High-repetition-rate eyesafe intracavity optical parametric oscillator

Arnaud Dubois, Stéphane Victori, Thierry Lépine, Patrick Georges, Alain Brun

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A. Dubois, S. Victori, T. Lépine, P. Georges, A. Brun

Institut d'Optique Théorique et Appliquée, Centre Universitaire d'Orsay, B.P. 147, 91403 Orsay, France

(Fax: +33-1/6935-8807, E-mail: patrick.georges@iota.u-psud.fr)

Abstract. We report a high-repetition-rate intracavity optical parametric oscillator (IOPO) based on a non-critically phase-matched KTP crystal placed inside the resonator of a Q-switched Nd:YAG laser. The IOPO, operating at 1 kHz, produces average powers up to 0.35 W at 1.57 μm and 0.15 W at 3.29 μm. The dynamics of the IOPO is in good qualitative agreement with numerical simulations.

Optical parametric oscillators (OPOs) are of particular interest in producing tunable coherent radiations, especially in the near infrared where no efficient solid-state lasers are available. In the usual configuration, the OPO and the pump laser are separate oscillators. Another configuration consists in placing the OPO cavity inside the laser cavity itself. The advantage of the intracavity optical parametric oscillator (IOPO) is to benefit from the pump intensity being much larger inside the laser cavity than outside. By using a high-finesse laser cavity, nearly all the photons produced by stimulated emission in the laser medium are available for pumping the IOPO. After the first experimental [1] and theoretical [2, 3] IOPO studies in the early 70s, the subject has been completely neglected during more than twenty years. Recently, new experiments were reported [4–7] and a simple theoretical model was proposed [8]. IOPOs seem to be very promising sources. However, their behavior is complex because IOPOs and their pump lasers are interdependent systems. Much work has still to be carried out to get a better understanding of the IOPO behavior and to be able to construct optimized systems, because in this theoretical model, one can get only the general behavior of the temporal profiles and not the real values of the energies versus time. In this paper, we report an infrared eyesafe IOPO based on the non-critically phase-matched potassium titanyl phosphate (KTP) crystal excited by a cw-lamp-pumped Q-switched Nd:YAG laser operating at 1 kHz. The radiation produced by the IOPO has a wavelength greater than 1.4 μm and as a consequence, the absorption of the vitreous humor is very strong and these radiations cannot reach the retina. The dynamics of the IOPO is studied and compared with numerical simulations based on the theoretical model recently proposed by Debuisschert et al. [8]. To our knowledge, this is the first published comparison between an IOPO theoretical model and experimental data.

In the IOPO model reported in [8], the time evolution of the population inversion density in the laser medium and the intracavity intensities of the laser pump and IOPO signal fields are described by a system of three coupled differential equations involving the population inversion of the laser (N) and the pump and signal powers (P_p and P_s):

$$\begin{cases} \frac{\mathrm{d}P_\mathrm{s}}{\mathrm{d}t} = P_\mathrm{s}\left(P_\mathrm{p}-1\right) + P_\mathrm{p}\Delta P_\mathrm{s} \\ \beta_\mathrm{p}\frac{\mathrm{d}P_\mathrm{p}}{\mathrm{d}t} = P_\mathrm{p}\left(N-1\right) - FP_\mathrm{s}P_\mathrm{p} + N\Delta P_\mathrm{p} \\ \beta_\mathrm{a}\frac{\mathrm{d}N}{\mathrm{d}t} = \sigma - N\left(1+\Gamma P_\mathrm{p}\right) \end{cases} .$$

Other parameters are described with details in [8]. The equation describing the evolution of the population inversion density results from a density matrix treatment. The equations for the pump and signal intensities are obtained from the coupled equations describing the evolution of the fields, which are derived from Helmholtz equations driven by two polarization terms, one resulting from the nonlinear interaction in the crystal, the other one resulting from the coupling of the pump field with the gain medium in the laser. Simplifications are made with the assumptions that the pump and signal cavities both have a high finesse and that the IOPO is singly resonant on the signal. The idler photon lifetime is then small compared to the signal photon lifetime in the IOPO cavity and the evolution equation of the idler field can be suppressed. With this so-called adiabatic elimination, the dynamics of the IOPO is governed only by the signal field.

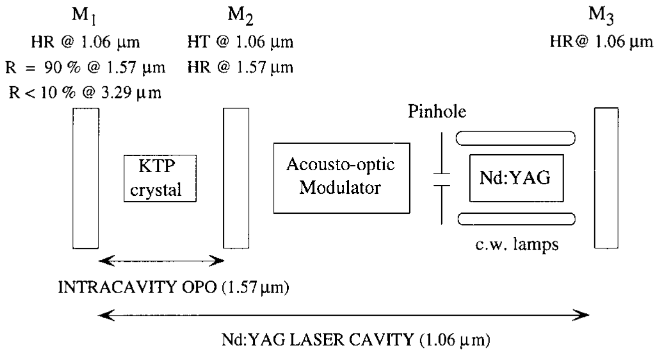

Fig. 1. Schematic of the intracavity optical parametric oscillator (IOPO)

1 Experimental

The experimental setup for our IOPO is shown in Fig. 1. A 20-mm-long KTP crystal is used in non-critical phase-matching configuration ($\theta = 90°$ and $\phi = 0°$) in order to have both a maximum effective nonlinear coefficient and no walk-off between the pump, signal, and idler beams. The result is that our OPO is not tunable, but it is still very interesting because it is very difficult to obtain a radiation at 1.57 µm directly with a laser. The signal and idler wavelengths are 1.57 µm and 3.29 µm, respectively. The Nd:YAG cavity is formed by two plane mirrors (M_1 and M_3) coated for high reflexion at the 1.064-µm laser wavelength. The cavity is stabilized by the thermal lens in the Nd:YAG rod pumped by two cw lamps. A 2-mm-diameter pinhole is inserted inside the cavity to operate the laser in the fundamental transverse mode. An acousto-optic modulator inside the cavity is used to Q-switch the laser and produce the pulses at 1 kHz. The IOPO cavity is formed by two plane mirrors (M_1 and M_2), separated by 30 mm. M_2 is high-reflexion coated for the signal wavelength and high-transmission coated for the pump on both faces. The output coupler for the IOPO (M_1) transmits 10% at the signal wavelength and more than 90% at the idler wavelength. The IOPO is singly resonant on the signal wave to minimize the overheating of the KTP crystal because of its strong absorption at the idler wavelength [9].

2 Results and discussion

The average output power produced by the IOPO is represented in Fig. 2 as a function of the electric current applied on the cw lamps which pump the Nd:YAG rod. We have checked that the optical power produced by the laser outside its cavity with an 80%-reflection ouput coupler was proportional to this electric current. We assumed that the intracavity pump power was also proportional to the electric current with the high-finesse laser cavity. However, the absolute value of this power was not available. The measurement of the residual pump power which went outside the high-finesse laser cavity would have led to a very uncertain estimation of the useful pump power inside the laser cavity because the efficiency of the IOPO is not known precisely. One can see in Fig. 2 that the total average power (signal + idler) produced by the IOPO increases with the pump power. At the maximum, average powers of 0.35 W for the signal and 0.15 W for the idler

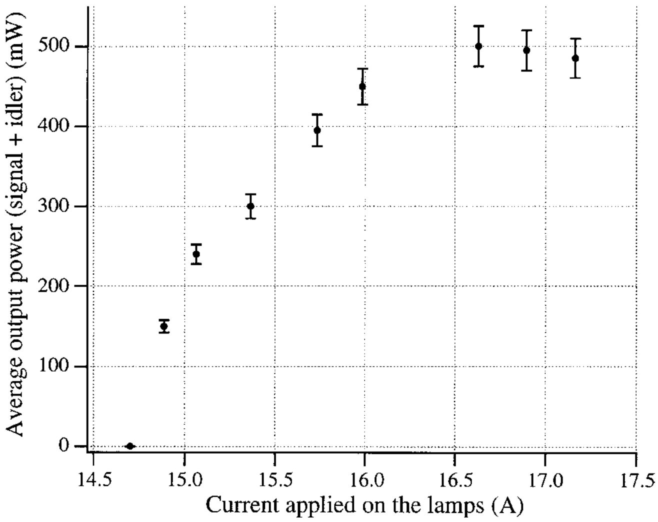

Fig. 2. Average output power produced by the IOPO (signal + idler)

are reached. The efficiency curve presented was obtained by measuring the total output power. But, at the maximum, the powers of the signal and idler were measured separately. For this, we first measured the total output power. Than, we put a thick glass plate (few cm) in the beam in order to block the idler. Taking into account the Fresnel coefficient and the absorption of the glass plate, we deduced the signal power, and then the idler power by subtracting the total power and the signal power. Then, because the parametric conversion efficiency in the non-linear crystal is very sensitive on the pump beam quality [10], the total average power decreases with the pump power due to the degradation of the pump beam quality when the laser gain becomes too high.

Fluence profiles of the signal beam were recorded with a Vidicon camera sensitive between 0.4 µm and 2 µm. The fluence profile of the signal beam was close to a Gaussian distribution (Fig. 3). By measuring fluence profiles in several transverse planes we have estimated the M^2 signal beam quality factor to be around 1.4.

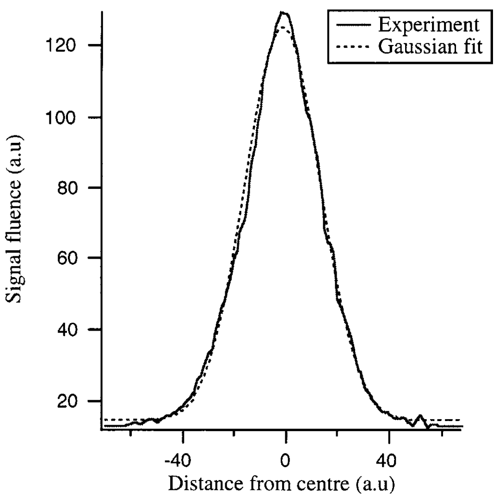

Fig. 3. Fluence profile of the signal beam measured 15 cm behind the output mirror of the IOPO

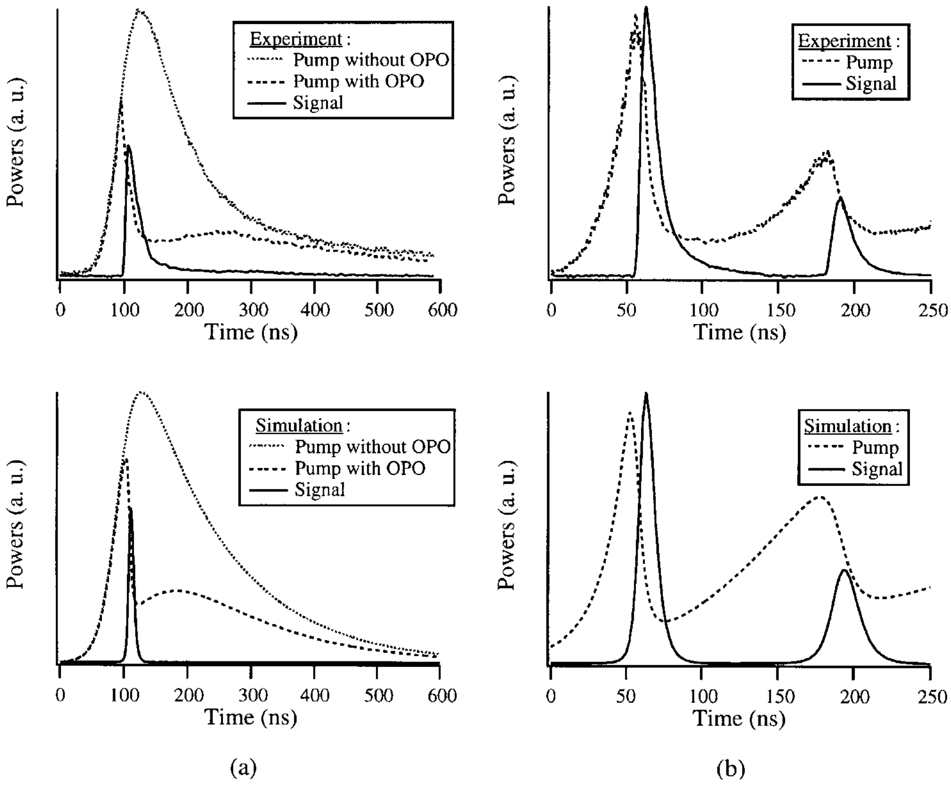

Fig. 4a,b. Experimental and theoretical temporal profiles of the signal and pump pulses for two different pump powers. **a** 300 mW (signal + idler). **b** 450 mW (signal + idler)

The dynamics of the IOPO and the pump laser were studied by recording the full-beam power profiles of the signal and pump pulses with germanium and silicon photodiodes. Examples of these temporal profiles are presented in Fig. 4 for two different pump powers. The dynamics of the IOPO and the laser are interdependent. During the buildup time of the IOPO, the pump power increases although the IOPO creates linear losses for the pump laser because of the linear absorptions of the crystal and the M_2 mirror at the pump laser wavelength (1.06 μm). As the pump power exceeds the IOPO threshold, a fast energy transfer occurs from the pump to the signal at 1.57 μm through the parametric amplification process. A signal pulse is created until the pump power drops under the IOPO threshold. The pump power then increases again and, when the gain in the amplifier laser medium is still high enough, the IOPO threshold is reached again and a second signal pulse is produced. We have observed up to four signal pulses produced during a single pump pulse. With a pump pulse duration of 150 ns, each signal pulse duration varied from 20 ns to 40 ns, increasing with the pump power. In the case of multiple signal pulse generation, the signal pulse duration increased progressively because of a decreasing rate of pump growth for each successive relaxation oscillation. The experimental profiles were well described by the numerical simulations (Fig. 4). The model was successful in predicting the production of several signal pulses when the laser power was increased.

3 Conclusion

We have demonstrated a high-repetition-rate intracavity optical parametric oscillator in the near IR. The dynamics of the IOPO was in good qualitative agreement with numerical simulations. We plan in the future to build an optimized IOPO based on a diode-pumped Nd:YVO_4 laser, which would make possible a compact all-solid-state highly efficient near-IR source.

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