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Linewidth measurement of mid infrared quantum cascade laser by optical feedback interferometry

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We estimated experimentally the linewidth (0.28 MHz) of a distributed feedback quantum cascade laser emitting at 6.2 μm using optical feedback interferometry. The method is simply based on the analysis of the histogram of laser self-mixing fringe periods measured directly as voltage variation across the laser terminals. We assessed the optimal experimental conditions estimating the influence of the optical feedback strength on the interferometric phase noise and compared our results with those reported using conventional interferometric methods based on the analysis of the frequency noise power spectral density.
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The mid infrared (mid-IR) portion of the electromagnetic spectrum is also known as the molecular fingerprint region because most of the structure-specific vibrational transitions occur in this spectral range. The commercial availability of mid-IR quantum cascade lasers (QCLs) operating in continuous wave even above room temperature boosted their application for gas sensing[1,2] and also tissue imaging.[3] Their recognized intrinsic stability[4] even in the presence of optical feedback makes mid-IR QCLs the lasers of choice for detector-less applications, such as optical feedback interferometry[5] and imaging.[6,7] The linewidth of distributed feedback (DFB) mid-IR QCLs has been previously measured either by using the heterodyne or self-homodyne detection of a beat note signal[8,9] or, indirectly, by analyzing the frequency noise power spectral density (FNPSD).[10,11] The latter is obtained by converting the laser frequency fluctuations into intensity fluctuations recorded by an external detector and processed by an electronic spectrum analyzer.

The capability of the optical feedback (self-mixing (SM)) interferometry to measure the linewidth of near infrared lasers has been demonstrated.[12] Preliminary results on the possibility to extend the technique at longer wavelengths are reported as not conclusive, due to the large minimum detection limit of the employed set-up.[13]

In this paper, we report on the measurements of the laser linewidth of a commercial mid-IR QCL by the SM interferometry using a simple set-up in which the laser is both the source and the detector of the investigated radiation and the SM signal is taken as the voltage variation across the laser terminals. In the best experimental condition under moderate optical feedback, we measured a linewidth as low as 0.28 MHz and discuss our results in terms of thermal tuning of QCLs.

Self-mixing in semiconductor lasers occurs when a small portion of the emitted light is back reflected by an external target into the laser cavity. The back reflected electric field interacts coherently with the oscillating laser mode creating a modulation in all relevant laser parameters, namely, the amplitude and phase of the electric field, the carrier density, and the laser frequency. When the remote target is displaced, the variation of the external cavity length induces a periodic modulation of the emitted optical power and of the voltage difference across the laser terminals, both of which can be conveniently measured to obtain information about the external cavity or the laser parameters. Under weak to moderate feedback, commonly referred to as the regimes in which the re-injected power is in the range 10^{-8}–10^{-6} of the emitted power, the self-mixing signal shows fringes for each half-wavelength target displacement, corresponding to phase changes of 2π of the coupled-cavity field.

The experimental set-up is shown in Fig. 1. The source was an Alpes Laser distributed feedback single longitudinal mode mid-IR QCL emitting at $\lambda = 6.2\,\mu$m. The laser was operated at a constant temperature T = 283 K, using a Peltier cooling stage, and was driven at either the constant current I = 500 mA or I = 540 mA, corresponding, respectively, to current values 1.02 and 1.10 times the threshold current I_{th}, by a low noise current generator (Wavelength QCL-1000) with a nominal current noise density of $2\,\mathrm{nA}/\sqrt{\mathrm{Hz}}$. The selected injection current levels, slightly above threshold for both cases, fall in the range where the laser sensitivity to SM is higher and the required feedback power is lower. The output beam was collimated by an AR-coated chalcogenide glass aspheric lens having numerical aperture NA = 0.56 and nominal focal length of 4 mm. A pinhole having a variable diameter was placed in front of the output beam to adjust the feedback strength and to preserve the moderate SM regime. The external target was a flat mirror mounted on a piezoelectric actuator driven by a sinusoidal voltage modulation. By using the folded-cavity configuration shown in Fig. 1, a maximum length $L_0 = 4.8$ m was obtained. In order to limit the mechanical fluctuations to those characteristics of the piezo actuator, the set-up was mounted on an anti-vibration optical table and covered by plastic shields to minimize systematic errors due to environmental noise. The measurements were repeated while varying the length of the external cavity in the range 0.6 m − 4.8 m in steps of 0.2 m.

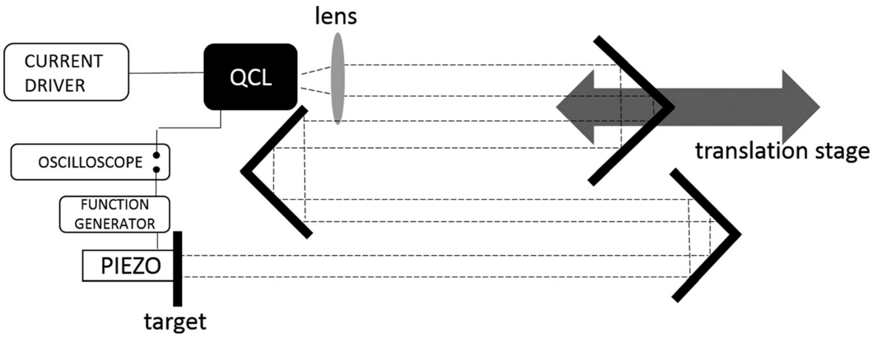

FIG. 1. Experimental set-up for measuring the mid-IR QCL linewidth by self-mixing interferometry.

Figure 2(a) shows a representative SM-voltage signal in the moderate feedback regime. The random phase fluctuations $\Delta\Phi$ of the laser output correspond to fluctuations Δt of the SM fringe period T, and their relationship being given by

$$\frac{\sqrt{\langle \Delta\Phi^2 \rangle}}{2\pi} = \frac{\sqrt{\langle \Delta t^2 \rangle}}{T}. \tag{1}$$

Random phase noise fluctuations thus correspond to random distribution of the switching time that can be conveniently analyzed by a Gaussian fitting analysis as shown in Fig. 2(b). Since the interferometric phase of the self-mixing signal is given by

$$\Phi = \frac{4\pi}{c}\nu L, \tag{2}$$

where c is light speed, ν is the laser frequency, and L is the distance of the external target from the laser output facet, the phase fluctuation of the interferometric electrical field allows to estimate the laser linewidth by differentiation of Eq. (2).[12] Assuming that the laser frequency and the target distance are uncorrelated variables, one can readily write

$$\sqrt{\langle \Delta\phi^2 \rangle} = \frac{4\pi}{c}\sqrt{\nu_0{}^2\langle \Delta L^2 \rangle + L_0{}^2\langle \Delta\nu^2 \rangle}, \tag{3}$$

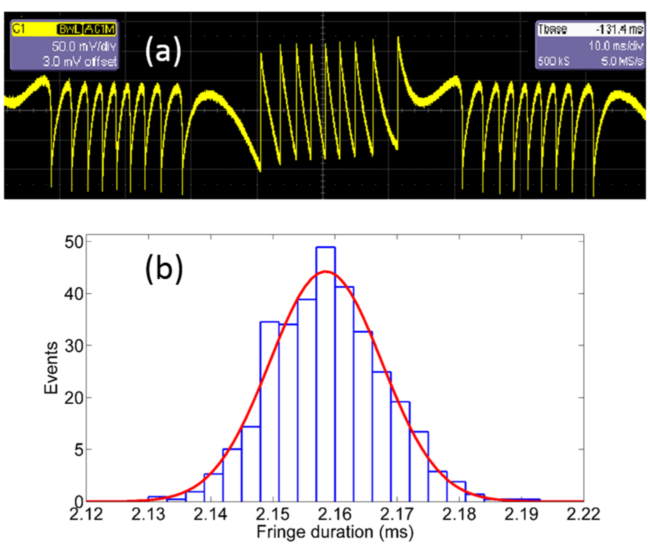

FIG. 2. (a) Representative self-mixing signal in the moderate feedback regime for a sinusoidal displacement of the target with amplitude of about 25 μm and frequency 16 Hz. (b) Histogram of the fringe period distribution over 300 acquisitions for a cavity length $L_0 = 0.6$ m, together with the best-fit Gaussian distribution (fitting parameters are $\mu = 2.16$ ms and $\sigma = 9\ \mu$s).

where the 0-subscripts indicate the mean values of the statistical distribution of the corresponding variable, respectively. The RMS phase noise, calculated according to Eq. (1), on varying of the length L_0 of the external cavity allows estimating the laser linewidth by fitting the experimental data with Eq. (3).

We assessed the optimal experimental conditions for the linewidth measurement estimating the influence of the optical feedback strength on the interferometric phase noise. The ratio $\sqrt{\langle \Delta t^2 \rangle}/T$ was measured for different feedback levels while keeping fixed the external cavity length at $L_0 = 1$ m. The feedback strength was increased from the level at which the SM signal developed sawtooth like fringes up to the level at which the SM signal became highly distorted and the fringe period distribution could be no longer described by a single Gaussian. The amplitude of the voltage envelope during one period of target oscillation grows with the carrier density and the feedback strength in the weak and moderate regimes and can be taken as proportional to the actual feedback increase. Throughout the investigated feedback strength range, the amplitude of the SM signal amplitude grew monotonically with the feedback strength, adjusted by varying the pinhole diameter, whereas the RMS of the period distribution showed a nonlinear fivefold broadening as reported in Fig. 3. On the other hand, the average fringe period changed by less than 5%, indicating a stationary laser emission mode with no evidence of mode-hopping, in agreement

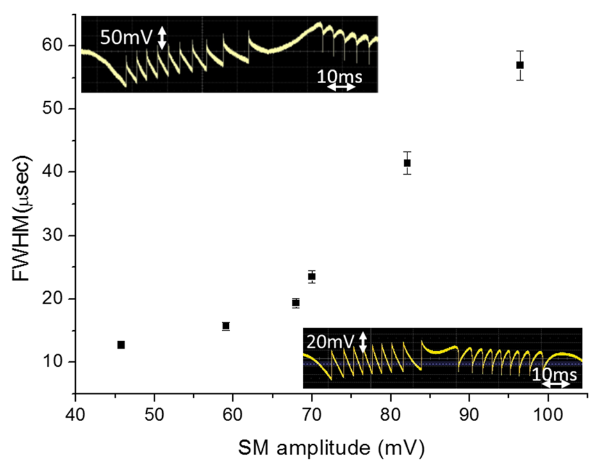

FIG. 3. FWHM of the Gaussian distribution of the fringe period acquired at increasing feedback strength in the moderate feedback regime where the amplitude of the SM signal grows with the feedback power. Error bars are the uncertainty on the fitting parameter σ. The lower and upper insets show representative self-mixing traces at the minimum and maximum investigated feedback levels, respectively.

with the stability analysis of mid-IR-QCL recently reported in Ref. 14. Great care was then taken to maintain the feedback strength at a constant level, corresponding always to the interferometric signal at the minimum feedback level showed in the inset at the bottom right of Fig. 3 for each value of the cavity length, while keeping the drift of the average fringe period within 1%.

Figure 4 shows the measured RMS phase noise versus target distance L_0, together with the fitting curve according to Eq. (3), from which we obtain the QCL linewidth and the mechanical noise at the constant injection currents of I = 500 mA and I = 540 mA. In the first case (Fig. 4(a)), the estimated values were 0.28 ± 0.06 MHz and 11.3 ± 4 nm, respectively, while at $I = 1.1I_{th}$ (Fig. 4(b)), the laser linewidth was 0.28 ± 0.08 MHz and the estimated mechanical noise was 15 ± 5 nm. A repeatability of about 8% was granted by repeating several time the same measurement. It has been common practice in previous works on SM linewidth measurement to linearize Eq. (3) in the long-cavity limit, where the first term can be neglected.[12] In our case, the first term is in the range $3–5.2 \times 10^{11}$ $(m/s)^2$ and is greater than the second term in Eq. (3) up to $L_0 \simeq 3$ m. The linear fitting of the experimental data for $L_0 > 3.4$ m is shown for comparison by the dashed lines in Fig. 4. The linewidth resulting for the slope of the zero-intercept line is about 0.3 MHz for both data-sets, in line with the 8% estimated accuracy of the measurement. Nonetheless, the full fitting by Eq. (3) considers all the experimental data point and would provide useful also in measuring linewidth of longer wavelength lasers, such as THz-QCLs, where the long-cavity approximation would need increasingly longer optical path lengths.

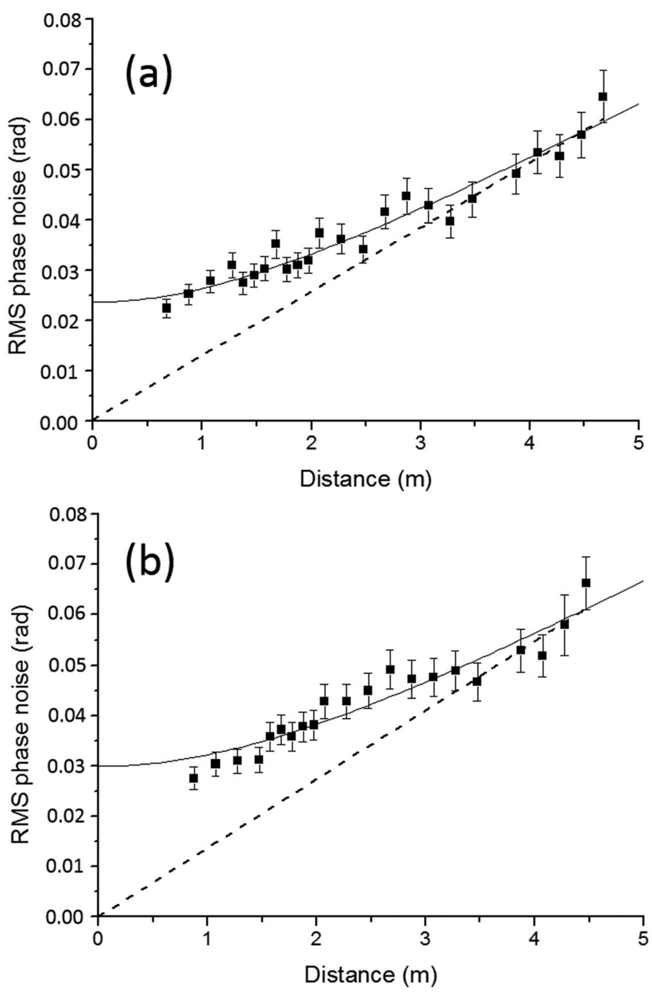

FIG. 4. Experimental RMS phase noise as a function of the target distance L_0 obtained at constant injection current of $I = 500\,mA = 1.02\ I_{th}$ (a) and $I = 540\,mA = 1.1\ I_{th}$ (b). The solid line is fitted to data using Eq. (3). The dashed lines are the zero-intercept linear fits for $L_0 > 3.4$ m.

Previously reported values for the linewidth of QCLs operating in the wavelength range 4–5 μm at room temperature, obtained by the analysis of the frequency noise measurements of the power spectral density[10,11] or the heterodyne beat spectrum, fall in the range 0.5–1 MHz. Unlike spectrally resolved measurements, SM experiments do not allow the discrimination of individual noise sources, providing only the integrated linewidth averaged over the fringe period. It is well known that the linewidth of a semiconductor laser may be influenced by the noise of the current generator providing the pumping process. However, current generator noise values of the order of 1–2 nA/$\sqrt{}$Hz, i.e., comparable to that of our current driver, are reported to have a moderate influence on the linewidth of mid-IR QCLs.[14] The effect of optical feedback on the linewidth of diode laser is known and debated, but no information is available for QCLs, to date. Some recent reports,[4,15] emphasizing the robustness of QCL to optical feedback compared to near infrared diode lasers, suggest a reduced perturbation of the laser parameters caused by the feedback strength. Nonetheless, a residual narrowing effect due to optical feedback, in spite of the measurement being taken at the lowest feedback strength, might contribute to the narrower linewidth reported here. In addition, thermal effects are known to be responsible for the small tuning coefficient of QCLs, which starts to drop with frequency beyond 1 kHz.[10] The estimated DC tuning coefficient of our device is 0.6 GHz/mA, a factor 0.7 smaller than the laser sampled in Ref. 10. A smaller tuning coefficient would dump the frequency fluctuations occurring above few tens of kHz resulting in a lower value of the measured linewidth over the 0.5 kHz averaged by our swept fringe period.

In conclusion, we presented a consistent direct measurement of the linewidth of a mid-IR QCL by the self-mixing technique. With respect to traditional interferometric methods like homodyne or heterodyne techniques, laser self-mixing has the great advantage to avoid external detectors and simplify considerably optical alignment procedures.

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[1]P. Patimisco, G. Scamarcio, F. K. Tittel, and V. Spagnolo, Sensors **14**, 6165–6206 (2014).
[2]S. Borri, P. Patimisco, I. Galli, D. Mazzotti, G. Giusfredi, N. Akikusa, M. Yamanishi, G. Scamarcio, P. De Natale, and V. Spagnolo, Appl. Phys. Lett. **104**, 091114 (2014).
[3]P. Bassan, M. J. Weida, J. Rowlette, and P. Gardner, Analyst **139**, 3856–3859 (2014).
[4]F. P. Mezzapesa, L. L. Columbo, M. Brambilla, M. Dabbicco, S. Borri, M. S. Vitiello, H. E. Beere, D. A. Ritchie, and G. Scamarcio, Opt. Express **21**, 13748–13757 (2013).
[5]T. Taimre, M. Nikolic, K. Bertling, Y. Y. L. Lim, T. Bosch, and A. D. Rakic, Adv. Opt. Photonics **7**, 570–631 (2015).

[6]F. P. Mezzapesa, M. Petruzzella, M. Dabbicco, H. E. Beere, D. A. Ritchie, M. S. Vitiello, and G. Scamarcio, IEEE Trans. Terahertz Sci. Technol. **4**, 631–633 (2014).
[7]F. P. Mezzapesa, L. L. Columbo, M. Brambilla, M. Dabbicco, M. S. Vitiello, and G. Scamarcio, Appl. Phys. Lett. **104**, 041112 (2014).
[8]H. Ganser, B. Frech, A. Jentsch, M. Murtz, C. Gmachl, F. Capasso, D. L. Sivco, J. N. Baillargeon, A. L. Hutchinson, A. Y. Cho, and W. Urban, Opt. Commun. **197**, 127–130 (2001).
[9]D. Weidmann, L. Joly, V. Parpillon, D. Courtois, Y. Bonetti, T. Aellen, M. Beck, J. Faist, and D. Hofstetter, Opt. Lett. **28**, 704–706 (2003).
[10]L. Tombez, J. Di Francesco, S. Schilt, G. Di Domenico, J. Faist, P. Thomann, and D. Hofstetter, Opt. Lett. **36**, 3109–3111 (2011).
[11]S. Bartalini, S. Borri, I. Galli, G. Giusfredi, D. Mazzotti, T. Edamura, N. Akikusa, M. Yamanishi, and P. De Natale, Opt. Express **19**, 17996–18003 (2011).
[12]G. Giuliani and M. Norgia, IEEE Photonics Technol. Lett. **12**, 1028–1030 (2000).
[13]T. Gensty, J. Von Staden, M. Peil, W. Elsaßer, G. Giuliani, and C. Mann, Proc. IEEE 20th International Semiconductor Laser Conference, pp. 65–66.
[14]L. Tombez, S. Schilt, J. Di Francesco, T. Führer, B. Rein, T. Walther, G. Di Domenico, D. Hofstetter, and P. Thomann, Appl. Phys. B **109**, 407–414 (2012).
[15]L. Jumpertz, M. Carras, K. Schires, and F. Grillot, Appl. Phys. Lett. **105**, 131112 (2014).