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New self-frequency converted $Nd^{3+}:KGd(WO_4)_2$ Raman lasers

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***Abstract*. The spatial orientation of the optical indicatrix axes in a nonlinear neodymium-doped potassium – gadolinium tungstate $Nd^{3+}:KGd(WO_4)_2$ crystal is determined more exactly in experiments. Miniature Raman lasers of two types emitting at 1538 nm are built based on this crystal. The laser of the first type has an output energy of 5 – 7 mJ and a pulse repetition rate of up to 1 Hz, while the laser of the second type has an output energy of about 20 mJ and a pulse repetition rate of up to 20 Hz.**

Keywords: *stimulated Raman scattering, neodymium-doped potassium – gadolinium tungstate, self-frequency conversion*

1. Introduction

Lately in the actively developing areas of research in the field of solid-state lasers there has been an upsurge of interest in the R&D of Raman lasers [1]. Such lasers provide emission in a broad spectral range, including eye-safe wavelengths. Raman lasers have been built on the basis of self-frequency conversion of picosecond [2, 3] and nanosecond [4 – 6] pulses in nonlinear media and by converting the radiation from solid-state lasers in various Raman-active crystals [7, 8].

The successful development of these studies is related, in particular, to the emergence of the nonlinear crystal of neodymium-doped potassium – gadolinium tungstate $Nd^{3+}:KGd(WO_4)_2$. This crystal exhibits a unique set of physical properties. For instance, the concentration of neodymium ions can be high (up to 10 %) without substantial reduction of the optical quality of the crystal, the Raman conversion threshold is low (~ 4 GW cm^{-1}), and the cross sections of the main lasing transitions are relatively large.

The optical properties of the nonlinear KGW crystal have been studied and classified, for instance, in papers [9, 10]. However, in our opinion, the new aspects of the application of KGW crystals, in particular as Raman converters, require establishing more exactly the spatial orientation of the axes of the optical indicatrix of this crystal with respect to the crystallographic axes. This has been the goal of our experiment.

We also present the parameters of new Raman lasers emitting at eye-safe wavelengths.

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2. Orientation of the optical-indicatrix axes of the KGW crystal

The biaxial KGW crystal belongs to the monoclinic system of the 2m group. Fig. 1 shows the spatial orientation of the optical-indicatrix axes relative to the crystallographic axes a, b, and c of this crystal, which we determined experimentally by the method described below. According to the common terminology (e.g., see Ref. [11]), the optical-indicatrix semiaxes N_p, N_m, and N_g are proportional to the principal refractive indices n_p, n_m, and n_g, with $n_p < n_m < n_g$. Note that the angle between the crystallographic axis c and the optical-indicatrix axis N_g is 20°, but the spatial position of the N_g axis differs from that reported in Ref. [9] by 40°. Fig. 1 also shows the orientation of one of the optical axes. The axis lies in the N_pN_g plane and makes an angle V_g with the N_g axis. The second optical axis is oriented symmetrically on the other side of the N_g axis at the same angle to the latter.

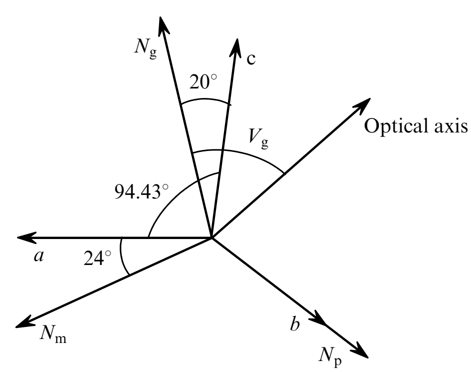

Figure 1. Orientation of the optical-indicatrix axes in a KGW crystal relative to the crystallographic axes.

Note that the orientation of the optical axes in monoclinic crystals depends on the wavelength [11], temperature, electric field, and mechanical stress. However, this is not mentioned in fact in papers devoted to KGW crystals, including Refs [9, 10]. The N_m and N_g axes, which correspond to different wavelengths, exhibit the fan-shaped orientation around the N_p axis perpendicular to it, while the direction of the N_p axis is the same for all wavelengths.

We have found no mention in the literature about the quantitative dependences of the spatial coordinates of the optical-indicatrix axes, i.e., their orientation, on the wavelength in the KGW crystal. In view of this, we estimate these quantities indirectly by calculating the dispersion of the angle of the optical axes inherent in the KGW crystal [11].

The angle V_g between one of the optical axes and the optical-indicatrix axis N_g is given by the expression [11]

$$\tan V_g = \left[\frac{(c/n_p)^2 - (c/n_m)^2}{(c/n_m) - (c/n_g)} \right]^{1/2},$$

where c is the speed of light in vacuum. The angle between the optical axes is, obviously, equal to $2V_g$. Let us find the angles V_g for $\lambda = 1064$ and 633 nm. These angles play an important role in experimental studies of KGW lasers, since at one of these wavelengths (633 nm) optical layouts are aligned (including azimuthal orientation of the active elements), while at the other the lasing characteristics are often studied.

Calculations based on the values taken from Ref. [10] ($n_p = 1.937$, $n_m = 1.986$, and $n_g = 2.033$ for $\lambda = 1064$ nm and $n_p = 1.95$, $n_m = 2.0$, and $n_g = 2.05$ for $\lambda = 633$ nm) yield the angles V_g(1064 nm) = 46.6° and V_g(633 нм) = 46.075°. Accordingly, the dispersion is $\mathrm{d}V_g/\mathrm{d}\lambda = 0.12 \times 10^{-3}$ degree of arc nm^{-1}. Thus, the dispersion of this angle is relatively small and can be ignored in experiments when the optical layout of lasers is aligned at a radiation wavelength differing from that at which the experiment is performed.

The spatial orientation of the optical-indicatrix axes was measured for a KGW crystal sample made in the form of an oblique parallelepiped with faces coinciding with the crystallographic axes *a*, *b*, and *c*. This sample was placed between two crossed polarisers is such a way that the direction of the laser beam coincided with the *b* axis. (Note that the commercially available laser active cylindrical elements fabricated from the KGW crystal are also cut along the *b* axis.) This axis, which coincides with the optical-indicatrix axis N_p, served as the rotation axis of the sample in the experiments.

Two identical laser beams of the same polarisation at 633 nm (He–Ne laser) and 1064 nm (YAG : Nd laser) were alternately transmitted through this system. By rotating the sample about the *b* axis we found the angular positions of the sample at which the transmission of the system was minimal. Taking into account that the two directions of polarization of the incident light corresponding to minimum transmission of such a system coincide with the directions of the optical-indicatrix axes N_m and N_g, we determined the angular position of these axes relative to the directions of the crystallographic axes *a* and *c* (Fig. 1), which are known for the given sample. Alternating the lasers emitting at 633 and 1064 nm, we also determined the wavelength dependence of this angular position. To within experimental error (equal to 1°), no differences in angular position of the N_m and N_g axes for these wavelengths were detected, which confirms the indirect estimates mentioned earlier.

We assume that the spatial orientation of the optical-indicatrix axes in the KGW crystal measured by us more exactly is required for determining the orientation of the laser elements that is optimal for obtaining high lasing efficiency, including self-frequency conversion in Raman lasers.

3. KGW Raman lasers emitting at 1538 nm

At present one of the most important applications of Raman lasers is the building of radiation sources emitting in the eye-safe wavelengths range. The output energy required from such devices depends on their specific applications. In particular, the output energy of laser rangefinders with a range of up to 10 km should be 5–7 mJ.

We have already reported about nanosecond self-frequency converted KGW Raman lasers [4–6, 12]. The1351-nm radiation is converted in the active element of such lasers into the first Stokes component at 1538 nm involving the 901-cm^{-1} Raman-active vibration.

The latest modification of our Raman laser uses a KGW crystal 3 mm in diameter and 50 mm in length and a $LiNbO_3$ *Q* switch (Fig.2). The energy characteristics of this laser (the high efficiency and low lasing threshold) are the best for the class of lasers emitting eye-safe radiation.

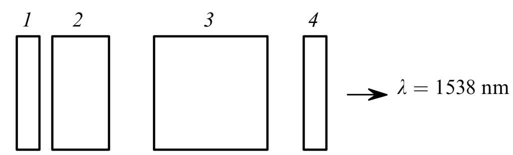

Figure 2. Block diagram of a Raman laser emitting at 1538 nm: (*1*) highly reflecting mirror; (*2*) $LiNbO_3$ electrooptical element; (*3*) active KGW element; (*4*) output mirror.

Fig. 3 [curve (*1*)] shows the dependence of the output energy of this laser on the pump energy. One can see that the differential efficiency of the laser is 0.5 % for a threshold energy of about 1 J. The operating temperature range of our laser extends from −50 to +60 °C. The FWHF duration of the laser pulse is close to 20 ns. The laser is designed as a miniature module whose weight is about 45 g. The flanged mount of the module makes it possible, if necessary, to conveniently match the module with a transmitting telescope or another device. The laser operates without forced cooling in the stationary regime at a maximum pulse repetition rate of up to 0.25 Hz; however, a modification of the laser makes it possible to increase a pulse repetition rate up to 1 Hz.

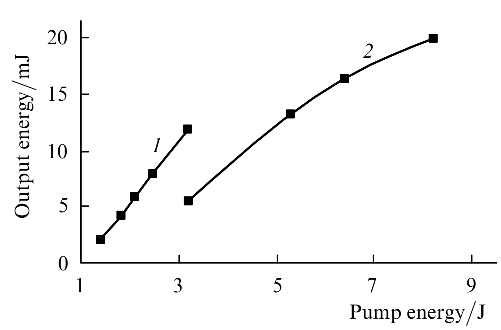

Figure 3. Dependences of the output energy of lasers with KGW crystals 3 mm (*1*) and 4 mm (*2*) in diameter on the pump energy.

Some of laser technology applications require using higher pulse repetition rates. We have built a miniature KGW Raman laser with the pulse repetition rate increased up to 20 Hz due to forced liquid cooling. The output energy of the laser was also raised to 20 mJ by using a larger active element 4 mm in diameter and 50 mm of length. Curve (*2*) in Fig. 3 shows the dependence of the output energy of the laser on the pump energy. When liquid coolants stable to negative temperatures were used, the operating temperature range for this laser was the same as for the previous laser.

Comparative analysis of lasers emitting radiation at the eye-safe wavelengths has shown that, judging by the factors that must be taken into account in designing laser systems such as efficiency, reliability, and operating capacity under various external conditions and cost effectiveness, self-frequency converted KGW lasers have great potential.

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