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All-Fiber Source of 20-fs Pulses at 1550 nm Using Two-Stage Linear–Nonlinear Compression of Parabolic Similaritons

B. Kibler, C. Billet, P.-A. Lacourt, R. Ferriere, and J. M. Dudley, *Member, IEEE*

Abstract—Parabolic pulses from a similariton amplifier at 1550 nm are compressed using a two-stage fiber compressor employing linear compression in photonic bandgap fiber and soliton effect compression in highly nonlinear fiber. Precise optimization of the compressor design using frequency resolved optical gating allows the generation of minimally chirped pulses as short as 20 fs. This duration corresponds to only four optical cycles of the underlying electric field at this wavelength.

Index Terms—Optical fiber amplifiers, solitons, ultrafast optics.

I. INTRODUCTION

MOTIVATED by numerous emerging applications in ultrafast photonics, the development of fiber-based sources of femtosecond pulses around 1550 nm is a subject of much current research [1]. A widespread fiber-based technique used for femtosecond pulse generation is soliton-effect compression, which exploits the initial nonlinear spectral broadening and temporal compression phase of higher order soliton propagation in the anomalous dispersion regime of an optical fiber [2]. In the context of generating pulses consisting of only a small number of optical cycles, however, achieving high pulse quality with this technique has required the use of multiple nonlinear stages and/or specially profiled dispersion decreasing fiber [3], [4]. The use of simpler single-stage soliton compression setups has typically yielded multiple pulse pedestals, or longer pulses in the range of 35–40 fs [2], [5], [6].

A recent technology that has attracted particular interest for compression applications is based on the generation of *similariton* pulses in fiber amplifiers with normal dispersion. In particular, similariton amplifiers based on both doped fiber and Raman gain have been shown to lead to the self-similar generation of parabolic output pulses possessing a strictly linear chirp that facilitates pulse compression to the femtosecond regime [7]–[11]. An additional important feature of such similariton pulses is that they possess improved resistance to input pulse noise because they are asymptotic attractors toward which any arbitrary input pulse of given energy will converge irrespective of its specific pulse profile or duration [10].

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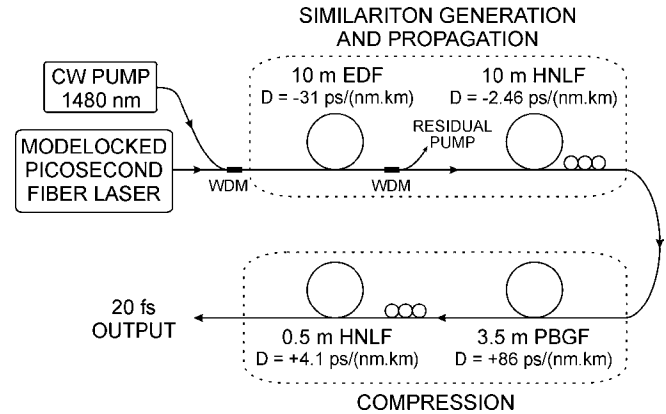


Fig. 1. Experimental setup. The wavelength-division multiplexer (WDM) is used to separate the 1480-nm pump from the 1550-nm signal pulses at the output of the EDF. All the other symbols have their usual meaning.

In this letter, we take advantage of the novel properties of similariton amplifiers to develop an all-fiber source of 20-fs pulses at 1550 nm based on a simple two-stage compression setup, and using only short lengths of commercially available specialty fibers. Specifically, we generate linearly chirped parabolic pulses from an erbium-doped fiber (EDF) amplifier followed by a length of normal dispersion highly nonlinear fiber (HNLF), and subsequently compress these pulses using two independent propagation steps. The first stage uses air-core photonic bandgap fiber (PBGF) to linearly compress the parabolic pulses to ~ 240 -fs duration, and this is followed by a second stage using nonlinear soliton-effect compression to generate 20-fs pulses in the few-cycle regime. An important feature of our setup is the careful optimization of the nonlinear compression through numerical simulations using frequency-resolved optical gating (FROG) measurements of the input pulses to the compressor as initial conditions [12].

II. EXPERIMENTAL SETUP AND RESULTS

Fig. 1 shows the experimental setup. A 19.8-MHz repetition rate passively mode-locked fiber laser (Pritel FFL) generates 1.4-ps [full-width at half-maximum (FWHM)] linearly polarized hyperbolic secant pulses of ~ 100 -pJ energy. FROG measurements confirmed that the pulses were minimally chirped. These pulses are then injected into an EDF similariton amplifier and a segment of HNLF to undergo self-similar amplification and propagation respectively.

The similariton amplifier is based on 10 m of commercially available La–Al-codoped EDF designed for

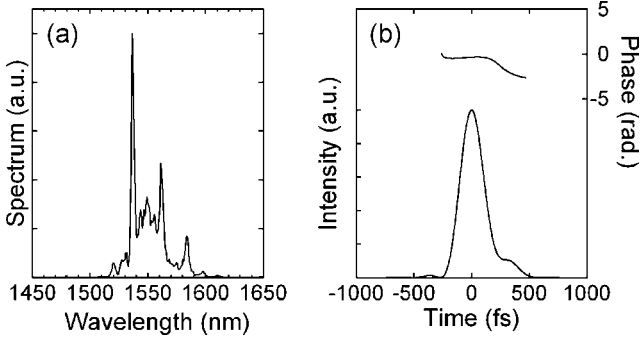


Fig. 2. Results after linear compression of similariton pulses in PBGF. (a) Measured spectrum, and (b) intensity (left axis) and phase (right axis) from FROG measurements. The intensity FWHM in (b) is 240 fs.

C-band operation (OFS R37003) with large normal dispersion $D = -31$ ps/nm · km and nonlinearity coefficient $\gamma = 6$ W⁻¹ km⁻¹. The amplifier is pumped codirectionally by a 1480-nm continuous-wave (CW) Raman laser (Keopsys), with 170 mW of pump power yielding 14.5-dB gain. Under these conditions, the average output power from the amplifier was 65 mW, and FROG measurements confirmed that the amplifier operated in the similariton regime generating high-quality parabolic pulses with linear chirp [11]. The pulse duration and spectral bandwidth (both FWHM) at the amplifier output were 5.4 ps and 17 nm, respectively.

These pulses were then injected into a 10-m segment of dispersion-flattened HNLF (OFS Specialty Fiber) to undergo further self-similar spectral and temporal broadening [9]. At 1550 nm, the fiber normal dispersion is $D = -2.46$ ps/nm · km, the dispersion slope is 0.002 ps/nm² · km, and the nonlinearity coefficient $\gamma = 7.9$ W⁻¹ km⁻¹. FROG measurements verified that this additional propagation step in the HNLF was also self-similar, with the output pulses retaining their parabolic profile and linear chirp even while undergoing significant temporal and spectral broadening [13]. The similariton pulses at the HNLF output had 380-W peak power and temporal and spectral FWHM of 6.1 ps and 34 nm, respectively.

The first (linear) compression stage used hollow-core PBGF (Crystal Fiber/BlazePhotonics HC-1550-02) possessing large anomalous dispersion $D \approx +86$ ps/nm · km around 1550 nm. The nonlinearity of this hollow core fiber is negligible at our power levels. Based on the FROG measurements of the similariton intensity and chirp, the length of PBGF required could be precisely determined from numerical simulations, avoiding the need for expensive trial and error. Optimal compression used a fiber length of 3.5 m, and yielded 240-fs compressed pulses with minimal phase structure. Fig. 2 shows the pulse spectrum and the intensity and phase of these linearly compressed pulses obtained from the FROG measurements. We note that although depolarization effects in the short lengths of EDF and HNLF used in our setup were negligible, precise control of the input polarization prior to injection in the PBGF was required for optimal compression.

These 240-fs compressed pulses were then injected into the second (soliton effect) compression stage. This was

based on dispersion-flattened HNLF (OFS Specialty Fiber) with anomalous dispersion $D = +4.10$ ps/nm · km, dispersion slope of 0.02 ps/nm² · km, and nonlinearity coefficient $\gamma = 9.4$ W⁻¹ · km⁻¹. Soliton effect compression requires that the fiber length be precisely tailored to the input pulse characteristics, and a number of analytic guidelines for this purpose have been developed [14]. However, because higher order soliton propagation is an intrinsically highly nonlinear process, even small intensity and chirp substructure on the input pulse can dramatically impact on the quality of the compressed pulse obtained. Moreover, the presence of any noise on the input pulse can induce pulse break through soliton fission, and lead to severe pulse-to-pulse fluctuations in the compressed pulse characteristics.

In this regard, however, recent studies of soliton fission in the context of supercontinuum generation have provided improved insight into the way soliton fission-related instabilities can be minimized [15], [16]. Two factors that are crucial are 1) the use of a low noise source to minimise the seeding of soliton fission by modulation instability and 2) the limitation of the soliton compressor fiber to a length where the injected pulse attains its maximum bandwidth, just prior to the point where soliton fission is generally induced. In our setup, these conditions are met 1) by taking advantage of the high quality of the compressed similariton pulses, and 2) by precisely determining the optimal fiber length through numerical simulations of the soliton compression process using the measured input pulse intensity and chirp as the initial conditions.

Because the input and output coupling between the PBGF and HNLF used nonoptimal simple physical contact, the 240-fs pulses from the PBGF excited only a moderate soliton order of $N \approx 6$ (1.2-kW peak power) when injected into the anomalous dispersion HNLF. For these injection parameters, and using the measured intensity and phase profile of the 240-fs pulses, numerical simulations predict a minimum achievable pulse duration of ~ 20 fs for an optimal HNLF length of 0.5 m. These simulation results were confirmed experimentally, and Fig. 3 shows the broadened spectrum and the pulse intensity and phase obtained from the FROG measurements at the output of the anomalous dispersion HNLF. To illustrate the accuracy of our numerical design procedure, the dashed line in Fig. 3(b) shows the expected output compressed pulse profile based on the numerical simulations of the soliton compression process described above. It is clear that there is very good agreement.

Although some residual energy ($\approx 13\%$) remains in low amplitude substructure in the wings, the central compressed pulse lobe has a peak power of ~ 14 kW and duration of 20 fs, corresponding to only four optical cycles under the FWHM. The residual pedestal arises because the nonlinear chirp across the propagating higher order soliton is dominated by self-phase modulation, and thus only the central part is compressed by anomalous group velocity dispersion. Energy in the wings remains uncompressed and appears as low amplitude substructure [14]. In addition, effects such as higher order dispersion can also play an important role in modifying the pedestal structure [17].

It is also instructive to consider a numerical reconstruction of the electric field waveform amplitude across the pulse centre,

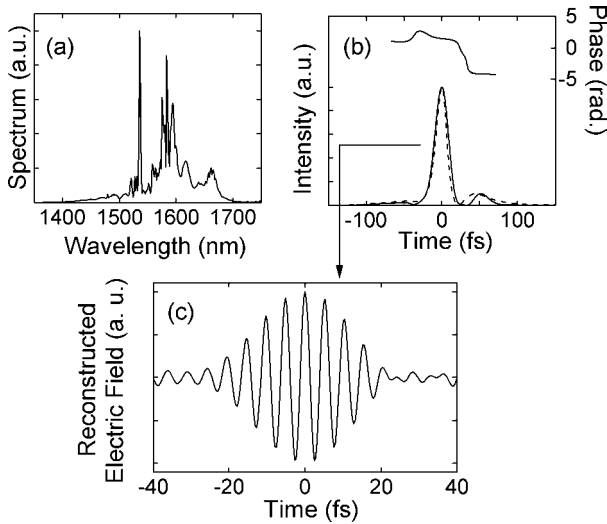


Fig. 3. Results after soliton-effect compression in HNLF showing (a) spectrum and (b) intensity (solid line, left axis) and phase (solid line, right axis) from FROG measurements. The intensity FWHM in (b) is 20 fs. The dashed line shows the optimally compressed intensity profile predicted from numerical simulations. The inset in (c) shows an illustrative reconstruction of the electric field over the central peak in order to highlight the few-cycle and chirp-free nature of the compressed pulse.

obtained by multiplying an ideal sinusoidal carrier by the retrieved complex pulse envelope [18]. This is shown in Fig. 3(c). Although such a reconstruction is somewhat artificial because the absolute carrier phase cannot be determined from FROG measurements alone, it does highlight clearly the chirp-free and few-cycle nature of the compressed pulses. Note in this regard that the absolute phase zero in Fig. 3(c) is set to the peak of the envelope.

III. CONCLUSION

The pulse amplification and compression system described here allows the generation of few-cycle pulses around 1550 nm using a compact experimental setup, with a total length of only 24 m of commercially available optical fiber. Although we have obtained pulses with duration as short as 20 fs, we have checked using numerical simulations that shorter pulses ~ 15 -fs duration should be obtainable with improved PBGF coupling efficiency and the corresponding use of a shorter soliton compressor HNLF segment. These results represent what we believe to be an exciting new phase in the development of similariton-related technology and applications, and we expect such sources to find wide use in ultrafast photonics.

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