All-fiber normal-dispersion femtosecond laser

K. Kieu and F. W. Wise
Department of Applied Physics, Cornell University, Ithaca, NY 14853
K. Kieu: kk532@cornell.edu

Abstract
Spectral filtering of a chirped pulse can be a strong pulse-shaping mechanism in all-normal-dispersion femtosecond fiber lasers. We report an implementation of such a laser that employs only fiber-format components. The Yb-doped fiber laser includes a fiber filter, and a saturable absorber based on carbon nanotubes. The laser generates 1.5-ps, 3-nJ pulses that can be dechirped to 250 fs duration outside the cavity.

1. Introduction
Recently, fiber lasers have attracted significant interest. CW and Q-switched fiber lasers are now capable of achieving high average power, comparable to or even better than traditional solid-state lasers such as Nd:YAG. The fiber format offers crucial practical advantages including passive air cooling and freedom from alignment and maintenance.

The development of new pulse-shaping mechanisms in fiber lasers allow the generation of high-energy femtosecond pulses. In stretched-pulse [1], self-similar [2] and wave-breaking-free [3] mode-locked lasers some degree of dispersion compensation is needed. When the laser is designed to operate around 1 μm wavelength, dispersion compensation is implemented either with bulk components, or with microstructured fibers or chirped fiber Bragg gratings [4, 5]. The former approach produces the best performance but undermines some of the benefits of fiber. The latter approach improves the integration but typically results in major performance sacrifices.

Recently, Chong et al. demonstrated a Yb-doped femtosecond fiber laser without anomalous dispersion in the cavity [6]. The pulse-shaping mechanism is based on strong spectral filtering of a highly-chirped pulse in the laser cavity, and the pulses are dissipative solitons [7]. Pulse energy as high as 26 nJ has been demonstrated with this design [8]. However, bulk components were also present in the laser cavity, which again sacrificed the advantages of fiber format.

All-fiber versions of the normal-dispersion lasers should have tremendous potential for applications. Several groups have investigated all-fiber lasers at 1 μm wavelength. Of course, dispersion control is not required for saturable-absorber mode-locking with picosecond pulse durations; under these conditions, dispersion and nonlinear phase modulation do not contribute appreciably to pulse-shaping. A simple dispersion-compensation-free laser which generates low-energy picosecond pulses was demonstrated by Herda et al. [9]. A semiconductor saturable-absorber mirror (SESAM) with high modulation depth shapes the pulses. An environmentally-stable low-energy picosecond all-fiber oscillator was demonstrated by Nielsen et al.. To achieve mode-locking through NPE a Faraday mirror was used in combination with angle-splicing of PM fibers [10]. Recently, a more complicated approach to fiber integration without dispersion compensation was also demonstrated [11]. In this work, the authors successfully integrated discrete bulk components into fiber-coupled modules, which were then spliced together to form the laser...
cavity. This laser generated 0.8-nJ and 627-fs pulses, which the authors attribute to self-similar evolution stabilized by a SESAM and nonlinear polarization evolution (NPE).

Here we demonstrate an all-fiber femtosecond laser with only normal dispersion in the cavity. The design of the laser is conceptually similar to what has been demonstrated previously, but fiber components replace the bulk components of earlier versions. Spectral filtering is achieved with a fused fiber coupler. Mode-locking is initiated and stabilized by a fiber-format saturable absorber based on carbon nanotubes [12]. All-fiber versions of the normal-dispersion femtosecond lasers should be very attractive for applications, and it should be possible to improve the performance achievable with the design described here.

2. Experimental setup

The laser demonstrated by Chong et al. [6] employed bulk components for the filter and the effective saturable absorber (SA). The SA was based on nonlinear polarization evolution (NPE). Fiber versions of these functions are required.

We employ a filter based on a fiber coupler operating in the over-coupled regime [13, 14]. It is well-known that a fused fiber coupler exhibits strong spectral filtering when it is made so that many power-transfer cycles occur along the tapered and fused portion of the coupler [13]. We fabricated the fused coupler in our laboratory, and observe (Fig. 1) a nearly sinusoidal transmittance, with pass-bands about 15 nm wide (full-width at half-maximum) and minimal loss (<10%). The maximum transmission of the through-port occurs at ~1030 nm, and we expect to use this port to form the laser cavity. A small fraction of the laser light is extracted by the cross-port of the filter, and this can be used as a monitoring output.

The fused-coupler filters that we have made to date have fairly strong polarization dependence. We observe that the output wavelength of the laser in continuous-wave operation can be tuned by adjusting the polarization controller. This feature is undesirable because it will lead to some residual NPE in the cavity. We have found it difficult to eliminate the polarization dependence of the filters with the present fabrication approach.

The inline SA is based on a fiber taper embedded in a composite of single-walled carbon nanotubes (SWCNTs) in a polymer host, and is illustrated schematically in the inset of Fig. 2. The SWCNTs were chosen to have diameter 0.8 nm, which places their absorption band around 1 μm. The version used in the 1-μm laser described here follows the geometry of Ref. 12, with the polymer modified to allow appropriate extension of the evanescent field into the nanotubes. The length and diameter of the fiber taper are ~300 mm and 5 μm, respectively. Simulation reveals that the optical field along the fiber taper waist is more confined in the case of 1-μm wavelength than with the 1.5-μm wavelength of Ref. 12. As a result, for given diameter the evanescent field outside the fiber taper is smaller, which reduces the interaction of the optical field with the carbon nanotubes. We considered several approaches to this problem: i) the use of fiber tapers with very small diameters, ii) increasing the concentration of SWCNTs in the host polymer, and iii) modification of the refractive index of the polymer to enhance the evanescent field outside the taper. SAs with small diameters tended to damage during laser operation. Increasing the concentration of SWCNTs produced greater non-saturable loss due to scattering. We found that modification of the refractive index of the host polymer was the most effective solution. The refractive index of the polymer used in this work is 1.44 at wavelengths around 1 μm. The modulation depth of the SA was estimated by measuring the transmittance of a femtosecond pulse train as a function of average power. Figure 2 shows the results of the measurement. The unsaturated transmittance of the SA is ~44%, and the measured modulation depth is ~15%.
We believe that this geometry for the saturable absorber offers significant advantages for high-power operation. Fiber lasers tend to have large output coupling, and thus require SAs with large modulation depth. This in turn tends to imply large energy deposition in the SA. Our experience is that semiconductor saturable-absorber mirrors (SESAMs) consistently tend to damage in high-power fiber lasers in our laboratory. Our limited experience with thin films of carbon nanotubes deposited on the end of a fiber is similar. In contrast to SAs in which the absorption (and generated heat) is localized in a thin (~1 μm) film, in taper-based SAs the absorption is distributed along the fiber taper, which is at least a few millimeters in length. As a result, the generated heat is distributed and the problem with damage is mitigated. Damage has been observed only when the taper is very thin (~1–2 μm diameter) and the loading of SWCNTs in the polymer host is high.

The fiber-format filter and saturable absorber are introduced into the laser cavity as shown in Fig. 3. All the fiber is single-mode fiber, with 6 μm core diameter. The total length of the ring cavity is about 4 m, which corresponds to ~50 MHz repetition rate. The 50-cm Yb-doped fiber is core-pumped by a 980-nm diode laser. The SA follows the gain fiber, and a 50/50 fused coupler serves as the output coupler. To enable unidirectional operation a fiber-coupled polarization-independent isolator is spliced in after the output coupler. The filter follows the isolator. The total cavity dispersion is ~ 0.090 ps².

3. Experimental results

As a control experiment, we attempted to mode-lock the laser without the spectral filter in the cavity, without success. Without the SA in the cavity we were also unable to observe any mode-locking. Due to the polarization sensitivity of the fused coupler filter, a polarization controller is needed in the cavity. Although we expect the SA to dominate the starting and stabilizing of the pulses, the operation of the laser is sensitive to the setting of the polarization controller. This suggests that NPE also plays some role in the pulse-shaping. At an arbitrary setting of the polarization controller the laser operates in an unstable Q-switched and mode-locked regime. Self-starting mode-locked operation is achieved by adjusting the polarization controller. The threshold pump power for mode-locking is ~350 mW. The laser produces a stable pulse train with ~50 MHz repetition rate. Single-pulse operation is verified by using a long range (~100 ps) background-free autocorrelator in combination with a fast detector with 500-ps resolution. The spectrum is confirmed to be free of modulation, which could imply the presence of multiple pulses. The average output power is 155 mW with 400 mW pump power, which is the maximum that can be delivered by the pump diode. The pulse energy and efficiency are 3 nJ and 40%, respectively.

Typical power spectra of the laser (Fig. 4(a, b)) exhibit the characteristic features of pulse-shaping by spectral filtering at normal dispersion: steep sides, with peaks at the edges that are reduced by the filtering [6]. The clear difference between output 1 and output 2 is evidence of the strong influence of the spectral filter on the pulse circulating inside the cavity. The laser generates 1.5-ps chirped pulses (Fig. 4(c)), which are dechirped to 235 fs duration (Fig. 4(d)) with a grating pair outside the cavity. The secondary structure in the interferometric autocorrelation is a consequence of the steep edges of the spectrum. For the pulse of Fig. 4(d), ~5% of the pulse energy resides outside the main peak, and this is typical of pulses generated by this laser.

The laser operates quite stably, and mode-locking is sustained for many hours without readjustment of the polarization controller. If the pump laser is switched off and on again, the laser returns directly to the mode-locked state. However, moving the fiber in the cavity will unlock the laser. In this case, readjustment of the polarization controller is needed to restore mode-locking. The SA does not exhibit any evidence of damage due to thermal
effects even at the highest pump power. However, we do observe a gradual reduction of the saturable loss of the SA. This makes it more difficult to mode-lock the laser after the SA has been used for a few days. At that point, the performance of the SA seems to stabilize at a fixed level and the laser performance is constant. We do not completely understand the mechanism that degrades the SA. It may be similar to what has been observed by Schibli et al. [15] and attributed to photo-oxidation of SWCNTs. We are working to understand this issue, to improve the performance and robustness of the laser. A soliton laser operating at 1.5 μm and using a similar SA has been operating for months without any sign of degradation [16].

4. Conclusion

In conclusion, the development of fiber-format filter and saturable absorber enables the construction of an all-fiber mode-locked laser at 1 μm without dispersion compensation in the cavity. The behavior of the laser is consistent with the known pulse-shaping based on spectral filtering of a chirped pulse. The performance (3 nJ and 250 fs pulses) will be adequate for some applications, and performance improvements can be made following existing understanding of the normal-dispersion lasers. Future work will also address reduction of the polarization sensitivity of the filter, which will in turn allow removal of a polarization controller from the cavity. Finally, it will also be interesting to develop a polarization-maintaining version of this laser, for ultimate stability.

Acknowledgments

This work was supported by the National Institutes of Health under grant EB002019 and by the National Science Foundation (ECS-0500956). The authors thank A. Chong and W. Renninger for numerous useful discussions.

References and links

1. Tamura K, Ippen EP, Haus HA, Nelson LE. 77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser. Opt Lett. 1993; 18:1080–1082. [PubMed: 19823296]
2. Ilday FO, Buckley JR, Clark WG, Wise FW. Self-similar evolution of parabolic pulses in a laser. Phys Rev Lett. 2004; 92:213902-1–213902-4. [PubMed: 15245282]
3. Ilday FO, Buckley JR, Lim H, Wise FW, Clark WG. Generation of 50-fs, 5-nJ pulses at 1.03 μm from a wave-breaking-free fiber laser. Opt Lett. 2003; 28:1365–1367. [PubMed: 12906091]
4. Lim, H.; Ilday, FO.; Wise, F. Femtosecond ytterbium fiber laser with photonic crystal fiber for dispersion control; Opt Express. 2002. p. 1497-1502.http://www.opticsinfobase.org/abstract.cfm?URI=oe-10-25-1497
5. Hartl, I.; Imeshev, G.; Dong, L.; Cho, GC.; Fermann, ME. Ultra-compact dispersion compensated femtosecond fiber oscillators and amplifiers. Conference on Lasers and Electro-Optics; 2005; Baltimore, MD. paper CTbG1
6. Chong, A.; Buckley, J.; Renninger, W.; Wise, F. All-normal dispersion femtosecond fiber laser; Opt Express. 2006. p. 10095-10100.http://www.opticsinfobase.org/abstract.cfm?URI=oe-14-21-10095
7. Renninger W, Chong A, Wise FW. Dissipative solitons in normal-dispersion fiber lasers. Phys Rev A. 2008; 77:023814.
8. Chong A, Renninger WH, Wise FW. All-normal-dispersion femtosecond fiber laser with pulse energy above 20 nJ. Opt Lett. 2007; 32:2408–2410. [PubMed: 17700801]
9. Herda R, Okhotnikov OG. Dispersion compensation-free fiber laser mode-locked and stabilized by high-contrast saturable absorber mirror. IEEE J Quantum Electron. 2004; 40:893–899.
10. Prochnow, O.; Ruehl, A.; Schultz, M.; Wandt, D.; Kracht, D. All-fiber similariton laser at 1 m without dispersion compensation; Opt Express. 2007. p. 6889-6893.http://www.opticsinfobase.org/abstract.cfm?URI=oe-15-11-6889
11. Nielsen CK, Keiding SR. All-fiber mode-locked fiber laser. Opt Lett. 2007; 32:1474–1476. [PubMed: 17546159]
12. Kieu K, Mansuripur M. Femtosecond laser pulse generation with a fiber taper embedded in carbon nanotube/polymer composite. Opt Lett. 2007; 32:2242–2244. [PubMed: 17671597]

13. Bilodeau F, Hill KO, Johnson DC, Faucher S. Compact, low-loss, fused biconical taper couplers: overcoupled operation and antisymmetric supermode cutoff. Opt Lett. 1987; 12:634. [PubMed: 19741823]

14. Bilodeau F, Hill KO, Faucher S, Johnson DC. Low-loss highly overcoupled fused couplers: fabrication and sensitivity to external pressure. IEEE J Lightwave Technol. 1988; 6:1476–1482.

15. Schibli T, Minoshima K, Kataura H, Itoya E, Minami N, Kazaoui S, Miyashita K, Tokumoto M, Sakakibara Y. Ultrashort pulse-generation by saturable absorber mirrors based on polymer-embedded carbon nanotubes. Opt Express. 2005; 13:8025–8031. [PubMed: 19498832]

16. Kieu K, Wise FW. unpublished data.
Fig. 1. Spectral response of the fused fiber coupler filter. Inset: diagram of the 2×2 fused coupler filter.
Fig. 2.
Transmittance of the inline fiber SA versus launched average power of a train of femtosecond pulses. Inset: diagram of the SA. The grey area represents the SWCNT/polymer composite.
Fig. 3.
Schematic diagram of the experimental setup. SA: carbon nanotube saturable absorber. PC: polarization controller.
Fig. 4.
(a) Spectra of the pulse from the 50/50 output coupler (output 1) and from the filter (output 2). (b) Spectra in linear scale. (c) Background-free autocorrelation trace of chirped pulses from output 1. (d) Interferometric autocorrelation trace of the dechirped pulses.