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65-fs Yb-doped all-fiber laser using tapered fiber for nonlinearity and dispersion management

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We implement an ultrafast Yb-doped all-fiber laser which incorporates tapered single-mode fibers for managing nonlinearity and dispersion. The tapered fiber placed in the oscillator cavity aims to broaden the optical spectrum of the intracavity pulse. At the oscillator output, we use another tapered fiber to perform pulse compression. The resulting 66.1-MHz Yb-doped all-fiber oscillator self-starts and generates 0.4-nJ, 65-fs pulses, which can serve as a compact and robust seed source for subsequent high-power, high-energy amplifiers.

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The past decade has seen tremendous development of mode-locked Yb-doped fiber lasers to meet the demand of both scientific research and industrial applications [1–6]. Because conventional single-mode fibers possess positive group-velocity dispersion (GVD) at 1.04 μm—the typical operational wavelength for Yb-doped fiber lasers—managing the intracavity dispersion of ultrafast Yb-doped fiber lasers is normally achieved by inserting free-space elements (e.g., a grating pair) into the laser cavity [7,8]. These mode-locked Yb-doped fiber lasers directly output chirped pulses. Another pair of diffraction gratings is normally used to compress these chirped pulses to the Fourier transform-limited (FTL) duration. Development of mode-locked Yb-doped lasers in an all-fiber format demands replacement of the free-space elements by compact fiber devices that can provide large negative GVD. Several types of these fiber devices were reported including solid-core photonic crystal fiber (PCF) [9], hollow-core PCF [10], chirped fiber Bragg grating [11], and higher-order mode fiber [12]. Although they have been incorporated into mode-locked Yb-doped fiber lasers, these devices have their disadvantages. For example, use of PCF undoubtedly introduces high loss and technical difficulties in splicing PCF and single-mode fiber. Higher-order mode fibers require additional long-period Bragg gratings for mode conversion between the fundamental mode and higher-order modes. A chirped fiber Bragg grating operates in the reflection mode and has to be used together with a circulator for a ring-cavity laser, which inevitably causes several dB insertion loss. Moreover, the common drawback of the fiber-based dispersion compensation elements mentioned previously is their low quantity of anomalous dispersion at 1.04 μm; to obtain a wider spectrum from the oscillator, the length of these devices inserted in the cavity should be long enough for a full dispersion compensation. This gives a limitation on repetition rate. Tapered single-mode fibers constitute an alternative solution in that the dispersion and loss properties can be easily controlled by fine tuning the taper waist diameter. Additionally, the associated small mode area greatly enhances the intracavity nonlinearity to broaden the output spectrum. Rusu *et al.* used a tapered single-mode fiber as a dispersion compensator in a semiconductor saturable absorber mirror (SESAM) mode-locked linear laser cavity [13]. By switching the taper insertion in the laser cavity, the laser can work in positive dispersion or negative dispersion regimes. Rusu *et al.* demonstrated a mode-locked Yb-doped all-fiber laser that produces 65-MHz, 3-ps pulses with 10-nm bandwidth.

In this Letter, we present an Yb-doped all-fiber ring-cavity laser employing two tapered single-mode fibers. The tapered fiber placed inside the cavity manages both dispersion and nonlinearity, and the one outside the cavity serves as the pulse compressor. The resulting all-fiber laser self starts and generates 66.1-MHz, 65-fs pulses, which, to the best of our knowledge, are the shortest pulses directly delivered from Yb-doped all-fiber ring-cavity lasers.

The tapered fiber was made from SM-28 fiber using the flame brush technique [14]. The tapering machine is from KAIPULE with all the taper pulling processes controlled by program. During tapering, a premixed hydrogen–oxygen burner is swept over a short span of fiber. The detailed length setting was based on our expected length and diameter of the tapering waist. As the two fiber ends were pulled in opposite directions at low speed, the heating region needs to be preprocessed and wiped clean. The tapering process is shown in Fig. 1. To ensure the taper waist with high uniformity and relatively

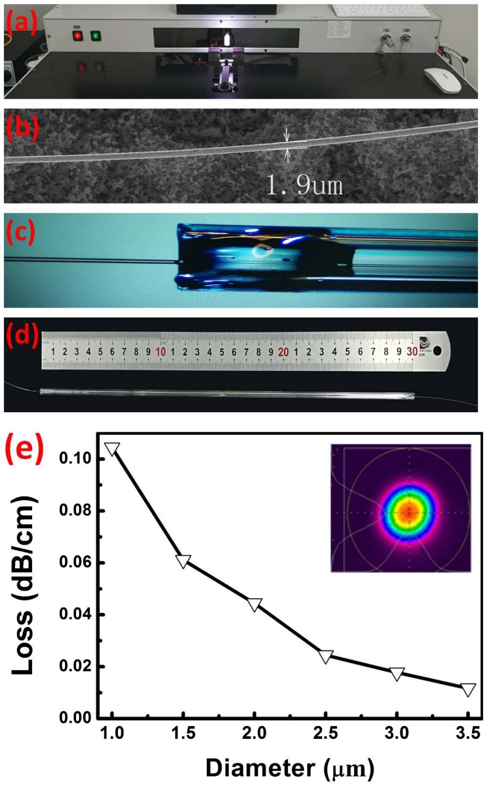

Fig. 1. Fabrication of the tapered fiber: (a) scan heating mode, (b) scanning electron microscopic image of taper waist, (c) gluing and UV curing process, (d) the taper fiber with encapsulation, and (e) measured loss of the tapered fiber with the waist diameter (inset is the far field spatial distribution).

short transition region, we adopt a two-stage pulling process. In the first stage, the fiber is heated in a relatively short region (<2 cm) and tapered down to a diameter of 10–20 μm. In the second stage, the sweep range of the torch flame nozzle varies linearly with the taper extension to achieve conical transitions as short as possible, as shown in Fig. 1(a). The taper waist can be pulled up to 23 cm, and a total conical transition zone length as short as 8 cm can be achieved by tightly controlling over the torch gas flow and brush speed.

A single-mode fiber (nominal diameter of 125 μm) can be tapered to a waist diameter less than 2 μm, as shown by the scanning electron microscope image of the taper waist in Fig. 1(b). After fabrication, each end of the taper pigtail was promptly glued on a clear fused quartz groove while the taper waist is suspended above the groove, as shown in Fig. 1(c). Tapered fiber with such small diameter is fragile and can be easily contaminated, which requires further quartz tube packaging [Fig. 1(d)]. The transmission loss of tapered fibers was measured by a laser diode at 976 nm with 1-nm bandwidth. The measured loss is plotted in Fig. 1(e), showing that the fiber taper loss increases monotonically with the reduced taper waist diameter.

The dispersion of a single mode fiber mainly includes material dispersion and waveguide dispersion. For single mode fiber HI1060, the GVD is ∼23 fs^2/mm at 1040 nm [15]. When the waveguide dimension is reduced to a scale comparable to the optical wavelength, significant waveguide dispersion is introduced and dominated [16–18]. Figure 2 shows the

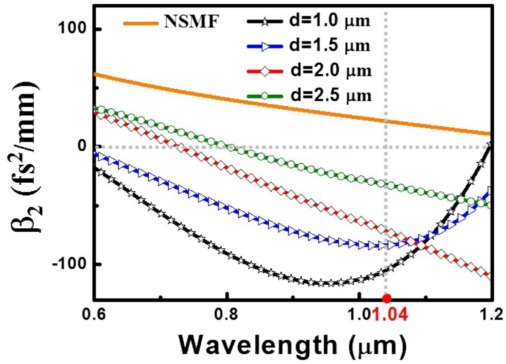

Fig. 2. Calculated GVD curve of tapered fiber for different waist diameter which varies from 1.0 to 2.5 μm with a step of 0.5 μm; the solid orange curve is the GVD of NSMF.

calculated dispersion by the finite element method for tapered fibers with different waist diameter (1.0, 1.5, 2.0, 2.5 μm) and dispersion of normal single-mode fiber (NSMF). As expected, the tapering process significantly modifies the fiber dispersion property. The zero-dispersion wavelength (ZDW) is blue-shifted with the reduced taper diameter. As the short-wavelength ZDW shifts below 1 μm, GVD at 1.04 μm (the center wavelength of this Yb-fiber oscillator) becomes negative, and the resulting tapered fiber can be used as an effective fiber-based dispersion compensation element in the all-normal-dispersion Yb-fiber laser. For the best choice of dispersion compensation at 1.04 μm, the most effective taper waist diameter is ∼1.0 μm, resulting in GVD of −110 fs^2/mm. However, the reduction in waist diameter corresponds to a gradually increased optical loss. Given the tradeoff between the dispersion and the optical loss, we chose the tapered fiber with 2-μm waist diameter. The tapered fiber exhibits −70 fs^2/mm GVD and 0.7 dB optical loss.

Two homemade tapered fibers were employed in a typical ring cavity Yb-doped fiber laser mode locked by nonlinear polarization evolution. The experimental setup is illustrated in Fig. 3. The ring cavity consists of 30-cm Yb-doped fiber (CorActive Yb-406). Two polarization controllers (PCs) were used for fine tuning the mode-locking state. One polarization maintaining optical isolator (PM-OI) ensures laser unidirectional operation. The laser diode (LD) was used as pump laser with maximum power of 800 mW, which is injected by a 976/1040 nm wavelength division multiplexer (WDM). A 20/80 optical coupler (OC) was used for the signal laser output device. A bandpass filter (BPF) (center wavelength at 1040 nm with 2.5-nm bandwidth) keeps the mode locked state more stable. Two tapered fibers were employed in constructing the laser. The one in the cavity was placed between PC and OC for dispersion management and spectrum broadening. The second tapered fiber was spliced at the OC output port for pulse compression.

For a comparison, we first constructed the laser cavity without the tapered fiber in the cavity. The devices used in the cavity are all fiber based. The total cavity length is ∼3.0 m, and the estimated net dispersion without tapered fiber in the cavity is ∼69,000 fs^2. Stable mode locking can be achieved at 420-mW pump power, leading to 28-mW signal output from the 20% port of the optical coupler. The output pulse is 1.6 ps in duration (measured by pulse check, A.P.E.) with 10-nm spectrum

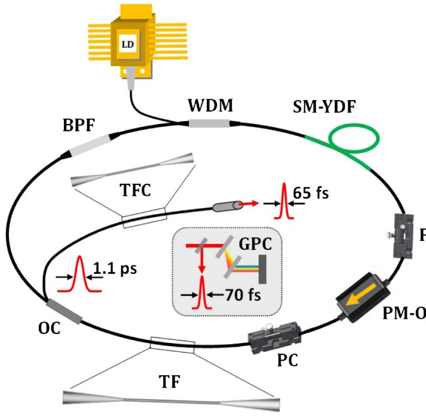

Fig. 3. Schematic of the Yb-doped all-fiber oscillator incorporating tapered fibers. Inset illustrates external-cavity pulse compression using a grating pair or a tapered fiber. LD: laser diode, PC: polarization controller, WDM: wavelength division multiplexer, YDF: ytterbium doped fiber, TF: tapered fiber, OC: optical coupler, PM-OI: polarization maintaining optical isolator, GPC: grating pair compressor; TFC: tapered fiber compressor; BPF: bandpass filter.

width. The optical spectrum is shown as the solid black curve in Fig. 4(a).

When 18-cm tapered fiber (with estimated GVD of ~ -70 fs^2/mm) was included in the cavity, the net cavity

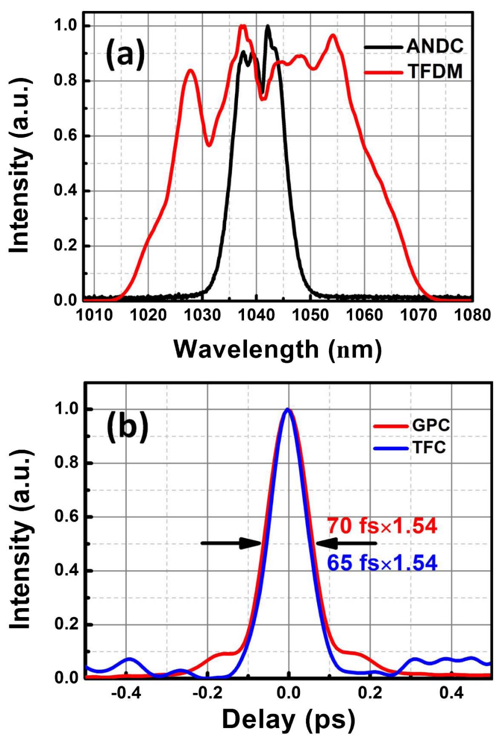

Fig. 4. (a) Spectrum of output mode-locked all Yb-fiber oscillator (the solid black curve is the spectrum from the oscillator without tapered fiber; the red solid curve is the spectrum from the oscillator with a tapered fiber); (b) autocorrelation traces for the pulses compressed by GPC (red) and compressed by TFC (blue) with assuming a sech^2 pulse shape.

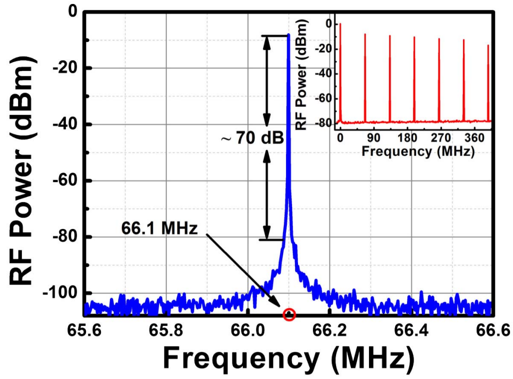

Fig. 5. RF spectrum of the Yb-doped all-fiber oscillator.

dispersion is reduced to $\sim$56,400 fs^2. Mode locking was achieved at a pump power of 680 mW due to the added insertion loss. We intentionally place the tapered fiber right before the output coupler to enhance the accumulated nonlinearity and therefore efficiently broaden the optical spectrum of the intracavity pulse. The red curve in Fig. 4 shows that the mode-locked pulse spectrum is $\sim$37 nm. The mode-locked output power from the OC is 46 mW. The output pulse duration from the OC was measured to be 1.1 ps.

To compress the pulses, we first used a grating pair compressor (GPC) to compress the pulse, which allows us to estimate the total dispersion that the compressor should provide to obtain a shorter pulse output. We then design a tapered fiber with similar amount of dispersion to replace the grating pair. The GPC includes two transmission gratings (groove density: 1000 lines/mm; incident angle: 31.3°) and a 0°HR roof mirror. By fine tuning the distance between the two gratings to near 3.5 mm, we obtained the compressed pulse duration near 70 fs [red solid line shown in Fig. 4(b)]. The estimated group-delay dispersion (GDD) that GPC provided is near −22,000 fs^2. We then used another tapered fiber with 12-cm pigtail length, 7-cm transition region, and 22-cm tapered waist length to replace the grating pair for pulse compression. The tapered fiber for the pulse compression has a smaller waist diameter of around 1 μm, which provides −24,200 fs^2 total GDD. As a result, the output pulses are compressed to 65 fs [blue curve in Fig. 4(b)]. The compressed pulse power is near 28 mW.

Figure 5 shows the RF spectrum measured by a RF analyzer (ROHDE and SCHWARZ FSW26). At the repetition rate of 66.1 MHz, the signal to noise ratio is better than 70 dB (300 Hz resolution bandwidth), indicating an excellent stable mode locking.

In conclusion, we developed a Yb-doped all-fiber oscillator mode locked by nonlinear polarization evolution. The laser directly delivers 66.1-MHz, 65-fs pulses with 28-mW average power. This provides a new way for delivering almost FTL pulses directly from a Yb-doped all-fiber oscillator. We expect that this type of all-fiber laser will find many applications.

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