*Quantum Electronics* **46** (2) 147 – 149 (2016) 

DOI: 10.1070/QEL15966

# On the use of a chirped Bragg grating as a cavity mirror of a picosecond Nd : YAG laser

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*Abstract.* **The first experimental evidence is presented that the use of a chirped volume Bragg grating (CVBG) as a cavity mirror of a *Q*-switched picosecond Nd : YAG laser with self-mode-locking leads to significant changes in the temporal parameters of the laser output. Measurements have been performed at two positions of the CVBG: with the grating placed so that shorter wavelengths reflected from its front part lead longer wavelengths or with the grating rotated through 180°, so that longer wavelengths are reflected first. In the former case, the duration of individual pulses in a train increased from ~35 to ~300 ps, whereas the pulse train shape and duration remained the same as in the case of a conventional laser with a mirror cavity. In the latter case, the full width at half maximum of pulse trains increased from ~70 ns (Nd : YAG laser with a mirror cavity) to ~1 μs, and the duration of individual pulses increased from 35 ps to ~1.2 ns, respectively, which is more typical of free-running laser operation.**

***Keywords:*** *chirped volume Bragg gratings, picosecond laser pulse, image-converter camera.*

## 1. Introduction

Volume Bragg gratings (VBGs) inscribed into photothermo-refractive glass [1] have found wide application in laser engineering owing to their high optical damage threshold, thermal and optical stability, high diffraction efficiency in a wide spectral range (from the visible to the near-IR) and good durability. The use of VBGs as intra- or extracavity diffractive optical components allows the spectral, temporal and spatial characteristics of laser light to be tuned for obtaining necessary output parameters [2 – 9].

A new class of VBGs is chirped volume Bragg gratings (CVBGs), whose period varies in the light propagation direction according to a certain law. Such gratings have high diffraction efficiency in a wide wavelength range. The depth at which light is reflected from a CVBG depends on the light wavelength, which leads to an increase in pulse duration and causes pulse phase modulation (chirp). Linearly chirped gratings, whose period varies linearly, are the most widespread. One application of such CVBGs was described by Vorob'ev et al. [10], who proposed and experimentally demonstrated a new method for temporal shaping of ultrashort laser pulses, based on the interference of chirped beams reflected from a grating. In recent years, CVBGs were thought to be rather attractive for use as stretchers and/or compressors in high-power laser systems that take advantage of chirped pulse amplification (CPA) (see e.g. Refs [11 – 13] and references therein).

In this paper, we examine the possibility of using a CVBG as a cavity mirror of a picosecond laser for obtaining chirped output pulses. Such a laser could be used directly in CPA laser systems, allowing their optical scheme to be simplified.

## 2. Experimental setup and results

The optical source used was a lamp-pumped picosecond Nd : YAG laser whose cavity was formed by a spherical mirror (M1) (radius $R$ = 1.7 m, 95% reflectivity), in optical contact with a saturable absorber (D) (dye 3274), and a flat dielectric output mirror (M2) (40% reflectivity) or CVBG (Fig. 1). To separate the fundamental transverse mode $TEM_{00}$, a 1.7-mm-diameter aperture (A) was placed in the laser cavity. The laser was *Q*-switched, with self-locking of longitudinal modes. The threshold pump energy was ~12.5 J. A single pulse was separated from a pulse train by a Pockels cell. In such a cavity, the full width at half maximum of a bell-shaped pulse train was 70 ± 10 ns, and the duration of a single pulse separated from the middle of a pulse train was $\tau \approx 35 \pm 5$ ps. The total pulse train energy was 1.3 ± 0.2 mJ, the spectral width at a centre wavelength of 1064 nm was 0.3 ± 0.03 nm, the pulse train repetition frequency was 5 Hz, and the pulse separation was about 8 ns.

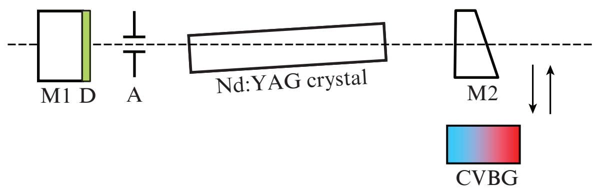


**Figure 1.** Picosecond Nd : YAG laser configuration.

The chirped volume Bragg grating used in our experiment was manufactured by the OptiGrate Corp. (Orlando, FL, USA) and had the following main characteristics: resonance wavelength $\lambda_0$ = 1064.2 nm; spectral bandwidth, 0.84 nm; diffraction efficiency, 93%; stretching factor, 580 ps $nm^{-1}$; aperture, 7.2 × 6 mm; length, 49 mm. In a geometry such that the

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Received 4 November 2015; revision received 18 December 2015
*Kvantovaya Elektronika* **46** (2) 147 – 149 (2016)
Translated by O.M. Tsarev

CVBG used as a laser cavity mirror (Fig. 1) gives a negative group velocity dispersion (GVD), reflected light with wavelengths $\lambda \leqslant \lambda_0$ leads light with wavelengths $\lambda \geqslant \lambda_0$. Rotating the grating through 180° (positive GVD) results in the opposite situation.

The pulse duration of the laser was measured using a PS-1/S1 image-converter camera (ICC) [14], designed at the Photoelectronics Department, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences. In linear sweep mode, the temporal resolution of the ICC reached ~1 ps. Images on the output screen of the camera were digitised by a Hamamatsu C8484 CCD camera and fed to a computer for further processing.

First, we measured the duration of a laser pulse reflected from the CVBG placed outside the cavity in negative-GVD stretcher mode, as recommended in the specifications for the grating. As a result, we found that a reflected pulse was typically bell-shaped and that its full width at half maximum, $t$, increased and varied from shot to shot in the range ~90 – 140 ps. The maximum stretching ratio $t/\tau$ was ~4. Note that the stretching ratio evaluated from the grating specifications was (0.3 nm × 580 ps nm$^{-1}$)/35 ps ≈ 5. The scatter in the duration of pulses reflected from the CVBG may be caused by changes in laser pulse duration and bandwidth. In addition, the high light intensity in the gain element may lead to self-phase modulation in it, which in turn will lead to a laser pulse frequency modulation (chirp). Moreover, a positive laser pulse frequency modulation [15, 16] ('red' frequency components lead 'blue' components) may be accompanied by a decrease in the net chirp of a pulse reflected from the CVBG.

When the CVBG was placed in the laser cavity instead of its output coupler, in negative-GVD mode the laser retained $Q$-switching with self-mode-locking, and the pulse train shape and duration were essentially the same as in the case of the Nd : YAG laser with mirrors M1 and M2. At the same time, the threshold pump energy dropped to ~10 J. The duration $t$ of a single pulse separated from the central part of a pulse train increased to ~300 ps (Fig. 2) and the stretching ratio $t/\tau$ increased to ~8.5. It seems likely that, at the onset of lasing, when the emission bandwidth is close to the luminescence bandwidth of Nd : YAG crystals (0.7 – 1 nm [17]) and is essentially identical to the spectral bandwidth of the CVBG (0.84 nm), the grating efficiency increases, leading to an increase in $t$. On the other hand, the reduction in light intensity in the gain element because of the longer pulse duration may cause a decrease in the amplitude of the positive chirp, and its effect on the total magnitude of the chirp will be weaker than that in the case described above.

After the grating was rotated through 180°, there was no lasing even at the maximum possible pump energy (50 J). To ensure laser operation at acceptable pump energies, the transmission of the saturable absorber had to be increased almost twofold, which most likely led to suppression of $Q$-switched laser operation. Under these conditions, with a threshold pump energy of ~16 J, the nature of the oscillation became more similar to free-running laser operation with self-mode-locking. The full width at half maximum of a bell-shaped pulse train increased from 70 ns to ~1 μs. Figure 3a shows an oscilloscope trace of the central part of a pulse train. It is seen

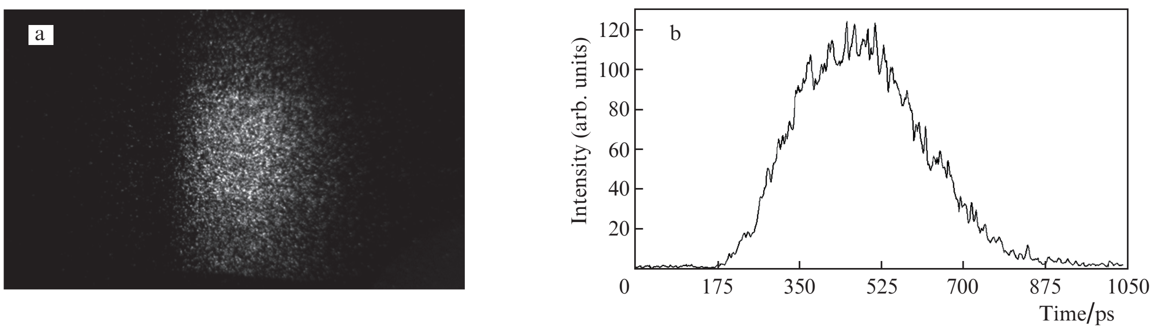


**Figure 2.** (a) Photograph of a pulse from the central part of a pulse train on the ICC screen and (b) microphotogram of the pulse in negative-GVD cavity geometry.

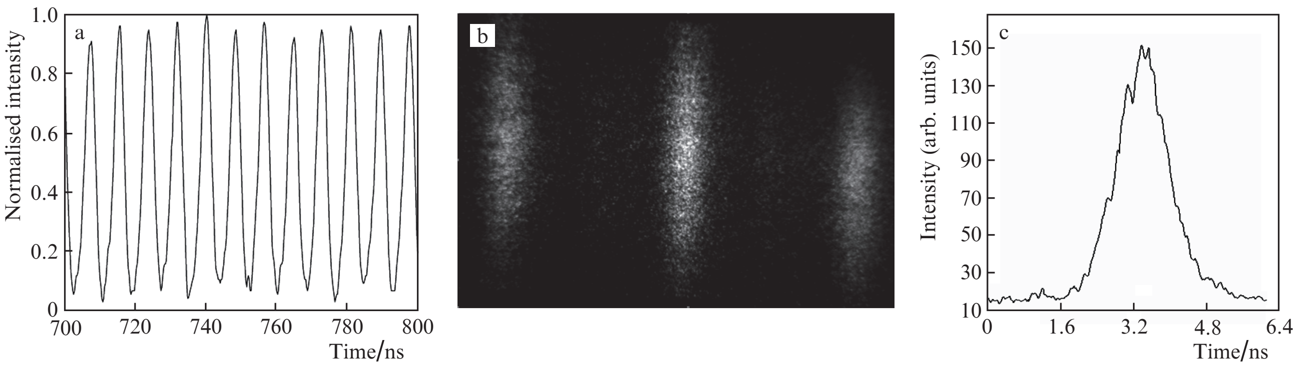


**Figure 3.** (a) Oscilloscope trace of the central part of a pulse train (250-MHz oscilloscope bandwidth), (b) photograph of three pulses in a train on the ICC screen (pulse separation of 8 ns) and (c) microphotogram of the central pulse in positive-GVD cavity geometry.

that, at the same pulse separation in the pulse train as above (~8 ns), the duration of individual pulses, $t$, increased considerably and reached ~1.2 ns. A photograph of three pulses in a train on the ICC screen and a microphotogram of the central pulse are presented in Figs 3b and 3c, respectively. We believe that, in the laser configuration in question, mode locking is due to both the saturable absorber and the CVBG, which introduces distributed feedback into the laser cavity. In contrast to a standard distributed feedback laser, whose cavity consists of an active medium that incorporates a periodic structure and thus ensures spectral selection, the CVBG is a nonperiodic structure maintaining a complete mode composition, which may, under certain conditions, lead to self-locking of longitudinal laser cavity modes.

Note also that, in all three cases (mirror and grating cavities), the spectral bandwidth of output laser pulses remained essentially constant at 0.3 ± 0.03 nm.

## 3. Discussion

The above data lead us to conclude that the use of the CVBG as an output coupler in the cavity of a picosecond Nd : YAG laser leads to significant changes in the temporal parameters of the laser output. In particular, when the grating is placed in the laser cavity so as to ensure negative GVD, the laser retains $Q$-switching with self-mode-locking, but the duration of individual pulses increases from ~35 to ~300 ps (stretching ratio $t/\tau \approx 8.5$). In positive-dispersion geometry, the nature of the oscillation is more similar to free-running laser operation with self-mode-locking, and the duration of individual pulses increases to 1.2 ns ($t/\tau \approx 34$). It seems likely that, at the onset of lasing, when the emission bandwidth is close to the spectral bandwidth of the CVBG, there is first a marked pulse stretching. Moreover, after many cavity passes, even a slight positive chirp in the gain element produces a cumulative effect that leads to an increase in overall chirp amplitude.

The marked difference in the nature of lasing between the two positions of the CVBG used as the output coupler of the Nd : YAG laser cavity is probably due to the nonlinear spatial dependence of the grating period, which is significantly influenced by rotation of the grating through 180°. It also should be noted that a slight deviation of the dispersion law of the CVBG from linearity may increase or reduce the cumulative effect.

## 4. Conclusions

We have carried out a preliminary experimental study of a picosecond Nd:YAG laser with a CVBG placed in the laser cavity instead of its output coupler with the aim of generating chirped pulses. The generation of such pulses has been demonstrated for two positions of the grating, but in substantially different laser operation modes. To understand the origin of the observed effect of the grating, further experimental work is needed, such as measurements of the sign and amplitude of the output pulse chirp and evaluation of the effect of CVBG parameters on laser operation, in conjunction with theoretical studies aimed at assessing the dynamics and mechanisms of Nd : YAG laser operation with a CVBG reflector.

***Acknowledgements.*** This work was supported by the Russian Foundation for Basic Research (Grant No. 13-02-00353).

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