

Angular feature of conical emission in an isotropic amorphous medium pumped by femtosecond pulses

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Abstract Broadband parametric upconverted conical emission (CE) has been investigated in an isotropic amorphous medium pumped by femtosecond laser pulses, which covers a broad range from 470 to 630 nm. Three theoretical models were analyzed to interpret the angular beam of CE. The CE spectra and their angular positions have been experimentally measured, which can be explained well by nonlinear X-wave model and Cerenkov type phase matching model rather than four-wave mixing (FWM) model.

Keywords conical emission (CE), femtosecond laser pulses, four-wave mixing (FWM), Cerenkov type process, X-wave model

1 Introduction

During the propagation of intense ultrashort laser light through nonlinear optical media, strong modification of spatial and temporal properties leads to extreme spectral broadening, resulting in the generation of white light supercontinuum (SC) surrounded by a rainbow-like conical emission (CE) during filamentation. The producing of axial-symmetric colored rings shows the specific feature of the laser beam experience nonlinear transformation in the process of filamentation. This attractive nonlinear effect was demonstrated experimentally in a variety of media, including gases [1–4], solids [5–8], and liquids [5,9,10]. CE has aroused strong interests and has been extensively studied, while this is not an entirely understood phenomenon. Several interpretations, such as four-wave

mixing (FWM), Cerenkov radiation, self-phase modulation (SPM) and nonlinear X-wave, have been proposed to explain CE associated with filamentation in the literature. Early in the 1990s, a few theoretical studies [10–12] proved that FWM process was responsible for the pulse splitting due to group velocity dispersion (GVD) and then induced a spatio-temporal dynamics resulting in CE. Some experiments demonstrated that the measured conical angle of CE was in agreement with the calculated data according to this approach [3,13], while other experiments with pulsed laser yielded some controversial results [14,15]. Cerenkov type process was proposed to interpret CE generated in H₂O or D₂O [16]. Nibbering et al. [1] proposed Cerenkov radiation from a leaky waveguide structure to simultaneously explain the self-guiding and CE phenomena. Then the conical second harmonic emission from a quadric crystal was interpreted in terms of Cerenkov type phase matching [17]. Conti et al. [18] claimed the connection between CE and nonlinear X-wave for the first time. The angular dispersion of CE was measured in different media [5], and the experiment results were in complete agreement with nonlinear X-wave model [8,19]. The numerical simulation on X-wave [20,21] indicated to be consistent with the interpretation of Cerenkov type process, resulting in the same prediction for the dependence of frequency component on the CE conical angle.

In this study, we have observed colored CE around SC by intense femtosecond laser pulses focused into a BK-7 glass experimentally. The angular beam of CE has been measured accurately, which have been compared with those of recent theoretical models. Researchers have not reached a consensus on CE in different media, and results in this study have provided an instructive experimental research on CE in the media of glass.

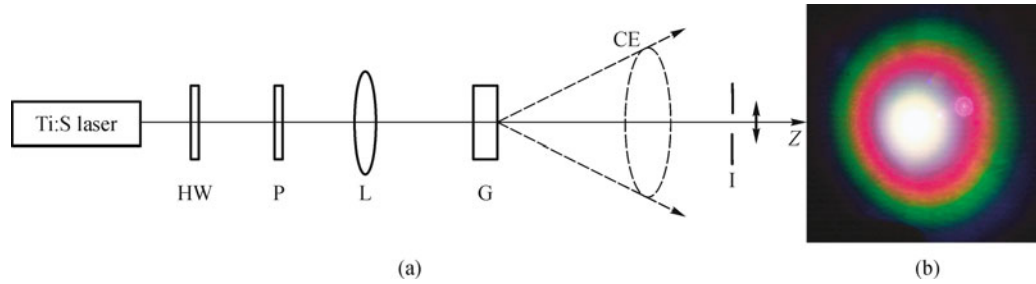


Fig. 1 (a) Setup employed in the experiment. HW, a half-wave plate in 800 nm; P, polarizer; L, lens with focus length of 20 cm; G, 1 cm-thick BK-7 glass; I, an iris with 0.5 mm diameter; (b) a typical picture of colored CE around SC

2 Experimental setup and result

Ultrashort laser pulses used in the present study were obtained from a regeneratively amplified Ti:sapphire (Ti:S) femtosecond laser (Spitfire, Spectra-Physics), which produced femtosecond pulses with the maximum pulse energy of about 1 mJ at 800 nm at 1 kHz repetition rate. The pulse width was determined to be about 80 fs by second order intensity autocorrelation. The experimental setup is shown in Fig. 1(a). A half-wave plate accompanied with a polarizer was employed to adjust the energy of the laser beam. Then the laser beam was focused into a 1 cm-thick BK-7 glass, with a lens of 20 mm focal length and the position of the focus was about 4 cm outside the front surface of the crystal. Here the glass was placed on a positioning mount, and the pump beam was sent perpendicular to the glass surface. As shown in Fig. 1(b), strong SC surrounded with rainbow-like colored cones was observed, the radial order of which was inverse of diffraction with bluer frequencies appearing on the outside rings. It can be seen that the wavelength of CE rings increases from the outside to the centre.

In order to measure the conical angle of the colored cones accurately, an iris with the diameter of about 0.5 mm was moved perpendicular to the propagation Z axis, and then a fiber coupled CCD spectrometer was used to detect the corresponding spectra of CE around SC in BK-7 glass, which are shown in Fig. 2. The spectrum of CE covers a broad range from 470 to 630 nm. Three theoretical models on the conical angle at different wavelength will be discussed in the following.

3 Description of theoretical models

3.1 FWM model

Luther et al. [11] presented that the theoretical model induces a four-wave interaction that can promote a transport of energy from the band of wave trains to sidebands. As shown in Fig. 3, the schematic diagram gives the FWM process involving two pump photons (\mathbf{k}_p , ω_0), a signal photon (\mathbf{k}_s , $\omega_0 + \Omega$) along with an idler photon

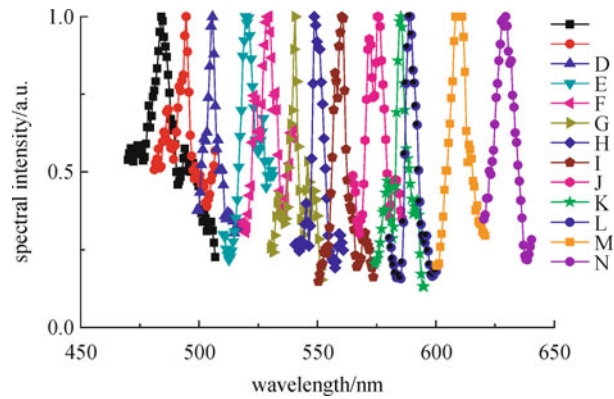


Fig. 2 Measured CE spectra from 470 to 630 nm at different conical angles

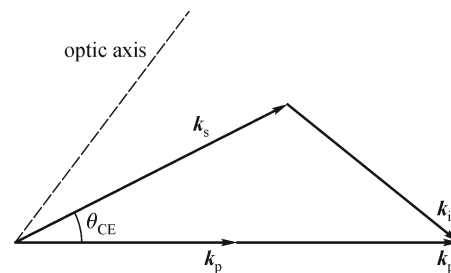


Fig. 3 Schematic representation of FWM process

(\mathbf{k}_{id} , $\omega_0 - \Omega$), from which the phase matching condition is given by $2\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_{id}$, here \mathbf{k}_p , \mathbf{k}_s and \mathbf{k}_{id} are the wave vectors of the pump, signal and the idler, respectively. Then the angle between the pump and the signal beam can be obtained by

$$\theta_{CE} = \Omega \sqrt{\frac{k_p''}{k_p}}, \quad (1)$$

where the detuning parameter $\Omega = \omega - \omega_0$ is the difference between the generated signal (CE) frequency and the pump frequency, the pump wave vector $\mathbf{k}_p = \omega_0 n_0 / c$, $n_0 = n(\omega_0)$, c is the velocity of the light and $k_p'' = \left. \frac{\partial^2 k}{\partial \omega^2} \right|_{\omega_0}$.

3.2 Cerenkov type process model

Golub [16] proposed a Cerenkov type process to interpret conical emission, in which the polarization generated by the filament results in an emission at frequencies fulfilling a Cerenkov condition at conical angle given by $\cos\theta = v_{ph}/v_{gr}$, where v_{ph} is the phase velocity of the emitted light and v_{gr} is the laser pulse group velocity. As shown in Fig. 4, when the pump wave propagates from M to N with phase velocity v_0 , the generated conical emission propagates from M to P with phase velocity v_c , so the phase matching condition is determined by

$$\cos\theta_{CE} = \frac{v_c}{v_0}. \quad (2)$$

As the phase velocity is defined as $v = \frac{c}{n}$, the conical angle can be rewritten as

$$\theta_{CE} = \arccos\left(\frac{n_0}{n_c}\right), \quad (3)$$

where n_0, n_c are the refractive indices of the pump wave and CEs, respectively.

3.3 X-wave model

X-type angular spectra could be obtained as a consequence of the spatiotemporal modulational instability in the nonlinear medium as the second order optical nonlinearity $\chi^{(2)}$. By introducing the detuning parameter and the wave vectors of pump and signal, Eq. (2) can be rewritten as follows:

$$\cos\theta_{CE} = \frac{k_p + \frac{\Omega}{v_0}}{k(\omega)}, \quad (4)$$

where the wave vector of generated CE $k(\omega) = k(\omega_0 + \Omega) = \frac{\omega n_c}{c}$. If the fundamental wave phase velocity v_0 is replaced by the group velocity v_g , the transverse wave vector can be written as [21]

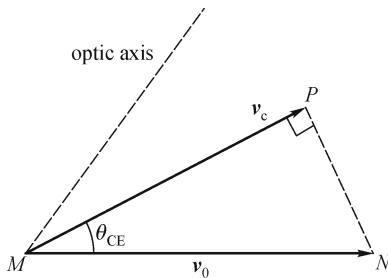


Fig. 4 Schematic representation of Cerenkov type phase matching process

$$k_{\perp} = \sqrt{k(\omega)^2 - k_z^2} \text{ with } k_z = k_p + \frac{\Omega}{v_g}. \quad (5)$$

As the CE angles are comparative small, Eq. (4) can be simplified as

$$\theta_{CE} = \sqrt{1 - \left(\frac{k_z}{k(\omega)}\right)^2}. \quad (6)$$

4 Comparison between experimental data and theoretical models

Different conical angles of corresponding wavelengths in Fig. 2 were measured experimentally with BK-7 glass, which are shown in Fig. 5 compared with theoretical curves of three models as described above. The experimental data do not accord with the three theoretical curves very well. It can be found that as the wavelengths in experimental data are shorter than 550 nm, conical angles are larger than those of three models, which are very close to the results of X-wave curve. However, as the wavelengths of experimental data are larger than 550 nm, conical angles are between those of X-wave model and Cerenkov model. It can be seen that the experimental data are almost consistent with X-wave curve.

As shown in Fig. 5, it seems that the slope of the experimental results is nearly matched to those of FWM model, and the difference of the conical angle between them is 2° . But as the conical angle is rather small, the results of FWM model are far away from the experimental results. Besides, two photons FWM process produces both the blue-shifted signal and the red-shifted idler components as to the pump wavelength. However, it is unfortunate that the red-shifted components have not been observed. Therefore, FWM model cannot be used to

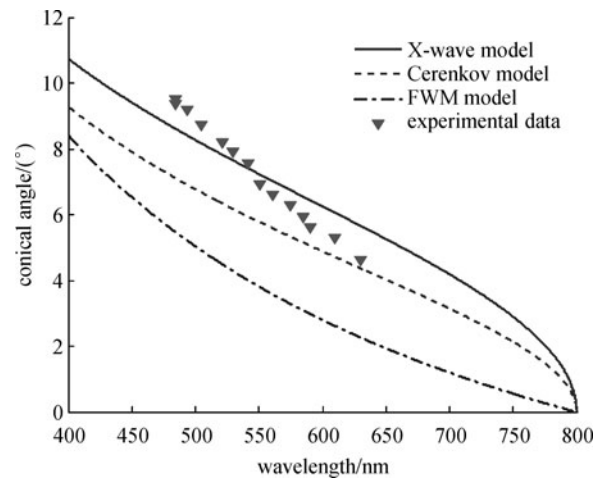


Fig. 5 CE angular spectra experimentally measured are compared with those of three theoretical models in BK-7 glass

explain the angular features of CEs along with SC adequately. However it may have some comparability in explaining blue-green CE by means of second harmonic generation (SHG) [22].

5 Conclusions

In this paper, we have observed colored CE around SC as ultrafast femtosecond laser pulses pumped BK-7 glass experimentally. The conical angular dispersion was analyzed respectively by different theoretical models: FWM, Cerenkov type process and nonlinear X-wave. The measured conical angles of CE with corresponding spectra in BK-7 glass have been compared with the theoretical models above, from which nonlinear X-wave model and Cerenkov type phase matching model are in according with the experimental results rather than FWM model.

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