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OPTICAL INSTRUMENTATION

Optical Parametric Oscillator within 2.4–4.3 μm Pumped with a Nanosecond Nd:YAG Laser

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Abstract—An optical parametric oscillator has been designed on the basis of MgO:PPLN periodic structure. A compact nanosecond Nd:YAG laser has been used as a pump source at 1.053 μm. The pump pulse length is 5–7 ns at a maximum pulse energy of 300 μJ and a frequency of 1000–5000 Hz. The oscillation threshold is 22 μJ at 3 μm and 48 μJ at 4.3 μm. The maximum conversion efficiency from incident pump power to the idler output is 3.9%.

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INTRODUCTION

The design of universal coherent IR sources is currently of interest. Despite reported laser generation at 5 μm at room temperature [1], the tuning range of industrial continuous solid-state lasers within the IR region is limited to 3 μm. Er^{3+} and tunable Cr^{2+} lasers are such sources of coherent IR radiation [2]. The main disadvantages of solid-state lasers are a restricted number of lasing lines in the IR region and a small number of active media, some of which can be used only at cryogenic temperatures. The main difficulties in the design of new IR sources are the search for appropriate laser transitions with a sufficient lifetime of the upper state and availability of an exotic pump laser. There are characteristic absorption bands of hazardous substances in the middle IR region. Designing high-sensitive analytical equipment for their detection, one may use optical parametric oscillators (OPO) pumped with a powerful single-frequency laser in the near IR region as intensive tunable IR sources [3, 4].

The use of oxide crystals as a nonlinear medium of an Nd:YAG laser pumped OPO allowed the range from near IR to 4.4 μm to be covered. A further increase in the tuning range of these devices is limited by absorption in the middle IR region [2].

The nanosecond pumping mode is optimal for PPLN OPO because of the optimal relationship between the mean power of OPO and the tuning range in the IR region [5, 6].

This work is devoted to an OPO designed on the basis of periodic structure of MgO-doped lithium niobate (PPLN–MgO). To provide for OPO performance reliability, a cubic solid cavity was used with caves for mounting corresponding optical elements of the OPO cavity and a PPLN crystal.

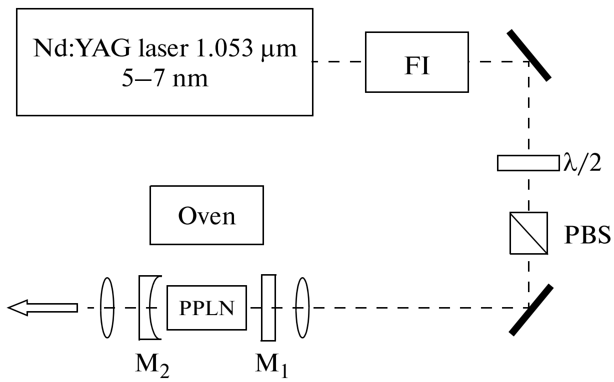
SOLID OPO CAVITY

The main requirement for the OPO design is maximum conversion efficiency during the parametric interaction; therefore, effective focusing in a PPLN crystal is a criterion for the design of the optical circuit of the cavity. As has been shown theoretically [7] and experimentally [8], the conversion efficiency is optimal if the confocal pump parameter inside the crystal is equal to the PPLN crystal length.

Two conditions should be taken into account when designing an OPO: the presence of an aperture sufficient for free passage through the pump crystal, 0.5 mm (along the z axis of the crystal), and the stability of the high-Q cavity for the signal wave [9]. To avoid the diffraction loss, causing an increase in the PLG threshold, the beam radius for the idler wave could not exceed 160 μm for a crystal of 500 μm in thickness.

When designing mechanical elements of the cavity, the influence of vibrations, temperature gradients, and convection air flows should be taken into account; they are present in the system, because the crystal temperature is within the 30–200°C range. Many optical

(a)



(b)

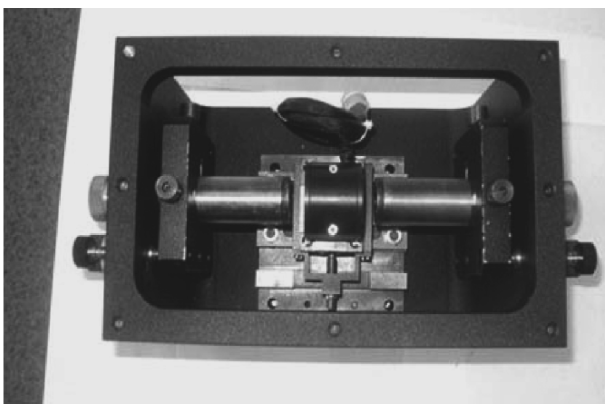


Fig. 1. OPO experimental setup: FI is the Faraday insulator, PBS is the polarizer, M_1 and M_2 are the OPO cavity mirrors (a); the solid OPO cavity (b).

cavities consist of discrete components mounted on the beam table. To exclude the effect of vibrations at adjusting elements, the optical elements should be mounted as low as possible over the beam table surface, i.e., the arm should be shortened. In other cases, the adjusting heads are fixed on Invar bars to ensure the mechanical stability.

The use of a solid cavity is an alternative approach. We have designed an original solid cavity (Fig. 1b): an aluminum cube has been milled to mount adjusted holders of the crystal. The cylindrical holders of OPO optical mirrors are fixed on two adjusted flanges. The position of the flanges with the optical mirrors has been rigidly fixed after adjustment of the monolithic block.

The optical cavity is a solid structure with two high-reflectivity mirrors at the signal wave. The output mirror is transparent at the pump and idler wavelengths; the input mirror has a high transmission coefficient at the pump wavelength. The designed monolithic block allows the cavity length correction by means of displacement of the cylindrical holders in the flanges. The monolithic block design allows a change in the cavity configuration (confocal, spherical, Fabry–Perot, and half-spherical).

The PPLN crystal is mounted on the hard-adjusted holder, designed by us, which allows adjustment of the crystal position inside the cavity and PPLN displacement along all tracks to provide for the OPO wavelength tuning. Our design allows the adjusted PPLN unit to be changed to another unit with $LiGaSe_2$, $LiInSe_2$, etc. bulk crystals for tuning in the long wavelength region (up to 9 μm in the future). In this case, the wavelength tuning can be ensured via varying the angle θ in the crystal.

CALCULATION OF OPO THRESHOLD PARAMETERS

According to the models suggested in [5, 6], the threshold pump power density and the threshold pump power of OPO can be calculated with the use of the following equations [5]:

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

$$P_{th} = \frac{n_p n_s n_i \varepsilon_0 c^4 \pi\left(W_p^2 + W_s^2\right)}{4\omega_s \omega_i d_{eff}^2 L^2} \alpha_s,$$

where n_p, n_s, and n_i are the crystal refraction coefficients at the pump, signal, and idler wavelengths, respectively; ω_s and ω_i are the frequencies of the signal and idler wavelengths, respectively; W_p and W_s are the Gaussian beam waists for the pump and signal wavelengths, respectively; γ is the ratio of the reflected to incident pump-field amplitudes in the PPLN crystal; α_d is the single-pass loss for the signal wavelength; α_s is the single-pass loss for the signal wavelength, including the loss at the input mirror; R_s is the reflection coefficient of the signal wavelength; τ is the pump pulse length; ε_0 is permittivity of vacuum ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m); c is the velocity of light ($c = 3 \times 10^8$ m/s); d_{eff} is the effective nonlinearity; L is the crystal length; L_{cav} is the optical length of the cavity; L_1 and L_2 are the distances from the cavity mirrors to the crystal.

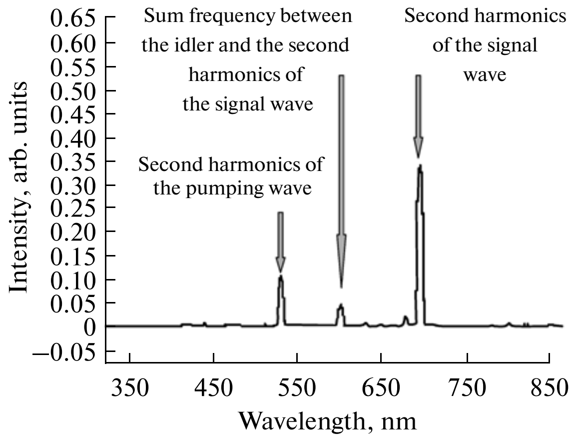


Fig. 2. Raman spectrum of PPLN–OPO in the visible range recorded with the Angstrom WS6 wavelength meter.

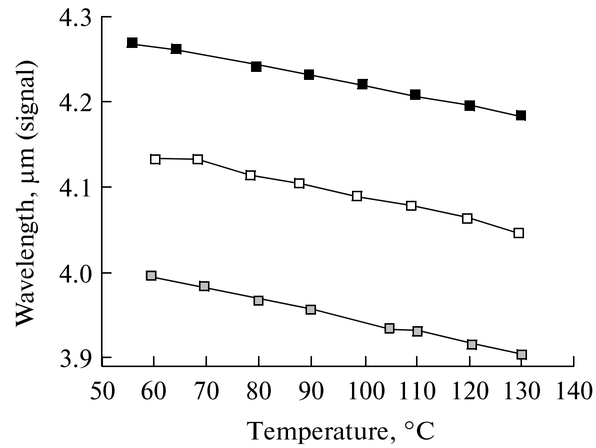


Fig. 3. Temperature tuning parameters of the OPO at MgO:PPLN tracks. $\Lambda = 27.91$, 28.28, and 28.67 μm.

SINGLE-PASS PUMPED HEMISPHERICAL CAVITY

A flat mirror with the parameters

$$HRr\,[0°–15°;\,(1310–1470 \pm 10)\ \text{nm}] > 99.9\% + Rr\,(0°–15°;\,1064\ \text{nm}) < 5\% + Rr\,(0°–15°;\,3000–6000\ \text{nm}) < 5\%$$

acts like the input mirror in a single-pass pumped hemispherical cavity. The output mirror is spherical, with the curvature radius

$$R = 75\ \text{mm},\ HR\,[0°;\,(1000–1530 \pm 15)\ \text{nm}] > 99.7\% + R\,[0°;\,(720–860 \pm 5)\ \text{nm}] < 5\% + R\,[0°;\,2100–4000\ \text{nm}] < 30\%.$$

The pump pulse length $\tau = 5–7$ ns (1000–5000 Hz), the single-pass loss for the signal wave $\alpha_s = 0.03$, the ratio of the passed to incident pump-field amplitudes in the crystal $\gamma = 0.1$.

The distances $L_1 = 14$ mm and $L_2 = 15$ mm, the waist radius is 112.15 μm. The PPLN crystal length ($d_{eff} = 14.4$ pm/V) is 20 mm. The PPLN crystal refraction coefficients $n_p = 2.13$, $n_s = 2.13$, and $n_i = 2.35$ are used.

The calculated threshold pump power density in such a configuration is $J_T = 0.085$ J/cm^2. The threshold pump power is 27 μJ at the beam diameter $\omega_0 = 112$ μm.

EXPERIMENTAL SETUP

The block-diagram of the experimental OPO is shown in Fig. 1a in the single-cavity configuration.

A diode-pumped single-mode Nd^{3+}:YAG laser (DTL-329QT, Laser-compact Group) was chosen as a pump source. It operates in the nanosecond mode implemented through the acousto-optic Q modulation. The maximum pulse power at 1–5 kHz is 300 μJ, and the wavelength is 1.053 μm.

The OPO cavity is formed by two Layertec mirrors (Germany). The input mirror M_1 is flat (AR(0°; 1064 nm) < 1.0% + AR(0°; 4000–6000 nm) < 2%, HRr[0°–15°; (1310–1470 ± 10) nm] > 99.9%), the output mirror M_2 has the curvature radius $R = 75$ mm ($R_{1.053\ \mu m} = 3\%$, $R_{1.3–1.6\ \mu m} = 99.9\%$, $R_{3–4.5\ \mu m} < 5\%$). A CaF_2 lens ensures the optimal matching between the pump radiation and the cavity parameters. The crystal waist radius $\omega_0 \approx 100$ μm.

The MgO:PPLN (Covesion LTD) crystal has nine tracks (27.91; 28.28; 28.67; 29.08; 29.52; 29.98; 30.49; 31.02, and 31.59 μm), displacement along these tracks allows the idler wavelength tuning within the 2.1–4.3-μm region. The crystal faces are covered with antireflection coatings: $R < 1.5\%$ for the pump wave 1064 nm, $R < 1\%$ for the signal wave 1400–1800 nm, and $R \sim 6\%$ for the idler wave 3% and 2600–4800 nm. A thermocontroller and an oven perform the thermal stabilization of the PPLN crystal in a wide temperature range (30–200°C) accurate to 0.1°C.

A Faraday isolator (Avesta) is used in this optical circuit to prevent the return coupling from the OPO cavity and optical elements of the circuit. A half-wave plate in combination with a polarizing cube (ThorLabs) provides the required polarization to start the process of parametric conversion.

Raman frequencies were observed in the visible range during the parametric conversion: the second harmonics of the signal wave (at 699–758 nm) and the sum frequency between the doubled signal and idler waves (at 600–660 nm). This allows the use of an industrial Angstrom WS6 wavelength meter with a silicon linear photodiode array for the diagnostics of the OPO wavelength tuning range. The OPO wavelengths measured at Raman frequencies are shown in Fig. 2.

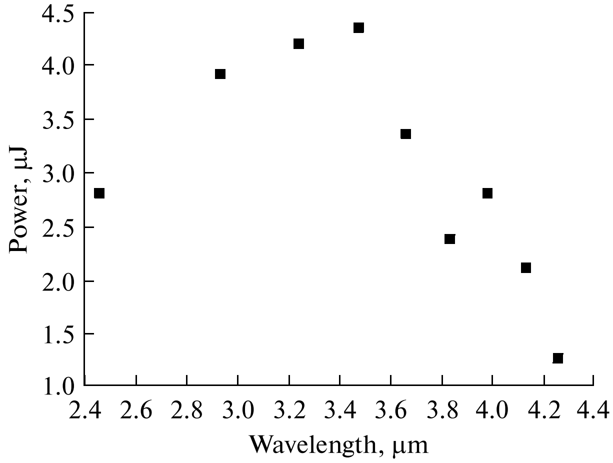


Fig. 4. The idler wave power versus λ at a fixed pumping energy of 112 μJ and the crystal temperature T_{cr} = 70 °C.

The OPO tuning parameters have been constructed for the idler wave from the Raman frequency measurement results (Fig. 3).

The tuning is shown for three last PPLN tracks with Λ = 27.91, 28.28, and 28.67 μm. As is seen, the idler wavelength changes by 80–100 nm with a change in temperature of 80 °C at each track.

POWER CHARACTERISTICS

The idler wave power is shown in Fig. 4 as a function of λ.

We changed the crystal position at a PPLM temperature of 70°C and a fixed pump power of 112 μJ so that the OPO power parameters could be compared at all nine tracks.

It was noted that the maximum pump-to-signal power conversion efficiency was 12.5% at the track Λ = 28.28 μm (λ_i = 3 μm). The minimum conversion efficiency approximately equal to 4% was recorded at the track Λ = 31.59 μm. A decrease in the conversion efficiency in the longwave region is connected with the beginning of multiphoton absorption in the PPLN structure. The OPO threshold varied within the 22–48-μJ range depending on the PPLN crystal position. The OPO idler wave tuning region varied from 2.4 to 4.3 μm.

CONCLUSIONS

An optical parametric oscillator has been designed on the basis of MgO:PPLN periodic structure. A compact nanosecond Nd:YAG laser (1.053 μm) has been used as a pump source. The measured parametric generation threshold of the MgO:PPLN-based OPO varied within the 22–48 μJ range at 2.1–4.3 μm, which corresponds to the calculated value (27 μJ). To ensure OPO performance reliability, a solid cubic cavity was used with cavities for mounting corresponding optical elements of the OPO cavity and the PPLN crystal.

The design of a coherent widely tuned IR OPO will allow designing universal diagnostic equipment on this basis for use in a wide range of scientific and engineering problems, e.g., diagnosis of different diseases (diabetes, tuberculosis, and bronchial asthma) and detection of trace explosive and toxic substances in the atmosphere.

The device described will be used at Special Technologies, Ltd. for the design of new gas analysis equipment. It is based on photoacoustic techniques for the detection of trace gases, absorption lines of which are within the 2.4–4.3 μm range.

Thus, we have designed a coherent optical radiation source, the use of which in systems similar to KARAT [10] and LGA-2 [11] allows an extension of the designated area of such systems.

ACKNOWLEDGMENTS

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