CMP7 **3:00 pm**

Dispersion-mode pulsed laser

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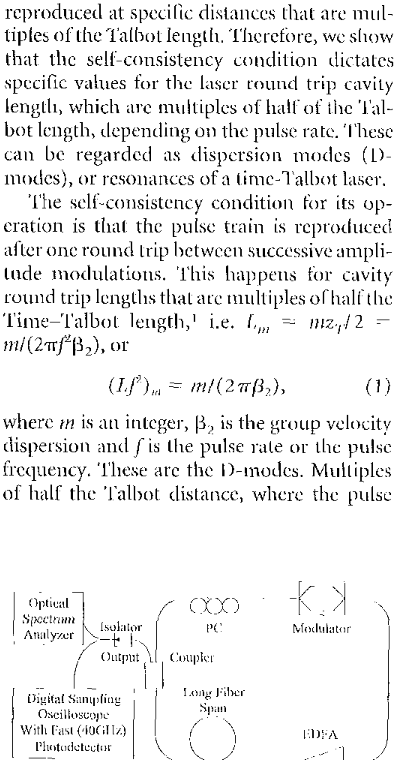
In this work we show a special pulsed laser operation in which strong dispersion imposes conditions on the laser cavity length and the pulse rate, raising a new self consistency condition and dispersion modes in such lasers. We also present an experimental demonstration of such a laser with a long fiber cavity.

Light pulses that propagate along dispersive media, change their shapes and spreads in a similar way that spatially confined waves, such as Gaussian beams, diffract and spread as they propagate in free space. Therefore, if we wish to construct an amplitude modulated laser that has a strong accumulated dispersion in its cavity, pulse oscillation will generally be problematic due to the lack of self-consistency condition for the dispersed pulses that don't reproduce themselves after one or more round trips in the resonator. This can cause a very lossy and complex pulse operation. Thus, for example, a mode-locked operation of a long fiber laser, with significant dispersion, is not likely to produce stable and good quality short pulse trains. Here we show that operation of such lasers is possible in a specific regime with a self-imaging pulse train condition. The pulse train self-imaging property is related to the spatial Talbot effect,[1] where periodic spatial patterns that propagate in free space, are self reproduced at specific distances that are multiples of the Talbot length. Therefore, we show that the self-consistency condition dictates specific values for the laser round trip cavity length, which are multiples of half of the Talbot length, depending on the pulse rate. These can be regarded as dispersion modes (D-modes), or resonances of a time-Talbot laser.

The self-consistency condition for its operation is that the pulse train is reproduced after one round trip between successive amplitude modulations. This happens for cavity round trip lengths that are multiples of half the Time–Talbot length,[1] i.e. $L_m = mz_T/2 = m/(2\pi f^2\beta_2)$, or

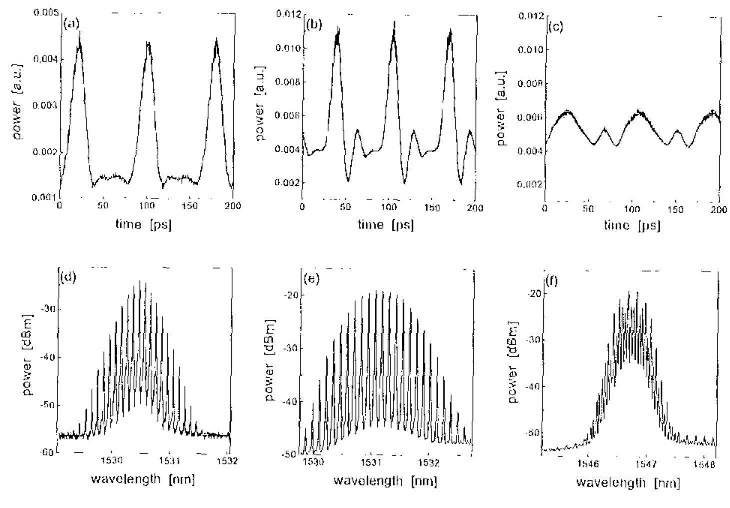
$$(Lf^2)_m = m/(2\pi\beta_2), \qquad (1)$$

where m is an integer, β_2 is the group velocity dispersion and f is the pulse rate or the pulse frequency. These are the D-modes. Multiples of half the Talbot distance, where the pulse trains are reproduced with a π phase shift, are sufficient for that requirement, since the phase can be compensated by propagation of half a wavelength. Less stringent cavity lengths may allow operation of the laser, especially for other rational fractions of the Talbot length, (where pulses can be retrieved after several cycles), but more complex and less stable pulse trains, as well as higher losses, and higher laser thresholds, are expected.



CMP7 Fig. 1. The experimental configuration for the pulsed laser with a fiber ring cavity, erbium-doped fiber amplifier and amplitude $LiNbO_3$ modulator.

The experimental laser configuration is shown in Fig. 1. It is a fiber laser with erbium-doped fiber amplifier and a $LiNbO_3$ amplitude modulator for mode-locking in the cavity. We used two types of fibers. A regular fiber with an anomalous dispersion of $\beta_2 \approx -20\ ps^2/km$, with a length of 50 km. The corresponding pulse rate for the first D-mode is $f = 12.59$ GHz. The second fiber had a positive and high dispersion $\beta_2 \approx +130\ ps^2/km$, that enabled shorter laser operation. Here the cavity length we used was $L = z_T/2 = 5.1\ km$, and the pulse rate for the first D-mode is $f = 15.36$ GHz. This fiber also ensured the lack of soliton formation in the pulsed laser operation.



CMP7 Fig. 2. The output signal from the time-Talbot lasers: (a) Operation at the first D-mode, with the first fiber ($\beta_2 = -20.1\ ps^2/km$, $L = L_1 = 50\ km$, $f = 12.59\ GHz$.) (b) Operation at a first D-mode, with the second fiber ($\beta_2 = +132\ ps^2/km$ $L = L_1 = 5.1\ km$, $f = 15.36\ GHz$. (c) Operation not at a D-mode. (The same fiber as in (b), $f = 12.00\ GHz$.) (d)–(f) Spectra of the output signal from the lasers corresponding to the (a)–(c) respectively.

The laser light output, the pulse trains and the spectra, are shown in Fig. 2. We see the behavior when the modulation frequency is tuned to the first D-mode of the above two fiber lasers, $f = 12.59\ GHz$, [Figs. 2(a), 2(d)] and $f = 15.36\ GHz$ [Figs. 2(b), 2(e)]. For other frequencies we obtained for the laser output, low quality pulses and more complex spectra.

For proper operation of a dispersive pulsed laser as a mode-locked laser, the modulation frequency has to match both, the pulse train frequency of a D-mode, as well as, a high harmonic of the regular mode-locking cavity resonance. Then, the pulse train perfectly reaches the successive modulations. Matching the D-mode requirement, is equivalent to the case where the free space propagation effect due to dispersion, shrinks to zero. This corresponds to a resonance state. In a more general scope, for a non D-mode-resonance operation, the round trip propagation in the cavity between two successive modulations, adds to the frequency components of the pulse train arbitrary phases. It leads to a different regime that was shown to exhibit a special localization effect in the side-band frequency domain, as we showed in a former work.[2] In such mode-locked lasers, the spectrum is confined, and a short pulse formation is limited.

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CMP8 **3:15 pm**

Passive harmonic mode-locked soliton fiber laser stabilized using an optically pumped saturable Bragg reflector

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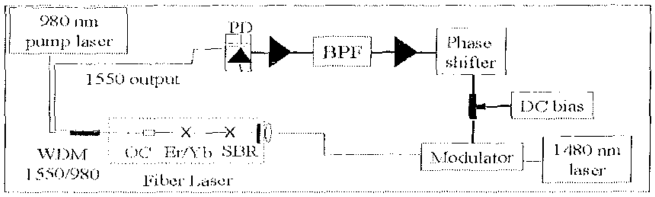
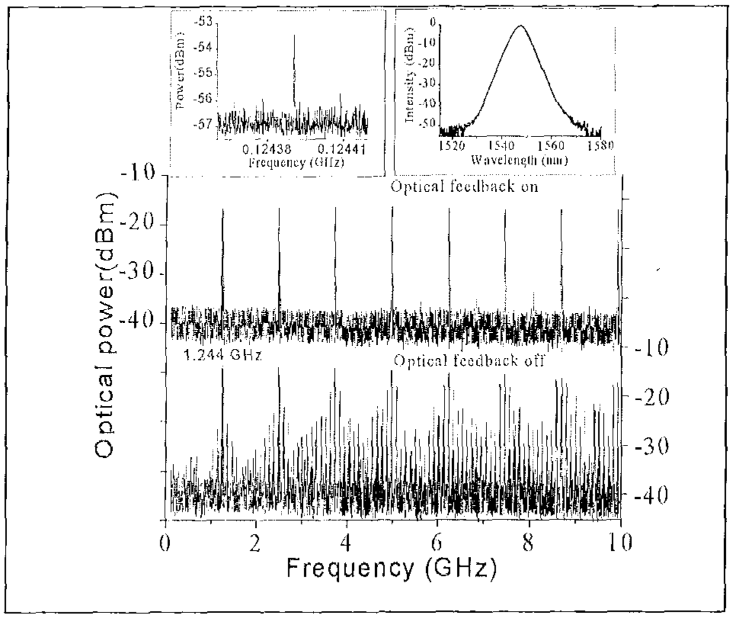
The development of ultrashort optical pulse sources with gigahertz repetition rates is a key element in the future of high-speed TDM and WDM networks.[1] Much attention has been given to actively mode-locked fiber lasers capable of producing picosecond pulses at high repetition rates. However, these lasers tend to have long and complex cavities operating with thousands of pulses per round trip. Passively mode-locked lasers, in contrast, have simple and compact cavities capable of generating sub-picosecond pulses at very high fundamental rates. In particular, Er/Yb fiber lasers mode-locked with saturable Bragg reflectors (SBR) have high fundamental rates (~100–300 MHz) and when operated in the soliton regime can run with up to 24 pulses per round trip producing multigigahertz pulse trains.[2] Unfortunately, the mechanism for self-stabilization of the pulse spacing is very weak (gain depletion and recovery in Er represents a modulation of $O(10^{-7})$)[3] resulting in soliton trains, which are not equally spaced.

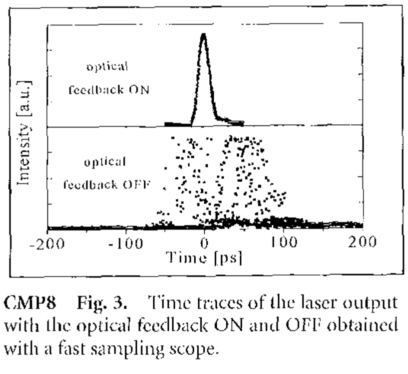


CMP8 **Fig. 1.** Diagram of the fiber laser and optical feedback.



CMP8 **Fig. 2.** RF spectra of the laser output with the optical feedback ON and OFF. Left inset: shows the suppression of the fundamental mode of the cavity by ~40 dB. Right inset: Laser spectrum.

In this work we present a new method for generating an equally spaced soliton pulse train from a harmonic passively mode-locked Er/Yb fiber laser. We modulate the saturable loss of the SBR's InGaAs/InP quantum wells by optically pumping it above the bandgap with an external laser amplitude-modulated at a high harmonic of the fundamental repetition rate. This results in a 40-dB suppression of the undesired harmonic modes. Pump-probe measurements show that the reflectivity of the SBR can be changed by 10^{-4}–10^{-5} producing a modulation in the loss of the cavity, which is more than two orders of magnitude larger than that caused by the self-stabilization mechanism. We implement our approach in a 103.6 MHz repetition rate fiber laser running in the 12th harmonic (1.244 GHz) producing ~500-fs soliton pulses. The diagram of the cavity and optical feedback is shown in Fig. 1. The pulse train is measured by a fast photodiode generating an electrical signal, which is amplified and filtered by a narrow band-pass filter (BPF) tuned to 2.488 GHz (24th harmonic). The electrical signal then externally modulates the intensity of a 1480-nm laser. A variable electronic delay aligns the phase of the optical feedback to the pulse train inside the laser cavity. The modulated 1480-nm laser light is then focused on the polished backside of the SBR structure.



CMP8 **Fig. 3.** Time traces of the laser output with the optical feedback ON and OFF obtained with a fast sampling scope.

Figure 2 shows the RF spectrum of the laser output with the optical feedback on and off. Suppression of the unwanted harmonics is ~40 dB in the optical power (see left inset). This is obtained without compromising the spectral characteristics of the soliton pulses created by this laser (see right inset) and using only standard telecommunications components. The dramatic effect of the optical feedback on the inter-pulse timing can be observed more clearly in Fig. 3. Without optical feedback the inter-pulse spacing can vary by more than 30 ps from pulse to pulse, however, the laser train becomes equally spaced when the optical feedback is turn on. The pulse jitter was reduce below the resolution of the scope (<10 ps). Although our method greatly improves the laser performance, laser instabilities still cause major perturbations over periods longer than a couple of minutes. We believe that the use of SBR structures engineered to provide optimal modulation of the absorption by optical pumping will improve the long-term stability.

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CMQ 1:30 pm–3:00 pm
Room 104

Short-Pulse Solid-State Lasers

Brent C. Stuart, *Lawrence Livermore Natl. Lab., Presider*

CMQ1 **1:30 pm**

Femtosecond microjoule pulses with 15.8 W average power from a passively mode-locked diode-pumped Yb:YAG thin-disk laser

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Femtosecond laser sources with multi-watt average powers and multi-kW peak powers are required for many applications. We have found a power-scalable concept to achieve this kind of performance directly with a diode-pumped passively mode-locked laser oscillator, not requiring any amplification stages. The concept is based on a Yb:YAG thin-disk laser,[1] which in continuous wave (cw) operation has delivered output powers of up to ≈100 W in a diffraction-limited beam.[2] We have now for the first time to our knowledge passively mode-locked such a laser using a semiconductor saturable absorber mirror (SESAM).[3] The laser head, which had generated 20 W cw near-room-temperature produced 680-fs pulses at 1030 nm with 15.8 W of average power in two nearly transform-limited beams (time-bandwidth product 0.33). This is to our knowledge the highest average power reported for a laser oscillator (without amplifier) in the subpicosecond regime. The pulse repetition rate was 15 MHz. Pulse energies of 2 × 0.5 μJ and peak powers as high as 2 × 680 kW were achieved. Autocorrelation and optical spectrum are shown in Fig. 1. To obtain subpicosecond pulse durations, we operated the laser in the soliton mode-locked regime using a Gires–Tournois Interferometer (GTI).