80-fs Nd:silicate glass laser pumped by a single-mode 200-mW diode

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Abstract: A Nd^{3+}-doped Schott LG680 silicate glass laser was pumped with a single-mode 200-mW diode. Efficient cw operation was demonstrated with 37.5 mW output power and 36% slope efficiency. Passive mode-locking with a semiconductor saturable absorber mirror yielded 80-fs pulses with a two-prism setup. Alternatively, pulses of ~200-fs, tunable over the range 1058-1076 nm, were obtained with either slit-tuning or a single-prism dispersive resonator. Output powers from 6 to14 mW have been measured.

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

References and links

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1. Introduction

Low-power femtosecond lasers pumped by single-spatial-mode laser diodes have attracted recently much attention as a cost-effective solution for many applications, such as seeding of ultrafast amplifiers and biomedical diagnostics [1–3], requiring only modest average powers

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of few milliwatts. Miniature Cr:LiSAF lasers first exploited the concept of low-cost, single-mode diode pumping for generation of 60-fs pulses with few milliwatt output power [4,5], and recently have reached more remarkable power levels of ~200 mW by multiplexing four 150-mW laser diodes [6]. Ytterbium and neodymium femtosecond lasers are especially interesting since they offer access to the 1-μm spectral region where direct diode-pumped high-power or high-energy amplifiers are available (either fiber or bulk). In particular, telecom-grade fiber-coupled 500-mW single-mode laser diodes were employed for pumping Yb:KYW [7] and Yb:YVO_4 [8], obtaining pulses as short as 61 fs and 54-mW output power.

Recently, we demonstrated a Nd:phosphate glass laser yielding 173-fs pulses and 12-mW output power, tunable over the range 1053-1069 nm, pumped by a single, low-cost 150-mW laser diode at 802 nm [9]. These femtosecond Nd:glass lasers get a certain advantage over Yb lasers pumped at ~980 nm with single-mode laser diodes, since pump threshold is conveniently minimized because of the four-level laser system used. Furthermore, lower power non-fiber-coupled 150-200 mW single-mode laser diodes at 800-810 nm are cheaper than single-mode fiber-coupled diodes used for pumping at 980 nm, which furthermore need a fine thermal control to carefully match the Yb^{3+} absorption line.

Here we report our investigation on a laser employing a Nd:silicate glass (Schott LG680) as the active medium. Its inhomogenous broadening is known to facilitate generation of shorter pulses [10] even though the thermo-mechanical properties of this particular glass matrix are worser than phosphate glasses. This drawback is avoided with low-power pumping by single-mode laser diodes, offering the opportunity to exploit sub-100-fs pulse generation with compact Nd:glass lasers.

Indeed, we achieved the highest reported cw slope efficiency of 36% in Nd:silicate glass lasers, with 37.8-mW pump threshold, whereas Fourier-limited pulses as short as 80 fs have been achieved in mode-locking operation. Several laser setups have been investigated for dispersion compensation: standard double-prism, dispersive Gires-Tournois mirror (GTI) and single-prism dispersive resonator.

2. Experiments

The resonator layout is depicted in Fig. 1, including all its variants for cw and mode-locking operation.

We employed a single-mode 200-mW laser diode (Intense Ltd.), emitting at 805 nm with a narrow 0.05-nm linewidth. The broad absorption spectrum of the 3% doped LG680 Nd:silicate glass centered at 805 nm yields 87% pump absorption in the 4-mm thick glass plate.

The glass plate was mounted on a mirror holder without any active thermal control and was oriented at Brewster angle.

The laser diode, initially with vertical fast axis orientation and horizontal polarization, was collimated by an antireflection-coated 8-mm focal length aspheric (numerical aperture = 0.5) and focused into the laser medium with a 50-mm plane-convex singlet lens. A 100-mm plane-convex lens was contacted with the 50-mm concave mirror (high reflectivity at 1000-1100 nm, high transmissivity at ~800 nm) to minimize its defocussing effect.

The pump beam was characterized with a CCD camera scanning along the propagation axis near the focal plane, yielding waist radii $w_{px} \times w_{py} = 23 \times 6.3$ μm^2 in air and beam quality parameters $M_x^2 = 1.0$ and $M_y^2 = 1.2$. The resonator beam waist radius was calculated to be ≈15-20 μm within the stability region. This particular laser diode produces a beam with an increased ellipticity (3.7:1) with respect to that employed in earlier experiments (1.8:1). After collimation with the 8-mm aspheric the available pump power was reduced to 170 mW owing to numerical aperture limitation and 167 mW was the maximum net power delivered to the Nd:glass plate.

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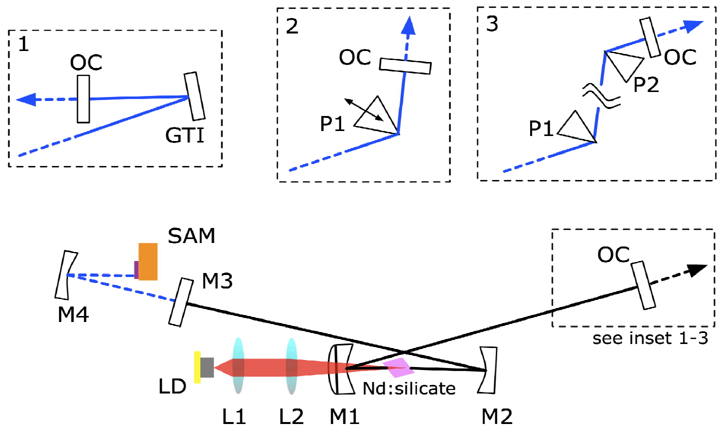

Fig. 1. Resonator layout. LD: pump laser diode; L1: aspheric lens (8-mm focal); L2: spherical singlet lens (50-mm focal); M1: concave mirror, 50-mm curvature, high-reflectivity (HR) at 1000-1100 nm, high-transmissivity (HT) at 800-810 nm; M2: concave mirror, 100-mm curvature, HR; M3: flat mirror, HR; M4: concave mirror, 75-mm curvature, HR; GTI: negative dispersion mirror; P1, P2: dispersive prisms; OC: output coupler, 30' wedge; SAM: saturable absorber mirror.

Operating the laser in cw regime we measured a maximum output power of 30.7 mW with an optimum output coupler (OC) of 3% and a 35.5% slope efficiency (Fig. 2). The output power was further increased to 37.5 mW (36% slope efficiency) when we rotated the laser diode by 90°, thus reducing the difference between Rayleigh ranges in x and y directions as well as their mismatch with the absorption length in the Brewster-oriented glass plate (the Rayleigh range in the horizontal direction is magnified by the square of the refractive index n). An antireflection-coated half-wave plate was also added to rotate the laser diode polarization. This pump setup was used for the mode-locking experiments.

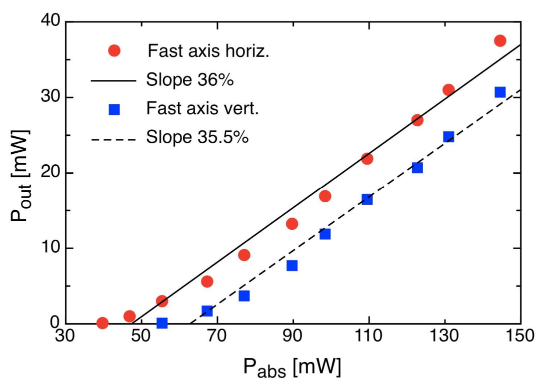

Fig. 2. Performance of the Nd:silicate laser in cw regime, with the optimum OC (3% transmissivity) and two orthogonal orientations of the laser diode.

For investigation of the mode-locking regime the mirror M3 was removed, whereas a concave 75-mm mirror M4 was chosen to focus the beam at ~15-30 µm radius on the semiconductor saturable absorber mirror (SAM) with 1.2% reflectivity modulation (0.8% non-saturable loss), depending on the resonator configuration chosen. The SAM was specified at 1.2% reflectivity modulation (0.8% non-saturable loss), 60-µJ/cm^2 saturation fluence and 1-ps recovery time. In the following discussion, mode-locking results correspond to the maximum available pump power, while the femtosecond regime was stable above ~80% of the maximum output power for each setup.

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Several OC-GVD management options, shown in Fig. 1, have been used. Figure 3 shows the shortest pulses of 80 fs, 14.6 nm bandwidth (product $\tau \times \Delta\nu \approx 0.31$) and 170-MHz repetition rate that were obtained with a SF10 prism pair (separation 280 mm) and 0.4% OC, yielding 6.5 mW output power. The RF spectrum showed a clean beat note with no self Q-switching modulations and good peak-to-floor contrast, further remarking the stability of the cw mode-locking train appreciated at the oscilloscope.

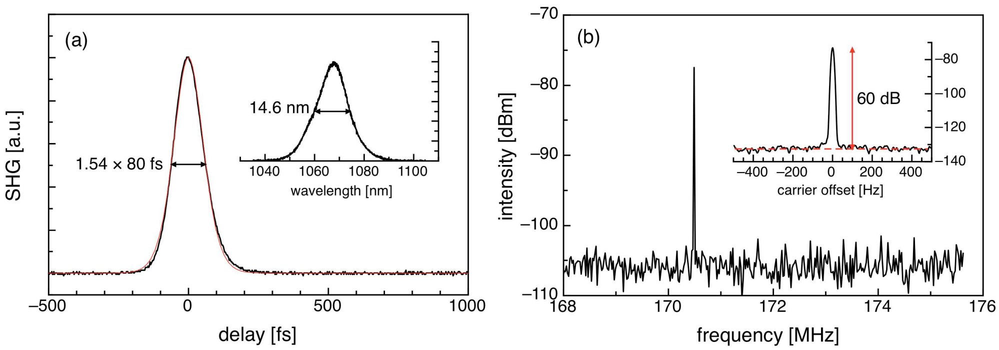

Fig. 3. a) Background-free autocorrelation of the shortest pulse measured (with best fit assuming *sech*^{2} intensity profile) and optical spectrum; b) RF spectrum remarking the absence of instabilities.

An X-folded resonator with a classic two-prism arrangement in fused silica (FS) glass was also tested. Though one does not expect significant limitation in pulse bandwidth with the SF10 prism pair arising from third order dispersion (pulses as short as 68 fs were reported in Ref [10].), the smaller refractive index of the FS prism allows easier and less critical alignment near the Brewster angle, as well as an intrinsically lower internal scattering loss. In turn, this might lead to higher intracavity energy and correspondingly higher SPM, resulting in shorter pulses.

Furthermore, the resonator length had to be increased due to the smaller prism dispersion, as the prism separation was about 550 mm: the stability zones narrowed and the overall alignment became slightly more critical. However, the resulting mode-locking was still very stable and self-starting. Under this experimental setup, the laser generated 90-fs pulses (13.6 nm) at 1068 nm with 8-mW output power and 120-MHz repetition rate. This suggests that this higher pulse energy did not increase the SPM that would lead to shorter pulses, this perhaps owing to bandwidth limitation and two-photon absorption occurring in the particular structure of the SAM [11].

A vertical slit near the OC provided an easy mean to perform tuning over 1058-1075 nm, though at expense of the pulse width (spectral narrowing) which increased to 188 and 270 fs at 1058 nm and at 1075 nm, respectively.

A more compact prism-less resonator with a Gires-Tournois interferometer (GTI) mirror with nominal second-order dispersion ≈-375 fs^2 yielded self-starting mode-locking with 7-mW, 147-fs pulses and spectral bandwidth of 8.6 nm, at 190 MHz repetition rate. The pulse width was minimized by fine tuning the incidence angle on the GTI in order to achieve the optimum dispersion compatible with the other laser parameters. Owing to the limited bandwidth of this GTI, shorter pulses were not possible; better pulse duration performance is expected with other matched GTI mirror pairs with lower single-bounce dispersion, used to optimize the number of bounces and thus the net intracavity dispersion per round trip while compensating for phase ripples.

Of particular interest is the single-prism setup [11] we already exploited in the Nd:phosphate glass laser [9]. ABCD dispersive ray tracing shows that the lateral dispersion $dx / d\lambda$ occurring in the gain medium, given the resonator setup, is proportional to the prism

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dispersion $dn/d\lambda$. Indeed, the effective bandwidth $\Delta\lambda_{eff}$ of the single-prism dispersive resonator can be heuristically estimated by assuming that the transverse shift $\delta = (dx/d\lambda)\Delta\lambda$ of the mode axis in the laser crystal at $\lambda + \Delta\lambda$ produce a round-trip maximum gain reduction comparable with the saturated gain g, given the gaussian pump distribution $\sim \exp[-2(x/w_G)^2]$ with radius w_G along the transverse x-axis:

$$1 - \exp[-(\delta / w_G)^2] \sim g \tag{1}$$

$$\Delta\lambda_{eff} \sim \frac{2\sqrt{g}}{|dx/d\lambda|} w_G \tag{2}$$

For this reason, we chose to use a (FS) glass prism instead of SF10 employed in Ref [9]. that has $dn/d\lambda$ twice as larger, to minimize the transversal wavelength dispersion in the gain medium that ultimately limits the pulse duration.

Pulses as short as 158 fs (9.8 nm) were generated at 1061 nm, while the tuning range extended from 1058 nm to 1076 nm (Fig. 4), with output power ≈7-14 mW and 250-MHz repetition rate. The pulse width increased to 240 fs at the extrema of this range. The OC used in this case was of 0.8% transmittivity, allowing more efficient power extraction given the total (non-saturable) intracavity loss of ~1% and considering the inability of the laser to sustain bandwidths larger than ≈10 nm owing to wavelength spatial dispersion in the glass medium.

All the other resonator setups we investigated yielded the shortest pulse widths with the lowest OC transmittivity available (0.4%): indeed the intracavity pulse energy with the 0.4% OC was ≈50% higher than with the 0.8% OC, adding increased self-phase-modulation (SPM) that evidently the single-prism resonator could not sustain, most likely filtering out the spectral wings with the transversal gain distribution.

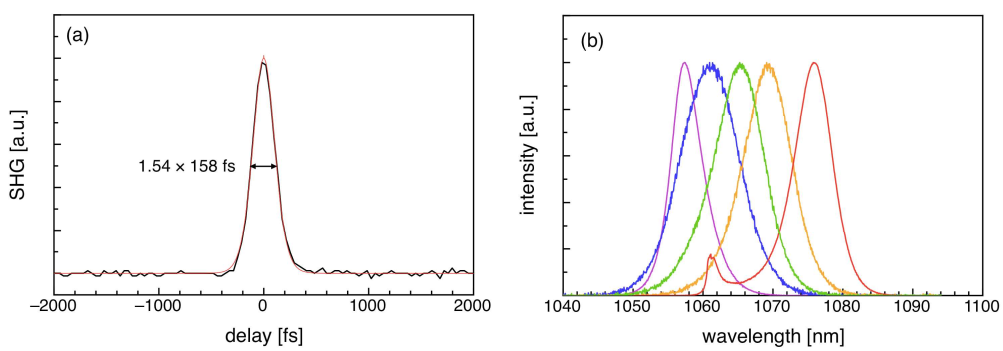

Fig. 4. Autocorrelation of the pulse at 1061 nm (a) and tunability of the single-prism setup (b). In all cases the pulses were nearly transform-limited, with τ × Δν ≈0.33 - 0.37.

3. Conclusions

Nd:glass femtosecond lasers have been proved easy to operate with single-mode low-power laser diodes. Here we have reported the results achieved with a silicate glass laser material (Schott LG680) yielding pulses as short as 80 fs and up to 14 mW output power (and 158-fs pulses with a single-prism setup easily tunable over 18 nm), employing a readily available 200-mW pump diode at 805 nm. The laser can be made reasonably compact (maximum repetition rate was 250 MHz) and can be used for a variety of applications that require no more than such power levels.

The simplification offered by the single-mode pump setup is significant when compared with previously reported Nd:glass lasers pumped by 1-2 W broad-area emitters [10,12,13]: i)

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microlensed diodes had to be employed if one manages to use only spherical lenses for collimation and focusing, but microlenses are known to reduce diodes lifetime; ii) non-microlensed diodes require very careful alignment of the beam reshaping optics (cylindrical telescopes) [13] in order to minimize astigmatism and deliver the smallest pump spot compatible with the absorption length; iii) the low-power single-mode laser diode is easily collimated with an aspheric and focused with a spherical singlet, furthermore it does not require cooling given the broad absorption band of Nd:glass and the modest heat released.

Considering our previous results with Nd:phosphate pumped by a single-mode 150-mW laser diode [9], we have achieved significantly shorter pulses with the GTI setup, i.e. 147 fs vs. 270 fs. With the single-prism setup we obtained comparable pulse widths with Nd:phosphate (173 fs) and Nd:silicate (158 fs) employing different prisms (SF10 and FS, respectively): the higher gain of phosphate glass compensates the larger spatial dispersion of SF10, yielding a comparable $\Delta\lambda_{eff}$ for both resonators (Eq. (2). It is expected that Nd:phosphate with a FS single-prism setup would yield shorter pulses, though mode-locking with homogeneous broadening is generally more difficult to deal with. In any case, the two-prisms setup allows stable sub-100-fs pulses at the (sometimes acceptable) price of somewhat greater layout complexity.

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