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Highly efficient pulsed Nd : YAG lasers with radiation frequency conversion

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***Abstract*. The output energy characteristics of Nd : YAG lasers with intracavity nonlinear-optical KTP frequency converters are studied. Conversion efficiencies of 1.0 and 0.55 % were obtained for flashlamp-pumped lasers in the regimes of intracavity SHG and intracavity parametric oscillation, respectively.**

Keywords: *solid-state laser, second harmonic generation, optical parametric oscillator, KTP crystal.*

1. Introduction

The use of nonlinear crystals allows a significant extension of the wavelength range of output radiation from solid-state lasers. In particular, the employment of nonlinear-optical frequency converters involving SHG and parametric oscillation provides an efficient conversion of neodymium-laser radiation at 1.06 μm to the visible and IR spectral ranges.

Among the nonlinear crystals, considerable attention is attracted to potassium-titanyl-phosphate $KTiOPO_4$ (KTP). The large nonlinear coupling coefficient, high resistance to radiation damage, and also large angular and temperature phase-matching widths predetermine its highly efficient use for the frequency conversion of pulsed Nd : YAG laser radiation [1, 2].

Experimental investigations show that the typical energy conversion efficiency in the KTP-assisted conversion of the fundamental radiation to the second harmonic or the signal-frequency wave of an optical parametric oscillator (OPO) (with a wavelength of ~1.6 μm) amounts to 40 % – 60 % [3 – 5].

Note that the optimal transmittance of the output mirrors of pulsed electrooptically *Q*-switched Nd : YAG lasers with a moderate output pulse energy is also equal to 40 % – 60 %. This circumstance establishes the prerequisites for an efficient nonlinear-optical conversion in the case when the nonlinear crystal is placed inside the Nd : YAG-laser cavity. Our paper is concerned with the experimental investigation of the efficiency of pulsed solid-state lasers with intracavity radiation frequency conversion in KTP crystals.

2. Intracavity SHG

To double the frequency of Nd : YAG-laser radiation in a KTP crystal, advantage is most often taken of the type-II phase matching in the *xy* plane ($\theta = 90^\circ, \phi = 23.5^\circ$) [1]. In the intracavity SHG there emerge certain difficulties associated with the fact that the fundamental radiation generally acquires elliptic polarisation after a passage through the KTP crystal. The linearly polarised fundamental radiation whose plane of polarisation makes an angle of 45° with the *z* axis of the crystal is directed to the KTP crystal, which possesses the type-II phase matching. Taking into account the difference between the refractive indices along the *z* axis and along the orthogonal direction shows that the phase incursion due to birefringence amounts to 2π over a crystal length of approximately 12 μm [5]. Since the length of a KTP nonlinear element is usually between 5 and 10 mm, generally the transmitted fundamental radiation is elliptically polarised.

Note that applying to the entrance crystal face the fundamental radiation with any of the above states of polarisation results in the same SHG efficiency. This circumstance open up numerous possibilities for designing original optical laser configurations with frequency doubling in the KTP crystal. Experiments show that the efficiency of conversion to the second harmonic of even the unpolarised radiation is rather high and amounts to 60 % – 70 % of the highest efficiency obtained in the conversion of linearly polarised radiation.

In particular, the existence of a polariser in an electrooptically *Q*-switched Nd : YAG-laser cavity is associated with additional losses arising from the depolarisation of the fundamental radiation in the nonlinear crystal. To retain the linear polarisation of the fundamental radiation in the laser cavity incorporating the KTP crystal, a phase quarter-wave plate is additionally placed between the crystal and the output mirror [6, 7]. However, employing this configuration does not eliminate the depolarisation due to spatially inhomogeneous birefringence produced by the pump flashlamp radiation in the cylindrical laser rod. As the average pump power increases, the fraction of depolarised radiation may rise to 12 % – 25 %, depending on the thermooptical properties of the laser rod in use. Moreover, the analysis of thermooptical distortions in laser rods given in Refs [2, 8] shows that the radiation depolarisation at every point of the cross section of the laser rod depends on the coordinates of

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this point. As a result, there occurs an enhancement of the spatial inhomogeneity of the structure of output laser radiation.

To achieve highly efficient intracavity SHG in a nonlinear crystal with the type-II interaction in the conditions of strong depolarisation of laser radiation in the laser rod, the authors of Ref. [9] came up with an optical configuration with a polarisation-closed cavity shown in Fig. 1. We will consider some operation features of this configuration.

First of all we point out the rotation of the plane of polarisation arising when the laser radiation makes the round trip in the left arm of the cavity. In particular, when linearly polarised radiation with the plane of polarisation inclined by an angle α is incident on the splitting polariser from the right (Fig. 1), after going round the loop segment of the cavity and the second passage through the splitting polariser the radiation acquires linear polarisation whose plane makes an angle $90^\circ - \alpha$ with the plane of eigenpolarisations of the splitting polariser. As a result, the plane of polarisation of the radiation entering the cavity arm will turn by an angle $\beta = 90^\circ - 2\alpha$ at each round trip.

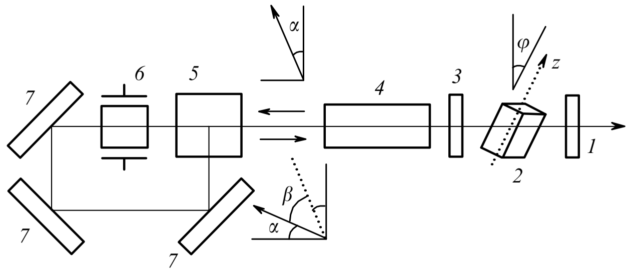

Figure 1. Optical schematic of the laser with intracavity SHG: (*1*) output dichroic mirror; (*2*) nonlinear type II interaction element; (*3*) retrodirective dichroic mirror; (*4*) laser rod; (*5*) polarisation beamsplitter; (*6*) electrooptical element; (*7*) mirrors.

When a polarisation-closed cavity is employed, lasing in an Nd : YAG laser rod can be realised for any polarisation state. Meanwhile, as noted above, the fundamental-to-second harmonic conversion efficiency is highest when the plane of polarisation of the fundamental radiation makes an angle of 45° with the z axis of the nonlinear KPT crystal and reduces to zero when this angle is equal to 0 or 90°.

Since the radiation output from the cavity is effected only at the second harmonic frequency, the fundamental radiation polarised at an angle of 0 or 90° to the z axis possesses the lowest lasing losses. Hence, when the z axis of the nonlinear crystal is oriented at an azimuth angle φ which makes 0 or 90° with the plane of eigenpolarisations of the splitting polariser, the Q factor proves to be highest for the two corresponding states of linearly polarised fundamental radiation whose planes of polarisation are either parallel to the z axis, or perpendicular to it. For these φ, the plane of polarisation of the fundamental radiation would rotate through an angle $\beta = 90^\circ - 2\varphi = \pm 90^\circ$ in going round the left cavity arm, i.e., both states of polarisation of the generated radiation persist, consecutively transforming into one another. The directions of the plane of polarisation of the fundamental radiation are also retained for $\varphi = 45^\circ$, since in this case $\beta = 90^\circ - 2\varphi = 0$.

In the remaining cases, when $0 < \varphi < 90^\circ$ and $\varphi \neq 45^\circ$, the direction of the plane of polarisation of the fundamental radiation changes at each round trip of the left cavity arm. On return of the radiation to the right cavity arm, this allows the fundamental radiation, initially polarised non-optimally from the viewpoint of SHG efficiency, to be converted to the second harmonic. Therefore, the fundamental radiation with an arbitrary orientation of the plane of polarisation generated in the Nd : YAG changes this orientation constantly when circulating in the cavity to be efficiently converted to the second harmonic. It leaves the cavity only when the polarisation state proves to be optimal at the instant the radiation passes through the nonlinear crystal.

Fig. 2 shows the experimental dependence of the output laser energy at the second harmonic frequency obtained by azimuth rotation of the KTP crystal around the Nd : YAG-laser cavity axis. One can see that the output pulse energy decreases for $\varphi = 0.45$ and 90°. The energy peaks observed at intermediate angles φ are due to the fact that the fundamental radiation polarised parallel or perpendicular to the z axis and therefore not converted to the second harmonic proves to be optimally polarised for the SHG upon going round the cavity and returning to the nonlinear crystal.

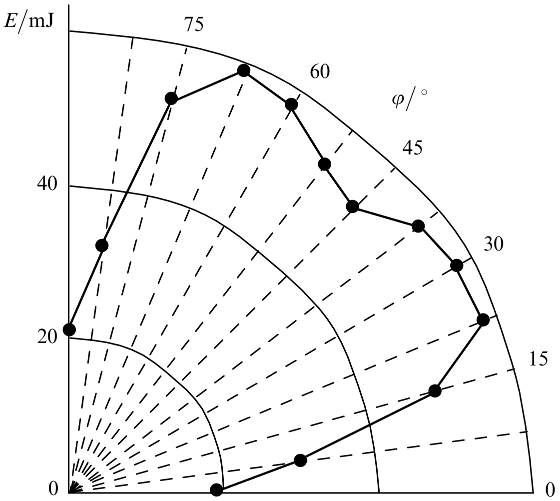

Figure 2. Energy of the output second-harmonic radiation as a function of rotation angle of the z axis of a nonlinear KTP crystal around the cavity axis corresponding to the phase-matching condition.

Consider the results of practical use of the above scheme in pulsed Q-switched lasers with radiation frequency conversion to the second harmonic. The lasing characteristics of an Nd : YAG laser with a lithium niobate electrooptical Q switch, which were obtained employing the traditional linear resonator with an extracavity radiation frequency doubling in a nonlinear KTP element, were compared with those of a laser with intracavity SHG using the same components as in the previous case. Our comparison shows that the intracavity-SHG laser efficiency attains a value of ~1 % to significantly exceed the efficiency of the laser with extracavity frequency doubling in the 20 – 70 mJ output energy range.

Some efficiency decrease in the 70 – 100-mJ range is associated with the fact that the optimal ratio between the output radiation flux and that circulating in the cavity increases with the gain coefficient. The increase of this ratio in the laser with intracavity SHG is hindered by the limitations on the efficiency of radiation conversion to the second harmonic due to the properties of the nonlinear crystal, its thermal regime, and also the energy and space–time characteristics of the fundamental radiation [10].

The above configuration ensures efficient laser operation for a high pump-pulse repetition rate. As already noted in the foregoing, an immanent feature of the laser with a polarisation-closed cavity is the almost perfect insensitivity of its lasing characteristics to the birefringence in the laser rod. Moreover, the high thermal conductivity of the KTP crystal in combination with low absorption and a weak temperature dependence of the refractive index ensure the low sensitivity of the SHG efficiency to the increase in average output power of laser radiation.

As a result, increasing the pulse repetition rate up to 500 Hz yielded an output pulse energy of 30 mJ, which corresponded to the average output laser power of 15 W at the second harmonic frequency [11]. We emphasise that the resultant output energy is, in this pump regime, hardly attainable with a single-stage Nd : YAG laser utilising the traditional linear configuration with electrooptical *Q*-switching. In the case under consideration, the decisive factor which limits the further increase in pulse repetition rate is the limiting value of specific electric power fed to the pump flashlamp.

3. Intracavity optical parametric oscillation

At present, lasers emitting at 1.5-μm region attract considerable attention in connection with the problem obtaining eye-safe laser radiation [2]. The possibility of efficient conversion of the 1.06-μm neodymium laser radiation to the required spectral range is provided by an OPO utilising the KTP crystal ($\theta = 90^\circ$, $\phi = 0$) [1]. The experimental investigation of a single-cavity OPO employing a 16 mm long KTP crystal pumped by a multimode pulsed Nd : YAG laser shows that conversion efficiencies above 40 % are attained when the threshold power density of the fundamental radiation is exceeded by a factor of 3–4 (Fig. 3).

Since the conversion efficiency essentially depends on the power density of the fundamental radiation, there is good reason to place the OPO inside the Nd : YAG laser cavity to improve the overall efficiency of the laser system. Furthermore, the use of collinear pumping in this case allows an improvement of the uniformity of the spatial distribution of output radiation intensity and ensures the most efficient use of the length of the nonlinear crystal.

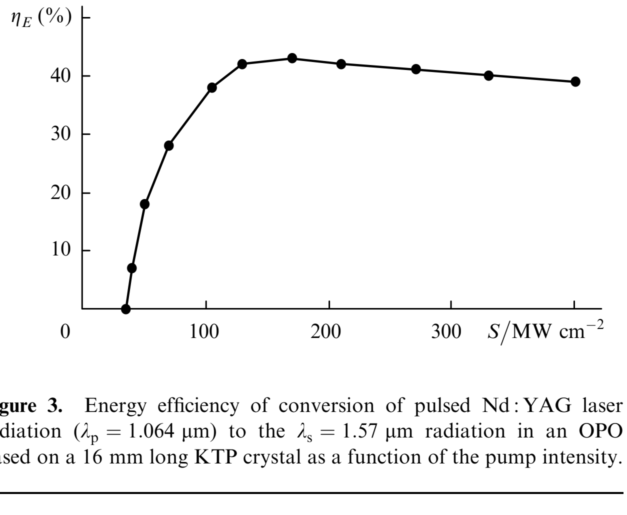

Figure 3. Energy efficiency of conversion of pulsed Nd : YAG laser radiation ($\lambda_p = 1.064$ μm) to the $\lambda_s = 1.57$ μm radiation in an OPO based on a 16 mm long KTP crystal as a function of the pump intensity.

A pulsed *Q*-switched Nd : YAG laser operated at a pump pulse repetition rate of 30 Hz was employed as the source of 1.06-μm fundamental radiation. The Nd : YAG laser rod measuring 50 mm in length and 5 mm in diameter was doped with neodymium ions to a concentration of ~1 %. The pumping was performed with an INP-3/45 pulsed xenon flashlamp with a dielectric coating deposited on the external flashlamp bulb wall to reject the UV part of the radiation spectrum. The discharge current pulse duration was 90 μs. A lithium niobate electrooptical element was employed as the *Q* switch.

Fig. 4 shows the time dependences of the fundamental radiation pulse and the pulse at the signal wave frequency obtained for an intracavity OPO. The optical length of the Nd : YAG-laser cavity was 50 cm in this experiment. In this case, the duration of the pump pulse with a wavelength of 1.064 μm was ~20 ns. Since the lasing at 1.57 μm has a threshold [10], the corresponding pulse was shorter (~15 ns).

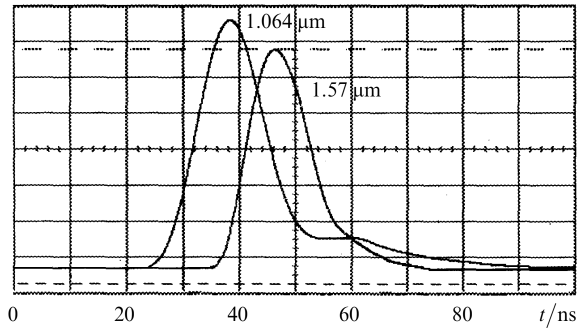

Figure 4. Oscilloscope traces of the pump radiation ($\lambda_p = 1.064$ μm) and the radiation at the signal wave frequency ($\lambda_s = 1.57$ μm) generated in a pulsed Nd : YAG laser with an intracavity KTP OPO.

Fig. 5 shows the dependences of the output pulse energy of an intracavity OPO on the electric pump energy delivered to the Nd : YAG-laser flashlamp, which were obtained for different reflectivities of the output mirror. It is clear from Fig. 5 that the output mirror with a reflectivity of about 50 % is optimal. Note that the dependence of the OPO pulse energy on the output mirror transmittance is represented with a gently sloping curve and ±10 % deviations from the optimal value do not result a significant reduction of the output energy.

Analysis of lasing threshold in a single-cavity OPO predicts a reduction of the threshold pump power density with decreasing the cavity length [10, 12]. This dependence manifests itself most markedly in the case of an extracavity OPO. For instance, the increase in the cavity length from 3 to 10 cm reduces the output pulse energy at the signal-wave frequency by 35 % for a fixed energy of the pump pulse [4]. Limiting the OPO cavity length to several centimetres in its turn results in an increase in radiation divergence up to 8–12 mrad, which is undesirable for a variety of practical applications. As demonstrated by our investigations, placing

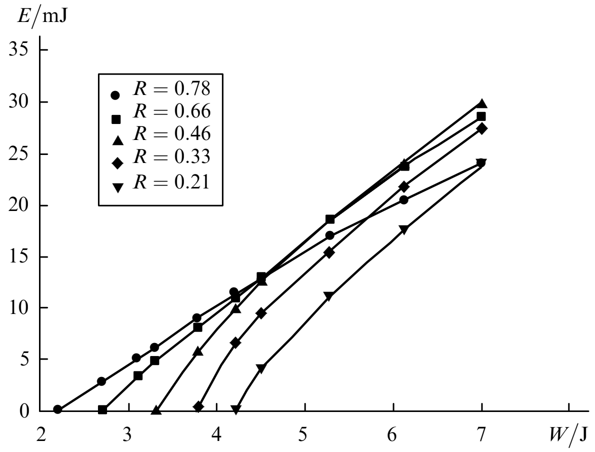

Figure 5. Output pulse energy of an intracavity OPO based on a 20 mm long KTP crystal as a function of the electric pump energy for different reflectivities of the output mirror R.

the OPO inside the cavity of the pump laser permits the OPO-cavity length to be varied over much wider limits. In particular, Fig. 6 shows the overall efficiency of the laser with an intracavity OPO measured when the OPO cavity length was increased to 41 cm.

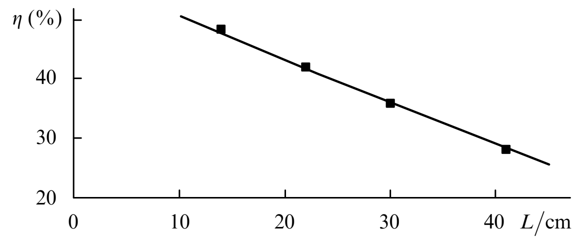

Figure 6. Ratio between the $\lambda_s = 1.57$ μm output pulse energy and the electric pump energy delivered to the flashlamp as a function of the cavity length of the OPO using a KTP crystal placed inside the Nd : YAG laser cavity.

Increasing the distance between the mirrors is the simplest and most efficient method for narrowing the laser radiation pattern [13]. However, unlike Nd : YAG lasers, the divergence of output OPO radiation depends not only on the cavity parameters, but on the pump radiation divergence as well. In experiments, advantage was taken of an OPO with a KTP crystal measuring 7 × 7 × 20 mm. The 12-cm long OPO cavity was formed by plane mirrors and in its turn was located inside the Nd : YAG-laser cavity. Measurements were conducted when the pump energy was two times higher than the OPO lasing threshold. In this case, the OPO radiation was multimode and the beam diameter was ~4.5 mm. Fig. 7 shows the divergence of the output radiation of the intracavity OPO versus the divergence of Nd : YAG-laser radiation. It is clear that a three-fold increase in pump radiation divergence from 1.8 to 5.4 mrad leads to only a minor variation of OPO radiation divergence from 6.2 to 7 mrad. Therefore, the results obtained suggest that the OPO radiation divergence is determined primarily by the configuration of its cavity.

When determining the efficiency of a laser with an intracavity nonlinear-optical frequency conversion, the energy of output radiation pulses is measured in relation to the electric energy delivered to the flashlamp of the pump laser – the source of fundamental radiation. This allows an experimental comparison between the efficiency of the generator of the second optical harmonic and the parametric light oscillator based on KTP crystals, which convert the fundamental radiation of a pulsed Nd : YAG laser. To obtain comparable results, all the measurements were performed on the same experimental facility for a pump pulse repetition rate of 30 Hz. The resultant energies of output radiation pulses with wavelengths of 0.53 and 1.57 μm are given in Fig. 8.

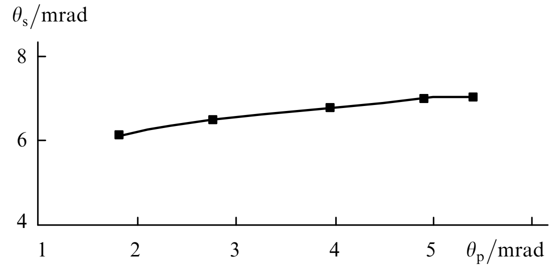

Figure 7. Divergence θ_s of the output $\lambda_s = 1.57$ μm radiation of the KTP-based OPO against the divergence of the $\lambda_p =$ μm pump radiation. This dependence was obtained for a cavity with plane mirrors.

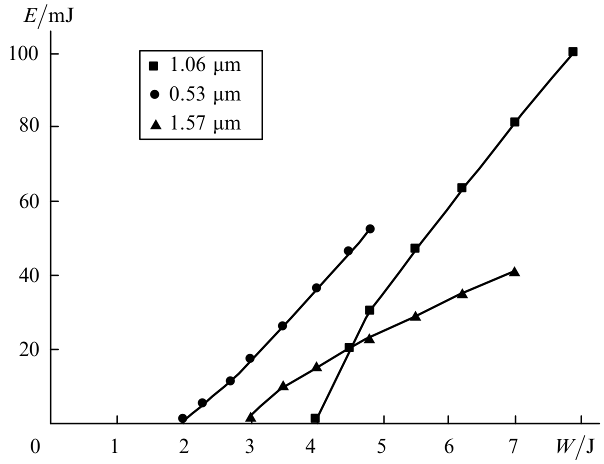

Figure 8. Output energy for the intracavity SHG (●) and intracavity OPO (▲) radiation pulses and also for the fundamental radiation pulses of the Nd : YAG laser (■) as a function of the electric energy of the pump flashlamp for different wavelengths.

The intracavity fundamental-to-second harmonic radiation conversion was accomplished in accordance with the optical setup of Fig. 1 in a thermostatically controlled frequency converter with an 8-mm long KTP nonlinear element. For an intracavity OPO, use was made of a 20-mm long KTP element and an output mirror with a reflectivity of 55 % at a wavelength of 1.57 μm. As an example, Fig. 8 also gives the corresponding dependence for the energy of the fundamental radiation pulses of the Q-switched Nd : YAG laser obtained for a reflectivity of the output mirror of 27 %. The highest efficiencies at the fundamental, second harmonic, and signal-wave OPO frequencies amounted to 1.2, 1.0, and 0.55 %, respectively.

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