Multimode instabilities in mid-infrared quantum cascade lasers

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Abstract—We present experimental evidence for a mid-infrared frequency *comb* based on AlGaAs/GaAs quantum cascade laser. The comb-like emission spectra span over ~50cm^{-1} at a center wavenumber ~1080cm^{-1}. The measured width of the comb lines is ≤ 20MHz. The instability sets in when the intracavity power is sufficiently large. In addition, intersubband transitions feature strong third-order optical nonlinearities $\chi^{(3)}$, due to a large matrix element between the upper and lower laser states, allowing a parametric process, due to four-wave mixing. The observed spectral behavior is similar, in many ways, to the Risken-Nummedal-Graham-Haken (RNGH) instability.

Multimode laser instability was predicted by Risken and Nummedal [1] and Graham and Haken [2]. A typical scenario that emerges from RNGH instability is a self-mode locking behaviour, in which the laser emits a regular train of pulses with a period equal to the round-trip time in the cavity. This instability was for the first time observed in a ring Er^{3+} fiber laser by Pessina *et al.* [3]. The theoretical framework to describe laser dynamics is based on coupled-plane wave Maxwell-Bloch equations for a homogenously broadened two-level system in a ring cavity exactly resonant with the active medium [4-5]. The multimode regimes are well-understood and documented in many types of lasers; however, the understanding of multimode regimes in quantum cascade lasers (QCLs) is still far from being complete [6-7].

In QCLs, unlike the situation in interband semiconductor lasers [8], because of an extremely fast gain recovery time (in sub ps range), which is at least one order of magnitude shorter than the time required by the pulse to complete one round-trip in the cavity, the mode locked operation is difficult to achieve [9]. So far, such a pulsed operation has only been achieved over a very narrow locking bandwidth of ~15cm^{-1}.

Despite the above limitations, coherent instabilities have been recently observed in quantum cascade lasers operated in a continuous wave [10], raising the question about their physical origin.

In this paper, we argue that a multimode operation over a much higher bandwidth than observed so far for mode-locking can be interpreted as frequency *comb* formation [11-12]. As shown in Fig. 1, in high power devices, the spectrum would switch abruptly from a single mode to highly-multimode operation; in our case ~50 cm^{-1} and up to 50 longitudinal modes.

The QCLs studied were based on $GaAs/Al_{0.45}Ga_{0.55}As$ heterostructure. Their active region was based on 3QW design, which relies on LO-phonon resonance to achieve population inversion [13]. The structures were grown by MBE [14]. The ridge-waveguide lasers were fabricated using a standard processing technology, i.e., wet etching and Si_3N_4 for electrical insulation. Double plasmon confinement with an Al-free waveguide has been used to minimize absorption losses. Both uncoated devices and devices with a metal coated back mirror were studied [15]. At cryogenic temperatures lasers delivered the record pulse powers; up to 6W at 77K [16-17], which was essential for triggering nonlinear effects responsible observed multimode instabilities.

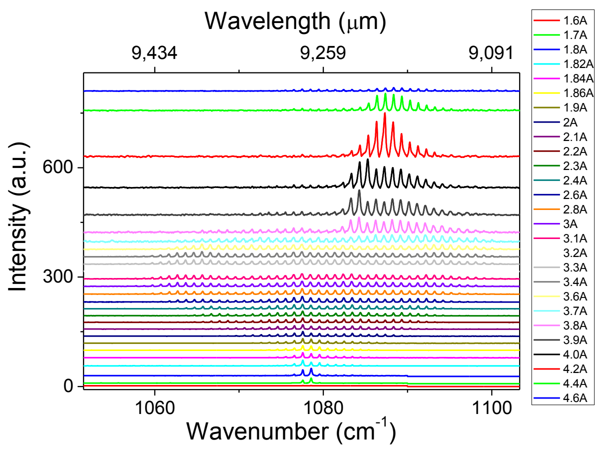

Fig. 1. Optical spectra vs. pumping ratio above threshold obtained at 77K with 15-μm ridge-waveguide laser emitting at 9.25μm. The lasers was cleaved into a 1.5-mm-long bar and soldered with indium onto copper heat sink. The spectra were measured with a Fourier transform infrared spectrometer and MCT uncooled detector.

The essential prerequisite for observing multimode instability is the high intensity of an optical field inside the cavity and a large dipole momentum of ISB laser transitions. For a longer cavity, as seen from Fig. 2, the threshold of instability is reached at higher currents, but it still refers to approximately the same current density.

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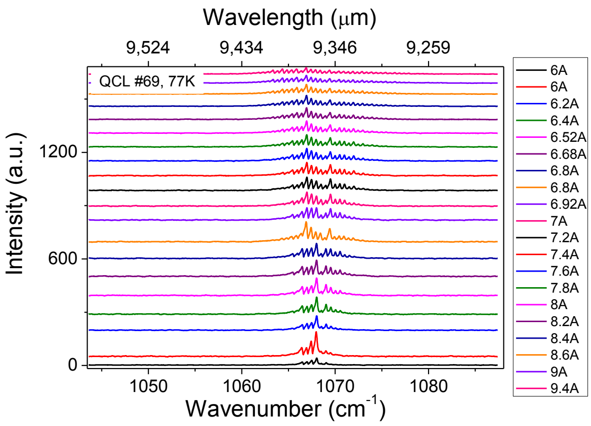

Fig. 2. Optical spectra vs. pumping ratio above threshold obtained at 77K with 15-µm ridge-waveguide laser emitting at 9.37µm. The lasers was cleaved into a 3-mm-long bar and soldered with indium onto copper heat sink.

At liquid He temperatures, for high pumping densities the laser spectrum splits into two separated mode combs (see Fig. 3). The difference between their centres increases linearly with the square root of the output power from one facet.

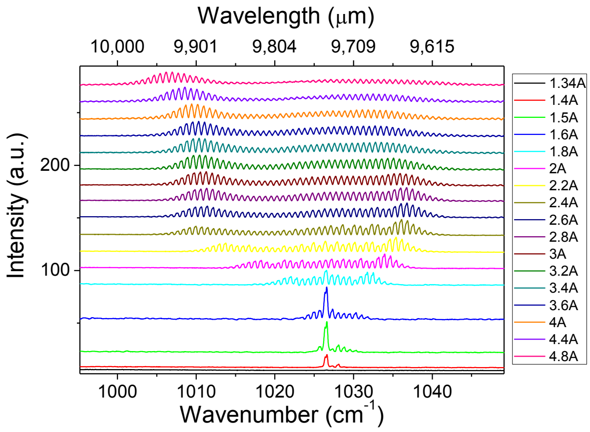

Fig.3. Optical spectra vs. pumping ratio above threshold obtained at 6K with 12-µm ridge-waveguide laser emitting at 9.75µm. The lasers were cleaved into a 2.5-mm-long bar and soldered with indium onto a copper heat sink.

The instability observed differs in some aspects from the original RNGH instability. The threshold of instability is only a few tens of percent higher than the laser threshold, whereas that predicted by pure RNGH can be as high as 10 times the threshold. In addition, there is a lack of central peak in the spectrum at a single mode frequency. The origin of these effects is still controversial; with the most probable cause being the presence of saturable absorption and spatial hole burning (SHB) [18]. It has been shown that the extension of Maxwell-Bloch equations to include a coupling between counter-propagating waves in the Fabry-Perot cavity and accounting for SHG generates theoretical spectra with a Rabi splitting and without a central peak [10], in agreement with the experiment. The Rabi angular frequency can be calculated from the formula

$$\Omega_{Rabi} \equiv \mu E / \hbar = \sqrt{2nI_{ave} / c\varepsilon} / \hbar$$

where µ is the electron charge times the dipole matrix element for laser transitions (z=1.71nm in our lasers) and I_{ave} is the average intracavity intensity, derived from the output power and facet reflectivity. A correlation between the experimental splitting and the twofold Rabi frequency is found (see Fig. 4), being a clear indication of RNGH instability. Because of extremely fast gain recovery, population inversion and polarization adiabatically follow the dynamics of an electromagnetic field. As a consequence, population inversion begins to oscillate at the Rabi frequency, modulating the gain in the laser and creating sidebands around the CW mode. The large dipole moment of ISB transitions plus high field intensity result in a large Rabi frequency (~1 THz).

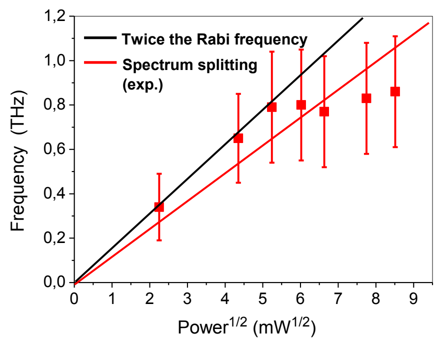

Fig. 4. Spectral splitting and twice the Rabi frequency $\Omega_{Rabi}/(2\pi)$ vs. square root of output power collected from the single laser facet.

With further increasing of the driving current, the laser enters the NDR region and emitted optical power rolls over (see Fig. 5).

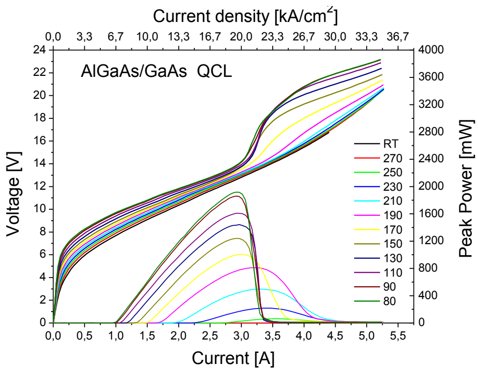

Fig.5. Current-voltage (I-V) and optical power versus current (P-I) characteristics of 15-µm RWG laser emitting at 9.25µm.

With a decrease of optical power in the cavity, two combs of modes combine into a few mode spectrum similar to the one just above the threshold (see Fig. 6).

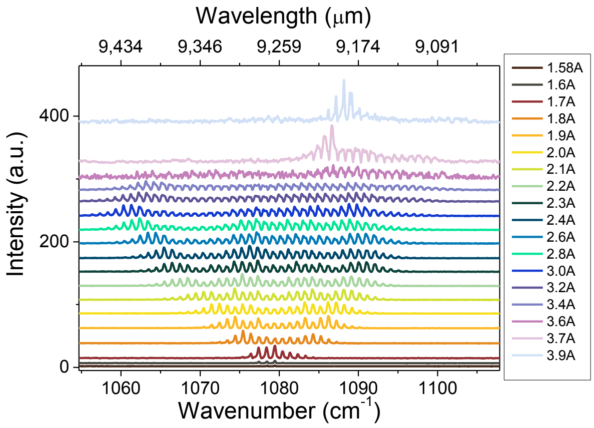

Fig. 6. Optical spectra vs. pumping ratio above threshold obtained at 6 K with 15-µm ridge-waveguide laser emitting at 9.25µm. The lasers was cleaved into a 1.5-mm-long bar and soldered with indium onto copper heat sink.

We have presented experimental evidence for a mid-infrared frequency *comb* based on AlGaAs/GaAs quantum cascade laser. The comb-like emission spectra span over ~50cm^{-1} at a center wavenumber ~1080cm^{-1}. The measured width of the comb lines is ≤ 20MHz.

The instability sets in when the intracavity power is sufficiently large. In addition, intersubband transitions feature strong third-order optical nonlinearities $\chi^{(3)}$, due to the large matrix element between the upper and lower laser states [19-20], allowing parametric process at frequencies detuned from the maximum of the gain curve by the Rabi frequency. The locking mechanism responsible for the formation of a frequency comb is four-wave mixing. Most important for the existence of these oscillations is the coherence of the system over at least one Rabi-oscillation. If this coherence is destroyed fast enough Rabi-oscillation cannot happen. The Rabi angular frequency has to be greater than the relaxation time scales of the gain medium; i.e., $\Omega_{Rabi} > (T_1T_2)^{-1/2}$, where T_1 is the gain relaxation time and T_2 is dephasing time.

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