Femtosecond Nd:Glass Lasers Pumped by Single-Mode Laser Diodes and Mode Locked With Carbon Nanotube or Semiconductor Saturable Absorber Mirrors

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***Abstract*—In this paper, single-mode 200-mW laser diodes have been demonstrated to be very effective pump devices for low-power Nd:glass lasers, yielding the remarkable continuous wave (cw) slope efficiency of 46.5% for silicate and 58.2% for phosphate glasses, respectively. Femtosecond operation has been investigated with both semiconductor saturable absorber mirrors (SESAMs) and a single-walled carbon nanotube SAM (SWCNT-SAM). Furthermore, a detailed comparison of the mode-locking performance with Nd:phosphate and Nd:silicate, employing either one of the SA devices is presented. Although not fully optimized for this particular application yet, SWCNT-SAs yielded sub-100-fs pulses for the first time in Nd:glass. With SESAM mode locking and a single-prism resonator for dispersion compensation, pulse duration as short as 92 fs has been measured, whereas shorter pulses down to 80 fs have been obtained with a two-prism resonator. Tuning range as broad as 30 nm and output power up to 55 mW have also been achieved, confirming the effectiveness of the proposed laser architecture.**

***Index Terms*—Optical pulse generation, solid lasers, ultrafast optics.**

I. INTRODUCTION

DIODE-PUMPED low-power femtosecond lasers at 1-μm wavelength are compact cost-effective light sources and very attractive for a variety of applications requiring power levels of only few tens of milliwatts, such as optical coherence tomography, nonlinear microscopy, generation and detection of terahertz radiation, and seeding of high-power ultrafast amplifiers.

Both ytterbium [1], [2] and neodymium [3], [4] femtosecond lasers have been investigated to this aim. In particular, low-threshold lasers were demonstrated using inexpensive, readily available single-mode pump laser diodes that provide effective tight focussing of the pump beam with a simple optical setup. Indeed, the four-level laser scheme of the Nd^{3+} ion enables a very low laser threshold, which is beneficial for low-power pumping [3].

Ultrashort pulses were achieved with either Kerr-lens mode locking (KLM) [1], [2] or semiconductor saturable absorber mirror (SESAM) mode locking [3], [4]. The shortest pulse width was reported to be 61 fs with a Yb:YVO_4 laser [2], whereas the highest output power achieved with telecom-grade 500-mW fiber-coupled single-mode laser diode was 227 mW with a femtosecond Yb:KYW laser [1].

More recently, the single-mode pump setup was power scaled with a state-of-the-art 5.5-W tapered distributed Bragg reflector laser diode pumping an Yb:KGW laser, yielding 1.1-W output power and 281-fs pulse duration [5].

With Nd:glass, much less expensive and readily available nonfiber-coupled laser diodes with lower output power could be used, since SESAM mode locking does not require a perfect circular symmetric pump profile as it is usually preferred in KLM [1], [2]. Pulses as short as 80 fs [4] were achieved in Nd:silicate pumped by a 200-mW single-mode laser diode with a strongly elliptic beam cross section. While the cw Nd:glass lasers were reasonably efficient, mode-locked operation yielded the shortest pulses only with very low output coupling, resulting in a maximum output power of only 14 mW.

Single-walled carbon nanotube SAs (SWCNT-SAs) [6]–[8] are relatively new devices that recently attracted much attention as potential replacement of SESAMs, owing to the significantly lower complexity of fabrication and costs. Furthermore, the operation wavelength of SWCNT-SAs is set by the nanotube diameter and chirality, and they exhibit much broader absorption band compared to SESAMs. SWCNT-SAs have already been demonstrated to successfully mode-lock solid-state and fiber lasers in the range 0.8–2 μm [9]–[14]. In this paper, we discuss and compare recent [15] as well as new results achieved with low-power Nd:silicate and Nd:phosphate lasers, using a 200-mW single-mode pump laser diode at 805 nm and employing either single-prism or double-prism resonators for dispersion compensation. Optimization of pumping efficiency leading to new remarkable results for both cw and femtosecond operation of Nd:glass lasers is reported. Results with both SESAMs

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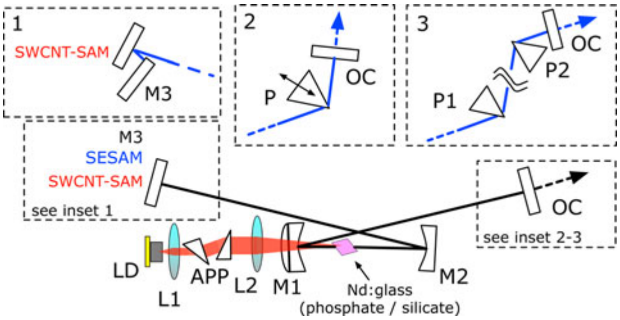

Fig. 1. Resonator layout. LD: pump laser diode; L1: aspheric lens (4.5-mm focal, NA 0.55); APP: anamorphic N-SF11 prisms pair; L2: spherical singlet lens (50-mm focal); M1: concave mirror, 50-mm curvature, high reflectivity (HR) at 1000–1100 nm, high transmissivity at 800–810 nm; M2: concave mirror, 100-mm curvature, HR; M3: flat mirror: HR, SESAM, or SWCNT-SAM depending on the experiment; P, P1, P2: FS prisms; OC: output coupler, 30' wedge.

and a SWCNT saturable absorber mirror (SWCNT-SAM), in Nd:phosphate and Nd:silicate lasers, will be compared in this paper for the first time. Both SA devices enabled sub-100-fs pulse operation with broad tuning ranges, extending up to 30 nm for SESAMs (fluorescence spectrum full-width at half-maximum (FWHM) is ≈24–36 nm in Nd:glasses investigated in this research). Presently, SESAMs benefit from a 20-year development history for applications in solid-state lasers [16], although their commercial availability is not as wide as it might be expected: they show proportionally lower nonsaturable losses and yield more efficient mode-locking operation in our setup, up to 40% optical-to-optical. However, the lower saturation fluence of the SWCNT-SAM allows simplified resonator setups with relaxed focusing, which can be beneficial for extending the lifetime of the device once it has been fully optimized for application with femtosecond Nd:glass lasers.

II. PUMP BEAM OPTIMIZATION AND LASER OPERATION IN CW REGIME

The resonator layout is shown in Fig. 1, including all its options for cw and mode-locked operation, for either Nd:phosphate or Nd:silicate active media. The pump source was a single-mode 200-mW laser diode (Intense Ltd.), emitting at 805 nm with a narrow single-longitudinal-mode 50-pm linewidth. Due to the small thermal load, no active cooling of the pump source was necessary. A pair of anamorphic prisms was employed to circularize the elliptical pump beam and optimize its overlap with the resonant mode inside the active glass. The maximum power incident on the active medium was 156 mW. Both laser glasses employed (Schott LG-760 phosphate glass and Schott LG-680 silicate glass) were 4-mm thick, 3%-doped, Brewster-oriented plates, and absorbed ≈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 $w_{px} \times w_{py} = 14.1 \times 14.4\ \mu\text{m}^2$ in air and beam quality parameters $M_x^2 = 1.0$ and $M_y^2 = 1.1$ for the most effective beam size employed in laser experiments. The resonator-mode waist radius was calculated to be ≈15–20 μm within the stability range.

Optimized matching between the pump and cavity mode inside the active medium, achieved by pump beam symmetrization, yielded a significant improvement in cw performance of both the phosphate and silicate glasses over our previous results [3], [4]. The optimum output coupling was T_{oc} ≈5% in both cases, yielding a remarkable slope efficiency of 58.2% for the phosphate glass and 46.5% [15] for the silicate glass (the highest reported for both materials, to our knowledge) with maximum output powers of 68 and 48 mW, respectively (see Fig. 2). The linearity of curves shown in Fig. 2 proves that thermal effects are not significant in this pump regime, hence there should be room for further improvement, for example, by pumping the laser glass from both ends.

III. FEMTOSECOND Nd:PHOSPHATE LASER

For Nd:phosphate glass mode-locking experiments, we chose a cavity configuration employing a single fused-silica (FS) prism for intracavity group velocity dispersion (GVD) compensation. It was shown [17] that such a cavity setup exhibits net negative GVD, provided that the separation between the prism and the second "virtual" prism, is sufficiently large. The position of such "virtual" prism, i.e., the crossing point of monochromatic rays at the left of the prism in the inset 2 of Fig. 1, is determined by ABCD ray-tracing technique and depends on the exact resonator geometry. Furthermore, the resonator must be designed to satisfy the usual stability criterion for existence of resonant TEM$_{00}$ mode, as well as to provide the correct beam size at the SA and gain medium. One drawback of this resonator setup is the transversal dispersion of monochromatic rays inside the gain element. In turn, this sets a limit for the effective bandwidth $\Delta\lambda_{\text{eff}}$ that can be sustained in the femtosecond regime. Given the lateral dispersion sensitivity $dx/d\lambda$ that can be readily calculated through ABCD analysis and is proportional to prism dispersion $dn/d\lambda$, $\Delta\lambda_{\text{eff}}$ is determined by the maximum reduction of the saturated round-trip gain g yielded by the overlap between the transverse gain profile and the dispersed resonant-mode profile [18]

$$\Delta\lambda_{\text{eff}} \sim \frac{2\sqrt{g}}{|dx/d\lambda|} w_g \tag{1}$$

where w_G is the mode radius in the gain medium. Therefore, the largest effective bandwidth is made available by gain optimization (hence, optimum pump beam focussing) and by selecting low-dispersive prisms allowing reasonably compact resonators. For example, with the gain and mode size parameters of the resonators investigated in this paper, a FS prism yielded the optimum performance, ensuring $\Delta\lambda_{\text{eff}}$ as large as ≈15 nm, a sizeable fraction of the fluorescence bandwidth of the laser glasses.

In addition, the single-prism cavity arrangement allows a straightforward central output wavelength selection by simply adjusting the horizontal tilt angle of the output coupler. This is particularly beneficial in case of phosphate glass, since its most homogeneously broadened fluorescence bandwidth can be efficiently exploited only forcing the laser output wavelength to red shift. This is most often realized with spectral filtering techniques, such as Kerr-shift mode locking [19], but can be easily achieved also with the single-prism cavity configuration.

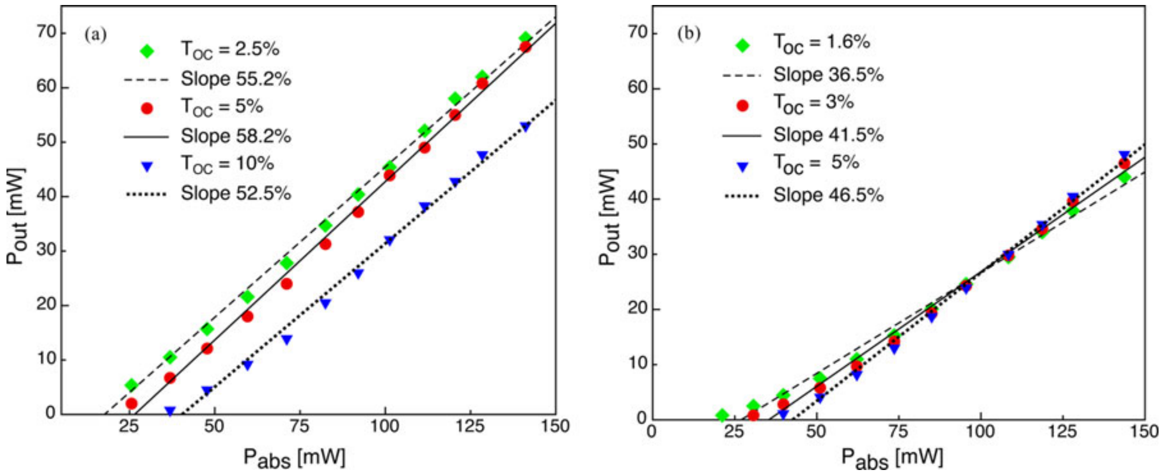

Fig. 2. Laser performance in cw regime. (a) Phosphate LG-760 glass. (b) Silicate LG-680 glass.

TABLE I
SAMs Parameters: Saturation Fluence, Recovery Time, Saturable, and Nonsaturable Losses

	F_{sat} (μJ/cm²)	τ_R (ps)	ΔR_S	ΔR_{NS}
SESAM-1	60	≈ 1	0.6%	0.4%
SESAM-2	60	≈ 1	1.2%	0.8%
SWCNT-SAM	5	< 1	0.21%	1.3%

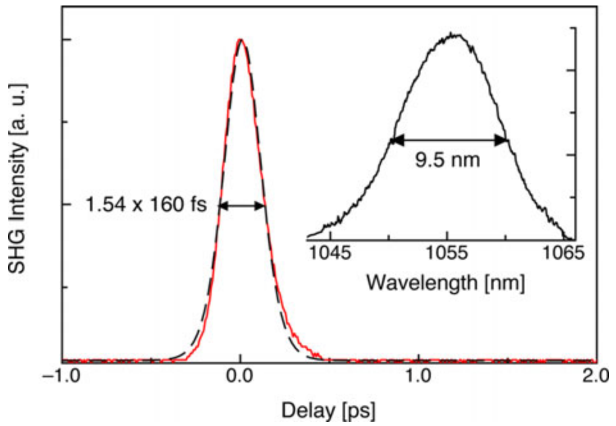

Fig. 3. Pulse autocorrelation and correspondent optical spectrum (inset) obtained with the Nd:phosphate laser, SWCNT-SAM and single prism setup. Also shown is the best fit with autocorrelation corresponding to *sech*^{2} pulse shape.

In the mode-locking experiments, the pulsewidth was measured with a home-made background-free noncollinear second harmonic autocorrelator. Optical spectra were characterized with an ANDO AQ6317B analyzer, whereas radio-frequency spectra were detected with a fast photodiode and an Agilent N9320B 3-GHz RF analyzer.

A Findlay–Clay analysis was also performed to determine the total loss (saturable + nonsaturable) introduced by the SWCNT-SAM employed in cw mode-locking experiments, which turned out to be ≈1.5%. The saturable losses were previously determined with a high-resolution pump-and-probe technique [20] to be 0.21% and the saturation fluence was measured to be 5 μJ/cm^2, whereas the nonlinear response was described by a biexponential decay with fast (<150 fs) and slow (<1 ps) components, corresponding to intraband and interband carrier recombination processes in semiconducting SWCNTs, respectively. By comparison, the nominal saturation fluence of the commercially available SESAMs employed in this paper (Batop, GmbH), with relaxation time ≈1 ps, was ≈60 μJ/cm^2. Saturable and nonsaturable losses were 0.6% and 0.4% for SESAM-1, respectively, and 1.2% and 0.8% for SESAM-2 (see Table I).

At first, we tested the SWCNT-SAM as an end mirror in a classical X-folded resonator. Referring to Fig. 1, 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, the separation between real and virtual prisms in this setup was about 400 mm. In this configuration, employing a $T_{\rm oc} = 0.4\%$ output coupler, 16-mW average power, and almost Fourier-limited 280-fs pulses were generated. As in all subsequent experiments, the output beam was always a very clean TEM$_{00}$, with M^2 ≈1. In order to increase the amount of nonlinear losses per roundtrip (although 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 ≈600 mm), we readily observed self-starting mode locking with an average output power of 8 mW. The 11-nm wide optical spectrum centred near 1061 nm sustained pulses as short as 141 fs. A small cw component near the fluorescence peak was present, suggesting a still too small modulation depth by the SWCNT-SAM. Actually, increasing the negative dispersion the pulse slightly broadened to 160 fs, but this cw component disappeared (see Fig. 3). The central wavelength could be tuned only between 1061 and 1075 nm. Pulse duration, mode-locked pulse train stability, and average output power were not significantly influenced by the spot position on the SA, thus accounting for the good sample homogeneity.

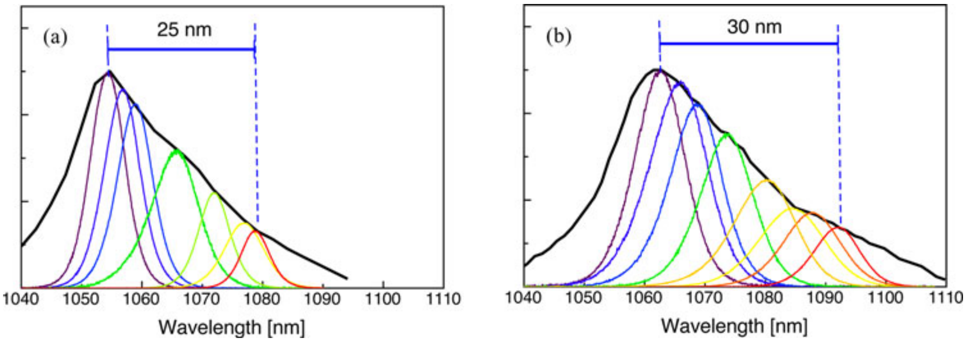

Fig. 4. (a) Nd:phosphate and (b) Nd:silicate fluorescence spectra (black line) and output wavelength tunability in SESAM cw mode-locked regime, single-prism cavity arrangement (colored curves).

TABLE II
ND:PHOSPHATE LASER (SINGLE PRISM CAVITY): OUTPUT POWER, PULSEWIDTH, AND TIME–BANDWIDTH PRODUCT

	P_{out} (mW)	τ_p (fs)	$\tau_p \times \Delta\nu$
SESAM-1	20 (T_{OC} = 0.4%)	140	0,34
	55 (T_{OC} = 2.5%)	250	0,37
SESAM-2	12	100	0,34
SWCNT-SAM	8	160	0,41

We then substituted the SWCNT-SAM with the SESAM-1. Due to higher SESAM saturation fluence with respect to the SWCNT-SAM, it was necessary to reduce the cavity mode size on the SA in order to obtain stable and self-starting mode locking. In this cavity configuration, this is easily done by simply varying the separation M2–SESAM and consequently adjusting the separation M1–M2 for stability optimization. Hence, in this new arrangement, the mirror separations were as follows: M1–M2 ≈100 mm, M2–SESAM ≈170 mm, M1–P ≈400 mm, and P–OC ≈40 mm. The separation between real and virtual prisms in this setup was ≈280 mm. The 20-mW average power, nearly transform-limited 140-fs pulses were obtained, as with the SWCNT-SAM. A central output wavelength tunability of about 25 nm, between 1054 and 1079 nm was also possible in this case [see Fig. 4(a)]. We also investigated the optimum coupling yielding the maximum output average power in soliton mode-locking regime. With $T_{\rm oc} = 2.4\%$, we obtained 250-fs-long stable mode-locked pulses, with as much as 55-mW average output power, corresponding to optical-to-optical efficiency as high as 40% with respect to the absorbed pump power (see Table II). This is the highest efficiency ever reported for femtosecond Nd:glass lasers and speaks clearly for the effectiveness of the single-mode pump architecture.

As expected and already experimentally confirmed with the SWCNT-SAM, increasing the SA modulation depth was beneficial for pulse shortening. Wider spectra and shorter pulses were obtained employing the SESAM-2. With the relatively compact cavity setup allowed by the single-prism concept, 100-fs-long pulses (13-nm wide spectra centered near 1068 nm) were obtained at a repetition rate of about 194 MHz. The autocorrelation trace and radio-frequency spectrum of the highly stable mode-locked pulse train are shown in Fig. 5.

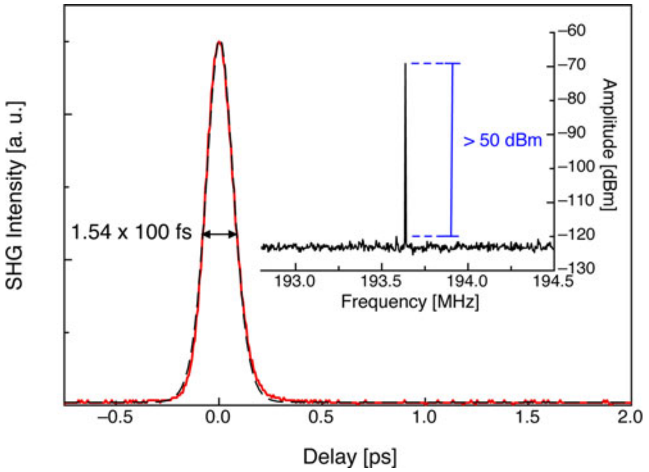

Fig. 5. Shortest pulse autocorrelation (corresponding spectrum width: 13-nm FWHM) obtained with the Nd:phosphate laser, SESAM-1 and single prism setup. Also shown is the best fit with autocorrelation corresponding to *sech*^{2} pulse shape. Inset: RF spectrum of the cw mode-locking pulse train.

This result is very interesting, since Nd:phosphate was often discarded as a laser glass capable of generating pulses ≤100 fs, whereas Nd:silicate and fluorophosphate were considered superior in this respect [19], [21]. Providing sufficient gain with the tight focussing allowed by the symmetric TEM_{00} pump profile, as proved by the excellent cw results, was indeed instrumental for achieving the necessary bandwidth required to support 100-fs pulses even with the intrinsic limitations of the single-prism resonator.

IV. FEMTOSECOND ND:SILICATE LASER

Beside poorer thermooptical properties, a negligible drawback at low pump power levels such as in the present experiments, Nd:silicate basically shows a lower emission cross section (2.5×10^{-20} cm^2 versus 4.5×10^{-20} cm^2 [22]) but a wider, almost purely inhomogeneously broadened, 36-nm fluorescence bandwidth with respect to Nd:phosphate (24 nm bandwidth). Indeed, no gain reshaping techniques are needed to fully exploit the bandwidth of the Nd:silicate glass and generation of shorter pulses down to 68 fs was reported [21].

At first, we tested the cavity configuration employing the SWCNT-SAM to startup and stabilize soliton mode locking, and a single FS prism for intracavity net negative GVD management. The cavity arrangement with the two-bounces SWCNT-SAM depicted in Fig. 1 (inset 1) was also investigated, but never allowed stable mode locking, probably due to the lower gain of Nd:silicate that could not sustain the increase in intracavity linear losses. Hence, we simply used the SWCNT-SAM as an end mirror. The mirror separations were as follows: M1–M2 ≈85 mm, M2–SWCNT-SAM ≈430 mm, M1–P ≈720 mm, and P–OC ≈40 mm, yielding a separation between real and virtual prisms of about 600 mm. Straightforward central output wavelength tunability in the range 1065–1080 nm allowed by this resonator setup was readily exploited in order to red shift the spectra and suppress the residual cw components taking advantage of the inhomogeneous broadening. Average output power of 10 mW, and 145-fs-long mode-locked pulses with 10-nm wide spectra centered near 1075 nm were obtained. Even wider spectra of ≈13 nm centered near 1070 nm were supported, but without appreciable pulse shortening.

The higher amount of saturable losses given by the SESAMs available contributed to cw components suppression as well as to significant pulse shortening. We obtained up to 22-mW output power, 92-fs-long pulses, 15-nm-wide spectra centered near 1074 nm with the SESAM-1. Also in this case, the single-prism resonator allowed generation of short pulses as with the phosphate laser; separation between real and virtual prism was ≈400 mm in this setup. The tuning range was as broad as 30 nm, covering almost all the available Nd:silicate fluorescence bandwidth from 1062 to 1092 nm. For any operating central wavelength within such a tuning range, the pulse spectrum FWHM was ≥9 nm, the pulsewidth was ≤120 fs, and the average output power was in excess of 20 mW. In Fig. 4(b), both Nd:silicate fluorescence bandwidth and the full central output wavelength tunability for this laser configuration are shown.

In order to further exploit the wider Nd:silicate glass bandwidth, we also tested a cavity configuration employing a classic pair of FS prisms for GVD compensation, thus avoiding the limitation imposed by (1). The distance between P1 and P2 (see Fig. 1, inset 3) was ≈650 mm. The SWCNT-SAM was placed at a distance of about 400 mm from M2, yielding a cavity mode radius on the SA of ≈80 μm. In these conditions, we obtained the broadest spectrum of 16.5 nm FWHM, at a central output wavelength near 1070 nm, with 10-mW output power. The autocorrelation trace yielded a pulse duration of 99 fs and is shown in Fig. 6 with the corresponding optical spectrum. A small perturbation was needed to startup the mode-locked operation, then it could sustain for several minutes. Local damaging was never observed on the SWCNT absorber. Even shorter pulses and wider spectra (up to ≈20 nm as in [21]) were observed when reducing the amount of net negative GVD. The modulation depth of the absorber was probably insufficient to compensate for the gain reduction due to broad-spectrum oscillation and to stabilize soliton mode locking. In these conditions, in fact, we systematically observed a quick onset of a cw component in the blue tail of the spectrum near the 1060-nm fluorescence peak, causing the mode-locking regime to became unstable and collapse to cw in short time. Increasing negative dispersion restored mode locking with narrower pulses, without changing the spot position on the SA. However, with this SWCNT-SAM, the mode-locking regime was definitely stable for pulse spectra narrower than ≈10 nm. We later substituted the SWCNT-SAM with SESAM-1.

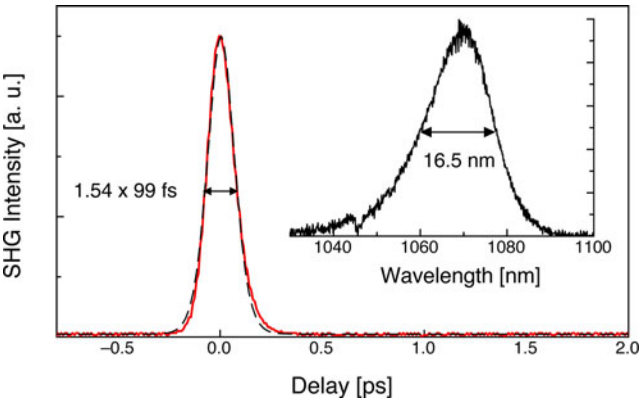

Fig. 6. Shortest pulse autocorrelation obtained with the Nd:silicate laser, SWCNT-SAM and two-prism setup. Also shown is the best fit with autocorrelation corresponding to $sech^2$ pulse shape. Inset: optical spectrum.

In order to obtain stable mode locking, the resonant mode size over the SA was conveniently reduced to about 30 μm by reducing the distance of M2–SESAM to ≈175 mm and adjusting the M1–M2 separation to ≈97 mm for optimal cavity stability. The reduction in mode area on the SA by a factor ≈7 is an indirect confirmation of the ratio of saturation fluences of the two kind of SAs.

Optimizing the net intracavity dispersion (the distance between P1 and P2 was ≈550 mm) and finely adjusting the alignment of cavity end mirrors, self-starting 87-fs-long pulses were obtained, with average power of 15 mW. The corresponding spectrum was centered near 1070 nm and its FWHM was 14 nm (very close to the Fourier limit for $sech^2$ shaped pulses) (see Table III).

Even shorter pulses and wider spectra (≈80 fs, with 15.5-nm FWHM spectra centered near 1078 nm) were obtained with the SESAM-2 with an average output power of 10 mW, as in [4]. The limitation here seems to be the reflectivity bandwidth of the dielectric mirrors, since the spectrum longer wavelength tail extends up to 1100 nm.

V. CONCLUSION

Single-mode laser diodes operating near 800 nm have been proved to be a very effective means for efficient operation of low-power Nd:glass lasers in both cw and femtosecond regimes. Record slope efficiency as high as 58.2% in cw regime and 40% optical-to-optical conversion with 250-fs pulses have been achieved for the first time with diode-pumped Nd:glass lasers.

The output powers and the pulse durations in some cases are not very far from those reported in earlier experiments that

TABLE III
ND:SILICATE LASER: OUTPUT POWER, PULSEWIDTH, AND TIME–BANDWIDTH PRODUCT

	SINGLE PRISM CAVITY			DOUBLE PRISM CAVITY		
	P_{out} (mW)	τ_p (fs)	$\tau_p \times \Delta\nu$	P_{out} (mW)	τ_p (fs)	$\tau_p \times \Delta\nu$
SESAM-1	22	92	0,36	15	87	0,32
SESAM-2	11	100	0,38	10	80	0,32
SWCNT-SAM	10	145	0,38	10	99	0,43

employed more powerful multimode laser diode pumps and more complex beam shaping setups [19], [21]. However, the main purpose of this research was the demonstration of compact, easily tunable Nd:glass ultrafast lasers delivering ∼100-fs pulses near 1-μm wavelength, that can be used for a broad range of applications requiring low power levels of few tens of milliwatts. In particular, the single-prism resonator concept together with the intense pumping here optimized with commercial high-brightness single-mode laser diodes permits relatively large bandwidths for femtosecond generation. We record for the first time 100-fs pulses obtained in a Nd:phosphate laser with a single-prism setup (in [17] only 200-fs pulses were reported): for not-too-short pulse durations, this is a very effective setup allowing easy tuning, which dispersive mirrors cannot readily ensured, for example.

The nearly Fourier-limited pulse generation with the single-prism cavity design shows that the transverse spatial chirp is not significant in the particular setup investigated. Furthermore, SWCNT-SAs have been proved to yield comparable performance to SESAMs in terms of pulse durations, for the first time achieving sub-100-fs operation in Nd:glass lasers, in contrast to what was suggested earlier [11].

It is worth noticing that in the past few years, SWCNTs have been largely employed by many research groups for passive mode locking of fiber lasers, and some commercial ultrafast fiber sources have been developed as well. This is understandable, since fiber lasers usually have much higher gain, and therefore, tolerate larger amount of losses. In fact, SESAMs with SA of few tens percent (with comparable nonsaturable losses) are most often chosen for such lasers.

Thus, it is perfectly clear that solid-state lasers requiring more carefully controlled saturable loss levels ∼1%, need a much more demanding minimization of nonsaturable losses. Indeed, only few papers concerning mode locking of solid-state lasers by SWCNTs have appeared to date.

Concerning the high nonsaturable loss of SWCNT-SAs, it is possible to decrease this fraction, thus improving both laser efficiency and mode-locking performance. One way is to reduce the concentration of PMMA, which was used as matrix of the SWCNT film, or replace it by other polymers with higher transmission. The other way is to control the curling and bundling behaviors of SWCNTs in the dispersion. Accordingly, this parameter crucial for bulk laser mode locking can be engineered. The modulation depth can be also varied to some extent while keeping the nonsaturable loss small. For instance, the nonsaturable loss was recently reduced down to $<0.5\%$ [8].

One important advantage of SWCNT-SAs compared to SESAM is that the SWCNT-SAs exhibit broader spectral applicability. Additionally, SWCNT-based devices can fill the spectral gap, where SESAMs are not well developed.

Recently, we have developed different types of SWCNT-SAs and applied them for bulk laser mode locking in different spectral ranges. Many of the SWCNT-SA samples are being used for more than 2 years with negligible degradation and similar performance as in the beginning. Even though there are further issues to be improved in the novel SWCNT-based SAs, they were successfully used for stable solid-state laser mode locking (even self-starting) with output powers of >200 mW [8], [12].

In conclusion, we believe that, notwithstanding the increasing success of ultrafast fiber lasers, compact Nd:glass oscillators, such as those investigated in this research, can compete in many application areas, also considering the generally favourable noise characteristics of diode-pumped femtosecond solid-state lasers.

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