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We report the generation of 63 fs pulses of 290 nJ energy and 4.1 MW peak power at 1050 nm based on the use of a polarization-maintaining ytterbium-doped fiber parabolic amplification system. We demonstrate that operation of the amplifier beyond the gain bandwidth limit plays a key role on the sufficient recompressibility of the pulses in a standard grating pair compressor. This results from the accumulated asymmetric nonlinear spectral phase and the good overall third-order dispersion compensation in the system.

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Ytterbium-doped fibers feature a number of important performance advantages regarding both the generation and the amplification of short optical pulses, which have made them an attractive alternative to conventional solid-state laser systems. Specifically, they feature outstanding thermo-optical properties, large gain bandwidth (>40 nm), high saturation fluence allowing the generation of millijoule pulses, and high optical pumping efficiency ($>80\%$).

However, the tight optical confinement within long interaction lengths inside the fiber core sets a severe limitation on the power and energy scaling due to the generally undesirable nonlinear pulse distortions. Chirped-pulse amplification (CPA) [1] in the linear regime (nonlinear phase shift $\Phi_{NL}<1$) is a first straightforward answer to these restrictions. Sufficient pulse stretching in the time domain, along with the enlargement of the fiber's mode-field diameter in CPA systems [2,3], has led to the generation of millijoule subpicosecond pulses [4] or high-average-power fs pulses [5]. Alternatively, high-peak-power and high-energy CPA systems have been demonstrated [6,7] in the particular regime where large amounts of nonlinear phase is accumulated ($\Phi_{NL}\geqslant\pi$). Last but even more emphatically denoting the fundamental importance of the fibers nonlinearity is the case of parabolic amplification [8].

Parabolic pulses are the asymptotic solution of the nonlinear Schrödinger equation accounting for flat spectral gain, self-phase modulation (SPM) and positive group velocity dispersion (GVD). The interplay between SPM and GVD in the presence of gain results in a wave-breaking-free propagation regime [9] and the generation of purely linearly chirped amplified pulses. However, this ideal asymptotic solution is experimentally largely limited due to additional deleterious effects such as a limited gain bandwidth of the fiber, the higher dispersion orders, and the stimulated Raman scattering (SRS) [10,11]. For broad spectrum parabolic pulses, third-order dispersion (TOD) becomes a significant restriction in their recompressibility, and special care has to be taken for the overall TOD compensation of the system. This issue has been addressed in our previous work [12] in the case of parabolic amplification by means of a hybrid gratings–prisms compressor arrangement below the gain bandwidth limit.

In this work we investigate parabolic amplification in terms of compressibility of the generated pulses when the amplifier gain is increased beyond the threshold of the gain bandwidth limited regime [13] but still below the SRS threshold. We report on a large-mode-area (LMA) Yb-doped fiber parabolic amplification system, followed by a conventional grating pair compressor, that generates high-quality 63 fs pulses of 290 nJ energy (about 260 nJ in the main peak of the pulse) and over 4.1 MW of peak power at 27 MHz, centered at 1050 nm. These performances are obtained with a simple, stretcher-free single stage amplifier setup. To our knowledge these are the shortest pulse duration and highest peak power ever reported for Yb-doped fiber based parabolic amplification systems and a first approach on demonstrating the potential operation in the gain bandwidth limited regime.

There are three main sources of TOD in our system. First is the TOD of the ytterbium-doped fiber amplifier (YDFA), which for typical LMA fibers is dominated by the material TOD, resulting in a positive third-order propagation constant of $\beta_3=6\times10^{-2}\ \mathrm{ps^3\ km^{-1}}$. The second source is the TOD of the compressor. Quite unluckily, the TOD to GVD ratio introduced by the YDFA has an opposite sign to that introduced by a grating pair compressor [12]. This means that if the compressor is set to perfectly compensate the GVD, the TOD of both the YDFA and the compressor will simply add, resulting in significant pulse broadening and pulse shape distortion. The third source of TOD originates from SPM of spectrally asymmetric pulses. In a strongly stretched pulse regime, the accumulated Φ_{NL} is approximately proportional to the spectral intensity [14]. Although for ideal parabolic pulses the spectrum is symmetric and this effect is negligible, in practice asymmetric spectra often arise due to the fiber spectral gain profile. The induced SPM thus results in an asymmetric phase contributing to a nonnegligible TOD. This effect can be used to compensate the other TOD sources in a CPA setup [6].

Our system consists in an diode-pumped passively mode-locked bulk $Yb:CaGdAlO_4$ laser oscillator, followed by a diode-pumped polarization-maintaining LMA Yb-doped fiber amplifier (YDFA) and a conventional grating pair compressor (Fig. 1). The oscillator employs a 5.5 m long cavity and provides 95 mW in 145 fs pulses of 15 nm bandwidth [time–bandwidth product (TBP)=0.65] centered at 1040 nm, at a repetition rate of 27 MHz. About 55 mW (2 nJ) are seeded into the YDFA through an optical isolator (to avoid feedback to the oscillator) and a half-wave plate for the coupling optimization in the polarization-maintaining fiber. The YDFA consists in a 6.5 m long double-clad Yb-doped LMA fiber (NA =0.06) with core/clad diameters of 20/400 μm (Nufern). The amplifier is pumped by a 25 W fiber-coupled diode at 976 nm, exhibiting absorption of 1.7 dB/m. Both fiber ends are angle cleaved at 8° to suppress parasitic lasing. At maximum pump power, the amplifier delivers 5.6 ps pulses of 48.5 nm bandwidth (TBP=74) and 11.5 W average power. YDFA's output pulses are compressed in a high-efficiency 1250 line/mm transmission–grating pair compressor arranged in the antiparallel configuration to allow increased flexibility (z_c in Fig. 1 varied between 5 and 10 mm). In the standard parallel grating configuration the required grating separation (<10 mm) could not be achieved due to the gratings' substrate thickness. The use of a half-wave plate at the compressor's input increased its overall efficiency to about 70%.

According to [13], for the parameters of the fiber used (i.e., $L=6.5$ m, $\beta_2 \approx 20\ \text{ps}^2\,\text{km}^{-1}$, $\gamma \approx 0.7\ \text{W}^{-1}\,\text{km}^{-1}$, and gain bandwidth $\Delta\nu_g \approx 10$ THz) and a fixed input pulse energy of 2 nJ, the maximum output power before reaching the YDFA's gain bandwidth limit is calculated at 1.8 W ($g=0.54\ \text{m}^{-1}$). The increase of the amplifier's pump power to its maximum ($g_{\max}=0.82\ \text{m}^{-1}$) reduces the maximum non-bandwidth-limited propagation length in the fiber to around 3.8 m.

Experimentally, the above mentioned bandwidth limitation is clearly observed on the spectral shape of the output pulses for output power exceeding 5 W. Above this value, a relatively steeper low-wavelength side of the spectrum is progressively developing, while a further increase of the gain results in the extension of the spectrum towards longer wavelengths [inset of Fig. 3(a)]. As expected, because of the reduced gain of the YDFA for longer wavelengths, beyond a certain pump power level, a clear spectral shaping generally resembling a "shark fin" is observed [6]. Since Φ_{NL} is expected to be approximately proportional to the spectral intensity, the specific spectral shape can result in a reverse of the φ_3 sign of the pulse and therefore even in a perfect matching of the φ_3/φ_2 ratio between the YDFA and the compressor.

To verify the above assumptions, with the use of a second-harmonic generation frequency-resolved optical gating (SHG FROG) setup, we performed a systematic measurement of the φ_3/φ_2 ratio of the amplified uncompressed pulses at various output power levels ($0.76 \leqslant g \leqslant 0.82\ \text{m}^{-1}$). While the value of φ_2 only varies between 0.073 and 0.065 ps^2 (0.079 to 00.73 ps^2 for ideal parabolic pulses), φ_3 not only varies remarkably within almost an order of magnitude but also exhibits the predicted change of sign. Figure 2 shows the φ_3/φ_2 ratio of the amplified uncompressed pulses for output power in the range of 7 to 11.5 W (error bars are due to spectral phase fitting error up to the 9th order of the Taylor series for central angular frequency determined by the maximum of the spectrum). In our setup, the φ_3/φ_2 ratio of the grating compressor is fixed to about −4 fs, thus optimal compression would require a φ_3/φ_2 ratio of the YDFA of −4 fs as well. We can therefore predict from Fig. 2 that a simultaneous compensation of both the GVD and the TOD is expected for YDFA's output power slightly above 9 W.

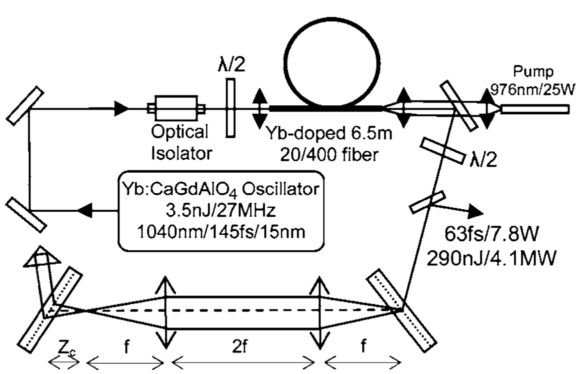

Fig. 1. Experimental setup.

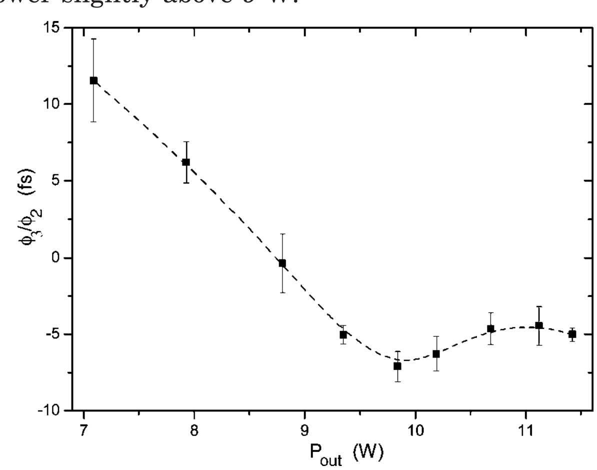

Fig. 2. φ_3/φ_2 spectral phase ratio of the amplified uncompressed pulses versus YDFA's output power.

Figure 3(a) shows the best compressed output pulses, retrieved from a SHG FROG measurement, for three representative cases (the corresponding 128×128 FROG traces with an error <0.0045 are shown as insets). At 1.1 W (below the 1.8 W gain bandwidth limitation threshold) the parabolic pulses are not efficiently compressed, exhibiting 143 fs duration and secondary pulses because of uncompensated TOD (estimated accumulated nonlinear phase shift $\Phi_{NL} \approx 5.7\pi$). At 8.7 W (6 W after compression) almost TOD perfectly compensated pulses are obtained (98% of the pulse energy in the main pulse peak), with 70 fs duration, 31 nm spectral bandwidth (TBP=0.6), and energy of 220 nJ corresponding to 3.5 MW peak power ($\Phi_{NL} \approx 18\pi$). At the maximum YDFA's output power of 11.5 W (7.8 W after compression), 63 fs pulses of 48.5 nm bandwidth (TBP =0.85) were produced (TBP for ideal parabolic pulses 0.73). Although in this case the satellite structure of the pulses is increased, their quality is still very high (89% of the pulse energy remains in its main peak), leading to a pulse energy of 290 nJ (about 260 nJ in the main peak) and peak power of 4.1 MW ($\Phi_{NL} \approx 21.2\pi$).

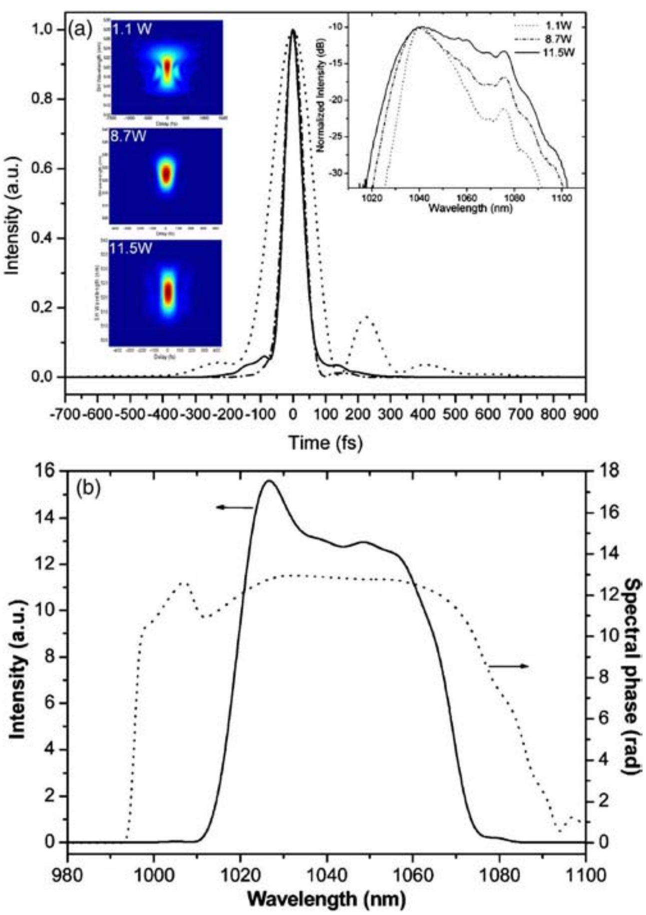

Fig. 3. (Color online) Retrieved (a) temporal intensity profile of the compressed pulses at different YDFA's output powers (the corresponding intensity spectra and FROG traces are shown as an inset). (b) Spectrum and spectral phase at maximum output power.

Figure 3(b) shows the SHG FROG retrieved the spectrum and spectral phase of the 63 fs pulses. Spectral shaping due to gain bandwidth limitation is clearly illustrated in this case. The resulting spectral phase is flattened as a result of sufficient TOD compensation in the YDFA/compressor combination due to the spectral asymmetry.

In conclusion, we have demonstrated the generation of 63 fs pulses of 4.1 MW peak power through the compression of nonideal parabolic pulses produced by a standard PM LMA YDFA. We strongly believe that further increase of the YDFA's gain in combination with the nonlinear spectral phase based TOD compensation scheme presented here could lead to the generation of pulses in the 1 μJ/sub 100 fs regime. To achieve this, the fiber characteristics (length, core size, doping level, and dispersion), the compressor line density, the repetition rate, and the pump power level should be carefully chosen so that overall TOD is compensated. The onset of SRS then limits the achievable pulse energy.

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