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Measurements of the linewidth of a continuous-wave distributed feedback quantum cascade laser

Vasili L. Kasyutich [a,b,*], Philip A. Martin [a]

[a] School of Chemical Engineering and Analytical Science, University of Manchester, Oxford Road, M13 9PL, UK
[b] Institute of Quantum Electronics, HPF F16, ETHZ, Schafmattstrasse 16, 8093, Zurich, Switzerland

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ABSTRACT

Two-sample (Allan) variance with a modified algorithm was applied to the determination of the experimental linewidth of a thermoelectrically-cooled continuous-wave distributed feedback quantum cascade laser at a wavelength of 4.333 μm. From successive laser transmittance scans over the CO_2 ν_3, (01^11-01^10) P(33) absorption line at 2307.653 cm^{-1}, two-sample variances were calculated for the laser frequency difference between different points on the sides of the absorption peak. From the minimum two-sample variance of the laser frequency difference between two adjacent points (5 μs between the points) on the same side of the absorption line the experimental laser linewidth was estimated to be less than 36(7) kHz at a laser power of ~25 mW, a laser current of 976 mA and a laser temperature of +19.5 °C.

1. Introduction

Quantum cascade lasers (QCL) [1] are important and useful light sources in mid-infrared laser absorption spectroscopy [2]. Tunable single-mode continuous-wave (cw) QCLs have been successfully used as gas sensors and analysers based upon a variety of techniques: direct absorption spectroscopy [3–6], wavelength modulation spectroscopy [3,7], frequency-modulation spectroscopy [8], cavity-ring down absorption spectroscopy [9–11], off-axis integrated cavity enhanced absorption spectroscopy [12–14], optical-feedback cavity enhanced absorption spectroscopy [15,16] and noise-immune cavity-enhanced optical heterodyne molecular spectroscopy [17]. Measurement of laser linewidths (LW) is of great interest as understanding the origin and main contributors to the LW broadening can be crucial for accurate and precise measurements in high resolution spectroscopy and in gas sensors. In the ideal case of a pure white frequency noise spectrum of the laser frequency fluctuations, the laser emission has a Lorentzian lineshape and a laser intrinsic LW due to quantum spontaneous emission fluctuations defined by a Schawlow-Townes and Henry limit [18,19]. An intrinsic LW of a free-running QCL can be estimated by using reasonable numerical values for the physical parameters of the QCL [20]. Free-running cw QCLs have been shown to have a Lorentzian lineshape and a narrow intrinsic LW (a full width at half maximum, FWHM) with the lowest floor limit of ~1 kHz [20]. However, the actual observed laser LW can be affected by additional contributions from the effective time-averaged broadening due to a combination of frequency flicker noise at low frequencies, frequency random walk noise, discrete frequency modulations and frequency drifts.

Two main approaches can be selected for the determination of the laser intrinsic LW. In a first approach, laser frequency-noise fluctuations can be estimated directly by means of an optical frequency discriminator such as a Fabry–Perot or a Michelson interferometer on the side of strong absorption line [21–23]. A laser frequency-noise power spectral density (PSD) can be extracted with a radio-frequency spectrum analyser from the intensity fluctuations of the transmitted laser beam when the laser frequency is tuned to the half-height of either an absorption peak or an interferometer optical fringe. The laser intrinsic LW can be determined from the lowest flattened level of the PSD at higher frequencies. It is difficult to determine precise estimations of an intrinsic LW using this approach as it requires calibration of many factors such as optical power and sensitivity of a frequency converter over a wide frequency range. In a second approach, the laser frequency-noise can be measured by means of a radio-frequency (rf) spectrum analyser from an rf beat note at the difference frequency of two heterodyning lasers [24,25], by self-heterodyning [26] or by self-homodyning [27]. Frequency noise analysis of the beat signal can be carried out in the time domain using two-sample variance of the laser frequency fluctuations [26] or in the frequency domain using a radio-frequency spectrum analyser [28]. In the time domain analysis an intrinsic laser LW can be estimated from the white noise coefficient determined from a log-log plot of the two sample variance of the laser frequency fluctuations against an averaging time interval [26]. However, in the frequency domain and time domain analysis the laser intrinsic LW can be easily overestimated as technical noise

* Corresponding author at: Institute of Quantum Electronics, HPF F16, ETHZ, Schafmattstrasse 16, 8093, Zurich, Switzerland. Tel.: +41 44633 2252; fax: +41 44633 1230.
E-mail address: kvasili@phys.ethz.ch (V.L. Kasyutich).

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fluctuations within the observation time may contribute and broaden the final width of the beat note [29].

The lowest values of QCL LWs have been observed for frequency stabilized and optically locked QCLs [21,23,30]. Extremely narrow LWs down to 5.6 ± 0.6 Hz have been measured from a heterodyne beat of two cw QCLs at 8.5 μm locked to two optical cavities [30]. An intrinsic LW of 510 ± 160 Hz was estimated from the measurement of the power spectral density of a DFB QCL which was tuned and locked to the half-peak side of a strong CO_2 absorption line [23]. An experimental Lorentzian LW of 12 kHz was evaluated from absorption line side-locking experiments and analysis of a power spectral density for the frequency-stabilized single-mode DFB QCL at 8.5 μm [21]. However, much larger experimental LWs have been observed and reported for unlocked and free-running cw QCLs. For instance, a free-running single-mode cw DFB QCL at a wavelength of 8.511 μm had a LW of 150 kHz estimated from the frequency fluctuations of the QCL tuned to the side of an N_2O absorption line [22]. LWs of 1.3–6 MHz were observed over a 0.5 s time period in heterodyne mixing of a free-running DFB QCL at a wavelength of 9.1 μm with a cw $C^{18}O_2$ gas laser [24]. A LW of 24 ± 12 MHz at 5.3 μm was determined by comparing experimental NO absorption spectra (averaging time of 1 s) against simulated absorption spectra [28]. LWs of ~48 MHz [31] and 240 MHz [5] were estimated from the deconvolution of direct absorbance spectra (a 1 s average) of low pressure NO (at 5.2 μm) gas samples. These observed larger LWs were explained by laser frequency fluctuations induced by current jitter and temperature variations of the QCL chip within the observation intervals. As current drivers exhibit higher noise at lower frequencies, the measured LWs depend markedly upon an observation or averaging time, and therefore the technical noise of the current driver and temperature controller may hinder measurements of the actual laser intrinsic LW.

Here, a simple approach for the measurement of the LW of a free-running tunable cw DFB QCL will be described for the first time to our knowledge. A strong CO_2 absorption line was periodically probed by a frequency sweep at a rate of 1 kHz. Successive transmittance signals (up to 6000 within 6 s) were recorded for further processing. Then two-sample variances (also called an Allan variance) [32,33] with a modified algorithm [34,35] have been calculated for the laser frequency fluctuations between two different points on the absorption peak. From the minimum of the two-sample variance maximal possible laser linewidths have also been determined for different laser powers.

2. A laser intrinsic linewidth

The frequency-noise PSD of the semiconductor laser frequency fluctuations can be approximated by a combination of several power-law components such as $S(f) = h_\alpha f^\alpha$ (with $-2 \le \alpha < 0$), together with white noise frequency fluctuations caused by spontaneous emission [26] and discrete modulation frequencies associated with the laser current driver technical noise frequencies and negligibly small white noise contribution of the laser current driver. Using these assumptions the one-sided laser frequency-noise PSD of a semiconductor laser can be given for a Fourier frequency variable f ($f < 10^9$ Hz)

$$S_\nu(f) = \frac{h_{-2}}{f^2} + \frac{h_{-1}}{f} + h_0 + \sum_i c_i \delta(f - f_i), \quad (1)$$

where h_{-2}, h_{-1}, h_0 are the coefficients of the random-walk, flicker and white noise laser frequency fluctuations, respectively, and $\delta(f–f_i)$ is the Kronecker function with c_i and f_i being the amplitude and the central frequency of the discrete noise frequencies. Fig. 1 shows a simulated one-sided frequency-noise PSD with $S_\nu(f)$ calculated for $h_{-2} = 10^8$ Hz^3, $h_{-1} = 5 \times 10^9$ Hz^2, $h_0 = 10^{10}$ Hz, $c_1 = 10^{14}$ Hz.

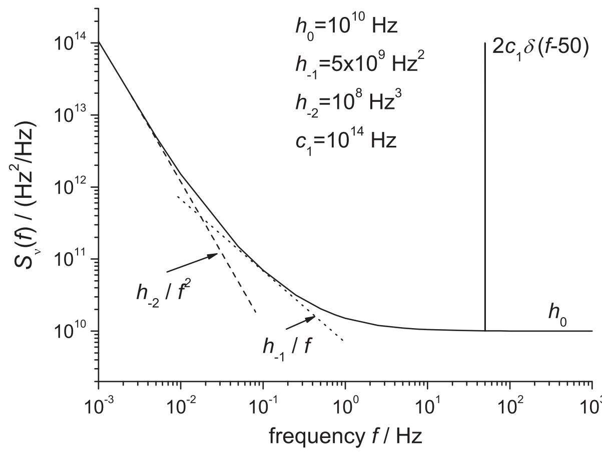

Fig. 1. Power spectral density simulated for $h_{-2} = 10^8$ Hz^3, $h_{-1} = 5 \times 10^9$ Hz^2, $h_0 = 10^{10}$ Hz, $c_1 = 10^{14}$ Hz.

The two-sample variance σ_ν^2 of laser frequency fluctuations for an averaging time interval τ can be obtained as [33,36]

$$\sigma_\nu^2(\tau) = 2\int_0^\infty S_\nu(f) \frac{\sin^4(\pi f \tau)}{(\pi f \tau)^2} df. \quad (2)$$

After substitution of Eqs. (1) into (2) the two-sample variance can be expressed by

$$\sigma_\nu^2(\tau) = h_0 \frac{1}{2}\frac{1}{\tau} + h_{-1} 2\ln 2 + h_{-2}\frac{2\pi^2}{3}\tau + 2\sum c_i \frac{\sin^4(\pi f_i \tau)}{(\pi f_i \tau)^2}. \quad (3)$$

The white noise coefficient h_0 in Eq. (3) can be derived from the two-sample variance plot of frequency fluctuations against the observation time interval. Fig. 2 shows a simulated two-sample variance plotted on a log-log scale. The sinusoidal variation with the descending amplitude is due to the discrete 50 Hz line frequency noise. Additional discrete frequency noise at other frequencies will give additional sinusoidal variations into the two-sample variance above a white noise baseline with a slope of −1. Contributions from the flicker noise (dotted line) and the random walk noise (dashed line) result in the two-sample variance deviating from the white noise line (dash-dotted line) at larger time τ. Under assumption that there is no contribution into the two-sample variance of other white noise sources (for instance,

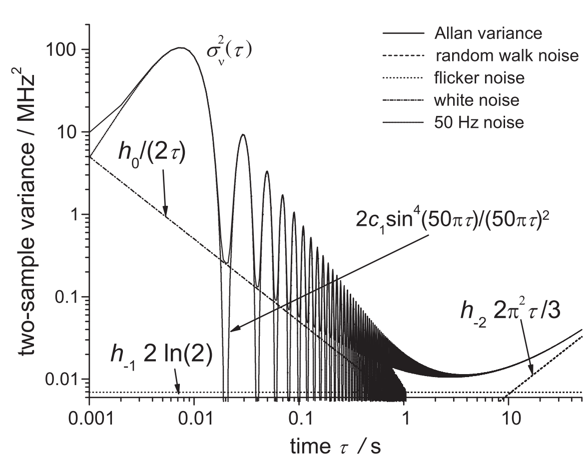

Fig. 2. Two-sample variance of frequency fluctuations simulated for $h_{-2} = 10^8$ Hz^3, $h_{-1} = 5 \times 10^9$ Hz^2, $h_0 = 10^{10}$ Hz, $c_1 = 10^{14}$ Hz.