Extremely Widely Tunable (1.0-1.7 μm) Yb-doped Fiber Mode-Locked Laser Source with ~100 fs Pulse Widths based on Raman Frequency Shift

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Abstract: A widely tunable (1.0-1.7μm) femtosecond laser source based on Raman induced frequency shift in a photonic crystal fiber pumped by a Yb-doped mode-locked fiber laser is presented. The output pulses are ~100 fs wide with ~0.5 nJ pulse energy.

Cost effective, widely tunable, femtosecond laser sources are important for a variety of applications such as optical communications, spectroscopy, and optical measurements. Raman self-frequency shift of optical pulses in fibers is a technique commonly used to realize tunable femtosecond laser sources [1-3]. Till recently, pulse frequency shifts of 100-300 nm had been demonstrated [1-3]. Recently, highly nonlinear fibers have been used to extend the tunability of femtosecond pulses to cover the entire wavelength range from 1.0 μm to 1.7 μm allowing for pulse tunability to cover an entire octave in frequency [4]. As pulses propagate in a highly nonlinear fiber, the longer wavelength components of the pulse gain energy at the cost of the shorter wavelengths via the Raman effect. If the input pulse energies and widths satisfy the fundamental soliton condition, the pulses continuously shift towards longer wavelengths without breaking up. However, if the input pulse widths and energies correspond to higher order solitons, the Raman nonlinearity breaks the higher order solitons into spectrally and temporally separated fundamental solitons, with each soliton undergoing Raman frequency shift independently [5].

In this paper we report on a widely tunable short-pulse laser source based on a Yb-doped mode-locked fiber laser and a highly nonlinear photonic crystal fiber. We show that ~100 fs optical pulses tunable from 1.0 μm to 1.7 μm and with pulse energies in the ~0.5 nJ range are possible. Even wider tunability is possible provided fiber losses at longer wavelengths can be reduced. We used a 30 MHz amplified modelocked fiber laser source [6]. The Yb-doped fiber amplifier provides up to 5 dB gain for the laser output pulses. The laser and the amplifier are pumped by 976 nm diode lasers delivering optical powers up to 450 mW each. The 4-5 ps wide amplified pulses are compressed by a grating pair pulse compressor to less than 200 fs. The output of the compressor is launched into a photonic crystal fiber with zero dispersion wavelength of ~945 nm and nonlinear coefficient γ of 23 $W^{-1}km^{-1}$ (at 1060 nm.) The group velocity dispersion of the fiber (β_2) is around -15 ps^2/km at the launch wavelength. The output of the fiber is sent to an optical spectrum analyzer and a second harmonic generation (SHG) autocorrelation.

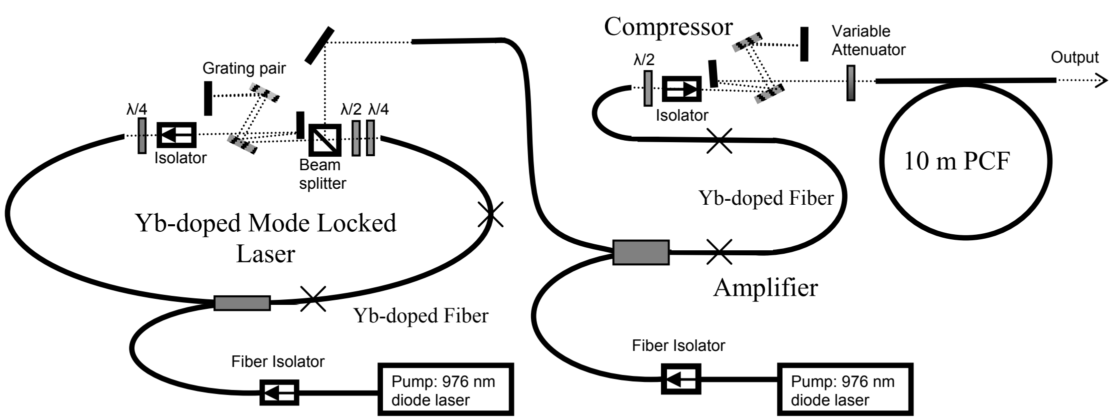

Figure 1. Diagram of the Yb-doped mode-locked fiber laser, amplifier, compressor and the photonic crystal fiber (PCF).

Fig. 2 shows the output spectra as the input pulse energies into the PCF is varied with a variable neutral density attenuator. The observation of multiple pulses at the output with various wavelength shifts is suggestive of fission of higher order solitons into fundamental solitons. The order N of the soliton is given by $N^2 = \gamma E_p \tau / \beta_2$ [5] where γ is the coefficient of fiber nonlinearity, *Ep* is the pulse energy, *τ* is the pulse width and β_2 is the fiber group velocity dispersion. For the large pulse energies of Fig.2, the soliton order is estimated to be >15. However, the number of distinctly frequency-shifted Raman solitons observed at the output of the PCF fiber is 4. Higher order solitons are strongly susceptible to perturbations, such as the Raman effect [7,8]. Although an input pulse may satisfy the conditions for a soliton of order *N*, in the presence of strong Raman nonlinearity it will not propagate long enough to complete even a single higher order soliton breathing period, and therefore the observed characteristics of input pulse breakup are not adequately captured in the traditional soliton fission model. The fiber dispersion profile and the nonlinear phase shift experienced by each soliton also allow for phase-matched blue-shifted radiation [10], which is seen at shorter wavelengths in Fig. 2.

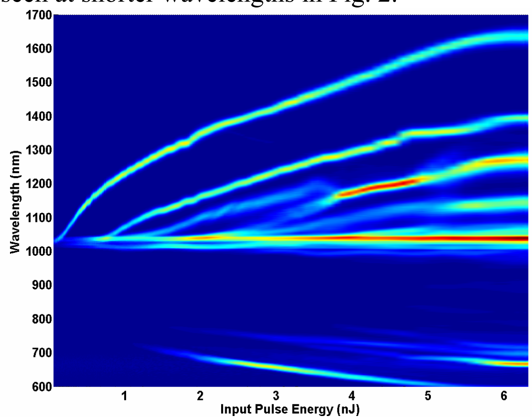

Figure 2. Spectra of the output of the photonic crystal fiber at various input pulse energies.

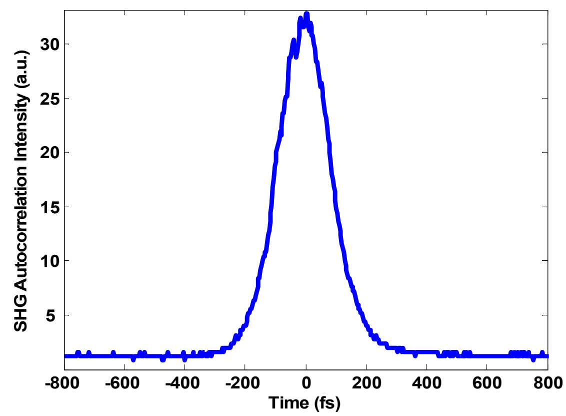

Figure 3. Autocorrelation of a typical Raman soliton at a wavelength near 1600 nm.

The individual frequency shifted solitons are filtered out separately and their pulse widths are measured using SHG autocorrelation. Fig. 3 shows the autocorrelation of the farthest shifted soliton near 1600 nm, corresponding to a pulse width of ~130 fs. Some of the higher energy solitons at shorter wavelengths exhibit pulse widths as short as 86 fs. The energies of the longest wavelength solitons exceed 0.5 nJ over the entire tuning range of 1100-1670 nm.

In conclusion, we report a femtosecond laser source that is continuously tunable over the entire wavelength range from 1.0 μm to 1.7 μm and has output pulse energies exceeding 0.5 nJ over this range. In this paper we will also discuss characteristics of widely tunable femtosecond laser sources employing the Raman effect and methods to achieve tunability over an entire octave in frequency.

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