NONLINEAR OPTICAL PHENOMENA

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Conical emission of a femtosecond laser pulse focused by an axicon into a K 108 glass

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Abstract. **The supercontinuum conical emission of a 50-fs laser pulse focused into a K 108 glass is studied experimentally and numerically. It is found that, as the pulse energy was increased from 2 to 30 μJ, the continuous picture of conical emission decomposed into speckles upon focusing with a lens and split into narrow rings upon focusing with an axicon.**

Keywords: *filamentation, axicon, supercontinuum, conical emission, femtosecond pulse*.

1. Introduction

The first experiments on the generation of broadband radiation upon focusing a laser pulse into condensed media have been performed in the 1970s [1]. In [2], the conical emission of the high-frequency supercontinuum tail was observed upon focusing a 1.06-μm picosecond pulse into a cell with water. The picture of conical emission at wavelength down to 340 nm appeared as diverging colour rings with the radius increasing with decreasing the emission wavelength. In the subsequent experiments with femtosecond pulses focused in water [3] and ethylene glycol [4, 5] and later with collimated pulses in air [6, 7], the frequency-angular distribution of conical emission was investigated. The development of physical mechanisms of conical emission produced upon the propagation of picosecond and femtosecond laser pulses in various media was analysed in papers [8, 9]. It was shown that the spatiotemporal self-phase modulation of an intense light field in media with the Kerr nonlinearity and in a nonlinear laser-induced plasma causes extremely strong broadening of the frequency and angular spectra of a femtosecond pulse.

The study of the supercontinuum spectrum in various media [10] showed that its broadening increases with increasing the energy gap of a dielectric. Experiments with pulses at different wavelengths focused into various optical materials and liquids were performed in [11]. It was found that the broadening of the spectrum to the short-wavelength region increased with increasing the energy gap-to-photon energy ratio and was independent of the pulse wavelength and properties of the medium.

The effect of the position of the geometrical focus in a barium fluoride sample on the supercontinuum produced by a femtosecond pulse with power exceeding the critical self-focusing power by three orders of magnitude was studied experimentally in [12]. The efficiency of supercontinuum generation in water for different regimes of focusing a femtosecond pulse of power exceeding by 3 – 10 times the critical self-focusing power was studied experimentally and numerically in [13]. It was shown that upon mild focusing, the efficiency of generation of the side components of the spectrum increased by a few orders of magnitude compared to that upon tight focusing, and the width of the spectrum also increased. This is explained by an increase in the length of a plasma channel in a filament and, hence, in the length of nonlinear-optical transformation of the pulse emission in a supercontinuum in the case of mild focusing. The influence of the plasma channel length on the efficiency of supercontinuum generation has the general character and is independent of the interaction medium and methods of increasing the filamentation length of the femtosecond pulse (geometrical focusing or phase modulation of radiation) [14]. The angle of conical emission of a focused pulse can be estimated by using the approximation of the additivity of the diffraction divergence and the divergence of the short-wavelength wing of the supercontinuum upon filamentation of collimated radiation.

One of the methods for increasing the length of nonlinear-optical interaction of laser radiation with a medium is based on focusing the pulse with a conical lens (axicon). In [15], conical emission was observed upon axicon focusing a 0.795-μm, 120 – 140-fs subterawatt pulse into transparent dielectrics. The authors explained the appearance of the short-wavelength emission in the pulse spectrum by the example of a K 8 glass by cascade parametric processes in a plasma induced by laser radiation in a dielectric target. The length of plasma channels produced upon filamentation of a femtosecond laser pulse focused into quartz with an axicon and various lenses was calculated theoretically in [16]. It was shown that a plasma channel produced upon axicon focusing is longer than that produced upon focusing with the help of parabolic lenses.

In this paper, we present the results of our experimental and numerical study of conical emission produced upon filamentation of a femtosecond laser pulse focused with an axicon and lenses into a K 108 glass.

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2. Experimental results

Conical emission upon pulse filamentation was studied on a femtosecond laser setup at the Centre of Collective Use at the Institute of Spectroscopy, RAS. The setup consists of a Tsunami HP femtosecond generator and a Spitfire HP regenerative amplifier (Spectra Physics). The generator was pumped at 532 nm by a diode-pumped 4.5-W cw Millenia-V Nd : YVO_4 laser. The amplifier was pumped at 527 nm by a diode-pumped 8-W pulsed Evolution-X Nd : YLF laser with a pulse repetition rate of 1 kHz. The energy of 50-fs, 800-nm output femtosecond pulses of the amplifier achieved 1 mJ at a pulse repetition rate of 1 kHz. The spectral full width at half-maximum (FWHM) of the pulses was ~ 20 nm. The half-width of the output laser beam was 4.5 mm.

Conical emission was obtained by focusing a femtosecond pulse into a K 108 glass sample of size 1 cm $\times$ 1 cm$\times$ 6 cm with the help of an axicon with the cone angle $\gamma = 179^\circ$ or a lens with a focal distance of 60 cm. The sample was placed so that its middle coincided with the centre of the axicon caustic or the geometrical focus of the lens. Radiation transmitted through the sample was incident on a screen placed at a distance of 15 cm from the sample middle. A picture formed on the screen was recorded with a Nikon COOLPIX 4300 digital camera, which provided the required spatial resolution and colour reproduction of the image. The pulse energy was varied from 1 to 50 μJ.

When the pulse with energy lower than 2 μJ was focused by a lens or an axicon, a white spot of a broadband supercontinuum emission appeared at the centre of the screen. Inside the sample a bright emitting region of micron size – a filament with a high energy density – was observed. Upon focusing 2-μJ pulses by the lens and 8-μJ pulses by the axicon, concentric colour emission rings appeared around the white spot on the screen. In both cases, a continuous white emission spectrum was observed. The wavelength dependence of the angular divergence of this emission was typical for conical emission at which the radius of the observed ring increased with decreasing wavelength. The divergence angle in the short-wavelength region of the conical emission spectrum was 0.13 rad.

As the pulse energy was further increased, the picture of conical emission on the screen depended substantially on the type of focusing. Figure 1 presents the images of conical emission on the screen obtained after exposure to 1000 pulses upon focusing by the lens and axicon. Upon focusing pulses of energy above 8 μJ by the lens, the conical emission rings decomposed into speckles (Fig. 1a). Upon axicon focusing, the emission pattern changed qualitatively when the pulse energy exceeded 13 μJ. The conical emission spectrum, which changed continuously in colour, transformed to narrow colour rings separated by thin black low-intensity rings (Fig. 1b).

The type of filamentation inside the sample changed with increasing the pulse energy. Upon focusing a pulse of energy above 8 μJ by a lens, the filament decomposed into many disordered adjacent filaments (Fig. 2a). In the case of axicon focusing, the filament transformed to a sequence of bright segments (Fig. 2b) appearing due to pulse refocusing upon filamentation [17]. As the pulse energy was increased, the number of such segments also increased; thus, when the pulse energy was 30 μJ, four bright segments were observed.

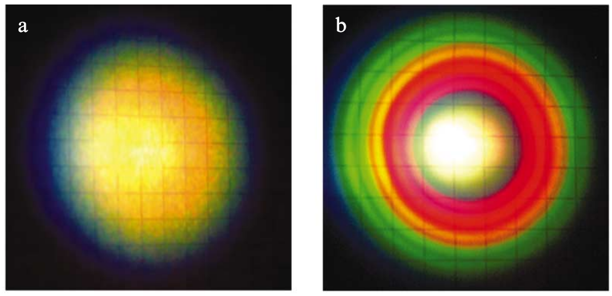

Figure 1. Conical emission patterns observed in the experiment upon filamentation of 800-nm, 50-fs pulses with a repetition rate of 1 kHz in a K 108 glass in the case of focusing 50-μJ pulses by a lens with a focal distance of 60 cm (a) and focusing 30-μJ pulses by an axicon with a cone angle of 179° (b). The scale division of the net on the images is 0.5 cm.

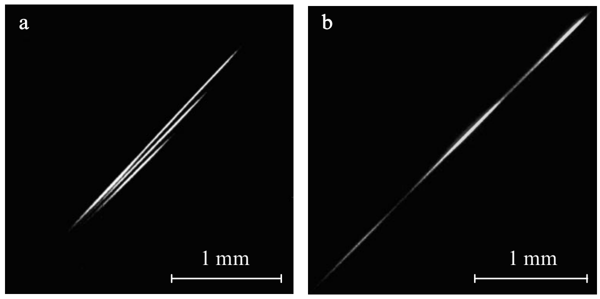

Figure 2. Typical pictures of filaments in a K 108 glass produced upon focusing 10-μJ pulses by a lens (a) and 18-μJ pulses by an axicon (b).

The emission patterns observed in our experiments can be qualitatively explained as follows. The peak power of a pulse with energy $10-30$ μJ is two orders of magnitude higher than the critical self-focusing power in a glass. Upon focusing such a pulse by a lens, many filaments and plasma channels related with them appear in front of its geometrical focus, which have a random spatial distribution. Each of the filaments together with its plasma channel is a source generating white light. The superposition of conical emission from this set of coherent sources [9, 18] produces a speckle pattern, which is irregular in the general case from pulse to pulse (see Fig. 1a). Upon axicon focusing, the superposition of converging waves results in multiple refocusing of a pulse propagating in a medium with a strong material dispersion [19]. A sequence of localised-energy regions and the corresponding plasma channel with several electronic-density maxima are formed in the filament. The distribution of supercontinuum sources proves to be spatially modulated along the filament, being stable to small fluctuations in the pulse. The multibeam interference of emission from the sequence of such sources gives rise to narrow interference maxima in the form of split conical emission rings (see Fig. 1b).

Note that the material dispersion of a medium considerably affects refocusing upon pulse filamentation. As shown in [19], in the case of a high material dispersion of a medium, multiple refocusing appears in a pulse whose peak power exceeds the critical self-focusing power in the medium by many times.

3. Numerical study of conical emission

We analysed the experimental results by simulating numerically the propagation of a femtosecond laser pulse in a glass under different focusing conditions. The problem was considered for the axially symmetric case. The equation for the complex amplitude $E(r,t,z)$ of a light field in a sample describes the diffraction and dispersion of the pulse as well as its nonlinear optical interaction caused by the Kerr effect and the nonlinearity of the laser-induced plasma:

$$2ik\left(\frac{\partial E}{\partial z}+\frac{1}{v_{gr}}\frac{\partial E}{\partial t}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right)-kk''_{\omega}\frac{\partial^2 E}{\partial t^2}+\frac{2k^2}{n_0}$$

$$\times(\Delta n_{\rm k}+\Delta n_{\rm pl})E-{\rm i}k\alpha E, \quad (1)$$

where v_{gr} is the group velocity; $k=2\pi/\lambda$ is the wave number; k''_{ω} is the expansion coefficient in the second-order dispersion theory; $\Delta n_{\rm k}=\frac{1}{2}n_2|E|^2$ is the change in the refractive index due to the Kerr effect; and n_0 is the refractive index of the medium. The increment of the refractive index in the laser-induced plasma is

$$\Delta n_{\rm pl}=-\frac{\omega_{\rm pl}^2}{2n_0(\omega_0^2+v_{\rm col}^2)}\left(1-{\rm i}\frac{v_{\rm col}}{\omega_0}\frac{\omega_{\rm pl}^2}{\omega_0^2+v_{\rm col}^2}\right), \quad (2)$$

where $\omega_{\rm pl}=(4\pi N_{\rm e}e^2/m_{\rm e})^{1/2}$ is the plasma frequency; $v_{\rm col}$ is the frequency of elastic collisions between electrons and molecules of the medium; ω_0 is the laser radiation frequency; and $m_{\rm e}$ is the electron mass. The electron concentration $N_{\rm e}(r,t,z)$ in the laser plasma is determined by the kinetic equation

$$\frac{\partial N_{\rm e}}{\partial t}=R(|E|^2)(N_0-N_{\rm e})+v_{\rm i}N_{\rm e}-\beta N_{\rm e}^2, \quad (3)$$

where $R(|E|^2)$ is the rate of multiphoton ionisation calculated by the Keldysh theory [20]; N_0 is the concentration of neutral molecules in the medium; $v_{\rm i}=e^2E^2v_{\rm col}\times[(2mW_{\rm g}(\omega_0^2+v_{\rm col}^2)]^{-1}$ is the frequency of inelastic collisions determining avalanche ionisation; $W_{\rm g}$ is the ionisation potential; β is the cross section for electron–ion recombination; $\alpha=m\hbar\omega_0I^{-1}R(|E|^2)(N_0-N_{\rm e})$ is the absorption coefficient upon multiphoton ionisation; m is the degree of the multiphoton process; and I is the laser pulse power density. The incident-radiation field $E(r,t,z)$ was described by the expression

$$E(z=0)=E_0\exp\left(-\frac{t^2}{2\tau_0^2}\right)\exp\left[-\frac{r^2}{2a_0^2}+{\rm i}\varphi(r)\right], \quad (4)$$

where $2\tau_0$ is the pulse duration at the ${\rm e}^{-1}$ level and a_0 is the beam radius at the front face of a sample. The phase $\varphi(r)$ was written as

$$\varphi_{\rm lens}(r)=\frac{kr^2}{2R_{\rm r}} \quad (5)$$

upon focusing by a lens ($R_{\rm r}$ is the distance from the centre of the sample, where the geometrical focus is located, to its front face) and as

$$\varphi_{\rm ax}(r)=kr(n_{\rm ax}-1)\cot\frac{\gamma}{2} \quad (6)$$

upon axicon focusing ($n_{\rm ax}$ is the refractive index of the axicon material).

The system of equations (1)–(3) with boundary conditions (4)–(6) was solved by using splitting over physical factors. In this case, the diffraction problem was solved by the sweep method in variables r and z for each temporal slice of the pulse, the dispersion problem was solved by integration in the spectral space ω, z for each value of r by using the fast Fourier transform algorithm, and the problem of nonlinear phase shift was solved in the space of variables r, t, z. Calculations were performed with a 2000-MHz Athlon PC whose parameters did not allow us to reproduce completely our experimental conditions. Because of a limited volume of the random-access memory (2 Gb), it was possible to obtain reliable results only for pulses of energy no more than 2 μJ.

For 2-μJ pulses, the temporal and spatial gradients of the light field in a filament and electron concentrations in a plasma channel were relatively small, and they could be reproduced by means of the calculation network of the maximum dimensionality allowed by our PC. The width of the conical emission spectrum for such pulses does not exceed 100 nm, which is considerably smaller than the width observed in experiments with 10–30-μJ pulses. Nevertheless, the results of the numerical experiment reproduce qualitatively the characteristic features of conical emission upon pulse filamentation in a glass. Figure 3 shows the pictures of conical emission calculated for the geometry of our experiment upon focusing 2-μJ pulse by a lens and an axicon. One can see the formation of thin interference rings in the conical emission of the pulse upon axicon focusing, in accordance with our experiments.

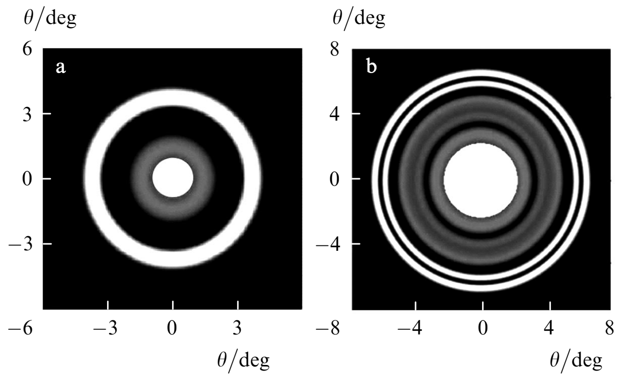

Figure 3. Conical emission patterns calculated numerically for focusing by a lens (a) and an axicon (b). The internal and external rings correspond to the conical emission wavelength equal to 750 and 700 nm, respectively.

4. Conclusions

Focusing 2–30-μJ femtosecond pulses into a glass produces filamentation accompanied by the generation of broadband conical emission. A change in the conical emission pattern with increasing the pulse energy depends considerably on the type of focusing. Upon focusing by a lens, the conical emission rings decompose into speckles due to stochastic filamentation of the pulse. Upon axicon focusing, the conical emission spectrum continuous over the angle splits into many narrow concentric rings, which is explained by the interference of emission from a set of supercontinuum sources appearing due to multiple refocusing upon pulse filamentation.

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