, and are applied to the gates of the FETs. The reported results in this paper are with the use of a pasive off-chip combiner. However a 4-40 GHz MMIC active combiner has also been developed [11], which can be used to combine the LO and RF signals and supply them as the input to this MMIC active mixer.

In this distributed mixer, an artificial input transmission line is formed by the time-averaged input impedance of each FET loading a high-impedance transmission line. A similar artificial transmission line is formed by the time-averaged output impedance of each FET loading another high-impedance transmission line. For broadband operation, the output signals at the drain of the FETs should add in-phase at the IF frequency. For high IF frequencies (1-13 GHz for this MMIC mixer), this phase synchronization is even more critical. Therefore the phase shifts between the FETs at the input and output transmission lines have to be equal over the IF frequency range of operation.

In FET mixers, the dominant nonlinearities are associated with the channel resistance R_{ds}, gate-to-source capacitance C_{gs}, and the transconductance g_m. Although the nonlinearities of R_{ds}, and C_{gs} are significant, usually the predominant nonlinearity used (as in this circuit) is that associated with g_m. For the HEMTs in this MMIC, g_m had a range of 0 to 80 millimsiemens under LO drive, with peak g_m at -0.4 volts V_{GS}. The optimum bias points, judged solely based on the maximum conversion gain, were near the pinch-off or forward turn-on voltages, as expected for a standard FET-like device.

In addition to HEMTs, high-impedance coplanar waveguides (CPWs) were used to form approximately 50 ohm transmission lines, with the time-averaged C_{gs} at the RF input, and the time-averaged C_{ds} at the IF output. CPWs for this application have the advantage of very low dispersion (when their ground-to-ground spacing is kept small), as compared with microstrip. This results in better phase control in the input and output circuit, which is critical to the broadband operation of the active mixer.

The schematic circuit diagram of the ditributed active mixer is shown in Figure 2. In addition to HEMTs and CPWs, one terminating thin-film resistor, one RF matching capacitor, and a bypass thin-film capacitor were used. A microphotograph of the MMIC distibuted active mixer is shown in Figure 3. The overall chip dimensions were 500 by 1000 μm, which included the input and output probe pads for on-wafer testing.

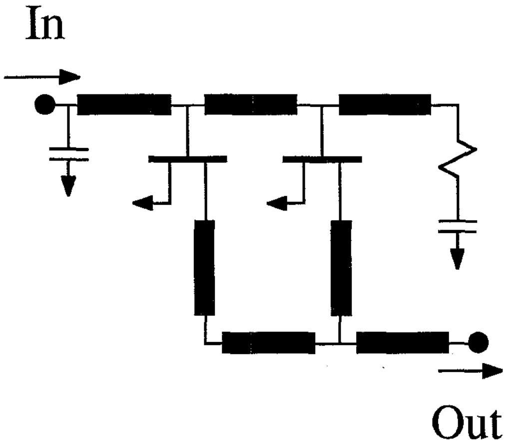

Fig. 2. Schematic circuit diagram of MMIC distributed mixer.

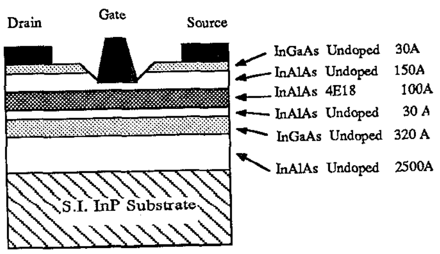

Fig. 1. Cross-section of InAlAs-InGaAs-InP HEMT.

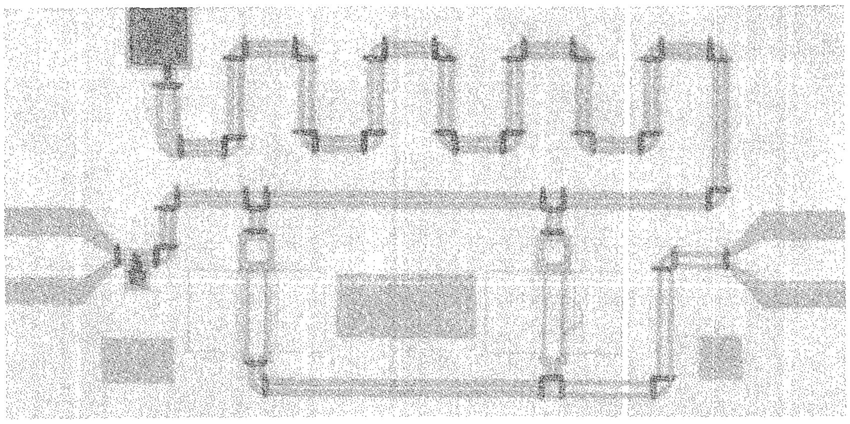

Fig. 3. Microphotograph of MMIC distributed mixer.

Measurement Results

The measured DC g_m of the $150\mu m$ devices had a peak value of 80 millisiemens, or approximately 533 millisiemens per millimeter. The measured pinch-off voltage was approximately -2.5 volts. The optimum bias points for the devices in this mixer circuit, were near pinch-off and near forward turn-on voltage. Biasing near pinch-off was used for maximum bandwidth, and biasing near forward turn-on was used for maximum conversion gain.

This mixer was designed to operate with primarily two fixed LOs of 20 and 28 GHz, to dowconvert the entire Ka-band of 26-40 GHz, to an IF range of 1-13 GHz. The actual fabricated MMIC however, had a roll-off in the conversion gain near 40 GHz. A +10 dBm, 20 GHz LO signal was used to downconvert 23-33 GHz RF signals to 3-13 GHz. Figure 4 shows the conversion gain (G_C), as a function of RF frequency for different bias currents. Biasing at 30 mA total current ($17\% I_{DSS}$ which is near pinch-off, at a V_{DS} of 3.0 volts, gave the maximum bandwidth (G_c flatness), and an average conversion gain of 0 dB. For RF signals in the range of 29-40.0 GHz, a +10 dBm, 28 GHz LO signal was used to drive the mixer. Figure 5 shows the conversion gain as a function of RF frequency for this range. The average conversion gain across this band was 0 dB, with the high-end rolling off near 40 GHz. The roll-off at 40 GHz is due to higher than expected time-averaged input capacitance of the HEMTs.

By increasing the bias current to 130 mA ($75\% I_{DSS}$) near HEMTs gate forward turn-on voltage, the average conversion gain was increased to of 5 dB. This was at the expense of higher roll-off above 35 GHz. The reduction in the bandwidth is primarily due to higher time-averaged input and output capacitances of the HEMTs at the higher channel current. The increase in the conversion gain is due to the increase in the peak and average transconductance over the LO signal range when biased near turn-on.

One of the advantages of having only two transistors in this distributed mixer is lower required LO power to drive them into nonlinear region. The conversion gain as a function of LO power was measured to determine the optimum drive LO power. Figure 6 shows the conversion gain as a function of power level of a 20 GHz LO signal. Although by increasing the LO power above +10 dBm, the conversion gain still increases, it was decided to use +10 dBm because of the relatively small gain increase.

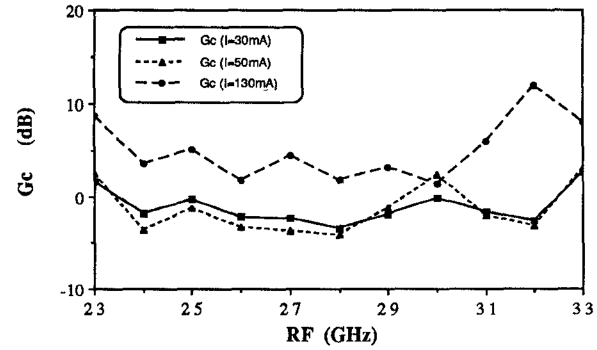

Fig. 4. Measured conversion gain of the MMIC distributed mixer, with a +10 dBM, 20 GHz LO signal.

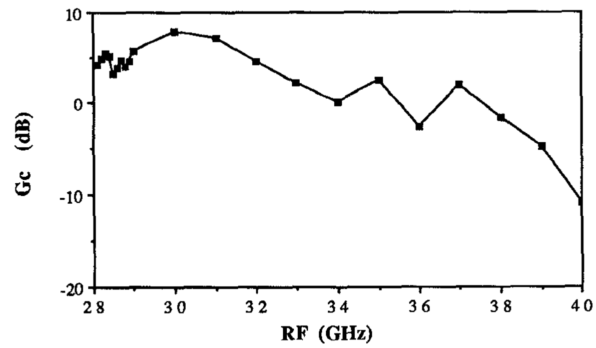

Fig. 5. Measured conversion gain of the MMIC distributed mixer, with a +10 dBM, 28 GHz LO signal.

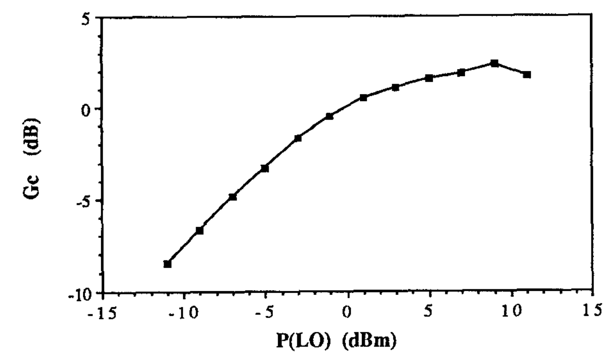

Fig. 6. Measured conversion gain of the MMIC distributed mixer, as a function of LO power (LO frequency=20 GHz).

Conclusions

We have reported a 23-40 GHz InP HEMTMMIC distributed mixer. The nonlinear elements inn this circuit are two $0.25\mu m$ by $150\mu m$ InGaAs-channel, lattice-matched HEMTs, on an InP substrate. When biased for maximum bandwidth this MMIC had an average conversion gain of 0 dB from 23 to 40 GHz, at an under-drive bias current of 30 mA. When biased for maximum gain, this MMIC had an average conversion gain of +5 dB from 23 to 33 GHz, at an under-drive current of 130 mA. The overall chip dimensions for this MMIC, were 500 by 1000 μm. These results represent the highest frequency and highest gain broadband FET or HEMT mixers.

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