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Q-switched quasi-phase-matched self-frequency doubling and summing in a laser based on a periodically poled Nd : Mg : $LiNbO_3$ crystal

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***Abstract*. Quasi-phase-matched second harmonic generation at 542 nm by self-frequency doubling laser radiation at 1084 nm and quasi-phase-matched sum-frequency generation at 464 nm by summing frequencies of laser radiation and of nonabsorbed fraction of diode laser pump radiation at 810 nm are experimentally achieved. These processes are realised in a *Q*-switched laser based on a periodically poled active nonlinear Nd : Mg : $LiNbO_3$ crystal.**

Keywords: *quasi-phase-matched generation, self-frequency conversion, active nonlinear crystal, periodically poled structure.*

1. Introduction

Recent progress in the development of self-frequency-conversion lasers was achieved due to the use of active nonlinear periodically poled crystals (PPCs) doped with rare-earth ions such as Nd, Er, and Yb [1 – 5].

The use of diode-pumped active nonlinear PPCs substantially extends the possibilities of obtaining self-frequency conversion, which is important for the development of compact and reliable solid-state lasers emitting in the blue, green, red, and IR spectral regions [6]. Active nonlinear PPCs placed in a laser resonator can be used to realise nonlinear-optical interactions involving laser radiation and its harmonics, as well as pump radiation [6, 7].

In this paper, we report the results of experiments on quasi-phase-matched self-frequency doubling and quasi-phase-matched summation of frequencies of laser and pump radiation in a *Q*-switched laser based on a Nd : Mg : $LiNbO_3$ PPC.

2. Nd : Mg : $LiNbO_3$ PPCs

An active nonlinear Nd : Mg : $LiNb_3$ PPC is a promising material for nonlinear-optical devices for quasi-phase-matched self-frequency conversion [2 – 5]. The Nd ions determine the active properties of the crystal [8], while the periodically poled structure allows the fulfilment of conditions for efficient nonlinear frequency conversion. The Nd : Mg : $LiNbO_3$ crystals were grown from a melt (whose composition was close to the congruent one) by the Czochralski technique along the normal to the close-packed $(01\bar{1}2)$ face [9]. Such crystals belong to the so-called facet-type crystals. The period Λ of the periodically poled structure in them is determined by the ratio of the speed of crystal pulling from the melt to the rotation velocity of the crystal during its growth. The periodicity of the domain structure and the concentration of the Nd_2O_3 and MgO impurities in crystals were studied by the methods of selective chemical etching and X-ray analysis [10]. Our studies showed that the average weight concentrations of Nd_2O_3 and MgO were $\sim 0.5\,\%$ and $\sim 0.8\,\%$, respectively, and the domain walls in the central part of a crystal boule were parallel to the $(01\bar{1}2)$ face (Fig. 1). We fabricated two elements with $\Lambda \sim 7$ and ~ 4 μm for experiments on quasi-phase-matched self-frequency doubling and summing.

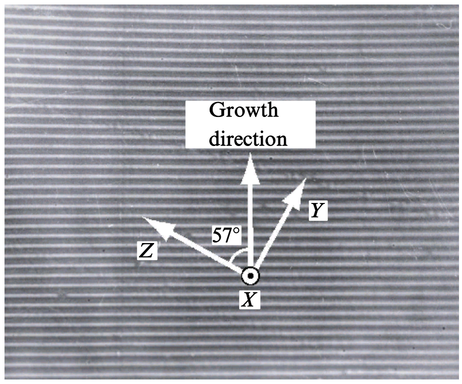

Figure 1. Photograph of the periodically poled structure in a Nd : Mg : $LiNbO_3$ crystal obtained by the method of selective chemical etching (X, Y, and Z are crystallographic axes).

3. Quasi-phase-matched self-frequency doubling in a Nd : Mg : $LiNbO_3$ PPC

The scheme of the experimental setup is shown in Fig. 2. The element of length 7 mm with the period $\Lambda = 7 \pm 0.2$ μm was placed inside a hemispherical resonator near a flat

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mirror. The radius of curvature of a spherical mirror was 20 cm and the resonator length was ~ 21 cm. The flat mirror had a high reflectivity at the laser wavelength of 1084 nm and the second-harmonic wavelength of 542 nm. The output spherical mirror had a high reflectivity at the laser wavelength and a high transmission ($\sim 80\,\%$) at the second-harmonic wavelength. The crystal was pumped by a cw ATC-C1000-150 diode laser at 810 nm and absorbed about of 0.4 W of pump radiation. The pump-beam diameter in the crystal was ~ 150 μm. Q-switching was achieved by means of an MZ-302 acousto-optic modulator.

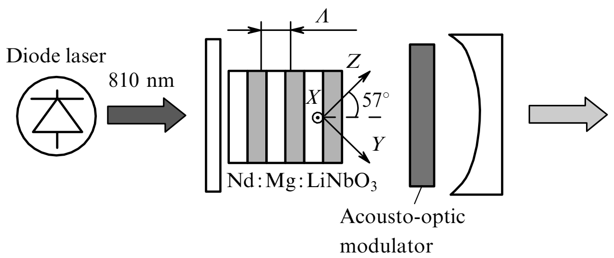

Figure 2. Scheme of the experimental setup.

The polarisation planes of laser radiation, second-harmonic and pump radiations were parallel and lied in the YZ plane. Therefore, the e – ee nonlinear interaction was realised in the crystal. The nonlinear coefficient d_{33} (the largest for lithium niobate) made the main contribution to the second harmonic generation. The effective nonlinear coefficient calculated for our experimental conditions was 12 pm V^{-1} (the calculation was performed based on data [11]). Figures 3 and 4 show the dependences of the average output power of the second harmonic at 542 nm, the peak power, and the second-harmonic pulse duration on the pulse repetition rate.

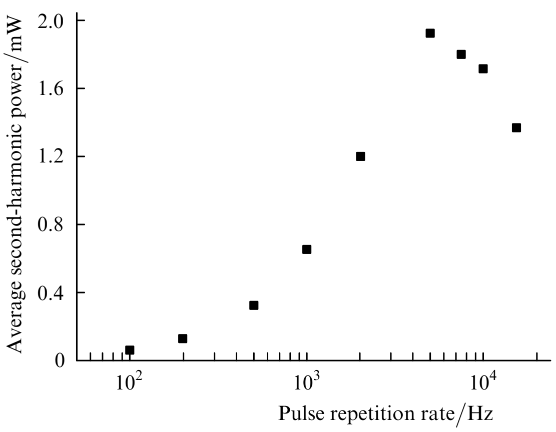

Figure 3. Dependence of the average output power of the second harmonic at 542 nm of the pulse repetition rate.

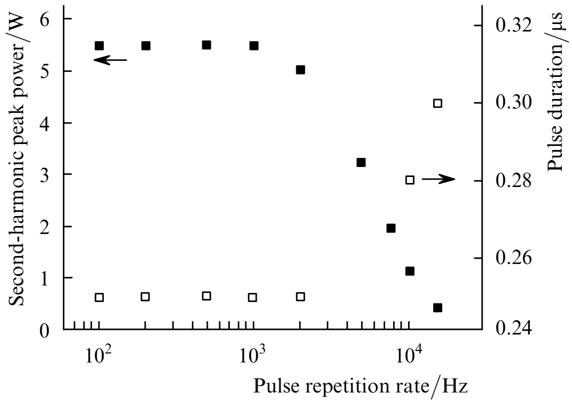

Figure 4. Dependences of the peak power (■) and the 542-nm second-harmonic pulse duration (□) on the pulse repetition rate.

4. Quasi-phase-matched summation of laser and pump radiation frequencies in the Nd : Mg : $LiNbO_3$ PPC

In this process, the absorbed fraction of pump radiation causes lasing, while its nonabsorbed fraction at 810 nm is used for summation (mixing) with laser radiation at 1084 nm. As a result, lasing occurs at the sum-frequency (at 464 nm) in the blue region. The Nd : Mg : $LiNbO_3$ crystal of length 6 mm with the period $\Lambda = 4 \pm 0.1$ μm was placed inside the hemispherical resonator near the flat mirror. The radius of curvature of the spherical mirror was 20 cm and the resonator length was ~ 21 cm. The flat mirror had a high reflectivity at the laser radiation wavelength, while the output spherical mirror had a high reflectivity at the laser radiation wavelength and a high transmission ($\sim 90\,\%$) for sum-frequency radiation.

The crystal was pumped by cw ATC-C1000-150 and ATC-C500-35 diode lasers at 810 nm and absorbed ~ 0.9 W of pump radiation. Q-switching was performed using the same MZ-302 acousto-optic modulator. The polarisation planes of laser radiation, pump and sum-frequency radiations were parallel and lied in the YZ plane, providing nonlinear e – ee interaction with the largest contribution from the nonlinear coefficient d_{33}. Figure 5 shows the dependences of the peak power and the sum-frequency pulse duration on the pulse repetition rate.

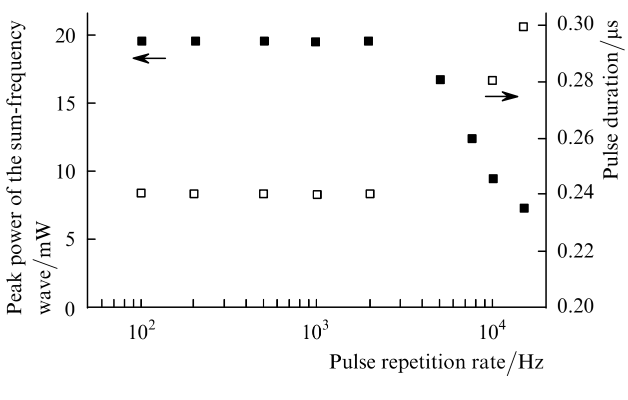

Figure 5. Dependences of the peak power (■) and pulse duration (□) at the sum-frequency (464 nm) on the pulse repetition rate.

5. Conclusions

We have realised and studied quasi-phase-matched processes of self-frequency doubling and summing in a Q-switched laser based on a nonlinear Nd : Mg : $LiNbO_3$ PPC. Although the efficiencies of second harmonic and sum-frequency generation proved to be rather low, nevertheless these are the best results obtained for PPC lasers so far. One can expect that a further optimisation of the domain-structure period and of other crystal parameters (optical quality, crystal length and concentration of active ions) will not only increase the efficiency of nonlinear frequency conversion considered in this paper but also will allow the realisation of more complicated self-frequency conversion processes in active nonlinear PPCs [6].

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