Single-frequency-mode Q-switched Nd:YAG and Er:glass lasers controlled by volume Bragg gratings

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Abstract: This paper presents the results of experimental studies on Q-switched flash-lamp pumped Nd:YAG and Er:glass lasers with resonators formed by volume Bragg gratings. This novel design results in single-frequency mode operation with millijoules pulse energy. The mode selection is performed only by volume Bragg gratings that dramatically simplifies laser design.

OCIS codes: (140.350) Lasers, solid-state; (090.7330) Volume gratings

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1. Introduction

Q-switched high peak power solid-state lasers find widespread application in nonlinear optics, free space optical communication, LIDARs and holography. Despite a number of advances in laser modeling and engineering, the design of these lasers remains nearly the same for the last 20 years. The general approach for such lasers is usually based on the use of rare-earth

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element-doped crystals or glasses as the gain media and passive or active Q-switching. For all these applications single-frequency mode (SFM) – one longitudinal and TEM_{00} fundamental transverse mode – generation is a key parameter.

The most common technique to produce TEM_{00} mode output is the use of a nearly plane-parallel resonator with an internal aperture for transverse mode selection. However, such a selection confines the area of the laser aperture, thus decreasing total output power. There are a number of techniques developed for increasing the TEM_{00} mode volume in an active element, which is normally considerably larger in diameter than the mode size. This is why resonators designed for TEM_{00} mode operation represent a compromise between conflicting goals of large mode area diameter, insensitivity to perturbation, effective mode discrimination and compact resonator length.

Longitudinal mode selection is a very difficult task that requires a complicated wavelength selective filter to suppress all longitudinal modes from lasing except a single one. Laser cavity design for a single-longitudinal mode is usually based on spectral selectors containing multiple dispersive elements. Several methods are commonly used to produce SFM operation. These methods include the usage of intracavity Fabry-Perot etalons, interferometric filters, surface gratings and prisms. In most cases multiple selective elements must be used to secure SFM. This results in a complex and unreliable laser design due to strict requirements for alignment of spectral selectors. Moreover, these lasers are very sensitive to vibrations and environment, which restricts their applications.

In recent publications a new type of longitudinal mode selector for solid state lasers was demonstrated [1]. This approach is based on intracavity mode selection by volume Bragg gratings (VBG) recorded in photo-thermo-refractive (PTR) glass. Unique properties of diffractive elements in PTR glass such as high laser damage threshold and unrestricted life time pave the way for various laser applications of this material [2]. Both reflecting and transmitting Bragg gratings can be developed in PTR glass with diffraction efficiency exceeding 99%. These gratings can have spectral selectivity as narrow as 30 pm and angular selectivity below 1 mrad. Various types of lasers with intracavity VBGs demonstrate an efficient selection of transverse and longitudinal modes [3]. The use of reflecting Bragg gratings as output couplers for CW and pulsed solid state and semiconductor lasers has shown narrowing and stabilization of laser emission spectra without a decrease in output power[1, 4-6].

In the present paper we report on the use of VBGs as intracavity optical elements for obtaining SFM generation in Q-switched Nd:YAG and Er:glass lasers.

2. Experiment

2.1 Volume Bragg Gratings for intracavity mode selection

The properties of PTR glass allow fabricating all types of VBGs in the bulk of the glass. The main advantages of VBGs in PTR glass are unrestricted life time, non-significant losses

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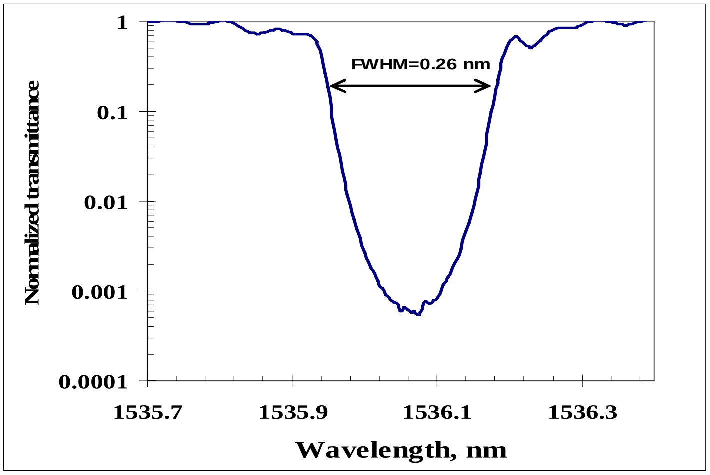

Fig. 1. Spectral profile of a collimated beam transmitted by a RBG used as a total reflector in an Er:glass laser. Transmittance below 0.001 corresponds to diffraction efficiency exceeding 99.7%.

and tolerance to high energy and power optical radiation. These properties combined with high uniformity of the glass enable their use in various optical and laser systems. However, up to now these gratings have been mostly applied in semiconductor laser design for wavelength stabilization [7].

In order to explore its application for mode selection in a pulsed solid state laser we fabricated VBGs with high diffraction efficiency at 1064 and 1550 nm. Reflective Bragg gratings (RBG) with narrow spectral selectivity were designed mainly for axial mode selection. Figure 1 shows the spectral dependence of diffraction efficiency of a RBG centered at 1536 nm. One can see that this grating has a bandwidth (FWHM) of about 0.26 nm and diffraction efficiency more than 99.7%. The most important feature of RBGs is that the diffraction efficiency depends strongly on incident wavelength. Thus, even the closely spaced axial modes of any laser cavity will be reflected with different efficiency.

For the selection of spatial modes a transmitting Bragg grating (TBG) with narrow angular selectivity was designed. It is necessary to point out that the TBG provides transverse (or spatial) mode selection in angular space. This approach, in contrast to traditional mode selection by an aperture, has several advantages. The diameter of the TEM_{00} mode will be determined by the angular acceptance of the TBG and not by an aspect ratio of a laser cavity. Thus, a large diameter of a diffraction limited laser beam can be obtained in a very short laser resonator and will be limited by aperture of intra-cavity elements. Figure 2 shows the dependence of diffraction efficiency on incident angle (i.e. angular selectivity) of a TBG designed for transverse mode selection in a Nd:YAG laser. This grating has a period of 3.6 μm and its angular selectivity (FWHM) is about 3 mrad.

2.2 Nd:YAG laser

Figure 3 shows the geometry of a SFM Nd:YAG laser based on two VBG gratings. The laser cavity consisted of a high reflectivity mirror, a TBG having diffraction efficiency ~90% and a RBG having reflectivity about 60% as an output coupler. Both gratings were aligned inside the cavity to operate at the highest diffraction efficiency that results in the smallest achievable for this cavity threshold pump energy. A Nd:YAG crystal of 4-mm-diameter and 77 mm length having 1 degree butt-end wedge was used in an assembled cavity pumped by a single flash-lamp. A Cr^{4+}:YAG saturable absorber with 50% transmittance provided passive Q-switching. An adjustable diaphragm secured the conventional transverse mode selection. Total

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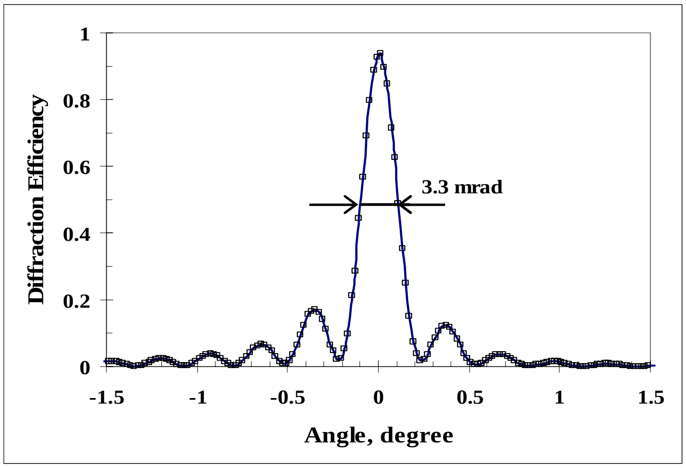

Fig. 2. Angular profile of diffraction efficiency of TBG used as a selector of transverse modes in a Nd:YAG laser

optical length of this cavity was about 30 cm which corresponded to ~1.9 pm axial mode spacing. The spectrum of the output laser radiation was measured by a Fabry-Perot etalon having 11.3 pm free spectral range at λ=1064 nm and 0.4 pm resolution. The spatial distribution of the output radiation was measured by a Spiricon CCD-camera.

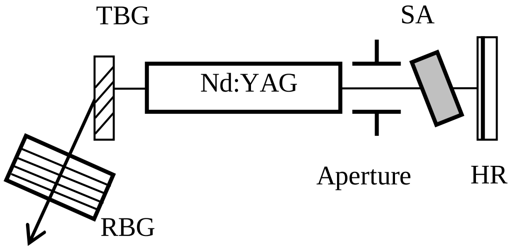

Fig. 3. Schematic diagram of SFM Nd:YAG laser. HR- high reflectivity dielectric mirror, SA-saturable absorber.

In this geometry the laser oscillated with one or two axial modes, ~ 40 ns pulse width, and output pulse energy of about 1 mJ at a repetition rate of 1 Hz. The spectral selectivity of the 4 mm thick RBG used as output coupler was 0.14 nm (FWHM). It was not enough to select a single axial mode. In order to obtain single longitudinal mode generation the RBG was tilted in the horizontal plane. This misalignment resulted in a shift of spectral profile of the grating with respect to the Nd:YAG luminescence peak. It provided robust SFM operation due to a decreased spectral width of the gain contour.

The SFM operation of this laser cavity with an opened diaphragm was achieved by the additional detuning of RBG from Bragg condition in the vertical plane. It resulted in matching the angular selectivity of reflecting and transmitting gratings in orthogonal directions. This approach allowed us to observe SFM oscillation with single longitudinal and almost pure TEM_{00} mode (Fig. 4 (A), (B)). The measured total spectral width of the output pulse was about 0.5 pm which was nearly four times less than the longitudinal mode separation. At threshold pump energy of Ep=Eth=15 J, the laser emitted ~40 ns Q-switched single pulse with energy of about 2 mJ [8]. It should be noted that single frequency operation was maintained even when the pump energy was increased 20% above threshold and the repetition rate was increased to 10 Hz.

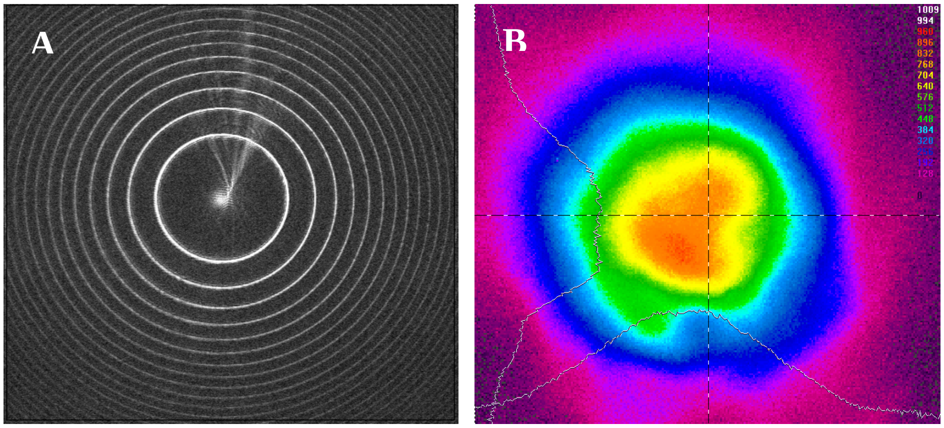

Fig. 4. Emission spectrum (A) and intensity distribution in the near field (B) of a Q-switched SFM Nd:YAG laser

2.3 Er:glass laser

The realization of SFM operation for an Er-doped glass laser essentially differs from the previous case of a Nd:YAG laser. This is due to the fact that unlike the four-level gain medium of the Nd:YAG lasers, the Er:glass lasers belong to the three-level system. As a result the single-pass gain of the Er:glass laser is approximately two orders of magnitude less than that for a Nd:YAG laser gain. On the one hand the pumping threshold of the Er:glass laser becomes relatively high, but a greater number of round trips inside the resonator facilitates the conditions of selection both for transverse and longitudinal modes [9-11].

The optical scheme of the Er-doped glass laser was the following. An Er:glass rod with one degree tilted polished ends and a narrow band antireflection coating for 1535 nm of 4 mm diameter and 77 mm length (Kigre QX/Er 8080) was used for the laser design. It was flash lamp pumped. The laser resonator was formed by a high reflectivity (HR) mirror at 1535 nm and a RBG with diffraction efficiency of 99.7% and spectral selectivity of 0.26 nm at the wavelength 1536 nm, and an output coupler. The output coupler was a 10% partially reflectivity mirror at ~1535 nm inserted into the cavity at an angle so that the laser had two equivalent outputs. An electro-optical modulator (EOM) was used to provide Q-switching. Active Q-switching was chosen to have the possibility of controlling buildup time for optimization of the SFM operation. The EOM consisted of a polarizer (Glan prism), a nonlinear BBO crystal and a quarter wave plate. The BBO crystal (Quantum Technology Inc.,) had low insertion losses at 1535 nm and high laser damage threshold (5 GW/cm^2, 10 ns) that enables design of high energy lasers.

Total optical length of the laser cavity was ~ 43 cm which corresponded to ~ 2.7 pm axial mode interval. The spectrum of output laser radiation was measured by a Fabry-Perot interferometer with free spectral range of about 24 pm and resolution of 1.7 pm.

Stable SFM operation of this laser was achieved for the free running mode even for multispike oscillation due to the long buildup time of ~ 1ms which results from a time difference between the pump pulse width (~ 300 μs) and Er:glass fluorescence time (~8 ms [12]). The long buildup time leads to suppression of an adjacent mode due to fact that RBG (see Fig. 1) has a small but

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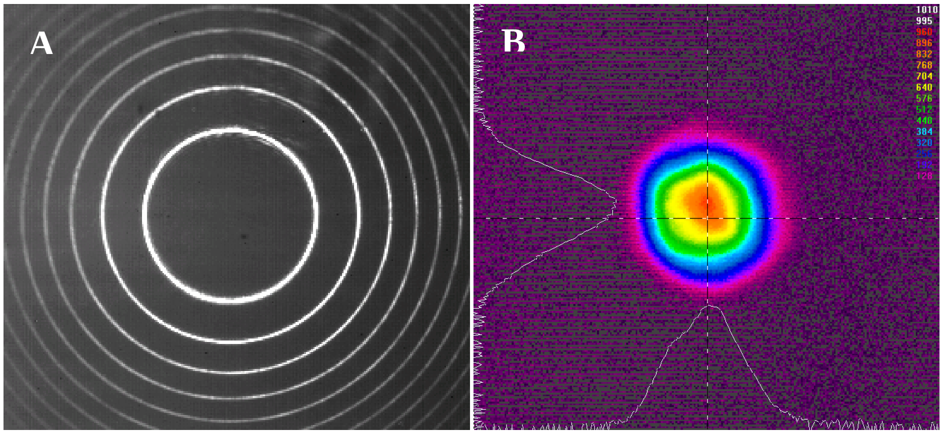

Fig. 5. Emission spectrum (A) and intensity distribution in the near field (B) of a Q-switched SFM Er:glass laser

distinct difference in reflectivity for each mode. In Q-switched operation this laser oscillated at two or three adjacent longitudinal modes. Distinction between these two regimes can be explained by the difference in buildup time. In the case of active Q-switching buildup time is mainly defined by a fast leading edge of a high voltage pulse applied to the Pockel's cell that was about 8 ns. It is necessary to mention that if this laser is based on conventional mirrors it oscillates several adjacent axial modes both in free running and Q-switched regimes.

In order to obtain SFM operation of in this laser the EOM was slightly open for increasing buildup time. In this case at the threshold pump energy of Ep=Eth=50 J, the laser emitted ~ 350 ns Q-switched pulse at a single axial and TEM_{00} mode (Fig. 5 (A), (B)). The SFM operation was kept safe while pump energy was increased and at Ep=70 J the laser generated ~ 200 ns pulse with energy of about 1.2 mJ at maximal repetition rate of 1 Hz. Further increasing pump energy resulted in two or three axial mode generation, spatial shape deformation of the pulse and appearance of the second transverse mode.

The passive Q-switched operation of this Er:glass laser was also realized. A saturable absorber, $Co^{2+}:MgAl_2O_4$ (MALO) crystal, with initial transmittance of 90% was introduced into the cavity instead of an EOM. The compact saturable absorber allowed us to shorten the laser cavity to 25 cm and resulted in increased axial mode separation from 2.7 pm to 4 pm. Moreover, the saturable absorber increased the buildup time and resulted in SFM oscillation of this laser with pulses of 1.6 mJ at 120 ns.

3. Conclusion

Volume Bragg gratings recorded in photo-thermo-refractive glass provided efficient selection of longitudinal and spatial modes in solid state lasers with large apertures. It was shown that VBG incorporated into the laser cavity resulted in single-frequency mode operation of Nd:YAG and Er:glass lasers in standing-wave resonators. This approach enables design of compact and robust single frequency lasers with several millijoules pulse energy.

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