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Femtosecond Red and Near-Infrared Lasers Due to Cascaded-Raman-Assisted Four-Wave Mixing in a Nonlinear Yb-Doped Fiber Amplifier

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Abstract: We demonstrated a straightforward approach to generate red and near-infrared laser emissions by a Raman-assisted four wave mixing (FWM) process in a nonlinear Yb-doped fiber amplifier, delivering 342 fs pulses of 241 nJ at 864 nm, 834 fs pulses of 21 nJ at 751 nm, and 1.9 ps pulses of 3.8 μ J at 1030 nm. A pair of gratings was employed as the pre-compressor to promote the intensity of the fundamental wave in the main amplifier. Multiple wavelengths from 751 to 1273 nm resulted due to cascaded-Raman-assisted FWM. The pre-compression also underlay the achievement of 25.1, 701, and 2000 kW peak power for the red (751 nm), near-infrared (864 nm), and fundamental (1030 nm) components respectively, which restrained the gain narrowing effect during the amplification. It finally led to shorter pulse duration under increased power.

Keywords: four-wave mixing; femtosecond fiber laser; fiber amplifier

1. Introduction

Supercontinuum generation via frequency conversion provides a way to extend the frequency coverage of a fiber laser, which is usually required in scientific and industrial applications, such as coherent anti-Stokes Raman scattering spectroscopy, stimulated emission depletion microscopy, fluorescence polymersomes, biological sensing, and ophthalmopathic treatments [1–4]. As we know, FWM in large mode area (LMA) fibers is desirable to generate supercontinuum spanning several octaves [5,6].

Up till now, various approaches have been extensively exploited to manage effective parametric wave generation by FWM processes. One way is to monitor the geometrical parameters in a photonic crystal fiber (PCF) in order to retain the phase matching for frequency conversion. By this scheme, watt-level supercontinuum was generated from either CW pumped or pulsed-systems [7]. Another way is to introduce birefringence-assisted FWM by propagating a fundamental wave along one of the polarization axes, while Stokes and anti-Stokes waves are propagated along the orthogonal polarization axis. For instance, in 2015, S. Petersen et al. demonstrated that the parametric gain can be tuned on and off by switching the polarization direction of the pump field between the fast and slow axes of a hybrid

PCF [1,8]. Besides, by manipulating the multimode dispersion in high-order modes to compensate the material dispersion, nonlinear parametric amplification was also realized during the amplification of the fundamental wave in LMA fibers [9,10]. Nevertheless, supercontinuum-generation-resolved applications usually prefer a multi-wavelength, ultrashort, pulsed laser with high peak intensity. For instance, in case of vibrational spectroscopic imaging in biology and medicine, pulses with durations larger than hundreds of picoseconds might induce inevitable heating effects, which might damage the biological samples [11]. Intense parametric wave generation usually gives rise to gain saturation, which limits the gain bandwidth and broadens the pulse duration. Besides, some of the approaches take hybrid PCF to implement parametric gain, which requires more instruments and brings about more losses in the system.

In this work, we present nonlinear parametric amplification in the red and near-infrared region via cascaded-Raman-assisted FWM processes by pre-compressing the input pulse of the main amplifier [12–14]. In this all-fiber scheme, a compact, self-made fiber laser oscillator provided the fundamental pulse at 1030 nm with 4.3 ps pulse-duration. After 3-stage pre-amplification, a pair of gratings was employed as the pre-compressor for optimizing the parametric gain in the main amplifier [7,9]. Pre-compression increased the peak power of the fundamental pulse before entering the main amplifier by shortening the pulse duration, which enhanced self-phase modulation in the main amplifier. It broadened the frequency coverage and led to shorter pulse duration. The gain of the main amplifier was obtained in a 1-m-long LMA Yb-doped PCF with a core diameter of 40 μm , which enabled the fundamental and parametric waves to propagate with different modes. This finally promoted the cascaded nonlinear frequency mixing in the main amplifier [4,15,16]. Therefore, up to five sidebands, such as 751, 864, 1134, 1203, and 1273 nm, were generated. Here, we concentrated on the anti-Stokes lines in red (751 nm) and near infrared (864 nm), since they exhibited high gain. The strong intensity of both the fundamental and parametric waves also guaranteed the compression, along with the amplification of the parametric components at 864 and 751 nm, which overcame the gain saturation and shortened the pulse duration during amplification [17].

2. Experimental Setup

A schematic diagram of the laser system is shown in Figure 1. The all-fiber laser system employed a pulsed laser oscillator, an acoustic-optical modulator (AOM), and three-stage fiber pre-amplifiers, a pre-compressor, and a main amplifier. The laser system was seeded by a SESAM mode-locked oscillator at 1030 nm. The first and second pre-amplifiers consisted of a Yb-doped, 6/125 single mode fiber (SMF) pumped by a pigtailed single-mode laser diode, and an isolator (ISO). The pulses were amplified from 4.5 mW to 230 mW through the first two pre-amplifiers. An AOM was installed to reduce the repetition rate from 25 MHz to 300 kHz. Laser gain for the third pre-amplifier was provided by 0.5 m, Yb-doped double-clad fiber (DCF) with core/cladding diameter of 10/125 μm . The third pre-amplifier was pumped by two fiber pigtailed 976 nm laser diodes via a $(2 + 1) \times 1$ fiber combiner. The power at the output of the third pre-amplifier was 105 mW. Since AOM brought extra attenuation for the fundamental pulse, the scheme of three-stage pre-amplification allowed sufficient power gain for the further amplification. As shown in Figure 1, the grating-based compressor contained two adjustable parallel transmission Bragg gratings, 1200 lines/mm, which were set before the main amplification. As for changing the distance between the grating pair, the output pulse duration can be tuned from hundreds of femtoseconds to several picoseconds. In our experiment, the total transmission through the pre-compressor was measured to be 61%, resulting in 64 mW seed power coupled into the main amplifier. The main amplifier was composed of 1-m-long, Yb-doped PCF (DC-200/40-PZ-Yb, NKT, $\beta_2 \approx 23 \text{ ps}^2/\text{km}$, $\beta_3 \approx 0.06 \text{ ps}^3/\text{km}$, $n_2 = 2.6 \times 10^{-20} \text{ m}^2/\text{W}$), with a doped core diameter of 40 μm (NA = 0.03) and a pump cladding of 200 μm (NA = 0.6). LMA PCF fiber was selected for the main amplifier due to its large mode area, which would guarantee the fundamental and parametric pulses propagating with different modes. This could compensate the walk off between the fundamental and parametric components [10]. To suppress the environmental disturbance and parasitic lasing, both

ends of the fiber were sealed and cleaved at 8 degrees. A fiber-coupled multimode laser diode with central wavelength of 976 nm was employed as the pump source. We pumped the Yb-doped PCF from the back with maximum pump power up to 27 W.

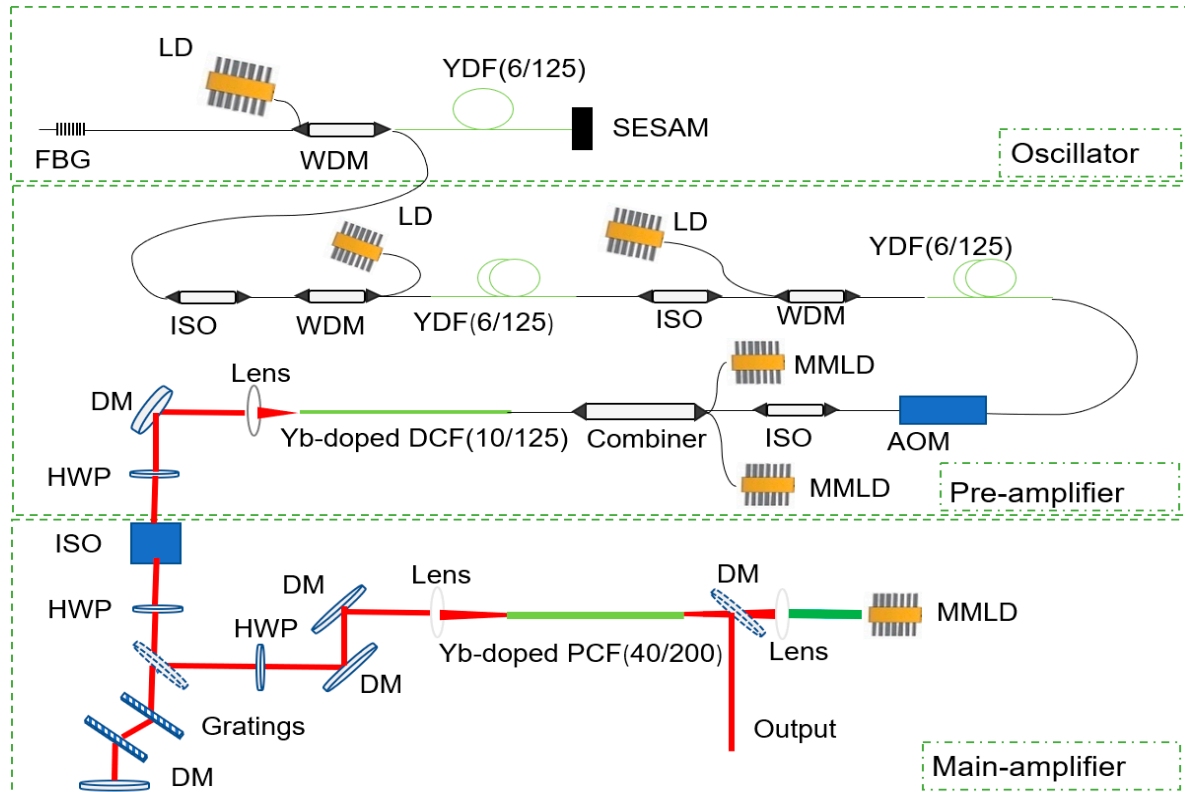


Figure 1. Schematic diagram of the laser system. FBG, fiber bragg grating; ISO, isolator; LD, laser diode; WDM, wavelength division multiplexer; YDF, Yb-doped fiber; DCF, double-clad fiber; PCF, photonic crystal fibers; MMLD, multi-mode laser diode; DM, dichroic mirror; HWP, half wave plate; AOM, acousto-optic modulator.

3. Experimental Results and Analyses

An autocorrelator (PulseCheck50 NIR, APE) and an optical spectrum analyzer (OSA, AQ6370, Yokogawa) were used to characterize the properties of the laser output. The spectral resolution for the OSA is 0.05 nm. The autocorrelator had a detection range from 700 to 1100 nm. For measurements, the laser output was incident on a dichroic mirror with $\approx 95\%$ reflection rate from 1000 to 1240 nm and $\approx 90\%$ transmission rate from 700 to 950 nm. The fundamental wave was selected by taking the reflection, while the transmission was used for further investigations of the red (751 nm) and near-infrared (864 nm) components. Bandpass filters centered at 1030, 750, and 850 nm with a 40 nm transmission band were also applied to separate the fundamental, red, and near-infrared components, respectively.

The oscillator emitted up to 4.5 mW average power at a repetition rate of 25 MHz and a central wavelength of 1030 nm, corresponding to 0.18 nJ for the pulse energy. The spectrum of the compressed pulses is depicted in Figure 2a. The spectrum covered a full width at half-maximum (FWHM) bandwidth of 12.5 nm, as compared with that of 1.3 nm for the laser oscillator. The autocorrelation trace in Figure 2b exhibited a FWHM of 653 fs, corresponding to a pulse duration of 371 fs by taking hyperbolic secant fitting.

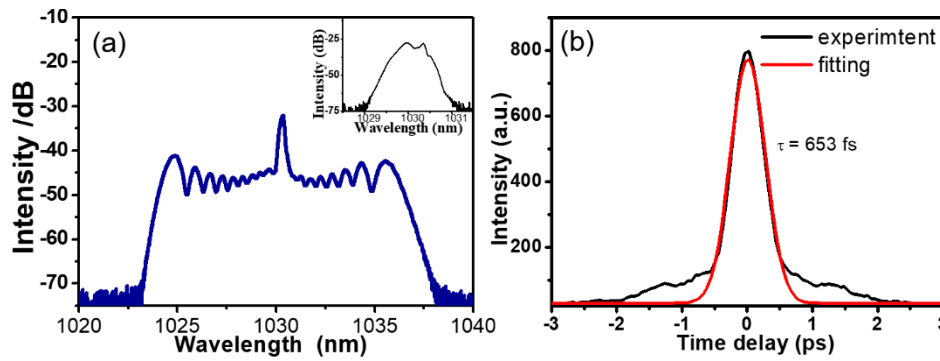


Figure 2. The measured (a) spectral intensity and (b) autocorrelation of the compressed pulse from the three-stage pre-amplifiers, which were measured after the grating-based compressor. The inset in (a) shows the spectral profile of the oscillator.

As the pump power exceeded 10.85 W, the parametric waves increased drastically, giving rise to a visualized red laser. In this case, the supercontinuum generated from the Yb-doped main amplifier covers from 751 to 1273 nm, which is shown in Figure 3. The Stokes series at 1134, 1203, and 1273 nm with 13 THz between adjacent lines was originated from cascaded Raman processes, which were attained at high peak powers [5,18]. Here, Raman components would also generate anti-Stokes through FWM processes with the fundamental pulse. Dramatically, FWM processes were promoted when the parametric waves coupled and overlapped with Raman spectrum [9,10,19].

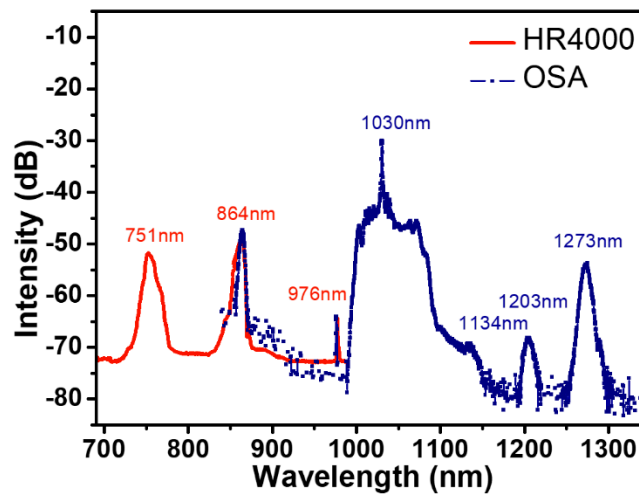


Figure 3. The spectrum measured by optical spectrum analyzer (blue curve) from 850 to 1350 nm and by HR4000 (red curve) from 700 to 1000 nm on a logarithmic scale. The spectral resolution for the HR4000 is 0.27 nm. Five parametric sidebands were generated, such as 751, 864, 1134, 1203, and 1273 nm, with the fundamental wave at 1030 nm. The peak at the wavelength of 976 nm indicates the residual pump laser.

As depicted in Figure 3, the first-order FWM process involved the fundamental wave at 1030 nm, signal wave at 864 nm, and idler wave at 1273 nm, while the second-order FWM process involved the second fundamental wave at 864 nm, signal wave at 751 nm, and idler wave at 1030 nm. The Stokes lines at 1134, 1203, and 1273 nm also satisfied the parametric relation. The cascaded FWM processes can be expressed as,

$$2 \times \omega (1030) = \omega (864) + \omega (1273), \quad (1)$$

$$2 \times \omega (864) = \omega (751) + \omega (1030), \quad (2)$$

$$2 \times \omega (1203) = \omega (1134) + \omega (1273). \quad (3)$$

In Equation (1), both signal $\omega (864)$ and idler wave $\omega (1273)$ generated in the first FWM process participated in the higher-order FWM process. This was realized by the high intensity of the fundamental and parametric waves during the amplification in the LMA PCF fiber. In our experiment, we did not observe the anti-Stokes lines corresponding to Stokes lines at 1203 nm and 1134 nm, since these two components were relatively weak compared with the Stokes line at 1273 nm.

As shown in Figure 4a, the output pulse energy of the fundamental wave centered at 1030 nm is linearly dependent on the pump power. The pulse energies for both parametric components at 861 and 751 nm versus pump power increase with a higher rate from 10.85 to ≈ 12.6 W and with a lower rate from ≈ 12.6 to 15.24 W (see Figure 4b,c). The 1.9 ps pulses of 3.8 μ J at 1030 nm (peak power 2000 kW), 342 fs pulses of 241 nJ at 864 nm (peak power 701 kW), and 834 fs pulses of 21 nJ at 751 nm (peak power 25.1 kW) were obtained at 15.24-W pump power (see Figure 4d–f). We also tried to characterize the energy of Stokes lines at 1134, 1203, and 1273 nm at 15.24 W pump power by employing 40 nm bandpass filters. The pulse energy of 1273 nm component was measured to be 3.9 nJ. However, the pulse energies of the 1134 and 1203 nm components were too weak to access.

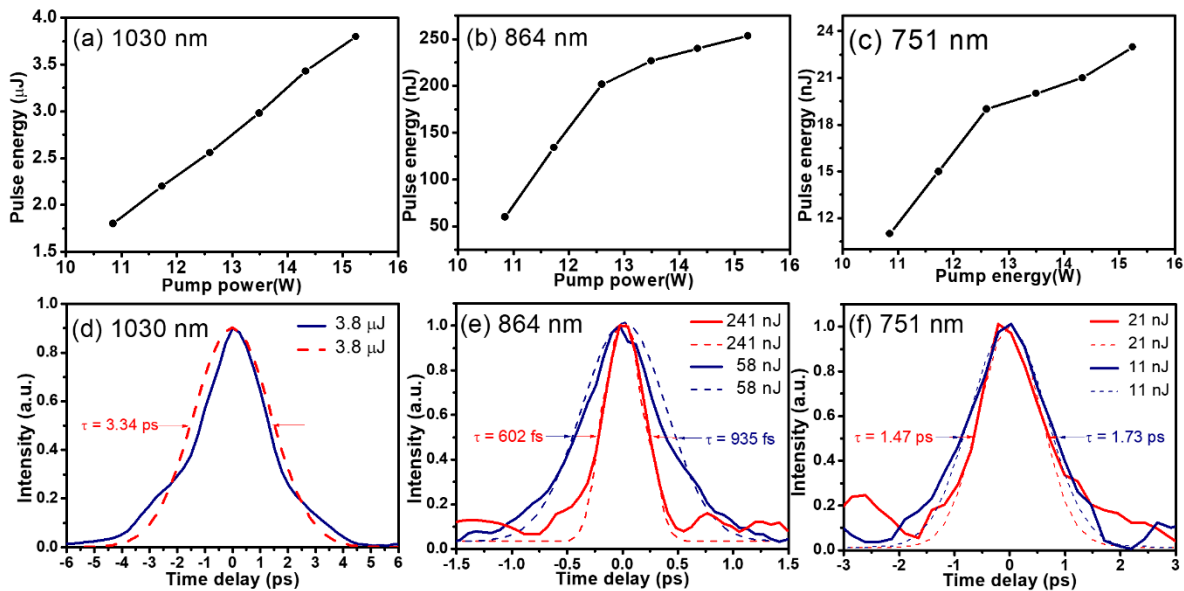


Figure 4. The evolution of the output pulse energy with increased pump power for the fundamental wave at 1030 nm (a), and anti-Stokes lines at 864 nm (b) and 751 nm (c). The measured autocorrelation trace for the fundamental wave at 1030 nm (d), and anti-Stokes lines at 864 nm (e) and 751 nm (f). The fundamental wave and anti-Stokes lines were selected by bandpass filters. In Figure 4d–f, the solid curves resulted from experimental measurements, while the dashed curves were via hyperbolic secant fitting.

Pulse compression along with the amplification is demonstrated in Figure 4e,f and Figure 5a. Under increased pump power, both parametric pulses are compressed monotonously. In our experiment, the highly intense fundamental (2000 kW), near-infrared (701 kW), and red (25.1 kW) waves imposed strong self-phase modulation (SPM) and cross-phase modulation (XPM) on the parametric gain, which extended the frequency coverage of the parametric components (see Figure 5b). This overcame the gain saturation, and resulted in compression of the pulse duration. Besides, in our experiment for the nonlinear LMA fiber, group velocity dispersion (GVD) in high-order modes could compensate for material group velocity mismatch, when fundamental and parametric waves were propagating with different modes [10,20]. Thus, efficient nonlinear parametric amplification was achieved.

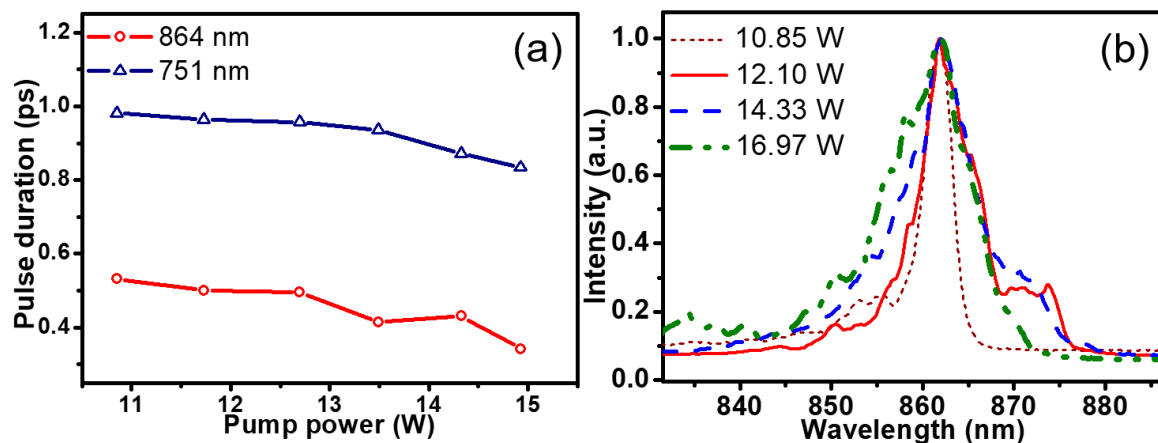


Figure 5. (a) The pulse duration of parametric waves as pump power increased. (b) Spectra for the parametric wave centered at 864 nm with different pump power levels. The spectra were taken by HR4000 with bandpass filters with 40 nm transmission band. The pulse duration in (a) was retrieved by hyperbolic secant fitting.

4. Conclusions

In conclusion, we have established a complete femtosecond, all-fiber laser system that used Raman-assisted FWM to generate a multi-wavelength output, delivering parametric components including 751, 864, 1134, 1203, and 1273 nm. In our case, nonlinear parametric generation was achieved in a multimode Yb-doped PCF amplifier during the amplification of the fundamental pulse. The highly intense fundamental and parametric pulses also gave rise to the process which was akin to self-similar evolution. The laser system finally produced 342 fs pulses of 241 nJ at 864 nm, 834 fs pulses of 21 nJ at 751 nm, and 1.9 ps pulses of 3.8 μ J at 1030 nm. In the future, by stronger pump power and PCFs with larger nonlinearity, a red and near-infrared laser with higher intensity and a shorter pulse duration are anticipated. Besides, we might also expect mid-infrared pulse generation at around 5 μ m via difference frequency by launching the parametric and fundamental pulses into crystals with high nonlinearity.

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