Flip-Chip Process Achieves Conversion Loss Under 8 dB in E-Band Diode Harmonic Mixers

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***Abstract* — A low-cost process in which discrete semiconductor chips are flip-attached by thermocompression bonding to 30-micron-diameter gold bumps on fine-featured passive integrated circuits was employed in the fabrication of diode harmonic mixers for use over the 71-76 GHz and 81-86 GHz ranges. Incorporated in the substrate were high-precision grounded heat sinks, semi-lumped filters, and matching networks in low-loss microstrip format. Measurements demonstrate an upconversion loss minimum of 6 dB and downconversion loss minimum of 8 dB respectively. The performance is attributable to the high cutoff frequency of the discrete diodes and the low loss of the passive circuitry.**

***Index Terms* — Millimeter-wave mixers, multichip modules, frequency conversion, millimeter-wave integrated circuits, integrated circuit design, flip-chip devices.**

I. INTRODUCTION

Since mixers generally have a large ratio of passive circuit area to semiconductor device area, it is attractive to consider a technology in which a small and inexpensive semiconductor chip containing the diodes is flip-attached onto a low-cost passive integrated circuit. Diode chips with exceptionally high cutoff frequencies are unavailable on microwave monolithic integrated circuits (MMICs) due to limitations on process complexity and surface topology, but specially-processed discrete diodes with cutoff frequencies approaching 2 THz can be obtained in chip form at low cost by virtue of their small size. The present work shows the results that can be achieved when these diodes are flip-attached onto low-loss passive integrated circuits to form E-band harmonic mixers.

II. THE TECHNOLOGY

The flip-chip-on-passive-integrated-circuit technology used in this study is termed MLMS™ (MultiLithic MicroSystem™). In MLMS™ technology small semiconductor dice containing the active or nonlinear elements are flip attached by way of an automated assembly process onto an inexpensive substrate that contains all of the passive elements of the subsystem. This passive integrated circuit substrate features 5-micron minimum trace and space widths, two metal layers, and integrated metal-insulator-metal capacitors and thin-film resistors. The die attachment is achieved through thermocompression welding of the pads on the semiconductor dice to 30-micron gold bumps on the substrate—the same metallurgy as in wire bonding. The technology lends itself to the integration of complete subsystems on a single substrate thereby avoiding the use of bond wires and other variables in the millimeter-wave path. These MLMS™ assemblies withstand repeated cycling between liquid nitrogen and a 300º C hot plate and repeated cycling between freezing and boiling while under water. They have been tested under mechanical shock at 3000 Gs, and, based on measured die pull forces, are expected to withstand 100,000 Gs.

The MLMS™ substrate, a cross-section of which is shown conceptually in Fig. 1, has built into it high-thermal-conductivity pedestals that are precisely shaped to thermally and electrically ground a bump while maintaining electrical isolation to other bumps spaced as little as 65 microns away center-to-center. The dielectric, with a thickness of 100 microns, is thin enough to allow microstrip circuitry to operate with low loss and good isolation up to 100 GHz and to allow low-inductance grounding through the pedestals. Its dielectric constant is less than half that of a typical MMIC substrate.

The harmonic mixers, one of which is shown in Fig. 2, reside on 2.6 mm by 1.5 mm substrates. A 0.36 mm by 0.32 mm custom-designed GaAs dual-diode chip is flip-attached onto the substrate. The Schottky diodes on this chip have a cutoff frequency of 2 THz.

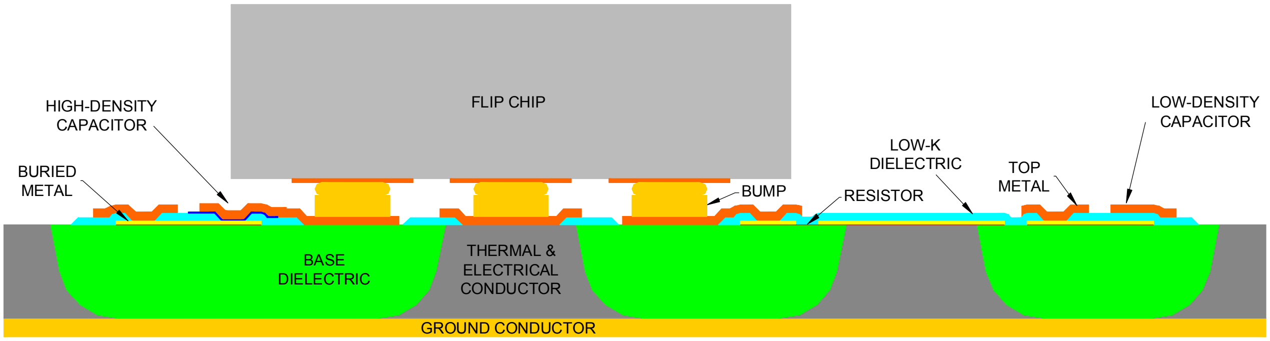

Fig. 1. Conceptual cross-section of a semiconductor die flip-attached to a passive integrated circuit.

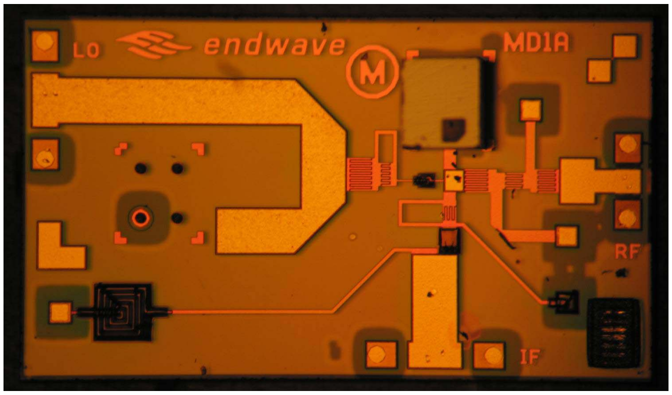

Fig. 2. Assembled MD1A 71-76 GHz harmonic mixer chip. The diode chip is visible just to the right of the circle-M.

Fig. 3 shows a functional block diagram of the mixers. Since the local oscillator (LO) signal comes in at half the RF ± IF frequency, its frequency is quite distant from that of either the IF or the RF frequency, and the filters can be broad in response. The filters are implemented with combinations of shorted microstrip stubs; high-impedance microstrip, single-loop and spiral inductors; and interdigitated and metal-insulator-metal capacitors. The diodes are grounded at one end to allow efficient heat sinking through a ground pedestal.

The mixers were designed to cover RF (radio frequency) frequencies of 71-76 GHz for the MD1A and 81-86 GHz for the MD2A and cover an IF (intermediate frequency) range of 1 to 16 GHz. They had to accommodate all possible LO frequencies needed for high-side and low-side conversion throughout these frequency ranges.

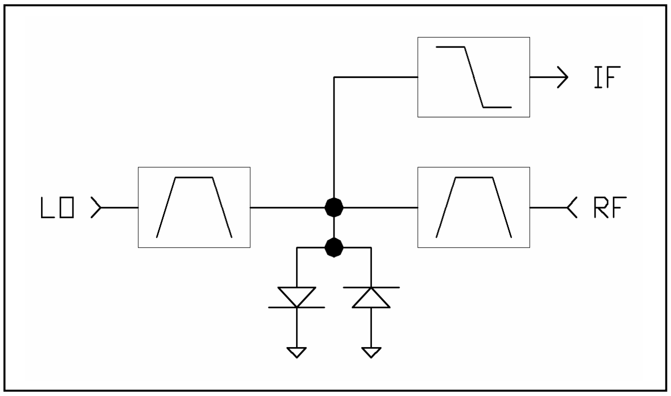

Fig. 3. Block diagram of the harmonic mixer.

The low-band mixer, the MD1A, has three distinct filters as indicated in Fig. 3. It is a modified version of mixers reported previously [1] that had been designed with an extrapolated diode model and without the aid of electromagnetic simulation. A new diode model was subsequently derived from S parameter measurements up to 110 GHz, and a 3-D electromagnetic simulator was applied in the characterization of the passive circuitry. It was found that the filters previously designed for the high band could be used successfully for the low band with some minor rephasing. For the MD1A no further modifications were needed.

The high-band mixer, the MD2A, was designed with a new merged-filter approach with potential for broader bandwidths. 3-D electromagnetic simulation was employed to verify the functioning of each of three portions of the filter network.

III. RESULTS

Fig. 4 shows some high-side upconversion results for the two mixers as simulated and as measured. Losses as low as 6 dB can be seen, and the conversion efficiency is high across the band. Though measurements covered only the E-band ranges, the simulations indicate broader frequency coverage.

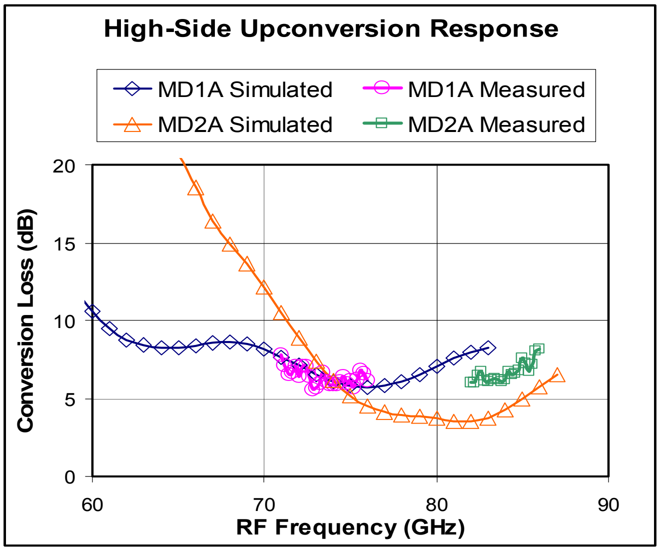

Fig. 4. Simulated and measured high-side upconversion responses for the MD1A and MD2A harmonic mixers with LO power of 19 dBm. The LO frequency is 42 GHz for the MD1A and 44 GHz for the MD2A.

Some low-side upconversion results are shown in Fig. 5, and some high-side and low-side downconversion results are seen in Fig. 6 and Fig. 7. The losses for downconversion are about 2 dB higher than those for upconversion.

The mixers have an LO power range of greater than 10 dB over which the conversion loss is flat to within ±0.5 dB. Such a characteristic is shown in Fig. 8.

Simulations indicate that higher LO power levels lead to greater linearity. Fig. 9 shows a measured compression characteristic with a 1-dB compression point exceeding 6 dBm.

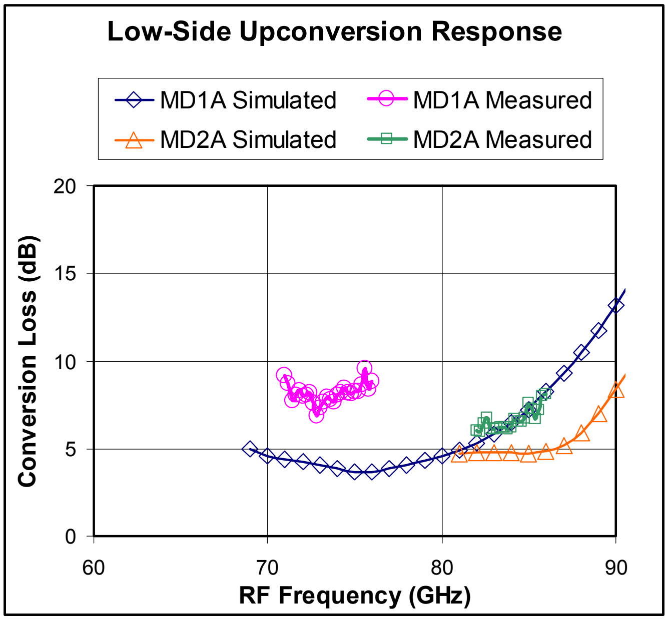

Fig. 5. Simulated and measured low-side upconversion responses for the MD1A 71-76 GHz and MD2A 81-86 GHz harmonic mixers with LO power of 19 dBm. The LO frequency is 34 GHz for the MD1A and 40 GHz for the MD2A.

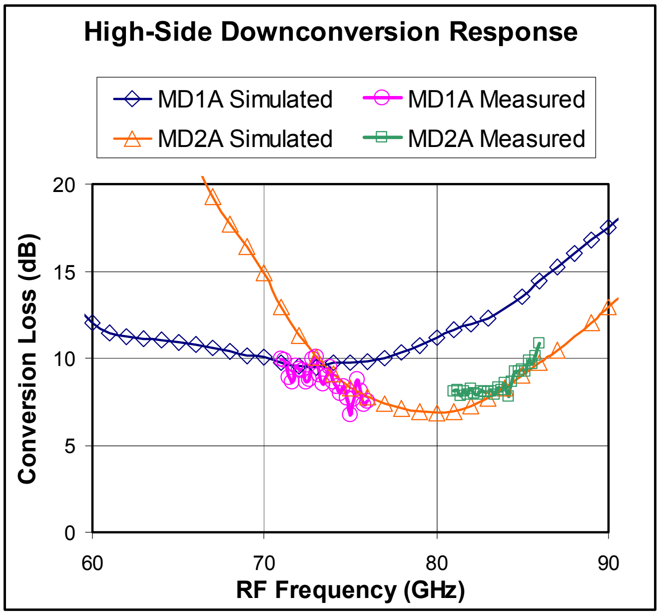

Fig. 6. Simulated and measured high-side downconversion responses for the MD1A and MD2A harmonic mixers with an LO power input of 19 dBm. The LO frequency is 42 GHz for the MD1A and 44 GHz for the MD2A.

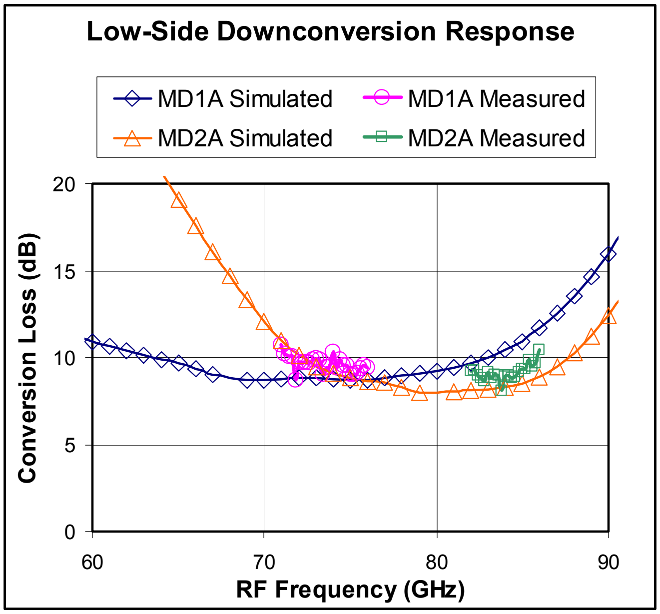

Fig. 7. Simulated and measured low-side downconversion responses for the MD1A and MD2A harmonic mixers with LO power of 19 dBm. The LO frequency is 34 GHz for the MD1A and 40 GHz for the MD2A.

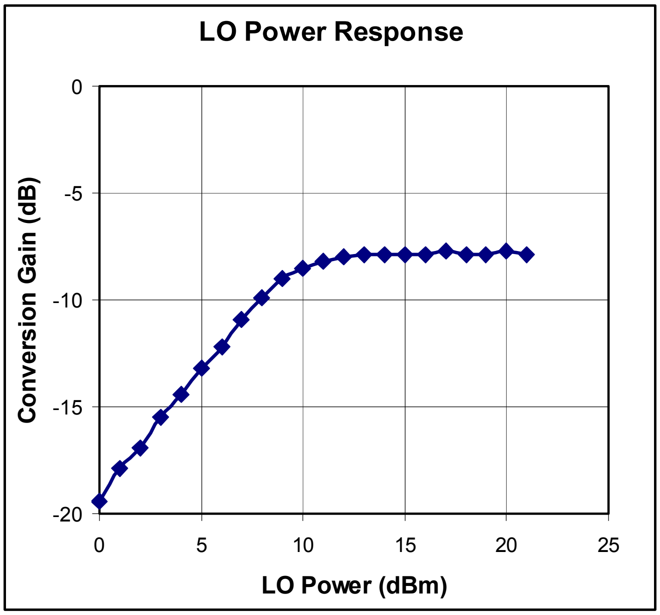

Fig. 8. Measured conversion gain as a function of LO input power for an MD1A mixer at an LO frequency of 35.2 GHz upconverting to 73.6 GHz.

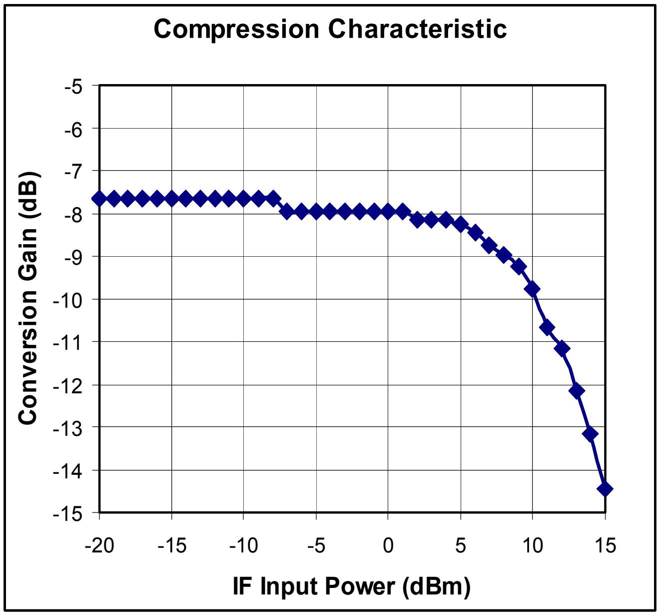

Fig. 9. Measured conversion gain as a function of IF input power for an MD1A mixer at an LO frequency of 36 GHz upconverting to 81 GHz. The LO input power is 19 dBm.

IV. CONCLUSIONS

The results demonstrate that a low-cost technology that allows flip attachment of small high-performance semiconductor chips onto a passive integrated circuit substrate can achieve state-of-the-art results. The performance of these E-band mixers exceeds that of any other E-band or V-band mixers known to the authors.

It is also evident that reasonably good performance predictions can be made for E-band flip-chip designs when electromagnetic simulation is used for the passive circuitry and higher-frequency S parameter measurements are used to derive the semiconductor device models.

Practical results are thus achievable at E-band in a low-cost technology that lends itself to higher levels of integration. The MD1A and MD2A mixers are currently in production and are being used in E-band transceiver products.

REFERENCES

[1] E. B. Stoneham, “High-Precision Flip-Chip Process Yields E-Band Harmonic Mixers with Potential Sub-10-dB Conversion Loss,” *Procedings of the 36th European Microwave Conference.,* Manchester UK, pp. 506-509, 10-15 September 2006.