Er-fiber laser enabled femtosecond source tunable from 1.3 to 1.7 µm for nonlinear optical microscopy

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Abstract: We demonstrate an Er-fiber laser based source that produces 100-200 fs pulses widely tunable from 1300 to 1700 nm, constituting an ideal driving source for three-photon excitation nonlinear optical microscopy.

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Nonlinear optical microscopy (NLOM) becomes a powerful tool for biomedical imaging due to the attractive features such as optical sectioning capability, various imaging contrast modalities, and the potential of deep tissue imaging [1]. For two-photon excitation NLOM, a femtosecond laser is normally employed as the driving source with the ideal wavelength coverage of 700-1300 nm. The typical solution combines a solid-state Ti:sapphire laser tunable from 700 to 1040 nm and a synchronously pumped optical parametric oscillator covering 1040-1300 nm. However, high complexity, high cost, and bulky size of such a solid-state laser solution has spurred intensive development of reliable, cost-effective, and compact ultrafast sources in fiber format [2]. Recently, we demonstrated a novel method of generating widely tunable femtosecond pulses [3]. The method employs self-phase modulation (SPM) dominated nonlinearities to broaden an input optical spectrum, followed by optical bandpass filters to select the leftmost or rightmost spectral lobes. Based on an Yb-fiber ultrafast laser at 1030 nm, ~100-fs (nearly transform-limited) pulses—tunable from 825 to 1210 nm with >1 nJ pulse energy—were obtained, constituting a simple solution for driving two-photon excitation NLOM [3]. In recent years, three-photon excitation NLOM gains increasing research efforts because it offers even larger penetration depth for deep tissue imaging. This microscopy modality demands a femtosecond laser source operating from 1300 to 1700 nm [4]. In this submission, we demonstrate that such an ultrafast source can be implemented by applying our method (i.e., SPM-dominated spectral broadening followed by spectral-lobe filtering) to an ultrafast Er-fiber laser centered at 1550 nm.

![Fig. 1. (a) Simulation of a 50-nJ, 300-fs pulse propagating inside an optical fiber. The corresponding optical pulse (blue curve) and the calculated TL pulse (red curve) from the filtered spectra are shown in (b) for the leftmost lobe and in (c) for the rightmost lobe. Insets: filtered optical spectra. TL: transform-limited.](image)

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To illustrate the method, we simulate the propagation of a 50-nJ, 300-fs Sech pulse (centered at 1.55 µm) in an optical fiber with a mode-field diameter of 4 µm and 10 fs²/mm group-velocity dispersion. Figure 1(a) shows that the optical spectrum is dramatically broadened towards both shorter and longer wavelength, manifesting as isolated spectral lobes. Using suitable optical bandpass filters to select either the leftmost or the rightmost spectral lobe generates nearly transform-limited pulses with the duration of 100-200 fs; see Fig. 1(b) and1(c). Figure 2(a) shows the schematic of our Er-fiber laser based femtosecond source tunable from 1300 to 1700 nm. The home-built all-fiber Er-fiber oscillator produces 31-MHz pulses, which are chirped-pulse amplified and then de-chirped by a pair of diffraction gratings, producing > 160-nJ and 290-fs pulses centered at 1550 nm. The highly nonlinear fiber (HNLF)
exhibits low dispersion in 1300-1700 nm and ensures that the spectral broadening is largely caused by SPM. The blue curves in Fig. 2(b) record the output spectra from 4-cm HNLF with the increased input pulse energy. At 28-nJ input energy, the spectrum covers the desired wavelength range of 1300-1700 nm. To show that this method is energy scalable using shorter fiber length, we reduce the fiber length to 2 cm and then increase the input pulse energy to generate the broadened spectra (red curves in Fig. 2(b)) that are nearly identical with those produced by the 4-cm HNLF. The experimental results in Fig. 2(b) strongly suggest that using shorter fiber length leads to higher pulse energy concentrated in the leftmost and rightmost spectral lobes.

Fig. 2. (a) Experimental setup. WDM: wavelength-division multiplexing, EDF: erbium-doped fiber, EYDF: erbium ytterbium co-doped fiber, M: mirror, ISO: isolator, HNLF: highly nonlinear fiber, HWP: half-wave plate, PBS: polarization beam splitter. (b) Spectral broadening versus coupled pulse energy for two HNLF lengths: 4-cm (blue curves) and 2-cm (red curves).

We use a set of optical bandpass filters to select the leftmost and rightmost spectral lobes of the optical spectra produced by the 2-cm HNLF. Covering 1300-1700 nm, the filtered spectra are shown in Fig. 3 and labeled with peak wavelength, corresponding average power, and resulting pulse energy. The pulse given by each individual filtered spectrum is measured by an autocorrelator and the measured autocorrelation traces are shown as the red curves in the right panel of Fig. 3. The pulse duration is estimated to be 97-182 fs (assuming the pulse is of Sech shape). Black dotted curves show the calculated autocorrelation traces of the transform-limited pulses given by the filtered spectra. A comparison between the black dotted curves and red curves indicates that the pulses due to spectral filtering are nearly transform limited.

Fig. 3. Filtered spectra and corresponding autocorrelation traces from 2-cm HNLF.

In conclusion, we demonstrate an Er-fiber laser based ultrafast source widely tunable from 1300 to 1700 nm with >4-nJ pulse energy. Ongoing work is focused on energy scaling beyond 10 nJ and application of the source to three-photon excitation NLOM for deep tissue imaging.

References