



Frequency-stabilized narrow-linewidth double-mode quantum cascade laser

Ismail Bayrakli¹

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Abstract

In this work, a narrow-linewidth double-mode quantum cascade laser (QCL) is demonstrated. The linewidth (full width at half maximum) of the DFB (distributed feedback) QCL has been narrowed from 45 MHz to 500 kHz by the laser frequency locking. An AOFS (acousto-optic frequency shifter) has been used to obtain a double-mode operation. The spectral distance between the both (zero and first order diffracted) beams can be adjusted by the acoustic wave frequency from 65 to 95 MHz by controlling the tuning voltage of the RF driver.

Keywords Quantum cascade laser · Frequency stabilization · Electromagnetically induced transparency

1 Introduction

The laser linewidth (usually described as full width at half maximum (FWHM) of the optical lineshape) describes the spectral purity of a laser. There are different noise sources limiting the frequency stability of a laser diode: Fundamental noise and flicker ($1/f$) or technical noise. Fundamental noise leads to the instantaneous (intrinsic) linewidth. The intrinsic linewidth of a laser results from the spontaneous emission in the gain medium and the photon shot-noise. These give rise to a white frequency noise power spectral density (PSD) S_0 , which leads to a Lorentzian lineshape ($\Delta\nu_L = \pi S_0$) with a theoretical linewidth given by the Schawlow-Townes formula (Schawlow and Townes 1958), modified by Henry (1982):

$$\Delta\nu = \frac{v_g^2 \hbar \nu n_{sp} \alpha_{tot} \alpha_m}{4\pi P} (1 + \alpha_H^2), \quad (1)$$

where v_g is the group velocity, n_{sp} is the spontaneous emission factor, α_{tot} is the total losses in the cavity, α_m is the mirror losses, P is the output power, and α_H is the linewidth enhancement factor, which is defined as the variations in the refractive index of the gain medium due to fluctuations of the carrier density (dN):

✉ Ismail Bayrakli
ismailbayrakli@aksaray.edu.tr

¹ Aksaray University, Aksaray, Turkey

$$\alpha_H = \frac{\Delta n_r}{\Delta n_i}, \quad (2)$$

Δn_r (dn_r/dN) and Δn_i (dn_i/dN) are the changes in the real and imaginary part of the refractive index. Δn_r leads to an additional phase shift that adds to the initial phase change induced by the spontaneous emission and Δn_i provides a change in the gain. Typical values for the linewidth enhancement factor of interband semiconductor lasers are in a range of 2 to 7 (Osinski and Buus 1987), whereas QCLs have smaller linewidth enhancement factor from 0.24 to 2.6 with an increase of the injection current (von Staden et al. 2006), resulting from the symmetrical gain curve because of the intersubband transition between discrete levels located in the conduction band. Owing to the smaller linewidth broadening factor and ultrafast radiative processes, QCLs have intrinsic linewidth on the order of several tens of hertz, which is close to the Schawlow-Townes limit. Zhao et al. experimentally observed the white frequency noise plateau of a 4.53- μm DFB-QCL operated at 20 °C at Fourier frequencies above 100 MHz around the frequency noise power spectral density of 21.1 Hz²/Hz, yielding an intrinsic line width of only 66 Hz (Zhao et al. 2020). Because the $1/f$ noise appears at low frequency, the white frequency noise of a QCL can be observed as a high-frequency plateau. A number of environmental disturbances, such as laser current noise, acoustic noise, mechanical vibration, thermal fluctuations, have an effect on the laser frequency. Therefore, these technical noises are added to the optical frequency of a laser. Hence, the linewidth observed in experiments is much broader than the theoretically linewidth given by the Schawlow-Townes formula. Owing to the frequency chirp effect that results from the thermal heating during the current pulses, the pulsed QCLs have the linewidths up to broader than 1 GHz, depending pulse duration (Kosterev et al. 2000; Germer and Wolff 2009). Free-running continuous-wave DFB QCLs have a much narrower linewidth in the 1- to 30 MHz range. Tombez et al. observed a FWHM linewidth of 850 kHz for a free-running 4.6 μm DFB-QCL for 300 ms observation time for CO molecule (Tombez et al. 2011). Mukherjee et al. measured a linewidth of 21 MHz for a free-running room-temperature external grating cavity quantum cascade laser from the width of the saturation peak at 10 mTorr pressure of NO₂ (Mukherjee et al. 2008). These spectral linewidths are most often sufficient for trace gas sensing, but may still be a limiting factor in some particular applications, such as electromagnetically induced transparency (EIT)- and high resolution spectroscopy. Therefore, the development of QCLs with narrower linewidth is of significant interest.

To narrow the laser linewidth, there are different stabilization techniques, such as (i) by locking the laser frequency to a high-finesse optical cavity (Taubman et al. 2002) or a gas absorption line used as a frequency discriminator (Cappelli et al. 2012), (ii) by utilizing the interference fringes in an imbalanced Michelson or Mach-Zehnder interferometer act as a frequency discriminator (Shehzad et al. 2019), (iii) by optical feedback (Zhao et al. 2020), or (iv) by transferring the high stability of near-infrared optical frequency combs to the QCL (Argence1 et al. 2015). Using these stabilization methods, the QCL frequency has been stabilized down to the kHz-level (Williams et al. 1999; Zhao et al. 2020), and sub-Hz level (Argence1 et al. 2015). However, the latter was reached by using a fairly complex and expensive setup.

In the present paper, a simple narrow-linewidth double-mode QCL has been realized. To decrease the noise levels, a side-of-fringe stabilization technique has been used. The linewidth (FWHM) of the QCL has been narrowed from 45 MHz to 500 kHz by the laser frequency locking. An AOFS has been utilized to achieve a double-mode operation. The spectral distance between the both (zero and first order diffracted) beams can be adjusted

by the acoustic wave frequency from 65 to 95 MHz by controlling the tuning voltage of the RF driver. Such setup can be used for various important applications, where single or double frequency-stabilized wavelengths with narrow-linewidth are needed, such as laser cooling, precision molecular spectroscopy, frequency metrology, Bose-Einstein condensates, THz wave generation, quantum memory, and electromagnetically induced transparency (EIT) experiments.

2 Experimental setup

A schematic of our sensor is shown in Fig. 1. A room-temperature continuous-wave (CW) distributed feedback quantum cascade laser (DFB-QCL) (Thorlabs, QD4474CM1AS) emitting at 4474 nm wavelength was used as excitation source. The QCL chip was installed in a thermo-electrically cooled mount (Thorlabs, LDMC20/M) and was driven by a laser driver / TEC controller (Thorlabs, ITC 4002QCL) in CW mode. The laser radiation was collimated by a 3-mm focal length aspheric lens (Thorlabs, C093TME-E).

To reduce the noise, the QCL was actively frequency-stabilized by using a side-of-fringe stabilization technique (Bayrakli 2016a, b). One needs the following elements for active feedback control of the laser frequency: (1) a discriminator, which converts the frequency fluctuations to voltage fluctuations, (2) A loop filter, which conditions the error signal for optimal feedback, and (3) a transducer, which makes the correction to the laser frequency. The laser frequency is locked to a relatively stable reference level, which can be a side of a Fabry-Perot cavity resonance or a molecular/atomic absorption line. In this work, the flank of a N_2O transmission peak was utilized as an optical frequency discriminator. After passing the light through the gas cell filled with pure N_2O gas (Wavelength References, Inc.), the error signal was measured by an InAsSb amplified detector with 9 MHz-Bandwidth (Thorlabs, PDA07P2). The error signal shows how much it deviates from the set (desired) value and tells us how good (or bad) the laser follows the reference. The optical frequency fluctuation ($\Delta\nu$) was converted from the variation in the voltage signal (ΔV) through a known discriminator slope of 7 V/GHz (Fig. 2a). The signal was then sent to a high-speed servo controller (Newport, LB1005)

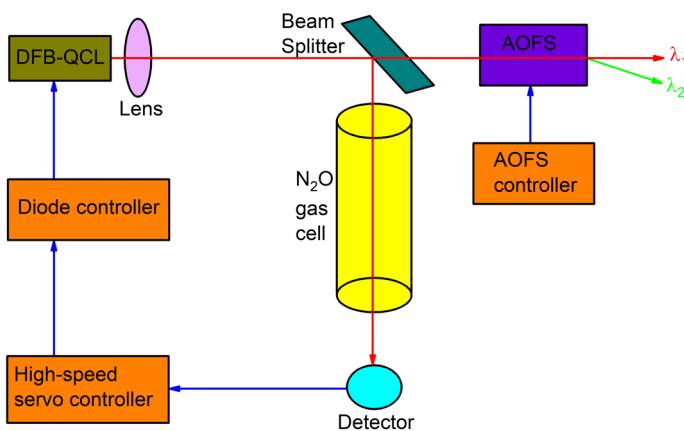


Fig. 1 Experimental setup. DFB-QCL: distributed feedback quantum cascade laser, AOFS acousto-optic frequency shifter

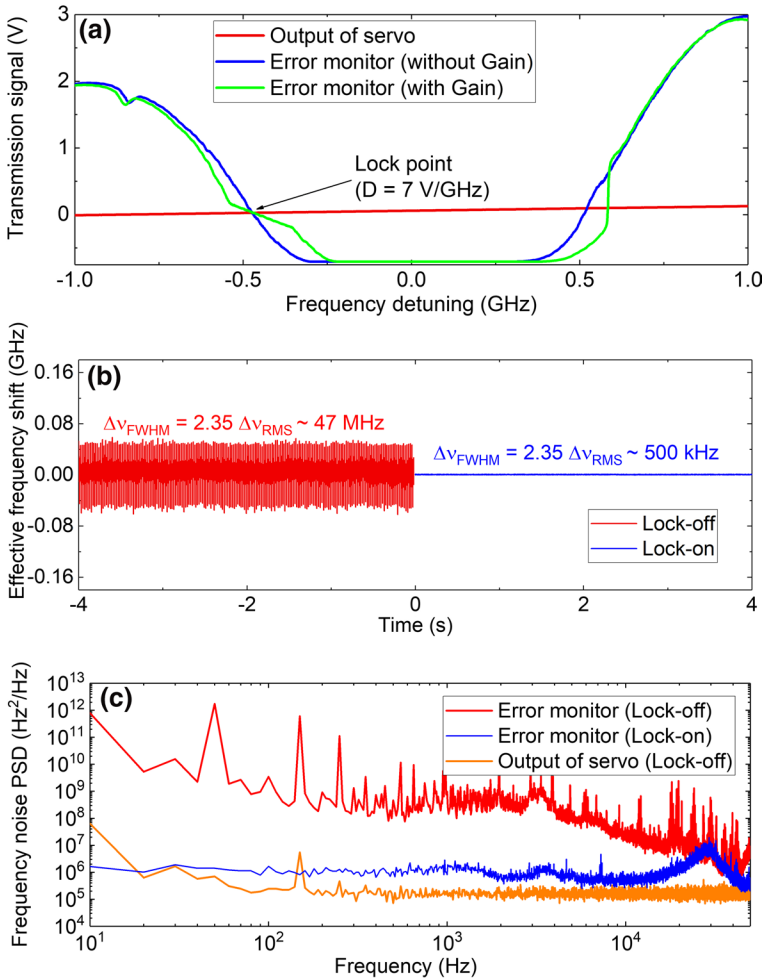


Fig. 2 **a** Measured N_2O absorption profile with (green line) and without (blue line) filter gain. The flank of the N_2O transmission peak with a slope of 7 V/GHz was utilized as an optical frequency discriminator. A linear fit of this flank at the working point provides the discriminator slope. **b** The effective frequency shift before and after switching on the servo loop. **c** Frequency noise PSDs of the unlocked and locked QCL acquired between 1 Hz and 50 kHz. In the locked case, the system achieved a noise cancellation below 30 kHz. (Color figure online)

with a proportional-integral (PI) corner frequency adjustable from 10 Hz up to 1 MHz and a proportional gain between -40 dB and +40 dB. The servo controller (loop filter) conditions the error signal for optimal feedback to reach its set point as fast as possible. The correction signal was sent to the modulation input of the diode controller (Thorlabs, ITC 4002QCL). The feedback signal was optimized to reduce laser frequency noise while maintaining stable operation. The noise suppression was monitored by examining the error signal in the time and frequency domain using the developed LabVIEW-based software platform with a DAQ (NI USB-6366). The frequency-stabilized QCL was combined with an acousto-optic frequency shifter (AOFS, Brimrose, GEF-80-20-4500)

controlled by a variable frequency RF driver (VA-80-20-B1-V7) to achieve a wavelength-tunable double-mode operation.

3 Results and discussion

A long time frequency stability can be reached by locking the laser frequency to a relatively stable reference level. In this way, the laser wavelength can be shifted so that it always stays fixed on the stable point, regardless of possible external disturbances. To reduce the noise and therefore to achieve a narrow linewidth in a QCL, the flank of a N_2O transmission peak with a slope of 7 V/GHz was utilized as an optical frequency discriminator (Fig. 2a). A linear fit of this flank at the working point provides the discriminator slope. To determine the gain sign, the gain was slowly increased from zero until distortion on the resonance was observed (green line in the Fig. 2a), while the laser was sweeping over the resonance. Each slope has different behaviors. On one side of the absorption line, the slope becomes steeper, indicating a positive feedback condition that is unstable, whereas on the other side, a flatter slope is observed, indicating a stable lock point. The feedback loop gain was increased until an oscillation is observed. At the frequency, where the total accumulated phase for the closed loop signal is -180° , the disturbance noise is not canceled by the applied correction signal, but instead be reinforced (the feedback becomes positive). The gain at this frequency needs to be decreased so that the loop gain is less than 0 dB (unity gain) for the feedback to operate in a stable manner.

Figure 2b shows the effective frequency shift before and after switching on the servo loop. One can clearly see from Fig. 2b that the frequency noise of the locked laser was significantly reduced as compared to the free-running QCL. The Gaussian FWHM can be estimated by the following equation (Elliott et al. 1982):

$$\Delta\nu_{FWHM} = 2.35\Delta\nu_{RMS}. \quad (3)$$

The root mean square deviation ($\Delta\nu_{RMS}$) was obtained by averaging the signal over an interval of ~ 4 s. A FWHM for unlocked DFB-QCL was measured to be ~ 47 MHz. When the laser frequency was locked, the linewidth was reduced to ~ 500 kHz. If one measures the linewidth of a laser, the measurement time is important. The processes and/or disturbances faster than the measurement time, will widen the linewidth of laser, while the slower processes will give rise to the laser's center frequency to drift between measurements.

Measurement the frequency noise power spectral density (PSD) provides detailed information on the laser noise components. Amplitude noise PSD (in V/\sqrt{Hz}) is the magnitude of the spectrum normalized to a 1 Hz bandwidth. Frequency noise PSD (in Hz^2/Hz) is derived from the squared amplitude noise PSD divided by the D^2 , where D is the previously mentioned discriminator slope. Figure 2c depicts the frequency noise PSDs of the unlocked and locked QCL between 1 Hz and 50 kHz calculated using the time-domain data. In the locked case, the noise was reduced on a bandwidth of 30 kHz. The servo bump, which is observed due to the oscillation in the feedback loop, indicates a locking bandwidth of ~ 30 kHz. The detector noise, where the laser is tuned out of the transmission peak, is also depicted in Fig. 2c (orange line).

To tune the wavelength of the frequency-stabilized QCL and to achieve a double-mode operation, an AOFs has been used. The spectral distance between the both (zero and first order diffracted) beams can be adjusted by the acoustic wave frequency from 65 to 95 MHz by controlling the tuning voltage of the RF driver. Acousto-optic devices can

be used as modulators, deflectors, Q-switches, tuneable filters, and frequency shifters. An acoustic wave at a radio frequency is produced in the crystal by applying a RF electronic signal to a piezo-electric transducer. The compression and rarefaction areas in the crystal bulk are generated, giving rise to periodic changes in the refractive index. This can be seen as the slits in a diffraction grating and light input to the AO device is diffracted into a number of orders at the output. However unlike a diffraction grating, AO devices are traveling wave devices. The acoustic wave moves from the transducer to the absorber. For the most applications, AO devices are designed to maximize diffraction of an input laser beam into a single first order. The device is then said to be operating in the Bragg regime. The AO device is needed to be correctly aligned and the drive power should be adjusted at or below the RF saturation level. To achieve a high diffraction efficiency, the polarization direction of the laser beam should be p-polarization (Transverse-Magnetic, TM). QCLs generate purely TM polarized light due to the intersubband selection rules, contrary to diode lasers (Ahn 2014).

Without RF drive power, the input beam travels straight through the AO device into the zero order position. There is small transmission losses from the absorption in the crystal. These are referred to as the "insertion loss" and typical values are 3% - 7%. When the RF power is applied, a significant percentage of the incident beam is directed into the first order. Diffraction efficiency (DE) of the used AOFS, defined as the ratio of the output zero order beam (RF off) and the first order beam (RF on), is 70 %. The zero order power is never at zero (100-30 %). Optimum efficiency is attained when the incident laser beam enters to the AOFS at the Bragg angle given by:

$$\theta_{Bragg} = \frac{\lambda f}{2V}, \quad (4)$$

where λ is the optical wavelength (4474 nm), f is the RF frequency (80 MHz), and V is the acoustic velocity (5500 m/s for Germanium). In our setup, the Bragg angle is ~ 32 mrad. The output separation angle between the zero and first order (~ 64 mrad) is given by

$$\theta_{Sep} = \frac{\lambda f}{V}. \quad (5)$$

The RF driver can be controlled for amplitude modulation of the first order intensity in a sine function. The transit time of the acoustic wave across the beam waist in the AO crystal determines the optical switching time. The optical rise time for a Gaussian beam is determined to be 118 ns from the following equation:

$$\tau = 0.65 \frac{d}{V}, \quad (6)$$

where d is the $1/e^2$ beam diameter (1 mm in the present setup). Modulation bandwidth of 2.96 MHz is approximated by

$$BW_{mod} = 0.35/\tau. \quad (7)$$

The full device RF bandwidth is calculated to be 5.92 MHz by using the equation:

$$BW_{full} = 2BW_{mod}. \quad (8)$$

The beam should be focused into the AOFS, in order to increase the modulation rate.

4 Conclusion

In this work, a simple narrow-linewidth double-mode quantum cascade laser has been developed. The linewidth of the QCL has been narrowed from 45 MHz to 500 kHz by the laser frequency locking. To decrease the noise levels, a side-of-fringe stabilization technique has been used. The flank of a N₂O transmission peak has been utilized as an optical frequency discriminator. To tune the wavelength of the frequency-stabilized QCL and to achieve a double-mode operation, an AOFS has been used. The spectral distance between the both (zero and first order diffracted) beams can be adjusted by the acoustic wave frequency from 65 to 95 MHz. This sensor can be utilized for various important applications, where single or double frequency-stabilized wavelengths with narrow-linewidth are needed, such as laser cooling, precision molecular spectroscopy, frequency metrology, Bose-Einstein condensates, THz wave generation, quantum memory, and EIT experiments.

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Declaration

Competing interests The author declares that they have no competing interests.

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