# Wavelength tunable ultra-short pulses based on a flat broadband spectrum generated in a nonlinear ytterbium-doped fiber amplifier*

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We present a nonlinear ytterbium-doped fiber amplifier based on enhanced nonlinear effects that can produce a flat broadband spectrum ranging from 1050–1225 nm with a maximum average output power of 7.8 W at 14 W pump power. Its repetition rate is 89 MHz. Using a pair of gratings and two knife edges as a filter, wavelength tunable picosecond pulses of tens to hundreds of milliwatts can be obtained in the broadband spectrum range. The output power, pulse width, and spectrum (center wavelength and linewidth) are adjusted by tuning the distance of the grating pair and/or the knife edges. Fixing the distance between the two gratings at 15 mm and keeping the output spectrum linewidth at approximately 20 nm, the shortest pulse width obtained is less than 1 ps centered at 1080 nm. The longest wavelength of the short pulses is around 1200 nm, and its output power and pulse width are 40 mW and 5.79 ps, respectively. The generation of a flat broadband spectrum is also discussed in this paper.

**Keywords:** tunable ultra-short pulse, broadband spectrum, nonlinear amplifier

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## 1. Introduction

Laser sources in the wavelength range of 1100–1200 nm are widely used in fields such as new pump sources, metrology, and remote sensing.[1–3] There is also a great demand for frequency-doubled 1100–1200 nm lasers for producing the yellow–red light applied in spectroscopy, laser guide star generation, ophthalmology,[4] and dermatology.[5]

To achieve lasers in the wavelength range of 1100–1200 nm, several approaches can be used. One common approach is ytterbium-doped (Yb-doped) fiber lasers and/or amplifiers.[6–10] In comparison with continuous wave (CW) lasers, the wavelength-tunable pulsed lasers are more widely used in biological applications such as photoacoustic microscopy (PAM) and Raman microscopies.[11–14]

To obtain wavelength-tunable pulses in this wavelength range, the Raman soliton method could be employed.[15,16] However, Raman solitons can only be generated in abnormal dispersion fibers, so photonic crystal fiber (PCF) is normally used to provide abnormal dispersion in this wavelength range. Moreover, seed pulses with high peak power are also essential in generating Raman solitons. Rigorous generation conditions together with the incompatibility of PCF increases the difficulty of obtaining Raman solitons and limits the application of this approach. Another option is to generate a broadband spectrum that covers this wavelength range through a nonlinear Yb-doped fiber amplifier seeded by pulses at shorter wavelengths. A programmable optical filter can then be used to achieve the part of the pulse that contains the target wavelength component.[17] Reference [18] achieved picosecond pulses with a high output power in this wavelength range, but their laser system is complex and requires a high pump power (about 30 W). Reference [19] investigated the particular nonlinear process in a nonlinear fiber amplifier, and compared the performance under seed pulses of different wavelengths. However, the spectrum is not particularly flat, as it is limited by the length of the fiber and the low Raman gain coefficient, as discussed in Ref. [20].

Here, we employ a long gain fiber to reduce the Raman threshold and enhance the nonlinear effects in the fiber amplifier. A largely flat broadband spectrum is generated. Utilizing a grating pair and two knife edges as a filter, tunable picosecond pulses of 1100–1200 nm wavelength can easily be obtained.

## 2. Experimental setup

A nonlinear Yb-doped fiber amplifier system is schematically depicted in Fig. 1. The system includes three parts: seed source, amplifier, and compressor combined with a filter.

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Figure 1(a) is a home-built passively mode-locked all-normal-dispersion (ANDi) laser with a spectral bandwidth of 12 nm from 1025 to 1037 nm. The pulse width is 4.58 ps with a repetition rate of 89 MHz. The maximum average output power of the seed source is 100 mW, and about 30 mW power is coupled into the collimator to seed the amplifier.

Figure 1(b) shows a nonlinear Yb-doped amplifier, which consists of two lasers for pumping and a 12 m long Yb-doped double-clad fiber. The Yb-doped fiber (Nufern) has a core diameter of 10 μm with a numerical aperture (NA) of 0.075, and an inner-clad diameter of 130 μm with a NA of 0.46. It has a hexagonal inner-clad geometry and a clad-pump absorption coefficient of 3.9 dB/m at 975 nm. The maximum output power of each fiber-coupled laser diode is 7 W at a center wavelength of 975 nm and 974 nm, respectively. Figure 1(c) is a pulse compressing system combined with a spectrum filter utilizing a grating pair and two knife edges. The groove density of the two gratings is 1000 lines/mm. Output 1 is the laser output from the amplifier without compression, and output 2 is the output port of the compressed and filtered pulses from output 1.

Figure 2(a) shows the spectrum of the seed pulses for a pump power of 600 mW. The spectral bandwidth is 12 nm ranging from 1025 to 1037 nm. Figure 2(b) shows the corresponding autocorrelation trace. The dissipative soliton has a Gaussian profile,[21] so after deconvolution, the pulse width is about 4.58 ps.

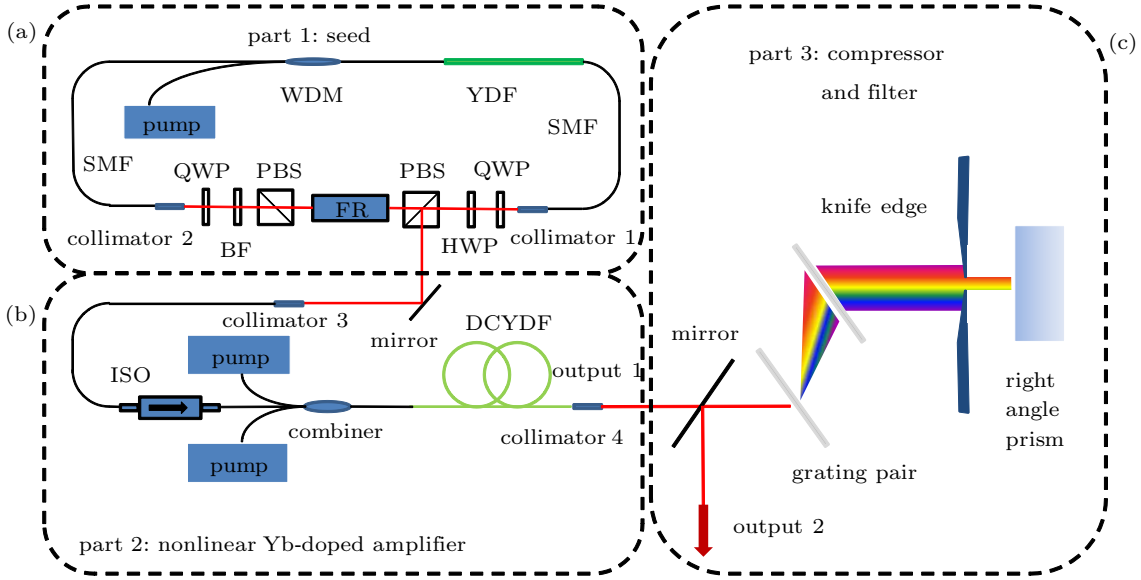



**Fig. 1.** (color online) Experimental setup for the nonlinear Yb-doped amplifier system. WDM: wavelength division multiplex, YDF: Yb-doped fiber, SMF: single mode fiber, QWP: quarter wave plate, HWP: half wave plate, PBS: polarized beam splitter, FR: Faraday rotator, BF: birefringence filter, ISO: isolator, DCYDF: double-cladding Yb-doped fiber.

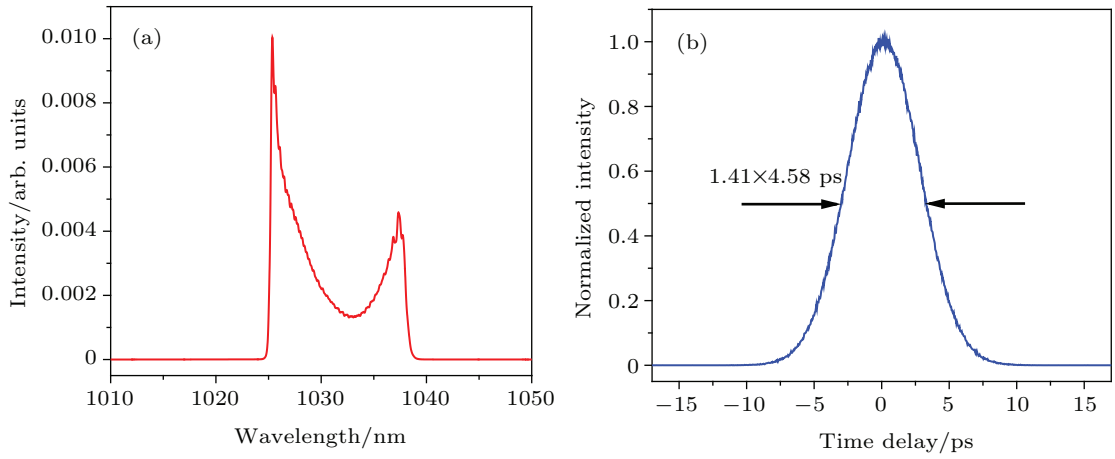



**Fig. 2.** (color online) (a) Spectrum and (b) autocorrelation trace of seed pulses. 1.41 is the deconvolution factor for Gaussian profile.

## 3. Results and discussion

Figure 3 shows the output power of the fiber amplifier (output 1) changed with the pump power. The maximum output power is approximately 7.8 W with a 14 W pump power. Output spectra (output 1) of the amplifier with different pump powers are shown in Fig. 4. The formation of a broadband spectrum in the nonlinear fiber amplifier is a complex process that includes nonlinear effects such as stimulated Raman scattering (SRS), self-phase modulation (SPM), modulation instability (MI), and soliton self-frequency shift (SSFS). Reference [20] points out that cascaded-SRS dominates the spectrum broadening in the normal dispersion region (wavelengths shorter than 1273 nm), whereas SSFS dominates in the abnormal dispersion region. The wavelength range of 1025–1225 nm is located in the normal dispersion region, so the cascade-SRS plays a very important role in the spectrum broadening process in this fiber laser.

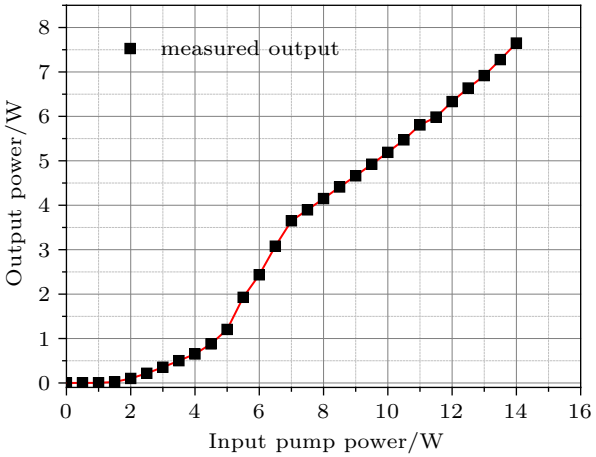



**Fig. 3.** (color online) Output power of the amplifier versus the pump power.

In Fig. 4, the generation of SRS in the amplifier stretches the spectrum considerably once the pump power exceeds the Raman threshold (about 5.0 W). As the incident pump power increases, the output spectrum becomes broader because of SPM and cross-phase modulation (XPM) effects. If the pump power is sufficiently high, second- or even higher-order SRS might be generated.

In terms of the flatness of the broadband spectrum, we should consider three factors: i) the long gain fiber reduces the Raman threshold, and can improve the energy transfer efficiency from the seed pulses to Raman Stokes light, while the generation of multi-order SRS will also benefit from the long gain fiber; ii) the gain of Yb ions will surely enhance different nonlinear effects in the wavelength range of Yb gain, as mentioned in Ref. [19]; iii) there is a certain length of low-pumped fiber that could absorb the power of the amplified seed pulses and convert the energy to a longer wavelength component through Yb ions gain (re-absorption effect and re-emission effect). This may also be why amplified seed pulses seldom remain.

Benefitting from the flat broadband spectrum, widely tuned ultrafast pulses in a broad wavelength range can be extracted using a filter composed of a pair of gratings and two knife edges (see part 3 of Fig. 1). Figure 5 shows the power of wavelength tunable pulses and their relative spectrum intensity at different wavelengths: 73.1 mW at 1062 nm, 250.0 mW at 1080 nm, 294.9 mW at 1102 nm, 201.3 mW at 1140 nm, 128.2 mW at 1161 nm, 56.4 mW at 1174 nm, 38.5 mW at 1200 nm.

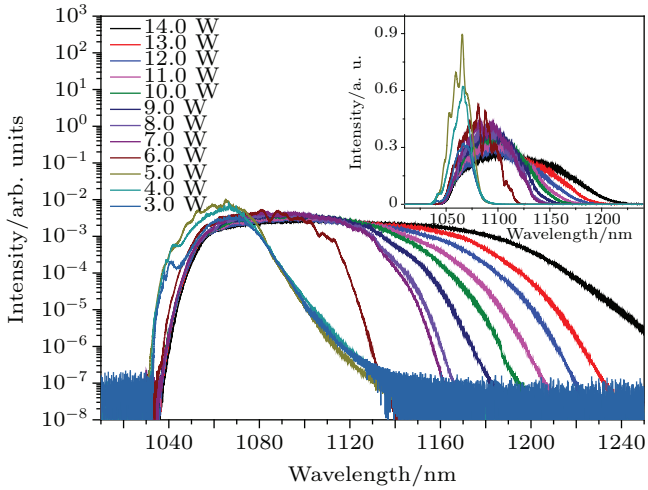



**Fig. 4.** (color online) Output spectra corresponding to different pump powers. The inset is the same spectrum in linear scale.

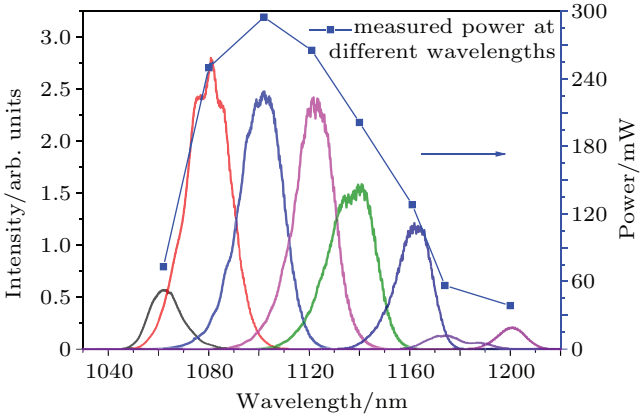



**Fig. 5.** (color online) Measured output power at different wavelengths.

Autocorrelation traces at different centers wavelengths were also measured by a commercial autocorrelator (FR-103XL manufactured by FEMTOCHROME). The results are shown in Fig. 6. If we regard these pulses as Gaussian waves, their pulse duration can be calculated as: a peak of 163 fs standing on a pedestal of 1.38 ps at 1080 nm, 1.92 ps at 1100 nm, 2.45 ps at 1120 nm, 3.80 ps at 1140 nm, 3.83 ps at 1160 nm, and 5.79 ps at 1180 nm. All the data were measured for a pump power of 14 W and a separation between the two gratings of 15 mm.

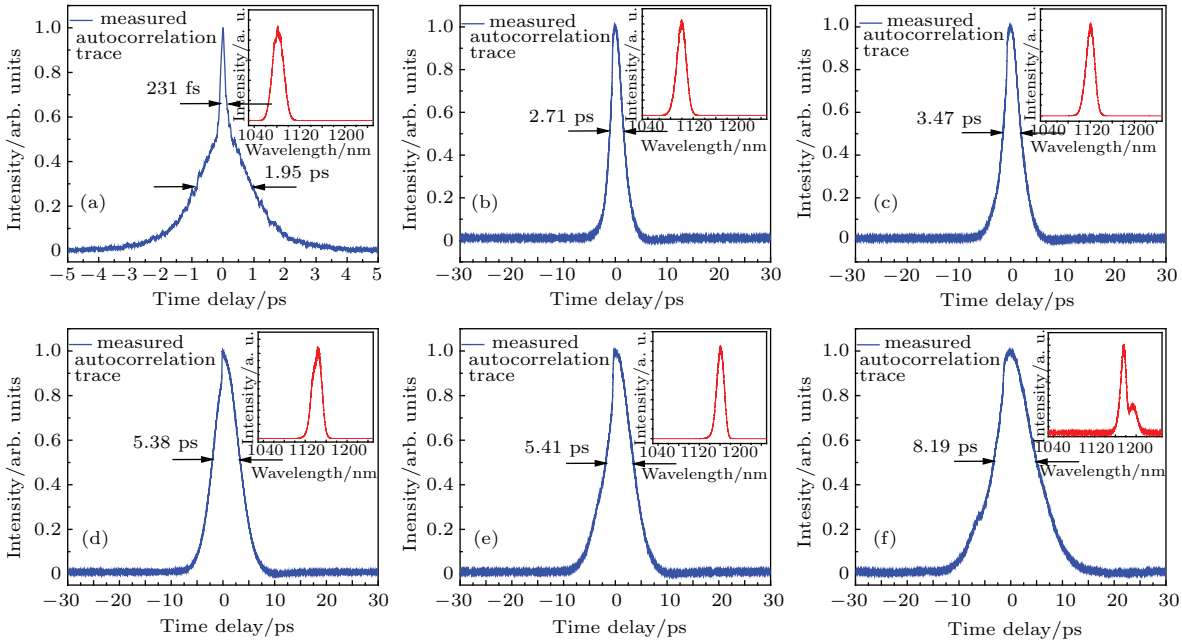



**Fig. 6.** (color online) Autocorrelation traces at different center wavelengths: (a) 1080 nm, (b) 1100 nm, (c) 1120 nm, (d) 1140 nm, (e) 1160 nm, and (f) 1180 nm. Insets are corresponding spectra.

## 4. Conclusion

We have demonstrated an easy way to achieve ultra-short pulses in the wavelength range of 1100–1200 nm by generating a flat broadband spectrum in a nonlinear Yb-doped fiber amplifier. In this system, a longer gain fiber is used to flatten the broadband spectrum. The maximal total output power is 7.8 W at 14 W pump power, and ultra-short pulses of tens to hundreds of milliwatts with a 3 dB-bandwidth of approximately 20 nm could be obtained by using a filter.

The performance of this fiber laser system could be improved by replacing the seed source with a CNT-based fiber laser, which has a highly environmental stability.[22] The bandwidth of the output spectrum may be further improved by increasing the pump power and/or adding a longer gain fiber, or even a longer general single mode fiber, which could enhance the SRS effect to generate more orders of Stokes light over longer wavelength ranges. However, a detailed numerical simulation is needed to examine the effects of long gain fibers in the spectrum flattening process. This will be the subject of future research.

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