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Colliding-pulse harmonically mode-locked fiber laser

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Abstract. A Fabry–Perot semiconductor saturable absorber has been implemented in a colliding pulse configuration for stabilizing a harmonically mode-locked fiber laser. An environmentally stable CPM design is shown to enhance supermode suppression.

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A mode-locking technique which relies upon the use of the nonlinear reflectivity of a semiconductor Fabry–Perot saturable absorber (FPSA) is attractive because it can be designed to operate in a wide spectral range, has ultrafast nonlinear dynamics and relatively large nonlinear reflectivity changes, and eliminates the need for critical cavity alignment. Ultrashort optical pulses have been produced with this technique using different semiconductor structures and mirror designs [1, 2].

For achieving higher repetition rates, the laser is operated at a multiple of the fundamental repetition rate. To overcome the tendency for supermode competition, pulse dropouts and noise in harmonically mode-locked lasers several techniques have been proposed. Recently, it was suggested that phase effects in semiconductor saturable absorbers can lead to pulse repulsion, which provides, in turn, self-stabilization of the pulse repetition rate [3]. However, pulse self-organization provided by saturable absorber is sensitive to absorber lifetime and uniform pulse distribution was not observed for absorbers with a carrier lifetime of less than 500 ps [4]. Stabilization of an active harmonically mode-locked fiber laser was also observed using the peak-intensity limiting action of two-photon absorption [5].

In this paper we demonstrate harmonic pulse stabilization in a colliding-pulse mode-locked (CPM) fiber laser based on the use of a multiple-quantum-well semiconductor structure as a saturable absorber. With this cavity design repetition rate stabilization is strongly enhanced, resulting in reliable harmonic mode-locked operation.

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1 Experimental

The mode-locked cavity of the erbium fiber laser is arranged as shown in Fig. 1. We employed a laser configuration with three Faraday rotators which allowed us to design a low-loss CPM cavity while still preserving environmental stability. A Faraday rotator FR1 and a Faraday rotator mirror were used for fiber birefringence compensation. A Faraday rotator FR2 directs the light reflected from the FPSA to a high-reflection (HR) mirror. The light returning from the HR mirror to the FPSA is in a polarization state orthogonal to that of the entering light. On again passing through the FR2, the light is returned to a polarizing beam splitter in the initial polarization state. In such a cavity, the stable harmonically mode-locked operation was achieved when two orthogonally polarized pulses collide in the saturable absorber. The required time delay between pulses colliding in the saturable absorber was obtained by translation of the high-reflection mirror. We have also successfully used a modified setup in which the Faraday rotator FR2 was replaced by the quarter-wave retarder. This configuration allowed changing of the ratio of the amplitudes of the colliding pulse by tuning the wave-plate.

The fiber cavity was constructed of a Corning SMF28 fiber and 2.2 m of erbium-doped fiber with a fundamental repetition rate of ~ 10 MHz. The erbium-doped fiber had an unpumped loss of 34 dB/m at 1.535 μm, a core diameter of 3.5 μm and a numerical aperture NA = 0.22. The laser was pumped with a single-mode laser diode, which provided

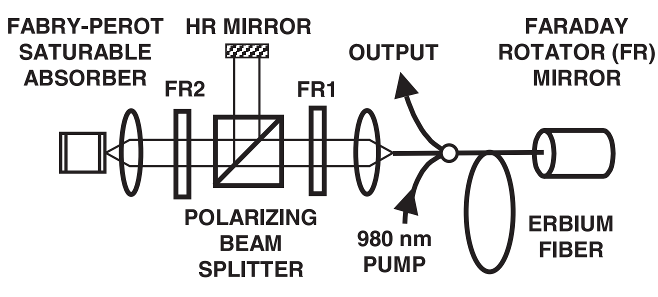

Fig. 1. Setup of the colliding pulse harmonically mode-locked fiber laser

a power of 120 mW at 980 nm. The output from the laser was taken via a 10% coupler. The fiber end was angle-cleaved to eliminate the influence of the Fresnel reflection. An AR-coated aspheric lens with a focal length of 2.0 mm was used to focus the beam onto the absorber. In this study we did not aim to get shorter pulses; therefore, no attempts were made to compensate for the cavity dispersion.

The saturable absorber region consists of six 6-nm-thick $Ga_{0.245}In_{0.755}As_{0.7}P_{0.3}$ quantum wells separated by 20-nm-thick $Ga_{0.245}In_{0.755}As_{0.49}P_{0.51}$ barriers grown by molecular beam epitaxy on an InP substrate. For FPSA we used a low-finesse Fabry–Perot metal-based design similar to the one described in [6]. A quantum well absorber is positioned within an InP spacer layer, which is transparent for the laser wavelength. The gold film was deposited as the bottom reflector. To improve the reflectivity of the metal-coated structure we inserted a SiO_2 layer between the metal and the semiconductor [6]. A dielectric coating was deposited onto the structure providing the top reflector with a reflectivity of 10%. Finally, the FPSA was glued onto a glass substrate.

An important feature of the CPM laser is that the fluence incident on the absorber should be adjusted to produce the optimal nonlinear reflectivity required for stable mode-locking when the two pulses collide in the saturable absorber. It is also clear that in this laser, the CPM action doubles the effective saturation efficiency for the colliding pulses as compared to the two pulses hitting the absorber independently. Although an FPSA with a specific saturation fluence could be designed by exploiting different top reflectors [1], in this study we used focusing optics to adjust the light intensity on the FPSA. Proper adjustment of the spot size on the FPSA to control the incident fluence and tuning the pulse delay to the fraction of the cavity round-trip time provided a stabilization mechanism through colliding-pulse mode-locking.

2 Results and discussion

Figure 2 shows oscilloscope traces of the regularly spaced pulses for different pump powers. The pump power varies between 50 and 110 mW. Increasing the pump power results in a systematic and near linear increase in the number of pulses, as shown in Fig. 3. By increasing the pump power to 110 mW, one can obtain a filled pulse pattern with one pulse in every time slot of the 20th harmonic of the fundamental repetition rate. Decreasing the pump power causes a decrease in the number of pulses; however, we have observed that the pulses were always organized in stable pulse streams (packets) with regular intervals between pulses corresponding to a harmonic repetition rate. This observation also confirms the CPM mechanism of pulse formation and stabilization. To ensure further that CPM-assisted mechanism is crucial for harmonic stabilization, we have studied the stabilization of different harmonics by translating the HR mirror to obtain corresponding pulse delays. Experiments show that the pulse train becomes equally spaced with a repetition rate always determined by the pulse delay in the auxiliary subcavity. This result clearly demonstrates the timing effect of the CPM cavity design. In these experiments, the highest repetition rate (400 MHz) was limited exclusively by the physical dimensions of the components (bulk optics and mounts) used to build the laser cavity.

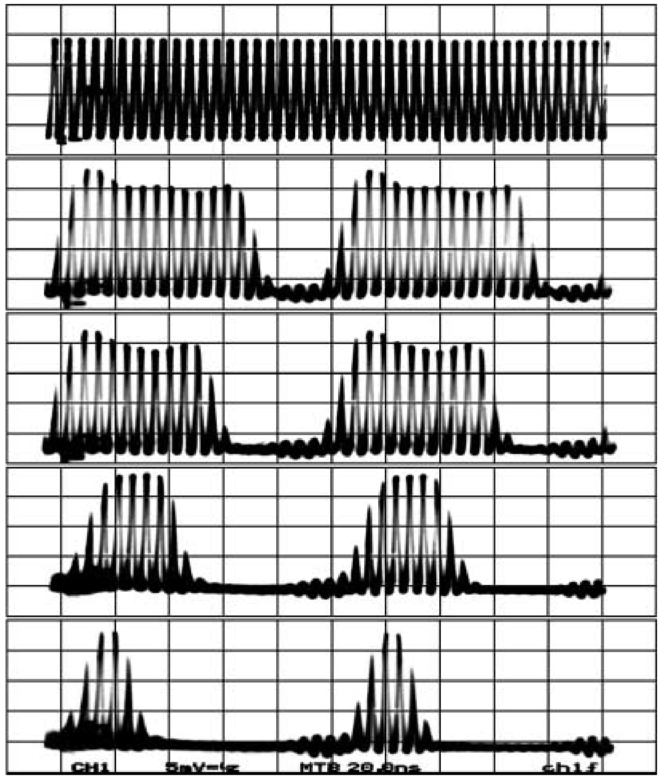

Fig. 2. Oscilloscope traces of the pulse train with various pump powers. *Horizontal scale:* 20 ns/div

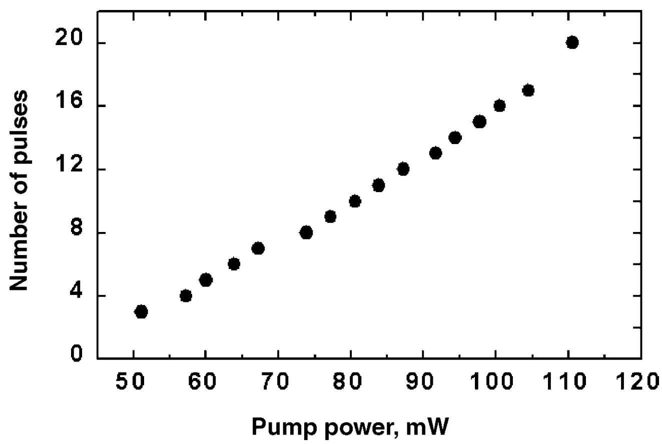

Fig. 3. Number of circulating pulses versus pump power

Figures 4 and 5 show oscilloscope trace of the filled pulse pattern with regularly spaced pulses and the corresponding RF spectrum measured with a fast photodiode. The average output power for this mode-locked regime was 3 mW. As one can see, nearly all the energy is contained in the 200-MHz mode and its harmonics demonstrating the suppression of the lower cavity harmonics by at least about 50 dB. Only the 200-MHz component is visible, which indicates uniform harmonic mode locking with a highly periodic pulse train. Since the suppression of the unwanted harmonics in the RF spectrum deteriorates to 37 dB with one pulse dropout per round trip [7], this laser is free of pulse dropouts and has a highly stable supermode.

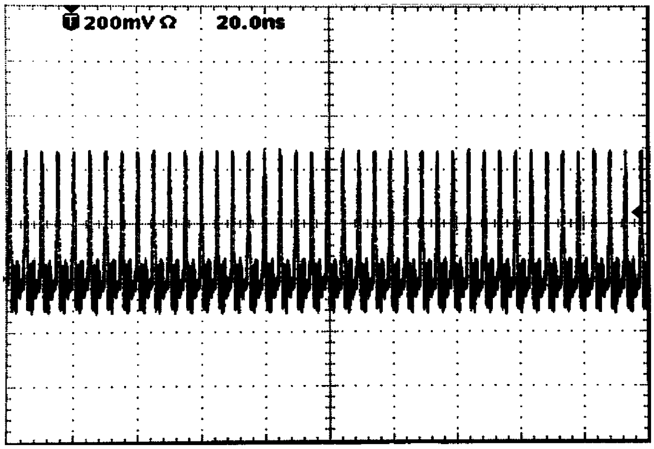

Fig. 4. Oscilloscope trace of the 200-MHz pulse train. *Horizontal scale:* 20 ns/div

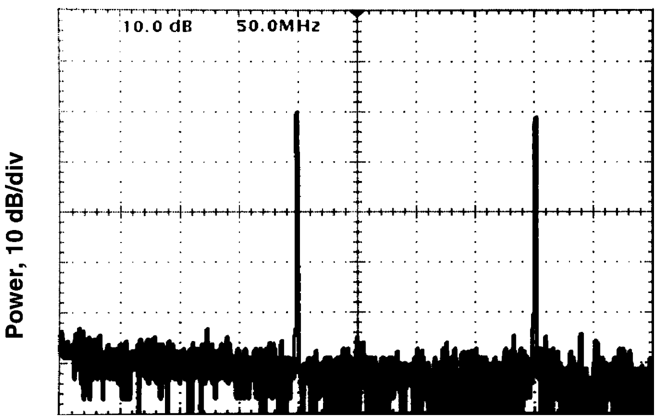

Fig. 5. Microwave power spectrum of the signal from the fast photodiode. *Horizontal scale:* 50 MHz/div, *vertical scale:* 10 dB/div

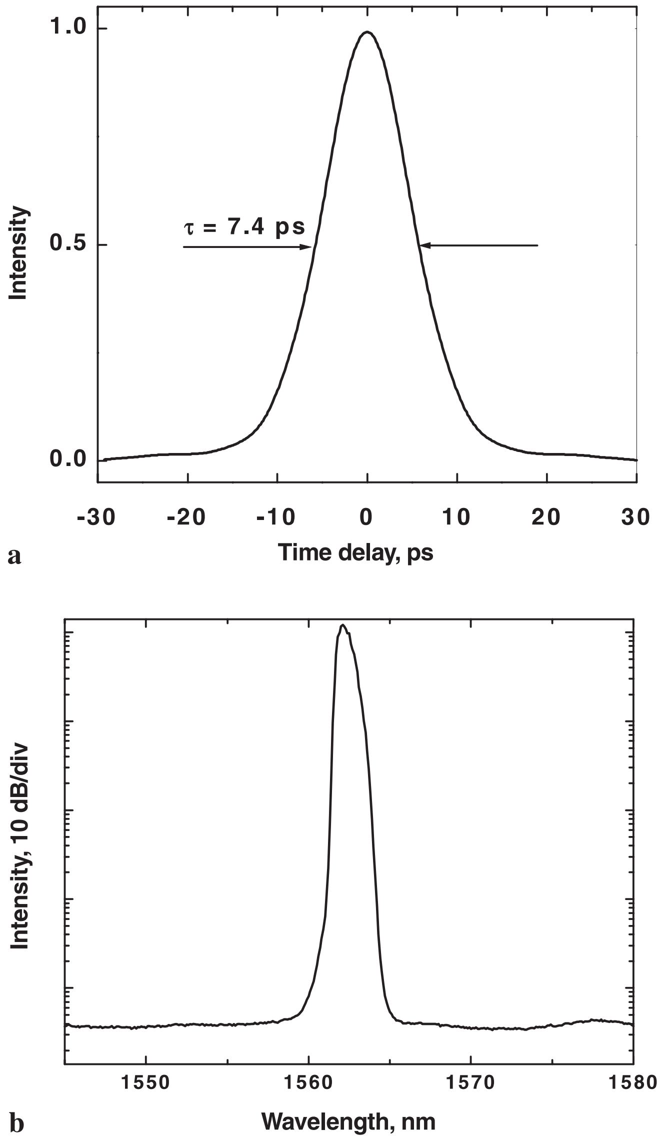

Fig. 6. **a** Autocorrelation trace of mode-locked pulse train, and **b** corresponding optical spectrum

It should also be mentioned that our setup provides multiple polarization clean-up of colliding beams per cavity round trip. However, to further reduce the leakage of unwanted polarization signals and to avoid coupled-cavity effects that may cause harmonic mode-locking, we have inserted two additional polarizers, one into the sub-cavity and another into the main cavity at the input of the polarizing beam splitter. We estimate the suppression of the leakage signal to be higher than 60 dB. Still, a similar suppression ratio of the cavity fundamentals was observed. This confirms that the coupled-cavity effect cannot be the mechanism for stabilization of harmonic mode-locking. Therefore, our observations are believed to hold only for the CPM-assisted action of the saturable absorber.

We also note that this suppression was never observed without implementation of the CPM configuration in the linear-cavity geometry. It was found that small pump fluctuations (~ 2 mW) did not lead to changes in the number of pulses, resulting only in minor variation of the pulse peak power. This demonstrates that CPM-assisted harmonic stabilization provides strong resistance against random walk of the multiple pulses in time. Although, solitonic pulse-shaping effects, e.g. resonant sidebands, were occasionally observed, it appears that the saturable absorber was dominantly responsible for the steady-state pulse shaping in the cavity.

At this stage it would be relevant to point out another method of stabilization of passive harmonic mode locking, which is similar to the stabilization technique proposed in this study. Recently, generation of an equally spaced soliton pulse train from a harmonic mode-locked fiber laser has been achieved by optical modulation of saturable absorption [8]. It was shown that the time ordering can be dramatically improved by pumping the saturable absorber above the bandgap with an external laser which is amplitude modulated at a high harmonic of the fundamental repetition rate. The method resulted in 35-dB suppression of the undesired harmonic modes of a 1.244 GHz – pulse train. Thus, it is believed that optical timing, either external or internal (i.e. using the CPM approach), has the potential to generate jitter-free pulse trains at high repetition rates.

The autocorrelation trace of pulses and the corresponding optical spectrum are displayed in Fig. 6a and b, respectively. The measured value of the time–bandwidth product suggests that some chirp on the pulses may be present. However, we could keep the time–bandwidth product of the output pulses to $\Delta\nu\tau < 0.43$, assuming a sech^2 profile. It was also found that the pulse shape remains unchanged with varying pump power. Therefore, the pulsewidth does not depend on the filling of the pulse sequence with the pulses. It is important to mention that unlike the coupled-cavity mode-locking, using an auxiliary cavity interferometrically coupled to the laser cavity, CPM does not exploit interferometric pulse interaction; therefore, the requirement for subcavity length matching is highly relaxed. Indeed, we have observed stable mode-locking with detunings of hundreds of micrometers. Combined with a birefringence compensated design, the laser was insensitive to environmentally induced cavity variations.

3 Conclusion

In summary, a Fabry–Perot semiconductor saturable absorber was implemented in a colliding pulse configuration for stabilizing a harmonically mode-locked fiber laser. In a new CPM setup, the FPSA performs a dual function: pulse shaping and stabilization of the harmonically mode-locked pulse train. We have observed that supermode suppression is enhanced considerably using FPSA in a colliding pulse configuration. This cavity design should eventually permit the generation of the pulse trains at gigahertz repetition rates.

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