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# 10-GHz Band Voltage Controlled Oscillator (VCO) MMIC for Motion Detecting Sensors

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## Abstract
In this work, a voltage controlled oscillator (VCO) monolithic microwave integrated circuit (MMIC) was demonstrated for 10-GHz band motion detecting sensors. The VCO MMIC was fabricated using a 2-μm InGap/GaAs HBT process, and the tuning of the oscillation frequency is achieved by changing the internal capacitance in the HBT, instead of using extra varactor diodes. The implemented VCO MMIC has a micro size of 500 μm × 500 μm, and demonstrates the value of inserting the VCO into a single chip transceiver. The experimental results showed that the frequency tuning characteristic was above 30 MHz, with the excellent output flatness characteristic of ±0.2 dBm over the tuning bandwidth. And, the VCO MMIC exhibited a phase noise characteristic of -92.64 dBc/Hz and -118.28 dBc/Hz at the 100 kHz and 1 MHz offset frequencies from the carrier, respectively. The measured values were consistent with the design values, and exhibited good performance.

**Index Terms**: HBT, MMIC, Motion Detecting Sensor, Oscillator, VCO

## I. INTRODUCTION

The design of microwave circuit technologies is rapidly developing with advances in commercial wireless communications, and is mainly focused on minimizing, integrating, and lightening the weight of the circuits. Recently, a large number of electronic modules have been developed for various purposes, such as vehicle collision prevention systems, human body detection security systems and robot sensors. In particular, studies on motion detection sensors are being actively conducted for vehicle collision prevention systems, for intelligent type automobiles, and for the power control units of future home networks [1, 2].

Microwave radar sensors can relatively easily detect motion, distance and speed without interference from external environments, compared to ultrasonic or infrared sensors. Doppler radar detects objects and distances using the frequency deviation between the transmitted signal and the reflected signal after a radio frequency signal is bounced against an arbitrary object. A voltage controlled oscillator (VCO) that is specifically applicable to microwave radar sensors is required.

In general, the transceiver integrated circuit (IC) does not contain a VCO because of resonant circuit size, so the VCO employs a discrete active device and is implemented separately on the microwave substrate. Then it is connected to the transceiver IC. In order to integrate the VCO including the resonator into single IC, it is necessary to design the VCO as a monolithic microwave integrated circuit (MMIC) using a compound semiconductor process. The VCO MMIC greatly simplifies the circuit configuration of the sensors, facilitates mass production, and improves unit price, size and production efficiency [3–5].

In this work, a VCO MMIC in the 10-GHz band was

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demonstrated for motion detection sensors. The internal nonlinear capacitance variation of the transistor was used to obtain the tuned frequency of the VCO instead of extra varactor diodes. The designed VCO MMIC was fabricated using a 2-µm InGap/GaAs Heterojunction Bipolar Transistor (HBT) process, and the measured electrical characteristics were found to be consistent with the design values, and exhibited good performance.

## II. VCO MMIC DESIGN

The MMIC design process for a 10-GHz band VCO consists of 17 layers, providing thin film resistor, MIM capacitor, spiral inductor, Schottky diode, STK capacitor and backside via-hole including the active device of InGap/GaAs HBT. In this paper, 2-µm InGap/GaAs HBT was used as the active device, and it had a maximum unit current gain frequency (ft) of 35 GHz and a maximum unit power gain frequency (fm) of 45GHz. Also, the maximum current density was 0.20 mA/$\mu m^2$ and the maximum power density was 1.0 mW/$\mu m^2$, respectively. [6]

Fig. 1 illustrates the circuit schematics of the designed VCO with LC resonator in the 10-GHz band. The most common structure used in microwave oscillators is a series feedback structure, which is less likely to shift frequency according to load, and suitable to implement the oscillator. The LC resonant circuit is composed of an inductor of L1 and a capacitor of C1 in series at the base terminal of the HBT, and it determines the oscillating frequency of the VCO. The L1 inductor was designed as a spiral inductor type, and the minimum width and gap of the microstriplines were determined by the process rules provided by AWSC. The C1 capacitor was a MIM capacitor consisting of metal-Si3N4-metal. The thickness of the insulation layer in the MIM capacitor was also determined by the process rules of AWSC. The capacitance was linearly proportional to the top or bottom metal area. The normalized capacitance and the breakdown voltage of the MIM capacitor was 570 pF/$mm^2$ and 60 V, respectively.

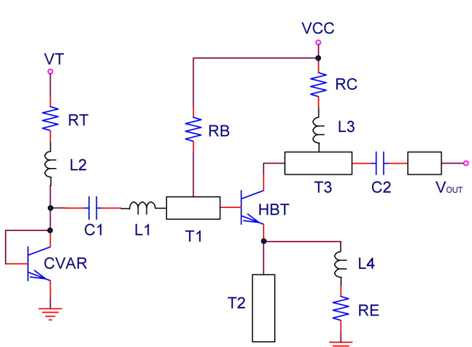


**Fig. 1.** Circuit schematics of the voltage controlled oscillator with LC resonator in the 10-GHz band.

The RC, RB and RE resistors, and the L3 and L4 inductors, were intended to implement the emitter feedback bias circuit of the HBT. The TaN material resistor has a sheet resistance of 50 Ω/□ and temperature coefficient of -100 ppm/K. The T1, T2, and T3 are microstriplines for connecting the LC resonant circuit at the base terminal, for the positive feedback circuit at the emitter terminal and for the output matching circuit at the collector terminal of the HBT, respectively. The RT resistor and the L2 inductor are bias circuits to provide a tuning voltage for a variable capacitor, to tune the oscillating frequency in the VCO. In this paper, the internal capacitance of the active device HBT was used as a variable capacitor instead of extra varactor diodes.

Fig. 2 shows a typical equivalent circuit of the HBT, and the capacitances of the Cbc and Cbe are nonlinear elements affecting the oscillating frequency of the VCO. The capacitance in the Cbc is generated by the width of the depletion layer in a pn junction diode, by the reverse bias voltage between the collector and base terminals. This means it operates as a variable capacitor by tuning the bias voltage at the collector terminal, and is capable of tuning the oscillating

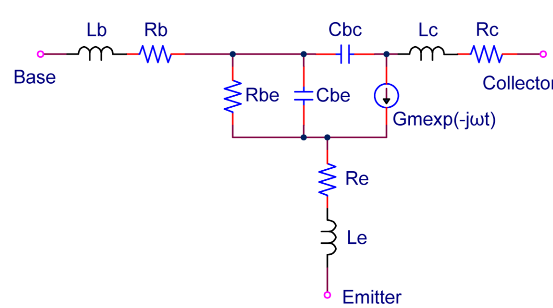


**Fig. 2.** The internal equivalent circuit of the InGap/GaAs heterojunction bipolar transistor.

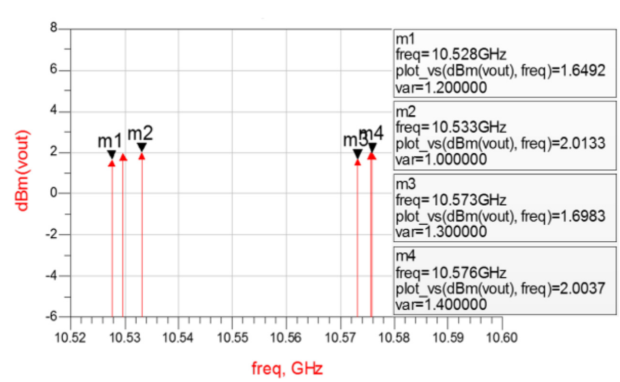


**Fig. 3.** The simulation results for the voltage controlled oscillator using the internal nonlinear capacitance of the Cbe in the HBT instead of an extra varactor diode.

frequency in the VCO.

The capacitance of the Cbe is also an internal nonlinear element that causes a significant change in the oscillating frequency, and can be also operated as a variable capacitor using the base voltage. This means that it can be used to tune the oscillating frequency in the VCO [7, 8].

Fig. 3 shows the simulation results of the VCO. The output power characteristics of 2 dBm are expected under the bias condition of 5 V, 15 mA. The tuning bandwidth of the oscillating frequent produced by the change in control voltage is 48 MHz, and excellent output power flatness, within ±0.2 dBm, is expected.

## III. VCO MMIC MEASUREMENTS

The VCO MMIC based on the 2-μm InGap/Gap HBT process was mounted on a TLY-5 PCB with a permittivity of 2.2, height of 0.51 mm and thickness of 0.5 oz, as provided by the Taconic Company for testing electrical performance. The fabricated VCO MMIC exhibited an oscillating frequency near 10.5 GHz. The LC resonant circuit was located on the base terminal of the transistor. The electrical performance, including the output spectrum and phase noise characteristics of the fabricated MMIC, were measured using a spectrum analyzer by Agilent.

Fig. 4 shows the spectrum measured up to 26.5 GHz of the full span in the spectrum analyzer. The secondary harmonic for the fundamental frequency of 10.58 GHz shows a suppression of about 27 dBc. Fig. 5 shows output power characteristics of 5.59 dBm, including a cable loss of approximately 1.5 dB.

Although the measured central frequency is slightly higher than the target frequency in a free running condition, it is possible to accurately adjust it to 10.525 GHz by fine tuning

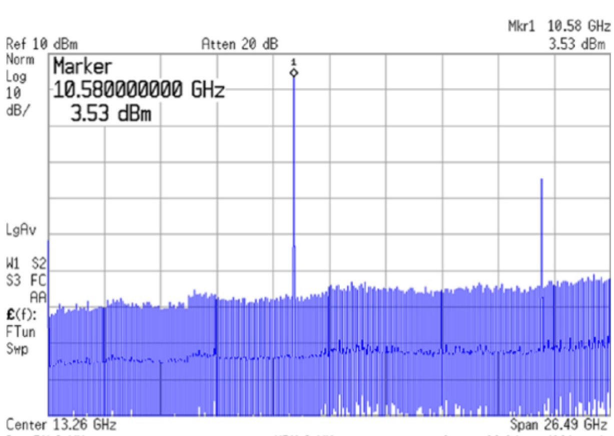


**Fig. 4.** Harmonic suppression characteristics above 27 dBc for the fabricated voltage controlled oscillator MMIC.

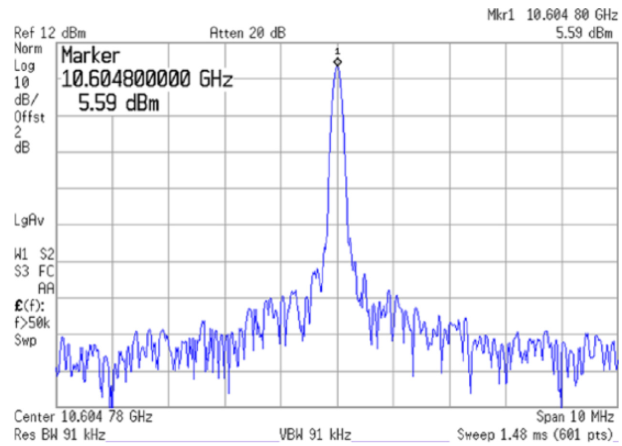


**Fig. 5.** Output power characteristics of 5.59 dBm for the fabricated voltage controlled oscillator MMIC.

the frequency tuning circuit.

The proposed VCO MMIC exhibited phase noise characteristics of -92.64 dBc/Hz and -118.28 dBc/Hz at the 100 kHz and 1 MHz offset frequencies from the carrier, respectively, as shown in Fig. 6. The final phase noise characteristics can be achieved by applying a measured delta value and a measurement calibration value of 2.5 dB - 10*log (1.2 * RBW).

A tuning bandwidth above 30 MHz was achieved using the internal capacitance of the HBT instead of a varactor diode in the frequency tuning circuit, as shown in Fig. 7. The excellent output power flatness performance of below ±0.2 dBm is also shown in Fig. 7. The output power flatness within the tuning bandwidth is a critical parameter determining the constant sensitivity of the sensors. Even though the fabricated VCO MMIC has a narrow bandwidth characteristic, it has enough bandwidth to implement a phase locked oscillator.

Table 1 summarizes the performance of the proposed VCO

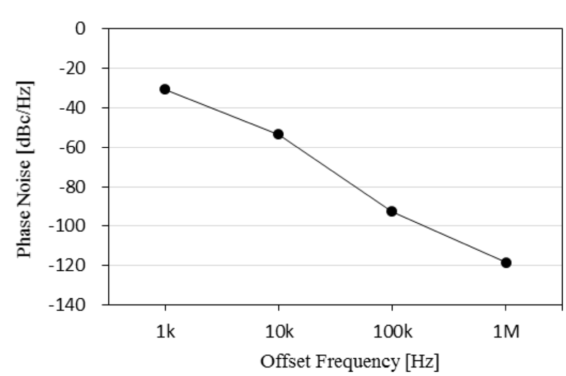


**Fig. 6.** The characteristics of phase noise versus offset frequencies of the fabricated voltage controlled oscillator MMIC.

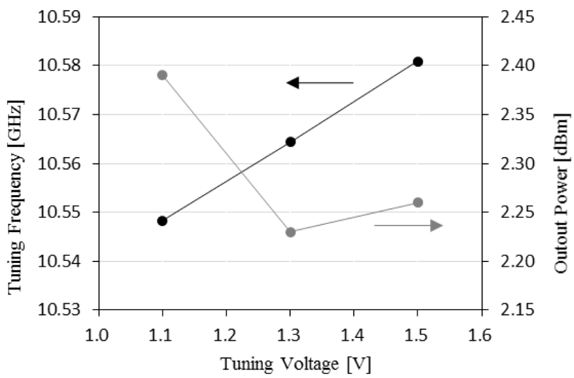


**Fig. 7.** Tuning frequency and output power versus tuning voltage of the fabricated voltage controlled oscillator MMIC.

**Table 1.** Electrical performances of the proposed voltage controlled oscillator MMIC

| Parameter | Requirement | Measurement |
|---|---|---|
| Oscillation frequency (GHz) | 10.525 | 10.6 |
| Output power (dBm) | >2 | 5.59 |
| Harmonic @2fo (dBc) | >25 | >27 |
| Phase noise (dBc/Hz) | | |
| @100 kHz | - | -92.64 |
| @1 MHz | - | -118.28 |
| DC power consumption at 5 V (mA) | <20 | 15 |
| Tuning range (MHz) | - | >30 |
| Flatness in tuning range (dBm) | ±0.2 | < ±0.2 |
| Chip size (μm) | 500 × 500 | 500 × 500 |

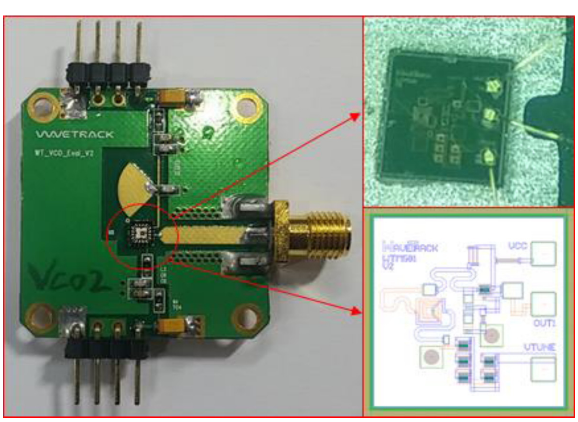


**Fig. 8.** The fabricated voltage controlled oscillator MMIC with the size of 500 μm × 500 μm.

MMIC, and indicates that the measurement results meet the design requirements. Fig. 8 shows a testing board photograph for measurement, and the chip of the VCO MMIC represents a small size of 500 μm × 500 μm.

## IV. CONCLUSION

In this paper, we demonstrated the design of a VCO MMIC without a varactor diode for motion detecting sensors. The proposed device technology relies on a 2-μm InGap/GaAs HBT process. In order to use the internal nonlinear capacitance of the HBT instead of a varactor diode, the base and collector terminals of the HBT are shorted. The obtained tuning frequency of the fabricated VCO MMIC was above 30 MHz, and the measured flatness of the output power showed excellent performance within ±0.2 dBm. The flatness characteristic is the most important parameter determining the sensitivity of motion detecting sensors.

Moreover, the small power consumption of the VCO MMIC was measured to be 5 V and 15 mA or 75 mW. The proposed VCO MMIC exhibited output power characteristics of 5 dBm or higher, with a secondary harmonic suppression of 27 dBc without using band pass filters, and a phase noise characteristics of -92.64 dBc/Hz and -118.28 dBc/Hz at the 100 kHz and 1 MHz offset frequencies from the carrier, respectively.

A conventional VCO is implemented using a discrete active device on a microwave substrate, installed separately from the transceiver IC, and is then connected with the transceiver IC later. Instead, by integrating the VCO into a single IC chip, it makes the design process radically simple, and also makes mass production possible. It can also greatly improve the unit price, size and production efficiency of the sensors.

This VCO MMIC design can be extended to push-push oscillators for higher frequency operation, and is applicable in various commercial and military MMIC designs, such as satellite communications transceivers, wireless LANs and cellular communications systems.

## ACKNOWLEDGMENTS

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