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# 3 W, 300 $\mu$ J, 25ns pulsed 473nm blue laser based on actively Q-switched Nd:YAG single-crystal fiber oscillator at 946 nm

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We report the realization of a frequency doubled, actively Q-switched and polarized oscillator based on Nd:YAG single crystal fiber. A laser output of 8 W, 10 kHz, 30 ns at 946 nm is reported. The laser is extracavity frequency doubled in a BiBO crystal to obtain 3 W, 300  $\mu$ J of blue laser with a beam quality of  $M^2_y=1.12$  and  $M^2_x=1.38$ . The obtained blue power is stable with a RMS stability less than to 2% in one hour. This is more than two times the previously reported average power and energy at 473 nm.

The realization of high average power, millijoule Q-switched 946 nm laser based on Nd:YAG has several applications in spectroscopy, material processing and LIDAR applications. The second harmonic at 473 nm can be used for underwater communication [1], optical storage or spectroscopy. The fourth harmonic of 946 nm at 236 nm allows the LIDAR detection of dangerous compounds [2].

So far the reported powers and energies at 946 and 473 nm were limited. At 946 nm, energies superior to the millijoule have only been obtained at repetition rates of tens of hertz [3][4]. At tens of kilohertz, energies up to 430  $\mu$ J have been demonstrated [5] [6]. At 473 nm, up to 1.5 W of average power and 150  $\mu$ J have been reported [6].

Indeed the main limitations of those lasers comes from the spectroscopic properties of the Nd:YAG 946 nm quasi-three level laser line. 946 nm laser operation in Nd:YAG suffers from reabsorption losses (0.7% of thermal population in the lower level  $^4I_{9/2}$ ) and low emission cross section that limit its overall efficiency ( $\sigma_{em946}=5 \times 10^{-20}$  cm<sup>2</sup>). It requires crystals with high doping concentration to achieve high power emission, but then suffers from strong thermal lens. On the opposite, a low doping value keep the thermal effects at a manageable level, but reduces the absorption over the crystal length. Single-crystal fiber (SCF) overcomes this problem by using low-doped (0.2 %) and long crystals (50 mm), with an excellent thermal management and pump confinement. They already have demonstrated a significant output power at 946 nm, with more than 30 W of output power, but in CW regime, with a spatially multimode and unpolarised beam [7].

In this paper we propose to use single-crystal fiber technology to realize a high power, high energy, polarized oscillator with good beam quality adapted for efficient nonlinear frequency conversion. We will first study how to

polarize efficiently a Nd:YAG oscillator. Then, we will detail how the laser parameters can be optimized for a Q-switched regime delivering an energy at the millijoule level with a significant average power. Finally, we will study a simple set-up of extracavity second harmonic generation in a BiB<sub>3</sub>O<sub>6</sub> (BiBO) crystal.

The first difficulty arises if the laser needs to be polarized for nonlinear frequency conversion. Nd:YAG, being a naturally non-birefringent material, suffers from strong thermal-stress induced depolarization losses when a polarizing element is inserted inside the cavity, the maximum losses being located in the crystal at 45° of the imposed polarization[8].

In this work we will use a technique proposed by Clarkson & al in 1999 [9] : a quarter-wave plate is inserted between the input mirror and the laser crystal to reduce the depolarization losses.. An intracavity thin film polarizer (TFP) is used as a polarizing element because of its higher extinction ratio compared to the commonly used Brewster-angle glass plate.

The experimental set-up is detailed in figure 1. The pump source is a 120 W, 200  $\mu$ m, NA 0.22 fiber coupled laser diode at 808 nm. It is focused inside the single-crystal fiber (SCF) at a pump spot diameter of 480  $\mu$ m. The laser crystal is a commercial Nd:YAG single-crystal fiber module (Taranis model, Fibercryst). It consists of a 50 mm long, 1 mm diameter, 0.2 % doped Nd:YAG, AR coated for 808 and 946 nm rod embedded in a cooling system, set at 12 °C. The pump absorption efficiency without laser operation was measured to be 96%. Thanks to the pump guiding in crystal fibers, a significant part of the pump power is still present at the bottom end. As demonstrated before [10] we can consider that about 50% of the unabsorbed pump power is located on the output face in a diameter equivalent to the pump spot diameter at the focus. This corresponds to

an intensity of about 1200 W/cm<sup>2</sup>, compared with the transparency intensity of about 500 W/cm<sup>2</sup>. [11]

The laser cavity is designed with two mirrors. The input plan mirror M1 is coated for high reflectivity (HR) at the 946 nm laser line, and high transmission (HT) at 808 nm and 1064 nm. A plano-concave mirror M2 of curvature radius 200 mm closes the cavity: different transmission values are used depending on the measurements. The cavity length is 270 mm, and the laser fundamental mode diameter at maximum pump power is 400  $\mu$ m, taking into account the 40 mm focal length of the thermal lens induced in the single crystal fiber. This thermal lens value was estimated with a theoretical calculation for a pump power of 100 W, and confirmed experimentally by studying the stability of a plano/plano cavity. In order to polarize the laser beam, an intracavity thin-film polarizer (TFP) coated for high reflectivity at 946 nm with an extinction ratio of 200:1 is placed between the SCF output face and M2. A quarter-waveplate (QWP) is inserted between the input mirror M1 and the SCF to compensate for the depolarization losses.

A first set of characterization is realized in continuous wave (CW) regime, where the M2 mirror is now an output coupler with a reflectivity of 98% to serve as a reference output for the determination of the depolarization losses. The measurements of those depolarization losses and the influence of the QWP are presented in Figure 2. Three output beams are simultaneously monitored (see figure 1). P1 gives the depolarization losses, P2 is the reference output and P3 is the 946 nm laser output. Those three measurements are used to calculate the round trip depolarization losses. We can see that until 50 W of pump power, the depolarization losses are reduced from 5 to 2%. Then, without the QWP, the depolarization losses raise to reach a maximum of 20% at 120 W of pump power. With the QWP, the round trip depolarization losses are partially compensated until 120 W of pump power where the QWP effect becomes negligible. This behavior was expected, as the quarter waveplate only compensates the depolarization at low powers [9]. Above 100 W of pump power, the beam quality starts to degrade. Therefore we limit our pump power to a 100 W, where the depolarization losses are 10%.

Coupled optimization of energy and average power in Q-switched require an accurate control of the laser parameters. Here we decided to act on two elements: the output coupling and the repetition rate.

In our experiment, we implement a variable output coupler based on a half-wave plate (HWP) and the TFP to have a complete overview of the laser behavior with an increase of cavity losses. By adjusting the HWP, the output coupling can be varied from 0 to 100%. In Figure 3, the “useful” CW output power (P2+P3, meaning the output on the 2% coupler plus the output from the variable output coupler) is plotted versus the output coupling (value coming from the HWP plus 2%) for 40, 60, 80 and 100 W of pump power. For every pump power value, the optimum output coupling is between 10 and 20 % of transmission. At 100 W, as much as 11.6 W of average power can be extracted for an output

coupling value of 12%. This optimum output coupling is close to the one reported in other papers [3][7].

This CW characterization gives an order of magnitude of what performances will be available in Q-switched operation. The lifetime in Nd:YAG is 230  $\mu$ s : therefore, one can expect the average power to drop in Q-switched operation for repetition rates between 5 and 15 kHz. Since we obtained 11.6 W in CW with an output coupler of 12%, we should be capable of operating the Q-switched laser around 10 kHz and reach an energy in order of the millijoule. However based on the SCF coating damage threshold of 3 J/cm<sup>2</sup> and the estimated beam diameter inside the SCF, we calculate the maximum output pulse energy cannot overcome 300  $\mu$ J with an output coupling value of 12%,.

Here comes the interest of the variable output coupler: it can be used to increase gradually the output coupling, in order to maximize the output energy while keeping a satisfying average output power and an intracavity energy under the components damage threshold. As can be seen on Fig.3, an output power of 10 W in CW can still be extracted with an output coupling of 30%. It means that mJ level pulses can be safely generated by this laser in Q-switched regime with average power in the multiwatt level, assuming that around 10 kHz the average power only drops by a little amount.

To obtain pulsed operation, we used acousto-optical Q-switching for the simplicity, and the large range of repetition rate available. A compact Gooch&Housego acousto-optic modulator (AOM) is placed between the SCF output and the TFP. The AOM is 35 mm long, coated for low reflectivity at 946 nm, and has a diffraction efficiency for a polarized beam of 60%. The cavity length was minimized in order to obtain the shortest possible pulse duration. As M2 mirror, we now use a high-reflectivity mirror for 946 nm instead of the 2% output coupler since the coupling is achieved by the thin film polarizer (output P3 on Fig 1). The output coupling is set to a transmission of 30% for the reasons described above. The passive losses in the laser cavity were about 3% without adding the depolarization losses.

In Q-switched operation we monitored at the same time the average output power, the repetition rate and associated pulse duration. The results are presented in figure 4. The maximum output energy of 1 mJ is obtained for a repetition rate of 7 kHz, with a pulse duration of 23 ns. As the average power starts to decrease severely under 15 kHz, we will operate the laser at 10 kHz, where the average power is 8 W, with a pulse duration of 30 ns (displayed in figure 5). This configuration, while producing a slightly lower energy, provides a better compromise between average power and energy. The beam profile at 946 nm is displayed in figure 6. It has a slightly elliptical Gaussian intensity profile, and we measured its beam quality to be M<sup>2</sup><sub>x</sub>=1.32 and M<sup>2</sup><sub>y</sub>=1.08. We found that the elliptical profile only appears at high pump powers. Therefore, we attributed it to the very strong thermal lens that will make the cavity very sensitive to a slight pump misalignment.

The laser output is stable with a measured fluctuation of 0.4% over one hour, calculated by dividing the standard deviation by the root mean square value (stability plot is displayed in figure 7).

The nonlinear crystal used for the type-I SHG of 946 nm to 473 nm is a 10 mm long BiB<sub>3</sub>O<sub>5</sub> [12] crystal cut at  $\theta=161.6^\circ$  and  $\varphi=90^\circ$ . For these cut angles, BiBO has a nonlinear coefficient  $d_{\text{eff}}=3.34$  pm/V, a walk-off angle of 40 mrad for the fundamental beam, and an acceptance angle of 1.28 mrad.cm. The BiBO crystal is kept inside an oven at a stabilized temperature of 50°C. The second harmonic generation is realized in a single-pass, extracavity set-up. In this experiment we try to preserve the fundamental beam quality as much as possible: we use a loose focusing with a beam diameter of 190  $\mu\text{m}$ , which results in a beam divergence of 1.5 mrad, only slightly higher than the BiBO acceptance angle. The resulting blue laser is filtered from the fundamental with a dichroic mirror. The conversion efficiency is displayed in figure 8: a maximum conversion efficiency of 37.5 % is obtained for an input power of 8 W, which results in an output 473 nm power of 3 W and energy of 300  $\mu\text{J}$ . The dotted line corresponds to the simulation made with the simulation software SNLO. The blue beam profile is displayed in figure 6, and the beam quality is only slightly degraded with a measured beam quality of  $M^2_x=1.38$  and  $M^2_y=1.12$ . The pulse duration is reduced to 25 ns (see figure 5). The blue beam is stable with a calculated RMS stability of 1.8% (displayed in Fig 7). The increased fluctuation of the blue power was expected, as SHG is a nonlinear process and dependent on the square of intensity.

In conclusion, we demonstrated a Q-switched 473 nm laser based on Nd:YAG single-crystal fiber. We first studied the polarization of Nd:YAG in CW regime, and extracted more than 10 W of average power for a polarized beam at 946 nm. Then, we used a variable output coupler to operate the laser in Q-switched mode at an energy level more than two times above the previously reported results. Finally, we realized an extracavity SHG in a BiBO crystal, and obtained an average output power of 3 W at 10 kHz, which is two times the previously reported results in both average power and energy. The pulse duration was 25 ns, and the beam quality was measured to be  $M^2_x=1.38$  and  $M^2_y=1.12$ . Many progress can still be made to increase the oscillator performances. While a straight increase in pump power will cause too severe thermal problems, alternative solutions can be found. In order to lower the thermal lens inside the crystal, pumping directly into the emitting level of Nd:YAG at 885 nm seems a promising solution [13]. The nonlinear frequency conversion could also be improved by using more elaborate set-ups such as double-pass SHG [6] or more efficient nonlinear crystals such as quasi-phase matched crystals [14].

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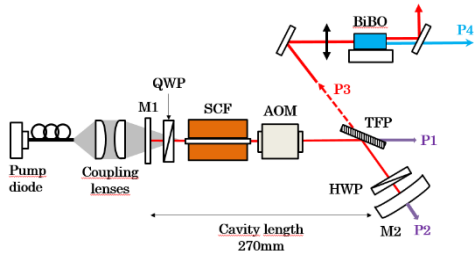


Figure 1: Experimental set-up

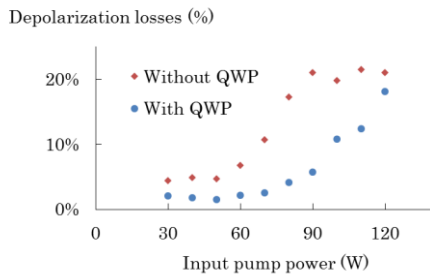


Figure 2: Depolarization losses with/without quarter-wave plate

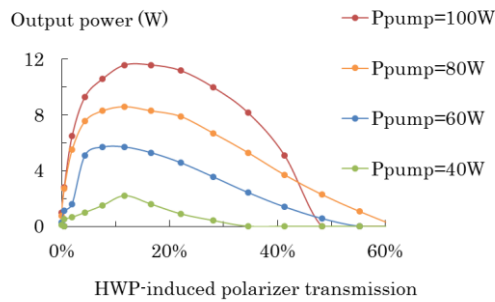


Figure 3: Output CW power at 946 nm in function of the half-wave plate induced polarizer transmission for different pump power values

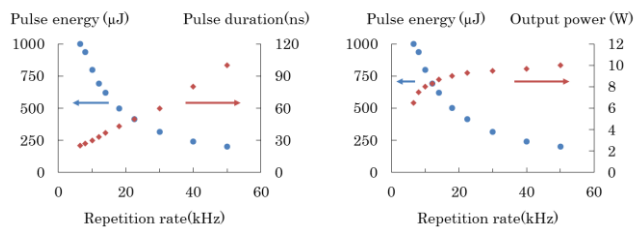


Figure 4: Pulse energy and pulse duration at 946 nm in function of repetition rate (left), and Pulse energy and average power at 946 nm in function of repetition rate

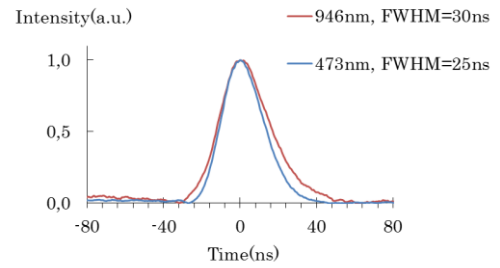


Figure 5: Pulse shape at 946 nm and 473 nm

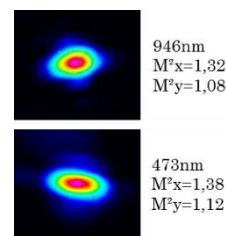


Figure 6: Beam profile and beam quality for 946 nm and 473 nm

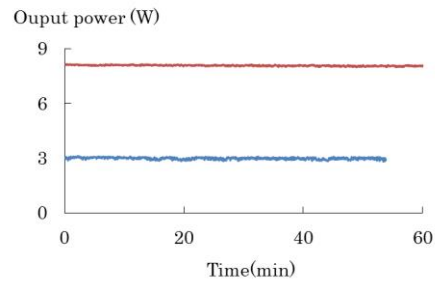


Figure 7: Output power stability for 8 W of 946 nm (red) and 3 W of 473 nm (blue)

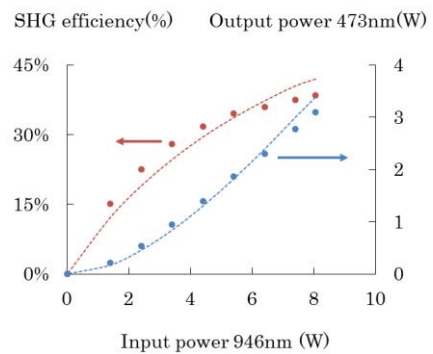


Figure 8: Output 473 nm average power and SHG efficiency

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