Grating-less, fiber-based oscillator that generates 25 nJ pulses at 80 MHz, compressible to 150 fs

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We report a passively mode-locked fiber-based oscillator that has no internal dispersion-compensating gratings. This design, which we believe to be the first of its kind, produces 25 nJ pulses at 80 MHz with the pulses compressible to 150 fs. The pulses appear to be self-similar and initial data imply that their energy is further scalable. © 2007 Optical Society of America

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We report details of a Yb-doped, cladding-pumped, fiber-based oscillator that generates mode-locked 25 nJ pulses at a repetition rate of 80 MHz, first reported orally as part of [1]. The high pulse energy is made practical by a grating-less cavity design in which the fiber length of 1–2 m is chosen to be just long enough so that its group delay dispersion (GDD) enables the formation of self-similar pulses [2]. Omitting the gratings simplifies the cavity and enhances its stability, and minimizing the fiber length increases the pulse repetition rate and reduces the tolerances needed to initiate and control the nonlinear polarization evolution (NPE) [3] mode-locking mechanism. With more careful control of the fiber length and cavity birefringence this cladding-pumped design should be scalable to even higher pulse energies and powers.

Since soliton fiber lasers were first introduced [4] they have evolved into an appealing alternative to bulk solid-state mode-locked lasers, offering superior beam quality, stability, and compactness. A deficiency of fiber-based lasers has been their pulse energies, which have generally lagged behind those of their solid-state counterparts. However, recent numerical simulations predict that self-similar pulses in fiber-based oscillators can have energies in excess of 100 nJ [5]. Subsequent experiments with grating-compensated fiber cavities have demonstrated pulse energies of 14 nJ [5] and 25 nJ [1], which match or exceed the energies from many commercial solid-state oscillators.

Generating a single train of high energy pulses in a fiber-based oscillator is a significant experimental challenge because the angular alignment tolerance of the cavity's wave plates is inversely proportional to the product of the pulse energy and the fiber length, a trend that can be inferred from [6]. We estimate that for a 25 nJ, 100 fs pulse propagating through a 10 m section of fiber having a modal effective area of 30 μm^2, a change in the polarization orientation of the order of a few hundredths of a degree is sufficient to alter the nonlinear phase shift by 2π, allowing an additional pulse stream to circulate.

The severe alignment tolerance can be mitigated by exchanging one of the cavity's half-wave plates for a pair of quarter-wave plates, which are adjusted in a counter-opposing fashion. This technique contributed to the 25 nJ result in the grating-compensated cavity of [1].

A simpler and more tractable solution, though, is to minimize the length of fiber in the cavity. Note that by reducing the fiber length from 10 to 1 m we increase the alignment tolerance by an order of magnitude. In addition, the GDD of 1 m of fiber is roughly the amount required to form 10 nJ pulses [7] and thus the cavity should no longer require a grating pair to trim its dispersion.

The oscillator cavity depicted in Fig. 1 is a unidirectional ring with the preferred direction forced by an internal isolator. The core of the Yb-doped, double-clad gain fiber has a diameter of 7 μm and a numerical aperture (NA) of 0.12, and its inner cladding has a diameter of 210 μm and an NA of 0.44 (Nufern SM-YDF-7/210). We varied the fiber length from 1 to 2 m. The gain fiber is pumped by a diode laser array

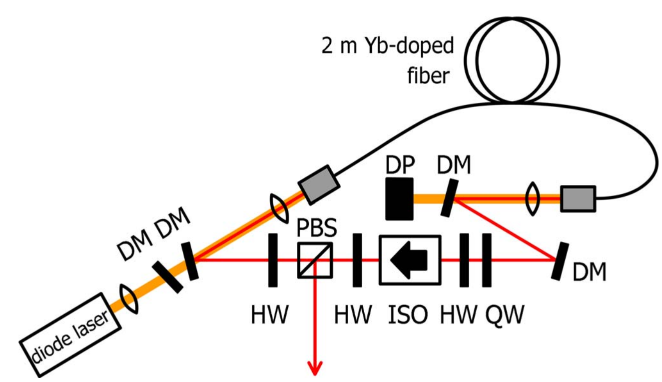

Fig. 1. (Color online) Schematic diagram of a grating-less fiber oscillator: HW, half-wave plate; QW, quarter-wave plate; ISO, isolator; PBS, polarizing beam splitter; DP, beam dumper; DM, dichroic mirror.

having a center wavelength of 976 nm and a maximum output power of 60 W; it is coupled to a fiber bundle having a diameter of 400 μm and an NA of 0.22 (LIMO 60-F400-DL976). A pair of dichroic mirrors, which transmit the pump and reflect the 1053 nm oscillator signal, couples the pump into the cavity. A pair is used to ensure that inadvertent Q-switched 1053 nm light from the cavity cannot feed back into the pump and damage the diodes.

A half-wave plate adjusts the polarization state into the doped fiber, and a quarter- and half-wave plate combination adjusts the state into the isolator. The relative angles of the plates are systematically adjusted until the fiber acts as a nonlinear half-wave switch—that is, until it allows the cavity to pass only high-energy pulses through the isolator (the NPE discriminator). The half-wave plate between the isolator and polarizing beam splitter adjusts the fraction of the power that exits the cavity; it was typically set so that 97% exits.

This cavity differs from the design of [8] in several aspects. First, bulk-optic pump coupling was chosen to eliminate the limitation of pump power, which gives us the wider range of fiber laser parameter compared with using WDM coupling. Second, only one kind of fiber is used to generate high energy mode-locked pulses. So the single-mode double-claded Yb-doped fiber acts as both a gain medium and a nonlinear phase shift medium. By using this multifunctional fiber, the splicing of fibers is not needed. Third, there is no additional spectral-shaping element such as a thin etalon or a band-pass filter inside the cavity to produce a stable mode-locked pulse train. Last, we locate an isolator before a polarizing beam splitter (PBS) so that the isolator, rather than the PBS, acts as an NPE discriminator. We chose this layout to ensure that accidental feedback could not reach the gain fiber.

We obtained higher pulse energies with longer lengths of gain fiber: 25 nJ for a 2.0 m length and 20 nJ for a 1.2 m length. In both cases higher pump power was available, but if applied resulted in multipulsing. Net dispersions of fiber are 0.004 ps^2 for 1.2 m length and 0.006 ps^2 for 2 m length. Corresponding maximum pulse energies are about 20 and 25 nJ for each, according to the numerical simulation plotted in Fig. 3(a) of [2]. They match with our experimental results in the aspect of parabolic pulse propagation for given net dispersions. Therefore, we conclude that the higher energy is due to the increased dispersion in the cavity, consistent with the theory [2,7]. Thus, the result implies that an even higher pulse energy can be achievable for a longer length of fiber as long as the nonlinear phase shifts are well managed.

We verified the single-pulse operation by monitoring the long range autocorrelation (600 ps range) and a fast photodiode signal (0.3 ns resolution). We also monitored the stability of the pulse train with a radio-frequency (RF) spectrum analyzer. The RF analyzer always showed a signal-to-noise ratio better than 80 dB RF (40 dB optical) and a linewidth less than 8 kHz.

Figure 2(a) shows the optical spectra associated with 9 and 25 nJ pulses from a grating-compensated oscillator [1]. The spectrum of the 9 nJ grating-compensated pulses exhibits the classic sharp-walled shape indicative of mode-locked pulse streams, while the spectrum of the 25 nJ grating-compensated pulses is decidedly more rounded. Though autocorrelation and pulse recompression measurements indicated that both are mode-locked pulse streams, the rounded 25 nJ spectrum of this oscillator does not encourage attempts at further scaling. Figure 2(b) shows the optical spectrum of the 25 nJ pulses for the grating-less design of Fig. 1 as well as the 25 nJ pulses from the grating-compensated cavity. The former exhibits the classic sharp-walled shape, implying that further energy scaling should be possible. In addition, the spectrum from the grating-less cavity matches the shape predicted by recent theory [8].

The pulse train was dechirped with an external grating pair. The pulse duration is measured by the autocorrelator and a frequency resolved optical gating (FROG) spectrometer; Fig. 3 shows the results obtained with the 25 nJ pulse. The deconvolved temporal width is 4.6 ps FWHM [inset in Fig. 3(a)] before compression and 150 fs FWHM after passing through the external gratings, which provided a negative GDD of 0.112 ps^2.

The pulse width of 4.6 ps before dechirp is about 2 times larger than the estimate expected from the chromatic dispersion of the gain fiber of 35 ps/nm/km for the bandwidth of 27 nm and the fiber length of 2 m. It is likely that nonlinear dispersion may contribute, considering the high pumping power. The origin for this extra dispersion is under investigation.

In conclusion, we have demonstrated what we believe is a novel design for a high energy fiber laser that does not contain a grating pair. This design exploits the energy scaling properties of self-similar pulses to eliminate the need for dispersion compensation inside the cavity, resulting in a simpler design whose polarization evolution can be readily controlled and maintained. With the grating-less Yb-doped fiber oscillator, 25 nJ pulse energy has been achieved at a repetition rate of 80 MHz, producing 2 W average output power. The pulses were compressible to 150 fs. To our knowledge, this is the high-

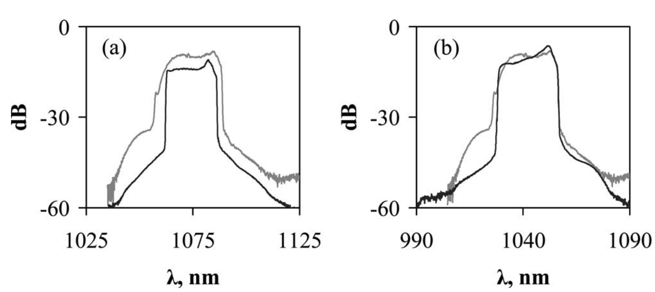

Fig. 2. (a) Spectrum of 9 nJ (black) and 25 nJ pulses (gray) from grating-compensated oscillator. (b) Spectrum of 25 nJ pulses from grating-less compensator (black) and grating-compensated oscillator. The latter is the same data as in (a), scaled to the center wavelength of the grating-less oscillator.

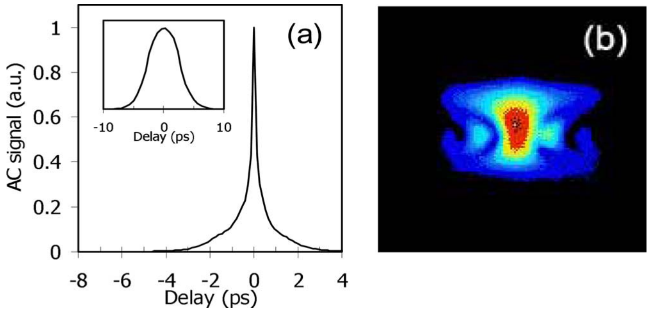

Fig. 3. (Color online) (a) Intensity autocorrelation trace after the compression. Inset, autocorrelation trace of chirped output pulses (b) FROG trace after the compression.

est energy and the highest average power reported for a femtosecond fiber oscillator to date. Further experiments to improve the pulse energy and analysis on the current propagation regime are in progress.

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References

1. M. J. Messerly, J. W. Dawson, C. P. J. Barty, J. An, and D. Kim, in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, Technical Digest (CD) (Optical Society of America, 2006), paper CThC7.
2. F. O. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, Phys. Rev. Lett. **92**, 213902 (2004).
3. M. Hofer, M. E. Fermann, F. Haberl, M. H. Ober, and A. J. Schmidt, Opt. Lett. **16**, 502 (1991).
4. L. F. Mollenauer and R. H. Stolen, Opt. Lett. **9**, 13 (1984).
5. J. R. Buckley, E. W. Wise, F. O. Ilday, and T. Sosnowski, Opt. Lett. **30**, 1888 (2005).
6. R. H. Stolen, J. Botineau, and A. Ashkin, Opt. Lett. **7**, 512 (1982).
7. F. O. Ilday, “Theory and practice of high-energy femtosecond fiber lasers,” Ph.D thesis (Cornell Univ., 2004).
8. A. Chong, J. Buckley, W. Renninger, and F. Wise, Opt. Express **14**, 10095 (2006).