Generation and nonlinear self-trapping of optical propelling beams

Peng Zhang,[1] Simon Huang,[1] Yi Hu,[1,2] Daniel Hernandez,[1] and Zhigang Chen[1,2,*]

[1]*Department of Physics and Astronomy, San Francisco State University, San Francisco, California 94132, USA*

[2]*The Key Laboratory of Weak-Light Nonlinear Photonics, Ministry of Education and TEDA Applied Physics School, Nankai University, Tianjin 300457, China*

**Corresponding author: zhigang@sfsu.edu*

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We generate optical beams with rotating intensity blades by employing the moiré technique. We show that the number of the blades and the speed and direction of rotation can be controlled at ease with a spatial light modulator, while no mechanical movement or phase-sensitive interference is involved. By applying a noninstantaneous self-focusing nonlinearity, we demonstrate both theoretically and experimentally self-trapping of such optical propelling beams.

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Optical beams with rotating intensity distribution have attracted much attention owing to both fundamental interest and technological applications [1–10]. Apart from the fascinating features of rotating beams in wave theory [1–4], it has been demonstrated that rotating beams can be used in a variety of studies, such as stirring Bose–Einstein condensates [5], rotating optical tweezers [6,7], improving imaging resolutions [8,9], and creating complex optofluidity [10]. In the nonlinear regime, the possibility of self-trapping of rotating beams into rotating solitons has been investigated [11–16]. It has also been shown that a rotating Bessel lattice can set solitons into circular motion [17]. Thus far, various techniques have been proposed to generate rotating beams, including the use of revolving mirrors [11], rotating apertures [10], optical interference of Laguerre–Gaussian modes or Bessel beams [4,6], and computer-generated holograms [18] or binary-phase diffractive elements [19]. In this Letter, we propose and demonstrate an approach to generate rotating intensity blades (we shall call them "optical propellers") by employing moiré techniques. We show that, by overlapping a moving straight-line grating with a stationary vortex-type grating, optical propellers with different numbers of blades can be generated and their rotation speed and direction can be controlled with ease. Self-trapping of such rotating beams is also realized in a slow-response nonlinear medium. These optical propellers may find applications in optical trapping and manipulation of microparticles and biological samples.

To create rotating beams with the moiré technique, let us overlap a simple straight-line grating (by interfering two plane waves) and a fork-bearing grating (by interfering a plane wave and a vortex beam), as shown numerically in Fig. 1(a). When both gratings are stationary, the resultant moiré fringes are also stationary, and they have different numbers of intensity blades as determined by the topological charges m of the vortices for creating the fork gratings [20,21]. By moving the straight grating along the grating-vector direction relative to the fork grating, the moiré patterns start to rotate clockwise or counterclockwise, depending on the moving direction and/or the sign of the topological charges. With appropriate spatial filtering, the rotating moiré patterns can be successfully retrieved, as depicted in Figs. 1(b)–1(d), where a broad Gaussian beam centered at the vortex singularity displaces the moiré patterns after passing through the overlapped gratings. From Figs. 1(b) and 1(c), it can be seen that, although the moving direction of the straight grating is the same, the output patterns rotate along opposite directions due to opposite signs of the vortex charges. Likewise, for the same sign of the vortex charges, the rotating direction is reversed when the moving direction of the grating is reversed, as depicted in Figs. 1(b) and 1(d). We should also

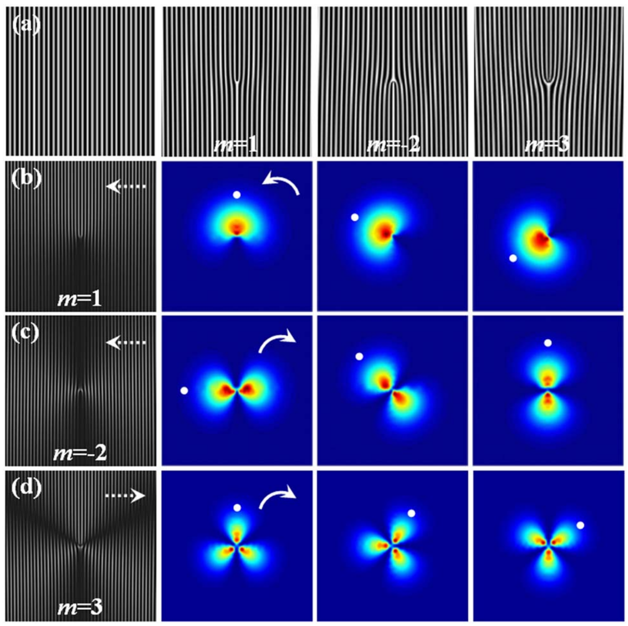

Fig. 1. (Color online) (a) Gratings employed for generation of optical propellers with the moiré technique. Shown from left to right are a simple straight-line grating and vortex fork-type gratings with topological charges $m = 1, -2$, and 3. (b)–(d) Rotating moiré patterns created by overlapping a moving straight grating with stationary fork gratings for $m = 1, -2$, and 3, respectively. The left panels show a snapshot of overlapped gratings, and the right three panels show corresponding first-order diffraction of an otherwise uniform Gaussian beam from the gratings. Dashed and solid arrows indicate moving and rotating directions of the grating and moiré patterns, and white dots mark one of the blades of the optical propellers (Media 1, 810 KB).

mention that the rotation speed of the optical propellers is proportional to the moving speed of the grating.

Let us now look at the possibility of nonlinear self-trapping of the above optical propellers in a slow-response medium. If the rotation of the moiré patterns is fast enough, the nonlinear material can respond only to the time-averaged intensity of the optical field, as in the case of incoherent solitons [22]. Therefore, although each instantaneous intensity pattern is not symmetric, a circularly symmetric waveguide can be induced by the time-averaged intensity pattern of the rotating beam in a noninstantaneous nonlinear medium. To describe the propagation of an optical propelling beam under noninstantaneous photorefractive nonlinearity, we use the following dimensionless theoretical model, akin to the so-called coherent density approach developed earlier [23]:

$$\left(\frac{\partial}{\partial z} - \frac{i}{2}\nabla^2\right) f(x,y,z,\theta) = iE_0 \frac{I}{1+I} f(x,y,z,\theta), \qquad \text{(1a)}$$

$$I(x,y,z) = \frac{1}{2\pi}\int_0^{2\pi} |f(x,y,z,\theta)|^2 \mathrm{d}\theta, \qquad \text{(1b)}$$

where $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$, E_0 is the applied electrical field, and $f(x,y,z,\theta)$ and I are the amplitude of the transient light field and the time-averaged intensity of the rotating beam, respectively. Note that the total intensity of the optical beam is the integral of the light field at different orientations, as denoted by the rotating angle θ. Figure 2 shows an example of our numerical results for nonlinear self-trapping of a single-blade rotating pattern created with a singly charged vortex ($m = 1$).

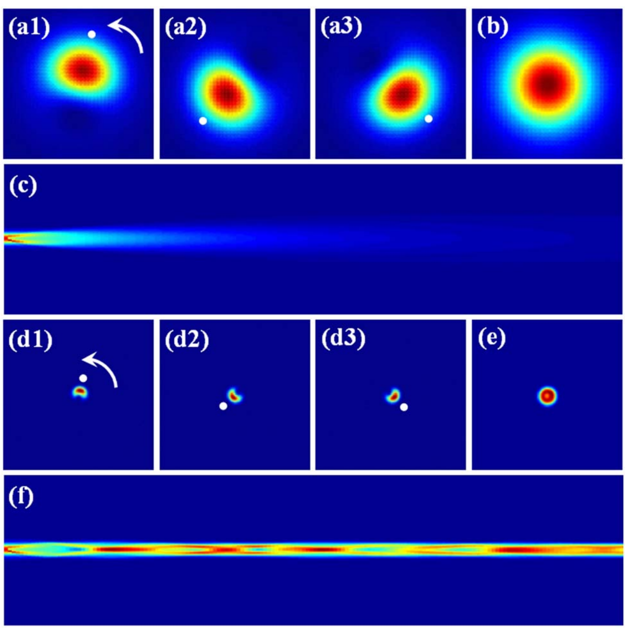

Fig. 2. (Color online) Numerical results of self-trapping of a single-blade optical propeller generated in Fig. 1(b). (a)–(c) show three snapshots of output transverse patterns, the corresponding time-averaged intensity pattern, and a side-view of the beam at linear propagation; (d)–(f) same as in (a)–(c), except that the beam is at nonlinear propagation (Media 2, 624 KB).

Without the nonlinearity, the single-blade beam undergoes linear diffraction while rotating counterclockwise [Figs. 2(a)–2(c)], but the time-averaged pattern is circularly symmetric as shown in Fig. 2(b). With the self-focusing nonlinearity, however, the rotating beam is self-trapped, as demonstrated in Figs. 2(d)–2(f). Again, the time-averaged intensity displays a circularly symmetric pattern [Fig. 2(e)]. From our numerical simulation, we find that self-trapping of multiblade rotating beams [Figs. 1(c) and 1(d)] is also possible with the noninstantaneous nonlinearity. This suggests that soliton solutions for these propelling beams might be available based on the theoretical model of Eqs. (1), which certainly merits further investigation.

Our experimental setup for generation and self-trapping of the aforementioned optical propelling beams is shown in Fig. 3(a). The overlapping gratings, as described in Figs. 1(b)–1(d), are created with a reflection-type spatial light modulator (SLM), and then a broad Gaussian beam (at 532 nm) reflected from the gratings is sent through a Fourier filtering system to retrieve the moiré patterns. To make the intensity blades rotate, the simple grating is set into linear motion, again controlled by the SLM. To demonstrate nonlinear self-trapping of the rotating beams, a biased 1-cm-long photorefractive strontium barium niobate (SBN:60) crystal is employed as a noninstantaneous nonlinear medium. (The typical response time of the crystal is about a few minutes at the intensity level we used, while the moiré pattern is rotating at a frequency of about 4 Hz.) The input and output intensity patterns are monitored with

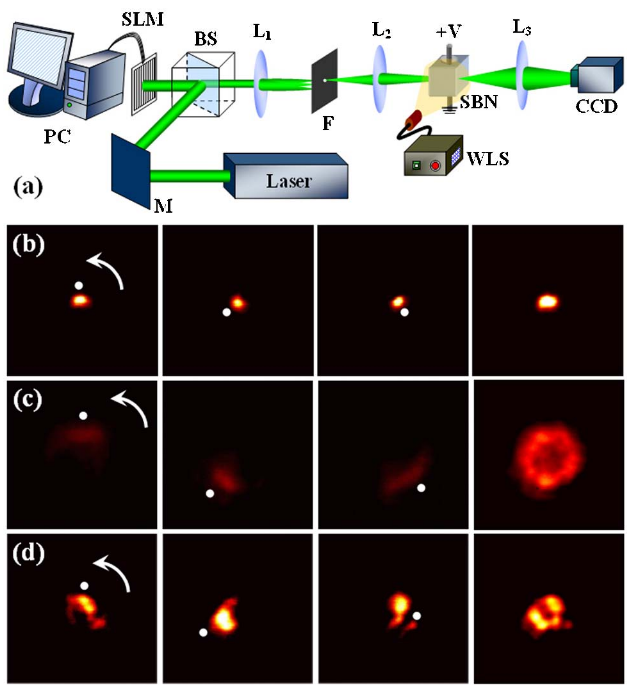

Fig. 3. (Color online) (a) Experimental setup. SLM, spatial light modulator; BS, beam splitter; F, spatial filter; WLS, white-light source. (b) Single-blade propeller generated in experiment corresponding to Fig. 1(b). Four panels are snapshots of three instantaneous patterns plus the time-averaged intensity pattern at input; (c) and (d) depict output patterns after (c) linear diffraction and (d) nonlinear self-trapping through the crystal, corresponding to Fig. 2 (Media 3, 48.1 KB).

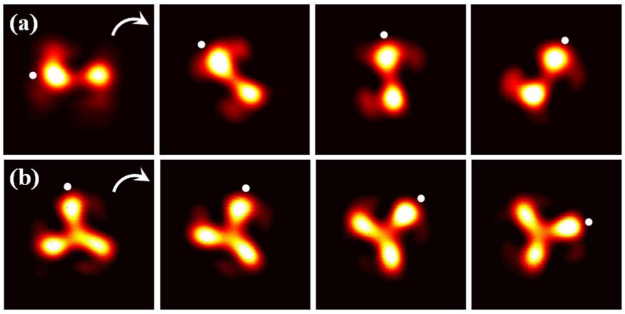

Fig. 4. (Color online) Experimental generation of optical propellers with (a) two and (b) three blades corresponding to the numerical results shown in Figs. 1(c) and 1(d). Four snapshots are taken from a movie shown online (Media 4, 212 KB).

a CCD camera. Typical experimental results corresponding to Figs. 1(b) and 2 for generation and self-trapping of a single-blade propeller are displayed in Figs. 3(b)–3(d). As expected, the rotating beam gets dimmer and broader after linear propagation thanks to diffraction, while maintaining its rotating features [Figs. 3(b) and 3(c)]. When a positive voltage (about 2 kV/cm) is applied, the output beam is self-trapped [Fig. 3(d)] owing to self-focusing nonlinearity. For both the linear and the nonlinear cases, the instantaneous snapshots taken at different time delays show clearly the rotating blade of the beam, while the time-averaged intensity exhibits a doughnutlike pattern. Experimentally, we also generated optical propellers with two and three blades corresponding to Figs. 1(c) and 1(d), which are shown in Figs. 4(a) and 4(b), respectively. Clearly, our experimental results agree well with those from our numerical simulations. Note that, in our experiment, the "beam interference" and "grating motion" are all done by the computer-controlled SLM, therefore, no phase-sensitive interference or mechanical movement is required. Because no coherent interference is involved in the process, we expect that these optical propellers could also be created with partially incoherent or while-light beams. We point out that our generation of these propelling beams represents a transition from linear translation to rotation and from vortex phase singularity to azimuthal intensity variation without any mechanic rotating device.

In summary, we have demonstrated the generation and self-trapping of optical propelling beams by employing the moiré technique. Research into finding exact soliton solutions for the optical propellers, as well as manipulating microparticles with these optical propellers, is currently under way. Our results bring about a novel approach for the creation of controllable rotating beams, which may find applications in optical and biological micromachines.

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