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3–5 μm $AgGaS_2$ Optical Parametric Oscillator with Prism Cavity[1]

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Abstract—Employing a coated right-angled sapphire prism as the OPO cavity mirror, $AgGaS_2$ type-I singly resonant optical parametric oscillator was demonstrated experimentally, which was pumped by a ns 1.064 μm Nd:YAG laser. Continuously tunable 2.35 to 5.27 μm radiation without changing cavity mirrors and maximum output energy 0.58 mJ per pulse are recorded.

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Tunable mid-infrared laser sources operating at the transparency windows of 3–5 μm in the atmosphere are more and more important for applications in laser remote sensing, laser target detecting, spectra analysis, atmospheric environment monitoring, space communication and applications in military. There are two effective methods to generate it: second harmonic generation (SHG) of CO_2 laser [1, 2] and optical parametric oscillator (OPO) [3–10]. The former has the limited tuning range at the atmospheric window, which is due to the limited tunable range of CO_2 laser. The latter is an effective tool to cover the 3–5 μm range. Mid-infrared OPO especially pumped by around 1 μm wavelength (such as Nd:YAG, Nd:YLF, Yb:YAG lasers) is more and more important with the development of growth technology of nonlinear crystals. The most important reason is that commercial Nd or Yb lasers, as a pumping source, have high output energy and good beam quality, which are widely distributed and used in mobile systems with compact design. In order to cover the ultra-broadband range of 3–5 μm, the nonlinear crystal in OPO is required to have the large optical transmission and can be phase matched around 1 μm. By far, commercial negative silver thiogallate crystal 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 $\lambda > 5$ μm region. $AgGaS_2$ (AGS) crystal has high nonlinear optical coefficient and high optical transmission from 0.5–12.0 μm, which makes it realistic to generate infrared parametric radiation. That is why numerous experiments with one or multistage OPO/OPG pumped by ns and ps IR dye, Nd:YAG and another near IR solid state lasers, so as by femtosecond Ti:sapphire and Cr:forsterite lasers, are carried out during last decade. Comparing with optical parametric superfluorescence, ultra-broadband tunable, mid-infrared OPO is a more challenging work due to the difficulty on its fabrication of ultra-broadband reflectivity coating.

In this paper, the presented setup is a simplified version of our earlier one [7]. A coated prism as the output coupling device of OPO was used to replace the common cavity mirror. It was also functionalized a filter to separate the pump and ultra-broadband tunable idler at the same time. The problem on ultra-broadband reflectivity coating has been avoided. $AgGaS_2$ type-I singly resonant optical parametric oscillator (SRO OPO) with prism cavity pumped by a ns 1.064 μm Nd:YAG laser was demonstrated experimentally. The ultra-wide tuning 2.35 to 5.27 μm and maximum output energy 0.58 mJ per pulse at idle light were obtained.

Due to the relatively low damage threshold of AGS crystal, how to lower the pump threshold was considered firstly. Threshold pump energy density is mainly determined as a function of cavity length, crystal physical length, pump spot size, pump pulse width as we discussed previously [7, 11]. The influence of the parameters on the threshold can be summarized: (1) the longer the OPO cavity length is, the higher the threshold; (2) when the AGS crystal length is less than 1 cm, the threshold is abruptly increased, when the length is more than 2 cm, it nearly keeps constant; (3) the increasing in threshold as well as the decreasing in gain is due to the small pump spot size as a result of Poynting vector walk-off, the estimated walk-off angle was 21.8 mrad at our pump wavelength and cut phase matching angle; (4) the relatively shorter pulse width is

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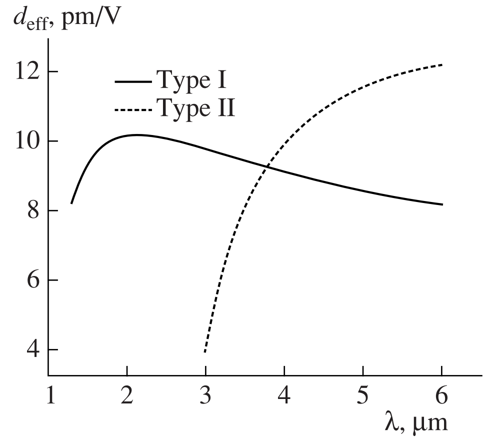

Fig. 1. Effective nonlinear coefficients of AGS OPO pumped by 1064 nm.

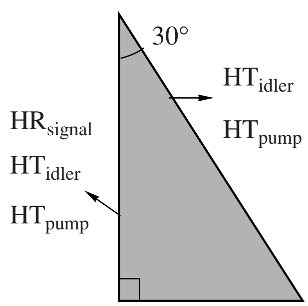

Fig. 2. Coated right-angled prism.

benefit to the lower threshold. Considering the analysis on the threshold, some methods to reduce the threshold (loss) were considered in our experiments.

Comparing the effective nonlinear coefficients for type I (e-o+o) and type II (e-o+e) as shown in Fig. 1, type I phase matching with high and relatively flat effective nonlinearity was better at our interested wavelength range, which was expected to benefit to ultrabroadband tuning. In our experiment, $AgGaS_2$ crystal used with 10×7 mm^2 in cross section, 20 mm in length, $\theta = 47°$ and $\varphi = 45°$ cut for type-I phase-matching centered around 4 μm was supplied by MolTech GMBH, Germany. In order to reduce the loss so as to the oscillation threshold, both cross sections were well antireflection AR coated: high transparent $HT_{1.06} > 99\%$ at pump wavelength 1.06 μm, and also at signal and idler wavelengths $HT_{1.3–1.7} \sim 97.5–99\%$, $HT_{3–5} \sim 97–98.5\%$, respectively. The flat mirrors M1 with coatings of $HT_{1.06} > 95\%$, $HR_{1.3–1.7} > 99–99.4\%$ and $HT_{3–5} > 88–98\%$, was used as the input cavity mirrors. A sapphire right-angled prism as shown in Fig. 2 was used as output coupling mirror, which can separate the pump and the idler automatically without any other filter due to its dispersion property. The surface inside was coated with the same parameters as M1 and the output surface was $HT_{1.06} > 95\%$ and $HT_{3–5} > 88–98\%$. So it was designed for singly resonant optical parametric oscillator (SRO OPO). The separated output pump beam was blocked by a plate P. A homemade electro-optically Q-switched Nd:YAG laser and amplifier pumped by flashlamp with pulse width 10–20 ns depending on the input energy was used as OPO pump source. A diaphragm was inserted in the cavity of pump laser to sustain the good fundamental mode TEM_{00} output. The laser could operate at the frequency of 1–20 Hz. The schematic setup was shown in Fig. 3. D1, detector of fast Si PIN photodiode made in China, on one hand was used to monitor pump laser and on the other hand as the trigger signal for D2, detector of MG30 made in Russia, which was used to detect the idle signal. Mirror, m1, was a BK7 glass mirror, which can reflect a little part of pump laser at 1.064 μm. Glan prism G combined with mirrors m2 and m3 was used to control the polarization direction of pump beam carefully. Mirror m5 had high reflectivity $R > 99\%$ at 1.064 μm. A He–Ne laser and a mirror m4, apertures A2, A3 were used to align the OPO cavity. The apertures can also be used to control the beam size. The wavelength of output idler was measured by a step-motor-driven computer-controlled monochromator with three gratings. Step-motor-driven computer-controlled rotational positioner with positioning accuracy 9″ was used for precision determination of the phase-matching angles.

The cavity length of AGS OPO was minimized to around 2.8 cm, just at the minimal distance allowed to rotate the 2 cm length of AGS crystal. The ultra-broadband wavelength tunable range from 2.35 to 5.27 μm has been achieved as shown in Fig. 3, which was pumped by a 1.064 μm Nd:YAG laser with pulse width 15 ns and spot diameter 1.5 mm. The drawback was that the angle of the idler changes when the OPO was tuned, due to the dispersion of the prism. The data were recorded by the corresponding change of detect system. The solid line in Fig. 4 was simulated tuning curve based on the Sellmeier's equation in [12], which gave the best agreement with our experimental data. The damage on the cavity mirror were seen when we attempted for wider wavelength.

Under the pump with the vertical incidence to the crystal surface, output energy of the idler was investigated carefully. Firstly, the output energy of idle light was measured with pump beam diameter 1.5 mm and pulse width (FWHM) 15 ns at frequency repetition rate of 1 Hz. The relation between pump energy and output energy was shown in Fig. 5. Square points were at fixed output wavelength 4 μm, 2.8 cm in cavity length. Maximum pulse energy 360 μJ and the maximum laser-to-idler conversion efficiency 4.5% were recorded without any damage appears. In order to improve the output energy, a telescope assembled with two lens of $f = 5$ and 10 cm was inserted between aperture A2 and A3 to

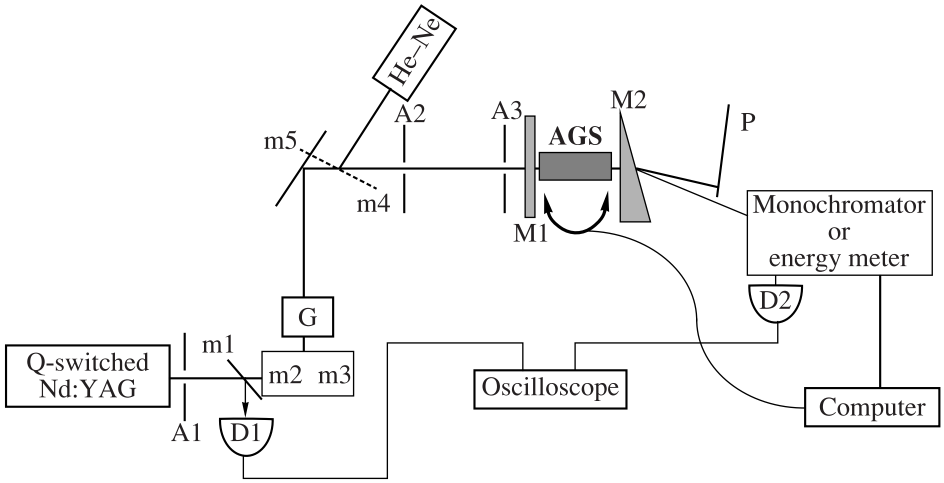

Fig. 3. Schematic setup of $AgGaS_2$ SRO OPO.

enlarge the pump spot size. A vacuum chamber with two windows was used to avoid the laser-induced plasma at the focus of lens in the air. Input pump energy can be increased with the same pump density. The output energy with telescope inserted was shown in Fig. 5 by the circular points. The maximum energy 580 μJ was recorded in our measurement, which is not shown in the curve. Further improvement was limited by the damage of coating on cavity mirrors. The optical damage of cavity mirror and oscillating surface of the prism appeared at the input pump power density up to 34 MW/cm^2, while no damage were seen both on the surfaces and inside of the crystal in OPO cavity, which we analyzed were contributed by the good growth, polishing and coating technique of the crystal comparing with other data [3–6]. This kind of cavity scheme can also be expected to benefit the linewidth and stability, which are going to be investigated in the near future.

In conclusion, nanosecond singly resonant type-I $AgGaS_2$ optical parametric oscillator pumped by a Q-switched 1.064 μm Nd:YAG laser was demonstrated experimentally. A coated right-angled sapphire prism was used as OPO output cavity mirror to replace the usual dielectric mirror and filter, which obviates the use of ultra-broadband filter to separate the pump and the idler. Continuously tunable 2.35 to 5.27 μm radiation and maximum output energy 0.58 mJ per pulse were obtained without changing cavity mirror and the prism, which was benefited from the good designs of pump source, AGS crystal and OPO cavity. With the simplified cavity scheme of earlier one [7], almost same parameters were already achieved.

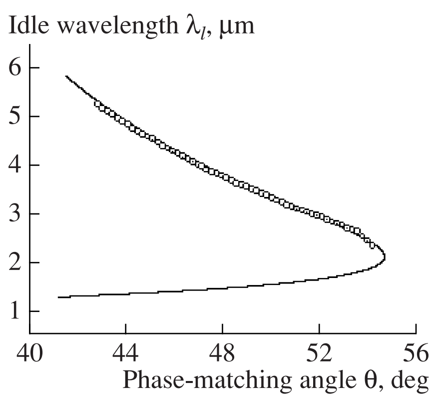

Fig. 4. Angular-tuning curve of AGS type-I SRO OPO. Solid line is theoretical calculation and circular points are experimental data.

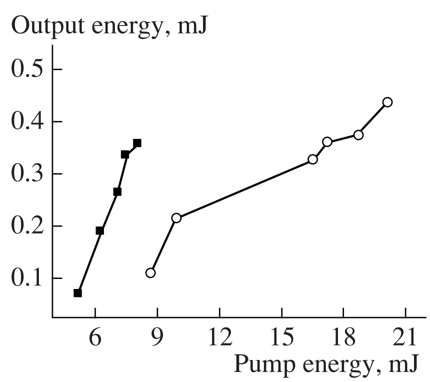

Fig. 5. Idle output energy at 4 μm: square points are recorded without telescope; circular points are recorded with telescope inserted.

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