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Extracavity parametric oscillation at 1.5 and 2 μm upon pumping from an Nd^{3+} : YAG laser

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Abstract. **The lasing characteristics of extracavity KTP optical parametric oscillators (OPOs) emitting at 1.57 and 2.14 (2.19) μm upon pumping by multimode Nd^{3+} : YAG lasers at 1.064 and 1.32 (1.34) μm, respectively, are studied. The thresholds, conversion efficiencies, and divergences of the output radiation for linear and ring OPOs emitting at 1.57 μm are compared. Low thresholds, a high (up to 40 %) conversion efficiency, and a low (no greater than 3.5 mrad) divergence of the output radiation were obtained in a three-mirror ring OPO when the pump energy exceeded the threshold by a factor of ten. Emission at 2.14 and 2.19 μm was obtained in a three-mirror ring OPO pumped by Nd^{3+} : YAG laser at 1.32 and 1.34 μm, respectively. The OPO lasing parameters are found to be of practical interest. A compact and efficient ring OPO is built for converting radiation from Nd^{3+} : YAG lasers to radiation in the 1.5–2-μm range.**

Keywords: *KTP crystals, optical parametric oscillator, eye-safe laser radiation.*

1. Introduction

Lasers emitting in the 1.5–2-μm range are of great interest for a variety of applications, since their radiation is eye-safe and lies into the atmospheric transparency window. A possible way to generate laser radiation in this spectral range is to use optical parametric oscillators (OPOs).

One of the types of OPOs is an extracavity parametric oscillator pumped by a *Q*-switched Nd^{3+} : YAG laser or by other lasers based on neodymium-doped crystals. KTP crystals, which have large nonlinear coefficients, good strength and thermal characteristics, and a high resistance to laser radiation, are of great interest as nonlinear elements. An important advantage of these crystals is the possibility of obtaining parametric oscillation under conditions of noncritical 90° phase matcing upon pumping by 1.06- and 1.3-μm radiation from neodymium crystal lasers.

The parameters of extracavity KTP OPOs pumped at 1.06 μm have been studied in many papers [1–8]. In these papers, OPOs with linear cavities have been usually investigated, which had a high efficiency and produced high energy outputs. However, the divergence of the output beam for high conversion efficiencies was also large [1–8].

The data on the parameters of KTP OPOs pumped at 1.3 μm are not available in the literature. In this paper, we build a low threshold highly efficient extracavity parametric oscillator converting radiation from a Nd^{3+} : YAG laser into weakly divergent radiation in the 1.5–2-μm range.

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2. Experimental studies

To establish the size of nonlinear KTP crystals and to determine the pumping conditions under which a low threshold, high efficiency, and reliable operation of the OPOs can be achieved without degradation of the cavity elements, we studied the lasing parameters of the OPO with a linear cavity.

2.1 OPO with a linear cavity

2.1.1 Experimental setup

The OPO was pumped by a *Q*-switched multimode Nd^{3+} : YAG laser with a 50-mm long active element 5 mm in diameter emitting 10-ns pulses at 1.064 μm with a pulse repetition rate of 12.5 Hz. The pump-pulse energy was varied over a broad range and reached 70 mJ. The optical scheme of the experimental setup is shown in Fig. 1.

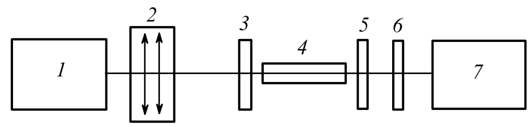

Figure 1. Experimental setup for extracavity parametric oscillation: (*1*) 1.064-μm Nd^{3+} : YAG laser; (*2*) focusing system; (*3*) mirror with $R_p < 5\,\%$ and $R_s = 100\,\%$; (*4*) KTP crystal; (*5*) mirror with $R_s = 60 - 70\,\%$; (*6*) mirror with $R_p = 100\,\%$ and $R_s = 10\,\%$; (*7*) detection system.

The pump radiation was focused by optical system (*2*) into the KTP crystal providing the required power density in the nonlinear medium. The diameter of the pump beam at the input to the nonlinear crystal was 1.8 mm. Parametric oscillation was observed under the conditions of noncritical 90° phase matching. The radiation of the pump wave, the signal wave, and the idler wave propagated along the *x* axis of the KTP crystal, the polarisations of the pump and signal waves were directed along the *y* axis, and the polarisation of the idler wave was directed along the *z* axis. The faces of the KTP crystal had antireflection coatings for the 1.5–1.6-μm range.

The OPO resonator consisted of two plane mirrors (*3*) and (*5*) one of which [mirror (*3*)] is transparent at the pump wavelength $\lambda_p = 1.064$ μm and totally reflecting ($R_s = 100\,\%$) at the parametric signal wavelength $\lambda_s = 1.57$ μm. The transmittance of the output mirror (*5*) at the signal wavelength was varied. Because the mirrors were deposited on glass substrates that absorbed radiation at wavelengths greater than 2.5 μm, the idler wave with $\lambda_i = 3.29$ μm produced upon parametric oscillation was absorbed almost completely by the substrate material. Upon measuring the output energy at 1.57 μm in the case of a single-pass gain, to suppress the pump radiation at 1.064 μm, for which the output OPO mirror is transparent, we used mirror (*6*) with $R_p = 100\,\%$ (at 1.06 μm) and $R_s = 10\,\%$ (at the lasing wavelength).

The detection system consisted of an IMO-2H power meter, a fast FD24-03 photodetector, and a C7-19 oscilloscope. Pulse durations were measured as the full width at half-maximum. The emission spectra were recorded with an MDR-2 monochromator with a 600 lines mm^{-1} grating. The laser-beam diameter was determined by the diameter of an aperture through which 86.5 % of the total beam energy passed. The beam divergence was determined by the beam diameter at the focus of a lens with a focal length of 1 m.

2.1.2 Results and discussion

Experiments with crystals of length up to 23 mm revealed that for OPO cavities longer than 5 cm and an output-mirror transmittance greater than 40 %, the lasing threshold substantially increased. In this case, attaining output parameters that are of practical interest requires high pump powers at which KTP crystals and the resonator dielectric mirrors can be damaged.

The efficient parametric oscillation was achieved for OPO resonator lengths $L_{res} = 23 - 30$ mm and output-mirror transmittance between 30 % and 40 %. Fig. 2 shows the 1.57-μm pulse energy as a function of the pump-pulse energy E_p for the OPO with KTP crystals of different lengths l_{cr}, different output-mirror transmittances R_s, and a small variation of the resonator length.

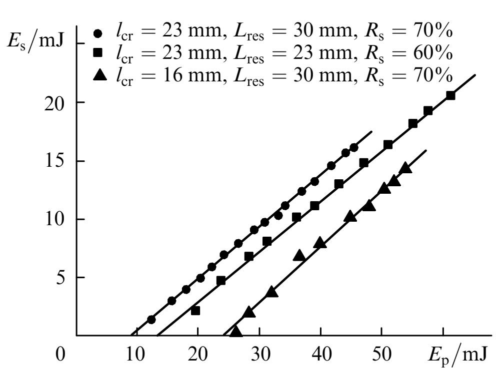

Figure 2. Dependence of the 1.57-μm output pulse energy E_s on the pump-pulse energy E_p for different l_{cr}, L_{res}, and R_s.

The dependences presented in Fig. 2 show that in the process of extracavity parametric oscillation the 1.064-μm radiation from a Nd^{3+} : YAG laser can be efficiently converted into radiation at 1.57 μm. The efficiency of energy conversion of the 1.064-μm pulse into the 1.57-μm pulse reached 40 %. Note that when the pulse repetition rate was varied within the 1 – 12.5-Hz range, these dependences did not change. No laser damage of the active element and OPO cavity mirrors was observed under these conditions.

By studying the OPO energy characteristics shown in Fig. 2, we can optimise the size of the nonlinear KTP crystals. One can see from Fig. 2 that for the 23-mm long ctystals (measured along the *x* axis) the lasing thresholds are roughly 10 mJ for a pump energy density of 0.4 J cm^{-2}, and the OPO output reaches 15 mJ for a pump energy of 40 – 45 mJ. In this case, the maximum pump intensity does not exceed 180 MW cm^{-2}.

Taking into account the fact that the pumping is performed by a multimode laser, for which the characteristic laser-beam nonuniformity (defined as the ratio of the local energy density to the energy density averaged over the beam cross section) is 2.5 – 3, we find that the maximum intensity does not exceed 540 MW cm^{-2}. This ensures the reliable operation of KTP ctystals, because the resistance of these crystals to 1.06-μm laser radiation is of about 1 GW cm^{-2} [9].

It follows from Fig. 2 that reducing the length of KTP crystals will require increasing the pump energy, which may lead to the laser damage of the crystals. The 4×4-mm aperture of the KTP crystals along the *y* and *z* axes was chosen for reasons of convenience of the OPO alignment.

The OPOs whose parameters are listed in Fig. 2 emitted 8-ns pulses upon pumping by 10-ns pulses. The signal radiation wavelength measured by us was 1573 ± 1 nm, and was in good agreement with the results of calculations. For the OPO resonator length $L_{res} = 30$ mm, the measured beam divergence was 7 mrad. The divergence can be reduced somewhat by increasing the OPO resonator length; however, in this case the pump energy should be substantially increased. Thus, while having good energy characteristics, an OPO with a linear cavity emits radiation with a high divergence when pumped by multimode lasers, which limits its applications.

2.2 OPO with a three-mirror ring cavity

2.2.1 The OPO cavity

To solve the beam divergence problem in the OPO, we selected a three-mirror ring cavity shown in Fig. 3. One can see that the outer rays in the lasing beam become the inner rays after each round trip in such a cavity, and vice versa. This noticeably compensates the inhomogeneity of the transverse structure of the laser field and substantially reduces the effect of optical inhomogeneities and the quality

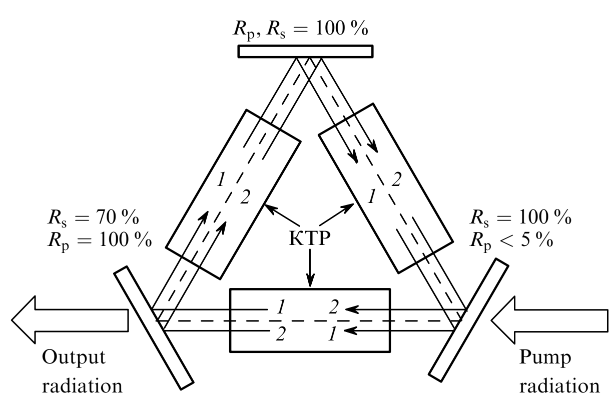

Figure 3. Optical scheme of a three-mirror ring parametric converter; the dashed line is the lasing-beam axis.

of the pump beam on the transverse structure of the laser field, resulting in a weaker divergence of the parametric radiation. The travelling-wave lasing regime ensures higher intensities in the cavity without causing damage to the crystal and to the dielectric coating of the mirrors.

The KTP crystals we selected for our research were $4 \times 4 \times 20$ mm along the x, y, and z axes, respectively; the pump and output radiation propagated in these crystals along the x axis, the polarisation of the pump and signal waves was perpendicular to the z axis, and the polarisation of the idler wave was parallel to the z axis. The faces of the crystals had antireflection coatings for the 1.5 – 1.6-μm range.

The output mirror had a reflectance $R_s = 70\,\%$ at the wavelength of the signal wave.

2.2.2 Parametric oscillation at 1.57 μm

The optical scheme of the experimental setup is shown in Fig. 4. The pump laser and the detection system were identical to those used in studies of linear-cavity OPOs. The pump radiation was focused on the OPO to a spot 1.6 mm in diameter.

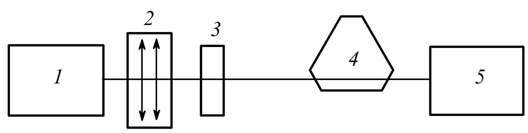

Figure 4. Experimental setup for parametric oscillation: (*1*) 1.064-μm (1.3-μm) Nd^{3+}:YAG laser; (*2*) focusing system; (*3*) attenuator; (*4*) ring converter; (*5*) detection system.

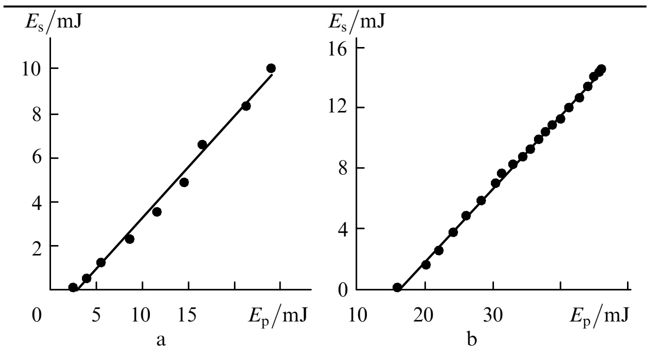

Figure 5. Energies E_s of output parametric radiation pulses at 1.57 μm (a) and 2.14 μm (b) as functions of the pump-pulse energy E_p.

Figure 5a shows the dependence of the output pulse energy E_s on the pump-pulse energy E_p. The threshold energy is 2.5 mJ, which corresponds to an energy density of 0.12 J cm^{-2}, with the conversion efficiency reaching 40 %. The divergence of the OPO beam in the entire range of pump energies does not exceed 3.5 mrad. The duration of the pulse emitted by the OPO is 8 ns. Thus, the use of a three-mirror ring OPO allowed to reduce substantially the lasing threshold and beam divergence.

2.2.3 Parametric oscillation at 2 μm

To obtain parametric oscillation at 2 μm upon pumping at 1.3 μm, we used a three-mirror ring resonator. The resonator length, the reflectance of the output mirror, and the size of KTP crystals were the same as in the case of parametric oscillation at 1.57 μm. The faces of the KTP crystals had antireflection coatings for the 2.1 – 2.2-μm range. The idler wave at 3.45 μm that appeared during parametric oscillation was almost completely absorbed by the mirror material.

Fig. 4 shows the scheme of the setup used in experiments. The pumping was performed at 1.3 μm by a Q-switched Nd^{3+}:YAG laser with an active element of diameter 5 mm and length 50 mm. In the abcence of a dispersion element in the pump-laser cavity, the laser emitted at 1.319 μm and 1.338 μm, because the cross sections for lasing transitions at these wavelengths are very close and are 0.95×10^{-19} cm^2 and 10^{-19} cm^2, respectively [10]. A Lyot filter inserted into the cavity made lasing possible at any one of these wavelengths independently. The laser pulse duration was 26 ns and the pulse repetition rate was 12.5 Hz. The pump radiation was focused onto the entrance mirror of the OPO to a spot 1.35 mm in diameter. The maximum pump-pulse energy was 50 mJ.

When the OPO was pumped at 1.319 μm, the parametric oscillation wavelength was 2.14 μm, while pumping at 1.338 μm resulted in lasing at 2.19 μm, and was in good agreement with the calculated parametric oscillation wavelengths. Note that when the OPO was pumped by a Nd^{3+}:YAG laser that had no Lyot filter in the cavity, simultaneous lasing was observed at 2.14 and 2.19 μm.

The dependence of the output pulse energy E_s at $\lambda_s = 2.14$ μm on the pump-pulse energy E_p at $\lambda_p =$ 1.318 μm is shown in Fig. 5b. The lasing threshold was 16 mJ, which corresponds to an energy density of 1.1 J cm^{-2}. The divergence of the parametric radiation did not exceed 4.5 mrad. The typical duration of the OPO pulse was 25 ns. The results of measurements at 2.19 μm when the OPO was pumped at 1.338 μm are practically the same.

Note that the K8 glass from which the substrate of the output mirror was manufactured appreciably absorbs the signal wave (up to 10 % of the energy of that wave is absorbed). The measured energies of the OPO signal wave shown in Fig. 5b do not take into account the losses related to the output mirror.

2.3 Discussion

The experimental data on parametric oscillation at 1.57 and 2.14 (2.19) μm show that the proposed three-mirror OPO design provides a low beam divergence and stable parametric oscillation with a high conversion efficiency at low threshold pump energy densities.

Note the large difference between the threshold energy densities for lasing at 1.57 and 2.14 (2.19) μm. Several factors affect the threshold energy density: the pump-pulse duration, the dispersion of the nonlinear coefficients, and the absorption coefficient for the idler wave in the nonlinear crystal (which in our case was substantial). A theoretical estimate of the threshold energy density done by the formula proposed in Ref. [11] yields 0.09 J cm^{-2} for parametric oscillation at 1.57 μm and 0.22 J cm^{-2} for parametric oscillation at 2.14 μm. This formula, however, does not take into account the effect of idler wave absorption on the lasing threshold.

Parametric oscillation in the presence of strong idler wave absorption was studied in Ref. [12]. In our case, the absorption coefficient for the idler wave is rather large, 0.5 cm^{-1} at 3.29 μm and 1.2 cm^{-1} at 3.45 μm [13]. Estimates made by the formula proposed in Ref. [12] show that, when absorption of the idler wave is taken into account, the thresholds should increase by 18 % for lasing at 1.57 μm and by 44 % for lasing at 2.14 μm, with the power densities amounting to 0.11 and 0.32 J cm^{-2}, respectively.

As a result, the calculated threshold for parametric oscillation at 2.14 μm proves to be three times lower than the experimental value, while for lasing at 1.57 μm the calculated estimates of the threshold are very close to the experimental values. A detailed analysis of the results of paper [12] has shown that the author of this paper used the solution of truncated equations for the three-wave interaction in the approximation of a weak variation of the signal wave, i.e., $d\mathscr{E}_s/dx = 0$, where $\mathscr{E}_s$ is the field strength in the signal wave, and x is the propagation direction of radiation. The threshold conditions for lasing were obtained by the parametric-gain extrapolation. In our opinion, such an approach is not quite correct and the problem requires further analysis.

3. Conclusions

We used the results of our research to build an extracavity OPO, whose appearance and dimensions are shown in Fig. 6. Such a design was used to convert radiation from Nd^{3+} : YAG lasers into eye-safe radiation with parameters mentioned above.

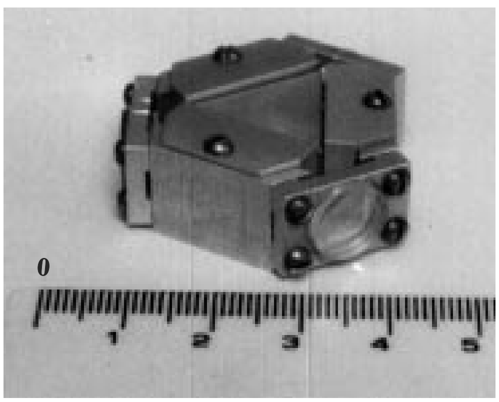

Figure 6. Parametric converter.

The converter is of practical interest and can be adapted for operation in conjunction with devices based on solid-state Nd^{3+} : YAG lasers emitting in the 1.5 – 2-μm range, e.g., for pumping optical parametric oscillators emitting in the longer-wavelength spectral region.

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