Solitonic Regime of Mid-infrared Filamentation at Highly Overcritical Power in Transparent Solids

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Abstract: Filamentation of femtosecond pulses in transparent solids with anomalous group-velocity dispersion is investigated for a broad range of the peak powers. Solitonic self-compression of multi-millijoule mid-IR pulses is achieved using a 1.5-mm-thick CaF_2 plate.

OCIS codes: (190.7110) Ultrafast nonlinear optics; (320.5520) Pulse compression; (190.5530) Pulse propagation and temporal solitons.

1. Introduction

The absolute majority of experiments on filamentation and supercontinuum generation in bulk transparent solids are implemented with ultrashort laser pulses with wavelengths in the region of normal group-velocity dispersion (GVD) of the material. Filamentation in the anomalous GVD regime is a relatively unexplored field of investigations. Recently very first experiments with high power mid-infrared (mid-IR) femtosecond source at 1.9 μm wavelength have demonstrated new regimes of filamentation in which the dynamics of spatial collapse are strongly coupled to a soliton-like dynamics of the pulse [1, 2]. Ultra-broadband continuum generation in mid-IR filaments in solids and efficient pulse self-compression was recently demonstrated also for a longer 3.1 μm laser wavelength [3, 4].

We report the first combined experimental and numerical investigation of mid-IR femtosecond filamentation in transparent solids in the broad range of peak powers ranging from a few to hundreds of the critical powers of self-focusing P_{cr}. We demonstrate that self-compression of femtosecond mid-IR laser pulses with peak powers orders of magnitude higher than P_{cr} becomes possible. The physical scenarios whereby the self-compression at this peak powers can occur before the beam breaks up into multiple filaments are identified.

2. Experimental results

Experiments were performed with the OPCPA system delivering up to 10 mJ, 80 fs (>120 GW peak power) pulses centered at 3.9 μm at the repetition rate of 20 Hz. An uncoated 1.5-mm thick CaF_2 plate was mounted on a movable holder in a 1.5-m long gas cell, evacuated to a pressure of 2 mbar and equipped with CaF_2 entrance and exit windows,. The mid-IR pulses have been focused into the cell by a f=750-mm focal length AR coated CaF_2 lens. The output pulses were characterized by using a second harmonic generation frequency resolved optical gating (SHG FROG) apparatus. In order to avoid distortions during the propagation of the pulse, near field from the CaF_2 plate was spatially reconstructed on an AGS second harmonic crystal by using a 4f telescope based on R=-1500 mm spherical mirror.

The dependencies of the spectrum and temporal pulse profile on the distance of the CaF_2 plate to the focus of the lens in the case of 2.2 mJ input pulses are presented in the Fig.1 (negative values of the distances mean that the CaF_2 plate was placed before the focus of the lens; the 0-represents the focal plane, the positive values indicate that the sample was placed after the focus of the lens). Increase in the intensity of the input pulse by moving the plate closer to the foci leads first to generation of the supercontinuum spanning over three octaves (Fig. 1a-c), in agreement with the results reported in [3]. However, further increase in the intensity causes narrowing in the central part of the spectrum and broadening in the wings. At the same time, formation of the intense UV emission peak at ≈390 nm wavelength with simultaneous suppression of the near IR-visible part of the spectrum is observed (Fig.1c).

This spectral dynamics is accompanied by an evident pulse shortening (Fig.1d,e). Close to the focus of the lens the 2.2-mJ pulses shorten nearly by a factor of two to the pulse duration of 40 fs FWHM which corresponds to three optical cycles. We estimate P_{cr} ≈30 MW which is about three orders of magnitude lower than the peak power in the input laser pulse. The self-compressed pulse has the energy of 1.7mJ and the difference in 0.5 mJ mainly correspond to the Fresnel losses due to the reflections from the uncoated output and input windows of the evacuated cell and from the sample (~3% reflection per surface).

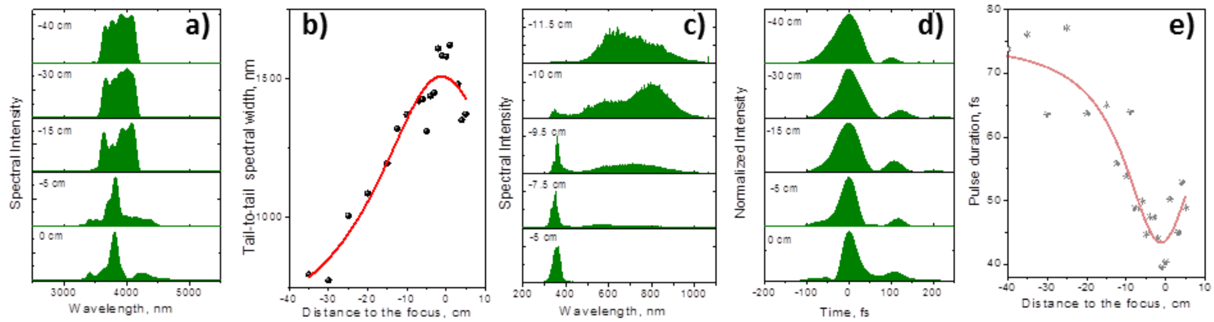

Fig. 1 a) Pulse spectra at different distances of the CaF2 plate from the focus(indicated in the panels); (b) dependence of the retrieved spectral width at the level of 0.5% of the amplitude (points)), the line is a guide for an eye; c) UV-visible part of the supercontinuum spectrum at different distances of the CaF2 plate from the focus(indicated in the panels); (d) pulse temporal envelopes at different distances of the CaF_2 plate from the focus (indicated in the panels); (e) dependence of the retrieved pulse duration (FWHM) on the distance from the focus (points), the line is a guide for an eye.

3. Numerical simulations

Experimental observations are backed up by the results of 3D numerical simulations of the multi-filamentation dynamics presented in Fig.2. Our calculations show that the pulse self-compression proceeds in the soliton-like regime even when the peak power significantly exceeds P_{cr}. The experimentally observed UV emission is very precisely reproduced in the simulations and its wavelength is consistent with the phase-matched wavelength of Cherenkov radiation, which supports the assumption of a solitonic regime of propagation.

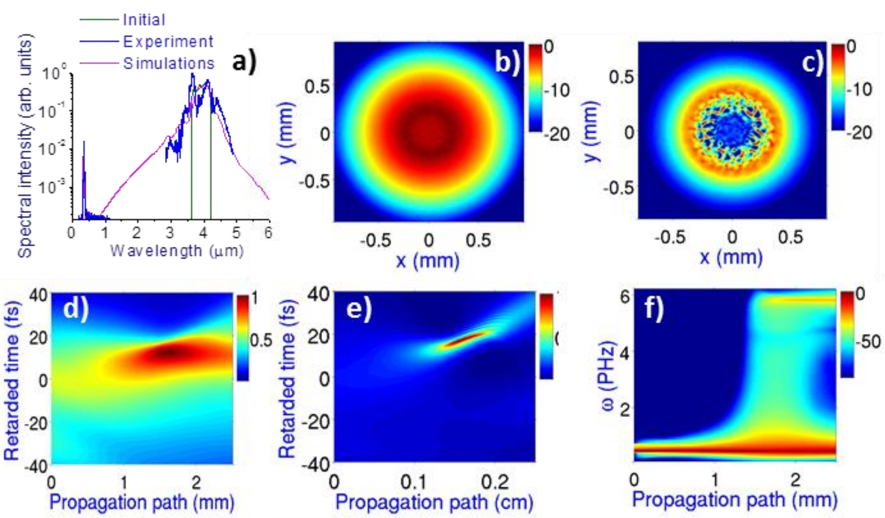

Fig. 2 a) Spectral broadening of a mid-infrared pulse with the input spectrum shown in green at the point of maximum pulse compression in a CaF_2 plate: (blue) experiments and (pink) simulations. (b, c) Spatial profiles of the laser beam at the point of maximum pulse compression (b) and after (c) formation of multiple filaments. (d – e) Temporal and spectral dynamics of the mid-IR pulse in the process of self-compression: field intensity integrated over the beam (d) and on the beam axis (e) and the spectrum integrated over the beam as a function of the propagation path.

In conclusion, we demonstrate for the first time to our knowledge the self-compression of millijoule mid-IR pulses in transparent solids. The experiments and numerical simulations validate a simple and robust way to generate multi-mJ few-optical-cycle laser pulses for strong field physics applications.

4. References

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