Nonlinear Propagation of mid-IR Femtosecond Pulses in ZBLAN Fiber

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Abstract: We demonstrate environmentally protected delivery of high-power femtosecond mid-IR pulses in a single-mode ZBLAN fiber by soliton formation. A 70-fs Cr:ZnS laser at 2.4 µm reaches this regime already at ~1.5 nJ launched pulse energy.

OCIS codes: 060.2390 Fiber optics, infrared; 060.5530 Pulse propagation and temporal solitons; 140.3070 Infrared and far-infrared lasers

1. Introduction

Mid-infrared femtosecond oscillators already now find a number of applications as broadband sources for molecular spectroscopy [1,2], as seed sources for amplifiers [3], and pumping sources for OPO [4] These applications put different requirements that include spectral width and low noise for spectroscopic and sensing applications, high peak power for nonlinear interactions and good temporal contrast for amplifier seeding. At the same time, the broadband mid-IR pulses are affected by molecular absorption lines in the atmosphere [4,5], making it necessary to evacuate or purge the oscillators [1]. For output of such oscillator to be of any use for real life applications, a way must be provided for environmentally-protected beam delivery, preferably by fibers. For high-energy pulses, one of the ways of delivery is to realize the soliton propagation regime [6].

In this work we test and demonstrate feasibility of high-energy beam delivery of a new femtosecond mid-IR Cr:ZnS laser with 70-fs pulses at 3.7 nJ pulse energy. By changing the launched pulse energy we are able to observe a transition from strongly chirped linear to solitonic propagation at launched energies as low as 1-1.5 nJ.

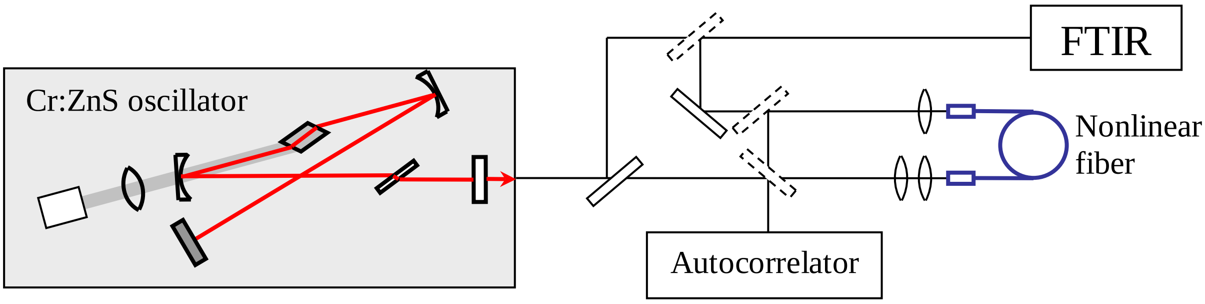

Figure 1: Schematic setup for characterization of mid-IR femtosecond pulse propagation in nonlinear fibers.

2. Experimental setup

The experimental setup is schematically shown in Fig. 1. As a source of the femtosecond pulses in mid-IR spectral region WE USE the Kerr-lens mode-locked Cr:ZnS oscillator. The laser was built on the basis of X-folded four-mirror cavity. It was pumped by the diode-pumped 5-W 1.61 µm Er-fiber laser from IPG Photonics. The mode-locking was achieved by soft-aperture Kerr-Lens effect. The compensation of the group-delay dispersion was performed by sapphire plate inserted into the cavity and chirped HR mirror. The laser produced pulses of about 69 fs at the central wavelength of 2.39 µm, repetition rate of 150 MHz and output power up to 550 mW, which corresponds to the pulse energy of 3.7 nJ. The spectral bandwidth of output emission reached 193 nm, which corresponded to the time-bandwidth product of 0.335 (Fig. 2). We assume the input pulse to be essentially chirp-free. The oscillator itself is a topic of a separate paper submitted to the ASSP 2012 conference.

About 80% of the laser output were delivered to the input end of the nonlinear fiber, while the other 20% of the emission were distributed between FTIR spectrometer, self-developed two-photon absorption based autocorrelator and fast photodetector. The oscillator emission was focused to the fiber input by a pair of uncoated fused silica lenses with focal distances of 30 and 50 mm. The fiber input facet was cut at the angle of 82° to exclude back reflection to oscillator. The emission from the fiber output was delivered either to spectrometer or autocorrelator. The launched energy was varied by a transverse translation of the fiber input facet against the excitation beam. The maximal coupling efficiency reached 50%, measured by the average power at the output end of the fiber.

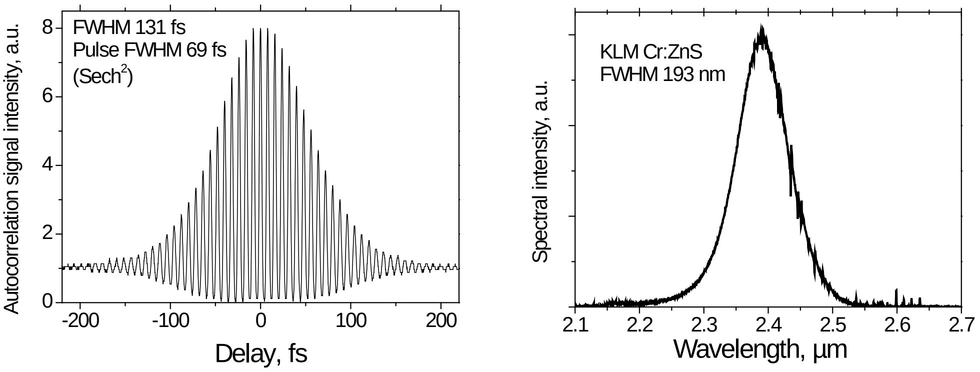

Figure 2. Autocorrelation trace and output spectrum of Cr:ZnS oscillator, used as a pulse source.

3. Results

The fiber used in the current experiment was a single-mode ZBLAN fiber (IRPhotonics) with numerical aperture of 0.17 core diameter of 9 µm and total length of 2.08 m. The zero-dispersion wavelength of this fiber is located around 1.6 µm making it not very suitable for spectral broadening, but allows the solitonic propagation regime. The fiber is thus interesting as a delivery channel for mid-IR femtosecond pulses.

At low pulse energies the spectrum of the emission passed through the fiber was quite similar with the input spectrum, while the autocorrelation showed strongly chirped temporal shape of the pulse, corresponding to essentially linear propagation under anomalous dispersion. While the pulse energies were increased, the pulse became less chirped and shorter. At the energy level above 1.2 nJ the spectrum becomes essentially sech^2 with strongly modulated wings. Such behavior is typical to the pulses with parameters close to the soliton propagation regime in the fiber with a third-order dispersion. The dependence of the autocorrelation traces and optical spectra of emission from the fiber output on the pulse energy coupled into the fiber is illustrated in the Fig.3. At transmitted energy of 1.47 nJ the pulse duration collapses to 170 fs from 1.4 ps at 0.67 nJ.

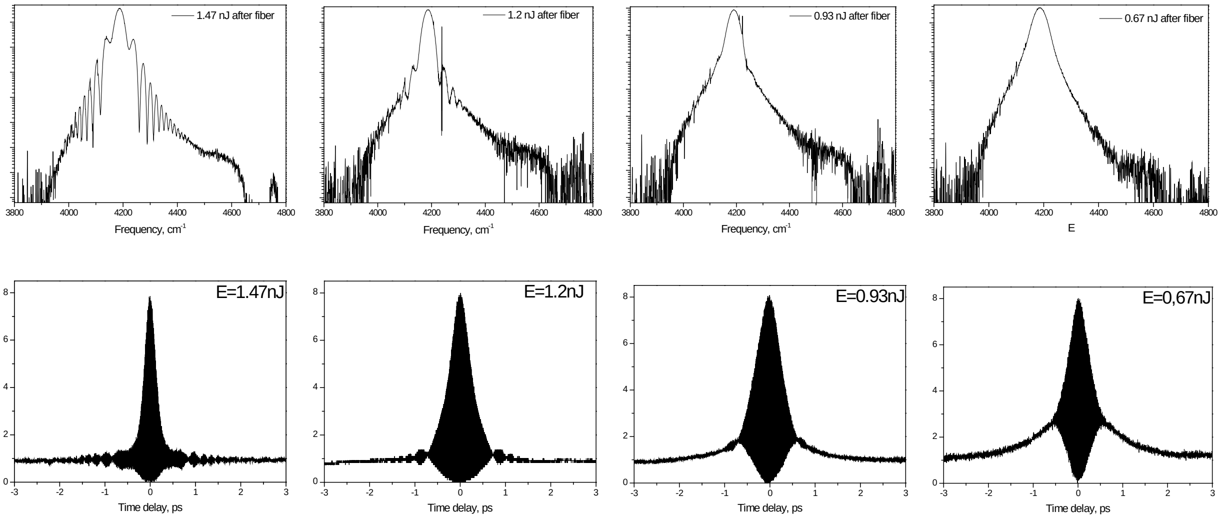

Figure 3. Spectra (log scale) and autocorrelation traces of femtosecond pulses after propagation in 2.08 m ZBLAN fiber.

4. Modeling

In order to understand and extrapolate the results to higher energies we performed modeling of the pulse propagation of initially 70 fs pulse through a ZBLAN step-index fiber with a core diameter of 9 µm and frequency-constant numerical aperture of NA = 0.17, as given by the manufacturer. This corresponded to mode area of $A_{\mathrm{eff}} = 96$ µm^2, group-velocity dispersion coefficient of $GDD = -250$ fs^2/cm, and a third-order dispersion coefficient of 1650 fs^3/cm with zero-dispersion wavelength at 1.74 µm. A nonlinear coefficient of 3.3×10^{-16} W/cm^2 was used [7]. The propagation model was based on the generalized nonlinear Schrödinger equation solved on the basis of symmetrized split-step Fourier method with 1 fs temporal step (2^{17} points in a mesh) and the propagation step of 10^{-3} part of a nonlinear length L_{NL} depending on the pulse energy. The simulation results are shown in Fig. 4, and summarized in Fig. 5.

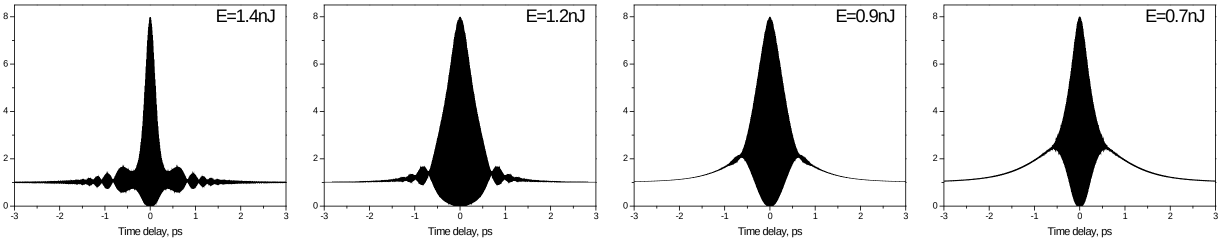

Figure 4. Simulated autocorrelation traces of femtosecond pulses after propagation in 2.08 m ZBLAN fiber.

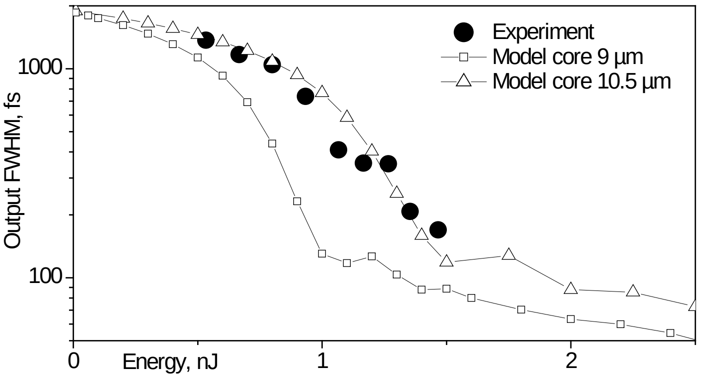

Figure 5. Comparison of simulated and observed pulse durations at fiber output.

The simulation results match very closely the observed autocorrelation traces, proving validity of our model and assumptions. At the same time, the agreement occurs at somewhat different values of energy and output pulse durations. A better agreement occurs when we assume effective core diameter value of 10.5 µm, corresponding to $GDD = -340$ fs^3/cm and $A_{\mathrm{eff}} = 130$ µm^2 (Fig. 5). The uncertainty in core diameter value might be caused e.g. by the fact that the fiber is graded-index rather than step-index as believed by the manufacturer.

5. Conclusion

We have successfully tested a single-mode ZBLAN fiber for mid-IR femtosecond pulse delivery. At low launched energies < 0.7 nJ the propagation is essentially linear with negligible spectrum modification. This regime is suitable for spectroscopic and sensing applications, providing means of safe signal delivery between sealed units.

At higher powers, the solitonic effect starts to dominate, resulting in rapid pulse shortening. This regime is suitable for high-power pulse delivery. For example, at 1.47 nJ and 170 fs output pulse duration, the peak power reached 8.7 kW, which is 30% higher than the peak power used in the successful subharmonic OPO pumping experiment [4]. As witnessed by the Fig. 5, using an optimized launching optics would result in significant further shortening.

Pulse energies of few nJ at 50–100 fs pulse duration are quite feasible for Cr:ZnS and Cr:ZnSe [8] oscillators, and fulfill conditions for solitonic propagation in suitable ZBLAN fibers. For delivery of significantly higher energies, one should consider transition to LMA fibers. Increase of an effective mode area to ~1500 µm^2 allows the energy scaling up to ~30 nJ that is feasible for the chirped pulse oscillators [8,9]. Since the pulse is pre-chirped in this regime, its squeezing in anomalously dispersive fiber would allow achieving sub-MW power levels on a target.

Acknowledgments

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