Regenerative Terahertz Quantum Detectors

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1. INTRODUCTION

Recent years saw an impressive development in the field of high speed / high frequency devices operating at THz wavelengths. Specifically, the demonstration and development of quantum cascade laser frequency combs first in the Mid-ir [1] and then in the THz [2] is having major impact in the field of spectroscopy [3] and holds high promise also for other areas such as telecom for the next 6G and local area networks [4]. As the development of THz QCL comb sources [5–7] and their understanding [8, 9] proceeds at a fast pace, the call for ultrafast, highly responsive THz detectors is imperative. Recent advances using graphene [10] and Quantum Well Infrared Photodetectors (QWIPs) inserted in nanoresonators [11] are promising but a highly responsive, ultrafast, high temperature, broadband THz detector is still lacking. We propose here an implementation of the concept of regenerative amplification for the detection of THz radiation. We leverage on the ultrafast dynamics of the quantum cascade active medium driven to perform resonant detection. In a regenerative amplifier, a very large overall signal gain is achieved by positive feedback onto the input of the amplifier. Initially developed and used in early radios [12], this approach was also considered for optical systems since a laser below threshold can be seen as a regenerative amplifier [13]. Low-light signal detection using regenerative amplification was nevertheless investigated experimentally [14, 15]. The key disadvantage of regenerative amplification is its narrow bandwidth, which is the reason why it is employed in optical systems mostly for amplification of short pulses [16] and not for the detection of optical signals. Indeed, in the visible and near infrared photodiodes combining very large quantum efficiencies (η > 0.5) and low dark currents, combined with low noise electronics, enable extremely sensitive optical receivers to be realized.

In contrast, in the THz this approach is much less attractive since the photon energy is smaller than \( k_B T \) at room temperature. Indeed, quantum cascade detectors [17] and quantum well infrared photoconductors [18] operating in the THz have been reported, with high frequency capabilities [19]. Nevertheless, and in contrast to the situation in the mid-infrared where the use of optimal doping [20] combined with microcavities [21] enabled the operation up to room temperature, the THz QCDs [11] operate below liquid nitrogen temperatures, and excellent performances are typically obtained at 4 K. The situation is even more extreme in superconductor hot electron bolometers where very low NEPs are achieved at millikelvin temperatures [22].

Quantum cascade lasers based on intersubband transition have enabled the generation of coherent radiation in the mid-infrared and the development of sensing applications because of their capability to operate at room temperature. The recent improvement of terahertz quantum cascade lasers, based on the simultaneous use of larger band discontinuities combined with a simple two-well quantum cascade structure and numerical optimization, has brought the operation temperature of these devices in the range of thermoelctric (Peltier) coolers [23–25].

One unique property of quantum cascade lasers is their ultrafast photon-driven transport, arising naturally from the combination of tunneling electron injection and an ultrashort upper state lifetime. As a result, the voltage-current characteristic of the device shows a sharp conductance discontinuity at threshold as the photon-driven transport is added to the non-radiative current [26]. The ultrafast nature of the response to that current is responsible for the very strong beatnote appearing at the round trip frequency observed in quantum cascade laser frequency combs; in this situation the laser is detecting its own radiation above threshold, we anticipate that a photocurrent can be induced in a quantum cascade laser driven below threshold but such that the active region, containing \( N_p \) periods has a gain of \( g \) at the photon energy \( h\nu \). The photocurrent generated in a
Fig. 1. A resonantly amplified quantum cascade detector (RAMP-QCD). a) Schematic representation of the resonant cavity with the different terms entering equation for the responsivity. b) Experimental setup: The source laser is driven in pulsed mode and its emission focused onto the detector laser driven in continuous wave below threshold. The signal is detected on a 150 Ω load resistor placed in series with the laser. The different components of the patch-array antenna-single mode QCL are indicated on the representation of the source laser. c) Spectra of the luminescence of the detector laser below threshold (blue) and of the emission source laser above threshold (orange). d) Detector responsivity as a function of source frequency for different detector bias currents. For each current the experimental data are fitted with equation. The values of gain resulting from the fit are reported in e) as a function of the detector bias current. The points corresponding to the curves reported in d) are indicated by the colored ⋆.
an amount $\hbar \Delta$ is proportional to their population difference $\Delta n$:

$$J(\Delta, \Delta n) = \frac{2e\Omega}{\tau_{\parallel}} \frac{\Delta n}{\Delta^2 + 1/\tau_{\parallel}^2} \tag{5}$$

where $\tau_{\parallel}$ is the in-plane scattering lifetime and $\hbar \Omega_{21}$ the coupling between the two subbands. When combined with a rate equation for the upper state and assuming a constant total electron density between the two subbands, the expression 5 yields for the current density for a given radiative current $J_{rad}$ from the upper state:

$$J(\Delta, J_{rad}) = \frac{2e\Omega}{1 + \Delta^2 + 4\Omega^2_{21} \tau_{\parallel}} \left(n_s + \frac{2\tau_3}{e}J_{rad}\right), \tag{6}$$

where $\tau_3$ is the upper state population lifetime. Equation 6 reverts back to the well-known result at $J_{rad} = 0$. Using the above result, the differential photoresistance (per period) can be extracted by computing

$$R_d = \frac{\hbar}{e} \frac{\partial J}{\partial J_{rad}} \bigg|_{J_{rad} = 0} = -\frac{\hbar}{e^2 \Delta n_s} \frac{\tau_3}{\tau_{\parallel}} \left(\Delta^2 \tau_{\parallel}^2 + 1 + 4\Omega_{21}^2 \tau_{\parallel} \tau_{\parallel}\right) \tag{7}$$

This resistance is in general smaller than the differential resistance of the structure operated below threshold:

$$R_{nr} = \frac{\hbar}{e} \frac{\partial J}{\partial J_{rad}} \bigg|_{J_{rad} = 0} = -\frac{\hbar}{e^2 \Delta n_s} \frac{\tau_3}{4\Omega_{21}^2 \tau_{\parallel}^3} \tag{8}$$

Indeed, the ratio of these two resistances is given by

$$\frac{R_d}{R_{nr}} = -\frac{4\Omega_{21}^2 \tau_{\parallel} \tau_{\parallel}}{\Delta^2 \tau_{\parallel}^2 + 1 + 4\Omega_{21}^2 \tau_{\parallel} \tau_{\parallel}} \tag{9}$$

As the photovoltage is proportional to $R_d$ and the noise voltage (caused by shot noise) to $R_{nr}$, it is of course desirable to bring the above ratio as close to unity as possible. This is the case for thin injection barriers in the strong coupling limit defined by

$$4\Omega_{21}^2 \tau_{\parallel} \tau_{\parallel} \gg 1 \tag{10}$$

This result enables us to write the noise equivalent power of the device, assuming the noise is dominated by the shot noise:

$$\text{NEP} = \frac{\sqrt{2e\hbar B}}{R_{\parallel}} \frac{R_{nr}}{R_d} \tag{11}$$

where $i_d$ is the current and the noise is detected in a bandwidth $B$.

2. EXPERIMENTAL RESULTS

An implementation of the Resonantly AMPlified Quantum Cascade Detector (RAMP-QCD) is achieved exploiting a patch-array antenna-single mode QCL [29] Fig. 1 b). The device consists of a double metal waveguide with a distributed Bragg reflector (DBR), acting as a high reflectivity mirror, and a first order distributed feedback (DFB) grating acting as a narrow-band front mirror. The two mirrors are designed with the help of finite element simulations performed with COMSOL which yielded a back mirror reflectivity of $R_{\text{back}} = 0.95$ [30] and a front mirror reflectivity of $R_{\text{front}} = 0.85$ with a bandwidth of $\approx 100\text{GHz}$ [supporting material section 1 (SM1)]. A patch-array antenna, integrated with the top metal contact, provides for efficient light out-coupling. At the same time it eases the in-coupling of light into the double metal waveguide, thus making the device suitable to work both as laser and RAMP-QCD. An in-coupling efficiency of $18\%$ is estimated with a full-wave 3D numerical simulation performed with the software CST [SM1].

Two devices are used in the experiment, the emission of one laser, used as source, is focused onto the second, which is kept below threshold and is used as detector (see experimental layout in Fig. 1 b). The spectra of the two lasers are centered around the same frequency (4.737 THz) as shown in Fig. 1 c), where the luminescence of the detector laser is compared with the spectrum of the source laser above threshold. The optical resonant response of the detector is measured by temperature tuning the source laser in the range 10-55 K for fixed values of the detector laser current. As the detector bias is increased but maintained below threshold, the gain of the structure grows, resulting in a higher responsivity and a narrower optical bandwidth. For current values above threshold the radiation emitted by the active region of the detector rapidly overcomes the incoming one. As shown in Fig. 1 d) where the computed responsivity is reported as a function of optical frequency, the resonant nature of the detector is clearly apparent. This resonant behaviour can be described with good accuracy by our model where $R_{\text{f/d}} / W = I_{ph} R_d / P_{in}$ and $I_{ph}$ is computed from Eqn. 3, assuming values of parameters described in detail in [SM1]. In particular, the values of optical gain assumed to compute the responsivities as a function of bias current are shown in Fig. 1 e). The optical efficiency $\eta_{opt} = 12\%$ is deduced from a comparison of the slope efficiency of the laser with the theoretical value. For each value of the injected current, the fit also yields a value of the differ-

![Fig. 2. Non-radiative differential resistance ($R_{nr}$) and photore- sistance ($R_d$) as a function of energy detuning $\Delta$. The orange * represent the experimental non-radiative resistances ($R_{nr-exp}$) measured in CW at a temperature of 20 K. The non-radiative resistance calculation based on the Kazarinov-Suris model (Eq. 8) is depicted with the orange solid line, the dashed line represents the same quantity with the addition of the series resistance ($R_{series} = 22 \Omega$). The photoresistance is reported in blue. The * indicates the values resulting from the fitting of the experimental measurement of responsivity with equation 3 ($R_{d-exp}$), while the solid line indicates the calculation based on the Kazarinov-Suris model $R_{d-KS}$ (Eq. 7).](image-url)
well with the computed one if one assumes an additional series (Fig. 3 a), i.e. when the source and detector laser frequencies pling between the injector and the upper state wavefunction noise to $R_{\text{NR}}$ noise of the detector. As the signal is proportional to $R_{\text{NR}}$, an improvement of this ratio would also benefit the NEP. A key feature of this approach to detect THz radiation is that the peak responsivity does not depend on the detector’s temperature as long as it is below the maximum operating temperature of the laser. The decrease of upper state lifetime due to temperature increase indeed only shifts the threshold to higher values, resulting in a slightly larger noise level. As a result, the detector performances are expected to show only a weak temperature dependence.

The detector’s temperature dependence is investigated experimentally and shown in Fig. 3 b). In this measurement, a detector laser with a slightly higher central frequency is used such that the frequency matching between source and detector QCL is obtained when the temperature of the source is smaller than the one of the detector. The result shows that the peak responsiveness stays approximately constant until 80 K ($T_{D\text{-max}}$), temperature at which the detector cannot reach its threshold anymore [SM3]. Below $T_{D\text{-max}}$ the peak responsivity lies in the 20 - 25 V/W range. This value is comparable with the one obtained with the detector laser used in the previous experiment. Above the maximum operating temperature, the maximum gain of the active region starts to decrease resulting in a reduced peak responsivity. The NEP relative to each point is computed from the bias current shot noise. Despite the fact that at higher temperatures the maximum responsivity is obtained at higher currents, the NEP does not increase dramatically, thanks to the decrease of non radiative resistance with temperature. Above $T_{D\text{-max}}$ the decrease of gain, hence of responsivity, causes a substantial increase in NEP.

Another fundamental advantage of exploiting QCLs for THz radiation detection is that, thanks to the ultrafast nature of the photon-driven transport in a QCL, the response of the RAMP-QCD can be extremely fast. The fact that electrical beatnotes...
Fig. 4. Optical detection of beatnote at GHz frequencies. (a) Comparison between the Active Region (AR) electroluminescence and spectrum of the source laser. The AR luminescence (blue trace) is measured on a 0.345 mm long and 70 µm wide non-lasing device biased at 8V and kept at 10 K [6]. The source laser spectrum (orange trace) is measured with a Bruker Vertex 80 FTIR. The laser is kept at 15 K and driven CW at $I_S = 290$ mA. Schematic of the experimental set-up b). The source and detector laser are placed on the foci of the parabolic mirrors. Both lasers are driven in CW, a 50 Ω load resistor is placed in series with the current source of the detector laser. A Rohde&Schwarz FSW-67 spectrum analyzer is also connected to the detector QCL through a bias-tee. Optical beatnote map as a function of detector bias current c). The source laser bias is fixed at 290 mA and kept at 15 K. The detector laser temperature is 25 K and its bias is swept from 135 mA to 151 mA. The spectrum analyzer is operated with a resolution bandwidth of 10 kHz. For each current the measurement is averaged on 20 samples. The electrical beat note measured on the bias tee of the source laser is reported in the inset. Maximum value of the beatnote intensity as a function of detector current e). The grey area indicates the region above threshold which is, in this configuration, $I_{D-th} = 148.4$ mA.

of the order of several tens of GHz can be observed in THz QCL frequency combs [6, 31–33], suggests indeed that the cut off frequency of the RAMP-QCD response should lie in the same range. The easiest way to verify this hypothesis is to optically measure the beatnote of a THz frequency comb employing the RAMP-QCD. The device presented so far is strictly single-mode above threshold, therefore it is not suitable for this purpose. For this reason a pair of lasers based on a broadband active region [6] is used, whose emission is centered around 3 THz (Fig. 4 a) blue trace). The devices consist of a double metal waveguide ridge 2 mm long and 40 µm wide. A silicon lens is placed on the front facet in order to lower its reflectivity and optimise the coupling inside/outside of the ridge. The source laser is placed in one of the foci of the setup and biased in CW at $I_S = 290$ mA. At this current the laser is in a comb state, displaying a wide spectrum with a bandwidth of $\approx 900$ GHz and a single electrical beatnote at $\approx 20$ GHz (Fig 4 a) orange trace, d). The electroluminescence of the detector (blue trace, Fig 4 a) overlaps very well with the laser’s signal. The detector is placed in front of the other mirror and connected to a spectrum analyzer through a bias-tee, and always biased below lasing threshold. In this configuration a clear optical beatnote can be observed on the spectrum analyzer for different bias of the detector laser (Fig 4 c), thus confirming that the electrical bandwidth of the detector is as high as 20 GHz. We would like to underline that we are not detecting the heterodyne signal of the incoming laser signal with the detector’s coherent field, as the detector is always below threshold. The detected signal is the optical beating of the modes of the comb inside the detector’s cavity, amplified by the detector’s gain. The increase of the gain as the detector current is brought towards the threshold is also reflected into an increase of the optical beatnote intensity (Fig 4 c, e).

3. DISCUSSION AND CONCLUSION

We presented the application of the concept of regenerative amplification to THz detection exploiting QCL active regions as gain medium. The ultrafast photon driven transport that characterises QCLs offers the possibility of reaching high responsivities, wide electrical bandwidths and high operating temperatures. A very promising outlook on future device architectures comes from the inspection of Eqn.4: a microcavity device would lead to
responsivities up to 80 kV/W and NEP down to 1.5 pW/Hz\(^{1/2}\) for a (10 x 10) \(\mu\)m\(^2\) microresonator with a quality factor \(Q=20\) and 2.5 kV/cm\(^2\) current density operating at 3.9 THz [24]. Such active region characteristics correspond to the high performance 2-well operating up to 210 K; in this perspective we would obtain a highly responsive device up to high temperatures. The inherent ultrafast bandwidth of the detection mechanism would then be fully exploited in a microcavity geometry that reduces to the minimum the capacitive and inductive parasitics. Studies using lenses-coupled broadband lasers proved the possibility of recording optical beatnotes, thus confirming that bandwidths as high as 20 GHz can be reached with our approach and very likely can be extended to much higher frequencies as electrical beatnotes from THz QCLs have been detected up to 50 GHz and higher [33]. Regenerative amplification proves to be an effective method for detecting THz radiation and has the potential to overcome the existing technology.

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