Broadly tunable picosecond pulses generated in a β-BaB_2O_4 optical parametric amplifier pumped by 0.532 μm pulses

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We report the generation of a highly intense, tunable source from 0.67 μm to 2.58 μm by optical parametric generation and amplification in β-barium borate (BBO) pumped by picosecond pulses at 0.532 μm. The maximum conversion efficiency from the pump to the signal is 13%. The output energy is in the range a few hundred μJ.

Optical parametric generation and amplification has been one of the most powerful methods to produce widely tunable optical sources for many years.[1] Following the recent development of a new nonlinear optical crystal, barium beta-borate or β-barium borate (BBO),[2,3] a number of groups have reported the generation of widely tunable sources from near ultraviolet to near infrared using optical parametric oscillation (OPO) and amplification (OPA) processes.[4–10] The broad tuning range of BBO is supported by its broad spectral transparency region and the large phase matching range. In addition, the unusually high optical damage threshold of BBO, close to 15 GW/cm^2 for a 100 ps pulse at 1.064 μm, has made it possible to produce ultrashort, widely tunable coherent radiation with extremely high intensities (e.g., a few hundred μJ with a pulse duration of 15 ps) when pumped by intense picosecond laser pulses. Indeed, Huang[9] and Susowski[10] have obtained high energy (>200 μJ), tunable ($0.4 \rightarrow 2$ μm) picosecond pulses in BBO optical parametric amplifiers (OPAs) pumped by 15 ps, 0.355 μm laser pulses. The latter are derived from tripling the output of an active-passively mode-lock/Q-switched Nd:YAG laser at 1.064 μm.

In this letter, we show experimentally that an efficient generation of a tunable source in a BBO optical parametric amplifier can also be achieved when pumped with 0.532 μm picosecond pulses. Our preliminary measurement yields a tunable output covering a wide spectral range from 0.67 μm to 2.58 μm with single-pulse energies in the range of 100–550 μJ in the entire tuning range. The maximum pump-to-signal energy conversion efficiency is close to 13%. We have extended the spectral tuning range from previously 2 μm to presently 2.58 μm (Ref. 9) without sacrificing the energy conversion efficiency. It appears that when the spectral range from 0.67 μm to 2.58 μm is adequate, using the second harmonics of the 1.064 μm pulses from an active-passive mode-locked/Q-switched Nd:YAG laser not only simplifies the OPA setup, but also improves the overall energy conversion efficiency by eliminating the process of generating 0.355 μm pulses. The latter reduces the energy conversion efficiency by both the nonlinear optical process itself and by worsening the OPA pump beam mode quality.

Our optical parametric generation setup is shown in Fig. 1. The pump pulses at 0.532 μm are obtained by frequency-doubling the output of an active-passive mode-locked/Q-switched Nd:YAG laser which produces 35 ps, 1.064 μm pulses. After the harmonic generator KDP, we propagate the 0.532 μm pulses by a distance of 100 cm. The propagation leads to an almost Gaussian-like mode structure with a beam diameter of 0.3 cm. The single-pulse energy before a 40% to 60% beam splitter is 8.0 mJ. The two BBO crystals for optical parametric generation (OPG) and amplification (OPA) have the same dimensions: 6 mm$\times$6 mm$\times$9 mm. They are cut at $\theta_0=27°$ for type-I phase matching. The crystals are placed in dry cells. The fused-quartz windows on the dry cells and the BBO crystals have no anti-reflection (AR) coating. 40% of the pump energy is diverted to the first BBO crystal to initiate the optical parametric generation. The energy density is about 2.5 GW/cm^2. The rest (60%) of the pump energy with an intensity 3.8 GW/cm^2 is sent to the second BBO crystal for optical parametric amplification.

The working principle of the setup as shown in Fig. 1 is the following: The superfluorescence output after one pass through the first BBO is first separated by a dichroic mirror (DM) from the residual 0.532 μm pulse. It is then sent back and amplified in the first BBO by the reflected, properly delayed, residual 0.532 μm pulse. The amplified

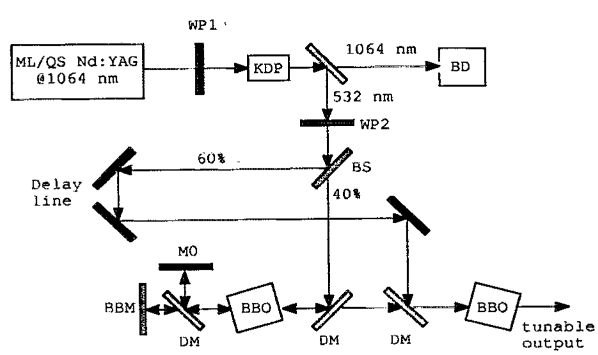

FIG. 1. Experimental arrangement of a barium beta-borate (BBO) optical parametric generator (OPG) and amplifier (OPA) pumped by 0.532 μm, picosecond pulses. WP1 and WP2 are $\lambda/2$ plates at 1.064 μm and 0.532 μm, respectively. BD is a beam dump. BS is a 40% to 60% beam splitter. DMs are dichroic mirrors which reflect 0.532 μm and transmit 0.65–1.1 μm. M0 is a 0° reflector. BBM is an aluminum mirror used as a broadband reflector.

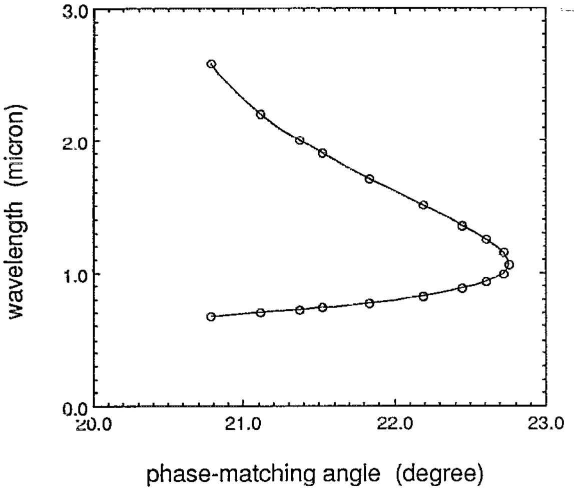

FIG. 2. The measured (open circles) and calculated (solid line) angle-tuning curves of the type-I phase-matched BBO optical parametric generation and amplification setup.

idler beam at wavelengths from 0.67 μm to 1.064 μm is injected into the second BBO crystal for power amplification by the second pump pulse [the rest (60%) of the original pump pulse]. The delay of the second pump pulse is optimized by maximizing the amplified output. The second BBO crystal is positioned at 45 cm away from the first crystal. The solid angle spanned by the pump beam (3.0 mm in diameter) is 3.5×10^{-5} radians. The tuning is achieved by synchronously rotating the two crystals.

The measured tuning curve and the calculated using the indices of refraction for BBO crystal[11] are depicted in Fig. 2. Both the measurement and the calculation cover from 0.67 μm to 2.58 μm. The agreement between the two is fairly good. The output energy as a function of the wavelength is shown in Fig. 3. It drops abruptly at wavelengths beyond 2.58 μm. Taking into account the reflection loss, the overall conversion efficiency in the second BBO crystal from the pump to the sum of the signal and idler output is over 10% in the entire tuning range from 0.67 μm to 2.58 μm. The peak conversion efficiency is about 20%. The maximum pump-to-signal conversion at 800 nm is about 13%. Quantitatively, our result compares well with the result of Huang *et al.*[9] In our case, the effect of a shorter amplification crystal (9 mm instead of 12 mm used in Ref. 9) is compensated by a higher pump intensity (3.8 GW/cm^2 presently, instead of 2.7 GW/cm^2 used in Ref. 9). The pulse-to-pulse energy fluctuation is close to the fluctuation of the pump beam, ±20%. This indicates that we are operating in the near saturation region as discussed by Huang *et al.*[9] In the entire tuning range, the mode structure of the tunable output beam was found similar to that of the pump beam which is close to a Gaussian-like distribution. In Table I, we summarize the parameters of the performance of our OPG/OPA setup. We note that these parameters have been obtained recently by Lin and co-workers in an OPG/OPA using another new nonlinear optical crystal, Lithium triborate (LBO), pumped also by 0.532 μm pulses.[12]

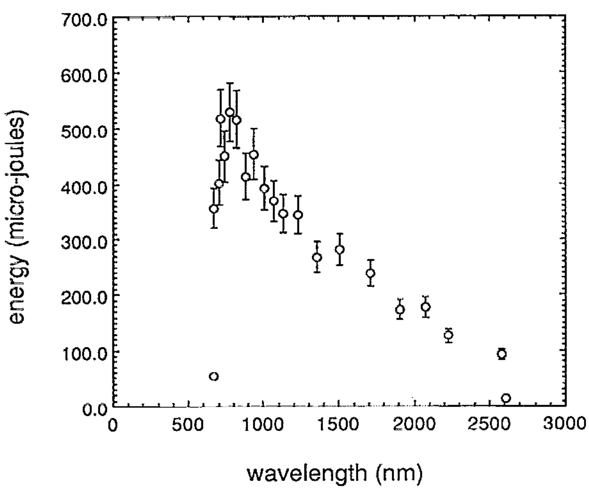

FIG. 3. The output energy of the BBO OPG/OPA setup as a function of the wavelength. The pump pulse energy at 0.532 μm in the second BBO crystal is 4.2 mJ.

TABLE I. Characteristics of the present OPG/OPA pumped by 0.532 μm pulses.

	Nd:YAG	Second harmonics	Tunable output
Wavelength:	1.064 μm	0.532 μm	0.67–2.58 μm
Energy:	15 mJ	8 mJ	100 μJ–550 μJ
Pulse duration:	35 ps	25 ps	18 ps
Spectral width:	2 cm^{-1}	2 cm^{-1}	⩾20 cm^{-1}

Since we had enough pump beam energy (~8 mJ) at 0.532 μm, the diameters of both pump beams are maintained at 3 mm. Consequently, we did not need to use a third BBO crystal to compensate for the walk-off effect.[9]

In the present setup, we did not use any other wavelength selection element to further reduce the output frequency bandwidth. Over a spectral range from 1.3 μm to 2.58 μm, the measured bandwidth of the output is about 20 cm^{-1} (almost independent of the output wavelength) which agrees with the calculation. The bandwidth can be significantly reduced when the back-reflection mirror is replaced by a grating as have been shown by Huang *et al.*[9]

In summary, we have demonstrated that the performance of a tunable source from a 0.532 μm picosecond pulse-pumped BBO OPG/OPA matches well with that of the previously reported OPG/OPA pumped by 0.355 μm pulses.[9,10] When an active-passively mode-locked/*Q*-switched laser operating at 1.064 μm is used to produce the pump pulses, using the second harmonics at 0.532 μm instead of the third harmonics at 0.355 μm can significantly simplify the experimental setup for the same output energy or conversion efficiency over the frequency range from 0.67 μm to 2.58 μm.

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