A COMPACT Ka-BAND MMIC VOLTAGE CONTROLLED OSCILLATOR: COMPARISON OF MESFET AND HEMT IMPLEMENTATIONS

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ABSTRACT

A novel, compact Ka-band MMIC voltage controlled oscillator (VCO) has been designed, fabricated, and tested. The VCO design is a "ring" configuration using two FETs with two isolated control terminals which provides increased tuning bandwidth. This design uses an active feedback topology resulting in greater device size for higher output power and circuit Q. This VCO was fabricated with both 0.25um gate length MESFET and HEMT processes designed to have similar RF equivalent circuits by engineering the device doping. To our knowledge, this is the first report of a monolithic millimeter-wave HEMT VCO. The measured MESFET VCO demonstrated a tuning bandwidth of 740MHz centered at 35GHz and output power of 8.3 dBm. Chip size is 30 x 34 mils. The measured HEMT VCO tuning bandwidth is greater, but phase noise is worse than the MESFET implementation. This limits HEMTs in the application of low phase noise millimeter wave oscillators.

INTRODUCTION

Millimeter-wave FET-based MMICs are replacing hybrid circuit functions, such as amplification, mixing and switching. However, there are very few reports of millimeter-wave monolithic FET based VCO and to our knowledge, no reports of millimeter-wave HEMT-based VCOs. We have developed a simple-to-integrate, compact and flexible millimeter-wave MMIC VCO design suitable for co-integration with either MESFET or HEMT amplifier or mixer circuits.

There have been only a few [1,2,3] attempts at monolithic millimeter-wave GaAs VCO designs [1] and only [2,3] employ the active elements (MESFET) as tuning elements. Varactor diode tuning elements [1] have been added to a standard 0.25um gate-length MESFET fabrication sequence; however, the increased process complexity required (MeV ion implantation) is difficult, especially ensuring compatibility with HEMTs. The conventional FET-only grounded-gate oscillator circuit architecture has no compatibility problems, but exhibits a tuning range and circuit Q performance limitation tradeoff primarily because of the diminished gain and higher series resistance of the single FET active element as the gate bias approaches pinchoff.

MMIC VCO DESIGN

This novel Ka-band voltage controlled oscillator circuit is a common-source oscillator, employing two FETs in a "ring" configuration with each FET gate AC connected to the other FET drain. Figure 1 illustrates a circuit schematic showing the two FETs, inductive resonator and an embedded bias network. The series drain resistors prevent low frequency resonances established by the drain bond wires and the circuit capacitance.

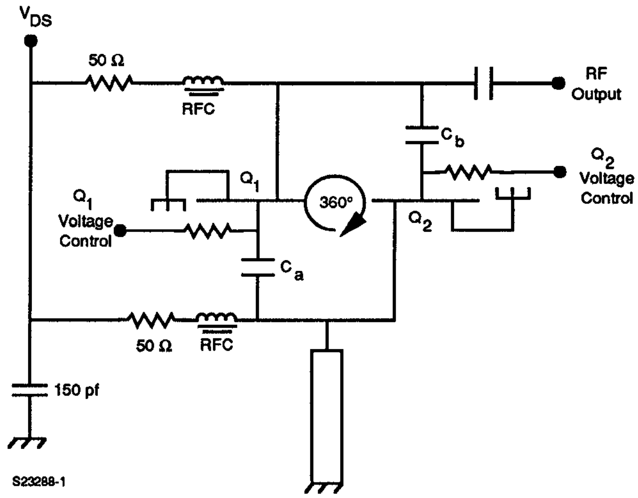

Figure 1. Ring VCO Circuit Schematic

The two FETs provide "active feedback" over a broadband because each gate-drain junction provides a 180 degree phase shift which is virtually independent of frequency. As a result, the "ring" oscillator configuration exhibits a broadband negative resistance over a decade in frequency for the 0.25um gate length MESFET and HEMT active devices employed. This circuit is an adaptation of R. L. Cravens' work on microwave oscillators [3], where a similar circuit was used to create a negative resistance over a broad band. We chose to use the gate-source (Cgs) capacitance change as a function of gate voltage as the tuning element. The capacitance formed by the combination of the input capacitance of one FET in the ring configuration and the output capacitance of the second FET is resonated with a shorted inductive microstrip line. This makes a very compact, easily integrated MMIC. This is similar to the shorted gate oscillator concept, but with some very important improvements.

Two isolated voltage control terminals exist; one at the gate of Q1 and the second at the gate of Q2, an immediate improvement of twice the tuning bandwidth over the conventional shorted gate oscillator method. In addition, the active feedback of Q2 sustains negative resistance to device pinch-off, thus further increasing the tuning bandwidth.

A second advantage — lower phase noise — is also obtainable with this circuit. Figure 2 illustrates the oscillators equivalent circuit. To more easily understand the oscillator operation, assume Q1 device gate width is much larger than Q2.
Then $C_{gs1} > C_{gs2}$ and $C_{gs1} \gg C_{ds2}$.

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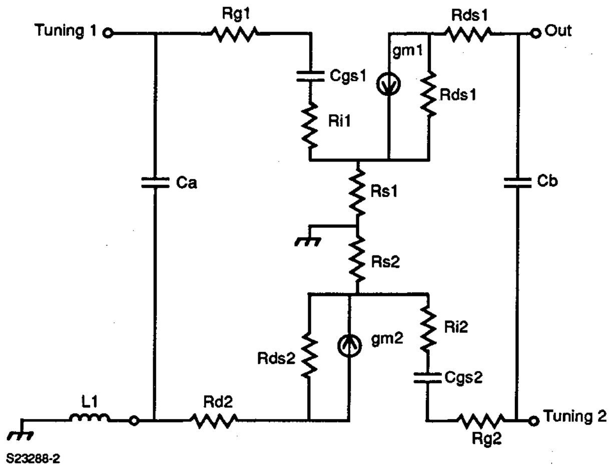
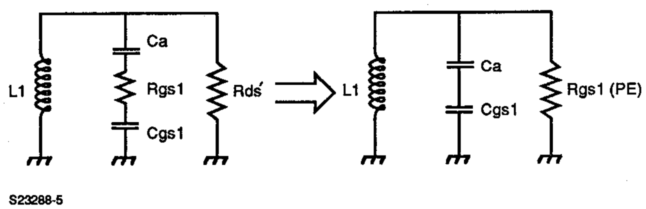


Figure 2. Ring VCO Equivalent Circuit

If we let Rgs1=Rg1+Ri1+Rs1 and Rdś1=Rd2+Rds2
then we can further reduce the resonant circuit as follows:



Since the gate width of Q2 is much less than Q1, Rdś>>Rgs1(parallel equivalent) Therefore Rdś has little affect on the circuit Q. By selecting the series gate DC blocking capacitor Ca = Cgs1 then from equation (1) circuit Q is improved by a factor of two.

$$Q = \frac{X}{R} = \frac{1}{Rgs_1\omega\left(\frac{Ca \cdot Cgs1}{Ca + Cgs1}\right)}$$

$$= \frac{2}{Rgs_1\omega\ Cgs} \quad \text{when Ca = Cgs1} \qquad (1)$$

Using the series combination of Ca and Cgs1 makes explicit the phase-noise/tuning bandwidth tradeoff; a larger Ca/Cgs1 ratio improves tuning bandwidth at the expense of phase noise. A final benefit of this circuit is the high output power capability associated with a large Q1. The output impedance of the ring oscillator circuit is relatively low compared to Zout of the shorted gate oscillator, because one FET of the ring oscillator acts as a buffer. This simplifies the output impedance match and lowers the required drain-source voltage supply in comparison to a single FET common gate design.

Three versions of the Ka-band VCO were designed, using 50, 100, and 150um wide Q1 FETs and 50um Q2 FET. Only the 100um wide FET was RF characterized in detail. Chip size was a very compact 30x34 mils, approximately a factor of four smaller than [1] previous reports.

FABRICATION

The Ka-band VCO was fabricated with both MESFET and HEMT device technologies primarily to allow a circuit phase noise performance comparison. Figure 3 illustrates the small signal equivalent circuit model used for the circuit simulation and design. This model was extracted from fitting on-wafer [S] measurements of a 0.25x100 µm ion-implanted MESFETs and an MBE grown AlGaAs/GaAs HEMTs fabricated using the Honeywell millimeter-wave recess-gate technology. The MESFET and HEMT equivalent circuits demonstrate unity current gain cutoff frequencies of approximately 35 GHz and 55 GHz and F_{max} over 110 GHz and 120 GHz, respectively.

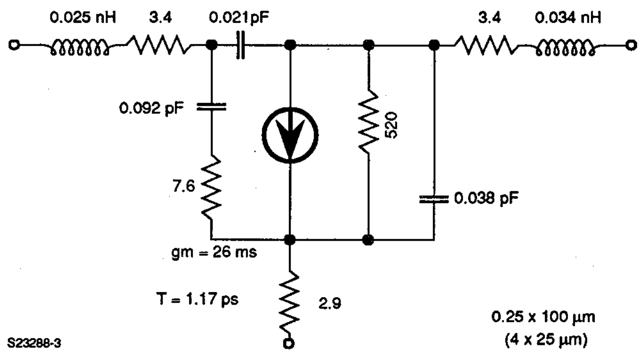


Figure 3. MESFET Equivalent Circuit

The MESFET wafers were ion implanted with Si29 at 50 and 100 KeV at 1e13/cm^2 dose. The HEMT wafers used a conventional 380 A n:AlGaAs layer doped to 2e18/cm^2 with a 500 A heavily doped GaAs cap layer: Fabrication was completely planar. Bulk resistors were used. Ion implanted isolation was followed by ohmic contact formation and electron-beam defined recess-gate formation. Metal-insulator-metal capacitors and FET passivation were formed with 2000 A of chemical vapor-deposited silicon nitride. Transmission lines were plated to 1.6 µm. The wafers were thinned to 100±10 µm and reactively ion-etched through-wafer vias were used. Typical FET parameter uniformity was 10 percent across the 3-inch wafers. Figure 4 illustrates the completed MMIC oscillator.

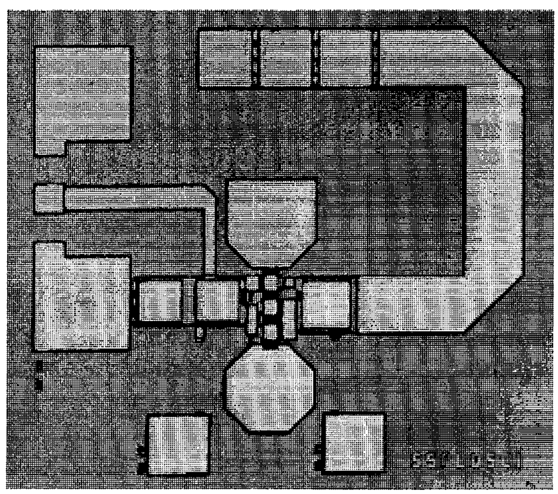


Figure 4. Ka-band MMIC VCO

MEASUREMENTS

The VCOs oscillated at the desired frequency after trimming of the airbridge resonator line shown in Figure 4. Tuning bandwidth of the MESFET design is 740MHz, centered at 35.3GHz. The output power is 8.3+0.3 dBm. Figure 5 illustrates the MESFET VCO output power and frequency versus modulation voltage, where the modulation voltage is applied to the gate of Q1 and the Q2 gate voltage was fixed at -0.5 V. Using both gate controls the tuning bandwidth is greater than 1.2 GHz. FM phase noise (measured as the -3 dB noise equivalent bandwidth) was 200 kHz.

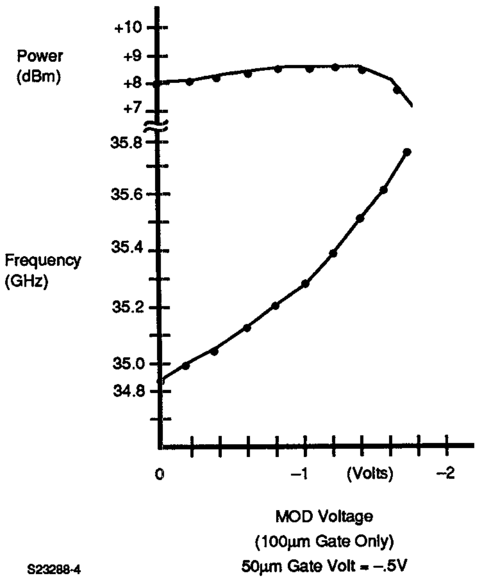


Figure 5. 100µm MESFET Performance

This is state-of-the-art millimeter-wave MMIC VCO performance in terms of power output x tuning range. A 150um shorted gate oscillator (with gate control as tuning element) with similar doping levels produced a tuning bandwidth of 450 MHz and output power of 8 dBm [4], thus demonstrating a 3:1 tuning bandwidth improvement for the "ring" configuration. The shorted gate oscillator exhibited similar phase noise characteristics.

HEMT VCOs of the same "ring" design as the MESFET demonstrated similar performance in terms of center frequency and output power, except for three important parameters:

- Frequency-modulation linearity was superior for the HEMT VCOs.

- Tuning bandwidth was 25 percent greater.

- The -3dB phase noise bandwidth of the HEMT VCO was significantly worse than the MESFET VCO.

Figure 6 illustrates the HEMT VCO output power and frequency vs. modulation voltage. The greater tuning bandwidth and improved linearity are attributed to the lower HEMT gate current near Idss. Typical FM phase noise bandwidths were 600 kHz

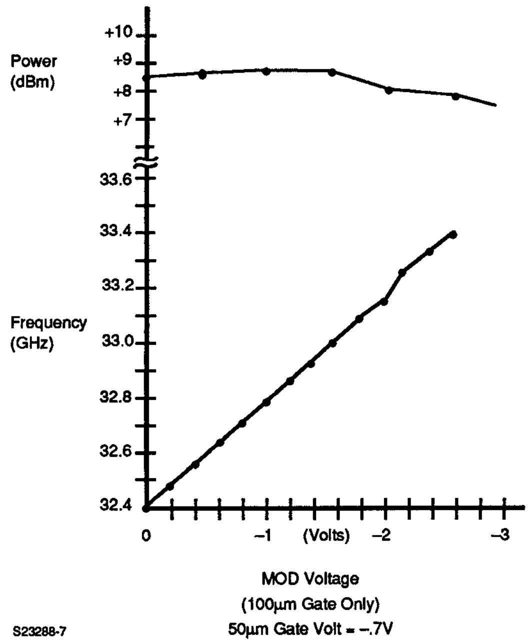


Figure 6. 100µm HEMT VCO Performance

for otherwise identical HEMT VCOs. This important result is the first data of phase noise in millimeter-wave HEMT oscillators and the first comparison of phase noise in ion implanted MESFET and HEMT oscillators.

A final "ring" VCO employing very highly doped MESFET material yielded 1.2 GHz tuning bandwidth and a 60 kHz 3dB noise equivalent bandwidth. This improvement in VCO phase noise confirms previous work [5] suggesting that lower 1/f flicker noise of FETs is accomplished by increasing the doping levels. As a comparison, typical varactor tuned GUNN diode microstrip VCO 3dB noise equivalent bandwidth is 6KHz.

CONCLUSIONS

The "ring" VCO offers improvements over the conventional shorted-gate VCO topology with no apparent degradation in phase noise characteristics.

The preliminary result on the HEMT VCO phase noise is disappointing from an integration viewpoint, since it strongly suggests that the demonstrated high performance of HEMT technology is not translated to the important VCO area.

Circuit Q enhancements of the "ring" VCO coupled with device doping could potentially rival hybrid VCO technology.

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3. J. Geddes, et al, Monolithic GaAs MM-Wave Transceiver Chip Set for FMCW Radar Applications, 1990 GoMAC Conference, pp. 355-358.

4. R. L. Cravens, Development of a Broadband Microwave Oscillator, M.Sc. thesis, University of Wisconsin-Madison 1990.

5. B. Hughes, et al, GaAs FETs with a Flicker-noise Corner Below 1MHz, 1987 IEEE Transactions on Electron Devices, pp 733-741.

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