Wide-tunable, high-energy AgGaS₂ optical parametric oscillator

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Abstract: Nanosecond AgGaS₂ type-I singly resonant optical parametric oscillator pumped by a Q-switched 1.064 μm Nd:YAG laser is demonstrated experimentally. Continuously tunable 2.6-5.3 μm radiation and output pulse energy up to 0.6 mJ at 4 μm are achieved in a single-stage conversion process. The analysis of pump threshold is investigated both theoretically and experimentally.

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OCIS codes: (190.0190) Nonlinear optics; (190.2620) Frequency conversion; (190.4970) Parametric oscillators and Amplifiers.

References and links


1. Introduction

Solid state lasers operated in the range of atmospheric transparency (3-5 μm, 8-12 μm) are of great interest for many applications such as eye-safety lidars, target designations, obstacle avoidance, and infrared countermeasures. Optical parametric oscillator (OPO) is an effective tool to cover the range. As a pumping source, Nd:YAG lasers, which have high output energy and good beam quality, are widely distributed and used in mobile systems, and in combination with well designed UV to visible range frequency converters permits to design extra-wide band 0.2-14.0 μm source of coherent radiation. In turn, frequency conversion of most efficient
wide-band 0.7 to 1.1 μm Ti:sapphire laser is the simplest way in design of middle IR tunable femtosecond sources. Unfortunately, most efficient middle IR nonlinear crystals such as CdGeAs₂, ZnGeP₂, TiAsSe₃ and AgGaSe₂ are not transparent or have big loss at near infrared and visible, and that is why they cannot be used as laser frequency converters in these cases.

Negative silver thiogallate (AgGaS₂ or AGS) crystal with high nonlinear optical coefficient and high optical transmission from 0.5-12 μm makes it realistic to generate infrared parametric radiation. Its most characteristic is that it is one of the few crystals which can be pumped by commercially available 1.064 μm Nd:YAG laser to achieve phase-matched down-conversion into the > 5μm region. That is why numerous experiments with one and multistage OPO/OPG pumped by ns and ps IR dye, Nd:YAG and another near IR solid state lasers, so as by fs Ti:sapphire and Cr:forsterite lasers, are carried out during last decade [1-9]. Significant attention is paid also to harmonic, sum and difference frequency generators, and up-converters. As high as from 0.1 to 30% efficiencies [4] and OPG at 1.2-10 μm wide range pumped by 20 ps Nd:YAG laser are demonstrated [1]. But usual tuning range of OPO pumped by ns Nd:YAG laser does not cover all 3-5 μm range [2, 3, 5] because surface damage of the crystal. The only wide-range 3.9-11.3 μm singly resonant non-selective cavity OPO pumped by ns Nd:YAG laser is designed. It is type-II OPO to maximize the effective second-order nonlinearity and minimize spectral bandwidth, which yields limited energy of 372 μJ output pulses [4].

In this paper, considering the low damage threshold, the methods to reduce the oscillating threshold are discussed. AgGaS₂ type-I singly resonant optical parametric oscillator (SRO OPO) pumped by a ns 1.064 μm Nd:YAG laser is demonstrated experimentally. We put our emphasis on the interested parametric wavelength range with 3-5 μm. A comparison on the threshold energy density is made between the single pump pass SRO OPO and the double pump pass both theoretically and experimentally.

2. Analysis of Oscillation threshold

Due to the low damage threshold in AGS crystal, how to lower the pump threshold is considered firstly. In order to describe the threshold pump energy density (oscillation threshold) of a pulsed single- and double pump pass single resonant oscillator, simplified theoretical model including the effects of Poynting vector walk-off is used [10]. Simplified expression for the threshold pump energy density (threshold fluency) is given by

\[
J_0 = \frac{2.25}{k g_{\text{eff}} l_{\text{eff}}^2 (1 + \gamma)^2} \left[ \frac{L}{2c \tau} \ln \left( \frac{P_c}{P_n} \right) + 2\alpha l + \ln \frac{1}{\sqrt{R}} + \ln 4 \right]^2
\]

(1)

Where \( g_s, l_{\text{eff}} \) and \( k \) are the signal spatial mode coupling coefficient and the effective parametric gain length and the interaction coefficient listed below, respectively.

\[
k = \frac{2 \omega_s \omega_i d_{\text{eff}}}{n_s n_i n_p \varepsilon_0 c^3}, \quad g_s = \frac{w_p^2}{w_p^2 + w_s^2}, \quad l_{\text{eff}} = l_w \text{erf} \left( \frac{\sqrt{\pi} l}{2 l_w} \right)
\]

(2)

The walk-off length \( l_w \) is given by

\[
l_w = \frac{\sqrt{\pi}}{2} \frac{w_p}{\rho} \sqrt{\frac{w_p^2 + w_s^2}{w_p^2 + w_r^2}}
\]

(3)

Note: \( \omega_s, \omega_i \) are frequencies for the signal and idle light; \( d_{\text{eff}} \) is effective nonlinear coefficient; \( n_s, n_i, n_p \) are refractive indexes for signal, idle and pumping light, respectively; \( C \)

#76203 - $15.00 USD
Received 18 October 2006; revised 30 November 2006; accepted 1 December 2006
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25 December 2006 / Vol. 14, No. 26 / OPTICS EXPRESS  13002
is the light velocity; $\tau$ is the pulse width of pumping light; $L$ are the cavity length and the crystal physical length, respectively; $\gamma$ is the ratio of backward to forward pump field amplitude inside the crystal; $\alpha$ is the ratio of the threshold power to noise power; $R$ is the effective cavity loss (the product of mirror reflectivities). The relations between the Gaussian mode electric field radii $w_p, w_s$ and the resonant spot radii $w_{ps}$ are

$$ \left( \frac{\pi}{2L} \right)^2 w_p^2 + \frac{w_s^2}{2} = 0, \quad w_s^2 = \frac{w_p^2}{2} - \frac{w_p^2}{2}. \quad (4) $$

If the ratio of backward to forward pump field amplitude $\gamma$ is fixed to zero and SRO is considered, the threshold pump intensity of a pulsed singly resonant oscillator including the effects of Poynting vector walk-off is concluded as follows:

$$ J_0 = \frac{2.25}{k_g l_{eff}} \tau \left( \frac{L}{2c} \right) \ln \left( \frac{P_p}{P_0} \right) + 2d + \ln \frac{1}{\sqrt{R}} + \ln 2 \right)^2. \quad (5) $$

Double pump pass means that pump wave passes through the nonlinear crystal twice. It is an effective method to lower the pump threshold. Figure 1(a) shows a comparison between single- and double pump pass (DSRO, double-pump singly resonant, SSRO, single-pump singly resonant). The different ratio of backward to forward pump field amplitude inside the crystal follows with the different threshold. With the increasing of $\gamma$, threshold declines obviously as shown in Fig. 1(b).

![Fig. 1. Comparison between oscillation threshold of the single and double pump pass (a), and threshold pump energy density as a function of the ratio of backward to forward pump field amplitude in the crystal $\gamma$ for DSRO (b), $L = 3\,\text{cm}$, $l = 2\,\text{cm}$, $\tau = 20\,\text{ns}$, $2\mu_p = 1.5\,\text{mm}$](image)

Threshold pump energy density is mainly determined as a function of cavity length, crystal physical length, pump spot size, pump pulse width. The influence of the parameters on the threshold is investigated as shown in Fig. 2. It is clear: (1) the longer the cavity length is, the higher the threshold is in Fig. 2(a); (2) when the crystal length is less than 1 cm, the threshold is abruptly increased, when the length is more than 2 cm, it nearly keeps flat in Fig. 2(b); (3) the increase in threshold as well as the decrease in gain is due to the small pump spot.
size as a result of Poynting vector walk-off in Fig. 2(c); (4) the relatively shorter pulse width is benefit to the lower threshold in Fig. 2(d). It is also evident that the oscillation threshold increase with the output wavelength (threshold at 5μm > that at 4 μm > one at 3μm) from the Fig. 2. It can be interpreted as: 1) the oscillation threshold is inversely proportional to the product of the idler and signal angular frequency as shown in Eq. (1), so as to the product of the two wavelength; 2) the effective nonlinear coefficient \( d_{\text{eff}} \) is decreasing at the range of 3-5μm as well as the gain in the AGS crystal, the oscillation threshold is inversely proportional to \( d_{\text{eff}} \), too. Thus a larger threshold is predicted at longer output wavelength certainly.

3. Experimental setup

The schematic setup is shown in Fig. 3. AgGaS2 crystal used with 10×7 mm\(^2\) in cross section, 20 mm in length, \( \theta \approx 47^\circ \) and \( \varphi \approx 45^\circ \) cut for type-I phase-matching is supplied by MolTech GMBH, Germany. In order to reduce the loss so as to the oscillation threshold, both cross sections are well antireflection AR coated: high transparent HT\( \lambda_{1.06} > 99\% \) at pump wavelength 1.06 μm, and also at signal and idler wavelengths HT\( \lambda_{1.3-1.7} > 97.5\% \)—— 99%, HT\( \lambda_{3-5} > 97\% — 98.5\% \), respectively. The two identical flat mirrors M1, M2, which are used as the cavity mirrors with coatings of HT\( \lambda_{1.06} > 95\% \), HR\( \lambda_{1.3-1.7} > 99-99.4\% \) and HT\( \lambda_{3-5} > 88-98\% \), are designed for SRO OPO. A homemade electro-optically Q-switched Nd:YAG laser and amplifier pumped by flashlamp with pulse width 10-30ns depending on the input energy is used as OPO pump source. A diaphragm is inserted in the cavity of pump laser to restrain the higher-order mode oscillation. The laser can operate at the frequency of 20 Hz.

As shown in Fig. 3, D1, detector of fast Si PIN photodiode, is used to monitor pump laser and also as the trigger signal for D2, detector of LN-cooled 1×1 mm\(^2\) sensitive area MCT P7752-10 photoresistor, which is used to detect the idle signal. Mirror, m1, is glass mirror, which can reflect a little part of pump laser at 1.064 μm. Glan prism G combined with mirrors

![Fig. 2. Oscillation threshold energy density as a function of OPO cavity length, crystal length, pump spot size and pulse width as shown in (a), (b), (c), (d), respectively. Solid line, dot line, dash dot line correspond to 3 micron, 4 micron, 5 micron of idle wavelength, respectively.](image-url)
m2 and m3 is used to control the polarization direction of pump beam. Filter F and mirror m5 with the identical coating have high reflectivity R>99% at 1.064 μm and transmission T~65%-90% at 3-5 μm, T~88% at 4 μm. A He-Ne laser and mirror m4 are used to indicate the idler radiation propagation. The output idler is measured by a step-motor-driven computer-controlled UV-FIR monochromator SBP300, Zolix Instruments Co., Ltd, China. Step-motor-driven computer-controlled rotational positioner with positioning accuracy 9” is used for precision determination of the phase-matching angles.

Fig. 3. Schematic setup of AgGaS2 SRO OPO.

4. Experimental results and analysis

Considering the theoretical analysis on the threshold, the cavity length for oscillation is about 2.8 mm, just at the minimal distance allowed to rotate by the 2 cm length of AGS crystal. The wavelength tuning range is from 2.6 to 5.3 μm as shown in Fig. 4, which is pumped by a 1.064 μm Nd:YAG laser with pulse width 15 ns and spot diameter 1.5 mm. To our knowledge, it is the biggest range for nanosecond AgGaS2 type-I SRO OPO. The solid line in Fig. 4 is simulated based on the Sellmeier’s equation in Ref. [11], which gives the best agreement with our experimental data. The longer wavelength is limited by the damage of cavity mirror.

Fig. 4. Angular-tuning curve of AGS type-I SRO OPO. Solid line is theoretical calculation and circular points are our experimental data.

In order to lower the oscillation threshold, the double-pump scheme is considered. As shown in Fig. 3, the pump laser is not fed back into the OPO cavity when pump laser is not vertical to 1.064 μm reflective filter, F, but the pump laser can be fed back into the cavity for a double pump pass by adjusting the filter, F vertical to pump laser. Figure 5(a) shows the pump threshold energy density as a function of various idle wavelength outputs for single and double pump pass AGS SRO OPO. 1.4 times higher oscillation threshold of SSRO than DSRO at 4 μm is concluded, which is well consistent with 1.6 times of the theoretical prediction in Fig. 1(a). The predicted variabilities of threshold on the idler are confirmed by
two schemes. The longer the output wavelength is, the higher the oscillation threshold is, which can be interpreted in section two.

![Graph](attachment:image.png)

Fig. 5. Oscillation threshold and output energy: (a) oscillation threshold for single and double pump pass of AGS SRO OPO versus idle output wavelength; (b) Idle output energy at 4 micron: square points are pumped by single pass without telescope; circular points are pumped by double pass with telescope inserted.

Output energy of the idler is our main interest. Firstly, the output energy of idle light is monitored with single pump pass. The pump pulse width (FWHM) is 15 ns and its beam diameter is 1.3 mm with frequency of 1 Hz. The relation between pump energy and output energy is shown in Fig. 5(b). Square points are at fixed output wavelength 4 μm, 2.8 cm in cavity length. 270 μJ is recorded with the maximum laser-to-idler conversion efficiency 3.5% without any damage appears. The optical damage of cavity mirrors inside occurs at the input pump power density up to 34 MW/cm², while no damage appears on the crystal surface in OPO cavity, which is due to the good growth, polishing and coating technique on the crystal. In fact, we also observe the backward energy output after mirror m5 as shown in Fig. 3.

In order to improve the output energy, a telescope with two lens of f=5 cm, f=10 cm is inserted between Glan prism G and mirror m5 to enlarge the pump spot size. The output energy with double pump pass is shown in Fig. 5(b) by the circular points. The maximum energy 560 μJ is recorded. Considering the filter’s loss at the idler, the maximum one of 620 μJ has been generated. Farther improvement is limited by the damage of coating on cavity mirrors.

5. Conclusion

Nanosecond singly resonant type-I AgGaS₂ optical parametric oscillator pumped by a Q-switched 1.064 μm Nd:YAG laser is demonstrated experimentally. Methods to reduce the oscillation threshold are investigated both theoretically and experimentally. The effect of parameters such as OPO cavity length, AGS crystal physical length, pump spot size and pulse width on the oscillation threshold is investigated theoretically. A comparison on the threshold pump energy density is made between the single pump pass SRO OPO and the double pump pass one both theoretically and experimentally. Continuously tunable 2.6 to 5.3 μm radiation and maximum output energy 0.6 mJ per pulse are obtained.

Acknowledgments

The authors would like to acknowledge the support from the National Natural Science Foundation under grant No. 10334010 and the international cooperation program by the Ministry of Education of China.