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Coherent Pulse Propagation in Mid-infrared Quantum-Cascade Lasers with Nonlinear Dispersive Gain Medium

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Abstract: Effects of group-velocity dispersion and self-phase modulation on coherent pulse progression in mid-infrared quantum-cascade lasers are investigated. The interaction between them is evaluated toward the soliton formation in the lasing cavity.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (190.4360) Nonlinear optics, devices; (190.5530) Pulse propagation and temporal solitons;

1. Introduction

Since the first demonstration in 1994, quantum-cascade lasers (QCLs) have become one of the most important solid-state mid-infrared (MIR) coherent light sources for various applications in environment sensing, medical diagnosis, and defense and free-space communication [1]. Dynamics analysis and stable pulse progression of MIR QCLs are crucial in order for QCLs to have reliable performance in these applications. An explicit description of dynamics of QCLs is inevitably complicated when compared to conventional lasers because of the unique combination of ultrafast carrier scatterings and gain recovery, significant nonlinearities [2] and dispersion effect [3] in a QCL medium.

Discussions on dynamics in MIR QCLs have been mostly focused on the stability analysis [4, 5]. However, the interplay between the nonlinearity and dispersion effect during the QCL coherent pulse progression has received less attention. Especially, in a nonlinear dispersive lasing medium, the combination of group-velocity dispersion (GVD) and self-phase modulation (SPM) could possibly lead to the soliton formation. A measurement of GVD in the MIR QCLs has been reported in [12]. The interaction between the GVD and the saturable absorber (SA) in the self-induced transparency (SIT) modelocking of QCLs is discussed in [6], where the analysis is based on the evolution of electric field only and the coherence effect in the lasing transition is not included. In our current study toward the soliton formation in QCLs, we got the opportunity to carefully examine each of those two effects and analyze their interaction on the coherent pulse progression in both time-domain and frequency-domain.

2. Theoretical model and numerical analysis procedure

In order to avoid the complication brought by the two-way wave propagation, we performed our analysis based on a QCL medium within a ring cavity instead of a Fabry-Perot cavity. We model the QCL gain medium as a two-level system described by the Maxwell-Bloch equations [4],

$$\frac{\partial E}{\partial t} = \frac{c}{n} \left[-\frac{\partial E}{\partial z} - P - \frac{1}{2} \left(l_0 - \hat{\gamma} |E|^2 + i \hat{\xi} |E|^2 \right) E - \frac{1}{2} i \beta_2 \frac{\partial^2 E}{\partial t^2} \right], \quad (1)$$

$$\frac{\partial P}{\partial t} = -\frac{1}{2} \sigma E - \frac{P}{T_2}, \quad (2)$$

$$\frac{\partial \sigma}{\partial t} = \frac{l_0(p_s - 1)}{T_1 T_2} - \frac{\sigma}{T_1} + (E^* P + E P^*), \quad (3)$$

where dependent variables E , P , and σ represent the normalized envelope of the electric field, the polarization and the population inversion in the gain medium. The coherence between the lasing field and the two-level atomic transitions are described by the coupling among these dependent variables. The GVD is included as the second-order time-derivative term with the coefficient β_2 indicating the dispersion strength. $\hat{\gamma} = \hbar^2 \gamma / \mu^2$, where γ is the coefficient describing SA strength. $\hat{\xi} = \hbar^2 \xi / \mu^2$, where ξ is the SPM coefficient. In Eq. (1), it can be found that the SA is accounted as the intensity-dependent amplitude modulation, while the SPM is the intensity-dependent phase modulation. All other coefficients follow the same definitions as in [5]. We employed the finite different method (FDM) with prior nondimensionalization to numerically solve the whole set of simultaneous dynamic equations (1-3).

3. Results and discussions

We take the buried heterostructure continuous wave (CW) 8.38 μm QCL with wafer No. 3251 [4] as the prototype of our theoretical analysis except for the GVD coefficient which is not addressed in [4]. Specifically, the SA coefficient γ is set as $2 \times 10^{-9} \text{ cm/V}^2$ and pumping strength as $p_r = 1.5$. We vary the SPM and GVD coefficients relative to their respective reference values in order to examine the trend of their effects. The reference value of SPM coefficient is taken as $\xi_0 = 1.2 \times 10^{-6} \text{ cm/V}^2$ based on the estimation of the nonlinear refractive index n_2 [4]. We borrow the measurement results from [3] for the reference value of GVD coefficient $\beta_{20} = -4.6 \times 10^{-6} \text{ ps}^2/\mu\text{m}$. Figure 1 presents the pulse progression in time-domain. We found that the SPM effect can shorten the pulse duration with slight change on the shape of the pulse. The GVD effect is shown to extend the pulse duration but significantly lower the peak intensity of the pulse. The combined GVD and SPM effects could recover the pulse duration with the peak intensity lowered by the GVD. In frequency-domain analysis, we examined the spectral responses under varying GVD and SPM coefficients. From Fig. 2, it is found that the side-modes splitting decreases with the increasing magnitude of anomalous GVD. However, the GVD has little impact on the linewidth of the central mode. Figure 3 shows that the SPM effect has notable effect on spectral broadening around central mode. Our results also show that the combined GVD and SPM effects exhibit as the narrowing of side-mode splitting and the linewidth broadening of central mode and side modes, which results in the cancellation effect on the pulse duration in time-domain.

In summary, we present our theoretical analysis on coherent pulse progression in MIR QCLs under both GVD and SPM effects with background SA. We predict that the cancellation of their combined effects in time-domain may lead to the formation of solitons in QCLs. To the best we know, there is yet no experimental report particularly addressing such combined effects in QCLs and we will pursue the experimental verification as our next step.

Figure 1. Time-resolved pulse propagation: (a) pulse progression 0~5ps; (b) enlarged view for 4-5ps.

Figure 2. The frequency spectrum with GVD ($\xi = 0$). Figure 3. The frequency spectrum with SPM ($\beta_2 = 0$).

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