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Self-Guided Intense Laser Pulse Propagation in Air

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Abstract

We report on observation of self-guiding of picosecond laser pulses in air that produces large-scale self-phase modulation. The converging picosecond laser beam produced a confined filament over 3 m of propagation with the white-light spectrum.

Keywords: propagation, nonlinear optics, self-guiding, self-phase modulation

1 Introduction

The observation of long-distance self-guiding of ultrashort pulses in air has attracted considerable attention. Besides the scientific interest, it could lead to number of useful applications, such as lightning channelling, LIDAR, generation of powerful white-light continuum, and finally, compression of optical pulses.

The observations of long-distance apparently self-guided femtosecond pulses in air and other gasses point to appearance of a confined single filament with diameter ~100 μm [1-4]. The interpretation of observed phenomena, however, can not be given as a simplified moving-focus model [3], as it predicts that only a small amount of energy can be found in a single filamentary mode. The self-guiding model [4] assumes channelling into stable propagation as a result of balance between two competing nonlinear effects: Kerr effect leading to self-focusing and defocusing effect of the electron plasma created by multiphoton ionization.

The experimental and theoretical studies of this phenomenon are rather difficult. On one hand, experimental investigations of the near field of a filament are hardly possible due to high intensity that far exceeds the optical damage of any reflecting material. On the other hand, the reliability of known material parameters is rather poor to characterize the accompanying effects in the beam propagation at high intensities, including diffraction, group-velocity dispersion, multi-photon ionization, plasma absorption and defocusing.

2 Experiment and Results

In the experiment we have observed self-guiding of the single filament produced in air by the converging intense laser beam. The picosecond laser pulse (τ=1 ps, λ=527 nm, second harmonic of Nd:glass laser) was sligthly focused by (f=+8 m) lens in air at atmospheric pressure and propagated over a distance of 14 m. The experimental setup is depicted in Fig. 1.

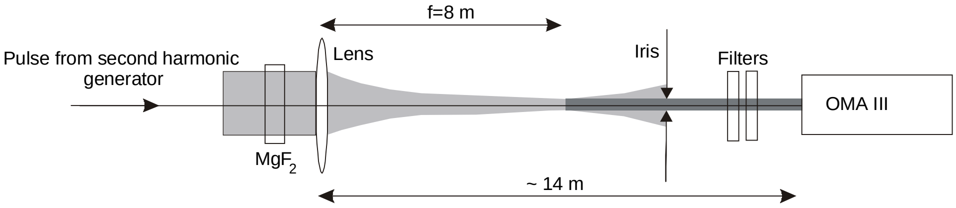

Fig. 1. Experimental setup.

The MgF_2 plate was used to change the linear polarization to circular of the input pulse. The initial laser beam at the input of the setup has a FWHM diameter of D=4.6 mm and energy adjustable from 0 to 4 mJ. With the increase of pulse energy we observed the appearance of a single filament, that exhibited self-guided propagation over a distance of 3 m. Further increase of energy has led to beam splitting into multiple filaments, and finally to breakdown of air.

Fig 2. illustrates the profile of laser beam as measured 14 m away from the focusing lens. Case (a) illustrates the beam profile of the low energy pulse (E=200 μJ). Apparently there is no sign of any beam self-action effect. Beam is not distorted and diverges as it propagates away from the focal point. Case (b) shows the self-guided propagation at E=4 mJ. The central part of the beam forms a single filamentary mode that propagates over a distance of 3 m. Energy measurement shows that it contains almost ~50% of the incident pulse energy. Along with formation of a single filament, we observed large-scale self-phase modulation that significantly broadens the spectrum of the pulse.

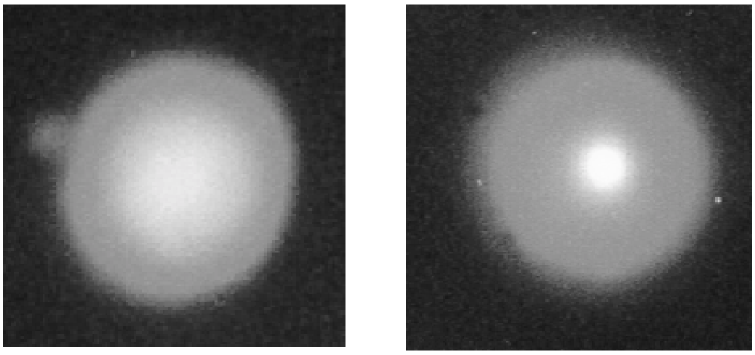
(a) (b)

Fig. 2. Beam profiles as measured at 14 m from the focusing lens.

(a) E=200 μJ, (b) E=4 mJ.

Application of different focusing schemes may lead to entirely different character of the self-modulation. If the picosecond pulse is focused with an ~f/50 optic, air breakdown is observed without a significant spectrum broadening. With numeric aperture of f/200-f/400 the spectral broadening of the pulse is observed, however, at high intensity it tends to split into multiple filaments, each of them producing slightly different spectrum. The largest factor of spectral broadening is achieved with focusing that yields the intensity just below the multiple filamentation threshold. This means that the focusing has to be matched to the available pulse energy in order to achieve maximal effect.

Spectral content of a single filament was recorded by spectrograph OMA III. The red-shifted spectrum of the self-modulated pulse (Fig. 3.) indicates that the orientation of polar molecules (N_2, O_2, CO_2) of the atmosphere significantly contributes to the third-order nonlinearity [5]. The same assumption is also supported by the fact that the spectral broadening is quite similar for pulses with different duration as long as they are shorter than the characteristic time of the rotational relaxation of gas molecules (several picoseconds as reported in [6]). The symmetric spectra can be obtained in noble gasses that possess purely electronic nonlinearity.

We found that effect of self-phase modulation is weaker with circularly polarized pulses. The similar effect has been recently observed in liquids [7]. The most probable explanation of this finding is that third-order nonlinearity in isotropic media is higher for the linearly polarized pulses as compared to that for circular and elliptical polarization.

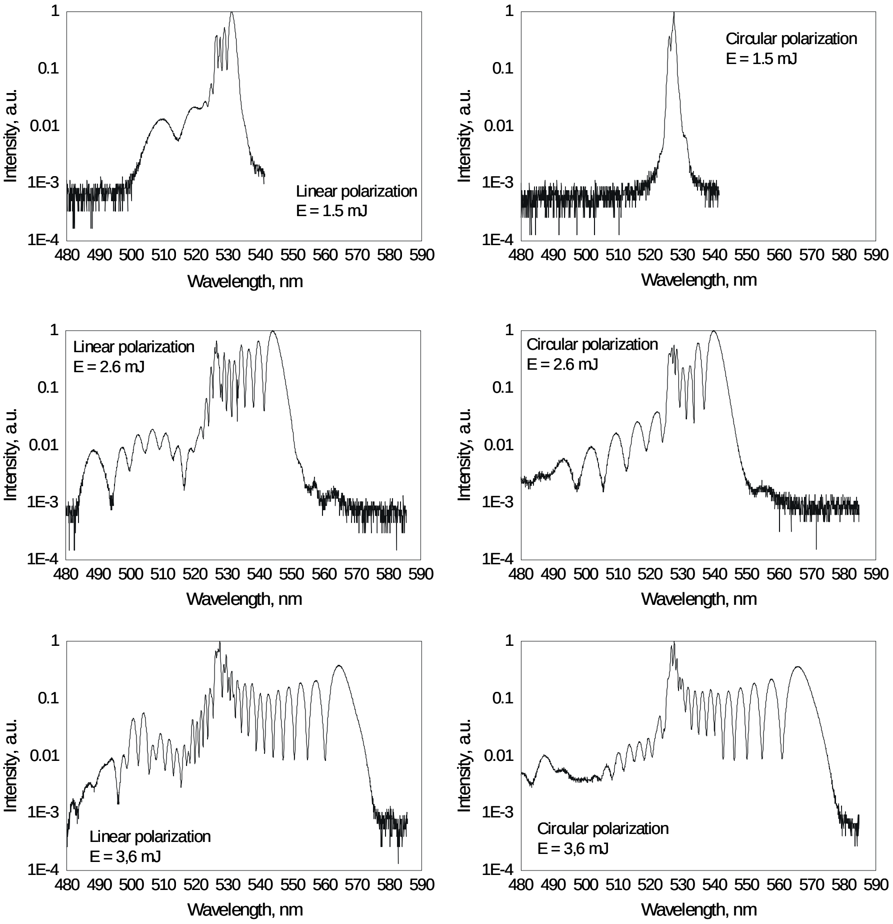

Fig. 3. Typical spectra of a single filamentary mode.

We believe that we observe self-phase modulation under conditions when the self-focusing due to Kerr nonlinearity of gas molecules is compensated by that of plasma created by the intense laser pulse. The optimal focusing is aimed to maximize the product of intensity and interaction length. In this connection we also note that the initial wavelength is of great importance since the Rayleigh range of the focused beam is inversely proportional to the wavelength. In our experiments we detected only slight modulation of picosecond pulses at fundamental wavelength (λ=1055 nm) whereas third harmonic pulses (λ=351 nm) exhibited similar extent of phase modulation at notably lower input energy.

Further extension of this work is to measure and characterize the pulse in time domain. Excellent reproducibility of spectra allows precise measurement of phase characteristics. There is a great potential for compression of such pulses to duration below 10 fs.

3 References

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