Generalized Hybrid Model for Extended Cavity Mode-Locked Laser Diodes

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Precision frequency metrology and timekeeping have largely been revolutionized by the advent of mode-locked lasers. Their integration on a photonic chip has extended their application range well beyond fundamental metrology to areas such as datacom, optical ranging and on-chip spectroscopy. However, the ability to efficiently model such devices while including relevant nonlinear and dispersive effects of an extended cavity has proven difficult. In an attempt to overcome these challenges, we developed a hybrid modeling strategy by unifying a traveling-wave model for the semiconductor sections with a split-step Fourier method for the passive cavity. This generalized hybrid model includes some previously neglected effects such as distributed gain dispersion and permits a wider range of applicability, enabling the study of various physical phenomena and the exploration of novel operating regimes.

Introduction

The integration of mode-locked lasers on a photonic chip has enabled numerous applications beyond the scope of traditional solid-state and fiber lasers [1]. In particular the recent advancements of on-chip mode-locked lasers with an extended cavity have brought about a considerable improvement in noise performance and unlocked record-low repetition rates [2-4]. However, their performance remains largely unpredictable as the design is largely based on experimental investigations due to a lack of adequate modeling tools. Ideally, such a model can incorporate the necessary physical details while minimizing the computational workload, enabling it to serve as a design aid, provide qualitative insight and enable parametric studies.

In recent years, mode-locked laser diodes have mainly been modeled through delay differential equations [5] or traveling-wave models [6-8]. Although these approaches can satisfactorily capture the semiconductor physics of the amplifier and saturable absorber, they are not geared to incorporate nonlinear and dispersive effects of a passive laser cavity. This is particularly troublesome when designing mode-locked lasers with a low repetition rate, which have a long extended passive cavity as compared to the length of the active laser sections. For such devices, the dispersion and nonlinearity of this passive waveguide can play a salient role.

Here, we demonstrate a hybrid simulation strategy in which a traveling-wave model for the semiconductor sections is combined with a split-step Fourier implementation of the extended nonlinear Schrödinger equation for the extended passive cavity. Compared to our first demonstration [9], this generalized hybrid model now includes distributed gain dispersion and offers a wider range of applicability, including pulsed regimes with nonvanishing backgrounds.

Hybrid model equations

A simple Traveling-Wave Model (TWM), based on earlier work [6,8], is adopted here to exemplify the hybrid modeling concept. If desired, it is straight forward to utilize a more elaborate TWM to yield a more detailed physical representation of the active semiconductor sections of the laser. The slowly varying amplitudes $A^{\pm}$ of the forward and backward traveling waves in the amplifier and saturable absorber can be modeled through the equations

$$\frac{\partial A^{\pm}}{\partial t} \pm \frac{\partial A^{\pm}}{\partial z} = \frac{j\omega_0 v_g \Gamma}{2n_{eff}c}\chi A^{\pm} - \frac{\beta}{2}A^{\pm} - \frac{\bar{g}v_g}{2}(A^{\pm} - p^{\pm}),$$

where $|A|^2$ has units of $\frac{W}{m^2}$ and the spatial variable z has been normalized with the group velocity, leading to a dimension in seconds. Γ represents the Multiple Quantum Well (MQW) optical confinement factor, β the internal losses and χ the electrical susceptibility. The polarization terms are included to take the gain dispersion into account through a Lorentzian distributed gain dispersion model, as proposed by Bandelow et al. [6] This yields more accurate results compared to a localized Lorentzian filter used in earlier work [9]. These polarization terms obey

$$\frac{\partial p^{\pm}}{\partial t} = \bar{\gamma}(A^{\pm} - p^{\pm}) + j\bar{\omega}p^{\pm},$$

Where $\bar{\gamma}$, $\bar{\omega}$, and $\bar{g}$ are the half width at half maximum of the Lorentzian (units rad/ps), the peak position of the Lorentzian with respect to ω_0 and the amplitude of the gain dispersion [6]. The evolution of the carrier density is modeled through the rate equation

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - R(N) + \frac{\Gamma\, Im\big(\chi(N)\big)}{\hbar n_{eff}c}|A|^2 - \frac{v_g}{\hbar\omega_0 v_g}Re\big[A^*\big(2\hat{\mathcal{D}}\big)A\big],$$

Where I is the injection current, $R(N) = \frac{N}{\tau} + BN^2 + CN^3$ incorporates the recombination terms [6], and the operator $\hat{\mathcal{D}}A^{\pm} = \frac{\bar{g}}{2}(A^{\pm} - p^{\pm})$. Finally, the carrier-dependent susceptibility is approximated as

$$\chi(N) = \frac{-n_{eff}c}{\omega_0}\chi_0(N - N_t)\left[\frac{j}{1 + \Gamma\epsilon\frac{|A^+|^2 + |A^-|^2}{v_g\hbar\omega_0}} + \alpha\right]$$

Where N_t is the transparency carrier density, α is the linewidth enhancement factor, ϵ is the nonlinear gain compression factor and χ_0 is a gain constant. For numerical evaluation of the above equations, the semiconductor sections are discretized into segments of normalized length $\Delta z = \Delta t$, where Δt is the time required for light to propagate over one segment and Δz is the physical length of the segment normalized with the group velocity. The extended passive cavity of the laser is modeled through a nonlinear Schrödinger equation and implemented using a split-step Fourier method, as elaborated in [9].

To interface the TWM with the passive waveguide model, a custom algorithm was developed, as illustrated in Figure 1. For the passive waveguide, a 'reservoir' array with a size R corresponding with the total roundtrip time of the laser $\frac{\Delta T_R}{\Delta t}$, and a 'queue' array with a size Q corresponding to twice the propagation delay of the spiral waveguide cavity (i.e. $\frac{2L_{spiral}}{v_g \Delta t}$) are defined. With every time step Δt, the leading signal sample of the forward propagating wave of the TWM is added to the reservoir. At the same time, a signal sample from the queue is added to the backward propagating wave of the TWM. The forward propagating field A^+ hence feeds the reservoir, whereas the backward propagating field A^- is fed by the queue. This step-wise process continues until the queue has no remaining signal samples available for the backward propagating wave of the TWM. At this point, the reservoir – with a time span matching the total roundtrip time of the laser – is propagated using a split-step Fourier method to impose the losses, dispersive and nonlinear effects of the extended passive waveguide cavity. The Q last signal samples of the propagated reservoir samples are subsequently substituted in the queue so that the simulation can continue. The R-Q leading samples of the propagated reservoir (highlighted in red in Fig. 1) are discarded as they solely served as dummy samples to match the split-step Fourier window to the total roundtrip time. These dummy samples are simply the trailing R-Q reservoir samples from the previous split-step Fourier step.
The incorporation of dummy samples to match the split-step Fourier window size to the pulse repetition rate ensures amplitude periodicity to comply with the periodic boundary conditions of the split-step Fourier method. For phase periodicity, which is generally not automatically satisfied, a linearly increasing or decreasing phase correction vector $e^{j\varphi}$ is multiplied with the reservoir prior to split-step propagation to avoid a phase jump between the first and last sample of the reservoir. After split-step propagation, the propagated reservoir samples are multiplied with the conjugate of the phase correction vector. This methodology allows one to consistently use the split-step method in contrast to our earlier work, enabling e.g. the modeling of pulsed regimes in nonvanishing backgrounds.

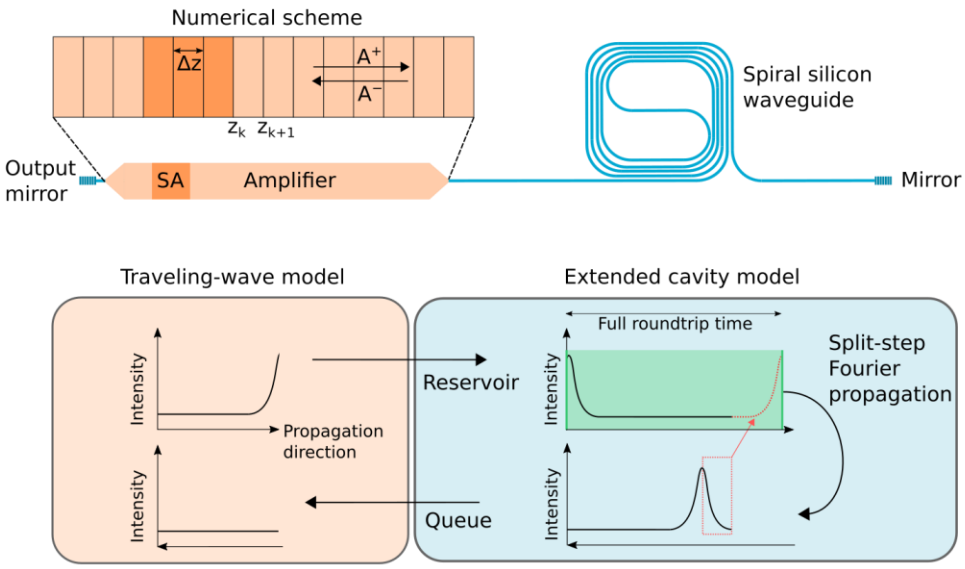

Figure 1: Mode-locked laser simulation flow, consisting of a traveling-wave model for the active semiconductor sections of the laser and a passive waveguide model based on an extended nonlinear Schrödinger equation and a split-step Fourier method.

Simulation results

To exemplify the hybrid model, it is applied to the 1 GHz III-V-Si mode-locked laser reported in [4]. The simulation results are depicted in Figure 2. A single broad input pulse was injected to circumvent the problem of self-starting. Some qualitative agreement can be observed with the reported experimental results, although some further optimization of the model's semiconductor parameters is needed.

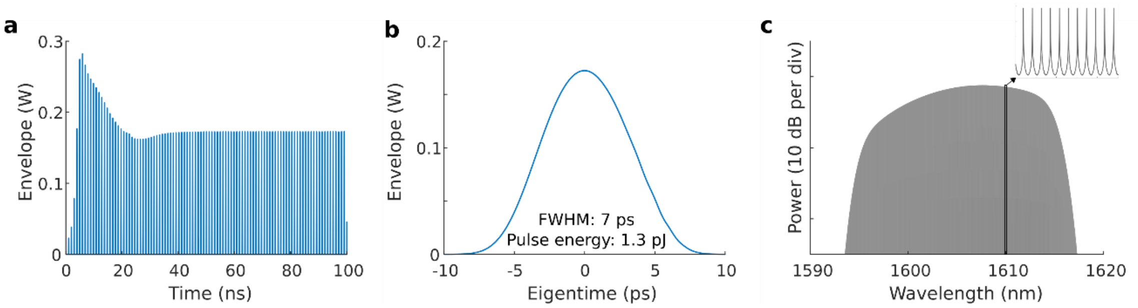

Figure 2: Mode-locked laser simulation example. (a) Signal build-up at the output facet. (b) Pulse profile. (c) Optical spectrum. The used parameters can be found on our GitHub repository.

Conclusion

We have demonstrated the hybrid modeling concept for model mode-locked laser diodes with an extended passive cavity. Some improvements were implemented to enhance physical accuracy and extend the model's application scope. The Python code of the model can be found on GitHub: https://github.com/stijncuyvers/GenHybridMLLmodel

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