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Few-optical-cycle pulse generation based on a non-linear fiber compressor pumped by a low-energy Yb:CALGO ultrafast laser

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Abstract: Pulse compression in a short, normal dispersion photonic-crystal fiber is investigated with a $Yb:CaGdAlO_4$ laser pumped by a low-power fiber-coupled single-mode diode that delivers 70-fs pulses at 1050 nm central wavelength, with 45-mW average power at 60 MHz repetition rate. A simple and power-efficient compressor based on a ~15-cm long, low-cost commercial nonlinear fiber, with normal dispersion at the laser wavelength, produces pulses as short as 14.9 fs, corresponding to ~4.25 optical cycles, with 29 mW average power after a prism-pair compressor in double pass configuration. Pulse quality was investigated with frequency resolved optical gating (FROG) analysis. Furthermore, a comparative analysis of noise properties of the oscillator, pump laser and compressed pulses has been performed.

1. Introduction

Solid-state Yb lasers such as $Yb:CaGdAlO_4$ (Yb:CALGO) [1] pumped by single-mode laser diodes based on a single-prism (SP) cavity were proved to be a simple and effective source for generating pulses as short as 36 fs using semiconductor saturable absorbers (SESAMs) [2]. Kerr-lens mode-locking (KLM), with more powerful, special high-brightness multiwatt fiber lasers at 976 nm, provides even faster modulation allowing the generation of pulses as short as 32 fs [3]. The same pumping technology has recently allowed to demonstrate a remarkable 21-fs $Yb:CaYAlO_4$ laser using KLM, although with a very modest power efficiency (13 mW output power vs. 5 W pump power) [4]. This shows quite clearly the shortcoming of pushing the pulsewidth of oscillators to extreme performance, which necessarily requires a trade off with efficiency, pump laser complexity and cost, as well as operation stability of the oscillator itself. On the other hand, low-energy pulses shorter than 20 fs are interesting for several applications such as nonlinear microscopy [5], time-domain spectroscopy [6], and the synthesis of compact broadband THz devices for spectroscopy or imaging [7].

A more practical engineering approach to reach this goal consists in using a robust and reliable sub-100-fs diode-pumped compact source with optimized pulse peak power, followed by a simple pulse compressor. A detailed investigation of such a system was reported earlier by Druon and Georges [8]. A relatively powerful 400-mW 110-fs Yb:SYS laser pumped by a multimode diode was used for pulse compression experiments with a 20-cm long photonic-crystal fiber (PCF) having zero-dispersion at 1065 nm. Reasonably clean pulses at 20.3-fs duration were reported. Even shorter pulses, with duration reduced to 14 fs, but with an autocorrelation trace revealing a

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complex multipulse structure were demonstrated. Numerical modelling showed that the shorter the initial pulse, the higher the quality of the compressed pulse [9,10].

In this paper we report a detailed investigation using a compact, robust Yb:CALGO SP cavity seeder, pumped by a readily available 400-mW single-mode telecom fiber-coupled diode, to generate low-intensity-noise, sub-20 fs pulses by means of non-linear fiber compressor. The oscillator is mode-locked with a SESAM and emits 70-fs Fourier-limited pulses at 60-MHz repetition rate, with 45-mW average power. A commercial off-the-shelf PCF with zero dispersion at ~1200 nm (LMA-PM-5, NKT Photonics, Inc.) is employed for non-linear pulse spectral broadening. A prism pair in double-pass configuration is used to compress the pulses after the spectrum broadens to ~180 nm. Depending on injected pulses energy, either 19.5-fs pedestal-free clean pulses or 14.9-fs pulses with >60% energy in the central peak are produced with 29-mW power at the output of the prism-pair compressor for the shortest pulses, corresponding to a transmission efficiency of ~65% and a peak power enhancement larger than two. The reconstructed field and phase profiles obtained with FROG characterization [11] are discussed, together with detailed noise measurements carried out on the pump diode, Yb:CALGO oscillator and the compressor output.

2. Experiments

A scheme of the experimental setup is shown in Fig. 1. To increase the pulse peak power of the seeder described in [2] still maintaining a sub-100-fs pulse duration, we reconfigured the SP resonator by reducing repetition rate to 60 MHz and increasing the output coupling to 1.6%. Self-starting cw mode-locked pulse train with 45 mW average power (0.75 nJ pulse energy) were readily obtained. The intensity autocorrelation and the spectrum of the t_0 = 70 fs, 20-nm full-width at half maximum (FWHM) bandwidth pulses are shown in the inset of Fig. 1. The corresponding pulse peak power of ~11 kW represents a ~3-fold increment with respect to [2].

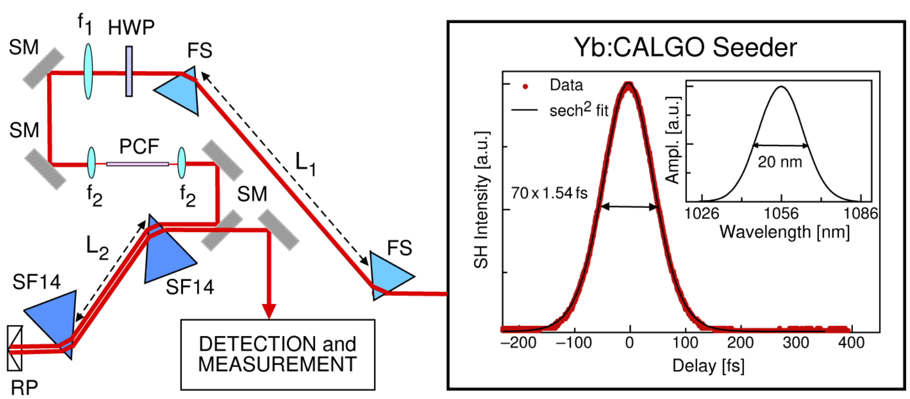

Fig. 1. Experimental setup. FS: Fused Silica prism; SM: Silvered Mirror; f_1: f = 1 m spherical lens anti-reflection (AR) coated at 1-1.1 μm; HWP: Half-Wave Plate; f_2: f = 4.5 mm, NA = 0.55 aspherical lens AR coated at 0.9-1.2 μm; PCF: Photonic-Crystal Fiber; SF14: Schott SF14 glass dispersive prism; RP: Roof-Prism. In the inset it is shown the seeder pulse autocorrelation trace and corresponding optical spectrum.

Out of the seeder, the laterally-dispersed spectral components were overlapped through a pair of fused silica (FS) prisms separated by a distance L_1 = 540 mm. A half-wave plate was used to control the polarization plane of the laser beam to match the fast axis of the polarization-maintaining PCF used for spectral broadening of the seeder pulses. The seeder beam was collimated by a f_1 = 1 m AR-coated spherical lens and redirected towards the PCF employing silver mirrors (see Fig. 1). A pair of aspherical lenses (f_2 in Fig. 1) were used to couple-in and collimate the beam out of the PCF. The uncoated PCF was specified for a mode-field diameter MDF = 4.4 μm at 1060 nm and NA = 0.2. By properly adjusting the alignment of the silvered mirrors and the position of the focusing aspheric lens, we achieved a maximum coupling efficiency of about 70%, corresponding to an average power of about 31 mW ($\simeq$ 0.5 nJ pulse energy, $P_p \simeq 7$ kW peak power) injected in the PCF. During our experiment we tested several different PCF lengths. Optimum length was 145 mm. Shorter or longer PCFs yielded either narrower or only slightly broader but uncompressible spectra.

To compress the spectrally-broadened pulses, we employed two SF14 prisms in double-pass arrangement. The second pass was separated from the first with a roof-prism acting in the vertical plane. The tip-to-tip separation of the two SF14 prisms was L_2 = 337 mm, resulting in a maximum negative group delay dispersion of about -6000 fs^2. To optimize pulse compression we initially monitored the output pulse train with a standard intensity autocorrelator (APE Pulsecheck), and adjusted the SF14 prism insertion to minimize pulse duration. Then, to fully characterize the pulses we used a home-made SHG-FROG setup mounting a 10-μm-thick BBO crystal for SHG.

Initially we investigated the condition producing the maximum spectral broadening in the PCF. The broadest spectrum obtained (dashed line of Fig. 2(c)) extended from 970 nm to 1180 nm. The measured and retrieved FROG traces are shown in Figs. 2(a) and (b) respectively. The structured pulse intensity profile and corresponding temporal phase are shown in Fig. 2(d). The main pulse peak, containing about 62% of the total energy by numerical integration, has a FWHM duration t_c = 14.9 fs, yielding an optimum compression factor $F = t_0/t_c \simeq 4.7$, corresponding to an output peak power of 21 kW. From the data-sheet of the PCF fiber [12], the nominal group velocity dispersion at 1050 nm is $K'' \simeq 15$ fs^2/mm. According to the normalization adopted in [9], this corresponds to a dispersion distance $z_D = t_0^2/|K''| \simeq 325$ mm. Following the notation in [9], from the optimum compression factor F we can estimate a non-linearity parameter $R = z_d \gamma P_p \approx (F/0.63)^2 \simeq 56$. This yields an optimum PCF fiber length $z_{opt} \approx 2.5 z_d/\sqrt{R} \simeq 110$ mm, in fairly good agreement with our experimental result. We can also estimate a PCF fiber nonlinear coefficient $\gamma = R/(z_d P_p) \simeq 24$ W^{-1}mm^{-1}.

Comparing the measured pulse temporal intensity profile with the transform-limited pulse corresponding to the measured optical spectrum (blue and dashed black lines in Fig. 2(d), respectively), it appears that the residual uncompensated higher-order dispersion terms mainly contribute to a reduction of the amount of energy in the main pulse lobe, but are not limiting the minimum achievable main lobe pulse duration. The spectral phase shown in Fig. 2(c) is almost flat around the main spectrum lobe centered at 1000 nm. The $\sim \pi$ shift at 1075 nm corresponds to a local zero value of the retrieved spectral intensity. On the red tail of the spectrum, the phase can be due to uncompensated higher order dispersion terms, which limit the attainable pulse compression and likely determine the splitting of the pulse in several lobes.

Clean, almost pedestal-free compressed pulses were obtained simply by reducing the injected pulse energy to about 0.35 nJ (21 mW average power), corresponding to $P_p \simeq 5$ kW. The same result could have been in principle obtained at full incident power by proportionally shortening the PCF fiber and properly adjusting the SF14 prism separation. The spectrum measured at the output of the PCF extended from 1000 nm to 1150 nm, as it is shown in Fig. 3(c). The measured and retrieved SHG-FROG traces are shown in Figs. 3(a) and (b), respectively. In Fig. 3(d), it is shown the temporal profile of the almost Fourier-transform limited pulse retrieved from the SHG-FROG measurement. The pulse duration is 19.5 fs and from numerical integration, about 90% of the pulse energy is contained in the main lobe (16 kW output peak power).

To assess the intensity stability of the ultrashort pulses, we measured the power spectral density of the relative intensity noise (RIN) of the pump diode source, of the Yb:CALGO seeder, and of the radiation at the output of the PCF. The results are summarized in Fig. 4(a). The RIN measurements are performed using a low-noise avalanche InGaAs photodetector with 400-MHz

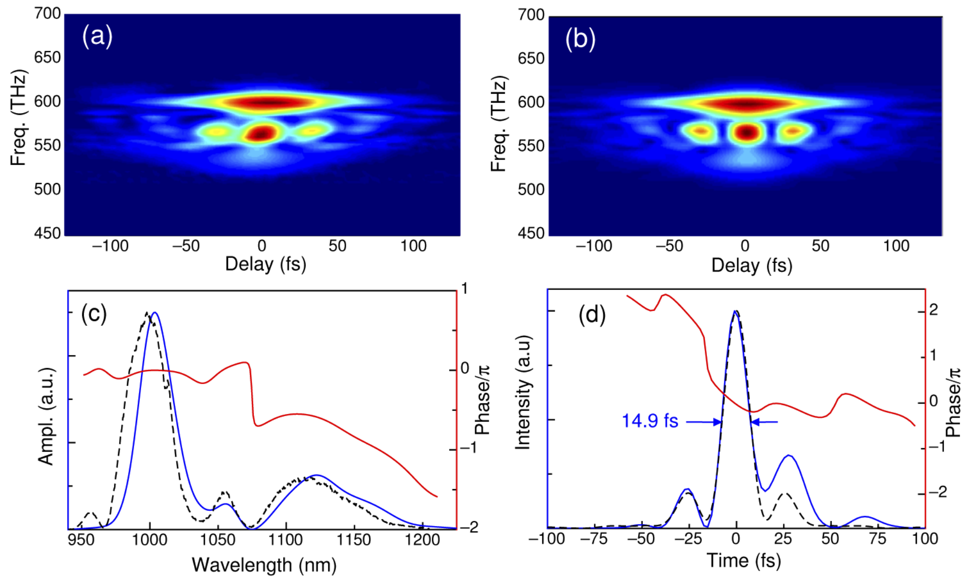

Fig. 2. (a) Measured SHG-FROG trace. (b) Retreived SHG-FROG trace with 0.017 error on a 128 × 128 grid. (c) Optical spectrum (black dashed line) at the output of the PCF at the maximum injected average power of 31 mW. In blue and red are shown the reconstructed optical spectrum and corresponding spectral phase in units of π. (d) In blue and red are shown the reconstructed temporal pulse intensity and phase in units of π. Black dashed line is the temporal intensity profile of the transform limited pulse calculated from the measured optical spectrum.

bandwidth and an electrical spectrum analyzer (ESA). In the Fourier frequency range from 10 to 1000 Hz, the RIN of the Yb:CALGO seeder is equivalent to that of the pump diode, which is mainly limited by a flicker noise contribution of the house-made diode current driver. For larger Fourier frequencies, the Yb:CALGO RIN spectrum is always lower than the pump diode due to a filtering effect of the Yb upper laser level lifetime (440 μs, corresponding to a cut-off frequency of ~360 Hz). For frequencies larger than 1-MHz the power spectral density of the RIN reaches the noise-floor at the level of -135 dB/Hz. Over the entire frequency range from 10 Hz to 10 MHz the cumulative standard deviation of the Yb:CALGO laser intensity amounts to 0.12%, a factor of ~3 times lower than the diode pump laser cumulative standard deviation (0.37%). The spectral densities of the RIN corresponding to the long (at around 1125 nm) and to the short (1000 nm) wavelength tails of the supercontinuum (SC) radiation shown in Fig. 2(c) are measured (with an optical bandwidth of ~ 10 nm) by placing the low-noise avalanche photodiode between the two SF14 prisms of the compressor stage. Overall, the SC RIN spectra closely resembles the RIN of the Yb:CALGO laser over all the analyzed spectral range, apart from a minor degradation in the low Fourier frequency range due to acoustic noise acting on the PCF coupling mounts at frequencies of 100, 140, 650, and 800 Hz. The resulting integrated RINs from 10 Hz to 10 MHz at the PCF output amount to 0.16% and 0.15% for the long and short wavelength tails, respectively. Intensity fluctuations at the same level of ~0.16% are also measured for the unfiltered SC radiation indicating that the stability of these ultrafast pulses is not particularly degraded with respect to the stability of the Yb:CALGO seed pulses (0.12%). It is worth to note that the intensity stability of the compressed SC radiation turns out to be more than one order of magnitude better than the 1.2-2.5% stability level reported in [13], thanks to the higher efficiency in the adopted SC scheme, which leads the generation of ~ 30 mW average

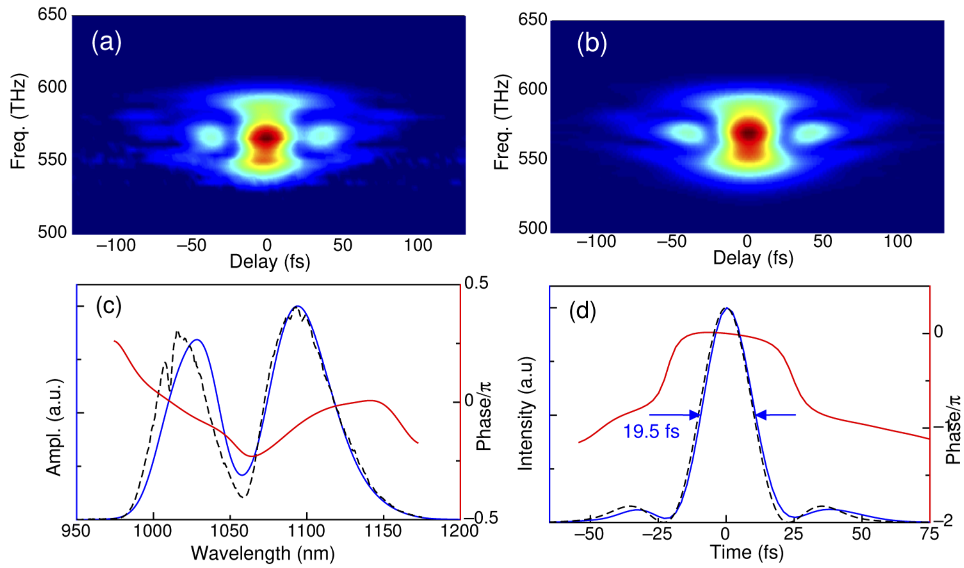

Fig. 3. (a) Measured SHG-FROG trace with incident average power reduced to 30 mW. (b) Retreived SHG-FROG trace with 0.014 error on a 128 × 128 grid. (c) Measured optical spectrum (black dashed line) at the output of the PCF. In blue and red are shown the reconstructed optical spectrum and corresponding spectral phase in units of π. (d) In blue and red are shown the reconstructed temporal pulse intensity and phase in units of π of the almost pedestal-free pulses. Black dashed line is the temporal intensity profile of the transform limited pulse calculated from the measured optical spectrum.

power SC covering the optical bandwidth from 950 to 1200 nm (two times narrower than [13]) using two order of magnitude lower input power and shorter fiber length (0.145 m with respect to 1 m).

In addition, the time jitter stability of the Yb:CALGO seed laser is also characterized by measuring the phase noise power spectral density of the pulse repetition frequency signal, $S_\phi(f)$ in [dB_{rad}/Hz], as obtained through the direct measurement of L-script power spectral density, $L(f) = \frac{1}{2}S_\phi(f)$ in [dB_c/Hz], by using the ESA. Figures 4(b) and 4(c) show the RF spectrum of the Yb:CALGO mode-locking pulses measured in a 190-MHz frequency span (300-kHz resolution bandwidth) and the measured $S_\phi(f)$ in the Fourier frequency range from 10 Hz to 10 MHz, respectively. The high fundamental carrier-to-noise (SNR) ratio of 78 dB and the absence of any Q-switch sidebands in the RF spectrum proves the excellent pulse-to-pulse stability of the seed laser pulses. From the power spectral density of the phase noise, it should be noted that the measured noise cannot be distinguished from the relative intensity noise (RIN). The corresponding integrated, from 10 Hz to 10 MHz, phase noise is 1.2 mrad, leading to a RIN limited absolute time jitter of ~ 2.5 ps [14].

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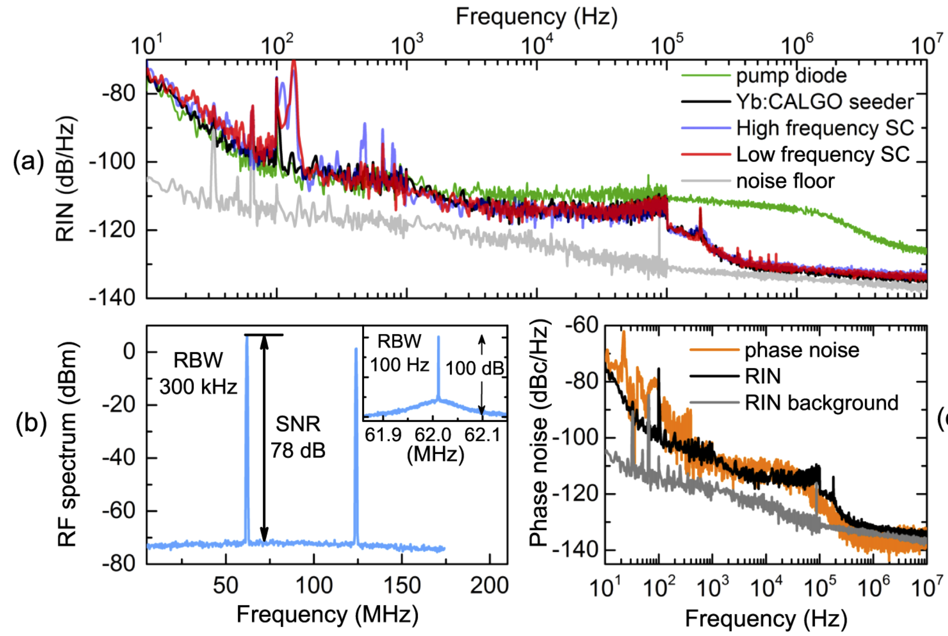

Fig. 4. (a) Power spectral density of the RIN versus Fourier frequency of the low-power single-mode pump diode, Yb:CALGO seed laser, and SC radiation at the PCF output both at the high and low optical frequency tails. (b) RF spectrum of the Yb:CALGO mode-locking pulses measured in a 190-MHz frequency span (300-kHz resolution bandwidth). In the inset it is shown the detail of the fundamental beat note in a 250-kHz frequency span (100-Hz resolution bandwidth). (c) Power spectral density of the phase noise at the fundamental repetition frequency versus the Fourier frequency.

3. Conclusions

We reported on the generation of sub-20 fs pulses at around 1050 nm based on a non-linear fiber compressor seeded by a passive mode-locked Yb:CALGO ultrafast laser pumped by a low-power single-mode diode laser. The 70-fs pulses at the central wavelength of 1050 nm provided by the compact Yb:CALGO laser have been compressed down to a minimum duration of 14.9 fs (corresponding to ~4.25 optical cycles) with an overall transmission efficiency of the non-linear fiber compressor of 65% and an optical-to-optical efficiency, from pump power to compressed pulses average power, of 7%. The excellent noise performance of our laser system further confirms the effectiveness of our approach to few-cycle pulse generation at 1 μm employing a highly stable, reliable and efficient low-power oscillator followed by a simple and cost-effective PCF non-linear pulse spectral broadening/prisms compressor stages. We demonstrated comparable, or even shorter, pulse duration than the minimum obtained to date directly from Yb-doped femtosecond oscillators [4], with similar average output power but a remarkable 27-fold improvement of optical-to-optical efficiency and a relative intensity noise level lower than −110 dB/Hz for Fourier frequencies larger than 1 kHz reaching a white noise floor at −133 dB/Hz for frequency larger than 1 MHz. The combination of ultrashort pulse duration and low-intensity-noise leads this ultrafast source to find interesting applications as ultrafast seeder for optical amplification stages as well as for low-power broad-band sensing.

Given the core size and nonlinearity of the PCF fiber and the pulse peak power, the maximum compressible spectral width (with good quality, pedestal free temporal profile) depends on initial pulse width and requires a certain fiber length for the corresponding SPM. Then, power scaling is certainly possible using shorter fibers, but in practice it can be very hard to cut fiber shorter than few cm: few hundreds mW is the expected maximum power for pulse compression in this kind of PCFs.

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Disclosures

The authors declare no conflicts of interest.

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