Russian Physics Journal, Vol. 56, No. 2, July, 2013 (Russian Original No. 2, February, 2013)

OPO CAVITY DESIGN FOR A 2.6–5.9 μm IR RADIATION SOURCE

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UDC 535.015

Calculation and modeling of the optical parametric oscillator (OPO) cavity for a 2.6–5.9 μm IR source are performed. The threshold generation parameters are calculated, and the optimal cavity configuration is chosen.

Keywords: IR source, optical parametric oscillator, nonlinear optical crystal, silver thiogallate, generation threshold.

INTRODUCTION

At present one of the important research directions is exhaled air gas analysis [1]. It is well known that more than 1000 components with mass concentration less than 0.01% are contained in the exhaled air together with a large variety of their compounds. Some of specific exhaled air compounds can be used as natural gaseous biomarkers [2]. The majority of absorption lines of these biomarkers lie in the mid-IR region (from 2 to 12 μm); therefore, the problem of developing a source tunable in a wide IR region is urgent now. It has not yet been solved.

1. PROBLEM FORMULATION

In the process of implementation of the Federal Special-Purpose Program “Research and Development of Priority Directions of the Development of Scientific and Technological Complex of Russia for 2007-2013” (State Contract No. 16.522.11.2001), the hardware-software complex “Gas Analyzer for Exhaled Air Composition by the Method of Photoacoustic Spectroscopy Based on a Wideband Optical Parametric Oscillator Using a Photoacoustic Detector” in the wavelength range from 2 to 11 μm is being developed. To solve this problem, it is necessary to develop a method of wavelength tuning in the wavelength range from 2.6 to 5.9 μm. As a nonlinear element, a silver thiogallate $AgGaS_2$ (AGS) crystal is used. In that case, the change of the nonlinear crystal position in the OPO cavity is limited by the angle $\alpha = \pm 7°$ [3]. The angle α depends on the OPO cavity design, which allows the required tunable range for the idler wave to be obtained.

2. PUMPING LASER AND NONLINEAR ELEMENT SELECTION

A single-mode Nd^{3+}:YLF laser with diode pumping (model DTL-429QT, Laser-compact Group) was used as a pumping laser source. The laser operated in Q-switched mode. The maximum pulse energy at frequencies of 1–5 kHz was 540 μJ, the wavelength was 1053 nm, and the pulse duration was 5–10 ns.

In [4, 5], the creation of the OPO pumped by a Nd^{3+}:YLF laser based on MgO:PPLN and PPLN crystals was reported. The tuning range of the OPO based on MgO:PPLN crystal was in the range from 2.1 to 4.3 μm, and its generation threshold was E = 22–48 μJ [4]. The tuning range of the OPO based on the PPLN structure ranged from

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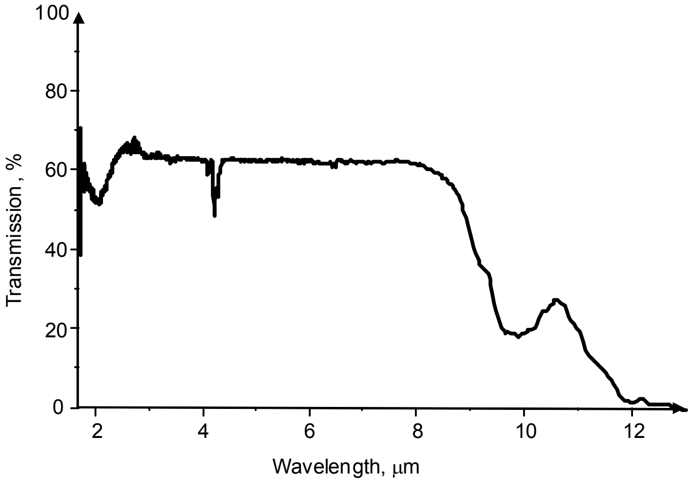

Fig. 1. AGS transmission spectrum.

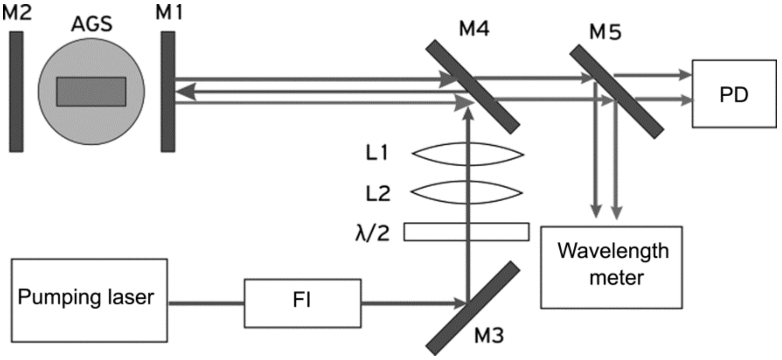

Fig. 2. Block diagram of the OPO setup comprising Faraday insulator (FI), telescope lenses (L1 and L2), nonlinear silver thiagallite ($AgGaS_2$) crystal (AGS), OPO cavity mirrors (M1 and M2), rotating mirror (M3), and dichroic mirrors (M4 and M5).

4.2 to 4.96 μm, and its generation threshold was 36 μJ at 4.2 μm and 49 μJ at 4.7 μm [4]. Wavelength tuning was performed by mechanical switch through sections of the PPLN crystal and temperature. The speed of system operation was limited by temperature transient in the crystal.

To develop a laser source in the mid-IR, thiogallate silver $AgGaS_2$ (AGS) crystals can be used as a nonlinear optical element [6–9]. The advantage of the AGS crystals is phase matching at the pump wavelength λ_P = 1.053 μm. The $AgGaS_2$ crystals are transparent in the wavelength range from 0.48 to 11.4 μm (Fig. 1), which has allowed us to use commercial lasers with wavelengths 1.053–1.064 μm for optical pumping of these crystals. The AGS crystals have nonlinear optical coefficient (12–14 pm/V), low thermal conductivity (1.5 W/(m·K)), and low damage threshold (0.2 J/cm^2). According to [10, 11], $AgGaS_2$ OPO can be tuned in the range 2.1–11.3 μm.

3. EXPERIMENTAL SETUP

Figure 2 shows the block diagram of the experimental AGS OPO. The AGS crystal was cut at $\theta = 48°$ and $\varphi = 45°$ for type I (*eoo*) phase matching, has 5×5 mm aperture and length of 15 mm. Anti-reflecting coatings were deposited on crystal surfaces to provide maximum transmittance at 1.053 μm and in the range 1.15–1.5 μm (for the signal wave), $R \leq 1\%$.

The OPO was pumped by the single-mode Nd:YLF laser operating at $\lambda_p = 1.053$ μm and providing a maximum pulse energy of 540 μJ. A telescopic collimator consisting of two lenses L_1 and L_2 ($f_{L1} = 100$ and $f_{L2} = 50$ mm) was used for pumping laser and OPO cavity matching.

Dichroic mirror M5 was used for separation of signal and idler waves. The idler pulse energy was measured with an OphirPE-10C pyroelectric detector. The signal wavelength was registered by an AngstromWS-6IR wavelength meter in the wavelength range 1.28–1.77 μm.

The OPO wavelength was tuned by rotation of the AGS crystal with respect to the optical axis of the cavity formed by two flat mirrors M1 and M2. The OPO cavity was 18–22 mm long.

4. CALCULATIONS OF OPO THRESHOLDS

To determine the OPO generation threshold, the computational model described in [12] was used:

$$j_T = \frac{1}{T_p} \frac{n_p n_s n_i \varepsilon_0 c^3}{2\omega_s \omega_i d_{\text{eff}}^2} \frac{2.25}{L^2} \frac{W_p^2 + W_s^2}{W_p^2} \frac{\tau}{(1+\gamma)^2} \cosh^{-1}\left(\frac{30 L_{\text{cav}}}{2\tau c} + \alpha_d - \ln\sqrt{R_s}\right), \quad (1)$$

where n_p, n_s, and n_i are refractive indices for the pump, signal, and idler wavelengths, respectively; ω_s and ω_i are frequencies of signal and idler wavelengths; W_p and W_s are Gaussian beam waists for pump and signal wavelengths; γ is the ratio of backward to forward pump field amplitudes in the crystal; α_d is the single-pass power loss for the signal disregarding output coupling; R_s is the signal reflectivity of the output coupler; T_p is the pump transmission though the input coupler and the crystal surface; τ is the pump pulse duration; ε_0 is the vacuum dielectric constant ($\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m); c is the velocity of light in vacuum ($c = 3 \cdot 10^8$ m/s); d_{eff} is the nonlinear optical coefficient ($d_{\text{eff}} = 31$ pm/V); L is the crystal length; and L_{cav} is the optical cavity length.

To obtain the optimal parameters of the OPO cavity, a series of experiments with different variants of the input mirror M1 was performed. In the first experiment, the OPO cavity was formed by two flat mirrors (the Fabry–Perrot cavity). Pump radiation through flat mirror M1, Layertech ($R > 99.9\%$ for 1.35–1.7 μm, $R < 1.0\%$ for $\lambda_p = 1.064$ μm, and $R < 2\%$ for $\lambda_i = 2.5$–4.5 μm) was injected into the OPO cavity, and signal and idler radiation was extracted. Silver mirror M2 of the cavity was flat. The pump pulse duration was $\tau = 5$–10 ns (1000 Hz). The threshold pump energy density calculated for the given configuration was $J_{th} = 11$–12 mJ/cm^2 at the edge wavelengths of the tuning range ($\lambda_i = 2000$–4000 nm).

The energy density calculated from the formula

$$J_{th} = \frac{E_{th}}{\pi (d/2)^2}, \quad (2)$$

was $J_{th} = 13$ mJ/cm^2, the beam diameter was $d = 1$ mm, and the minimum pump energy at which generation was observed was $E_{th} = 103$ μJ. When the AGS crystal ($\theta = 48°$ and $\varphi = 45°$) was rotated about the optical axis through ±3.5°, the tuning range for the idler wave was 3.5–5 μm.

After replacement of mirror M1, Layertech, by ZnSe mirror, LaserOptics ($R > 99.9\%$ for 1.15–1.65 μm, $T > 99.9\%$ for $\lambda_p = 1.053$ μm, and $T > 99.8\%$ for $\lambda = 2.0$–12.0 μm), the threshold pump energy density was $J_{th} = 11.59$ mJ/cm^2 for the same input beam parameters. The minimum pump energy at which generation was observed was $E_{th} = 91$ μJ. The calculated energy density was the same as in the previous experiment. Thus, the change of the mirror caused no significant changes of the generation threshold. However, in this case the tuning range for the idler wave was expanded from 2.6 to 5.9 μm due to optical coating in the signal wave range (1150–1650 nm).

TABLE 1. Parameters of the OPO Cavity with the Indicated Mirrors

Parameters of input mirror M1 of the OPO cavity	J_{th}, mJ/cm^2		E_{th}, μJ	
	Theory	Experiment	Theory	Experiment
Flat mirror, Layertech $R > 99.9\%$ for 1.35–1.7 μm $R < 1.0\%$ for $\lambda_p = 1.064$ μm $R < 2\%$ for $\lambda_i = 2.5$–4.5 μm	11–12	13	65	103
ZnSe mirror, LaserOptics $R > 99.9\%$ for 1.15–1.65 μm $T > 99.9\%$ for $\lambda_p = 1.053$ μm $T > 99.8\%$ for $\lambda = 2.0$–12.0 μm	11	11.59	65	91
Spherical ZnS mirror, LaserOptics; $r = 2000$ mm	8–9	18.72	64.2	147

To compare the tuning characteristics, the AGS crystal was changed to type II (*eoe*) phase matching ($\theta = 67°$ and $\varphi = 0°$). Calculations demonstrated that possible tuning range for the idler wave expanded from 3.5 to 5 μm. The calculated energy density was about 40 μJ/cm^2, and the tuning range expanded from 3.39 to 3.88 μm.

In another variant, the spherical ZnS mirror, LaserOptics, with $r = 2000$ mm was used for mirror M1. The calculated spherical mirror parameters were the following: J_{th} = 8–9 mJ/cm^2, generation threshold energy density $J_{th} = 18.72$ mJ/cm^2 for beam diameter $d = 1$ mm, the minimum pump energy at which generation was observed was $E_{th} = 147$ μJ, and the tuning range for the signal wave ranged from 2.9 to 4 μm. The measured and calculated parameters of the OPO cavity with these mirrors are presented in Table 1.

CONCLUSIONS

The source of coherent optical radiation in the wavelength range λ_i = 2.6–5.9 μm based on AGS OPO with nanosecond Nd:YLF laser twopass pumping has been developed. The $AgGaS_2$ crystal ($\theta = 48°$ and $\varphi = 45°$) was used as a nonlinear element. To obtain the optimal threshold characteristics, the following mirrors were chosen for the OPO cavity (Table 1): input ZnSe mirror M1 and flat silver mirror M2, LaserOptics. The threshold energy density was J_{th} = 11.59 mJ/cm^2, which was in good agreement with its theoretical value (11 mJ/cm^2). The idler energy in the range λ_i = 2.6–5.9 μm increased from 3 to 5.5 μJ at pump pulse energy of 300 μJ.

The authors are greatful to PhD L. I. Isaenko (Institute of Geology and Minearology of the Siberian Branch of the Russian Academy of Sciences) for kindly provided silver thiogallate $AgGaS_2$ crystal.

This work was supported in part by the Federal Special-Purpose Scientific-Technical Program "Research and Development of Priority Directions of the Development of Scientific and Technological Complex of Russia for 2007-2013" (State Contract No. 16.522.11.2001) and by the Russian Foundation for Basic Research (grant No. 10-02-00422-a).

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