A Broadband HBT MMIC IQ Modulator and Millimeter-wave Vector Signal Characterization

Hong-Yeh Chang*, Tian-Wei Huang*, Huei Wang*,
Yu-Chi Wang**, Pane-Chane Chao** and Chung-Hsu Chen**

* Department of Electrical Engineering and Graduate Institute of Communication Engineering,
National Taiwan University, Taipei, Taiwan 106, ROC
** WIN Semiconductors Corp., Hwaya Technology Park, Taoyuan, Taiwan 333, ROC

Abstract — **A broadband 50-110 GHz HBT MMIC IQ modulator and a vector signal measurement system for millimeter-wave applications are reported in this paper. For the digital modulation measurement, a QPSK modulation format was used with a 2-Mbps data rate for the IQ modulation. Using the 50-110 GHz vector signal measurement system, this MMIC chip shows an error vector magnitude (EVM) of within 12 % rms and a carrier rejection of more than 21 dB. The 110-GHz operation frequency of this MMIC is the highest among all the reported HBT vector modulators. Also, this is the first time the EVM test was performed for an IQ modulator at V-band and W-band. This MMIC is suitable for software defined radio (SDR), linearization techniques of power amplifier and related transmitter applications both in V-band and W-band.**

I. Introduction

Direct carrier modulator has the advantages of reducing the complexity of transmitters and thus their cost. For conventional designs, the IQ modulators consist of two BPSK modulators, a 90° phase shifter and an in-phase power combiner. Most of BPSK modulators are composed with a doubly-balanced mixer [1]-[3] due to superior spur performance, linearity and port to port isolation. However, they usually need a high LO drive power and require a built-in driver amplifier. Alternately, by using Si (CMOS, BJT or SiGe HBT) and GaAs (HBT or HEMT) technologies, the IQ modulators based on the Gilbert cell architecture have been reported in recent years [4]-[6]. Although they showed the performance of good amplitude and phase match and high LO rejection, most of them operated below 10 GHz.

In this paper, the IQ modulator is based on the quadrature modulation architecture, which contains two sets of BPSK modulators, a 90° hybrid and a combiner. We use a balanced reflection-type phase shifter [7] for the BPSK modulator, which utilized a Lange coupler as a 90° hybrid and two shunt cold-mode devices as switching devices. The cold-mode devices can be fabricated with HEMT, FET, or HBT technologies. Although the BPSK modulators can be implemented in HEMT process [7]-[9], however, they require negative biasing voltage to perform modulation function. On the other hand, the HBT based BPSK modulators have been reported in literatures [10]-[11] with operating frequency below 50 GHz. Recently, we have reported a HBT based BPSK modulator above 50 GHz successfully [12]. Using this BPSK modulator in our IQ modulator design, this MMIC chip demonstrated a superior broadband performance, good amplitude/phase match and low insertion loss.

Vector signal measurements at 38 GHz can be found in literatures [3], [13]. For a real digital modulation signal coming from an IQ modulator, the amplitude and phase states are time variant. The amplitude and phase states of the dynamic signal cannot be measured via a network analyzer or a scalar spectrum analyzer. Therefore, a vector signal analyzer was used to detect the performance of the IQ modulator such as EVM, phase error, amplitude error, quadrature error, I-Q imbalance, DC offset and the impairment of an imperfect LO source. In this paper, we use a QPSK modulation format with a 2-Mbps data rate to test this IQ modulator MMIC between 50 GHz and 110 GHz. Due to the equipment limitations, the test is performed only with a data rate of 2-Mbps.

II. MMIC Process and Circuit Design

The IQ modulator design is based on the 6" 1-μm GaAs HBT MMIC process on a 4-mil substrate provided by WIN Semiconductors. There are three metal layers, metal-insulator-metal (MIM) capacitors, via-holes, spiral inductors and thin film resistors in this process. The polyimide and SiN_x are used for the isolated layer between metal and metal layers. The one emitter finger and emitter size of 1.4x10 μm^2 HBT device (Q2B101) is selected for the IQ modulator design. This device exhibits a peak unit current gain frequency f_T of 70.5 GHz and peak maximum oscillation frequency f_{max} of 104 GHz at 1.5-V and 7-mA collector bias, typical collector-to-emitter breakdown voltage of 9 V and maximum collector current of 11.2 mA [14].

The photograph of the IQ modulator is shown in Fig.1 with a chip size of 2x2 mm^2. The MMIC consists of two BPSK modulators, a Lange coupler and a Wilkinson power combiner. The BPSK modulator [12] is based on a balanced reflection-type phase shifter, which features low insertion loss, broadband and good amplitude and phase balance. In Fig. 1, IP and IN are the voltage control ports of in-phase BPSK modulator; while QP and QN are the voltage control ports of quadrature-phase BPSK modulator. The vector summation of in-phase and quadrature-phase BPSK modulators can be many phase and amplitude states by adjusting the control voltages (IP, IN, QP and QN). The transmission coefficient S_{21} of the modulator can be expressed as:

$$S_{21} = \frac{1}{4}[(\Gamma_I - \bar{\Gamma}_I) - j(\Gamma_Q - \bar{\Gamma}_Q)] \qquad (1)$$

where Γ_I and Γ_Q are the HBT off-state reflection coefficients of the in-phase and quadrature-phase BPSK modulator respectively; while $\bar{\Gamma}_I$ and $\bar{\Gamma}_Q$ are the HBT on-state reflection coefficients. For optimum design of the IQ modulator, the magnitude of the on-state and off-state reflection coefficients must be close to 1 with 180° out of phase.

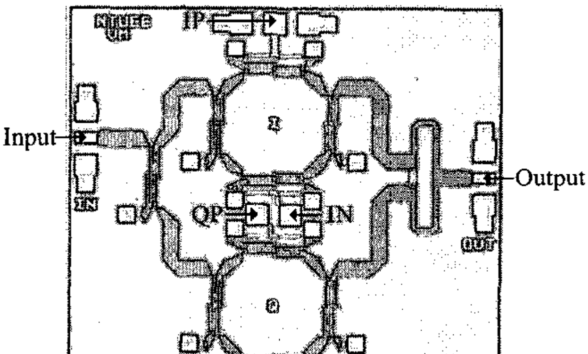


Fig. 1. The microphotograph of the HBT IQ modulator with a chip size of 2 x 2 mm^2.

The HBT Gummel Poon model provided by WIN Semiconductors [14] is used for the circuit simulation. The base bias of on-state is 4 V with 5 mA current consumption; adversely, the base bias of off-state is 0 V. The transmission line, Lange coupler and Wilkinson power combiner are simulated using the full-wave EM-simulator (Sonnet Software) [15]. For QPSK operation, there are four phase states (0°, 90°, 180°, 270°) with the same amplitude, which are represented as state (0, 0), state (0, 1) , state (1, 0) and state (1, 1). The simulated insertion losses are lower than 10 dB, amplitude imbalance is below 2 dB, and phase imbalance is below 2.5° between 40 GHz and 100 GHz. The simulated input and output return losses are better than 10 dB between 50 GHz and 110 GHz.

III. Measurement Results

The *S*-parameters measurements of the IQ modulator were performed via on-wafer probing. For 10-50 GHz, we utilize HP 8510C network analyzer with coaxial cable connected to Cascade ACP50 probes. Above 50 GHz, we use HP V85104A millimeter-wave *S*-parameters test-set with WR-15 waveguide connected to Cascade ACP75 probes for 50-75 GHz and HP W85104A millimeter wave *S*-parameters test-set with WR-10 waveguide connected GGB W-band probes for 75-110 GHz.

The measured insertion losses of four states from 10 GHz to 110 GHz are plotted in Fig. 2. The insertion losses of four states are below 12.5 dB, amplitude imbalance is within 2.5 dB and phase imbalance is within 15° between 50 GHz to 85 GHz. The measured input and output return losses are better than 8 dB between 50 GHz to 110 GHz.

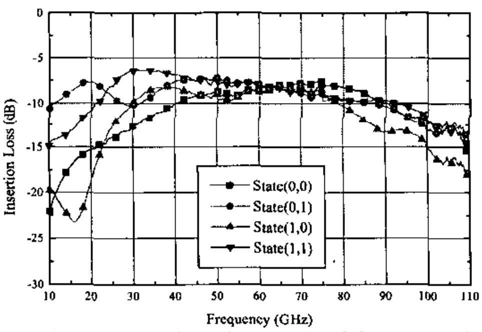
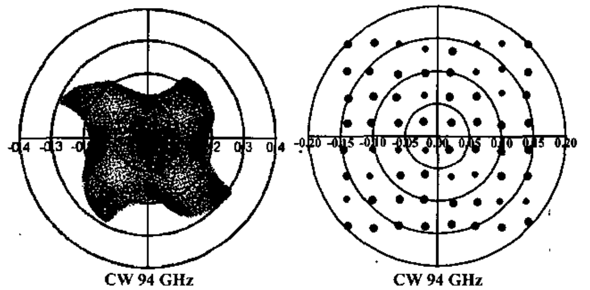


Fig. 2. The measured insertion losses of four states from 10 GHz to 110 GHz for the HBT IQ modulator.

The transfer function of the HBT input reflection coefficient versus control voltage is a nonlinear curve. If apply the high level modulation format (n-QAM, n-PSK) to the IQ modulator directly, the amplitude and phase states will be distorted seriously. Therefore, we use the calibration bias method [9] to extract exact amplitude/phase states and minimize the amplitude imbalance and phase imbalance of the IQ modulator. The static constellation diagrams were obtained from CW-mode *S*-parameters measurement with a computer control setup. The forward transmission coefficients at 94 GHz are plotted in Fig. 3 (a) with linear polar format, where the control voltages of IP, IN, QP and QN have been swept from 0 V to 4 V with step of 0.02 V. Based on forward transmission coefficients, EVM calculation is used to extract the best amplitude and phase states. We can generate the static constellation diagrams of QPSK or higher order QAM modulations. We use 64-QAM as an example, to plot the extracted constellation diagram in Fig. 3(b), which features a minimum insertion loss of 14 dB, amplitude imbalance of 1 dB and phase imbalance of 1°.



(a) (b)

Fig. 3. The measured static constellation diagram of the HBT IQ modulator at 94 GHz, (a) sweep I and Q control voltage with a step of 0.02 V, (b) extracted 64-QAM.

The block diagram of the vector signal measurement system is plotted in Fig. 4 for the millimeter-wave IQ modulator. The HP 85105A millimeter-wave test set is used to provide the carrier signal. The HP 11970-series harmonic mixer and the HP 70000 spectrum analyzer are used as a down-converter to convert millimeter-wave signal to an IF frequency of 21.4 MHz. Finally, the 21.4-MHz IF signal is fed into HP 89441A vector signal analyzer for the analysis of the digital modulation quality. Two HP 33120A arbitrary waveform generators are used as the baseband IQ signal sources, which are controlled with a computer and HP VEE software. The IQ sources are fed into a single-to-differential circuit network to produce differential IQ sources (IP, IN, QP and QN). For channel power measurement, the HP 70000 spectrum analyzer is replaced with the HP 8565EC spectrum analyzer with built-in channel power measurement software. The overall measurement system features maximum operation frequency of 110 GHz, maximum symbol rate of 2-Mps, maximum analysis bandwidth of 3 MHz and supports multiple digital modulation formats.

The measured output spectrum of QPSK modulation is plotted in Fig. 5 and the output power is about -21.3 dBm with a channel bandwidth of 2 MHz. The measured QPSK modulation quality results at 94 GHz are plotted in Fig. 6, including I-Q vector diagram, eye diagram, error versus time plot and performance summary. The LO power is about -8 dBm and the amplitude of the baseband IQ signal is 2-V_{pp}. The baseband IQ is coded with a QPSK modulation format, a 2-Mbps data rate, pseudo random noise code and the mapping table used with the extracted results from static constellation diagram measurement. For minimum the spectrum spread, we use a root raised cosine (RRC) filter with a 0.5-α value to filter the baseband IQ signal. The measured EVM is below 9.7 %, the amplitude error is below 7.3 % and the phase error is below 3.7° in root-mean-square (RMS) format.

The EVM degradation is due to the quadrature error and IQ imbalance within the IQ modulator. Additionally, the imperfect LO/IQ sources in the test setup will also degrade the EVM performance. For the W-band applications, the phase noise and amplitude noise of the LO source may result in 3-5 % EVM degradation, which was analyzed with a THRU pad. The EVM analysis of CW-mode LO source is like an all-0 data modulation signal. On the other hand, the EVM may be degraded 3-4 % from the IQ sources, which was measured with a vector signal analyzer. This EVM degradation from IQ sources is due to high data rate operation of the arbitrary waveform generators and the nonlinearity of the single-to-differential circuit network. The performance summary of the IQ modulator is summarized in Table I. As can be observed, this MMIC demonstrated wider bandwidth, low EVM degradation and good LO rejection. The success of this chip development provides many potential applications in millimeter-wave communication systems.

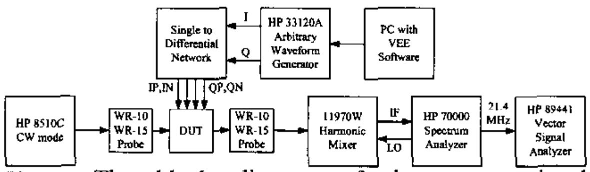


Fig. 4. The block diagram of the vector signal measurement system for the millimeter-wave IQ modulator.

IV. CONCLUSION

A broadband HBT IQ modulator and a vector signal measurement system for millimeter-wave IQ modulator have been implemented and proposed in this paper. This IQ modulator MMIC is suitable for broadband digital modulated applications due to its wide bandwidth, low insertion loss, low amplitude/phase imbalance and good input/output return loss. Also, this MMIC has been tested and verified under the vector signal measurement successfully. The vector signal measurement system presented in this paper provides a dynamic signal test bench for the IQ modulator. For the digital modulation signals, the dynamic signal measurement is more meaningful than the static signal measurement. Therefore, we can figure out the characteristic of the MMIC circuit and the impairment coming from the imperfect signal source.

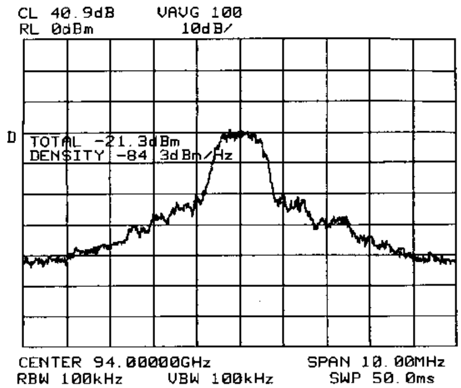


Fig. 5. The measured output spectrum of the HBT IQ modulator is applied QPSK modulation format and the output power is -21.3 dBm with a channel bandwidth of 2 MHz.

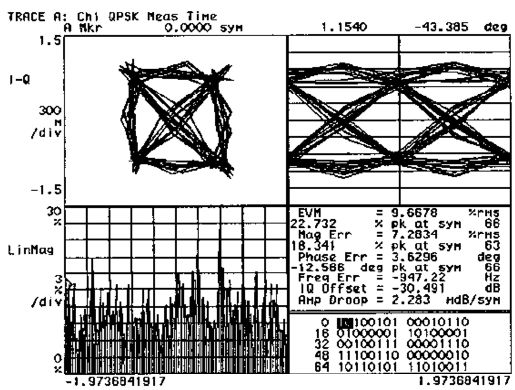


Fig. 6. The measured QPSK modulation quality results at 94 GHz, I-Q vector diagram, eye diagram, error vector versus time plot and performance summary.

Table I Performance Summary of the HBT IQ modulator

Frequency	50 GHz	60 GHz	77 GHz	94 GHz	110 GHz
Insertion Loss	9 dB	8 dB	9 dB	14 dB	18 dB
EVM#	<7%*	<11.5%	< 12%	< 10%*	< 12%*
LO Rejection	>21	>23 dB	>21 dB	>30 dB	>21 dB

*With calibration bias; #QPSK modulation with 2-Mps data rate

ACKNOWLEDGEMENT

This work is supported in part by National Science Council (NSC 89-2213-E-002-178 and NSC 90-2219-E-002-007) and Research Excellence Program funded by Department of Education of Republic of China (ME-89-E-FA06-2-4-6). The MMIC chip is fabricated by WIN Semiconductors. The authors would like to thank Mr. G. G. Boll of GGB Inc. for his providing the W-band probes for chip on-wafer testing.

REFERENCES

[1] R. Desrosiers, *et al*, "Monolithic 14 GHz widerband InP HBT BPSK modulator," *1998 Gallium Arsenide Integrated Circuit Symposium*, pp.135-138.

[2] Isabell Telliez, *et al*, "A compact monolithic microwave demodulator-modulator for 64-QAM digital radio links," *IEEE Trans. on Microwave Theory and Tech.*, vol. 39, no. 12, December, 1991, pp.1947-1954.

[3] G. Samuel Dow *et al*, "Vector signal measurement for 38 GHz digital radio applications," *Microwave Journal*, October, 1999.

[4] A. Alexanian, *et al*, "A SiGe transceiver chipset for 100 Mbps/1 Gbps digital communication over cable system," *2002 IEEE Radio Frequency Integrated Circuits Symposium*, pp.119-122.

[5] Andrew Weetzei, "A stable 250 to 4000 MHz GaAs IQ modulator IC," *1997 IEEE International Solid-State Circuits Conference*, pp.364-365.

[6] Angel Boveda, Felix Orilgoso, Jose I. Alonso, "A 0.7-3 GHz GaAs QPSK/QAM direct modulator," *IEEE Journal of Solid-State Circuits*, vol. 28, no. 12 December, 1993, pp. 1340-1349.

[7] Dennis C. W. Lo, *et al*, "Novel monolithic multifunctional balanced switching low-noise amplifiers," *IEEE Trans. on Microwave Theory and Tech.*, vol. 42, no. 12, December, 1994, pp.2629-2634.

[8] T. Lodhi, *et al*, "A 77 GHz coplanar waveguide MMIC BPSK Vector Modulator realized using InP Technology," *2000 IEEE GaAs IC Symposium Digest*, pp.183-186.

[9] AliE. Ashtiani, *et al*, "Direct multilevel carrier modulation using millimeter-wave balanced vector modulators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 12, December 1998, pp. 2611-2619.

[10] S. Nam, *et al*, "Monolithic millimeter-wave balanced bi-phase amplitude modulator in GaAs/InGaP HBT technology," *1999 IEEE International Microwave Symposium*, vol. 1, pp. 243-246.

[11] A.E. Ashtiani, *et al*, "Monolithic GaAs/InGaP HBT balanced vector modulator for millimeter-wave wireless systems," *2000 IEEE Radio Frequency Integrated Circuit Symposium Digest*, pp.187-190.

[12] Hong-Yeh Chang, *et al*, "A 45-90 GHz BPSK Modulator Using HBT Technology", *2002 Asia Pacific Microwave Conference*, Nov. 2002, Kyoto, Japan..

[13] S. G. Dow, *et al*, "Vector signal characterization of 38 GHz power amplifier with 100 Mbps QPSK modulation," *2000 IEEE International Microwave Symposium*, pp.1847-1850.

[14] GaAs 1 μm HBT Model Handbook 1.0, WIN Semiconductors Corp., July, 2001.

[15] Sonnet User's Manual, Release 6.0, Sonnet Software Inc., Liverpool, NY, April 1999.