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Filamentation Process of Femtosecond Laser Pulse in Air and Associated Phenomena

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Abstract. The paper presents experimental studies of physical processes and conditions for generate high-directional white-light supercontinuum in visible range. It was shown that it occurs in filamentation area and postfilamentation channel under different spectral broadening mechanisms step by step. Experimentally shown that these phenomena can be realized under aberration focusing.

Keywords: femtosecond laser, laser filament, white-light supercontinuum, simulated Raman scattering, coherent anti-stokes Raman scattering, Four-wave mixing.

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Introduction

One of the most interesting phenomena of modern nonlinear physical optics is the effect of supercontinuum (SC) generation. A significant broadening of laser pulse spectrum during the propagation in transparent media, including air, under self-focusing, channeling and filamentation conditions leads to generation of white-light SC. Studies of SC generation present not only fundamental interest, but also a practical one. The first is associated with the diversity of nonlinear optical mechanisms involved in the formation of wide SC spectra and determining the set of its properties, which can change both when using different optical media and when varying the parameters of pump. Interest in the use of SC in various applications arose and increased not only due to transportation of light energy over long distances, but also due to fundamental possibility of remote monitoring of the environment and study of ultrafast processes. In this case, not only the spectrum width, but also the directionality of the SC is important from both scientific and practical points of view.

The listed parameters depend on the physical characteristics of the laser radiation such as, for example: central wavelength, power and intensity, pulse duration and steepness of its leading and trailing edges, width and shape of the pulse envelope, distribution of radiation in the beam, etc., as well as environmental parameters: media composition and concentration of elements, nonlinear responsibility, external influences. In addition, the spectral parameters of the SC depend not

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only on the propagation medium parameters, but also on the conditions and mechanisms of interaction of the electromagnetic field with the external environment. Moreover, environment conditions strongly depend on the beam parameters in the case of high-intensity beams.

SC generation in air has a particular interest, which is accompanied by the filamentation phenomenon during propagation of a powerful ultrashort laser pulse. This effect was first described by Brown in [1]. Studies of various scientific groups were devoted to the investigation of processes occurring during filamentation. Thus, the filament structure was studied by the teams of MSU and Quebec Laval University [2–6], the same groups considered the process of broadening of SC conical spectrum arising from self-phase modulation (SPM) during filamentation of collimated beams [7, 8]. The groups of National Research Institute of Quebec and Laval University investigated the broadening of axial SC arising from focusing a beam in air [9, 10]. In this case, using dual-frequency pumping, the four-wave Raman mixing (FWRM) process with broadening of the spectrum into the anti-Stokes region was realized. The generation of separate anti-Stokes lines is also caused by the rotational SRS processes described in [11, 12].

The filamentation process under fs pulse focusing in gases (air and nitrogen under pressure) is considered in this paper. It is shown that under these conditions axial broadband SC is generated by the alternate implementation of various spectrum broadening mechanisms which is promoted by aberration focusing.

1. Results and discussion

The experiments were carried out on the laser complex 'Start-480M' (Avesta project, Russia) with the following parameters: central wavelength of 940 nm, pulse energy up to 10 mJ, pulse duration of 60±10 fs. Radiation focusing was performed both by lenses with a focal length of 400 to 1000 mm and by mirror with same foci. Laser beam was focused in a cell filled with air at atmospheric pressure or with nitrogen of 1–3 atm. The tilt angle of the lens (mirror) and the gas pressure were selected such that the laser pulse was transformed into an axial white supercontinuum. The supercontinuum spectrum was recorded using an Ocean Optics HR4000 spectrometer (200–1100 nm): reflected beam sent directly to the spectrometer. The duration of the pump pulse was measured using an autocorrelator ASF-20 (Avesta Project, Russia). The energy parameters were recorded by a power and energy meter Gentec Maestro. The experimental setup is shown in Fig. 1.

The experimental spectra, which are obtained from experiments with producing 2 beams, are shown in Fig. 2. Results were similar for experiment with 1 beam. Spectral measurements were made both in the middle of filamentation area (Fig. 2a) and at a distance of 10 meters from it (Fig. 2b). To obtain stable generation of white light, the tilt angle of the lens (to obtain one white-light beam) or the mirror (to obtain two white-light beams) was adjusted in each experiment; in both cases, the tilt angle was about 15°. When focusing with a mirror, two beams of white light arise due to diffraction on the plasma near the first geometric focus of the system [13]. All presented spectra were recorded in atmospheric air.

In our investigations [14, 15] it was shown that when focusing a high intensity fs pulse in air medium, SRS on rotational transitions of nitrogen occurs. At the same time, coherent anti-Stokes Raman scattering (CARS) is observed, producing a peak in the blue wing of the spectrum (Fig. 2a). The presence of the resulting triplet triggers a cascade FWRM process in the anti-Stokes region up to 300–500 nm (Fig. 2b). The evidence that it is precisely these processes lead to spectrum broadening, versus, for example SPM [7] are: high conversion efficiency; dependence

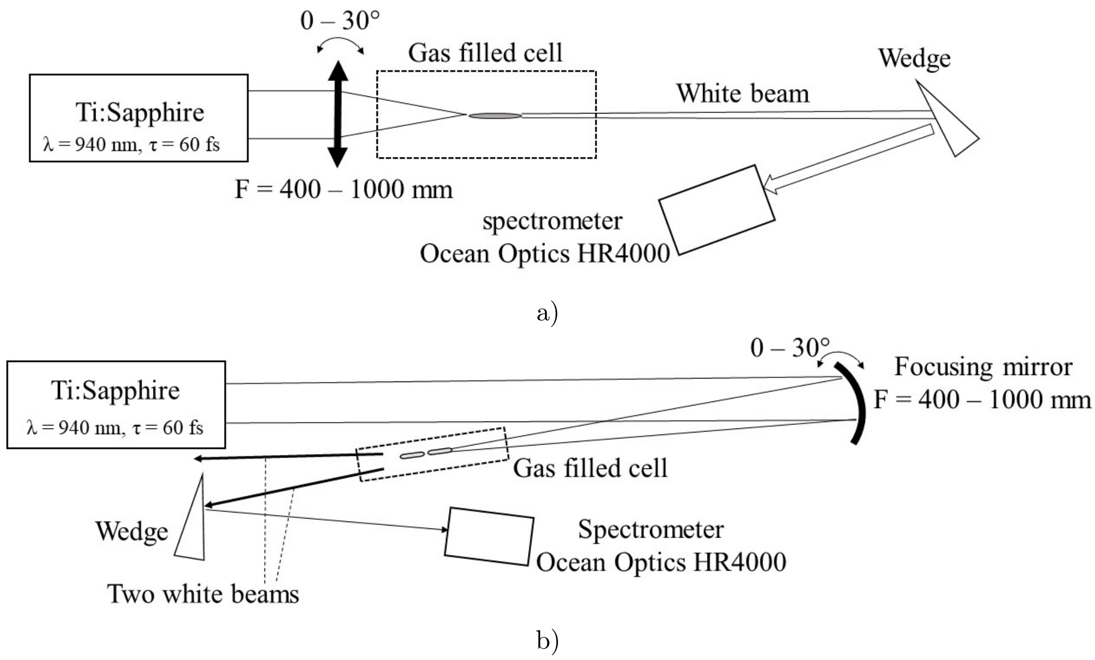

Fig. 1. Experimental setup: a) with focusing lens, b) with focusing mirror

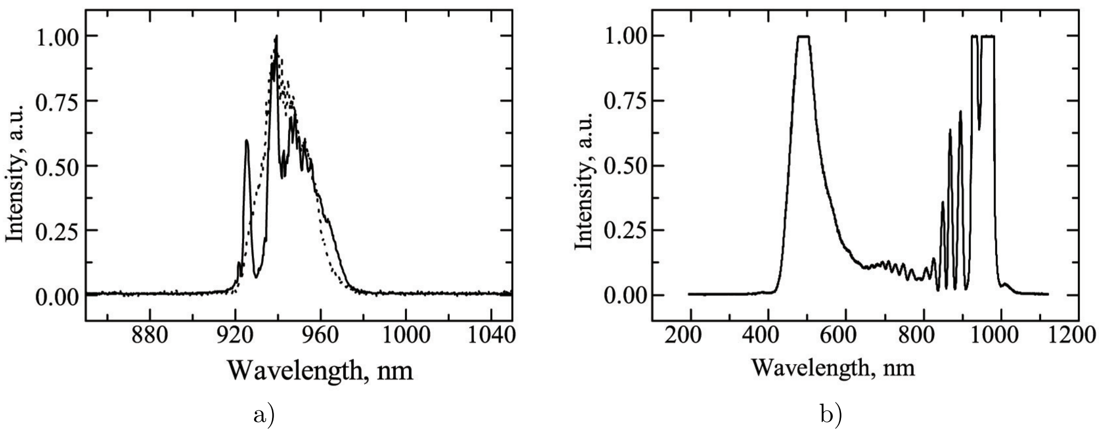

Fig. 2. Spectral measurements: a) in filamentation area (dotted line is spectra from output laser); b) at distance of 10 m from filamentation area

of the threshold value of the pump energy required to generate a white-light beam on the pump wavelength (in [16] the conditions of a same experiment to produce white-light with pumping at 800 nm are described, but no explanation of the conversion mechanisms is given). Also, the dependence of intensity of white-light beam on the gas pressure in the cell was obtained in experiments. When the spectrum is broadened due to the SPM process such phenomena should not be observed.

However, the fact of need to use aberration focusing to produce white light has previously remained unnoticed. A number of experiments to determine the optimal lens (mirror) tilt angle have shown that the optimal angle is 15±5°. At this tilt angle, stable generation of a narrow-

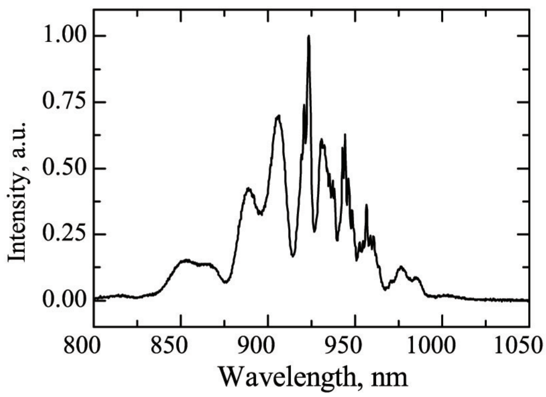

Fig. 3. Four-wave Raman mixing near the central wavelength spectral region

Fig. 4. Photo of filamentation area under aberration focusing by mirror. Light propagation from left to right. Bright regions are geometrical focuses. Plasma formation between two thick beams in second foci region is an energetic reservoir

beam white-light supercontinuum is observed. A study of the spectral component of the white supercontinuum in the 600–1000 nm region at different lens (mirror) tilt angles has shown that at non-optimal angles, a process of FWRM to the anti-Stokes region containing only a few peaks is observed (Fig. 3), whereas in the optimal mode, a cascade process is observed (Fig. 2b). An analysis of different sources [17, 18] shows the contribution of the energy reservoir to the formation of a stable beam. The same energy reservoir in the region of the second geometric focus of the system (Fig. 4) contributes to the processes of radiation amplification, which leads to cascade generation of spectral lines.

Conclusions

The presented results allow us to state that aberration focusing of femtosecond radiation causes a number of physical processes that lead to ultra-wideband broadening of the pump pulse and formation of a beam with a divergence close to the diffraction limit. In the prefilament area, stimulated Raman scattering on nitrogen molecules occurs, leading to the generation of first- and second-order Stokes lines. Further, in the filamentation area, as a result of the process of CARS an anti-Stokes component is generated. In the filament and post-filamentation channels, a cascade process of FWRM is started, the seed components of which are the pump pulse and the anti-Stokes line. Aberration focusing provides the cascade process, supplement energy from the paraxial energy reservoir. High intensity of white-light beam promotes self-channeling in the post-filamentation area, providing a divergence close to the diffraction limit.

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Процесс филаментации фемтосекундного излучения в воздухе и явления ее сопровождающие

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Аннотация. В работе приводятся экспериментальные результаты исследований условий и механизмов формирования высоконаправленного широкополосного суперконтинуума в видимой области спектра. Показано, что формирование такого излучения происходит в области филамента и постфиламентационном канале путем последовательной реализации различных механизмов уширения спектра. Экспериментально подтверждается, что данное излучение наиболее устойчиво формируется при создании аберраций на волновом фронте излучения накачки.

Ключевые слова: фемтосекундный лазер, лазерный филамент, суперконтинуум, вынужденное комбинационное излучение, когерентное антистоксово рассеяние света, четырехволновое взаимодействие.