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Frequency Ageing and Noise Evolution in a Distributed Feedback Quantum Cascade Laser Measured Over a Two-Month Period

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***Abstract*—We report on the evaluation of the frequency stability of a distributed feedback quantum cascade laser (QCL) at 8 μm that was continuously monitored over a 2-month period using a spectroscopic setup. The QCL was operated in continuous wave mode at room temperature (21.4 °C). It was driven by a home-made low-noise controller at a nominal current of $\sim$600 mA located in the middle of its operation range. Two distinctive behaviors were observed. A monotonous frequency drift of about 1.8 GHz was observed during slightly more than the first month, followed by a stable regime in the second month where the frequency remained within a 100 MHz range. In addition, the electrical flicker noise of the QCL was regularly measured during the same period, and similarly showed two different regimes. The noise regularly decreased at a small rate of about 0.3%/day during the first month, whereas it tends to stabilize during the second month. We believe that an improvement of the QCL contacts over time is responsible for this behavior. After the initial one-month period, the QCL showed a remarkably stable behavior that is beneficial for many applications that require stable long-term operation.**

***Index Terms*—Laser noise, laser reliability, laser stability, quantum cascade laser.**

I. INTRODUCTION

SEMICONDUCTOR lasers are attractive light sources for a wide range of applications owing to the ability to precisely tune their emission wavelength via their injection current. The long-term stability of their emission wavelength is crucial in applications such as atomic clocks, optical telecommunications or trace gas sensing. Various test procedures have been implemented to assess the long-term behavior of near-infrared laser diodes. However, these tests generally focused on the laser output power as the most relevant parameter. For instance, international standards routinely applied to qualify telecom-grade laser diodes, such as the Telcordia standard [1], rely on monitoring the laser output power to detect possible failures during different environmental tests or to assess the laser lifetime from accelerated ageing tests realized at elevated temperatures. However, the most relevant reliability criteria in various spectroscopic applications do not only concern the laser output power, but other parameters are of higher importance. For example, laser-based trace gas sensing requires that the laser remains tuned to the proper wavelength corresponding to the probed molecular transition even in absence of the target gaseous species over long timescales that can extend up to the sensor lifetime of several years. In such a case, it is primordial to ensure the long-term frequency stability of the laser source. This aspect has been much less considered so far in laser reliability tests than the optical power.

A few studies were reported about the long-term behavior of some spectral properties of near-infrared lasers. The wavelength shift of a 780-nm vertical-cavity surface-emitting laser (VCSEL) was measured during an ageing process [2] and a similar measurement was realized during the radiation test of a 1.55-μm distributed feedback (DFB) laser [3]. The drift of the laser current at resonance of an Rb vapor cell transition has also been studied over several months in various DFB lasers at 780 nm, both at atmospheric conditions and under vacuum [4]. These studies have been realized so far with near-infrared laser diodes, but no similar investigation has been performed in mid-infrared lasers.

Quantum cascade lasers (QCLs) constitute a versatile type of coherent light source in the mid-infrared spectral region and are widely used in numerous spectroscopic applications [5], especially in the fields of high-resolution molecular spectroscopy and trace gas sensing. Few works have been published so far on the reliability and lifetime of QCLs, and all reported investigations considered the output power as the relevant parameter. For instance, Lyakh and co-workers showed more than 3500 h of continuous wave operation at more than 2 W output power [6]. Evans and Razeghi [7] reported measurements of two high-power continuous wave QCLs emitting at 4.6 μm conducted over a period of 4000 h at a heat sink temperature of 25 °C [7]. They observed a strong power increase (65–75%) and a reduction in the laser threshold current during the first 500 h, which they attributed to a current-induced annealing of the metal-semiconductor interfaces. Xie *et al.* also observed

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improved output power in several QCLs at the same wavelength during the first 1000 h of an aging test performed over 5000 h [8]. In this case, a reduction of leakage currents outside of the laser core through a semi-insulating InP layer or at the interface between the laser core and the semi-insulating InP, was believed to be the cause of the observed power change.

For applications such as trace gas sensing in the mid-infrared spectral range, it is important to study the long-term frequency stability of QCLs. Other spectral properties of QCLs are also essential for these applications, such as the frequency noise and associated linewidth. QCLs are known to have a very narrow intrinsic linewidth at the 100-Hz level [9], but they suffer from extra flicker (1/*f*) noise that significantly broadens the actual linewidth encountered in practice, typically to the megahertz level [10]. Several experimental studies of frequency noise in QCLs were performed in the last years [9], [11]–[14]. In this context, we showed that electrical noise measured on the voltage drop across the QCL is a powerful mean to investigate noise processes in QCLs as it constitutes the main contribution to the laser frequency noise [12], [14]. Recently, Yamanishi *et al.* also proposed a theoretical model of the origin of this electrical flicker noise in ridge-waveguide QCLs in terms of fluctuating charge-dipoles [15].

In this article, we present an experimental study of the frequency stability of a QCL continuously assessed over a period of two months. In addition, we also investigated a possible change in the noise properties of the laser during the same period by regularly measuring its voltage flicker noise.

II. Experimental Setup and Methods

The laser under test was a DFB-QCL with a buried-heterostructure (BH) geometry, emitting at 7.96 μm and manufactured by Alpes Lasers. The device was mounted in a standard laboratory laser housing (LLH) package from Alpes Lasers containing a thermo-electrical cooler (TEC) and equipped with a 10-kΩ negative temperature coefficient resistor for precise temperature stabilization. As the laser was operated close to room temperature in this experiment (21.4 °C for the spectroscopic setup described after), no active cooling of the LLH was implemented. The QCL was driven by a home-made controller incorporating a highly-stable thermal regulator and a low-noise current source. The temperature controller stabilizes the QCL temperature at the mK level, which is important for long-term reliability. The current source has a low enough noise level of $<$1 nA/Hz$^{1/2}$ at Fourier frequencies higher than 1 kHz, which enables observing the noise induced in the QCL itself without technical limitation from the driver [10]. Before being implemented in the long-term experiment reported here, the QCL under test has barely been operated during a few hours.

For an accurate determination of the spectral properties of the laser over time, the spectroscopic setup depicted in Fig. 1 was used. It is similar to the experimental arrangement commonly used to measure the frequency noise spectrum of QCLs [9], [11]–[14]. The absorption slope of a molecular transition converts frequency fluctuations of the laser into intensity fluctuations that are subsequently detected by a photodiode. A sealed gas cell with a length of 10 cm and filled with 2 mbar of pure N_2O was used for this purpose. The experimental setup further incorporated a laser locking scheme to frequency-stabilize the QCL onto the center of a N_2O transition, which was used for long-term continuous monitoring of the QCL frequency. For this purpose, the laser current was modulated at 50 kHz and the signal from the photodiode at the gas cell output was demodulated at the same frequency to generate a derivative-like signal of the N_2O absorption line by the standard method of wavelength modulation spectroscopy [16]. The strong absorption signal occurring at the center of the N_2O transition in the reference gas cell tends to distort the demodulated signal for small modulation amplitudes. Therefore, a large enough current modulation depth $\Delta I = 500$ μA was applied to the laser, which induced a broadening and smoothing of the error signal. This current dithering corresponds to a frequency modulation depth $\Delta\nu \approx 200$ MHz, which is about five times the $\sim$40-MHz half width at half maximum of the N_2O transition at the considered pressure. The smooth behavior of the error signal obtained at the center of the transition shown in Fig. 1 was suitable for laser frequency stabilization. Precise and continuous determination of the laser emission wavelength was obtained by stabilizing the laser to the center of the P32e transition in the ν_3 absorption band of N_2O at 1256.4 cm^{-1} [17]. This was achieved at a laser heat sink temperature of 21.4 °C and a current slightly above 600 mA, which is located approximately at mid-range between the laser threshold ($\sim$370 mA) and the roll-over current (740 mA). The laser frequency-stabilization was realized using a proportional-integral (PI) servo-loop filter implemented in the QCL controller together with the laser modulation and signal demodulation. The feedback signal was applied directly to the QCL current in order to keep the laser at the center of the absorption line. The resonance current was continuously monitored and recorded over a period of about two months at a sampling rate of 1 s, together with other relevant parameters such as the laser voltage, temperature, TEC current, etc.

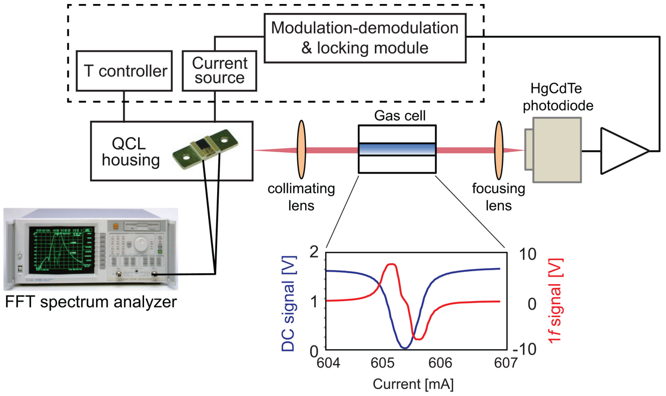

Fig. 1. Scheme of the spectroscopic setup used to measure the long-term wavelength stability of the QCL. All functionalities enclosed in the dashed area are realized by the home-made QCL controller. The derivative-like signal of the N_2O absorption line obtained after demodulation (red line) is shown in the lower part of the figure together with the direct absorption signal (blue line).

The time evolution of the current maintaining the laser at the center of the absorption line was used as an indicator of the

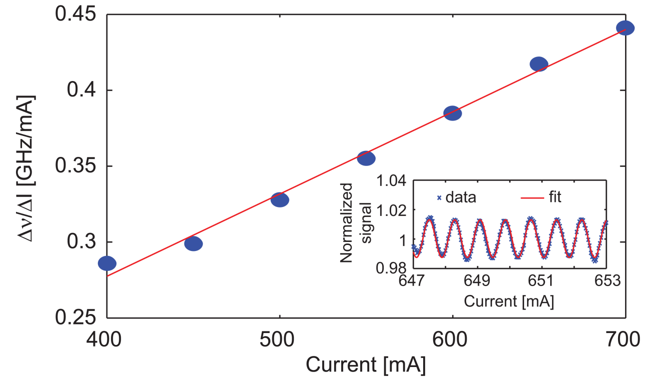

Fig. 2. Dependence of the QCL current-tuning coefficient ($\Delta\nu/\Delta I$) as a function of the laser dc current. The circles represent the experimental data and the red line is a linear fit. Inset: example of the fitted fringes pattern used to determine the frequency variation $\Delta\nu$ induced by a current change ΔI.

frequency drift of the free-running QCL. The current variations were converted into equivalent optical frequency changes of the unstabilized laser using the measured current-tuning coefficient. This coefficient slightly depends on the laser dc current. Hence, a precise determination was obtained by using the fringe pattern induced by a low-finesse optical cavity of known length during a laser scan. This was realized by slightly tilting the photodiode shown in Fig. 1 to induce a weak reflection towards the laser that produced a low-finesse cavity with a length of 43.5 cm. By fitting the fringe pattern recorded during a linear current scan of amplitude ΔI by a sine waveform (see inset of Fig. 2), the corresponding frequency tuning $\Delta\nu$ of the laser was determined, from which the tuning coefficient $\Delta\nu/\Delta I$ was retrieved. This measurement was repeated at various dc currents in order to determine the linear dependence of the tuning coefficient as a function of the dc current that is displayed in Fig. 2. A tuning coefficient $\Delta\nu/\Delta I = -0.39$ GHz/mA was thus determined at $T = 21$°C and $I = 600$ mA, and was used for the aforementioned current-to-frequency conversion. The same method was applied to determine the temperature-tuning coefficient of the QCL, $\Delta\nu/\Delta T = -2.9$ GHz/K (at $I = 500$ mA).

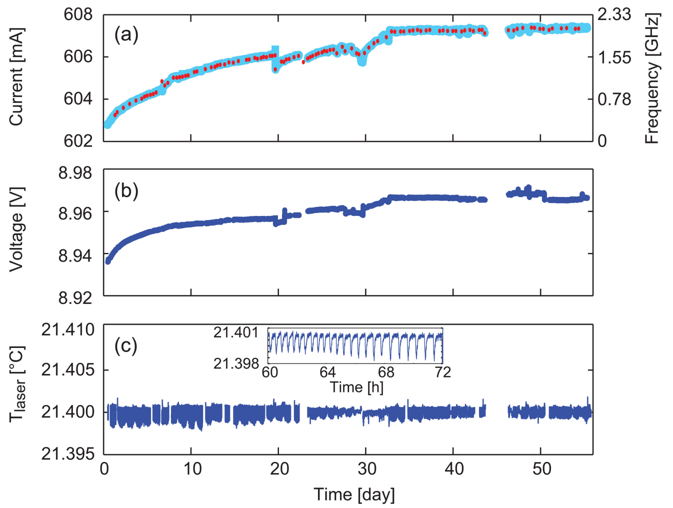

Fig. 3. "Long-term" measurement of the QCL frequency stability performed continuously over a period of two months. (a) Evolution of the laser current (left scale) and corresponding optical frequency drift (right scale) obtained by converting the current variations into relative optical frequency using the tuning coefficient $\Delta\nu/\Delta I$. The thick (blue) line shows the data obtained from the continuous stabilization to the N_2O transition. The (red) points are complementary data obtained from occasional current scans through the transition. (b) Evolution of the voltage across the laser. (c) Evolution of the laser temperature. The inset shows the influence of the laboratory air conditioning over a period of 12 hours. The white gaps in all plots correspond to periods where the laser was unlocked for different reasons. At day 23, a power failure in the laboratory led to a complete restart of the experiment. The jump in the laser frequency and voltage at day 19 is due to an erroneous set current applied to the laser that resulted in a large temperature change. During days 44–46, a problem with the monitoring photodiode prevented the laser to be stabilized to the N_2O transition.

III. RESULTS

Fig. 3 shows the evolution of the laser current, of the corresponding optical frequency drift, laser voltage and temperature measured over a 2-month period of continuous operation. During a first period extending over slightly more than one month (days 0–32), a monotonous drift of the laser current of about 4.6 mA is observed, corresponding to a frequency change of ~1.8 GHz. At the same time, the laser bias voltage also slightly increased by ~3%, as a higher bias voltage is required to drive a higher current through the laser. The observed behavior is not related to environment temperature changes, as the laser temperature was maintained stable within ~2 mK during the entire measurement period (see Fig. 3(c)). Thermal fluctuations associated to daily ambient temperature variations and to much faster fluctuations induced by the laboratory air conditioning system (~15-min cycle) are visible on the stabilized laser temperature (with maximum peak-to-peak amplitude of 2–3 mK, see inset of Fig. 3(c)). However their impact on the stabilized laser current and thus on the optical frequency is barely observable. The laser frequency drift observed during this initial period is comparable to the value of < 2 GHz/month reported for near-infrared DFB laser diodes at 852 nm [18].

The frequency drift observed during the first month of operation is acceptable for QCL applications in the field of trace gas sensing at ambient atmospheric conditions where molecular transitions are pressure-broadened to typical values of a few gigahertz. However, it could become detrimental if it was persisting at the same rate over several months. But our experimental results show that after this initial one-month period, the change in the QCL current is strongly reduced and the optical frequency remains within a range of ~100 MHz during more than 20 days, up to the end of our experiment. The QCL voltage also becomes much more stable than in the first part of the experiment.

The continuous monitoring of the QCL frequency assessed from the stabilization to the N_2O transition was complemented by additional measurements of the absorption line for further verification. Two or three times per day, the laser was unlocked and a current scan was recorded. The current corresponding to the center of the N_2O transition was determined from the minimum transmitted intensity. These data are also plotted as individual points in Fig. 3(a). They are in very good agreement

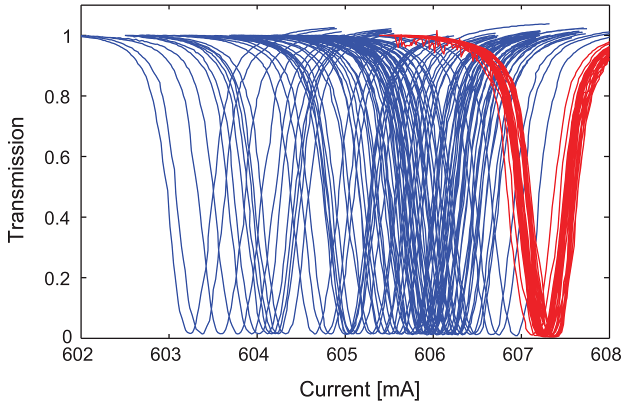

Fig. 4. View of the current scans of the N_2O transition recorded during the entire experiment. The blue curves measured during the first month of the experiment (days 0–31) show the significant shift observed during this period, which corresponds to several widths of the transition. The set of (red) curves grouped on the right side and measured during the second part of the experiment show a very stable emission wavelength. The width of the absorption line in current unit remains qualitatively constant (~0.57 mA) throughout the experiment, but the resolution of the current scan was not sufficient to precisely assess a possible tiny change in the current-tuning coefficient $\Delta\nu/\Delta I$.

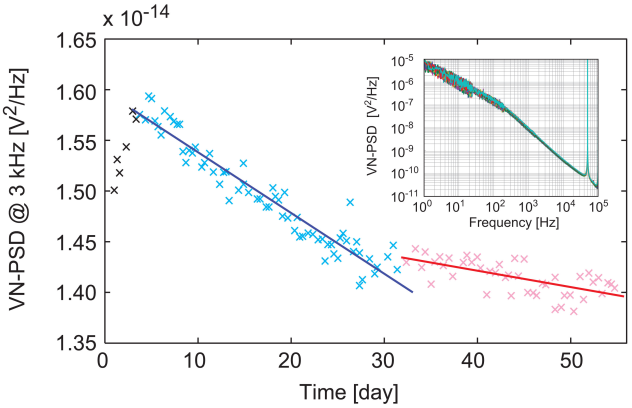

Fig. 5. 3-kHz component of the QCL voltage noise power spectral density (VN-PSD) plotted as a function of time. The crosses correspond to the experimental data and the lines represent linear fits as guides for the eyes, performed over the data of days 5 to 31 (blue) and 32 to 56 (red). The same periods represented by the same color code are considered here as for the QCL frequency drift shown in Fig. 4. The inset shows a superimposition of all voltage noise spectra recorded during the experiment. The peak at 50 kHz originates from the laser modulation applied for frequency stabilization to the N_2O line.

with the current measured from the continuous stabilization to the N_2O transition. The recorded scans are displayed in Fig. 4 and make the current-shift of the transition clearly visible. From these numerous scans, one also qualitatively notices that the width of the N_2O absorption line remains relatively constant in terms of current, which indicates that the laser current-tuning coefficient $\Delta\nu/\Delta I$ did not change significantly throughout our experiment. However, the resolution of the current scans was not sufficient to enable a precise determination of the transition width and hence to detect a possible tiny variation of the tuning coefficient over time.

In addition to the N_2O absorption line, the QCL electrical flicker noise was also measured at the same time on the voltage across the laser using a fast Fourier transform (FFT) spectrum analyzer (Stanford Research SR-760) in the range of 1 Hz to 100 kHz. In order to obtain clean measurements with a good spectral resolution over the entire considered frequency range, each spectrum was obtained from the combination of several FFT spectra measured in different frequency ranges (one spectrum for each frequency decade), after co-averaging 5000 individual FFT traces. After each measurement, the laser was relocked to the absorption line and the monitoring was pursued.

The noise spectra recorded during the 2-month duration of the experiment appeared very similar when displayed in a log-log plot, but some trend was observed when one looked in more details at the noise evolution over time. Fig. 5 displays the time evolution of the noise component at 3 kHz extracted from each spectrum, which was used as a representative quantity of the electrical flicker noise as considered in former studies [12]. After an increase of the noise during the first 3−4 days, a regular monotonous decrease at a small rate of about 0.3%/day is observed until day 31. Over this entire period, a noise reduction of about 6% is observed. After this, the variation becomes much weaker and the noise tends to be more or less constant over time. A similar behavior was obtained when considering the integrated noise (in the range of 200 Hz to 40 kHz), but the data were slightly less reliable due to the presence of some spurious noise peaks (electronic artefacts) in some spectra.

IV. DISCUSSION AND CONCLUSION

By comparing Figs. 3 and 5, a good correspondence is observed between the time where the noise starts to stabilize and the point where the QCL wavelength drift is reduced (at day ~30). A possible explanation of the observed behavior is an improvement of the laser contacts over time resulting from an annealing effect, which slightly reduces the voltage drop in the contacts and the associated laser heating. This assumption is similar to the statement given by Evans and Razeghi for the initial power increase observed in their QCLs reliability tests [7] The laser contacts can be a source of noise in QCLs by acting like Schottky diodes, in a similar way as the interface between the n-doped regions (cladding and gain medium) and the iron-doped lateral insulator was considered as a potential source of noise in BH-QCLs [14].

The monotonous increase of the laser current observed in Fig. 3(a) to keep the QCL wavelength constant can also result from the same improvement of the laser contacts. The slightly reduced heating associated with the improvements of the contacts results in a small increase of the laser current to keep the laser active zone at constant temperature, which is necessary to maintain the emission wavelength constant. After this annealing period, one notices that both the emission wavelength and the voltage noise of the QCL remain remarkably stable over time, which is very beneficial for many applications of this type of mid-infrared lasers that require stable long-term operation.

In the future, it may be interesting to extend such tests over longer timescales and to study more samples to get some statistics on the frequency ageing of DFB-QCLs. Other experiments of interest include the investigation of the effect of temperature cycling on the spectral properties of QCLs, as well as their frequency stability during on/off cycling of different durations. The results of our experiment showed an initial period of about 700 h (30 days) where the spectral properties (emission frequency and voltage noise) of the QCL under test drifted. This period lies at mid-range between the value of about 500 h (Evans and Razeghi [7]) and 1000 h (Xie *et al.* [8]) previously reported in the literature about reliability tests of QCLs relying on the monitoring of the emission power only. In both cases, an improved output power was noticed during the initial period in a similar way as for the noise decrease and improved wavelength stability observed in our experiment. A similar annealing effect occurring during the initial operation of the QCL might be the reason of these effects.

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