Round-Trip Time and Dispersion Optimization in a Dual-Wavelength Actively Mode-Locked Er-Doped Fiber Laser Including Nonchirped Fiber Bragg Gratings

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***Abstract*— Round-trip time and intracavity dispersion were optimized in a dual-wavelength actively mode-locked Er-doped fiber laser including two nonchirped fiber Bragg gratings. This optimization allowed to generate nearly transform-limited pulses as short as 16 and 13 ps at 1547 and 1562 nm, respectively, at a 3-GHz repetition rate only limited by the modulator bandwidth. In the experiment, the round-trip time difference between pulses at two wavelengths was adjusted using a fiber strecher. Intracavity dispersion was managed at each wavelength separately.**

***Index Terms*—Active mode-locking, dual-wavelength pulse generation, fiber Bragg gratings, fiber lasers.**

OPTICAL sources emitting high-repetition-rate picosecond pulses at two wavelengths simultaneously around 1.5 μm are attractive devices for wavelength-multiplexed communication systems, optical sensing, fiber-optic metrology and time-resolved spectroscopy. Dual-wavelength pulse generation was first demonstrated in actively mode-locked Er-doped fiber lasers by employing birefringence [1], and with chirped [2] or nonchirped fiber Bragg gratings (FBG's) [3]–[5]. Indeed, FBG's offer great flexibility for controlling the wavelength and optical bandwidth of the generated pulses. While pulses as short as a few picoseconds can be generated from actively mode-locked Er-doped fiber lasers [6], pulses of much longer duration and with high chirp have been reported until now in dual-wavelength actively mode-locked Er-doped fiber lasers using FBG's (e.g., [5]).

In this letter, we tackle the following issues related to the generation of dual-wavelength mode-locked pulses. First, due to the large homogeneous broadening of Erbium gain medium at room temperature ($\approx$10 nm), it is difficult to obtain simultaneous lasing of several wavelengths [7]. Precise adjustment of gain or loss for each wavelength is required because of the strong competition between the different wavelengths. Second, the round-trip time must be precisely tuned to the modulation frequency for each wavelength. Depending on the arrangement of the FBG's inside the laser cavity, the geometrical cavity lengths for each wavelength may be different or identical. Even in the latter case (e.g., [5]), the optical cavity lengths can be different due to chromatic dispersion and wavelength-dependent cavity birefringence. Third, intracavity dispersion should be optimized at each wavelength in order to obtain transform-limited (i.e., chirp-free) pulses. In [2], two erbium-doped fiber amplifiers (EDFA) were used in separate Fabry–Perot cavities, ended by chirped FBG's. Although there is no competition between wavelengths in this configuration, the use of two EDFA's (one for each wavelength) may be regarded as a disadvantage. In unidirectional ring cavity configuration and with only one EDFA, dual-wavelength pulse generation was obtained using two nonchirped FBG's connected to the ring either in parallel [3] or in series [4]. In [3], pulses were generated at 1532 and 1550 nm at a 50.4-MHz repetition rate, but no autocorrelation measurement of pulse duration was reported. In [4], pulses of duration $\approx$113 ps were generated at 1547 and 1557 nm, at a 1-GHz repetition rate. However, pulse spectral widths of $\approx$0.1 nm indicated that the pulses were far from transform-limited. Recently, pulses of 80-ps duration, also far from transform-limited, were generated at wavelength separations of 3.5 and 20.1 nm with a laser in which the geometrical cavity lengths were intrinsically identical for all wavelengths selected by FBG's [5]. While the issue of gain/loss balance was taken into account in all previous experiments, the issues of round-trip time and dispersion optimization have received much less attention until now. In this letter, we report on nearly transform-limited pulses with 16- and 13-ps durations at 1547 and 1562 nm, respectively, obtained by optimizing round-trip time and intracavity dispersion in a dual-wavelength actively mode-locked Er-doped fiber laser including two nonchirped FBG's.

The laser used in our experiment (Fig. 1) is similar to the one we used to demonstrate a novel stabilization method

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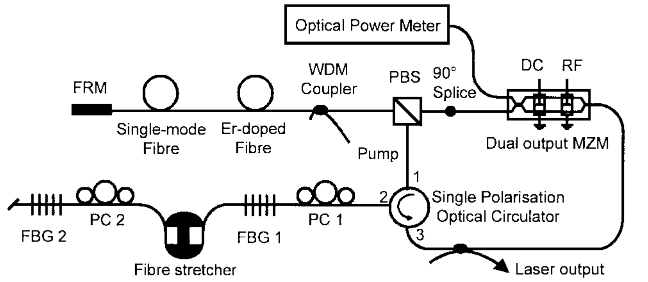


Fig. 1. Actively mode-locked Er-doped fiber laser for dual-wavelength pulse generation. FBG: Fiber Bragg grating. FRM: Faraday rotation mirror. PC: Polarization controller. PBS: Polarization beam splitter. MZM: Mach–Zehnder modulator.

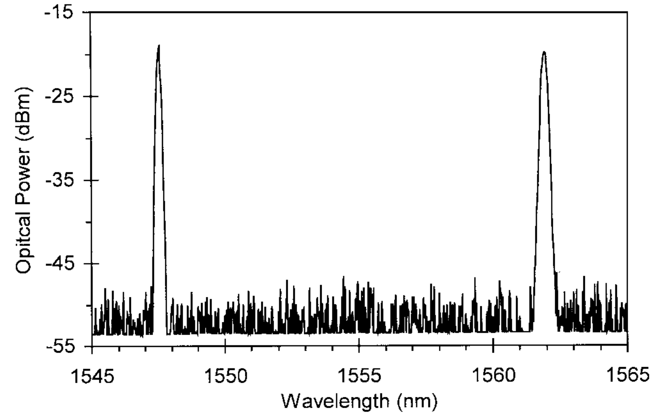


Fig. 2. Optical spectrum of the dual-wavelength mode-locked fiber laser output. Resolution: 0.1 nm.

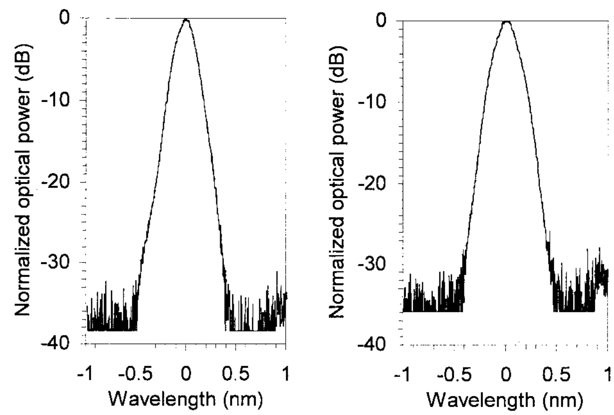
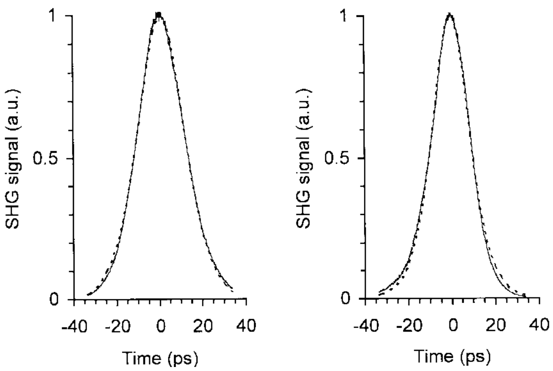


Fig. 3. Optical spectra (normalized to peak) (a) around 1547.4 nm and (b) 1562.1 nm, indicating pulse spectral widths (at −3 dB) of 0.18 and 0.21 nm, respectively.

[8]. The laser consists of three sections: 1) a unidirectional polarization-maintaining ring (Fig. 1, right); 2) a nonpolarization maintaining double-pass gain section (Fig. 1, left, upper branch); and 3) a wavelength-selective section (Fig. 1, left, lower branch). As in previous configuration [8], Sections I and II form a so-called σ-cavity that is insensitive to environmentally induced polarization fluctuations [6]. The laser output is taken from a 80:20 polarization-maintaining coupler placed in the ring. Two high-reflectivity (≈90%) nonchirped FBG's (#1 and #2) are connected to the polarization-maintaining ring through a single-polarization optical circulator which routes the light from port 1 to port 2 and then from port 2 to port 3. In addition, the circulator acts as an isolator because it blocks light transmission from port 3 to port 1. For simultaneous lasing at λ_1 and λ_2, the cavity losses at λ_1 and λ_2 must be balanced. Since the circulator acts as a polarizer, changing the settings of polarization controllers PC1 and PC2 makes the transmission from port 2 to port 3 different at λ_1 and λ_2. For mode locking, the modulation frequency (f_m) must be adjusted to be a multiple of the cavity round-trip rate $(1/\tau_r)$. In the dual-wavelength case, the round-trip rates at both λ_1 and λ_2 have to be considered. Once $1/\tau_{r,1}$ is adjusted to $f_m, 1/\tau_{r,2}$ must also be adjusted to exactly the same frequency f_m in order to achieve optimal mode locking at both λ_1 and λ_2. Consequently, a fiber stretcher is used to adjust $\tau_{r,2}$. As an index of optimal mode locking, the average interpulse noise power is measured at the second output of a dual output Mach–Zehnder modulator [8] (Fig. 1). A feedback loop to compensate for long-term drift of the cavity length [8] was not implemented in the present experiment. Although the principle of stabilization reported in [8] could be also applied here, it would require modifications of the feedback loop presented in [8]. Detection of the average optical power at the modulator second output would still provide the feedback loop with an error signal. Because both wavelengths contribute to interpulse noise, spectral components of the average optical power at λ_1 and λ_2 should be separated (e.g., by optical filters) before being used by the feedback loop [8].

In our experiment, a 20-m-long Er-doped fiber (440 ppm) was pumped by a pigtailed 980-nm laser diode (∼80 mW maximum output power). Normal dispersion of Er-doped fiber was estimated to be −50 ps/(km × nm) around 1.5 μm. The ∼3-GHz-bandwidth Mach–Zehnder modulator [8] operated in the linear part of its modulation characteristic and was driven at ∼3 GHz in order to generate a pulse train through harmonic mode locking. In a fiber laser, cavity dispersion can be changed by choosing appropriate lengths of fibers with normal or anomalous dispersion. Moreover, if total cavity dispersion is in the anomalous regime, nonlinear pulse shortening is possible through the soliton effect [6]. Total cavity dispersion was set in the anomalous dispersion regime for pulses at λ_1 and λ_2 by inserting 86 m of standard single-mode fiber (∼16 ps/(km × nm) at 1540 nm) between the Faraday rotation mirror and the Er-doped fiber. With this fiber length, total dispersion was optimal for pulses at λ_1, i.e., it led to minimal time-bandwidth product for pulses at this wavelength. To optimize dispersion independently for pulses at λ_2, 20 m of the same fiber, partly wound on the fiber strecher, was inserted between PC2 and FBG1. The two wide-bandwidth (>1 nm) nonchirped FBG's were written with 275-nm light from an Ar laser in hydrogen-loaded fibers. Their peak wavelengths, reflectivities and 3-dB bandwidths were 1547.4 and 1562.1 nm, 89.5 and 92.8%, 1.0 and 1.44 nm, respectively. The wide bandwidth of the gratings is a necessary (although not sufficient) condition for short pulse generation.

By adjusting PC1 and PC2 we first balanced the cavity losses at λ_1 and λ_2. Next, the modulation frequency was



(a) (b)

Fig. 4. Autocorrelation traces of pulses at (a) 1547.4 nm and (b) 1562.1 nm fitted to sech^2 functions (dashed lines). Corresponding FWHM pulsewidths are $\Delta\tau_1 = 16.5$ ps and $\Delta\tau_2 = 13.1$ ps, respectively. SHG: Second-harmonic generation.

precisely adjusted ($f_m = 2999.455$ MHz) to achieve optimal mode locking at λ_1. Then, the fiber stretcher was tuned to adjust the round-trip time at λ_2 to the modulation frequency. With an optical spectrum analyzer, we checked that the laser was lasing at both wavelengths simultaneously, with no switching between wavelengths. Fig. 2 shows the optical spectrum of the dual-wavelength laser output ($\lambda_1 = 1547.4$ nm and $\lambda_2 = 1562.1$ nm), with about equal powers at both wavelengths. Full-width at half maximum (FWHM) of the optical spectra around λ_1 and λ_2 were $\Delta\lambda_1 = 0.18$ nm and $\Delta\lambda_2 = 0.21$ nm, respectively, (Fig. 3). Note that single-wavelength pulse generation (at λ_1 or λ_2) could be also achieved by proper settings of PC's and modulation frequency. Using a tunable optical filter (3-nm FWHM), the pulse train at λ_1 (or λ_2) was selected from dual-wavelength laser output radiation and fed into a second-harmonic-generation autocorrelator. Background-free autocorrelation traces of pulses at λ_1 and λ_2 are shown in Fig. 4. Best fits to curves (also shown in Fig. 4) were obtained with sech^2 functions of FWHM widths $w_1 = 25.6$ ps and $w_2 = 20.2$ ps. For a sech^2 pulse shape, these values lead to FWHM pulsewidths of $\Delta\tau_1 = 16.5$ ps and $\Delta\tau_2 = 13.1$ ps ($\Delta\tau_i = w_i/1.55$). Corresponding time-bandwidth products are 0.37 and 0.34, respectively. These values are very close to that of transform-limited sech^2 pulses (0.315) and confirm that the pulses are nearly transform-limited at each wavelength. The different pulsewidths at λ_1 and λ_2 are attributed to the different bandwidths of the two FBG's.

In conclusion, pulses as short as 16 and 13 ps (sech^2 shape), with time-bandwidth products of 0.37 and 0.34, were generated at 1547 and 1562 nm, respectively, from a dual-wavelength actively mode-locked Er-doped fiber laser including two nonchirped FBG's. To obtain such short-duration chirp-free dual-wavelength pulses, the optimization of round-trip time and intracavity dispersion at each wavelength, together with the use of wide-bandwidth nonchirped FBG's were crucial. Pulse repetition rate (3 GHz) was only limited by the available bandwidth of the dual-output electrooptic modulator.

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