ISSN 0020-4412, Instruments and Experimental Techniques, 2012, Vol. 55, No. 2, pp. 263–267. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © D.B. Kolker, M.K. Starikova, R.V. Pustovalova, A.I. Karapuzikov, A.A. Karapuzikov, O.M. Kuznetsov, Yu.V. Kistenev, 2012, published in Pribory i Tekhnika Eksperimenta, 2012, No. 2, pp. 124–128.

A Nanosecond Optical Parametric Oscillator in the mid-IR Region with Double-Pass Pump

D. B. Kolker[a,b,c,*], M. K. Starikova[a], R. V. Pustovalova[b], A. I. Karapuzikov[b], A. A. Karapuzikov[c], O. M. Kuznetsov[b], and Yu. V. Kistenev[d]

[a] *Novosibirsk State Technical University, pr. K. Marksa 20, Novosibirsk, 630092 Russia*
[b] *Institute of Laser Physics, pr. Lavrent'eva 13/3, Novosibirsk, 630090 Russia*
[c] *Special Technologies Ltd., ul. Zelenaya gorka 1/3, Novosibirsk, 630060 Russia*
[d] *Siberian State Medical University, Moskovskii trakt 2, Tomsk, 634050 Russia*
**e-mail: kolker@ngs.ru*

Received May 26, 2011; in final form, June 20, 2011

Abstract—An optical parametric oscillator (OPO) with double-pass pump based on MgO:PPLN and PPLN periodic structures is described. A compact nanosecond Nd:YLF laser has been used as a pump source at 1.053 μm (the pumping pulse duration is 5–7 ns at a maximum pulse energy of 300 μJ at frequencies of 1–7 kHz). The oscillation threshold of the OPO based on MgO:PPLN was varied in a range of 11–28 μJ at wavelength of 2.1–4.3 μm. The conversion efficiency from the pump wave to an idler wave decreased from 8.6 to 2.5% in the range of 2.0–4.3 μm. For PPLN-OPO the measured threshold was 36 μJ at 4.2 μm and 49 μJ at 4.7 μm. The conversion efficiency of the pump energy into the energy of an idler wave was 3.3–0.4% at wavelengths of 4.2–4.7 μm.

DOI: 10.1134/S0020441212010174

INTRODUCTION

Monitoring of gas chemical agents in atmosphere and, as a particular case, by medical researchers for exhaled breath analysis is now of special interest. To solve this problem, a resonance method of opticoacoustic spectroscopy was proposed. On its basis, a photo acoustic laser gas analyzer was developed [1]. Because the spectrum of a CO_2 laser does not satisfy the requirements of the formulated problems completely, it was decided to use an optical parametric oscillator (OPO) as a source of widely tuned IR radiation in the range 2.3–4.3 μm (4.2–4.7 μm) [2, 3].

Below, we describe a OPO with double-pass pump based on periodically polarized MgO:PPLN and PPLN lithium niobate structures. In order to provide reliable operation of the OPO, a monolithic cavity was used, which was designed in the form of a cube with cavities cut out for the appropriate optical elements of the OPO cavity and MgO:PPLN and PPLN crystals to be installed there.

MONOLITHIC CAVITY OF THE OPO

The main requirement for the development of a OPO is the achievement of the maximum conversion efficiency during the parametric interaction; therefore, attaining the optimal focusing in the PPLN crystal is a criterion in the development of the cavity optical scheme. It was shown theoretically [4] and experimentally [5] that the conversion efficiency is optimal when the pump confocal parameter b inside the crystal is equal to the length of the crystal.

Two circumstances must be taken into account during development of the optical cavity: (1) the aperture equal to 0.5 mm must be enough for the free passage of pumping radiation (along the z axis) through the crystal (for a 500-μm-thick crystal, the beam radius for an idler wave must be ≤160 μm in order to avoid diffraction losses that lead to an increase in OPO oscillation threshold); and (2) the high-Q cavity for a signal wave must be stable [6].

The monolithic OPO cavities consist of two high-reflectivity mirrors at the signal wave (Fig. 1). The output mirror is transparent at the pump and idler wavelengths; the input mirror is transparent at the pump wavelength. The second mirror with a 50-mm radius of curvature is "dense" for all three wavelengths (Ag ThorLabs). The designed monolithic block allows correcting the cavity length by means of changing the distance between two cylindric holders at the flanges. The monolithic block design allows varying the cavity configuration (confocal, spherical, Fabry–Perot, and half-spheric).

The PPLN crystal is mounted on the guard-adjusted holder, which allows adjustment of the crystal position inside the cavity and PPLN displacement along all periods to provide for the OPO wavelength tuning.The described device provides the replacement of adjustable PPLN block by block with $LiGaSe_2$, $LiInSe_2$ [2], and other bulk crystals for tuning in the

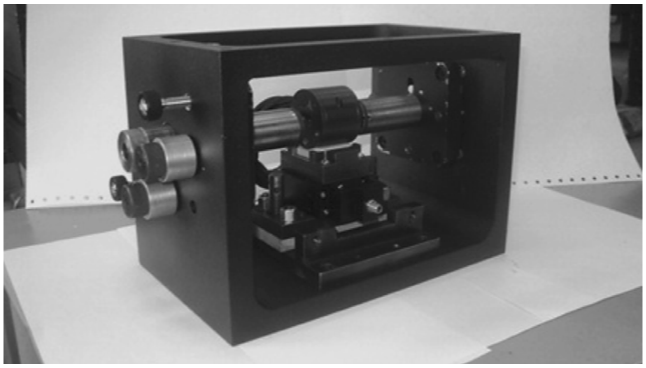

Fig. 1. Monolithic PLG cavity.

long-wavelength region (up to 9 μm at a later date). In this case, wabelength tuning can be ensured via varying the angle θ in the crystal.

CALCULATION OF THE OPO THRESHOLD CHARACTERISTICS

According to the models proposed in [7, 8], the pump energy density threshold and the pump energy threshold of the double-pass OPO can be calculated as:

$$J_T = \frac{1}{T_p}\frac{1}{F}\frac{n_p n_s n_i \varepsilon_0 c^4}{2\omega_s\omega_i d_{eff}^2}\frac{2.25}{L^2}\frac{W_p^2 + W_s^2}{W_p^2}\frac{\tau}{(1+\gamma)^2} \times \cosh^{-1}\left(\frac{30L_{cav}}{2\tau c} + \alpha_d - \ln\sqrt{R_s}\right);$$

$$P_{th} = \frac{\alpha_s\alpha_i n_s n_i c^4 \varepsilon_0 \pi}{4\omega_s\omega_i\omega_p d_Q^2 L\bar{h}_m},$$

where n_p, n_s, and n_i are the crystal refraction ion coefficients at the pump, signal, and idler wavelengths, respectively; ω_s and ω_i are the frequencies of the signal and idler waves, respectively; W_p and W_s are the waists of Gaussian beams for pump and signal waves, respectively; γ is the amplitude ratio of reflected and incident waves of the pump field; α_d is the loss per single pass for the signal wave; α_s is the loss per single pass for the signal wave including the loss at the output mirror; R_s is the reflection coefficient for the signal wave; T_p is the transmission coefficient for pump wavelength; τ is the pump pulse duration; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the dielectric constant for vacuum; $c = 3 \times 10^8$ m/s is the velocity of light; d_{eff} is the effective nonlinearity; L is the crystal length; L_{cav} is the optical; $\bar{h}_m$ is the Boid–Cleiman coefficient (in the double-pass scheme, $\bar{h}_m$ = 0.186); and F is the sharpness of resonance at pump frequency (in the double-pass scheme, $F = 1.8$).

HALF-SPHERIC CAVITY WITH DOUBLE-PASS PUMPING

In a half-spheric cavity with double-pass pump, a flat mirror with the following parameters is used as the entrance and output mirror: *HRr* (0°–15°, (1310–1470) ± 10 nm) > 99.9% + *Rr* (0°–15°, 1064 nm) < 5% + *Rr* (0°–15°, 3.0–6.0 μm) < 5%. The second mirror is spherical with a radius of curvature R = 50 mm and silver-coated (ThorLabs). The pump pulse duration is τ = 5–7 ns (1000–5000 Hz), the loss per pass for a signal wave is $\alpha_s = 0.04$, and the amplitude ratio of the transmitted and incident waves of the pump field in the crystal is $\gamma = 0.1$.

The distances between crystal and optical mirrors M_1 and M_2 (L_1 and L_2, respectively) are determined from the minimum distance of cylindrical holders in the flanges of the optical mirrors to the adjustable holder of the PPLN crystal. The half-spheric cavity ensured the required beam-waist radius (92 μm) at the chosen distances L_1 = 7 mm and L_2 = 7 mm and a crystal length of 20 mm.

The PPLN crystal length was 20 mm. The following values of the refractive indices of the PPLN crystal were used in calculations: $n_p = 2.13$, $n_s = 2.13$, and $n_i = 2.35$. In this configuration, the calculated pump energy density threshold (λ_p = 1.053 μm, λ_s = 1.5 μm, and λ_I = 3.53 μm) was J_T = 0.024 J/cm^2 at a beam radius of ω_0 = 92 μm and the pump energy threshold was 10.6 μJ.

EXPERIMENTAL SETUP

Figure 2 shows a diagram of the experimental setup of the single-cavity OPO with double-pass pump. A single-mode Nd^{3+}:YLF laser (DTL-329QT model by Laser-Compact Group) was used as the pump source. The laser operates in the nanosecond regime, which is implemented owing to the acousto-optic Q-switching. The maximum pulse energy at frequencies of 1–5 kHz is 300 μJ. The pump wavelength is 1.053 μm.

The OPO cavity is formed by two mirrors (Fig. 2): flat mirror M_1 (Layertec) (*AR* (0°, 1064 nm) < 1.0% + *AR* (0°, 4.0–6.0 μm) < 2%, *HRr* (0°–15°, (1310–1470) ± 10 nm) > 99.9%) and mirror M_2 (ThorLabs) with Ag coating, R = 50 mm. CaF_2 lens (focal length f = 200 mm) provided the optimal matching of the pump radiation to the cavity parameters. The waist radius on mirror M_1 was $\omega_0 \approx 92$ μm. The pump radiation was injected through the mirror M_1, and radiations at the signal and idler waves were extracted also through the mirror M_1. Heater with a periodically polarized $LiNbO_3$ crystal (PPLN) was placed in the OPO cavity.

Faraday isolator (Avesta) was used in the optical scheme for excluding feedback owing to the OPO cavity and optical elements of the system. A half-wavelength plate combined with a polarization cube (Thor-

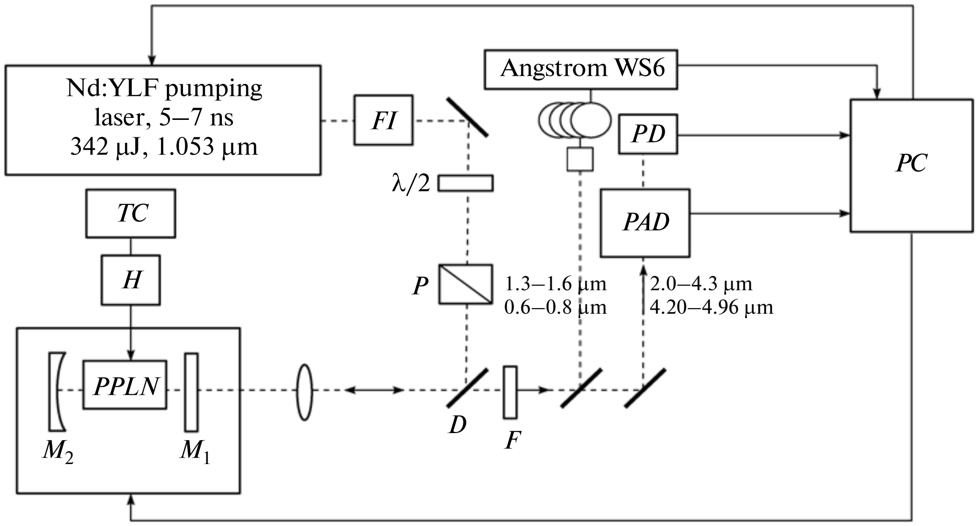

Fig. 2. Schematic diagram of the experimental PLG setup: (*FI*) Faraday isolator, (M_1, M_2) mirrors of the OPO cavity, (*PAD*) photo-acoustic detector, (*PC*) personal computer, (*P* polarizer), (*TC*) thermocontroller, (*H*) heater, (Angstrom WS6) wavelength meter, (*PD*) pyroelectric detector, (*D*) dichroic mirror, (*F*) filter, and (λ/2) half-wavelength plate.

Labs) provided the required polarization for initiating the parametric conversion process.

OPO BASED ON MgO:PPLN

The MgO:PPLN crystal (Covesion LTD) was 20 mm long and consisted of nine periods with a 0.5 mm width each (27.91, 28.28, 28.67, 29.08, 29.52, 29.98, 30.49, 31.02, and 31.59 μm). The crystal heater was placed on *X*-coordinate stage, which provided switches of the structure relative to the pumping beam, thus allowing the OPO to be tuned in the region 2.1–4.3 μm. Both crystal surfaces were antireflection coated: pump, $R < 1.5\%$ for 1064 nm; signal, $R < 1\%$ for 1400–1800 nm; and idler, $R \sim 6–3\%$ for 2600–4800 nm. The crystal thermocontroller and heater provided thermal stabilization of the PPLN in a wide temperature range (30–200°C) with an error up to 0.1°C.

Combination frequencies were observed during the parametric conversion: the second harmonic of signal wave (at 699–758 nm) and the summary frequency of double signal frequency and the idler wave frequency (in range 600–660 nm). This allowed to use an Angstrom WS6 commercial wavemeter with a silicon photodiode rule for diagnosing the OPO tuning region.

Combination frequencies measurment results were used to measure OPO tuning characteristics for the idler wave (Fig. 3). The characteristics are presented for three periods of the PPLN with $\Lambda = 27.91$, 28.28, and 28.67 μm. Figure 4 shows the dependence of the idler-wave energy on Λ for MgO:PPLN crystal. At a temperature of the PPLN crystal of 70°C and a fixed pumping energy of 112 μJ, the crystal position was changed so as to compare the OPO energy characteristics on all nine periods. It was noticed that the maximum efficiency of pumping-to-signal energy conversion was 8% on the period with $\Lambda = 28.28$ μm ($\lambda_i = 3$ μm). The minimum conversion efficiency (≈4%) was observed on the period with $\Lambda = 31.59$ μm. Decresing in the conversion efficiency in the long-wavelength region is associated with the onset of the multiphoton absorption in the PPLN structure.

The measured parametric generation threshold in the MgO:PPLN system was varied in a range of 11–28 μJ when tuning idler wave in the range 2.1–4.3 μm, which corresponds to the calculated value (10.6–27.0 μJ).

OPO:PPLN (OPO-1 COVESION LTD)

The 20-mm-long PPLN crystal (OPO-1 Covesion LTD) consisted of nine periods (25.00, 25.25, 25.50, 25.75, 26.00, 26.50, 26.75, and 27.00 μm). The thermocontroller and heater of the crystal provided the PPLN thermostatting in the temperature interval 100–200°C with an error of 0.1°C. Switching the pump beam along tracks and changing the temperature in a range of 100–200°C allowed idler wavelength tuning within a range of 4.2–4.7 μm. Both crystal surfaces were antireflection coated: pump, $R < 1.5\%$ for 1064 nm; signal, $R < 1\%$ for 1340–1420 nm; and idler, $R \sim 6–3\%$ for 4200–4700 nm.

The results of measuring combination frequencies (the second harmonic of signal wave and summary frequency of second harmonic of the signal wave and idler wave) with the Angstrom WS-6 commercial wave meter were used to plot the OPO tuning characteristics in the temperature range 163–195°C (Fig. 5), which properly agree with the calculated curves presented in www.covesion.com.

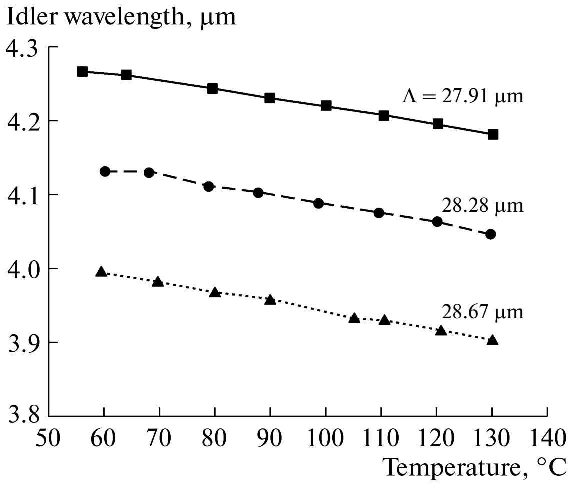

Fig. 3. The temperature tuning characteristics for OPO based on MgO:PPLN for three periods with Λ = 27.91, 28.28, and 28.67 μm.

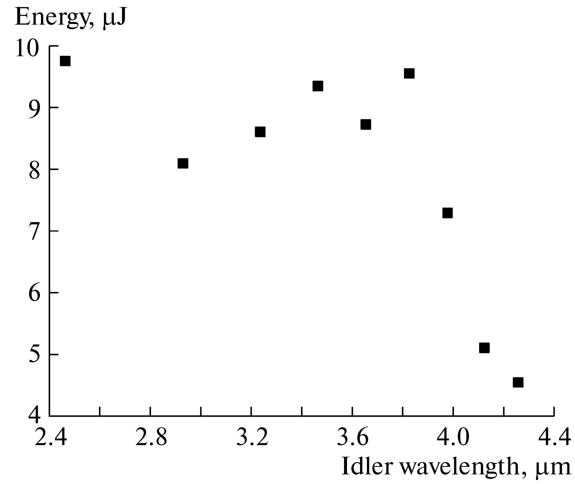

Fig. 4. The wavelength dependence of the idler-wave energy at a fixed crystal temperature ($T = 70°C$, a pumping energy of 116 μJ) for the OPO based on MgO:PPLN.

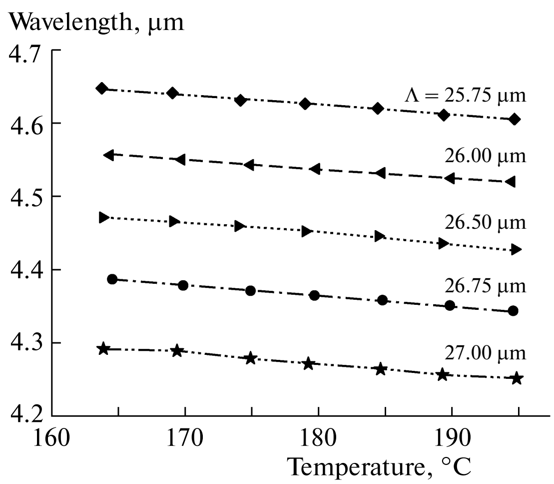

Fig. 5. The temperature tuning characteristics for the OPO:PPLN.

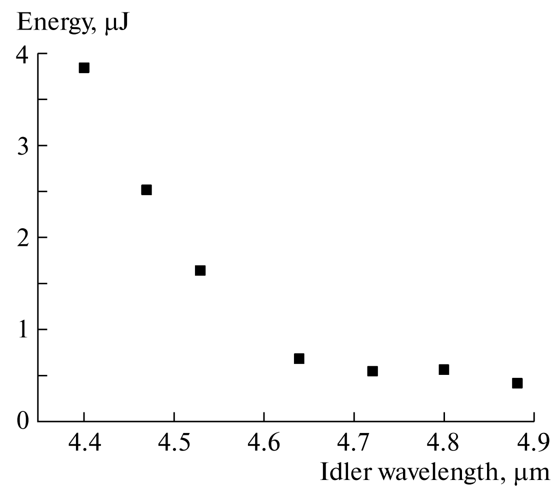

Fig. 6. The dependence of the idler-wave energy on λ for the OPO:PPLN.

Figure 6 shows the energy dependence of the idler-wave for the OPO-1 PPLN crystal at a fixed pump energy of 112.9 μJ and a temperature of the PPLN chip of 194.9°C. The idler-wave energy decrases abruptly from 3.7 to 0.5 μJ in long-wave region (pump energy 112-μJ). Idler-wave energy decreasing in the in range of 4.3–4.7 μm is associated with the multiphoton absorption in the PPLN crystal.

Generation of signal frequency and harmonics of signal and idler waves was observed on all nine periods of the crystal at temperature range (100–200°C). Generation of the idler wave was observed even in a range of 4.70–4.96 μm using the Angstrom IR lambda meter with a pyroelectric array.

The oscillation thresholds of the OPO:PPLN were 36 and 49 μJ in the range of 4.2 and 4.7 μm, respectively.

CONCLUSIONS

A source of coherent IR radiation has been developed based on optical parametric oscillator (MgO:PPLN and PPLN) with double-pass pump by a nanosecond compact Nd:YLF laser at a wavelength of 1.053 μm. Monolithic cavity was designed in the form of a cube with cavities cut out for installing the corresponding optical elements of the OPO resonator and the PPLN crystal used to ensure reliable OPO operation.

OPO provides the tuning of the idler wavelength (MgO:PPLN and PPLN) in a wavelength range of 2.0–4.3 μm. The conversion efficiency of the pump energy to the idler-wave energy decreases from 8.6 to 2.5% in the wavelength range 2.0–4.3 μm. The conversion efficiency of the pump energy to the idler-wave energy was 3.3–0.4% in the range 4.2–4.7 μm.

ACKNOWLEDGMENTS

This study was supported by the Federal Target Program for 2007–2013 (project no. 02.740.11.0083 and project no. 16.522.11.2001) and the Russian Foundation for Basic Research, (project no. 10-02-00422-a).

The authors are grateful to A.K. Potekhin, S.I. Goncharov, and Yu.F. Tomashevskii (Angstrom LTD) for their participation in the experiment on the OPO wavelength measurement mid using the IR-III lambda meter.

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