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GENERAL EXPERIMENTAL TECHNIQUES

A Narrow-Band Optical Parametric Oscillator Based on a Periodically Polarized Structure of Lithium Niobate with Volume Bragg Grating

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Abstract—A narrow-band radiation source based on a MgO:PPLN-crystal near-degenerate optical parametric oscillator (OPO) with a volume Bragg grating (VBG) and a wavelength of 2128 nm was developed. The signal wavelength of the developed OPO is tuned in a wide range of 2041–2106 nm; the idler wavelength is tuned in the spectral range of 2152–2224 nm with a linewidth of approximately 0.5–0.89 nm. Five types of mirrors with different reflection coefficients for generated radiation (R = 55, 60, 66.5, 79.5, and 88.6%) were used as the output coupler of the OPO cavity. The maximum achieved OPO radiation power was ~1 W (200 μJ) for a mirror with R = 55% at a wavelength of 2128 nm. The measured OPO beam quality factor in the vertical and horizontal planes amounted to 3.6 and 4.2, respectively.

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1. INTRODUCTION

Laser sources that generate radiation in the eye-safe spectrum region (~2 μm) have many applications, such as environmental monitoring, medicine, and scientific research. The presence of absorption lines of some atmospheric gases, including CO_2 and N_2O, in this spectral region allows the use of two-micron radiation sources for lidar systems [1, 2]. The minimum penetration depth of such radiation into the human-body tissues and the absorption of water in this range make it possible to use these sources for neurosurgery, otolaryngology, urology, and other medical applications [2–4]. Two-micron sources can also be used as pumping sources for optical parametric oscillators (OPOs) in the mid-infrared range [2, 5]. In this region of the spectrum, the main sources are discretely tunable solid-state lasers based on crystals doped with thulium Tm^{3+} and holmium Ho^{3+} ions [2, 6, 7]. An alternative method for generating radiation with a wavelength of 2 μm is the use of a degenerate OPO pumped with a neodymium laser at a wavelength of 1 μm [5, 8]. In such systems, it is necessary to additionally apply special methods for narrowing the width of the spectral line, e.g., to use injection lasers [9] or selective elements, such as diffraction gratings [10], prisms [10], Fabry–Perot etalons [11], and volume Bragg gratings (VBGs) [5, 12].

The periodic modulation of the refractive index of VBGs, which are also called volume holographic gratings, makes it possible to achieve the reflection at a fixed wavelength in a certain narrow light-transmission band, which is narrower than that of selective mirrors by several orders of magnitude [12]. The use of a VBG as an element of the OPO cavity was demonstrated for the first time in 2005 [13]. The authors managed to reduce (to 0.16 nm) the signal-wave linewidth of the OPO based on a PPKTP crystal (periodically poled potassium titanyl phosphate) with pumping by radiation of the second harmonic of a Nd:YAG laser with a wavelength of 532 nm. This idea was used later for an OPO in the degenerate mode with a wavelength of 2 μm [5, 14, 15]. In [14] devoted to an OPO based on periodically poled lithium niobate (PPLN) with a VBG, the linewidth of a signal wave was 0.44 nm at a wavelength of 2008 nm, while the linewidth of the idler wave was 0.72 nm at 2264 nm; the maximum achieved output-radiation energy level was 156 μJ at a pulse repetition rate of 10 kHz. In this case, the radiation wavelength was not adjusted. A very high energy level (50 mJ) at a repetition frequency of 30 Hz was achieved in [15]. Such record-breaking energy characteristics were achieved by using a 36-mm-long PPLN crystal with a large aperture (5 × 5 mm). The output-radiation wavelength was fixed and was 2128 nm with a linewidth of 1.5 nm. Paper [9] describes a PPKTP-based scheme of a parametric amplifier with injection of OPO radiation. In this configuration, an output energy level of 52 mJ at a wavelength of 2131.3 nm was demonstrated. The width of the injection radiation line was 0.56 nm, while the wavelength was tuned within a narrow range (~21 nm).

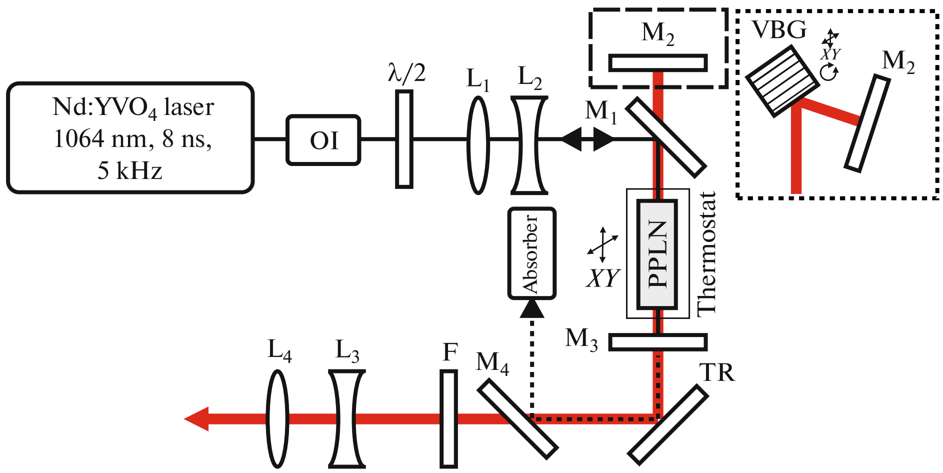

Fig. 1. Optical scheme of the OPO based on the MgO:PPLN crystal operating in the near-degenerate mode: (OI) Faraday optical insulator; (λ/2) half-wave plate; (L_1–L_4) lenses; (M_1–M_4) dielectric dichroic mirrors; (TR) reflecting mirror; and (F) filter. The variant of the scheme with the VBG is in a dotted frame.

In [16], we demonstrated a PPLN-based OPO with a VBG that was specified to reduce the width of the radiation line with a wavelength of 2117 nm at the normal angle of incidence. The length of the idler wave was adjusted in the range from 2050 to 2117 nm for the signal wave and from 2140 to 2208 nm for the idler wave with a linewidth of ~1 nm. At the same time, the average output-radiation power was 617 mW at a pulse repetition rate of 5 kHz.

In this paper, an optimized scheme of the experimental setup is presented. The use of a VBG that was specified for reflecting radiation with a wavelength of 2128 nm at the normal angle of incidence and the output mirror of the OPO cavity with a reflection coefficient of 55% made it possible to increase the conversion efficiency of the pumping radiation from 10 to 18.7%. The dependence of the output-radiation power level on the reflection coefficient of the output mirror for generated radiation was studied. It is shown that, when using a mirror with a reflectance of 55%, the maximum level of the average output power of ~1 W is reached. The described approach made it possible for the first time to obtain such a wide wavelength-tuning range (2041–2128 nm for a signal wave and 2128–2224 nm for an idler wave) for a narrow-band OPO based on a periodically polarized lithium niobate crystal doped with magnesium oxide (MgO:PPLN) in a near-degenerate mode with a VBG.

2. EXPERIMENTAL SETUP

Figure 1 shows a diagram of the experimental facility of the MgO:PPLN-based OPO that operates in the near-degenerate mode. The OPO was pumped with a pulsed Nd:YVO4 laser (Canlas Laser Processing GmbH) with a wavelength of 1064 nm. The laser emitted pulses with a length of 8 ns and a repetition frequency of 5 kHz. The width of the pump-laser radiation line was measured using an Angstrom LSA L IR spectrometer (HighFinesse GmbH) with a spectral resolution of ~45 pm and was 230 pm. The spatial beam profile is close to Gaussian and the beam quality index is $M^2 \approx 1.2$. A Faraday optical isolator (OI) that prevents the back incidence of reflected radiation on the laser output window was used to prevent damage to optical elements of the laser emitter. The vertical polarization of pumping radiation was provided using a half-wave plate (λ/2), on whose working surfaces an antireflection coating was applied. A telescope that consisted of two lenses L_1 and L_2 with focal lengths of f_1 = 174 mm and f_2 = –100 mm provided a required beam size in the PPLN crystal: d_x = 1.3 mm and d_y = 1.5 mm (at a level of e^{-2}) with a full divergence angle of ~0.25 rad. A dichroic mirror M_1 with a high reflectance for pumping radiation (HRs (45°, 1064 nm) > 99.9%) and a high transmittance for radiation with a wavelength of ~2 μm (Ts (45°, 2100–2150 nm) ≈ 95%) was used to inject pumping radiation into the OPO cavity, which is formed by mirrors M_2 and M_3. The dielectric mirror M_2 reflects 99.9% of generated radiation. Five mirrors with a high reflectance for pumping radiation (HRs (0°, 1064 nm) > 98.4%) and different reflectances for generated radiation (R = 55, 60, 66.5, 79.5, and 88.6%) are used as the output mirror M_3.

A periodically poled structure of lithium niobate—a MgO:PPLN crystal (HC Photonics Corp.) with a period of a regular domain structure of 32.25 μm was used as the nonlinear OPO element. The PPLN crystal with a length of 25 mm had an aperture of 3 × 3 mm with planeness of no worse than λ/6 for radiation with λ = 633 nm. An antireflection coating (AR) that provided a high transmittance for both pumping and generated radiation was applied to the working faces of

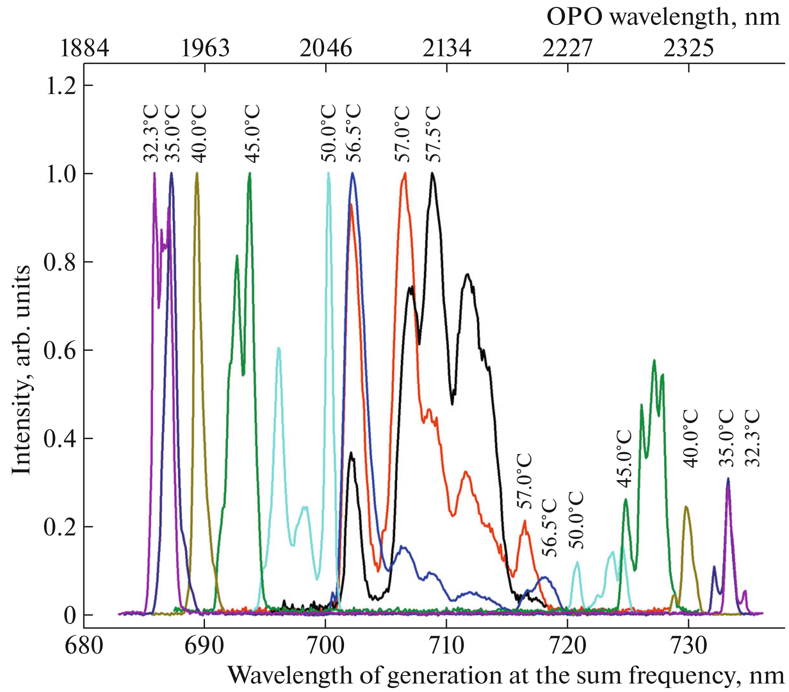

Fig. 2. Radiation spectra for generation at the sum frequency without the VBG for different PPLN crystal temperatures.

this crystal. The PPLN crystal was placed inside a thermostat (HC Photonics Corp.), which maintained an optimal crystal temperature at a level of 30–70°C with an error of 0.1°C at most. The thermostat was fixed on a precision linear *XY* moving device.

The scheme of the experimental facility was upgraded in order to narrow the spectral width of the OPO radiation line: instead of the mirror M_2 (dashed line in Fig. 1), a set of this mirror and a VBG was used; the latter was placed on a linear *XY* moving device and a precision rotating device (dotted line in Fig. 1).

The OPO cavity with and without the VBG, which was positioned normally to the cavity axis, was 50 mm long. However, the OPO wavelength was tuned via rotation of the VBG, and the cavity length increased to approximately 80 mm. The VBG with dimensions of 7 × 7 × 5 mm was manufactured at the ITMO university jointly with the AO LLS and specified to reduce the linewidth of radiation with a wavelength of 2128 nm (degenerate mode) with a diffraction efficiency of 95% at the normal angle of incidence.

OPO-emitted radiation was reflected by the mirror TR and guided to the measuring head of a power meter (12A, Ophir). Radiation with a wavelength of ~2 μm was additionally filtered using a mirror M_4 that was placed at an angle of 45° to the beam axis, reflected pumping radiation (HR (45°, 1064 nm) = 99.9%) to the beam absorber, and transmitted radiation with a wavelength of ~2 μm T(45°, 2050–2200 nm) = 92%. Additional selection was performed using a filter (F) that transmitted radiation with a wavelength longer than 1500 nm and had a high transmittance (HT) for generated radiation (0°, 2000–2200 nm) > 97%. The divergence of output radiation was reduced using a system of lenses L_3 and L_4 with focal lengths of $f_3 = 30$ mm and $f_4 = 125$ mm.

3. RESULTS AND DISCUSSION

A Thorlabs CCS200/M spectrometer with a spectral resolution of 2 nm and the spectral range of 200–1000 nm was used to measure the OPO radiation wavelength. Using this spectrometer, the wavelength of generated radiation at the sum frequency, which is produced by the interaction of pumping radiation and the idler or signal wave in a nonlinear crystal, was measured. The generation of the sum frequency is a weak parasitic effect in our case. However, it is this parasitic effect that allows us to estimate the lengths of the signal and idler waves of the OPO according to the following formula:

$$\lambda_{s,\mathrm{id}} = 1/(1/\lambda_{\mathrm{SFG}} - 1/\lambda_p), \quad (1)$$

where λ_{SFG} is the measured wavelength for generation at the sum frequency, λ_s is the OPO signal wavelength, λ_{id} is the idler wavelength of the OPO, and λ_p is the pump wavelength, 1064 nm in our case.

Figure 2 shows the results of measurements of the radiation spectra generated at the sum frequency for various crystal temperatures. To measure the radiation wavelength at the sum frequency, the collimator of the Thorlabs CCS200/M spectrometer was placed in front

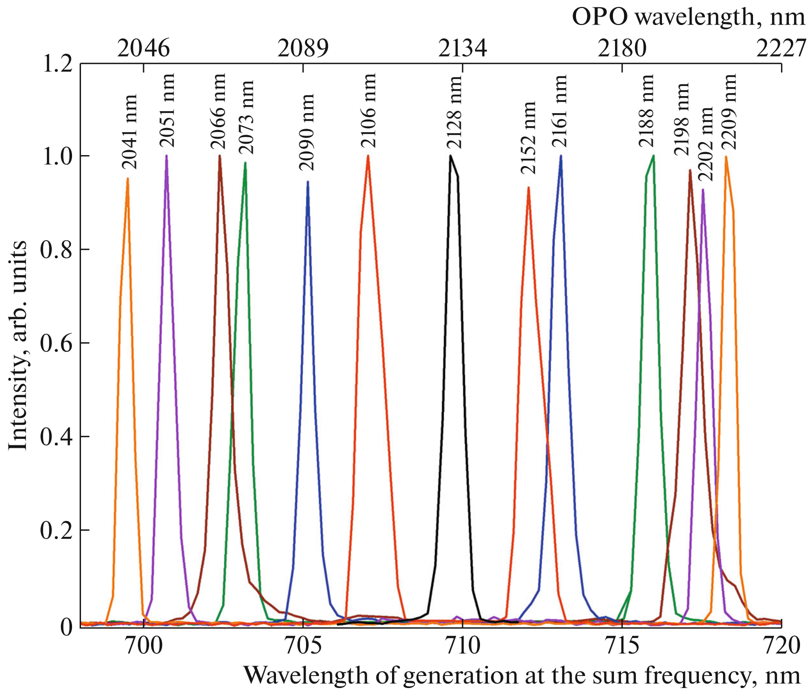

Fig. 3. Radiation spectra for generation at the sum frequency for different VBG angles of rotation at fixed temperatures of the PPLN crystal: 57 and 50°C (two extreme peaks on both sides of the figure).

of the lenses L_3 and L_4 according to the experimental scheme. In this case, the filter F was removed from the optical scheme. According to Fig. 2, the degenerate generation mode was observed at a crystal temperature of 57°C.

The radiation spectrum of parasitic generation at the sum frequency in the OPO scheme with the VBG at different angles of rotation is shown in Fig. 3. The wavelengths of the signal and idler waves are indicated above each corresponding peak. The wavelength of generation at the sum frequency was measured with the same spectrometer as in the scheme without the VBG. At large rotation angles of the VBG (more than 20° from the normal), the crystal temperature decreased to 50°C to increase the power level. As can be seen from Figs. 2 and 3, the radiation linewidth in the VBG-containing scheme has significantly decreased.

The OPO radiation wavelength at different VBG rotation angles was measured using a WS/5L VisIR2 spectrometer (HighFinesse/Ångstrom) with the spectral range of 500–2250 nm and a resolution of 30 pm (2 GHz). Figure 4 shows the measured emission spectra for the OPO signal and idler waves. At the normal radiation angle of incidence on the VBG, the radiation wavelength was 2128 nm. This case corresponds to a degenerate generation mode in which the lengths of the signal and idler waves are equal to each other. A turn of the VBG relative to the cavity axis allows one to tune the signal wavelength in the range of 2041–2106 nm and the idler wavelength in the range of 2152–2224 nm. At the same time, the measured linewidth of the output radiation (FWHM) was 0.5–0.89 nm. The design of this spectrometer does not allow measuring the radiation wavelength if the linewidth exceeds 5 nm; therefore, the measurement of the OPO radiation wavelength and linewidth without the VBG was not performed directly using this spectrometer.

To estimate the linewidth of output radiation of the OPO without the VBG, we decided to convert the output radiation into the second harmonic in a nonlinear BBO crystal. A BBO crystal with dimensions of 5 × 5 × 10 mm and cut angles of $\varphi = 90°$ and $\theta = 22°$ was manufactured for this experiment. The acceptance angle $\Delta\theta$ for the selected *oo-e* type of interaction, which was calculated on the basis of the dispersion dependence from [17], was only 0.063° (1.1 mrad). The small acceptance angle in the BBO crystal allows it to be used to scan the OPO radiation wavelength. For this purpose, the BBO crystal was placed on a precision rotary platform (with a step of 2.4′). Radiation of the second harmonic was injected into the collimator of the WS/5L VisIR2 spectrometer (HighFinesse/Ångstrom). To estimate the width of the spectral line for the OPO without the VBG, the temperature of the PPLN crystal was set at 57°C, and the BBO crystal was precisely rotated relative to the beam axis. Thus, the acceptance angles in the BBO crystal were scanned, i.e., the crystal acted as a tunable spectral filter. This approach made it possible to estimate the OPO output radiation linewidth without the VBG as

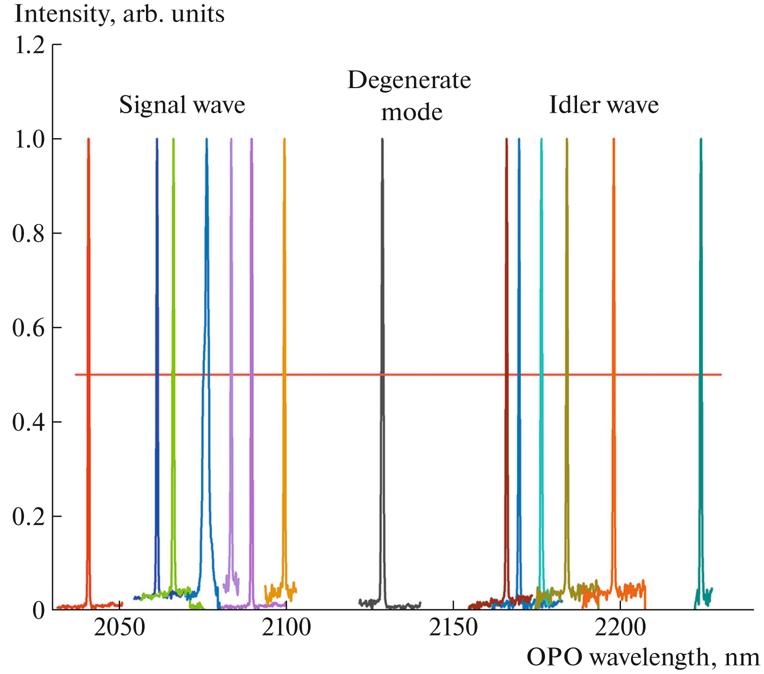

Fig. 4. Radiation spectra of the signal and idler waves of the OPO at different VBG angles of rotation.

approximately equal to 180 nm. Figure 5 shows the emission spectra of the generated second harmonic at different BBO-crystal angles of rotation.

The level of the average pump-radiation power was measured using an L50(150)A (Ophir) power meter placed after the system of lenses L_1 and L_2. The OPO radiation power was measured with a 12A power meter (Ophir) that was located in front of the lens system of L_3 and L_4. Figure 6 shows the dependences of the average radiation power for the OPO without the VBG

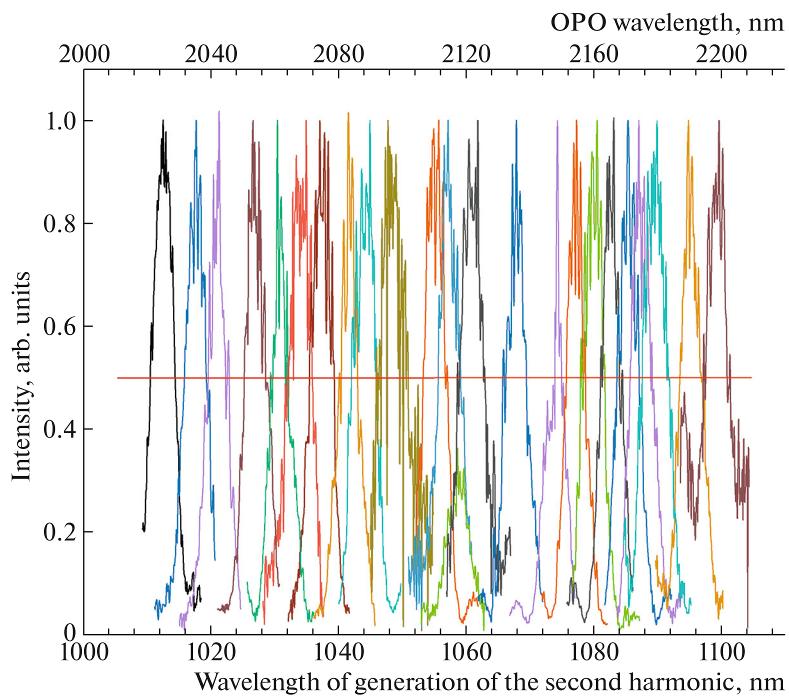

Fig. 5. Radiation spectra for generation at the sum frequency at different BBO-crystal angles of rotation.

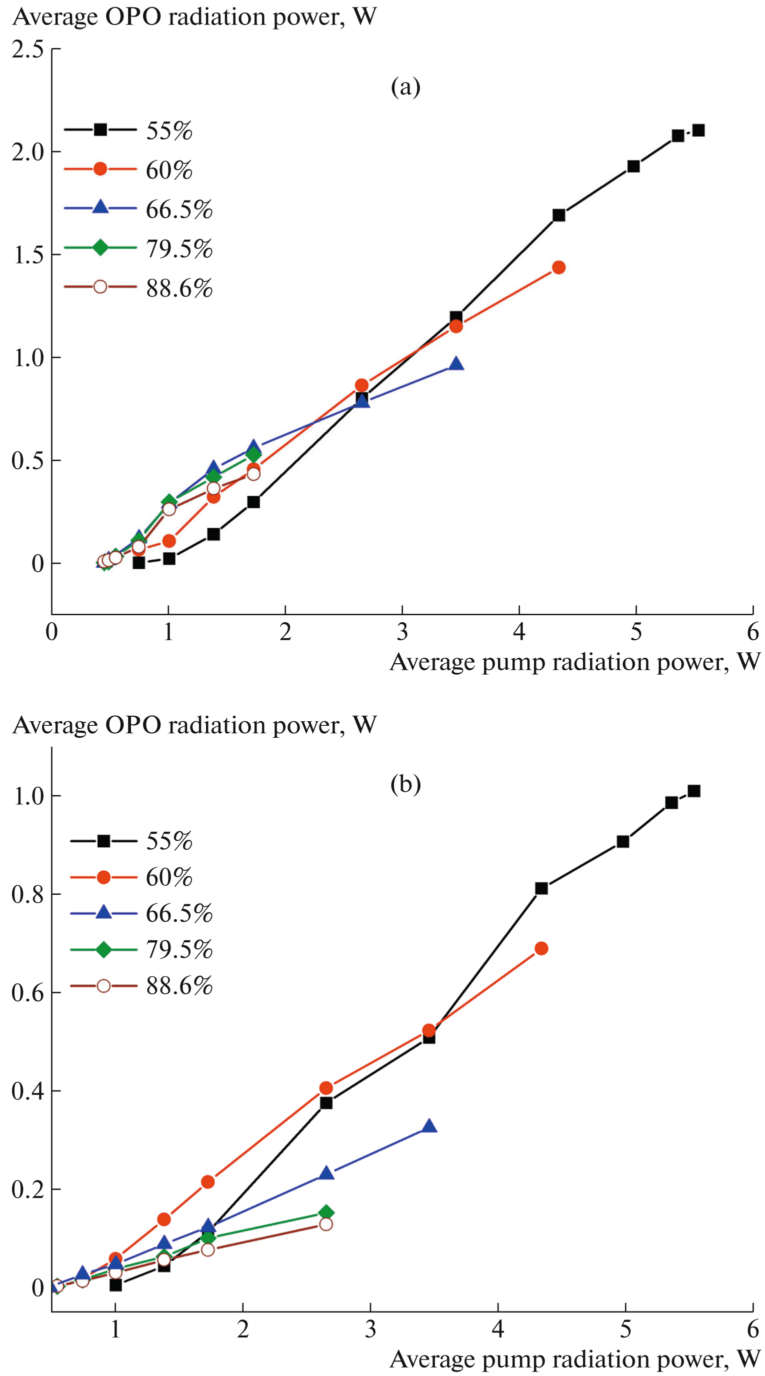

Fig. 6. Dependences of the average power of OPO radiation in the degenerate mode (at a wavelength of 2128 nm) (a) without the VBG and (b) with the VBG on the pump power for the output mirrors of the cavity with different reflection coefficients (numbers near the curves) for generated radiation.

(Fig. 6a) and with the VBG (Fig. 6b) on the pump-power level for the output mirrors of the OPO cavity with various reflection coefficients for the generated radiation: 55, 60, 66.5, 79.5, and 88.6%.

As is seen in Fig. 6a, the maximum OPO radiation power (2.1 W) was achieved when using a mirror with a reflectance of 55%, while the conversion efficiency was 38.6%. With high reflection coefficients, the saturation effect occurs at lower power levels and there is a danger of optical damage to the nonlinear crystal.

In the scheme with the VBG (Fig. 6b) in the degenerate mode, the maximum power level of 1.01 W was also achieved when using a mirror with a reflectance of 55%, while the conversion efficiency was 18.7%.

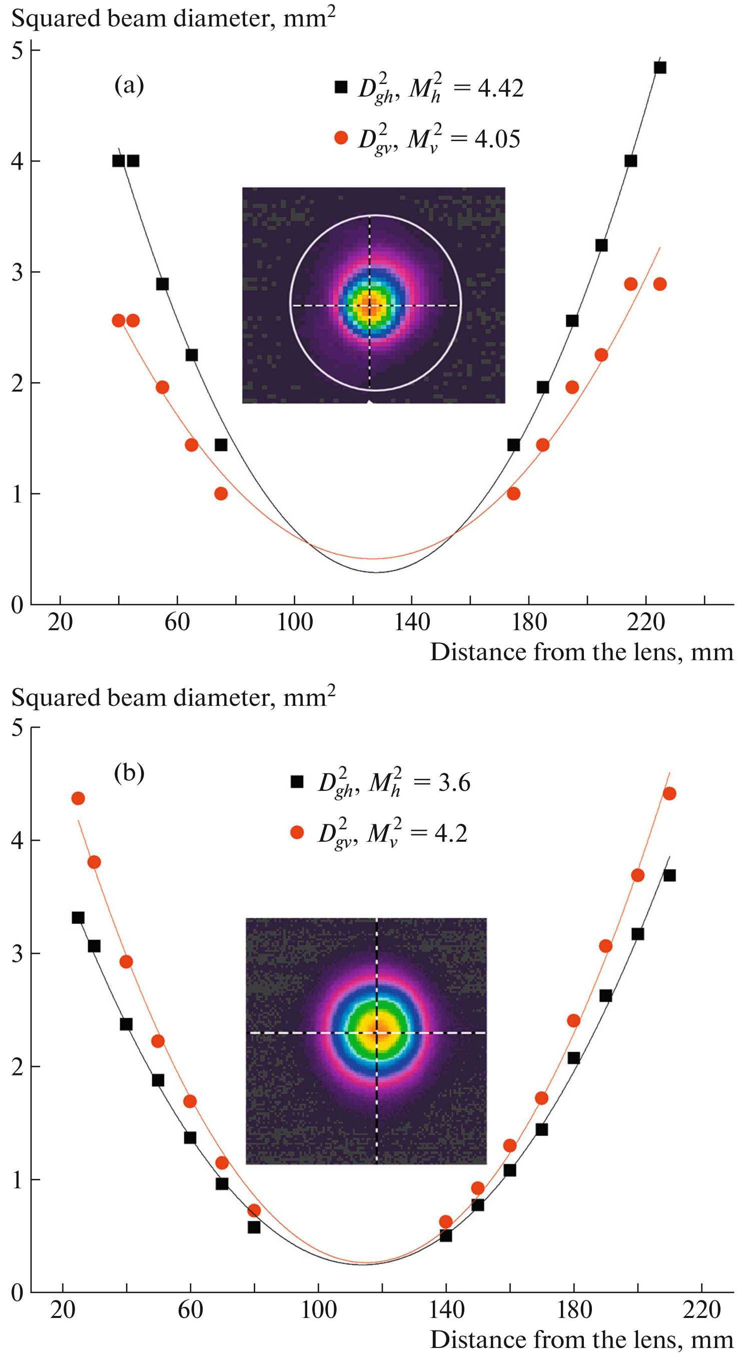

Fig. 7. Results of measuring M^2 for OPO radiation (a) without the VBG and (b) with the VBG at the normal angle of incidence; 2D beam profiles are shown in the insets to the figures.

The divergence of OPO output radiation was measured using a Pyrocam IV profilometer camera (Ophir) located in the optical scheme in front of the lenses L_3 and L_4. Half of the OPO radiation divergence angle without the VBG was 2.58 mrad in the horizontal plane and 3.21 mrad in the vertical plane; for the OPO with the VBG at the normal angle of incidence, the divergence angle was 2.51 mrad in the horizontal plane and 3.29 mrad in the vertical plane. A telescope that consisted of two lenses with focal lengths of $f_3 = -30$ mm and $f_4 = 125$ mm was additionally used to reduce the divergence angle of radiation from the OPO with the VBG. The use of the telescope made it possible to increase the beam diameter to $d_x = 9.4$ mm and $d_y = 10.5$ mm (at a level of e^{-2}) and noticeably reduce the beam divergence to 0.41 mrad in the horizontal plane and to ~0.64 mrad in the vertical plane. To measure the beam quality index M^2, the OPO radiation was focused by a CaF_2 lens with a focal length of 100 mm. Figure 7 shows the 2D profiles of the OPO beam in the degenerate mode (2128 nm) without the VBG (Fig. 7a) and with the VBG in the position of the normal incidence (Fig. 7b) as well as the results of approximation of M^2.

As is seen in Fig. 7, when VBG was used, the beam quality index slightly improved.

4. CONCLUSIONS

A narrow-band tunable MgO:PPLN-crystal-based OPO with a VBG has been developed. The maximum achieved average power level was ~1 W (5 kHz) at a wavelength of 2128 nm. The radiation wavelength in the spectral range of 2041–2106 nm for a signal wave and in the range of 2152–2224 nm for an idler wave was adjusted by rotating the VBG relative to the axis of the OPO cavity. At the same time, the width of the radiation line did not exceed 1 nm and was 0.5–0.89 nm. The use a VBG made it possible to narrow the width of the OPO radiation line by more than 300 times. The measured divergence of the OPO radiation beam in both cases (with and without the VBG) virtually did not change. The beam quality parameter practically did not change when using the VBG and was estimated as $M_h^2 = 3.6$ in the horizontal plane and $M_h^2 = 4.2$ in the vertical plane. Tunable narrowband 2-μm radiation sources are in demand for solving various environmental, medical, and scientific problems.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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