Direct generation of optical bottle beams from a tightly focused end-pumped solid-state laser

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Abstract: We demonstrate that various optical bottle beams can be directly generated from a tightly focused end-pumped Nd:YVO4 laser. By controlling the size of pump beam and intracavity aperture in a planoconcave cavity, we obtain well contrasting optical bottles with semiconfocal, 1/3-, and 1/5-degenerate cavity configurations. These beams result, respectively, from the superposition of the fundamental mode and the corresponding lowest degenerate transverse eigenmode, which is in-phase at their beam waists. Unlike that of our previous simulation model, this new observation is universal; it is suitable for any kind of gain media in tightly end-pumped lasers.

OCIS codes: (140.3300) Laser beam shaping; (140.3410) Laser resonators; (140.7010) Trapping; (140.3580) Lasers, solid-state.

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1. Introduction

Optical tweezers [1] is a useful technique for manipulating microparticles and biological samples such as DNA. With a similar technique, atoms can also be trapped by use of dipole force [2]. If the trapping beam is blue-detuned from the resonant transition of the atoms, the atoms will seek the dark or the low-field region so that the field distribution will not substantially be disturbed by the presence of atoms. Thus the storage time can approach the order of 1 s [3]. The same characteristic of seeking the darkness can also be applied to the microparticles that have a lower refractive index than the surrounding medium [4].

An optical bottle beam has a low-intensity zone surrounded by a high-intensity shell [5-8]. Previously, it has been generated by use of a hologram constructed with Laguerre-Gaussian LG00 and LG20 modes that destructively poses interference at their beam waists. Here the first subscript index of LG modes is the radial mode index and the second one is the angular mode index. Recently, we have shown that a bottle beam can be generated from a simple laser near the 1/3 transverse degeneracy, but the laser beam consists of many degenerate LG modes that are in-phase at the beam waist [9]. In this paper we experimentally demonstrate that various optical bottle beams can be generated from a simple laser when it is operated with the degenerate cavities. Moreover, optical bottles with good contrast can be achieved by controlling the size of the pump laser and intracavity aperture.

2. Motivation

We first show in Figs. 1(a) and 1(b) the differences of the bottle beams with destructive and constructive interference of LG00 and LG20 modes at the beam waist with a width W0. We see that there are two optical bottles ahead and behind the waist in Fig. 1(b) owing to Gouy phase shift, while only one bottle of destructive interference is located at the waist in Fig. 1(a). The beam with two bottles in Fig. 1(b) forms a double-well potential for blue-detuned cold atoms, and so it may be useful for investigating the interaction between two groups of cold or even Bose-Einstein condensate atoms [10]. We show the three-dimensional potential wells in the right-hand column of Fig. 1. Note that the potential wells are plotted only from 0 to 3Wo in the radial direction and the fundamental beam waists are assumed to be the same in Figs. 1(a)-1(d). The depth of the potential well that is proportional to the beam intensity is shallower in Fig. 1(b) than it is in Fig. 1(a), but the deeper and narrower potential wells can be constructed by use of LG00 and LG30 modes as well as LG00 and LG50 modes, as shown in Figs. 1(c) and 1(d), respectively. We show in the following that the bottle beams of Figs. 1(b)-1(d) can be directly generated from a simple laser near the transverse degeneracies of 1/4, 1/3, and 1/5, respectively.

Considering the simplest two-mirror cavity with the specified mirror curvatures *R1*, R2 and the effective cavity length L, the resonance frequencies of the longitudinal-plus-transverse modes can be given by $\nu m,n,q = q\ \nu l + (m + n + 1)\nu t$, where $\nu l = c/2L$ is the longitudinal mode spacing, $\nu t = (\nu l / \pi)\ \arccos[(g1g2)1/2]$ is the transverse mode spacing, q is the longitudinal mode number, m and n are the transverse mode numbers, and $g1,2 = 1\text{-}L/R1,2$ being the cavity parameters, respectively [11]. The configurations $g1g2 = 1/4$, 1/2, and $(1+\sqrt{5})2/16$ corresponding to $\nu t/\nu l = 1/3$, 1/4, and 1/5 are denoted as 1/3-, 1/4-, and 1/5-degenerate configurations, respectively. In our previous studies [9, 12], we have shown that an end-pumped Nd:YVO4 laser by a small Gaussian pump beam will result in generation of a bottle beam while it is operated with the 1/3-degenerate resonator configuration. However, the contrast between

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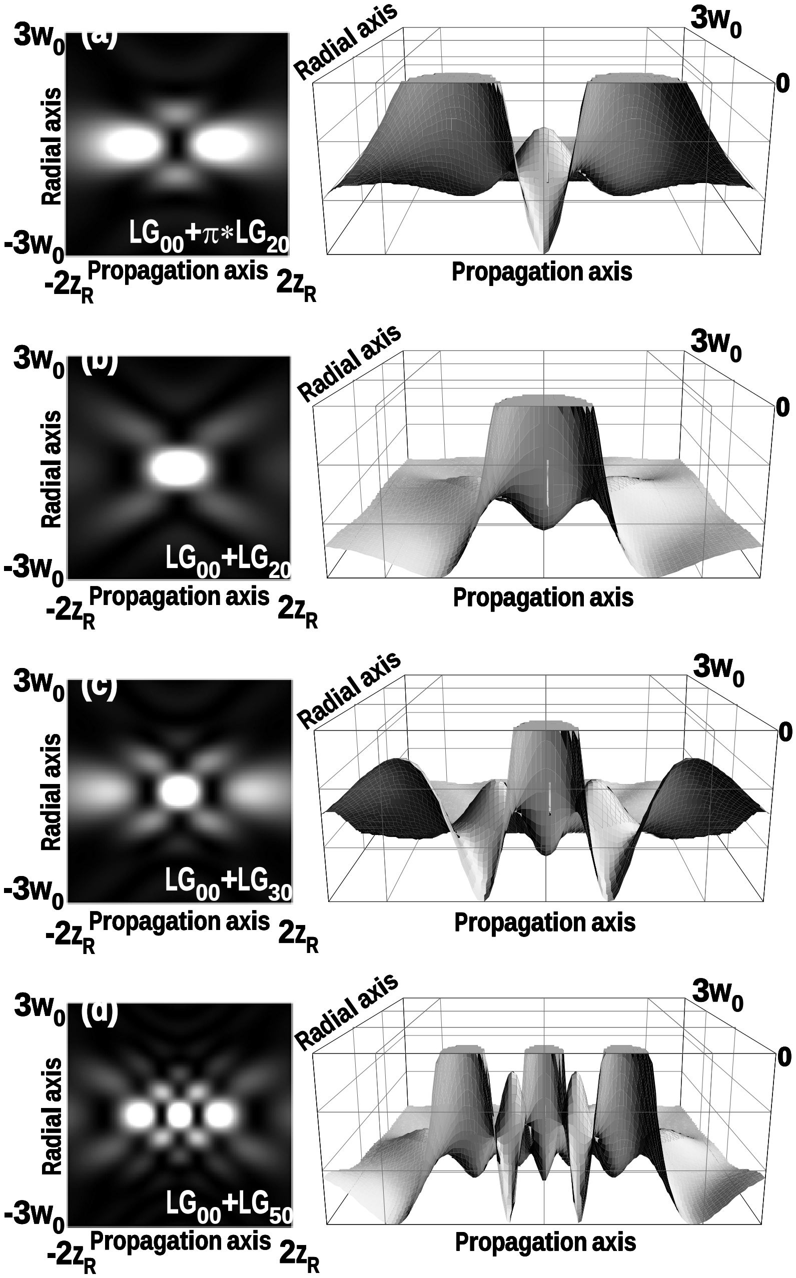

Fig. 1. Intensity patterns and their corresponding three-dimensional profiles. (a) Out-of-phase summing up LG00 and LG20 modes at beam waist, (b-d) in-phase adding LG00 and LG20, LG00 and LG30, as well as LG00 and LG50 modes, where W0 is the beam waist, and zR is the Rayleigh length.

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the dark center and barrier of the optical bottles was not so good as in Fig. 1(c) because many degenerate eigenmodes are simultaneously excited near the 1/3-degenerate cavity. Furthermore, unequal mode weightings will lead to a nonperfect destructive interference bottle with nonzero on-axis intensity even when the proper eigenmodes are selected, for example, only LG00 and LG30 modes being excited. However, we can control the sizes of pump beam and an intracavity aperture in the end-pumped Nd:YVO4 laser to obtain good bottle beams, as depicted in Figs. 1(b)-1(d).

3. Experimental setup and discussion

The experimental setup is similar to those of our previous studies [12]. A planoconcave laser cavity contains a 1-mm-thick Nd:YVO4 crystal and an output coupler with radius of the curvature Rc = 8 cm having 10% transmission at the lasing wavelength of 1.064 μm. One surface of the crystal facing the pumping beam acts as a flat mirror of the cavity and is dichroically coated with reflection greater than 99.8% at 1.064 μm and transmission greater than 99.5% at the pump wavelength of 808 nm; and the other surface was antireflectively coated at 1.064 μm to avoid the intracavity etalons effect. The output coupler was mounted on a translation stage so that we could tune the cavity length around the degenerate configurations where semiconfocal configuration or so-called 1/4 degeneracy is at L = 4 cm, 1/3 degeneracy at L = 6 cm, and 1/5 degeneracy at L = 5.2 cm. The pump source is a continuous-wave Ti-sapphire laser with TEM00 mode. In our experiment we used several pump sizes that were determined by the standard knife method. To control the lasing modes, we insert a knife-edge into the cavity against the gain medium as a hard aperture that allows the oscillation of mere fundamental mode and a single degenerate transverse mode. For example, the aperture is set ∼300 μm from the optical axis for sustaining only LG00 and LG20 modes in the semiconfocal or 1/4-degenerate resonator.

The Nd:YVO4 laser output was split into two beams. One of these was used to project the far-field pattern on a screen located at a distance of ∼50 cm from the flat mirror; the other beam was propagated through a transform lens (TL) to study beam propagation and then was detected by a charge-coupled device (CCD) camera. To image the mode pattern directly behind the TL with less noise, we replaced the camera lens of the CCD with a laser line filter and added some adequate absorptive neutral-density filters.

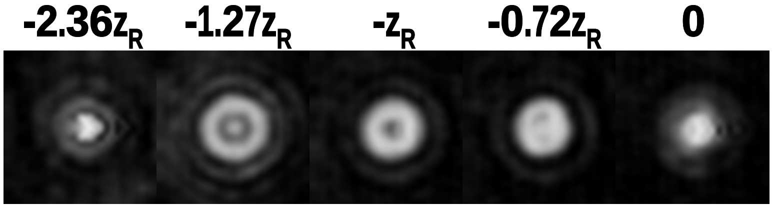

Fig. 2. Radial intensity patterns of the optical bottle generated from a laser operated with the 1/4-degenerate cavity at various distances from the transform lens, which is indicated above the photographs, where zR is the Rayleigh range.

To verify the optical bottles of the above-mentioned modes, we showed in Fig. 2 the intensity distribution of the optical bottle along the propagation distance when the laser is operated at 1/4 degeneracy. We have normalized the propagation distance to the Rayleigh length zR that was indicated above the photographs. The observed optical bottle is ahead of the beam waist at z = 0, and its extended range is ∼2.36 zR. Similar but shorter extended regions of optical bottles for the 1/3 and 1/5 degenerates can also be observed owing to rapid variation of Gouy phases of LG30 and LG50, respectively. Behind the beam waist at z = 0 we can also observe a similar optical bottle, which is consistent with Figs. 1(b)-1(d) but appears farther from the waist. However, the double optical bottles of Figs. 1(b)-1(d) should appear symmetrical to the beam waist because of the symmetrical variation of Gouy phases around the waists. In the experiment, however, we observed unsymmetrical double optical bottles after the transform lens (TL). This can be explained by excess Gouy phase shifts of the higher-order transverse modes, and therefore formation of both LG00 and LGp0 images are at different distances. Assume that both the LG00 and LGp0 modes are in-phase at the waist; they experience different Gouy phase shifts while they reach the TL. Looking back through the TL, those two modes seem to come from two different point sources because they experience different phase shifts or optical path lengths. Their images therefore will be slightly separated, resulting in asymmetric double optical bottles. We can bring these two images together again to produce symmetric optical bottles, as in Figs. 1(b)-1(d), by using two lenses to collimate and then focus the collimated beam to form symmetric double optical bottles.

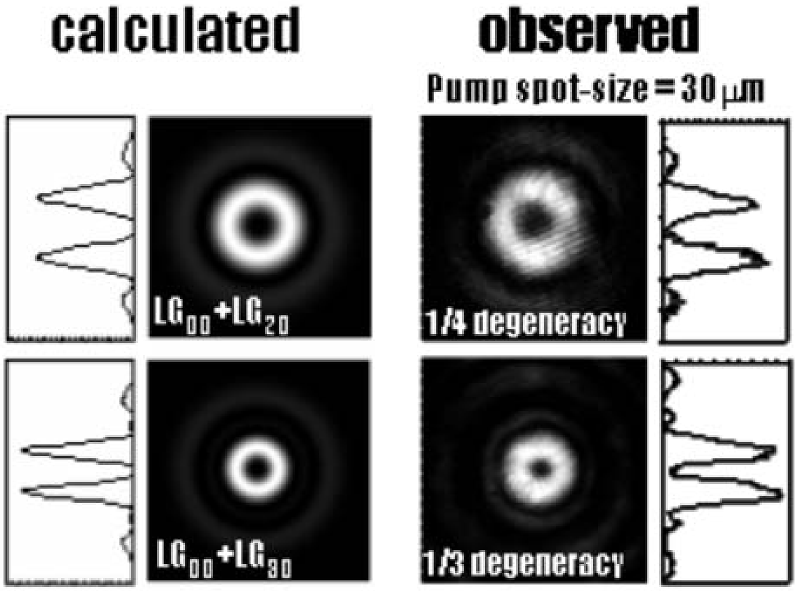

Fig. 3. Calculated radial intensity distributions and the experimentally observed beam profiles. The calculated transverse profile of LG00 + LG20 is at z = zR and of LG00 + LG30 at $z = zR/\sqrt{3}$ that correspond to the photographs taken at 1/4 and 1/3 degeneracy, respectively.

Because there are only 30 × 30 pixels in the photographs of Fig. 2, the spatial resolution is too low to show the detailed beam character. We expanded the laser beam by 5 times to monitor the radial distribution of the center of various optical bottles. Shown in the right-hand column of Fig. 3 are the photographs of the bottle beams under 300-mW pumping with a pump size of 30 μm when the laser is operated at 1/4 degeneracy with an intracavity aperture of 300 μm, and at 1/3 degeneracy with 350-μm aperture, respectively. The parallel streaks on the photographs are caused by interference from the protection window of the CCD. By in-phase summing the LG00 and LG20 modes for 1/4 degeneracy and the LG00 and LG30 modes for 1/3 degeneracy at the beam waist (z = 0), we show the calculated optical bottle profiles in the left-hand column of Fig. 3 at z = zR and at $z = zR/\sqrt{3}$, respectively. We see the excellent agreement between the experiments and the calculations. However, there is ∼5% observed residual intensity at the center of the bottle for both of the 1/4- and 1/3-degenerate configurations. It must be mentioned that each pixel of CCD is 7 × 7 μm^2, which may not be able to resolve the region of lowest intensity of only several micrometers even after 5× magnification. The central pixel may detect some energy adjacent to the optical axis, and the actual residual intensity should be lower than the measured 5%.

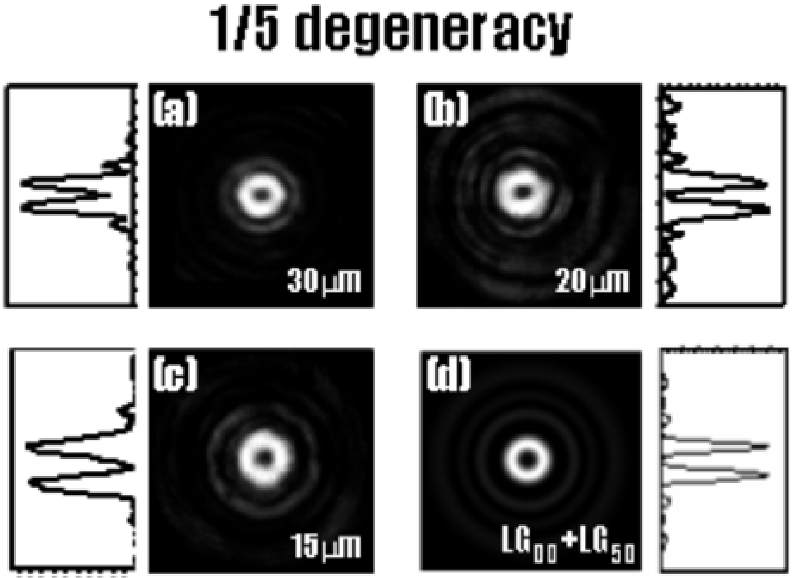

Fig. 4. Depth of optical bottle versus different pumping size and corresponding calculated profiles at 1/5 degeneracy. The CCD images in (a-c) are the beam patterns when the laser is operated with pump size of 30 µm, 20 µm, and 15 µm, respectively. (d) The calculated profile of LG00 + LG20 is at z = 0.324 zR.

Because the central portion of the LG50 mode is more localized than that of LG00, LG20, or LG30, the smaller pump size can effectively decrease the mode weight of the fundamental mode to enhance the LG50 mode. The higher degenerate configuration tends to generate a narrower and deeper optical bottle by choosing a smaller beam size to pump the laser. To obtain the narrower and deeper optical bottle, we pay attention to the 1/5 degeneracy. Note that the fundamental mode radius is 113 µm in this case. With intracavity aperture of 450 µm, we show the experimental results in Figs. 4(a)-4(c) for the pump radius of 30, 20, and 15 µm, respectively, and in Fig. 4(d) is the calculated bottle with LG00 + LG50 at z = 0.324 zR. Comparing Fig. 4(b) with Fig. 4(d), we see the bottle with three obvious concentric rings, which means the aperture has properly selected only LG00 and LG50 modes. We also see from Figs. 4(a) to 4(c) that the central intensity decreases from ∼13% to 2.5%. We used the smaller pump size of 20 µm for the 1/5 degeneracy instead of using pump size of 30 µm for the 1/4 degeneracy and 1/3 degeneracy to achieve the same residue intensity as on the right-column of Fig. 3. This means that the mode weighting can be experimentally controlled by the pump radius. A small pump size gives the mode weight ratio approaching 1, which leads to an optical bottle with good contrast.

One may ask how to practically ensure that the laser is operated at the degeneracy and how to properly determine the aperture size. We discuss these experimental details in the following. Because the Gouy phase difference of LG00 and LG50 modes is 5π at the far field where the profile exhibits a dark center, we can easily identify the point of 1/5 degeneracy where the laser has the lowest threshold. By counting the number of concentric rings, we can identify whether

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the aperture size is proper, for example, a single concentric ring for LG00 + LG20, two rings for LG00 + LG30, and three rings for LG00 + LG50. In addition, one can focus the pumping beam near the rim of the crystal instead of actually placing a real aperture against the crystal inside the cavity.

Optical bottle beams have been generated with a holograph [5], a spatial light modulator (SLM) [6], and two-beam interference [3, 8]. Each method requires enormous calculation (1) to prepare a suitable holograph with low conversion efficiency, (2) for good control of phase retardation for each pixel of SLM, and (3) for two overlapped beams to make the destruction interference that is occurring at the beam center. Our method of generating the bottle beams directly from a simple laser may be convenient for some applications. The demonstration of the Nd:YVO4 laser in this experiment that emits at a wavelength of 1064 nm may not be suitable for blue-detuned light trapping of atoms. However, using the Collins integral together with rate equation to study pattern formation and laser dynamics, as stated in previous studies [9, 12], we found that the bottle beam from a laser is independent of the active medium as long as it satisfies the thin slab approximation and the homogeneous four-level assumption. If only the pump size is properly controlled and smaller than the beam waist of the fundamental mode of the cavity, and an aperture is introduced to eliminate unwanted high-order modes, an optical bottle beam with double wells results from cooperative frequency locking of the lowest two degenerate transverse modes. Therefore, one can choose an appropriate gain medium and employ it with the degenerate cavity configurations to generate a bottle laser beam for trapping atoms in the dark field.

4. Conclusion

In conclusion, we have demonstrated direct generation of various optical bottle beams from the degenerate cavity configurations in a compact solid-state laser for appropriate pumping size and aperture. In particular, the good optical bottle is achieved with the superposition of LG00 and LG50 modes from the 1/5-degenerate cavity. This new scheme of generating bottle beams from end-pumped solid-state lasers may be applied to optical atom trapping.

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