Spatiotemporally mode-locked soliton fiber laser at 2.8 μm

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Abstract Spatiotemporal mode-locking creates great opportunity for pulse energy scaling and nonlinear optics research in fiber. Till now, spatiotemporal mode-locking has only been realized in normal-dispersion dissipative soliton and similariton fiber lasers. In this letter, we demonstrated the first experimental realization of spatiotemporally mode-locked soliton laser in mid-infrared fluoride fiber with anomalous dispersion. The mode-locked fluoride fiber oscillator directly generated a record pulse energy of 16.1 nJ and peak power of 74.6 kW at 2.8 μm wavelength. This work extends the spatiotemporal mode-locking to soliton fiber lasers and should have a wide interest for laser community.

Key words: spatiotemporal mode-locking, soliton fiber laser, mid-infrared

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I. INTRODUCTION

In recent years, multimode fiber has aroused numerous attentions as a new platform to study the complex nonlinear interaction and mode-locking dynamics\cite{1-5}. Some novel phenomena and physics mechanisms such as self-beam cleaning, mode self-organization, acceleration of wave condensation, etc. have been found in multimode fiber. In 2017, L.G. Wright, et al. first realized the spatiotemporal mode-locking in multimode fiber laser, in which the longitudinal modes and transverse modes are locked in phase and thus the laser generates a variety of spatiotemporal profiles\cite{6,7}. The spatiotemporal mode-locking extends one-dimensional longitudinal mode-locking to three-dimensional longitudinal and transverse mode-locking, and provides a platform for complex nonlinear interaction and mode-locking dynamic research. In the meanwhile, spatiotemporal mode-locking in multimode fiber expands the effective area of fibers and has a potential to significantly improve the mode-locked pulse energy of fiber lasers. The spatiotemporal mode-locking should be very attractive for pulse energy scaling of soliton fiber lasers, in which the pulse energy is limited according to soliton area theorem\cite{8}. So far, spatiotemporal mode-locking has been realized in dissipative soliton, similariton, dispersion-managed soliton fiber lasers and Mamyshev oscillators around 600 nm, 1 μm and 1.5 μm wavebands\cite{9-16}.

In the recent decade, fluoride fiber mode-locked lasers around 3 μm wavelength have attracted wide interests due to their great potential in mid-infrared supercontinuum generation, molecular spectroscopy, medial surgery, semiconductor processing, and frequency down-conversion\cite{17-24}. Since fluoride gain fiber has a large anomalous dispersion, the fluoride fiber mode-locked lasers generally operate in soliton regime\cite{25-30} and the mode-locked pulse energy is limited by soliton area. Through dispersion management, the pulse energy of mode-locked fluoride fiber laser has been increased by times\cite{31,32}. Due to the anomalous dispersion of fluoride fiber in
mid-infrared, it is difficult to realize the dissipative soliton and similariton in fluoride fiber that generally can produce higher pulse energy. Thus, it should be interesting to demonstrate spatiotemporal mode-locking in mid-infrared fluoride fiber, which may significantly scale up the pulse energy by exploiting the multimode fiber with large mode area.

In this letter, we report on a spatiotemporally mode-locked soliton fiber laser for the first time. By using Er\textsuperscript{3+}-doped ZBLAN multimode fiber as gain medium and nonlinear polarization rotation mode-locking, spatiotemporal mode-locking was realized. The spatiotemporally mode-locked soliton fiber oscillator directly produced a record pulse energy of 16.1 nJ and peak power of 74.6 kW with an average output power reaching 1.09 W at 2.8 μm wavelength. The soliton pulse energy has the potential to be further improved by adopting larger-core multimode fiber. This work extends spatiotemporal mode-locking to soliton regime and mid-infrared wavelength, and should be interesting for laser community.

II. EXPERIMENTAL SETUP

The experimental setup of the spatiotemporally mode-locked soliton Er:ZBLAN fiber laser is illustrated in Figure 1. A fiber-coupled laser diode (LD) operating at 976 nm was used as a pump source. The core diameter of the pigtailed fiber is 105 μm, and the numerical aperture (NA) is 0.22. The maximum output power from the laser diode is 30 W. The pump beam was collimated by a spherical lens L1 (f = 10 mm) and then focused by an aspherical lens L2 (f = 12.7 mm) into an Er\textsuperscript{3+}-doped double cladding ZBLAN fiber (FiberLabs, Japan). The multimode Er:ZBLAN fiber has a core diameter of 30 μm with a length of 2.4 m and an Er-doping of 6 mol.%. The refractive indices of core and clad at 2.8 μm wavelength are 1.4916 and 1.4850, respectively. The numerical aperture (NA) of Er:ZBLAN fiber is 0.14. The group velocity dispersion (GVD) of the fiber at 2.8 μm wavelength is -110.5 fs\textsuperscript{2}/mm. The pump absorption ratio of the fiber is 3~5 dB/m, and the fiber
loss at 2.8 μm wavelength is 0.1–0.2 dB/m. The V parameter of the fiber at 2.8 μm wavelength is 4.72, which supports approximately eight transverse modes. The cladding diameter of the Er:ZBLAN fiber was 300 μm for efficiently coupling the pump light into fiber. The two end facets of fiber were cleaved at 8° angle, avoiding the parasitic oscillation from fiber facets. The 2.8 μm laser from gain fiber was collimated by aspherical lens L₃ with a focal length of 12.7 mm. The utilization of aspherical lens will reduce the adverse effects caused by the aberrations. The output coupler (OC) had a transmission of 40%. A half-wave plate (HWP), an isolator including polarizers, and a quarter-wave plate (QWP) were inserted into the cavity for realizing the mode-locking of nonlinear polarization rotation (NPR)\[33\]. The isolator had a cleaning diameter of 4 mm, which could serve as a spatial filter for spatiotemporal mode-locking. The HWP, isolator, and QWP were coated with a high transmission at 2.8 μm wavelength. A 45°-placed dichroic mirror (high reflectivity for 2.8 μm and high transmission for 976 nm) was used to combine the pump beam and laser beam, and then the two beams were coupled into gain fiber through aspherical lens L₂. The forward-pumping scheme was applied, which helps faster accumulating of nonlinear phase shift for NPR mode-locking.

The coexistence of multiple transverse modes is of vital importance as it is the prerequisite of realizing spatiotemporal mode-locking. In the experiment, the axial positions of two aspherical lenses L₂ and L₃ could be adjusted to control the high order transverse modes. The off-focus of the two aspherical lenses will couple the beam into high order modes. In addition, the off-focus of the two aspherical lenses also changes the beam size on the isolator, which acts as a spatial filter. In the experiment, the isolator cleaning aperture was only a bit larger than the size of fundamental mode, which helps to filter very high order transverse modes. The spatial filtering effect of the isolator is helpful to realize stable spatiotemporal mode-locking.
**Figure 1.** Schematic of the spatiotemporally mode-locked soliton Er:ZBLAN fiber laser. LD: laser diode, L$_1$: spherical lens, L$_2$ and L$_3$: aspherical ZnSe lenses, M: dichroic mirror, OC: output coupler, HWP: half-wave plate, QWP: quarter-wave plate, ISO: isolator. Inset: the enlargement of fiber facet obtained by a scanning electron microscope, showing 30-μm fiber core diameter.

**III. EXPERIMENTAL RESULT AND DISCUSSION**

The output beam patterns of the fiber laser were recorded by a mid-infrared CCD (Tigris-MWIR-MCTBB-640, Xenics), as shown in Figure 2(a-d). From the beam patterns, we clearly observed the coexisting multiple transverse modes oscillation. The beam profile in CW operation [Figure 2(a)] was obviously different from those in spatiotemporal mode-locking operations [Figure 2(b-d)], as observed in spatiotemporally mode-locked laser\(^6\). However, in spatiotemporal mode-locking operation, the beams have very similar profiles in spite of different pump powers. In addition, the $M^2$ factor was also measured with knife-edge method in the spatiotemporal mode-locking operation, as shown in Figure 2(e). The $M^2$ factors in x and y directions were measured to be 2.93 and 2.84, respectively, further showing multiple transverse modes operation in the mode-locked laser.
Figure 2. (a) The output beam patterns recorded in continuous-wave operation. (b-d) The output beam patterns recorded in spatiotemporal mode-locking operation at different pump powers. (e) The measured $M^2$ factors of output beam at pump power of 4.40 W in spatiotemporal mode-locking operation.

Through finely adjusting the waveplates, stable spatiotemporal mode-locking could be realized in the multimode fiber laser. A high-speed mid-infrared photoelectric detector and an oscilloscope with 1 GHz bandwidth was used to record the mode-locked pulse trains. The spatiotemporal mode-locking shows a stable mode-locking pulse trains in nanosecond and millisecond scales [Figure 3(a)], with a pulse period of ~15 ns. To further testify the simultaneous mode-locking of multiple transverse modes, we sampled the mode-locked pulse trains at different spatial positions in the beam by placing a pinhole in front of the photoelectric detector. The pinhole and the photoelectric detector can be moved for sampling. The mode-locked pulse trains at different spatial positions along X axis (dashed line in Figure 2(b)) are recorded, as shown in
Figure 3(b). For the different positions in the beam of multiple transverse modes, mode-locked pulse trains could be observed. Besides, the intensities of pulse trains detected at different spatial positions are plotted in Figure 3(c). The intensities show an irregular change without symmetry along X axis, also suggesting that mode-locking is made up of multiple transverse modes, because single-transverse-mode mode-locked pulse intensity should be symmetry along X axis. These mean the generation of spatiotemporal mode-locking in the laser.

**Figure 3.** (a) Recorded mode-locked pulse trains in 200 ns and 1 ms time scales. (b) Sampled pulse trains at different spatial positions. (c) Intensities of sampled pulse trains versus spatial positions.

The radio-frequency (RF) spectrum in Figure 4(a) shows a signal-to-noise ratio (SNR) of 71 dB at fundamental frequency of 68 MHz. The intensity roll-off in the wide-range RF spectrum was due to the limited bandwidth of mid-infrared detector. The high SNR indicates that a stable continuous-wave mode-locking was realized. The pulse duration of the mode-locked pulses was measured with a commercial mid-infrared autocorrelator. As shown in Figure 4(b), the mode-
locked pulses have a pulse duration of 216 fs, assuming a sech² pulse profile. The output spectrum of spatiotemporally mode-locked fiber laser was measured with a mid-infrared spectral analyzer, which covers a wide range of 1-5 μm wavelength. The central wavelength of the mode-locked pulse was located at 2.8 μm, as shown in Figure 4(c). From the mode-locking spectrum, Kelly sideband can be observed, which is a typical characteristic of soliton mode-locking. The sidebands of shorter wavelength disappear, which may be attributed to vapor absorption in this band.

**Figure 4.** (a) Measured radio-frequency (RF) spectrum of the mode-locked pulses. Inset: RF spectrum with 500 MHz span. (b) Measured autocorrelation trace of the mode-locked pulses (black dots) with a sech² fit (blue solid line). (c) Optical spectrum of mode-locked pulses. These results were measured under the average output power of 1.09 W.

In the experiment, the minimum pump power that initiated soliton mode-locking was 3.29 W, and the corresponding average output power was 335 mW. As we increased the pump power, the
average output power increased linearly with a slope efficiency of 10.4%, as shown in Figure 5. The pulse duration slightly decreased with the increase of the pump power, which is owing to the spectrum broadening induced by self-phase modulation. The achieved maximum average output power was 1.09 W under the pump power of 10.89 W. Considering the pulse duration of 216 fs and the repetition rate of 68 MHz, the corresponding pulse energy and peak power were 16.1 nJ and 74.5 kW, respectively.

![Figure 5](image)

**Figure 5.** The output average power and pulse energy versus pump power for the spatiotemporally mode-locked soliton fiber laser. The recorded data is the corresponding pulse duration and peak power.

The soliton splitting and collapse will occur in soliton laser if the excessive nonlinear phase shift is accumulated. The soliton splitting was observed in mode-locked soliton fluoride fiber laser when the pulse energy reached 7.6 nJ[27]. In our work, the soliton splitting and collapse were not observed even though a much higher pulse energy was generated. This owes to the extension of spatial scale resulting from spatiotemporal mode-locking. According to the soliton area theorem, the soliton area is inversely proportional to the nonlinear parameter $\gamma$, and the nonlinear parameter $\gamma$ is inversely proportional to the guiding mode area of fiber. Therefore, the larger guiding mode
area of multimode fiber decreases the nonlinear parameter $\gamma$, and thus increases the upper limit of soliton pulse energy.

The pulse energy of soliton Er:ZBLAN fiber laser has potential to be further improved. For example, using a commercially available Er$^{3+}$-doped ZBLAN fiber with 70-μm core diameter, the guiding mode area will be enlarged by more than 20 times compared to single mode fiber. The spatiotemporally mode-locked soliton pulse energy is expected to exceed one hundred nanojoules, and the pulse peak power is expected to reach hundreds of kilowatts. This means that it is possible to scale up the soliton pulse energy and peak power in mid-infrared by an order of magnitude, promising a wide application prospect.

The pulse energy from fiber mode-locked lasers has exceeded microjoule level around 1 μm wavelength\[^{34}\]. However, the pulse energy of 3 μm fiber mode-locked lasers was lower by two orders of magnitude since the existing high-energy mode-locking pulse mechanisms such as dissipative soliton and similariton are difficult to operate in anomalous-dispersion fibers. So far, pulse energies from 3 μm fiber femtosecond mode-locked lasers have not exceeded 10 nJ yet even though various ways have been tried\[^{27-32}\]. The introduction of spatiotemporal mode-locking to mid-infrared creates the possibility for narrowing the gap with near infrared.

**IV. CONCLUSION**

In conclusion, we successfully demonstrated a spatiotemporally mode-locked soliton fiber laser for the first time. By using Er:ZBLAN fiber with anomalous dispersion as gain medium and NPR mode-locking, soliton spatiotemporal mode-locking was realized with a SNR ratio of 71 dB. Using Er:ZBLAN fiber with a core diameter of 30 μm, the spatiotemporally mode-locked soliton fiber laser directly produced a record pulse energy of 16.1 nJ and peak power of 74.5 kW at 2.8 μm
wavelength, the corresponding average output power reached 1.09 W with pulse duration of 216 fs. The mid-infrared pulse energy and peak power have potential to be further scaled up if the spatial scale of fiber is further enlarged. The work provides a feasible way to scale up the pulse energy and peak power of mid-infrared mode-locked fiber lasers.

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References


