Femtosecond Nd:glass Lasers Mode-Locked with Carbon Nanotube Saturable Absorber Mirror

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Abstract: We present femtosecond Nd:glass lasers pumped by single-mode 200-mW diodes, mode-locked by single-walled carbon nanotube saturable absorbers. We obtained sub-150-fs and sub-100-fs stable pulse trains with phosphate and silicate glasses, respectively.

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

1. Introduction

Single Walled Carbon NanoTube Saturable Absorbers (SWCNT-SAs) are attracting attention as practical solutions for passive mode-locking of ultrafast solid state and fiber lasers. The interest in this new technology is motivated by the favourable combination of intrinsic nonlinear properties of SWCNT (very fast recovery time, low saturation fluence and absence of two photon absorption) as well as the ease and low cost of the fabrication process. This is especially true if the comparison is made with the technology involved in the realization of SEmiconductor Saturable Absorber Mirrors (SESAMs), which is presently the most successful solution for mode-locking of ultrafast lasers. Moreover, SWCNT-SAs can be realized on a large variety of different substrates and easily fabricated for a specific laser transition simply choosing the right diameter and chirality of nanotubes that are readily available on the market [1].

Passive mode-locking of femtosecond bulk lasers requires low linear losses, due to the relatively low gain of the wide-bandwidth laser media, in particular for 1-μm lasers. Indeed, SWCNT-SAs have been earlier employed for mode-locking of high-gain ultrafast fiber lasers. Nevertheless, some refinements in the synthesis techniques and a careful control of the carbon nanotubes dispersion and deposition processes made available SWCNT-SAs with the combination of low linear loss, small modulation depth and fast recovery time desirable for femtosecond bulk lasers. To date, femtosecond regime has been demonstrated in wide-bandwidth bulk laser systems in a broad range of wavelengths extending from 1 to 2 μm [2,3]. Apparently, lasers based on Nd^{3+}-doped glasses have not been deeply investigated: only a preliminary result of ~ 200 fs pulses with a Nd:phosphate glass was recently reported [3]. In this work we present sub-150-fs and sub-100-fs stable mode-locking pulse trains obtained with Nd^{3+}-doped phosphate and silicate glasses, respectively. A particularly effective low-threshold laser design using a 200-mW single-mode pump laser diode was exploited.

2. Experimental setup and results

The resonator layout is shown in Fig. 1, including all its variants for cw and mode-locked operation of both Nd:phosphate and Nd:silicate lasers. The pump source was a single-mode 200-mW laser diode (Intense Ltd.), emitting at 805 nm with a narrow 0.05-nm linewidth. A pair of anamorphic prisms was employed to circularize the elliptical pump beam and optimize its overlap with the resonant mode inside the active medium. The maximum power delivered to the active medium was 156 mW. Both active media tested (phosphate glass Schott LG760 and silicate glass Schott LG680) were 4-mm thick, 3%-doped, Brewster-oriented plates absorbing about 90% of the available pump power.

The pump beam was characterized with a CCD camera scanning along the propagation axis near the focal plane, yielding waist radii $w_{px} \times w_{py}$ = 14.1 × 14.4 μm^2 in air and beam quality parameters M_x^2 = 1.0 and M_y^2 = 1.1. The resonator beam waist radius was calculated to be ≈ 15-20 μm within the stability range.

Initially, a characterization of the resonator in the cw regime was carried out for both active media under investigation. The optimum output coupling was T_{oc} = 5% in both cases yielding a remarkable slope efficiency of ≈ 58% for phosphate and ≈ 46.5% for silicate glass (the highest reported for both materials, to our knowledge) with maximum output powers of 68 mW and 48 mW, respectively.

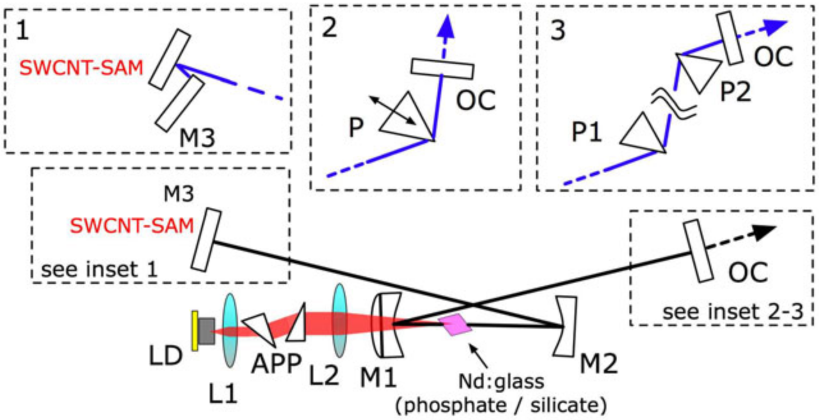

Fig. 1. Resonator layout. LD: pump laser diode; L1: aspheric lens (4.5-mm focal); APP: anamorphic prisms pair; L2: spherical singlet lens (50-mm focal); M1: concave mirror, 50-mm curvature, high-reflectivity (HR) at 1000-1100 nm, high-transmittance at 800-810 nm; M2: concave mirror, 100-mm curvature, HR; M3: flat mirror, HR; P, P1, P2: Fused Silica prisms; OC: output coupler, 30' wedge.

With the same resonator setup, the Findlay-Clay analysis was performed to determine the total loss (saturable + non-saturable) introduced by the SWCNT-SAM employed in mode-locking experiments, which turned out to be ≈ 1.5%. This value is in reasonable agreement with the nonlinear reflectivity measurements of the same sample which gave a saturable loss of 0.21% and a non-saturable loss of 0.7%. The saturation fluence was measured to be 5 $\mu J/cm^2$, whereas the nonlinear response was described by a biexponential decay with a fast (< 150 fs) and a slow (< 1 ps) component [4].

For the passive mode-locking experiments, the cavity was modified as follows: the end-mirror M3 was replaced by the SWCNT-SAM. Either one [5] or two Fused Silica (FS) prisms were used to obtain the net negative intracavity Group Velocity Dispersion (GVD) required for soliton mode-locking. The output coupler transmittance for the mode-locking experiments was 0.4%. The cavity mode size on the SWCNT film was varied by changing the length of the corresponding cavity arm M2 – M3 and consequently adjusting the M1 – M2 separation to manage the resonator stability.

2.1 Nd:phosphate mode-locking experiments

For Nd:phosphate glass mode-locking experiments, we chose a cavity configuration employing a single FS prism for intracavity GVD compensation. This cavity arrangement allows a straightforward central output wavelength selection by simply adjusting the output coupler horizontal tilt angle. This is particularly beneficial in case of phosphate glass, since in this material the mostly homogenously broadened fluorescence bandwidth can be efficiently exploited only forcing the laser output wavelength to red shift. This is usually realized with spectral filtering techniques such as Kerr-Shift mode-locking [6], but can be easily achieved also with the single-prism cavity configuration.

The mirror separations were as follows: M1 – M2 ≈ 84 mm, M2 – SWCNT-SAM ≈ 400 mm, M1 – P ≈ 500 mm and P – OC ≈ 40 mm. According to ABCD modeling as outlined in Ref. [5], the separation between real and virtual prism in this setup was about 40 cm. In this configuration, almost Fourier-limited 280-fs long mode-locked pulses were obtained. In order to increase the amount of nonlinear losses per roundtrip (albeit at the expense of increasing linear losses, too), we used the SWCNT-SAM as a folding mirror close to the HR flat end-mirror, within the Rayleigh range of the cavity mode waist (see Fig. 1, inset 1). Increasing the length of the M1 – P cavity arm to ≈ 700 mm (separation between real and virtual prism was ≈ 60 cm), we readily observed self-starting mode-locking with an average output power of 8 mW. The autocorrelation trace of the 141-fs long pulses and the corresponding 11-nm optical spectrum (time-bandwidth product ≈ 0.41) are shown in Fig. 2(a). A residual cw component in the blue tail of the spectrum was present, probably suggesting an insufficient modulation depth by the SWCNT- SAM.

2.2 Nd:silicate mode-locking experiments

With the Nd:silicate glass, a classic pair of FS prisms was used for GVD compensation, in order to fully exploit the potential of this material. The distance between P1 and P2 (see Fig. 1, inset 3) was ≈ 65 cm. Given the smaller emission cross section of silicate glass with respect to phosphate glass, SWCNT-SAM was employed as resonator end-mirror at a distance of about 400 mm from M2, yielding a cavity mode radius on the saturable absorber $w_a \approx 80$

μm. Stable 99-fs long pulses, 10-mW average output power with 16.5 nm wide spectrum centered around 1070 nm (time-bandwidth product ≈ 0.43) were obtained (see Fig. 2(b)).

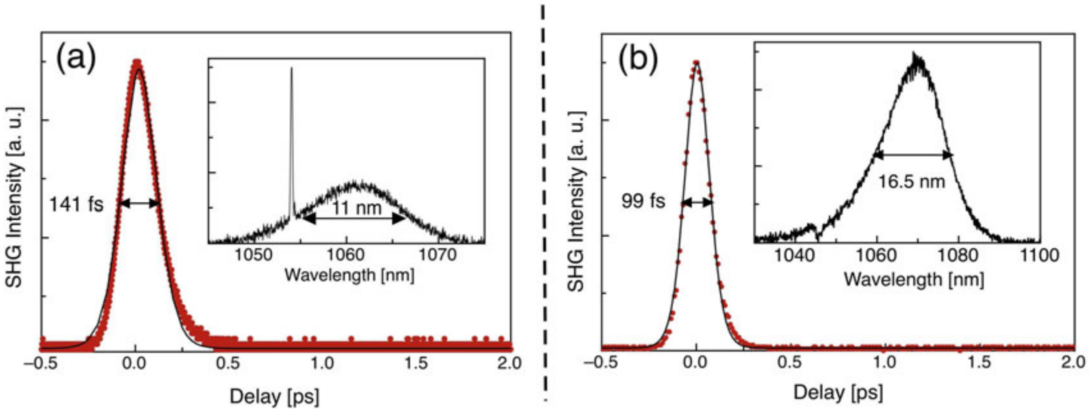

Fig. 2. (a) Autocorrelation trace of the mode-locked Nd:phosphate laser, in the inset the corresponding optical spectrum. (b) Autocorrelation trace of the mode-locked Nd:silicate laser, in the inset the corresponding optical spectrum

In these conditions, the mode-locking regime was not self-starting but could be sustained for several minutes once it was built-up through a small perturbation. No local damage occurred to the SWCNT absorber layer: in any case, if interrupted, mode-locking could be restored by gently shaking a mirror mount or moving a prism. Accounting for the good sample homogeneity, pulse duration, mode-locked pulse train stability and average output power were not significantly influenced by the spot position on the SWCNT-SAM.

3. Conclusions

In summary, we have demonstrated the first sub-100-fs Nd:silicate and the first sub-150-fs Nd:phosphate laser mode-locked by a SWCNT-SAM. Owing to symmetrized beam shaping of the single-mode laser diode yielding circular profile optimally matched to the Nd:glass resonator mode, remarkable results in terms of cw operation have been achieved. Higher efficiency, shorter pulses with better mode-locking stability, comparable to that allowed by SESAMs, are expected with SWCNT-SAM as well, through improvement of the ratio between saturable and non-saturable losses, allowing larger nonlinear modulation. The relatively small saturation fluence of the SWCNT-SAM ≈ 5-10 $\mu J/cm^2$ according to measurements reported in Ref. [4], is a favourable parameter, relaxing the focusing requirements on the saturable absorber, simplifying the resonator design and making the operation of SWCNT-SAM safe and highly reliable especially for this class of low-pump power femtosecond sources**.**

4. References

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