Bandwidth studies of an injection-seeded β-barium borate optical parametric oscillator

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Received October 7, 1994

Spectral and temporal properties of a scanning injection-seeded β-barium borate optical parametric oscillator pumped by the third harmonic of a 10-Hz Nd:YAG laser have been studied. The seed source was a cw diode laser with a wavelength of 830 nm tunable over a range of 50 GHz. We measured the bandwidth of the seeded optical parameter oscillator, using a two-photon resonance in barium and a Fabry–Perot étalon, to be approximately 400 MHz for pump power levels more than two times above threshold. This is ~2 times the Fourier-transform-limited bandwidth. At lower pump powers the bandwidth was smaller.

A solid-state optical parametric oscillator (OPO) is an attractive source of coherent radiation that is tunable over a broad wavelength range. This has been recognized since the first demonstration of the OPO in 1965,[1] but at that time high-quality and efficient nonlinear crystals were not available, hampering widespread use of OPO's in, for example, spectroscopic applications. Recently this situation changed dramatically because of the availability of new materials such as β-barium borate (BBO), lithium triborate, and potassium titanyl phosphate with large nonlinear coefficients and high damage thresholds. Our main interest is the development of nanosecond OPO's pumped by the second and third harmonics of a Nd:YAG laser for spectroscopic applications. A free-running OPO does not provide the required narrow-band radiation; however, the bandwidth can be reduced considerably by use of intracavity elements such as gratings[2] and étalons[3] or by injection seeding with a narrow-band laser on either the signal or the idler wavelength.[4] When the bandwidth of the pump laser is sufficiently small, the energy conservation condition for the OPO ensures that the signal and the idler have comparable bandwidths. Hence, if one of these waves is constrained to be narrow band, then the other will be likewise constrained. When the bandwidth of the seed laser is also small, the bandwidth of the seeded OPO (both signal and idler) may in principle be reduced to the Fourier-transform limit.

In this Letter we report the operation of a BBO OPO seeded with a cw diode laser. The experimental setup is shown in Fig. 1. We use a type I BBO crystal (6 mm × 6 mm × 12 mm) cut at an angle of $\Theta = 30°$. It is pumped by the third harmonic (355 nm) of a Q-switched Nd:YAG laser (Spectra-Physics GCR-3; repetition rate, 10 Hz; injection seeded for operation in a single axial mode; bandwidth, ~90 MHz). The pump beam has a diameter of 7 mm and a pulse duration of 5 ns. The beam diameter of the Nd:YAG laser is reduced by a factor of 2 with a telescope.

The OPO cavity has a three-plane-mirror ring configuration and is 10 cm long, preventing the backreflection of pump light from the mirrors into the pump laser. This setup is also advantageous for injection-seeding experiments. The three identical mirrors have high reflectance on the idler wavelength (90%), whereas the reflectance for the signal wavelength is 10%. The transmission for the pump wavelength is >90%. One of the

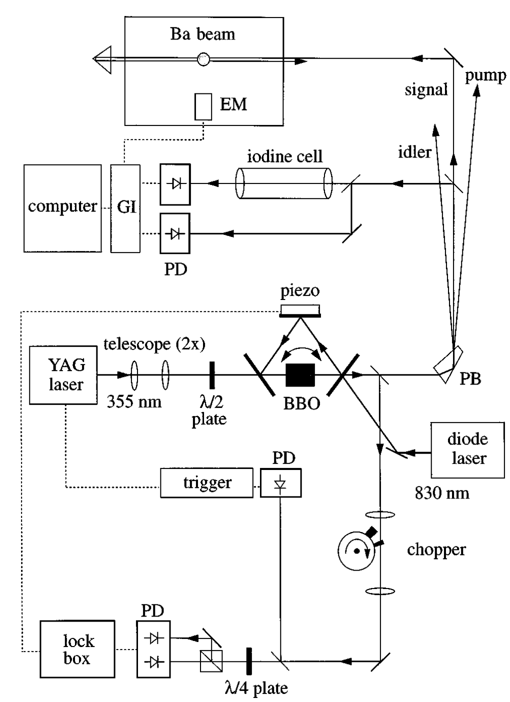

Fig. 1. Schematic of the experimental setup: PD's, photodiodes; PB, Pellin-Broca prism; EM, electromultiplier; GI, gated integrator.

0146-9592/95/040380-03$6.00/0

mirrors is mounted on a piezoelectric transducer for optimization of the length of the cavity. The seed source is a low-power linearly polarized cw diode laser (Sharp type LT015 MF) that generates radiation at an idler wavelength of 830 nm. The bandwidth of the diode laser is ~40 MHz. It is temperature (<1 mK/h) and current (<1 μA/h) stabilized and is continuously tunable over ~50 GHz by variation of the current. The diode-laser beam is directed into the cavity through the outcoupling mirror (see Fig. 1).

To operate a seeded OPO as a scanning device, one must continuously adjust the length of the low-finesse cavity to the wavelength of the diode laser. For this purpose we use the Hänsch–Couillaud stabilization scheme[5] that is frequently used to lock cavities of cw lasers.[6] A polarization-sensitive element, which in our case is the BBO crystal itself, is required inside the cavity. Part of the diode-laser light is transmitted into the cavity and experiences a frequency-dependent phase shift after one round trip. The directly reflected diode light serves as a reference. At resonance the superposition of transmitted and reflected light is linearly polarized; off resonance it will be elliptically polarized. To detect this ellipticity, we transmitted the reflected light through a $\lambda/4$ retarder and a beam splitter. The resulting two signals are detected with photodiodes, and the difference signal is fed, after integration and amplification (in a home-built lockbox), to a piezoelectric transducer on one of the cavity mirrors, thus keeping the cavity on resonance. Rotation of the BBO crystal during a diode laser scan of 50 GHz is not required.

The idler light of the OPO follows the same optical path as the diode laser. The intense pulsed light may easily damage the cw stabilization optics and disrupt the locking of the cavity. To prevent the pulsed light from reaching the photodiodes, we use a mechanical chopper, and behind the chopper a third photodiode is mounted to detect the interception of cw diode-laser light. The chopper has two small vanes and rotates at 10 Hz. The interception of the cw light by the first vane externally triggers the flash lamps of the Nd:YAG laser, resulting in a laser pulse 3 ms later that is intercepted by the second vane. The chopper is placed in the focus of a lens to reduce the interception time and thus prevent disruption of the locking of the cavity.

The measured threshold of this OPO is 15 mJ of pump energy, whereas its slope efficiency is 20–30%, depending on the wavelength. A diode-laser power as low as 1 mW inside the cavity suffices to seed the OPO; however, to keep the seeding optimal at all times, we use the maximum power available (~50 mW measured before coupling into the cavity).

The signal OPO light at 620 nm is employed in an absorption experiment on barium. A beam of metastable atoms[7] is orthogonally intersected by the OPO radiation (see Fig. 1). After excitation the atoms are ionized by the remaining power of the OPO, and photoelectrons are detected with an electron multiplier. We observed the two-photon transition $6s5d\,^3D_2 \rightarrow 5d7d\,^3P_0$ at 16 112.864 cm^{-1}, as shown in Fig. 2(a). Figure 2(b) gives an iodine spectrum used for reference purposes (see Fig. 1). The pump power was 60 mJ, and the total output of the OPO was 10 mJ when seeded; without seeding, the OPO power drops ~30%. The observed linewidth (FWHM) of this transition is limited by the OPO bandwidth and is ~600 MHz. Since a two-photon transition was observed, an OPO bandwidth of ~400 MHz resulted.

We also measured the pulse duration of the OPO signal and observed it to increase with increasing pump power, in agreement with the measurements of Fix *et al.*[4] In these measurements we removed the telescope in the pump beam, and to reduce the size of the pump beam to 5.5 mm we used a pinhole. In this case the threshold increased to 50 mJ. The time measurements were performed with a fast photodiode (rise time, ≤0.5 ns) and a 600-MHz oscilloscope (LeCroy 9360). In the same setup we also measured the pulse shape of the OPO pulse, and in all cases we found that the OPO pulse is delayed in time with respect to the pump pulse. The rise time of the OPO pulse is shorter than the fall time and shorter than the rise time of the (Gaussian) pump pulse. This shorter rise time of the OPO pulse causes the bandwidth of the OPO to exceed the Fourier-transform bandwidth of a Gaussian pulse with the same duration as the OPO pulse. For the seeded OPO this rise time was constant irrespective of pump power, with a resulting bandwidth of 185 MHz. Obviously the directly measured bandwidth exceeds this value.

To investigate the discrepancy between the bandwidth derived from time measurements and from the barium experiment, we used a scanning Fabry–Perot étalon (free spectral range, 2.5 GHz; finesse, 10) to

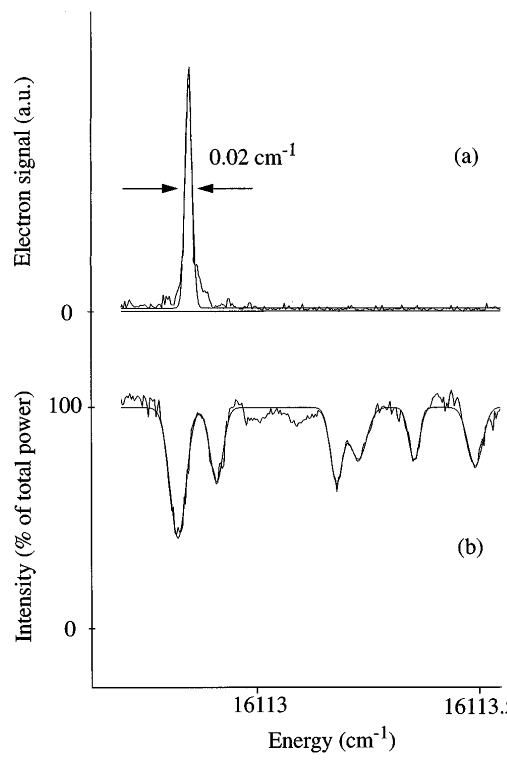

Fig. 2. (a) Two-photon transition in barium at 16 112.8640 cm^{-1}. (b) Reference iodine absorption spectrum. The smooth curve in each is a fit to the data.

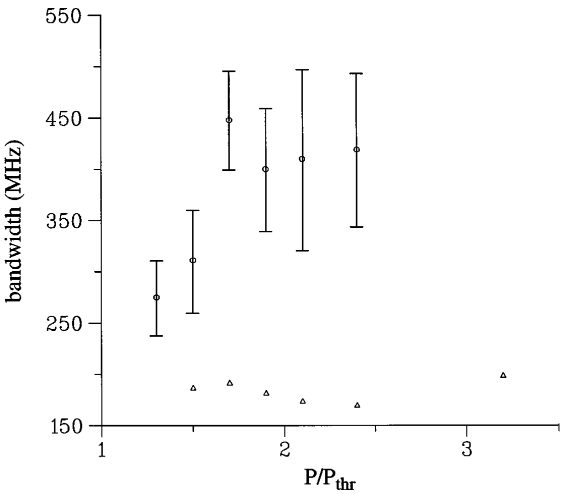

Fig. 3. Linewidth measurements of the idler of the seeded OPO as a function of pump power obtained with the étalon (circles) and deduced from the rise time of the pulse (triangles). P, pump power; P_{thr}, pump power at the threshold of the OPO.

determine directly the bandwidth at the idler wavelength at a fixed frequency. We made the measurements by slowly stepping the étalon spacing and integrating over ten pulses. Under these circumstances it suffices to adjust manually the voltage to the piezoelectric transducer on the cavity mirror to optimize the cavity length. A reduction in diode-laser power by a factor of 2 did not change the bandwidth of the OPO, although it became more difficult to keep the OPO seeded in just one mode. However, changing the pump power did influence the bandwidth. In Fig. 3 the measured bandwidths (FWHM, corrected for the finesse of the étalon) as a function of pump power are shown, along with the values deduced from the time measurement. As the figure shows, the bandwidth of the idler wavelength initially increases with the pump power and flattens off at pump powers greater than two times above threshold at a value of ~410 MHz. The size of the error bars is due mainly to shot-to-shot jitter in the OPO wavelength. The measured signal bandwidth in the scanning experiment is consistent with these results.

In conclusion, we have designed an injection-seeded BBO OPO with a cavity that is actively stabilized on the wavelength of the scanning diode laser. It was demonstrated on a two-photon transition in barium and by an étalon measurement that the seeded OPO may be used as a scanning device with a bandwidth of 400 MHz (both signal and idler waves). We also showed that the bandwidth of the OPO increases with pump power, probably as a result of chirp effects.[8]

We gratefully acknowledge financial support from the Nederlands Centrum voor Laser Research bv. We thank K. S. E. Eikema, R. van Leeuwen, W. Vassen, and W. Ubachs for their help in completing the experiments.

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