A Monolithic GaAs HBT Upconverter

A. Y. Umeda, C. T. Matsuno, A. K. Oki, G. S. Dow,
K. W. Kobayashi, D. K. Umemoto, and M. E. Kim

TRW Inc., Electronics and Technology Division
One Space Park, Redondo Beach, CA 90278

ABSTRACT

A 2.6 to 5.5 GHz upconverter/mixer has been implemented with a GaAs heterojunction bipolar transistor (HBT) IC technology. The upconverter consists of a transconductance multiplier based on a Gilbert cell topology, followed by a two-stage Darlington-coupled amplifier. Measured conversion gain is greater than 20 dB up to an RF output frequency of 5.5 GHz. This upconverter is believed to be the first reported using the GaAs HBT technology.

INTRODUCTION

The GaAs heterojunction bipolar transistor (HBT) has demonstrated a variety of analog and microwave functions with significant advantages over advanced Si bipolar and GaAs FETs (MESFET and HEMTs) in combinations of bandwidth, power consumption, harmonic distortion, phase noise, radiation hardness, and size [1]. The GaAs HBT's exponential output current (collector)/input voltage (base-emitter) transfer characteristic is used to achieve nonlinear mixing/upconversion, believed to be the first demonstrated for the GaAs HBT technology. This upconverter monolithically combines an analog four-quadrant multiplier/mixer (Gilbert cell) with a highly-linear output amplifier to achieve high conversion gain and broadband performance. The circuit was designed to provide compact, high frequency mixing capability for a mix-and-divide frequency synthesizer used in a smart weapon transceiver. Compared to conventional double-balanced diode mixers, the GaAs HBT upconverter has advantages of low drive local oscillator (LO) and the ability to provide positive conversion gain. Compared to similar MESFET upconverters, the GaAs HBT circuit is 5-6 times smaller in overall chip area, while compared to silicon Gilbert-cell mixer versions, the HBT upconverter has 7 dB more gain and 5 times higher output frequency performance [2].

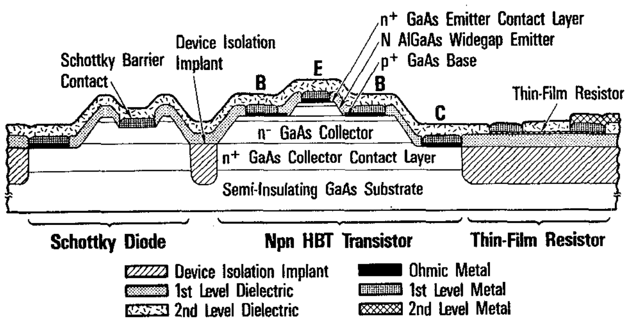


Fig. 1. Integrated Circuit Cross-section of Fabricated HBT Transistor, Schottky Diode, and Thin-Film Resistor.

GaAs HBT DEVICE/IC TECHNOLOGY

The GaAs HBT upconverter is based on an IC fabrication technology which integrates 3 μm emitter-up Npn self-aligned base ohmic metal (SABM) HBTs, Schottky diodes, NiCr thin-film resistors (Fig. 1), and metal-insulator-metal capacitors in conjunction with a simplified molecular beam epitaxial structure. The details of this fabrication process is described in [1]. A representative dc transfer characteristic is shown in Fig. 2 for a 3x10 μm^2 single-emitter device. The I-V curves are characterized by very low output conductance (high Early voltage ≈800 V) which gives HBT devices their excellent linearity and advantage in supressing unwanted spurious response in mixer and amplifier applications. The corresponding HBT has f_T, f_{max}≈20-

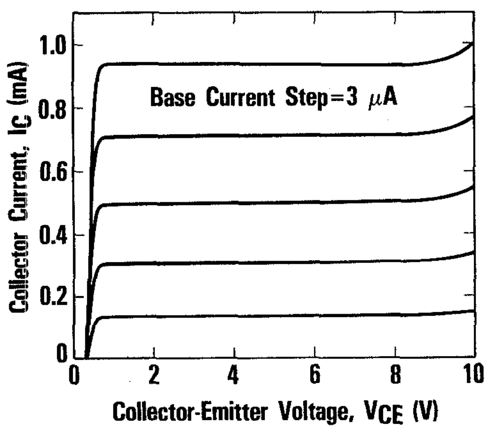


Fig. 2. Collector Current (Ic) vs. Collector to Emitter Voltage (Vce) for a 3 x 10 μm^2 HBT.

90CH2869-6/89/0000-0077$01.00 © 1988 IEEE

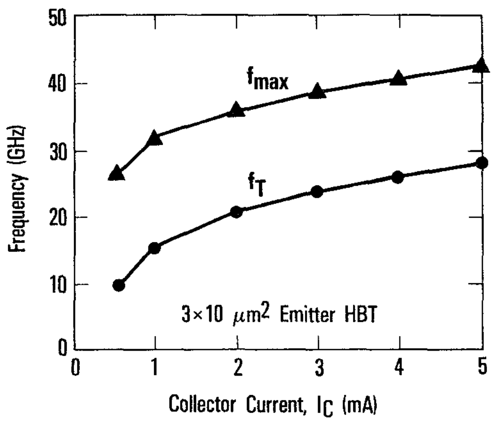
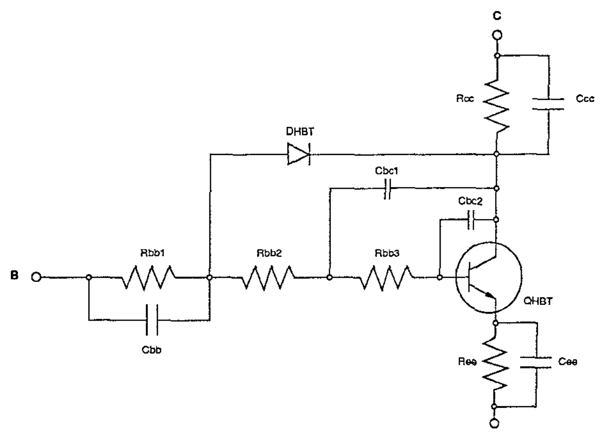


Fig. 3. f_t and f_{max} vs. Collector Current For a 3 x 10 μm^2 HBT.

30 GHz (Fig. 3) providing the high intrinsic frequency performance for wideband upconversion. A high frequency device model for a 3x10 μm^2 single-emitter HBT is shown in Fig. 4, and the model's match to measured S-parameters is shown in Fig. 5. The 3 μm SABM HBT MMIC process using simplified MBE growth structure provides a combination of high performance, compact size, and producibility for wideband RF applications.

CIRCUIT DESIGN

A block diagram of the upconverter is shown in Fig. 6. The upconverter is composed of an input balun on the IF input, a four-quadrant multiplier/mixer, and two Darlington direct-coupled amplifiers. The circuit has



SPICE Parameters

	Bipolar Junction Transistor, QHBT		Diode, DHBT
Rbb1 = 9 Ohms			
Rbb2 = 12 Ohms	IS = 8E-24 amps	RE = 0 0 Ohms	IS = 1 0E-24 amps
Rbb3 = 9 Ohms	NF = 1 179	BF = 169	RS = 0 7 Ohms
Rcc = 4 Ohms	ISE = 30E-21 amps	BR = 0.1	CJO = 13 fF
Ree = 3 Ohms	NE = 1 6	VJE = 1 7 volts	N = 1 7
Cbc1 = 3 fF	RB = 34 Ohms	MJE = 0 5	M = 0 5
Cbc2 = 3 fF	RC = 6 Ohms	CJE = 17 fF	PB = 1 7
Cbb = 18 fF	VJC = 1 21 volts	TF = 4 psec	
Ccc = 37 fF	MJC = 0 5 volts	VAF = 150 volts	
Cee = 114 fF			

Fig. 4. HSPICE Model For a 3 x 10 μm^2 HBT.

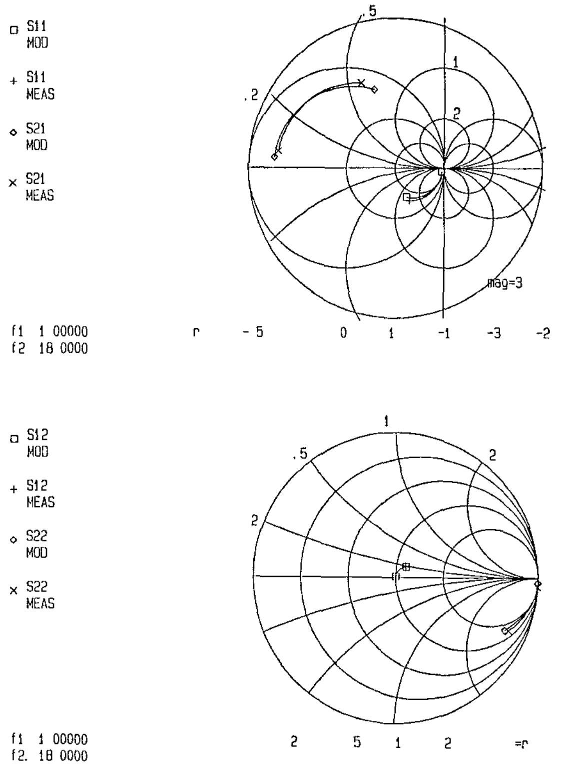


Fig. 5. Comparison of Measured and Simulated S-Parameters For a 3 x 10 μm^2 HBT (Vce = 3 V, Ic = 4.4 mA).

on-chip voltage references and runs off +12 and -9 V supplies. The circuit topology is shown in Fig. 7. The Gilbert cell mixer topology was selected for its double-balanced implementation which offers improved spur performance and high conversion gain in a very compact size. The mixer subcircuit uses external emitter degeneration to suppress intermodulation products. The IF input balun is used to provide a single-ended to differential conversion in which emitter degeneration is used to suppress harmonics. A common-base cascode stage is used at the output of the mixer to improve output frequency response. The output balun stage reduces even-order spurs and harmonics generated in the mixer.

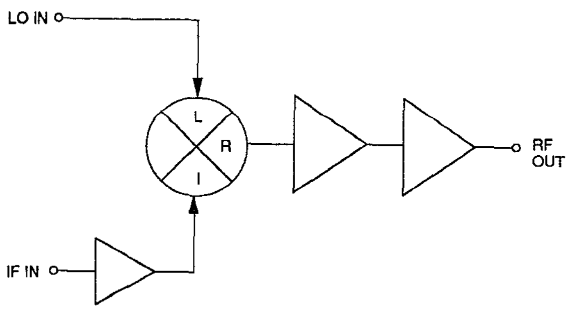


Fig. 6. Upconverter Block Diagram.

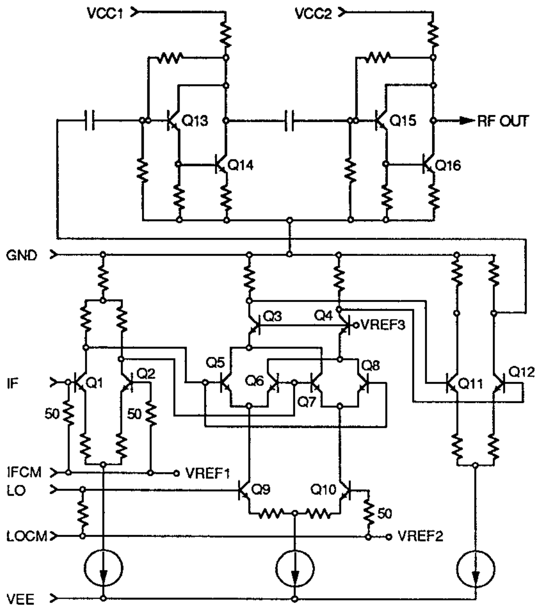


Fig. 7. Simplified Upconverter Schematic Diagram.

The output of the mixer consists of two single-stage Darlington-coupled feedback amplifiers in cascade. The single-stage amplifier has a measured gain of 10-11 dB of gain with flat gain performance (±0.5 dB) up to 6 GHz. The amplifier has an excellent IP2 of ≈40 dBm and a 1-dB power compression of about 11 dBm at 6 GHz. Details of this amplifier have been previously described [3].

HSPICE was used to predict both conversion gain and intermodulation product performance. Internal distributed transmission line effects were neglected because the on-wafer electrical connections between components were less than one-tenth of a quarter-wavelength.

UPCONVERTER FABRICATION AND PERFORMANCE

A photomicrograph of the fabricated GaAs HBT upconverter is shown in Fig. 8. The circuit has 50 transistors; the corresponding chip size is 1x1.5 mm^2. The circuit consumes 1.6 watts of power from +12 and -9 V supplies.

The upconverter circuits were characterized on-wafer using coplanar RF probes. A plot of conversion gain versus frequency is shown in Fig. 9. The conversion gain is 23 dB at 2.6 GHz RF out, and rolls off 3 dB at 5.5 GHz. Measurements were taken between RF output frequencies of 2.6 and 6.6 GHz. The mixer can be operated to lower RF output frequencies and is limited by dc blocking capacitors which pass frequencies as low as 1 GHz with virtually no effect on performance. A plot of output power versus input power of the upconverter is shown in Fig. 10. The circuit achieves an output power of 1.5 dBm at 1-dB compression. Typical spurious output product

Fig. 8. Photomicrograph of HBT Upconverter. (50 HBTs; 1.5 mm x 1.0 mm).

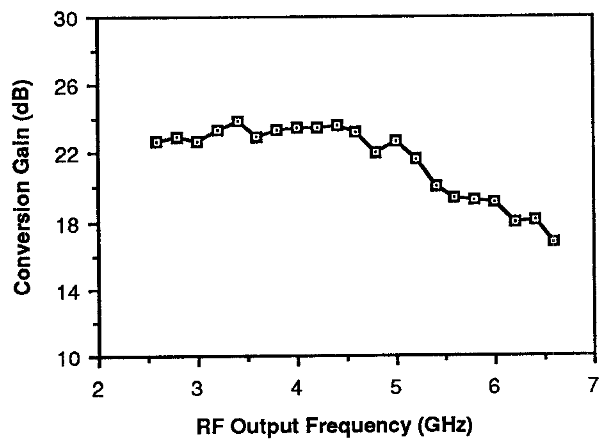


Fig. 9. Conversion Gain vs. Frequency (IF = 1.2 GHz, -22 dBm ; LO = 1.4 - 5.4 GHz, -5 dBm).

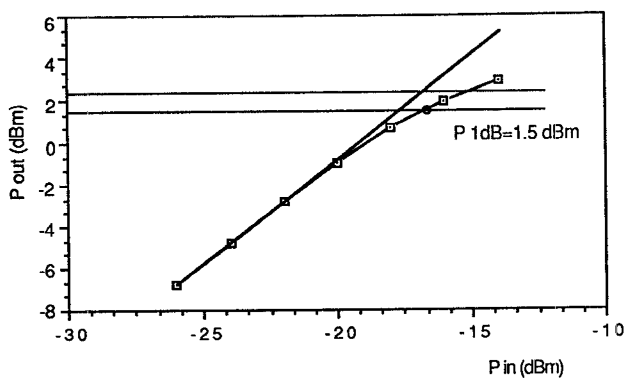


Fig.10. RF Output Power at 4.951 GHz vs. IF Input Power (LO = 3.85 GHz, IF = 1.101 GHz).

SPUR ORDER		SPUR SUPPRESSION (dBc)
LO	IF	
8	1	>95
7	1	>95
6	3	>95
5	3	89
4	0	72
3	2	57
2	2	48
0	1	32
1	0	3

Table 1. Upconverter Intermodulation Performance (LO = 3.850 GHz, -5 dBm; IF = 1.101 GHz, -26 dBm; RF = 4.951 GHz, -2 dBm).

suppression is shown in Table 1. Spurious output product performance is comparable to that of diode mixers when the output power of the fundamental is normalized to the levels typically applied in hybrid diode mixers. Noise figure at a 5 GHz upconverted RF output frequency was measured to be 17 dB. This relatively high noise figure is comparable to that of silicon bipolar downconverters utilizing Gilbert cell multipliers at much lower output frequency and gain [2].

SUMMARY AND CONCLUSIONS

A GaAs HBT monolithic broadband (2.6 to 5.5 GHz), high conversion gain (20 dB) upconverter has been demonstrated. The circuit achieves over five times the frequency and 7 dB higher gain than advanced silicon bipolar versions, lower LO drive requirement and higher conversion gain than diode mixers, and six times smaller circuit area than similar MESFET mixer circuits. While this initial GaAs HBT upconverter offers important advantages over alternative device technology approaches, significant improvements are expected to be realized with optimized HBT design, epitaxial structure, and circuit design.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of M. Iiyama, L. Tran, M. Hafizi, K. Stolt, D. Streit, J. Camou, L. Pawlowicz, G. Gorman, D. Yang, T. Naeole, S. Thomas, M. Baca, E. Yamada, G. Wong, C. Russell, A. Paxton, C. Hanson, F. Garcia, A. Lopez, and R. Kam. The GaAs HBT upconverter development was supported by the DARPA Microwave/Millimeter-Wave Monolithic Integrated Circuit (MIMIC) Phase 1 Program, Contract No. DAAL01-88-C-0835, Department of the Army, U.S. Army Electronics Technology and Devices Laboratory, Fort Monmouth, N.J. 07703.

REFERENCES

[1] M. E. Kim, A. K. Oki, G. M. Gorman, D. K. Umemoto, and J. B. Camou, "GaAs heterojunction bipolar transistor device and IC technology for high performance analog and microwave applications," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp.1286-1303, Sept. 1989.

[2] J. Wholey, I. Kipnis, and C. P. Snapp, "Silicon bipolar double balanced active mixer MMIC's for RF and microwave applications up to 6 GHz", in 1989 *IEEE MTT-S International Microwave Symp. Dig.* (Long Beach), June 1989, pp.281-285.

[3] K. Kobayashi et al. "GaAs heterojunction bipolar transistor MMIC dc to 10 GHz direct-coupled feedback amplifier," in 1989 *IEEE IC Symp. Dig.* (San Diego), Oct. 1989, pp. 87-90.