SYNCHRONOUSLY PUMPED OPTICAL PARAMETRIC OSCILLATION IN BETA-BARIUM BORATE

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Optical parametric oscillation in beta-barium borate has been demonstrated using synchronous pumping by the frequency doubled output train from an actively mode-locked and Q-switched Nd:YAG laser. The parametric oscillator converts up to ~30% of the pump train to produce broadly tunable pulses (0.68 to 2.4 μm) of ~75 ps duration, with peak idler powers of up to ~1.6 MW. The tuning range has been extended up to 0.53 μm by frequency doubling the idler output with up to ~3% efficiency.

1. Introduction

Optical parametric generators have a particular advantage over other tunable sources in that they offer extremely wide tuning ranges. As a means of producing widely tunable pulses in the picosecond range, the most intensitively developed device has been the superluminescent optical parametric amplifier (OPA) [1,2]. While the OPA has the merit of simplicity, a synchronously pumped optical parametric oscillator (OPO) offers better control over both the spatial coherence and bandwidth of the generated radiation. In addition, the OPO has a lower intensity threshold for operation, and consequently is less prone to optical damage than OPA devices. Despite these potential advantages, the synchronously pumped OPO has remained a relatively unexplored device since its first reported demonstration in 1972 by Burneika et al. [3]. Their device used KDP as the nonlinear medium, but later papers have also reported operation in $LiIO_3$ [4], $LiNbO_3$ [5], α-HiO_3 [6] and in both KDP and $LiNbO_3$ [1].

In this paper we report the first demonstration of a synchronously pumped OPO using the new nonlinear material, β-BaB_2O_4 (BBO) [7,8]. Attractive features of this material include the broad transmission range (200 nm to 3500 nm), its large effective nonlinear coefficient (6 times that of KDP at 1.064 μm), and its high damage threshold (10 $GWcm^{-2}$ for 250 ps pulses at 0.53 μm [9]). Parametric oscillation in BBO has already been demonstrated by Fan et al. [10] using the frequency doubled output from a Q-switched Nd:YAG laser. Their results, and the properties of BBO given above, indicated that a BBO OPO, synchronously pumped by the second harmonic of a mode-locked Nd:YAG laser, would give damage free operation over a wide tuning range in the near infrared. This was confirmed by our experimental results.

2. The pump laser

We pump the OPO with the frequency doubled output of an actively mode-locked and Q-switched Nd:YAG laser (Lumonics AML 2000) with two stages of amplification (fig. 1). To obtain a long train of mode-locked pulses the laser is run under low gain conditions. The reduction in output energy that this would usually cause is avoided by the use of a telescopic resonator [11] to give operation with a large TEM_{00} mode volume in the oscillator rod. The laser is pulsed at a repetition rate of 5 Hz, and the output consists of a train of ~30 mode-locked pulses, separated by ~7.5 ns, in an ~200 ns (intensity fwhm) Q-switched envelope. The duration of the 1.06 μm mode-locked pulses was determined by a background free second harmonic autocorrelation technique to be ~85 ps (intensity fwhm, gaussian pulse shape assumed). However, as this measurement was

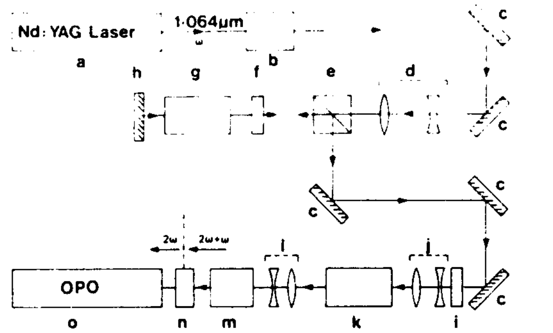

Fig. 1. Schematic layout of OPO and pump laser. (a) Nd:YAG AML oscillator; (b) Pockels cell shutter; (c) HR 1.06 μm mirrors; (d) ×2 telescope; (e) polariser; (f) λ/4 plate; (g) amplifier 1; (h) HR 1.06 μm mirror, (i) λ/2 plate; (j) ×3/2 telescope; (k) amplifier 2; (l) ×½ telescope; (m) KD*P doubling crystal; (n) filter; (o) OPO cavity.

taken over typically 500 laser shots and was averaged over all mode-locked pulses in the train, this result represents a mean pulse width.

To avoid feedback to the oscillator during the prelase period, a Pockels cell shutter is used which opens only to transmit the Q-switched train. This train has an energy of ~1.5 mJ and is double-passed through a 3″×¼″ Nd:YAG amplifier, and then through a 3″×⅜″ rod, to give a final fundamental train energy of ~180 mJ. (The beam is telescoped up before each stage to make full use of the active volume of each amplifier rod).

The beam is then frequency doubled to 532 nm in a 30 mm long type II deuterated KDP crystal with an energy efficiency of ~40%. After filtering to remove the residual fundamental, and after suffering Fresnel losses on entering the OPO cavity, the maximum remaining 532 nm pump energy available at the BBO crystal is ~40 mJ.

3. The optical parametric oscillator

The BBO crystal we use is 7.2 mm long with uncoated faces of area 4.5×4.5 mm^2, and is cut for type I phase-matching. As a precaution against surface damage due to atmospheric water vapour, the crystal is held in a windowless oven at a constant (50±1)°C. Earlier experience with a crystal exposed to the atmosphere at ambient temperature revealed BBO to be prone to hygroscopic damage. The current crystal has been in use for several months and there is no sign of surface degradation. The OPO is angle-tuned, and the oven assembly is mounted on a rotating stage that allows the external angle of the BBO crystal to be set to an accuracy of ~0.02°.

The OPO cavity mirrors have a reflectivity near 100% over the signal wavelength range (~0.7 to 1.0 μm) while having much lower reflectivities (10–20%) over the corresponding idler wavelengths. After one cavity round trip the intensity of the fed back idler is less than ~4% of the signal, so that operation is essentially singly resonant.

A collinear phase-matching scheme was used, in which the visible 532 nm pump beam was used to align the resonator mirrors and therefore also defined the cavity axis.

The OPO cavity design (fig. 2) was subject to three constraints. Firstly, synchronous pumping required the cavity round-trip time of the circulating signal pulse to equal that separating successive mode-locked pump pulses. This meant that the optical length of the OPO cavity had to closely match that of the source laser. Secondly, Poynting vector walk-off and the crystal damage intensity limits the pump spot-size in the crystal to be no smaller than ~0.4 mm ((1/e) E-field radius). Finally, to avoid optical damage to dielectric coatings, the minimum spotsize that could be tolerated at the input mirror was ~1.0 mm. As the confocal parameter for the 532 nm pump beam with a 0.4 mm waist is ~2 m, a telescopic resonator was needed to satisfy the above three conditions. The final resonator design is symmetric with two ×2 intracavity telescopes, each consisting of one +50 cm and one −25 cm lens. None of the lenses were antireflection coated. The values of the focal lengths were chosen so that the cavity would remain stable over the small (~few mm) length variations needed to adjust for synchronism.

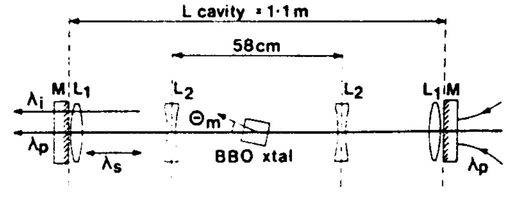

Fig. 2. Schematic of OPO cavity design. L_1 = +50 cm lens. L_2 = −25 cm lens. M = resonator mirror.

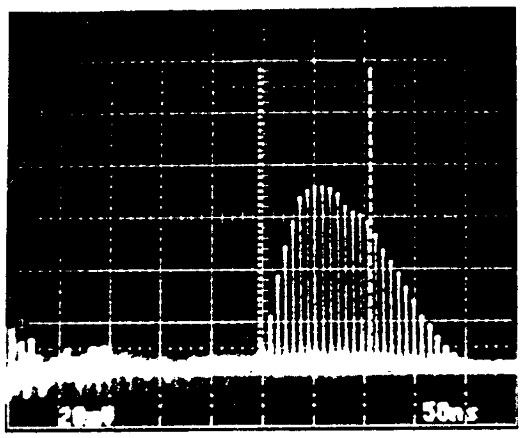

Fig. 3. Photograph of an oscilloscope trace showing a typical idler output pulse train.

3. Performance details

Using a vacuum photodiode with ~1/3 ns rise-time, we observe operation of the OPO by monitoring either the output train directly (fig. 3) or the transmitted depleted pump train (fig. 4).

Oscillation threshold was determined by reducing the pump level until oscillation just occurred and then measuring the energy incident on the crystal. We found this to be ~14 mJ, which corresponds to a peak pump intensity ($2P/\pi W^2$) of ~2.2 GW cm^{-2}. With a maximum pump energy of ~40 mJ, the OPO could be run at up to ~3 times above this threshold intensity. This is still well below the BBO damage limit.

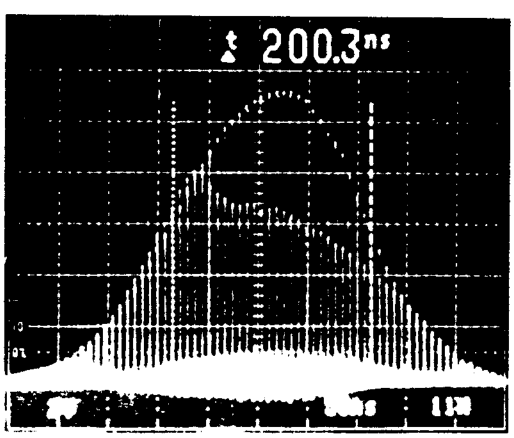

Fig. 4. Double exposure photograph showing traces of undepleted (upper) and depleted pump train envelopes.

As the stability of the OPO output was found to be better at higher pump energies, the device is generally operated close to the upper limit. However, after more than one hundred hours of operation there are still no signs of optical damage.

The total energy conversion efficiency of the OPO to both signal and idler radiation was determined by measuring the difference in pump energy transmitted by the cavity when oscillating, and when misaligned. (The latter was achieved by rotating the crystal to an angle at which phase matching could not occur). Fig. 5 shows energy efficiency as a function of tuning angle. The maximum efficiency of ~30% compares favourably with typical values quoted for parametric oscillators pumped by Q-switched lasers [10]. It should be noted that measuring the difference between undepleted and depleted pulse heights for the largest mode-locked pulse in fig. 4 implies a peak conversion efficiency to both signal and idler of ~40%.

The idler output pulse width, also measured by second harmonic autocorrelation, was found to be ~75 ps. This value remained unchanged across the OPO tuning range. This observed lack of any significant pulse narrowing in the OPO is consistent with the conclusions reached by Becker et al. [12], who show that for a mode-locked OPO operating with significant pump depletion, gain saturation will broaden the parametric pulses to widths comparable to that of the pump. Compared with Weisman and Rice [4], we found the pulse length to be insensitive to small cavity length variations (~10 μm). We are, however, using pulses one order of magnitude longer

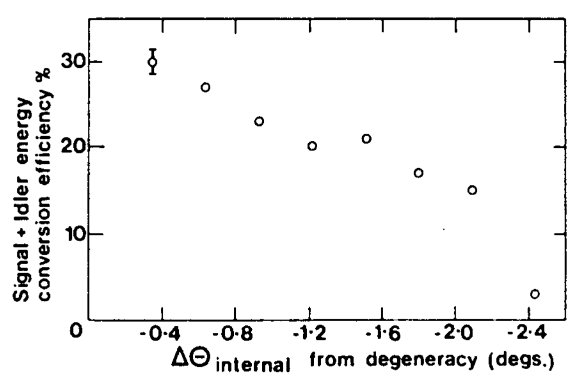

Fig. 5. Energy conversion efficiency of the OPO as a function of crystal angular displacement from degeneracy.

and have a higher gain in our crystal. The maximum energy measured in the idler output train was ~2 mJ, with an energy of ~130 μJ in the largest idler mode-locked pulse. This corresponds to a peak idler power of ~1.6 MW.

Using a scanning photodiode array, the far-field divergence of the signal beam at 680 nm was found to be ~0.2 mrad (half-angle). This is far smaller than values quoted for superluminescent OPA devices (e.g. Seilmeier and Kaiser [2]), and confirms that our OPO output is essentially diffraction limited.

The signal and idler tuning curve (fig. 6) was determined using a 1/3 m monochromator with a Ge detector at the exit slit. The use of this detector limited us to direct measurement of idler wavelengths shorter than ~1.8 μm. Idler wavelengths above this limit were inferred from the corresponding measured signal wavelength. Our tuning range at present is probably limited predominantly by the fall-off in mirror reflectivity below 680 nm, although the corresponding idler wavelength of 2.4 μm lies in the roll-off region of the BBO transmission curve. The calculated and experimental tuning curves are in rough agreement, although some degree of discrepancy is expected as the Sellmeier equations used for the theoretical curves (after Eimerl and Kaato [13]) were only fitted to BBO refractive index data in the range ~400 nm to ~1000 nm.

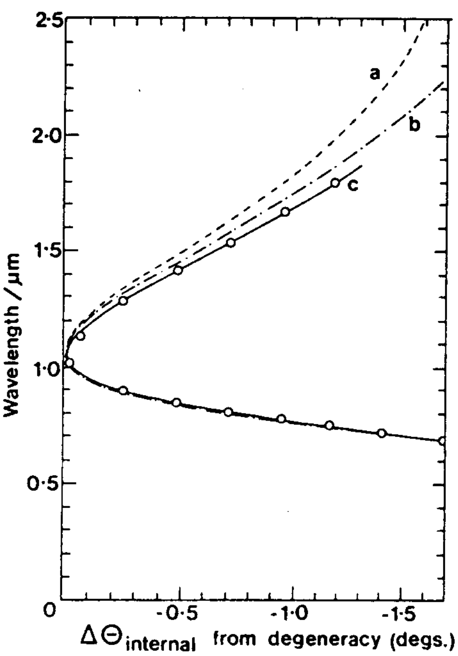

Fig. 6. OPO tuning curve. Signal and idler wavelengths as a function of crystal angular displacement from degeneracy. Calculated curves after (a) Kato and (b) Eimerl.

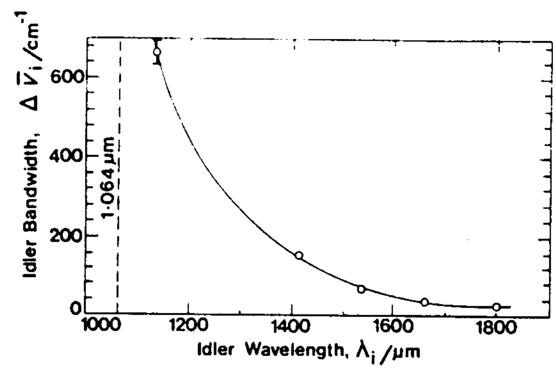

Fig. 7. Idler bandwidth as a function of crystal angular displacement from degeneracy.

Our tuning range has been extended to wavelengths up to ~0.53 μm by second harmonic generation of the idler output. Using a second type I 4.5 mm long BBO crystal gave a maximum doubling efficiency of ~3%.

As expected for a resonator having no bandwidth limiting elements, measurement of the idler bandwidth gave values of several hundred reciprocal centimetres near degeneracy, decreasing monotonically to ~20 cm^{-1} at 1.8 μm (fig. 7).

4. Summary

We have demonstrated the first synchronously pumped optical parametric oscillator to use β-BaB_2O_4. This device provides an intense source of short pulse radiation, ~75 ps, tunable from 0.68 to 2.4 μm. The idler beam divergence, 0.2 mrad is much better than typical values for OPA devices.

Future work will investigate the use of a diffraction grating as a feedback mirror in the cavity as a means of producing bandwidth limited operation.

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