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Continuous Wave Room Temperature External Ring Cavity Quantum Cascade Laser

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An external ring cavity quantum cascade laser operating at ~5.2 µm wavelength in a continuous-wave regime at the temperature of 15 ^{0}C is demonstrated. Out-coupled continuous-wave optical powers of up to 23 mW are observed for light of one propagation direction with an estimated total intra-cavity optical power flux in excess of 340 mW. The uni-directional regime characterized by the intensity ratio of more than 60 for the light propagating in the opposite directions was achieved. A single emission peak wavelength tuning range of 90 cm^{-1} is realized by the incorporation of a diffraction grating into the cavity.

In recent years there has been considerable interest in the development of mid infrared external cavity (EC) systems based on quantum cascade laser (QCL) gain material. In addition to providing the tunability needed for a wide range of spectroscopic applications such as clinical diagnostics (breath analysis), process monitoring, environmental studies, plant physiology, metrology and analytical chemistry, ECs provide a promising platform for the development of new functionalities such as active mode locking and frequency comb generation Ref.[1,2,3]. For spectroscopic applications, single mode operation can be produced in conventional ridge QCLs by incorporating distributed feedback (DFB) gratings into the waveguide cladding. DFB-QCLs are well suited for applications requiring single-mode emission, but suffer from inherently restricted wavelength tunability Ref.[4]. QCLs operating in an external linear cavity configuration with a grating serving as one of the resonator mirrors have much better wavelength tuning characteristics but may suffer from mode hopping Ref.[5,6]. Moreover, spatial hole burning (SHB) effect associated with the standing waves greatly affects the laser temporal and spectral stability in all linear cavity resonators. It has been suggested Ref.[7,8] that the use of ring cavity resonator with two (counter-propagating) traveling waves can dramatically reduce SHB. Under a uni-directional regime, where light propagates around the ring cavity exclusively in one direction, SHB can be suppressed entirely. S-shaped race track geometry Ref.[7] was tested to encourage the laser to emit mainly in one preferable direction achieving the ratio about 9 between the light emitting in this direction and the opposite direction. Similar ratios of ~9 - 10 were achieved in external free-space ring cavity resonator Ref.[8]. The QCLs in both these ring cavity geometries operated only in the pulsed regime. For that reason the observed emission spectra were multi-mode with appreciable narrowing occurring over a period of 100's of microseconds.

In this paper we demonstrate the operation of a QCL in continuous-wave regime at room temperature in the free-space-coupled ring cavity resonator with a wavelength tunable single peak emission. Output powers of more than 20 mW are produced for wavelengths around 5.25 μm, providing a promising basis for future development of spectroscopic and ultrasensitive trace gas detection systems.

A 4.5 mm long 9 μm wide $\lambda \sim 5.25$ μm QCL buried heterostructure Ref.[9] with both facets having anti-reflection (AR) coatings is used as a gain medium. The remaining reflectivity of less than 1% for the AR coating was achieved by using two-layered structure of mixed metal fluoride and ZnSe materials. These AR coatings are expected to provide strong suppression of the Fabry-Perot (FP) modes of the laser ridge. The laser chip was indium soldered epilayer-up onto a copper submount. A thermoelectric cooler held the submount at a temperature near 15 ^{0}C. Two high numerical aperture (0.56) AR coated chalcogenide glass aspheric lenses with focal length of 4 mm were used for collimation/coupling the light from/on to the laser facets. Four un-coated silver flat mirrors with reflectivity ~97% were positioned to create an X-shape resonator with the total ring cavity length of ~1.27 m (see Fig.1). A 0.5 mm thick CaF_2 plate having an AR coating on one side, was inserted into the ring cavity and served as a beamsplitter to out-couple light from the cavity and to direct it either onto a stand-alone mercury cadmium telluride (MCT) detector "Vigo" (3-4 ns rise time) for the alignment purposes or an FTIR Bruker IFS66 spectrometer for spectral recordings or a thermopile detector for optical power measurements. The QCL was mounted in such a way that its emission was s-polarized relative to the external mirrors and the beamsplitter. The ring cavity QCL was tested in both continuous wave, driven by a standard laboratory dc power supply, and pulsed (100 ns - 1 ms long pulses from Avtech pulse generator) regimes.

Measurements taken prior to the laser receiving AR coatings gave a pulsed threshold current of the "as-cleaved" FP QCL of 400 mA. After the AR coating, the optical feedback from the facets was reduced to the extent that the laser no longer operated as a free running pulsed laser device up to the roll-over current of ~700 mA. Initially, the ring cavity QCL was aligned and tested in the pulsed regime (~10 μs long pulses) before a dc driving current was introduced. The absence of optical feedback means alignment of the ring cavity must be performed using the very weak $\lambda \sim 5.25$ μm electroluminescent emission. By using the MCT detector and an additional red diode laser, we were able to develop a careful step-by-step procedure for the ring cavity alignment. The pulsed threshold current of the AR coated QCL, when operating inside the ring cavity, is 360 mA. Such a greatly reduced threshold current indicates a high level of external feedback and suggests that a well aligned system can exhibit high collection/coupling efficiencies. Based on the value of the threshold current, the feedback from the ring cavity is estimated to be over 30 % for each facet.

Under dc bias the threshold current increased to only 400 mA and the ring cavity QCL was tested up to the maximum current of 600 mA. Typical light-current (L-I) and current-voltage (I-V) characteristics of the ring cavity QCL are presented in Fig.2. The I-V characteristics near laser threshold are shown for two regimes: when the ring cavity laser is emitting normally (ON) and when the cavity is blocked inside (OFF). For a given voltage above the laser threshold the existence of the light emission results in the increased current flowing through the laser. We suggest that this excess of the current is "spent" for generating the optical power while the rest of the current is converted into heat. The value of this additional current can be used to estimate the optical power which circulates inside the ring cavity. For example, in the case of the I-Vs presented in Fig.2 the maximum optical power at the maximum current of 600 mA can be calculated for a voltage value of 8.65 V multiplied by the additional current ΔI = 32 mA, giving around 277 mW. This power constitutes the total optical power for the light propagating in both CW (clockwise, see Fig.1) and CCW (counter clockwise) directions and is considerably greater than the optical power out-coupled using a beamsplitter. The laser was found to emit in both CW and CCW directions, but not equally. The L-Is shown in Fig.2 are for three consecutive measurements for each directions. The intensity of the laser emission was found to be unstable, jumping not only during the L-I measurements but also differing from one test to another, most probably resulting from shifts in wavelength/cavity modes caused by slight thermal and/or mechanical instabilities. Because of that the detailed analysis of the correlation between the intensity of the light propagating in the opposite directions was very difficult. The maximum intensity ratio observed between the counter-propagating light exceeded 60, leading to the laser preferentially emitting in one direction; however, most of the time this ratio was much less and strongly dependent upon the particular alignment of the cavity (the positions of the mirrors and the lenses) and the value of the current. The total out-coupled optical power for CW (12.3 mW) and CCW (0.2 mW) directions, taking into account the 5% reflectivity of the beamsplitter, suggests an optical power inside the cavity of 250 mW. This value compares very well with that estimated from the I-V curves. The highest out-coupled optical power achieved in our experiments was 17 mW for one direction. This value gives the estimated optical power inside this ring cavity of at least 340 mW. Such a power inside the ring cavity compares very well with the optical power obtained for the QCLs with the same design Ref.[9], proving the suitability of the QCL ring cavity geometry as a high power mid-infrared source. To out-couple more light from the ring cavity a beamsplitter with higher reflectivity (~40%) was also tried. For such a beamsplitter the out-coupled power increased up to 23 mW, however, the increased reflectivity of the beamsplitter results in higher optical losses and greatly reduced optical power inside the ring cavity. A slight asymmetry in the facet reflectivity is the most likely reason for the ring cavity QCL to emit preferentially in the CW direction. When L-I measurements were carried out with the laser chip rotated 180 degrees on its mount then the CCW direction became dominant.

In order to investigate the evolution of the ring cavity emission spectra, time resolved spectral measurements were performed. All spectra were detected for the CW direction at 0.25 cm^{-1} resolution. The laser was driven at 410 mA with 1 ms long pulses at a repetition rate of 10 Hz. The emission spectra were obtained using the fast MCT detector positioned after the FTIR interferometer. The signal from the detector was measured by an oscilloscope functioning in a boxcar integrator regime. The spectra have been recorded at the following intervals from the beginning of the driving current pulse : 100 ns, 1 μs, 10 μs, 100 μs and 1 ms (Fig.3), with the time windows of less than 5% of each time intervals. The narrow time windows were used in order to keep the estimated frequency chirp during these time windows at least one order less than the calculated QCL FP mode separation. However, despite of this precaution no such FP laser cavity modes are observed, presumably suppressed by the high quality AR coatings on the laser chip facets, in contrast to the spectral experiments described in Ref.[8] where the FP modes were present all the time. The spectra recording time intervals correspond approximately to 25, 250, 2500, 25000 and 250000 complete round trips of the ring cavity. After the light made just 25 round trips the emission has a very broad (~45 cm^{-1}) continuous spectrum line. After approximately 250 round trips the emission starts to significantly narrow towards a single peak shape, however, the detected signal appears very noisy, with amplitudes suddenly collapsing and then redeveloping throughout the driving pulse. Closer investigation revealed that, for a given set of conditions, successive pulses evolve in one of a small number of ways. This suggests that stochastic processes dominate during the start of the pulse which then give way to a more deterministic evolution, resulting in some small set of "paths" the laser can traverse. Under such conditions accurate spectra measurements became very problematic and long averaging times were introduced in order to extract the data. As a result of the signal averaging the emission spectra measured after more than ~2500 round trips usually contain several peaks, most probably due to contribution from different single peak emission regimes. Single peaks were observed more readily towards the end of 1ms pulses, however, most of the times some additional emission lines are still observed. The used spectral resolution was insufficient to observe individual ring cavity modes (the estimated cavity mode separation is ~0.004 cm^{-1}).

The observed emission spectrum of the ring cavity QCL operating in the continuous wave regime (Fig.4) is characterized mainly by a single narrow peak, sometimes several narrow peaks, with the side mode suppression ratio of more than 30 dB and with its spectral width of around 0.45 cm^{-1}, mainly limited by the spectrometer resolution used. The emission spectra at currents just above the threshold are almost entirely single peak, at higher currents the laser tends to operate at several wavelengths. In general, the position of the single peak emission can be found in a wide energy range of ~1890 – 1925 cm^{-1} depending on the value of the current, the alignment of the ring cavity. Moreover, the wavelength tends to shift abruptly during the alignment process, after breaking the beam inside the cavity or by simply changing the current.

In order to control the emission wavelength two approaches have been explored. First, a 0.35 mm thick un-coated CaF_2 plate (with ~6% reflectivity on both sides) serving as a FP etalon, was inserted into the ring cavity at an angle ~ 45 degrees to the laser beam. The use of the CaF_2 plate results in the intensity of the emission became much more stable, much less dependent on other conditions such as alignment or driving current and the spectral measurements confirm this increased stability with more prevalent single peak emission. By rotating this etalon the wavelength of the single peak emission was tuned, however, only in the limited range of ~1900 - 1910 cm^{-1}, defined by the etalon free spectral range. This particular wavelength range corresponds to the maximum of QCL gain. Because of the narrow free spectral range of the used etalon sometimes two emission lines were also observed. The absorption of water in the air was found to have a very strong effect on the ring cavity QCL emission with FP etalon present. It was not possible to push the laser to operate exactly at the wavelengths of the water absorption lines. In such cases the laser works either in close vicinity of these absorption lines or jumps to a wavelength corresponding to the neighboring etalon mode.

In another set of experiments one of the external mirrors in the ring cavity was replaced by a 300 lines/mm diffraction grating to act as a wavelength tuning element. The use of the diffraction grating, similar to the case of the FP etalon, resulted in a very stable single peak emission with optical power reduced only by ~20%. Moreover the tuning range increased considerably. For example, at dc current of 540 mA it was possible to tune the single peak emission from 1875 to 1965 cm^{-1} (Fig.5). Diminished intensity is observed in the vicinity of the multiple water absorption lines. If a driving current was chosen to be just slightly above the threshold it was possible to shut down the QCL emission completely by tuning the wavelength towards the water absorption lines. The ring cavity geometry provides a very long interaction distance between the light and the surrounding gas medium. This high level of interaction and the laser emission being very sensitive around the threshold lead to this On/Off operation behavior when the emission wavelength is swept across the absorption lines of a gaseous media.

In summary, we have demonstrated an external ring-cavity QCL operating in continuous wave regime at room temperature. The laser emission is predominantly uni-directional and the single peak emission can be widely tuned by a diffraction grating. The realization of this high power ring cavity QCL has implications for a wide range of spectroscopic applications and may also contribute to the future developments of the active mode locking and comb generation in QCLs.

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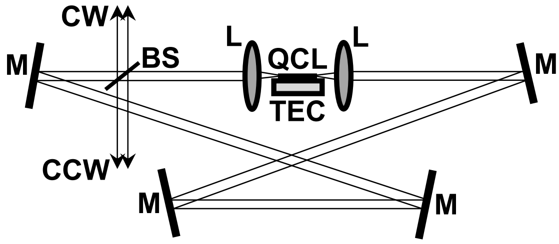

Fig.1 Free-space external ring cavity setup. The light from a quantum cascade laser (QCL) mounted on a thermoelectric cooler (TEC) is collimated by aspheric lenses (L) and coupled back onto the opposite laser facet with mirrors (M). The light propagating in clockwise (CW) and counter clock wise (CCW) directions are out-coupled with CaF_2 beamsplitter (BS). The total optical length of the ring cavity is 1.27 m.

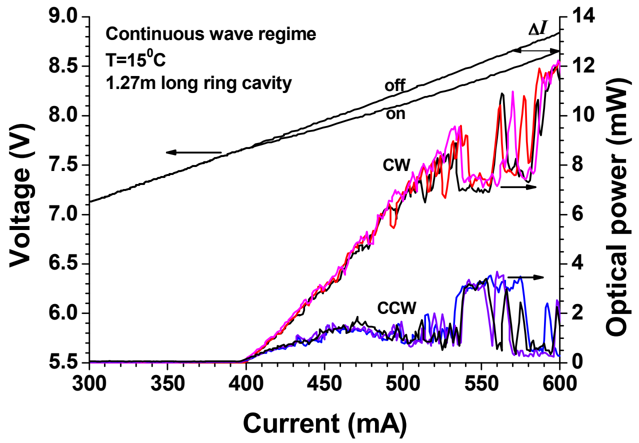

Fig.2 Voltage current and light current characteristics for the external ring cavity QCL in the continuous wave regime. The I-V curves are: with the presence of the emission (marked as “on”) and when the cavity was blocked (marked as “off”). Three consecutive L-I measurements have been obtained for each CW and CCW directions.

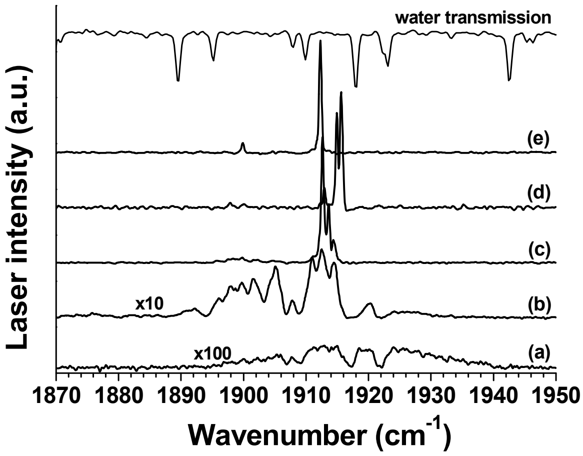

Fig.3. The time resolved emission spectra of the ring cavity QCL measured at the following times from the beginning of the 1 ms long driving current pulse: (a) – 100 ns (25 round trips), (b) – 1 μs (250 round trips), (c) – 10 μs (2500 round trips), (d) - 100 μs (25000 round trips) and (e) – 1 ms (250000 round trips). The dips in the emission spectra correspond to the energy positions of the absorption lines of water vapor in the air. The spectra are vertically shifted for clarity.

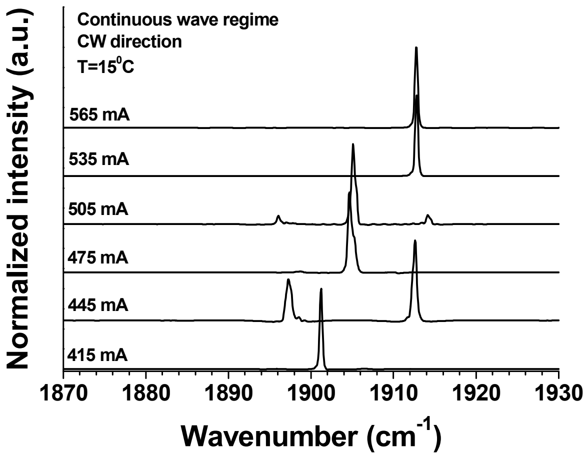

Fig.4. The emission spectra of the ring cavity QCL operating in the continuous regime for the various dc driving current and fixed cavity alignment. The spectra are vertically shifted for clarity.

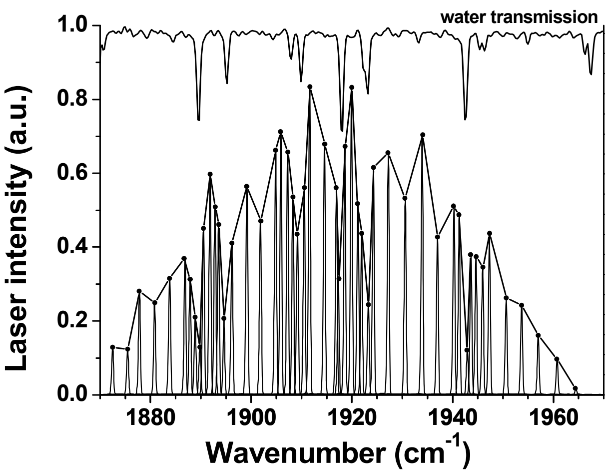

Fig.5. The single peak emission spectra of the ring cavity QCL tuned by rotation of the diffraction grating. The water absorption spectrum is shown as a reference. The wavelength tuning steps near water absorption lines were reduced to allow more precise detection of these lines.

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