Pulse generation without gain-bandwidth limitation in a laser with self-similar evolution

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Abstract: With existing techniques for mode-locking, the bandwidth of ultrashort pulses from a laser is determined primarily by the spectrum of the gain medium. Lasers with self-similar evolution of the pulse in the gain medium can tolerate strong spectral breathing, which is stabilized by nonlinear attraction to the parabolic self-similar pulse. Here we show that this property can be exploited in a fiber laser to eliminate the gain-bandwidth limitation to the pulse duration. Broad (∼200 nm) spectra are generated through passive nonlinear propagation in a normal-dispersion laser, and these can be dechirped to ∼20-fs duration.

OCIS codes: (320.7090) Ultrafast lasers; (320.5540) Pulse shaping; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

The shortest light pulse that can be generated by a laser oscillator will always be of fundamental interest to the field of ultrafast science, and it will determine the time resolution or bandwidth of many measurements. A critical factor in the design of an ultrashort-pulse laser is the bandwidth of the gain medium. Almost all lasers that generate few-cycle ($\sim$10 fs) pulses exploit the huge ($2\pi \times 44$ rad THz) gain bandwidth of titanium-doped sapphire. Spectra that exceed the gain bandwidth, and pulses that approach a single cycle in duration, have been generated through nonlinear spectral broadening and preferential output coupling of the edges of the spectrum [1].

Much of our understanding of mode-locked lasers comes from analytic solutions of equations based on the assumption of small changes in a pulse as it traverses the cavity [2]. The intracavity pulse evolution in even a 10-fs Ti:sapphire laser is not dramatic, because the crystal comprises roughly one characteristic dispersion length (L_D) of propagation: $L_D = \tau^2/|\beta_2| \sim 1$ mm, where τ is the pulse duration and β_2 is the second-order dispersion coefficient. When the approximations of the model break down, perturbative [3] and numerical analyses are employed.

Fiber oscillators have not reached the few-cycle regime. Few-cycle pulses can be generated by pulse compression or by interfering the spectra of two separate continuua seeded by a fiber laser [4]. Direct generation from an oscillator should impact applications by improving the stability, and reducing the complexity and cost of the source. Applications would include generation of seed pulses for attosecond science, frequency metrology, and nonlinear microscopy [5], among others.

The gain bandwidth of ytterbium-doped silica fiber [6] is about one-quarter that of Ti:sapphire. Significant gain typically extends over 100-150 nm, with the short-wavelength limit of the gain determined by the pump absorption band. The cut-off wavelength, below which the fiber supports multiple transverse modes, may present an ultimate limitation to the bandwidth of a fiber laser: even small higher-order-mode content significantly reduces the multi-

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pulsing threshold of modelocked fiber lasers [7]. Single-mode fiber (SMF) designed to operate near 1 μm typically has a cut-off wavelength near 900 nm. Modelocked Yb fiber lasers produce bandwidths up to $\sim$120 nm at the -20-dB points, and pulses as short as $\sim$30 fs [8, 9]. Broader output spectra can be produced with noise bursts [10, 11], which are not self-consistent solutions of the laser cavity. The gain bandwidth will present a clear challenge to the generation of 10-fs pulses. A fiber laser typically includes around 1 m of fiber. $L_D \sim 2$ mm for a 10-fs pulse, so a 10-fs fiber laser will comprise hundreds of dispersion lengths. The pulse evolution in such a laser will likely involve extreme spectral and temporal changes. Whether such dramatic evolution can be controlled is an important question.

Here we describe a new approach to the design of fiber lasers, which decouples the pulse bandwidth from the limitations of the gain spectrum. In a resonator with large normal dispersion, spectral broadening in fiber after the gain segment produces output bandwidths that substantially exceed the gain bandwidth. The overall evolution is stabilized by filtering and the nonlinear attraction to the self-similar solution in the gain medium. Bandwidths approaching 200 nm and pulses as short as 21 fs (the shortest from a fiber laser to date) are generated in initial experiments. This demonstration introduces a class of fiber lasers with clear potential for few-cycle pulse generation, and more broadly for producing a range of useful output pulses. In contrast to prior work aimed at generation of the shortest pulses, this approach cannot be understood within averaged-cavity models [2].

Self-similar evolution is a powerful technique to avoid distortion of optical pulses that propagate nonlinearly. Pulses with a parabolic intensity profile and linear frequency chirp,

$$A(z,t) = A_0(z)\sqrt{1-(t/t_0(z))^2}e^{i(a(z)-b(z)t^2)} \tag{1}$$

for $t \leq t_0(z)$ are asymptotic solutions of the nonlinear Schrodinger equations that govern pulse propagation in passive [12] or active [13] fiber with positive nonlinear refraction and normal group-velocity dispersion (GVD). These pulses accumulate substantial nonlinear phase shifts without undergoing wave-breaking or more-dramatic distortions such as pulse fission. For an amplifier with constant gain, the asymptotic solution is a nonlinear attractor; a range of inputs to the amplifier evolve to the self-similar solution [13]. The chirped self-similar pulses (sometimes referred as "similaritons") can be compressed to the Fourier-transform limit by passing them through a dispersive delay.

Short-pulse lasers based on self-similar pulse propagation in their gain segments were recently reported [14–17]. Spectral breathing occurs in these lasers, with the bandwidth varying by an order of magnitude as the pulse traverses the resonator. Strong filtering stabilizes the evolution by allowing a short pulse to evolve to the parabolic solution before the end of the gain fiber [15]. A remarkable feature of these lasers is that the similariton is a local nonlinear attractor in the gain segment of the laser. The pulse can change dramatically, or it can be intentionally manipulated, in the rest of the cavity, as long as the input to the amplifier can approach the asymptotic solution. This property of the amplifier similariton evolution will be a valuable degree of freedom in the design of high-performance instruments.

The spectral bandwidth of a similariton grows exponentially in an amplifier. However, the self-similar evolution is disrupted when the pulse bandwidth approaches the gain bandwidth of the amplifier, and this limits the pulse energy and duration that can be achieved [18]. The generation of pulses shorter than 30-40 fs from a self-similar amplifier based on Yb fiber will be difficult. Spectral broadening in a similariton-soliton laser [14] will likely be limited by soliton fission in the anomalous-dispersion segment. It may be possible to extend or continue self-similar pulse evolution beyond an amplifier. For example, a fiber with lower dispersion and/or higher nonlinear coefficient than the gain fiber can induce substantial spectral broadening. The linearly-chirped parabolic pulse produced by the amplifier will maintain close to a

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parabolic shape and linear chirp in the passive fiber. This evolution is related to the parabolic pulse compression scheme discussed by Anderson [12].

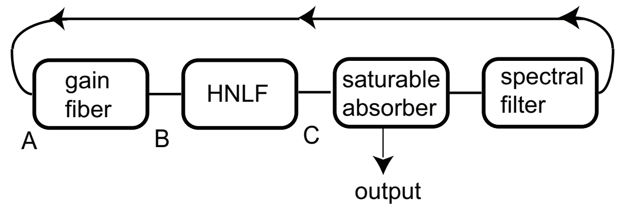

Fig. 1. Conceptual schematic of the laser. HNLF: Highly nonlinear fiber.

2. Numerical simulations

Although self-similar propagation in gain and passive fibers are well-known, prior studies of single-pass propagation from a given initial condition do not address whether the evolution will develop from noise in a system with feedback. Numerical simulations were performed to assess the feasibility of the desired evolution. The simulated cavity (shown conceptually in Fig. 1 and with experimental detail in Fig. 2) contains 30 cm of SMF ($\beta_2 = 230$ fs^2/cm), 80 cm of Yb-doped gain fiber (gain coefficient = 6.8/m), and another 20 cm of SMF. Higher-order dispersion is neglected. The gain fiber and SMF have a nonlinear coefficient of 4.5×10^{-4}/(W m). We assume that 35% of the light is coupled into a segment of passive fiber with parameters (given below) that correspond to a highly-nonlinear photonic-crystal fiber (PCF) with normal dispersion. After the passive fiber, 80% of the energy is coupled out, and the remaining 20% traverses a saturable absorber and a Gaussian filter with 3-nm bandwidth. Without the PCF, the laser is an established self-similar laser [15]. Simulations based on the standard split-step algorithm were performed for varying parameters of the PCF. The initial field was taken to be white noise.

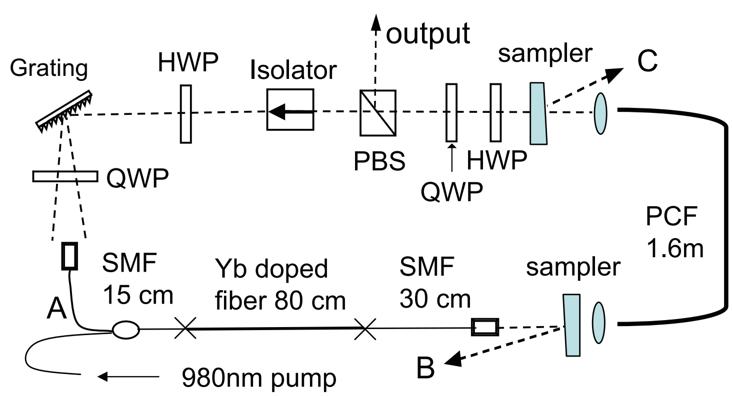

Fig. 2. Fiber laser schematic. QWP: quarter-waveplate; HWP: half-waveplate; PBS: polarizing beam-splitter.

The simulations converge for wide ranges of parameters, and exhibit the desired evolution for narrower but reasonable ranges of the parameters of the PCF: mode-field diameters between 2.2 and 2.8 μm, dispersion coefficient from 40 to 130 fs^2/cm, and lengths from 1.5 to 3 m. The broadest spectra are generated for PCF lengths between 1.6 and 2 m, with results for 2 m shown

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in Fig. 3. The narrow Gaussian spectrum produced by the filter broadens and develops the structure characteristic of a chirped parabolic pulse [15] (Fig. 3, middle row). A parabolic temporal profile is clearly established in the gain fiber (top row of Fig. 3). The spectrum broadens further in the passive fiber (Fig. 3, middle row). The pulse energy is 0.6 nJ. Impressing a quadratic spectral phase on the output produces a dechirped pulse that is close to the transform limit. The dechirped pulses are 20-fs long (Fig. 3, top row, inset).

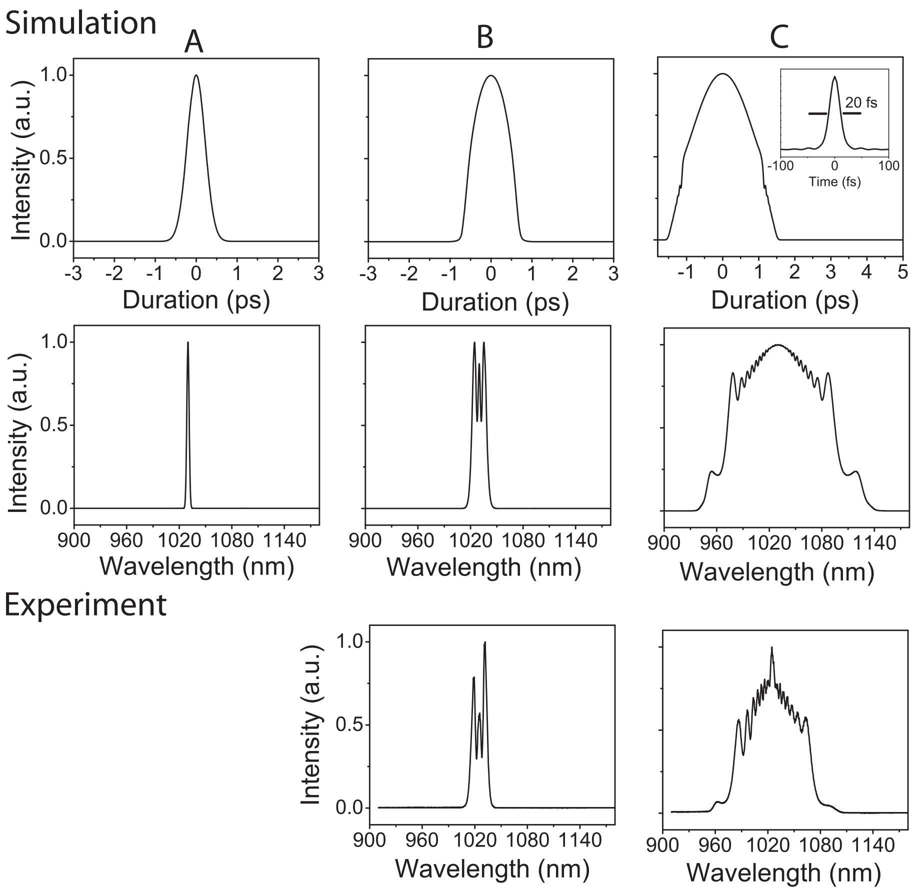

Fig. 3. Comparison of simulation to experiment at the indicated locations in the cavity. Simulations assume 2-m length of PCF with $\beta_2 = 70$ fs^2/cm and nonlinear coefficient 9 times larger than that of the gain fiber. Top row: simulated chirped pulses. The inset is the numerical transform-limited pulse from location C. Middle row: simulated spectra. Bottom row: experimental spectra.

3. Experimental results

PCF (NL-1050-NEG-1 from NKT Photonics A/S) with 2.2-μm mode-field diameter is employed in the experimental setup (Fig. 2). The PCF has $\beta_2 = 130$ fs^2/cm and nonlinear coefficient 9 times larger than that of the gain fiber. A 300 l/mm grating and a collimator create a Gaussian spectral filter with 4-nm bandwidth. Nonlinear polarization evolution (NPE) is an effective saturable absorber, implemented by the quarter- and half-wave plates and polarizer. The laser is constructed with some bulk components to facilitate variation of the cavity pa-

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rameters, and sampling beam-splitters allow monitoring of the intracavity pulse evolution. The pulse-repetition rate is about 60 MHz. Single-pulse operation is verified by monitoring the output with a photodetector and sampling oscilloscope with 30-GHz bandwidth and recording the autocorrelation for delays up to $\sim$100 ps.

The laser is mode-locked by adjusting the wave plates. Mode-locked operation occurs with segments of PCF between 1.5 and 3 m long, as predicted by the simulations, with the broadest spectra produced with 1.6 to 1.7 m of PCF. The bottom row of Fig. 3 shows the spectra recorded at the indicated points of the cavity, for 1.55 m of PCF. After the gain segment, the spectrum has the structure of a chirped parabolic pulse [15]. The 30-nm bandwidth of the pulse from the gain segment increases dramatically in the PCF. The full-width at half-maximum bandwidth is 100 nm, which exceeds the gain bandwidth. The spectrum exhibits all of the qualitative features of the simulation result, along with a continuous-wave peak near 1025 nm that is difficult to avoid. The simulated spectra in the middle row of Fig. 3 were obtained assuming a passive fiber with the nonlinear coefficient of the PCF and $\beta_2 = 70$ fs^2/cm, which is half the nominal value of the PCF. Considering the uncertainties in the parameters of the PCF and the sensitivity of self-similar lasers to all cavity parameters, we consider this reasonable agreement. The pedestals at the base of the spectrum are a signature of incipient wave-breaking, which is also visible in the simulated temporal profile (Fig. 3, top row, point C).

The chirped output pulse energy is 1 nJ. The energy is limited by the available pump power, but simulations show multi-pulsing at 2 nJ, so we do not expect much higher energies. The output spectrum (Fig. 4(b)) maintains the overall bandwidth, but typically exhibits some modulation, and may become asymmetric. Some spectral structure can be expected to arise from the NPE process. Birefringence of the PCF may play a role, but that remains to be assessed carefully. We used multiphoton intrapulse interference phase scan (MIIPS) [19] to characterize the phase of the output pulse. The quadratic, cubic, and quartic phases are typically 12,000 fs^2, -6$\times$10^4 fs^3, and 2$\times$10^6 fs^4, respectively. The quadratic phase is smaller than the cavity dispersion, which is typical for amplifier-similariton lasers [15]. The sign and magnitude of the cubic and quartic phases are consistent with the third- and fourth-order dispersion of the PCF. This suggests that the residual phase is accumulated in the PCF without disrupting the intended propagation. After phase correction by MIIPS the pulse is dechirped to the transform limit, with a full-width at half-maximum (FWHM) duration of 25 fs (Fig. 4(c)). The pulse energy after dechirping by the MIIPS apparatus is 0.5 nJ. A consequence of the structured output spectrum is that about 20% of the energy is in the secondary structure. Although the CW peak is undesirable, it does not seem to have major impact on the pulse quality nor the stability of the laser. The pulses could be dechirped with a standard grating compressor with the use of a PCF with smaller third- or fourth-order dispersion. However, the MIIPS system allows adaptive compensation of any subsequent optics.

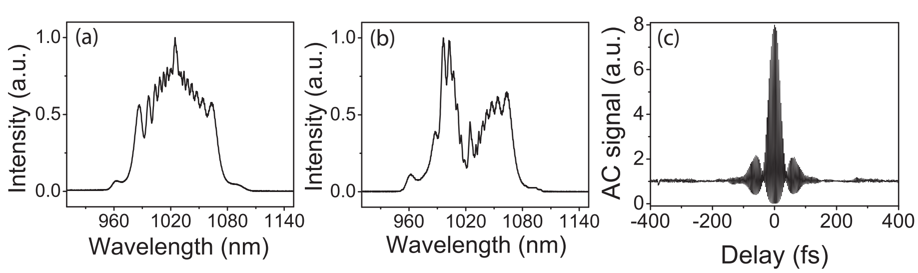

Fig. 4. Experimental (a) spectrum after the PCF, (b) output spectrum, and (c) output autocorrelation signal after phase correction by MIIPS for a 25-fs pulse.

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An example of the broadest spectra that we have observed is shown in Fig. 5. A 1.6-m segment of the PCF was used to obtain this result. Significant energy extends over nearly 200 nm at the base of the spectrum. The pulse energy is 1 nJ. The production of spectra with $\sim$ 20% of the energy below the pump wavelength (where there is no gain) and the excellent agreement between calculated and measured spectra demonstrate that the Yb gain bandwidth does not limit the output spectrum. The FWHM pulse duration is 21 fs, which corresponds to 6 cycles of the field. The pulse does have significant structure in the wings, with energy extending beyond 100 fs from the peak. Nevertheless, these pulses were used to produce high-resolution images by third-harmonic generation microscopy [20].

The pulse evolution in this laser exhibits some remarkable aspects. The spectrum broadens from 4 to 30 nm in the gain fiber, and then to 110 nm in the passive fiber, for an overall spectral breathing ratio of 27. The intracavity pulse duration varies between 1 and 10 ps, yet the pulse can be dechirped outside the cavity to $\sim$20 fs. With respect to that pulse duration, the laser is equivalent to 300 dispersion lengths of propagation. For comparison, in a 5-fs Ti:sapphire laser the spectrum exceeds the gain bandwidth by $\sim$ 30%, the spectral breathing is less than a factor of 2, and the intracavity pulse duration varies from 10 to 50 fs [21].

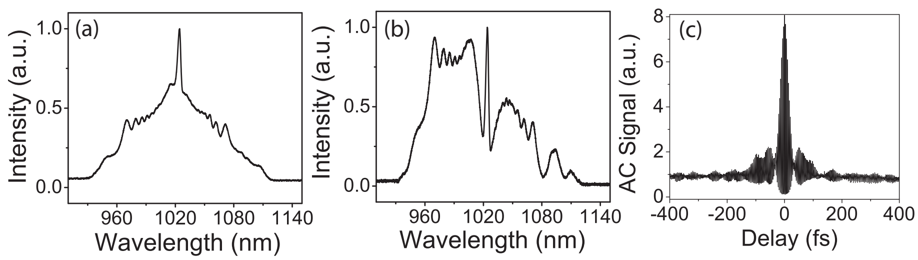

Fig. 5. Experimental (a) spectrum after the PCF, (b) output spectrum, and (c) output autocorrelation signal after phase correction by MIIPS for a 21-fs pulse.

4. Discussion

The results presented here show that substantial bandwidth enhancement by nonlinear pulse propagation can be stabilized in a self-similar laser. Systematic studies of the behavior of the laser with varying parameters should be performed. We have not identified the factors that limit the operation or performance of this kind of laser. We do observe indications of wave-breaking (as in Fig. 3) near the boundaries of convergence of the simulations. The simulations neglect higher-order dispersion, so this suggests that the higher-order dispersion does not limit the stability of the laser. The influence of higher-order dispersion of the nonlinear segment on the generated pulse should be studied, however. It should be possible to produce pulses with more-linear chirp by better design of the nonlinear segment. The existence of the CW component, and its influence on the mode-locked state, also need further investigation. We conjecture that the CW solution of the average cavity model can co-exist with the desired self-similar solution. The PCF has a cut-off wavelength around 300 nm, so extremely broad spectra can be accommodated without risk of multimode propagation. With broader spectra, the loss from filtering will present a challenge.

This work can be extended by continuing the ideal self-similar evolution from the gain segment in a section without bandwidth limitations. This is theoretically possible with a dispersion-decreasing fiber, where the resulting system is formally equivalent to a gain fiber [22]. In addition to the potential of unbounded bandwidth, we expect the pulse to be closer to a parabola and therefore have a nearly-linear chirp. Indeed, initial numerical simulations show that the

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use of a dispersion-decreasing fiber should allow the generation of broader and less-structured spectra, with smaller higher-order phase to be corrected. The generation of parabolic pulses in dispersion-decreasing fiber has been reported [23,24], but the dispersion varies over kilometers. If such a fiber can be fabricated with the dispersion varying on the scale of meters, this will be another promising way to extend the work presented here.

Finally, the laser described here is designed to illustrate the pulse evolution. To construct a version that would be a long-term stable instrument, one would remove the sampling beam-splitters and replace the free-space coupling into the PCF with a spliced connection. Ultimately, an all-fiber version will be desired.

5. Conclusion

In conclusion, we have shown that the gain bandwidth does not present a fundamental limitation to the minimum pulse duration in an amplifier-similariton laser. The spectrum can be broadened in a separate nonlinear segment, and filtering produces the seed pulse to the amplifier that allows a self-consistent solution. This opens a promising route to the development of few-cycle fiber lasers.

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