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Spatial Hole Burning in Actively Mode-Locked Quantum Cascade Lasers

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Abstract: A theoretical study of active mode-locking in quantum cascade lasers including spatial hole-burning is presented. It is found that spatial hole-burning reduces the pulse duration at the expense of slight pulse instability and strongly structured pulse shapes.

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Short pulse generation from Quantum Cascade Lasers (QCLs) emitting in the mid-infrared wavelength region (3.5-20 μm) could serve many applications ranging from time-resolved spectroscopy, nonlinear frequency conversion, high-speed free space communication to frequency metrology [1]. QCLs, directly electrically-pumped sources, potentially can generate sub-picosecond mid-infrared laser pulses over a wide wavelength range, due to the flexibility offered by band structure engineering. However, short pulse generation from QCLs by mode locking is difficult due to the fast gain recovery time of QCLs, typically in the few picosecond range, which acts as an inverse saturable absorber driving pulse formation inherently unstable [2]. Therefore, most recently, QCLs with a long upper state lifetime, by implementing a “superdiagonal” gain structure design [3], have been fabricated showing upper state lifetimes of 50 ps similar to the cavity roundtrip time (40-70 ps) and active mode locking with isolated pulses has been achieved [4]. In this paper, we analyze the stability of mode locking in these lasers by numerical simulations and demonstrate that spatial hole burning (SHB), also considerably reduced in influence due to the long upper state lifetime, is still strong enough to enable multimode lasing over an increased wavelength range in comparison to the case without SHB. However, as has been observed in actively mode-locked solid-state lasers, strong SHB results in incomplete mode locking.

To demonstrate the impact of SHB, the QCL gain structure is modeled as an open two-level system described by Bloch equations and the pulse propagation through the gain medium situated in the Fabry-Perot cavity is described by a one-dimensional wave equation [2]. We assume a homogeneously broadened gain medium with energy recovery time of $T_1=50$ ps and a dipole dephasing time of $T_2=50$ fs. The cavity is 2.6 mm long (refractive index $n \approx 3.2$) and has a short, 240 μm long, electrically isolated section at the begin of the cavity. The short section and the rest of the cavity are equally strong continuously pumped (DC pumping). Active mode locking is achieved by sinusoidal modulation of the pump current injected into the small section at the round-trip frequency of the passive cavity, which is 17.86 GHz. No other nonlinear effects are included. Output coupling occurs via the front uncoated facet of the semiconductor Fabry-Perot cavity.

Fig. 1 shows the intensity profile and interferometric autocorrelation (IAC) traces for the QCL, with parameters discussed above, if SHB is neglected in the Maxwell-Bloch equations describing the laser dynamics. The DC pumping parameter is set to 1.1, 1.45 and 1.61 times the threshold current and we keep the amplitude of the modulation term constant (5 times the threshold value). Note, since the modulation frequency is already close to the inverse gain recovery time, the modulation of the population inversion is about 6 times smaller and is delayed by almost 90° . From the pulse trains depicted in Fig.1.a, 1.c and 1.e we observe that for low DC pumping the train consists of isolated short pulses with a steady state pulse shape. As DC pumping increases, the gain with its inverse saturable absorption behavior increases and consequently the pulses lengthen. The saturable gain counteracts the pulse shaping by the modulator. This becomes even more obvious in the corresponding computed interferometric autocorrelation traces in Fig.1.b, 1.d and 1.f shown underneath the intensity profiles. For higher DC pumping levels the IAC traces start to overlap. For the case of neglected SHB, the IAC traces and in fact the computed electric fields do not show any chirp, i.e. nontrivial phase over the pulse. This is in contrast to the experimental results [4].

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Experimental results show the same trend in pulse lengthening when varying the DC pumping, however there is a major difference. The pulses in Fig. 1 are in general longer than the pulses in the experiment. For the case of DC pumping 1.1 times the threshold, the pulse width in Fig. 1.a is 7 ps, while it was approximately 3 ps in the experiment. The experimentally observed spectra are also much more broadband. This indicates that SHB is important and must be incorporated in the model. SHB is strong in Mid-IR QCLs since the strength of diffusion, which combats the carrier density modulation, scales with the square of the wave number k [2]. One can show that the strength of the carrier density modulation or gain grating is proportional to $1/(1+4k^2D T_l)$ [2], where D is the diffusion coefficient. In regular ($T_l=5$ ps) Mid-IR QCLs, $4k^2D$ is roughly the same as $1/T_l$ and SHB is strong. Even for the long upper state lifetime $T_l=50$ ps of the “superdiagonal” QCL structure, the effects of SHB cannot be neglected. Fig. 2 shows the intensity profiles and corresponding IAC traces for the same parameters as used for Fig. 1, but including SHB. For higher pump levels the pulses do no longer reach a steady state and even for low pumping the pulse shape is strongly modulated. The pulse spectra (not shown) and the IAC traces become much closer to the measured IAC traces in actual devices [4]. The main peaks of the pulses do get shorter, 2 ps for the case in Fig. 2.a. For higher levels of DC pumping, the pulses become more structured (Fig 2.c and 2.e), i.e. there is nonlinear phase on the pulse, as is evident in the corresponding IAC traces. For both cases, including and not including SHB, if the DC pumping is kept constant and the amplitude of the AC modulation is increased the pulse quality improves.

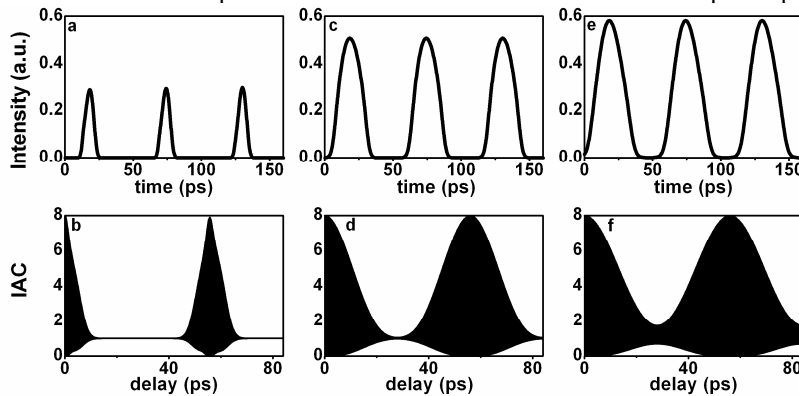


Fig 1. Top row, intensity profile and bottom row corresponding interferometric autocorrelation (IAC) of output pulse train for modulation with AC amplitude 5 times the threshold for different DC pumping levels without including SHB. a) and b) for DC pumping 1.1 times the threshold; c) and d) for DC pumping 1.45 times the threshold; e) and f) for DC pumping 1.61 times the threshold.

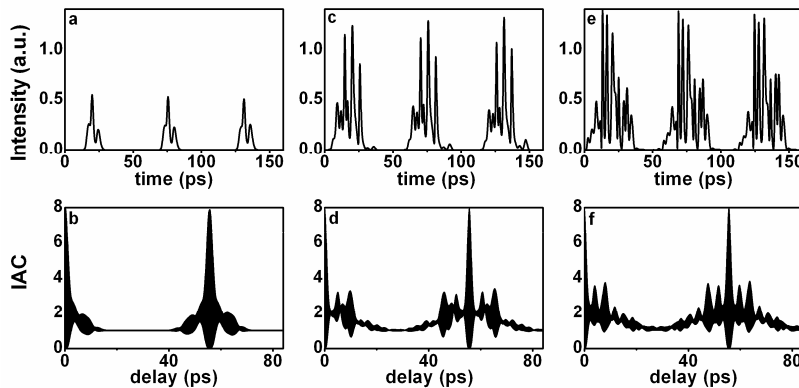


Fig 2. Top row, intensity profile and bottom row corresponding interferometric autocorrelation (IAC) of output pulse train for modulation with AC amplitude 5 times the threshold for different DC pumping levels including SHB. a) and b) for DC pumping 1.1 times the threshold; c) and d) for DC pumping 1.45 times the threshold; e) and f) for DC pumping 1.61 times the threshold.

The presentation will include more details of the model as well as more detailed simulation results over extended parameter ranges, indicating parameter ranges for stable pulse trains from actively mode-locked QCLs.

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