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Generation of Broadband Radiation During Filamentation of a Femtosecond Laser Pulse in the Atmosphere

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Abstract. The causes and mechanisms of generation radiation in a wide frequency range during the filamentation of femtosecond laser pulses are analyzed in this work. The reasons for the high directivity of the resulting radiation are considered.

Keywords: femtosecond laser, laser filament, supercontinuum, four-photon interaction.

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Introduction

Among the large number of physical phenomena that occur during the propagation of femtosecond (fs) laser radiation through transparent media, some phenomena are of great interest such as filamentation [1] and generation of supercontinuum (SC) [2]. The phenomenon of filamentation of high-power fs laser beams was first discovered in the second half of the 1990s [3]. Filamentation with SC generation which occurs when fs pulse is focused in air was first described in [4] and the term "white-light filament" was introduced by the Teramobile project group in [5, 6]. The most complete description of the mechanisms and conditions for the origin of a broadening of the filament spectra which occurs during the propagation of a high-power collimated fs laser beam in the atmosphere was presented in [7].

The SC spectra for axisymmetric and aberrational focusing of femtosecond IR laser radiation in air are experimentally studied and the mechanisms of focusing and broadening fs pulses which make it possible to explain the characteristic features of directional SC are analyzed in the present work.

1. Experimental results and discussion

Laser system included fs Ti:Sa laser TiS-20 (Avesta Project, Russia) pumped by diode laser Coherent Verdi V8 (Coherent, USA) based on Nd:YVO4. It produces radiation at central wavelength 950 nm, average power 200 mW, pulse duration 50 fs and pulse repetition rate 80 MHz. The radiation duration was increased to 100 ps in the stretcher after 2 passes. Then one pulse was isolated using the Pockels cell and amplified by pairs of regenerative and multipass amplifiers with pump of YAG:Nd3+ laser Lotis-2145D (Lotis, Belarus) and another pair of the same amplifiers pumped by a YAG:Nd3+ laser Solar LQ-929 (Solar, Belarus). After all the amplified

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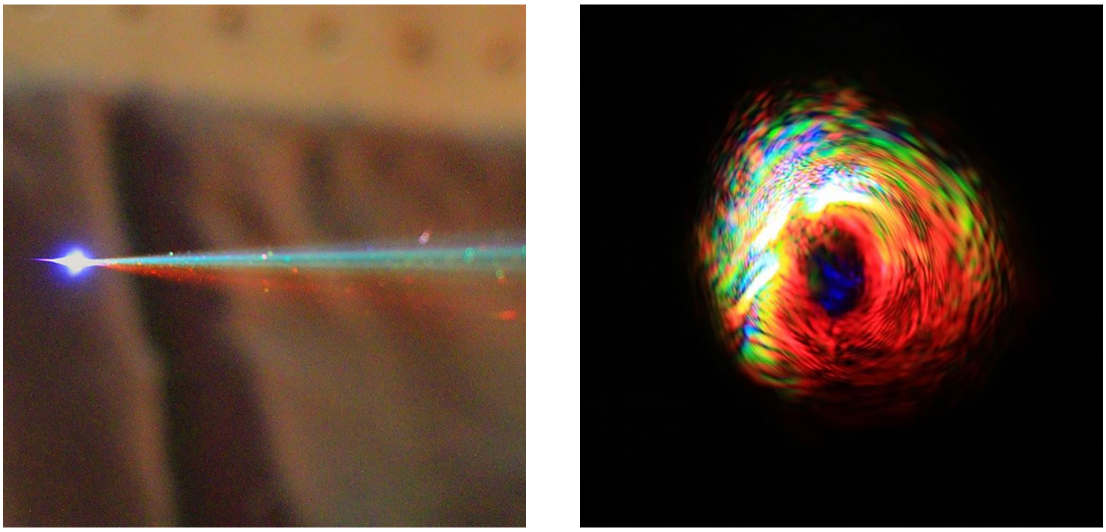
radiation was directed to the compressor on diffraction gratings which made it possible to obtain a pulse with energy up to 20 mJ and duration about 50–70 fs. Pulse repetition rate was 10 Hz.

Laser radiation was focused in air by spherical lens (axisymmetric focusing) and spherical mirror with focal length F = 750 mm (aberrational focusing). The angle between incident and reflected from mirror beams was about 20–30°.

During the work, 3 cases were considered:

1.1. Case 1

The pattern (Fig. 1) observed when the fs laser pulse is focused by lens F = 5–20 cm is formed in the plasma of the laser filament. Multiple filamentation occurs due to self-focusing caused by the Kerr effect and scattering of pump radiation by the resulting plasma in the filamentation area. Further mixing of fs pulse spectrum components in nonlinear medium (laser plasma) and random interference of different wavelengths forming the overall picture.



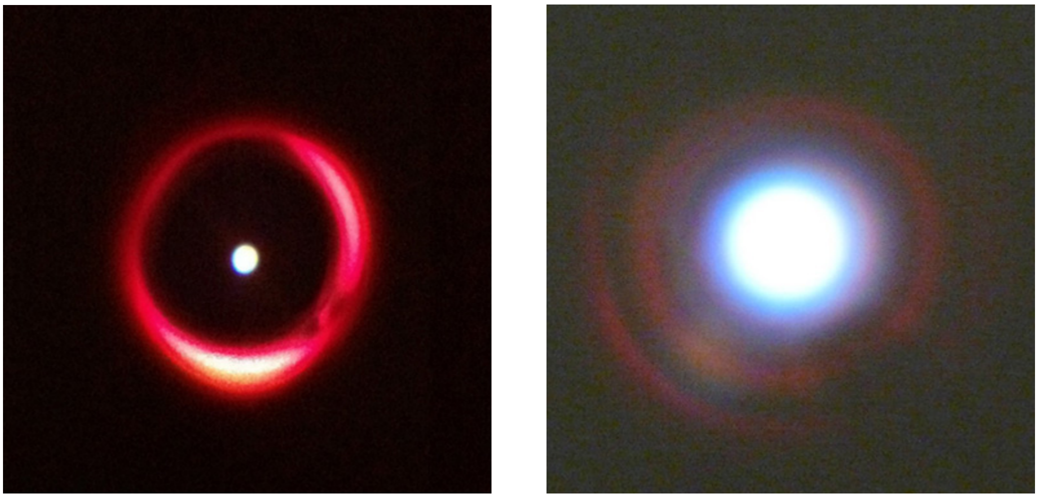
(a) (b)

Fig. 1. Laser spark (a) and image of supercontinuum on screen (b) with using short-focus lens

1.2. Case 2

Conical SC (Fig. 2a) forming is observed when using a lens F = 0.5–1 m. In this case the energy is redistributed as follows: the short-wavelength components are shifted to the center, while the long-wavelength ones are shifted to the outer edge (Fig. 4a). Pump pulse spectrum is shown in Fig. 3.

Increasing the focal length to F = 5–10 m leads to the disappearance of the conical SC and forming on axis white SC spot with a number of wide rings (Fig. 2b) caused beam diffraction on a point obstacle — the laser plasma of filament. The spectrum of the axial part of the SC is shown in Fig. 4b.



(a) (b)

Fig. 2. Image of supercontinuum on screen at focusing F = 0.5–1 m (a) and F = 5–10 m (b)

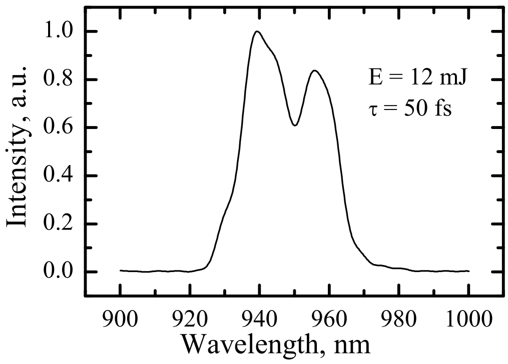


Fig. 3. Pump pulse spectra

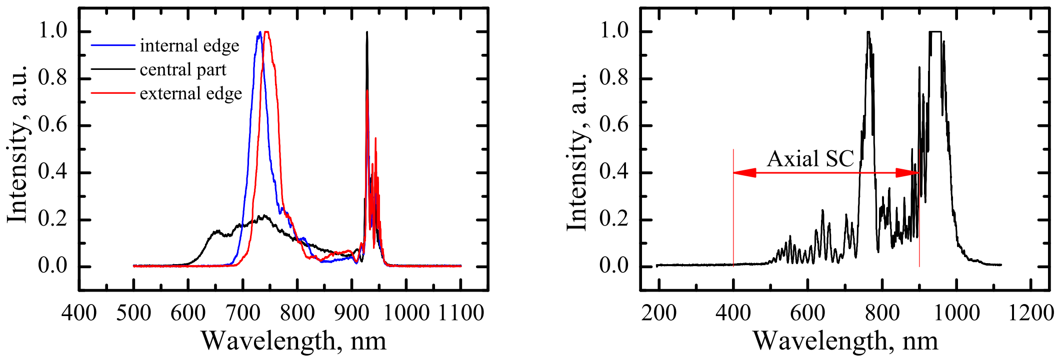
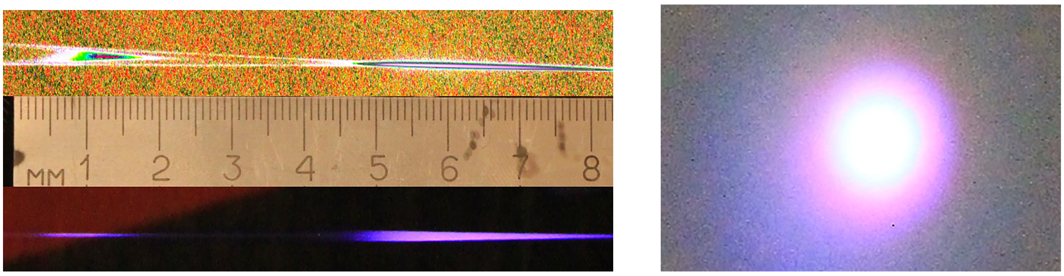


Fig. 4. Supercontinuum spectra at focusing F = 0.5–1 m (a) — axial part and F = 5–10 m (b) — cone part

1.3. Case 3

It is worth noting separately the case of aberrational focusing of laser beam. A focusing mirror was used in experiment. The radiation was reflected at an angle resulting in the formation of two white light beams [8] with diffraction divergence [9]. Filament structure (the direction of beam propagation from right to left; increased brightness, contrast and scale in the top view; in the side view, the photo is given "as is") presented in Fig. 5a. The white light beams are identical



(a) (b)

Fig. 5. Laser filament (a) and supercontinuum spot (b) produced under aberrational focusing

and have the same polarization as the pump radiation; a photo of one of the beams on the screen is shown in Fig. 5b. Typical SC spectra with aberrational focusing recorded for various pulses presented in Fig. 6. There is a transfer of energy from the long-wavelength part of the spectrum when the SC spectrum is shifted to the short-wavelength region. The total part of energy in 2 beams is about 12% from pump pulse [8].

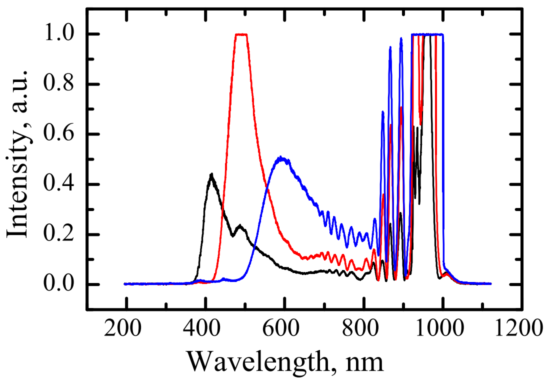


Fig. 6. Supercontinuum spectra at length 10 m after focusing mirror

Let us consider in detail the broadening of the spectrum in cases 2 and 3 given above. Broad spectrum of fs pulse produces a SC with series of peaks (blue-branch in short-wavelength region and red-branch in long wavelength). The width of the initial spectrum is sufficient for the four-photon interaction of different components (ω_1 and ω_2) of the pump pulse to produce peaks in the long $\omega_R = 2\omega_{R-2} - \omega_{R-1}$ and short-wavelength $\omega_B = 2\omega_{B-2} - \omega_{B-1}$ (where integers B and R $\geqslant$ 3) regions of the spectrum in this case. Typical spectrum of cascade four-photon processes was pronounced for the pump spectrum consisting of two peaks (Fig. 3). The frequency step between neighboring peaks was equal to the difference between the interacting components of the pump pulse $\Delta\omega = \omega_2 - \omega_1$. Also the fact of 1–10 % part from pump pulse of energy in SC in our experiment was argue about four-photon parametric process [10]. Energy in SC in case of self-phase modulation should be 2 orders of magnitude less.

Conclusion

Performed experiments allow us to state that broadband coherent directional radiation (axial supercontinuum) with a high conversion efficiency of pump pulse is achieved through a cascade four-photon process.

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Генерация широкополосного излучения при филаментации фемтосекундного лазерного импульса в атмосфере

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Аннотация. В данной работе проанализированы причины и механизмы генерации излучения в широком диапазоне частот при филаментации лазерных импульсов фемтосекундной длительности, проводится анализ причин высокой направленности получаемого излучения.

Ключевые слова: фемтосекундный лазер, лазерный филамент, суперконтинуум, четырехфотонное взаимодействие.