Homodyne mixing at 150 GHz in a high electron mobility transistor

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***Abstract*— we explore the possibility of using an AlGaN/GaN high electron mobility transistor (HEMT) as a free-space coupled homodyne mixer. We used 150 GHz radiation from a Free Electron Laser, hence 5 times higher than the HEMT nominal band center at 30 GHz. The homodyne mixing provides a quasi-dc output signal, which makes the HEMT a detector of the radiation at 150 GHz.**

I. Introduction And Background

Three-terminal devices are routinely used as mixers in the microwave range since many decades[1]. The mixing principle has been exploited in the terahertz range with both local oscillator (LO) and radiofrequency (RF) signals optically coupled to the mixer. Recently developed quantum cascade lasers should provide a compact LO source for routine applications, instead of bulky gas lasers. On the other hand, different devices have been proposed as mixers in the terahertz range, such as superconducting bolometers, Josephson tunnelling junctions, GaAs-based Schottky diodes. In this work, we explore the possibility of using a high electron mobility transistor (HEMT) as a free-space coupled homodyne mixer. Given the increasing interest for routine applications of terahertz radiation, a HEMT is an attractive device, since it is relatively cheap and reliable, and it operates at room-temperature.

The HEMT used for the experiment is fabricated by optical and electron beam lithography on AlGaN/GaN heterostructures with a room temperature mobility of the 2-dimensional electron gas around 2000 cm^2/Vs and an electron density of 10^{13} cm^{-2}. The gate foot is 500 nm long and has a Schottky contact with the AlGaN/GaN surface. The gate, source and drain ohmic contact pads have a size of the order of 100 microns. Pads and bonding wires are expected to work as antennas coupling the free-space radiation at 150 GHz produced by the ENEA Compact Free Electron Laser[2] (FEL) to the transistor channel. The FEL radiation was directed to the HEMT by positioning it about half a wavelength (1 mm) below the aperture of an open-end WR-6 waveguide (WG). The FEL power was monitored by a Schottky diode detector positioned inside the WG and receiving a fraction of the power emitted by the open-end WG.

II. Results

The HEMT was biased with 20 V dc to the drain-source circuit with a load resistor R_d = 1 kΩ. For different dc gate bias V_g, we observed on an oscilloscope the transient drain voltage V_d* during illumination. In the Figure, V_d* is shown for V_g=0 (drain-source current i = 19.9 mA) and V_g=-4.8V (i = 3.4 mA). Two clearly different regimes are observed for different V_g. For V_g=0 a positive V_d* peaked at +0.1 V is observed. For V_g=-4.8 V, a negative V_d* peaked at -1.2 V is observed instead. In both regimes V_d* is in phase with the FEL pulse, as both HEMT signals temporally overlap with the signal of the Schottky diode installed in the waveguide.

The positive V_d* (red line in Fig. 1) appears in the linear region of the transistor characteristics (V_g=0, i=19.9 mA) and can be explained in terms of a partial rectification of the oscillating FEL electric field. Although it is difficult to say where and how exactly the rectification effect takes place, one possibility is that the Schottky gate contact partially rectifies a local oscillation at 150 GHz of the gate-to-channel potential, and the rectified signal adds up to V_d. This effect would be similar to that of the fast Schottky diode sensor installed in our WG (black dotted line in Fig. 1). Since the radiation power seen by the HEMT should be one order of magnitude higher than that seen by the Schottky detector, we conclude that this detection mechanism is not very efficient, either because of the large gate capacitance (compared to the frequency of 150 GHz) or because of poor radiation coupling.

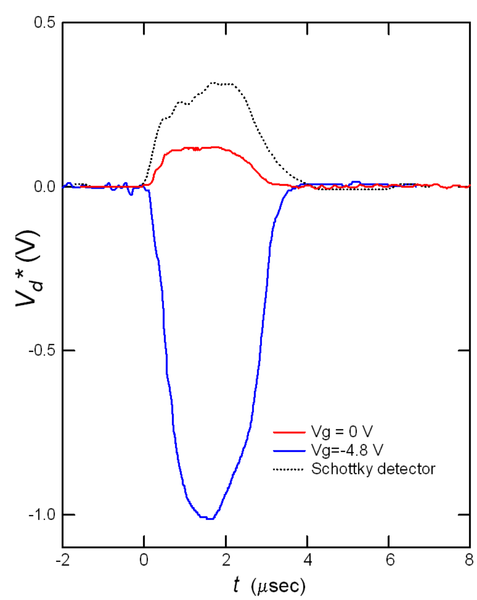

FIGURE 1. Transient drain signal during illumination by a 150 GHz pulse. The dotted line is the reference Schottky detector inside the waveguide. Radiation power levels are different for the two detectors.

A completely different effect should be responsible for the

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large negative V_d* observed in the saturation region for V_g=-4.8 V, but still in the conduction regime (the channel is closed at V_g=-5.8 V). Note that the rise and decay times observed in Fig. 1 and, moreover, the change of sign with different V_g, are not compatible with a thermal (bolometric) mechanism. The peak value of -1.2 V in V_d* is comparable to both the voltage drop in the channel (around 16 V for V_g=-4.8 V) and to the gate-to-channel voltage. This clearly indicates that the transistor parameters, e. g. the transconductance $g_m = \partial i/\partial V_g$, are "pumped" by the strong FEL field[1]. We now propose a possible mechanism for such an effect.

The detection mechanism in the saturation region relies on the high frequency component (ω = 150 GHz) of the drain voltage and current induced by the radiation and whose amplitudes are proportional to the time-varying FEL field. As a consequence of that, an oscillating voltage at 150 GHz is produced in the channel and this leads to a gate-to-channel voltage variation $\Delta V_{gc}(t)= \Delta V_{gc}\ sin(\omega t)$ (in our configuration the gate contact is grounded by an external capacitor with respect to a time-varying signal, so that the variation V_{gc} is indeed related to the variation of the channel voltage). If ΔV_{gc} induced by the FEL field is large enough, one expects that g_m changes during the oscillation at frequency ω, ending up in a $g_m(t)$ with periodicity ω. The mathematical details will be presented in a forthcoming paper. As a result of the mixing between $\Delta V_{gc}(t)$ and the time-varying transconductance[1] $g_m(t)$, we will have:

- a linear response at 150 GHz, which should be much smaller than the excitation, as the unity gain of the HEMT is at 30 GHz.
- a down-converted component of the drain current i* which adds up to the dc bias current i during the FEL pulse illumination. The current i* is positive, since the mixing derivative $\partial g_m/\partial V_g$ is always positive[1].
- eventually, mixing terms at frequency 2ω or higher, which cannot be observed in the present experiment.

After unavoidable low-pass filtering by parasitic capacitances in our device (whose unity gain is indeed at 30 GHz), the transient drain voltage V_d* measured at the drain connector and reported in Fig. 1, can be approximated by V_d* = - $i^* \cdot R_d$ and has a negative sign. The peak transient current i* can be evaluated around 1 mA, a large fraction of the dc current i = 3.9 mA

Considering the typical variation of g_m with V_g in a HEMT, the mixing effect takes place wherever $\partial g_m/\partial V_g > 0$, i.e. approaching the saturation region from small negative V_g down to the threshold voltage. However, we have seen that for V_g=0 the FEL field produces a positive transient signal at the drain, so that the mixing action can be clearly observed only at large negative V_g. We suggest that higher mixing signals can be obtained with device designs which increase $\partial g_m/\partial V_g$ like a large number of parallel channels in a small detector area (interdigitated schemes) and/or different heterostructure engineering with higher $\partial g_m/\partial V_g$. Mixing effects have been indeed predicted for 2-dimensional electron gases[3] and reported in GaAs-based grating-gate HEMTs, although only at low temperatures[4].

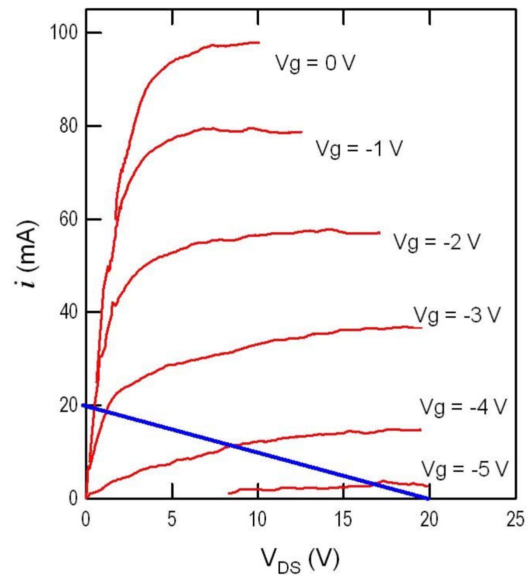

FIGURE 2. dc characteristics of the AlGaN/GaN HEMT (red lines) with the load line (blue line) used in the present experiment. The mixing signal appears close to the intersection of the load line with the Vg=-5V line.

III. CONCLUSIONS

We proposed a mechanism for the generation of a negative dc signal in a HEMT when an electric field at 150 GHz, generated by a FEL, is free-space coupled to both the gate and the source-drain circuit at the same time (homodyne mixing). The HEMT unity gain was 30 GHz, hence below the excitation frequency. As a future perspective, heterodyne mixing should also be possible in our HEMT[4].

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