A W-Band Monolithic Pseudomorphic InGaAs HEMT Downconverter

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ABSTRACT

This paper presents the design, fabrication, and evaluation of a fully integrated W-band monolithic downconverter based on InGaAs pseudomorphic HEMT (PHEMT). The downconverter consists of a two-stage low-noise amplifier (LNA) and a singly balanced HEMT gate diode mixer. Measured results of the complete downconverter show a conversion gain of 5.3 dB and a noise figure of 6.8 dB at 94 GHz. The whole downconverter is a first pass design and has a high circuit yield. Furthermore, this is first reported monolithic downconverter in the W-band frequency range, and represents the state-of-the-art in monolithic millimeter-wave technology.

INTRODUCTION

The W-band downconverter is a key component for smart munitions, millimeter-wave imaging, and radiometer applications. Both hybrid and monolithic W-band amplifiers and mixers have been reported recently[1]-[8]. The performance of these amplifiers and mixers are summarized in Table I and II, respectively. Although all these circuits have shown very encouraging performance at the W-band, no attempt has been tried to integrate the amplifier and mixer in a single downconverting chip. This is because the W-band monolithic diode mixers [6,7] were mostly developed for MESFET technology; therefore not compatible with the W-band LNA which requires HEMT devices. On the other hand, the PHEMT active mixer[8] is capable of integration with the PHEMT LNA, but due to insufficient device model data, its realization is less reliable. The intention of this work is to explore the feasibility of high level integration of a W-band LNA and a singly balanced diode mixer in a single chip using monolithic HEMT technology.

Table I Performance Summary of the W-band LNAs

Device Technology	No. of Devices	Gain/NF (dB) @ 94 GHz	Monolithic/Hybrid
GaAs-based PHEMT	1	5.0 / NA	Monolithic [1]
GaAs-based PHEMT	1	4.5 / NA	Monolithic [2]
InP-based HEMT	2	7.0 / NA	Monolithic [3]
GaAs-based PHEMT	2	8.0 / 4.5	Hybrid [4]
GaAs-based PHEMT	2	11.3 / 5.2	Monolithic [5]

Table II Performance Summary of the W-band Mixers

Device Technology	Mixer Circuit	Conversion loss (dB)	Remark/Reference
GaAs MESFET	Singly balanced diode	7.5	MOCVD, monolithic [6]
GaAs MESFET	Singly balanced diode	10	Ion Implanted, monolithic [7]
GaAs-based PHEMT	Single-ended Active HEMT	6.0	MBE, hybrid [8]
GaAs-based PHEMT	Singly balanced diode	7.5	Monolithic, present work

A fully integrated PHEMT downconverter MMIC, which consists of a two-stage low-noise amplifier and a singly balanced diode mixer, has been successfully designed, fabricated and tested. The downconverter is designed to receive 90 to 98 GHz RF signals and downconvert to 1 to 8 GHz IF output. At 94 GHz the two-stage LNA shows 5.2 dB noise figure and 11.3 dB associated gain; the singly balanced mixer has 7.6 dB conversion loss with a 10 dBm LO power input. When the complete downconverter receives a 94 GHz input signal and converters it to an IF of 1 GHz, it shows 5.3 dB conversion gain and 6.8 dB noise figure. At 92 GHz input, the downconverter has 6.0 dB noise figure and 7.3 dB conversion gain. This is a first pass design and the first reported monolithic downconverter in the W-band frequency range.

CIRCUIT DESIGN

Figure 1 shows the block diagram of the W-band downconverter. It consists of a two-stage LNA and a singly balanced mixer. A photograph of the complete downconverter chip is shown in Figure 2. The chip size is 1.2 x 4.0 mm^2.

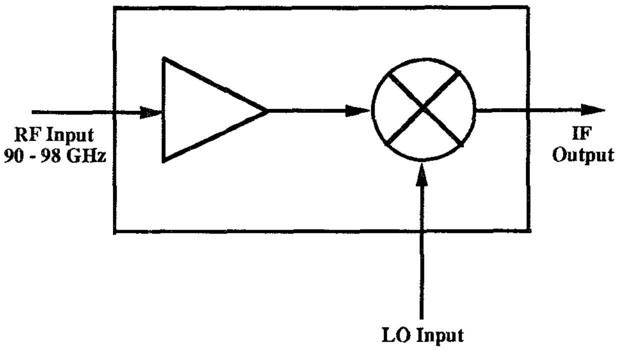

Figure 1 Bolck diagram of the W-band MMIC downconverter.

The two-stage LNA is designed using two 0.1 x 40 μm T-gate InGaAs pseudomorphic HEMT devices to operate from 80 to 98 GHz. A small signal linear equivalent circuit, which is based on the S-parameter measurement up to 40 GHz, along with the reactive matching is used for the amplifier design. Furthermore, edge-coupled microstrip lines and radial stubs are employed for DC blocking and RF bypass to insure a high circuit yield. Stability resistors are also included in the bias networks. More details of the amplifier design is described in [5].

For process compatibility and bandwidth considerations, a singly balanced diode mixer configuration is chosen for the design of the W-band monolithic mixer. Figure 3 is the circuit schematic of the mixer which includes a 180° rat-race hybrid for the RF and LO signal inputs and a matched pair of 16 μm InGaAs HEMT gate Schottky diodes for the mixing elements. A nonlinear model of the 16 μm HEMT diode is created from the measured S-parameter and DC I-V curves. A low pass filter constructed with series high impedance line and shunt radial stubs provides a short for RF and LO frequencies at the output port. The diode matching circuits are realized with high impedance microstrip lines and shunt open stubs. Edge-coupled microstrip lines are used for blocking the diode DC returns from the RF and LO ports. No DC bias is required for the mixer circuit. All the passive elements have been characterized with a full wave EM analysis [9] during the design phase. Since the

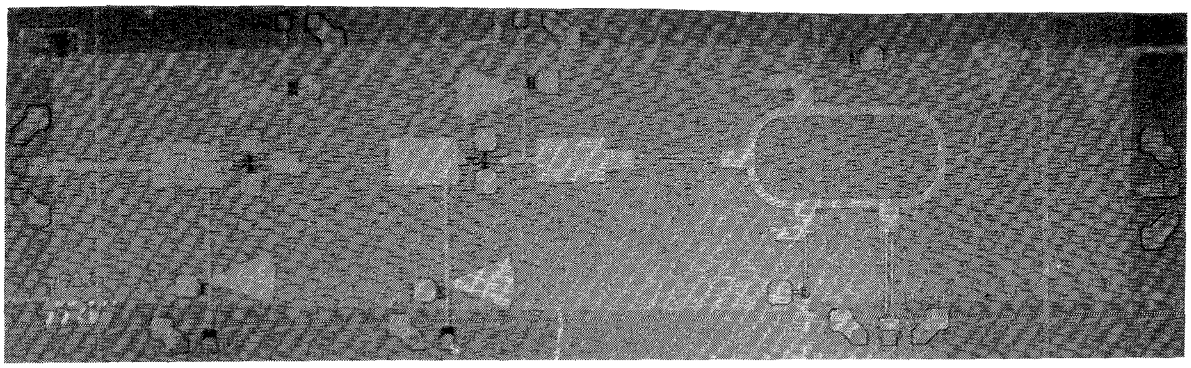

Figure 2. Photograph of the W-band MMIC downconverter.

LNA and mixer are both designed for a 50-ohm impedance system, the complete downconverter is realized by simply connecting the two-stage LNA and mixer with a DC blocking capacitor. All the circuits are realized on a 100 μm thick GaAs substrate. In addition to the downconverter chip, each individual subcircuit is also included on the same wafer for evaluation and diagnosis.

CIRCUIT FABRICATION

The MMIC downconverter was fabricated on an InGaAs/GaAs heterostructure HEMT wafer grown with MBE. The process started with multiple oxygen implantation to obtain device isolation. This implantation process is critical for uniform EBL gate processing. Ohmic contacts are deposited using Ni/AuGe/Ag/Au evaporation and lift-off process, and alloyed using rapid thermal anneal at 540° C. A thin layer of metal (Ti-Au) is deposited to form the first level metal. E-beam lithography is used to define the 0.1 μm gate length resist patterns. Gate recess etching is performed and is then followed by gate metal deposition.

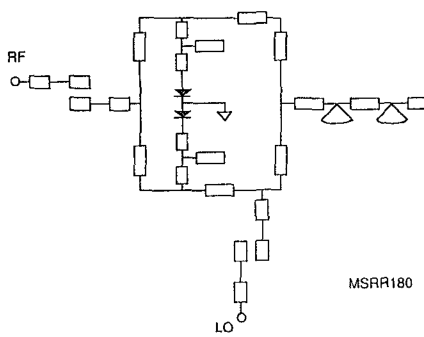

Figure 3 Circuit schematic of the singly balanced mixer.

Figure 4 shows a cross section of the 0.1 x 40 μm T-gate planar-doped InGaAs HEMT devices used in this work. The 0.1 μm T-gate HEMT typically has a DC transconductance of 670 mS/mm with a ft of 130 GHz. The cutoff frequency of the 16 mm HEMT gate Schottky diode is 370 GHz at zero bias.

CIRCUIT PERFORMANCE

All the amplifier, mixer, and downconverter have been tested in special test fixtures. Finline transitions are used to couple the RF and LO signals from waveguide to microstrip. The insertion loss of transitions (back to back) ranges from 1.7 to 2.0 dB in the frequency range of 88 to 98 GHz.

The low-noise amplifier has a 11.3 dB small signal gain at 94 GHz and 17 dB at 89 GHz. Input return loss is better than 10 dB from 91 to 97 GHz and output return loss is better than 5.0 dB across the same bandwidth. Noise figure is 5.2 dB from 91 to 95 GHz as shown in Figure 5. The mixer downconverts a 90-98 GHz RF signal to 1-8 GHz IF frequency range. Typical conversion loss at IF = 1 GHz is 7.5 ~ 8.5 dB with -10 dBm input power and a LO drive of 10 dBm. Figure 6 shows the measured mixer conversion loss between 90 to 98 GHz.

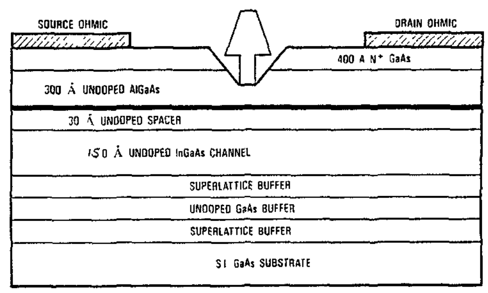

Figure 4 A cross section of the Pseudomorphic InGaAs HEMT device structure.

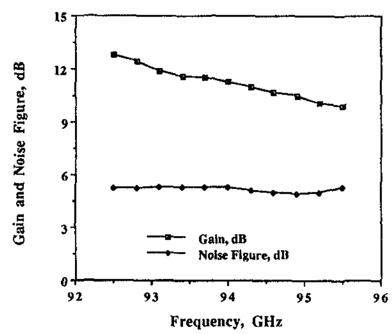

Figure 5. Measured small signal gain and noise figure of the two-stage LNA.

Figure 7 shows the measured downconverter gain from 90 to 98 GHz with IF fixed at 1 GHz and LO power of 10 dBm. The gate and drain of the LNA are biased at zero and three volts, respectively. The drain current is about 13 mA per HEMT. Also included in the Figure is the noise figure of downconverter below 94 GHz. When the complete downconverter receives a -30 dBm input signal at 94 GHz and converter it to an IF of 1 GHz, it shows 5.3 dB conversion gain and 6.8 dB noise figure. With a 92 GHz input, the downconverter has 6 dB noise figure and 7.3 dB conversion gain. All the measurement data described above have been corrected for the RF and LO transition losses. We have evaluated more than eight different chips of amplifier, mixer, and downconverter, and they all pass the first DC and RF tests.

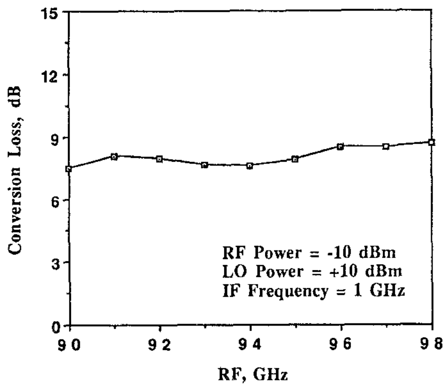

Figure 6. Measured conversion loss of the singly balanced mixer.

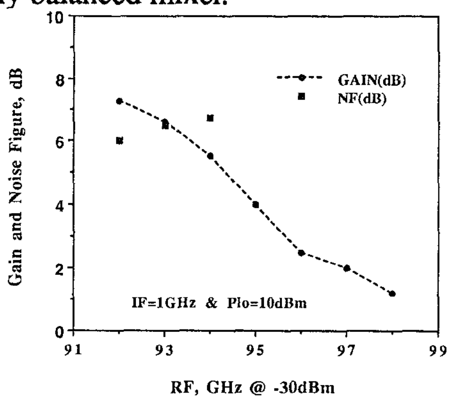

Figure 7. Measured noise figure and associated conversion gain of the W-band down-

CONCLUSION

A W-band monolithic downconverter based on InGaAs/GaAs HEMT devices technology has been designed, fabricated and tested. This downconverter integrates a two-stage RF LNA and a singly balanced diode mixer into a single chip. Measured results of the complete downconverter show a conversion gain of 5.3 dB and a noise figure of 6.8 dB at 94 GHz. The whole downconverter is a first pass design and has a high circuit yield. This is the first successfully developed single chip MMIC downconverter in the W-band frequency range.

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