# OPTIMIZED X & Ku BAND GaAs MMIC VARACTOR TUNED FET OSCILLATORS

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## ABSTRACT

Continuous tuning operation has been achieved in X- and Ku-band monolithic VCOs which operate over an extended temperature range with as much as one octave bandwidth. The use of nonlinear circuit analysis has lead to circuit improvements, including a novel lateral varactor structure realizing better Q.

## INTRODUCTION

Monolithic varactor tuned FET oscillators have shown great promise during this decade.[1-5] In particular, the wide band VCOs reported [4] hold the promise of low cost high volume production replacing hybrid VCOs in current and future systems. However, this promise has been unrealized due to discontinuous tuning characteristics observed in X- and Ku-band MMIC VCOs, a problem that is exacerbated at elevated temperatures.

This paper describes the modeling techniques used to understand and predict the phenomena of frequency hops and holes in X- and Ku-band MMIC VCOs. The insight into circuit behavior resulted in several circuit optimizations, including a unique lateral varactor diode structure compatible with FET devices and uniform ion implantated material. New circuits were fabricated with the optimized devices for both frequency bands. Measured results demonstrating the elimination of discontinuous tuning characteristics are presented for both the X- and Ku-band VCO chips.

## MODELING TECHNIQUES

Two oscillator circuits are treated here; both having the schematic representation shown in Figure 1. The oscillator circuits are tuned by varactors in both the FET gate and source termination networks. The highly nonlinear characteristics of lateral varactor diodes using a standard FET active region is illustrated in Figure 2. Both reactance and resistance are strong functions of voltage, illustrated by the variation of both capacitance and quality factor (Q). A harmonic balance technique was used to model the FET circuit operation. Previous applications of this technique have proven accurate for mixer and amplifier circuits.[6] Power output levels and, more significantly, internal

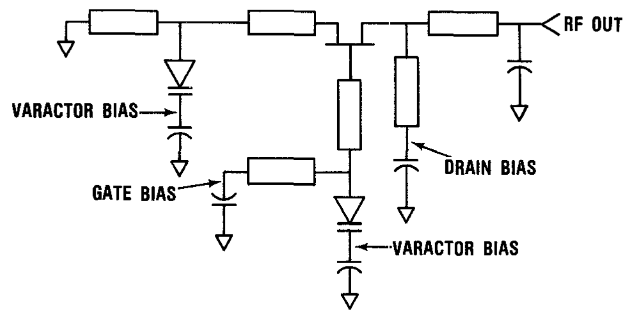


Figure 1. X- and Ku-Band VCO Schematic.

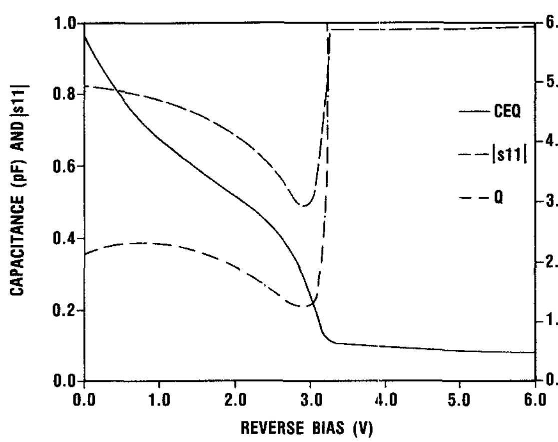


Figure 2. Varactor Characteristics, Nominal Structure.

node voltages were obtained from the nonlinear simulation. Voltage levels across the varactors were typically several volts peak. As a result, loop gain expansion or compression occurs with increasing signal level, depending on the DC bias point of the varactor. Such behavior is shown in the varactor reflection coefficient measurement at different power levels, Figure 3.



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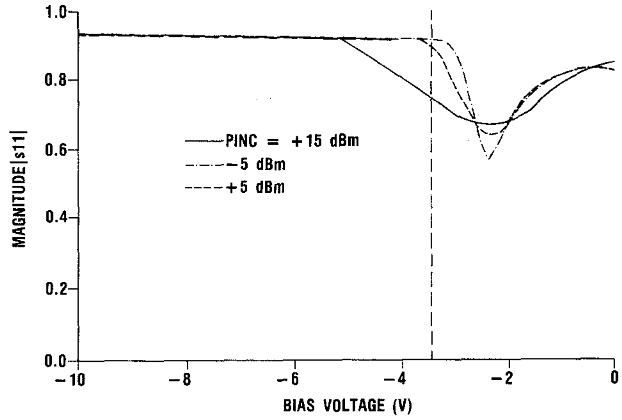


**Figure 3. Varactor Reflection Coefficient at Several Power Levels.**

Typical resultant loop characteristics are shown in Figure 4. A stable operating point occurs when the gain contour intersects the unity gain line with a negative slope. Two such points are shown in the figure. The nonmonotonic loop gain versus signal level curve indicates potential instability in the operating signal level of the circuit at a single DC bias condition. Also, the variation of frequency with signal level indicates resultant frequency instability as well. For example, if the oscillator is operating at a local maxima when it is tangent to the unity loop gain line, an infinitesimal reduction in loop gain will result in migration of the operating point down in power to the next intersection of the loop gain contour with the unity gain line. The infinitesimal change in loop gain may result from an infinitesimal change in varactor or FET bias, due either to tuning voltage or temperature. If such a point exists, then the oscillator has experienced a discrete change in frequency and power for an infinitesimal change in a control parameter, for example tune voltage. This is termed a hop. If such an intersection point does not exist, then the oscillator ceases to function. This is termed a hole. Several approaches may be taken to ensure continuous tuning: (1)-force the loop gain curve to be monotonic and above unity gain for small signals, (2)-force all local minima to be above the unity gain line under all conditions, (3)-force all local maxima to be above the unity gain line under all conditions and ensure continuity between maxima as a function of bias. Notice that condition 1 is that which is normally assumed for oscillator design.

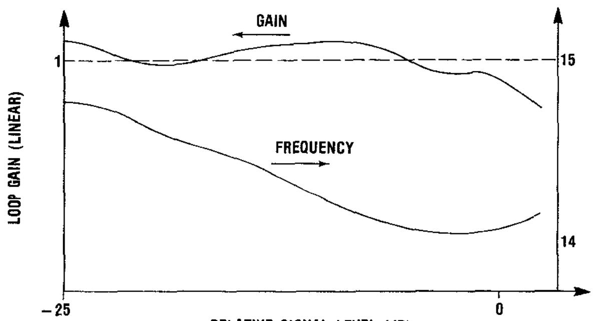


**Figure 4. Loop Characteristics, Gain and Frequency vs Signal Level.**

## CIRCUIT OPTIMIZATIONS

To eliminate hops and holes, circuit modifications to realize condition 3, if not condition 1, were devised. Small signal loop gain was improved through two circuit elements: FET structure and transmission lines. Nonlinear circuit simulation showed that gate to source breakdown voltages exceeded requirements. Thus, to improve extrinsic transconductance at the expense of breakdown voltage, gate to source spacing was reduced by 0.38 µm. Simulations predict a 4.9% increase in maximum transconductance. The inductive portion of the resonant circuit is provided by microstrip transmission lines. The dimensions of the microstrip lines were changed to yield higher loop gain in the desired frequency bands. Large signal gain characteristics were optimized via a change in the structure of the varactor. The standard lateral varactor exhibits a sharp rise in series resistance and drop in Q at punch through as seen in Figure 2. Near this punch through region, the varactor exhibits significant gain variation with RF signal level. Such variation results in the nonmonotonicity observed in the loop gain contour. To alleviate this effect, a unique varactor structure, compatible with uniform ion implant MESFET processes, was devised. Two regions with offset punch-through voltages are realized. Figure 5 shows calculated varactor parameters of the improved lateral structure varactor. A 21 % increase in minimum Q and reduction in variation of Q and capacitance with bias voltage are the predicted effects.

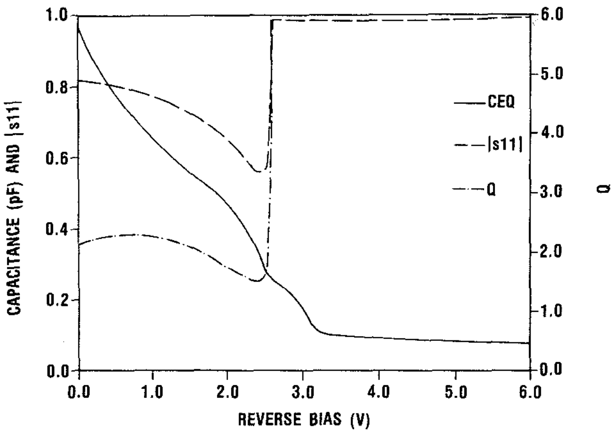


**Figure 5. Varactor Characteristics, Improved Structure.**

## MEASURED RESULTS

Several lots of both X-band, Figure 6, and Ku-band, Figure 7, VCOs, were processed at Texas Instruments' DSEG GaAs MMIC facility using uniform ion implanted material. A matrix of circuits allowed

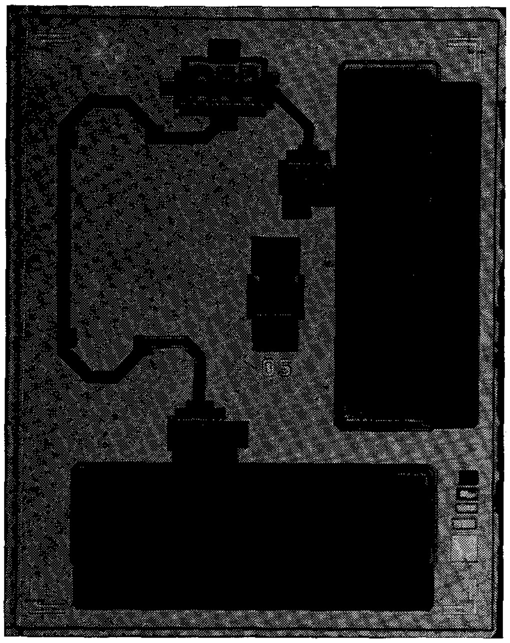

Figure 6. X-band Monolithic VCO.

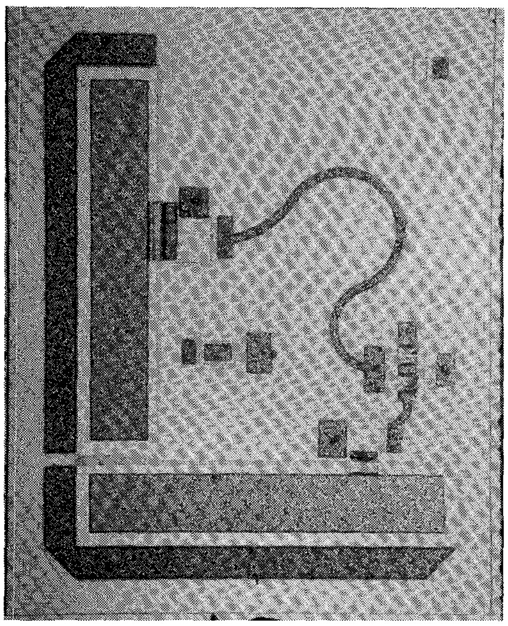

Figure 7. Ku-band Monolithic VCO.

for determination of individual component alterations' effects. The modified varactors showed a 25% improvement in minimum Q and reduced Q variation as shown in Figure 8. Capacitance values decreased 1% and reverse breakdown voltage increased 10% for the new structure. The reduced FET gate to source spacing resulted in an average transconductance increase of 3.8% and, a reduction in gate to source breakdown voltage of 2.6%

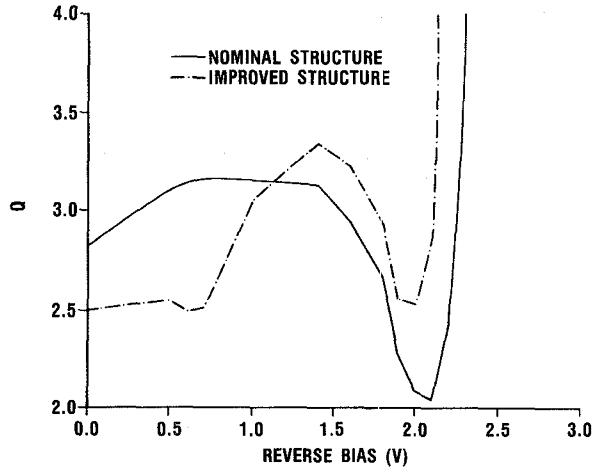


Figure 8. Measured Varactor Comparison, Measured at 15 GHz.

Transmission line dimension changes moved peak loop gain up about 500 MHz. RF yield was highest for chips using all modifications. Comparison of optimized and nonoptimized VCOs is shown in Figures 9 and 10 for X- and Ku-band respectively. Examples of the X- and Ku-band chips exhibited bandwidths of 72% (5.9 - 12.6 GHz) and 63% (10.6 - 20.4 GHz) respectively. Phase noise measurements at an offset of 1 MHz were less than -95 dBc/Hz for the Ku-band VCO, and less than -100 dBc/Hz for the X-band VCO across the operating frequency range. Oscillators were characterized over the temperature range of -55 to +90°C. Each tested example using all of the circuit optimizations maintains continuous tuning characteristics across its entire frequency range. The temperature drift was within ±200ppm/°C or 3 MHz/°C for the Ku-Band VCO. This coefficient was highly variable with bias condition, and hence frequency, to the extent that even its sign changed.

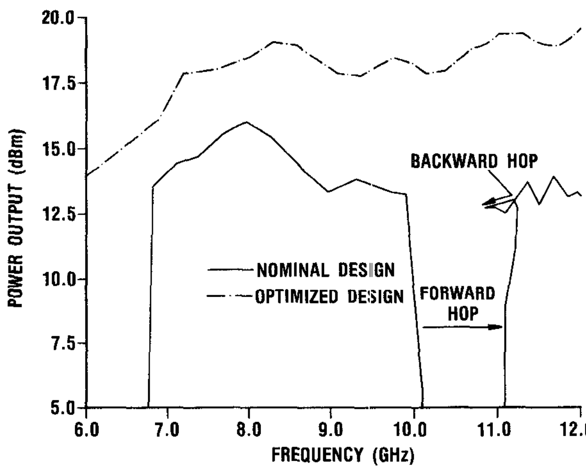


Figure 9. Measured X-band VCO Comparison, at 90°C.

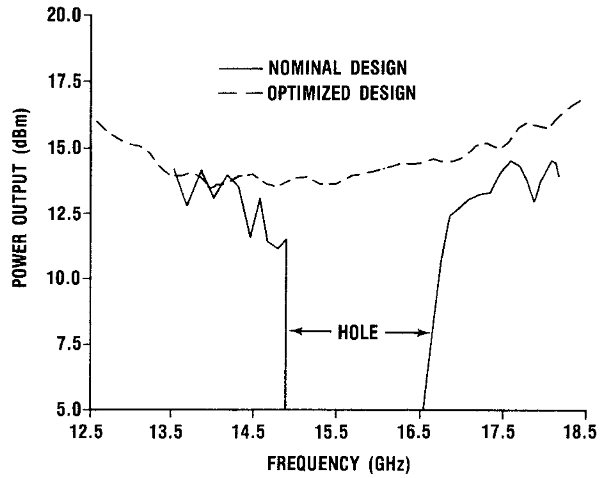


**Figure 10. Measured Ku-band VCO Comparison, at 90°C.**

## CONCLUSION

The use of nonlinear modeling and new design considerations for the continuous tuning of VCOs have resulted in improvements to monolithic VCO circuit design and varactor structure. Devices were fabricated and tested, confirming the validity of the modeling and design approaches. Monolithic X- and Ku-band VCOs realized continuous tuning over 5.9-12.6 GHz and 10.6-20.4 GHz, respectively: continuous tuning was retained over the temperature range -55 to +90°C.

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