Low Phase Noise Ka-Band VCOs using InGaP/GaAs HBTs and Coplanar Waveguide

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ABSTRACT
Ka-band voltage controlled oscillators (VCOs) have been designed using InGaP/GaAs HBT technology. The best measured VCO shows a phase noise of -95 dBc/Hz at 100 kHz offset and -112 dBc/Hz at 1 MHz offset, delivering 5.3 dBm output power at 40.8 GHz. Variations of circuit topology and resonator type were fabricated to evaluate their contribution to phase noise and tuning range.

I. INTRODUCTION

InGaP/GaAs HBTs have shown lower 1/f baseband noise than HEMT or AlGaAs/GaAs HBT devices [1], making them a choice technology for low phase noise monolithic oscillators. Ka-band oscillators can easily be doubled for use in W-band automotive collision avoidance radar systems or used as sources for point-to-point links. We have designed, fabricated, and tested Ka-band VCOs, comparing output power, tuning range, and phase noise to those reported in recent literature [2-5]. Two circuit topologies were designed, each with three variations of a monolithic resonator. This assessment of the resonator aims to understand design tradeoffs for its use in millimeter wave VCO design.

II. DEVICE FABRICATION AND CIRCUIT DESIGN

The HBT structure and fabrication process has previously been reported. [6] The device profile is shown in Figure 1. Typical device performance has an f_t and f_{max} of 66 GHz and 109 GHz respectively, for a 3x10 um^2 area device biased at Ic=11mA and Vce=2V. Common-base (CB) and common-emitter (CE) topologies were designed (Figure 2-5). Coplanar pads are used to measure the output power and apply the tuning voltage. A 2x5 um^2 emitter area device was used as a current source to pull 10mA through the 3x10 um^2 device at a 3V collector bias.

The resonator circuit incorporates a reverse-biased diode, which is either a 320 um^2 active area base-collector diode (BC) or a 150 um^2 active area base-emitter diode (BE). Another resonator is made, shorting the transmission line stub where the varactor would normally be located (SHORT). This resonator will be used to evaluate the varactor contribution to phase noise.

The initial oscillator design was performed using the following small-signal equations:

$$|\Gamma_r|+|\Gamma_d|>1$$

$$\angle(\Gamma_r)+\angle(\Gamma_d)=0$$

Γ_r and Γ_d represent the reflection coefficient looking into the resonator and the device, respectively. Shorted stubs are placed at the emitter (base for CB) to maximize Γ_d at the design frequency. The resonator is then adjusted to give a phase matching condition at the design frequency.

The BC circuit was designed to be sensitive to the varactor impedance, while the BE circuit was designed such that the resonator would present the circuit with a relatively constant impedance with tuning voltage. The purpose of these two different designs was to compare the phase noise of a VCO with a wide tuning range versus one with a narrow tuning range.

Accurate large signal models were developed for use in harmonic balance and time-domain simulations to predict output power and oscillation frequency. CPW modeling was done to verify passive components used in the design.

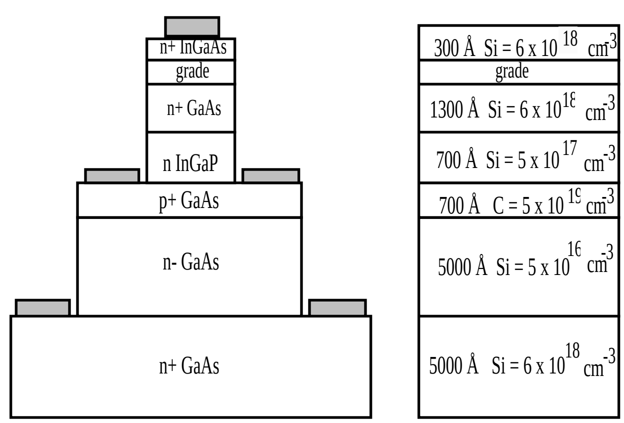

Fig 1. InGaP/GaAs HBT device structure

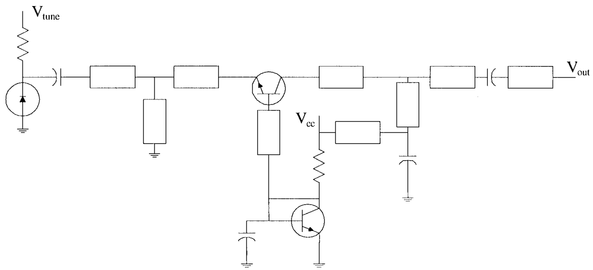

Fig. 2. Common base design

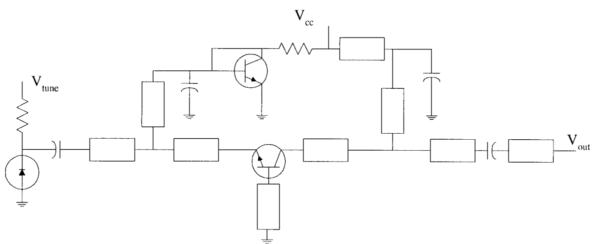

Figure 3: Common emitter design

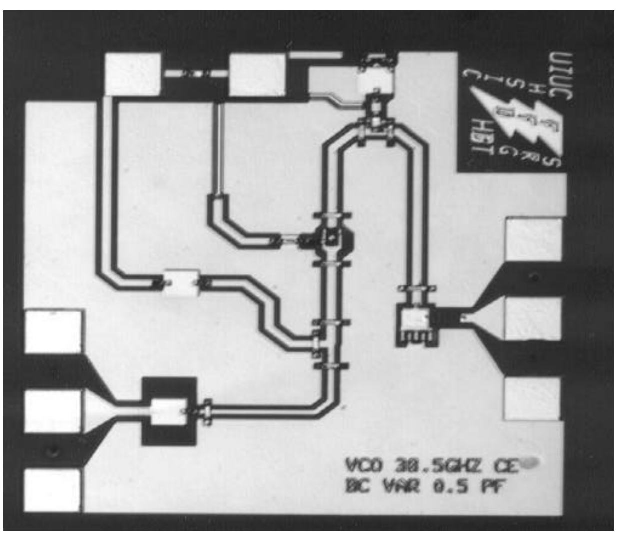

Fig. 4. Photograph of Common Emitter Design

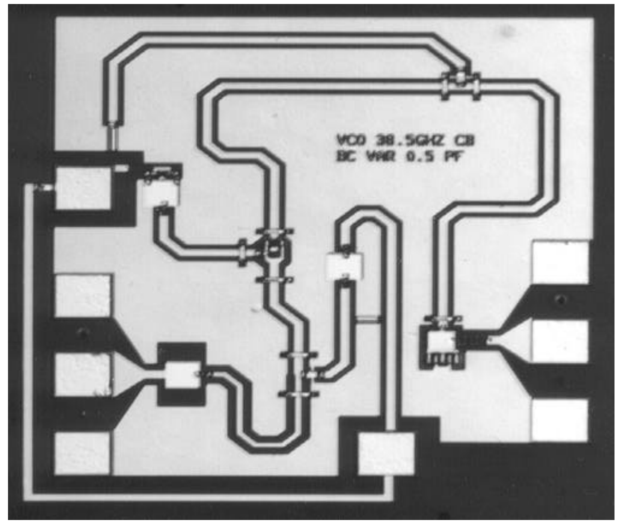

Fig. 5: Photograph of common base design

III. RESULTS AND DISCUSSION

The output power, center frequency, and phase noise were measured for each VCO with the aid of an HP 8565E Spectrum Analyzer, while the tuning voltage was swept from -1 to +1 volts. A 3V battery was used to reduce power supply noise. The cable from the probe station to the spectrum analyzer had a loss of -6.1 dB at 38 GHz, which was calibrated out of the measurement. Results are shown in Table I, along with those from the literature [2-5]. The circuits are designated by their topology and varactor type as discussed above.

Figure 6 shows the measured output spectrum for the CE/BC circuit, using a resolution bandwidth of 1 kHz. The power level for a given offset frequency was estimated by taking a mean of the maximum and minimum levels on the "skirt" in Figure 6. A phase noise estimate is then obtained, accounting for the resolution bandwidth of the spectrum analyzer [7]:

$$L(f_{offset})=P(f_{center})-P(f_{offset})-10Log(RBW)$$

A plot showing the tuning characteristic of the CB/BC circuit is shown in Figure 7. Over a 2V sweep in tuning voltage, the center frequency ranged from 36.4 GHz to 38.0 GHz, with a variation in output power of 0.7 dBm.

Both CE and CB circuits had output power greater than those from [2-5]. CB/BC had less tuning range than the circuit from [1], with comparable phase noise. The VCO from [2] had somewhat better phase noise than CB/BC, with less tuning range. Both phase noise and tuning range was not reported in circuits from [4]. The efficiency of the CB circuits was 4%.

The CE designs were insensitive to tuning voltage, but as a result showed excellent phase noise. The BC diode exhibited a greater tuning ratio than the BE diode for both CE and CB circuits, but did not show a significant difference in phase noise contribution. The magnitude of the varactor diode contribution to the phase noise to the CB circuit can be seen in CB/SHORT, which has 13 dBc/Hz less phase noise than CB/BC at 100 kHz offset. In the CE circuit, the phase noise was constant for all three designs, as expected.

The overall phase noise of these VCOs can be attributed to the following:

(1) Intrinsic baseband noise of the device.
(2) The losses (Q) of the varactor and passive elements in the circuit.
(3) The mechanism in which these are up-converted to the oscillation frequency.

The first component can be measured, and is useful in evaluating the device at a given bias to other bias points and other devices. However, it should be understood that the device is in a non-oscillatory condition in a low frequency noise measurement. The Q of the diode and passive elements can also be estimated. The mechanism in which baseband noise is up-converted is difficult to model and has been the subject of numerous publications.

To analyze the mechanism in which baseband noise is up-converted, the oscillator can be described as a element with loop gain and feedback having $2\pi n$ phase delay [8] or a negative resistance device phase matched to a passive resonator [9]. Both methods describe the sensitivity of the impedances of the device and resonator with regard to bias point. These impedances shift due to the large signal variation of current through both components. Other methods use perturbation theory to evaluate the schochastic and deterministic behavior of the oscillator [10].

From these data shown here, a tradeoff between phase noise and tuning range for VCOs is apparent. The contribution to phase noise from the resonator for a certain topology is dominated by the sensitivity of its impedance with respect to tuning voltage. Since this sensitivity determines the tuning range of the VCO, an improvement in tuning range will result in a degradation in phase noise. These limitations can be used in future VCO design to meet a desired performance specification.

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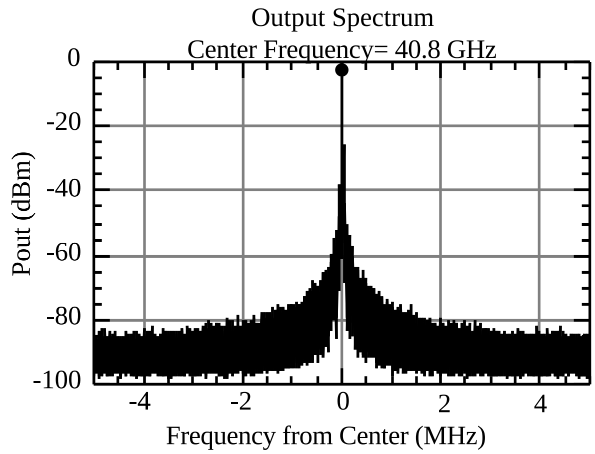

Fig. 6. Spectral output of CE/BC VCO

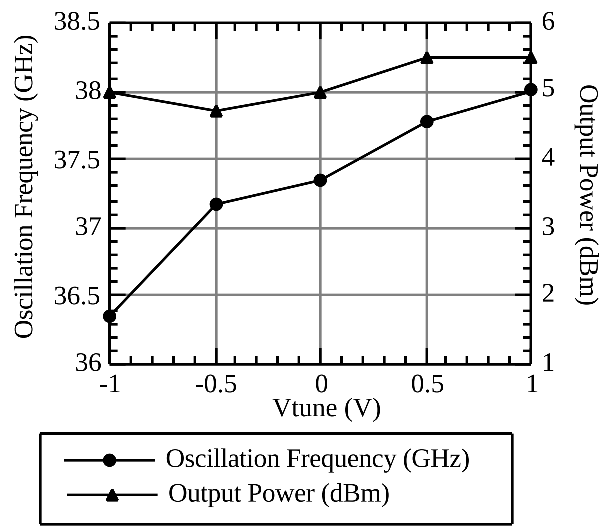

Fig. 7. : Tuning characteristic for CB/BC VCO

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Table I
Performance Specifications for Ka-band HBT VCOs

Circuit Name	Center Frequency	Tuning Range	Phase Noise 100 kHz Offset	Phase Noise 1 MHz Offset	Output Power
	(GHz)	(GHz)	(1/Hz)	(1/Hz)	(dBm)
CB/BC	37.3	2.34	-64 dBc	-101 dBc	5.1
CB/BE	36.7	.58	-69 dBc	-97 dBc	5.7
CB/SHORT	37.4	N/A	-77 dBc	-108 dBc	3.6
CE/BC	40.8	.012	-95 dBc	-113 dBc	5.3
CE/BE	40.9	.001	-91 dBc	-115 dBc	4.7
CE/SHORT	40.9	N/A	-92 dBc	-112 dBc	3.6
Thomson-CSF [2]	28.5	5.5	-65 dBc	-----	-5 to -9
Bell Labs† [3]	33.5	1.2	-79 dBc	-107 dBc	-1.43
Daimler-Benz [4]	35	-----	-80 dBc	-107 dBc	3.0
Daimler-Benz [4]	37	1.1	-----	-----	2.3
Daimler-Benz [4]	40	1.1	-----	-----	1.0
Ferdinand-Braun†† [5]	38.25	-----	-55 dBc	-----	2.0

† InGaAs/InP based

†† SiGe based