Fiber grating compression of giant-chirped nanosecond pulses from an ultra-long nanotube mode-locked fiber laser

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We demonstrate that the giant chirp carried by coherent, nanosecond pulses generated in a 846 m-long, all-normal dispersion, nanotube mode-locked fiber laser can be compensated using a chirped fiber Bragg grating compressor engineered to achieve a specific chirp profile. Compression to 154 ps is reported; a compression factor of ∼7. Experimental results are supported by numerical modeling, which is also used to probe the limits of this technique. Our results unequivocally conclude that ultra-long cavity, giant-chirp fiber lasers can support stable dissipative-soliton attractors.

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It has long been understood that cavity dispersion and nonlinearity strongly influence the formation and steady-state characteristics of light pulses generated in a mode-locked laser [1]: for normal (or positive) dispersion the mutual interaction of linear and nonlinear (self-focusing) effects leads to a monotonic and positive frequency sweep (or up-chirp) across the pulse, such that the steady-state mode-locked pulse width is many times larger than its transform-limited duration [2]. Thus, compression techniques have been employed to obtain ultra-short pulses [2].

Recent trends in the development of fiber lasers have built on this understanding of dispersion engineering, exploiting the properties of linearly-chirped pulses to scale the energy beyond the limits imposed by the quantization of conservative optical solitons [3, 4]. Consequently, a modern terminology has evolved, and been largely adopted by the community, to describe and extend established regimes and dynamics in the context of state-of-the-art mode-locked fiber systems, where the flexibility of the waveguide permits extension of such ideas to new parameter ranges [5, 6].

Giant-chirp oscillators (GCOs) [6], that can be categorized as a sub-class of all-normal dispersion (ANDi) lasers [5], are an extreme example of exploiting the properties of frequency swept pulses, typically utilizing cavity lengths in excess of several hundred meters [7–10]) – only reasonably achievable using a fiber platform – to obtain a large dispersion. This extreme regime of mode-locking is distinct from typical mode-locked laser cavities with few-meter cavity lengths, producing hundreds of femtosecond to few picosecond-duration pulses. The increased cavity length also results in a reduced repetition rate, yielding higher pulse energies and peak powers for the same average power, suggesting suitability as a simple pump source for supercontinuum generation [11]. The chirp profile of nanosecond-duration giant-chirped pulses has been shown to be predominantly linear with a residual quartic phase [9, 12]. However, until now, this giant chirp had yet to be compensated and the question of pulse compressibility remained open [13].

In this Letter, we demonstrate experimentally and numerically, that the giant chirp of nanosecond pulses from a long-cavity nanotube mode-locked laser can be compensated using a custom-engineered 200 mm-long fiber Bragg grating, reducing the pulse width by almost an order of magnitude. Up-chirped pulses can be compressed using an optical element providing anomalous dispersion. Typically, such components include bulk diffraction and fibre Bragg gratings, standard fibre (for wavelengths longer than 1.27μm) and photonic crystal fiber (PCF) where the microstructure enables control of the dispersion spectrum. However, for GCO pulses, the most suitable scheme is a chirped fibre Bragg grating (CFBG) as the dispersion and operating wavelength can be carefully engineered to match the specific parameters of the laser system [14–16].

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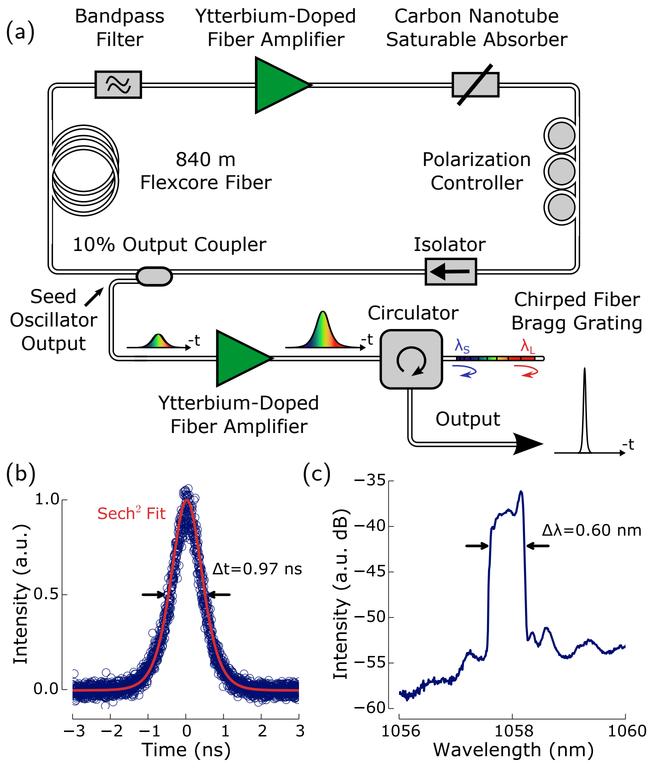

Fig. 1. (a) Experimental setup of giant-chirp seed oscillator and grating-based compression system. To illustrate the pulse chirp, pulse shapes are shown and filled with color to highlight the corresponding spectral components. The CFBG is also colored to show at which point along the grating each spectral component will be Bragg reflected. (b) Streak camera trace of pulses generated by seed oscillator. (c) Corresponding pulse spectrum.

Our all-fiber giant-chirp pulse source is shown in Fig. 1(a). We used a ring cavity design including a ytterbium-doped fiber amplifier (YDFA), polarization controller, isolator to ensure unidirectional propagation, 10% output coupler and carbon nanotube-based saturable absorber (CNT-SA) to initiate mode-locking. A 10 nm bandpass filter was also included to fix the lasing wavelength although this was not required to achieve stable pulsing – instead, pulses were stabilized by the limited gain bandwidth of the system, including a spectral filtering effect of the CNT-SA which acted to reduce the wings of the chirped pulses. An ∼840 m length of Flexcore fiber (mode-field diameter = 6.5 $\mu m, \beta_2 =$ 17.6 ps^2 km$^{-1}, \gamma =$ 2.9 W^{-1} km^{-1}) was also included to elongate the cavity and provide a large dispersion to produce a giant up-chirp. The total cavity length was ∼846 m. It should be noted that this cavity design is similar to our initial report of nanosecond pulse generation from a nanotube mode-locked laser [17]; a recent and full characterization of the nanotube saturable absorber used here can be found in Ref. [10].

Stable, self-starting mode-locking was observed, producing a train of pulses at 244 kHz repetition rate. The pulses were fitted well by a sech^2 profile, with 0.97 ns full-width at half maximum (FWHM) duration [Fig. 1(b)]. The pulse spectrum was centered at 1058.0 nm and exhibited steep spectral edges and an ‘M-shaped’ top [Fig. 1(c)]. Due to the structured peak, a spectral bandwidth measurement was made using the full-width at quarter maximum (FWQM), rather than the FWHM, which was 0.60 nm. These spectral features are characteristic of coherent pulses from ANDi lasers, which are optical examples of dissipative solitons that are commonly encountered in other nonlinear dispersive systems [18]. The time-bandwidth product of 156 (∼500 times greater than the transform limit of 0.315) highlights the giant up-chirp of these pulses (which we have previously directly measured by recording the pulse spectrogram [9]).

To compensate the linear chirp, we designed a chirped fiber Bragg grating (CFBG) with reflection band and chirp rate matched to the pulse spectrum. For our up-chirped nanosecond pulses, the long-wavelength component at the front of the pulse arrives at the grating 1 ns earlier than the short wavelength component at the rear of the pulse. By gradually decreasing the grating pitch so the Bragg reflection wavelength, $\lambda_B(z)$ decreases with position, z, along its length, L, longer wavelength pulse components propagate further into the grating before being reflected, introducing a delay between them. For a pulse with bandwidth $\Delta\lambda$, the delay τ introduced between long and short wavelength components at either side of the reflected pulse is given by:

$$\tau = 2\frac{n}{c}\frac{\Delta\lambda}{\frac{d\lambda_B}{dz}} \quad (1)$$

where n is fiber refractive index, c is the vacuum speed of light and $\frac{d\lambda_B}{dz}$ is the grating chirp rate. Therefore, by matching the CFBG delay to the duration of the chirped pulse, the spectral components will temporally realign upon reflection from the CFBG, compensating the chirp and compressing the pulse.

We verified this compression technique by numerical modeling. For the oscillator, we solved the nonlinear Schrödinger equation for each component, taking the input to the next component as the output field from the previous component [12]. We included the full propagation constant (β) for the long length of Flexcore fiber, which was computed by finding eigenmodes of the wave equation for this step index fiber geometry. The simulated pulse evolved from an initial noise field (equivalent to one photon per mode) over thousands of round trips, ultimately exhibiting a pulse duration of 0.99 ns and spectral FWQM of 0.63 nm, in good agreement with the experiment. The pulse spectrogram confirmed the linear chirp [Fig. 2(a), as experimentally verified previously [9]].

We modeled the CFBG using a piecewise-uniform approach for non-uniform gratings [19]. Fiber grating properties can be determined from solving forwards and backwards coupled wave equations, for which analytical solutions only exist for uniform gratings. By splitting the grating up into hundreds of uniform segments, with progressively varying properties, we computed the transfer matrix for each segment and then determined the overall CFBG response and complex reflection coefficient by multiplying all the transfer matrices together. The interaction between the pulse and grating is a convolution in the time domain, more efficiently computed as a product in the frequency domain between the complex field and grating reflection coefficient (converting between time and frequency domain using a Fast Fourier Transform).

Using this model, we determined the optimum CFBG parameters for maximum compression of the simulated giant-chirped pulses. Fig. 2(b) shows the reflectivity and group delay of this CFBG with refractive index $n_0 = 1.45$, grating strength $\delta n = 5 \times 10^{-5}$, chirp rate $\frac{d\lambda_B}{dz} = 0.0048$ nm/mm, length $L = 200$ mm and a Gaussian apodization profile, $g(z) = \exp\left(-\frac{(z-0.5L)^2}{2w^2}\right)$ where $z = 0$ is defined as the start of the grating and the Gaussian envelope FWHM is $2w\sqrt{2ln2}$ [20], which was chosen to be 60 mm here. The CFBG reflection band was designed to be wider than the pulse spectrum to minimize interaction with grating edges, which are known to give rise to strong dispersion which could distort the reflected pulse [20, 21]. Additionally, a Gaussian apodization profile was used to gradually decrease the index modulations to zero at the ends of the grating, avoiding Fabry-Pérot reflections from the boundary between grating edges and surrounding fiber, which prevents sidelobes and oscillations in the reflection spectrum and group delay [21]. Our model showed that pulses reflected from the gratings could be compressed to 8.4 ps, well-fitted with a Sech^2 profile [Figs. 2(c) and (d)]. We note that this is still several times larger than the transform limit of ∼1.9 ps and a small pedestal is visible, which is attributed to the chirp not being perfectly linear as a result of higher order dispersive effects in the ultra-long cavity [9]. The chirp is also plotted on Figs. 2(c) and (d) as a change of instantaneous frequency, showing a linear frequency sweep across the input pulse but a relatively constant frequency across the compressed pulse, apart from features at the pedestal indicating uncompensated higher-order chirp. Using Eqn. 1, the grating-induced delay between components at either side of the pulse spectrum was calculated to be 1.27 ns. It should be noted that this exceeds the FWHM duration of the pulse (0.99 ns), although is in better agreement with the FWQM (1.34 ns), suggesting that spectral components in the wings of the pulse must be aligned to achieve optimum compression.

Fabricating high-quality long (>10 cm) FBGs is experimentally challenging since conventional holographic fabrication techniques rely on phase masks which limit the maximum grating length [16, 22]. While it is possible to obtain longer FBGs by stitching together a large number of smaller FBGs [22], this is not a practical approach for chirped gratings, where the properties continually vary along their length. Recently, a new grating fabrication technique was proposed [23], adapted from Ref. [24] based on a piezo-mounted phase mask (PMPM), enabling control of the amplitude and phase of a long grating with great precision [16, 23]. Here, the phase mask is secured to a piezoelectric translation stage which is driven by a ramp signal at a fixed repetition rate to produce a moving fringe pattern at a fixed position. A hydrogen-loaded optical fiber, mounted on a linear translation stage, is placed at the focus and slowly translated along, at a speed synchronized to the ramp signal repetition rate. This technique can be used to quickly produce gratings with an arbitrary chirp, apodization profile and phase shift by varying the ramp signal [16].

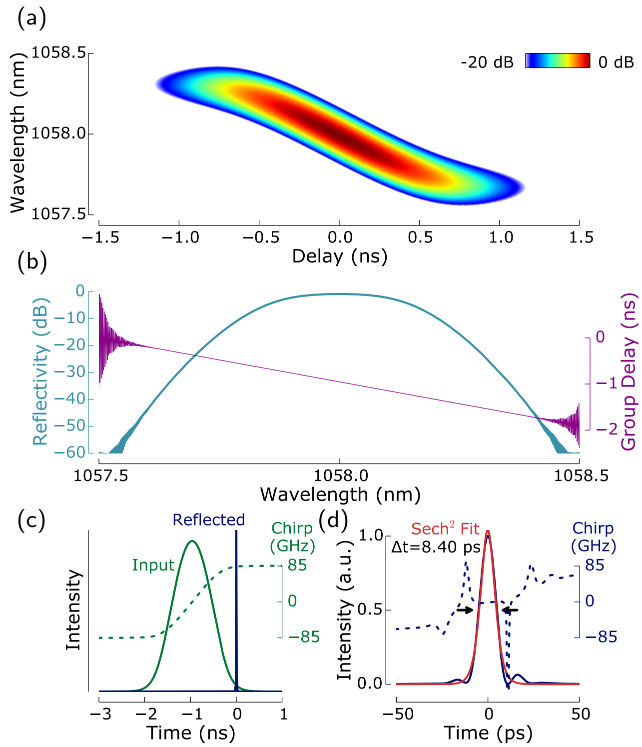

Fig. 2. Numerical modeling results: (a) Giant-chirped pulse spectrogram. (b) CFBG reflectivity and group delay, for CFBG properties: $n_0 = 1.45$, $\delta n = 5 \times 10^{-5}$, $\frac{d\lambda_B}{dz} = 0.0048$ nm/mm, $L = 200$ mm and 60 mm FWHM Gaussian apodization envelope. (c) & (d) Incident and reflected pulses from the CFBG, showing pulse compression.

We used this PMPM fabrication technique to produce a 200 mm long CFBG with the properties determined from the simulations that are required to compress the giant-chirped pulses. A phase mask was chosen which produces index modulations with pitch ∼365 nm (assuming fiber refractive index, $n_o = 1.45$), corresponding to a Bragg wavelength of ∼1058.0 nm. The CFBG was written into single-mode Flexcore fiber to enable low-loss splicing to the laser system, ensuring it remains fully-fiber integrated. After hydrogen loading, the fiber is exposed to 5 mW of 213 nm light from a Q-switched

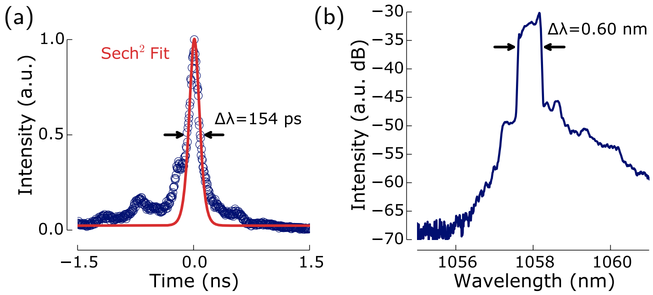

Fig. 3. Compressed pulse characteristics at output of the circulator: (a) streak camera trace; (b) spectrum.

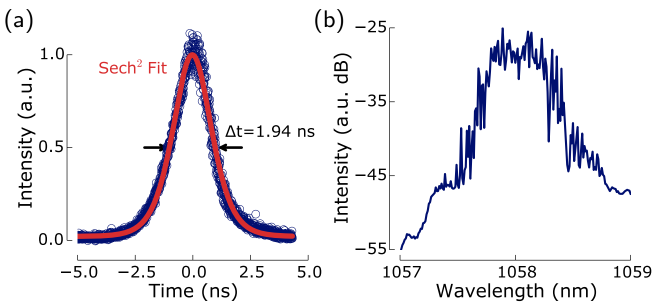

Fig. 4. Pulse characteristics at output of the circulator when the oscillator is operating in a noise-burst regime: (a) streak camera trace; (b) spectrum.

Nd:YAG laser. The high photosensitivity of the fiber at this wavelength means only low powers are required to alter the core index to produce the grating [23]. To obtain the correct chirp profile, the ramp frequency driving the piezo-mounted phase mask is swept, gradually changing the pitch of refractive index modulations along the 200 mm fiber length into which the grating is written. Due to the sensitive nature of the grating fabrication process, the temperature was maintained within 0.2°C at all times during writing.

This CFBG was integrated into our experimental setup through a circulator, following a YDFA to increase the pulse energy [Fig. 1(a)]. We stretch-tuned the CFBG to optimize spectral alignment betweens its reflection band and the pulse spectrum. A streak camera (∼20 ps resolution) was used to measured the compressed reflected pulses at the circulator output. It was also possible to marginally vary the pulse bandwidth by ∼0.2 nm by changing the power. As expected, this changed the compressed pulse duration since it varied the delay introduced between the extrema of the chirped pulse as it was reflected in the CFBG. With careful tuning, we were able to achieve compression to 154 ps, almost an order of magnitude shorter than the pulses generated from our mode-locked laser. This confirms that nanosecond pulses from GCOs exhibit a dominant linear chirp.

By adjusting intracavity power and polarization, it is possible to vary the operating state of mode-locked lasers. Long-cavity mode-locked lasers have been reported to operate in noise-burst regimes, generating bursts of incoherent noise-like pulses [7, 25], which has previously been identified as partial mode-locking [26]. These noise-like pulses are not linearly chirped and the lack of phase coherence between pulses makes them incompressible [25]. We note that in our laser, in which we employ a *real* saturable absorber, the operation is more robust against perturbations due to polarization variation and pump power, compared to *artificial* saturable absorber-based lasers that have a narrow range of stable mode-locked states. However, we are still able to force partial mode-locked operation by adjusting the polarization controller and pump power, characterized by a noisier and more rounded spectrum [Fig. 4(b)] [26].

When operating in this regime, the reflected pulses from the CFBG were not compressed, but broadened by a factor of ∼2 [Fig. 4(a)]. Since the noisy bursts are unchirped, the spectral components are not distributed linearly through the pulse – so the delay introduced for pulse components at either side of the spectral bandwidth affects multiple parts of the temporal waveform, broadening the pulse by ∼1.27 ns.

Our experimental compression factor is lower than that achieved in numerical simulations, for which there are numerous possible explanations. During CFBG fabrication, manufacturing tolerances can result in deviations from an ideal periodic structure, so the grating chirp may not be truly linear. Additionally, the simulated pulse does not include jitter which could account for measurement of a broader pulse than expected due to the averaging nature of the sampling streak camera.

In conclusion, we have experimentally and numerically demonstrated the generation of nanosecond giant-chirped pulses from a nanotube mode-locked laser and compression by almost an order of magnitude using a custom-engineered chirped fiber Bragg grating. This paves the way to more compact, fully-fiber integrated chirped pulse amplification schemes and low-repetition rate, high-energy, short-pulse sources.

Acknowledgments

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