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Route to the minimum pulse duration in normal-dispersion fiber lasers

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Abstract

The factors that control the pulse duration in all-normal-dispersion lasers are identified. To minimize the pulse duration, the cavity dispersion should be as small as possible. For fixed dispersion, increasing pulse energy leads to shorter, but more-structured, pulses. Experiments performed with ordinary single-mode fiber at 1 μm wavelength agree reasonably with numerical simulations, and produce clean ~ 80 -fs pulses. The simulations indicate that 30-fs pulses can be reached at higher energies.

The generation and undistorted propagation of femtosecond light pulses generally relies heavily on the ability to compensate group-velocity dispersion (GVD). The design of mode-locked lasers based on soliton-like pulse-shaping has been guided largely by the master equation analysis [1]. According to the master equation, the shortest pulse duration is reached with the net cavity GVD small and anomalous. With broadband gain media such as Ti:sapphire, the minimization of pulse duration essentially amounts to compensation of the cavity dispersion to as many orders as possible. This has culminated in devices such as double-chirped mirrors, which compensate dispersion over a huge bandwidth and allow the stable formation of pulses as short as 5 fs [2].

Pulse-shaping in the all-normal-dispersion (ANDi) fiber laser is based on the spectral filtering of a highly-chirped pulse in the cavity [3]. Because the lossy filtering dominates the pulse formation, the pulses in ANDi lasers are referred to as dissipative solitons [4]. The GVD of an ANDi fiber laser will typically correspond to that of several meters of fiber, which is one to two orders of magnitude higher than that of a fiber laser with a dispersion map, and three orders of magnitude higher than that of a solid-state laser. Even with such large GVD, ANDi lasers generate reasonably short pulses. For example, a Yb-doped ANDi laser with 16 m of fiber in the cavity generates 150-fs pulses [5]. In this case, the cavity is 45 times the dispersion length corresponding to that pulse duration.

In contrast to soliton-like lasers that operate near zero net GVD, the role of dispersion in limiting the pulse duration in an ANDi laser is unclear. With such large GVD, the effects of higher-order dispersion may be negligible. With typical fiber parameters, the pulse bandwidth would have to be $\sim 1 \text{ fs}^{-1}$ for the cubic phase to be comparable to the quadratic phase, *e.g.* Moreover, the pulses in an ANDi laser are generally highly-chirped. Thus, what determines the minimum pulse duration in an ANDi laser is an interesting and important unanswered question. On the practical side, a laser that generates <100 -fs pulses without an intracavity anomalous GVD segment will be attractive for various applications.

Here we outline the route to the minimum pulse duration in ANDi lasers. We find that shorter pulses are generated with lower cavity GVD. For fixed GVD, shorter pulses can be generated with larger pulse energies. Practical lengths of readily-available fibers restrict the GVD to large values ($\gg 0.01 \text{ ps}^2$). Numerical simulations of Yb-doped fiber lasers indicate that ~ 30 -fs pulses are possible for a realistic design with off-the-shelf components. Experiments are constrained by the available pump power, but ~ 75 fs pulses are obtained in the range $0.03 - 0.05 \text{ ps}^2$, in agreement with the numerical results.

A guide to the generation of short pulses is provided by a systematic study of the ANDi laser [6]. The pulse parameters are strong functions of the cavity GVD, the nonlinear phase shift accumulated by the pulse (Φ^{NL}), and the spectral filter bandwidth (BW). The mode-locked spectrum tends to broaden with decreasing GVD, decreasing filter BW, and increasing Φ^{NL} . Theoretical calculations with arbitrary parameters produce arbitrarily-short pulses. However, the pulse duration will be limited by the parameters of realistic lasers (*e.g.*, limited gain BW). A systematic search of the multi-parameter solution space will require a lengthy and tedious study. Instead, we focus on the specific case of Yb-doped fiber with standard components, which is of greatest current interest. However, the concepts discussed here will be relevant to other gain media and wavelengths.

We undertook a numerical study in two steps: a first set of simulations with representative parameters to identify the trends, and a second set to optimize the performance. For the first set, the simulated cavity contains a segment of single-mode fiber (SMF) of variable length, 60 cm of Yb-doped gain fiber, and a second segment of SMF 1 m long. A spectral filter with 12 nm BW follows the fiber section. Adjustment of the length of the first SMF segment and the pump power yields various combinations of GVD and Φ^{NL} . The results are summarized in Fig. 1.

The spectral BW increases as the cavity GVD decreases, and the pulse can generally be dechirped to within 10% of the Fourier-transform limit. Increasing the pump power and therefore Φ^{NL} has a similar effect. Figs. 1(a)-(c) show the mode-locked spectra obtained with three combinations of GVD and pump power. Starting from the roughly parabolic spectrum of Fig. 1(a), decreasing the GVD while holding the pump power constant produces a more-structured but wider spectrum (Fig. 1 (b)). Increasing the pump power at fixed GVD has a similar effect. The dechirped pulse durations corresponding to Fig. 1(b) and (c) are similar. However, the sharper features of Fig. 1(c) degrade the pulse quality slightly. The general conclusion is that the spectrum is broadened by decreasing the GVD or increasing Φ^{NL} , but the best pulse quality is obtained by reducing the GVD. The strategy to generate short pulses is therefore to design a cavity with smallest possible GVD, and pump the gain fiber as much as possible to generate substantial Φ^{NL} , with an appropriate spectral filter BW. Independent control of the GVD and Φ^{NL} is difficult at $1 \mu\text{m}$ because the coefficients of ordinary SMF are not flexible. Photonic-crystal or -bandgap fibers allow some design freedom, which could be exploited. Here we will focus on lasers with ordinary SMF, which is the most practical case.

To search numerically for the shortest pulses, simulations were performed with the shortest cavity length (~ 1 m) one can reasonably build in the laboratory. The cavity contains 50 cm of SMF, 20 cm of gain fiber (with 40-nm gain BW), another 50 cm of SMF, and a spectral filter with 40 nm BW. The shortest dechirped pulse produced by this cavity is shown in Fig. 2. The spectrum develops sharp structure near its edges (Fig. 2(a)) and as a consequence, the dechirped pulse has some structure (Fig. 2(b)). The dechirped pulse duration is 34 fs. The laser thus comprises ~ 100 dispersion lengths. The pulse energy is 44 nJ, which would correspond to 7 W average power. Attempts to obtain shorter pulses by increasing the pump power failed to produce mode-locking. We conclude that the minimum pulse duration for

realistic fiber parameters is ~ 30 fs. Shorter pulses may be generated if the laser parameters can be adjusted independently. The flexibility of commercial fibers at $1.55 \mu\text{m}$ may allow Er fiber lasers to generate shorter pulses than Yb fiber lasers, *e.g.* The simulation also confirms that the ANDi fiber laser can generate very high pulse energies, which is plausible considering that the pulse shaping mechanism benefits from substantial values of Φ^{NL} .

The simulations exhibit the expected weak influence of third-order dispersion (TOD) on the pulse duration. Doubling of the TOD coefficient of the fiber, or setting it to zero, produces only slight changes ($<10\%$) in the ~ 30 fs pulse. Therefore, the compensation of higher-order dispersions in ANDi lasers should not affect the performance appreciably. Stability is a separate issue. The master equation model predicts instability around zero GVD with nonzero TOD. It is reasonable to conjecture that the stability of ANDi lasers will not be sensitive to higher-order dispersion, and this issue will be addressed systematically in the future.

In practice, the power level of ~ 30 fs laser is not reachable by core-pumping. When the pulse energy is limited to 2-3 nJ (which corresponds to 200-400 mW average power) in the simulation, the minimum pulse duration increases to the range of 70-80 fs, and these parameters should be possible in SMF lasers pumped in-core. Based on the simulation results, an ANDi laser was built (Fig. 3). We increased the length of SMF after the gain segment to enhance the value of Φ^{NL} that can be reached with modest pulse energy. The fiber section consists of 44 cm of SMF, 17 cm of Yb-doped fiber, and 170 cm of SMF. The cavity GVD is 0.053 ps^2 . Two 980-nm diodes supply ~ 900 mW pump power. The combination of half-wave plate, quarter-wave plate, and polarizing beam splitter (PBS) acts as the nonlinear polarization evolution (NPE) ejection port (output 1). To improve the pulse quality, we included a second PBS as the main output (output 2), to couple out the circulating pulse, which is a well-known way to improve pulse quality [7]. A birefringent filter with 15 nm BW is placed after the second PBS. The output pulse train is monitored with a photodetector/sampling oscilloscope combination with a bandwidth of 30 GHz. The autocorrelation is monitored for delays up to ~ 100 ps. A variety of self-starting mode-locked states are observed by adjusting the waveplates. The structured spectrum of output 1 (Fig. 4(a) inset) is similar to the simulation result (Fig. 2(a)). The pulse taken from output 2 is much cleaner (Fig. 4(a)), as expected. The pulse can be dechirped to 70 fs duration (Fig. 4(b)), and the time profile has some sidelobes as a consequence of the steep edges and remaining fringes on the spectrum. The average power from output 2 is 172 mW, which at 80 MHz repetition rate corresponds to 2 nJ pulse energy.

The pulse quality can be improved while approximately maintaining the pulse duration, by decreasing the GVD and nonlinearity appropriately. This process is equivalent to moving from the condition of Fig. 1(c) to that of Fig. 1(b). While keeping the same pump power, the segment of SMF after the gain fiber was reduced to 75 cm, which reduced the GVD to 0.033 ps^2 and increased the repetition rate to 130 MHz. The best result is presented in Fig. 4(c) and (d). The mode-locked spectrum (Fig. 4(c) inset) is somewhat smoother than in the previous case (Fig. 4(a) inset), as expected. The autocorrelation (Fig. 4(d)) shows an 80 fs dechirped pulse with minimal structure. The 155-mW average power corresponds to 1.2 nJ pulse energy.

The filter plays a crucial role in formation of the shortest pulses. Without the filter, the 80-MHz laser cannot be mode-locked. The 130-MHz laser can be mode-locked without a filter, but only with a narrow (~ 10 nm) spectrum. These results also agree with numerical simulations.

Recently, Ruehl *et al.* reported the generation of 75-fs pulses from an Er-doped fiber laser with large normal GVD [8]. We believe that the spectral filtering mechanism of the ANDi laser must be playing a role in that laser. Raman-shifting is also clearly important, but it has not been included in the analysis of ANDi lasers. Thus, more work is needed to understand the pulse shaping in the laser reported by Ruehl *et al.*, along with its relation to the issues discussed here.

To summarize, we have explained how to minimize the pulse duration in an ANDi laser. The cavity GVD should be as small as possible, and will generally be limited by practical constraints. For fixed GVD, increasing pulse energy leads to shorter, but more-structured, pulses. Experiments performed with ordinary single-mode fiber at 1 μm wavelength agree reasonably with the predictions of numerical simulations, and produce clean 80-fs pulses. The simulations indicate that 30-fs pulses should be reached at higher energies. This will require double-clad gain media. This direction is very promising as it could lead to a combination of high pulse energy and short duration that is so far unprecedented for fiber lasers.

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Fig. 1. Calculated spectral bandwidth vs. GVD. Insets: spectra obtained at indicated points.

Fig. 2. Results of numerical simulation. a) spectrum, b) dechirped intensity profile (inset: chirped pulse directly from the laser (4.3 ps duration)).

Fig. 3. Schematic of laser: QWP: quarter-waveplate; HWP: half-waveplate; PBS: polarizing beam-splitter; WDM: wavelength-division multiplexer.

Fig. 4.

Experimental results. Panels a) and b) are for the 80-MHz laser, panels c) and d) are for the 130-MHz laser. a) output 1 spectrum (inset) and output 2 spectrum, b) dechirped autocorrelation (68 fs duration), output of the 130 MHz laser: c) output 1 spectrum (inset) and output 2 spectrum, b) dechirped autocorrelation (77 fs duration)