Free-running frequency stability of mid-infrared quantum cascade lasers

T. L. Myers, R. M. Williams, and M. S. Taubman

Pacific Northwest National Laboratory, P.O. Box 999, Richland, Washington 99352

C. Gmachl, F. Capasso, D. L. Sivco, J. N. Baillargeon, and A. Y. Cho

Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974

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The intrinsic frequency fluctuations of two single-mode quantum cascade (QC) distributed-feedback lasers operating continuously at a wavelength of 8.5 μm are reported. A Doppler-limited rovibrational resonance of nitrous oxide is used to transform the frequency noise into measurable intensity fluctuations. The QC lasers, along with recently improved current controllers, exhibit a free-running frequency stability of 150 kHz over a 15-ms time interval. © 2002 Optical Society of America

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Lasers with low intrinsic frequency noise are important in a variety of applications, such as remote sensing, high-resolution spectroscopy, time and frequency standard measurements, and communication networks. Capasso and co-workers have developed quantum cascade (QC) lasers[1,2] that have opened up the possibility of stable optical sources in the mid-IR region because of the lasers' intrinsically stable frequency performance. QC lasers can be operated in a pulsed configuration at room temperature or continuously (cw) at cryogenic temperatures with high output power. Single-longitudinal-mode performance has been achieved by incorporation of a distributed-feedback (DFB) grating into the device.[3]

QC lasers operate differently than conventional semiconductor diode lasers. Photon generation in diode lasers results from a conduction-band electron recombining with a hole in the valence band. The distribution of states of the two bands with opposite curvature results in an asymmetric gain curve with respect to frequency, so the laser linewidth is greater than that predicted from the Schawlow–Townes formula by a factor of $(1 + \alpha^2)$,[4] which can range from 5 to 30.[5,6] The α parameter accounts for variations in the refractive index of the gain medium, which result from changes in the electron density because of spontaneous emission. However, in QC lasers, photons are generated as the injected electrons cascade down an energy staircase in the conduction band of a multiple-quantum-well heterostructure. Since transitions occur between discrete subbands of the same band, i.e., subbands with the same sign of the curvature, the laser's gain spectrum is expected to be symmetric as in gas and solid-state lasers and well approximated by a Lorentzian. Thus, the Henry α factor is expected to be near zero,[1,2] and the intrinsic laser linewidth of QC lasers is predicted to be narrower than for diode lasers operating in the same spectral region. Previous measurements have shown that nonstabilized QC lasers have linewidths of $\sim$1 MHz.[7] Since the laser frequency and output power depend on the injection current and the temperature, frequency-stable operation requires a current source with low current noise and excellent dc stability. Enabled by recent improvements in our current controllers, we report new measurements for the frequency fluctuations of two 8.5-μm QC DFB lasers (described in Ref. 3) that demonstrate the free-running laser frequency noise has been reduced by a factor of 6.

Techniques that are based on converting laser frequency fluctuations into intensity variations for evaluation of the laser frequency stability use a suitable optical frequency discriminator such as the side of a fringe or interferometric techniques. As shown in Fig. 1, we use the steep slope of a Doppler-limited nitrous oxide (N_2O) absorption feature to transform small frequency changes into measurable intensity variations. This method allows us to apply simple gas absorption cell techniques to characterize frequency noise. To verify that these measurements are not

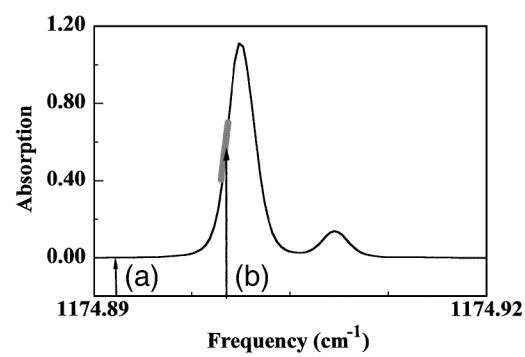

Fig. 1. Absorption profile of N_2O plotted on an absorbance scale. The arrow that is (a) off the molecular resonance shows the region in which the intensity fluctuations are measured, and the arrow (b) on the side of the molecular resonance corresponds to the region in which the frequency fluctuations are measured. The thick gray line represents the region of the profile that is used to determine the frequency–intensity conversion factor.

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limited by either laser power fluctuations or the noise floor of the detector–preamplifier, we compare the changes in the transmitted light through an absorption cell when the laser is tuned to the side of a strong rovibrational resonance of N_2O with the intensity changes when the laser is tuned off of the molecular resonance and when the laser beam is blocked.

The free-running QC DFB devices are installed in commercial liquid-nitrogen Dewars without any further temperature stabilization. Our current controllers have been improved to reduce parasitic noise from the controller, which can contribute to $1/f$-type frequency noise and the measured linewidth. We can superimpose a sawtooth modulation (typically 1 kHz) upon the dc current to sweep the laser frequency over an absorption profile. With an injection current near 600 mA, the QC laser produces approximately 20 mW of optical power under these conditions. A fraction of the collimated cw laser output is passed through a 15-cm-long absorption cell filled with approximately 1 Torr of N_2O. Approximately 40 μW of the transmitted light is focused onto a biased mercury cadmium telluride photovoltaic detector connected to a custom low-noise transimpedance amplifier with a 2-MHz bandwidth. The signal is recorded with a digital oscilloscope and transferred to a personal computer for further analysis.

We obtain a spectrum containing several absorption features by scanning the laser over 6 GHz and averaging the transmitted intensity. The frequency scale is calibrated from the known frequencies of the observed transitions by use of the HITRAN database.[8] An accurate frequency–intensity conversion factor is obtained from the strong rovibrational molecular resonance located at 1174.90 cm^{-1} by extrapolation of the slope in the half-height region of this absorption feature. This approximation is justified since the maximum excursions do not exceed $\pm 1\%$ of the peak absorbance. The laser is then tuned to the side of this transition by manual adjustment of the laser-current source to the appropriate dc level and measurement of the transmitted light for 15 ms by means of recording the ac filtered output of the detector–preamplifier with a 1-Msample/s sampling rate and 11-bit analog–digital conversion resolution. The intensity variations of the transmitted light are converted into relative frequency fluctuations by use of the inverse slope [Hz/V] calculated from the side of the N_2O rovibrational resonance. We then tune the laser off the molecular resonance to record the laser-power fluctuations. Similarly, we determine the noise floor of the detector–preamplifier combination by blocking the laser beam. Figure 2 shows the data from these three measurements.

A fast Fourier transform of the relative frequency fluctuations yields the frequency-noise spectral density [$Hz/\sqrt{Hz}$], which is plotted on a bilogarithmic scale in Fig. 3 as a function of the Fourier frequency. The noise spectral density represents the square root of the power spectral density normalized to a 1-Hz bandwidth and is determined up to the Nyquist frequency of 500 kHz for these measurements. The dashed line in Fig. 3 represents the detector–preamplifier noise floor, which is a combination of the shot noise from the substantial room-temperature blackbody radiation striking the detector and the current noise from the preamplifier circuit. As shown in Fig. 3, the frequency noise exhibits a $1/f$-type dependence out to 500 kHz, where it begins to blend in with the detector–preamplifier noise floor. Furthermore, no spectrally flat region, or white noise, is observed in these measurements; therefore, the Lorentzian component of the laser linewidth, or the fast linewidth, cannot be determined. An increase in signal-to-noise ratio along with improved detector–preamplifier bandwidth is necessary for further exploration of the frequency dependence of the frequency fluctuations. The noise floor can be reduced by use of cold IR bandpass filters to minimize the amount of blackbody radiation striking the detector, in conjunction with improved preamplifier circuits and detectors.

Since the QC lasers exhibit increasing noise at lower frequencies, the linewidth depends on the observation or averaging time. In this Letter we fit a Gaussian line shape to a histogram of the relative frequency fluctuations to present the standard deviation of the center frequency. This analysis reveals that, during

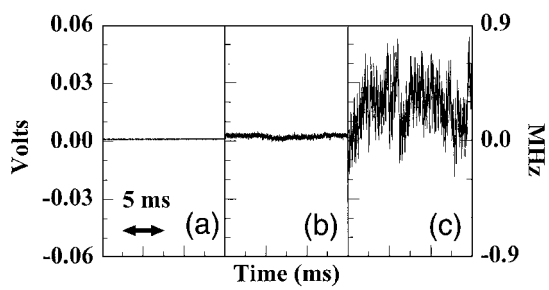

Fig. 2. Time-series measurements of (a) detector–preamplifier noise floor measured when the laser is blocked, (b) laser intensity fluctuations measured when the laser is tuned off of the molecular resonance, and (c) frequency fluctuations measured when the laser is tuned to the side of the molecular resonance. All panels have identical vertical axis scaling. The right-hand vertical axis for Fig. 2(c) also plots the relative frequency fluctuations, which are obtained by use of the conversion factor.

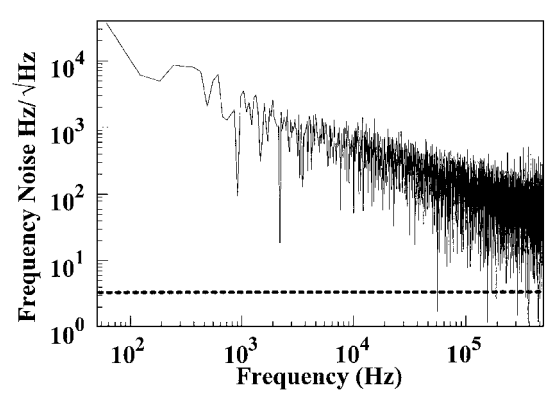

Fig. 3. Frequency-noise spectral density normalized to a 1-Hz bandwidth and plotted on a bilogarithmic scale. The dashed line represents the detector–preamplifier noise floor 5 $pA/\sqrt{Hz}$.

the 15-ms measurement, the laser's frequency is within ±150 kHz of the mean 68% of the time. The redesigned laser current controllers have substantially reduced the frequency fluctuations, since previous measurements with earlier versions of the current controller indicated a frequency stability of ±1 MHz over the 15-ms measurement time.[7] As an alternative measurement, we also observed the heterodyne beat note between the free-running QC laser and a QC laser locked to a cavity with a linewidth of <5 kHz. Single scans of the beat note observed on a spectrum analyzer by use of a 14-ms sweep time and 30-kHz resolution bandwidth showed 3-dB linewidths of approximately 150 kHz, which agrees with the analysis presented here. Consistency between different devices is also observed, since similar results are obtained for a different QC laser operating at a wavelength of 8.5 μm.

The spectral stability of the tested QC DFB lasers strongly supports their use as stable optical sources. Although in this Letter we present what is believed to be the lowest linewidth reported to date,[7,9] the current controllers remain the limiting factor for the free-running linewidth and contribute to the observed low-frequency fluctuations. Additional improvements to the current controllers should allow us to approach the Schawlow–Townes limit,[10] which is approximately 15 kHz for the QC lasers used in these experiments. We have surpassed this limit by locking the laser to the side of a rovibrational resonance of N_2O in which a stabilized linewidth of 12 kHz was achieved.[11] Attempts are also underway to actively stabilize the QC lasers to a scanning Fabry–Perot cavity to attain linewidths of <1 kHz.

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