A Low-Cost W-Band MIC Mixer Using Flip-Chip Technology

R. S. Virk, *Member, IEEE*, S. A. Maas, *Fellow, IEEE*, M. G. Case, *Member, IEEE*, M. Matloubian, *Member, IEEE*, P. Lawyer, H. C. Sun, C. Ngo, and D. B. Rensch

***Abstract*—This letter describes a novel mixer fabricated using a unique low-cost approach to achieve effective conversion performance. By utilizing flip-chip GaAs Schottky diodes mounted on a duroid substrate, this radio frequency (RF) probeable mixer achieves 11.3-dB conversion loss at 77 GHz with an IF frequency of 500 MHz. This new technology demonstrates an affordable alternative to standard millimeter-wave circuit fabrication while offering the capability to integrate a variety of device technologies in the same circuit.**

I. Introduction

THE HIGH COST of monolithic microwave integrated circuits (MMIC's) has prevented the development of affordable millimeter-wave systems for commercial applications. This has been due primarily to the limited yield and the high cost of semiconductor "real estate" required for passive components in high-performance monolithic circuits. Flip-chip technology allows the passive structures of a millimeter-wave circuit to be produced on a low-cost medium while reserving the expensive semiconductor substrate area for the fabrication of discrete active devices. These active components are then flip-chip mounted onto the low-cost substrate for integration with the passive circuitry. This method also offers several other advantages including: a low-inductance repeatable bump interconnect, the freedom to utilize many device technologies for optimum circuit/system performance, and the option to replace defective components if necessary [1].

There has been a great deal of work on searching for an effective diode mixer which can be readily integrated into an existing monolithic technology [2]–[5]. The desired goal in each of these cases is to complement a proven process with a monolithically integratable W-band mixer without sacrificing the benefits the device technology provides. The mixer described here performs comparably with those mixers and offers the added benefit of being integratable with all of these processes at a lower cost through the utilization of flip-chip technology.

II. Flip-Chip Technology

The low-cost technology demonstrated in this paper uses standard 0.010-in-thick duroid board ($\varepsilon_r = 3$) as the circuit substrate. In a high-volume production environment, this material can be processed for ~\$0.03 mm^2, as compared to \$1–\$10 mm^2 for GaAs or InP substrates, while discrete diodes can be fabricated and mounted for less than \$0.70 each. Microstrip transmission lines are etched in the copper-clad board to form the passive circuitry, and "plated-thru" vias provide access to the ground plane. Due to the thickness of the duroid substrate, circuits are designed in an 80-Ω system to reduce transmission line width and to simplify interconnections during circuit integration. The W-band signals are applied through a special CPW-to-microstrip transformer which is used to convert the 50-Ω CPW signal at the probe tip to an 80-Ω microstrip mode. These transitions were analyzed using an electromagnetic (EM) simulator and had less than 1.3-dB loss over 75–90 GHz.

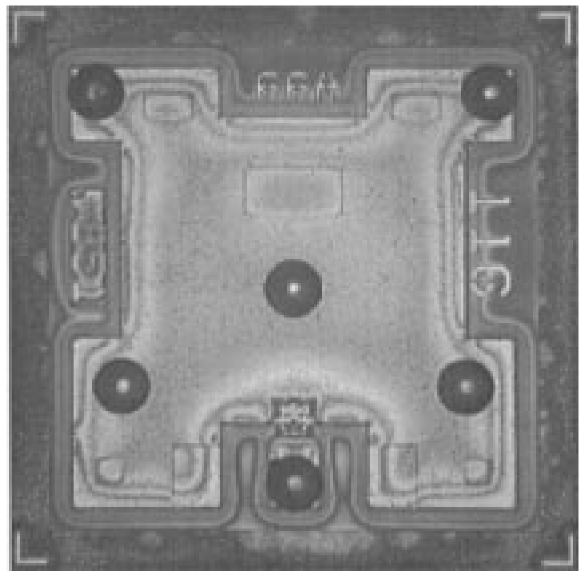


Fig. 1. Photograph of a 4 μm × 4 μm flip-chip diode. The PbSn bumps are 50 μm in diameter and 37 μm high.

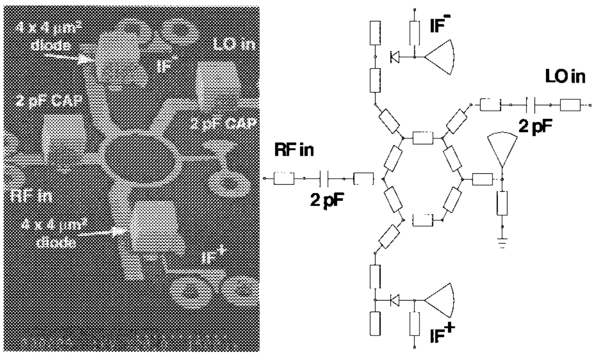
The nonlinear components used in the mixer are 4 μm × 4 μm GaAs Schottky diodes similar to the one shown in Fig. 1. The photograph displays the PbSn bumps, which are 50 μm in diameter and 37 μm high, and are used to mount the diode to the substrate. By placing the chip face down on the copper traces and heating to the eutectic temperature of the alloy, the PbSn bumps wet to the substrate metallization and form an effective electrical and mechanical bond when cooled. Using a self-alignment process, the accuracy in placing the components is ±2 μm, as required for millimeter-wave circuit fabrication

Manuscript received April 14, 1997.

R. S. Virk, M. G. Case, M. Matloubian, P. Lawyer, H. C. Sun, C. Ngo, and D. B. Rensch are with Hughes Research Laboratories, Inc., Malibu, CA 90265-4799 USA.

S. A. Maas is with Nonlinear Technologies, Inc., Long Beach, CA 90807 USA.

Publisher Item Identifier S 1051-8207(97)06165-5.



(a) (b)

Fig. 2. (a) SEM photo of flip-chip mixer circuit. The rat-race mixer is fabricated on 0.010-in-thick duroid where GaAs Schottky diodes and DC blocking capacitors have been flip-chip mounted onto the substrate. (b) Schematic of the single-balanced mixer circuit.

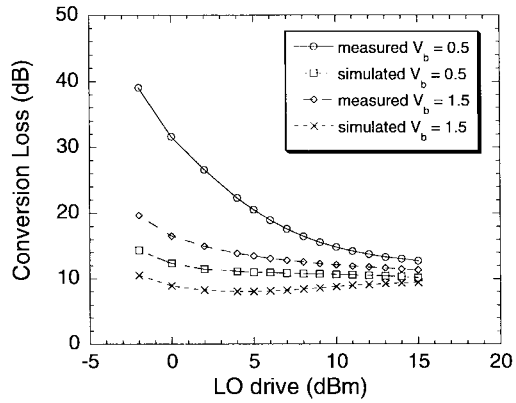


Fig. 3. Comparison of measured and simulated data for conversion loss as a function of LO drive and diode bias (V_b) where $f_{\rm RF} = 77$ GHz and $f_{\rm LO} = 76.5$ GHz. The measured conversion loss is 11.3 dB for $V_b = 1.5$ V and $P_{\rm LO} = +15$ dBm.

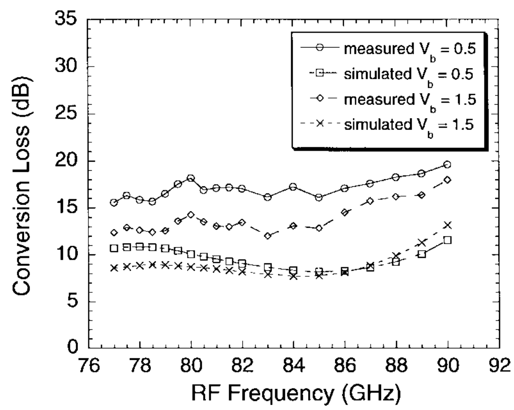


Fig. 4. Comparison of measured and simulated data for conversion loss as a function of RF frequency and diode bias (V_b) where $P_{\rm LO} = +9$ dBm and $f_{\rm LO} = 76.5$ GHz. The measured conversion loss is ~12.5 dB for $V_b = 1.5$ V and $f_{\rm IF} < 2.5$ GHz.

and repeatability. The diode, including bump parasitics, has been modeled up to 40 GHz.

III. Mixer Design

The single-balanced mixer design, shown in Fig. 2, has a rat-race configuration and is contained in an area of 5.4 × 6.6 mm^2. The ring is composed of six quarter-wave sections at the local oscillator (LO) frequency while a radial stub presents each diode with a short circuit at its respective IF port, where DC bias can also be applied. Unlike conventional rat-race mixers, both diodes are oriented identically, and their DC and IF return paths are provided through a "plated-thru" via. These structures were designed using an EM simulation tool and, in addition to the diode matching circuit, ensure that the injected LO signal pumps the diodes 180° out of phase.

Because of the diodes' identical orientations, the signals at the two IF output ports are 180° out of phase. The two IF signals can be recombined using an operational amplifier or 180° hybrid circuit, depending upon the IF frequency. This balanced output configuration was chosen to reduce the influence of environmental noise, while offering the same advantages of a standard single-balanced mixer. These benefits include rejection of LO noise, rejection of some spurious responses, and good LO-to-RF isolation [6].

IV. Results

The RF and LO signals were injected to the mixer via the specially designed CPW-to-microstrip transitions using millimeter-wave wafer probes. Each IF output power was measured at its respective port through a microwave wafer probe where a DC bias (V_b) was being applied through a resistor and bias tee. The mixer conversion performance could then be obtained by combining the two IF signals through an ideal coupler. Note that the losses through the input transitions and blocking capacitors have been removed.

The resulting conversion performance as a function of LO drive is illustrated in Fig. 3. The optimal performance was measured for $V_b = 1.5$ V and $P_{\rm LO} = +15$ dBm where the mixer provided 11.3 dB conversion loss ($f_{\rm LO} = 76.5$ GHz and $f_{\rm IF} = 500$ MHz). Fig. 4 shows the mixer conversion performance as a function of RF frequency with the LO drive and frequency held constant at +9 dBm and 76.5 GHz, respectively. The conversion loss is ~12.5 dB for IF frequencies below 2.5 GHz ($V_b = 1.5$ V), where the IF output circuits are designed to operate.

Both plots display a noticeable difference between the simulated and measured results. Although a portion of the error is caused by the use of a 40-GHz diode model, EM simulations suggest that the sections of the board metallization, which support the device by bonding to the bumps along the chip's periphery, influence each diode's matching circuit. By reducing this extrinsic metallization or adjusting the matching circuit to compensate, the conversion performance and LO drive requirement should both improve. A mixer-ring test circuit also exhibited a 0.8-dB imbalance in the distribution of the LO signal, causing one diode to perform more of the mixing and preventing optimal conversion. By addressing each of these issues in the next design, the mixer performance could be noticeably improved.

V. Conclusion

A novel W-band mixer, which is composed of copper microstrip on a duroid substrate and flip-chip mounted components, has been shown to provide a conversion loss of 11.3 dB. This mixer can be readily integrated with similar circuits on the same substrate to provide a low-cost alternative to MMIC's. These flip-chip components can easily consist of several different technologies and, unlike their higher-costing monolithic counterparts, can be replaced if damaged.

REFERENCES

[1] M. Matloubian, "Flip-chip components for realization of low-cost millimeter-wave systems," in *Proc. Asia-Pacific Microwave Conf.*, 1996, p. 1619.

[2] R. S. Virk *et al.*, "A comparison of W-band MMIC mixers using InP HEMT technology," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1997.

[3] Y. Kwon *et al.*, "A planar heterostructure diode W-band mixer using monolithic balanced integrated approach on InP," in *GaAs IC Symp. Dig.*, 1992, p. 67.

[4] H. Matsuura *et al.*, "A monolithic W-band CPW rat-race mixer with HBT IF amplifier," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1996, p. 389.

[5] E. W. Lin *et al.*, "Monolithic millimeter-wave Schottky-diode-based frequency converters with low drive requirements using an InP HBT-compatible process," in *GaAs IC Symp. Dig.*, 1995, p. 218.

[6] S. A. Maas, *Microwave Mixers*, 2nd ed. Norwood, MA: Artech House, 1993.