A *W*-Band Monolithic 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 (PM) HEMT technology. The monolithic downconverter consists of a two-stage low-noise amplifier and a single-balanced mixer. The single-balanced mixer has been designed using the HEMT gate Schottky diodes inherent to the process. Measured results of the complete downconverter show a conversion gain of 5.5 dB and a double-sideband (DSB) noise figure of 6.7 dB at 94 GHz. Also presented in this paper is the downconverter performance characterized over the −35°C to +65°C temperature range. The downconverter design was a first pass success and has a high circuit yield. Furthermore, this is the first reported monolithic downconverter in the *W*-band frequency range, and represents the state-of-the-art in monolithic millimeter-wave technology.**

I. Introduction

The *W*-band downconverter is a key component for smart munitions, millimeter-wave imaging, and radiometer applications. Both hybrid and monolithic *W*-band low-noise amplifiers (LNA's) and mixers have been reported recently [1]–[11]. The performance of these amplifiers and mixers are summarized in Table I and Table II, respectively. Although all these circuits have shown encouraging performance at *W*-band, no attempt has been made to integrate the amplifier and mixer in a single downconverting chip. This is because the *W*-band monolithic diode mixers [8], [9] were mostly developed for MESFET technology; therefore not compatible with the *W*-band LNA which requires HEMT devices. On the other hand, the HEMT active mixers [10], [11] are capable of integration with the HEMT LNA, but its realization is less reliable due to insufficient device model data. The intention of this work is to explore the feasibility of high level integration of a *W*-band LNA and a single-balanced diode mixer in a single chip using the monolithic PM HEMT technology.

A fully integrated PM HEMT downconverter MMIC, which consists of a two-stage low-noise amplifier and a single-balanced diode mixer, has been successfully designed, fabricated and tested. The downconverter is designed to receive 90 to 98 GHz RF signals and downconverts to 0.1 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 single-balanced mixer has 7.6 dB conversion loss with a 10 dBm local oscillator input power at 93 GHz. The complete downconverter with a 95 GHz LO and a 1 GHz IF exhibits 5.5 dB conversion gain and 6.7 dB DSB noise figure. At 93 GHz LO, the downconverter has 6.0 dB DSB noise figure and 7.3 dB conversion gain. This design was a first pass success and is the first reported monolithic downconverter in the *W*-band frequency range.

The downconverter configuration is discussed in Section II. The MMIC circuit design and fabrication are presented in Sections III and IV, respectively. Section V summarizes the circuit performance and is followed by a conclusion.

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II. Downconverter System Configurations

Fig. 1 illustrates a simplified block diagram of a typical downconverter. It consists of an RF amplifier, a frequency downconverting mixer, an IF amplifier, and the LO source and LO buffer amplifier. At microwave and lower frequencies the whole downconverter can be realized in a single chip [12], because at these frequencies all the downconverter components are readily designed with high yield using same device technology (0.25 μm MESFET's or AlGaAs HEMT's). However, as the frequency increases from the microwave to the low millimeter-wave range, the LO source and buffer amplifier are more likely to be separate [13], [14], since they are difficult to realize using the same device technology as the other components. Partition of a millimeter-wave downconverter into different chips at the millimeter-wave frequencies seems inevitable at the present time, because the individual circuits of the whole system are still dominated by the available device technology. In designing the *W*-band monolithic downconverter, we have examined three different partition configurations that are shown in Fig. 2 (a)–(c). In all three configurations the LO chip is considered as an external source which needs to be developed in the future. The potential advantages and disadvantages of each configuration are summarized in Table III. The major disadvantages of configuration 1 and 2 are related to the circuit yield and process complexity. For example, in configuration 1 the IF amplifier does not require a 0.1 μm T-gate device technology which is an essential for the RF low-noise amplifier. Due to the lower expected yield of 0.1 μm devices, it may not be cost-effective in a production environment. In configuration 2, if MESFET's

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TABLE I
PERFORMANCE SUMMARY OF THE *W*-BAND LNA'S

Device Technology	No. of Devices	Gain/NF (dB) @ 94 GHz	LNA Design Features
GaAs-based PM HEMT	1	5.0/NA	MMIC one-stage [1]
GaAs-based PM EMT	1	5.0/NA	MMIC one-stage [2]
InP-based HEMT	2	8.0/NA	MMIC cascode configuration [3]
InP-based HEMT	5	6.0/NA	MMIC distributed amplifier [4]
InP-based HEMT	7	6.0/NA	MMIC distributed amplifier [5]
GaAs-based PM HEMT	2	9.7/4.2	Hybrid [6]
InP-based HEMT	2	11.5/3.3	Hybrid [6]
GaAs-based PM HEMT	2	11.3/5.2	MMIC two-stage, present work

TABLE II
PERFORMANCE SUMMARY OF THE *W*-BAND MIXERS

Device Technology	Mixer Circuit	Conversion Gain (dB)	Mixer Design Features
GaAs MESFET	SB* diode	−7.5	MOCVD, monolithic [8]
GaAs MESFET	SB* diode	−10	Ion implanted, monolithic [9]
AlGaAs HEMT	SE** active HEMT	−6.0	MBE, hybrid [10]
InP-based HEMT	SE** active HEMT	2.0	MBE, hybrid [11]
PM InGaAs HEMT	SB* diode	−7.5	Monolithic, present work

*SB-Single-balanced
**SE-Single-ended

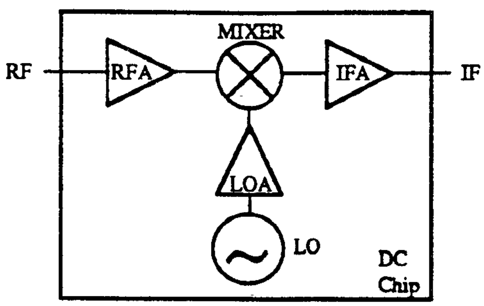


Fig. 1. Simplified block diagram of a downconverter.

or AlGaAs HEMT's were used for the mixer and IF amplifier circuits then a special device process is required for an acceptable mixer design whether it is a passive or active mixer circuit. Moreover, an external RF interconnection between the LNA chip and downconverter chip may degrade the overall system performance. Since all these problems can be effectively eliminated in configuration 3, we have chosen this configuration with a passive diode mixer in our design.

III. CIRCUIT DESIGN

Low-Noise Amplifier

The two-stage LNA design is similar to that reported in [7] except the matching circuit is slightly different. Fig. 3(a) and (b) are circuit schematic and photograph of the amplifier chip, respectively. The chip size is 1.2×2.2 mm^2. The 0.1 μm T-gate, four-finger 40 μm device was used in each stage, and the total dc power consumption of the amplifier is about 80 mW.

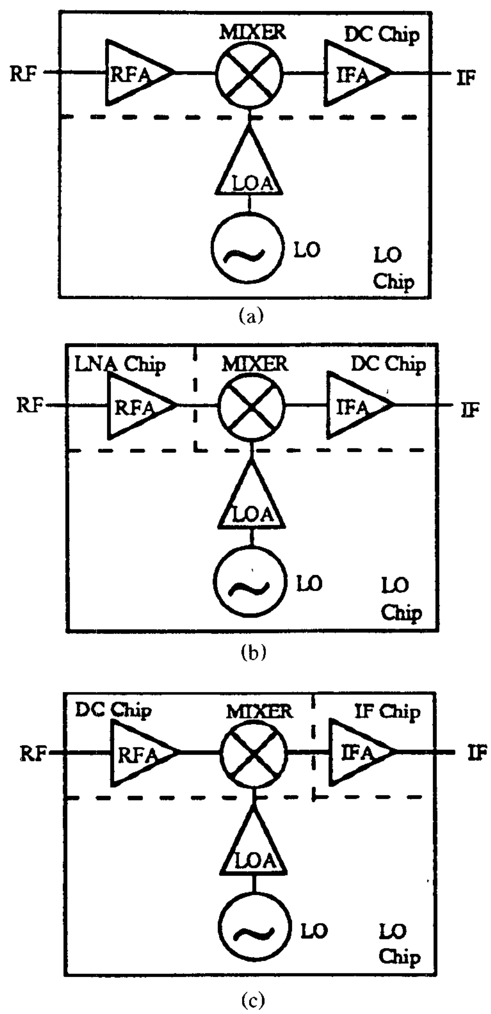
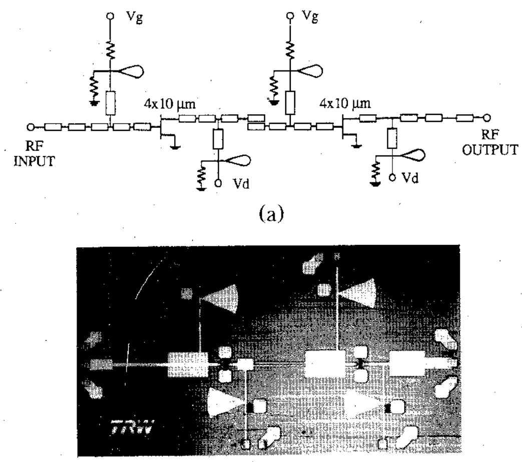


Fig. 2. Three configurations of a monolithic downconverter. (a) DC chip and LO chip. (b) LNA chip, DC chip, and LO chip. (c) DC chip, IF chip, and LO chip.

TABLE III
TRADE-OFF OF THE THREE DOWNCONVERTER CONFIGURATIONS

System Configuration	Advantages	Disadvantages
1. Fig. 2(a)	Simple, compact	IF amplifiers use same device technology with RF amplifiers (0.1 μm T-gate); circuit yield may be a concern
2. Fig. 2(b)	Currently existing for MESFET (DC chip) and HEMT technologies (LNA chip)	RF connection between chips is required; special diode process for mixer is required
3. Fig. 2(c)	1. True monolithic downconverter 2. Currently existing for MESFET (IF chip) and HEMT technologies (DC chip) 3. Active mixer can be used to reduce LO power	Requires more chips than configuration 1



(b)

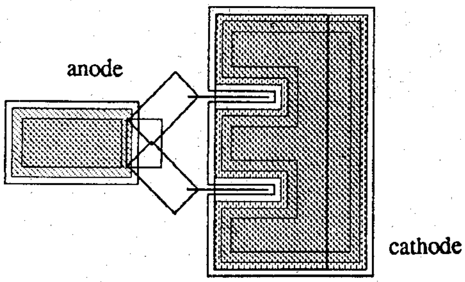
Fig. 3. (a) Circuit schematic of the two-stage LNA. (b) Photograph of the two-stage LNA.

Single-Balanced Mixer

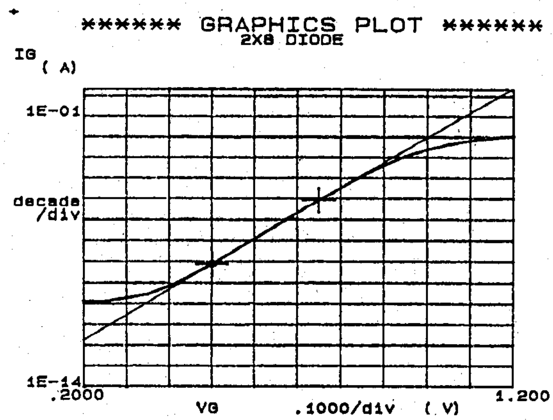
Although the spurious and linearity requirements for a mixer at W-band is not as critical as those for the microwave applications, in which the spectrum is already fully occupied with crowded signals, the W-band mixer ultimately will be a balanced configuration. Furthermore, it is advantageous in a transceiver to have a common mixer circuit that can be utilized both for frequency upconverting and downconverting functions. The diode mixer is a mature technology at millimeter-wave frequencies, and is relatively easier to design as compared with the HEMT active mixer, although the latter may operate with a lower LO drive for a similar conversion loss performance [10]. A passive mixer can be used for both upconverting and downconverting applications with the same circuit, and hence simplify future high level monolithic integration requirements. From these considerations, a single-balanced diode mixer configuration was chosen for the design of the W-band monolithic mixer. The design procedure for the diode mixer is described in [15].

The top view of the planar Schottky diode is depicted in Fig. 4(a); it is constructed by connecting the source and drain metallizations of a HEMT device as the cathode of the diode. The gate pad is used as the anode. The key advantages of using the PM HEMT gate Schottky junction as a diode are the process compatibility with the HEMT device and its good millimeter-wave performance in the mixer circuit. Typical dc I-V characteristics of a two-finger 16 μm diode is shown in Fig. 4(b). The series resistance Rs, reverse leakage current Is, and ideality factor n of the diode are calculated from this I-V curve. In addition, the S-parameters of the same diode at different bias conditions are also used to model the diode junction capacitor Cj and device parasitics. A diode nonlinear model based on both the dc I-V and S-parameter measurement data is shown in Fig. 4(c). The cutoff frequency of a 16 μm diode is estimated to be 550 GHz using the calculated Rs and Cj of the model at zero bias.

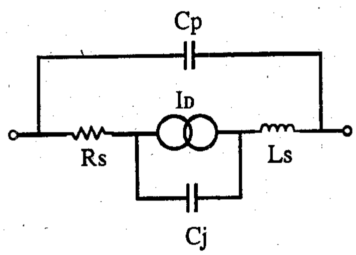
Fig. 5(a) and (b) are circuit schematic and photograph of the mixer chip, respectively. The chip size is 1.2×2.0 mm^2. The mixer includes a 180° rat-race hybrid for the RF and LO signal inputs and a matched pair of 16 μm InGaAs HEMT gate Schottky diodes for the mixing elements. The use of MIM capacitors and complex circuit structures have been eliminated for a better circuit yield. Because of the small size of the rat-race ring, the diodes are positioned outside the ring and the IF signal is tapped out from the ring circumference. 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 capacitors at the RF and LO ports. No dc bias is included for the current mixer circuit although a dc bias may be added to reduce the required LO power for the same conversion loss. All the passive elements were characterized with a full wave EM analysis [16] during the design phase.



(a)



(b)



Rs = 18 ohms Cj = 16 fF Is = 1.9E-14 A n = 1.4

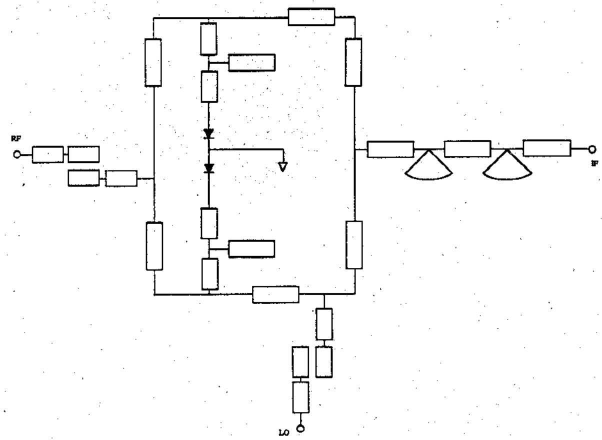
$$I_D = I_s \{ \exp [q(V_D - R_s I_D) / (n K_B T)] - 1 \}$$

(c)

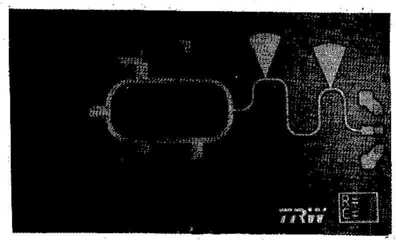
Fig. 4. (a) Top view of the HEMT gate diode. (b) DC *I-V* curve of a 16 μm diode. (c) Nonlinear model of a 16 μm diode.

Monolithic Downconverter

The block diagram of the *W*-band downconverter is shown in Fig. 2(c). It consists of a two-stage LNA and the single-balanced diode mixer described in the previous section. A photograph of the complete downconverter chip is shown in Fig. 6. The chip size is 1.2×4.2 mm^2. Since the LNA and mixer are both designed for a 50 Ω impedance system, the complete downconverter is realized by simply connecting the two-stage LNA and mixer with a dc blocking edge-coupled line. All the circuits are realized on a 100 μm thick GaAs substrate. In addition to the downconverter chip, each individual subcircuit was included on the same wafer for evaluation and diagnosis.



(a)



(b)

Fig. 5. (a) Circuit schematic of the single-balanced diode mixer. (b) Photograph of the single-balanced diode mixer.

IV. Circuit Fabrication

Both MMIC mixer and downconverter were fabricated on an InGaAs/GaAs heterostructure HEMT wafer. The planar-doped PM HEMT wafer was grown by MBE with a channel InGa mole fraction of 22%. The device cross-section is shown in Fig. 7. Hall mobility measurements performed on calibration wafers indicate a room temperature 2-DEG concentration of 2.55×10^{12} cm^{-2} with a mobility of 6250 cm^2/V s, and 77 K 2-DEG concentration of 2.44×10^{12} cm^{-2} with a mobility of 17000 cm^2/V s.

The MMIC process is similar to that previously reported [17], [18]; it starts with multiple oxygen implantation to obtain device isolation ($R > 10^7$ Ω). Ohmic contracts are deposited using Ni/AuGe/Ag/Au evaporation and lift-off process, and alloyed using rapid thermal anneal at 540°C. The 0.1 μm T-gate consisting of Ti/Pt/Au was defined using a Philips EBPG-3 electron-beam lithography system with a two-layer PMMA/P(MMA-MMA) resist system. Discrete device yields are typically greater than 80% using this T-gate process. A thin layer of metal (Ti-Au) is deposited and lifted-off to form the low resistance first level metal interconnects. The airbridge and transmission lines consist of 2 μm of Ti/Au. Via holes with a diameter of 40 μm were etched through the 100 μm GaAs substrate using RIE to provide low source grounding inductance.

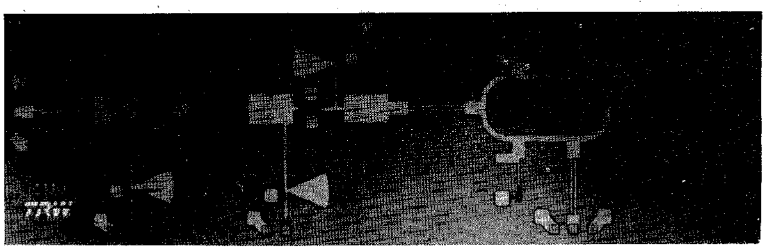


Fig. 6. Photograph of the *W*-band downconverter.

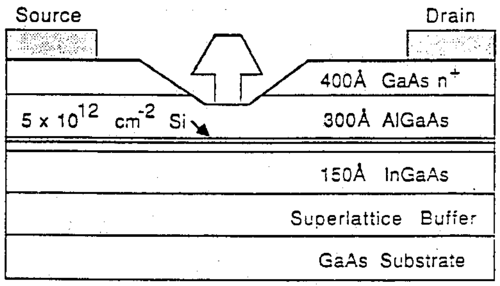


Fig. 7. Cross section of the InGaAs PM HEMT.

V. Circuit Performance

The amplifier, mixer, and downconverter have been tested in waveguide test fixtures. Finline transitions are used to couple the *W*-band 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 96 GHz. All the measurement data described hereafter have been corrected for the RF and LO transition losses.

Low-Noise Amplifier

The two-stage low-noise amplifier has a 11.3 dB measured 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 Fig. 8. The noise figure and gain of this amplifier are 0.3 dB and 2.0 dB, respectively, lower than that of the two-stage amplifier reported in [7].

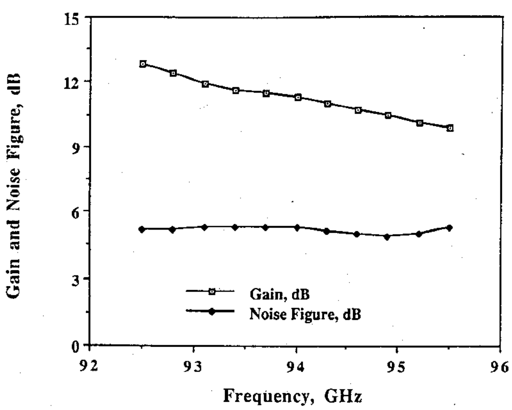


Fig. 8. Measured small signal gain and noise figure of the two-stage LNA.

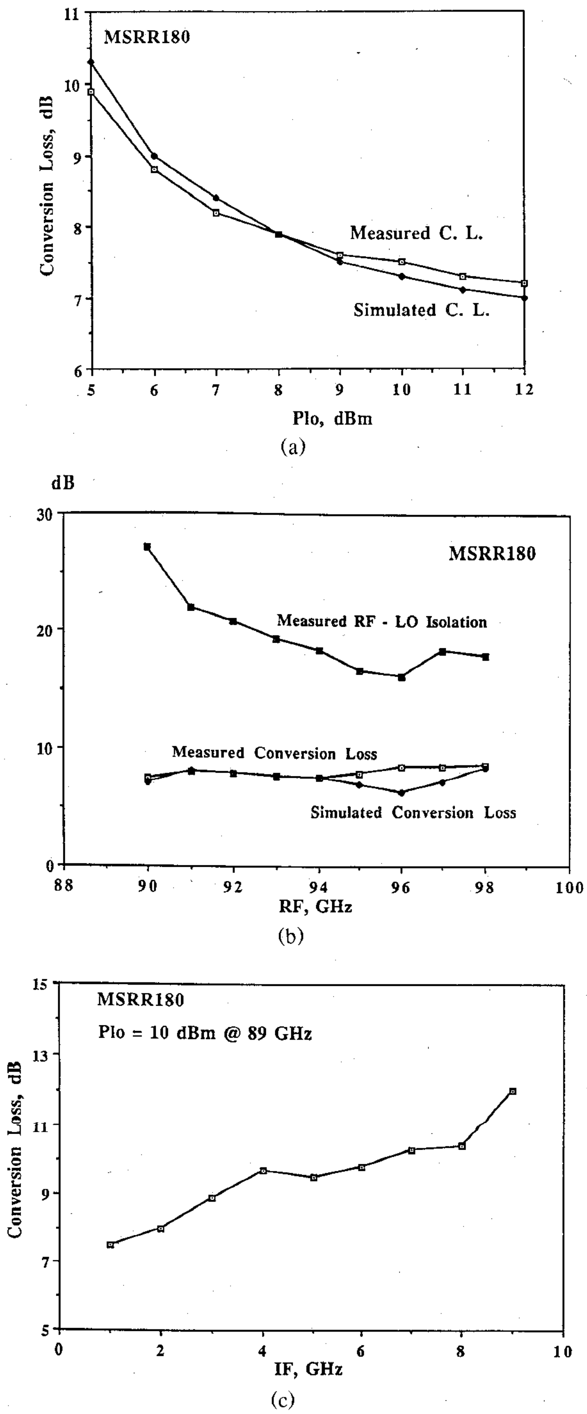


Fig. 9. (a) Measured and simulated conversion loss of the single-balanced mixer as a function of the LO power. The RF and LO frequencies are 94 GHz and 93 GHz, respectively. (b) Measured and simulated conversion loss of the single-balanced mixer as a function of the RF frequency. The IF frequency is fixed at 1 GHz. (c) Measured conversion loss of the single-balanced mixer as a function of the IF frequency.

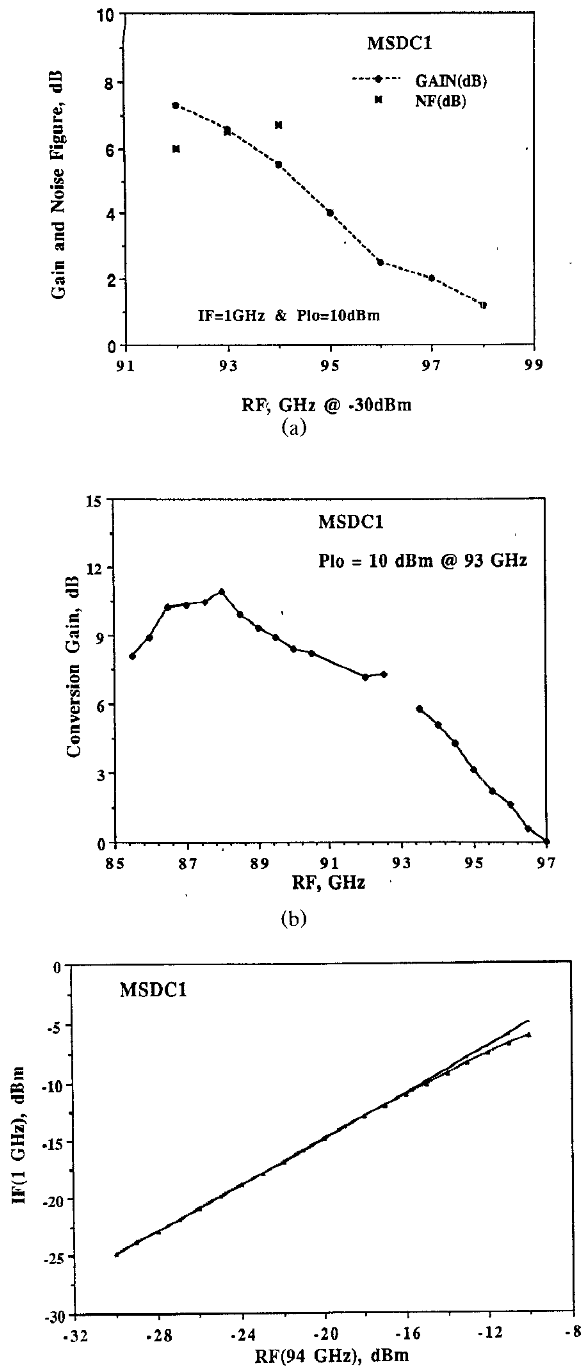


Fig. 10. (a) Measured noise figure and associated conversion gain of the W-band downconverter. The IF is fixed at 1 GHz. (b) Measured conversion gain of the W-band downconverter as a function of the RF frequency. (c) Measured compression characteristic of the W-band downconverter.

Single-Balanced Diode Mixer

The mixer downconverts a 90-98 GHz RF signal to 0.1-8 GHz IF frequency range. Fig. 9(a) illustrates the measured and simulated mixer conversion loss as a function of the LO power. The RF and LO frequencies are fixed at 94 and 93 GHz, respectively. Conversion loss improved by 2.4 dB as the LO power was increased from 5 dBm to 10 dBm, and remained almost unchanged even with more LO power. The following measurements were taken at this LO power level. Typical conversion loss at IF = 1 GHz is 7.5 ~ 8.5 dB with an input power of −10 dBm and a LO drive of 10 dBm. Fig. 9(b) shows the measured and simulated mixer conversion loss between 90 to 98 GHz. The agreement between the measured and simulated results is within 2.5 dB. The RF to LO isolation is between 16 and 27 dB within the same frequency range. Fig. 9(c) is the measured mixer conversion loss for IF frequency ranging from 1 to 8 GHz, the LO frequency is fixed at 89 GHz. The conversion loss is less than 10 dB for IF frequencies below 6 GHz. For most of RF frequencies, minimum conversion loss can be achieved with the LO frequency around 93–94 GHz.

Monolithic Downconverter

Fig. 10(a) shows the measured downconverter gain from 90 to 98 GHz with the 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 the downconverter below 94 GHz. The complete downconverter with a 95 GHz LO and a 1 GHz IF exhibits 5.5 dB conversion gain and 6.7 dB DSB noise figure. At 93 GHz LO, the downconverter has 6.0 dB DSB noise figure and 7.3 dB conversion gain. The downconverter conversion gain as a function of the RF frequency is shown in Fig. 10(b). The LO frequency is fixed at 93 GHz in this case.

The measured compression characteristic of the downconverter is plotted in Fig. 10(c). The RF and LO frequencies are fixed at 94 and 93 GHz, respectively. The calculated output 1 dB compression point is about −6 dBm. Finally, the conversion gain and noise figure of the downconverter at 94 GHz RF frequency and 0.3 to 0.5 GHz IF frequencies over the −35°C to +65°C temperature range are shown in Table IV. In general, the gain and noise frequency response tracks over the whole temperature cycle. The gain variations may be compensated by a specially designed bias network.

TABLE IV
MEASURED CONVERSION GAIN AND NOISE FIGURE OF THE W-BAND DOWNCONVERTER

Temp. (°C)	IF (GHz)	NF (dB)	Conversion Gain (dB)
−35	0.3	4.9	8.6
	0.4	4.8	8.7
	0.5	4.7	8.8
23	0.3	6.0	7.1
	0.4	6.0	6.9
	0.5	6.0	7.0
65	0.3	6.7	5.8
	0.4	6.6	5.8
	0.5	6.6	5.7

VI. 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 LNA and a single-balanced diode mixer into a single chip. Measured results of the complete downconverter show a conversion gain of 5.5 dB and a DSB noise figure of 6.7 dB at 94 GHz. The 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.

Acknowledgment

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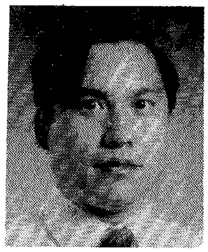

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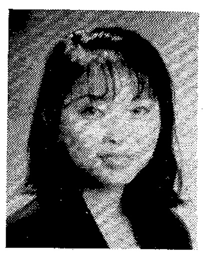
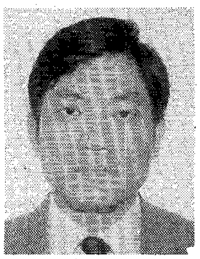


Stacey B. Bui received her B.S. degree in chemical engineering from the University of California, Berkeley in 1983.

From 1983 to 1987, she was with Avantek Inc., Santa Clara, CA, where she was responsible for the process integration of high speed GaAs digital IC's. Since 1987 she has been with TRW, Inc., Redondo Beach, CA, where she is a member of Technical Staff in the TRW's Electronics and Technology Division. She is currently involved with HBT device reliability studies, power HBT development, HBT materials, and processing for A/D, digital, analog, and microwave/millimeter-wave applications. She has also worked on *W*-band HEMT monolithic IC process development and advanced device structures.

Tzu-hung Chen (S'83–M'84) was born in Taiwan, R.O.C. on May 17, 1954. He received the B.Ed. degree in physics from National Changhwa University in 1972, the M.S. degree in physics from National Taiwan Normal University in 1978, and the Ph.D. degree in electrical engineering from University of Minnesota in 1984.

From 1984 to 1986 he was with GE, Syracuse, NY, working on the MMIC design and device modeling of MESFET and HEMT. From 1986 to 1988 he was a Senior Engineer in Microwave Semiconductor Corp., Somerset, NJ, where he worked on MMIC design and device modeling and characterization. In 1988 he joined the Electronics Technology Division, TRW, Redondo Beach, CA, where he is a Staff Engineer working on the nonlinear device modeling and monolithic microwave and millimeter-wave integrated circuit design.



Gee Samuel Dow (S'78–M'82) was born in Tainan, Taiwan on April 12, 1954. He received the diploma in electrical engineering from Taipei Institute of Technology, Taipei, Taiwan in 1974 and the M.S.E.E. degree from University of Colorado, Boulder, in 1981.

From 1981 to 1983 he was with Microwave Semiconductor Corporation, where he worked on the development of *Ku*-, *K*-band MESFET power amplifiers and multipliers. From 1984 to 1987, he was with Hughes Aircraft Company, Microwave Products Division, where he was engaged in the characterization of power MESFET devices, development of wideband, high effenciency power amplifiers, and DRO's. Currently, he is with TRW Electronics Technology Division, where he manages a MMIC design section. During the past several years, this group has published extensively in the area of microwave and millimeter-wave monolithic circuits design up to 100 GHz.

Mr. Dow has authored and co-authored over 30 publications in the area of MIC/MMIC design.

J. Berenz is a TRW Space & Defense Sector Technical Fellow and a Senior Scientist for the Electronics and Technology Division Microwave Technology and Development Operation. He has over 18 years experience in the design and fabrication of III-V semiconductor devices and integrated circuits. Before joining TRW in 1980 he was employed by Varian Associates and Hughes Aircraft Company.

Dr. Berenz has co-authored over 60 papers in this field.

Thuy-Nhung Ton (M'86) received the B.S.E.E. degree from the University of California, Irvine in 1983.

In 1983, she joined Microwave Product Division, Hughes Aircraft Company as a member of the Technical Staff where she was involved with the analysis, design, fabrication, and characterization of millimeter-wave components and subsystems. Since 1987, she has been with Microwave Technology and Development Operation of the Electronics and Technology Division of TRW. She is responsible for the design and development of microwave and millimeter-wave MMIC's using MESFET and HEMT technologies. In addition, she is investigating the packaging techniques for module integration using MMIC's.

Ms. Ton has published several papers on millimeter-wave integrated CPW receivers, high dynamic range mixers, and filters.

Diane C. Garske received the A.S. degree in electronics technology from North Central Technical Institute, Wausau, WI, in 1984. She is currently pursuing the B.S. degree in electrical engineering at Santa Monica College.

Since joining TRW, Redondo Beach, CA, in 1984, she has been involved in millimeter-wave monolithic integrated circuits, HEMT and HBT high efficiency amplifiers, low noise amplifiers, receiver and transceiver hardware.

T. Shyan Lin was born in Taiwan, Republic of China, on December 19, 1945. He received the B.S. degree in Physics from the National Cheng-Kung University, in 1967, the M.S. degree in Physics from the National Taiwan University in 1970, and the Ph.D. degree in Solid State Electronics from the University of California, Los Angeles, in 1982.

In 1977 he joined TRW in Redondo Beach, CA, where he was engaged in the research and development of GaAs MESFET MMIC Technology. In 1989 he became the Assistant Manager of the Millimeter-Wave Technology Department responsible for high electron mobility transistor (HEMT) device development and MMIC fabrication. Presently he is a Senior Staff Engineer. His current interest is in developing millimeter-wave power HEMT and HBT devices.

Louis C. T. Liu (S'77–M'81) received the B.S. degree in electrical engineering from the National Taiwan University, Taipei, Taiwan, in 1974 and the M.S. and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, NY, in 1978 and 1981, respectively.

While at Cornell, he worked as a graduate research assistant in the field of microwave broad-band circuit synthesis and design with applications in both low-noise and high-power GaAs MESFET amplifiers, as well as monolithic microwave integrated circuits. In May 1981, he joined the Torrance Research Center of Hughes Aircraft Company, where he was responsible for the development of various monolithic low-noise and power amplifiers, as well as monolithic components for receive and T/R modules operating from *S*-band to *Ka*-band. In February 1986, Dr. Liu joined TRW. Currently, he is Assistant Manager of the Communication Systems Development Department and is responsible for the development of microwave and millimeter-wave monolithic amplifiers, mixers and phase shifters. He is also responsible for establishing the CAD methodology and workstation for MMIC designs.