Airy beam laser

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A method to design lasers that emit an arbitrary beam profile is studied. In these lasers, output-coupling is performed by a diffraction grating that imposes a phase and amplitude distribution onto the diffracted light. A solid-state laser emitting beams with a two-dimensional Airy intensity profile is demonstrated both theoretically and experimentally. In this case, the diffraction grating adds a transverse cubic phase to the diffracted light. An Airy beam is obtained by performing optical Fourier transform of the out-coupled light. The laser beam profile and power characteristics are shown to agree with theory. © 2011 Optical Society of America

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Airy beams are optical beams whose profile is described by the Airy function [1,2]. These beams possess several unique features, such as propagation along a curved trajectory, very low diffraction [1,2], and self-healing, i.e., they restore their canonical form after passing small obstacles [3]. Applications of Airy beams include plasma waveguiding [4], microparticle manipulation [5], generation of light bullets [6], and nonlinear frequency conversion [7,8].

Whereas the ideal Airy beam carries infinite energy, the unique properties (acceleration, self-healing, and slow diffraction) are still observed with finite energy Airy beams, in which the Airy function is multiplied by a Gaussian window. Finite energy Airy beams are experimentally obtained by passing a Gaussian beam through a phase mask that adds a cubic phase modulation in the transverse direction [2], followed by an optical Fourier transform. In search for a more compact source of Airy beams, Longhi theoretically demonstrated that Airy beams could be generated directly from a microchip laser having slightly tilted facets and with appropriate pumping conditions [9].

In this Letter, a method to realize lasers emitting arbitrary beam profiles is discussed. The Airy beam laser, demonstrated experimentally here, is a proof of principle of the general method. The basic idea is the use of a reflection diffraction grating as the laser output mirror. The grating reflects most of the light back into the cavity, as an ordinary mirror, while the remainder is reflected out of the cavity via the various diffraction orders. Furthermore, this grating is modulated to impose a phase and amplitude onto the diffracted light, thus providing it with the same functionality as a phase and amplitude mask, only here the modulating element is the output coupling mirror of the laser. In the case of the Airy beam laser, the phase modulation is cubic. Thus an Airy beam is obtained by performing optical Fourier transform of the out-coupled light. This scheme is more compact than the conventional method, which requires a phase modulating element outside the laser cavity in addition to a laser.

As mentioned above, the key component of the system presented here is an aperiodic binary diffraction grating, which enables it to modulate both the phase and amplitude of the diffracted beam [10]. For the Airy beam, we require only phase modulation, and in this case the grating's profile is described by the function

$$h(x,y) = \frac{1}{2}h_0[\mathrm{sign}\{\cos[2\pi x/\Lambda + \phi(x,y)]\} + 1], \quad (1)$$

where h_0 is the ridge height, Λ is the fast-modulation carrier period, and $\phi(x,y)$ describes the phase modulation in the x and y axes, respectively. Assuming a TEM_{00} Gaussian beam incident on the grating and using the scalar approximation, the complex amplitude of the mth order diffracted beam is [11]

$$\tilde{A}_{m\neq 0}(x,y) = A_0 \frac{2}{m\pi}\sin\left(\frac{m\pi}{2}\right)\sin\left(\frac{2\pi}{\lambda}h_0\right) \cdot \exp\left(-\frac{x^2+y^2}{r_g^2}\right)\exp[im\phi(x,y)], \quad (2)$$

where A_0, λ, and r_g are the amplitude, wavelength, and radius of the incident beam, respectively. Thus, if $\phi(x,y)$ is chosen such that it imposes a cubic phase onto the Gaussian beam, an Airy beam could be obtained via optical Fourier transform of the diffracted light. Moreover, diffraction efficiency can be controlled by the ridge height h_0. When using the grating as a laser output mirror, this amounts to controlling the degree of output coupling.

In the experiment detailed below, the carrier period was $\Lambda = 5\,\mu\mathrm{m}$, the phase modulation term was

$$\phi(x,y) = (x/150\,\mu\mathrm{m})^3 + (y/150\,\mu\mathrm{m})^3, \quad (3)$$

and the ridge height $h_0 = 61\,\mathrm{nm}$, corresponding to a zero-order reflectivity of $\eta_0 = 87.6\%$ and diffraction efficiency of $\eta_1 = 5\%$ for each of the two first-order diffraction beams, at the laser wavelength $\lambda = 1064\,\mathrm{nm}$.

The diffraction grating was fabricated in a standard e-beam writing technique: a 70 nm thick layer of silver, which is ~6 times the penetration depth at the wavelength of 1064 nm, was evaporated onto a 15×15 mm silicon substrate. Subsequently, the silver layer was covered with polymethyl methacrylate (PMMA), which was subjected to e-beam writing (using Raith 150 E-beam lithography system) of the desired modulation pattern over an area of 1×1 mm. An additional layer of silver 61 nm thick was then evaporated on top of the patterned PMMA. Finally, the sample was immersed in acetone, which resulted in liftoff of the PMMA and any silver that was on top of it, leaving only the desired silver diffraction grating pattern resting on the original 70 nm thick silver layer.

The experimental system used for the proof-of-principle demonstration of the solid-state Airy beam laser is schematically illustrated in Fig. 1. A $\lambda_p = 808$ nm laser diode was used to pump a 1% neodymium-doped yttrium aluminum garnet (Nd:YAG) rod (∅3 mm × 8 mm), through a facet coated for high transmittance at 808 nm and high reflection at 1064 nm. The opposing rod facet was coated for high transmittance at 1064 nm. The only additional element in the cavity was the diffraction grating, placed such that the overall cavity length was 76 mm. Folding mirrors (not shown) were used to direct one of the first-order diffraction beams into a lens with focal length $f_1 = 100$ mm, placed such that it performs optical Fourier transform of the beam at the plane of the diffraction grating. This lens was followed by a 4f system, with focal lengths $f_2 = 150$ mm and $f_3 = 50$ mm, which imaged the Fourier transformed beam with a magnification of 1/3. This was done in order to make the beam fit into the aperture of a CCD camera (Spiricon SP503U) that was placed at the output of the 4f system.

Figure 2(a) depicts the intensity profile of the beam as recorded by the CCD camera at the imaged Fourier plane, showing a characteristic two-dimensional (2D) Airy beam profile. Figure 2(b) shows the corresponding theoretical profile, with good correspondence to the experimental observation. In order to demonstrate that the observed beam is indeed an Airy beam, a self-healing experiment has been conducted. A knife was placed in the Fourier plane such that it blocks the main lobe, and the beam profile was recorded in various distances from the imaged Fourier plane. The results of this experiment are displayed in Figs. 2(b)–2(d), and their theoretical counterparts in Figs. 2(f)–2(h). Both in the experiment and in the simulation, the beam recovers its original profile to a large degree.

The Airy beam laser power was characterized experimentally. Figure 3 shows the experimentally measured output power versus diode laser pump power. The lasing threshold pump power was 1.4 W and the slope efficiency 13.5%, corresponding to a maximum output power of 67.5 mW at a pump power of 1.94 W. Notably, a similar amount of power is also emitted through the −1 diffraction order; hence if we define slope efficiency to include both first diffraction order beams power, the slope efficiency would be 27% and the maximum power 135 mW.

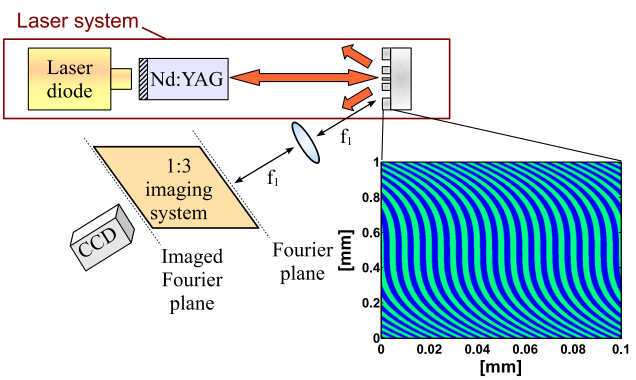

Fig. 1. (Color online) Experimental system. The bottom-right view shows part of the modulation pattern of the diffraction grating.

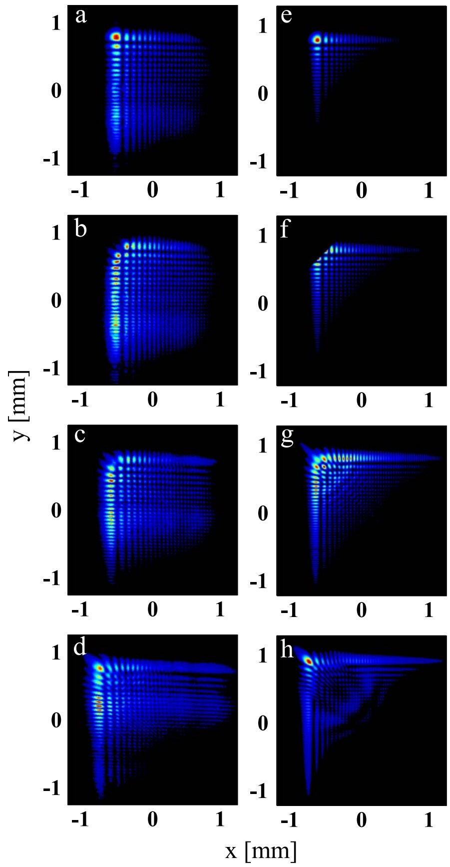

Fig. 2. (Color online) Beam intensity profile. Each image on the right hand panels (e)–(h) is the theoretical calculation corresponding to the experimentally recorded image to its left (a)–(d). (a) and (e) show the unperturbed beam at the imaged Fourier plane. In (b)–(d) and (f)–(h) the main lobe is blocked in the Fourier plane. The beam is shown at the imaged Fourier plane [(b) and (f)], and after propagating distances of 25 mm [(c) and (g)] or 55 mm [(d)and (h)].

A simple laser model [12] was used to theoretically analyze the laser. In this model, the output power is

$$P_{\text{out}} = \frac{1}{2}\hbar\pi\omega r_g^2 \eta_1 \cdot \left\{ \frac{[1-\exp(-\alpha_p l)]}{\hbar\omega_p \pi r_{\text{rod}}^2 \left[\delta_p + \ln\left(\frac{1}{1-\eta_0}\right)\right]} P_{\text{pump}} - \frac{1}{2\sigma\tau} \right\}, \quad (4)$$

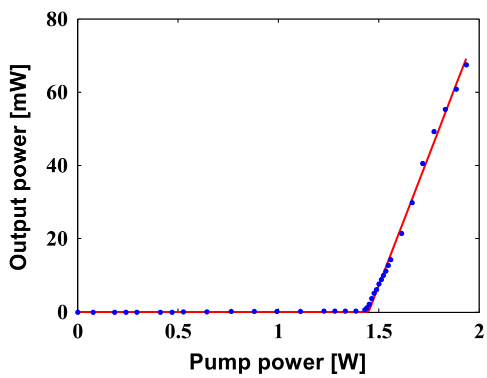

Fig. 3. (Color online) Airy beam laser output power versus diode laser pump power. The blue dots are experimental results and the red curve is a theoretical fit.

where $\omega = 2\pi c/\lambda$ and $\omega_p = 2\pi c/\lambda_p$ are the laser and pump angular frequencies, respectively, r_{rod} and r_g are the beam radii in the laser rod and on the diffraction grating, respectively, $\alpha_p = 8\,\text{cm}^{-1}$ is the pump absorption coefficient in Nd:YAG, $l = 8\,\text{mm}$ is the Nd:YAG rod length, δ_p is the logarithmic round-trip losses excluding output coupling, P_{pump} is the laser diode pump power, $\sigma = 28 \times 10^{-20}\,\text{cm}^2$ is the emission cross-section, and $\tau = 230\,\mu\text{sec}$ is the fluorescence lifetime. Three parameters were fitted based on the experimental results: the beam radii in the laser rod $r_{\text{rod}} = 328\,\mu\text{m}$ and on the grating $r_g = 425\,\mu\text{m}$, and the logarithmic round-trip loss $\delta_p = 0.092$. The two fitted beam radii are reasonable considering the cavity length, thermal lensing, and the fact that the pump beam is focused to a roughly $200 \times 200\,\mu\text{m}$ square in the Nd:YAG rod, and exhibits high diffraction. The fitted value of δ_p corresponds to a linear round-trip loss of $1 - \exp(-\delta_p) = 8.8\%$. Using an overlap integral [12] between the beam at the pumped facet of the rod and the beam that propagates back to it from the diffraction grating, the diffraction loss was calculated to be 5.1%. The remaining 3.7% loss is related to scattering and absorption in the silver grating. The fitted power is also displayed in Fig. 3, showing excellent correspondence to the experimental results.

The theoretical model suggests that the most significant factor limiting the laser's performance is overlap between the pump and the oscillating power. This can be improved by using a shorter cavity length, introducing an intracavity lens, or using a different cavity design. Such schemes can also help reduce diffraction losses. Further improvement can be obtained by improving the grating's surface quality to reduce scattering, or using a different material with higher reflectivity at 1064 nm, e.g., gold. Another option would be to use a blazed grating that has low diffraction efficiency for $m \neq 0, 1$ [13].

In conclusion, a solid-state laser emitting an Airy beam was demonstrated both theoretically and experimentally. The laser's beam was shown to have a 2D Airy intensity profile and undergo self-healing. The laser was also characterized in terms of power and was fitted to a theoretical model with good correspondence. Furthermore, the same technique can be used to directly generate holograms or other beam profiles, e.g., higher Hermite-Gaussian modes, vortex beams [14], Bessel beams [15], etc. As a further improvement, the diffraction grating can be replaced by a spatial light modulator, resulting in a laser with a dynamically controllable beam profile. Moreover, since the oscillating transverse mode is different from the emitted mode, this scheme could be used to operate lasers with multiple oscillating modes, thus exploiting a larger volume of the laser gain medium, while emitting a TEM_{00} Gaussian beam [16]. Finally, we would like to note that the same method can be used to construct optical parametric oscillators with arbitrary beam profiles.

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