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Widely Tunable Middle Infrared Optical Parametric Oscillator Pumped by the Q-Switched Ho:$GdVO_4$ Laser *

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We demonstrate a middle infrared $ZnGeP_2$ optical parametric oscillator pumped by the Q-switched Ho:$GdVO_4$ laser. When the incident Ho pump power is 4.12 W, the maximum average output power of the ZGP-OPO laser is 2.05 W, corresponding to a slope efficiency of 74.6%. The ZGP-OPO laser produces 4.2 ns mid-infrared pulses at a pulse repetition rate of 5 kHz. In addition, we obtain 0.8 μm of tunable range for the signal wave and 2.1 μm of tunable range for the idler wave.

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Tunable middle infrared (mid-IR) lasers have many important applications in remote sensing, molecular spectroscopy and directed infra-red countermeasures (DIRCM). Currently, widely tunable high-power mid-IR laser source must be employed by nonlinear optical conversion techniques. Among these lasers, the most attractive mid-IR sources are zinc germanium phosphide ($ZnGeP_2$, ZGP) optical parametric oscillators (OPOs) pumped by Q-switched 2-μm lasers. The ZGP crystal has a wide optical transmission range of 2–12 μm, excellent thermal conductivity (0.36 $W{\cdot}cm^{-1}K^{-1}$) and high nonlinear coefficient ($d_{36} = 75$ pm/V). With these advantages, ZGP crystal is capable of resulting in high efficient and high-power OPO operating in the mid-IR range. Many ZGP-OPOs have been investigated with various schemes, such as planer cavity,[1] rotated image singly resonant twisted rectangle cavity,[2] V-shaped three-mirror ring resonator,[3] and four-mirror ring cavity.[4] Maximum average output power of up to 41.2 W was achieved in mid-IR ZGP-OPO pumped by a Q-switched Ho:YAG laser.[4] Actually, the key point in this technical approach is to develop a Q-switched 2-μm pump laser with high average output power and good beam quality. In the past few decades, many Q-switched Ho lasers based on various host materials were investigated as the pump source of ZGP-OPO.[5–7] This is due to the fact that resonantly pumped Ho lasers with low quantum defect are the most efficient way to obtain the high power and high beam quality 2-μm laser.[8,9]

Among numerous laser hosts, gadolinium vanadate ($GdVO_4$) crystal is a promising host material for Tm or Ho-doped laser at 2 μm. The thermal conductivity of $GdVO_4$ is over a factor of two higher than that of YVO_4 and is comparable with YAG. In 2014, our group improved the laser performance of Ho:$GdVO_4$ crystal at room temperature.[10] In 2015, maximum average output power of 10.2 W is achieved in an actively Q-switched Ho:$GdVO_4$ laser with the pulsed repetition frequency (PRF) of 10 kHz,[11] which can be used as an excellent pumping source of the mid-IR ZGP-OPO. However, so far there has been no report on ZGP-OPOs pumped by a Ho:$GdVO_4$ laser, to our best knowledge.

In this Letter, we report on a ZGP-OPO pumped by a Q-switched Ho:$GdVO_4$ laser. The maximum average output power of the ZGP-OPO mid-IR laser is 2.05 W with a slope efficiency of 74.6% and a pulse width of 4.2 ns. The 0.8 μm of tunable range for the signal and the 2.1 μm of tunable range for the idler are achieved. In addition, the maximum average output power of 4.39 W and the minimum pulse width of 5.1 ns are achieved in the Q-switched Ho:$GdVO_4$ laser at a pulse repetition rate of 5 kHz, which corresponds to a slope efficiency of 26.3%.

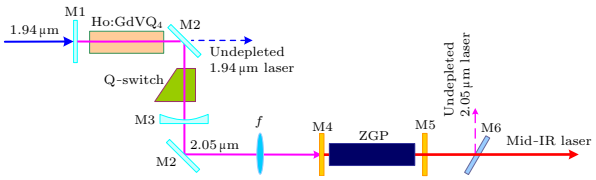

Fig. 1. Experimental setup of the ZGP-OPO pumped by the Q-switched Ho:$GdVO_4$ laser.

The experimental setup is schematically shown in Fig. 1. The dimension of *a*-cut Ho:$GdVO_4$ crystal doped with Ho ion concentration of 1.0 at.% is 4 mm × 4 mm in cross section and 20 mm in length. Two end faces of the crystal were antireflection ($T \sim 99.7\%$) coated at both a pump wavelength of 1.94 μm and a lasing wavelength of 2.05 μm. The Ho:$GdVO_4$ crystal was wrapped in indium foil and mounted into a copper water-cooled heat sink. The temperature of the cooling water is controlled at 20℃. A home-made diode-pumped FBG-locked Tm fiber laser with

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output power of 50 W was used as the pump source. Its output wavelength and linewidth are 1942 nm and 0.15 nm, respectively. The pump beam diameter was measured to be 500 μm in the Ho:$GdVO_4$ crystal. Considering the transmission loss, we also measured that the actual single-pass absorptions of Ho:$GdVO_4$ crystal is 74% at pump wavelength.

An L-shaped resonator with a physical cavity length of about 100 mm was used for the Ho:$GdVO_4$ laser. The cavity mirror M1 was flat with high reflectivity ($R \sim 99.8\%$) at 2.05 μm and high transmission ($T \sim 99.5\%$) at 1.94 μm. The flat 45° dichroic mirror M2 had high transmission ($T \sim 96\%$) for the pump light and high reflectivity ($R \sim 99.8\%$) at 2.05 μm. The output coupling M3 was plane-concave with the radius of curvature of 200 mm and transmittance of 40%. A 35-mm-long acousto-optic (AO) Q-switch (AOM) with an acoustic aperture of 1.1 mm was employed for Q-switched operation. The radio-frequency input power at frequency of 41 MHz is rated for 20 W.

The ZGP-OPO cavity configuration is also shown in Fig. 1, which consists of two flat mirrors M4 with $T \sim 99.4\%$ at 2.1 μm for the p-polarized component and $R \sim 99.9\%$ at 3–5 μm for the s-polarized component, and a plane output coupler M5 with $T = 50\%$ at 3–5 μm. M6 is a 45° flat dichroic mirror with the hit transmission ($T \sim 97\%$) for the 3–5 μm and high reflectivity ($R \sim 99.5\%$) at 2.05 μm. An 18.0-mm ZGP crystal cut for type I phase matching (55° to the c-axis) was used in this experiment. The ZGP crystal was wrapped in indium foil and mounted into a copper block, both end faces of which were AR-coated ($T \sim 99.5\%$) at the pump and laser wavelengths.

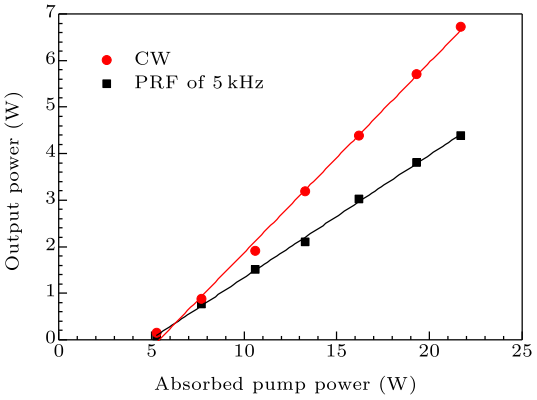

Fig. 2. The output powers of Ho:$GdVO_4$ laser with CW and Q-switched modes.

The Ho:$GdVO_4$ laser performance was investigated with both CW and Q-switched modes. With CW mode, the output powers as a function of the absorbed pump power are shown in Fig. 2. As a result, the maximum output power of 6.72 W was obtained at the absorbed pump power of 21.7 W, corresponding to a slope efficiency of 40.9% and an optical-to-optical efficiency of 31.0%. When the laser runs in the Q-switch mode, as shown in Fig. 2, a maximum output power of 4.39 W at pulse repetition rate of 5 kHz was achieved, corresponding to a slope efficiency of 26.3%. The output spectrum of the cw Ho:$GdVO_4$ laser was recorded by a wavemeter (Bristol 721 A), as shown in Fig. 3. The central wavelength of 2048.2 nm was obtained with the full width at half maximum (FWHM) of 0.2 nm. In addition, the beam quality of the M^2 factor was measured to be 1.2 at the maximum cw output power of the Ho:$GdVO_4$ laser.

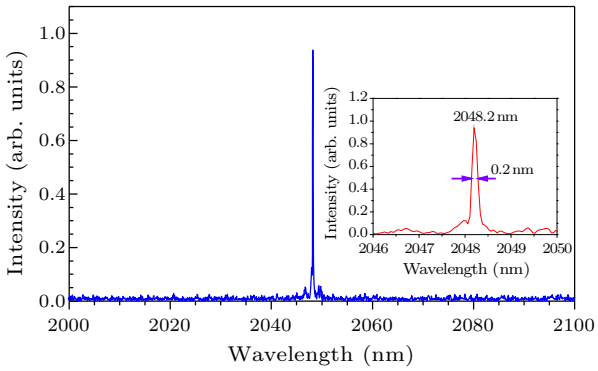

Fig. 3. The output spectrum of the Ho:$GdVO_4$ laser under cw mode.

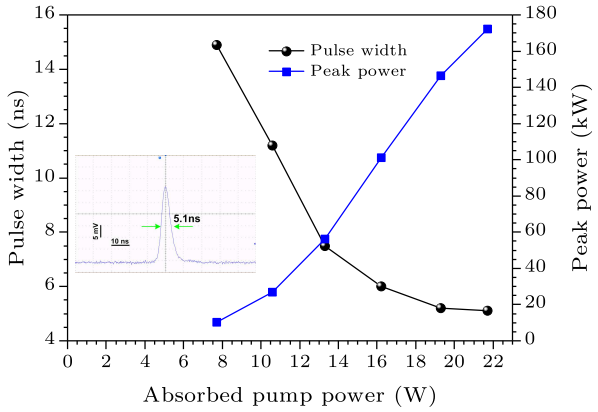

Fig. 4. The dependence of pulse widths and peak powers on absorbed pump power. Inset: the minimum pulse profile of the Q-switched Ho:$GdVO_4$ laser at a pulse repetition rate of 5 kHz.

The pulse profiles of the Q-switched Ho:$GdVO_4$ laser were detected by an InGaAs photodiode and recorded by a 350 MHz digital oscilloscope. The pulse width shows a steady decrease with the absorbed pump power up to 21.7 W, as shown in Fig. 4. The minimum pulse width was 5.1 ns at the same pump level, as also shown in Fig. 4. We obtained a maximum pulse energy of 0.88 mJ with a peak power of approximately 172.2 kW.

Firstly, we have investigated the output characteristics of the ZGP-OPO, which is the combined sum of the signal wave and the idler wave. The influence on the output performance of the ZGP-OPO laser with several different cavity lengths and pump diameters was investigated, as shown in Fig. 5. When the pump diameter is 0.7 mm, the average mid-IR output power with different cavity lengths was measured as a func-

tion of the incident pump power, as shown in Fig. 5(a). The maximum output power of 2.05 W was obtained with the cavity length of 30 mm and the pump power of 4.12 W, corresponding to the slope efficiency of 74.6% and the optical efficiency of 49.8%. Meanwhile, with the same pump power, the minimum pulse profile of 4.2 ns (as shown in Fig. 6) was recorded with an oscilloscope and HgCdTe detector, corresponding to the peak power of 97.6 kW. In the case of the cavity length of 60 mm, the output power of 1.67 W and the slope efficiency of 65.4% were achieved. With the cavity length of 100 mm, the output power and the slope efficiency of the ZGP-OPO decreased to 1.34 W and 55.6%, respectively. Furthermore, when the OPO cavity length is 100 mm, the average mid-IR output power with different pump diameters was measured as a function of the incident pump power, as shown in Fig. 5(b). When the pump diameter increased to 0.8 mm, the output power of ZGP-OPO decreased to 1.06 W, corresponding to a slope efficiency of 51.3%. In the case of the pump diameter of 0.9 mm, the output power of 0.73 W and the slope efficiency of 44.7% were obtained with the same pump power. To our best knowledge, this is the first time the ZGP-OPO pumped by the Ho:$GdVO_4$ laser has been investigated.

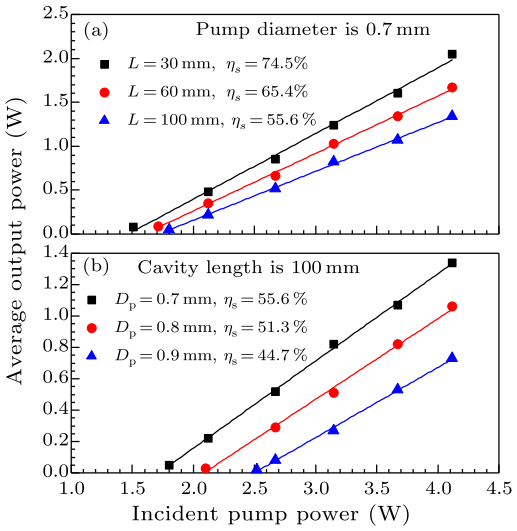

Fig. 5. The output performances of ZGP-OPO pumped by the Q-switched Ho:$GdVO_4$ laser: (a) different OPO cavity lengths with the pump diameter of 0.7 mm, and (b) different pump diameters with the cavity length of 100 mm

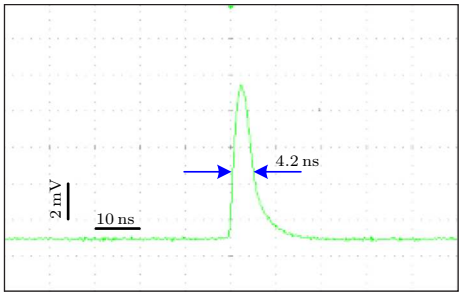

Fig. 6. The maximum pulse profile of ZGP-OPO.

Next, we measured the output spectrum of ZGP-OPO using a 300-mm WDG15-Z monochromator and a HgCdTe detector, as shown in Fig. 7. We observed a broad spectrum envelope with a FWHM of approximately 141 nm for the signal and 137 nm for the idler.

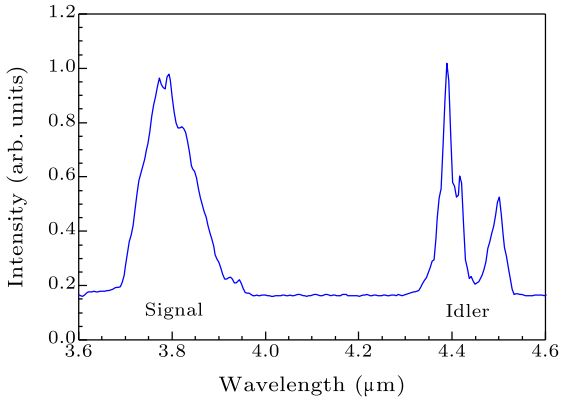

Fig. 7. The output spectrum of ZGP-OPO.

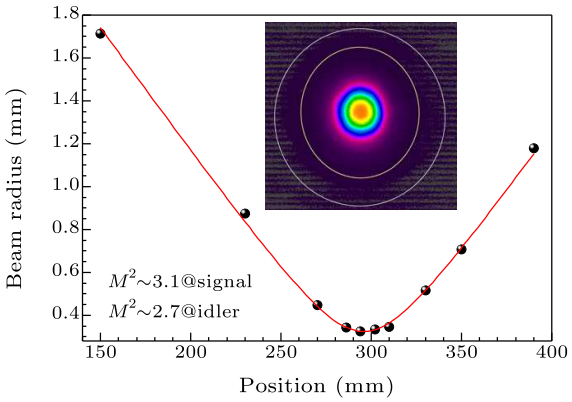

Fig. 8. The beam radius of the ZGP-OPO. Inset: the typical 2D beam profiles.

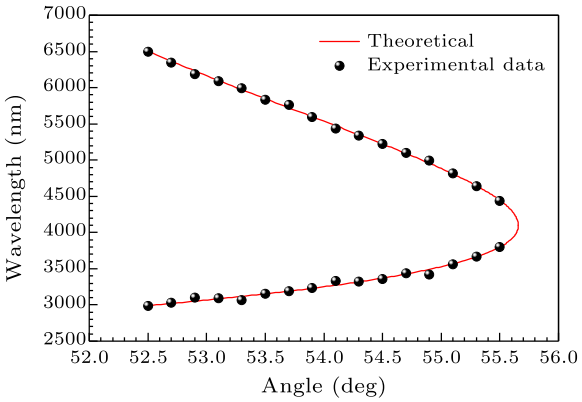

Fig. 9. Tunable output wavelengths of the ZGP-OPO pumped by the Q-switched Ho:$GdVO_4$ laser.

For ZGP-OPO, its beam quality factor is best in this work when the pump diameter and the cavity length are 0.7 mm and 100 mm, respectively. Thus we measured the M^2 factor of ZGP-OPO with these conditions. To determine the beam quality of the ZGP-

OPO, we measured the $1/e^2$ beam radius along the propagation direction after passing through a 150 mm focal length uncoated CaF_2 lens. Figure 8 shows the beam propagation characteristics at the maximum output power. By fitting the Gaussian beam standard expression to these data, the fit yields $M^2 = 3.1$ for the output wavelength of 3.78 μm and $M^2 = 2.7$ for the output wavelength of 4.39 μm. In addition, the 2D beam intensity distribution of ZGP-OPO was measured with the camera Spricon Ⅲ, as shown in Fig. 8.

Finally, the output wavelength of ZGP-OPO was tuned by rotating the crystal. The angle of ZGP was achieved with the accuracy of 0.2°. With the angle changed from 52.5° to 55.5°, the signal wave was tunable from 3.0 to 3.8 μm and the idler wave was tunable from 4.4 to 6.5 μm as shown in Fig. 9.

In summary, a mid-infrared $ZnGeP_2$ optical parametric oscillator pumped by the Q-switched Ho:$GdVO_4$ laser has been demonstrated for the first time. For the ZGP-OPO, at the pulse repetition rate of 5 kHz, the maximum output power of 2.05 W and the minimum pulse width of 4.2 ns are achieved with 30-mm of physical length and 0.7 mm of pump diameter, corresponding to a slope efficiency of 74.6% with respect to the incident Ho pump power. With the pump diameter of 0.7 mm and the cavity length of 100 mm, a beam quality factor is estimated to $M^2 \sim 3.1$ for the output wavelength of 3.78 μm and $M^2 \sim 2.7$ for the output wavelength of 4.39 μm. Also we have obtained 0.8 μm of tunable range for signal and 2.1 μm of tunable range for idler. In addition, up to 4.39 W average output power and minimum pulse width of 5.1 ns are achieved in the Q-switched Ho:$GdVO_4$ laser at a pulse repetition rate of 5 kHz.

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