

# Low-threshold femtosecond Nd:glass laser

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**Abstract:** Using a 150-mW single-transverse-mode laser diode at 802 nm for pumping an Nd:phosphate laser, we achieved efficient cw operation (40% slope efficiency) with pump threshold as low as 12 mW at optimum coupling, and a maximum output power of 53 mW. Under passive mode-locking operation, we obtained nearly Fourier-limited 270-fs pulses in a prismless dispersion-compensated cavity and 173-fs pulses with a single-prism setup. This compact laser is especially interesting for applications requiring low power levels, such as seeding amplifiers and for biophotonics.

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**OCIS codes:** (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3480) Lasers, diode-pumped.

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## 1. Introduction

Neodymium glass lasers were first investigated as potentially compact, cost-effective femtosecond solid-state laser sources that could be directly diode-pumped [1]. Pulse durations of 60 fs were achieved in a diode-pumped Nd:fluorophosphate glass laser [2], whereas pulses as short as 38 fs were generated by a dual gain-media laser oscillator allowing for a broadened gain bandwidth, pumped by a Ti:sapphire laser [3].

Owing to the poor thermal characteristics of glass laser materials with respect to crystalline hosts, Nd:glass femtosecond lasers were mostly studied with pump power < 2 W and output power in the range 30-200 mW [1-4], even though a successful design solution for output power upscaling to the 1-W level was demonstrated [5].

The most interesting applications of low-power femtosecond oscillators emitting at 1  $\mu\text{m}$  are as seeders of neodymium- or ytterbium-doped amplifiers (bulk or fibre) [6] and their use in various diagnostic techniques, such as nonlinear microscopy [7], THz generation and detection [8] and optical coherent tomography [9].

Such applications usually require a modest average power of few tens milliwatts, hence the pump setup can be conveniently simplified by taking advantage of the excellent beam quality and narrow spectrum of commercially available, low-cost single-transverse-mode laser diodes emitting at  $\approx 800$  nm. The pump power of  $\approx 100$  mW, made available by such devices, is sufficient to be employed in an efficient and extremely simple pump setup, that has been recently exploited in Cr:LiSAF and ytterbium lasers [10-13]. Owing to the excellent mode-locking performance, Nd:glass is a promising candidate for expanding this class of ultralow pump power, compact and low-cost femtosecond lasers.

Among laser glasses, Nd:phosphate is particularly attractive for low-power diode-pumping because of its high emission cross section and low fluorescence quenching. Unfortunately, its fluorescence bandwidth is mostly homogeneously broadened, making generation of pulses shorter than 200 fs more difficult than with other glasses [1].

We report the results, for both cw and mode-locking operation, obtained with an Nd:phosphate laser, pumped by a single high-brightness low-power diode laser.

## 2. Experiments

Initially we designed the cavity setup for the femtosecond laser employing two folding mirrors with 100-mm radius of curvature [14], and pumping the Nd:phosphate with a 1-W diode laser (100 $\times$ 1  $\mu\text{m}^2$  single emitter), which achieved cw threshold level at an absorbed power as low as 50 mW. From these preliminary results one can expect that the replacement of the 100-mm concave mirror with a 50-mm one, and with significantly better pump beam quality, will reduce by a factor of  $\approx 4$  the mode area, and, correspondingly, the absorbed pump power at threshold.

We then switched to a single-mode 150-mW device (Axcel Photonics, Inc.), emitting at 802 nm with a narrow linewidth of  $\approx 0.15$  nm. Given the relatively broad absorption spectrum near 800 nm for the Nd:phosphate this last requirement is not compelling, but it helps minimize the absorption length, which is beneficial for tight focusing.

The laser diode was collimated by an 8-mm focal length aspheric (numerical aperture = 0.5) and focused into the active laser glass with a 50-mm plane-convex singlet lens (Fig. 1). A 100-mm plane-convex lens was contacted with the 50-mm concave mirror (high reflectivity at 1000-1100 nm, high transmissivity at 802 nm) to counterbalance its defocusing effect.

A CCD camera scanning along the pump axis around the focal plane then analyzed the pump beam. According to the manufacturer's specifications, the beam proved to be nearly

diffraction limited (horizontal and vertical directions:  $M_x^2 = 1.0$ ,  $M_y^2 = 1.4$ ) with a markedly elliptical shape (minor-to-major axes ratio  $\approx 1:2$ ). The pump spot radii were measured to be  $w_{px} \times w_{py} = 14 \times 7 \mu\text{m}^2$  in air, while the resonant mode radius was calculated to be  $\approx 15\text{-}20 \mu\text{m}$  within the resonator stability range. This was the simplest pump setup with minimal optical elements we intended to investigate. A more refined setup, which could better mode matching, would have required an anamorphic prism pair before focusing to circularize the pump spot.

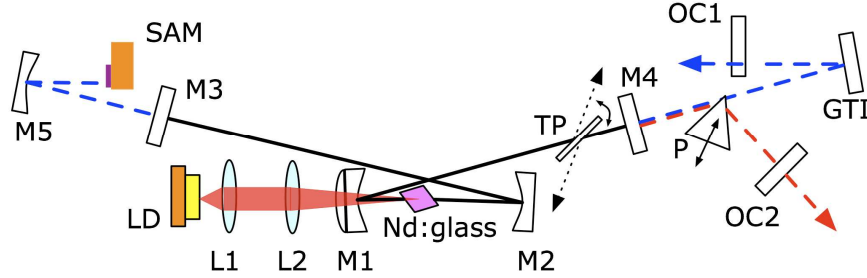


Fig. 1. Resonator layout. LD: pump laser diode; L1: aspheric lens (8-mm focal); L2: spherical singlet lens (50-mm focal); M1: concave mirror, 50-mm curvature, high-reflectivity (HR) at 1000-1100 nm, high-transmissivity (HT) at 800-810 nm; M2, M5: concave mirror, 100-mm curvature, HR at 1000-1100 nm; M3, M4: flat mirrors, HR at 1000-1100 nm; TP: thin plate (fused silica); GTI: negative dispersion mirror; P: SF10 prism; OC1, OC2: output coupler mirrors, 30° wedge, for the dispersion-compensated cavity using GTI or prism, respectively; SAM: saturable absorber mirror.

As active medium, we used an Nd:phosphate N31 glass [14], which was chosen for the shortest absorption length allowed by the high doping concentration of 4%. Other phosphate glasses such as Kigre Q98 and Schott LG760 were also available but with lower doping levels; however they performed comparably well in our tests with the 1-W pump diode.

The 5-mm long Brewster-cut N31 glass slab was put in the pump focusing optics focal plane, kept in place by a mirror holder without any active thermal control. Almost all the diode power was absorbed by the Nd:glass, owing to the high transmission optical coatings of the lenses L1 and L2 and the mirror M1 (147 mW out of 150 mW was measured to reach the laser glass).

The laser resonator was first aligned for cw operation. The coefficient  $\kappa = g_0/P_i$  (being  $g_0$  the single-pass small-signal gain and  $P_i$  the incident pump power) and the intracavity loss  $L$  were deduced by the measured data applying a Findlay-Clay analysis [15] to the four-level laser model. A fused-silica glass plate was used as a variable output coupler with equivalent transmissivity  $T_{oc}(\theta)$  (Fig. 2).

The ideal four-level model considered is [16]:

$$P_o = \eta \frac{\lambda_p}{\lambda_L} \frac{T_{oc}}{T_{oc} + L} (P_i - P_{th}) \quad (1)$$

$$P_{th} = \frac{\lambda_L}{\lambda_p} \frac{(L + T_{oc}) P_{sat}}{\eta} \quad (2)$$

where  $P_o$  is the output power,  $P_{th}$  the threshold pump power,  $P_{sat}$  the saturation power,  $\lambda_p$  and  $\lambda_L$  the pump and laser wavelengths,  $\eta$  the pump efficiency given by the product (quantum efficiency)  $\times$  (mode-matching efficiency)  $\times$  (absorption efficiency) [16].

Notice that the slope efficiency deviates from the dependence expected for an ideal four-level laser at equivalent output couplings  $> 3\text{-}4\%$ . This is likely due to parasitic upconversion

processes, which significantly reduce the effective quantum efficiency [17] and eventually the pump efficiency  $\eta$ . Limiting the numerical fitting to a range of output coupling  $< 4\%$  and to the correspondent plate angles, we found the passive loss  $L \approx 0.5\%$ , coefficient  $\kappa \approx 1.35 \text{ W}^{-1}$ , saturation power  $P_{sat} \approx 347 \text{ mW}$  and pump efficiency  $\eta \approx 59\%$ .

The saturation power, given by the product of saturation intensity [16] and the effective modal area, turned out in fair agreement with the numerically fitted value.

The excellent pump beam quality allowed remarkable improvements in terms of slope efficiency with respect to the multimode 1-W pump diode (40% instead of 32%), as well as very low pump threshold,  $\approx 12 \text{ mW}$  at the optimum coupling ( $T_{oc} = 3\%$ ), which further reduced to only  $\approx 2 \text{ mW}$  using all high-reflectivity mirrors.

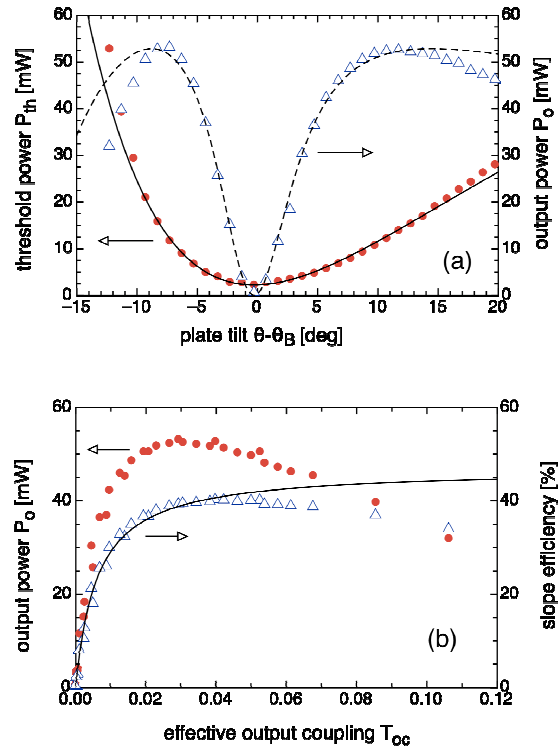


Fig. 2. Performance of Nd:phosphate in cw operation, as a function of the glass plate deviation from Brewster angle ( $\theta - \theta_B$ ) or the corresponding effective output coupling  $T_{oc}(\theta)$ . a) Output power (measured from the glass plate reflections) and threshold pump power; b) slope efficiency and output power. Best-fit curves are also indicated (see the text for a detailed discussion of the method and the results).

The resonator was then modified to accommodate a semiconductor saturable absorber mirror (BATOP, GmbH) with 1.2% reflectivity modulation (0.8% nonsaturable loss). A 100-mm focusing mirror M5 was chosen. A 1.6% output coupler (element OC1 in Fig. 1) was used. Several combinations of negative dispersion Gires-Tournois mirrors (GTIs) were tried to optimize the mode-locking regime. A single GTI with dispersion of  $\approx -400 \text{ fs}^2$  produced the best results, yielding self-starting mode-locking with 18-mW, 270-fs pulses and spectral bandwidth of  $\approx 5.8 \text{ nm}$ , at 250 MHz repetition rate. However, shorter pulses of 230 fs, with the same output power, were produced finely tuning the dispersion with a single prism [4] of SF10 glass in place of the GTI, using the same 1.6% output coupling (OC2). ABCD modeling showed that the crossing point of monochromatic rays (the position X of the virtual prism,

according to the notation used in Ref. 4) was at  $\approx -15$  mm, i.e. preceding the 50-mm concave mirror in the path toward the OC, allowing for a comparably compact cavity design in this case, too. The separation M1-P was 170 mm.

Reducing the output coupling (OC2) to 0.8%, in order to maximize intracavity power and self-phase-modulation, pulses as short as 173 fs were generated, with 8-nm bandwidth and 12-mW output power (Fig. 3). It is worth noticing that in all these configurations a self-starting and robust mode-locking was obtained. The product bandwidth  $\times$  pulsewidth was in the range 0.37 - 0.4, higher than the Fourier limit of 0.32 for *sech*<sup>2</sup> pulse shape. However, given the asymmetric spectral shape (Fig. 3), the autocorrelation inferred by the numerical inverse-Fourier transformation indicates an even smaller deviation ( $\approx 5\%$ ) from the theoretical Fourier limit.

The clear advantage of the single-prism setup was the straightforward optimization of the intracavity dispersion, as well as the smooth tuning in the range 1053 - 1069 nm that for example, is highly beneficial for seeding pulse amplifiers.

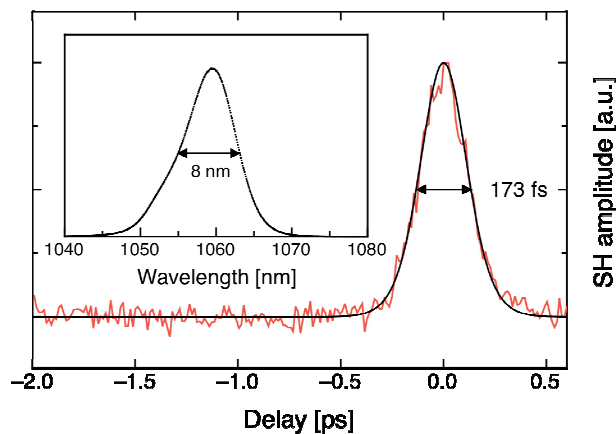


Fig. 3. Non-collinear second-harmonic autocorrelation and spectra of mode-locking pulses, corresponding to GVD compensation with the prism and 0.8% OC2. Autocorrelation best-fit is done assuming *sech*<sup>2</sup> intensity profile.

### 3. Conclusions

We have demonstrated what is, to the best of our knowledge, the first mode-locked femtosecond Nd:glass laser pumped with a simple, cost-effective, single-mode laser diode. A detailed analysis of highly efficient cw operation has been also presented. An actively mode-locked 10-ps Nd:glass laser pumped by a single-mode 30-mW laser diode was reported as early as 1988 [18], with only 9.1% slope efficiency in cw operation and 0.3 mW output power. Clearly, the significant advances reported in this work have been possible owing to the progress in technology (more powerful single-mode laser diodes, high-quality semiconductor saturable absorbers, negative dispersion mirrors) as well as to the development of new design concepts for dispersion-compensated resonators.

Comparing to similar ytterbium lasers pumped by single-mode low-power diodes, Nd:glass has several advantages. The ultralow threshold of the four-level material allows lower pump power. Furthermore, dichroic pump optics for Nd:glass are cheaper and less demanding since the pump and laser wavelengths are well separated.

This makes compact femtosecond Nd:glass oscillators ideal for low-power applications, with pulse duration as short as 173 fs and tunable wavelength over 16 nm. Although ytterbium lasers maintain the advantage of generating shorter pulses, down to 61 fs [13], it is not unlikely

to expect that Nd:silicate and Nd:fluorophosphate, which exhibit an inhomogeneous gain broadening, could approach at least the 100-fs limit with this same laser setup.