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High-Power, CW, Airy Beam Optical Parametric Oscillator

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Abstract: We demonstrate a new class of optical parametric oscillators producing high-power, output beam in 2-D Airy intensity profile. The Airy beam has output power >8 W, longest ever acceleration length (>2 m), and wavelength tunability across 1.51-1.971 μm.

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Airy beam, a non-diffraction waveform, has peculiar properties of self-healing and self-acceleration [1]. Due to such unique properties, the Airy beam finds many applications including curved plasma wave-guiding [2], micro-particle manipulation [3], long distance communication, nonlinear frequency conversion, and many more. However, some of the applications demand Airy beam with higher power, wavelength tunability, and long acceleration length. While ideal Airy beam possess infinite energy, experimentally one can generate only finite energy (truncated) Airy beam. Typically, such Airy beam is generated through the Fourier transform of a cubic phase modulated Gaussian beam [1]. However, not a single Airy beam reported so far has high power, wavelength tunability, and long acceleration length. Attempts have been made to generate Airy beam through intra-cavity cubic phase modulation of laser [4] with low output power and no wavelength tunability. Therefore, it is still an open challenge to demonstrate Airy beam with all above said features from a single device.

On the other hand, optical parametric oscillators (OPOs) especially in singly-resonant (SROs) configuration offers the most viable solution for high-power radiation over extended spectral regions inaccessible to lasers. Therefore, direct generation of Airy beam from the SROs can be an interesting proposition to address the challenge. However, unlike lasers, SROs are substantially low gain systems. As a result, success of Airy beam OPOs require careful management of the system losses. Here, we report, for the first time to the best of our knowledge, a compact source of high-power, continuous-wave (cw), tunable radiation in 2-D Airy intensity profile based on cubic phase modulation of a continuous-wave (cw), SRO. The source provides Airy beam with power as high as 8 W, acceleration length >2 m across 1.51-1.97 μm. This is a generic approach, which in principle can be extended to any desired wavelength across the electromagnetic spectrum in all time scales (continuous-wave and pulsed).

The schematic of the experimental setup of Airy beam SRO is shown in Fig. 1. A cw fiber laser (IPG-1064) of 50 W output power at 1.064 μm is used to pump the SRO. The SRO is designed in a compact four mirror ring cavity [5] consisting of two curved mirrors, M_1 and M_2 with radius of curvature, *r*=100 mm, and two plane mirrors M_3 and M_4. All the OPO mirrors are having high reflectance (R>99%) for signal across 1.45-2 μm and high transmittance (T>80%) for pump and idler over 2.1-5 μm. A 50-mm long multi-grating MgO:PPLN crystal, with grating periods varying from Λ= 28.5-31.5 μm in 0.5 μm steps, housed in an oven is used for SRO. The oven temperature can be varied from 30-200 °C with temperature stability of ±0.1 °C. A lens (L_1) of *f*=100mm is used to focus the pump beam to the nonlinear crystal. A transmission based diffraction cubic phase mask (CPM) of 2 x 2 mm^2 aperture and a carrier period Λ=5μm is placed in between plane mirrors, M_3 and M_4 for phase modulation of the resonant signal beam. The phase mask has 0th order diffraction efficiency of ~98 % at 1.6 μm resulting ~2% coupling of the intra-cavity signal into Airy beam. The estimated beam size at the phase mask is ~700 μm. For Fourier transformation the lens (L_2), *f*=300 mm, is used.

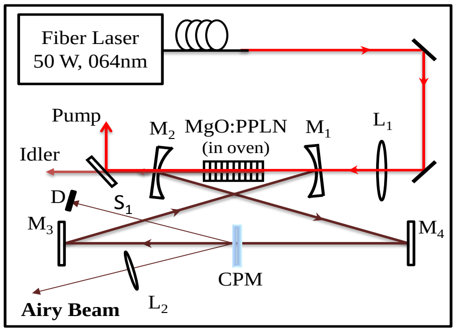

Fig. 1. Schematic diagram of the experimental setup for the Airy beam OPO. $M_{1\text{-}4}$, mirrors; L_1,L_2 lenses; S1, wavelength separators; MgO:PPLN, nonlinear crystals for SRO, CPM, cubic phase mask.

To verify the generation of Airy beam, we measured the self-acceleration, non-diffraction and self-healing properties of the beam with the results shown in Fig. 2. Adjusting the grating period and temperature of the MgO:PPLN crystal we operated the SRO at signal wavelength of 1.647 μm. For self-acceleration study, we have recorded 2-D intensity distribution of the Airy beam together with a reference Gaussian beam along the propagation direction with z=0cm as Fourier plane of the lens, L_2 and calculated the departure of the Airy beam away from the Gaussian beam with results shown in Fig. 2(a). As evident from Fig. 2(a), the Airy beam have curved away from the straight line path (Gaussian beam) with a transverse shift >2.2 mm over a propagation distance of 2 m. Bending of the Airy beam along propagation distance is also evident from the beam snaps (inset Fig. 2(a)) recoded at three different positions, z=0 cm, 120 cm and 200 cm. Using theoretical fit to our experimental results we have calculated the characteristic parameter (x_o) and the truncated parameter (a) [1] of the generated Airy beam to be 0.42 mm and 0.04 respectively. Similarly, we measured the line profile of the generated Airy beam of wavelength 1.947 μm at different propagation distances z=0 cm, 120 cm and 200 cm with the results shown in Fig. 2(b). The full width at half maxima (FWHM) of the central lobs at all the distance is 0.65 ± 0.085 mm confirming non-diffraction (no change in beam size with propagation) behavior of the Airy beam. To verify the self-healing behavior, we blocked the central lob of the Airy beam using a knife edge right before the Fourier plane of lens L_2 and recorded the beam intensity distribution at different distances, z=0 cm, 60 cm, 120 cm and 200 cm. As evident from Fig. 2(c), the Airy beam has no central lobe at z=0 cm, however, during propagation the beam shows sign of healing at a distance ~60 cm with almost complete regeneration at a distance of ~120 cm. The beam maintains same intensity distribution in the course of further propagation. Although the Airy beam shows self-healing property at other wavelengths, however, the self-acceleration distance of the Airy beam decreases with decreasing signal wavelength. Such observation may be attributed to the reduction of x_o-value with decrease in wavelength [1].

Pumping with a constant power (30 W), we measured the output power of the Airy beam while tuning its wavelength across 1.51-1.971 μm through the variation of crystal temperature and grating period over 35^oC-200^oC and 30.0-31.5 μm respectively, with the results shown in Fig. 2(d). As evident from Fig. 2(d), the output power of the Airy beam varies from 2.3 W at 1.51 μm to 2.9 W at 1.971 μm with a maximum of 5.18W at 1.615μm with extraction efficiency of 17.2%. Additionally, the source provides Gaussian beam output in the idler wavelength range across 2.31-3.6 μm with maximum idler power of 8 W at 2.312 μm. We also measured the power scalability of the source while measuring the variation of Airy beam power at wavelength 1.571 μm with pump power. The results are shown in Fig. 2(e). The output power of the Airy beam increases almost linearly with pump from an operation threshold of 17.5 W resulting a maximum of 8.1 W Airy beam power for 42 W of pump power (extraction efficiency ~19%). No sign of saturation indicates the possibility of further enhancement in Airy beam power with increase of pump power.

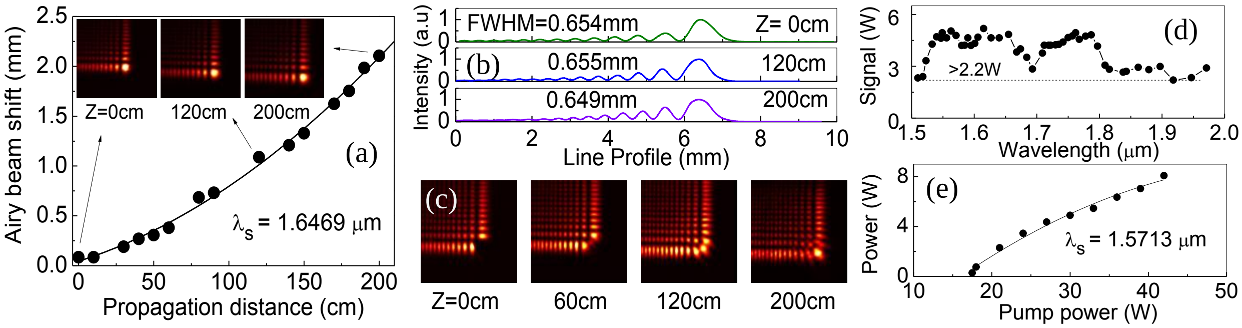

Fig. 2. (a) Shift in the central lob position of the Airy beam along propagation direction, (Inset) Experimental images at different propagation distances, (b) Line profile of the Airy beam at different propagation distances, (c) Experimental images showing the self-healing of the Airy beam, (d) Output power of the Airy beam across tuning range, (e) Power scaling of the Airy beam source. Lines are guide to eyes.

In conclusion, we have demonstrated a high-power, continuous-wave source of widely wavelength tunable coherent radiation in 2-D Airy intensity profile. Detailed experimental results on the output power characteristics and dynamics of the generated Airy beam and the theoretical simulations will be presented.

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