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Laser radiation frequency doubling in a single-crystal fibre based on a stoichiometric $LiNbO_3$ crystal*

V.V. Kashin, D.A. Nikolaev, S.Ya. Rusanov, V.B. Tsvetkov

Abstract. **We demonstrate the employment of single-crystal optical fibres based on lithium niobate for doubling the laser radiation frequency. The measured characteristics of the fibre confirm its high quality and spatial homogeneity. Parameters of the frequency doublers for neodymium laser radiation (λ = 1 μm) based on fibre and bulk single crystals are compared. Single crystals are grown by the method of laser-heated pedestal growing with heating by radiation of a CO_2 laser (LHPG-method).**

Keywords: *single-crystal fibre, lithium niobate, radiation frequency doubling.*

1. Introduction

Parametric frequency conversion of low-peak-power laser radiation is an actual problem of nonlinear optics. This problem cannot be solved by increasing the light field intensity via tight focusing of the beam for obtaining a small transversal dimension of the waist because this approach results in a shorter length of effective interaction (due to a shorter waist length and possible influence of extraordinary wave walk-off). The length of nonlinear interaction of radiation with constant intensity can be made greater by using elongated nonlinear media of small cross section which possess waveguide properties.

To this end, we have produced single-crystal fibres on the basis of a stoichiometric $LiNbO_3$ crystal which possesses high nonlinear and optical properties. The fibres are intended for doubling the radiation frequency of Nd:YAG lasers and have been grown with the angle of 90° to the optical axis. The properties of the fibre as a frequency doubler and its spatial homogeneity are studied by a single-mode Nd:YAG laser which ensures small waist dimensions and possibility of scanning over the sample volume. It was the aim of the present work.

2. Growing of single crystal fibres

Single crystal fibres based on lithium niobate were obtained by using the method known as LHPG [1], in which a single crystal fibre is grown on an oriented single-crystal seed from the melt drop produced on a face (pedestal) of the initial preform that is heated by radiation of a CO_2 laser. Presently, there is a series of works concerning technological problems in producing single crystal fibres of high optical quality from lithium niobate [2–4]. The main attention is paid to choice of the composition of initial preforms and regimes of growing single crystal fibres.

No material science aspects of growing such fibres are considered in the present work. As preforms we used rods of dimension 1.2×1.2 mm with the length of 30–50 mm cut from a bulk single crystal of lithium niobate (with a stoichiometric composition). The seed was a thin rod of size 0.5×0.5 mm cut from the same material so that its axis was normal to the optical axis of lithium niobate single crystal. In cutting the preforms, the single crystal was oriented by using an X-ray diffractometer. The optimal rate of growing was ~50 mm h^{-1}, the length of single crystal samples reached 150 mm and their diameter was 300–800 μm (depending on the drawing rate). After growing, the fibres were annealed (by holding at a temperature of ~1000 °C for 1 h with the following cooling for 6 h). The sample surfaces were of optical quality (see, for example, Fig. 1). Plane faces of crystalline fibres were polished prior to carrying out experiments.

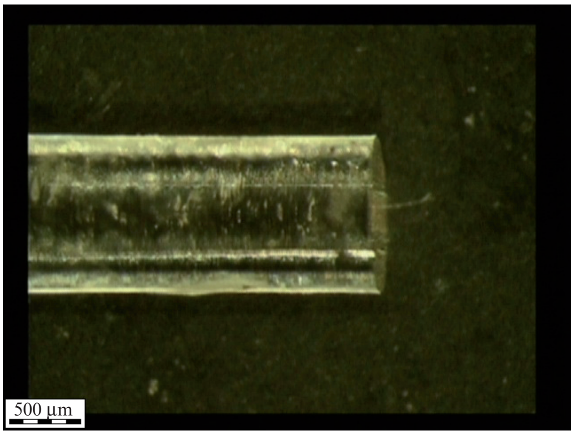

Figure 1. Photograph of a fragment of a single-crystal fibre made of lithium niobate.

3. Study of optical properties of fibre

Spatial homogeneity and optical parameters of the single-crystal $LiNbO_3$ fibre used as a frequency doubler were investigated on the experimental setup that is schematically shown

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in Fig. 2. As a source of probe radiation we used a single-mode, Q-switched Nd:YAG laser. A cw JOLD-22-CPXF-1L diode module with a fibre output optically pumped the active element (AE). The centre wavelength of the diode radiation was 808 nm. A two-lens system FS focused the output radiation of the diode module into the AE bulk in the form of a beam of diameter approximately 300 μm, which provided generation in a single fundamental transverse mode.

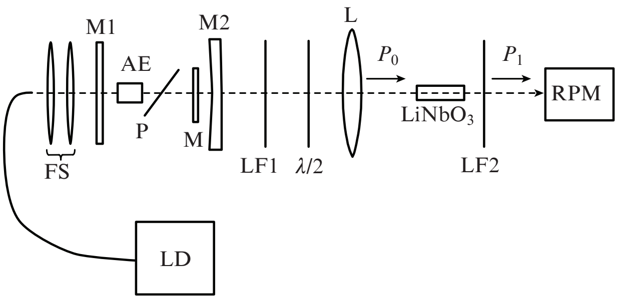

Figure 2. Optical scheme of experiment: (LD) pump laser diode; (FS) lens focusing system; (M1, M2) cavity mirrors; (AE) active element Nd:YAG; (P) polariser; (S) Q-switch of the cavity; (SF1, SF2) spectral light filters; ($\lambda/2$) half-wave phase plate; (L) focusing lens; ($LiNbO_3$) sample under study; (RPM) radiation power meter.

The cavity Q-switch based on a Cr^{4+}:YAG crystal provided generation of an instantaneous comb of giant pulses with the pulse repetitive rate of 10 kHz and pulse duration (FWHM) τ = 20 ns. The output radiation of the laser was linearly polarised with the electric field vector lying in the plane of Fig. 2. This was provided by an intracavity polariser (P). The phase plate $\lambda/2$ was used to vary the polarisation vector of radiation inside the $LiNbO_3$ crystal relative to the initial polarisation. A spectral light filter (SF1) eliminated the 808-nm radiation of diode pumping unabsorbed in the AE. The single-crystal fibre under study had the diameter of 600 μm and length of 18 mm (see Fig. 1). The fibre faces had no antireflection coatings. The laser radiation was focused to the bulk of crystalline fibre by the collecting lens L with the focal length of 53 mm. The waist diameter $2\omega_0$ inside the fibre was about 37 μm (at the level e^{-2}). The length of waist inside the fibre was $2Z_0 = (2\pi n^{o}_{\lambda_p}\omega_0^2)/\lambda_p \approx 4.2$ mm. Here, λ_p = 1.064 μm is the pump wavelength, $n^{o}_{\lambda_p} = 2.234031$ is the refractive index of an ordinary beam at wavelength λ_p. The maximal beam radius inside the fibre at the waist positioned in the plane of a fibre face did not exceed 140 μm. Thus, the geometry of the experiment allowed one to investigate the spatial homogeneity of nonlinear properties in the cross section of crystalline fibre (as along so and across the axis) at the waist centre separated from the fibre axis by distances of up to 150 μm. The position of the beam waist in the fibre volume was varied through longitudinal and transversal displacements of the fibre.

The coefficient K of conversion of laser radiation with wavelength λ_p = 1064 nm to radiation with wavelength λ_{SH} = 532 nm was experimentally studied. To this end, the average power P_0 of radiation (1064 nm) entering the single crystal fibre and the average power P_1 of the output radiation (532 nm) from fibre that has passed through the spectral filter SF2 were measured by a FieldMaster GS power meter. Light spectral filter SF2 was used to remove the residual radiation at λ = 1064 nm that had not been absorbed in the fibre. The transmission coefficient of the filter SF2 was 0.76 at a wavelength of 532 nm and it was $\leqslant 10^{-6}$ at a wavelength of 1064 nm. Power P_0 remained constant in the experiments and was 600 mW. Power P_1 strongly depended on a turn angle of the plate, $\lambda/2$, and was actually independent (within the experimental error of 10%) of the waist position in the fibre. This fact confirms high spatial homogeneity of nonlinear optical parameters of the fibre. The maximal value of P_1 was 1.2 mW. Thus, the conversion coefficient of radiation with λ_P = 1065 nm to the second harmonic $K = P_1/P_0TT_1^2$ is homogeneous over the volume and equals 3.6×10^{-3}. Here, $T_1 = 0.866$ is the transmission coefficient of a face of the fibre with the refraction coefficient of 2.23. Measurements have been performed at a fibre temperature of 300 K.

The geometry of the experiment was mainly aimed at studying spatial homogeneity of the optical properties of the fibre. A relatively low intensity of the pump wave and non-zero phase mismatch of interacting waves prevented obtaining high values of K. One may compare (in the approximation of the constant pump intensity) the measured coefficient K with that expected in our experimental conditions for a bulk $LiNbO_3$

$$\eta(z) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_{\lambda_p}(x,y,t)\eta'(I_{\lambda_p}(x,y,t),z)\,\mathrm{d}x\mathrm{d}y\mathrm{d}t}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_{\lambda_p}(x,y,t)\,\mathrm{d}x\mathrm{d}y\mathrm{d}t}. \quad (1)$$

Here, $I_{\lambda_p}(x,y,t)$ is the spatially transverse and temporal distribution of the pump beam intensity; and η' is the coefficient of converting the pump radiation to the second harmonic. In the waist plain the distribution of the pump intensity is

$$I_{\lambda_p}(x,y,t) = I_0\exp\left[-2\frac{x^2+y^2}{\omega_0^2} - 4(\ln 2)\frac{t^2}{\tau^2}\right], \quad (2)$$

where $I_0 \approx 500$ MW cm^{-2}. The conversion coefficient for a constant-intensity plane wave propagating along the z axis is

$$\eta'(z) = \frac{I_{\lambda\mathrm{SH}}(L)}{I_{\lambda_p}(0)} = \frac{32\pi^2 d_{\mathrm{eff}}^2}{(n^{o}_{\lambda_p})^2 n^{e}_{\lambda\mathrm{SH}}\lambda_p^2\varepsilon_0 c\,|\Delta k|^2} I_{\lambda_p}(0)\sin^2\left(\frac{\Delta kz}{2}\right), \quad (3)$$

where λ_{SH} = 532 nm; $\varepsilon_0 = 8.85\times10^{-12}$ F m^{-1}; and $c = 3\times10^8$ m s^{-1} [5]. The mismatch of the wave vectors is

$$\Delta k = 4\pi(n^{e}_{\lambda\mathrm{SH}} - n^{o}_{\lambda_p})/\lambda_p. \quad (4)$$

The values of refractive indices $n^{o}_{\lambda_p}$ and $n^{e}_{\lambda\mathrm{SH}}$ for ordinary and extraordinary waves propagating in the direction normal to the optical axis of the $LiNbO_3$ crystal, and the value of the effective interaction constant d_{eff} have been obtained by using the SNLO database [6] and were, respectively, 2.234031, 2.233156 and −4.52 pm V^{-1}. By using these parameters and Eqns (1)−(4) we obtained the calculated value of the maximum conversion coefficient $\eta_{\max} \approx 3.3\times10^{-3}$. The value of $\eta_{\max}$ obtained with the parameters taken from literature for a stoichiometric $LiNbO_3$ crystal well agrees with the value of K measured in the single-crystal fibre.

The fibre was tested for structural crystal defects by rotating the polarisation plane of the laser beam and simultaneously scanning the fibre volume by the waist domain. In this case, the relative variation in the second harmonic power at the output from the sample was measured versus a turn angle of the half-wave plate around the axis [Fig. 3, curve (*2*)]. The observed dependence was the same at different positions of the laser beam waist within the boundaries of the fibre. For comparison, in the same figure the similar dependence is shown that was obtained using a commercial $LiNbO_3$ crystal and the dependence calculated from (1). The bulk $LiNbO_3$ sample had the dimensions 10×10×40 mm and was cut in the direction normal to the optical axis. In measurements, it was placed instead of the single-crystal fibre under investigation.

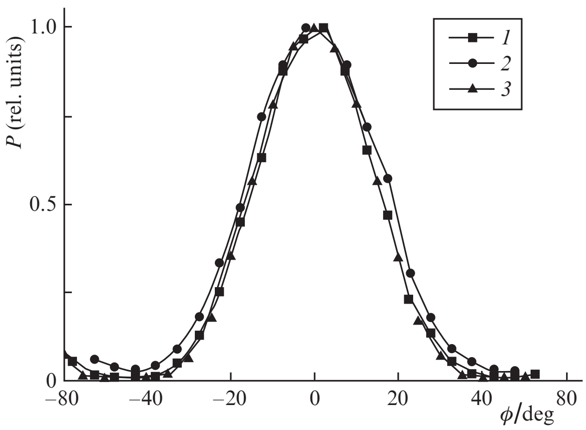

Figure 3. Dependences of the relative power P of the second harmonic at the output from fibre on the turn angle ϕ of the phase plate $\lambda/2$ in the case of (*1*) bulk crystal $LiNbO_3$, (*2*) single-crystal fibre and (*3*) the calculated curve.

4. Conclusions

The method is developed for producing single-crystal fibres based on a stoichiometric $LiNbO_3$ crystal with the required direction of growing relative to its optical axis. The method of laser-heated pedestal growing with heating by radiation of a CO_2 laser is used for manufacturing the fibres. The experiments performed show that the parameters of the single-crystal fibre used as a frequency doubler correspond to those of bulk samples. Single crystal fibres possess high optical quality and structural quality, which gives a possibility to use them for doubling the frequency of fibre laser radiation.

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