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Narrow–linewidth tunable laser source for long-wavelength optical coherence tomography at 1700 nm

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Abstract. We present a widely tunable laser source with narrowed linewidths at the level of 0.4 – 1.1 nm. The laser source incorporates a comb-profile fiber (CPF) which allows for spectral compression of the tunable optical pulses to the linewidths below 1 nm. The spectral compression factor is as high as 37.2 and is the highest obtained for this wavelength range. With the use of an electro-optic modulator (EOM), the laser system ensures rapid tuning up to 10 GHz. Together with the wide spectral range of 1600-1900 nm, and compressed spectral width, the source meets the requirements of the optical coherence tomography (OCT).

1 Introduction

Rapidly tunable and narrow-linewidth laser sources find applications in many areas including spectroscopy, optical communication, and optical coherence tomography (OCT). By adapting the nonlinear phenomena that occur in anomalous dispersion fibers when pumped with an ultrafast laser, it is possible to obtain tunable optical pulses (solitons) in a wavelength range of 1600-1800 nm which is especially desirable for biomedical applications. The 1700 nm bandwidth has been reported to offer lower scattering in tissue, and hence increased penetration depth compared to the popular 1300 nm spectral window [1], and therefore it can be used as an alternative for OCT sources. The requirements for potential OCT swept-source include narrow instantaneous spectral linewidth for proper penetration depth and a broad range sweeping with rapid tuning for high axial resolution. The possibility of using a tunable pulsed laser with compressed linewidth opens new opportunities in this area.

In this work, we present an all-fiber laser system tunable in the wavelength range of 1622–1900 nm, with spectral linewidths in the level of 0.43–1.11 nm. We demonstrate the combination of the nonlinear effects that allow for spectral tuning of the solitons and a spectral compression technique that provides a spectral narrowing of the frequency-shifted pulses. The system also incorporates an amplification stage based on a Thulium-doped fiber amplifier (TDFA), adjusted for the 1700–1800 nm wavelength range. As a result, the laser source features parameters adjusted for potential biomedical imaging.

2 Numerical analysis

Due to the soliton effect, when a pulse of a soliton order, N, between 0.5–1.5 enters an optical fiber, it aims to become a fundamental soliton, with $N = 1$. The soliton order is a function of a fiber's nonlinear coefficient γ, a peak power of the input pulse P_0, pulse duration T_{FWHM}, and the second-order dispersion coefficient, β_2, as given [2]:

$$N^2 = \frac{\gamma P_0 T_{\mathrm{FWHM}}^2}{3.11|\beta_2|}.$$

Therefore, when a pulse is provided to the optical fiber with an increasing absolute value of β_2, it gets temporally stretched, and, due to the soliton condition, it becomes spectrally compressed.

In order to properly design the CPF structure, the numerical analysis has been performed based on the standard split-step Fourier method with the Generalized Nonlinear Schrödinger Equation solver [3]. The CPF was modeled to reflect the experiment, and therefore its structure consists of several segments of either single-mode fiber (SMF) or dispersion-shifted fiber (DSF). The variation of β_2 and the pulse spectral width as a function of the CPF length is presented in Fig. 1.

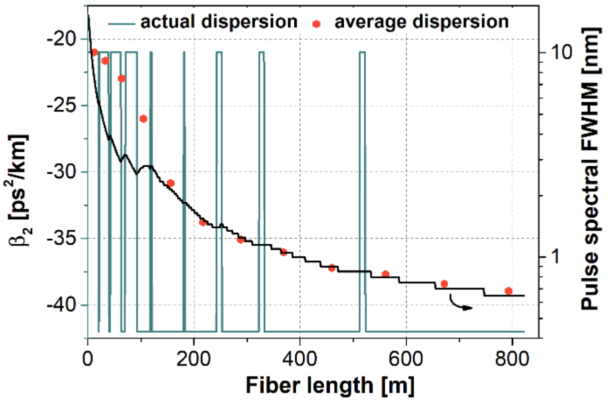

Fig. 1. Dispersion profile of the CPF and the evolution of the pulse spectral width.

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The CPF in the simulations consists of 18 segments of SMF and DSF, and the total fiber length is 822 m. At 1730 nm wavelength, the average value of β_2 for the resulting CPF starts from –21 ps^2/km (which corresponds to β_2 for the DSF) and is consequently decreased, reaching –38 ps^2/km which is very close to the SMF's dispersion that amounts to –42 ps^2/km. Simultaneously, the pulse spectral width decreases with the fiber length, reaching around 0.5 nm at the end of the propagation.

3 Experimental results

The experimental setup is presented in Fig. 2. The Erbium-doped oscillator is used as a seed source, followed by an electro-optic modulator (EOM), and an Erbium-doped fiber amplifier (EDFA). The EDF laser generates 42 fs pulses with a 50 MHz repetition rate, centered at 1560 nm. These pulses are then provided to the polarization-maintaining (PM) SMF allowing for a spectral conversion up to 1.92 µm due to the soliton self-frequency shift (SSFS) effect. Since the spectral tuning is intensity dependent, the optical solitons can be rapidly swept up to 10 GHz due to the use of the EOM. The initial bandwidths of the solitons are between 14.9–16.2 nm.

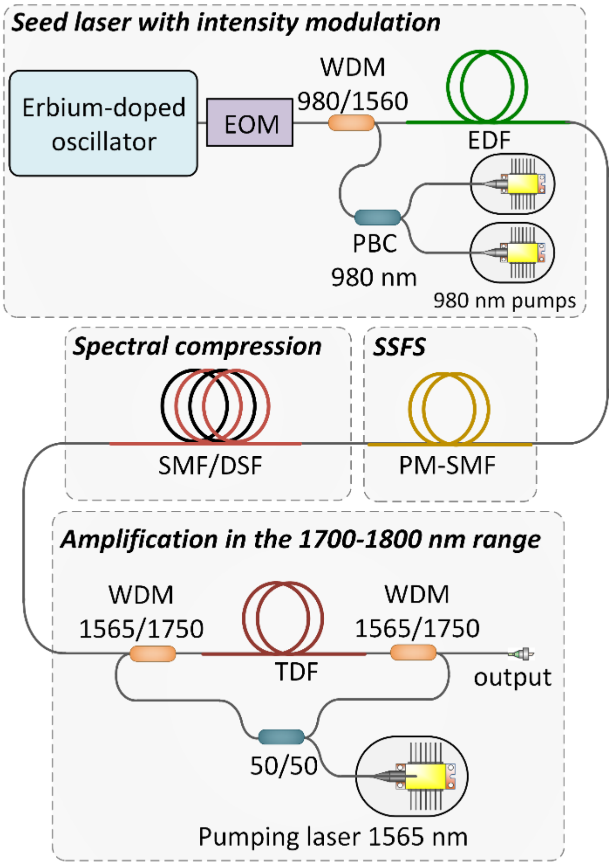

Fig. 2. The schematic of the experimental setup. EOM: electro-optic modulator; WDM: wavelength division multiplexer; PBC: polarization beam combiner; EDF: Erbium-doped fiber; SSFS: soliton self-frequency shift; PM-SMF: polarization-maintaining single-mode fiber; DSF: dispersion-shifted fiber; TDF: Thulium-doped fiber.

The tunable pulses from the PM-SMF are then provided to the CPF which is made of alternating segments of SMF and DSF, according to the numerical model. The CPF structure allows for spectral compression of the frequency-shifted pulses to the linewidths of 0.43-1.11 nm in the wavelength range of 1622-1900 nm. The optical spectra of the compressed solitons are presented in Fig. 3.

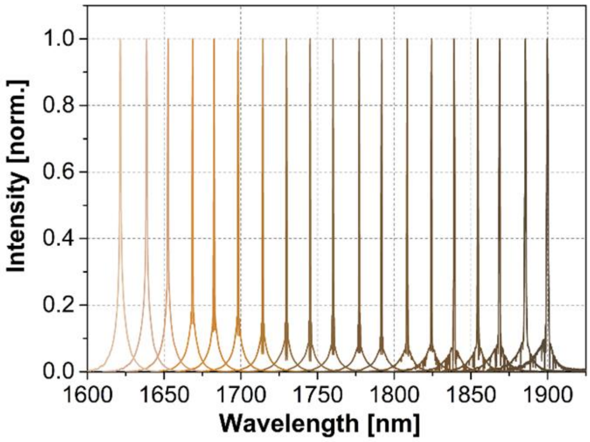

Fig. 3. The optical spectra of the tunable solitons after spectral compression.

Lastly, the compressed spectrally-shifted solitons are amplified in the TDFA adjusted for short-wavelength operation. The use of a short segment of Thulium-doped fiber (TDF) and two wavelength division multiplexers (WDM) adjusted for 1750 nm wavelength allow for the amplification of the solitons in the spectral range of 1669–1860 nm. The linewidths of the solitons after the amplification stage are at the level of 0.48–0.79 nm. The maximum average optical power is achieved for soliton at 1770 nm and equaled 446 mW. The achieved power levels are satisfactory for further OCT analysis.

To summarize, the obtained results indicate that the laser source would be suitable as a possible swept-source for OCT. What is more, the laser system is entirely fiberized, and therefore, not susceptible to beam misalignment

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