A 25-65 GHz Broadband Low-LO-Driving Wide-Modulation-Bandwidth Monolithic BPSK Modulator in GaAs PIN Diode MMIC Process

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***Abstract*—In this paper, a 25-65 GHz broadband low-LO-driving wide-modulation-bandwidth monolithic BPSK modulator using PIN diode MMIC process is described. The PIN diode is employed in the reflection-type modulation as a varying reflection load. Based on the modified reflection-type BPSK topology, the high-performance BPSK modulator is achieved. Between 25 and 65 GHz, the measured amplitude and phase imbalances are within 0.9 dB and 6˚, respectively. With a LO driving power of -15 dBm, the measured error vector magnitude (EVM) of the BPSK modulation is within 1.8% at 30 GHz. The measured modulation bandwidth is wider than 500 MHz, and the demodulation shows good eye-pattern opening up 0.5 Gbps. This work is suitable for high speed digital applications due to its superior performance.**

Keywords*—*BPSK, GaAs PIN diode, MMIC, modulator, phase shifter, reflection-type modulator

I. Introduction

The PIN diodes are usually used in some microwave and millimeter-wave (MMW) control devices, such as switch [1]-[2] and phase shifter [3], and they features higher power handling and lower loss as compared with the MESFET or HEMT technology. The PIN diodes can be fabricated using SiGe [1], GaN [2], and GaAs [3] compound semiconductor processes. The PIN-based monolithic microwave integrated circuits (MMICs) are widely adopted for some MMW circuits to enhance performance and reduce cost. The binary phase-shift keying (BPSK) modulator is an essential building block for the modern digital modulation scheme [4], and the key specifications are RF bandwidth, modulation bandwidth, local oscillation (LO) driving power, and modulation accuracy [5]. A Gilbert-cell mixer was employed in the BPSK circuit design to reduce the conversion loss [6], but it usually consumes some DC power. The diode-based mixer also can be adopted to perform the BPSK modulation/demodulation, but the LO driving power is usually high. The HBT PN-junction diodes with dc bias were utilized in the BPSK circuit to reduce the LO driving power down to 0 dBm [7]. The conventional reflection-type BPSK demonstrates broad RF bandwidth with a LO driving power of -8 dBm [4]. Moreover, the BPSK modulators based on a modified reflection-type topology were proposed to reduce the amplitude and phase errors over the process variation [8]-[9]. A BPSK modulator using control amplifiers with 180˚ hybrid in InP process was proposed to achieve a data rate of 10-Gbps, but the DC power consumption is up to 400 mW.

In this paper, a broadband low-LO-driving wide-modulation-bandwidth monolithic BPSK modulator is proposed using a GaAs PIN diode MMIC process. To further enhance circuit performance, the proposed BPSK modulator is designed using a modified reflection-type BPSK topology, and the PIN diode is adopted for the reflection terminations. As compared with the conventional diode-based BPSK modulators, this work demonstrates a LO driving power of -15 dBm. With a symbol rate of 1 MS/s, the measured error vector magnitude (EVM) is within 4% from 10 to 70 GHz. The measured modulation bandwidth is wider than 0.5 GHz, and the BPSK demodulation shows good eye-pattern opening up to a symbol rate of 0.5 GS/s. The proposed BPSK modulator is suitable for high speed low power digital modulation applications. Furthermore, this is the first attempt to use PIN diode MMIC process to demonstrate high-performance BPSK modulation with low LO driving power.

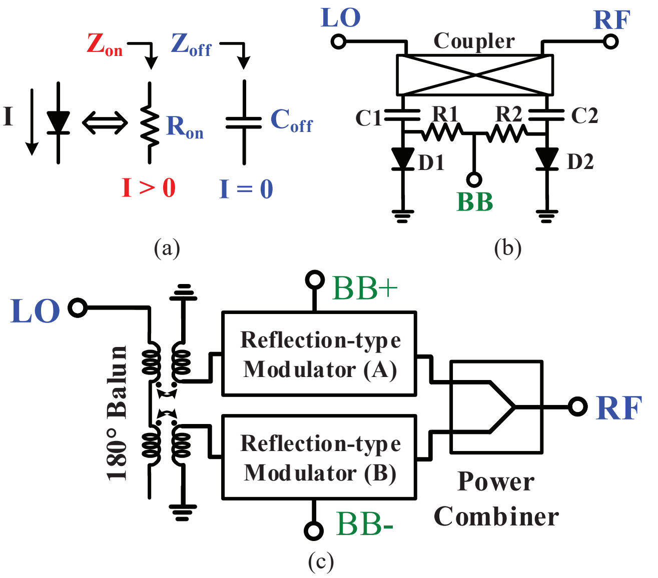


Fig. 1. (a) Equivalent circuits of the GaAs PIN diode with/without dc current, (b) schematic of the PIN-diode reflection-type modulator, and (c) schematic of the PIN-diode BPSK modulator.

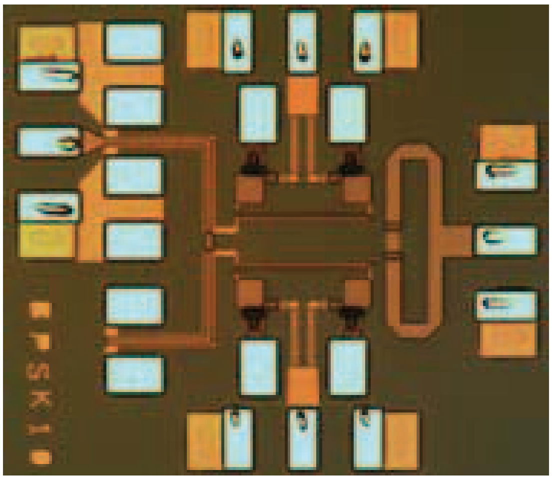


Fig. 2. Chip photograph of the PIN-diode BPSK modulator with a chip size of 0.7x0.8 mm^2.

II. Circuit Design

The proposed BPSK modulator was fabricated using a GaAs PIN diode MMIC process provided by the WIN Semiconductors Corporation. There are 3 metal layers for the circuit interconnection. The thinness of the GaAs wafer is 4 mil for the gold plating of the backside and reactive ion etching via-holes are used for RF and DC grounding. The thin film resistor and metal-insulator-metal capacitor are also available in this process. A PIN diode size of 15×15 μm^2 is selected for the circuit design, and it exhibits a parasitic resistance (R_{on}) of 2.7 Ω for the turn-on status and a parasitic capacitor (C_{off}) of 38 fF for the turn-off status.

The equivalent circuit of the turn-on and -off PIN diode is shown in Fig. 1(a). The diode is turned on as a short-circuit impedance, Z_{on}, (low-resistance resistor) with a certain DC bias current, while the diode is turned off as an open-circuit impedance, Z_{off}, (low-capacitance capacitor) without DC bias. The short and open terminations can be further applied to a reflection-type modulator as shown in Fig. 1(b) to perform the BPSK modulation, and the insertion loss would be reduced due to the high reflection coefficients of the short and open terminations [5]. The amplitude modulation can be also performed using various impedances with different DC biasing currents. The coupler in Fig. 1(b) is designed based on an edge-coupled 90˚ coupler. Two capacitors, C1-2, are performed as DC block to prevent the dc current through the coupler. Two resistors, R1-2, are used to provide the DC bias paths and also performed as RF choke, and the resistance is a design tradeoff between the modulation bandwidth and the insertion loss. To further reduce phase and amplitude errors of the BPSK modulation, the modified reflection-type BPSK topology in [8] is adopted for the circuit design. The schematic of the proposed BPSK modulator is show in Fig. 1(c), which is composed of two identical PIN-diode reflection-type modulator, a Wilkinson power combiner, and an 180˚ Marchand balun. There are two phase states (0 ˚ and 180˚) with the same insertion loss for the circuit operation. For the state-0, the logic level of baseband BB+ is high and the baseband BB- is low; for the state-1, the baseband BB+ is low and the baseband BB- is high. The baseband input ports BB+ and BB- should be differential signals. The chip photograph of the proposed PIN-diode BPSK modulator is shown in Fig. 2 with a chip size of 0.7×0.8 mm^2. The passive components, including balun, combiner, resistors, capacitors, and transmission lines, are all simulated using a full-wave EM simulator [11].

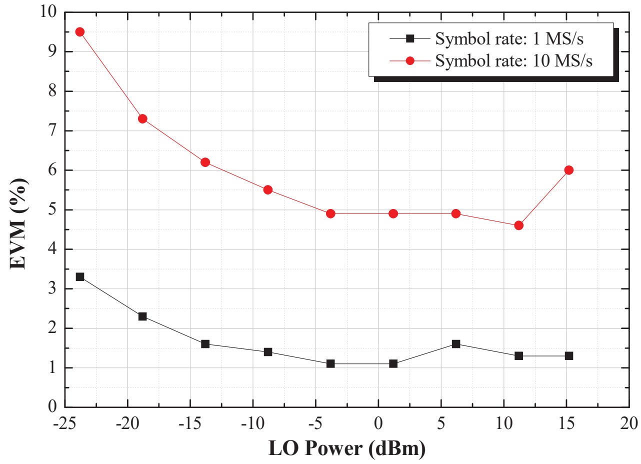


Fig. 3. Measured EVM versus LO power of the PIN-diode BPSK modulator at 30 GHz with various symbol rates of 1 and 10 MS/s.

III. Experimental Results and Disscussions

The proposed BPSK modulator is measured via on-wafer probing, and four GSG RF probes are adopted. The *S*-parameters are measured using an Agilent E8361A vector network analyzer. The measured insertion losses of the two states are lower than 10 dB from 25 to 65 GHz, and the minimum insertion loss is 6 dB at 50 GHz. Between 10 and 70 GHz, the BPSK modulator features an amplitude error of within 2 dB and a phase error of within 6˚. For the BPSK modulation measurement, the LO signal is generated using a Keysight E8257D signal generator, the differential baseband signals are generated using an Agilent E4438C arbitrary waveform generator, and the output spectrum is measured using an Agilent E4448A spectrum analyzer with a 11974V harmonic mixer. An Agilent 89600S vector signal analyzer is adopted to receive the down-converter IF signal from the spectrum analyzer for the BPSK demodulation. The measured EVMs versus LO power of the PIN-diode BPSK modulator at 30 GHz are plotted in Fig. 3 with various symbol rates of 1 and 10 MS/s. As the LO power is -15 dBm, the measured EVMs for symbol rates of 1 and 10 MS/s are within 1.8% and 6.4%, respectively, and the proposed BPSK modulator demonstrates ultra-low LO-driving power with good modulation quality. The measured EVMs versus RF frequency of the PIN-diode BPSK modulator are plotted in Fig. 4 with symbol rates of 1 and 10 MS/s. Between 10 and 70 GHz, the measured EVMs for symbol rates of 1 and 10 MS/s are within 4% and 9%, respectively. The measured output spectrum and constellation diagram of the PIN-diode BPSK modulator at 38 GHz are shown in Fig. 5, where the symbol rate of the baseband is 1 MS/s with a root-raised-cosine filter and an α-value of 0.5. The BPSK modulator features good modulation quality with measured EVM of within 2%. We assume the channel bandwidth and spacing are both 2 MHz, and the measured adjacent channel power ratio is better than -40 dBc.

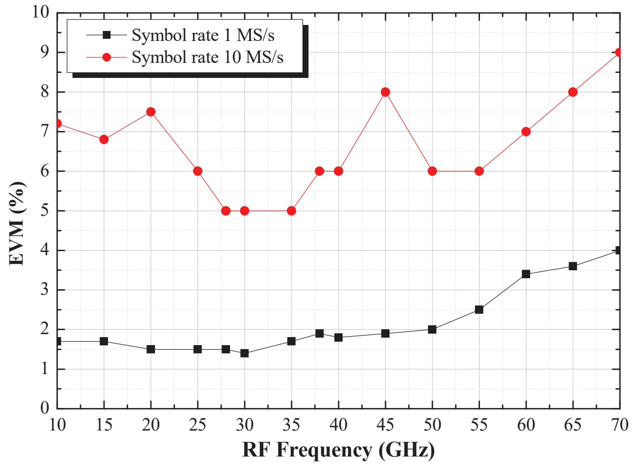
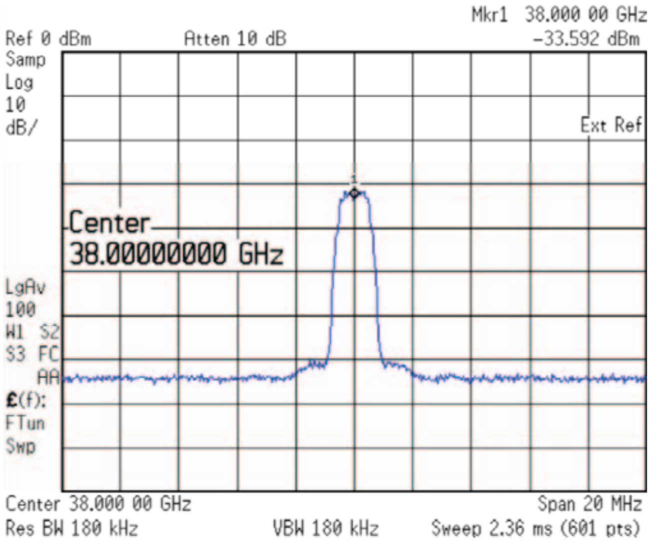
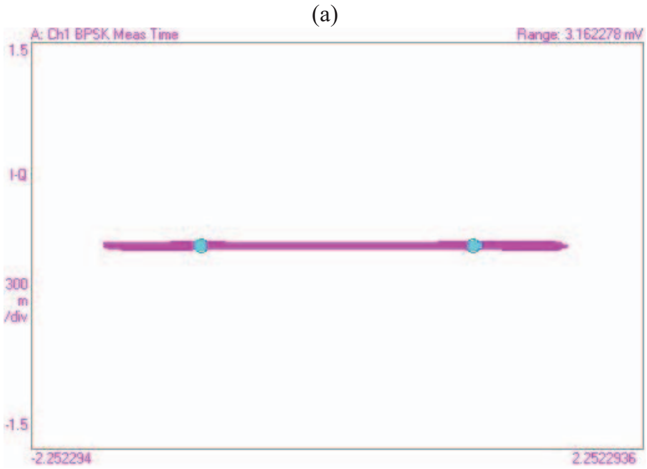


Fig. 4. Measured EVM versus RF frequency of the PIN-diode BPSK modulator with symbol rates of 1 and 10 MS/s.



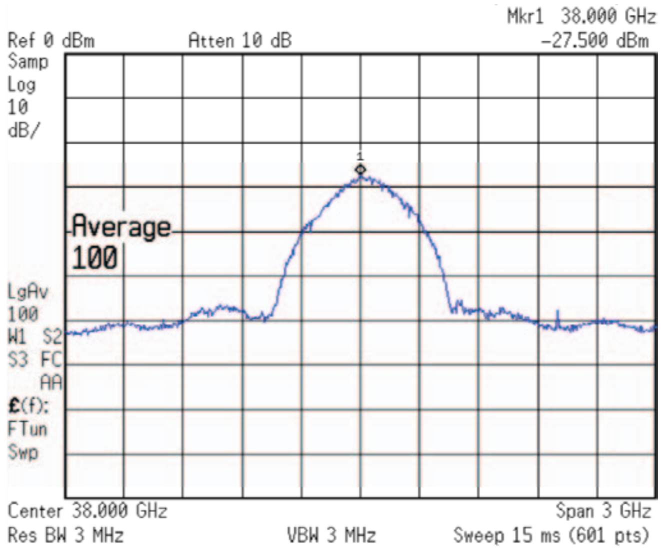
(a)



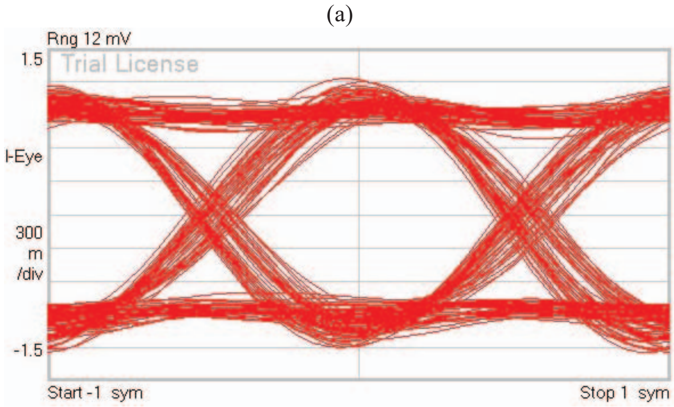
(b)

Fig. 5. Measured (a) output spectrum and (b) constellation diagram of the PIN-diode BPSK modulator at 38 GHz with a symbol rate of 1 MS/s.

To further evaluate the modulation bandwidth of wider than 100 MHz, an Agilent N4903B pulse generator is adopted for the baseband signal. A harmonic mixer is employed in the down-converter with an IF frequency of 1 GHz. An Agilent MSO9254A oscilloscope with 89600 software is used to perform the BPSK demodulation. The measured output spectrum and eye diagram of the PIN-diode BPSK modulator at 38 GHz is shown in Fig. 6 with a symbol rate of 0.5 GS/s. The sinc-like spectrum is due to the unfiltered baseband signal, and the BPSK demodulation shows good eye-pattern opening and signal-to-noise ratio. The comparison of the previously reported state-of-the-art BPSK modulators and this work are summarized in Table I. The proposed PIN-diode BPSK modulator demonstrates an ultra-low LO driving power of -15 dBm and it is very suitable for the low-power applications. The modulation bandwidth is wider than 500 MHz, and the measured results show the modulation capability of up to 0.5 Gbps with good quality.



(a)



(b)

Fig. 6. Measured (a) output spectrum and (b) eye diagram of the PIN-diode BPSK modulator at 38 GHz with a symbol rate of 0.5 GS/s.

IV. Conclusion

A high-performance monolithic BPSK modulator is successfully presented in this paper using a GaAs PIN diode technology. Based on the modified reflection-type topology, this work has broadband RF bandwidth, wide-modulation capability, and good modulator quality under ultra-low LO driving power. In the future work, the proposed BPSK

TABLE I.
PERFORMANCE SUMMARY OF THE PREVIOUSLY REPORTED STATE-OF-THE-ART BPSK MODULATORS AND THIS WORK

Reference	MMIC Process	Frequency (GHz)	LO Driving Power (dBm)	Modulation BW (MHz)	Phase Im. (°)	Amplitude Im. (dB)	EVM @ symbol rate 1 MS/s (%)	Chip Size (mm^2)
[5]	1-μm HBT	50 - 110	-8	3	5	2.5	<6	1×1
[6]	0.13-μm CMOS	25 - 55	12	15			4	0.64×0.67
[7]	2-μm GaAs	30 - 50	0	3000			<11	1×1
[8]	0.13-μm CMOS	15 - 75	4	>1000	3	0.5	3	0.5×0.35
[9]	0.5-μm GaAs HEMT	30 - 130	-10	>1000	5	0.8	<5	0.8×0.7
[10]	0.1-μm InP HEMT	115 - 135		10000	5	0.2	5	1×2
This work	**GaAs PIN Diode**	**25 - 65**	**-15**	**>500**	**<6**	**<0.9**	**<4**	**0.7×0.8**

modulator can be employed in an IQ modulator for the modern advanced digital modulation schemes and applications.

ACKNOWLEDGMENT

This work was supported in part by the Ministry of Science and Technology (MOST), Taiwan, under Grants MOST 103-2221-E-008-070-MY3, MOST 105-2221-E-008-020-MY3, and MOST 106-2628-E-008-001-MY3, and the Chung-Shan Institute of Science and Technology (CSIST), Taoyuan, Taiwan, under GrantsNCSIST-ACV-V101. The chip was fabricated by the WIN Semiconductors Corp., Taoyuan, Taiwan. The authors thank Shawn Cheng, Taiwan Keysight, Jhongli City, Taiwan, for the measurement helps.

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