A Very Wide-Tuning Range 5-GHz-band Si Bipolar VCO Using Three-Dimensional MMIC Technology

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ABSTRACT

The first completely integrated, wide-tuning range 5-GHz-band 0.5-μm Si bipolar transistor voltage-controlled oscillator (VCO), based on three-dimensional MMIC technology, is presented. A 33 % frequency tuning range from 4.02 to 5.35 GHz is obtained at the collector voltage of 3 V because the base-emitter resistance of the active transistor works like a varistor with a large ratio. Furthermore, the oscillation frequency is remarkably linear against the controlled base bias. The achieved phase noise is -108 dBc/Hz at 1 MHz offset from the carrier.

INTRODUCTION

A fully-monolithic, low power, low noise and wide tuning range VCO is urgently needed as the local oscillators in microwave and millimeter-wave systems. Silicon bipolar transistors (BJT's) are considered excellent candidates for low phase noise VCO applications because they offer lower 1/f noise than MESFETs and HEMTs. Several monolithic Si VCO's have been reported recently [1]-[3]; however, few papers have demonstrated Si VCO MMIC's for frequencies above 5 GHz due to the losses of the silicon substrate.

Three dimensional MMIC technology [4]-[7] has the potential to solve this problem. This is because three-dimensional MMICs can provide passive circuits that are shielded from the effects of the lossy Si substrate. In addition, three-dimensional MMIC technology can expand the application region of Si devices to higher frequencies by using reactive matching as is possible with GaAs MMICs. This paper uses three-dimensional MMIC technology to create the first monolithic 5-GHz-band 0.5-μm Si bipolar VCO. A fabricated MMIC VCO achieves the very wide tuning range of more than 33 %; the ratio of the base-emitter resistance of the Si BJT can range from 1 to above 8. Furthermore, the oscillation frequency is linear against the base bias within the frequency tuning range. The measured phase noise is -78 dBc/Hz at 100 kHz and -108 dBc/Hz at 1 MHz offset from the carrier; 2-dB better than a recently reported 4-GHz HBT VCO [8] with a 29 % tuning range.

5-GHz-band VCO Design

A circuit schematic of the 5-GHz-band Si BJT VCO is shown in Fig. 1. The VCO uses a series feed back topology with the BJT in common emitter configuration. The Si BJT is fabricated by the 0.3-μm Super Self-Align Technology (SST1C) [9]. Transistor size in the VCO is 0.3 μm x 13.4 μm x 9. A resistance, R_1, of 1 kΩ is inserted between base port and base bias point so that the base current smoothly increases with the base bias. The base is connected to the ground through a 40-Ω, 30-μm-wide, thin film microstrip (TFMS) [10] line short-circuited stub. The collector is connected to the VCO output port via a section of TFMS line for impedance matching.

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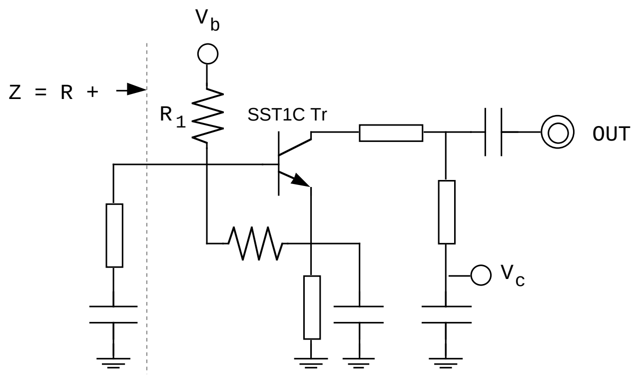

Fig. 1 Circuit schematic of a 5-GHz-band Si BJT VCO.

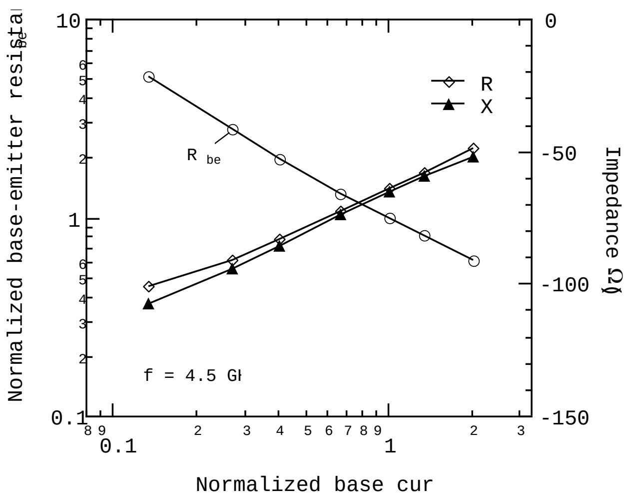

Fig. 2 Base-emitter resistance of SST1C transistor and input impedance at the base in the circuit as a function of base current.

The oscillation frequency of the VCO can be controlled by the base current. The base-emitter resistance, R_{be}, of the SST1C transistor decreases in inverse proportion to the base current as shown in Fig. 2. Thus the base-emitter resistance works like a varistor with a ratio of 1 to more than 8. In Fig. 2, the resistance is normalized to its value at the standard current. We applied the base-emitter resistance to the circuit in Fig. 1 and calculated the input impedance, Z, at the base port at the frequency of 4.5 GHz; the results are shown in Fig. 2. The reactance, X, changes with the base current, indicating that the base-emitter resistance works as variable reactance. That is why the VCO can, by using the SST1C transistor, achieve a wide frequency tuning range without varactors.

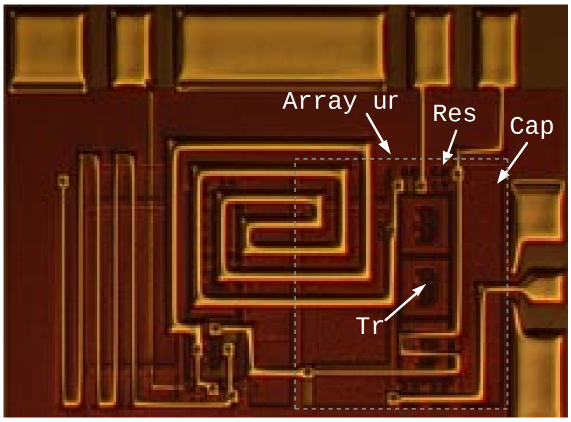

Fig. 3 Microphotograph of the fabricated 5-GHz-band Si BJT VCO (chip size: 1.3 x 0.9 mm^2).

MEASURED RESULTS

A microphotograph of the fabricated 5-GHz-band VCO MMIC chip is shown in Fig. 3. The total chip size, prototype design, is 1.3 x 0.9 mm^2, however some of this area is consumed by unnecessary transistors, capacitors, ground and RF probe pad because the VCO was manufactured on a masterslice Si substrate [11],[5]. The integrated VCO can be optimized to consume an area of less than 0.8 x 0.6 mm^2. The transistor's electrode and MIM capacitance bottom electrodes are connected to TFMS lines using via-holes.

Figure 4 shows a typical measured output spectrum of the 5 GHz-band VCO. At 5.075 GHz, an RF power of 5.4 dBm is obtained at the collector; the base biases were V_c = 2 V, V_b = 2.3 V, I_c = 54.94 mA and I_b = 2.10 mA. The oscillation frequency and output power as a function of base bias are plotted in Fig. 5. The VCO achieves a very wide frequency tuning range from 4.00 to 5.21 GHz with output powers ranging from -0.3 to 6.3 dBm at the collector bias of 2 V. In addition, the linearity of oscillation frequency versus the controlled base bias is excellent within the tuning range. Figure 6 shows the tuning range versus base bias, V_b, for three different collector bias values. The collector bias of the VCO enhances the frequency tuning range. At V_c = 3.0 V, a 33 % tuning range from 4.02 to

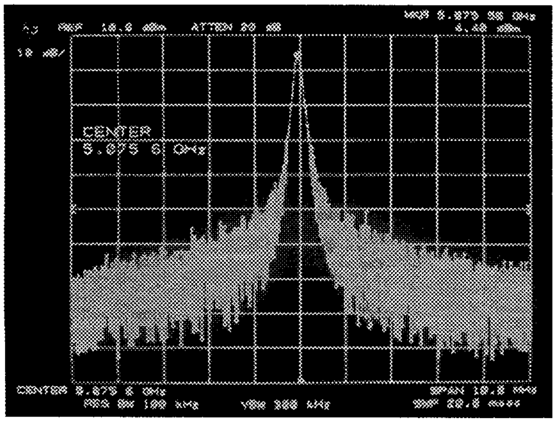

Fig. 4 Output spectrum of the 5-GHz-band Si BJT VCO at $V_c = 2.0$ V and $V_b = 2.4$ V.

5.35 GHz is obtained; the output power ranges from 2.3 to 8.5 dBm. Even at the low dc bias voltage of V_c = 1V, the VCO achieves a 20 % tuning range. The frequency sensitivity of 820 MHz/V is obtained at V_c = 1V.

Figure 7 shows the phase noise as a function of the offset frequency from the center frequency. The phase noise of the VCO was directly measured using an HP8566B spectrum analyzer. At V_b = 2.3 V, the phase noise is -78 dBc/Hz and -108 dBc/Hz at offset frequencies of 100 kHz and 1 MHz, respectively. Within the frequency tuning range, phase noise as low as -102 dBc at 1 MHz offset can be obtained as shown in Fig. 7.

CONCLUSION

The first prototype three-dimensional 5-GHz-band VCO MMIC has been demonstrated by utilizing 0.5-µm Si bipolar transistor technology. The fabricated VCO offers a very wide tuning range (33 %) and highly linear oscillation frequency. The achieved phase noise is as low as -102 dBc/Hz at 1 MHz offset from the carrier within the frequency tuning range. Measured results show that three-dimensional Si VCO MMICs can be developed that yield frequencies above 5 GHz. Furthermore, the three-dimensional Si MMIC is suitable for

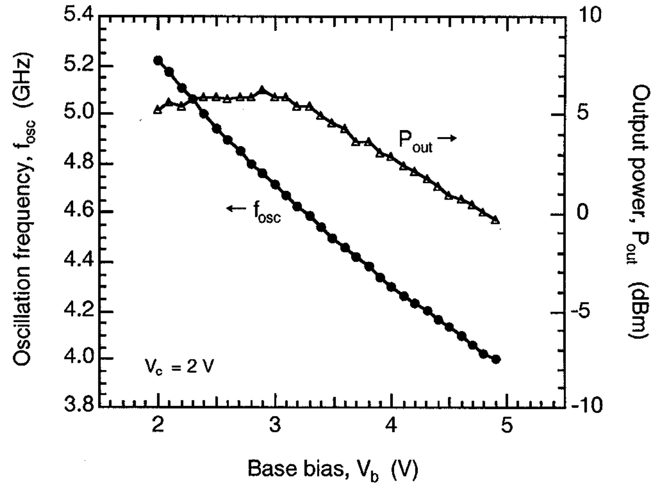

Fig. 5 Oscillation frequency and output power of the VCO as a function of the base bias, V_b.

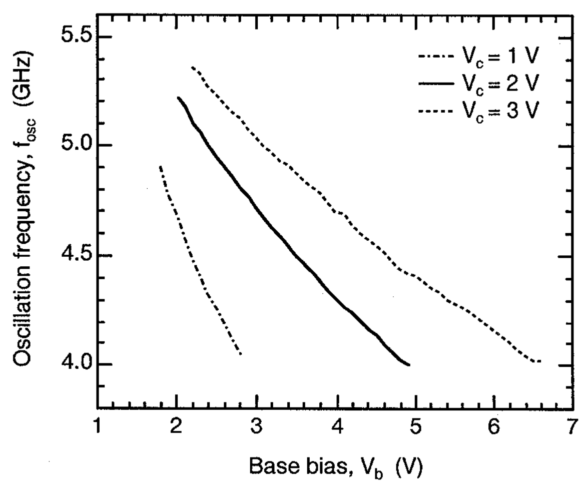

Fig. 6 Frequency tuning range versus the collector bias, V_c.

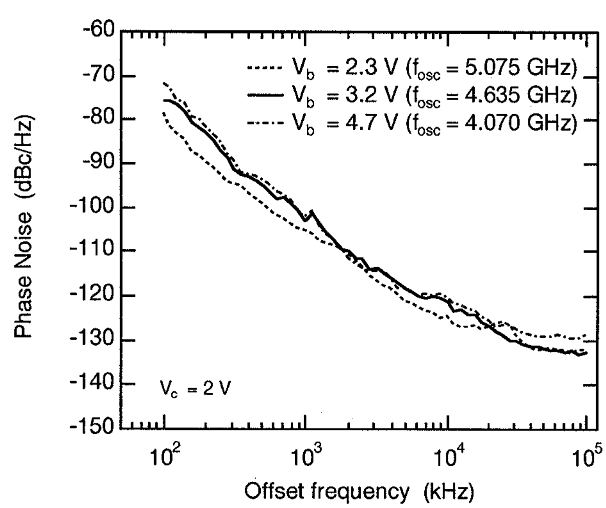

Fig. 7 Phase noise performance of the 5-GHz-band VCO.

realizing lower-cost, small chips, and high density integrated circuit applications up to 30 GHz because Si BJT's have demonstrated that they can achieve f_{max} values of 70 GHz [12].

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