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Temperature dependence of the frequency noise in a mid-IR DFB quantum cascade laser from cryogenic to room temperature

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Abstract: We report on the measurement of the frequency noise power spectral density in a distributed feedback quantum cascade laser over a wide temperature range, from 128 K to 303 K. As a function of the device temperature, we show that the frequency noise behavior is characterized by two different regimes separated by a steep transition at ≈200 K. While the frequency noise is nearly unchanged above 200 K, it drastically increases at lower temperature with an exponential dependence. We also show that this increase is entirely induced by current noise intrinsic to the device. In contrast to earlier publications, a single laser is used here in a wide temperature range allowing the direct assessment of the temperature dependence of the frequency noise.

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1. Introduction

The impressive scientific and industrial progress achieved in the field of quantum cascade lasers (QCLs) since their first demonstration [1] led to the development of continuous wave (CW) room-temperature devices [2]. For a wide variety of mid-IR wavelengths, these lasers are now commercially available with low threshold currents, making them an increasingly convenient tool for field-applications such as spectroscopy, defense, and trace gas sensing for environmental and biomedical sciences. Nevertheless, some of their properties and dependences upon device parameters and operating conditions are still not fully understood.

For instance, there has been a growing interest during the last years for the study of the spectral properties of singlemode QCLs. Frequency noise in QCLs was at first investigated at cryogenic temperatures in various experimental configurations [3–5]. More recently, we reported the first measurement of the frequency noise spectrum of room-temperature 4.6-µm QCLs [6,7]. A surprising outcome of this work was that room temperature devices showed a considerable reduction of two orders of magnitude in terms of frequency noise power spectral density (PSD) compared to a cryogenic device from the same manufacturer and operating at a close wavelength [5]. This observation was also confirmed by similar results obtained for a room-temperature QCL from a different supplier [8]. So far, all the works dealing with frequency noise of QCLs at different temperatures have been obtained with different devices, making the direct assessment of the impact of temperature difficult, because of the possible influence of other parameters such as the different dimensions, design and fabrication of these lasers. The temperature dependence of the frequency noise has never been studied yet with a single QCL.

In contrast to previous works, we used a single QCL operated in our experimental setup from room temperature down to cryogenic temperature. We were therefore able to measure the frequency noise of the same device over a wide temperature range from 128 K to 303 K. The results reported here show an increase of the frequency noise PSD of almost two orders of magnitude at low temperature, in agreement with the noise levels previously measured in other devices operated at fixed temperatures [5–8]. But more important, we show here for the first time how the frequency noise raises with decreasing temperature. Our experimental results clearly show that there is not a regular increase of the noise with decreasing temperature, but two different regimes are observed with a steep transition around 200 K. In the second part of this paper, the temperature dependence of the laser frequency noise is analyzed in more details and is compared to the electrical noise measured across the device. The clear correlation observed between these two parameters is an indication of the origin of the frequency noise increase that occurs at low temperature.

2. Experiment

Frequency noise measurements are performed in the same way as in Refs [3–8] with the QCL tuned to the side of a molecular absorption line acting as a frequency-to-intensity converter, also referred to as a frequency discriminator. The output radiation of the laser is collimated and traverses a 1-cm long gas cell filled with pure carbon monoxide (CO) at a nominal pressure of ≈20 mbar. The transmitted light is detected with an HgCdTe photodiode. After amplification, the output voltage fluctuations are analyzed with a Fast-Fourier Transform (FFT) analyzer. The measured slope of the absorption line around the laser operating point (the so-called discriminator slope) is used to convert the recorded voltage PSD into laser frequency noise PSD.

QCLs have a narrow intrinsic linewidth arising from their close-to-zero α-factor [9] (linewidth enhancement factor [10]) and more profoundly from a stable single mode operation at high power levels with recourse to the presence of very fast non-radiative relaxation processes [11]. However, the linewidth observed in real-world applications is much broader because of the presence of 1/*f* (flicker) noise. In this sense, it is important to study the temperature evolution of the noise at low frequency, which has the largest contribution to the linewidth [12]. Moreover, results from previous studies did not show such a large change in the high-frequency white noise with temperature as for the two-order of magnitude increase of the 1/*f* noise [8]. For all these reasons, we restricted our measurements to Fourier frequencies below 100 kHz in the present study.

The laser used in our experiment is a DFB-QCL provided by Alpes Lasers SA, Switzerland, emitting in the 4.55-µm wavelength range. It uses a buried heterostructure with epi-side up mounting and benefits from a low threshold current. The laser was mounted in a cryostat so that stable and controlled operation was achieved from 128 K to 303 K, with threshold currents i_{th} ranging from 75 mA to 120 mA. The operating current spans from 110 mA to 180 mA with an optical output power of 10-20 mW. A low-noise current source developed at TU-Darmstadt [12] was used to drive the laser, which has a sufficiently low current noise (≈350 pA/√Hz at all frequencies below 100 kHz) not to contribute to the measured frequency noise in the considered frequency range [12]. The laser temperature could not be lowered below 128 K because of the increasing voltage across the QCL at low temperature, which exceeds the compliance voltage of the low-noise current driver (≈15 V).

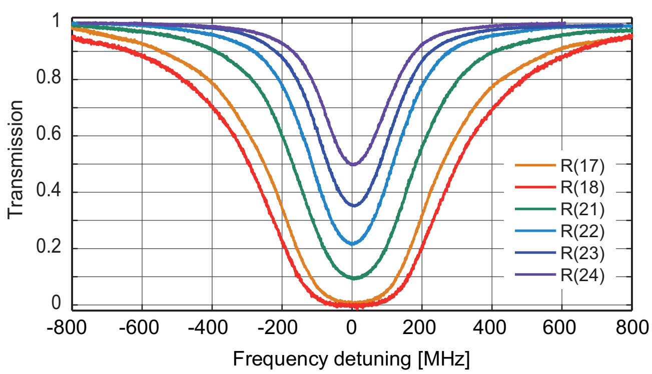

Fig. 1. Transmission spectra corresponding to various ro-vibrational transitions in the R-branch of the fundamental (0→1) CO vibrational band. These experimental curves are obtained for a 1-cm pathlength through the gas cell filled with ≈20 mbar of pure CO.

In order to compare the frequency noise at various temperatures in similar conditions, an equivalent drive current $i_0 \approx 1.5 \cdot i_{th}$ was used in each measurement. Therefore, the operating current and temperature were carefully selected in order to tune the laser wavelength to a CO absorption line. Different ro-vibrational transitions ranging from R(15) to R(24) in the fundamental CO band were used with weakening absorption as the laser temperature decreased, as shown in Fig. 1. From ≈2200 cm^{-1} achieved at room temperature, which lies close to the center of CO R-branch, the laser frequency shifts up to ≈2230 cm^{-1} at low temperature. In the same time, the absolute absorption as well as the discriminator slope decrease.

For a proper determination of the laser frequency noise, the discriminator slope needs to be accurately determined for each CO absorption line. The frequency axes of the spectra were calibrated based on the laser current-tuning coefficients, which were carefully characterized at each respective temperature with a Fabry-Pérot analyzer. Figure 2(a) shows the laser current-tuning coefficient systematically measured at different temperatures and currents. As the main frequency tuning mechanism in QCLs results from the thermal heating of the laser active region produced by the drive current, the laser tuning rate is also displayed in Fig. 2(b) in terms of the dissipated electrical power.

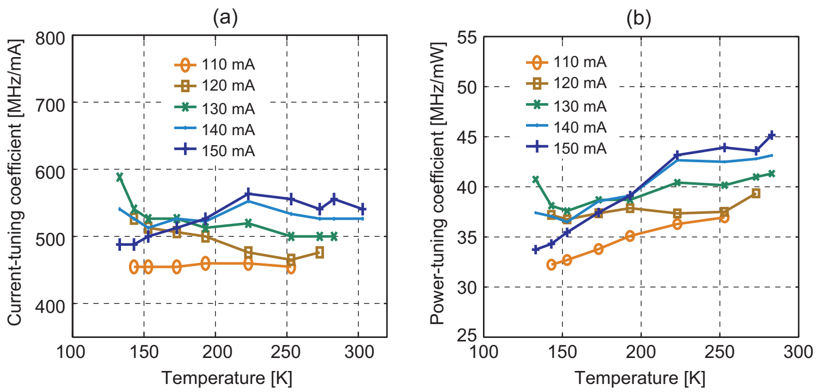

Fig. 2. (a) Current-tuning coefficient of the laser measured for several operating conditions, showing an average value close to 500 MHz/mA. (b) Power-tuning coefficient of the laser obtained at different temperatures and currents.

The QCL emission spectrum was also measured with a Fourier Transform Infrared (FTIR) spectrometer over the entire temperature range, in order to check that the laser was always operating singlemode without any mode hop. All frequency noise measurements were performed under these conditions, with the same lasing mode analyzed from room temperature down to cryogenic temperature.

3. Results

Typical frequency noise spectra measured in our experiment are shown in Fig. 3 for different temperatures of 128 K, 155 K, 178 K, 223 K, 263 K, and 283 K. As in previous works, $1/f$ noise is observed from low frequencies up to 100 kHz at all temperatures. While the frequency noise spectra are almost unchanged in the high temperature range (283, 263, 223 and 201 K), the noise strongly increases at lower temperature and is enhanced by almost two orders of magnitude in terms of PSD at 128 K.

Although all the measurements were initially performed at $i_0/i_{th} \approx 1.5$, the dependence of the frequency noise upon drive current was also investigated. As the laser frequency needs to be always tuned to a particular CO transition for the frequency noise measurements, the drive current cannot be simply changed at a fixed temperature. However, a small temperature decrease of only 1 K is sufficient to keep the laser tuned to a transition when the current is increased by about 10 mA. Owing to the low threshold current of our laser, it is possible to significantly change the i_0/i_{th} ratio whereas the temperature excursion remains small, in the range of a few Kelvins. We observed that the frequency noise does not depend on the drive current for several values of i_0/i_{th} ranging from 1.2 to 1.8. All over the temperature range, no influence of the drive current onto the laser frequency noise could be observed beyond the measurement uncertainty, which is by the way negligible compared to the strong noise increase observed at low temperature. As our laser benefits from a low threshold current, the thermal heating associated with an increase of the current is rather low. However, one cannot exclude a different behavior, and maybe a slight dependence of the frequency noise upon drive current at low temperature, for a laser operating at higher current for the same range of i_0/i_{th} values.

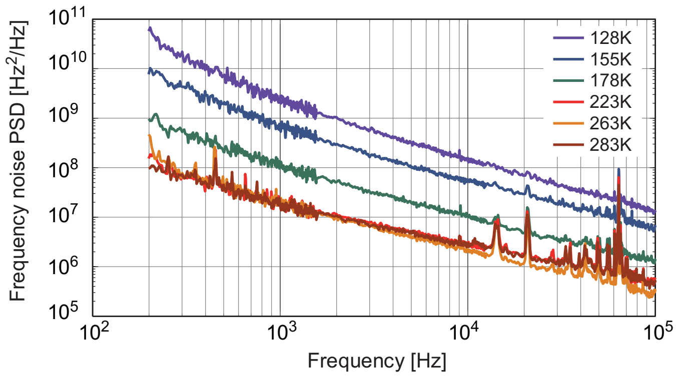

Fig. 3. Frequency noise PSD of a 4.55-µm DFB-QCL measured at different temperatures ranging from 128 K to 283 K. The laser operating current is in the range 120-180 mA and was adjusted to $i_0/i_{th} \approx 1.5$ at each temperature.

4. Discussion

In Fig. 4, we show the frequency noise PSD at a Fourier frequency of 3 kHz, S_{3kHz}, as a parameter to characterize the temperature dependence of the laser frequency noise. This plot displays the first measurement of the temperature dependence of the frequency noise in a single QCL. The main feature of this figure is the existence of two different regimes separated by an abrupt transition observed around 200 K. Above 200 K, the frequency noise PSD is almost independent of temperature, at a level slightly below 10^7 Hz^2/Hz. On the other hand, the laser frequency noise drastically increases when the temperature is lowered below 200 K, with an exponential dependence, $S_{3kHz} \approx 2 \cdot 10^{12} \exp(-0.06 \cdot T)$, with respect to temperature. A level of $7 \cdot 10^8$ Hz^2/Hz is reached at 128 K.

It is important to note that these results are comparable to previous data reported at corresponding single temperatures for different QCLs emitting at close wavelengths. At room-temperature, the data are very similar to our previous results obtained with another QCL from Alpes Lasers SA emitting at the same wavelength (at T = 277 K and i_0 = 350 mA) [6, 7] as well as to the values reported in Ref [8]. for a different QCL from Hamamatsu Photonics emitting at a slightly shorter wavelength of 4.36 µm (T = 288 K, i_0 = 776 mA). The same agreement applies at cryogenic temperature even though we could not reach the temperature used with the cryogenic 4.33-µm QCL of Ref [5]. (T = 85 K, i_0 = 219 mA). We find a similar increase of two orders of magnitude in terms of frequency noise PSD at our lowest measured temperature (128 K) relative to the devices operated at room temperature. But more important, the complete evolution of the frequency noise of a QCL from room temperature down to 130 K is shown here, which constitutes a significant outcome of this study. The fact that the frequency noise does not increase regularly from room temperature to cryogenic temperature, but shows instead a sudden transition at ≈200 K, gives a new insight towards the understanding of the origin of the frequency noise in QCLs.

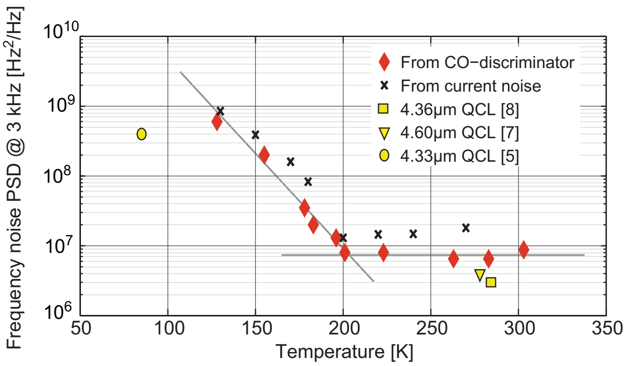

Fig. 4. Temperature dependence of the frequency noise PSD of the QCL measured at 3 kHz Fourier frequency (red diamonds). While constant at high temperature, the frequency noise strongly increases below 200 K. The grey lines result from a fit of the experimental data on both sides of the transition, corresponding to $S_{3kHz} = 7\cdot10^6$ Hz^2/Hz for $T > 200$ K and $S_{3kHz}(T) \approx 2\cdot10^{12}\exp(-0.06\,T)$ for $T < 200$ K. The black crosses represent the noise measured on the voltage across the laser, converted into an equivalent frequency noise using the laser differential resistance and the current-tuning coefficient. The yellow markers represent published values of QCLs frequency noise obtained at different temperatures [5, 7, 8].

All the values reported in the literature for different QCLs are also shown in Fig. 4 for comparison with our data. We observe that the frequency noise values measured at a given temperature coincide quite well despite the different characteristics of these lasers. This result tends to indicate that the temperature dependence of the frequency noise in QCLs is related to intrinsic effects in the QCL semiconductor structure. Indeed, while the various QCLs compared here have different designs and fabrication parameters, are made by different manufacturers and have different operating conditions, they all show a comparable noise level at room-temperature and a similar increase of roughly two orders of magnitude at cryogenic temperature. At this point, it is important to emphasize the fact that frequency noise is reported here as a function of the cryostat or laser heat-sink temperature, but the actual temperature in the laser active region is higher due to thermal dissipation. The temperature difference between the active region and the heat-sink depends on the laser thermal resistance and on the electrical power dissipated in the laser, therefore on the drive current and bias voltage. As a consequence, the internal temperature of our device is very likely closer to the heat-sink temperature than for the cryogenic QCL compared in Fig. 4, because of the lower operating current and thermal resistance. In our case, we estimate the laser active zone to be between 15 and 23 K above the heat-sink temperature in the entire temperature range of our study (see after), while the temperature difference might be at least two times higher in the cryogenic QCL of Ref [5]. If the frequency noise was plotted in Fig. 4 as a function of the internal laser temperature rather than of the heat-sink temperature, the position of the cryogenic QCL would become closer to our points in the low temperature range. However, one should point out that this qualitative reasoning concerns the direct comparison of the frequency noise as a function of temperature in different QCLs. When looking at the mechanism generating the frequency noise, as discussed in the following of this paper (i.e. internal current noise), the frequency noise data should be scaled by the laser thermal resistance in order to make the comparison in terms of the relevant parameter.

In order to have a deeper insight into the frequency noise increase at temperatures below 200 K, we performed several additional experiments. First of all, we monitored the emission spectrum of our laser with an FTIR spectrometer as well as with a Fabry-Pérot analyzer to check that no other mode was present. The occurrence of a second mode could lead to an increase of the frequency noise as a result of modes competition [13]. Secondly, we measured the voltage noise across the QCL as a function of temperature. The measured voltage noise PSD was converted into current noise using the corresponding laser differential resistance. This noise that we refer to as the laser internal current noise (Fig. 5) has the same $1/f$ nature than the measured frequency noise and also shows a drastic increase at temperatures below 200 K. As for the frequency noise, the internal current noise showed no significant change in the range of operating bias current considered here. We attribute this behavior to the low threshold current of our QCL, which makes the overall current change moderate. However, we observed a quadratic increase of the internal current noise over a wider range of current (up to 400 mA) in the QCL of our Ref [7], which has a higher threshold current. It is important to note here that the noise of the current driver (≈350 pA/√Hz) lies well below and does not contribute to the current noise reported here. In order to evaluate the impact of the internal current noise, we determined its contribution to the laser frequency noise, taking into account the corresponding current-tuning rate measured at each temperature and drive current (from Fig. 2(a)). The 3-kHz component of the frequency noise induced by the internal current noise was also extracted and is displayed in Fig. 4 for comparison with the optically-measured frequency noise. The good agreement observed between the two curves, which show the same temperature dependence with an abrupt increase below 200 K, is evident. This observation tends not only to explain that the higher frequency noise present at low temperature is due to an increase of the internal current noise, but gives also a more general clue that frequency noise in QCLs is governed by current noise intrinsic to these devices.

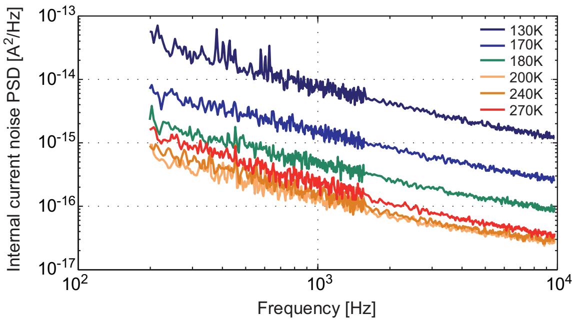

Fig. 5. Current noise PSD (A^2/Hz) measured directly between the QCL anode and cathode at different temperatures. It shows the same 1/*f* nature and the same increase of two orders of magnitude at cryogenic temperature than the optically-measured frequency noise.

The hypothesis that frequency noise arises from internal current noise was previously proposed, based on a qualitative analysis of the frequency noise and frequency tuning response in a QCL [14]. Here, our direct measurement of the internal current noise showing its contribution to the laser frequency noise confirms this assumption. The small difference observed between the frequency noise measured from the optical discriminator and the one inferred from the current noise is attributed to a slight systematic bias in the laser differential resistance value and current-tuning coefficient that are both needed to convert the voltage noise into laser frequency noise. This difference is by the way negligible compared to the strong influence of temperature below 200 K. Finally, one should notice that the slight current noise increase that seems to appear in the range 200-300 K lies within the experimental uncertainty and is therefore not significant.

According to our experiment, the frequency noise in QCLs results from the internal current noise δi, inducing temperature variations and subsequent refractive index fluctuations of the DFB grating. The temperature fluctuations δT scale with the electrical power δP dissipated in the laser:

$$\delta T = R_{th}\delta P = R_{th}U_0\delta i \tag{1}$$

where U_0 is the voltage across the laser and R_{th} is the thermal resistance, which can be computed from the ratio of the laser power- and temperature-tuning coefficients [15]:

$$R_{th} = \left(\Delta\nu / \Delta P\right)\cdot\left(\Delta\nu / \Delta T\right)^{-1} \tag{2}$$

While it has been suggested that the frequency noise increase observed between a room-temperature and a cryogenic QCL results from an increase of both the internal current noise and of the laser thermal resistance [8], our new experimental results tend to show that the internal current noise increase is the only cause. The thermal resistance can indeed vary between two different QCLs, but we do not expect it to have a large effect in our experiment based on a single device. The only variation of the thermal resistance originates from the temperature dependence of the thermal conductivity, which is however small over the temperature range considered in our experiment [16]. Moreover, the thermal conductivity increases when decreasing the temperature and the laser thermal resistance varies in the reverse direction. The effect of power fluctuations on the device temperature, and therefore on the laser frequency noise, should be even lower at cryogenic temperatures. The temperature behavior of the thermal resistance in QCLs was simulated in Ref [17]. and shows indeed that the thermal resistance slightly rises with increasing temperature. The sensitivity of the laser frequency to current fluctuations is nothing else than the current-tuning coefficient, which was measured for our QCL all over the temperature range. It is clearly demonstrated in Fig. 2(a) that the laser current-tuning coefficient does not depend much on temperature. The dependence upon electrical power is also shown in Fig. 2(b) since it is the real quantity affecting the laser temperature. This parameter shows only a slight trend to decrease when lowering the temperature, which agrees qualitatively with the prior discussion about the thermal conductivity. Assuming that the laser frequency depends on temperature only, the thermal resistance can be computed from Eq. (2) using the laser tuning coefficients. For our laser, we find values of 8.5 K/W at 130 K and 10.5 K/W at 298 K, leading to a temperature difference $\Delta T = R_{th} \cdot U_0 \cdot i_0$ between the laser active region and the heat-sink comprised between 15 and 23 K all over the temperature range. All this discussion shows that the laser thermal resistance changes only marginally in the temperature range of our experiment. Therefore, the strong increase of the laser frequency noise observed at low temperature is attributed to the increase of the laser internal current noise only.

Although we gave the experimental evidence that the optically-measured frequency noise is induced by the electrical noise intrinsic to the device as previously presumed [14], the mechanism of this latter is not well understood and is a complex subject in itself. Noise in semiconductors and more specifically its $1/f$ origin has been widely studied for a long time in various experiments [18]. The temperature dependence of the low-frequency noise in semiconductors was also investigated in a few cases, for instance for InP [19] and very recently in GaN/AlGaN structures [20], but the considered devices are very different from a QCL as studied here. Therefore, it is difficult to make a direct comparison with these studies. Further measurements will be necessary in order to have a better understanding of the origin of $1/f$ internal current noise in QCLs, as well as of its increase at low temperature. An experiment involving frequency noise measurement and determination of the active junction temperature for different QCLs, as well as a complete characterization of the electrical noise as a function of the drive current would give new clues on the origin of the noise and of its dependence over the device temperature. At this point, it is difficult to say whether the extra current noise originates from the contacts, lattice scattering [19], from carriers trapped by material defects [20] or from fluctuations of electron tunneling through the multi-barriers QCL structure [14].

Finally, we report in Fig. 6 the corresponding laser full width at half maximum (FWHM) linewidth computed from the frequency noise spectra using the formalism presented in Ref [21]. From ≈770 kHz at high temperature, the linewidth follows the frequency noise increase and broadens up to ≈10 MHz at 128 K (at 5 ms observation time). Therefore, sub-MHz linewidth for free-running QCLs appears achievable in devices operated near room temperature, but not in cryogenic conditions. We still want to emphasize the fact that sub-MHz linewidths in a free-running QCL can only be achieved along with the use of a low-noise current driver [12]. However, a narrower linewidth is in principle achievable with a noisier driver or laser (e.g. at cryogenic temperature) if active stabilization to a high-finesse reference cavity is implemented for linewidth reduction [22].

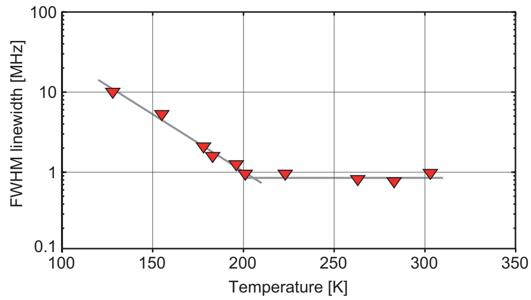

Fig. 6. Temperature dependence of the QCL FWHM linewidth calculated from the measured frequency noise spectra (at 5 ms observation time). Constant sub-MHz linewidth is achieved above 200 K, whereas an exponential increase occurs below 200 K.

5. Conclusion

In this work, we presented the frequency noise properties of a single DFB-QCL measured over a large temperatures range, from 128 K to 303 K. We showed that the temperature dependence of the frequency noise is characterized by a two-regime behavior with a transition temperature around 200 K. The frequency noise increases exponentially below 200 K, while it remains nearly constant in the range 200-300 K. In addition to filling the gap between room and cryogenic temperature, our data agree with the frequency noise PSD previously reported for distinct devices operated at these fixed extreme temperatures. This gives a first clue that the frequency noise behavior in QCLs might be specific to their semiconductor structures. Moreover, we measured the internal current noise of the QCL versus temperature. Our results showed quantitatively that the frequency noise is entirely induced by electrical noise intrinsic to the device. This gives the experimental evidence of the frequency noise origin in QCLs and validates previous hypotheses [8, 14]. Although the first purpose of this work was to investigate the laser frequency noise through optical measurements, a deeper understanding will require further electrical characterization of such structures. Finally, it is worth noting that the present work provides a new significant argument that besides all the practical advantages of room-temperature QCLs, they are essential for the most demanding applications where narrow-linewidth is required. Along with a low-noise current driver, sub-MHz linewidths can be achieved in a free-running device, whereas the spectral broadening exceeds 10 MHz at cryogenic temperatures.

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