Quantum Electronics **41** (9) 804–808 (2011)

PACS numbers: 42.65.Ky; 42.65.Re; 42.60.By
DOI: 10.1070/QE2011v041n09ABEH014632

Second harmonic generation of spectrally broadened femtosecond ytterbium laser radiation in a gas-filled capillary

N.V. Didenko, A.V. Konyashchenko, P.V. Kostryukov, L.L. Losev, S.Yu. Tenyakov

Abstract. **A 300-fs radiation pulse of an ytterbium laser with a wavelength of 1030 nm and energy of 150 μJ were converted to a 15-fs pulse with a wavelength of 515 nm by broadening the emission spectrum in a capillary filled with xenon and by generating the second harmonic in a KDP crystal. The energy efficiency of the conversion was 30 %.**

Keywords: *femtosecond pulses, second harmonic, pulse compression.*

1. Introduction

Femtosecond lasers with active elements doped with ytterbium ions (ytterbium lasers) are widely employed due to a combination of a high average power and efficiency, which are realised under diode pumping [1, 2]. However, it is not possible to obtain radiation pulses with the duration shorter than 185 fs in ytterbium laser systems designed according to the generator–amplifier scheme and operating in the energy range 10^{-2} – 1 mJ [3, 4]. Pulse duration can be shortened by broadening the spectrum of the pulse when the latter propagates in a gas-filled capillary and then applying time compression [5]. In this way, in our previous work [6] we succeeded in compressing a 290-fs laser pulse to a 27-fs pulse at the energy efficiency above 50 %.

A powerful source of femtosecond visible light pulses with a central wavelength of 515 nm can be created on the basis of ytterbium laser radiation converted to second harmonic. Such light pulses with the duration of 10–50 fs and energy of ~100 μJ may be widely used (for example, as a pump source for variable-frequency generators of the femtosecond range). Hence, the problem of fabricating an efficient second harmonic generator of femtosecond ytterbium laser pulses with a capillary compressor is topical. There are two possible schemes for generating the second harmonic in such a system. The first one is an ytterbium laser – a gas-filled capillary – a compressor – a frequency doubling crystal. The second is an ytterbium laser – a gas-filled capillary – a frequency doubling crystal – a compressor.

The first scheme is a standard one and in the efficient conversion regime allows obtaining second-harmonic light pulses with a duration close to that of pulses at a fundamental frequency.

The second scheme may produce a twice shorter second-harmonic pulse as compared to the first scheme. This is explained by broadening the spectrum of a phase-modulated pulse during second harmonic generation. The phase modulation of the pulse (frequency chirp) arises initially in the process of pulse nonlinear propagation across a gas-filled capillary. Consider, for example, a transform-limited pulse of the Gaussian profile with a duration τ, which passes to a capillary entry. We may choose the conditions such that the pulse duration slightly increases due to dispersion, and the spectrum broadening $K = \Delta\nu_{\rm ch}/\Delta\nu$ ($\Delta\nu_{\rm ch}$ is the spectrum width for the chirped pulse at the capillary output and $\Delta\nu$ is the spectrum width for the initial transform-limited pulse) is caused by phase self-modulation. In this case, the amplitude of the light wave E_ω for the chirped pulse is given by the expression

$$E_\omega(t) = A_0 \exp\left\{-\left(\frac{t}{\tau}\right)^2 + {\rm i}\left[\omega_0 t + a\left(\frac{t}{\tau}\right)^2\right]\right\},$$

where A_0 is the peak amplitude; ω_0 is the central frequency; a is the frequency chirp. For a Gaussian pulse, the frequency chirp and spectral broadening are related by the expression $a = \sqrt{K^2 - 1}$ [7].

After the high-efficiency conversion, where the peak field amplitudes of second harmonic and the fundamental-frequency radiation are close, the field of second harmonic can be written in the form [8]

$$E_{2\omega}(t) \approx A_0 \exp\left\{-\left(\frac{t}{\tau}\right)^2 + 2{\rm i}\left[\omega_0 t + a\left(\frac{t}{\tau}\right)^2\right]\right\}.$$

It is therefore concluded that the chirp of the second-harmonic pulse is twice that of the pulse at the fundamental frequency. In view of the fact that the spectrum width and frequency chirp are related as $\Delta\nu \sim \sqrt{1 + a^2}$ [7] and taking into account the interrelation between the frequency chirp and spectrum broadening we obtain the following ratio for the spectrum widths of chirped second harmonic pulse $\Delta\nu_{2\omega}$ and fundamental radiation:

$$\frac{\Delta\nu_{2\omega}}{\Delta\nu_{\rm ch}} = \sqrt{\frac{1 + 4a^2}{1 + a^2}} = \sqrt{\frac{4K^2 - 3}{K^2}}.$$

N.V. Didenko, P.V. Kostryukov, S.Yu. Tenyakov Avesta Project Ltd., P.N. Lebedev Physics Institute, KRF-2 building, 142190 Troitsk, Moscow Region, Russia; e-mail: tenyakov@avesta.ru;
A.V. Konyashchenko P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Avesta Project Ltd., P.N. Lebedev Physics Institute, KRF-2 building, 142190 Troitsk, Moscow Region, Russia; e-mail: fs@avesta.ru;
L.L. Losev P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia;
e-mail: losev@pluton.lpi.troitsk.ru

Received22 April 2011; revision received 18 July 2011
Kvantovaya Elektronika **41** (9) 804–808 (2011)
Translated by N.A. Raspopov

Thus, the spectrum of the chirped second-harmonic pulse in the case of the efficient conversion may be approximately twice wider at negligible broadening of the spectrum of an initial fundamental-frequency pulse ($K > 2$) caused by phase self-modulation in the capillary. Correspondingly, after performing time compression, the duration of the second-harmonic pulse will be twice shorter than that of the compressed fundamental-frequency pulse. The effect of spectrum broadening and compression of second-harmonic pulses due to phase modulation of the fundamental radiation was demonstrated in our work [9], where the modulation was provided by guiding the pulse of fundamental radiation through a dispersive element. Compression of the second-harmonic pulse in a nonlinear process of phase self-modulation of the fundamental-frequency pulse has not been studied yet.

The present work is aimed at experimental investigation of the schemes described above for converting radiation of a femtosecond ytterbium laser to the second harmonic.

2. Experimental setup

The optical scheme of the experimental setup is shown in Fig. 1. A femtosecond ytterbium TETA-10 laser (Avesta-Project) is designed according to the generator – regenerative amplifier scheme. As a generator, a fibre laser was used. In the amplifier, the active medium was the crystal doped with ytterbium which was pumped by laser diodes. Chirped pulses were amplified and compressed. The transform-limited pulses after compression had the duration of 300 fs. An autocorrelation function of output pulses is shown in the inset in Fig. 1. The pulse repetition rate was 10 kHz, the average power of output radiation was as high as 1.5 W, and the central radiation wavelength was 1030 nm. The divergence of the Gaussian light beam did not exceed 1.05 M^2.

The ytterbium laser radiation was focused to an input of the glass capillary with a length of 20 cm and inner diameter of 140 μm placed into a cell made of stainless steel. The capillary transmittance at optimal focusing was 60 %. The cell was filled with compressed xenon.

The light beam leaving the capillary was collimated and directed to a second harmonic generator and compressor. Two optical schemes were studied (see Fig. 1): scheme A, in which the pulse chirped in the capillary was first compressed and then passed to a nonlinear crystal for generating the second harmonic; and scheme B, which realised compression of the second-harmonic pulse. The second harmonic was generated with type I synchronism in a 2-mm-thick KDP crystal. The spectral band of synchronisation for such a crystal is ~1500 cm^{-1} [10]. The KDP crystal was placed in a focal plane of the lens focusing the fundamental radiation.

The chirped pulses of both the fundamental and second harmonic frequencies were compressed by means of a prism compressor with the prisms made of fused silica. The distance between the prisms was ~2 m in compressing pulses at λ = 1030 nm and ~1 m for the pulses at λ = 515 nm.

The pulse durations were measured with an AFS-20 autocorrelator, and spectra were detected with an ASP-100M spectrometer (both devices are products of Avesta-Project).

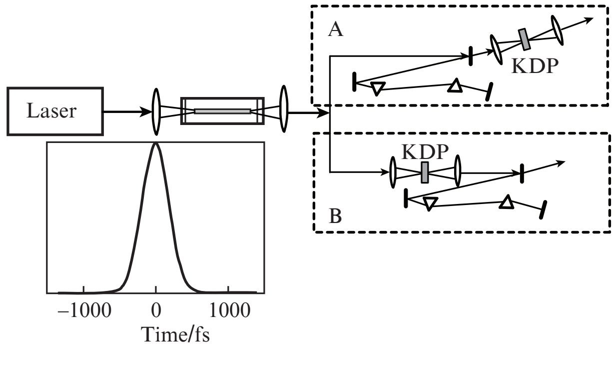

Figure 1. Optical scheme of the experimental setup with two schemes for pulse compression. The inset presents an autocorrelation function of the pulse intensity of the ytterbium laser corresponding to the duration of 300 fs.

3. Experimental results and discussion

Figure 2 shows emission spectra of an ytterbium laser at the input and output of the capillary. The spectrum at the capillary output was detected at a xenon pressure of 4 atm. It has a peaked structure specific for the spectra broadened in the process of phase self-modulation [5]. Measurements show that the spectrum width is proportional to the gas pressure. At a xenon pressure above 4 atm, a sharp fall in the capillary transmittance is observed. Also, the profile of the output radiation intensity is changed due to excitation of higher modes in the capillary [11]. In exciting the fundamental capillary mode EH_{11} the maximal width of the emission spectrum at the output of the capillary exceeded the width of the input emission spectrum by approximately an order of magnitude.

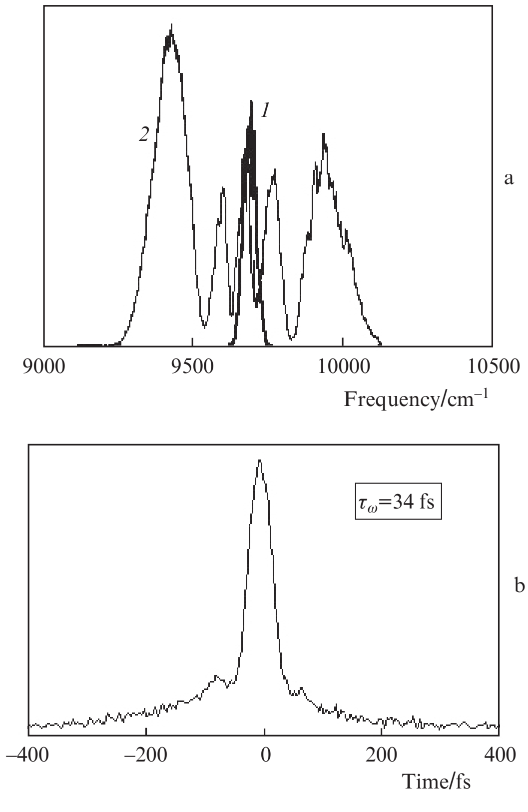

Figure 2. Spectra of pulses at outputs of the ytterbium laser (*1*) and capillary (*2*) (a), and the autocorrlation function of the compressed pulse intensity at the wavelength of 1030 nm (b). The pressure of xenon in a capillary is 4 atm.

At the first stage we investigated the process of second harmonic generation of a compressed pulse at the fundamental frequency (scheme A). Figure 2b presents an autocorrelation function of the compressed pulse intensity with the central wavelength of 1030 nm (the corresponding spectrum is shown in Fig. 2a). Under the assumption that the pulse shape is sech^2 (we also assumed such a shape in all the measurements with the autocorrelator) the pulse duration was 34 fs.

Second harmonic radiation was generated by focusing the fundamental-frequency radiation to the KDP crystal, which was placed in the focal waist. The laser radiation intensity inside the crystal was varied by changing the focal length of the lens. Figures 3a and b show the spectra and autocorrelation function for the second-harmonic pulse at the peak intensity of fundamental radiation on a crystal surface $I_\omega \sim 0.3$ TW cm^{-2}. At the fundamental pulse duration $\tau_\omega = 34$ fs, the second-harmonic pulse duration reduced to 31 fs (see Fig. 3b). By comparing the autocorrelation functions for the fundamental frequency and second-harmonic pulses one can see that the low-intensity component with the pulse duration of ~100 fs is removed due to a nonlinear transformation, which enhances the pulse contrast [12]. Correspondingly, the spectrum of the second-harmonic pulse becomes more uniform as compared to that of a fundamental pulse. The widths of the spectra are approximately equal. The efficiency of converting to the second harmonic in this case is 25%: the fundamental frequency pulse energy is 40 μJ, whereas that of the second harmonic is 10 μJ. The conversion efficiency increased at a higher intensity of radiation on the crystal surface. Measurement results obtained at the peak intensity of fundamental frequency radiation ~1 TW cm^{-2} are presented in Figs 3 c and d. The conversion efficiency at such an intensity reached 45%; however, the spectrum was broadened (Fig. 3c), duration of the second harmonic pulse became longer and it split to several sub-pulses (Fig. 3d). Seemingly, the effect is related to the time profile of the compressed pulse at the fundamental frequency – it is a short intensive pulse on a low-intensity pedestal (Fig. 2b). In the case of the efficient conversion of the low-intensity part of the pulse, the peak component intensity becomes sufficient for inducing concurrent nonlinear effects – phase self-modulation, and inverse conversion of the second harmonic into the fundamental radiation. An increased duration and distorted shape of the second-harmonic pulse may substantially limit the range of applicability for the second harmonic generator.

The results of experiments on converting chirped laser pulses to the second harmonic according to scheme B are presented in Fig. 4. The spectra were taken and autocorrelation functions were measured for compressed pulses of second harmonic radiation at various xenon pressures in the capillary. The spectrum of the second-harmonic pulse was approximately twice wider than that of the fundamental frequency pulse (compare the spectra in Figs 2a and 4a), the widths of the spectra being proportional to the xenon pressure in the capillary. The shapes of second harmonic and fundamental frequency pulses also agree sufficiently well. This confirms validity of the mechanism of second harmonic spectrum broadening discussed in Introduction.

The minimal duration of the second-harmonic pulse after compression was 15 fs (Fig. 4b). An inverse proportion between the pulse duration and xenon pressure in the capillary was observed.

The efficiency of converting to the second harmonic in this scheme was independent of the width of the chirped fundamental pulse (of xenon pressure in the capillary) and equalled ~50%. The radiation intensity I_ω on the surface of the KDP crystal was ~0.6 TW cm^{-2} and, in contrast to scheme A, no distortions were observed in the shapes of the compressed pulse and spectrum of the second harmonic at such an intensity. This is related to the fact that the time shape of the

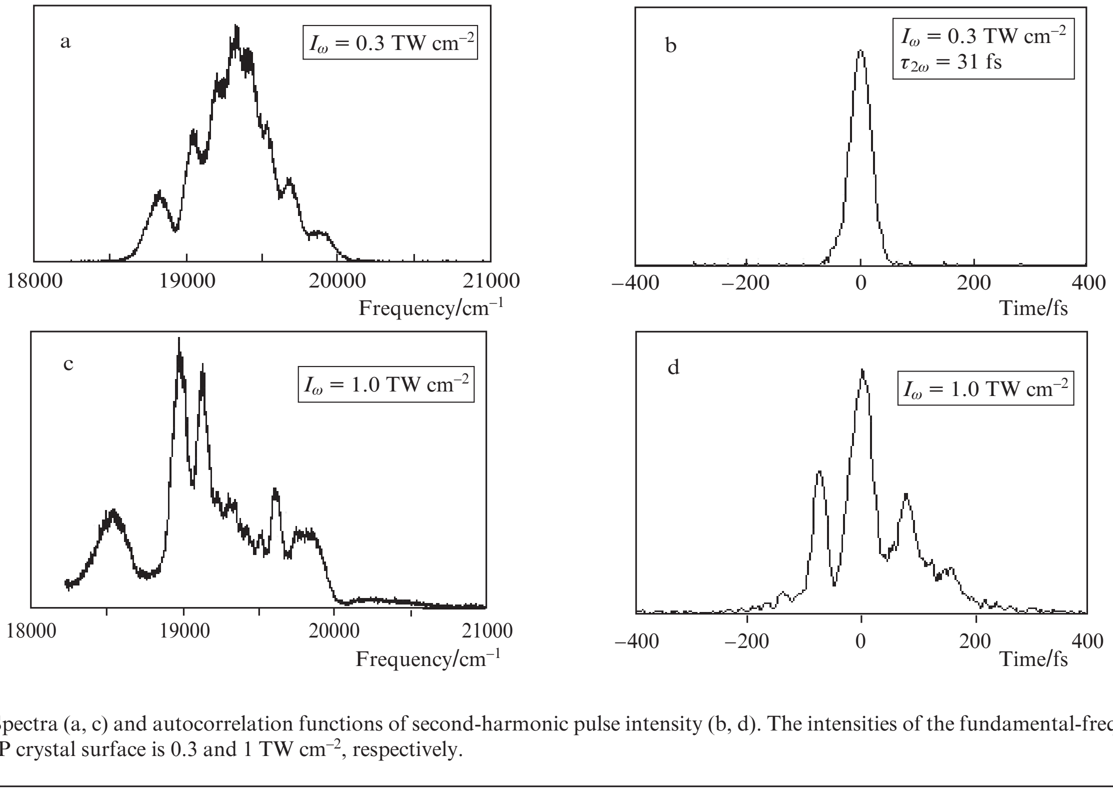

Figure 3. Spectra (a, c) and autocorrelation functions of second-harmonic pulse intensity (b, d). The intensities of the fundamental-frequency pulse on the KDP crystal surface is 0.3 and 1 TW cm^{-2}, respectively.

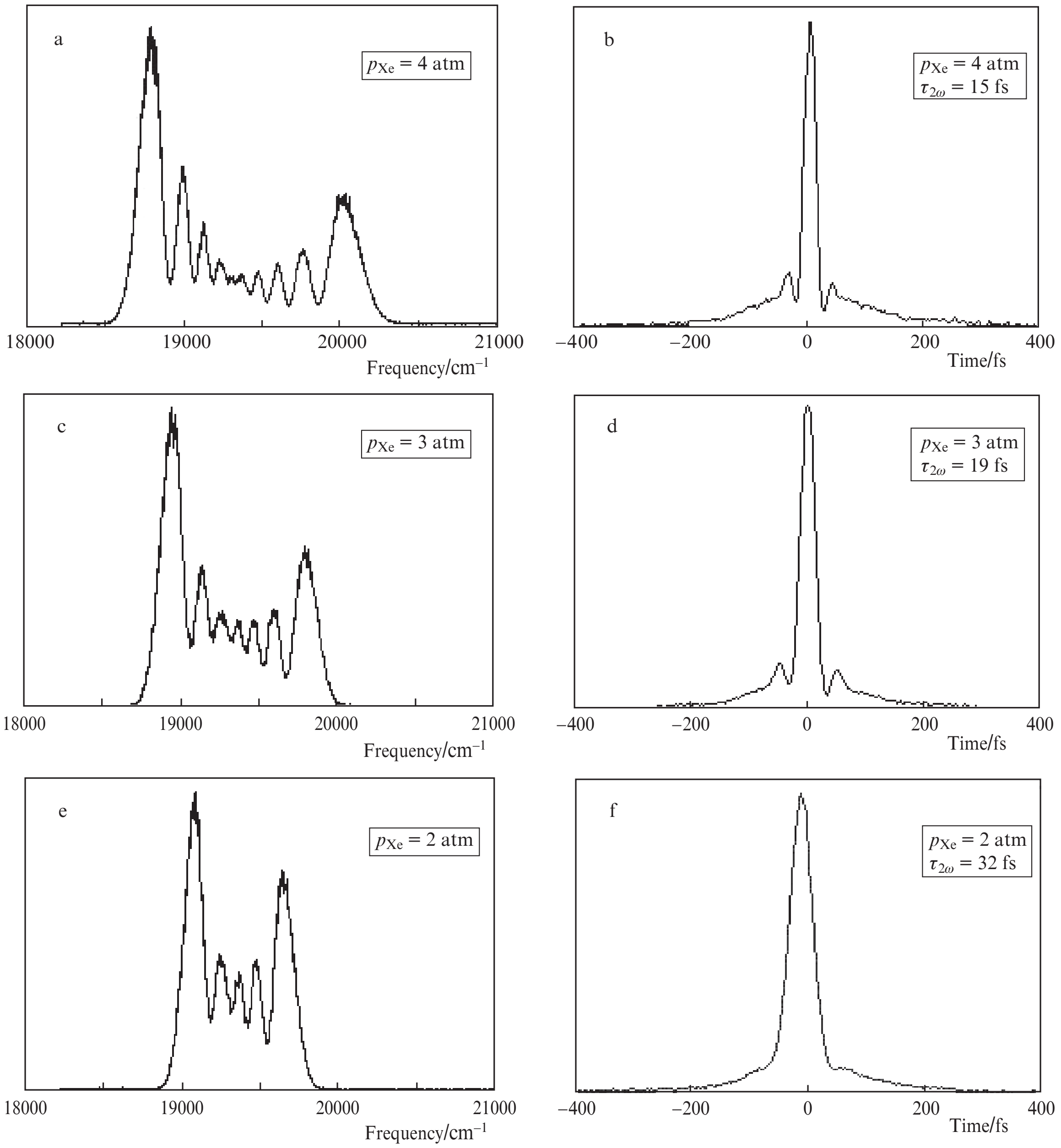

Figure 4. Spectra (a, c, d) and autocorrelation functions of the intensity of the compressed second-harmonic pulse (b, e, f) at the xenon pressure of 4, 3, and 2 atm in the capillary.

fundamental-frequency pulse, which is close to that of the pulse entering the capillary and has the duration of ~300 fs, has no intensity spikes.

Note that by employing antireflection optics it is possible to reach the energy efficiency of converting to the second harmonic with a gas-filled capillary as high as 30% of the ytterbium laser output energy. The conversion efficiency is limited by losses during radiation propagation across the capillary (the capillary transmittance is ~60%) and, in fact, by the efficiency of generating the second harmonic in the crystal (~50%). Because the duration of the second-harmonic pulse may be approximately 20 times shorter than that of the pulse at the fundamental frequency a six-fold increase in the peak power of the second-harmonic pulse may be reached as compared to the output power of the ytterbium laser.

4. Conclusions

We have studied two schemes for generating the second harmonic from a 300-fs spectrally broadened pulse of a 1030-nm ytterbium laser in a gas-filled capillary.

It has been shown that a preliminary compression of the pulse at the fundamental frequency to ~30 fs provides obtaining contrast second-harmonic pulses of approximately the same duration at the conversion efficiency of 25% (the first scheme).

Generation of a spectrally-broadened chirped second-harmonic pulse with the duration of ~300 fs, followed by its compression, make it possible to increase twice the degree of compression and obtain the second-harmonic pulses with the duration of 15 fs at the 50% conversion efficiency with respect to energy (the second scheme).

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