Simulation of Mode-locked Ring Lasers Including Integrated Passive Components for Dispersion Compensation

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We have developed a model to simulate integrated mode-locked ring lasers including passive components like AWGs, with the aim to use it as a design tool for developing femtosecond integrated pulse sources. The possibility to include passive components into the laser cavity allows for the design of integrated equivalents of bulk and fiber optic approaches to obtain femtosecond pulses, using dispersion control.

Simulations based on the InP/InGaAsP active-passive technology show the possibility of a laser design that is able to generate pulses with pulsewidths down to 300fs.

Introduction

State of the art mode-locked semiconductor laser sources are able to produce pulses with widths down to 2ps and having a good extinction ratio [1]. For future terabit applications, pulsewidths well into the femtosecond regime (around 300fs FWHM) are necessary. In monolithic semiconductor mode-locked laser sources the output pulses are upchirped due to the self-phase modulation (SPM) in the semiconductor material. Combined with the positive cavity dispersion, this SPM broadens the pulse.
Bulk and fiber optics have been used in combination with the semiconductor laser to manage the chirp of the pulse by intracavity [2] or extracavity dispersion compensation [3]. Also the self-phase modulation (SPM) in the semiconductor material can be minimized by operating the laser in a 'breathing-mode' configuration [4]. The last two techniques are able to produce pulsewidths below 300fs, whereas intracavity dispersion compensation only has limited effect on the pulsewidth.
We have developed a flexible model to simulate integrated passively mode-locked ring lasers that include passive components like arrayed waveguide gratings (AWGs) and phase modulators. With this model we have a toolkit to simulate complex laser structures which we aim to realize in InP/InGaAsP active-passive material [5]. In this paper we present simulations of the integrated equivalents of the bulk and fiber optic configurations for intracavity [2] and extracavity [3] dispersion compensation and also the 'breathing mode' configuration [4].

Model

For the simulation of the semiconductor optical amplifier (SOA) and saturable absorber (SA) of a mode-locked ring laser, we use rate equations based on [6], extended with the more advanced SOA dynamics presented in [7]. For the simulation of cavity dispersion, bandwidth limitation and AWG-transmission we use complex transmission filters in the frequency domain.
We have developed an algorithm based on a discrete fourier transform to switch between a pulse description in the time domain to apply the SOA and SA rate equations

and the frequency domain to apply the complex transmission filters. This algorithm is numerically fast and stable. However it only takes unidirectional pulse propagation into account, which allows us to describe the pulse in a moving-time coordinate reference frame.

Laser designs

Intracavity dispersion compensation

To test the feasibility and effect of intracavity pulse compression [2] using the dispersion of the laser cavity, we simulate the configuration as presented in Fig. 1. Using a total cavity dispersion of 0.01ps^2, which is a typical value for a 40GHz cavity, the output pulse is simulated as in Fig. 2. The output pulse has a FWHM of 1.8ps and is upchirped. This would mean that adding negative cavity dispersion decreases the pulsewidth.
Now we assume that the dispersion of the cavity can be tuned or that an intracavity dispersive element can be added. Tuning the intracavity dispersion to -0.01ps^2 leads to a minimum pulsewidth of 0.9ps. By varying laser parameters it is observed that this type of compression is limited to about 50%, which was already predicted by [8]. The nonlinear chirp causes pulse breakup when increasing the dispersion compensation beyond this point. So concluding it can be stated that this approach is rather limited in obtaining femtosecond pulses.

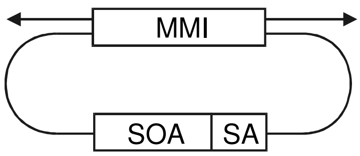

Fig. 1. 40GHz mode-locked ring laser configuration based on [9]. For simulation purposes the SOA and SA lengths are respectively L_{SOA}=500µm and L_{SA}=50µm. The MMI is a 50/50 splitter.

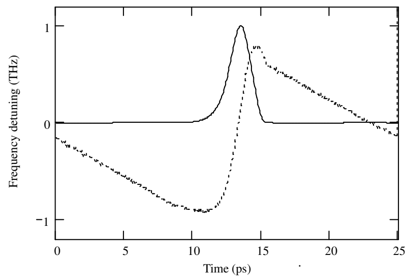

Fig. 2. Pulse power (solid, a.u.) and chirp profile (dotted) using I=130mA. The cavity dispersion is 0.01ps^2.

Extracavity pulse compression

Another option to compress the pulse is to add a dispersive element at the output, i.e. extracavity pulse compression [3]. Applying a total dispersion of -0.1ps^2 on the pulse as given in Fig. 2 results in a pulse compression below 500fs FWHM. The maximum achievable compression is strongly dependent on the operating conditions which affect the resulting chirp over the pulse.
To translate this concept to an integrated design we use an AWG-pair with tunable delay lines based on [10]. The laser configuration used for the simulation is given in Fig. 3. The simulation is done using a discrete phase filter presented in [11] to account for the finite channel spacing of the AWGs.
This approach turns out to be well suited for obtaining femtosecond pulses. By increasing the injection current to 200mA the chirp over the pulse is increased and pulses can be compressed down to 300fs. However due to the non-flat transmission

satellite pulses arise. Flattening of the AWG transmission can reduce this effect. This is under investigation. Note that we have used feasible AWG parameters, namely 20 channels spaced at 200GHz.

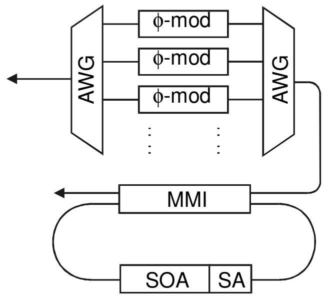

Fig. 3. AWG-pair with tunable delay lines added to the output of the ring laser of Fig. 1. The AWGs have a 200GHz channel spacing and a Gaussian transmission. The phase modulators are indicated by Δϕ. The dots indicate the variable number of phase modulators.

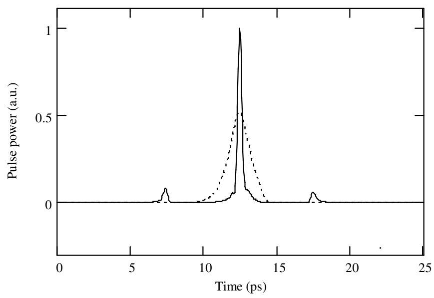

Fig. 4. Simulated optical pulse before (dotted) and after (solid) compression by the AWG-pair configuration of Fig. 3. The simulation is done using I=200mA. The AWG-pair dispersion is -0.1ps^2. The compressed pulsewidth is 300fs. 20 delay lines are used.

Intracavity pulse shaping

The SPM can be reduced by operating the mode- locked ring laser in a 'breathing mode' configuration [4], where typically the pulse is stretched before entering the SOA section and recompressed afterwards. We apply this concept in a different way, as can be seen in Fig. 5. The SOA sections are placed between two AWGs. As a result low bandwidth pulses will pas through the individual SOAs. These pulses are stretched and lower in intensity as compared to the pulses passing through the SA section. Three remarks about this configuration should be made. The first point is that the SPM is indeed minimized by a factor 10 (i.e. from ±1THz to ±100GHz), as can be seen in Fig. 6, with a resulting downchirp due to the SA dynamics. As a second point we can say that pulse rate multiplication occurs due to the non-flat transmission of the AWGs and the resulting laser mode-selection. In this case we used AWGs with 200GHz channel spacing, leading to five pulses in the 40GHz cavity. The last point is that we note that the bandwidth of the laser can be tailored by adding SOAs or increasing the channel spacing of the AWGs.

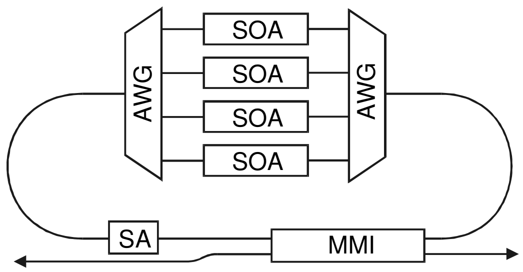

Fig. 5. Intracavity pulse shaping, using four SOAs of 500μm. The AWGs have a channel spacing of 200GHz. A 40GHz cavity is assumed and L_{SA}=50μm.

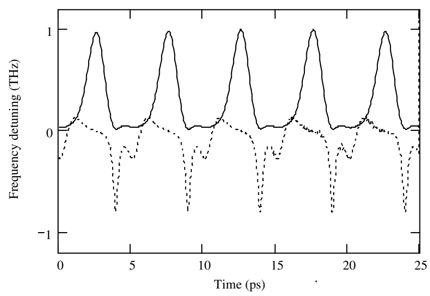

Fig. 6. Simulated output pulse power (solid, a.u.) and chirp (dotted) from the laser configuration of Fig. 5.

Conclusion

To obtain femtosecond pulses with semiconductor laser sources, control of the chirp of the pulses is necessary. Using a discrete fourier transform based algorithm we are able to simulate integrated mode-locked ring lasers including passive components such as AWGs and phase modulators. The use of these passive components in the laser cavity enables us to translate bulk and fiber optics approaches for obtaining femtosecond pulses into an integrated equivalent. Three of these concepts have been studied and simulated.
Intracavity dispersion compensation has only a limited effect on the pulsewidth, effectively shortening the pulse up to 50% as compared to a ring laser without any added dispersion. Simulations show that extracavity pulse compression is more effective and that 300fs pulses may be achievable. The formation of satellite pulses is an issue. Our integrated equivalent of the 'breathing mode' configuration shows the possibilities of obtaining high repetition rate pulses with low chirp and the tuning of the bandwidth of the laser output. These configurations will be realized.

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