Generation of super-high-order petal-like laser beam using Theon-sieve resonator

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The Laguerre–Gaussian (LG) mode beam has very important applications in many research fields. Here, the Theon sieve is first introduced into the laser resonator to generate petal-like laser beams by coherently superimposing two high-order LG modes. The effectiveness was verified by GLAD software. The petal-like laser beam is derived from the light field redistribution and coherent superposition caused by the diffraction effect of the Theon sieve. The relationship between the order of the petal-like laser and the cavity structures has also been investigated in detail. Light field operation in the laser cavity greatly simplifies the optical structure and is more beneficial to optical diagnostics and imaging.

Keywords: generation; super-high order; petal-like laser beam; Theon sieve.

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The Laguerre–Gaussian (LG) beam can be obtained by solving the Helmholtz equation in the condition of cylindrical symmetry. Different from the fundamental mode in a resonator, the LG beam carries orbital angular momentum. High-order LG transverse electromagnetic ($\mathrm{TEM}_{p,l}$) mode, where p and l are the radial and azimuthal order, respectively, exhibits some interesting and unique physical properties[1–4] and has been widely used in the field of precise manipulation and optical information transfer[5–8]. The petal-like beam that can be generated by coherently superimposing two high-order LG beams with a zero order in the radial direction and conjugate orders in the azimuthal direction[9–11] has better performance in the field of controlling the rotation of trapped microparticles[12,13]. Due to its special intensity distribution and great applications, the petal-like laser gradually catches people's attention. The method of generation of the petal-like laser can be divided into two types, intra-cavity[9,14–16] and extra-cavity shaping techniques[17–19]. Note that the intra-cavity method cannot output high-energy and high-power laser beams, while the extra-cavity method is more complex and cannot have simple operation. In addition, the order of the petal-like beam generated by previous methods is usually not very high.

The Theon sieve (TS)[20,21] is a kind of diffractive optical element with two axial focal spots, and the transmissive rings of TS are replaced by a large number of isolated pinholes. In this paper, we propose a simple, stable, and adjustable structure by inserting a TS into a resonator to generate a super-high-order petal-like laser. The model of the proposed resonator is established and simulated by the optical software GLAD, and the per round trip energy loss of the resonator and the intensity distribution of the output beam are obtained. The influence of the location of TS on the output beam and the stability of the optical resonator cavity are also analyzed.

The electric field of high-order LG modes can be written as[22]

$$u_{p,l}=\sqrt{\frac{2p!}{\pi(p+|l|)!}}\frac{1}{\omega(z)}\left[\frac{\sqrt{2}r}{\omega(z)}\right]^{|l|}L_p^{|l|}\left[\frac{2r^2}{\omega(z)^2}\right]\times\exp\left[\frac{-r^2}{\omega(z)^2}-\frac{ikr^2}{2R(z)}\right]\times\exp\left[-i(2p+|l|+1)\arctan\left(\frac{z}{z_R}\right)\right]\exp(-il\Phi), \tag{1}$$

where p and l are the radial and azimuthal order, respectively, r is the radius, Φ is the azimuthal angle, z is the distance from the beam waist, z_R is the Rayleigh range, $\omega(z)$ and $R(z)$ are the radius of curvature and beam width of a Gaussian beam, and $L_p^{|l|}$ is the generalized Laguerre polynomial. The superposition field of the petal-like mode can be expressed as[9]

$$\begin{aligned}u_{0,\pm l}&=u_{0,+l}+u_{0,-l}\\&=\sqrt{\frac{2p!}{\pi(p+|l|)!}}\frac{1}{\omega(z)}\left[\frac{\sqrt{2}r}{\omega(z)}\right]^{|l|}\exp\left[\frac{-r^2}{\omega(z)^2}-\frac{ikr^2}{2R(z)}\right]\\&\quad\times\exp\left[-i(|l|+1)\arctan\left(\frac{z}{z_R}\right)\right]\exp(-il\Phi).\end{aligned}\tag{2}$$

The intensity profile of this structure will result in $2l$ petals around a circle.

Based on the parallel plane mirror resonator with two condenser lenses inserted inside, we replaced one of the lenses with a TS. The focal length of the TS needs to be confirmed by the stability conditions of the resonator. The structure of the proposed resonator is shown in Fig. 1. M_1 and M_2 are a pair of parallel planar mirrors. L_1 is a condenser lens that is placed a distance z_1 away from M_1, and C_1 is a pinhole close to M_1. S_1 is a TS that is placed a distance z_2 away from M_2. The distance between S_1 and L_1 is d. The LG_{0l} mode is nearly circularly symmetric in the resonator. Two high-order LG beams with zero order in the radial direction and conjugate orders in the azimuthal direction have identical loss and coherently superimpose in the same position.

GLAD software is used to simulate the properties of the resonator by the Fox–Li iteration method[23]. Although the calculation process of the Fox–Li iteration method is tedious, it has universal applicability. The most important point is that GLAD is suitable for the modeling of the physical process, such as various diffraction effects that cannot be ignored in the design of the optical system. In fact, it is possible to calculate the self-reproducing mode in any resonator.

In the numerical calculation, the focal length of L_1 is 80 mm, the radius of pinhole C_1 is 0.45 mm, z_1 and z_2 are both 100 mm, d is 95 mm, and the initial optical field is set to random noise. A TS is designed with a diameter of 8.2 mm and focal lengths of 55.07 mm and 73.03 mm, respectively, as indicated in Fig. 2.

The simulation starts from the left plane mirror, and the light goes through L_1, S_1, M_2, S_1, L_1, C_1, and M_1 in turns. In the end, the normalized light field intensity distribution on the left surface of M_1 and the per round trip energy loss percentage are obtained after 800 times propagation in the resonator. From these results, as shown in Fig. 3, we know that the output light is a petal-like laser beam, and the TS resonator mode becomes stable when the beam propagates for about 200 cycles. Figure 3(a) shows the normalized intensity distribution on the left surface of M_1. The number of the petals is 36, and the radius from the center of petal-like laser beam is 0.3 mm.

Changing the distance between the TS and L_1, the radii and the number of the petals versus the distance d are described in Table 1. The normalized intensity distributions of the petal-like beam are presented in Figs. 4(a)–4(f), and the per round trip energy loss percentage is shown in Fig. 5. In Figs. 4(a)–4(c), the distance between the TS and L_1 is 87 mm, 90 mm, and 102 mm, respectively, and the number

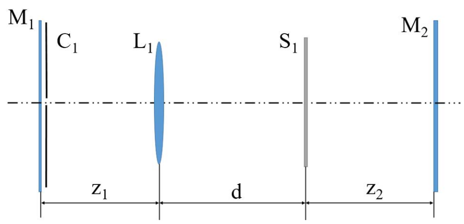

Fig. 1. Theon-sieve (TS) resonator.

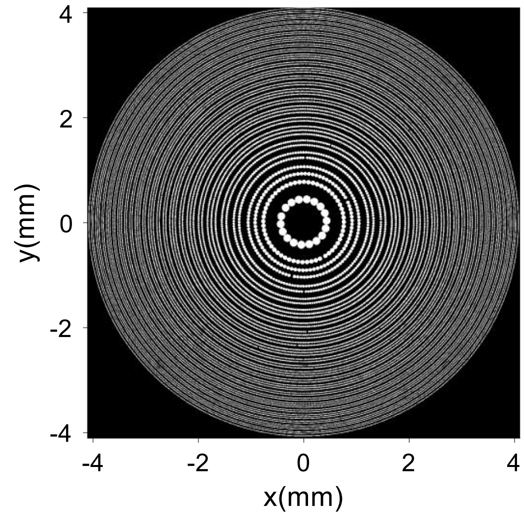

Fig. 2. Structure of the TS.

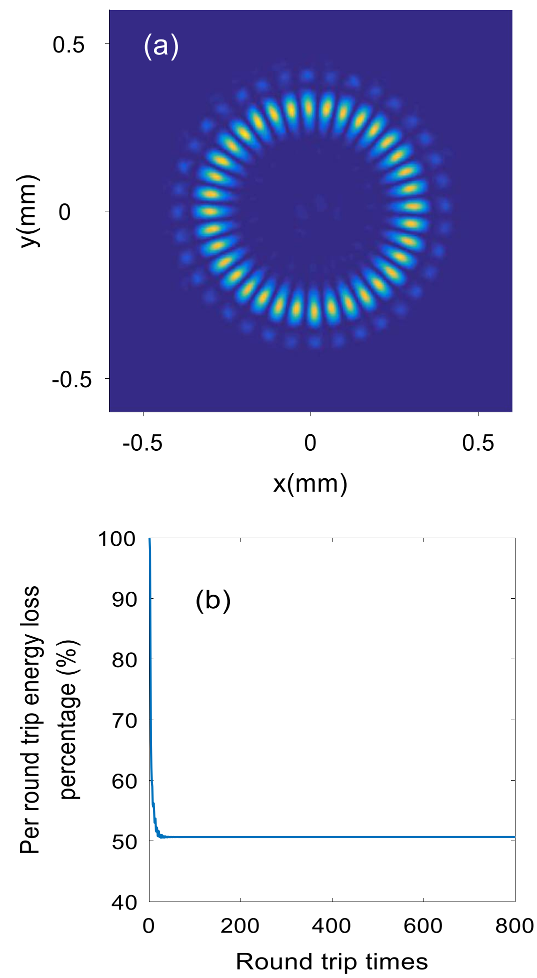

Fig. 3. TS resonator: (a) normalized intensity distribution; (b) per round trip energy loss percentage.

of the petals is 36, the same as that of $d = 95$ mm. A distance of at least 15 mm can generate the same transverse mode with 36 petals. In Figs. 4(d)–4(f), it is seen that the numbers of the petals are 26, 46, and 54, when the

Table 1. Radii and Number of Petals at Different Distances

d (mm)	87	90	102	65	120	140
Petal number	36	36	36	26	46	54
Radius (mm)	0.32	0.31	0.30	0.30	0.31	0.31

distances between TS and L_1 are 65 mm, 120 mm, and 140 mm, respectively. Obviously, the number of the petals increases with the increase of the distance. Besides, higher-order petal-like beams can also be generated by adjusting the parameters of the TS resonator appropriately. On the basis of the data in Table 1, the radius of the petal-like laser decreases with the increase of distance in the condition of the number of the petals being invariable. Although the size of the diffraction pattern, which is generated by TS, at the plane L_1 varies with the distance between the TS L_1, the clear aperture of the L_1 is invariable. On the other hand, different distances correspond to the different ABCD matrices of the resonator. Therefore, there is a big difference in the per round trip energy loss, just as shown in Fig. 5.

Figure 6 shows the relationship between the number of petals and the distance between the TS and L_1. Obviously, the ABCD matrix of the laser resonator will change according to the variation of the distance, meaning that different losses exist in the cavity. In this case, different

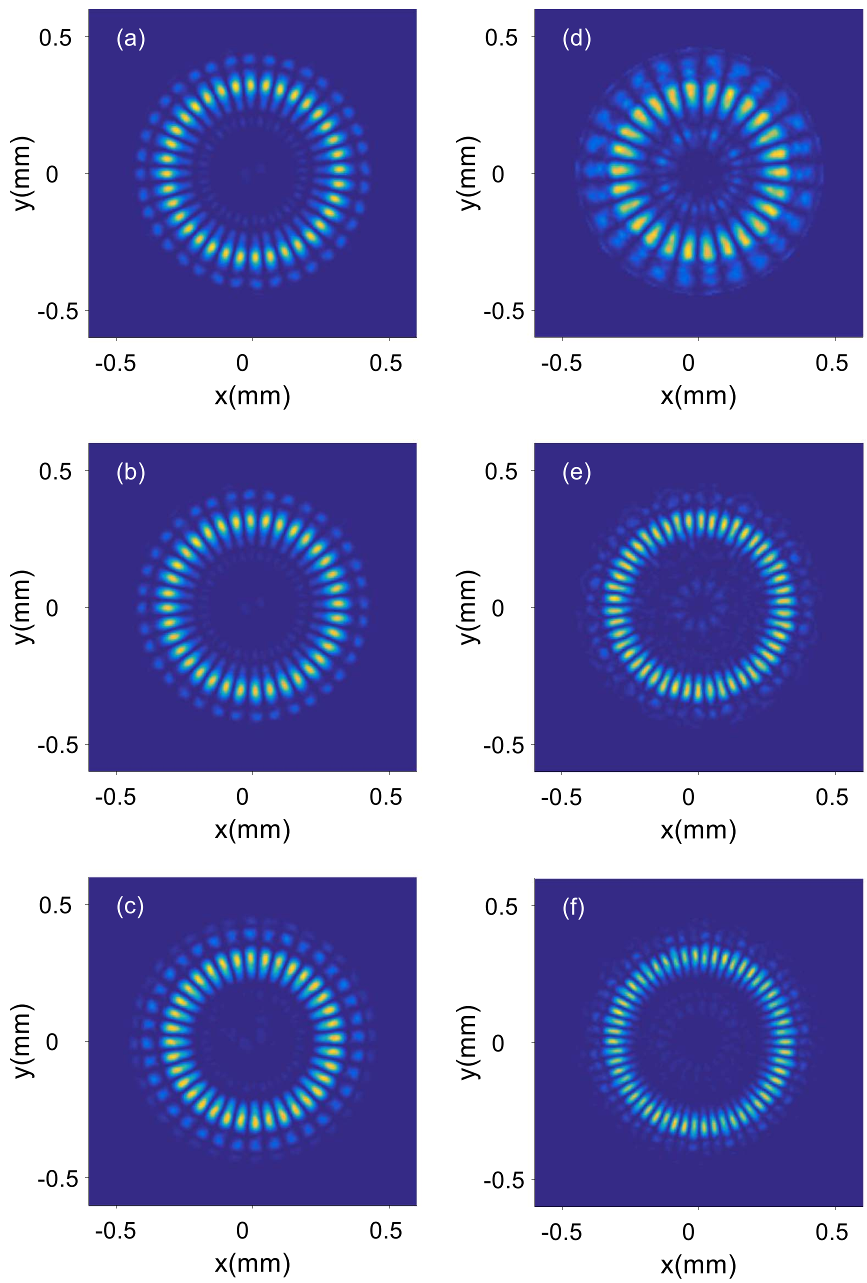

Fig. 4. Simulation of petal-like modes at different distances between TS and L_1. (a) $d = 87$ mm; (b) $d = 90$ mm; (c) $d = 102$ mm; (d) $d = 65$ mm; (e) $d = 120$ mm; (f) $d = 140$ mm.

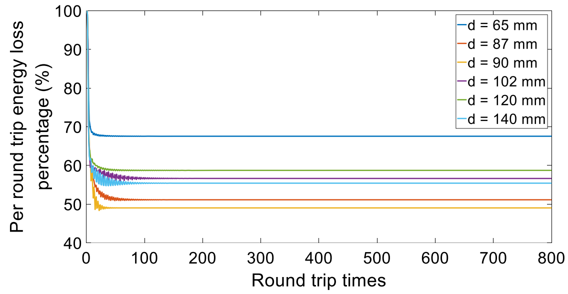

Fig. 5. Per round trip energy loss percentage versus different distances.

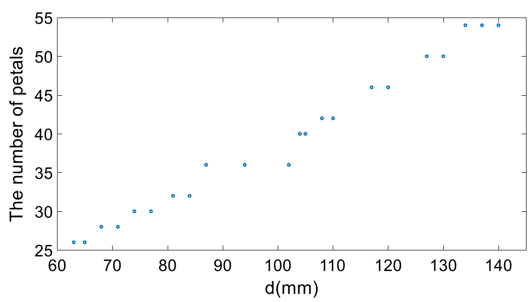

Fig. 6. Number of petals versus different distances.

resonator modes will be generated. Note that for a stable resonator, a slight disturbance of the system parameters has no influence on the mode of the output laser.

In conclusion, we propose a stable and adjustable structure to generate super-high-order petal-like laser beams by inserting a TS into the resonator, and the effectiveness is verified by GLAD software. The output normalized intensity distribution and the per round trip energy loss percentage are obtained successfully by the Fox–Li iteration method. The relationship among the radius, the number of petals, and the distance between the TS and lens is also analyzed in detail. The proposed method can enlighten us in constructing more complex light fields so as to be beneficial to interference diagnostics and interferometric imaging.

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References

1. A. Mair, A. Vaziri, G. Weihs, and A. Zeilinger, Nature **412**, 313 (2001).
2. Y. Eric, F. A. Sonja, C. Johannes, M. J. Padgett, and S. M. Barnett, Opt. Express **14**, 13089 (2006).
3. Q. Zhang, J. Yu, B. Shi, F. Tang, and J. Li, Chin. Opt. Lett. **17**, 051402 (2019).
4. Z. Zhang, W. Wei, L. Tang, J. Yang, J. Guo, L. Ding, and Y. Li, Chin. Opt. Lett. **16**, 110501 (2018).
5. P. Bouchal and Z. Bouchal, Opt. Lett. **37**, 2949 (2012).
6. H. Huang, G. D. Xie, Y. Yan, N. Ahmed, Y. X. Ren, Y. Yue, D. Rogawski, M. J. Willner, B. I. Erkmen, K. M. Birnbaum, S. J. Dolinar, M. P. J. Lavery, M. J. Padgett, M. Tur, and A. E. Willner, Opt. Lett. **39**, 197 (2014).
7. M. Woerdemann, C. Alpmann, M. Esseling, and C. Denz, Laser Photon. Rev. **7**, 839 (2013).
8. Y. Shi, B. Shen, L. Zhang, X. Zhang, W. Wang, and Z. Xu, Phys. Rev. Lett. **112**, 235001 (2014).
9. D. Naidoo, K. Aït-Ameur, M. Brunel, and A. Forbes, Appl. Phys. B **106**, 683 (2012).
10. V. John, B. Matt, V. Reeta, and S. Surendra, J. Opt. Soc. Am. A **25**, 823 (2008).
11. I. A. Litvin, B. Liesl, and F. Andrew, Opt. Express **15**, 14065 (2007).
12. I. A. Litvin, A. Dudley, F. S. Roux, and A. Forbes, Opt. Express **20**, 10996 (2012).
13. R. Rop, A. Dudley, C. Lópezmariscal, and A. Forbes, J. Mod. Opt. **59**, 259 (2012).
14. Y. F. Chen and Y. P. Lan, J. Opt. B **3**, 146 (2001).
15. S. Ngcobo, I. Litvin, L. Burger, and A. Forbes, Nat. Commun. **4**, 2289 (2013).
16. I. Akihiko, K. Yuichi, and S. Shunichi, J. Opt. Soc. Am. A **27**, 2072 (2010).
17. J. Yu, C. Zhou, W. Jia, J. Wu, L. Zhu, Y. Lu, C. Xiang, and S. Li, Appl. Opt. **54**, 1667 (2015).
18. M. P. MacDonald, K. Volke-Sepulveda, L. Paterson, J. Arlt, W. Sibbett, and K. Dholakia, Opt. Commun. **201**, 21 (2002).
19. Z. Zhou, Y. Li, D. Ding, W. Zhang, S. Shi, and B. Shi, Opt. Lett. **39**, 5098 (2014).
20. S. Xu, J. Zhang, S. Zhou, Y. Ma, and J. Zhu, Appl. Opt. **57**, 1993 (2018).
21. J. Zhang, Opt. Express **23**, 30308 (2015).
22. A. Vaziri, G. Weihs, and A. Zeilinger, J. Opt. B **4**, S47 (2002).
23. http://www.aor.com/html/applicat.html.