A FAMILY OF MONOLITHIC INDUCTOR-VARACTOR SiGe-HBT VCOs FOR 20GHz TO 30GHz LMDS AND FIBER-OPTIC RECEIVER APPLICATIONS

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ABSTRACT

A family of low-phase noise, monolithic inductor-varactor SiGe-HBT VCOs in the 20GHz to 30GHz band was fabricated in a production SiGe technology. The unbuffered differential VCOs have 10-15% tuning range and deliver -3...-2dBm directly into each of the 50Ω loads, and 0dBm differentially. Phase noise is as low as -101dBc/Hz at 1MHz from the 20GHz carrier and -87dBc/Hz at 100KHz from the 26GHz carrier. The VCO core draws 10mA from a 5V supply.

INTRODUCTION

SiGe HBT technology has become a leading contender for highly integrated wireless and fiber-optic systems in the 5 to 10GHz range [1,2]. This paper proposes to demonstrate that commercially available SiGe HBT technology is ready, in terms of both active and passive components, to take on applications in the 20GHz through 50GHz range. While oscillators above 20GHz have been attempted before in either SiGe [3,4] or Si [5] technologies, these were generally single-transistor architectures with coplanar [4] or microstrip [3] resonators, resulting in large area, and having either a fixed frequency [4,5] or poor phase noise [3-5] and output power performance [3,5]. Monolithic SiGe VCOs are ideal for receiver PLL applications [2] due to their potential low phase noise, low-cost and very high yield. One critical condition for the integration of a monolithic VCO into a larger single-chip system is that its tuning range be wide enough (typically >10%) to cover varactor diode process variations. This paper describes a family of monolithic 20-30GHz varactor-tuned LC oscillators which have been scaled up from previous designs at 1.5GHz [6] and 4GHz [1] that concomitantly achieve low-phase noise, high output power and more than 10% tuning range. For the first time, inductors with Q's higher than 12 over the 20 to 50GHz range and with resonant frequencies beyond 50GHz are demonstrated on a silicon substrate.

CIRCUIT DESIGN

The VCO schematic, shown in Fig.1, has a differential varactor-tuned LC Colpitts topology in common-base configuration, with either two inductors L_B, or a single, center-tapped 3-terminal inductor.

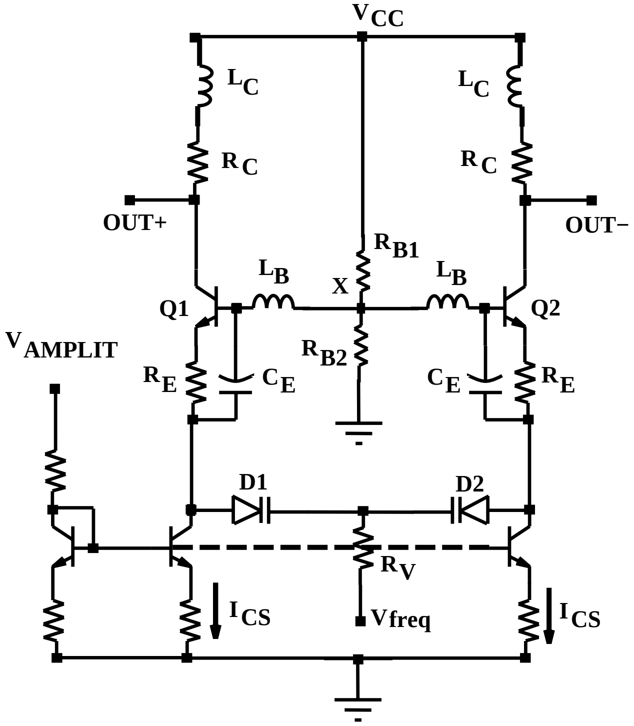

Figure 1: VCO schematic.

The fundamental frequency signal is collected at the differential outputs OUT+ and OUT-. In addition, as suggested recently for an oscillator with different topology [7], the second harmonic can be extracted directly at node X. Popular Si bipolar or CMOS LC RF oscillators [2,8] rely on cross-coupled differential pairs to generate the negative resistance and, as a result, the output frequency is limited by the delay around the feedback loop. Furthermore the resonator tank is directly loaded by the buffer stage, thus increasing the noise current in the tank. The present design builds on the higher speed advantage of classical negative-resistance microwave oscillators [3,4] and uses a single-transistor half-circuit topology where the tank circuit, located in the base of the transistor, is readily isolated from the collector load. The

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architecture ensures the lowest possible noise by minimizing the number of transistors in the circuit. The negative resistance is the result of the capacitive loading (due to the varactor) of the emitter. The tank impedance, shown in Fig.2, is maximized by designing the largest possible inductor value that still has a Q higher than 10 at the desired frequency. This concurrently ensures the smallest possible bias current for a desired tank voltage. Inductors L_C are added to the 50Ω resistors in the collector in order to tune out transistor capacitance at the oscillation frequency and improve the output return loss. The transistor that generates the negative resistance also buffers the tank from the load. Any additional buffer attached to the VCO core is separated from the tank, therefore reducing its impact on the VCO phase noise. Given this optimal low-noise topology, phase noise was also of prime concern in the design of the circuit components, and three steps were undertaken to minimize it. First, the Q of the resonant tank, consisting of inductor L_B, varactor D_1 and capacitor C_E, was maximized. The Q of the tank inductor is 12 to 15 at the oscillation frequency, even in the case of the 30GHz designs, as illustrated in Fig 3. The tank Q is typically 8 for a 4GHz version [1], 4 for the 20GHz, 24GHz and 26GHz designs, and about 2 for the 30GHz design. In the 4GHz design, the Q of the tank is limited by that of the inductor, whereas at 20GHz and above, the tank Q is limited by the Q of the varactor diode, Fig.4. Second, the transistor was biased at the minimum noise current density at the particular oscillation frequency [9] and its emitter size was adjusted as in an LNA design [9] to provide optimal noise matching to the tank impedance. Third, resistive emitter degeneration R_E is employed to suppress harmonics and to reduce up(down) converted noise. The amount of emitter degeneration was optimized so as to permit bias current control of the amount of negative resistance required to achieve oscillation and to limit the associated thermal noise.

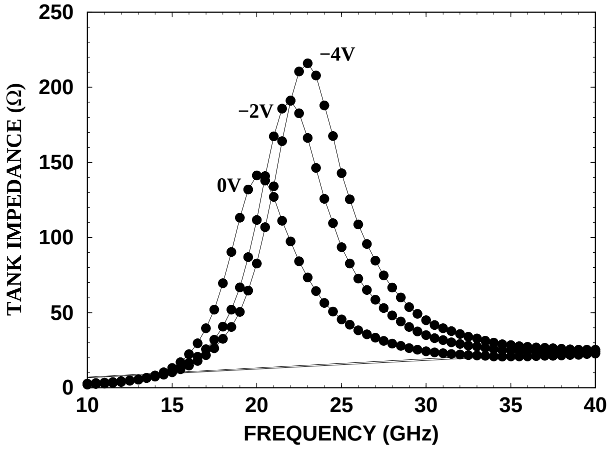

Figure 2: Measured L-C-varactor resonant tank impedance for 3 values of the varactor control voltage.

MEASURED PERFORMANCE

The VCOs were fabricated in a preliminary version of Nortel Networks' commercial SiGe1 technology featuring transistors with f_{MAX} values of 75GHz at V_{CE}=1.5V, J_C=1mA/μm^2 and BV_{CE0}=3.3V. The technology also features trench isolation, varactor and Schottky diodes, as well as inductors using the 3μm thick AlCu top metal layer. Rectangular, octagonal and three-terminal inductors were designed for the 20-50GHz range. Typical measured inductance values are 150 to 450pH and Q's are 12 to 15, irrespective of the geometry, Fig. 3. In the case of the three-terminal inductor, the differential inductance is 520pH and the differential Q is 14, the latter being about 50% higher than the half-circuit Q. These inductor Q's are slightly higher than those achieved for scaled inductor values in a similar technology at lower frequencies [1]. The measured varactor diode Q vs. frequency characteristics are shown in Fig.4 for control voltages between 0 and -5V. The Q remains higher than 4 up to 50GHz even at a varactor diode voltage of 0V.

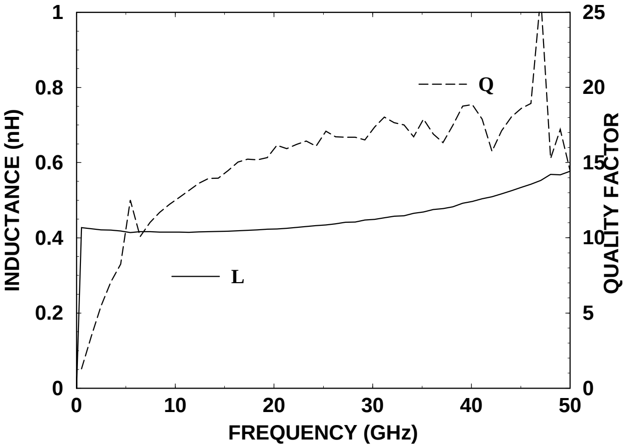

Figure 3: Inductance and Q of a 425pH octagonal inductor.

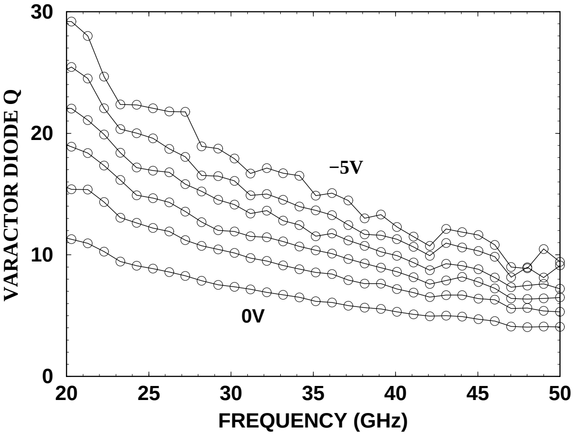

Figure 4: Q of a 2x1.6x20μm^2 varactor diode for control voltages. between 0V and -5V.

Fig.5 shows the measured tuning characteristics of 4 VCOs covering most of the 20-30GHz band. In all cases, as in [1], the tuning range is 12-15%, sufficient to cover more than 20% of process variation in the varactor capacitance. The broadband and narrowband spectra measured at a single-ended output of the 20GHz VCO are shown in Figs.6a and 6b, respectively. The losses in the cables of the test set-up, typically 2-3dB in the 20-30GHz band, have not been calibrated out in the spectrum analyzer reading. The second harmonic is 26dB below the fundamental. Simulations indicate that if the signal is extracted differentially the second harmonic is more than 40 dB below the fundamental. The measured phase noise characteristics of the 20GHz and 26GHz VCOs, the latter with a three-terminal inductor tank, are shown in Figs. 7a and 7b, respectively. To the best of the authors' knowledge, the values of -101dBc/Hz at 1MHz from the 20GHz carrier and -87dBc/Hz at 100KHz from the 26GHz carrier are records for monolithic Si or SiGe VCOs in this frequency range. They scale closely from the value of -100dBc/Hz at 100KHz and -120dBc/Hz at 1MHz, respectively, that we have reported recently for a 4GHz VCO[1].

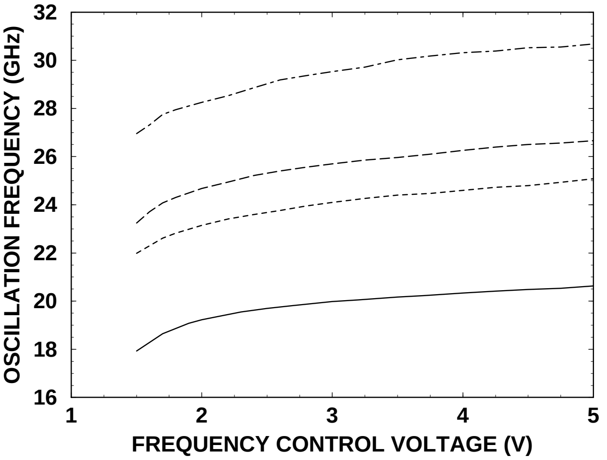

Figure 5: Tuning range of 20GHz, 24GHz, 26GHz and 30GHz VCOs.

The VCO core operates from a 5V supply, drawing 10mA. An additional 5mA current is drawn by the bias current mirror also used for controlling the oscillation amplitude. Wide, low-inductance top metal lines over first metal planes are used to provide bias supply. Appropriate resonance-free MIM-capacitor based de-coupling is employed on the supply and control lines.The chip area is 0.4mmx1mm, Fig. 8, including the pads, the isolation region around the VCO core, and on-chip bias de-coupling capacitors. All VCOs worked at first pass with performance within 5% of nominal simulation. The measurements reported here have been performed on wafer using multiple wedge probes.

SUMMARY

A robust, low-noise differential VCO topology has been scaled up from 1.5GHz and 4GHz to create a family of low-phase noise SiGe HBT VCOs in the 20 to 30GHz range. This was made possible by the design and fabrication of the first inductors on a Si substrate with Q's higher than 12 in the 20 to 50GHz band. The results also indicate that, with good resonator tank design, fundamental VCOs at 20GHz can readily compete in terms of performance, cost and simplicity with solutions that involve multiplication. Possible applications include integrated PLL circuits for LMDS and for 20Gb/s and 40Gb/s fiber-optic receivers.

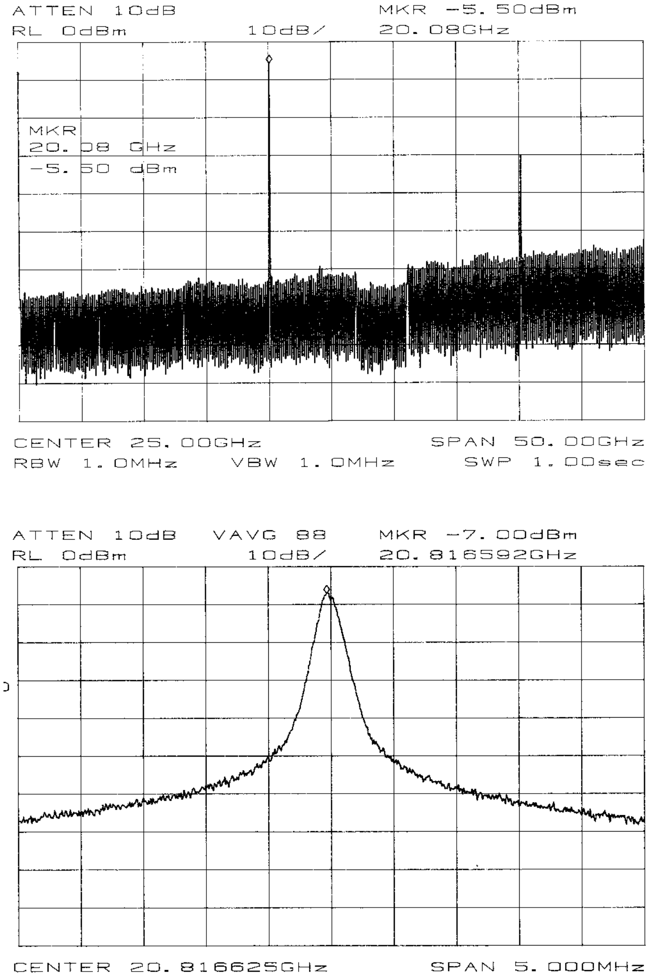

Figure 6: 20GHz VCO (a) broadband and (b) narrowband spectra measured at a single-ended output. Cable losses have not been calibrated out of the power reading.

ACKNOWLEDGEMENTS

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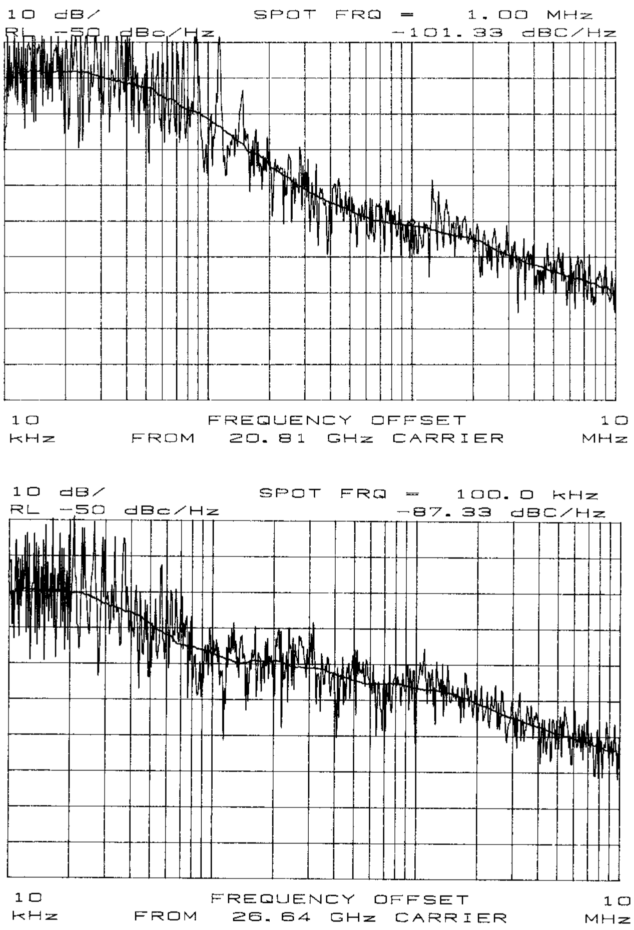

Figure 7: Phase noise of (a) 20GHz and (b) 26GHz VCOs measured at a single-ended output.

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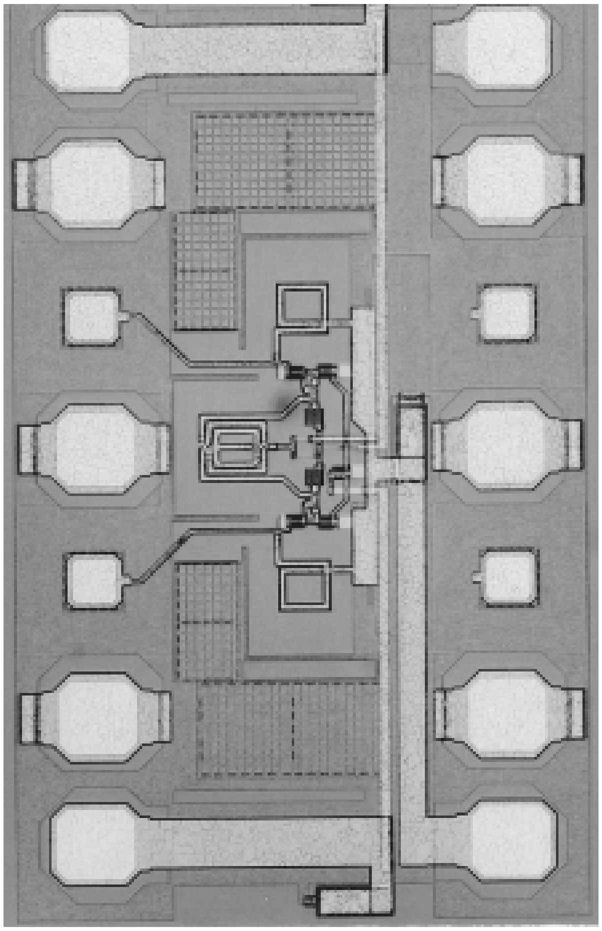

Figure 8 Layout of 26GHz VCO with three-terminal inductor.