Field-Effect Transistor Based Detector for Measuring Power Fluctuations of 4.75-THz Quantum-Cascade Laser-Generated Radiation

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***Abstract*— In order to understand the formation of massive young stars, observation of a major coolant of dense interstellar medium, neutral atomic oxygen which has a fine-structure line at 4.7448 THz, is an important task. It requires high-sensitivity and high-resolution spectroscopy systems in the terahertz (THz) frequency range. One of such systems is in the Stratospheric Observatory For Infrared Astronomy (SOFIA). It essentially requires stable local oscillator (LO) source for heterodyne detection. Therefore, we explore a field-effect transistor based THz detector (TeraFET) with an integrated resonant patch antenna fabricated in commercially available standard 90-nm CMOS technology.**

At 4.75 THz, the detector exhibits an area-normalized minimal noise-equivalent power (NEP) of 404 pW/√Hz and a maximum responsivity of 75 V/W where the effective area is 1750 µm^2 and directivity reaches 7.4 dBi. These sensitivity and responsivity values contributes to the state of the art for room-temperature electronic detectors operating at around 4.7 THz.

We demonstrate experimentally, that the TeraFET detector can monitor the intensity of THz QCL radiation using only a small fraction of the beam power with S/N ratio of 40 dB and does not require chopping and could be employed in a heterodyne instrument.

I. Introduction

High-resolution and high-sensitivity heterodyne-based spectroscopic observations for astronomy require stable local oscillator (LO) sources operating in terahertz (THz) frequency range. For example, a major coolant of dense interstellar medium, neutral atomic oxygen has a fine-structure line at 4.7448 THz. Monitoring of this line became an important tool in order to understand the formation of massive young stars [1].

One of the monitoring laboratories is the Stratospheric Observatory For Infrared Astronomy (SOFIA). For high-resolution and high-sensitivity measurements at various frequencies, the heterodyne spectrometer GREAT (German REceiver for Astronomy at Terahertz frequencies) employs multiplied microwave sources in all channels except the highest one at 4.7 THz where a solution of this kind is not available. Instead, a quantum cascade laser (QCL) is employed to cover this frequency, which emerged as an alternative THz source solution to the gas lasers for such measurements [2].

It is desirable, that the power of the THz QCL can be continuously monitored. However, commercial devices like pyroelectric detectors [3] require implementation of chopping techniques, that is undesired because of space constrains. Therefore, here started with explorations of practical applicability of compact field-effect transistor based THz detector (TeraFET) [4]. Here we continue with our explorations and show the ability of low-NEP TeraFET detector to monitor the QCL power in continuous wave (CW) mode.

II. TeraFET Design

Reported TeraFETs are fabricated in commercially available standard 90-nm CMOS technology. The dimensions of the patch antenna are 13×13 µm^2, the antenna is surrounded by a 32×32 µm^2 metal cup formed using all 10 metal layers. Such a structure is meant to isolate antenna from surrounding wiring and other detectors, although the modeling showed that the directivity of emission (and concomitant effective cross-section of receiving antenna) stays unperturbed.

The FET inside detector has a channel length of 100 nm and a width of 400 nm. The whole chip die is glued and bonded into a ceramic dual-in-line (DIL) package.

III. Experimental Methods

The LO of the GREAT 4.75 THz line is based on a QCL mounted on the cold finger of the two-staged Stirling cryocooler (model Ricor K535) where the second stage is doubled in symmetrical manner to avoid large mechanical vibrations. The default cooling fins of the cryocooler heat sink are changed to the custom ones meeting standards of the SOFIA devices.

The QCL has a temperature sensor and a heater attached to it with a temperature stabilization based on field programmable gate array (FPGA). Such a cooling system maintained the QCL's temperature of 49 K during a whole experiment.

The constant-current source supplies the QCL with a varied current from 450 to 600 mA. The electrical power consumption of the QCL operating in continuous-wave (CW) mode at 600 mA was 4.13 W, which did not overcome the range of the cooling capacity of the Stirling cryocooler. The QCL is placed in vacuum to prevent condensation of water molecules.

Fig. 1. Optical setup. The same as in the SOFIA system. The emitted THz radiation passes through the high-density polyethylene (HDPE) window and is collimated with 25.4 mm focal length off-axis parabolic (OP) mirror. The beam splitter can be changed into various transmission levels. The radiation power is measured by Ge:Ga and TeraFET detectors.

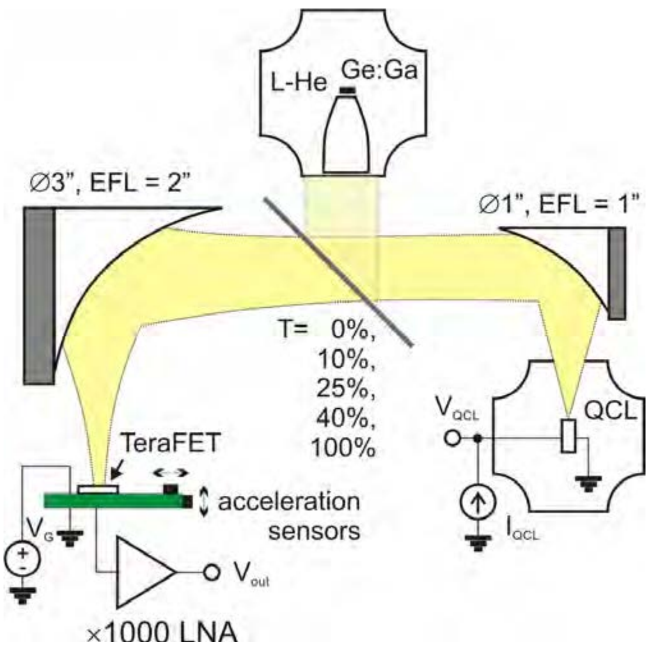

Fig. 1. Optical setup. The same as in the SOFIA system.

IV. TeraFET Application in SOFIA System

During the experiment, physical parameters of LO system, such as temperature, current and voltage of the QCL, power of the heater, and pressure inside the vacuum chamber, were measured and sampled simultaneously along the output voltage of the TeraFET detector which also had acceleration sensors attached.

At 4.75 THz, the detector exhibits an area-normalized minimal noise-equivalent power (NEP) of 404 pW/√Hz and a maximum responsivity of 75 V/W where the effective area is 1750 μm^2 and directivity reaches 7.4 dBi. These values are comparable with state-of-the art Schottky-Barrier Diode (SBD) detector for 4.92 THz based on 130-nm CMOS technology showing the complete device performance of 383 V/W at 300 Hz modulation frequency and shot-noise-limited NEP of 4950 pW/ √Hz [5].

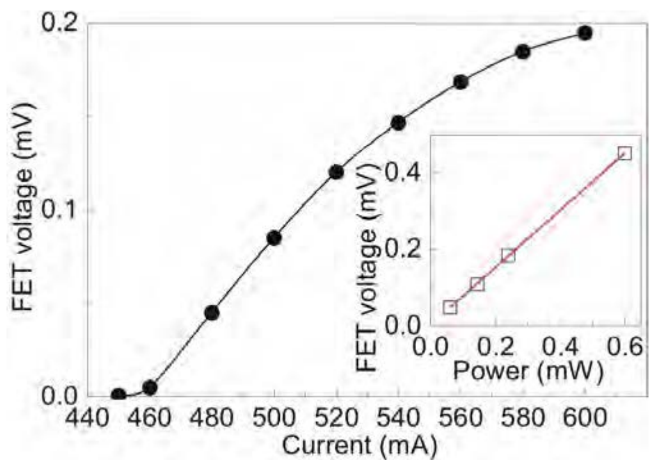

Fig. 2. Measured FET signal response at different QCL currents with 40 % attenuation with the inset of linear response-power dependency for different attenuation levels.

The dependency of the detection response to the incoming power is shown in the inset of Fig. 2. The detector response is linear in a whole power range up to 0.6 mW. The main graph shows the measured TeraFET response to the applied QCL current which controls to the emitted QCL power.

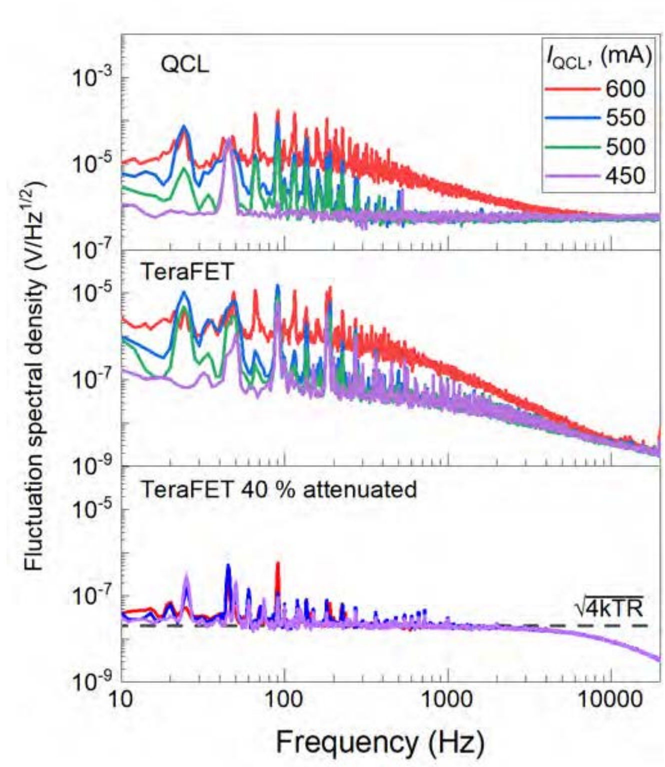

Fig. 3. Spectral voltage noise density of QCL (above), TeraFET (center), and TeraFET with a blocked radiation (bottom). Applied voltage of the QCL for corresponding graphs is shown in the legend and the dashed line shows the thermal noise curve of TeraFET.

Fig. 3. shows evaluated spectral voltage noise density of QCL (above), TeraFET (center), and TeraFET with a 40 % attenuated radiation power (bottom). Spectra exhibit the same frequency modulations caused by the table vibrations

transferred through the cables of the setup. Applied current of the QCL for corresponding graphs is shown in the legend and the dashed line shows the thermal noise curve of TeraFET. At higher radiation power, we see a simultaneously increasing noise level in TeraFET and QCL voltage.

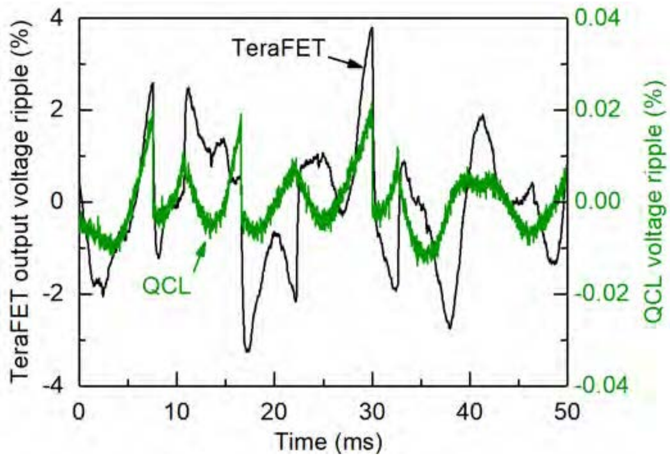

Fig. 4. Detected QCL and TeraFET voltage ripples.

Another important result making the TeraFET a better option for the heterodyne detection than a pyroelectric detector is an extremely low 1/f noise. At the bottom of Fig. 3 we show the TeraFET spectra when THz signal is 40 % attenuated. The dashed line shows the calculated thermal noise of the detector. We can see that the 1/f noise does not influence the spectrum and therefore the detector is very sensitive also for the real-time measurements of QCL power. Moreover, the noise of the detector does not depend on the QCL current and is only limited by the thermal noise to 20 nV/√Hz. And for the effective measurement bandwidth of 1 Hz the S/N ratio is 40 dB what shows the TeraFET ability to monitor the QCL power from a small fraction of the beam power (ca. 250 μW).

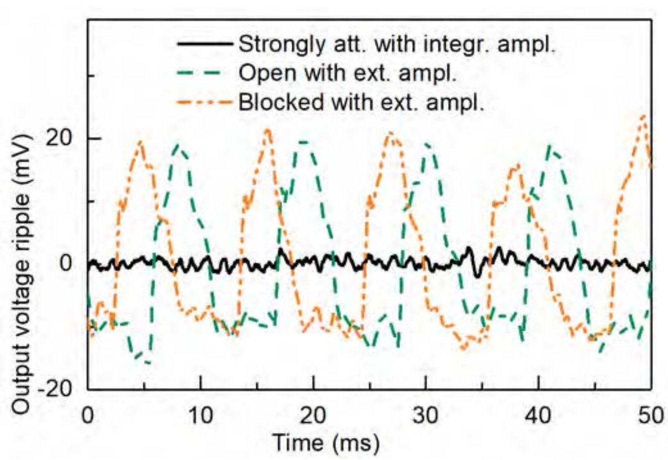

Fig. 5. Detected TeraFET signals with different amplifier configurations.

The measured signals of TeraFET response and QCL voltage are shown in Fig. 4. The QCL voltage ripple of 0.02 % can be monitored as 2 % ripple of the TeraFET signal. This phenomena has been caused by back reflections from the TeraFET. It can be seen that both distortions are equivalent in both noise spectra. We have achieved stable operation by replacing a 2 inch parabolic mirror by a Winston cone (data is not shown here).

The last issue we would like to mention from our experiments is the signal distortion using long coaxial cables and external amplifier. The Fig. 5 shows the time dependent signals measured with an external amplifier by blocked (dash dot line) and present (dash line) THz radiation in comparison to the integrated amplifier by a strongly attenuated THz signal which clearly reduced oscillations originating from cryocooler produced vibrations. Same oscillations are observed in reference Ge:Ga detector.

Conclusions and Discussion

We demonstrate a detector for application at 4.75 THz exhibiting an area-normalized minimal noise-equivalent power (NEP) of 404 pW/√Hz and a maximum responsivity of 75 V/W where the effective area is 1750 μm^2 and directivity reaches 7.4 dBi.

We demonstrate that the TeraFET detector has a linear power dependency in a whole power range of the QCL and can monitor the intensity of THz QCL radiation using a fraction of the beam power (ca. 250 μW) with S/N ratio of 40 dB.

We show a strong cross-correlation between the QCL voltage fluctuations and fluctuations at the detector output induced by a strong back-reflection. This fact directly proves that TeraFETs allow tracking of the intensity fluctuations on a millisecond time scale.

The reflection-induced intensity fluctuations in emitted QCL radiation can be improved by the use of attenuator, which reduce back-reflection or a Winston cone.

Since the TeraFET does not require chopping, it has an advantage over alternative room-temperature detectors (such like a pyroelectric sensor) and can be employed in a heterodyne instrument as a reference detector for real-time QCL power monitoring.

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