Widely-tunable mid-infrared (2.6–5 μm) picosecond vortex laser

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We report on a widely-tunable mid-infrared picosecond optical vortex laser source that employs a synchronously-pumped optical parametric oscillator optimized for mid-infrared emission up to 5 μm. Vortex output with a continuously-tunable wavelength range of 2.6–5 μm could be obtained simply by translating the MgO:PPLN crystal. At the maximum pump power of 15 W, the maximum idler output powers were measured as 3.7, 1.7, and 0.165 W at the wavelengths of 2.6, 3.8, and 5 μm, respectively. The corresponding photon conversion efficiencies were estimated to be 60% at 2.6 μm, 40% at 3.8 μm, and 5.2% at 5 μm.

Optical vortex beams with helical wavefronts which have a characteristic azimuthal phase term of \( e^{i\varphi} \) carry an orbital angular momentum of \( \hbar \) per photon, \( \hbar \) represents the integer quantum number of the orbital angular momentum, which in turn can be positive or negative, and has a magnitude corresponding to the number of \( 2\pi \) phase rotations along the azimuthal direction \( \varphi \). The unique properties of optical vortices have given rise to the development of a variety of important applications such as quantum information systems, multi-division free-space telecommunications, and control and manipulation of trapped micro-particles based on the direction of the OAM. The ring-shaped spatial form with a central dark core has found significant application in super-resolution microscopes, offering high spatial resolution which exceeds the diffraction limit. Optical vortices also have the capacity to twist molten materials resulting in the formation of micro- and nano-chiral structures.

The capacity to effectively generate and modulate optical vortices, both directly and indirectly, is essential for the development and progression of the aforementioned research and application areas. Much like conventional lasers, wavelength diversity of vortex beams is necessary in order to expand their fields of application. Nonlinear optical frequency conversion methods based on second- and third-order nonlinear processes, such as second harmonic generation, sum frequency generation, optical parametric oscillation, optical parametric amplification, and stimulated Raman scattering, have proven highly effective in the development of solid-state optical vortex lasers with wavelength tunability. In particular, optical vortex lasers in the mid-infrared spectral region have many interesting applications such as super-resolution molecular absorption microscopy and molecular spectroscopy. In optical parametric oscillators (OPOs), the nonlinear process not only results in the conversion of laser wavelengths but also a mechanism by which the OAM of a vortex laser beam can be transferred. Many efforts have been made to generate optical vortices in the mid-infrared region through the frequency conversion of high-energy nanosecond, picosecond, femtosecond, and continuous-wave near-infrared vortex lasers using OPOs.

Recent studies on vortex beams applied to materials processing have shown that picosecond pulsed vortex laser beams can be used to produce high aspect-ratio chiral nanostructures on materials with their unique cold ablation effect. Wavelength-tunable picosecond vortex pulses in the mid-infrared region give potential scope for important applications, for instance, fabrication of twisted organic materials, and super-resolution molecular spectroscopy. To date, several bodies of work have demonstrated the generation of picosecond optical vortex pulses in the near- and mid-infrared wavelength regions based on OPOs. Summarized in Table I, are recent reports of picosecond pulsed vortex lasers demonstrated in the wavelength range 1.1–1.2 μm (single grating MgO:PPPLT), 3–4 μm (multi grating MgO:PPLN) based on a synchronously-pumped OPO formed using an X-configuration cavity. The increased photon absorption of PPLN crystals at mid-infrared wavelengths (longer than 4 μm) limits efficient vortex generation at wavelengths greater than 4 μm. One of the most significant challenges in this field of research is how to control the transfer of OAM from wavelengths of 1 μm to a wavelength of more than 4 times longer. It is also important to examine methods by which the handedness of the vortex output from the OPO can be controlled.

We report, the demonstration of a widely-tunable, high-power mid-infrared picosecond optical vortex laser source that uses a synchronously-pumped optical parametric oscillator optimized for mid-infrared emission up to a wavelength of 5 μm. The synchronously-pumped, singly resonant signal beam cavity features a high Q-factor which enables the transfer of the orbital angular momentum of the pump field to the idler field. Here, vortex laser output in the continuous tuning range of 2.6–5 μm could be obtained simply by translating the PPLN crystal. In this work, we also demonstrate the chiral control of a synchronously-pumped OPO. Here, the handedness of the vortex output is controlled via inverting the handedness of the pump vortex beam. At the maximum pump power of 15 W, the maximum idler output power was measured as 3.7, 1.7, 0.165 W at the wavelength of 2.6, 3.8, 5 μm, respectively. And the corresponding photon conversion efficiencies were estimated to be 60% at 2.6 μm, 40% at 3.8 μm and 5.2% at 5 μm. More than 2 W (1 W) vortex output power was achieved in the tuning range of 2.6–3.8 μm (3.8–4.2 μm).
The experimental setup of the widely-tunable, high-power, mid-infrared (2.6–5 μm) picosecond vortex parametric oscillator based on a fan-out-grating MgO:PPLN crystal is shown in Fig. 1(a). The pump beam was generated from an all-solid-state Nd:YVO₄ laser with a pulse repetition rate of 120 MHz, pulse duration of ~15 ps, and a wavelength of 1.064 μm. The maximum average output power of 15 W was produced from the pump laser and the power level was controlled using a half-wave plate and a thin film polarizer. The Gaussian spatial profile of the laser output was converted into a right-handed optical vortex beam with an OAM \( l \) of +1 by using a 16-segmented spiral phase plate (SPP) made of silica glass, shown in Figs. 1(b) and 1(c). The output was converted into a left-handed optical vortex beam with an OAM \( l \) of −1 by inverting the spiral phase plate relative to the pump beam as shown in Figs. 1(d) and 1(e). We note that a pair of upward Y-shaped fringes on the right and downward Y-shaped fringes on the left denote a right-handed vortex. Conversely, downward Y-shaped fringes on the right and upward Y-shaped fringes on the left denote a left-handed vortex.

The polarization of the pump beam was aligned by the HWP to be parallel along a crystallographic axis of the crystal to achieve type-0 \((e \rightarrow e + e)\) phase matching between the pump, signal and idler fields. The pump vortex beam was then re-imaged into the PPLN crystal at a beam waist radius of \( \omega_0 = 90 \mu m \) by using a lens with a focal length of 125 mm. The nonlinear crystal used in this work was a MgO:PPLN crystal with a fan-out grating which had a continuous grating period of 26–32 μm. It was 50 mm long, 16 mm wide, and 2 mm thick, and it was mounted onto a translation stage to enable the grating period seen by the pump beam to be varied, so as to achieve wavelength tuning. The two end faces of the crystal were anti-reflection-coated for a 1.064 μm (pump), 1.3–2 μm (signal), and 2.5–5 μm (idler) fields. The large grating period (26–32 μm) and coating range of the crystal then support the wide wavelength tunability.

The OPO was designed to be singly resonant and was comprised of five mirrors in a standing-wave Z-cavity with high precision adjustment capability. The mirrors M2 and M3 were concave, each with a radius of curvature of \( r = 150 \text{ mm} \) and with a 180 mm separation. Mirror M4 had a radius of curvature \( r = 500 \text{ mm} \), and mirrors M1 and M5 were flat. All mirrors, M1-M5 were coated high-reflecting \([0–10^°, 1350–1700 \text{ nm}]\), HR > 99.9% for the signal and anti-reflecting \([AR, 0–10^°, 1064 \text{ nm}] < 0.5% + AR (0–10^°, 2500–5000 \text{ nm}) < 2\%\) for the pump and idler fields, so as to ensure singly-resonant operation of the signal field.

The OPO cavity was synchronized to the pump repetition rate of 120 MHz and had a total cavity length of ~1250 mm. The resonant beam mode radius distribution of the signal beam along the axis is depicted in Fig. 2. There is an excellent overlap of the pump and resonant signal fields inside the crystal, and the signal field waist radius of ~90 μm was calculated. The very high Q-factor, singly resonant operation of the signal field which was very well mode matched with the pump field, enabled an efficient generation of the idler field with high power and wide wavelength tunability.

Figure 3 shows the experimentally measured spatial profiles and self-referenced interference fringes of the idler field at a range of wavelengths across the idler field tuning range of 2.6–5 μm. When the OPO was pumped by a left-handed vortex pump field, the idler field had a ring-shaped spatial profile with an OAM \( l \) of \(+1\), as evidenced by a pair of upward Y-shaped fringes on the right side, and downward Y-shaped fringes on the left side, identical to that of the pump beam shown in Figs. 3(a) and 3(b). When the OPO was pumped by a left-handed vortex beam, the self-referenced interference fringes of the idler beam were the same as that of the left-handed pump vortex beam with an OAM \( l \) of \(-1\), as evidenced by a pair of downward Y-shaped fringes on the right side, and the upward Y-shaped fringes on the left side, as shown in Fig. 3(c). These results indicate that the handedness of the synchronously-pumped vortex OPO outputs could be selectively controlled without destroying the phase singularity.

In the singly resonant OPO, the parametric gain of the resonant field depends upon the mode overlap of the interacting fields. In this synchronously-pumped, singly resonant high-Q cavity, the resonating signal beam undergoes many round trips inside the cavity. Vortex cavity modes have higher diffraction losses in such a cavity and as a result, the fundamental, Gaussian mode dominates. This prevents the signal field from lasing as a vortex mode, and instead, the idler field takes on the OAM of the pump beam as it is not constrained in any way by a resonant cavity. In these experiments, the orbital angular momentum of the pump field was observed to be completely transferred to that of the idler field at all idler wavelengths in the range 2.6–5 μm. When pumping with the optical vortex with \( l > 2\), we believe that the orbital angular momentum will also be transferred to the idler output.
changing the transmission loss of the output coupler. To understand fully this interesting phenomenon, further investigation is needed by employing various output couplers with appropriate reflectivity.

The spectral tunability of the idler field as produced by translating the MgO:PPLN crystal across the pump field is shown in Fig. 4. Figure 4(a) shows discrete idler field wavelengths as measured using a spectrometer (SpectraPro HRS-500). The idler field output power as a function of the idler wavelength at a pump power of 15 W is shown in Fig. 4(b). The maximum output power of 3.7 W was measured at a wavelength of \( \sim 2.6 \) \( \mu \)m with more than 1 W output power achieved across the tuning range of 2.6–4.2 \( \mu \)m. More than 0.5 W vortex output power was achieved across the tuning range 4.2–4.5 \( \mu \)m. The large wavelength difference between the pump and idler fields results in quantum loss and low wavelength conversion efficiency. Wavelength-tunable vortex output was achieved across the tuning range of 2.6–5 \( \mu \)m with a wavelength span of approximately 2.4 \( \mu \)m. To the best of our knowledge, this is the widest wavelength tuning range ever demonstrated from a mid-infrared vortex source based on a synchronously-pumped, picosecond, synchronously-pumped parametric oscillator.

Fig. 1. (Color online) (a) Schematic showing the layout of the optical vortex-pumped picosecond, synchronously-pumped parametric oscillator. Cavity components include: SPP, spiral phase plate; M1-M5 OPO mirrors. (b) and (c) are the spatial profile and self-referenced interference fringes of the right-handed vortex beam. (d) and (e) are the spatial profile and self-referenced interference fringes of the left-handed vortex beam.

Fig. 2. (Color online) Plot of the theoretically calculated intracavity mode radius of the signal field at various points within the OPO cavity.

Fig. 3. (Color online) Images showing the spatial profiles and self-referenced interference fringes of the idler outputs across a range of idler wavelengths in the tuning range of 2.6–5 \( \mu \)m. Panel (a) depicts the spatial profiles of the generated idler fields; panel (b) depicts the self-referenced interference fringes of the idler fields, each generated using a right-handed vortex pump field; panel (c) depicts the self-referenced interference fringes of the idler fields, each generated using a left-handed vortex pump field.

Fig. 4. (Color online) Plots showing the (a) wavelength spectrum of the idler outputs; and (b) output power of the idler vortex field as a function of idler wavelength at a pump power of 15 W.
pumped OPO. The Gaussian signal output power was significantly low (<0.5 mW) in the entire tuning range of 1.35–1.8 μm owing to extremely low transmission loss from the high-Q cavity for the signal output.

Figure 5 shows the idler vortex fields as a function of the incident pump vortex power at idler wavelengths of 2.6 μm, 3.8 μm, and 4.98 μm respectively. The maximum idler output powers were measured to be 3.7 W, 1.7 W, and 0.165 W at these respective wavelengths and for an incident pump power of 15.3 W. The corresponding optical–optical conversion efficiencies were estimated to be 24% at 2.6 μm, 11.1% at 3.8 μm and 1.1% at 4.98 μm.

In conclusion, we have demonstrated a widely-tunable mid-infrared picosecond optical vortex source using a synchronously-pumped optical parametric oscillator which was optimized for mid-infrared emission up to 5 μm. The OPO comprised a MgO:PPLN crystal with a fan-out grating with periods ranging from 26–32 μm. The synchronously-pumped, singly-resonant cavity for the signal field had a very high Q-factor. This cavity design enabled the OAM of the pump field to be transferred to that of the idler field. Continuously-tunable vortex output in the wavelength range of 2.6–5 μm could be simply obtained by translating the MgO:PPLN crystal across the pump beam and varying the grating period.

We also investigated the means by which the handedness of the idler field output from the OPO could be selectively controlled. Here, it was found that the handedness of the idler field could be controlled just by inverting the handedness of the pump vortex field. At the maximum incident pump power of 15 W, the maximum idler output powers were measured as 3.7 W, 1.7 W, and 0.165 W at the idler field wavelengths of 2.6 μm, 3.8 μm, and 5 μm respectively. The corresponding photon conversion efficiencies were estimated to be 60% at 2.6 μm, 40% at 3.8 μm, and 5.2% at 5 μm. Greater than 2 W (1 W) vortex output power was achieved in the tuning range of 2.6–3.8 μm (3.8–4.2 μm).

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