

Electron-to-photon noise transfer in midinfrared semiconductor lasers

Irene La Penna¹,* Tecla Gabbriellini², Simone Borri, Luigi Consolino, Francesco Cappelli³, and Paolo De Natale⁴

LENS—European Laboratory for Non-Linear Spectroscopy, Via Carrara 1, 50019 Sesto Fiorentino, Florence, Italy and

CNR-INO—Istituto Nazionale di Ottica, Largo Fermi 6, 50125 Florence, Florence, Italy

Borislav Hinkov⁵

Silicon Austria Labs GmbH, Europastraße 12, 9524 Villach, Austria

Robert Weih⁶

Nanoplus Nanosystems and Technologies GmbH, Gleimershäuser Straße 10, 98617 Meiningen, Germany

Naota Akikusa

SSD Advanced Innovation Headquarters, Hamamatsu Photonics K.K., Shizuoka, 431-2103, Japan

Lorenzo Mischi⁷ and Alessio Montori⁸

ppqSense, Viale Ariosto 492B, 50019 Sesto Fiorentino, Florence, Italy

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Noise characteristics of state-of-the-art light sources are crucial parameters in understanding their limitations regarding quantum applications. This work describes a method to study the electrical noise transfer of current driver sources to the intensity noise of midinfrared emission by commercial quantum and interband cascade lasers (QCLs and ICLs, respectively). A current driver with sub-shot-electrical-noise in a specific frequency range (up to 10 dB below the shot-noise level) was developed for this purpose. This enables testing of the performance of midinfrared lasers when they are driven via such a quiet pump source. By using this current driver, we identify the fundamental noise of a QCL and an ICL, which is the laser intensity noise resulting solely from the internal dynamics of the laser under test. The proposed method allows us to retrieve the noise transfer function from current to light, showing that the main limitations in observing the quantum properties of the emitted photons come from laser excess noise and poor matching between the laser and the detection system in terms of bandwidth and optical power. From the analysis of the measured parameters, we highlight current technological limitations and suggest which key features should be optimized in midinfrared systems for matching the performance required by quantum applications.

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I. INTRODUCTION

The control and reduction of frequency and intensity noise of coherent-light sources are of broad interest for different applications, such as metrology, interferometry, and spectroscopy, which require highly stable light sources [1–3]. In the unceasing quest to increase the sensitivity and precision of midinfrared (MIR) spectroscopy techniques,

the frequency noise of the most commonly used compact light sources, which are quantum cascade lasers (QCLs) and interband cascade lasers (ICLs), has been extensively studied. Previous studies include theoretical modeling and validation [4–8] as well as development of novel techniques aimed at narrowing the laser linewidth [9–16]. However, less effort has been put in the reduction of intensity noise, with only a few literature entries accounting for its study in MIR lasers [3,8,17–21]. This is despite it being a key quantity for several topics, including sensing and communication [22,23]. Such applications would significantly benefit from the use of low-intensity-noise optical sources, which would increase the signal-to-noise ratio drastically. Recently, the development and commercialization of novel technology in the MIR region is opening up

*Contact author: lapenna@lens.unifi.it

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the possibility of accessing squeezed states of light in this spectral region [24]. The emission of potentially quantum-correlated twin beams was predicted to occur in QCLs emitting harmonic frequency combs [25,26] since these devices exhibit high intrinsic nonlinearities characterizing their active medium [27]. In particular, their high third-order nonlinearity triggers intermodal four-wave-mixing processes among the generated emission modes [25,28]. The first successful attempt to set up a balanced detector capable of detecting nonclassical states of MIR light (i.e., signals below the shot-noise level of reference) is reported in Ref. [24]. This detector has been applied to test state-of-the-art MIR laser sources [20,21,29] and correlated twin modes emitted by QCLs [25]. This configuration allowed the observation of correlations at the classical level. However, the excess intensity noise in harmonic combs emitted by QCLs prevented the revelation of correlations at or below the shot-noise level. Recently, ICLs have also emerged as interesting candidates for possible nonclassical light generation [20,21]. The possibility of generating frequency combs resulting from nonlinear effects in QCLs is similarly present in ICLs [30,31]. This makes ICLs, in principle, also capable of producing squeezed states of light.

Triggered by these possible applications, this work describes and assesses a method to study the reduction of the intensity noise of MIR lasers. This is done by our following the path suggested by Yamamoto *et al.* [32], i.e., pumping the laser with a quiet pump to reduce the intensity fluctuations of the emitted light. The hypothesis of a transfer of the statistics from the pump process to the emitted light was first theoretically described by Golubev and Sokolov [33] in 1984. In electrically pumped devices, the electron statistics of the bias current is transferred to the emitted light proportionally to the quantum efficiency of the optical emission process, possibly yielding a sub-Poissonian emission. To date, the generation of sub-shot-noise radiation has been observed with the use of high-efficiency, near-infrared semiconductor lasers pumped with a low-noise current [34–39]. This well-established technique is applied in the work reputed here to MIR laser sources via a custom-made ultralow-noise (sub-shot-noise-level) current driver. For this purpose, we measure the electron-to-photon noise transfer in two different MIR cascade devices to compare their specific performance.

To sum up, this work aims at assessing the possibility of intensity noise reduction in MIR cascade lasers by using a sub-shot-noise drive current. This is done by our studying and quantifying the contribution of electrical current fluctuations to the intensity noise of radiation emitted by QCLs and ICLs. In addition, we evaluate the suitability of the tested lasers and the detector to perform quantum measurements in the MIR region in view of future improvements.

II. METHODS AND DISCUSSION

A. Device characterization

Typically, noise analysis requires preliminary measurements to qualify both the lasers to be characterized and the detector used, as well as an optimized noise-suppressed current driver, as detailed below.

1. Lasers

Concerning the devices under test, a characterization of light-power-current-voltage (P - I - V) curves and emission spectra has been performed. The candidates for this comparison are two MIR lasers whose active region is based on multiple quantum wells but relies on different light-generation mechanisms. These lasers, whose device structure is explained in detail in Appendix A, are (1) a ridge-waveguide distributed-feedback (DFB) ICL whose emission wavelength is approximately 4.5 μm and (2) a commercial ridge-waveguide DFB QCL emitting at 4.57 μm . In the following, we refer to them simply as ICL and QCL, respectively.

The optical spectra of the lasers are presented and discussed in detail in Appendix B (see Fig. 7), to ensure that both lasers have single-mode emission under all operating conditions investigated. This ensures that no extra noise and irregularities in the power versus current curves are introduced by the presence of multiple modes. The P - I - V curves of the two lasers operating in continuous-wave (cw) mode at room temperature are displayed in Fig. 1. In each plot, an orange-shaded area has been added to visually show the region of operation that was investigated in the noise measurements for each laser [e.g., the region under study for the QCL ranges from 120 to 180 mA, as visible in Fig. 1(a)]. We see that while the slope of the QCL's P - I curve is almost constant after reaching the threshold current, the corresponding value for the ICL changes at approximately 70 mA [Fig. 1(b)]. This coincides with a mode jump as described in Appendix B. The range of drive current for the noise analysis is chosen such that the laser has the widest possible range of operation while maintaining a stable regime of emission during modulation. From the P - I curves, it is possible to extract the electron-to-photon conversion rate. This parameter, defined for electrically pumped lasers, is called the “laser “quantum efficiency” (QE). More precisely, the QE is the ratio between the number of generated photons and the number of pumped electrons, per stage, of the active medium. The QE at a certain operating point can be calculated as the power P at a bias current I_{bias} , multiplied by the electron charge e , divided by the energy of the emitted light $h\nu$ and by the number of cascade stages N_C :

$$\eta_Q = \frac{P/h\nu}{I_{\text{bias}}/e} \times \frac{1}{N_C} = \frac{P}{I_{\text{bias}}} \times \frac{e}{h\nu} \times \frac{1}{N_C}. \quad (1)$$

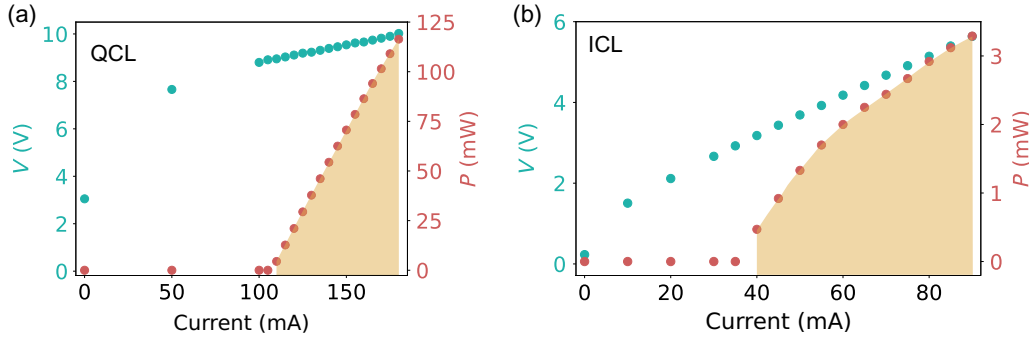


FIG. 1. Measured cw P - I - V curves at $T = 20^\circ\text{C}$ of (a) the QCL and (b) the ICL. The turquoise circles represent voltage, while the pink circles represent optical power, both as a function of the applied current. In both plots, the orange-shaded region represents the range of bias current that was investigated in the subsequent noise analysis. The orange area highlights the profile of the P - I curve, showing that the slope of the line is not constant in the region under test for the ICL. The laser temperature is the same as the one used later in the noise analysis.

A further device-characterizing parameter that can be extracted from the P - I - V curves is the wall-plug efficiency (WPE), which is the fraction of electrical power that is converted into optical output power of the respective laser. The WPE can be calculated as the ratio between the optical power P measured at the output and the input electrical power $P_{\text{el}} = V \times I_{\text{bias}}$, where V is the voltage applied to the laser chip:

$$\eta_{\text{WPE}} = \frac{P}{V \times I_{\text{bias}}}. \quad (2)$$

Table I reports the QE and WPE of the two lasers calculated at their maximum attainable operating points, where both the QE and the WPE are also at their maximum. From Table I, it is observed that the QCL shows better performance in terms of both WPE and QE (η_{WPE} 6.4% and η_Q 9.5%) than the ICL (η_{WPE} 0.3% and η_Q 2.2%).

2. Detector

The detector used is a commercial Vigo mercurium-cadmium-telluride (MCT) detector (PVI-4TE-5-2x2) with a nominal bandwidth of 175 MHz. The detector responsivity, i.e., the slope of the linear trend of generated photocurrent when plotted against incident power, is 1.48 A/W, leading to a quantum efficiency (ratio between the number of generated electrons and the number of incident photons) of 41% for incident radiation at a wavelength of

4.5 μm . For the same wavelength, saturation occurs when the incident power exceeds approximately 1 mW. Finally, the detector background noise level is on the order of $1 \times 10^{-5} \text{ nA}^2/\text{Hz}$. Note that the declared background noise is obtained with the detector switched on and covered. Throughout all the work reported here, the detector was operated in its linear regime to avoid detector saturation and other disruptive effects.

3. Current driver

The current driver used in these experiments is a custom-made low-noise current driver provided by ppqSense (QubeCL) [40]. In particular, this device has been specifically developed to have reduced current noise in the bias current range of the lasers tested (i.e., around 100 mA). The device capability in terms of current noise reduction was characterized in this work as described in detail in the following section. In particular, the noise features are shown in Figs. 4(a) and 5(a).

B. Measurement procedure and data analysis

1. Setup and measurements

To study the contribution from the driver's electrical current noise to the laser's emitted intensity noise, we measure the transfer function from the bias current fluctuations $\langle(\Delta I_{\text{bias}})^2\rangle$ to the laser optical power fluctuations $\langle(\Delta P)^2\rangle$ using the following procedure: We drive the cw lasers with the high-performance, low-noise current driver provided by ppqSense (QubeCL). The emitted laser light is then collected on the Vigo detector, whose photocurrent output signal is sent to a real-time spectrum analyzer (Tektronix RSA5106A). For the subsequent signal analysis, the spectra provided by the spectrum analyzer were rescaled to match a double-sided power spectral density (PSD). The driver comes with an integrated modulation unit, used to add a white noise modulation on top of the bias current.

TABLE I. η_{WPE} and η_Q of the two lasers calculated at their maximum attainable operating points, and their number of cascades N_C .

	QCL at 180 mA	ICL at 90 mA
η_{WPE}	0.064	0.003
η_Q	0.095	0.022
N_C	25	6

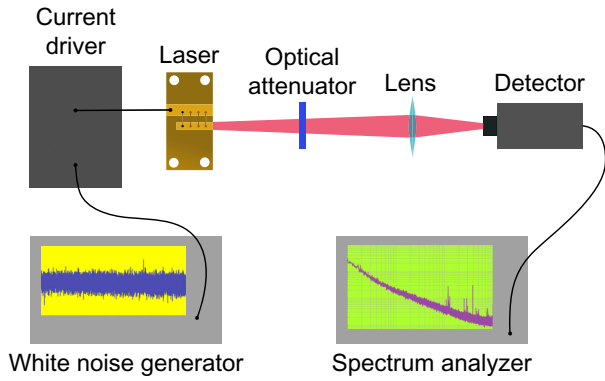


FIG. 2. Setup used for the measurement of the lasers' INPSD. The laser tested is supplied with the low-noise current driver. The current is modulated by means of the driver modulation unit, with white noise generated by an arbitrary function generator. While the laser's operating point is tuned across the respective orange range in the plots in Fig. 1, for each value of bias current the peak-to-peak amplitude of the white noise is varied. The laser light is then collected on a detector whose signal is processed by a spectrum analyzer to retrieve the INPSD.

A scheme of the setup is shown in Fig. 2, where a further component—namely, an optical attenuator placed in front of the laser—is depicted. Attenuation of the laser beam was necessary for both lasers to avoid detector saturation.

The laser operating point is varied by a stepwise increase of the bias current, and at each operating point, the bias current is modulated with white noise at different amplitudes. For each of these modulation amplitudes, the detector ac signal is recorded on the spectrum analyzer. The result is a set of intensity noise power spectral densities (INPSDs) for each operating point. The modulation applied to the bias current was generated by an arbitrary function generator (Tektronix AFG31252) set to white Gaussian noise. This function has a nominal bandwidth of 360 MHz, but we are limited by the driver's modulator unit, which has a bandwidth of 5 MHz.

If we want to compare noise spectra from different lasers, we should take into account that each laser emits radiation at different power. This is done by our computing the relative intensity noise (RIN) of the laser ($\text{RIN}_{\text{laser}}$), which is a measure of the mean square fluctuations in photocurrent $\langle (\Delta I_{\text{PC}})^2 \rangle$ per unit frequency, divided by the square of the average photocurrent $\langle I_{\text{PC}} \rangle$:

$$N_{\text{RIN,laser}} = \frac{\langle (\Delta I_{\text{PC}})^2 \rangle}{\Delta f_{\text{RBW}} \times \langle I_{\text{PC}} \rangle^2} = \frac{N_{\text{IN}}}{\langle I_{\text{PC}} \rangle^2}, \quad (3)$$

where Δf_{RBW} is the resolution bandwidth of the instrument used for acquisition, i.e., in this case, the spectrum analyzer, and where $N_{\text{IN}} = \langle (\Delta I_{\text{PC}})^2 \rangle / \Delta f_{\text{RBW}}$ [41].

To understand the impact of the photocurrent noise on the laser intensity noise in view of a possible control, we are particularly interested in comparing $\text{RIN}_{\text{laser}}$ with the

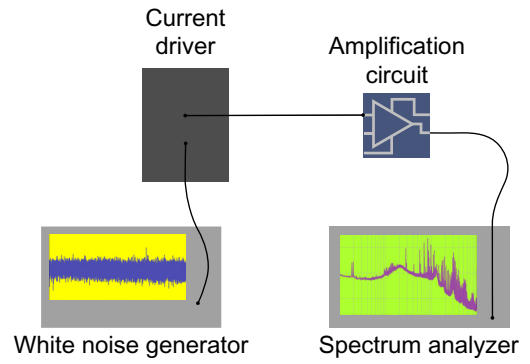


FIG. 3. Setup for the measurement of the driver's INPSD. The bias current is converted to a voltage signal via a home-made amplification circuit, whose core consists of two operational amplifiers (AD797N and AD8001), and which is battery-supplied to extinguish the electric noise from the wall plug. The amplified signal is sent to the spectrum analyzer. For each value of the bias current, the latter is modulated with white noise of varying amplitude by means of a function generator. In the same fashion, the lasers' bias current is modulated for the measurements of the lasers' INPSD. The op-amps are manufactured by Analog Devices.

RIN of the driver ($\text{RIN}_{\text{driver}}$); in other words, the RIN of the photocurrent from the detector with the RIN of the bias current generated via the current driver. The INPSD of the bias current is directly measured by our connecting the driver's output to the spectrum analyzer after proper amplification with a battery-backed amplification circuit (see Fig. 3). The signal is acquired through a spectrum analyzer. This is done for all values of bias current used to supply the ICL and the QCL, i.e., from 40 to 180 mA, in 10 mA steps. At each step, the driver's bias current was modulated with white noise of varying amplitude, the same way as it was done with the lasers' bias current when the INPSD of the lasers was measured. The driver's INPSD is divided by the square of the average bias current $\langle I_{\text{bias}} \rangle$ to get $\text{RIN}_{\text{driver}}$, similarly to Eq. (3):

$$N_{\text{RIN,driver}} = \frac{N_{\text{IN}}}{\langle I_{\text{bias}} \rangle^2}. \quad (4)$$

2. Noise analysis and transfer function

The result of the noise measurements of the lasers and the current driver is a set of RIN spectra for each value of the bias current. Figure 4(a) reports the driver's RIN spectrum with no modulation applied, for a bias current of 180 mA, together with the driver's shot-noise power spectral density ($N_{\text{PSD,sn}} = 2eI_{\text{bias}}$ [24]). This is to highlight the fact that the bias current intensity fluctuations are below the shot-noise level, i.e., they are sub-shot-noise. In particular, we observe that in the frequency range highlighted by the orange-shaded area, $\text{RIN}_{\text{driver}}$ lies 7.3 dB below the shot

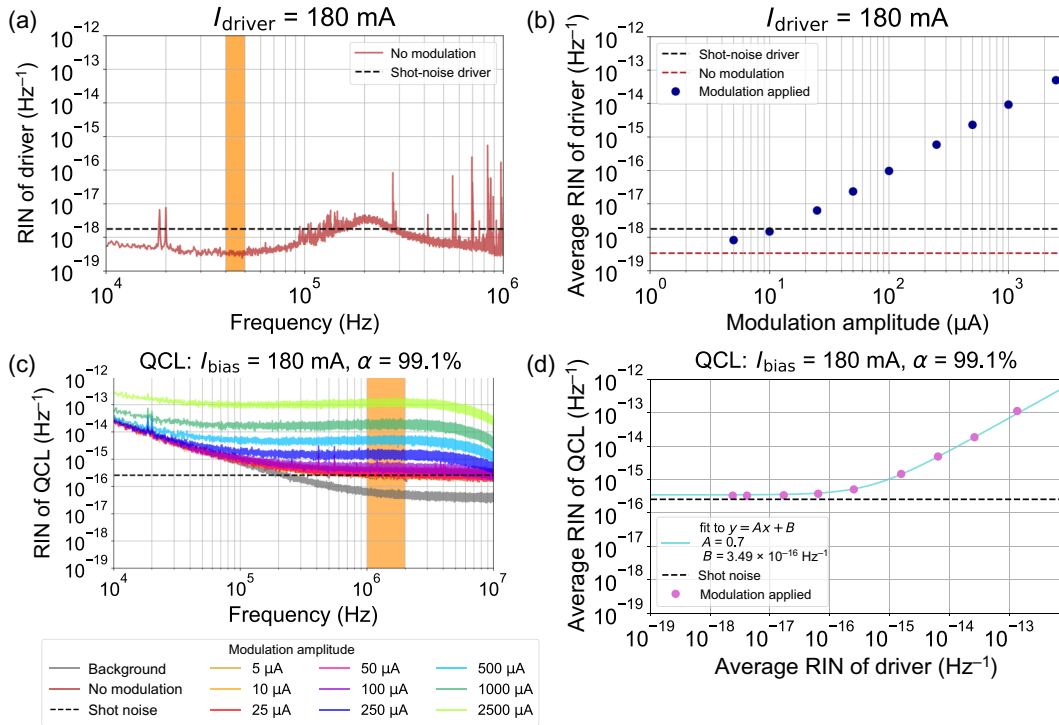


FIG. 4. (a) RIN spectrum of the driver supplying 180 mA of bias current. $\text{RIN}_{\text{driver}}$ was measured for different amplitudes of applied modulation, similarly to the graphic in (c); however, for clarity, the plot shows only the trace corresponding to the nonmodulated current signal, together with the computed corresponding shot-noise level symbolized by the dashed black line. The orange-shaded area indicates the frequency range where the spectra were averaged. (b) Average $\text{RIN}_{\text{driver}}$ vs the corresponding modulation amplitude. The dashed red line is the average $\text{RIN}_{\text{driver}}$ of the nonmodulated current signal, taken as a reference, while the average RIN of the modulated signal is represented by blue dots. The dashed black line represents the corresponding shot-noise level. (c) RIN spectra of the QCL pumped at 180 mA, with an attenuation of the optical power α of 99.1%. Traces of different colors correspond to different peak-to-peak amplitudes of the white noise added to the bias current, as reported in the legend, while the term “no modulation” stands for the nonmodulated signal. The gray line represents the detector’s background, while the dashed black line is the computed laser’s shot noise. The orange-shaded area shows the frequency region from 1 to 2 MHz, where the averaging of the RIN spectra was performed. (d) Similarly to (b), this plot represents the average RIN_{QCL} vs the average $\text{RIN}_{\text{driver}}$, i.e., the transfer function from the driver’s bias current to the photon flux. The transfer function is a line whose slope A and offset B are stated in the legend.

noise [dashed black lines in Fig. 4(a)]. The orange-shaded area indicates the frequency range where the spectra are averaged for the subsequent analysis. Averaging the spectrum in the frequency range where it is flattest, and with fewer peaks or flicker-noise contributions, provides information about how the RIN evolves with increasing modulation amplitude, as is visible in Fig. 4(b). In this graph, the average $\text{RIN}_{\text{driver}}$ at 180 mA, computed between 40 and 50 kHz, is plotted against the applied white-noise modulation amplitude in microamperes. The nonmodulated current signal and the driver’s shot noise (dashed red and black lines, respectively) are also plotted for reference. This plot clearly shows that the nonmodulated current signal is sub-shot-noise and that by addition of a modulation with varying amplitude, the noise increases accordingly. Note that the increment in $\text{RIN}_{\text{driver}}$ occurs as soon as a small modulation is applied, suggesting that the driver’s modulation unit responds immediately to the additional, external modulation. The same analysis is performed for

the laser noise with the $\text{RIN}_{\text{laser}}$ spectra. Figure 4(c) depicts the spectra of the RIN of the QCL RIN_{QCL} driven at 180 mA, each color corresponding to a different modulation amplitude of the bias current, as reported in the legend. The plot also comprises the RIN of the nonmodulated signal, as well as the detector’s background noise (gray trace), which is the signal measured with the detector turned on and covered. The RIN_{QCL} traces are well above this trace, assuring that the detector’s background does not limit the measurements. Finally, the computed PSD_{SN} of the incident radiation, measured in terms of the generated photocurrent I_{PC} by the detector, is displayed as a dashed black line. This value is estimated from the detector’s photocurrent as $N_{\text{PSD,sn}} = 2e(I_{\text{PC}})$. The fact that the RIN_{QCL} spectra at low modulation amplitudes are at the shot-noise level is mainly due to the strong attenuation factor α (99.1%, as given in the plot’s header). We point out that optical attenuation in front of the detector corresponds to a loss of photons from the emitted flux, which may

prevent us from observing sub-Poissonian photon statistics [42]. From a quantum optics perspective, attenuation irreversibly changes the photon statistics toward a Poissonian distribution, thus letting the fluctuations in photon number (i.e., the INPSD) approach the shot-noise level [24,43]. Despite this major impact, attenuation is strictly necessary to avoid detector saturation.

For a verification of the shot-noise level by means of balanced detection, see Appendix C. For the analysis of the RIN_{QCL} spectra, we choose again to average them in the frequency range where they are flattest and few peaks are present, i.e., the region from 1 to 2 MHz. In particular, in Fig. 4(d) the pink dots show the trend of the average RIN_{QCL} as a function of the average $\text{RIN}_{\text{driver}}$ when amplitude-modulated with the white-noise modulation. The relationship between these two RIN quantities is the transfer function from the current driver to the laser's photon flux. The trend is linear, as shown by the linear fit performed on the dataset, represented by the light-blue line. The fitting parameters A and B , representing the slope and the offset of the linear fit, respectively, are reported in the legend. By comparing the transfer function with the behavior of the average $\text{RIN}_{\text{driver}}$ versus modulation amplitude of Fig. 4(b), we notice that $\text{RIN}_{\text{driver}}$ has a

significant contribution to RIN_{QCL} starting with a value of approximately 10^{-16} Hz^{-1} , corresponding to a modulation amplitude of $100 \mu\text{A}$. At lower values, the noise from the current driver is buried in the intrinsic noise of the QCL, which in this case is at the shot-noise level because of the strong attenuation being used.

Similar results are obtained with the ICL after we perform the same analysis of the RIN at each operating point (i.e., from 40 to 90 mA of bias current, in 10 mA steps). Figure 5 displays four plots analogous to those in Fig. 4, related to $\text{RIN}_{\text{driver}}$ at 90 mA [Figs. 5(a) and 5(b)] and to the RIN of the ICL (RIN_{ICL}) driven at 90 mA, with an optical attenuation α of 69.7% [Figs. 5(c) and 5(d)]. At this operating point, the driver is 3.9 dB below the shot noise in the range between 40 and 50 kHz, as marked by the orange-shaded area in Fig. 5(a). The average $\text{RIN}_{\text{driver}}$ reaches and exceeds the shot-noise level as soon as a modulation is applied, as is visible in Fig. 5(b). The RIN spectra of the ICL shown in Fig. 5(c) are slightly above the shot-noise level. This is because the ICL emits much less power than the QCL (see Fig. 1), and therefore less attenuation was needed to stay in the detector's linear regime of responsivity. Finally, Fig. 5(d) shows the transfer function from the driver's bias current to the ICL's emitted photon flux.

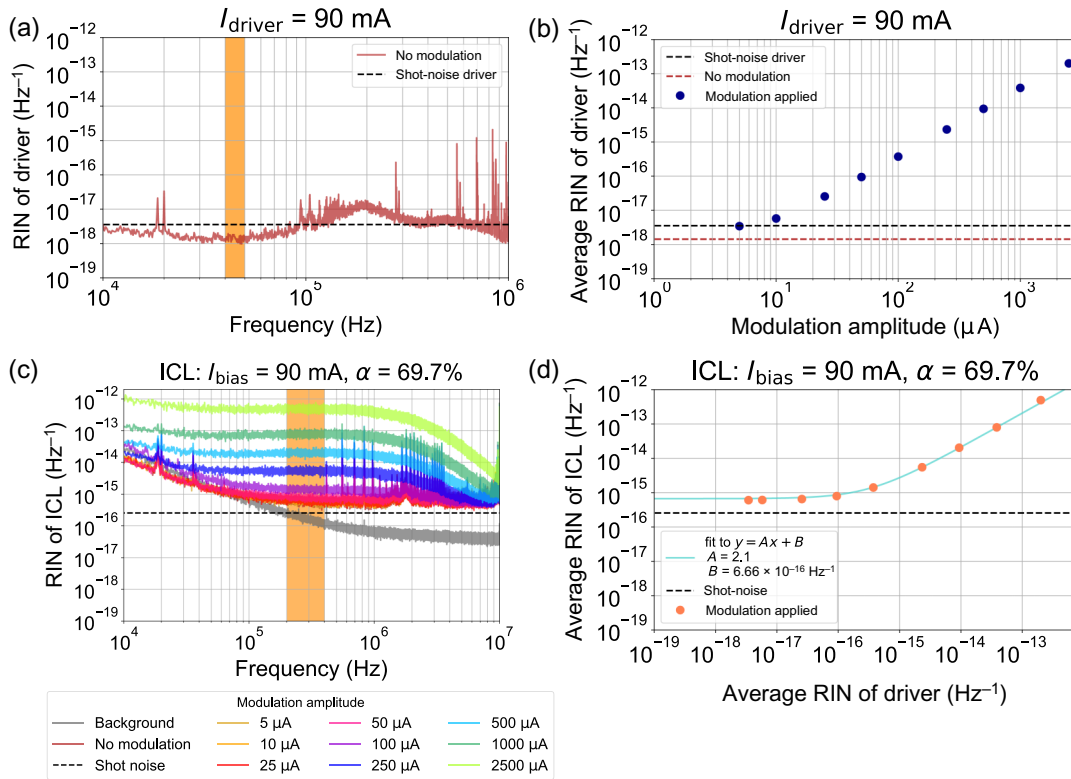


FIG. 5. Noise analysis for the ICL at a bias current of 90 mA. Panels (a)–(d) are similar to Figs. 4(a)–4(d), where (a),(b) refer to $\text{RIN}_{\text{driver}}$ at 90 mA, while (c),(d) refer to RIN_{ICL} when the ICL is driven at 90 mA, with optical attenuation α of 69.7%. RIN_{ICL} has been averaged in the range between 200 and 400 kHz.

Similarly to the QCL, the ICL's average RIN is significantly affected by the external modulation only starting with an amplitude of 100 μA , corresponding to an average $\text{RIN}_{\text{driver}}$ of $3.7 \times 10^{-16} \text{ Hz}^{-1}$.

We are now interested in studying the transfer function from electric current noise to photon flux noise. The input variable is $\text{RIN}_{\text{driver}}$, and the output quantity is the measured $\text{RIN}_{\text{laser}}$. This means the transfer function T relates the normalized bias current fluctuations $\langle (\Delta I_{\text{bias}})^2 \rangle / \langle I_{\text{bias}} \rangle^2$ to the normalized output power fluctuations $\langle (\Delta P)^2 \rangle / \langle P \rangle^2$. The optical power is measured with a photodetector, which basically converts photons into photoelectrons, meaning that power fluctuations are directly proportional to the photocurrent fluctuations $\langle (\Delta I_{\text{PC}})^2 \rangle / \langle I_{\text{PC}} \rangle^2$ of the detector operated in the linear responsivity regime:

$$T: \frac{\langle (\Delta I_{\text{bias}})^2 \rangle}{\langle I_{\text{bias}} \rangle^2} \rightarrow \frac{\langle (\Delta I_{\text{PC}})^2 \rangle}{\langle I_{\text{PC}} \rangle^2}. \quad (5)$$

In practice, we want to study the trend of the parameter A , i.e., the slope obtained from the fit procedure shown in Figs. 4(d) and 5(d), by varying the bias current. For both the QCL and the ICL, the transfer function $T: x \rightarrow y$ [Eq. (5)] was observed to follow a linear trend, and was thus fitted to a line: $y = Ax + B$. We define parameter A as the *transfer coefficient*, which is a measure of the laser's sensitivity to the current fluctuations. On the other hand, B represents the initial offset, which is the lasers' average RIN when no modulation is applied. It is interesting to see the evolution of the transfer coefficient A in relation to the bias current. The transfer coefficient at each operating point is extrapolated as a fit parameter from the linear regression on the average $\text{RIN}_{\text{laser}}$ [as reported in the legends in Figs. 4(d) and 5(d)]. Specifically, A is the slope of the transfer function, defined as the ratio between the increment in y and the increment in x . The variables y and x are $\text{RIN}_{\text{laser}}$ and $\text{RIN}_{\text{driver}}$, respectively, as stated in Eq. (6). The detector's photocurrent is proportional to the laser power, and therefore it can be regarded as being proportional to the bias current I_{bias} minus the laser's threshold current I_{th} . As a result, we have the following dependence of the transfer coefficient A on the bias current:

$$\begin{aligned} A &= \frac{y - B}{x} = \frac{\langle (\Delta I_{\text{PC}})^2 \rangle / \langle I_{\text{PC}} \rangle^2}{\langle (\Delta I_{\text{bias}})^2 \rangle / \langle I_{\text{bias}} \rangle^2} + b \\ &\approx a \times \frac{\langle I_{\text{bias}} \rangle^2}{\langle I_{\text{bias}} - I_{\text{th}} \rangle^2} + b. \end{aligned} \quad (6)$$

The relationship between the transfer coefficient A and the bias current as given by Eq. (6) is highlighted in Fig. 6, where the transfer coefficient of the two lasers is displayed as a function of I_{bias} , and fitted with the model $y = ax^2 / (x - I_{\text{th}})^2 + b$. This relation holds as far as a and b can be considered as constant parameters and the curve does

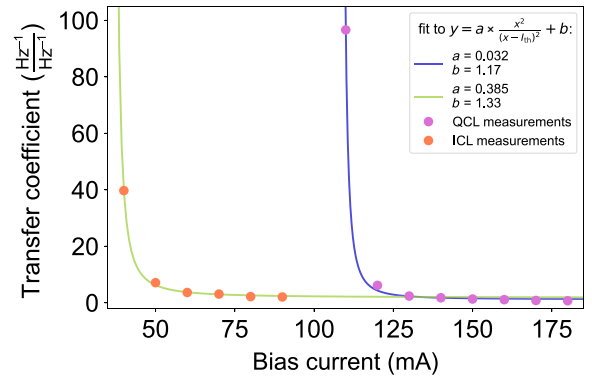


FIG. 6. Transfer coefficient A as a function of the bias current for the ICL (orange dots) and the QCL (pink dots). The green and blue lines represent the fits performed according to the equation given in the legend, whose fitting parameters a and b are also given in the legend for each fit.

not diverge. The first condition happens when the ratio between the absolute fluctuations $\langle (\Delta I_{\text{PC}})^2 \rangle / \langle (\Delta I_{\text{bias}})^2 \rangle$ is constant and when the variation of B/x is negligible with respect to that of the quantity y/x . The second condition breaks when I_{bias} approaches I_{th} and the function diverges. As a consequence, the transfer coefficient has its peak value near the laser threshold, and rapidly decays toward $a + b$ with increasing bias current, as shown by the values of parameter b in the legend in Fig. 6, which is approximately 1.2 for the QCL and 1.7 for the ICL. This fact demonstrates that the laser above threshold reaches a stable regime of operation not only in terms of emitted power but also in terms of power fluctuations.

C. Discussion

For this specific application, we would like the transfer coefficient to be as high as possible, meaning that the laser has high sensitivity to the pump current fluctuations. This will, in turn, result in an immediate reduction of noise when the pump current fluctuations are further suppressed. From Fig. 6, where the transfer coefficient of the two lasers is plotted against the respective values of the drive current, it is evident that the transfer coefficient is highest near threshold. However, this is mainly related to the fact that the RIN of the lasers is also at its highest near threshold (ideally when the current tends to zero, the RIN tends to infinity). As already pointed out in the discussion of Eq. (6), the data analysis holds as long as we work relatively far from threshold. The transfer coefficient's trend tends toward an asymptotic stabilization when we move away from threshold. In detail, the reason why the transfer coefficient A diverges near threshold is because the denominator of Eq. (6) goes to zero. Physically, this means that the laser is operated near threshold, where laser emission follows a highly nonlinear law. In these conditions, the emitted optical power is close to zero (while the

TABLE II. Overview of the performances from other studies regarding the generation of sub-shot-noise light by lasers backed by a quiet pump. The overall QE comprises both the laser's and the detector's QE. The amount of squeezing achieved by the reference studies relates to how far below the shot-noise level the measured intensity noise of the laser is. LED, light-emitting diode; VCSEL, vertical-cavity surface-emitting laser.

Device	References	η_Q (%) (laser and detector)	Amount of squeezing (dB)
LED	[34]	48	14
LED	[35,37]	66 (laser only)	1.4
VCSEL	[38]	20	0.4
Quantum dot laser	[39]	86	1.7
ICL at 90 mA	This work	0.9	
QCL at 180 mA	This work	3.9	

fluctuations are finite) and the RIN diverges. Simultaneously, any variation in injected bias current causes the laser to change its regime of operation, going from below to above threshold, and hence the laser RIN is highly dependent on the fluctuations in the bias current. This is the physical explanation for the transfer coefficient diverging when I_{bias} approaches the threshold current I_{th} .

Comparison of the two set points reached reveals that the ICL has a higher value of b (i.e., 1.33 for the ICL versus 1.17 for the QCL), indicating higher sensitivity in terms of noise transfer. This analysis offers a comprehensive description of classical noise transfer from the laser bias current to the emitted output power. In addition, this work demonstrates that $\text{RIN}_{\text{laser}}$ is insensitive to small bias current fluctuations, as can be deduced from Figs. 5(d) and 4(d). This suggests that by driving state-of-the-art MIR lasers with a sub-shot-noise bias current, the laser's intensity noise cannot be significantly reduced. From a qualitative point of view, we expected the transfer coefficient to be directly proportional to the QE of the laser. A higher rate of electron-to-photon conversion is directly related to a higher probability of transfer from electron statistics to photon statistics. This trend would be visible if the QE of the lasers tested were higher, as reported in Refs. [34,35,37–39]. In these experiments, performed in the near-infrared spectral range (from 800 nm to 1.2 μm), the overall QE of the laser and the detector reaches 86%, with a minimum of 20%. In the present work, however, the QE of the lasers is limited to about 1% or below for all of the devices tested. An overview of our performance compared with that in other representative studies is shown in Table II. Therefore, on the pathway toward controlling the intensity noise of midinfrared cascade lasers (QCLs and ICLs) at the quantum level by acting on the bias current electron statistics, the QE of the lasers should be increased, which involves optimization of the design and fabrication process of such devices.

III. CONCLUSIONS

In this work, we investigated the electron-to-photon noise transfer in midinfrared semiconductor lasers when

driven by a custom-made, sub-shot-noise current source. In particular, we compared how two different types of single-mode MIR laser—namely, a QCL and an ICL—convert the injected electric bias current noise into intensity noise of the emitted light. The analysis was based on the characterization of key parameters such as quantum efficiencies, wall-plug efficiencies, and noise transfer coefficients, which play a crucial role in controlling the intensity noise of the laser when acting on the driving current.

The results show in both cases that the transfer of noise, evaluated in terms of the transfer coefficient, rapidly reaches a set point as far as the bias current deviates from the threshold value. The measured trends suggest that the tested ICL is more responsive to bias fluctuations than the QCL. We point out that the two selected lasers are state-of-the-art, commercially available devices. Therefore, this work offers, on the one hand, a tested method of characterization applicable to a wider set of MIR laser sources. On the other hand, it points out the limits of these devices when noise is reduced via an active control of the injected bias current.

In general, efficient noise transfer from an electric current to optical power fluctuations is desired, as this means that by further decreasing the current noise, we could, in principle, generate sub-shot-noise light. Comparing the two devices under test with lasers from other studies, emitting radiation in the near-infrared region, we clearly see a significant gap in terms of quantum efficiency, which needs to be filled to proceed in the same direction with MIR lasers. This work succeeds, however, in assessing the level of intrinsic laser noise, i.e., noise that is independent of the current driver's contribution, as far as the bias current noise has a negligible contribution to the intrinsic laser noise. The path toward control at the quantum level of the intensity noise of MIR cascade lasers by acting on the bias current electron statistics should include optimization of laser design and fabrication strategies. In this regard, nonequilibrium Green's function-based quantum-transport theoretical models including phonon, impurity, and interface-roughness scattering, coherence-dissipation competition, and spatial current conservation [44] and highlighting the key parameters to be further optimized

for increasing the laser quantum efficiency can be highly beneficial. This optimization should take into account a good matching between the laser and the detection system in terms of power and bandwidth, meaning that the emitted laser power should be consistent with the detector saturation level, and the detector bandwidth should be adjustable according to the desired range of analysis. Additionally, alternative approaches where quantum simulation with ultracold atoms of carrier transport in semiconductor heterostructures [45] could further help to unveil the possible presence of noise generation and transfer mechanisms in such complex structures.

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The authors declare that they have no conflicts of interest.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: LASER CHARACTERISTICS

1. Quantum cascade laser

The QCL is from Hamamatsu and has an emission wavelength of around $4.57\ \mu\text{m}$. It has a ridge waveguide with a top DFB grating, in a buried heterostructure geometry. The cavity length is 2 mm. The active region consists of InGaAs/InAlAs quantum wells with a total of 25 stages and with a thickness of $1.325\ \mu\text{m}$. The core is sandwiched between two InP-based cladding layers grown on an InP substrate. The out-coupling facet is uncoated and has a reflectivity of 30%, and the back facet has a high-reflectivity coating to obtain a reflectivity exceeding 98%.

2. Interband cascade laser

The ICL is from Nanoplus and has an emission wavelength of around $4.5\ \mu\text{m}$. It has a ridge waveguide with a top DFB grating. The cavity length is $900\ \mu\text{m}$. The active region consists of the W-type quantum well sequence AlSb(2.50 nm) / InAs(2.22 nm) / $\text{In}_{0.35}\text{Ga}_{0.65}\text{Sb}$ (2.50 nm) / InAs(1.83 nm) / AlSb(1.0 nm) with a total of six stages. The active region is enclosed by two 400-nm-thick GaSb separate confinement layers. The lower and upper InAs/AlSb superlattice cladding layers have a thickness of 3.5 and $2.0\ \mu\text{m}$, respectively.

APPENDIX B: OPTICAL SPECTRA

The optical spectra of the two lasers are measured via an optical spectrum analyzer (Bristol, 721A and 721B) for different values of the laser drive current and temperature.

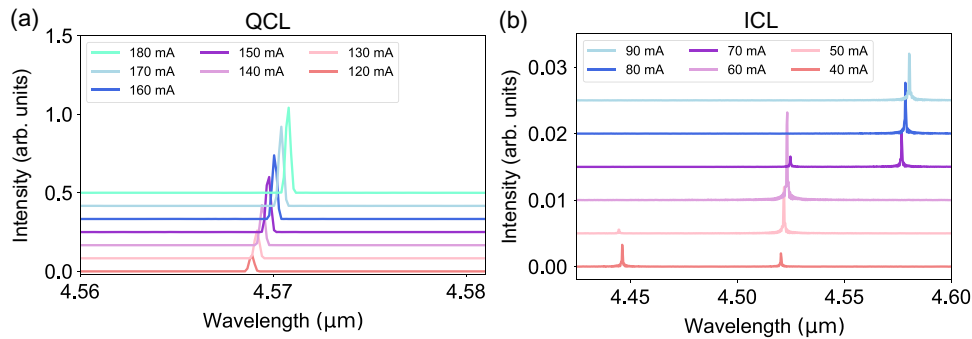


FIG. 7. Optical spectra of the two lasers at the values of the drive current and temperature used in the RIN analysis: (a) for the QCL at $T = 20^\circ\text{C}$. and (b) for the DFB ICL at $T = 20^\circ\text{C}$.

Figure 7 shows the optical spectra of the lasers at the values of temperature and current that were eventually used for the noise measurements. Both the QCL and the ICL were operated at a temperature of 20 °C. In both plots, we observe the typical frequency tuning with drive current occurring in most semiconductor lasers. This is mostly due to variations in carrier density inside the layers, modifying the materials' properties such as the refractive index and thus the path length. To a minor extent, increasing current also affects temperature and therefore the cavity

length. The spectra clearly show single-mode emission for the QCL [Fig. 7(a)] at a peak wavelength of around 4.75 μm . The spectra of the DFB ICL in Fig. 7(b) present two mode jumps, characterized by bicolor emission at two operating points, namely, 40 and 70 mA, as mentioned in Ref. [21]. In both cases, however, there is a dominant peak that can be regarded as the laser's emission frequency. This is demonstrated by the common mode rejection ratio, i.e., the ratio between the major peak's intensity and the secondary peak's intensity, this being 1.6 at 40 mA and 3.3 at

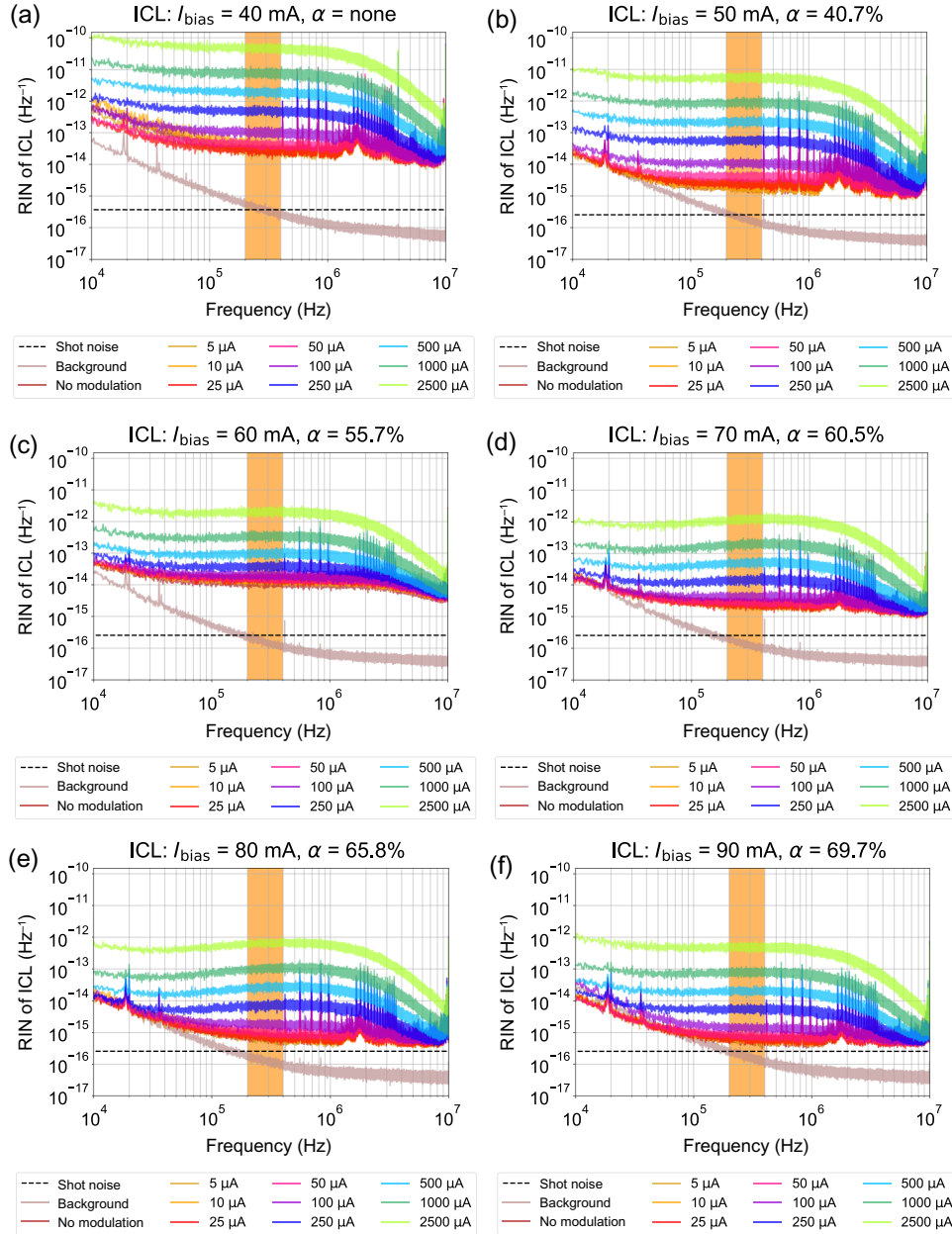


FIG. 8. RIN of the ICL for different values of the applied modulation's amplitude, as specified in the legends. Panels (a)–(f) refer to different values of the bias current from 40 to 90 mA as specified in the plot titles. The dashed black line is the shot noise of the driver's current. The orange-shaded area corresponds to the frequency range where the spectra were averaged to study the dependence of the driver's RIN to the applied modulation.

70 mA. As a result, the DFB ICL can be considered eligible for the second part of the work.

In addition, the mode competition caused by the mode jumps occurring near 40 and 70 mA might affect the noise transfer measurements. Here we want to show that mode competition at these operating points does not influence the analysis. Figure 8 shows the effect of the mode jump on the RIN_{ICL} spectra. In general, when the bias current above threshold is increased (therefore the laser's output power is increased), the RIN decreases. This is true for all plots depicted in Fig. 8, with exception of the plot in Fig. 8(c). At $I_{bias} = 60$ mA, RIN_{ICL} suddenly increases with respect to RIN_{ICL} at lower bias currents. This excess of noise is traced back to the competition between the two modes. It is therefore true that the mode jump has an impact on RIN_{ICL} . However, we do not observe any influence of this mode hopping on the transfer coefficient.

APPENDIX C: COMPARISON WITH BALANCED DETECTION MEASUREMENTS

Attenuation alters the light photon-number statistics toward a Poissonian distribution on the detector, in which case the INPSD coincides with the shot noise [43]. To verify that the computed level of shot noise is correct, we performed additional measurements with a shot-noise-limited balanced detector, which had previously been calibrated [24]. Given a certain radiation power, balanced detection allows absolute measurement of the corresponding shot-noise level through the computation of the difference between the two signals from the two balanced detector's arms. In our case, the MIR radiation, obtained by attenuation of the laser source i.e., the QCL, is split via a 50:50 beam splitter, and the two parts are sent to two identical detectors (see Fig. 9). The detectors' signals are acquired simultaneously with an oscilloscope and

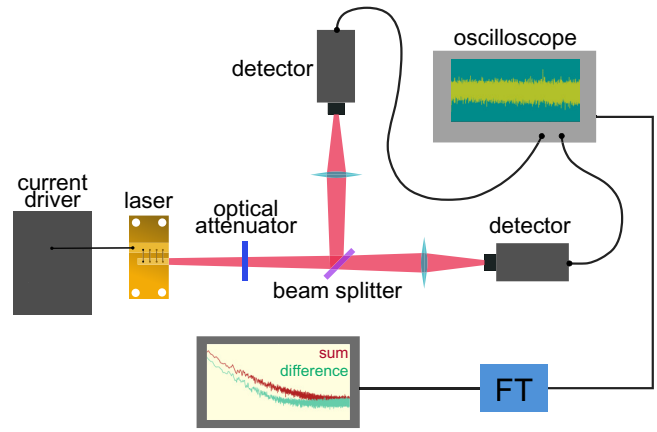


FIG. 9. Balanced detector setup. The attenuated MIR radiation is equally split onto two equal photovoltaic detectors by means of a 50:50 beam splitter. The resulting photocurrent signals are acquired simultaneously in the time domain via a fast oscilloscope. The Fourier transform (FT) of the sum and the difference of these signals is then computed to obtain the corresponding INPSD.

processed to find the Fourier transform of the sum and the difference between them. The sum represents the total INPSD of the incident light, while by computation of the difference, the excess of common noise is canceled out, and one is left with the shot-noise power spectral density (this is possible if the common mode rejection ratio between the excess of noise and the expected shot-noise level does not exceed the limit tolerated by the assembled setup, which is in our case Fourier-frequency dependent and up to a maximum of 40 dB [24]). Following the procedure described in the main text, the INPSD is then converted into the RIN, by renormalization of it to the square of the sum of the average photocurrents generated

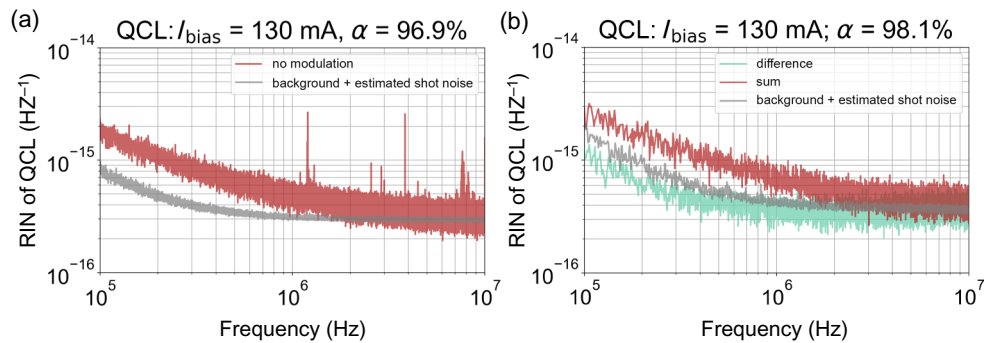


FIG. 10. (a) RIN spectrum of the nonmodulated QCL pumped at a bias current of 130 mA (red trace) and sum of corresponding computed shot noise and the detectors' background (gray trace). (b) RIN spectra of the QCL at the same value of the bias current, measured with the balanced detector depicted in Fig. 9. In particular, the red trace is the RIN of the sum of the two signals from the two arms of the balanced detector, representing the total laser RIN, while the green trace is the difference between the two signals from the two arms, representing the shot noise. We see that the difference (green trace) approximates the gray trace, which represents the sum of shot noise (computed from the sum of the two detectors' photocurrents) and the detectors' background, meaning that the system is properly calibrated.

via the two detectors. The technique described was used to acquire the data displayed in Fig. 10(b). This plot depicts the QCL's RIN measured at $I_{\text{bias}} = 130$ mA as reported in the header, with an optical attenuation α of 98.1%. The red trace represents the RIN of the sum of the two signals, the green trace is the Fourier transform of the difference between the two signals, and the gray trace is the Fourier transform of the sum of the two detectors' backgrounds, plus the shot noise as evaluated from the detectors' photocurrent. By looking at Fig. 10(b), we can state that the measured shot noise (i.e., the green trace) is fairly approximated by the computed shot noise (gray trace), as the green trace approaches the estimated level of shot noise. Again, the red traces representing the total QCL's RIN ($\text{RIN}_{\text{laser}}$) approach the shot noise because of the strong attenuation. What we also deduce from the balanced detection measurements is the accuracy of our calculation of the lasers' RIN, more precisely, of the constants and conversion parameters used to calculate the RIN from the signal acquired via the spectrum analyzer. The balanced detection measurements are independently acquired in the time domain with the oscilloscope, and the Fourier transform is performed downstream of the signal conversion. In other words, these are absolute measurements and can be used to calibrate the measurements performed with the spectrum analyzer. By comparing the red traces in Figs. 10(a) and 10(b), obtained at equal bias current, we can conclude that they are in good agreement with each other.

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