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Compact sub-100-fs Nd:silicate laser

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ABSTRACT

We present a compact Nd:silicate laser pumped by a single 1-W high-brightness commercial laser diode that generates pulses as short as 88 fs (nearly Fourier limited) when passively mode-locked with a saturable absorber mirror. We also tested a prismless cavity setup employing a single Gires–Tournois mirror, yielding 100-fs pulses. These setups are significantly simpler and more compact than those reported previously for short pulse Nd:silicate lasers.

1. Introduction

Compact diode-pumped femtosecond lasers at 1 μm are efficient and cost-effective sources for many applications like seeding high power amplifiers [1,2], pumping femtosecond optical parametric oscillators [3], performing spectroscopic investigations [4] and even substitute more complex Ti:Sapphire laser systems for ultrafast applications at 1 μm.

Diode-pumped femtosecond fiber oscillators [5] are very attractive owing to their compactness and robustness, and are indeed becoming increasingly popular as their technology and reliability improves at a fast rate. However, ytterbium and neodymium diode-pumped ultrafast oscillators still offer a valid and cost-effective alternative, with performance comparable with commercial fiber lasers. While ytterbium lasers are very efficient and support pulses with duration $\leqslant$100 fs [6–9], their quasi 3-level nature makes their design more challenging with respect to Nd:glasses, owing to higher threshold and a much smaller quantum defect requiring expensive, sharp dichroic pump mirrors.

Neodymium doped glasses have shown in the last decades their effectiveness as laser media for ultra-short pulse generation at 1 μm [10–12]. Their broad emission bandwidth, typically about 20–30 nm, can sustain sub-100 fs pulses and their broad absorption near 800 nm is attractive for direct diode pumping.

Both phosphate, silicate and fluorophosphate Nd:glass femtosecond lasers have been studied [13,14]. Phosphate glass shows the most favorable optomechanical properties, allowing the best slope efficiencies and the highest output power to date [15]. Unfortunately, its homogenous linewidth broadening limits the possibility to easily obtain wide bandwidth mode-locking pulses. Indeed, gain shaping techniques such as Kerr-shift mode-locking are usually required to obtain sub-200-fs pulse generation [14]. In spite of its poor thermal properties and lower emission cross section, the best results in terms of short pulse duration have been achieved with inhomogenously broadened silicate glasses. It is worth noticing that even if $\approx$30 nm wide fluorescence bandwidth should sustain ultra-short pulses, duration shorter than 100 fs (typically around 60 fs) have been achieved with Nd:silicate only employing high-brightness Ti:Sapphire pump lasers or quite complex pump schemes based on a couple of laser diodes pumping the active medium from two sides [10–12]. Single-emitter pump diodes were usually collimated in the fast-axis direction by a cylindrical microlens, allowing easier tight focussing with two spherical lenses. Unfortunately, putting microlenses in front of the diode emitting facet generally introduces unwanted back reflections that perturb and broaden the emission spectrum or compromise the laser diode reliability.

The availability of increased brightness 1-W single-emitter laser diodes with $M^2 < 10$ along the slow-axis (compared with $M^2 \approx 20$–30 of the previous generation) offers the possibility to improve the effectiveness of pump schemes for diode-pumped femtosecond oscillators and to approach performances previously limited to Ti:Sapphire pumped sources at reduced costs, complexity and dimensions.

In this Letter we present a femtosecond Nd:silicate laser mode-locked by a semiconductor saturable absorber mirror (SAM), pumped by a single, commercially available 1-W laser diode of higher brightness with respect to those previously employed with Nd:glass lasers. Performing a careful optimization of the pump

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setup carried out with a CCD camera monitoring the pump spot during pump setup alignment, and employing a couple of SF10 prisms for group-velocity dispersion (GVD) compensation, we obtained stable mode-locking with nearly Fourier limited 88-fs long pulses with 17 nm wide spectra and an average output power of 35 mW. We also observed unstable spectra as wide as 21 nm, close to the maximum reported in literature for this material.

In an even simpler cavity arrangement employing a single Gires–Tournois mirror for GVD compensation we obtained 100-fs long, self-starting mode-locking pulses with 16 nm wide spectra. This is the best result to our knowledge for a prismless Nd:silicate oscillator [16].

2. Experiments

The laser cavity was the X-folded resonator shown in Fig. 1. The pump diode was a $50 \times 1\ \mu\text{m}^2$ broad area emitter (Frankfurt Laser Company, GmbH), with a maximum output power of 1 W at 808 nm. It was collimated by an 8 mm focal aspheric lens L1, expanded by a factor 10 in the slow-axis direction with a cylindrical lens telescope (C1, C2) and eventually focused in the Nd:silicate sample by a 75 mm focal achromat L2.

The careful control of the pump beam quality and spot size through the optimization of the pump telescope plays an important role in determining the laser gain as well as the femtosecond oscillator performances. This is especially true in the case of low power direct diode pumping of relatively low emission cross section media such as Neodymium doped silicate glasses ($\sigma_{\text{em}} \approx 2.5 \times 10^{-20}\ \text{cm}^2$ for Schott LG680). A CCD camera was employed to characterize the pump beam profile in the focal region of the optical system during the alignment of the pump telescope. In this way we first performed a careful alignment of the lens axes to the pump beam fast-axis, hence we optimized the relative positioning of the cylindrical telescope lenses to minimize astigmatism inside the laser glass plate. We also measured both the beam quality factor M^2 and the pump waist in the horizontal and sagittal planes by scanning the CCD along the beam propagation direction. Beam propagation best fit as well as an image of the pump spot in the focal plane are displayed in Fig. 2. The pump beam waist radii were $\approx 28 \times 10\ \mu\text{m}^2$ along the (horizontal) slow- and fast-axis, respectively, with $M_x^2 \approx 9.5$ and $M_y^2 \approx 2$.

The active medium was a Schott LG680 Nd:silicate 4-mm thick disk, 3% doped. The maximum absorbed pump power was 685 mW corresponding to a fractional absorption of about 88% of the incident pump power.

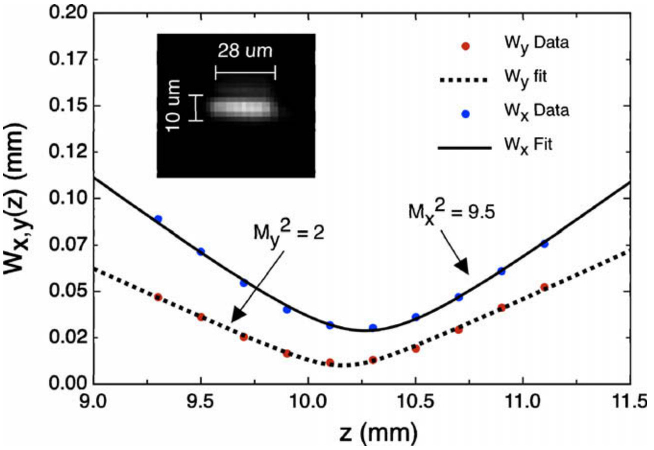

Fig. 2. Pump beam characterization results. In the inset a picture of the pump beam near the waist.

Referring to Fig. 1, the waist radius of the cw X-shaped cavity was 30 μm, as calculated according to ABCD modeling. CW laser operation was obtained in the M3–M2–M1–OC1 resonator. The distances between cavity mirrors were: M1–M2 = 105 mm, M2–M3 = 400 mm, M1–OC1 = 320 mm. Output couplers (OC1) with power transmittivity 0.8%, 2.4% and 5% were used for cw experiments, achieving up to 165 mW with 30% slope efficiency with the 5%-transmittivity OC1, as shown in Fig. 3. The lasing thresholds measured in cw experiments, as low as 62 mW with the 0.8% OC1, were obtained realigning the cavity and opportunely readjusting the separation between M1 and M2 at low pump power levels, suggesting that thermal effects in the silicate glass affect the behaviour of the cavity at maximum pump power. Nevertheless all of our results were obtained without any active cooling of the laser medium.

First experiments on mode-locking regime were performed using the SAM–M4–M2–M1–OC2 ($T = 0.8\%$) resonator, as presented in Fig. 1. The distance between SF10 prisms was fixed at approximately 27 cm in order to ensure enough negative GVD. In order to focus the cavity mode on the saturable absorber, an additional focusing mirror M4 replaced the flat HR-mirror M3. SAMs with 1% and 2% nominal total absorption (BATOP GmbH) were used as the cavity end mirror. The saturable reflectivity modulation was ≈50% of the total absorption, according to the manufacturer specifications. Mirror separations of this modified laser setup

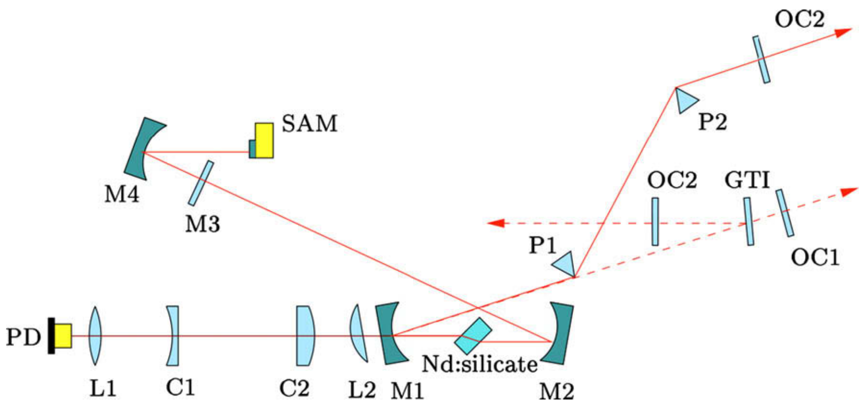

Fig. 1. Resonator layout. PD: pump laser diode; L1: aspheric lens; L2: achromat lens; C1, C2: cylindrical lenses (10× telescope); M1, M2: concave mirrors, 100 mm curvature, high-reflectivity (HR) at 1030–1100 nm, high-transmissivity at 800–810 nm; M3: flat mirror, HR at 1030–1100 nm; M4: concave mirror, HR at 1030–1100 nm with 50 mm or 100 mm radius of curvature; OC1: cw output coupler mirror, 30' wedge.; OC2: $T = 0.8\%$ output coupler, 30' wedge; P1, P2: SF10 prisms; GTI: −375 fs^2 1030–1080 nm per bounce.

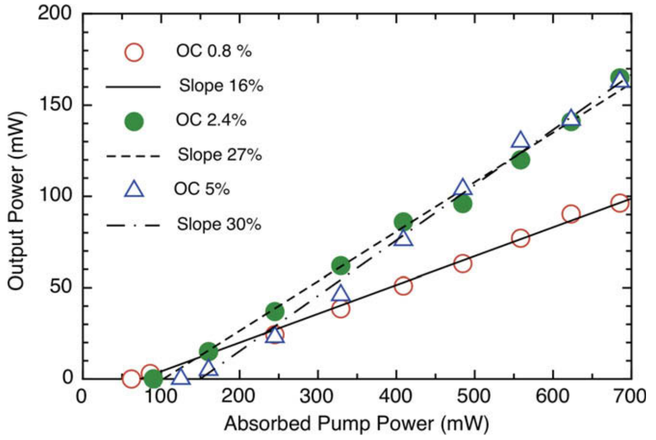

Fig. 3. System performance during cw operation.

were: M1–M2 = 105 mm, M2–M4 = 460 mm, M1–OC2 = 320 mm, while the separation between M4 and SAM ranged from 30 to 70 mm depending on the radius of curvature chosen for M4.

Employing the 1% SAM and tightly focusing the cavity mode on the saturable absorber mirror with the 50 mm radius of curvature M4 mirror, we obtained the wider spectra and shorter pulses. At the maximum available pump power, 17 nm wide spectra with 88-fs long pulses with a time-bandwidth product of ≈0.39 close to the transform-limit for *sech*^{2} shaped soliton pulses, were obtained. The average output power was about 35 mW. The autocorrelation trace and relative spectrum are shown in Fig. 4. In these conditions, mode-locking was not self-starting, but once the femtosecond oscillation had been started up it was stable for minutes. Particular cavity alignment conditions and a proper insertion of the prisms yielded wider spectra (up to 21 nm), but they were not sufficiently stable to allow a pulse duration measurement. The absorbed pump power threshold supporting such wide spectra was very close to the maximum available pump power. Decreasing pump power, mode-locking spectrum progressively narrows and shifts to shorter central wavelength. The mode-locking threshold was set to ≈260 mW of absorbed pump power. As reported in literature[11], spectra wider than about 10 nm were obtained only when the central output wavelength shifted from 1064 nm to higher wavelengths (1070–1075 nm). In our case this process was not induced by some kind of spectral gain filtering, instead occurred spontaneously when the proper GVD and cavity alignment conditions were matched. Employing the 1% SAM a residual cw component was also present in pulses spectra, accounting for the general mode-locking instability. Such a component completely disappeared when we increased the modulation depth with the 2% SAM. In this setup, mode-locking was self-starting and generally stable. We measured 92-fs long pulses with 16 nm wide spectra, with a comparable time-bandwidth product ≈0.39. According to the higher losses related to the increased modulation depth of the saturable absorber, the average output power slightly decreased to 30 mW.

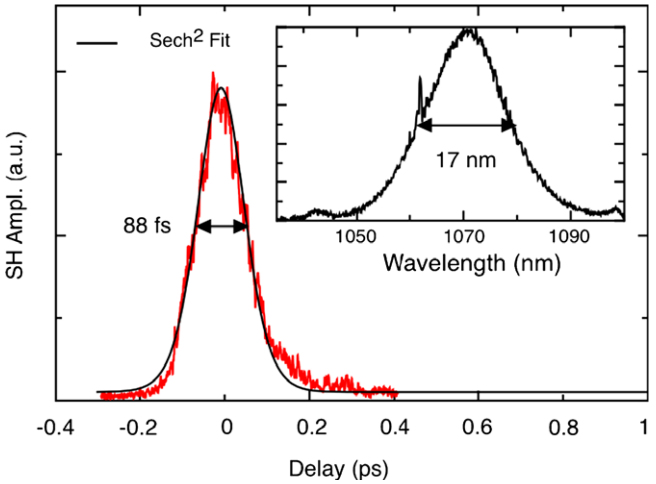

Fig. 4. Non-collinear second-harmonic autocorrelation trace of mode-locking pulses. Also shown is the autocorrelation best fit curve corresponding to *sech*^{2} pulse shape. Inset: correspondent pulse spectrum.

In order to further reduce the folded resonator footprint and complexity, we tested the SAM–M4–M2–M1–GTI–OC3 (T = 0.8%) arrangement as shown in Fig. 1 in which the prisms P1, P2 were replaced by a single Gires–Tournois Interferometer (GTI) high-reflectivity mirror. Since this kind of mirrors give a fixed amount of negative GVD per bounce, it is not possible to manage intracavity dispersion as finely as it was possible with a couple of prisms, but on the other end, intracavity losses are conveniently reduced and system simplicity and reliability increase.

We obtained the best results employing a $-375\ \text{fs}^2$ GTI mirror in a single bounce configuration yielding a total roundtrip negative dispersion amount of $-750\ \text{fs}^2$. In these conditions we measured self-starting and very stable 100-fs long mode-locking pulse train with 16-nm wide spectra with about 30 mW average output power. The slightly increased time-bandwidth product (≈0.42) suggests the possibility of further pulse shortening with an improved design of the GTI mirror dispersion.

3. Conclusions

Diode-pumped Nd:glass lasers can take advantage of recent improvement of laser diode technology, allowing simplified pump systems with a single high-brightness commercial laser diode. Efficient cw operation with slope efficiency as high as 30% demonstrates the effectiveness of this approach, as well as the importance of careful pump optics optimization (cw efficiency ⩽20% was reported previously in diode-pumped Nd:silicate lasers [11,13]). Stable sub-100-fs mode-locking was readily achieved either with prisms or GTI mirrors. Further improvements in pulse duration and output power might come with better SAMs with smaller non-saturable loss.

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