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Parametric amplification of broadband radiation of a cw superluminescent diode under picosecond pumping

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Abstract. **It is proposed to use cw superluminescent diodes with a spectral width of about 300 cm^{-1} and high spatial coherence as seed radiation sources in parametric amplifiers with picosecond pumping in order to form broadband picosecond pulses. A two-cascade parametric amplifier based on BaB_2O_4 (BBO) crystals is pumped by 20-ps pulses of the second harmonic of an Nd:YAG laser. For a superluminescent diode spectral width of 275 cm^{-1} (centre wavelength 790 nm), the spectral width of picosecond pulses at the parametric amplifier output is 203 cm^{-1}. At a total pump energy of 7.2 mJ for BBO crystals, the energy of the enhanced emission of the superluminescent diode is found to be 0.6 mJ.**

Keywords: *parametric amplification, picosecond pumping, superluminescent diode.*

1. Introduction

Picosecond pulses with a spectral width of several hundred cm^{-1} are necessary to solve a number of problems [1], in particular, for implementation in picosecond coherent anti-Stokes Raman scattering (CARS) spectroscopy of gas flows (including flows in different-type engines) in order to determine the gas temperature [2, 3]. If picosecond dual-broadband pure rotational CARS spectroscopy is applied to measure temperatures at a level of 2000 K, and nitrogen molecules are used as working, one needs pulses with a spectral width of 200–300 cm^{-1} [4]. A probe pulse delay with respect to excitation pulses in picosecond CARS spectroscopy allows one to exclude nonresonant background [5] and, due to this, significantly reduce the error in measuring temperature [6, 7]. The use of modeless dye lasers as broadband seed radiation sources for picosecond parametric amplifiers in picosecond CARS spectrometers makes it possible to obtain radiation free of mode (longitudinal modes) structure, with a spectral width of about 350 cm^{-1} (which is necessary for uniform excitation of rotational molecular components) and an energy on the order of 1 mJ [8]. The bandwidth of parametric amplifiers reaches several hundreds of cm^{-1} (or even more when using crystals with a length of about 1 mm) due to the application of noncollinear interaction [9, 10].

A standard way to obtain broadband seed radiation under femtosecond pumping of parametric amplifiers is the generation of supercontinuum via the formation of a filament in the field of focused (for example, into a 2-mm-thick sapphire plate) low-energy femtosecond pulses [11, 12]. In this way, pumping of a parametric amplifier based on a $LiIO_3$ crystal provided 2-μJ femtosecond (30-fs) pulses, tunable in the range of 3–4 μm [11]. In a similar way, 20-fs pulses, tunable in the range of 550–690 nm, were obtained in a parametric amplifier based on a 1-mm-thick BBO crystal [12]. Unfortunately, the filament formation in the field of picosecond pulses is unstable. At the same time, modeless dye lasers have stable parameters under picosecond pumping; therefore, these lasers were used as seed radiation sources in [8]. However, the application of a modeless dye laser means that the optical scheme ceases to be completely solid-state.

Transform-limited pulses were successfully generated in schemes of pico- or femtosecond parametric amplifiers using seed radiation of diode lasers with a sufficiently narrow spectrum and, if necessary, radiation of single-frequency diode lasers. These schemes were implemented for the first time in [13, 14]. A single-cascade picosecond parametric amplifier of cw PbS laser radiation ($\lambda \approx 4000$ nm), working at nitrogen temperature, was designed in [13]. A two-cascade picosecond parametric amplifier of cw single-frequency GaAs laser radiation with a maximum output power of 50 mW, also operating at nitrogen temperature, was implemented in [14], due to which transform limited pulses with an energy of 2 mJ and width of 17 ps, tunable in the range of 100 cm^{-1} (near the wavelength of 850 nm), were obtained. This two-cascade parametric amplifier was incorporated into a picosecond CARS spectrometer as a source of one of excitation pulses, which made it possible to increase the CARS signal from a supersonic nitrogen jet by two orders of magnitude [15].

The parametric amplification of the seed radiation of single-frequency external-cavity diode lasers with a power of about 1 mW, tunable in the range of 1260–1630 nm, was used to form transform limited picosecond pulses (with a width of about 5 ps), tunable in the range from 1260 to 1630 nm (idler wave) and from 920 to 790 nm (signal wave) [16]. These pulses were used to study the nonlinear effects in waveguides based on $LiNbO_3$ crystals. A scheme (based on a $MgO:LiNbO_3$ crystal) of femtosecond parametric amplification of seed radiation of a pulsed InGaAs laser diode ($\lambda \approx 1064$ nm) with a

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peak power of 2 W, under pumping by a 30-fs Ti:sapphire laser, was also implemented in [17]. A double pass through a 1-mm-thick nonlinear crystal provided pulses with an energy of 2 μJ, a width of 50 fs, and a wavelength in the mid-IR range (near 3500 nm).

The seed radiation of narrow-band diode lasers was also used to form sufficiently narrow-band nanosecond pulses with the aid of optical parametric oscillators in [18], where a single-frequency external-cavity diode laser with a power of 4.5 mW, tunable in the range of 930–960 nm, was applied. The parametric oscillator was pumped by the second harmonic (180 mJ) of a high-power Nd:YAG laser. In contrast to femtosecond and picosecond pumping, where parametric amplifiers are successfully applied, parametric oscillators must be used under conditions of nanosecond pumping (and, correspondingly, much lower parametric gain). In this case, it is necessary to tune the oscillator mode frequency to the diode laser frequency, e.g., by displacing one of the oscillator mirrors by means of piezoelectric ceramics. Frequency-tunable pulses with an energy of 40 mJ and a bandwidth of 190 MHz were obtained, which made it possible to use this radiation source for on-board measurements of water vapor content in the upper layers of atmosphere.

A question arises: can the seed radiation of diode sources be used to form a broadband spectrum in picosecond parametric amplifiers? A transition to a wide spectrum free of the structure related to longitudinal modes is implemented when diode sources (as in the case of dye lasers) on the basis of the modeless scheme are applied. Specifically superluminescent diodes (SLDs) implement the modeless version of diode sources. There are SLDs with a high spatial coherence and a spectral width reaching 300–400 cm^{-1} [19]. Correspondingly, it is necessary to apply noncollinear geometry of parametric interaction in a nonlinear crystal in order to form a sufficiently wide gain spectrum. However, broadening of the parametric-gain spectrum increases the intensity of the noise component caused by quantum noise [20], as a result of which the contrast of parametrically amplified seed radiation decreases. The purpose of this study was to analyse the possibility of forming broadband (200–300 cm^{-1}) picosecond pulses with a high contrast under conditions of amplification in a two-cascade parametric amplifier with picosecond pumping of the seed radiation of a cw broadband superluminescent diode.

2. Experimental setup

A schematic of the experimental setup is presented in Fig. 1. To generate picosecond 25-ps pulses with an energy of 1.3 mJ and a wavelength of 1064 nm, we used a master picosecond diode-pumped Nd:YAG laser (Sinkhrotekh, Moscow), operating with a pulse repetition rate of 3 Hz. Pulses were amplified in a double-pass lamp-pumped amplifier and then converted into second-harmonic pulses (λ = 532 nm) in a DKDP crystal. The energy of the second-harmonic pulses, used to pump noncollinear parametric amplifiers based on BBO crystals, was varied up to 10 mJ. Mirror M1 was used to split the second-harmonic beam into two beams. The beam reflected from this mirror pumped the BBO-1 crystal, while the transmitted beam pumped the BBO-2 crystal. The crystals were cut so as to implement the oo–e interaction at an angle of 22.5° with respect to the optical axis.

The ratio of the reflected and transmitted beam energies was 1:5. The pump beam for the BBO-2 crystal was formed using a telescope consisting of lens L1 with a focal length F = + 300 mm and lens L2 with F = –100 mm. To form a pump beam in the BBO-1 pump channel, a telescope composed of lens L3 with F = +300 mm and lens L4 with F = –100 mm was applied. A delay line based on prisms P1 and P2 was installed in the BBO-2 pump channel to equalise the transit times of picosecond pulses in both channels. The BBO-1 and BBO-2 crystals had an aperture of 4 × 6 mm and a length of 10 mm. The input crystals surfaces were made antireflective for the second-harmonic radiation, while the output surfaces were made antireflective for the SLD radiation with an average wavelength of 790 nm.

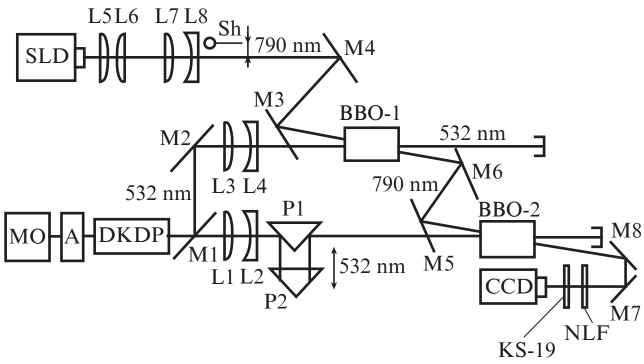

Figure 1. Schematic of the experimental setup: (MO) master picosecond Nd:YAG laser; (A) amplifier; (SLD) superluminescent diode; (M1–M8) mirrors; (Sh) shutter to block SLD radiation; (CCD) array detector; (L1–L8) lenses; (P1, P2) prisms; (NLF) neutral light filter; (KS-19) filter.

The seed radiation source for the parametric amplifiers was a LED module based on high-efficiency quantum-dot SLDs with a comb-like spatial-single-mode active channel (Superlumdiode, Moscow) [21]. The power of its cw output radiation was 70 mW at a maximum current of 300 mA (according to the calibration curve). The SLD output aperture was 1×4 μm in size. Note that in the direction of the 'fast' axis the SLD radiation was strongly divergent and did not enter completely the aperture of the condenser formed by lenses L5 and L6. As a result, along with the central spot, a diffraction structure was observed in the SLD radiation passed through the condenser. Lenses L7 (F = +90 mm) and L8 (F = –75 mm) were used to form a central spot with a diameter of 2 mm on the BBO-1 surface, due to which the seed beam diameter was aligned with the pump beam diameter (1.5 mm).

The seed radiation power at an SLD injection current of 260 mA after mirror M3 (i.e., practically before the BBO-1 crystal) was measured by a Field Master (Coherent) power meter with an entrance aperture of 8 mm to be 15.2 mW. All our experiments were performed with this power. The distance between the SLD output aperture and mirror M3 was 950 mm. A shutter was installed after lens L8, which blocked the SLD radiation when necessary. Using mirror M4 and dichroic mirror M3, which was made antireflective for a wavelength of 532 nm and reflective for 790 nm, the second-harmonic and SLD beams were aligned in the BBO-1 crystal at an internal noncollinearity angle of 2°, providing a parametric-gain bandwidth of 200–300 cm^{-1} (which is typical of 10-mm-long nonlinear crystals [8]). The amplified SLD radiation emerging from the BBO-1 crystal arrived at the BBO-2 crystal at an angle providing the same internal noncollinearity angle: 2°. The pump beam diameter on the BBO-2 crystal surface was 3 mm. The optical path of the 790-nm radiation between the BBO-1 and BBO-2 crystals was 110 mm.

The spatial intensity distributions of the amplified SLD radiation and parametric superluminescent (PSL) radiation were measured using an SDU-415 array detector (Spetsteletekhnika, Moscow), spaced at a distance of 150 mm from the BBO-2 crystal. A KS-19 filter and a necessary set of neutral light filters (NLFs) were placed before the recorder. When measuring the energy of amplified SLD radiation, a photodiode with a sensitive area diameter of 200 μm, spaced at a distance of 630 mm from BBO-2, was installed in the central part of the amplified SLD beam. The photodiode signal was observed using a Tektronix DPO 4104 oscilloscope.

3. Results and discussion

An important parameter characterising the parametric amplification of seed radiation is ratio K of the power (energy) density of the amplified SLD radiation to the power (energy) density of the PSL radiation, which is due to the quantum noise amplification. In experiments, this ratio should be determined in the unsaturated region of parametric amplification, where the parametric gain is the same for the seed radiation and quantum noise [14].

Figure 2 shows a dependence of the photodiode signal (i.e., the energy in the central part of the amplified SLD beam) on the pump energy of the BBO-2 crystal. The dependence levels off at a pump energy of 6 mJ (this energy corresponds to the BBO-1 pump energy: 1.2 mJ). In this case, the energy of amplified SLD radiation was 0.6 mJ. The pump and amplified SLD radiation energies were measured using a Labmaster Ultima meter (Coherent). In accordance with the dependence in Fig. 2, we measured the K value at a BBO-2 pump energy of 3.5 mJ. The signals recorded by the array detector in the presence of SLD radiation and with the shutter closed differed by a factor of about 100. The dynamic range of the array detector was two orders of magnitude; therefore, to provide a reliable measurement of both signals in this dynamic range, the amplified SLD radiation was weakened by two NLFs with a total transmittance of 0.032. In this case, the amplified SLD signal exceeded the superluminescence signal by a factor of 3. Hence, we find that $K = 93$.

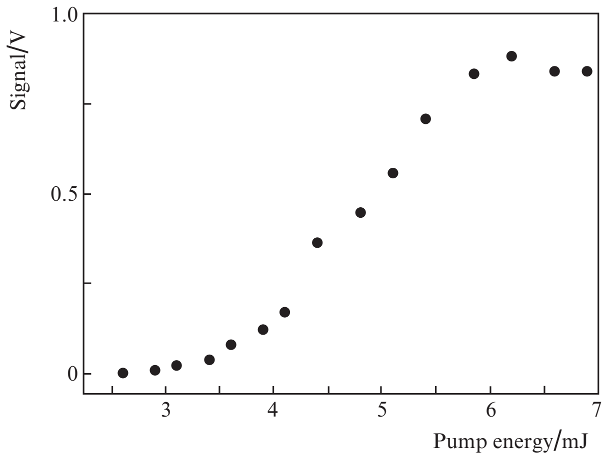

Figure 2. Dependence of the photodiode signal, proportional to the amplified SLD radiation energy, on the BBO-2 pump energy at a diode radiation power before the BBO-1 crystal equal to 15.2 mW.

With an increase in pump energy, the amplified SLD signal tended to a constant value. At the same time, the weaker PSL signal did not level off yet. Therefore, the K_{sat} value measured under these conditions should be less than K. Figure 3 shows spatial intensity distributions of the amplified SLD and PSL beams at a BBO-2 pump energy of 6.3 mJ. For better visualisation, the intensity profiles were equalised (to this end, the PSL signal was multiplied by 17). With allowance for the transmittance (0.47) of the NLF attenuating the amplified SLD signal, $K_{sat} = 36$. The vertically elongated PSL radiation forms a part of the PSL ring. This ring can easily be observed at the output of a single parametric crystal [8].

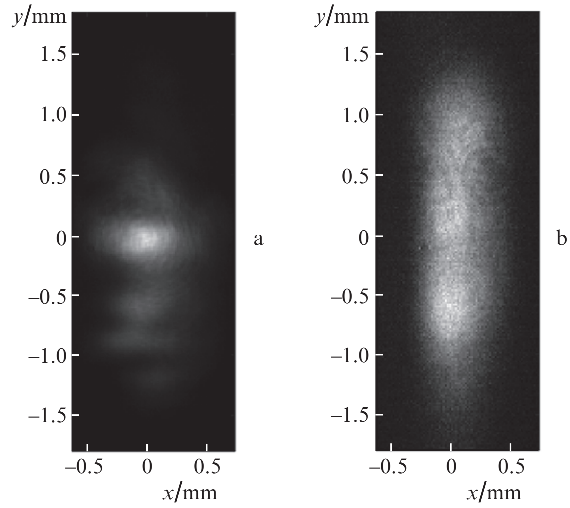

Figure 3. Spatial intensity distributions for (a) amplified SLD radiation and (b) parametric superluminescence (for convenience of comparison, the signal amplitude in the case of parametric superluminescence is multiplied by 17). The BBO-1 pump energy is 6.3 mJ, and the diode radiation power before the BBO-1 crystal is 15.2 mW.

The measured spectra of the initial and parametrically amplified SLD radiation are presented in Fig. 4. The measurements were performed using an MDR-6 monochromator in the single-pass mode and an SDU-415 array detector. The amplified radiation spectrum was measured under the same conditions as the spatial intensity distributions (Fig. 3). One can see in Fig. 4 that, at an SLD spectral width of 17.2 nm (275 cm^{-1}), the amplified signal spectrum narrows as a result of parametric amplification to 12.7 nm (203 cm^{-1}). The influence of this narrowing can be reduced by applying somewhat shorter BBO crystals, which would cause broadening of the parametric-gain spectrum. The width of the amplified SLD picosecond pulses was measured by an Agat-SF streak camera (resolution 2 ps) to be 21 ps.

The power density of the SLD seed radiation must be compared with the quantum noise power density. According to an estimate, at an SLD radiation power of 15.2 mW before the BBO-1 crystal and a diode radiation spot on the BBO-1 crystal surface with a diameter of 0.2 cm, the seed power density is 380 mW cm^{-2}. The spectral density of quantum noise power, determined from the formulas reported in [20], turned out to be 5800 mW cm^{-2} cm^{-1} sr at a wavelength of 790 nm. With allowance for the parametric-gain bandwidth, equal to approximately 200 cm^{-1}, and the solid angle ($\sim 0.6 \times 10^{-6}$ sr) in which the pump beam spot on the BBO-1 crystal surface

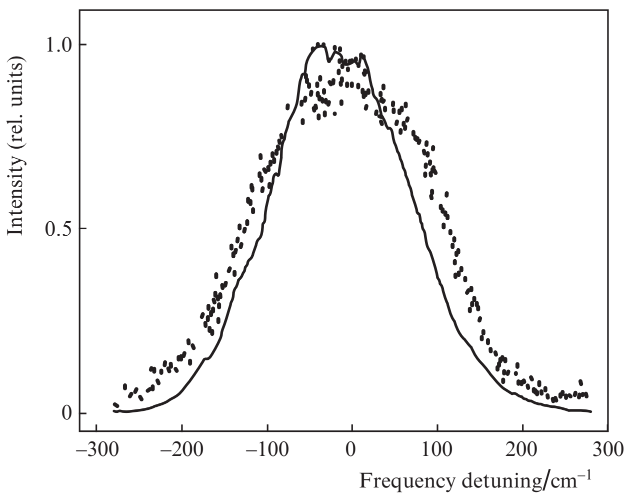

Figure 4. Spectra of (dots) SLD radiation and (solid line) parametrically amplified diode radiation, averaged over 30 laser shots. The diode radiation power before the BBO-1 crystal is 15.2 mW.

can be seen from the centre of the amplified SLD radiation spot (see Fig. 3), the quantum noise power density is 0.7 mW cm^{-2}. Thus, the ratio of the power densities of the seed radiation and quantum noise is $K = 540$. The experiment yielded the value $K = 93$. A possible reason for the discrepancy is that a certain part of the SLD radiation power that is present in the diffraction structure falls in the aperture of the FieldMaster meter power (8 mm) but is beyond the central spot (2 mm in diameter) of this structure and, therefore, does not contribute to the amplified SLD beam.

Thus, we showed that cw superluminescent diodes with a radiation spectral width of about 300 cm^{-1} and a power at a level of several tens of milliwatts can successfully be applied as seed radiation sources in two-cascade parametric amplifiers with picosecond pumping in order to obtain broadband picosecond pulses. At a total BBO pump energy of 7.2 mJ, the energy of broadband picosecond pulses amounted to 0.6 mJ.

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