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Optical parametric mid-IR $HgGa_2S_4$ oscillator pumped by a repetitively pulsed Nd : YAG laser

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***Abstract*. An efficient optical parametric $HgGa_2S_4$ crystal oscillator pumped by a *Q*-switched Nd : YAG laser is developed. The oscillator can be continuously tuned in the region from 3.7 to 5.7 μm. The average output power at 4 μm was 67 mW for a pulse repetition rate of 20 Hz. The energy conversion efficiency achieved 4.9 %.**

Keywords: *optical parametric oscillator, mercury thiogallate, Nd:YAG laser.*

1. Introduction

High-power laser radiation sources tunable in the mid-IR region from 3 to 12 μm, which can be based on optical parametric oscillators (OPOs), are required for many applications in science and technology. Optical parametric oscillators pumped at ~ 1 μm by widely used and convenient Nd-doped crystal lasers can be tuned in the near- and mid-IR regions. While OPOs emitting in the visible and near-IR regions have been long used, commercial mid-IR OPOs are still not manufactured. This is mainly explained by the fact that the transparency range of high-quality oxygen-containing crystals used in OPOs such as KTP, KTA, $LiNbO_3$, and others [1 – 4] does not allow one to obtain lasing at $\lambda > 4$ μm.

Some foreign commercial companies manufacture OPOs based on these crystals pumped by Nd lasers. Thus, Opotek presented OPOs tunable within ~ 500 nm in the spectral range from 2.6 to 3.5 μm and emitting ~ 5 mJ at a pulse repetition rate of 10 Hz [5]. Another type of nonlinear-optical crystals, which can be used in OPOs pumped by one-micron radiation, are chalcogenide crystals. They include silver thiogallate ($AgGaS_2$) [6, 7] and mercury thiogallate ($HgGa_2S_4$) [8 – 12]. Note that the $HgGa_2S_4$ crystals surpass in some properties the $AgGaS_2$ crystals [11] and appear to be more promising for the development and manufacturing OPOs. Such OPOs pumped by femtosecond pulses were studied in [13 – 15]. In this paper, we studied experimentally an OPO based on a mercury thiogallate crystal pumped by a commercial repetitively pulsed Nd : YAG laser.

2. Experimental setup

We used in our experiments an $HgGa_2S_4$ crystal grown by the Bridgman – Stockbarger method at the Laboratory of High Technologies at the Kuban State University. The crystal of size $10.1 \times 13.8 \times 13.3$ mm was cut at the angle $\theta = 52.7^\circ$ to the crystal axis oriented to the type I phase matching. The working faces of the crystal of size 13.8×13.3 mm were covered with a dielectric coating with the reflection coefficient less than 2 % for the pump radiation at 1.064 μm and less than 0.5 % for the signal-wave emission at 1.2 – 1.4 μm.

The OPO resonator was formed by two plane dichroic mirrors covered by a dielectric reflecting coating. The reflection coefficient of the input mirror made of a K8 glass was $\rho \approx 95\,\%$ in the region between 1.20 and 1.45 μm. The front surface of the input mirror had an antireflection coating with $\rho < 0.1\,\%$ for the pump radiation. The reflection coefficient of the output mirror made of a barium fluoride had $\rho \approx 85\,\%$ in the range from 1.1 to 1.4 μm. The distance between the mirrors was 3 cm. Thus, the single-resonator scheme was realised. The signal wave was the resonance wave, the resonator *Q* factor for this wave being maximal. The idler wave was extracted from the resonator with small losses (the transmission coefficient of the output mirror was ~ 10 %). To provide the decoupling from the pump laser, the OPO was located at a distance of ~ 3 m from the former. In addition, the use of the spatial decoupling allowed us to place the OPO in the far-field zone of the pump beam, which was favourable for lasing stabilisation and increased the conversion efficiency. The OPO wavelength was tuned by rotating the crystal in the phase-matching plane with respect to the pump beam.

Unlike previous papers [8, 9], pumping was performed by a 1.064-μm Nd : YAG laser (Quantel Brio model with the super Gaussian resonator) emitting pulses with a pulse repetition rate up to 20 Hz. The pulse energy was 100 mJ and stable within ±2 %. The FWHM of the laser pulse was 4.5 ns and the divergence of the laser beam did not exceed 0.3 mrad. To avoid the optical damage of a crystal, the

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pump-beam diameter was increased up to 6 mm (at the 1/e^2 level) by means of a telescope with the double magnification inserted to the scheme.

The pump-pulse energy was measured by directing a part of the pump energy with the help of an optical wedge to a PE10BB-SH-V2 power meter (Ophir). The radiation energy at the idler wavelength was measured with a similar power meter located behind the output mirror of the OPO. The idler wave was separated by a filter consisting of calcium fluoride plates with a dielectric selective covering and a germanium plate, which was mounted between the detector and the output mirror. The output wave of the OPO was measured with a Digikrom CM112 monochromator equipped with a MG-30 pyroelectric detector.

During the operation of the OPO in the repetitively pulsed regime, various thermal effects can be observed. The estimates of temperature variations on the crystal axis caused by the absorption of pump radiation, based on the solution of the stationary heart conduction equation, showed that, when the average pump power was increased up to 2 W, the crystal temperature increased by a few tenths of degree (~ 0.3 °C). This does not introduce any considerable changes in the parametric oscillation process, and therefore, there is no need for the thermal stabilisation of the crystal.

3. Experimental results

The tuning range of the idler wave was 3.69 – 5.69 μm. In this case, the external rotation angle of the crystal was 20°. The spectral width of the tuning range was determined by the reflection coefficient of mirrors and the crystal size. For example, the tuning range for a similar crystal obtained in [8] was 2.3 – 4.4 μm. Thus, we have managed to shift the emission spectrum of the OPO to the longer-wavelength region, which is inaccessible for OPOs based on oxygen-containing crystals. Note that the OPO was studied in [8] in the single pulse regime, whereas in this paper we investigated the repetitively pulsed regime. Figure 1 presents the wavelength dependence of the average OPO power. The maximum power was obtained at 4.03 μm for pump radiation normally incident on the crystal.

Figure 2 presents the dependence of the average (for a pulse train) output energy of OPO pulses on the average pump energy. Measurements were performed for the OPO radiation at 4.03 μm at a pulse repetition rate of 5 Hz. The threshold pump energy was ~ 10 mJ and the maximum output energy of the OPO averaged over a pulse train achieved 3.3 mJ. The energy conversion efficiency was 4.9 %. As the pulse repetition rate was increased up to 20 Hz, the output pulse energy almost did not change. The maximum average output OPO power for the idler wave was 67 mW. No radiation damage of the OPO was observed during the operation in this regime for ~ 1 h.

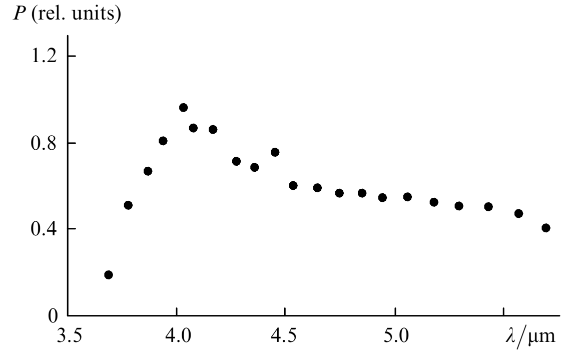

Figure 1. Dependence of the average OPO power (idler wave) on the wavelength.

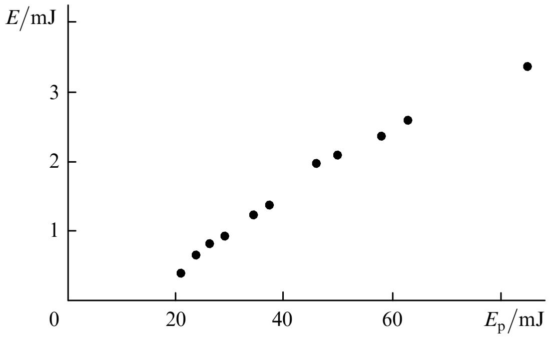

Figure 2. Dependence of the average OPO pulse energy (idler wave) on the pump-pulse energy averaged over a pulse train.

As the pulse repetition rate was changed, no change in the output radiation wavelength of the OPO was observed. This confirms the fact that the influence of temperature gradients caused by the heat release in the crystal and related temperature phase mismatch is insignificant.

By studying the OPO emission dynamics, we measured the shape of the OPO pulse to determine its duration. Measurements were performed with a BP-10 pyroelectric detector with a time resolution of 10^{-10} s and a TDS-3054B oscilloscope. A filter mounted in front of the detector rejected the pump and signal wave radiation. Simultaneously, the pump-pulse shape at the OPO input was measured. Figure 3 presents the oscillograms obtained. The FWHM of the OPO radiation pulse at 4.03 μm was ~ 3 ns, which is virtually equal to the pump-pulse duration. The OPO pulse delay with respect to the pump pulse was 1 ns.

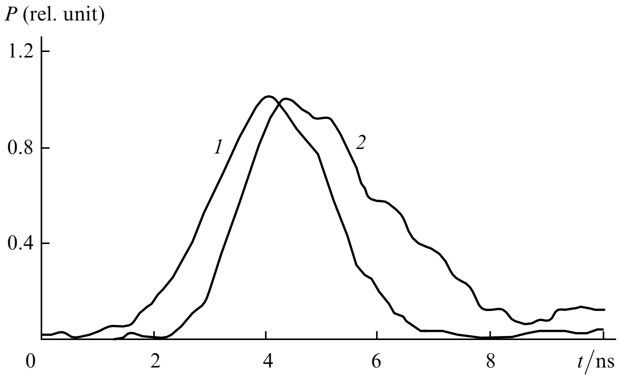

Figure 3. Pump pulse shape (*1*) and the OPO pulse shape at the idler wave frequency (*2*).

The distribution of the output OPO radiation over the beam cross section at a wavelength of 4.03 μm was detected with an IR Pyrocam III camera. Figure 4 presents the near- and far-field intensity distributions. According to the estimate, the divergence of the OPO beam is ~ 10 mrad.

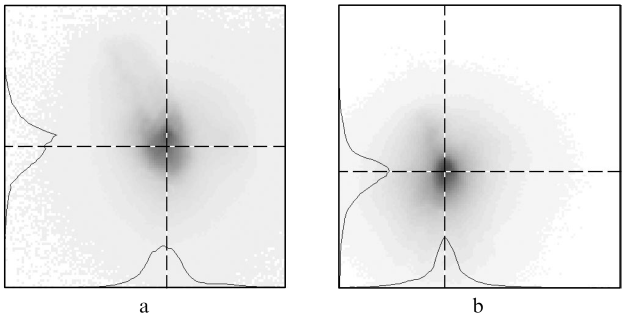

Figure 4. Idler-wave intensity distributions at the OPO output in the near field at a distance of 5 cm from the output window (a) and in the far field in the lens focus ($F = 80$ mm) (b).

4. Conclusions

We have fabricated the Nd : YAG laser-pumped OPO based on a mercury thiogallate crystal continuously tunable in the range from 3.69 to 5.69 μm with the maximum output power of 67 mW at a pulse repletion rate of 20 Hz. This OPO can be used as a prototype for the development of commercial mid-IR OPOs. The tuning range of the OPO is determined by the spectral parameters of its mirrors and the orientation of a nonlinear-optical crystal. Thus, similar commercial OPOs can operate in the range from 2 to 9 μm with the continuous tuning range of width ~ 2 μm and the average power up to 100 mW.

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