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Generation of a highly directional supercontinuum in the visible spectrum range

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ABSTRACT

This paper presents the results of experimental studies on the formation conditions of a highly directional supercontinuum (SC) produced via filamentation of a femtosecond laser pulse in air. The laser beam had an energy of 8–15 mJ, radiation wavelength of 940 nm and pulse duration of 70 fs. A spherical mirror, with or without aberrations, was used to focus the laser beam. It is shown that a SC forms behind a visible filament through a step-by-step conversion of the spectral composition from long wavelength to short wavelength (to 350 nm). The radiation is most stable when it is generated in the presence of aberrations in the wave front of the laser beam. On the track section 35–135 cm from the filament, radiation propagates in the form of a spatially stable structure similar to a soliton with a transverse dimension ≤300 µm. In this case, the SC significantly differs from the conical off-axis emission that occurs in the aberration-free filament, in that it displays a divergence close to the diffraction limit, linear polarisation and a shorter-range wing of the spectrum. The infrared component of the SC has a duration 2.8-times shorter than the pulse duration of the initial laser beam.

1. Introduction

Currently, many papers present observations from the study of a supercontinuum (SC) in the visible spectrum range (white light laser) by filamentation of the laser pulses with femtosecond duration in air [1–11]. The basis of SC formation is a nonlinear optical space-time conversion of radiation of ultra-short high-intensity laser pulses in a medium with a cubic nonlinearity. Research development in the field of SC generation in the visible spectrum range has shown the availability and great practical significance of this type of radiation for solving tasks in metrology, telecommunications, nanotechnology, optical coherence tomography and remote analysis of the atmosphere, among many others.

Braun et al. [1] were the first to observe SC generation in the visible spectrum in air. Under certain conditions, conical and axial emission was recorded. The term "white light laser” was introduced in the publications resulting from the European Teramobile Program, in which a white glow was observed upon the propagation of femtosecond laser beams in the atmosphere [2,3]. Other authors subsequently adopted this term [4]. In [5], radiation with a modulated spectrum was used to obtain a SC. It was shown that when the distance between the spectral peaks was increased, the SC wave cutoff was shorter (up to 230 nm). The authors attributed the main mechanism of radiation conversion to four-wave parametric mixing. An overview of works devoted to the study of SC is presented in [7] and it is shown that the main mechanism of SC appearance is self-phase modulation. In the abovementioned works, SC is distributed, as a rule, in the form of a cone and the radiation was recorded only in some cases. In [8], it was shown that the filament was formed upon the long focal length (F=6–12 m), focusing the radiation at a wavelength λ=950 nm in air and this filament was the source of directional white light on an axis (axial SC). Its appearance and direction depended on the beam power and the lens focus. At low intensities, the SC spectrum range was extended in the short-wavelength region of 450–500 nm. With increasing intensity, the SC range extended to λ=300–350 nm but became mostly conical. That is, the conditions of axial SC existence are very limited.

The formation conditions of the filament and SC by aberration focusing of a femtosecond radiation pulse by a lens tilt were studied in [9–13]. In [9] it was shown that the intensity of the SC in the visible spectrum range decreased with an increase of the tilt angle of the lens with a focal length F=1 m. At the same time, in [10] the dependence of the SC spectrum on the lens tilt angle was investigated and it was shown that at an increase of angle up to 8° resulted in a shift to shorter wavelengths; however, at angles of 15–20°, the spectral shift to shorter

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wavelengths decreases. Observations of one or two bright-light jets after the formation of a filament due to the shifting or tilting of the lens to a certain angle are reported in [11]. The filament is formed in air when the lens (F=10 cm) focuses the 50 fs radiation pulse at λ=800 nm. It is shown that the brightness of the light jets is also dependent on the polarisation of the laser beam. The authors associate the emergence of the SC with a four-wave mixing. In [12] it is shown that by focusing the radiation with femtosecond pulse duration in air, the pump intensity and electron density in the filament increase when the lens is tilted. In [13] it is reported that astigmatic focusing enhances the radiation energy behind the filament and the spectral broadening of the SC. The authors demonstrated the pulse compression after the filament from 100 fs (FWHM) for the input pulse to 13 fs for the output pulse. This is due to the increase of critical power, Rayleigh length and the multi-filamentation threshold. In contrast to [12], the authors assume that the peak intensity achieved in the filament by astigmatic focusing must decrease by a factor of six. As can be seen from the above articles, the conditions of the appearance of a SC in the visible range by interaction of femtosecond radiation with air differ significantly among the different publications. In addition, in the cited papers the properties of white SC are not studied.

The aim of the present work is to investigate the formation conditions of a highly directional SC in a visible spectrum range obtained by spherical mirror focusing of a radiation pulse with a wavelength of 940 nm and duration of 70 fs in air and further, to define of the SC parameters via these experimental studies.

2. Experimental set-up and research methods

In the experiments, a solid-state starter complex, "Start 480", developed and manufactured by the Russian company “AVESTA PROJECT Ltd.”, was used to form the radiation of femtosecond duration. The complex includes a Ti:Sa master oscillator with a continuous pump laser, optical stretcher, one regenerative and two multi-pass amplifiers with pulsed pump lasers and a compressor on two diffraction gratings. The output radiation parameters were as follows: a central wavelength of 940 nm, spectral width of 26 ± 2 nm (FWHM), pulse duration of 70 ± 3 fs, energy up to 50 mJ and a beam diameter of 10 mm. The complex operated with a pulse repetition rate of 10 Hz and the energy stability was 3%. The output radiation was linearly polarised (horizontally) and the beam quality factor M^2=2. To measure the spectral parameters of radiation, a HR4000 spectrometer was used operating in the range of 193–1100 nm with a spectral resolution of 0.75 nm. Gentec and Ophir gauges were used to measure the energy of the laser pump beam and the converted radiation. The duration of the radiation pulse was measured by ASF-20 femtosecond autocorrelators operating at wavelengths of 950 and 475 nm. The spatial distribution of radiation fluence was recorded by a SP620U profilometer and beam pattern on photographic paper. Processing of images was performed using Beam Gage and Beam programs, respectively. The electron density in the filament plasma was calculated from measurements of the charge change on the electrodes installed across the axis of radiation propagation.

3. Experimental results and discussion

The results on the formation of a directional axial SC in air without aberrations show that it is most stable when the focusing system has a low numerical aperture of (NA < 0.0015). This condition is obtained using a long focus of a spherical mirror or a small diameter of the laser beam. With a numerical aperture NA ≥0.01, only a conical SC is obtained whose directivity is extremely low. In our opinion, the observed difference is due to the following conditions. With a large NA the geometric and nonlinear focuses are close to each other and a significant portion of the radiation passes through the filament in which the refraction on plasma electrons is large. In this case, the directional axial SC after the filament is virtually absent. The decrease of NA reduces the plasma concentration in the filament and increases the field dominance length of Kerr nonlinearity on electron refraction. Under these conditions, an axial SC is possible. However, as previous experiments have shown, the range of axial SC conditions is quite narrow. For example, at F=12.2 m and radiation energy of 10 mJ, the filament arises and the red components of axial SC appear at its end. The spectral composition of SC does not change with further propagation of radiation. As the energy is increased, the white components of SC arise from the filament. However, at the radiation energy of 15 mJ the spectral SC components were extremely unstable and acquired an angular dispersion, which changed from pulse to pulse. The short wave cutoff was changed from 350 to 650 nm.

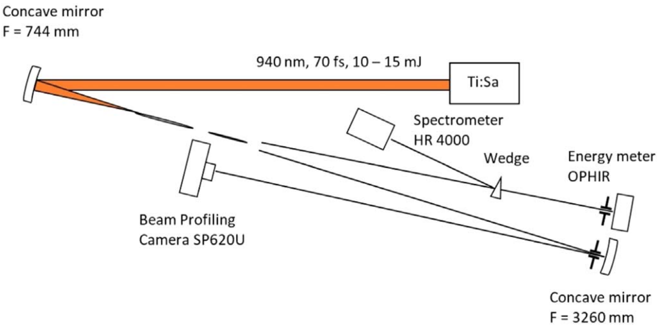

Fig. 1. Experimental setup.

Study of the SC by astigmatic focusing of the laser beam was carried out in the optical setup shown in Fig. 1. Focusing of radiation was achieved using a spherical mirror with F=744 mm. After the filament a conical SC emission was only observed for all radiation energies when the incidence angle of radiation on the focusing mirror was minimal (~1°). The emission intensity of the filament decreased and split into two parts located on the same axis when the incidence angle was increased. The first part was brighter and corresponded to the meridional plane; the second part corresponded to the sagittal plane (this was also observed in [9]). At a certain incidence angle (10–13°) and radiation energy more than 10 mJ, a ray of white light with a high directivity arose after visible filament. With a further increase of the angle, a second beam appeared and then both beams disappeared in the same order. The beams propagated to the left and right of the axis of the filament at an angle in the horizontal plane. Our measurements show that the angle was ~ 0.7°.

Fig. 2 shows a photograph of the SC radiation spread after the filament at an incidence angle of the radiation on the mirror of 15°, in the polarisation plane of incident radiation. It can be seen from the photograph that there are two directed light beams after the filament.

As the distance from the filament increases, the light beams change colour from red to blue. The insets on the right show photographs of radiation luminescence on a screen mounted at distances of 10, 20, 40 and 80 cm from the end of the filament. They also clearly show the changes in the colour of the rays. The inset on the left presents the spectral composition of the radiation at a distance of 100 cm from the end of the filament. The spectral range of the bean did not practically change upon further transport. The emergence of white light depended on the incidence angle of radiation and the degree of restriction of the original beam. When close to the threshold, restriction of the laser beam on the left results in the appearance of a left beam and its restriction on the right results in the appearance of a right beam. If the threshold was exceeded then the beamconstraint on the left leads to disappearance of the right beam and its constraint on the right leads to disappearance of the left beam. Upon deviation of the mirror axis in the vertical plane perpendicular to the plane of laser beam polarisation, two bright directed beams also appeared; however, the energy threshold of their appearance was increased 1.5-times, similar to that