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تولید پیوستار نور سفید حاصل از پالس‌های فمتوثانیه

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چکیده- گزارشی از تولید پیوستار نور سفید با کانونی کردن پالس‌های لیزری فوق کوتاه با طول موج ۸۰۰ نانومتر و انرژی کمتر از میلی ژول درون بلور کلسیم فلوراید ارائه می گردد. در این تحقیق، طیف نور سفید ایجاد شده با تغییر پارامترهای مختلفی از قبیل انرژی پالس، طول پالس و قطر کمر باریکه لیزر اندازه گیری گردید. طیف بسیار پهنی در محدوده ۳۵۰ نانومتر تا ۹۵۰ نانومتر مشاهده گردید در حالی که پهنای طیف پرتو لیزر دمنده حدود ۴۴ نانو متر است. مقدار پهن شدگی طیف تابعی از شدت بیشینه باریکه لیزر است که با انرژی پالس نسبت مستقیم و با طول پالس و همچنین با شعاع کمر باریکه نسبت عکس دارد. نتایج اندازه گیری دو نوع پهن شدگی متقارن و نامتقارن حول طول موج مرکزی لیزر دمنده را نشان می دهد. نوع متقارن آن برای پالس‌های بلندتر با طول پالس چند صد فمتوثانیه مشاهده گردید که حاصل فرایند خود مدولاسیون فازی است. برای پالس‌های کوتاهتر از ۱۰۰ فمتوثانیه مشاهده گردید که پهن شدگی طیف نامتقاون است طوری که مولفه های طیفی آنتی-استوک بسیار شدیدتر تولید شده و طیف به سمت طول موج‌های کوتاهتر بیشتر پهن می گردد.

کلید واژه- تولید پیوستار نور سفید، پالسهای لیزری فوق کوتاه، خود مدولاسیون فازی، پهن شدگی طیف.

White light suppercontinuum generation using femtosecond pulses

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Abstract- In this work, we report on white light continuum (WLC) generation by focusing sub-mJ ultrashort laser pulses at central wavelength of 800 nm into the bulk of Calcium Fluoride (CaF_2) crystal. The WLC spectrum was measured for various focusing conditions, different pulse energies and different pulse durations. A broadened spectrum ranging from 350 nm up to around 950 nm was observed whereas the pump laser has a bandwidth of about 44 nm. The extent of spectrum broadening was found to be increased by enhancing the peak intensity either via increasing the pulse energy or decreasing the pulse duration or decreasing the beam waist radius. However, two different broadening types were observed; almost symmetric broadening around the pump wavelength and strong asymmetric broadening that is extended much more toward the blue side. We distinguished two time regimes of few-100 fs in which symmetric broadening occurs as a result of self phase modulation (SFM) and sub-100 fs in which anti-Stock spectral components are created more strongly as an indication of predominance of the multi-photon ionization (MPI) process.

Keywords: supercontinuum, white light generation, self phase modulation, ultrashort pulses.

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1. Introduction

The propagation of an intense pulse through a transparent medium can lead to extensive broadening of its spectrum and thus results in producing a wide optical spectrum. This phenomenon is known as supercontinuum (SC) generation or white light continuum (WLC) generation [1].

Spectral broadening was first observed by Alfano in 1970 [2]. Since then, WLC generation using femtosecond laser pulses has gained a lot of interest. SC generation has been reported by focusing ultrashort laser pulses in various materials in different phases; gases such as Argon [3, 4], liquids such as water [5] and solids such as bulk crystals [6, 7], photonic crystals [8, 9] and optical fibres [10].

A combination of different nonlinear effects is responsible for broadening the spectrum of the laser light propagating through a transparent medium depending on the peak power and focusing condition. The self phase modulation (SFM) is the most effective optical nonlinear process in SC generation [11]. SFM refers to the phenomenon in which the laser beam imposes a phase modulation on itself while propagating in a medium. This modulation can be spatially due to the spatial intensity distribution of the laser beam which leads to self focusing/defocusing or can be temporally due to the temporal intensity distribution of the laser pulses. The temporal variation of the laser intensity leads to an SPM in time. The time derivative of the phase of a wave gives the angular frequency of the wave thus new frequency components can be appeared as the result of phase distortion arising from time-dependent light intensity and therefore, the output beam emerges with a self-induced spectral broadening.

In this work the WLC was generated by focusing a femtosecond laser beam in the bulk of Calcium Fluoride (CaF_2) and the spectrum of output laser beam was measured and compared for different pulse energies, different pulse durations and various focusing conditions using different focusing lenses.

2. Experimental setup

In this work a compact pro Ti:sapphire laser amplifier was used as the pump source for WLC generation. The central wavelength of this system is 800 nm lies in the transparency region of CaF_2. The laser is a chirped pulse amplification (CPA) system in which the pulses are compressed to less than 30 fs using a pair of prism-pair. The amount of chirp and therefore, the pulse duration can be controlled by adjusting the prism-pair position and orientation. In this way we could alter the pulse duration up to about 500 fs. The maximum output power is about 1 W at repetition rate of 1 kHz leading to 1 mJ pulses. A variable neutral density (ND) filter was used before the crystal in order to alter the pulse energy. The laser beam after the ND filter was focused into the bulk of CaF_2 by plano-convex lenses with different focal length of 75, 150, 200, 300, and 400 mm. The CaF_2 crystal was mounted on a 2D translation stage in order to adjusting the focal point inside the crystal as well as moving the focus to refresh the exposed point.

3. Results and discussion

Figure 1 shows a comparison between the laser source spectrum and the WLC spectrum.

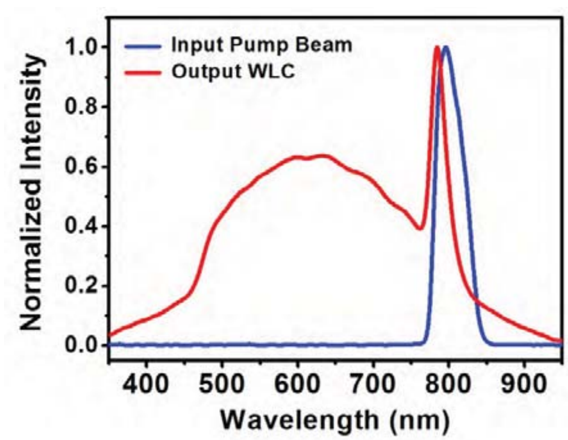

Fig. 1. WLC was generated using 30 fs, 300 μJ pulses focused by a 75 mm focal length lens.

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Blue solid curve shows the spectrum of the femtosecond laser system with a spectral range from 770 to 840 nm having a FWHM bandwidth of about 44 nm. This input spectrum is broadened more than 10 times ranging from 300 nm to about 1000 nm when 30 fs pulses with 300 μJ energy is focused inside the CaF_2 using a 75 mm focal length lens.

The femtosecond laser amplifier delivers a 10 mm diameter beam with beam quality factor of about 1.15. Focusing such a beam leads to a waist diameter of about 9.2 μm using a 75 mm focal length lens according to $w_0 = M^2 \lambda f / \pi w$ where w is the beam radius on the lens, f is the focal length, λ is the wavelength and M^2 is the beam quality factor. Assuming Gaussian temporal distribution for laser pulses the peak on axis intensity, I_0, could thus reach 2.89×10^{16} W.cm^{-2} according to Eq. (1) when 30 fs, 300 μJ pulses are focused by a 75 mm focal length lens.

$$I_0 = 4\sqrt{\frac{\ln 2}{\pi}}\left(\frac{E}{\pi w_0^2 \tau}\right) \qquad (1)$$

where τ is the pulse duration and E is the pulse energy. The extent of spectral broadening arising from SFM is given by Eq. (2) that depends on the peak on axis intensity.

$$\Delta\omega(t) = \left(\frac{4 n_2 \pi L}{\lambda \tau} I_0\right) \qquad (2)$$

where n_2 (1.05×10^{-16} cm.W^{-1} for CaF_2) is the nonlinear refractive index, L is the crystal length (10 mm in this work) and λ is the central wavelength of the pump laser (800 nm). For such conditions a substantial spectral broadening can occur due to SFM. Based on this assumption, the WLC spectral range can be given by $\omega = \omega_0 \pm \Delta\omega$ that presents a symmetrical broadening around the central wavelength (i.e. generation of Stock and anti-Stock frequency components).

Figure 2 shows the WLC produced by different pulse durations when 300 μJ pulses were focused by a 75 mm focal length lens.

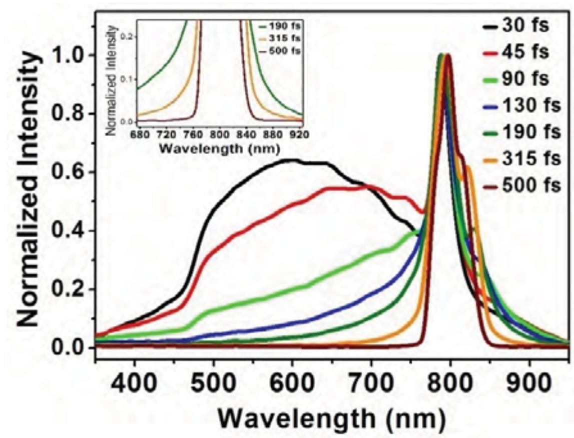

Fig. 2. The spectrum of WLC generated by different pulse durations ranging from 30 fs to 500 fs.

The inset in Fig.2 shows a zoom in long pulse duration regime. It is apparent that the spectrum is broadened symmetrically when the pulse duration is set in the range of few-100 fs. As the pulse duration becomes shorter the spectrum turns asymmetric in which anti-Stock spectral components are more strongly created. This is an evidence indicating that other optical nonlinear processes are contributing to WLC generation. The strong hump at the blue side could be attributed to multi-photon (MP) and then avalanche ionization.

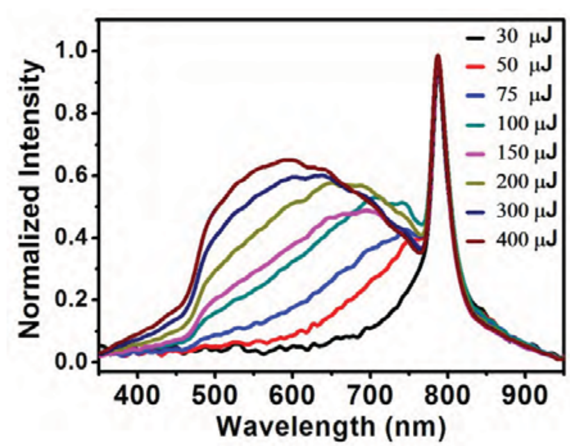

Fig. 3. The spectrum of WLC generated by different pulse energies ranging from 30 μJ to 400 μJ.

According to Eq. (1) and (2), the extent of spectrum broadening can be controlled via varying the pulse energy as well as the focus spot size (i.e. changing the focal length of the focusing lens).

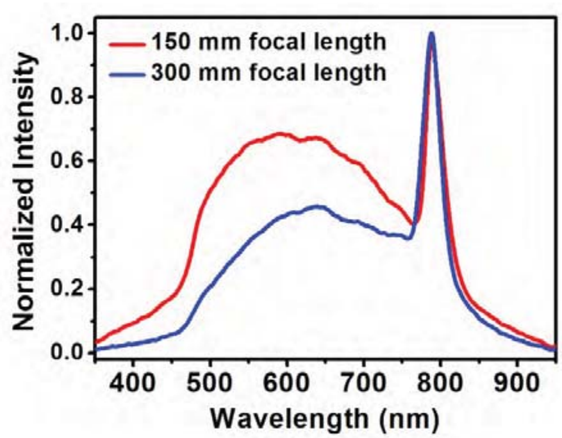

Fig. 4. The spectrum of WLC generated by different focusing lenses of 150 and 300 mm focal length.

Figure 3 indicates the WLC produced by different pulses energies when 30 fs pulses were focused by a 75 mm focal length. Fig. 4 shows the WLC produced by 30 fs, 300 μJ pulses focused by two different lenses with focal length of 150 mm and 300 mm.

As can be seen easily in both Fig. 3 and Fig. 4, the spectrum extends in the blue side much more compared to the red side. This happened by increasing the peak intensity either by increasing the pulse energy or by decreasing the focus spot size resulted from decreasing the lens focal length.

By comparison between Fig. 2 and Fig. 3&4 it can be concluded that there are two distinguished time regimes in which different mechanisms are predominant in spectrum broadening. In long pulse regime (i.e. few-100 fs) the most dominant process for WLC generation is SFM that leads to an almost symmetrical broadening (inset in Fig. 2) whereas, in short pulse regime (i.e. sub-100 fs) other nonlinear effects such as MP ionization and parametric processes are mostly predominant.

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