Supercontinuum generation in a standard single-mode fiber by a Q-switched Tm, Ho: YVO_4 laser

Jiancun Ren (任建存)[1], Renlai Zhou (周仁来)[1*], Shuli Lou (娄树理)[1], Wenbo Hou (侯文博)[2], Youlun Ju (鞠有伦)[3], and Yuezhu Wang (王月珠)[3]

[1]*Department of Control Engineering, Naval Aeronautical and Astronautical University, Yantai 264001, China*

[2]*Navy Unit 91404, Qinhuangdao 066001, China*

[3]*National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150080, China*

**Corresponding author: zrlhit@126.com*

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Broadband mid-infrared (IR) supercontinuum laser is generated in standard single-mode fiber-28 directly pumped by a 2054 nm nanosecond Q-switched Tm,Ho:YVO_4 laser. The average output powers of 0.53 W in the ~1.95–2.5 μm spectral band and 0.65 W in the ~1.97–2.45 μm spectral band are achieved at pulse rate frequencies of 7 and 10 kHz, and the corresponding optic-to-optic conversion efficiencies are 34.6% and 42.4% by considering the coupling efficiency. The output spectra have extremely high flatness in the range 2060–2400 and 2060–2360 nm with negligible intensity variation (<2%), respectively. The output pulse shape is not split, and pulse width is reduced from 29 to ~15.4 ns. The beam quality factor M^2 is 1.06, measured using traveling knife-edge method, and the laser beam spot is also monitored by an IR vidicon camera.

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Broadband mid-infrared (IR) sources have been a topic of continuous research because of their wide applications, including remote sensing[1], spectroscopy[2], free-space communications[3], and biology medicine[4]. In explosive and chemical detection region, this band allows compact real-time monitoring of chemical processes as it exploits the strongest absorption peaks of common organic compounds within the mid-IR band[5,6]. In stand-off detection of solid samples using diffuse reflectance spectroscopy, the solar illumination can be replaced by an active light source such as the supercontinuum (SC), so it enables newer applications of the well-established technique.

With the recent development of various special optical fibers, including microstructure fibers[7–9], fiber tapers[10], highly nonlinear fibers[11], fluoride fibers, tellurite fibers, and chalcogenide fibers, broadband SC laser can be efficiently generated by pumping with high-power pulsed lasers (femtosecond, picosecond, and nanosecond pulses) or even with continuous-wave lasers. Most pump sources of the reported SC lasers are 1064/1550 nm ytterbium/erbium-doped fiber-based systems[12–14]. Although the spectra of generated SC laser can range from 500 to 2400 nm with watt-level average power, the spectrum density is relatively lower in > 2000 nm region. Thulium-doped fiber amplifiers (TDFAs) have recently aroused much interest for mid-IR SC generation > 2000 nm[15–18]. An up to 25.7 W power scalable TDFA-based SC laser spanning from ~2 to 2.5 μm was recently demonstrated by Alexander *et al.*[16]. However, when the power of SC laser got to maximum, the pulses repetition frequency (PRF) was ~1.1 MHz, and the pulse energy was only ~23.4 μJ. In addition, due to the modulation instability (MI) nonlinear optical effects in fiber, the output time-domain pulse shape was broken up from nanosecond pulses into several hundred femtosecond pulses, and the output pulse energy was also dispersed. Compared with SC generation in various special optical fibers, significantly smaller attention has been given to SC generation in the mid-IR range with the use of cheap and widely commercially available standard single-mode fiber (SMF) pumped by 2000 nm nanosecond pulses solid lasers.

In this letter, we have demonstrated, for the first time to the best of our knowledge, the SC generation in conventional standard SMF pumped by nanosecond Q-switched Tm,Ho:YVO_4 laser. The SC spectrum spreads mainly in the eye-safe spectral band > 1950 nm and is characterized by a relatively flat spectral distribution of the intensity (< 2%) in the wavelength interval of 2060–2400 and 2060–2360 nm. By increasing the pump power, up to 75.7 and 65 μJ pulse energies are obtained at PRFs of 7 and 10 kHz. The output pulse shape is measured, and the pulse is not broken up into a series of short pulses.

The experiment configuration of SC generation in standard SMF pumped by nanosecond Q-switched Tm,Ho:YVO_4 laser is as shown in Fig. 1.

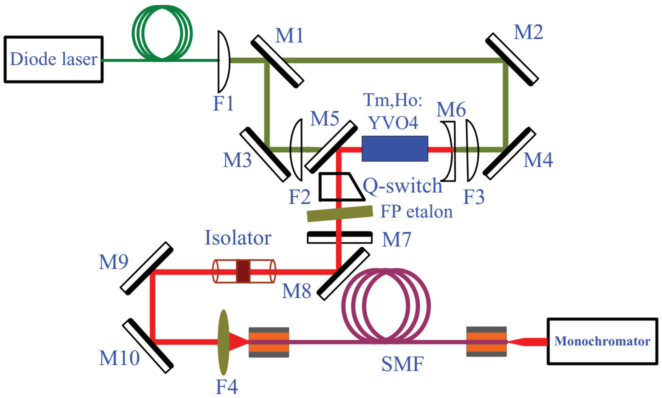

Fig. 1. Experimental configuration of SC light laser pumped by Q-switched Tm,Ho:YVO_4 laser.

The fiber-coupled laser diodes (LDs) with maximal output power of 35 W was used as the pump source. The emitting wavelength was in the range of 798–802 nm, depending on the heat sink temperature and the pump current. The diameter of output coupler fiber was 400 μm, and the numerical aperture was 0.22. The Tm,Ho:YVO_4 laser resonator geometry was plano-concave with a 800 mm radius of curvature concave input coupler, and the physical cavity length of the resonator was about 300 mm. The output coupler (M7) was a flat mirror with 40% transmission in the wavelength range of 1.9–2.2 μm. F1 was a coupling lenses with 25 mm focus. The mode matching lenses (F2 and F3) had a 50 mm focal length. M1 was a 45° dichromatic mirror with partial reflectivity of 50% at around 800 nm and M2, M3, and M4 were 45° dichromatic mirrors with reflectivity of 99.5% at around 800 nm. The Tm,Ho:YVO_4 for the experiment was cut with dimensions of 3 × 3 × 8 (mm), and the ion dopant concentrations were 4 at% Tm^{3+} and 0.4 at% Ho^{3+}. Both end faces of the crystal were antireflection coated for the laser wavelengths around 2 μm and the pump wavelength around 800 nm. The Tm,Ho:YVO_4 crystal was placed in the vicinity of lens focus (F2 and F3), and the confocal spot of 800 nm pump laser, inside of the Tm,Ho:YVO_4 crystal surface, was measured to be approximately 0.75 mm. The laser crystal was wrapped in indium foil and clamped in a copper heat sink and placed in a Dewar which was used as the liquid nitrogen reservoir. Q-switching experiment was achieved with a 46 mm long fused silica acousto-optical Q-switch. Its maximum radio frequency (RF) power was 50 W and the repetition rate could be tuned continuously from 1 Hz to 100 kHz. To achieve a 2050 nm wavelength operation, a Fabry–Perot etalon was also inserted into the optical path, and the thickness was 0.1 mm. The M8, M9, and M10 were 45° dichromatic mirrors with high reflectivity (≥ 97%) at 2.05 μm pulse laser and highly transmitting (≥ 90%) at around 800 nm diode lasers. The 2.05 μm pulse laser was directly coupled to standard SMF by a focusing lens (F4), and the focal length was about 7 mm. The SMF was perpendicular cleaved, and clamped in a copper heat sink, and the measured coupling efficiency was around 40%. In order to prevent Tm,Ho:YVO_4 laser from being influenced by the fiber end feedback and the nonlinear stimulated Brillouin scattering (SBS) laser, an optical isolator was placed into the pump path.

The output characteristics of Q-switched Tm,Ho:YVO_4 laser are shown in Fig. 2. Under pumping power of 32.9 W available from the LD, the maximum output powers

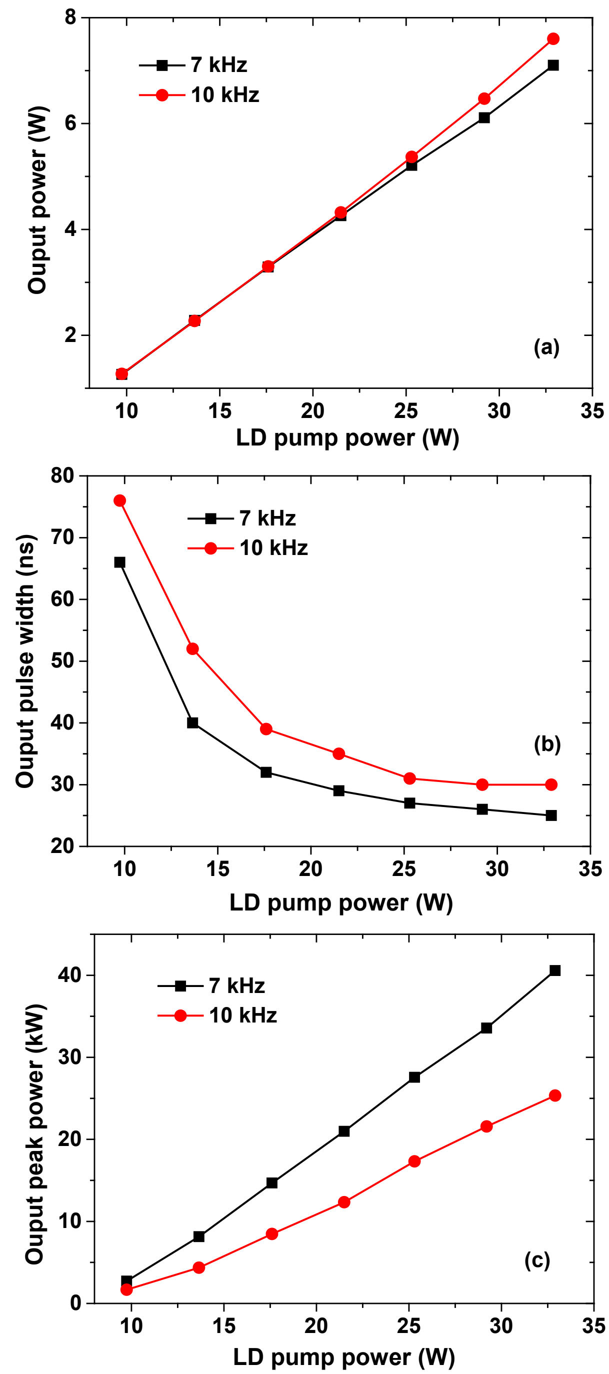

Fig. 2. Output characteristics of Q-switched Tm,Ho:YVO_4 laser at 7 and 10 kHz.

were 7.1 and 7.6 W at the PRFs of 7 and 10 kHz, respectively. The changing of slope efficiency was not obvious at different PRFs, and the slope efficiency was about 27.2% at 10 kHz (Fig. 2(a)). Figure 2(b) depicts the variation of pulse width versus the incident pump power measured. The pulse width began to narrow at the same repetition rate with the increasing laser output power, and the minimum pulse width obtained with PRFs of 7 and 10 kHz were 25 and 30 ns. From the measured pulse width and output power, the peak power can be estimated, and the peak power as a function of pump power is also shown in Fig. 2(c). The highest peak powers were 40.6 and 20.3 kW at 32.9 W pump power.

The output SC light source was directly coupled to a monochromator (300 mm focal length, 600 lines/mm grating blazed at 2.0 μm) and the resolution was 1.6 nm. The incident aperture of monochromator could be adjusted to obtain appropriate SC laser power. The lasing radiation divided from monochromator was monitored by an InGaAs detector with a SR830 lock-in the amplifier for signal extraction. The length of standard SMF in this experiment was about 15 m. Figure 3 illustrates the SC spectrum recorded for several values of average output power at PRFs of 7 and 10 kHz. It can be noted that higher pump power yields wider spectrum that can be achieved. At 0.81 W pump power, a weak SC spectrum was observed, and the spectrum broadening was inconspicuous. When the pump power was increased up to 1.53 W (the SC output power was ~0.53 W), the SC spectrum extended generation from 1950 to 2500 nm (Fig. 3(a)), and the full-width at half-maximum (FWHM) bandwidth was ~400 nm (from 2000 to 2400 nm). Compared with Fig. 3(a), the FWHM bandwidth of SC spectrum was shorter in Fig. 3(b), and was ~370 nm. The main reason is the pump peak power was lower when the PRF was increased from 7 to 10 kHz, and the SC spectral broadening was limited. Also note that the flatness of SC spectrum increases with an increase in pump power. At maximum pump power, the output spectrum had excellent flatness without any modulation behavior observed, and was also very stable in time in the whole wavelength range with deviation of $< 2\%$ which was very important for many applications. However, of particular importance to emphasize is the fact that the extremely stable output spectrum is a result of averaging over many laser pulses, and the main reason can be attributed to the slow detector used in the experiment. One can see that the intensity falls rapidly (in the case of maximum output power) for wavelengths higher than 2400 nm in standard SMF due to the exponential growth of the optical losses caused by the vibration absorption band of silicate glasses.

The average power of the SC light source was monitored by a power meter (Institute of Physics CAS, LPE-1A) with thermal sensor response range of 0.19–11 μm, covering the entire SC spectrum band. The achieved

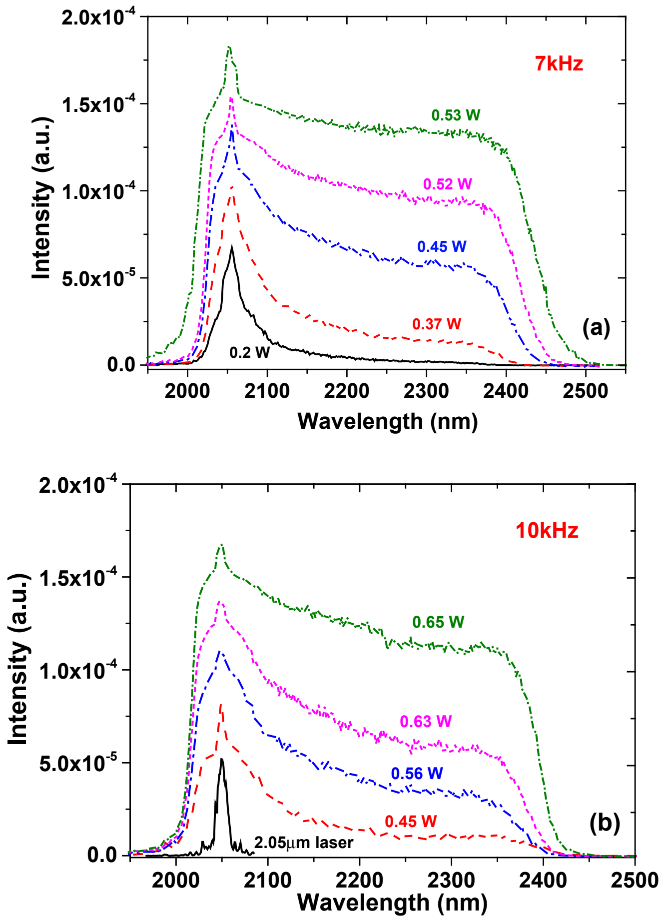

Fig. 3. Output spectra of SC laser for different average-time output powers at 7 and 10 kHz.

average SC output power on pump power, including the pump peaks at 2050 nm, is shown in Fig. 4(a), and the maximum obtained output power were 0.53 and 0.65 W at PRFs of 7 and 10 kHz in the experiment. The deviation from linearity of the curve of the average SC output power versus pump power launched into the SMF occurred for pump power higher than ~1 W (SC output power of 0.45 W) for which the spectrum tail was shifted beyond 2400 nm. The drop of conversion efficiency between the SC output power and pump power resulted from the fact that with the increase in pump power the SC power was distributed more and more toward longer wavelengths that experience larger material losses, and thus reducing the total output power. The SC output pulse energies were also estimated and the maximum were ~75.7 and ~65 μJ (Fig. 4(b)) at PRFs of 7 and 10 kHz. At 7 kHz, when pump power was higher than ~1.1 W, the linearity of the curve of the SC output energy versus pump power began to deviate, a further increase in the pump power did not lead to linear increase in the SC output energy.

Mechanisms responsible for SC generation in optical fibers have already been studied theoretically and experimentally, and widely demonstrated[19,20].

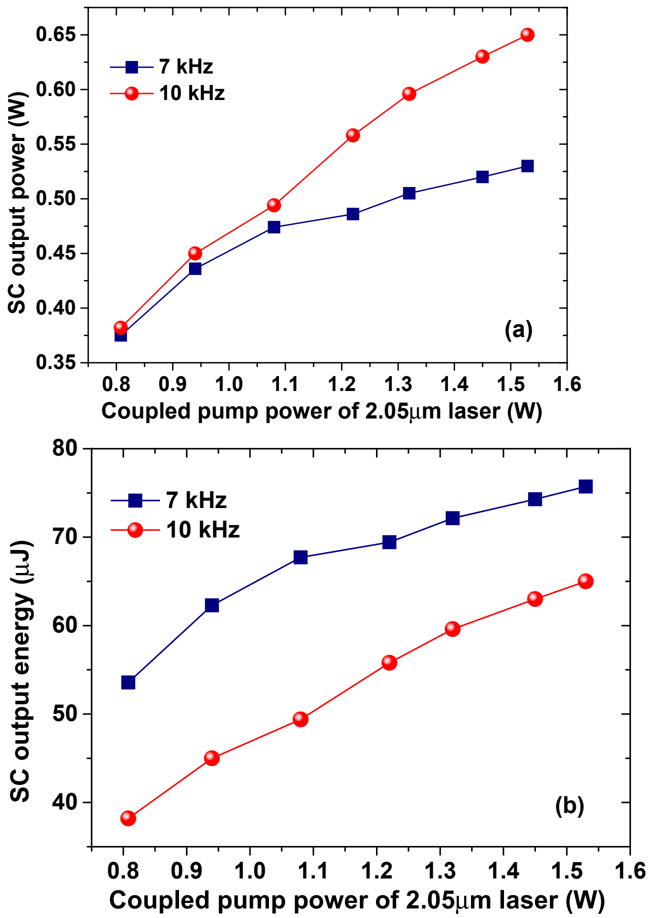

Fig. 4. SC output power and pulse energy versus pump power.

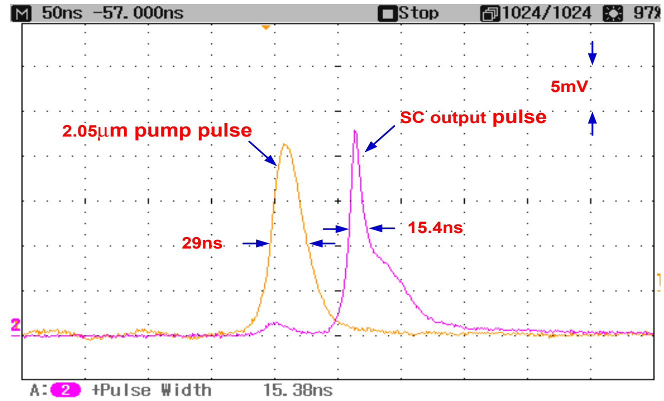

Fig. 5. Time-domain waveforms of input pump pulse and output SC pulse at 7 kHz.

The standard SMF used to generate SC light source in our approach works in its anomalous dispersion region, and the SC spectra are shifted only toward the long-wavelength side (Fig. 3). We believe the physical mechanism for SC generation are the MI, which plays an important role in the initial stage of SC generation, and the soliton self-frequency shifted Raman scattering, which leads to the SC spectra shift toward the long-wavelength side. The SC light pulse was detected by an InGaAs photodiode (rise/fall time ≤ 23 ns) that has a spectral range from 1.2 to 2.6 μm and frequency response up to 15 MHz. A 350 MHz digital oscilloscope (Wavejet 332, Lecroy) was used to record time-domain pulse duration. At output energy of 75.7 μJ, the input pump and output SC pulse shape are illustrated in Fig. 5. Compared with the pump pulse, the FWHM of output pulse duration begins to shorten, and reduces from ~29 to ~15.4 ns, which is due to the backward propagating SBS induced by the pump pulses in SMF, they counteract with the pump pulses, and induce narrowing of the output pulse. Unlike the reported time-domain pulse duration of SC pumped by mode-locked laser or nanosecond laser (pulse width ~1 ns)[21], the output pulse is not broken up into a series of short pulses, so the pulse energy is concentrated, and is also important in many applications. One can see that the output SC pulse shape is distortion for the input pulse, and this fact allows one to believe that MI effect is involved in the SC generation.

In order to measure the beam quality of the SC spectrum, the output of the SC light is passed through a 45° dichromatic mirror with high reflectivity (≥ 90%) at ~2.1 μm. The separated SC light is then focused by an f = 150 mm coated lens, and the intensity profile of the laser beam is mapped at different axial locations around the focal spot by using a 90/10 knife-edge cutting across the beam. The M^2 value is estimated by fitting the beam shape to the Gaussian beam propagation profile. Figure 6 shows the measured beam radius at different positions after the lens, and the beam quality is estimated to be M^2 = 1.06. At 0.53 W, the output laser beam spot and laser beam profile were monitored by an IR vidicon camera (Model PY-128-100A, Co. SPIRICON), and the figure is as shown in the inset of Fig. 6.

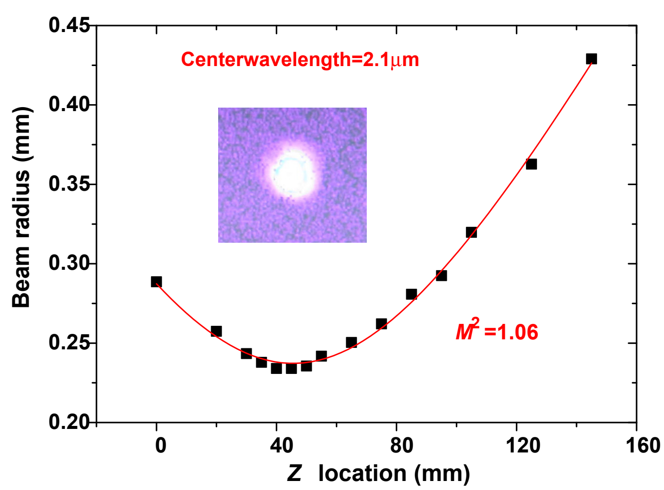

Fig. 6. Beam quality factor and laser beam spot of SC light at maximum output pulse energy.

In conclusion, we demonstrate the generation of a mid-IR SC laser with an ultra-flatness spectrum when a 15 m standard SMF is directly pumped by nanosecond Q-switched Tm,Ho:YVO_4 laser with central wavelength of 2054 nm. The output spectrum, covering a wavelength range of ~1950–2500 nm, is very stable and has a low-noise level. For a pump power of 1.53 W, the maximum SC output power and pulse energy are 0.65 W and 75.7 μJ. The time-domain output pulse duration is not broken into multi-pulses, and minimum pulse width is reduced to 15.4 ns. The near-diffraction-limited SC light beam is monitored by an IR vidicon camera, and the estimated beam quality M^2 is 1.06. The average SC output power has to be further scalable by coupled more pump power, and the maximal average power may be limited to damage threshold of SMF end.

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