High-power, high-repetition-rate picosecond optical parametric oscillator tunable in the visible

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We describe an intracavity frequency-doubled high repetition-rate picosecond optical parametric oscillator for the visible based solely on the nonlinear crystal LiB_3O_5 and synchronously pumped by a self-mode-locked Ti:sapphire laser. Under temperature-tuned noncritical type I and type II phase matching, average visible output powers of 320 mW have been generated at an 81-MHz repetition rate. With the available mirror set, continuous tuning from 584 to 771 nm is demonstrated for a range of phase-matching temperatures. Transform-limited pulses with durations of 840–880 fs have been obtained across the visible range for pump pulse durations of 1–1.2 ps. © 1996 Optical Society of America

Recently, Ti:sapphire-pumped optical parametric oscillators (OPO's) have proved to be ideal in meeting the need for ultrafast light sources in new spectral regions. Advances in Ti:sapphire-pumped OPO's have been particularly rapid in the femtosecond domain, in which several devices based on nonlinear materials such as KTP, KTA, RTA, and BBO operating from the visible to the mid infrared have been demonstrated.[1–4] Internal frequency doubling of femtosecond OPO's to provide visible pulses has also been effected by the use of thin crystals of BBO. The first demonstration of such a device was by Ellingson and Tang,[5] who used a critically phase-matched 47-μm-thick BBO crystal inside the ring cavity of an x–z-plane critically phase-matched femtosecond KTP OPO to provide 100-fs pulses tunable over 580–657 nm at 2.1% conversion efficiency. Recently, Reid *et al.*[6] also demonstrated intracavity doubling of a femtosecond RTA OPO with a 200-μm-thick BBO crystal as the doubling medium, producing 60-fs pulses in the range of 620–660 nm, with average powers as high as 170 mW. In the meantime, significant progress has been made in the development of Ti:sapphire-pumped OPO's for the picosecond regime. We recently reported a Ti:sapphire-pumped picosecond OPO based on LIB_3O_5 (LBO) that covers the continuous wavelength range of 1.150–2.260 μm, with the signal branch tunable from 1.150 to 1.560 μm.[7] Frequency doubling of these signal pulses will give one access to the important wavelength range of 575–780 nm, which lies between the fundamental and the second harmonic of the Ti:sapphire laser. In this Letter we report what is, to our knowledge, the first Ti:sapphire-pumped intracavity-frequency-doubled picosecond OPO. This system, which is based entirely on LBO, uses type I and type II temperature-tuned noncritical phase matching (NCPM) in the material to provide efficient frequency doubling of the signal pulses into the visible wavelength region.

For frequency doubling of picosecond OPO's, material requirements are more stringent than for femtosecond oscillators because the lower available peak powers require longer interaction lengths and tightly focused beams for efficient nonlinear conversion. In this context NCPM is the critical material parameter. We selected LBO as the frequency-doubling crystal mainly because of its unique NCPM capability across the entire signal-tuning range of the LBO OPO under temperature tuning. For second-harmonic generation (SHG), LBO can be phase matched in a number of geometries under both type I and type II interaction, with nonvanishing nonlinear coefficients. In particular, NCPM can be accomplished along the principal optic axes of the crystal, which minimizes the undesirable effects of spatial walk-off. The NCPM geometry also possesses large angular acceptance bandwidths, so that SHG conversion efficiency is not compromised by the use of tightly focused beams. The temperature-tuning capability of LBO is also highly advantageous in this case, as it avoids the need for angle tuning, which can result in reductions in SHG efficiency and an increase in OPO threshold as well as requiring realignment of the OPO resonator. In our experiment, we used two noncritically cut LBO crystals to achieve efficient frequency doubling across the available signal-tuning range of 1.16–2.26 μm. The first crystal was cut for type I SHG along the optical x axis ($\phi = 0°$, $\theta = 90°$), and the second was cut along the z axis ($\phi = 0°$, $\theta = 0°$) for type II SHG.

In the context of ultrashort-pulse SHG, a particularly important consideration is the temporal walkaway between the fundamental and the second harmonic, which determines the degree of temporal overlap between the interacting pulses. This can limit the useful length of the nonlinear crystal over which efficient interaction can occur. We have calculated the temporal walkaway between the fundamental and the second harmonic for type I (II) SHG in the x- (z-) cut LBO to be limited to only approximately 20–40 (10–15) fs/mm across the signal-tuning range. These values imply that with fundamental pulses of 1-ps duration, frequency-doubling crystals of up to 50 (20) mm in length can be used without appreciable loss in conversion efficiency or significant pulse broadening. Therefore the temporal walkaway in LBO is not a limiting factor in the attainment of sufficiently high conversion from infrared to visible pulses. These

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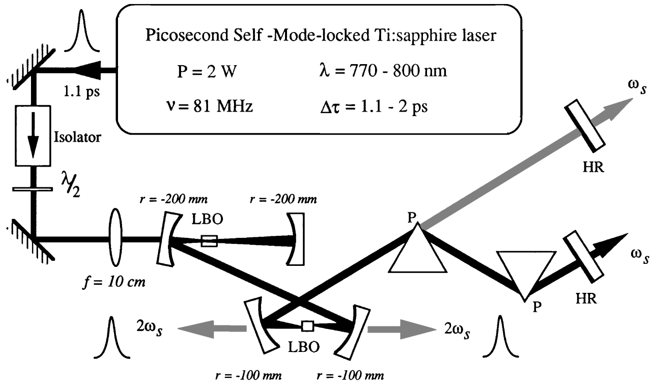

Fig. 1. Schematic of the frequency-doubled picosecond Ti:sapphire-pumped LBO OPO. P, prism; HR, high-reflector.

considerations indicate that LBO is a highly attractive crystal for SHG of ultrashort pulses.

The pump source for the OPO was a commercial self-mode-locked picosecond Ti:sapphire laser. It delivered a maximum average output of 2 W. The duration of the pump pulses was typically 1.1–2 ps, and the pulse-repetition rate was 81 MHz. The laser could be tuned from 770 to 910 nm. The intracavity frequency doubling is performed in two 16-mm-long LBO crystals located at the second intracavity focus of a standing-wave five-mirror resonator as shown in Fig. 1. The OPO cavity comprised a plane mirror, two $r = -200$ mm curved mirrors that formed the primary focus in the OPO crystal, and two $r = -100$ mm mirrors that formed the secondary focus in the doubling crystal. The 30-mm-long LBO OPO crystal was cut for noncritical propagation along the x axis $(\phi = 10^0, \theta = 90°)$. The frequency doubling was performed with a combination of type I and type II phase matching with temperature tuning. Because of the limitations imposed by the design of the oven, continuous coverage in the visible necessitated the use of two crystals with type I and type II phase matching to maintain the SHG process above room temperature. To achieve the demonstrated visible range, we used two sets of OPO mirrors with highly reflecting ($R > 99.7\%$) coatings centered at 1180 and 1400 nm.

In Fig. 2 the experimental tuning range of the frequency-doubled LBO OPO is shown as a function of phase-matching temperature. The SHG output was tuned from 584 to 771 nm, for Ti:sapphire pump wavelengths covering 770–800 nm and OPO crystal temperature from 110 to 230 °C. The corresponding SHG phase-matching temperatures were in the range 20–120 °C. The solid curves are the predicted tuning range derived from the Sellmeier equations of Ref. 8 and the temperature dependence of the refractive indices given in Ref. 9. The operation of the frequency-doubled OPO was very stable across the entire tuning range, with an output intensity fluctuation of only 3% without active stabilization. This was attributed to the temperature stability of the oven (better than 0.1 °C) and the large temperature acceptance bandwidth of LBO, which, for the 16-mm crystal length, was 6–8 °C (FWHM) for type I and 7–12 °C for type II phase matching across the doubling range.

The variation in the SHG output power across the visible range of the oscillator is shown in Fig. 3. The data were obtained for 2 W of pumping at the input to the OPO crystal, with a cavity configured with all highly reflecting mirrors at the signal wavelength. This configuration corresponded to the maximum extraction of visible output and a minimum pump power threshold of 700 mW. It can be seen that as much as 320 mW of output power was extracted in the second harmonic, with the power remaining greater than 150 mW almost over the entire visible tuning range. Of the total visible power, ~50% was contained equally between the two main beams, with another 35% measured in smaller outputs through the other high-reflector OPO mirrors. The remaining 15% was lost at the surfaces of the SHG crystal. The total conversion efficiency from the pump to the second harmonic was 7.5–16%. The single-pass conversion efficiency was 3.5%.

A typical intensity and interferometric autocorrelation and the corresponding spectrum of the frequency-

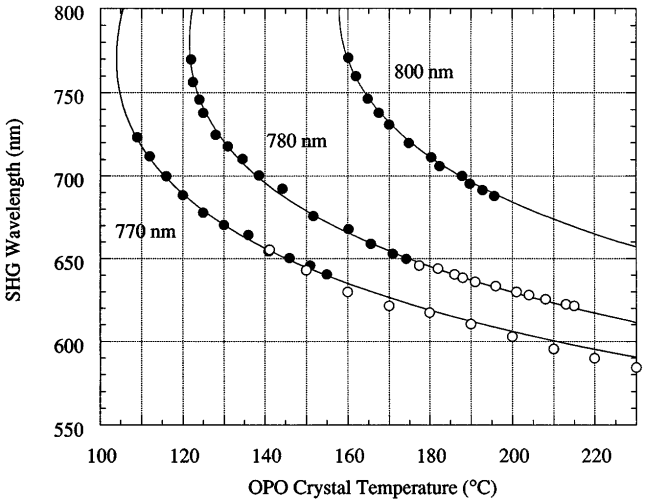

Fig. 2. Visible range of the frequency-doubled LBO OPO. Filled circles, 1.4-μm mirror set; open circles; 1.18-μm mirror set.

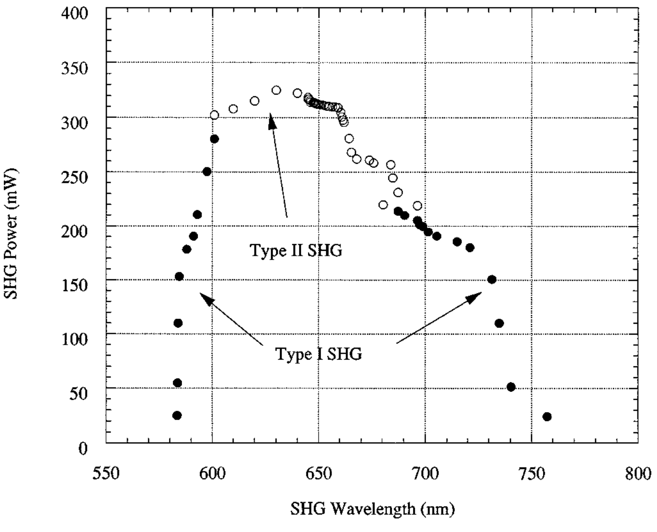

Fig. 3. Variation of frequency-doubled signal power as a function of wavelength for a pump power of 2 W.

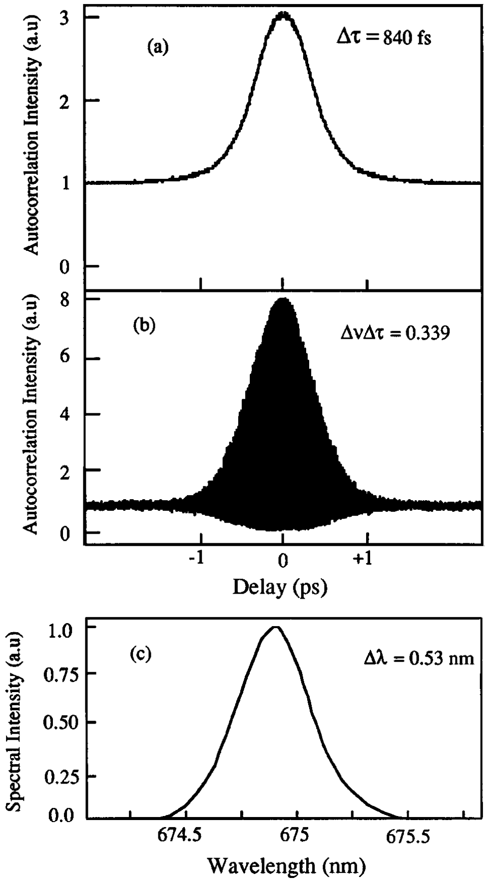

Fig. 4. (a) Intensity, (b) interferometric autocorrelation, and (c) spectrum of frequency-doubled signal pulses at 675 nm. The pulse duration is 840 fs, with a corresponding time–bandwidth product 0.339. The pump wavelength is 780 nm.

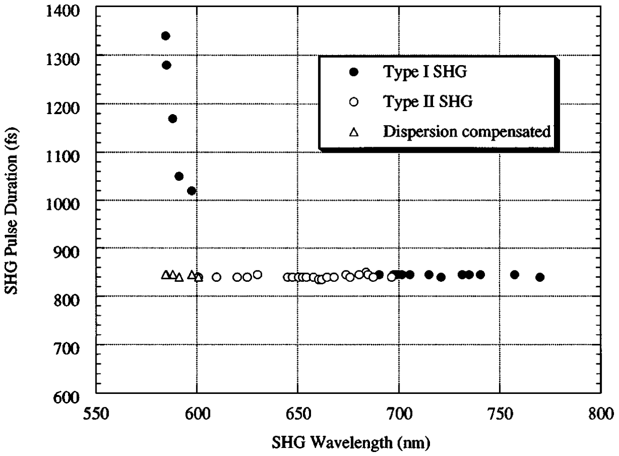

Fig. 5. Variation in the visible pulse durations across the tuning range of the frequency-doubled LBO OPO for a pump power of 2 W.

doubled signal pulses at a wavelength of 675 nm are shown in Fig. 4. The pulse duration is 840 fs for a pump pulse of 1.1 ps. The shape of the interferometric autocorrelation is indicative of chirp-free pulses. The spectrum has a smooth profile with a spectral width of 0.53 nm and a time–bandwidth product of 0.339. These pulses are therefore essentially transform limited.

The intracavity-doubled OPO was operated with and without a dispersion-compensating prism sequence. In the negative group-velocity dispersion regime, the visible pulses are chirp free and transform limited across the entire range of 600–771 nm without the need for dispersion compensation. In the positive group-velocity dispersion regime, on the other hand, the doubled signal pulses become increasingly chirped, as was the case with the OPO itself,[7] with pulse durations increasing to 1.4 ps at 584 nm, as shown in Fig. 5. Intracavity dispersion compensation was therefore necessary for operation below signal wavelengths of 1.2 μm, corresponding to the positive group-velocity dispersion regime in LBO.[7] This was achieved by the insertion of a pair of SF 14 glass prisms (apex separation 40 cm) into the OPO cavity, as in Fig. 1. This resulted in the generation of transform-limited second-harmonic pulses of 840–880-fs duration across the entire tuning range of 584–771 nm, as shown in Fig. 5. The SHG pulse duration is determined mainly by the nonlinear pulse shortening, because of the small temporal walk-off in LBO. Because the nonlinear gain remains constant across the tuning-range, there is little change in the SHG pulse duration with wavelength.

In conclusion, we have demonstrated a new source of tunable high-repetition-rate picosecond pulses for the visible based on an internally doubled, Ti:sapphire-pumped OPO that uses temperature-tuned LBO as both the OPO and the SHG crystal. We have obtained oscillation for an input pump power of 700 mW and have generated total output powers in excess of 320 mW, with conversion efficiencies of as much as 16%. The system is continuously tunable from 584 to 771 nm and can provide transform-limited visible pulses with durations of 840–880 fs across the available range. The combination of the Ti:sapphire tuning range (770–910 nm), its second harmonic (385–455 nm), the frequency-doubled OPO (585–771 nm), and the output of the OPO itself (1.150–2.260 μm) provides an almost continuous tuning capability from 385 nm to 2.260 μm. The use of a better mirror set for the Ti:sapphire laser will allow the remaining gaps to be filled.

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