# Generation of vortex beams by an image-rotating optical parametric oscillator

Arlee V. Smith and Darrell J. Armstrong

Dept. 1118, Sandia National Laboratories, Albuquerque, NM 87185-1423

arlee.smith@osa.org

**Abstract:** We generate optical vortex beams in a nanosecond optical parametric oscillator based on an image-rotating resonator. This efficient new method of vortex generation should be adaptable to pulsed or continuous lasers.

© 2003 Optical Society of America

**OCIS codes:** (140.3410) Laser resonators; (190.4970) Parametric oscillators and amplifiers

#### **References and links**

- 1. K. T. Gahagan and G. A. Swartzlander, Jr., "Simultaneous trapping of low-index and high-index microparticles observed with an optical-vortex trap," J. Opt. Soc. Am. B 16, 533-537 (1999).
- T. Kuga, Y. Torii, N. Shiokawa, T. Hirano, Y. Shimizu, and H. Sasada, "Novel optical trap of atoms with a doughnut beam," Phys. Rev. Lett. 78, 4713-4716 (1997).
- H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, "Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity," Phys. Rev. Lett. 75, 826-829 (1995).
- A. G. Truscott, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, "Optically written waveguide in an atomic vapor," Phys. Rev. Lett. 82, 1438-1441 (1999).
- G. A. Swartzlander, Jr. and C. T. Law, "Optical vortex solitons observed in Kerr nonlinear media," Phys. Rev. Lett. 69, 2503-2506 (1992).
- C. T. Law, X. Zhang, and G. A. Swartzlander, Jr., "Waveguiding properties of optical vortex solitons," Opt. Lett. 25, 55-57 (2000).
- P. DiTrapani, W. Chinaglia, S. Minardi, A. Piskarskas, and G. Valiulis, "Observation of quadratic optical vortex solitons," Phys. Rev. Lett. 84, 3843-3846 (2000).
- Z. Chen, M. Segev, D. W. Wilson, R. E. Muller, and P. D. Maker, "Self-trapping of an optical vortex by use of the bulk photovoltaic effect," Phys. Rev. Lett. 78, 2948-2951 (1997).
- E. Abramochkin, N. Losevsky, and V. Volostnikov, "Generation of spiral-type laser beams," Opt. Commun. 141 59-64 (1997).
- R. Oron, N. Davidson, A. A. Friesem, and E. Hasman, "Efficient formation of pure helical laser beams," Opt. Commun. 182, 205-208 (2000).
- L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes," Phy. Rev. A 45, 8185-8189 (1992).
- V. Y. Bazhenov, M. S. Soskin, and M. V. Vasnetsov, "Screw dislocations in light wavefronts," J. Mod. Opt. 39, 985-990 (1992).
- N. R. Heckenberg, R. McDuff, C. P. Smith, and A. G. White, "Generation of optical phase singularities by computer-generated holograms," Opt. Lett. 17, 221-223 (1992).
- E. Abramochkin and V. Volostnikov, "Beam transformations and nontransformed beams," Opt. Commun. 83 123-135 (1991).
- M. W. Beijersbergen, L. Allen, H. E. L. O. van der Veen, and J. P. Woerdman, "Astigmatic laser mode converters and transfer of orbital angular momentum," Opt. Commun. 96, 123-132 (1993).
- A. V. Smith and D. J. Armstrong, "A nanosecond optical parametric oscillator with 90° image rotation: design and performance," J. Opt. Soc. Am. B. 19, 1801-1814 (2002).
- 17. D. J. Armstrong, M. C. Phillips, and A. V. Smith, "Generation of radially polarized beams using an image-rotating resonator," to be published in Applied Optics.



Fig. 1. Nonplanar ring OPO cavity with  $90^{\circ}$  image rotation on each cavity pass.

### 1. Introduction

Optical vortex beams have a cylindrically symmetric irradiance with a dark center that persists with propagation. They have been used to trap or guide particles which seek the dark beam center [1, 2], to spin absorbing particles [3] that acquire the angular momentum of the absorbed light, for light guiding of light [4, 5, 6], as dark solitons in self defocusing media [5, 7, 8], and to increase the mode volume in a laser cavity [9, 10].

Vortex beams can be conveniently expressed as unique linear combinations of Laguerre-Gauss modes. These are cylindrically symmetric modes characterized by two integer indices, p and m, which are unaltered by propagation. A line integral of the phase gradient around the dark beam center is equal to  $(m2\pi)$ , where m is the vortex charge. This charge gives them an orbital angular momentum of  $m\hbar$  per photon along the propagation axis [11] in addition to the usual spin angular momentum associated with polarization. They have p + 1 radial nodes. Any vortex beam of charge m can be decomposed into a linear combination of Laguerre-Gauss modes, each of charge m but possibly having different p's. These constituent modes each propagate without changing character, so their dark center is preserved. Hence any vortex beam maintains its charge as it propagates, and will always have a null at the beam center, although its radial irradiance pattern will generally change due to propagation related phase shifts among the different p modes.

Vortex beams can be created from a lowest order Gaussian mode using holographic gratings [12, 13] or using a helicoidal phase mask [8]. They can also be created from higher order Hermite-Gaussian modes using a mode converter comprising spherical and cylindrical lenses [14, 15]. Alternatively, they can be directly generated using a laser resonator that contains a spiral phase plate [10] or one that induces image rotation [9].

#### 2. Vortex modes of the OPO

In this paper we describe generation of vortex beams using an optical parametric oscillator (OPO) based on an optical cavity that produces a 90° image rotation on each cavity pass. Our cavity is the nonplanar ring consisting of four plane mirrors arranged as diagrammed in Fig. 1. This RISTRA (rotated image singly-resonant twisted-rectangle) cavity is described in more detail in an earlier paper [16]. Briefly, a 15 ns, 532 nm pump pulse enters through mirror  $M_1$  and exits through mirror  $M_2$ . Its beam diameter

#2288 - \$15.00 US (C) 2003 OSA

is  $\geq 4 \text{ mm} (1/e^2)$  making diffraction insignificant, and it is large compared with the 700  $\mu$ m birefringent walkoff of the signal beam in the nonlinear crystal. Parametric gain is provided by a single 15 mm long KTP crystal cut at  $\theta = 58^{\circ}, \phi = 0$  to phase match the *e*-polarized 800 nm signal and the *o*-polarized 1588 nm idler to the *o*-polarized 532 nm pump. The cavity resonates the 800 nm signal wave but not the 1588 nm idler wave, with mirror  $M_2$  serving as the output coupler for the signal wave as well as an input coupler for the cw beam that injection seeds the OPO. Mirrors  $M_3$  and  $M_4$  are identical high reflectors. The plane containing  $L_4$  and  $L_1$  is at right angles to that containing  $L_1$  and  $L_2$  so an *e*-wave at the crystal is an *s*-wave for mirror  $M_1$  and a *p*-wave for mirror  $M_2$ . Similarly, an *s*-wave at mirror  $M_3$  becomes a *p*-wave at mirror  $M_4$ . For leg lengths  $L_1 = L_3$  and  $L_2 = L_4$  with  $L_1/L_2 = \sqrt{2}$ , this cavity rotates the image of a circulating beam by 90° on each cavity pass. With the half-wave plate adjusted to rotate the polarization by 90°, it is straightforward to show that the Jones polarization matrix for a round trip of the empty cavity, apart from an overall phase shift, is

$$M = \begin{pmatrix} -r_{s2}r_{p1}e^{i\phi_1} & 0\\ 0 & r_{s1}r_{p2}e^{i\phi_2} \end{pmatrix}$$
(1)

where  $r_{s1}$  is the reflection amplitude for an *s*-polarized wave at mirror  $M_1$ ,  $\phi_1$  is the phase shift of a *p*-wave relative to an *s*-wave at mirror  $M_1$ , and the basis states are the *e*- and *o*-polarized waves indicated in the figure. The eigen polarizations of the empty cavity at the location of the crystal are thus *e*- and *o*-waves, which are also the eigen polarizations of the nonlinear crystal. Hence the *e*-polarized signal wave can be resonated in the cavity without depolarization.

A 90° image rotating cavity has a unique optical axis even when it uses only flat mirrors [16]. We find that when the seed beam is aligned to this cavity axis and its frequency is scanned, the longitudinal mode spacing is c/L where L is the round-trip length of the cavity, or approximately 105 mm. When the seed light is tuned to be resonant with one of these cavity modes, the OPO oscillates on the chosen longitudinal mode with a transverse profile that is approximately the lowest order Gaussian. This is illustrated by the measured far-field signal fluence profile shown in Fig. 2.



Fig. 2. Far field signal fluence profile for on-axis seeding. The subscript  $\parallel$  denotes the direction parallel to birefringent walkoff in the KTP crystal, while  $\perp$  denotes the direction perpendicular to walkoff.

If the seed beam is offset laterally from the cavity axis, but aligned parallel to the

#2288 - \$15.00 US (C) 2003 OSA

axis, the circulating light will exactly overlap the injected beam after four trips around the cavity rather than after a single pass. The mode spacing is then c/4L, so there are three extra resonances between the original modes associated with perfect seed alignment. They correspond to single-pass phase shifts of  $\pi/2$ ,  $\pi$ , and  $3\pi/2$  relative to the original mode. After four passes they have total phase shifts of  $2\pi$ ,  $4\pi$ , and  $6\pi$ . To illustrate how tuning the seed light to a mode with  $2\pi$  phase shift can create a vortex beam, consider the first four-times-around mode on the blue side of the original mode, with the seed beam offset in the vertical, or 12 o'clock, direction. The top circle in Fig. 3 represents the input seed beam and the upward arrow represents its relative phase. After one trip around the cavity the beam is offset to the 3 o'clock position and has a phase of  $\pi/2$  relative to the seed. After the second, third, and fourth trips it is at 6 o'clock, 9 o'clock, and 12 o'clock with phases of  $\pi$ ,  $3\pi/2$ , and  $2\pi$ . Notice that the beams on opposite sides of the four-lobed pattern have opposite phases so the center of the resonated pattern is dark due to destructive interference. The resonated light resembles an optical vortex with a phase ramp and a dark center. If the seed beam is offset from the cavity axis by only a small fraction of its diameter, this pattern is close to a Laguerre-Gauss mode with mode index (0,1) or charge +1. If we tune the seed to the first red four-times-around mode rather than the first blue four-times-around mode. the phase ramp is reversed so the mode index and charge change sign. If we tilt the seed beam slightly so its phase matches the local tilt of the Laguerre-Gauss mode the coupling of the seed to the cavity mode is somewhat improved. Abramochkin et al. [9] reported similar observations for an Ar<sup>+</sup> laser with a Dove prism image rotator in a stable cavity configuration. In order for our OPO to produce a vortex pulse, the gain



Fig. 3. Formation of a vortex beam from an off-axis seed beam when the cavity is tuned to a four-times-around longitudinal mode. The circles represent the seed beam after 0, 1, 2, and 3 passes around the cavity. The arrows represent the relative phases in each portion of the beam.

of the seeded vortex mode must be large enough to turn on before the lowest order mode at the once-around resonance frequency which normally has the highest gain. We find that seeding with a 1 mW cw beam offset from the cavity axis by a fraction of its diameter reliably causes the vortex mode to oscillate, exhausting the pump beam and preventing the appearance of the lowest order mode. Fig. 4 shows the far-field fluence profile for such operation.

To demonstrate the existence of a phase ramp, or vortex charge when the OPO

#2288 - \$15.00 US (C) 2003 OSA



Fig. 4. Far field signal fluence profile for off-axis seeding with the cavity tuned to a four-times-around resonance.

is tuned to the first red four-times-around mode, we use a filtered Mach-Zehnder interferometer to interfere a spherical wavefront with the OPO beam. As Fig. 5 clearly demonstrates, the phase is a spiral of  $2\pi$  around the dark center. The direction of the spiral reverses when the OPO is tuned to the first blue four-times-around mode.



Fig. 5. Interference pattern of OPO beam and spherical wave showing spiral phase with charge 1.

It is interesting to compare the image-rotating cavity with a similar cavity without image rotation. For example, this could be a four-mirror ring-cavity of otherwise similar dimensions with all the mirrors in a single plane. Such an OPO could generate vortex beams if it were injection seeded with a strong vortex beam. However, the vortex modes of opposite charge are frequency-degenerate with one another and with the filled beam of charge zero. Image rotation lifts this degeneracy, making it possible to select the vortex mode by selecting the oscillation frequency to match one of the vortex modes, either by injection seeding or by using an intracavity frequency selective element such

#2288 - \$15.00 US (C) 2003 OSA

as a narrow gain spectrum or an intracavity etalon.

Radially or azimuthally polarized beams can expressed as the coherent summation of vortex modes with left and right circular polarization and charges m = +1 and m = -1. We have demonstrated that our RISTRA cavity supports the generation of such modes when the waveplate is removed and an isotropic gain medium is used instead of the birefringent [17] crystal.

## 3. Conclusions

We have demonstrated that using a cavity with  $90^{\circ}$  image rotation on each pass breaks the frequency degeneracy of vortex modes of different charge. With appropriate seeding this allows us to reliably and efficiently generate high quality vortex beams.

## Acknowledgments

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.