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Optical feedback in dfb quantum cascade laser for mid-infrared cavity ring-down spectroscopy

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Abstract A simple external optical feedback system has been applied to a distributed feedback quantum cascade laser (DFB QCL) for cavity ring-down spectroscopy (CRDS) and a clear effect of feedback was observed. A long external feedback path length of up to 4m can decrease the QCL linewidth to around 50kHz, which is of the order of the transmission linewidth of our high finesse ring-down cavity. The power spectral density of the transmission signal from high finesse cavity reveals that the noise at frequencies above 20kHz is reduced dramatically.

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1 Introduction

In recent years, interest in spectroscopy at mid-infrared (MIR) wavelength regions has increased since many important atmospheric molecules have strong absorption in this region. Particularly a measurement of the radiocarbon isotopologue $^{14}CO_2$ with a natural abundance of 10^{-12} has received a lot of attention, because radiocarbon is widely used for carbon dating in archeology [1] or as a sensitive tracer in the environment, animals or humans. In drug development, a new technique called "microdose study" in which ^{14}C labeled compounds can be used is under development [2]. Implementation of such a new technique would lead to significant decrease of cost and time invested to develop new medicine. To satisfy the needs of microdose studies, ^{14}C measurements based on cavity ring-down spectroscopy (CRDS) technique [3] of enhanced laser absorption spectroscopy using a high reflectivity cavity has been developed toward this medical application [4, 5].

Among MIR lasers, popularity of distributed feedback (DFB) quantum cascade laser (QCL) systems is growing as they are commercially available and easy to handle with a wide mode-hop free tuning range of several nm and single-mode emission with a typical linewidth of a few MHz. Although this is sufficient for many spectroscopic techniques, a linewidth below 100kHz is necessary for efficient coupling of a laser to a high finesse optical cavity (reflectivity R >99.9 %) typically used in CRDS systems. Laser linewidth reduction is possible by fast electronic feedback using a frequency discriminator; for example by phase-locking or the Pound-Drever-Hall (PDH) stabilization technique [6]. However, these techniques necessitate high speed electronics, which may be expensive and error-prone. Furthermore, high bandwidth modulation is required for the laser source. An alternative method is using optical feedback [7, 8], also known as delayed self-injection. Applying this passive feedback to QCL can reduce the laser linewidth with minimal expenses.

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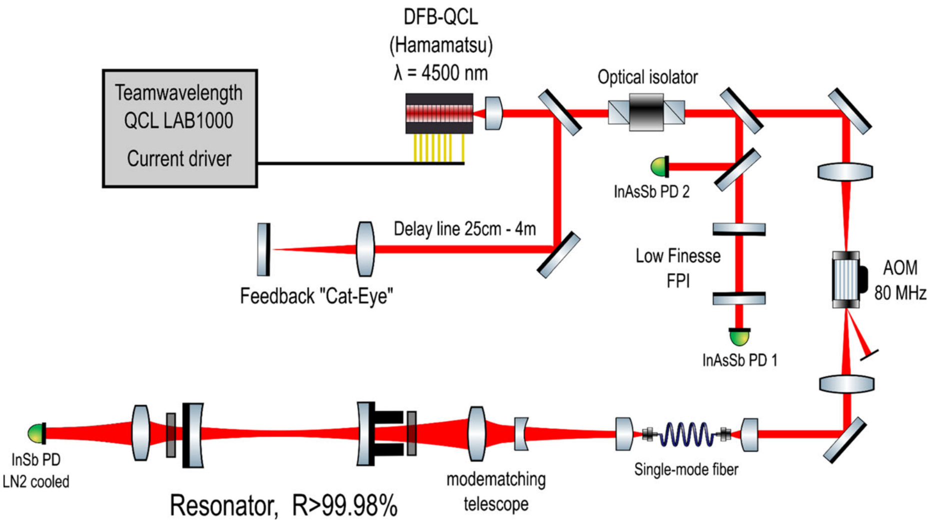

Fig. 1 Schematic of the QCL system. This system is designed for CRDS measurement as well as the study of optical feedback. Whole laser system including FPI, acoustic optical modulator (AOM) and fiber coupling is installed on a 60x60 cm optical breadboard, allowing easy transport without realignment

2 Experimental setup

A schematic of the optical layout is shown in Fig. 1. The DFB QCL (Hamamatsu, L12004-2209H-C) was operated by a low noise current driver (Wavelength electronics, QCL1000LAB) and laser wavelength was modulated by scanning the applied current. A fraction of the laser light was picked off using 50/50 beam splitter (actual experimental reflectivity R = 40 %) for feedback. After a variable delay path from 25 cm to 4 m this light was focused onto a gold mirror, which functioned as a so-called "cat-eye" reflector. This cat-eye reduces the dependence of the back reflection on angular adjustments, which helps in easy alignment for reinjection into the QCL.

To study the effects of the feedback on laser power as well as frequency change, a low finesse Fabry-Perot interferometer (FPI) with a free spectral range (FSR) of 1.86(1) GHz and finesse of about 4.5 made of two 50/50 beam splitters was installed.

Two low cost high bandwidth (>1MHz) InAsSb photodiodes (Hamamatsu, P13243-011MA), operating at room temperature, acquired a power reference signal as well as the transmission signal through the FPI. From these, the power normalized FPI transmission signal during a current scan was calculated.

After single mode fiber coupling, the laser light was introduced into our CRD cavity (R >99.98, length L = 30 cm) with an experimentally determined finesse of approximately 10,000. The cavity length was scanned by a piezo actuator. The light transmits through the cavity only close to or at the resonance condition: $L = N\lambda/2$ ($N = 1, 2...$). Typically in ring-down measurements the laser is quickly modulated by turning off the acoustic optical modulator (AOM, Isomet, 1208-G80-4) which can be used as the optical fast switch modulating the laser path at the transmission peak; here however the AOM was continuously kept turned on to evaluate the effect of the feedback on the laser linewidth. The transmitted light was measured using a liquid nitrogen cooled InSb photodetector (Teledyne Judson

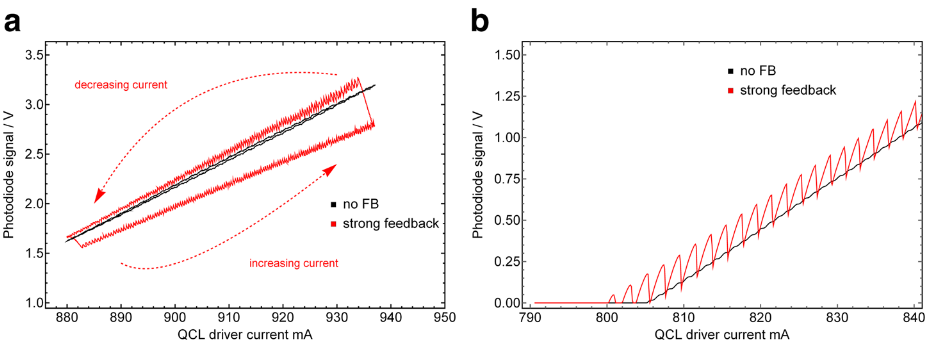

Fig. 2 The effect of feedback on power (**a**) when modulating the current with a triangle voltage ramp and (**b**) close to the lasing threshold in increasing current

Technologies, J10D-M204-R100U-60), amplified by a hi-speed current amplifier (Femto, HCA-40M-100K-C).

3 Effect of feedback

The QCL current was modulated by applying a triangle voltage ramp to the modulation input of the current driver. For the case of no optical feedback, a beam block was placed just after the focusing lens of the cat-eye reflector. Figure 2 shows the power dependence for a change in the applied current. The influence of the feedback is evidently visible. The oscillation of the power, caused by mode-hopping of the QCL occurs every FSR of the external cavity by feedback in Fig. 2a, strong hysteresis effects of the feedback in decreasing current is observed. Moreover, the lasing threshold of the current was reduced by several mA, as shown in Fig. 2b. Monitoring this reduction helps in optimization of the feedback level since stronger feedback leads to a lower lasing threshold. Figure 3 shows the FPI transmission signal during a current ramp. The mode-hopping of the QCL was more clearly observed here. A slight general frequency shift was observed when feedback was turned on, likely caused by thermal effects from the reinjected power.

The effect of feedback on the laser linewidth was studied by monitoring the transmission through the CRD cavity. For this, the QCL current was fixed at 850 mA and the cavity length was scanned very slowly across a transmission peak. Figure 4 shows the transmission peaks of CRD cavity. Due to the steep frequency dependence near resonance peak, the amplitude fluctuations of signal provide information about the frequency distribution of the laser source. Without feedback the signal shows many spikes over wide range of scan, meaning that the QCL frequency shows fast fluctuations, likely caused by current noise of the QCL despite use of a low noise current driver. On the other hand, the transmission signal of the QCL with feedback has a single clear peak with only slight fluctuations. This suggests that the leaser linewidth was the order of the cavity transmission peak width, which was around 50 kHz. It is evident that the feedback reduces the laser line width dramatically. The spectral density of the noise was calculated from 100 individual transmission events using a periodogram (Fig. 5). Intensity fluctuations at high frequencies are generally attenuated, due to the low-pass filtering effect of the cavity. Nevertheless, at frequencies above 100kHz optical feedback decreased the noise level by more than 30 dB. A longer feedback path length seems to further improve laser stability, however low frequency noise

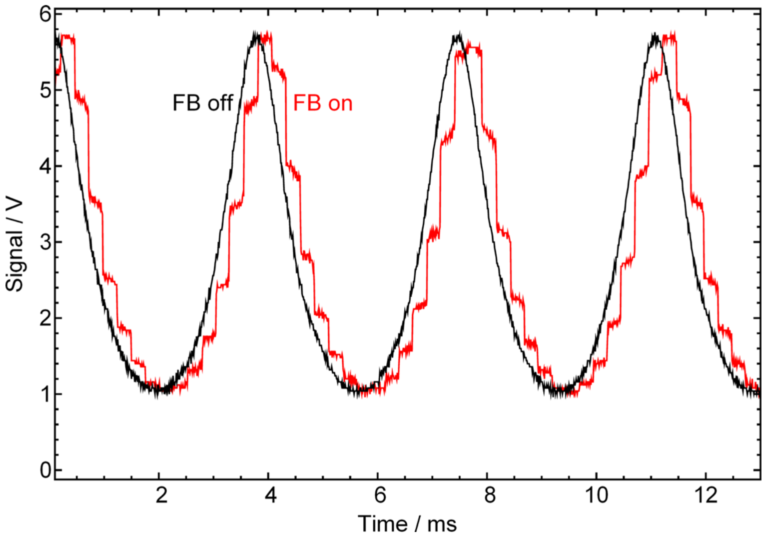

Fig. 3 Power normalized low finesse FPI transmission signals with and without feedback

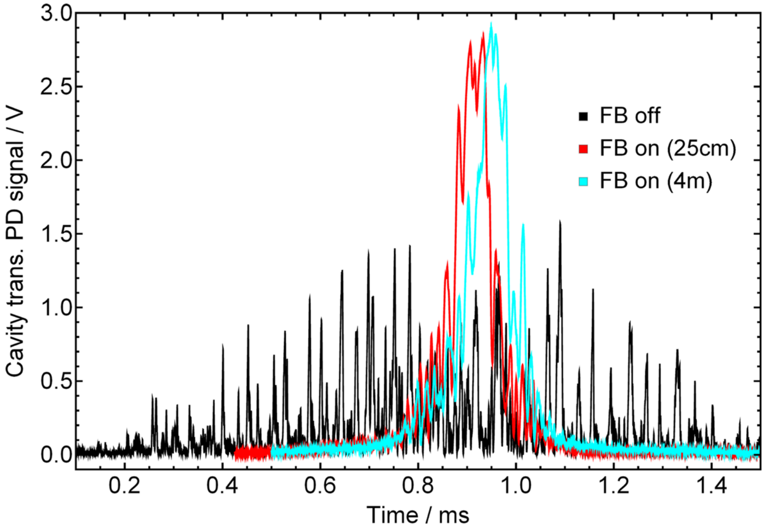

Fig. 4 Photodiode signal of transmission from CRD cavity during scan over cavity transmission line

at acoustic frequencies below 5 kHz was increased. This lower frequency part of the spectrum was likely influenced by acoustic vibrations, air flow and the temperature instability of the feedback path. To improve long term stability of the laser, the laser system should be shielded from influence of air flow, e.g. though active stabilization of the path length using a piezo actuator, which is under investigation as well.

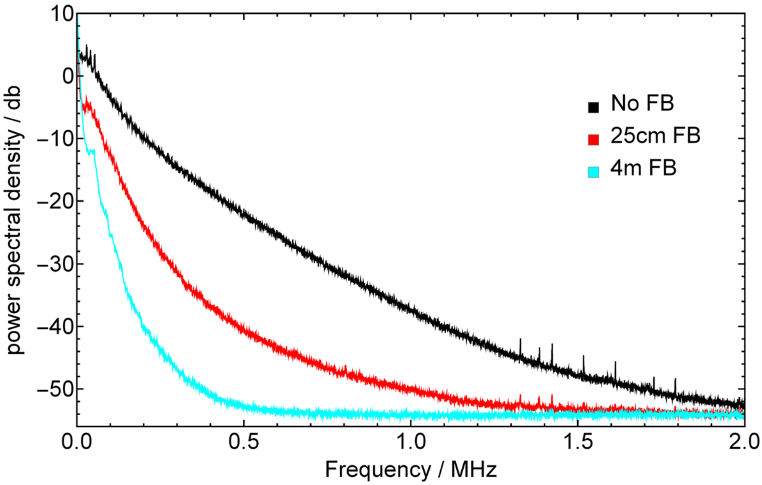

Fig. 5 Power spectral density of photodiode signal averaged using periodogram

4 Conclusion and outlook

For $^{14}CO_2$ measurement based on CRDS, an external optical feedback system has been to a DFB QCL. The effect of feedback was clearly noticeable by mode-hopping which corresponding frequency shifts and by laser linewidth reduction. Presently this feedback has limited mode-hop free tuning range, but wide mode-hop free tuning range may be accomplished by modulating the external cavity length with a piezo actuator similar to standard external cavity diode laser. Improved active or passive stabilization of the external feedback path length will be necessary for long-term frequency stability. In parallel, alternative linewidth reduction methods such as PDH locking and referencing to a molecule absorption line or a MIR fiber based frequency comb [9] to QCL with optical feedback will be investigated.

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