Letter

Tunable near- and mid-infrared (1.36–1.63 µm and 3.07–4.81 µm) optical vortex laser source

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Abstract

The generation of near- and mid-infrared vortex mode is demonstrated from a 1 µm nanosecond optical vortex pumped optical parametric oscillator using a multi-grating MgO-doped periodically poled lithium niobate crystal with five grating domains. This system enables the orbital angular momentum between the signal and idler outputs to be exchanged simply by controlling the cavity Q-factor, and a vortex output in the wavelength ranges of 1.36–1.63 µm or 3.07–4.81 µm could be obtained. A maximum signal (idler) vortex output energy of 4.3 mJ (2.2 mJ) was achieved at a pump energy of 21 mJ, which corresponds to an optical–optical conversion efficiency of over 20% (10%).

Keywords: optical vortices, nonlinear optics, singular optics, parametric oscillators and amplifiers

(Some figures may appear in colour only in the online journal)

1. Introduction

An optical vortex beam exhibits a ring-shaped spatial form and carries an orbital angular momentum (OAM) defined by \( \ell \) (a topological charge), due to a helical wavefront with an on-axial phase singularity [1–6]. Optical vortex beams have been widely investigated in a variety of fundamental sciences and advanced technologies, such as quantum optics, optical manipulation and trapping [7–10], scanning fluorescence microscopy [11–13], spatial multiplexing optical communications and data-storage [14–16], and laser materials processing [17–24].

External spatial phase modulation elements, such as azimuthally continuous or segmented spiral phase plates (SPP) [25–27], \( q \)-plates [28–30], spatial light modulators [31, 32], and cholesteric liquid crystal chiral superstructures [33] are commonly used as mode converters to generate an optical vortex beam. However, these elements are designed for
a specified wavelength, and they inherently constrain the wavelength versatility of optical vortex beams. A widely tunable optical vortex source with a lasing wavelength that can be matched to the absorption bands of target materials is strongly desired for applications. An optical parametric oscillator (OPO) is a promising way to develop tunable solid-state lasers. In particular, a tunable optical vortex source in the near- (~1.5 μm) and mid-infrared (3–5 μm) region, in which many molecules have eigenfrequencies and their overtones originating from vibration modes [34–36], will open the door towards next-generation molecular sciences and applications, such as super-resolution molecular spectroscopy with a high spatial resolution beyond the diffraction limit, and organic materials processing without the destruction of chemical structures.

Tunable 1–3 μm vortex laser sources based on LiBiO3 [37, 38], KTiOPO4 (KTP) [39–43], and MgO-doped periodically poled stoichiometric LiTaO3 (MgO: PPLT) [44] OPOs have been demonstrated. Widely tunable far-infrared (5–18 μm) vortex laser sources formed of a KTP-OPO in combination with a ZnGeP2 or AgGaSe2 difference frequency generator have also been developed [45, 46]. However, there are still few studies on 3–5 μm optical vortex sources with a moderate energy level [47, 48]. To date, we have successfully demonstrated a millijoule-level 3 μm optical vortex source formed of MgO-doped periodically poled lithium niobate (MgO:PPLN) with a grating period of 30 μm [49]. However, this system was tuned only within a wavelength range of 3.36–3.68 μm, despite the wide transmission band of the PPLN crystal within the range of 0.45–5 μm. Most recently, we have developed a tunable mid-infrared (2.2–4.8 μm) nanosecond laser formed of an OPO by employing a multi-grating MgO:PPLN [50].

Here, we extend this tunable mid-infrared laser source to fill in the frequency gap (3–5 μm) of the mid-infrared vortex source. Interestingly, the system also enables the topological charges between the idler (low energy photon) or signal (high energy photon) outputs to be exchanged simply by adjusting the reflectivity of the output coupler, thereby generating a vortex output in the wavelength ranges of 1.36–1.63 μm or 3.1–4.8 μm. Such topological charge exchange based on the Q-factor control of the cavity has been never discussed, so far.

2. Experiments and discussion

Figure 1 shows a schematic diagram of the developed mid-infrared optical vortex pumped PPLN-OPO. A conventional Q-switched Nd:YAG laser (LS-2136LP; pulse duration, 25 ns; wavelength, 1.064 μm; pulse repetition frequency (PRF), 50 Hz; Gaussian spatial profile) was used as a pump source, and its output was converted into a first-order optical vortex with a topological charge ℓ of 1 with a SPP. The optical vortex pump beam was loosely focused onto the OPO by a lens to form an annular spot with a diameter of 1 mm.

A nonlinear crystal used was a 5 mol% MgO-doped PPLN transversely segmented into five grating domains with periods of 26–30 μm and a step of 1 μm; the dimensions were 40 mm long, 10 mm wide and 2 mm thick. Both end faces of the crystal were anti-reflection (AR)-coated for 1.064 μm (pump), 1.3–1.7 μm (signal), and 3–5 μm (idler). The polarization of the pump beam was then aligned parallel along a crystallographic axis of the crystal to achieve type-0 (e → e + e) phase matching among the pump, signal and idler outputs. The crystal was placed in an oven, so as to control the temperature within 25 °C–200 °C with an accuracy of 0.1 °C. The crystal was also mounted onto a transverse translator to ensure the pump beam passed through an individual grating domain.

A single resonant high-Q cavity for the signal was made from a flat input mirror (IM) with high reflectivity for the signal and idler, and high transmission for the pump, and a flat output mirror (OC1) with high reflectivity for the signal output and pump beam (for double-pass pumping) and high transmission for the idler; its physical length was fixed to ca. 100 mm. The undesired pump beam was also removed by employing an AR-coated filter with a high transmission of >95% for 1.9 μm.

The nonlinear gain for the signal in this singly resonant cavity is determined by the spatial overlapping efficiency η, between the resonant signal and pump fields (non-resonant idler always exhibits the almost same beam size as that of pump beam), given as follows:

\[ \eta = \frac{\int E_p(E_s)^* r d r d \phi}{\int |E_p|^2 r d r d \phi \cdot \int |E_s|^2 r d r d \phi} \]  (1)

The signal beam is here assumed to lase at a vortex mode in the cavity, and it can then be given by a following expression:

\[ E_{p,s} = \left( \frac{r}{\omega_{p,s}} \right) \exp \left( -\frac{r^2}{\omega_{p,s}^2} \right) e^{i \phi} \]  (2)

where \( E_p \) and \( E_s \) are the electric fields of the pump and signal beams, respectively, and \( \omega_p \) and \( \omega_s \) are the beam radii of the pump and signal beams. Therefore, the general relationship for η is given by

\[ \eta = \frac{4 \omega_p^2 \omega_s^2}{(\omega_p^2 + \omega_s^2)^2}. \]  (3)

![Figure 1. Schematic diagram of the experimental setup for the near-and mid-infrared optical vortex parametric laser. Two insets show the experimental spatial form and self-referenced fringes of the pump beam.](image)
This formula suggests that the spatial overlapping efficiency $\eta$ decreases significantly as the increase of the signal mode radius $\omega_s$.

The plane-parallel cavity used in this experiment is classified into a stable–unstable resonator, and it prevents the signal output to lase at a higher–order mode, such as the vortex mode, with an infinite beam radius due to severe diffraction loss ($\eta$ is almost zero).

Figure 2 shows the experimental spatial forms and wavefronts of the signal and idler outputs observed using a pyroelectric camera (Spiricon Pyrocam III; spatial resolution: 75 $\mu$m) and a self-reference interferometer. The idler output exhibits an annular spatial form, and its topological charge is identical with that of the pump beam, as evidenced by a pair of Y- or fork-shaped fringes (figures 2(a) and (b)). In contrast, the signal output shows a Gaussian profile without any phase singularities (figures 2(c) and (d)). These results indicate that the OAM of the pump beam is selectively transferred into the idler output. The idler output can also be tuned within the wavelength range of 3.07–4.81 $\mu$m by controlling the crystal temperature and selecting the grating domain (figure 3(a)). A simulated tuning curve by employing the Smelleier equation can also support well the experiments [51, 52]. This tuning range is the widest, to the best of our knowledge, obtained by a mid-infrared vortex source based on an OPO. The system enables the frequency gap of the mid-infrared vortex sources to be filled. The maximum idler output energy was measured to be 2.2 mJ at a wavelength of 3.42 $\mu$m. The incident pump energy was then 21 mJ. The corresponding optical–optical conversion efficiency was estimated to be >10% (figure 3(b)).

The idler output typically had a narrow spectral bandwidth (FWHM) of $\Delta \lambda_i \approx 4.3$ nm (ca. 1.85 cm$^{-1}$); however, it became extremely broadband ($\Delta \lambda_i \approx 23$ nm, ca. 24.4 cm$^{-1}$) near a wavelength of 3.1 $\mu$m due to the relatively wider phase matching acceptance of the crystal at high temperature (figure 4).

The OC1 was replaced by a flat partial reflective OC2 with 50% reflectivity for the signal, high reflectivity for the pump, and high transmission for the idler. Such a low-Q cavity should act as a near optical parametric generator and significantly impact the signal to be confined in the cavity as an eigenmode (in fact, the signal output only makes one or two round trips in the cavity), so as to ensure that the signal beam holds the OAM of the pump beam. The signal output did lase at the vortex mode, as evidenced by its annular spatial form and Y-forked fringes (figures 5(a) and (b)). The signal output was also tuned into the wavelength range of 1.36–1.63 $\mu$m. The idler output had a Gaussian profile without any phase singularities (figures 5(c) and (d)). Thus, control of the cavity Q-factor enables us to exchange the OAM between the signal and idler outputs. Selective control of the OAM will therefore
become available with an electric Q-switching element, such as an acoustic–optical modulator, as a future work. It should also be noted that a maximum signal vortex output energy of 4.3 mJ was obtained at 1.51 µm with an optical–optical conversion efficiency of over 20% (figure 6). The energy and spatial form of the vortex output also remained unchanged during a long observation time of over 3 h. Further improvement of the optical–optical conversion efficiency of this OPO system will be possible by optimization of the output mirror reflectivity.

3. Conclusions

We have demonstrated a widely tunable, near- (~1.5 µm) and mid-infrared (3–5 µm) vortex laser by employing an optical vortex pumped singly resonant OPO formed of MgO:PPLN crystal with five grating domains. This system enables the frequency gap of the mid-infrared optical vortex sources to be filled and it also allows the OAM between the signal and idler outputs to be exchanged simply by controlling the cavity Q-factor. Such a tunable near- and mid-infrared optical vortex source will open the door towards next-generation molecular sciences and applications, including super-resolution molecular spectroscopy, and laser materials processing of polymeric materials.

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References

[1] Allen L, Beijersbergen M W, Spreeuw R J C and Woerdman J P 1992 Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes Phys. Rev. A 45 8185–9
[2] Indebetouw G 1993 Optical vortices and their propagation J. Mod. Opt. 40 73–87
[3] Padgett M J, Courtial J and Allen L 2004 Light’s orbital angular momentum Phys. Today 57 35–40
[4] Soskin M S and Vainshtein M V 2001 Prog. Opt. 4 219–76
[5] Yao A M and Padgett M J 2011 Orbital angular momentum: origins, behavior and applications Adv. Opt. Photonics 3 161–204
[6] Padgett M J 2017 Orbital angular momentum 25 years on Opt. Express 25 11265–74
[7] Dholakia K and Čížmár T 2001 Shaping the future of manipulation Nat. Photon. 5 335–42
[8] Grier D G 2003 A revolution in optical manipulation Nature 424 810–16
[9] Kuga T, Torii Y, Shiokawa N, Hirano T, Shimizu Y and Sasada H 1997 Novel optical trap of atoms with a doughnut beam Phys. Rev. Lett. 78 4713–16
[10] Shen Y, Wang X, Xie Z, Min C, Fu X, Liu Q, Gong M and Yuan X 2019 Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities Light Sci. Appl. 8 90
[11] Bretschneider S, Eggeling C and Hell S W 2007 Breaking the diffraction barrier in fluorescence microscopy by optical shelving Phys. Rev. Lett. 98 21813
[12] Willig K H, Harke B, Medda R and Hell S W 2007 STED microscopy with continuous wave beams Nat. Methods 4 915–18
[13] Heller I, Sitters G, Broekmans O D, Farge G, Menges C, Wende W, Hell S W, Peterman E J G and Wuite G J J 2013 STED nanoconfocal combined with optical tweezers reveals protein dynamics on densely covered DNA Nat. Methods 10 910–16
[14] Wang J 2016 Advances in communications using optical vortices Photonics Res. 4 B14
[15] Willner A E et al 2015 Optical communications using orbital angular momentum beams Adv. Opt. Photonics 7 66–106
[16] Bozinovic N, Yue Y, Ren Y, Tur M, Kristensen P, Huang H, Willner A E and Ramachandran S 2015 Terabit-scale orbital angular momentum mode division multiplexing in fibers Science 340 1545–8
[17] Omatsu T, Miyamoto K, Toyoda K, Morita R, Arita Y and Dholakia K 2019 A new twist for materials science: the formation of chiral structures using the angular momentum of light Adv. Opt. Mater. 7 1801672
[18] Toyoda K, Miyamoto K, Aoki N, Morita R and Omatsu T 2012 Using optical vortex to control the chirality of twisted metal nanostructures Nano Lett. 12 3645–50
[19] Takahashi F, Miyamoto K, Hidai H, Yaratov K, Morita R and Omatsu T 2016 Picosecond optical vortex pulse illumination forms a monocrystalline silicon needle Sci. Rep. 6 21738
[20] Barada D, Juman G, Yoshida I, Miyamoto K, Kawata S, Ohno S and Omatsu T 2016 Constructive spin-orbital angular momentum coupling can twist materials to create spiral structures in optical vortex illumination Appl. Phys. Lett. 108 051108
[21] Ni J, Wang C, Zhang C, Hu Y, Yang L, Lao Z, Xu B, Li J, Wu D and Chu J 2017 Three-dimensional chiral microstructures fabricated by structured optical vortices in isotropic material Light Sci. Appl. 6 e17011
[22] Syubaev S, Zhizhinchenko A, Kuchmizhak A, Porfireva A, Pustovalov E, Vitriko O, Kulchin Y, Khonina S and Kudryashov S 2017 Direct laser printing of chiral plasmonic nanojets by vortex beams Opt. Express 25 10214–23
[23] Syubaev S, Zhizhinchenko A, Vitriko O, Porfireva A, Fomchenkov S, Khonina S, Kudryashov S and Kuchmizhak A 2019 Chirality of laser-printed plasmonic nanoneedles tunable by tailoring spiral-phase pulses Appl. Surf. Sci. 470 526–34
[24] Kohmura Y, Zhakhovsky V, Takei D, Suzuki Y, Takeuchi A, Inoue I, Inubushi Y, Inogamov N, Ishikawa T and Yabashi M 2018 Nano-structuring of multi-layer material by single x-ray vortex pulse with femtosecond duration Appl. Phys. Lett. 112 123103
[25] Beijersbergen M W, Coerwinkel R P C, Kristensen M and Woerdman J P 1994 Helical-wave-front laser-beams produced with a spiral phaseplate Opt. Commun. 112 321–7
[26] Oemrawsingh S S R, Eliel E R, Woerdman J P, Verstegen E J K, Kloosterboer J G and Hoof G W T 2004 Half-integral spiral phase plates for optical wavelengths J. Opt. A Pure Appl. Opt. 6 S288–90
[27] Sueda K, Miyagi G, Miyanaga N and Nakatsuka M 2004 Laguerre–Gaussian beam generated with a multilevel spiral phase plate for high intensity laser pulses Opt. Express 12 3548
[28] Cardano F, Karimi E, Slussarenko S, Marrucci L, De Lisio C and Santamato E 2012 Polarization pattern of vector vortex beams generated by q-plates with different topological charges Appl. Opt. 51 C1–C6
[29] Marrucci L 2013 The q-plate and its future J. Nanophotonics 7 075059
[30] Karimi E, Piccirillo B, Nagali E, Marrucci L and Santamato E 2009 Efficient generation and sorting of orbital angular momentum eigenmodes of light by thermally tuned q-plates Appl. Phys. Lett. 94 231124/1–4
[31] Matsumoto N, Ando T, Inoue T, Ohtake Y, Fukushima N and Hara T 2008 Generation of high-quality higher-order Laguerre-Gaussian beams using liquid-crystal-on-silicon spatial light modulators J. Opt. Soc. Am. A 25 1642–51
[32] Forbes A, Dudley A and McLaren M 2016 Creation and detection of optical modes with spatial light modulators Adv. Opt. Photonics 8 200–27
[33] Chen P et al 2018 Digitalizing self-assembled chiral superstructures for optical vortex processing Adv. Mater. 30 1705865
[34] Shaw R A, Kotowich S, Mantsch H L and Leroux M 1996 Quantitation of protein, creatinine, and urea in urine by near-infrared spectroscopy Clin. Biochem. 29 11–19
[35] Raymond E A, Tarbuck T L, Brown M G and Richmond G L 2003 Hydrogen-bonding interactions at the Vapor/Water interface investigated by vibrational sum-frequency spectroscopy of HOD/H2O/O2O mixtures and molecular dynamics simulations J. Phys. Chem. B 107 546–56
[36] Huth F, Goyadzhanov A, Kuzmin S, Kuksa S and Haslauer R 2012 Nano-FTIR absorption spectroscopy of molecular fingerprints at 20 nm spatial resolution Nano Lett. 12 3973–8
[37] Abulikemu A, Yusufu T, Mamuti R, Miyamoto K and Omatsu T 2015 Widely-tunable vortex output from a resonant optical parametric oscillator Opt. Express 23 18338–44

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[38] Abulikemu A, Yusufu T, Mamuti R, Araki S, Miyamoto K and Omatsu T 2016 Octave-band tunable optical vortex parametric oscillator Opt. Express 24 15204–11
[39] Martinelli M, Huguenin J A O, Nussenzveig P and Khoury A Z 2004 Orbital angular momentum exchange in an optical parametric oscillator Phys. Rev. A 70 013812
[40] Miyamoto K, Miyagi S, Yamada M, Furuki K, Aoki N, Okida M and Omatsu T 2011 Optical vortex pumped mid-infrared optical parametric oscillator Opt. Express 19 12220–6
[41] Yusufu T, Tokizane Y, Yamada M, Miyamoto K and Omatsu T 2012 Tunable 2-µm optical vortex parametric oscillator Opt. Express 20 23666–75
[42] Yusufu T, Tokizane Y, Miyamoto K and Omatsu T 2013 Handedness control in a 2-µm optical vortex parametric oscillator Opt. Express 21 23604–10
[43] Alves G B, Barros R F, Tasca D S, Souza C E R and Khoury A Z 2018 Conditions for optical parametric oscillation with a structured light pump Phys. Rev. A 98 063825
[44] Aadhi A, Samanta G K, Kumar S C and Ebrahim-Zadeh M 2017 Controlled switching of orbital angular momentum in an optical parametric oscillator Optica 4 349–55
[45] Furuki K, Horikawa M T, Ogawa A, Miyamoto K and Omatsu T 2014 Tunable mid-infrared (6.3–12 µm) optical vortex pulse generation Opt. Express 22 26351–7
[46] Araki S, Ando K, Miyamoto K and Omatsu T 2018 Ultra-widely tunable mid-infrared (6–18 µm) optical vortex source Appl. Opt. 57 620–4
[47] Aadhi A, Sharma V, Singh R P and Samanta G K 2017 Continuous-wave, singly resonant parametric oscillator-based mid-infrared optical vortex source Opt. Lett. 42 3674–72
[48] Camper A, Park H, Lai Y H, Kagayama H, Li S, Talbert B K, Blaga C I, Agostini P, Ruchon T and DiMauro L F 2017 Tunable mid-infrared source of light carrying orbital angular momentum in the femtosecond regime Opt. Lett. 42 3769–72
[49] Yusufu T, Niu S, Tuersun P, Tulake Y, Miyamoto K and Omatsu T 2018 Tunable 3 µm optical vortex parametric oscillator Japanese J. Appl. Phys. 57 122701
[50] Niu S, Aierken P, Wang S, Ahabaik M and Yusufu T 2020 Widely tunable, high-energy, mid-infrared (2.2–4.8 µm) laser based on a multi-grating MgO:PPLN optical parametric oscillator Infrared Phys. Technol. 104 103121
[51] Jundt D H 1997 Temperature-dependent Sellmeier equation for the index of refraction, ne, in congruent lithium niobate Opt. Lett. 22 1553–5
[52] Cao Z, Gao X, Chen W, Wang H, Zhang W and Gong Z 2009 Study of quasi-phase matching wavelength acceptance bandwidth for periodically poled LiNbO3 crystal-based difference-frequency generation Opt. Lasers Eng. 47 589–93