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# Highly Sensitive Room Temperature Heterodyne Detection with Stabilized Qc Lasers

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**Abstract**—A heterodyne detection system, made with unipolar devices operating @4.5 $\mu\text{m}$ , reaches a record noise equivalent power of 200 fW at room temperature. Key elements of this setup are frequency stabilized QC lasers and high-speed detectors.

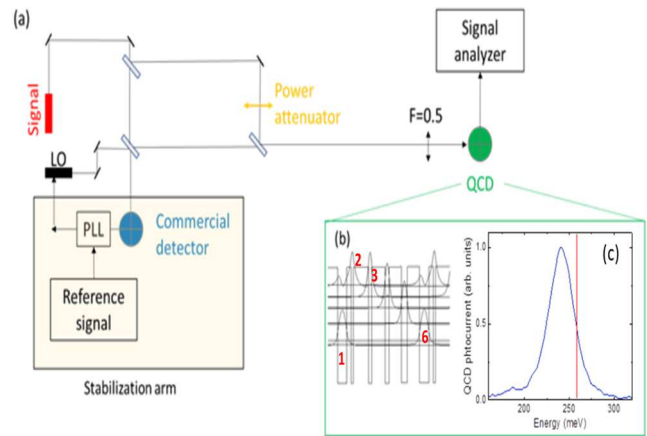
## I. INTRODUCTION

Promoting highly uncooled sensitive photodetection in the mid-wavelength infrared (MIR) range is a challenging open problem essential for many sensing applications such as LIDAR systems for measuring the velocity and distance of objects approaching vehicles, high-frequency free-space communication, quantum metrology [1-4]. A possible solution to this issue is the use of heterodyne detection where a weak signal is amplified by the beating with a powerful local oscillator on a fast detector (QWIPs and QCDs). Mid-infrared (MIR) quantum cascade lasers (QCLs) are reliable, powerful sources of radiation that can be used as local oscillators for coherent low-noise detection [5].

This work presents the latest progress on heterodyne detection using room temperature QWIPs and QCDs. We measure a noise equivalent power (NEP) of hundreds of fW, two orders of magnitude better concerning previous results [6].

QCLs are light sources in the MIR range (from 3 to 25 $\mu\text{m}$ ). However, their frequency stability is limited by many different external sources of noise. Therefore, the typical free-running linewidths are partially in the MHz level due to the noise that arises from electrical current [7] and other technical low-frequency fluctuations. However, the linewidth of the beating in a heterodyne setup can be strongly reduced by an active stabilization that locks the frequency of one laser to the other by injecting a corrective current derived from a phase-lock-loop (PLL) [8]. The heterodyne RF-beating is produced by two QCLs (one as a local oscillator and the other as the signal, 96 mW and 47 mW respectively).

In the experimental setup, two different paths have been implemented (Figure 1a). The first arm is for the active stabilization and the heterodyne beating is measured on a commercial photodetector (VIGO). The RF beating is compared to an RF stable reference signal and the PLL is used to actively change the injection current of the signal laser allowing us to stabilize the RF-beat note between the two lasers (commercial QCLs from AdTechPhotonics) down to the Hz level. The second is used to perform coherent detection measurements with stabilized laser on QWIPs and QCDs. Figure 1b presents the band structure of the 5  $\mu\text{m}$



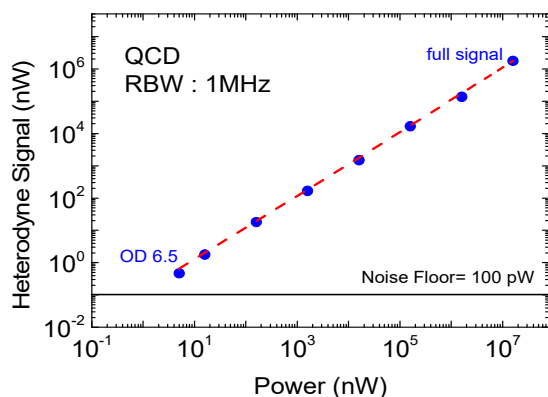
**Fig. 1.** (a) Diagram of the experimental setup, the yellow square shows the stabilization arm. The signal optical power is attenuated with optical densities (OD). (b) Band structure of the 5  $\mu\text{m}$  QCD and (c) Room temperature photocurrent spectrum (red-line shows laser emission line).

InGaAs/InAlAs quantum cascade detector, based on a diagonal transition design. Electrons are photoexcited from state 1 to state 2 by means of photon absorption. After the excitation, electrons relax quickly through interaction with longitudinal optical phonons into the ground state (from state 3 to 6). This unipolar detector operates in a photovoltaic regime. The appearance of a pseudo electric field due to asymmetry of the cascade region forces the electrons' movement towards one direction only, resulting in a photocurrent. The QCDs and QWIPs work at room temperature and are optimized for high-speed operation by fabricating an air-bridge structure which reduces the time constant of the effective RC circuit and thus allows greater frequency response. Figure 1c presents the room temperature photocurrent spectrum for the QCD at 5 $\mu\text{m}$  centered at energy very close to the laser emission line (red lines).

## II. RESULTS

To investigate what is the lowest power possible to detect, we use different optical densities (OD) to attenuate the signal. OD 1 corresponds to an attenuation of 1 order of magnitude, therefore, for the lowest signal measured, we had to attenuate of 6.5 orders of magnitude the initial signal power for QCD in case of free-running laser (no lock implemented at this stage). Figure 2 shows ( for QCD) the peak power of the heterodyne

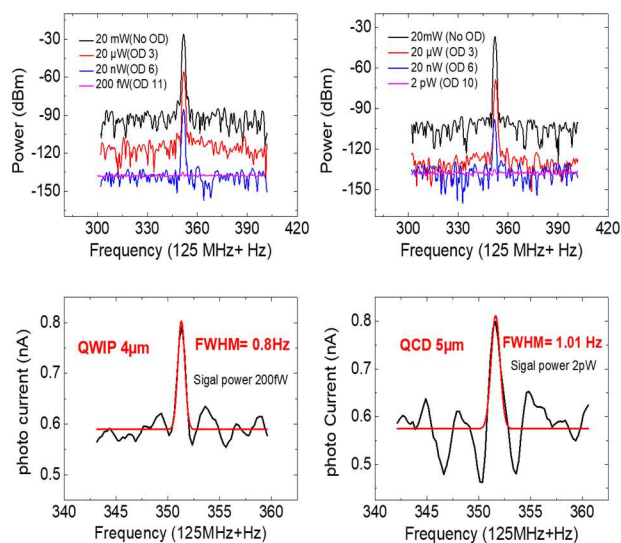
signal as a function of the signal power at the detector position in free-running mode (which means there is no phase lock between two lasers thus the beat note is shaking under a few MHz). The signal is amplified with low noise 10Kohm transimpedance amplifier. It's evident how, without any stabilization, at 5  $\mu\text{m}$  a linear behavior is maintained over 6.5 orders of magnitude with a resolution bandwidth of 1MHz (1MHz of resolution bandwidth is the limit for our setup due to instability of beat note). Starting from a full signal power of 15 mW at the detector position, for QCD NEP of 5 nW is obtained. In such a configuration, for the fixed resolution bandwidth (1MHz) the noise level is at 100 pW, limited by the thermal noise of the QCD.



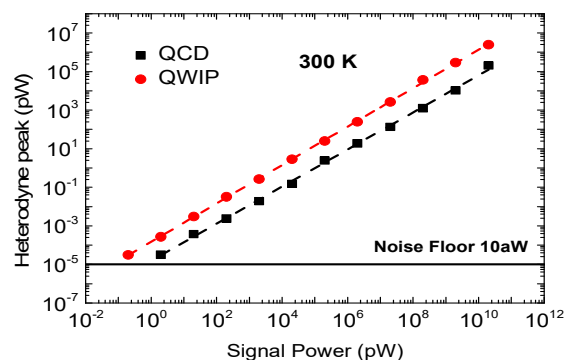
**Fig. 2.** Peak signal in nW measured on the QCD as a function of the optical power of the signal after attenuation at room temperature for a QCD in free-running mode (no active locking between two laser). Dashed line shows the linear fit.

Figure 3 stands for the actively stabilized setups at room temperature without any amplification. For the lowest signal measured, we had to attenuate of 10 orders of magnitude the initial signal power on QCD. The attenuation values should be increased to 11 orders of magnitude in the QWIP case, due to higher responsivity in comparison with QCD. Top panels display the different beating signals on the detectors at room temperature for different attenuation of the signal power (top left and right panels for QWIP and QCD respectively). The calculated heterodyne efficiency  $\eta$  is 55 percent. Lower panels show the stabilization of the laser down to Hz level using the spectrum analyzer at 1Hz of resolution bandwidth. As it is shown in the Gaussian fitting (red lines) the 1Hz FWHM is achieved for both cases (QWIP and QCD).

Figure 4 shows the attenuation of the heterodyne peak power for different signal power (red and black for QWIP and QCD respectively). QWIP shows higher peak power due to higher responsivity compared to the QCD. The signal detected displays a linear dynamic (dashed lines show the linear fit) range over 11 (10) orders of magnitude for QWIP (QCD). The noise floor of 10aW is limited only by the signal analyzer noise floor. Using this setup, we have been able to measure a signal power down to 200 fW for QWIP (2pW for QCD) at room temperature which is a 2 order of magnitude enhancement from the last measurement on the patch antenna QWIP at 9  $\mu\text{m}$ .



**Fig. 3.** Top panels: Beating measured for different attenuated signal power (left and right for QWIP and QCD respectively). Lower panels: Gaussian fit (Redline) of the heterodyne signal at RBW=1Hz.



**Fig. 4.** Peak signal in pW measured as a function of the optical power of the signal after attenuation at room temperature for a QWIP (in red) and QCD (black).

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