Ultra Low-Power VCO Based on InP-HEMT and Heterojunction Interband Tunnel Diode for Wireless Application

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***Abstract* — The monolithic integration of tunneling diodes (TDs) with other semiconductor devices such as HEMTs or HBTs, creates novel quantum functional nonlinear devices and circuits with unique properties: the Negative Differential Resistance (NDR) and the extremely low DC power consumption. In this paper we present an InP-HEMT\TD based voltage controlled oscillator operating in the 6GHz band suitable for wireless applications. The circuit draws a current of 1.75mA at 500mV and generates an output power of –16dBm. The maximum tuning range is 150MHz and the single sideband-to-carrier ratio (SSCR) is of –105dBc/Hz at 5MHz.**

I. Introduction

The increasing demand for smaller, faster and low power consumption systems has created a remarkable opportunity for innovative semiconductor devices, ICs and wireless systems. One new technology able to meet such requirement is based on the incorporation of quantum devices (QDs) in the circuits [1]-[2]. QDs like tunneling diodes (TDs) have demonstrated the potential for highest speed-lowest power consumption operation. Several microwave circuit using QDs have been demonstrated: bi-directional amplifier [3], mixer [4], frequency multiplier [5] and oscillators [6].

A circuit that has received good attention in the past is the sinewave oscillator. Solid-state three terminal device based oscillators were not optimized and tunnel diode oscillator represented a good choice. However these circuits are not quite suitable for wireless products due to their high power consumption and large physical size. Low power consumption monolithic voltage controlled oscillators (VCOs) are required for portable communication products. Phase noise characteristics of free-running oscillator based on tunnel devices reported up to now are worse than those reported with conventional technology. Systematic theoretical investigation of phase noise mechanism of NDR devices and experimental data on tunnel diode VCOs incorporating a phase lock loop (PLL) system are not yet available. Significant research effort in this field is expected in the coming years.

In this paper we report on the DC and RF performance of an ultra low-power VCO comprising of an InP Heterojunction Interband Tunneling Diode (HITD) monolithically integrated with a HEMT.

II. The Quantum Microwave Monolithic Integrated Circuit Technology

There are many types of tunnel diodes such as interband homojunction Esaki type diodes [1], interband heterojunction tunnel diodes [7] or intraband resonant tunneling diodes [8]. They have been realized in many different material systems. The basic device characteristics of all of them however are similar. HITDs allow the highest peak-valley current ratio and an excellent cut-off frequency. The semiconductor structure of the HITD adopted here is shown in Table I. These tunnel diodes have shown very high current densities (50-60KA/cm^2) and peak to valley ratios between 10 and 15, [7]. Analysis of microwave performance shows a maximum frequency of oscillation to be around 60GHz for a 2.5x2.5μm^2 diode.

Table I: HITD's layer structure

p^+ - InGaAs	Top contact layer
nid - InAlAs	Barrier
nid - InGaAs	Well
n^{++} - InAlAs	Ohmic contact
N^+ InGaAs	Bottom contact layer
InP	Substrate

A recent advancement in this class of devices is in the monolithic integration of the tunnel diode to the structure of a three terminal device, resulting in a novel NDR device having three terminals. The resulting device is called Heterojunction Interband FET (HITFET). The third terminal can be used as gate control [6]. In the present work the HITD is integrated in series to the drain electrode of an InP-HEMT, namely a drain-HITFET, although different configurations like integration in the source or gate a HEMT may be adopted. The current–voltage, characteristics of a HITFET is shown in Figure 1. The bias voltage spans from 0 V to 1 V while the gate control voltage spans from 0V to –0.8V (at step 100mV). The

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shift of the NDR region towards higher drain bias voltage is observed as gate bias magnitude is increased. For gate voltage close to 0V an increase in the magnitude of the NDR region is also observed. This results in a decrease in the cut-off frequency as the gate bias changes from 0V to pinch-off voltage due to the increase in drain-source resistance of the HEMT that is in series with the HITD. The HEMT also introduces a reactive component that modifies the self-resonant frequency slightly.

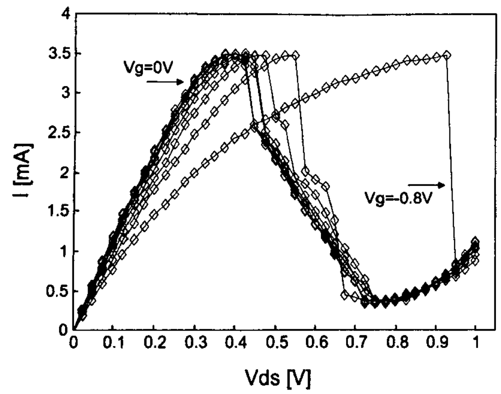

Fig.1: I\V characteristic of the HITFET. Vg=0 to -0.8V, step 100mV

At the gate bias voltage of Vg=-0.8V the characteristic becomes strongly discontinuous and the NDR vanishes completely. The increasing value of the drain-source resistance associated with the HEMT device, which is in series with the HITD, moves the onset of HITFET NDR region to higher drain voltage. The overall effect is a reduction of the peak-valley voltage range. The negative differential resistance goes to zero and HITFET is no longer functional.

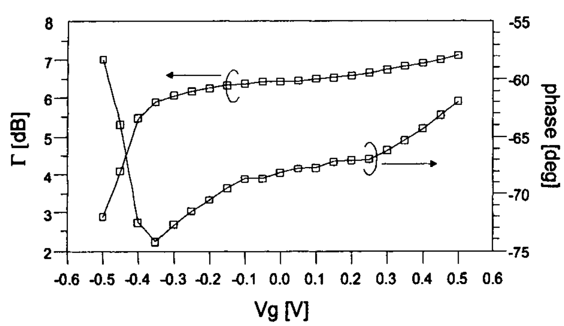

Fig.2: Drain-HITFET's reflection coefficient as seen from the source terminal at 6.2 GHz, V_d=500mV as a function of the gate control voltages

In Figure 2 the dependence of reflection coefficient, Γ, of the drain-HITFET as seen from the source terminal is plotted as a function of the gate control voltages. The measured Γ is greater than 1 due to the NDR associated with the diode. In fact it is possible to tailor the size of the HITD or, equivalently, increase the peak current in order to reduce the NDR in absolute value. A higher value of Γ could be achieved at the expense of an increased parasitic junction capacitance and reduced cut-off frequency. A proper choice of the NDR is necessary to meet the requirement of high frequency operation and a high Γ value that provides enough margins to satisfy the oscillation condition.

The phase swing of Γ depends mainly on the variation in the drain-source to channel capacitance. The effect due to the HITD junction capacitor is minimal since it is an order of magnitude lower.

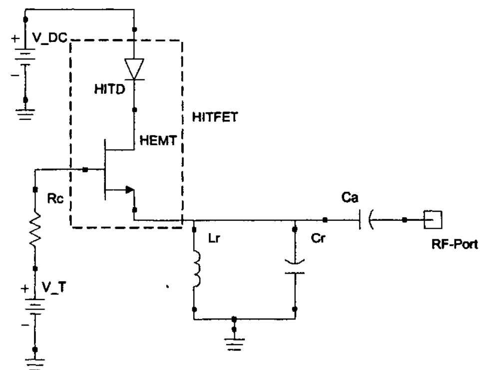

Fig. 3: HITFET based VCO circuit schematic

III. THE HITFET VCO: CIRCUIT IMPLEMENTATION

The voltage controlled oscillator based on a HITFET is represented in Figure 3. It is composed of the HITFET in source follower configuration, controlled by an external tuning voltage V_T, the simple LC resonator (Lr, Cr) and an AC coupling capacitor Ca.

The insertion of external impedance in series to a tunnel diode faces a number of problems in terms of low frequency stability, [9], [10]. The VCO is configured as a series circuit where the HEMT and the LC resonator are actually in series with the HITD. Low frequency stability constrains as shown in equation (1) is derived

$$\frac{Ls+Lr}{Cd\cdot Rd^2}<\frac{Rs+Rds}{Rd}<1, \qquad (1)$$

In the derivation the following assumption are made: the capacitor Ca is an open circuit; the capacitor Cr is negligible with respect to the inductor Lr and the drain-source capacitor of HEMT is negligible with respect to its drain-source resistance Rds. In equation (1) Rd is magnitude of the negative HITD resistance, Ls is the distributed series inductor due to contacts, Rs and Cd are the HITD series resistance and parallel junction capacitance. Rd is bias dependent with a minimum of 150Ω for the HITD considered in the study. Estimated values of components are Ls = 0.05nH; Rs = 8Ω Cd = 0.08pF. R_{DS} value increases linearly with the tuning voltage. Under these conditions equation (1) gives the bounds for the values of Lr and R_{DS}. Setting Lr= 0.6nH the HEMT has been scaled such that, during the tuning, Rds assumes the values:

$$46\Omega < Rds < 142\Omega \qquad (2)$$

It is worth noting that to satisfy the condition in (2) with a circuit bias voltage around 500mV, the HEMT operates in the linear region with Vds near zero, which is also a low noise region for the HEMT.

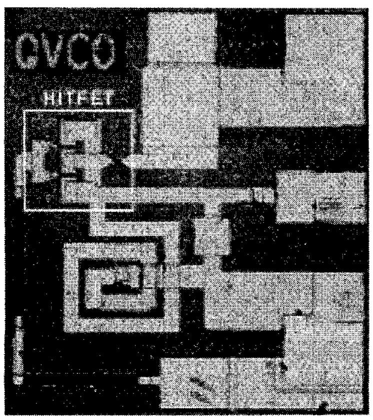

Fig.4: Chip photograph of the HITFET based VCO.

IV. HITFET Based VCO: Experimental Results

A prototype of HITFET based VCO has been designed, in accordance with the guidelines discussed above and the photo of the fabricated chip is shown in Figure 4. The overall chip size is around 450x550μm^2. The design method adopted is well known technique commonly used in reflection oscillator. The HITFET is considered as the negative resistance element, which must resonate with a proper load to obtain the oscillation. To achieve this, the reflection coefficient (Γ^{LC}) of LC resonator and reflection coefficient (Γ^{HITFET}) of the HITFET must obey the equation:

$$\Gamma^{HITFET} \cdot \Gamma^{LC} = 1 \qquad (3)$$

This would lead to the value of Cr.

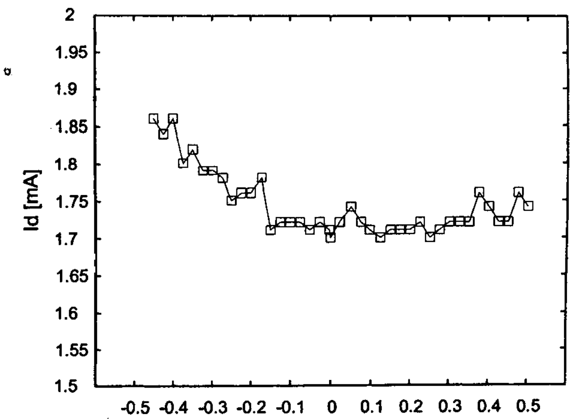

Fig.5: VCO prototype's DC current as a function of the tuning voltage for a bias voltage of 500mV.

The chip is biased at 500mV through the HITD's anode while the tuning potential is applied to the HEMT's gate through a 1KΩ resistor. The current drawn by the circuit at the drain for a bias voltage of 500mV is plotted in Figure 5 as a function of control voltage in the range from –0.5V to 0.5V. The current is in the range of 1.7mA to 1.85mA and DC power consumption is about 850μW. This value, to the best of our knowledge, is the lowest DC power consumption for MMIC VCO in operating in this frequency range.

The application of this kind of a circuit is foreseen in the area of RF-TAG for ID or sensor where the low power consumption and the low data rate are common required features. Moreover, the extremely low-voltage supply makes this technology interesting for battery-less solar-cell powered equipment.

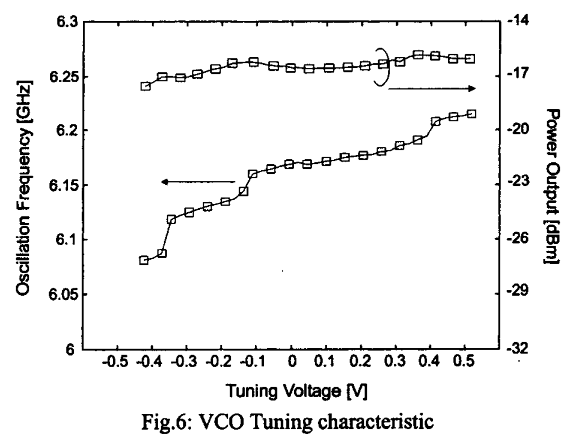

Fig.6: VCO Tuning characteristic

The tuning characteristic of the free-running VCO is shown in Figure 6 for a wide range of tuning voltage. A frequency swing in the 6.1GHz to 6.2GHz range with a nearly constant power level has been observed. The graph shows a range between –0.4V and –0.1V in which the frequency changes quickly. This is due to the parabolic shape in the phase of reflection coefficient associated with an almost constant value of the magnitude. For higher level of tuning voltage the reflection coefficient has a linear behavior in magnitude and phase, this produces consequent linear frequency swing as shown in Fig.6.

The power output is about –16dBm, which leads to an efficiency of around 2.75%. The roughly constant value of the output power is a direct consequence of the I/V characteristic of the HITFET. The change in drain current is small (as reported in Fig. 5) and the drain voltage was held constant at 500 mV. Since the reflection coefficient is positive and the condition expressed by the equation (3) are satisfied, the oscillation level is constant.

The power level and consequently the efficiency could be improved by choosing a larger ac-coupling capacitor Ca. This option may make equation (3) more stringent and could reduce the tuning range.

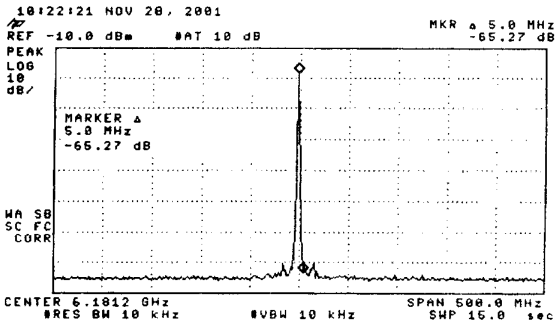

Fig.7: Output spectrum SSCR is –105dBc/HZ at 5 MHz

The phase noise performance of the oscillator was estimated from spectrum analyzer measurement. At 5MHz offset from the center frequency, single-sideband noise-to-carrier ratio of –105dBc/Hz was obtained. A study at system level have shown that for a microwave data link which adopt a GFSK modulation with a BT=0.5 and a modulation index of 0.3, the measured phase noise enable a BER=10^{-3}, assuming a carrier to noise ratio at the receiver input of 24dB. The phase noise can be improved if the VCO is inserted in a PLL system.

V. Conclusion

A MMIC InP-HEMT\TD based VCO operating in the 6GHz band has been presented. A simplified analysis technique to determine low frequency stability condition and range of useful operation of drain-HITFET VCO is discussed. The prototype has demonstrated an output power of –16dBm with a single sideband-to-carrier ratio of –105dBc/Hz at 5MHz away from the center frequency. The unique feature of the circuit is ability to operate at very low supply voltage. The DC power consumption of the circuit was only about 850 μW. This value makes the prototype suitable for RF-TAG as well as for ID beacon or as data transfer for remote sensor where the low power consumption and the extremely low-voltage is a killer application.

Acknowledgement

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