Practical low-noise stretched-pulse Yb^{3+}-doped fiber laser

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We report on the development of what we consider to be a practical and highly stable stretched-pulse laser based on Yb^{3+}-doped silica fiber. The Fabry–Perot cavity uses nonlinear polarization rotation as the mode-locking mechanism, and a semiconductor saturable-absorber mirror to ensure robust self-starting and incorporates a diffraction grating pair to compensate for the normal dispersion of the fiber. Use of a single-mode grating-stabilized telecommunications-qualified pump laser diode ensures reliable, low-noise operation (~0.05% amplitude fluctuations at 10-Hz measurement bandwidth). The laser generates high-quality, 60-pJ pulses of <110-fs duration at a repetition rate of ~54 MHz (3-mW average power). © 2002 Optical Society of America

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Stable, low-noise sources of ultrashort pulses are important for a wide range of applications including ultrafast spectroscopy, multiphoton microscopy, and the pumping of parametric devices. Passively mode-locked, stretched-pulse fiber laser cavities based on Er^{3+}-doped fiber can operate with low amplitude noise and timing jitter,[1] and such lasers are now available commercially. Yb^{3+}-doped silica fiber, with its broad gain bandwidth, represents an attractive medium for the generation and amplification of ultrashort optical pulses. However, constructing a stretched-pulse cavity operating at 1 μm requires the inclusion of a prism/grating dispersive delay line (DDL) to compensate for the normal dispersion of the fiber. Here we report the development of a compact and highly stable stretched-pulse laser operating at 1.06 μm, based on Yb^{3+}-doped fiber. The system's stability is attributable largely to the use of a grating-stabilized, telecommunications-qualified 976-nm laser-diode pump laser. Pump coupling is both conveniently and reliably achieved with a 976/1050-nm fused-tapered wavelength-division multiplexer coupler. We believe that this oscillator will prove attractive for use in a wide range of scientific and industrial applications.

In our first demonstration of an ultrashort pulse (~65-fs) Yb^{3+} silica fiber oscillator in 1996,[2] we used a unidirectional cavity design incorporating an optical circulator arrangement and an intracavity prism-based DDL. Nonlinear polarization evolution in the fiber acted as the fast saturable absorber. The laser exhibited good self-starting performance and generated <100-fs pulses. However, the cavity was large and complex and was pumped with a Ti:sapphire laser. A passively mode-locked stretched-pulse laser based on a Nd-doped fiber in a Fabry–Perot cavity with a prism-based DDL was reported in 1993.[3] Nonlinear polarization evolution was used as a fast saturable-absorber mechanism, and a semiconductor saturable-absorber mirror (SESAM) was used to induce self-start mode locking.[4] Although the laser's performance in terms of pulse duration and quality seemed good, no data were presented on system stability and reliability. Moreover, this system was end pumped with two polarization-multiplexed 150-mW laser diodes (808 nm) or with a Kr^{3+} laser (to produce the shortest pulses), so the system was still not practical for wide application. There have been a number of reports of stretched-pulse lasers operating at 1 μm with high-power broad-stripe pump diodes and cladding-pumped Yb^{3+} or Nb^{3+}-doped fiber. Cladding-pumped fiber readily permits scaling of the pulse energies that are achievable from diode-pumped cavities to the nanojoule regime, but high-power diode-pump sources are typically not stable against wavelength drift and are noisier than the grating-stabilized high-brightness single-mode didoes that have been developed for core pumping of Er-doped fiber amplifiers. Moreover, because of the reduced overlap of pump and signal fields in dual-clad fibers, cladding-pumped fiber lasers are ordinarily much longer than core-pumped fiber lasers. Cladding-pumped lasers are thus inherently likely to be far less stable than cavities based on core-pumped fiber.

We now report a mode-locked Yb^{3+} fiber system that, in contrast to the lasers discussed above, is compact, simple to build, and reliably self-starting and has low amplitude noise. The laser employs a fiber-coupled grating-stabilized diode pump and is based on a simple Fabry–Perot cavity design with a compact, grating-based DDL.

A schematic of our laser is shown in Fig. 1. Mode-locked operation is based on the stretched-pulse principle[5]; it employs nonlinear polarization evolution as a fast saturable absorber.[6] The cavity contains a grating-based intracavity dispersion compensator, ~1.0 m of high-concentration, moderately birefringent Yb^{3+}-doped fiber with angle polished ends to suppress intracavity reflections, and a 976/1050-nm wavelength-division multiplexer coupler. Two polarizers and associated wave plates are included to control

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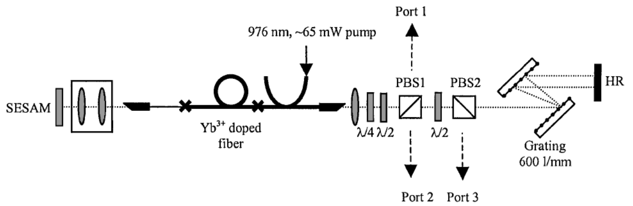

Fig. 1. Experimental configuration: HR, high-reflectivity mirror.

the bias of the polarization switch and adjust the output coupling. A suitably optimized SESAM device (InGaAs multiple-quantum-well absorbed, with a rear Bragg mirror made from AlAs–GaAs quarter layers) is also incorporated to facilitate reliable self-start mode locking.[3] The laser is pumped with a 976-nm pump diode (~65 mW), as described above. The output is extracted from either polarizing beam splitter PBS1 or PBS2. The polarization switch is PBS1, where the rejected part of the pulse appears at Port 1. The half-wave plate between PBS1 and PBS2 provides adjustable output coupling; positively chirped pulses are output from PBS2 at Port 3, and negatively chirped pulses are output from PBS1 at Port 2. The pulses, which have a linear chirp, are compressible external to the cavity, for example, by use of a diffraction grating pair at Port 3 or by propagation of the pulses from Port 2 along an ~80-cm length of single-mode fiber.

The large normal group-velocity dispersion [$D = -50$ ps/(nm/km)] introduced into the cavity by the fiber is balanced by the anomalous dispersion of the grating-based DDL. However, the third-order dispersion of the grating pair is of the same sign as that of the fiber, so to reduce the pulse distortion due to third-order dispersion we minimized the length of active fiber in the cavity. The ~1-m length of high-concentration (2300 parts in 10^6 by weight) Yb^{3+}-doped silica fiber (NA, 0.21; cutoff, ~940 nm) pumped at 976 nm (close to the Yb^{3+} absorption maximum at 975 nm) was used for all the results presented below. The total length of fiber in the cavity was 1.46 m, and the second- and third-order dispersions of the 1.46 m-length of fiber were estimated to be 5.1×10^4 fs^2 and 2.9×10^4 fs^3, respectively, at 1056 nm.

The DDL comprised a 600-line/mm diffraction grating pair, with the beam incident at a 30° angle with respect to the grating normal. We adjusted the dispersion of the DDL by varying the grating separation. The most stable operation and the shortest pulse durations were achieved with a grating separation of 5.4 cm, corresponding to second- and third-order dispersions (double pass) of -8.3×10^4 fs^2 and 1.5×10^5 fs^3, respectively. The total second- and third-order dispersions in the cavity, including a double pass of 1.46 m of fiber and the DDL set with the optimum grating separation of 5.4 cm, were estimated to be 1.9×10^4 and 2.1×10^5 fs^3, respectively, at 1056 nm, which corresponds to a small, net normal group-velocity dispersion that is typical for stretched-pulse cavities.[5] With suitable adjustment of the wave plates and at increased pump powers, the oscillator would also mode lock with either larger grating separation (soliton regime) or smaller grating separation (substantial net normal dispersion). The soliton regime was characterized by stable mode locking but often with multiple pulses circulating in the cavity. With substantial net normal dispersion, mode-locked operation was typically more difficult to initiate and was less stable.

With the optimum grating separation of 5.4-cm, highly reliable and stable self-starting stretched-pulse mode locking could be achieved for pump powers as low as 62 mW. The maximum average output power of the laser was 3 mW (~60-pJ pulse energy). At increased pump powers [which we obtained by switching to a higher power (300-mW) single-mode master-oscillator power-amplifier pump source], multiple pulse operation was observed. There was almost no hysteresis for the range of pump powers below the self-start threshold for which mode locking could be maintained. At lower pump powers, Q-switched mode locking and cw operation were observed.

The output pulse spectrum from Port 2 or Port 3 of the laser is shown in Fig. 2(a). The spectrum was centered at 1056 nm, and the spectral bandwidth was 18.6 nm. Figure 2(b) shows the autocorrelation of the uncompressed pulses directly from Port 3 (measured to be similar at output Ports 1 and 2). The output pulses had a strong temporal chirp, and the pulse duration was ~2.4 ps. To compress the pulses from Port 3 by elimination of the positive temporal chirp, we used a diffraction grating pair and recorded the autocorrelation duration to optimize

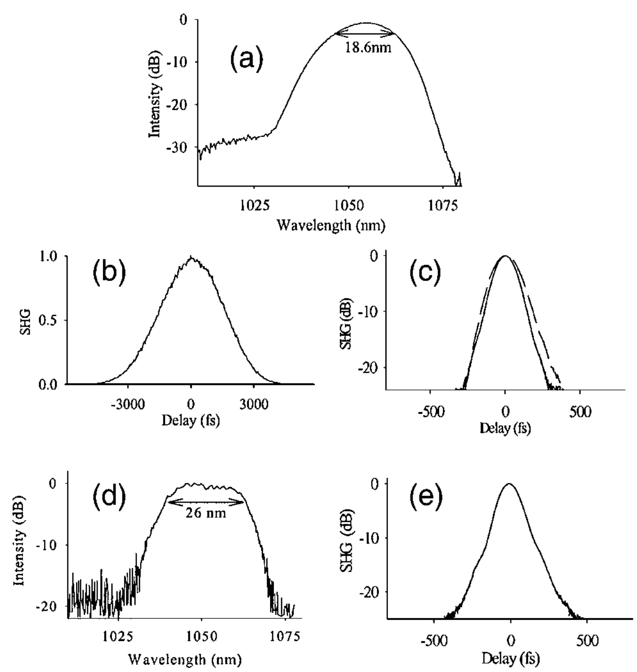

Fig. 2. (a) Spectrum of pulses extracted from Port 2 or Port 3, (b) autocorrelation of uncompressed pulses from Port 3 (FWHM, 2.4 ps), (c) autocorrelation of compressed pulses from Port 2 (dashed curve; FWHM, 136 fs) and Port 3 (solid curve, FWHM, 108 fs), (d) spectrum of pulses extracted from Port 1 (rejected by the polarization switch), (e) autocorrelation of compressed pulses from Port 1 (rejected by the polarization switch; FWHM, ~110 fs). SHG, second-harmonic generation.

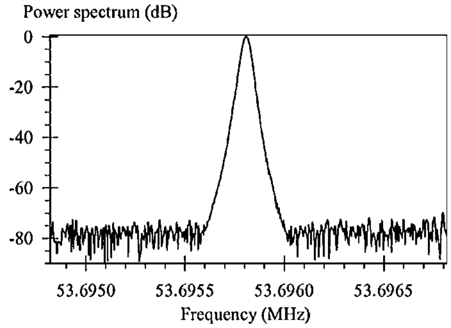

Fig. 3. rf spectrum at the cavity round-trip frequency, highlighting the low-amplitude noise of the laser.

the compressor grating separation. To compress the pulses from Port 2 by elimination of the negative temporal chirp, we coupled the pulses into various lengths of normally dispersive fiber. The dashed and solid circles in Fig. 2(c) show the autocorrelation of the compressed pulses from Port 2 and Port 3, respectively. The shortest pulses had an estimated FWHM of 108 fs (assuming a Gaussian pulse shape), indicating a compression factor of the order of 20×. The corresponding time–bandwidth product of the compressed pulses was ~0.54, typical for the this type of laser. Both the autocorrelation and the spectrum can be seen to be extremely clean over the available dynamic range of the measurement equipment. We note that the pulse width was not limited by the Yb^{3+} gain bandwidth, which has been demonstrated to support at least 65-fs pulses experimentally[2] and ~30 fs theoretically. We did not seek to obtain shorter pulses from our cavity but consider that such should have been possible with further optimization of fiber length and overall dispersion compensation.

We used an external diffraction grating pair to demonstrate that the rejected pulses from Port 1 of our laser were also compressible. The spectrum of these pulses is shown in Fig. 2(d), and the compressed pulse autocorrelation is shown in Fig. 2(e). The spectrum is slightly less smooth than that of the circulating pulses, but the compressed pulses can be seen to be of a similar quality (FWHM, ~110 fs). Following the earlier research of Tamura *et al.*[7] we may therefore be able to eliminate other outputs to extract higher-power (and still short) rejected pulses at Port 1 or to reduce even further the pump power required for self-start mode locking. We also note that the grating pair passes the first-order diffracted beam, which leaves the zero-order beam available as a monitor port or as an additional output.

Figure 3 shows the rf spectrum at the cavity's fundamental frequency (53.7 MHz), which we measured by directing the laser output onto a low-noise detector (~3-GHz bandwidth) and analyzing the pulse intensity signal[8] with a rf spectrum analyzer (Marconi Instruments Model 2382). The resolution bandwidth for the scan shown in Fig. 3 was 10 Hz (span, 2 kHz), which highlights the low amplitude noise of the laser (calculated to be ~0.05%). No effort has been made to stabilize the laser against external environmental changes. However, our daily startup procedure has not required adjustment of the intracavity wave plates, provided that the laboratory air conditioning maintained similar ambient temperature, and we envisage that enclosing the cavity in a temperature-controlled housing would lead to adjustment-free operation. Alternatively, susceptibility to environmental changes could be eliminated by inclusion of intracavity Faraday rotators.[9]

In conclusion, we have demonstrated a practical and stable stretched-pulse laser operating at 1.06 μm based on Yb^{3+}-doped silica fiber. The Fabry–Perot cavity incorporates a SESAM to initiate self-start mode locking and is pumped with a grating-stabilized telecommunications-qualified single-mode laser diode. Highly reliable and stable streched-pulse mode locking (employing nonlinear polarization evolution) could be achieved for pump powers as low as 62 mW. The maximum average output power of the laser in this instance was 3 mW, at a repetition rate of 53.7 MHz, corresponding to ~60-pJ pulse energy. The pulses have been demonstrated to have a smooth spectrum, are compressible externally to 108 fs (assuming a Gaussian pulse profile), and have minimal amplitude jitter (~0.05%). We believe that laser will prove useful for wide range of future applications; indeed, it has already provided useful service in a range of projects under way at the Optoelectronics Research Centre, University of Southampton. For example, the laser recently seeded soliton experiments in a Yb^{3+}-doped holey fiber amplifier. The combined system produced cw tunable, ultrashort (~200-fs) pulses across the wavelength range 1.06–1.33 μm by exploiting the soliton-self-frequency shift in the holey fiber.[10]

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