A Hybrid Self-Oscillating Mixer Based on InP Heterojunction Interband Tunnel HEMT for Wireless Applications

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Abstract — **The monolithic integration of Tunneling Diodes (TDs) with other semiconductor devices, creates novel quantum functional devices and circuits with unique properties: the Negative Differential Resistance (NDR) and the extremely low DC power consumption. In this paper we present the design, fabrication and characterization of a Self-Oscillating Mixer (SOM) based on InP-HEMT\TD technology. The circuit is based on a 2.526 GHZ VCO that draws a current of 1.3mA at 500mV and generates an output power of –21.5dBm on a 50Ω load. The SOM is able to down-convert RF signals in the 2.25–2.85 GHz band to an IF frequency in the 20-300 MHz band, with a conversion loss in the range 32-40 dB.**

I. INTRODUCTION

The increasing demand for ultra-compact and fast wireless products with low power consumption has led to many innovative semiconductor devices and ICs. The Quantum Microwave Monolithic Integrated Circuit (QMMIC) technology, which is based on the incorporation of Quantum Devices (QDs) in a microwave monolithic circuit, has demonstrated the ability to meet such requirements [1]-[2]. In particular NDR devices like Tunneling Diodes (TDs) have shown the potential for highest speed-lowest power consumption operation. Several microwave circuits using TDs have been already developed and implemented: bi-directional amplifier [3], [4] mixer [3], [5], [6] frequency multiplier [3], [7] and oscillators [3], [8].

The Self-Oscillating Mixer (SOM), whose principle and benefits have been described by several authors [9]-[12], is a further application that can take advantage of TDs' inherent simplicity and good mixing properties.

In this paper we report on the DC and RF performances of an ultra low-power SOM based on a Drain Heterojunction Interband Tunneling FET (Drain-HITFET), which is a three-terminal NDR device obtained by integrating a Heterojunction Interband Tunneling Diode (HITD) in series to the Drain electrode of an InP-HEMT. The HITFET is forced to oscillate by adding a series inductor on the Drain; as shown in [3],[8] the frequency of oscillation can be set by properly tuning the value of the series inductance. The prototype shown in this paper oscillates at 2.526 GHZ with an output power of –21.5 dBm.

The down-conversion mechanism of the SOM has been experimentally shown for an RF signal in the 2.25-2.85 GHz band with a power ranging from –35 to –15 dBm.

In these operating conditions the circuit produces an output IF signal in the 20-300 MHz band with a conversion loss ranging from 32 to 40 dB.

II. SELF OSCILLATING MIXERS: PRINCIPLES OF OPERATION

A SOM is basically a two-port oscillating circuit which down-converts the input RF signal to the output IF signal; nevertheless, the mixing properties of the circuit are rather different than a conventional mixer's ones.

Following the analytical treatment described in [9], the down-conversion mechanism can be seen as the result of both a modulation of the Local Oscillator (LO) and a self-mixing of the resultant modulated signal.

When the frequency f_{RF} of the injected RF signal is within the bandwidth of the resonator, the LO undergoes both an Amplitude and a Phase modulation. The actual RF voltage across the diode can be written in the following form:

$$v(t) = V_{LO}\left(1 + m\cos 2\pi f_m t\right)\sin\left(2\pi f_{LO} + \frac{\Delta f}{f_m}\sin 2\pi f_m t\right) \tag{1}$$

where f_{LO} and V_{LO} are, respectively, the oscillator frequency and amplitude, f_m is the mixing frequency ($f_m=|f_{RF}-f_{LO}|$), m is the amplitude modulation index and $\Delta f/f_m$ is the phase modulation index. After some algebraic manipulations, equation (1) can be expanded as a combination of Bessel (J_n) and trigonometric functions:

$$\begin{aligned} v(t) &= \sum_{n=0}^{+\infty} V_n^+ \sin\left[2\pi\left(f_0 + nf_m\right)t\right] + \\ &+ \sum_{n=1}^{+\infty} V_n^- \sin\left[2\pi\left(f_0 - nf_m\right)t\right] \end{aligned} \tag{2}$$

where:

$$\begin{aligned} V_n^- &= V_{LO}\cdot J_n\left(\Delta f/f_m\right)\left[1 + \frac{mn}{\Delta f/f_m}\right] \\ V_n^+ &= V_{LO}\cdot\left(-1\right)^n J_n\left(\Delta f/f_m\right)\left[1 - \frac{mn}{\Delta f/f_m}\right] \end{aligned} \tag{3}$$

The IF signal is than obtained as a self-mixing of the RF voltage across the device. Due to the non linear current-voltage characteristic, the instantaneous current across the device is given by:

$$i(t) = \sum_{k=1}^{m} g_k \cdot v(t)^k \qquad (4)$$

where g_n in the n-th order conductance.

NDR devices like Tunnel or Gunn Diodes usually show a second-order non-linearity, therefore it is sufficient to take into account only the first three terms of (4).

For m=2 the IF current (i.e. the current at frequency f_m) can be written in the following form:

$$i_{fm} = V_{LO}{}^2 \cdot \left[C_1 \cdot m + C_2 \cdot m \left(\Delta f / f_m \right)^2 \right] \qquad (5)$$

where C1 and C2 are constants.

Under some simplifying assumptions [9] m does not depend on the injected signal frequency (f_m) and power (P_{RF}), while Δf depends only on the ratio between P_{RF} and the LO power P_{LO}. If we assume to have small injections, so that f_{LO} and P_{LO} are not heavily perturbed by the RF signal, we obtain:

$$\Delta f / f_m \cong \left(f_{LO} / f_m \right) \cdot \left[C_3 \cdot \sqrt{P_{RF} / P_{LO}} + C_4 \left(P_{RF} / P_{LO} \right) \right] \qquad (6)$$

where C_3 and C_4 are constants.

An important difference between a SOM and a conventional 2nd harmonic mixer arises from equations 5 and 6: while in a conventional mixer (below the compression point) the IF power is proportional both to the LO and RF power, in a SOM the IF power is proportional to the product of the square of P_{LO} and a polynomial function of $(P_{RF}/P_{LO})^{1/2}$.

III. THE QMMIC TECHNOLOGY

The technology adopted in the present paper has been fully described elsewhere [3], [8] and therefore will be only shortly summarized.

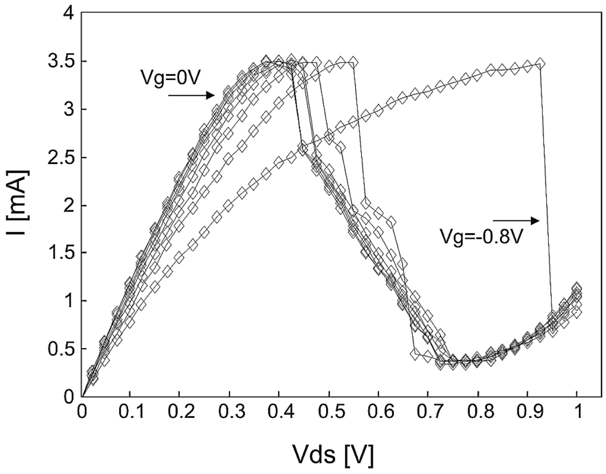

Fig. 1. HITFET's Drain to Source I\V characteristic, Vg=0 to -0.8V, step 100mV.

The current–voltage characteristics of a HITFET is shown in Fig. 1. Depending on the doping levels the peak current may span from 1.5 and 3.5 mA.

The Gate bias Vg is used as a control voltage: if the Gate bias magnitude is increased a shift of the NDR region towards higher drain bias voltage is observed. When the Gate voltage Vg is set to -0.8V, the DC characteristic becomes strongly discontinuous, the NDR vanishes completely and HITFET is no longer functional.

In Figure 2 the dependence of the Drain-HITFET's reflection coefficient Γ, as seen from the drain terminal, is plotted as a function of different voltage biases.

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.

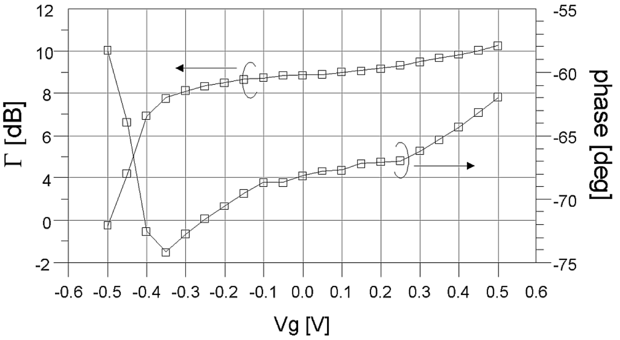

Fig. 2. Drain-HITFET's reflection coefficient as seen from the drain terminal at 2.55 GHz, V_d=500mV as a function of the gate control voltages.

IV. THE HITFET BASED SOM: CIRCUIT IMPLEMENTATION AND EXPERIMENTAL RESULTS

The HITFET, when biased in the NDR region, shows a capacitive small signal impedance or, equivalently, a self-scattering parameter with a negative phase (see Fig.2). Considering the need to properly bias the device, the simplest way to design a HITFET-based tunable oscillator is to add a proper inductance (or LC resonator) in series with the device. The Hybrid SOM proposed in this paper is based on a VCO obtained by connecting an external SMD inductance L=10nH to the Drain of the device. The details of the design are provided in [8].

For a gate bias Vg=0, the free-running frequency of oscillation is F_{LO}=2.526GHz and the oscillator output power (on a 50Ω load) is P_{LO}=-21.5 dBm (see Fig. 3).

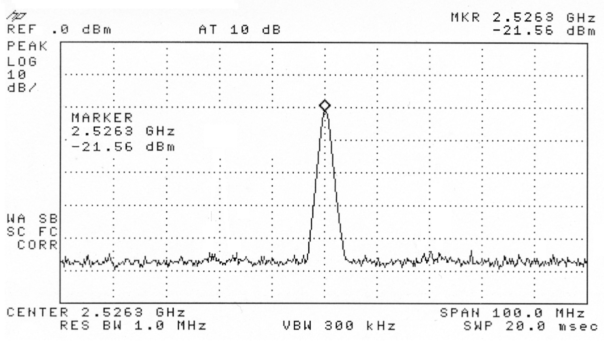

Fig. 3. HITFET based VCO Output Spectrum

Note that the VCO used in this work is based on a 2.5mA peak-current HITFET, therefore the output power is about 10dB lower than the one of the prototypes shown in [8], which were based on a 3.5 peak-current HITFET.

The SOM is than obtained by adding a Directional Coupler (DC) on the output port of the VCO. The RF signal is injected on the coupled port of the DC, while IF signal is taken from the RF-isolated port. In the actual circuit this arrangement can be easily replaced by a diplexer.

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 schematic of the SOM is represented in Fig. 4; all the components connected to the HITFET are off-chip.

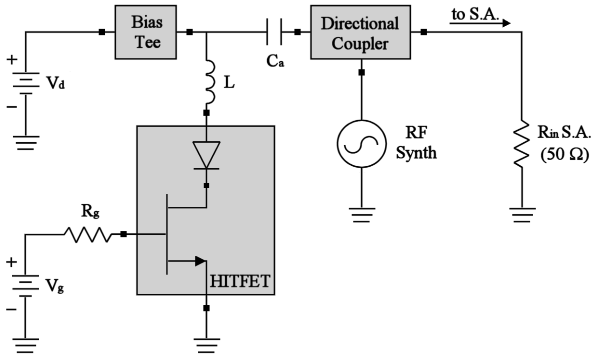

Fig. 4. HITFET based SOM circuit schematic

The Drain current drawn by the circuit for a bias voltage V_d=500mV is about 1.3 mA, giving a DC power consumption of about 650μW. This value, to the best of our knowledge, is the lowest DC power consumption for SOM operating in this frequency range. By changing the DC Gate voltage V_g in the range –500 +500 mV, the oscillating frequency can be tuned from 2.50GHz to 2.55GHz, a range that can be increased to about 140 MHz by using an inductor on the source [8].

The phase noise performance of the oscillator was estimated from spectrum analyzer measurement. At 100KHz offset center frequency, single-sideband noise-to-carrier ratio (SSCR) of –104dBc/Hz was obtained.

In Fig. 5a and 5b the output spectrum of the SOM for (f_{LO}-f_{RF})=20 MHz and for an available RF power P_{RF}=-25dBm is reported.

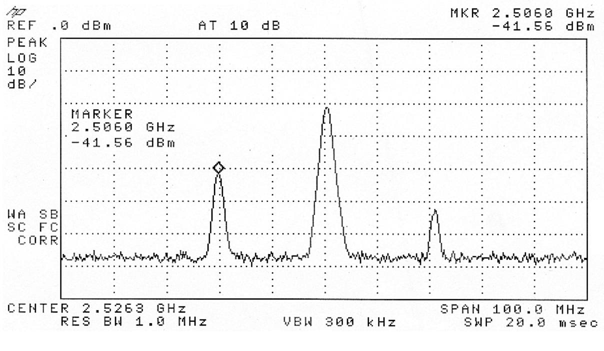

Fig. 5a. SOM's output RF spectrum for (f_{LO}-f_{RF})=20MHz, P_{RF}=-25 dBm .

Note that, due to the measurement setup (Fig. 4), the signal at f_{RF}=2.506 GHZ is not the RF signal actually injected in the SOM, but the sum of three different signals: the LO AM/PM modulated signal, the scattered RF signal and the leakage of the injected RF signal to the Out port of the DC.

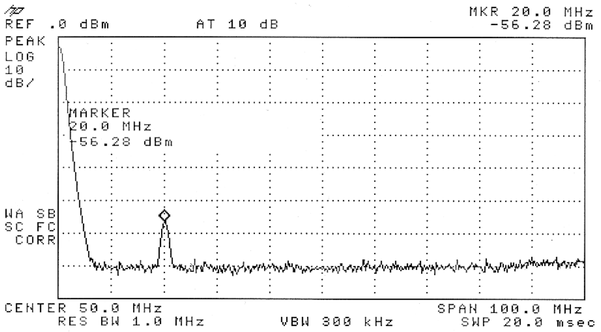

Fig. 5b. SOM's output IF spectrum for (f_{LO}-f_{RF})=20MHz, P_{RF}=-25 dBm (same setup as Fig. 5 a).

Taking into account the loss in the measurement bench a conversion gain of –31.2 dB is achieved.

A second set of measurements has been carried out by changing the RF to LO frequency offset in the range 20-300 MHz. The results in terms of Conversion Gain are reported in Fig. 6.

If the frequency offset between the RF and LO signals is decreased below 20 MHz, the oscillator is heavily perturbed by the injected RF signal, therefore the assumption of having an AM/PM modulation made in section II is no longer valid and the mixing properties of the circuit are compromised.

The circuit shows increasing conversion losses as the offset from the LO is increased; moreover the slope of the curve is higher if f_{RF}-f_{LO}>0. Both these results are due to the low-pass filtering effect of the series inductance and are not correlated to the HITFET's mixing properties.

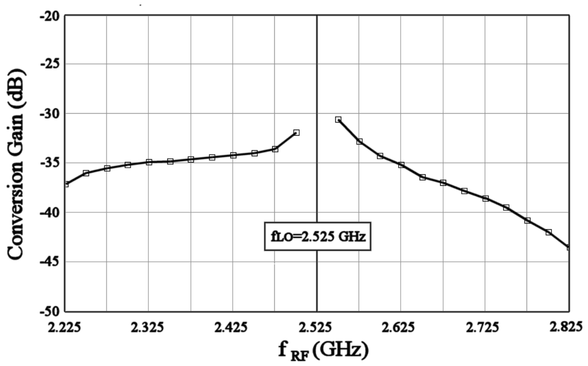

Fig. 6. SOM's Conversion Gain versus f_{RF}, @ P_{RF}=-25 dBm.

Finally a last set of measurement has been carried out by setting f_{LO}-f_{RF}=20MHz and changing the RF input power from –35 to –15 dBm. As it is reported in Fig. 7 in the chosen range the circuit shows a constant Conversion Gain vs. Input Power characteristic.

If the RF Signal power is increased over –15 dBm the same LO perturbation effect described in the previous case is observed. The maximum power of the RF signal depends on the RF to LO frequency offset. If the offset is increased the LO perturbation is observed at a higher RF power level.

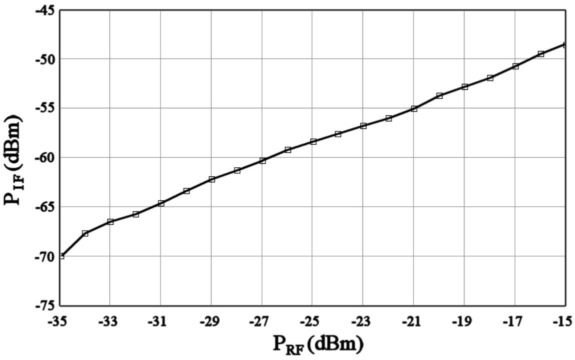

Fig. 7. SOM's output power for (f_{LO}-f_{RF})=20MHz, P_{RF} spanning from -35 to – 15 dBm.

V. CONCLUSION

A InP-HEMT\TD based SOM operating in the 2.25-2.85 GHz band has been presented. The unique feature of the circuit is the extremely low power consumption, along with proper conversion properties. The prototype can be considered as a mixer driven by a –21.5 dBm LO which provides a conversion loss in the range 32–40 dB. Due to the LO tuning properties, the SOM is also suitable for a fixed f_{IF} down conversion of a 100 MHz wide RF band. The straightforward applications of the presented SOM are in the field or wireless communication with stringent requirements in terms of power consumption. A proper investigation on the optimum terminations at RF and IF, which should include the extraction of the conversion matrix for this device, may increase the conversion performance but it is well beyond the aim of this paper.

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