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Sub-picosecond pulse generation employing an SOA-based nonlinear polarization switch in a ring cavity

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Abstract: We demonstrate the generation of sub-picosecond optical pulses using a semiconductor optical amplifier (SOA) and a linear polarizer placed in a ring-laser configuration. Nonlinear polarization rotation in the SOA serves as the passive mode-locking mechanism. The ring cavity generates pulses with duration below 800 fs (FWHM) at a repetition rate of 14 MHz. The time-bandwidth product is 0.48. Simulation results in good agreement with the experimental results are presented.

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OCIS codes: (250.5980) semiconductor optical amplifier; (320.7110) ultrafast nonlinear optics; (140.4050) mode-locked lasers.

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1. Introduction

Light sources capable of producing ultra-short optical pulses play a key role in optical communication systems [1, 2]. Fiber ring-lasers have been shown to be useful in producing continuous wave (CW) light as well as ultrashort pulses [3-8]. Considerable research related to fiber ring-lasers was concentrated on soliton pulse generation in relation with compression schemes [5]. In such approach, high optical peak powers in the ring cavity are required to employ the fiber nonlinearity for the generation of solitons. Such approaches have been successful for generation of optical pulses with duration as short as 42 fs [8]. Higher repetition rates in fiber ring-lasers can be realized by employing active mode locking [9].

Optical pulse sources based on semiconductor technology are described in [10-12]. Such devices often contain two elements: a gain medium that is responsible for the amplification of the pulse and a saturable absorber that is responsible for the compression of the pulse. Such devices can operate at high repetition rates, which make them interesting for applications in telecommunication systems.

In this paper, we report on the realization of a passively mode-locked ring-laser based on a semiconductor optical amplifier (SOA) and a linear polarizer. Essential in our system is a polarization switch based on SOA nonlinearities [13]. Self-polarization rotation in the SOA followed by polarization projection is employed as the mode-locking mechanism [14]. In this way, the SOA not only acts as an amplifying element, but also provides the nonlinearities needed for pulse compression. We demonstrate a stable low-power train of pulses with duration below 800 fs at a repetition rate of 14 MHz. No dispersion compensating element is implemented in the ring cavity.

Employing nonlinear polarization rotation for pulse compression avoids the use of a saturable absorber and thus simplifies the laser configuration. This concept might offer advantages for the realization of integrated light sources operating at high repetition rates. In integrated mode-locked light sources, the recovery-time of both the amplifying element as well as the recovery-time of the saturable absorber play important roles in the pulse narrowing. In the present scheme, the role of saturable absorber is played by the combination of nonlinear phase-shift and polarization discriminating element. The former is an ultrafast process while the latter is nearly instantaneous.

2. Concept

A schematic of our mode-locked laser is depicted in Fig. 1. One task of the SOA is to act as a laser gain medium. The second functionality of the SOA is to introduce nonlinear polarization rotation, similar as described in [13]. The isolator allows the light to propagate in one direction only and the filter selects the central wavelength. A small fraction of the light is monitored by using a 90/10 output coupler.

Self-polarization rotation plays an essential role in this mode-locking concept [14]. Due to the fact that the leading edge of the pulse saturates the SOA, the gain experienced by the leading edge of the pulse differs from the gain experienced by the trailing edge. Since, the SOA gain saturation is polarization dependent, the refractive index saturation is also polarization dependent. The polarization controller PC1 adjusts the polarization of the SOA input light to be approximately 45° with respect to the orientation of the semiconductor layers. As the pulse propagates through the SOA, it experiences a change of polarization due to different gain and optical path length for the transverse electric (TE) and transverse magnetic (TM) components. Most of this polarization change is a linear effect, but for a pulse with large amplitude also a nonlinear contribution to the polarization change occurs due to

polarization-dependent saturation. This latter effect is directly coupled to the spectral-hole burning dynamics and leads to the leading edge of the pulse experiencing different and stronger polarization rotation than the trailing edge. Hence, by properly aligning the polarization controller PC2 with the orientation of the polarizing beam splitter (PBS), one can set the system such that only the leading and trailing edges of the pulse are blocked by the PBS. In this way, the nonlinear polarization switch acts not only as an amplifying element, but also as a pulse compressive element.

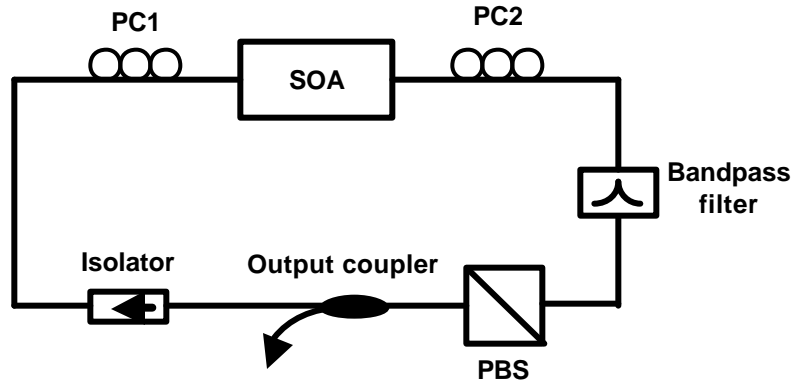


Fig. 1: Experimental set-up of the SOA based ring-laser. SOA: semiconductor optical amplifier, PC1 and PC2: polarization controllers, PBS: polarizing beam-splitter.

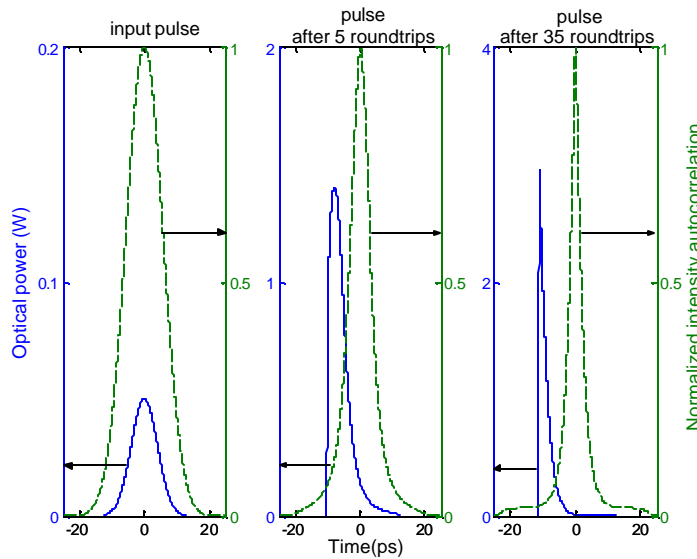


Fig. 2: Numerical simulation of the pulse evolution. The solid curves represent the powers and the dashed curves are corresponding normalized intensity auto-correlations. Initially the pulse had duration of 10 ps and the pulse energy was 0.5 pJ. After 5 roundtrips the pulse duration has decreased to 5.3 ps. The pulse energy has increased to 8.9 pJ. After 35 roundtrips the pulse has shortened further to 1.7 ps and the pulse build-up has stabilized.

A numerical simulation that illustrates the pulse formation is shown in Fig. 2. We have modeled the polarization dependent nonlinear gain and index dynamics in the SOA using the

model presented in [15]. The nonlinear polarization switch is modeled in the fashion of [16]. We numerically investigate the pulse build-up using a pulse with duration of 10 ps (full width at half maximum, FWHM) and a pulse energy of 0.5 pJ. Figure 2 shows the evolution of the pulse as a function of the roundtrip time. The filter in the system is modeled by a Lorentzian transfer function with a width of 8 nm (FWHM) at a central wavelength of 1552 nm. It is clearly visible in Fig. 2 how the pulse builds up. After 5 roundtrips the pulse has narrowed to 5.3 ps and the pulse energy has increased to 8.9 pJ. After 35 roundtrips, the pulse has stabilized at a width of 1.7 ps and the pulse energy has become 8.86 pJ. The corresponding optical spectra are presented in Fig. 3. Initially, the spectral-width is 0.35 nm (44 GHz). After 5 roundtrips the spectral-width of the pulse has increased to 1.6 nm (0.2 THz), and after 35 roundtrips the compression of the pulse stops, the pulsewidth becomes stable. At this point the time-bandwidth product is 0.68.

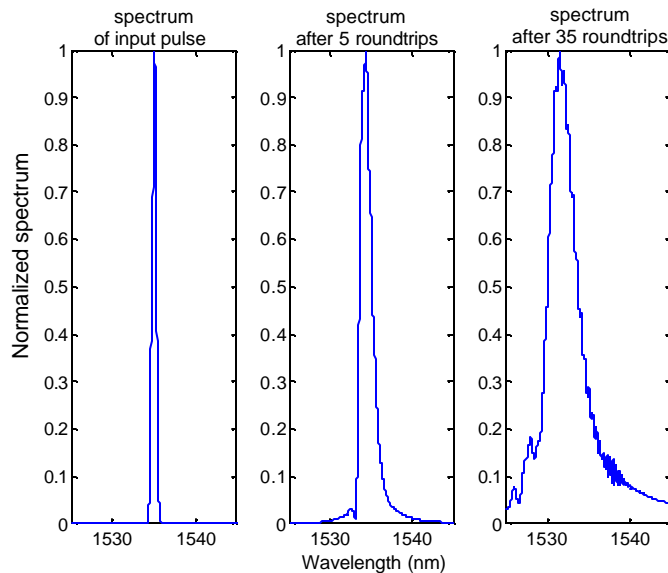


Fig. 3: The optical spectra corresponding to Fig. 2. Initially the spectral-width was 44 GHz. After 5 roundtrips, the spectral-width has increased to 0.2 THz, and after 35 roundtrips the spectral-width has become 0.4 THz.

In our scheme, the pulse compression is realized by the combination of nonlinear polarization rotation in the SOA and the subsequent cutting away of the (weak) pulse part that suffered linear polarization rotation only. The required nonlinear polarization rotation is realized thanks to the combination of a nonzero value of the self-phase modulation parameter α and sufficient large pulse amplitude, such that the smaller the value of α is, the larger pulse amplitude is needed for successful mode-locked operation. This explains why the mode-locking does not start by itself through build-up from noise, but requires a sufficiently large initial pulse. It is indeed observed that the mode-locking can start from noise, leading to a CW-type steady state or even an off-state, while a strong perturbation is needed in order to get it into mode-locked operation. In practice, mode-locking operation can be realized by a polarization change through tuning PC1 (or PC2), by changing the injection current of the SOA, or by injecting a strong external pulse inside the cavity. This is all confirmed by a detailed theoretical description of our device operation, which will be published in a separate paper [17].

3. Experimental results

The mode-locked ring-laser is implemented using commercially available fiber-pigtailed components. The SOA was manufactured by JDS-Uniphase and has a strained bulk active region of 800 μm . The polarizing beam splitter has an extinction ratio of 20 dB and the tunable filter has a FWHM-bandwidth of 13 nm. The total cavity length of the commercially available fiber-pigtailed components is in the order of 20 m.

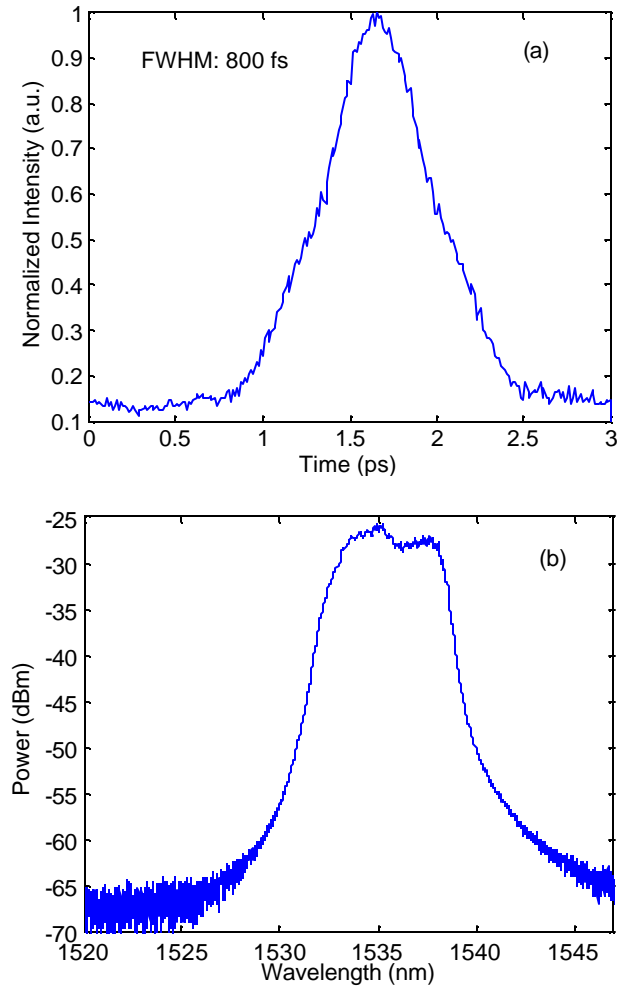


Fig. 4: Autocorrelation trace (a) and the spectrum (b) of the pulses. Assuming a sech^2 pulse shape, the pulse width (FWHM) is about 800 fs.

Figure 4(a) shows the autocorrelation trace of the pulses that output of the ring when the injection current is 276 mA. We observe a repetitive pulse train with a repetition rate of 14.15 MHz. The pulses have a duration of 800 fs (FWHM), assuming a sech^2 pulse shape. Increasing the SOA injection current leads to a higher output power, but we observed mode-locking only when the SOA injection current was greater than 160 mA. For each injection current, the pulse width and the intensity of the output beam can be optimized by tuning of the polarization controllers. Figure 4(b) shows the measured optical spectrum of the output signal. The FWHM-bandwidth of the output signal is greater than 5 nm (0.62 THz). This indicates a

time-bandwidth product of 0.48, which means that the pulse that outputs the laser is nearly transform limited. We observed an average power in the cavity of about 0.2 mW.

It follows from Fig. 4(b) that the noise level was 35 dB lower than the signal level. Since we did not implement a stability mechanism in the cavity, some instabilities may occur due to temperature dependent polarization mode dispersion (PMD) and temperature dependent variations of the optical path-length in the cavity. We did not observe mode-hopping; the spectrum depicted in Fig. 4(b) is very stable in time. Once mode-locked operation was realized, the system remained stable for hours.

4. Conclusions

We have demonstrated the generation of sub-picosecond (800 fs) optical pulses using a SOA-based nonlinear polarization switch in a ring resonator. Passive mode-locking is achieved for the first time by the simultaneous use of two SOA functionalities, saturable amplification and nonlinear polarization rotation, in combination with a linear polarizer. Our experiments indicate that low-power, sub-picosecond pulses can be obtained using a simple SOA-based ring-laser configuration. Simulation results have been presented for the pulse compression due to the nonlinear polarization rotation in the SOA. These results are in good agreement with the experimental results.

We have been conservative in our estimation of the observed pulse-width. In our estimation, we did not compensate for the pulse broadening in the fiber pigtailed that connect the laser output with the auto-correlator. Numerical simulations reveal that pulses generated by this system may be as short as 400 fs.

The concept is interesting for applications in telecommunication systems that are operated by ultrashort optical pulses at low optical power. For applications in telecommunication, the system should allow photonic integration on a single chip. However, the realization of compact photonic integrated polarizers and polarization controllers is still a nontrivial achievement and a challenging area of research. It should be noted in this respect that it may be well possible to realize a similar system as presented in this paper based on self-phase modulation instead of self-polarization rotation. In that case, the nonlinear polarization switch can be replaced by a (Mach-Zehnder) interferometer so that the system allows photonic integration.

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