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ABSTRACT

In a Quantum Cascade Detector, photocurrent is generated by the absorption of infrared and terahertz radiation in the quantum-well-based modules arranged in series. Consequently, the current responsivity is by construction inversely proportional to the number of cascading modules. Upon absorption of a photon, the electron travels through only a single period of the detector, with a mean free path corresponding to the period length. Therefore, the shot noise power density is expected to decrease by the same factor under sufficiently high illumination, reflecting the same inverse relationship with the number of cascading modules. This phenomenon leads to sub-Poissonian noise characteristics. We experimentally observe this effect in a 90-period Quantum Cascade Detector operating at 4.5 μm, confirming a reduction in the shot noise contribution by the anticipated Fano factor of 1/90. This measurement underscores the suitability of these detectors for coherent detection scenarios, particularly where shot noise dominates.

In heterodyne measurements, where a weak signal is mixed with a strong local oscillator at a slightly different frequency, shot noise will be the dominating noise source if large enough local oscillator powers can be injected in the detector.[1] Unlike other noise sources that can be mitigated, shot noise remains intrinsic due to the stochastic nature of the charge carriers' arrival times.[2] Its crucial role in constraining measurement sensitivity is thus underscored.

One detector type that is employed for such heterodyne measurements in the mid-infrared and THz spectral region is the Quantum Cascade Detector (QCD). This unipolar device is based on intraband transitions in thinly stacked semiconductor layers. Due to their cascaded extractor regions, bias-free operation enables low-noise detection schemes at high optical intensities.[3,4] In addition to these favorable inherent noise properties arising from the absence of dark currents, sub-Poissonian noise statistics are expected to apply to the shot noise of QCDs.

Landauer[5] showed that for mesoscopic resistors, where carriers undergo stochastically independent motion over a path of length l smaller than the total sample length L, shot noise is reduced by a Fano factor of l/L to enter the sub-Poissonian regime. This noise reduction is also anticipated for QCDs comprised of N periods, since upon photoabsorption, an electron traverses a single cascade through multiple scattering events, covering $1/N$-th of the total detector thickness. Consequently, N photons need to be absorbed for the transport of an electron across the full detector region L, resulting in a responsivity that is inversely proportional to the number of modules N. This $1/N$-proportionality is predicted to equally apply to the noise spectral power density of a QCD.[6,7] This can be seen in the prefactor of the universal microscopic current noise formula:

$$S_I^{micro} = \frac{2e}{N}\left(I^+ + [I^- + I_{opt}]\right). \tag{1}$$

Here, we consider a QCD operating under illumination, generating an optical current I_{opt}. The elementary charge is denoted as e, and I^+ and I^- represent currents in opposite directions.[2] As a consequence, both the responsivity and shot noise of a QCD experience an attenuation by a factor of 1/N, thus preserving a signal-to-noise ratio that remains independent of the number of periods.

It is worth noting that Eq. (1) considers both shot noise and thermal Johnson–Nyquist noise, treating them as indivisible, in line with the theoretical approach of Landauer and Delga *et al.*[5,6] In practice, especially when examining limiting cases, it is convenient to treat the two noise sources as additive. Throughout this work, we refer to shot noise as the excess noise generated by optical illumination. While the dark noise of the QCD has been explored both in theory and experiment,[8] its photocurrent noise gain has so far eluded experimental confirmation.

In this work, we measure the noise characteristics of a QCD under increasing illumination and are able to retrieve the expected noise gain of $1/N$. Given that the contribution of shot noise is relatively small compared to other noise sources in the system, namely Johnson–Nyquist noise and laser noise, we employ a differential technique to specifically extract the contribution of the photocurrent.

For that purpose, we devised a setup (see Fig. 1) consisting of a fast **QCD** (P16309-01, Hamamatsu Photonics)[9] under illumination by a high-power 4.5 μm quantum cascade laser (**QCL**) up to the detector's saturation around 250 mW (see Fig. S4). When the QCL is operated below approximately 380 mA, it exhibits lasing in a narrow spectral range that strongly differs from the coherent low-noise broadband comb operation seen at higher currents (see also Figs. S1–S3).[10,11] To comprehensively capture the AC-components of both the laser's current and the detector's photocurrent, we used synchronized spectral analyzers **SA1**/**SA2** (FSW67/FSW26, Rohde & Schwarz) in the frequency range of 6–18 GHz. Analysis of the modulation of the laser current allows us to monitor the state of the quantum cascade laser and account for laser noise, while the root mean square of the detector's photocurrent provides a measurement of the total noise spectral density (see Fig. S5). As measurements were performed significantly above the system's corner frequency, any potential contribution of the 1/f-noise is expected to be negligible. Additionally, we employed a low-noise preamplifier **A** (ZX60-06183LN+, Mini-Circuits) with a noise figure of 2.1 dB and a gain of 25 dB to mitigate excess amplifier noise. Simultaneously, the DC-photocurrent of the QCD was monitored through a transimpedance amplifier **TIA** (DHPCA-100, Femto) connected to a multimeter **V** (34465 A, Keysight) to determine the photo-induced current (I_{opt}). Finally, to reduce slow variations of the Johnson noise due to temperature instabilities, water cooling was applied to amplifier **A**.

To extract the shot noise of the QCD, four main steps were carried out in the data analysis. First, the electrical spectra obtained from the QCL were examined using a peak-finding algorithm to categorize each laser state as either a coherent comb state (low phase noise) or a decoherent multimode state (high phase noise), based on the prominence and linewidth of the beatnotes around 10 GHz (see Fig. S3).[10,11] In this context, the presence of an electrical beatnote is taken as evidence of a frequency comb since it results from the interaction of equidistant lines within the optical spectrum. Second, the beatnote was identified and masked in the data measured simultaneously on the QCD to retain only the noise floor, which was then averaged. Subsequently, the interpolated average noise of the intermediate dark measurements was subtracted from the illuminated case. This procedure enabled the determination of the relationship between excess bright noise and photocurrent (see Fig. 2). After identifying outliers using the random sample consensus (RANSAC) algorithm,[12] the remaining data were separately linearly fitted for the high and low phase noise regimes (see Fig. 3). Since the initial decoherent multimode regime contains

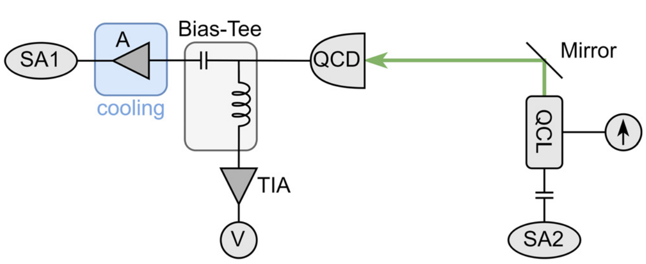

FIG. 1. Experimental setup. A quantum cascade laser illuminates the QCD, whose AC and DC outputs are tracked, respectively, on a spectral analyzer (SA1) and a voltmeter (V) after amplification (A, TIA). Simultaneously, a second spectral analyzer (SA2) monitors the state of the laser by measuring its electronic beatnote.

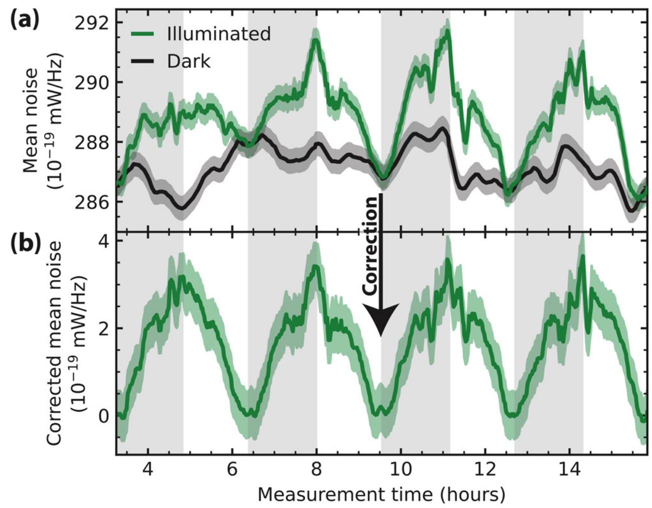

FIG. 2. Noise data background correction. (a) Comparison of spectrally averaged noise on the QCD with (green) and without (black) illumination, with shaded standard deviation. (b) The dark noise is interpolated and subtracted from the illuminated case. The resulting corrected noise (green) exhibits a distinct dependence on the incident optical power as the laser is ramped up (gray shading) and down (no shading) repeatedly during several hours of measurement.

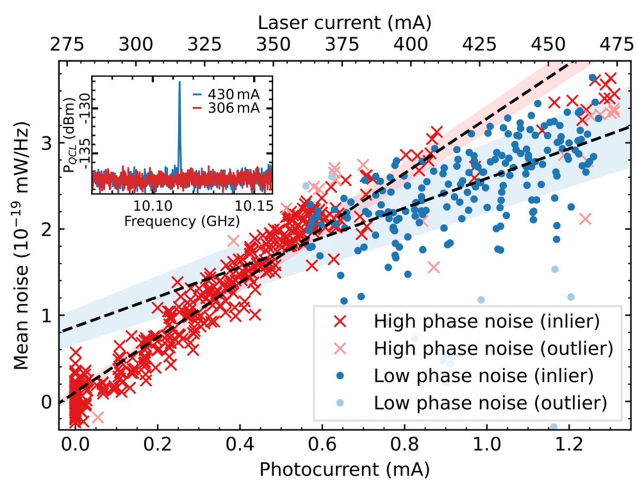

FIG. 3. Sub-Poissonian shot noise. Mean noise power densities in the low (blue) and high (red) phase noise regimes of the QCL for increasing laser currents (top axis) and photocurrents in the QCD (bottom axis). The inset illustrates the qualitative difference between the two operation regimes, showcasing the presence (absence) of an electrical beatnote for the low (high) phase noise regime at laser currents of 430 mA (306 mA). The fitted slope (black with shaded fit uncertainty) in the low phase noise regime experimentally underpins the noise gain of 1/N in the QCD.

excess relative intensity noise of the laser, the mean noise depends more sensitively on the photocurrent and displays a higher slope (red in Fig. 3). It is, therefore, unsuited to determine the Fano factor of the shot noise suppression and instead only the data taken from the comb regime is further analyzed.

The measured slope of the mean noise in the coherent low phase noise state of the laser, $(1.72\pm0.20) \times 10^{-19}\mathrm{WHz}^{-1}\,\mathrm{A}^{-1}$, corresponds to the upper limit of the sought-after prefactor of the shot noise. It aligns closely with the theoretical value $2eR/90 = 1.78 \times 10^{-19}$ $\mathrm{WHz}^{-1}\,\mathrm{A}^{-1}$ in Eq. (1), where $R = 50\,\Omega$ is the resistance of SA1, with a deviation of only 0.3 σ. This corresponds to an inverse Fano factor of $N = 93\pm11$ for the investigated 90-period QCD. The high uncertainty of this result (shaded blue in 3) arises from instabilities of the different comb configurations (see Figs. S2 and S3). This agreement confirms the theoretical prediction, thereby experimentally corroborating a noise gain in a QCD equivalent to the inverse of its number of periods—in this instance, 1/90.[9]

Looking forward, the QCD's potential finds special relevance in multi-heterodyne dual-comb experiments.[13] Despite its limited responsivity, combining QCDs with low-noise amplifiers achieves a favorable signal-to-noise ratio. Leveraging the QCD's inherent high absorption quantum efficiency,[8] it becomes a promising candidate for dual-comb setups, advancing high-precision spectroscopy and related applications.

See the supplementary material for details on the QCL used within this work, including further explanation of its two operating regimes, as well as technical data on the QCD.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Ina Heckelmann: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Mathieu Bertrand:** Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal). **Andres Forrer:** Formal analysis (equal); Software (supporting); Supervision (equal); Writing – review & editing (equal). **Mehran Shahmohammadi:** Resources (equal); Writing – review & editing (equal). **Mattias Beck:** Resources (equal); Writing – review & editing (equal). **Jerome Faist:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in ETH Research Collection at https://doi.org/10.3929/ethz-b-000651144, Ref. 14.

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