Spectral and temporal control of an actively mode-locked fiber laser

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ABSTRACT

We report theoretical and experimental investigations on the spectral and temporal control of a mode-locked fiber laser using a chirped fiber Bragg grating and a loss modulator in either a undirectionnal ring cavity or a standing-wave cavity. The fiber laser generates picosecond pulses with a rapid tuning over a large bandwidth. Tuning is achieved by controlling the frequency of the applied modulation waveform. The adjustement of pulse duration between 40 - 500 ps and the rapid tuning from 1513 nm to 1588 nm are described.

Keywords: tunable lasers, mode-locked lasers, fiber lasers

1. INTRODUCTION

There are numerous mode-locked laser systems available on the market, but they are generally operated at fixed wavelength and pulse duration, with a reliable operation limited to a certain range of power level. Some laser systems can generate tunable short laser pulses (such as optical parametric oscillators), but they tend to be complex and expensive, with a limited flexibility in terms of pulse duration and power. To the best of our knowledge, there are no mode-locked sources emitting pulses in the picosecond range with adjustable duration and frequency, despite the fact that a number of applications are awaiting for such a source. Among potential applications we mention in-vivo imaging in biophotonics and tests and measurements in optical communications where more flexible, compact and reliable pulsed laser sources are needed.

In this paper, we describe an innovative scheme of picosecond fiber laser allowing for a rapid tuning over a large bandwidth and an adjustable pulse duration. First, we discuss the theory of active mode locking with a dispersive laser cavity based on the Kuizenga-Siegman model. The oscillating laser wavelength is selected by choosing the modulation frequency. We also describe an experimental setup where the dispersive element is a chirped fiber Bragg grating (CFBG). We made some numerical simulations for the pulse duration as a function of the global dispersion parameter of the laser cavity and the transmission window of the modulator. Laser tuning in a dispersive cavity is also investigated by simulations. We will discuss our experimental results for the wavelength selection and pulse duration as a function of the modulation parameters.

2. MODE LOCKING IN A DISPERSIVE CAVITY

Actively mode-locked lasers can generate short pulses whose duration depends on the length of the cavity, the round-trip losses, the gain bandwidth and the applied modulation signal. The modulation frequency f_m must be equal or a multiple of the inverse of the duration of a cavity round trip. In an all-fiber laser, the modulation frequency is given by

$$f_m = \frac{c_o}{2^* n_{fiber} L_{cavity}}, \tag{1}$$

where f_m is the modulation frequency, c_o is the velocity of light in vacuum, n_{fiber} is the group index of the fiber and L_{cavity} is the length of the cavity. For a standing-wave cavity $2^* = 2$, while for a ring cavity $2^* = 1$.

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We consider a Gaussian pulse circulating in the laser cavity. We use the Kuizenga-Siegman model where the effects of loss modulation, round-trip delay and cavity dispersion are taken into account. We assume that a medium with a very large dispersion is inserted in the cavity; that medium could be a chirped fiber Bragg grating [3,4] or a pair of diffraction gratings, amoung other possibilities [5]. The spectrum of the pulse after the dispersive element will be described by

$$\widetilde{E}_2(\omega) = (1-a)\exp\left[i\omega T_0\right]\exp\left[\frac{i}{2}B_2(\omega-\omega_o)^2\right]\exp\left[\frac{g_{ns}}{1+I_{av}/I_{sat}}z\right]\widetilde{E}_1(\omega), \tag{2}$$

where a is the loss of the cavity, T_0 represents the group delay at reference frequency ω_o and B_2 (in ps^2) the group-velocity dispersion for a complete round-trip; the third exponential on the right represents the saturated gain factor where g_{ns} is the gain coefficient at low power, I_{av} is the average intensity of the pulse, I_{sat} is the saturation intensity of the active medium and ω is the optical frequency. The effect of the modulator is modeled in the time domain as follows

$$\widetilde{E}_3(t) = \exp\left[-\frac{1}{2}\Delta_M\left(\frac{2\pi t}{\Delta t_M}\right)^2\right]\widetilde{E}_2(t), \tag{3}$$

where Δ_M is the depth of the modulation and Δt_M is the width of the modulation window. The dispersion will impart a different group delay to all laser frequencies (or wavelengths). To maintain the regime of active mode locking we must ensure that the modulation frequency verifies the self-consistency requirement:

$$\widetilde{E}_3(t) = \widetilde{E}_1(t - T_{mod}), \tag{4}$$

where T_{mod} is the modulation period. Since the group delay is frequency dependent, the periodic loss modulation has the effect of adjusting the steady-state laser frequency. Tuning of the laser frequency is achieved by tuning the modulation frequency. We can find the pulse duration if we assume steady-state operation and a Gaussian pulse shape. The duration of the pulse is then given by

$$\boxed{\Delta t_p = 2\sqrt{\ln 2}\left[\frac{2B_2}{\Delta_M}\right]^{1/4}\left[\frac{\Delta t_M}{2\pi}\right]^{1/2}}. \tag{5}$$

Let us now describe the dispersive medium which will be a CFBG in our experiments. The advantage of this element is that it creates a large dispersion and it is also compatible with fiber components; hence it allows to easily select the oscillating wavelength in a fiber laser. A CFBG is fabricated with a variation of the refractive index of the fiber core throughout its length. The variation of the index is of sinusoidal type whose period, in principle, increases linearly according to the chirp factor (see Figure 1). The Bragg wavelength $\lambda_B(z)$ determines which wavelength will be reflected by the CFBG and it is defined by:

$$\lambda_B(z) = 2n_{eff}\Lambda(z), \tag{6}$$

where n_{eff} is the effective refractive index of the core and $\Lambda(z)$ is the period of the CFBG at position z.

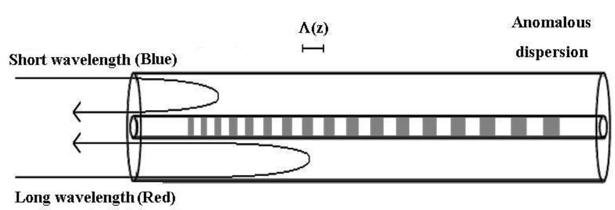

Figure 1. Chirped fiber Bragg grating

3. SPECTRAL CONTROL

Dispersion induces a wavelength-dependent round-trip delay in the cavity. This allows to select the oscillating laser wavelength by applying a suitable modulation frequency (in this case, a periodic temporal window acts as an effective spectral filter). It was already shown that it is possible to select the wavelength by mode-locking with an electroabsorption modulator [6]. Considering the period of modulation equal to the period of one round trip (T_{mod}= $T_{cav}(\omega)$) including the dispersion of the CFBG, the duration of a round trip at optical frequency ω is then given by :

$$T_{cav}(\omega) = T_{cav}(\omega_0) + B_2(\omega - \omega_0), \tag{7}$$

where $T_{cav}(\omega)$ and $T_{cav}(\omega_0)$ are the durations of a round trip in the cavity at frequencies ω and ω_0, respectively.

The dispersion induces a fractional mismatch x of the period of the modulator compared to the round-trip duration of the cavity at reference optical frequency ω_0, such that $T_{mod} = (1 + x)T_{cav}(\omega_0)$. We can deduce the oscillating laser optical frequency for different modulation frequencies from :

$$\omega = \frac{xT_{cav}(\omega_0)}{B_2(\omega_0)} + \omega_0. \tag{8}$$

Thus, the frequency of the optical pulse depends linearly on the period of the modulator. The response of CFBG is not a purely linear chirp due to the manufacturing process which introduces fluctuations in the group delay. This type of response affects the tuning of the laser signal with the modulation frequency. The fluctuations have been modeled in the simulations by adding a sinusoidal term to the Bragg grating dispersion as a function of frequency. The effect of such a term was not obvious to predict analytically since it could, in principle, allow several to frequencies oscillate in the cavity if they possess the same round-trip delay.

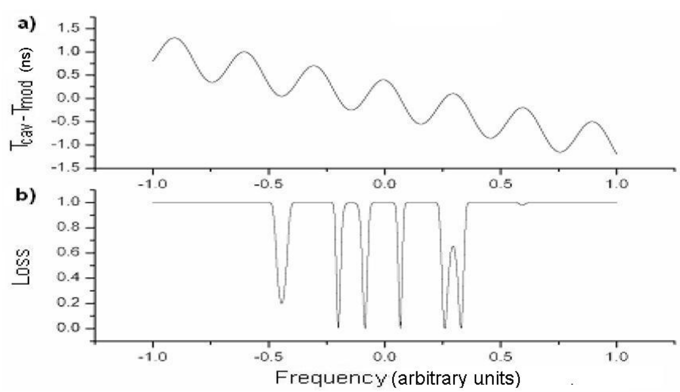

Figure 2. a) The difference between the duration of a round trip in the cavity and the period of modulation. b) The loss for different laser frequencies in the cavity as a function of T$_{mod}$ -T$_{cav}$.

If a sinusoidal ripple is introduced in the response of the CFBG, the simulations show that only one laser pulse can oscillate in the cavity, leading to more stable operation and continuous tuning if we choose a modulation window of small temporal width. We can explain this behaviour by the fact that, when the modulation window of the modulator is short, the pulse becomes shorter in time and it is made of a broader spectral content. Hence the pulse has a frequency spectrum larger than the period of the fluctuations of the CFBG response; as a result the pulse responds to the mean value of the dispersion parameter and any distortion of the CFBG is averaged out.

4. EXPERIMENTAL SETUP

The setup is shown in Figure 3. The beam of the pump diode at 980 nm is injected by the external coupler and passes through the active polarization maintaining (PM) fiber to excite an erbium-doped fiber. This active fiber provides a gain covering the 1.5 to 1.6 μm band. The circulating laser signal is filtered by the temporal window of the modulator and it will be reflected by the CFBG to introduce a dispersive delay. The dispersed signal will pass again through the modulator. It is possible to retrieve the laser signal after the coupling mirror. We also used the same basic design with a unidirectional ring cavity.

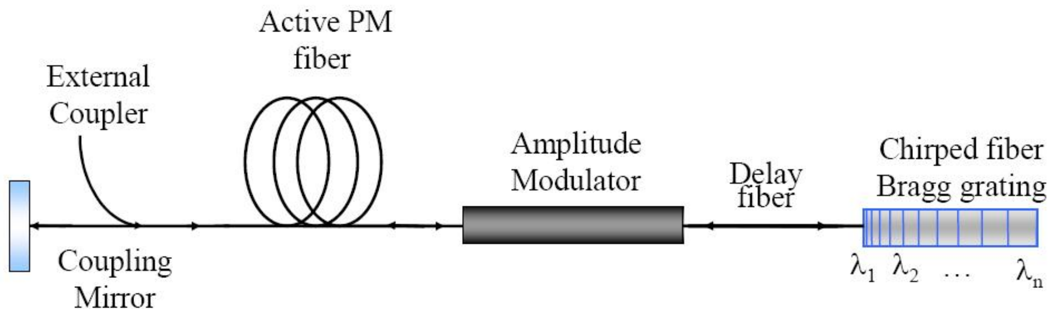

Figure 3. The setup for the temporal and spectral control of a mode-locked fiber laser is composed of a coupling mirror, an erbium-doped fiber, an amplitude modulator fed by a signal generator, a delay fiber to easily modify the duration of a cavity round trip and a highly dispersive medium, which is a chirped fiber Bragg grating.

5. NUMERICAL AND EXPERIMENTAL RESULTS

5.1 Numerical results

The simulation results were obtained for a ring cavity setup equivalent to that shown in Figure 3. We propagated a scalar signal which is the complex envelope of the laser field using the methods described in Siegman[1] and Agrawal[2] textbooks. The propagation in the fibers is simulated using the split-step Fourier method. We have evaluated the duration of the pulse as a function of two different parameters which are the dispersion of the cavity and the temporal width of the modulation window.

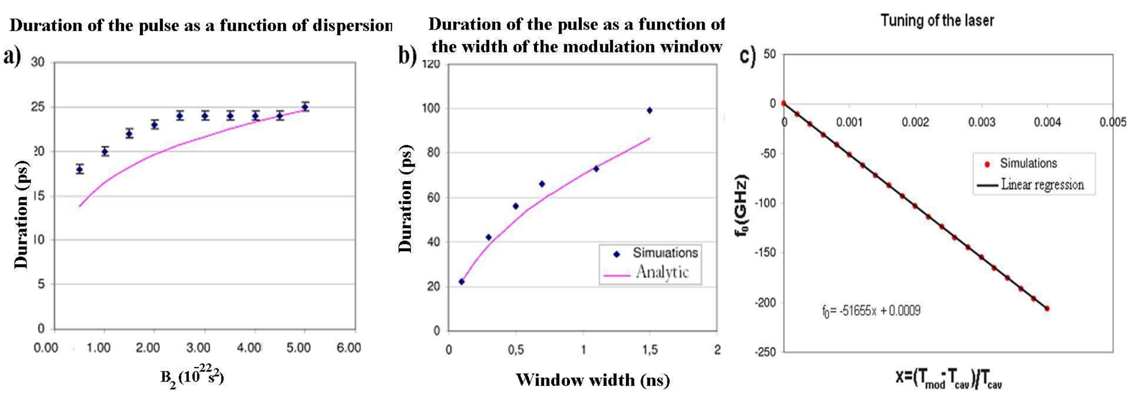

Figure 4. a) Pulse duration as a function of the absolute value of the dispersion coefficient (B_2) obtained by simulations and the Siegman-Kuizenga model. b) Influence of the width of the modulation window on the pulse duration. c) The mismatch between the modulation period and the round-trip duration allows to tune the laser wavelength.

For the simulations of the pulse duration as a function of the width of the temporal window we used a value of B_2 equal to $-1.2746 * 10^{-22} s^2$.

5.2 Experimental results

The experimental results demonstrate that it is possible to select the oscillating laser wavelength which depends on the modulation frequency through its mismatch parameter x (see Eq. (8)). The experimental results were obtained with a unidirectional ring cavity [4] whose basic repetition rate is 30 MHz.

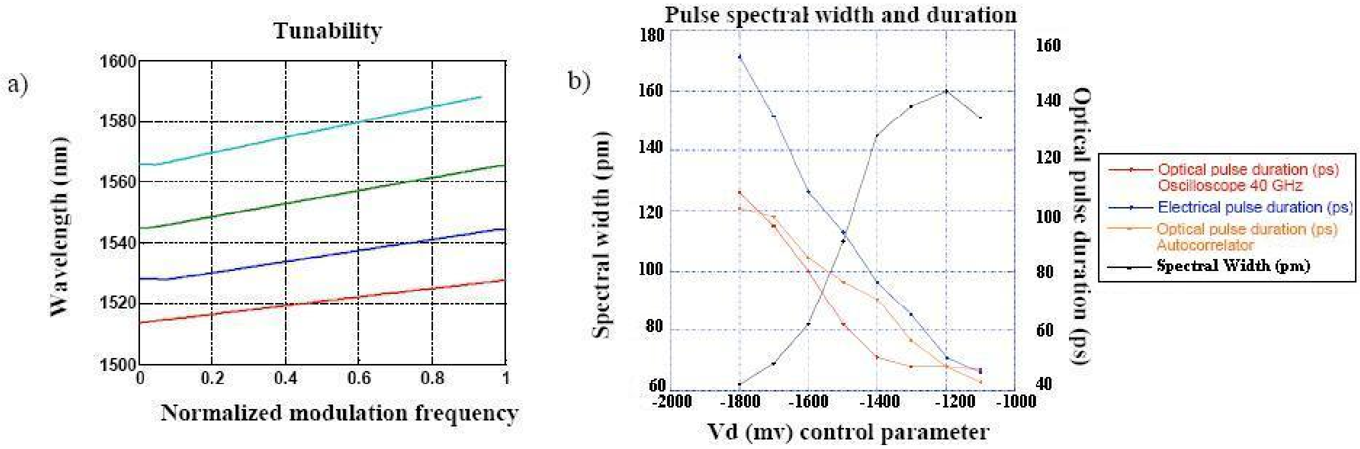

Figure 5. a) Experimental results for the wavelength selection between 1513 nm to 1588 nm as a function of normalized modulation frequency. The normalization was done for each line with the formula $(f - f_{min})/(f_{max} - f_{min})$, where f is the frequency in the range of the line, f_{min} is the minimum frequency of the line and f_{max} is the maximum frequency of the line. b) Variation of the duration and spectral width of the laser pulse as a function of the delay line voltage. The width of the modulation window is also shown.

The experimental results show the variation of the pulse duration as a function of the temporal width of the modulation window. The pulses produced in our experiment are slightly longer than in our simulations. Tuning of laser emission was achieved from 1513 nm to 1588 nm; it was found that the laser frequency varied linearly as a function of normalized modulation frequency, as we have predicted with our simulation results.

6. CONCLUSION

It was demonstrated that it is possible to choose the wavelength of laser emission by varying the modulation frequency in a dispersive cavity. It was also shown that it is possible to vary the duration of the pulses depending on the value of the round-trip dispersion and the temporal width of modulation window. The pulse duration varied between 40 and 500 ps in our experiments. It was demonstrated theoretically and experimentally that the distortion due to the response of the chirped fiber Bragg grating can be reduced by selecting an optimal width of modulation window. This leads to continuous tuning and decreases the fluctuations. An advantage of this concept is that all the laser parameters can be controlled externally and can be rapidly changed.

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