Novel Hybrid Modeling Strategy for Semiconductor Mode-Locked Lasers

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Abstract: We demonstrate a novel hybrid model for semiconductor mode-locked lasers by combining the merits of a traveling-wave model for the active regions and a split-step Fourier algorithm for the extended passive cavity. © 2020 The Author(s)

1. Introduction

Integrated semiconductor mode-locked lasers are of utmost importance for many applications. While a number of these devices has already been demonstrated, their design and fabrication remains a non-trivial effort [1]. It is evident that accurate models are needed to reliable design and realize these devices. Ideally, this model can provide a set of design rules to acquire targeted parameters such as pulse duration, output power and comb shape. Many models have been developed that can be categorized into two classes [2], distributed and discrete models. Distributed models rely on the Haus master equation and are useful to study the basic dynamics of pulse evolution [3]. However, these models presume that the pulse is near equilibrium when traveling inside the laser cavity. Discrete models on the other hand, model each component of the laser separately and therefore eliminate this stringent requirement.

In recent years, traveling-wave discrete models (TWM) have been favored for semiconductor mode-locked laser (MLL) modeling because they can incorporate the rich physics of semiconductors and are not as computationally demanding when compared to finite difference methods [2,4,6]. One important limitation is that most TWM's fail to incorporate nonlinear and higher-order dispersive effects. Although recent work successfully included nonlinear terms in a TWM model [6], these models are computationally demanding and are therefore not convenient to aid the design of low repetition rate-mode-locked devices, which have a long passive cavity as compared to the length of the active region. The well-known split-step Fourier method on the other hand is well suited to rapidly simulate pulse evolution in passive waveguides with arbitrary dispersion and nonlinearity. It is therefore useful to combine a complex TWM for the semiconductor regions, and a split-step Fourier approach for the passive cavity. In this work, we propose a first implementation of such a hybrid model and illustrate that one can incorporate nonlinear effects of the passive cavity in a computationally efficient way.

2. Implementation and results

In this work, we model a 2.5 GHz III-V-on-silicon anti-colliding MLL, similar to [7]. The active regions are modeled through a simplified TWM based on previous work [4,5]. One simplification is the localized frequency dependence of the gain by means of a Lorentzian-shaped filter with a 2 THz bandwidth, which is placed at the output mirror. This simple picture suffices for our first tests and can be motivated by the narrow reflection spectra of the Bragg gratings. It is nevertheless straight forward to use the hybrid model with more complex TWM implementations such as the one presented in [6] or based on FreeTWM software [5]. The equations of our TWM are provided below and parameters are listed in Fig. 1. The split-step Fourier algorithm simulates the nonlinear pulse propagation and dispersion of the extended cavity. The interface between both models is depicted in Fig. 1.

$$\begin{cases} A^+(t+\Delta t, z_{k+1}) = A^+(t, z_k) \exp \left[-\frac{\beta \Delta z}{2} + \frac{\omega_0 \Gamma \chi_0 v_g}{2n_{eff}c} \cdot \int_{z_k}^{z_{k+1}} \left[2 \tan^{-1} \left(\frac{N}{N_t} \right) - \frac{\pi}{2} - j \ln \left(1 + \left(\frac{N}{N_t} \right)^2 \right) + j \frac{1}{2} \ln(1+b^2) \right] dz \right] \\ A^-(t+\Delta t, z_k) = A^-(t, z_{k+1}) \exp \left[-\frac{\beta \Delta z}{2} + \frac{\omega_0 \Gamma \chi_0 v_g}{2n_{eff}c} \cdot \int_{z_k}^{z_{k+1}} \left[2 \tan^{-1} \left(\frac{N}{N_t} \right) - \frac{\pi}{2} - j \ln \left(1 + \left(\frac{N}{N_t} \right)^2 \right) + j \frac{1}{2} \ln(1+b^2) \right] dz \right] \\ N(z_k, t) = N(z_k, t-\Delta t) + \Delta t \cdot \left[\frac{I}{qV} - \frac{N(z_k, t-\Delta t)}{\tau} + \frac{2\pi \Gamma \chi_0}{\hbar n_{eff}c} \left[\frac{\pi}{2} - 2 \tan^{-1} \left(\frac{N(z_k, t-\Delta t)}{N_t} \right) \right] \cdot (|A^+(t, z_k)|^2 + |A^-(t, z_k)|^2) \right] \end{cases}$$

The forward propagating wave of the TWM fills the reservoir of the passive section. Once the reservoir is full, a segment of the signal trace is selected in a way that maximizes the energy centralization in the window. The segment is subsequently propagated with split-step Fourier and is added to the queue that feeds the backward propagating wave of the TWM. If the energy is not centralized, for example at laser startup, the passive section is simply modeled by loss and a delay. It is observed that once pulsed behavior is reached, split-step Fourier is

Fig. 1. Mode-locked laser simulation flow (left) and parameters used (right). SA is saturable absorber, SOA is semiconductor optical amplifier and ISO is isolation section.

Fig. 2. Impact of nonlinearity on the output pulse shape (a) and pulse stability map as a function of injection current with strong nonlinearity $\gamma = 55 \text{ m}^{-1} \text{ W}^{-1}$ (b) and without nonlinearity (c).

consistently employed. Fig. 2 shows the impact of the nonlinearity on the pulse shape and stability. A timestep $\Delta t = \Delta z/v_g = 20 \text{ fs}$ was used. One can see that for the parameters of Fig. 1, a higher nonlinearity leads to a shorter pulse. Moreover, it is noted that the nonlinearity can significantly narrow the stable region of fundamental mode-locking. As a next step we intend to compare the model with experimental data and explore soliton mode-locking.

3. Conclusion

We have demonstrated a hybrid modeling strategy for semiconductor mode-locked lasers by combining a TWM with split-step Fourier propagation. We believe this approach paves the way to interface elaborate semiconductor models and accurate pulse propagation in the cavity in a computationally efficient fashion. It was shown that the inclusion of nonlinear effects of the passive cavity can largely impact the pulse characteristics and locking region.

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