

光学学报

可调谐手性结构光场的产生及调控

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摘要 提出一种环形相位构造方法,并通过实验产生了一种可调谐手性结构光场。在螺旋相位的基础上引入径向相位与等相位形成环形子相位,在平面波上加载该相位产生单环手性结构光场。进一步利用相位叠加原理,组合多个不同环形子相位构成一个环形相位,进而利用其调控产生多环手性结构光场。研究发现,通过控制拓扑荷数、等相位因子、径向偏移因子,能够灵活控制螺旋强度瓣叶的数量以及手性方向。此外,通过引入等相位梯度实现了光场的动态旋转。所构建的可调谐手性结构光场有益于手性结构微加工,在光学微操纵及光学通信领域也有较大的潜在应用价值。

关键词 物理光学; 光场调控; 相位调制; 结构光场; 手性光场

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1 引言

涡旋光束携带 lh 轨道角动量(OAM),其中 l 为拓扑荷数, h 为约化普朗克常数。涡旋光束的显著特征是具有螺旋波前和相位奇点、光强呈现环形分布^[1-2]。由于其独特的光学性质,涡旋光束受到人们的广泛关注^[3],在超分辨率成像^[4-5]、激光微加工^[6-7]、光学操纵^[8-9]、超大容量光通信^[10-11]、光学测量^[12-13]等方面具有巨大的应用潜力。

涡旋光场的轨道角动量具有“扭曲”熔融物质的作用,可用于手性纳米结构微加工^[14-15]。近年来,具有扭曲强度分布和携带 OAM 的手性结构光场在光学微加工与微操纵中具有明显优势,引起了人们极大的研究兴趣^[16-18]。Alonzo 等^[19]利用螺旋相位和圆锥相位的乘积构建螺旋锥相位,产生具有手性强度分布的螺旋锥光场。随后, Li 等^[20]提出一种具有自动聚焦效应的幂指数-相位螺旋光场,这种幂指数-相位螺旋光场结构可以通过调节幂指数因子来控制^[21-22]。然而,上述手性光场结构单一。因此,产生灵活可调谐手性结构光场成为一个重要的研究方向。Yang 等^[23]基于环形螺旋相位产生一种扭曲的多波瓣手性光场,其光场可调谐能力得到显著提升。Ma 等^[24-25]通过叠加多个基元相位,产生了结构可控的紧聚焦手性光场。这些研究极大地推动了手性结构光场的发展,而灵活操纵手性光场仍然是手性结构微加工的关键。

本文提出一种简单且高效的可调谐手性结构光

场,其光强呈现出多层扭曲波瓣分布。通过调控径向偏移因子、等相位因子以及拓扑荷数,可以灵活地操纵手性光场结构。此外,通过操控引入等相位梯度,能够旋转所产生的手性光场,这种可调谐的多层手性结构光场可以应用到光学微加工、光学编码、微粒操纵中。

2 理论

光场 $U(X, Y, Z)$ 在傍轴近似情况下遵循菲涅耳衍射积分,可表示为

$$U(X, Y, Z) = \frac{\exp(ik^2 x_0^2 Z)}{i2\pi x_0^2 Z} \iint U(X', Y', 0) \times \exp\left[i\frac{(X-X')^2 + (Y-Y')^2}{2Z}\right] dX' dY', \quad (1)$$

式中: $x_0 = 0.02$ mm 为比例常数; $k = 2\pi/\lambda$ 为波数; $Z = z/(kx_0^2)$ 为无量纲传播距离; $U(X', Y', 0)$ 为初始光场。光场产生原理如图 1(a) 所示,即相位调制后的光场 $U'(X', Y', 0)$ 经过一个薄透镜,形成初始光场,可表示为

$$U(X', Y', 0) = U'(X', Y', 0) T(X', Y', 0), \quad (2)$$

式中: $T(X', Y', 0)$ 为薄透镜的相位变换函数。

$$T(X', Y', 0) = \exp\left(-ik\frac{X'^2 + Y'^2}{2f}\right), \quad (3)$$

式中: $f = 600$ mm 为薄透镜焦距; U' 表示经相位 $\phi(r, \theta)$ 调制后的光场。 U' 用极坐标可表示为

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$$U'(r, \theta) = A_0 \exp\left(-\frac{r^2}{\omega^2}\right) \exp[i\phi(r, \theta)], \quad 0 < r < r_{\max}, \quad (4)$$

式中： A_0 为任意常数； ω 为高斯光束的束腰半径； $\phi(r, \theta)$ 为所构建的环形子相位。

图 1(b) 展示了构建环形子相位 $\phi(r, \theta)$ 的过程。首先，考虑经典的涡旋相位分布 $l\theta$ ，并对通光口径 r 进行限制 ($r_{si} < r < r_{so}$)，形成图 2(a1) 所示的环形涡旋相位。这里对相位范围进行限制，是为了形成能量更加集中的环形涡旋光，进而使手性结构光场的能量集

中在扭曲的波瓣上。该相位产生能量更加集中的“甜甜圈”状光强分布，如图 2(b1) 所示，其中 r_{si} 、 r_{so} 分别为环形涡旋相位的内、外半径。然后，在上述环形涡旋相位中叠加径向偏移 ηr 因子，形成径向环形涡旋相位 $l\theta + \eta r$ (η 为径向偏移常数)，相位分布如图 2(a2) 所示，所产生的光场分布如图 2(b2) 所示，该光场呈现收缩的“甜甜圈”状分布。进一步引入等相位 β 因子，将其通光口径限制于 $r_{ei} < r < r_{eo}$ ，其中 r_{ei} 、 r_{eo} 为等相位的内、外半径，其外径大小与环形涡旋相位内径相等，即 $r_{eo} = r_{si}$ 。将径向环形涡旋相位与等相位组合，形

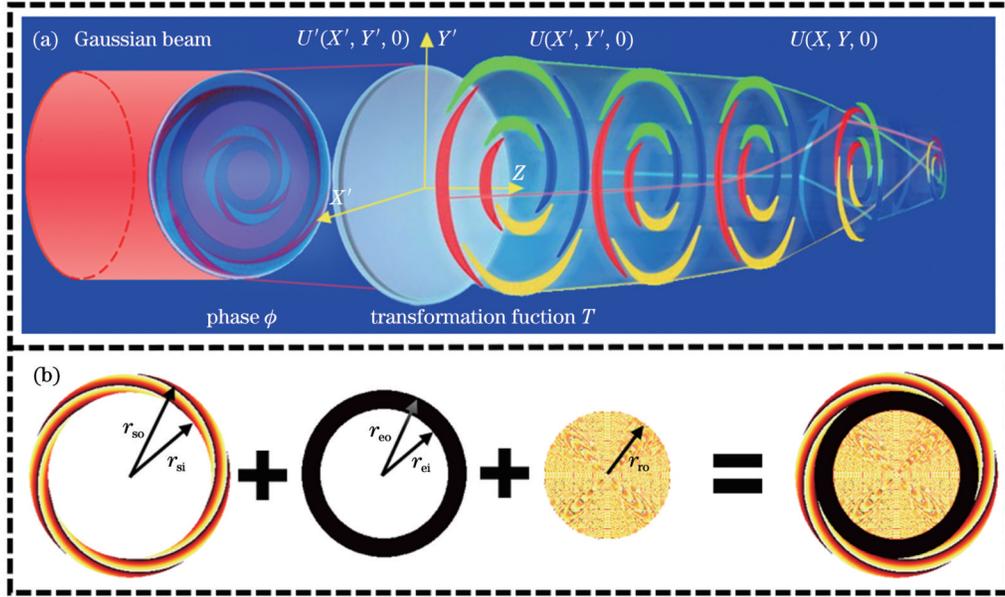


图 1 光场产生原理。(a) 手性光场形成；(b) 环形子相位的构建

Fig. 1 Principle of light field generation. (a) Generation for chiral structured beams; (b) construction of circular sub-phase

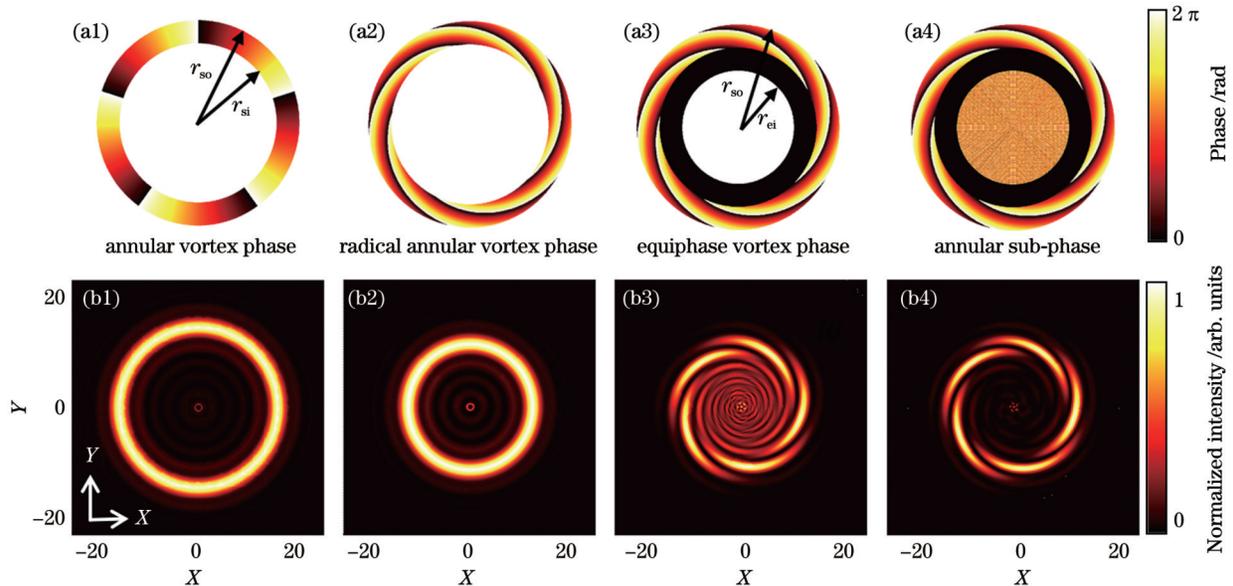


图 2 环形子相位的构建及相应的光场。(a1)(b1) 环形涡旋相位及光场；(a2)(b2) 径向环形涡旋相位及光场；(a3)(b3) 等相涡旋相位及光场；(a4)(b4) 环形子相位及光场

Fig. 2 Construction of annular sub-phase and corresponding light fields. (a1)(b1) Annular vortex phase and light field; (a2)(b2) radical annular vortex phase and light field; (a3)(b3) equiphase vortex phase and light field; (a4)(b4) annular sub-phase and light field

成图 2(a3) 所示的等相涡旋相位。等相位起到破坏螺旋连续性的作用, 环瓣间无光强分布, 如图 2(b3) 所示, 呈环形“扭曲”状光场分布。最后, 引入另一项径向相位 γr 因子, 将其范围限制于 $0 < r < r_{ro}$ (r_{ro} 为径向相位的外径)。因此, 环形子相位可由涡旋相位适当引入径向相位和等相相位因子组成 [图 1(b)], 可表示为

$$\phi(r, \theta) = \begin{cases} l\theta + \eta r, & r_{si} < r < r_{so} \\ \beta, & r_{ei} < r < r_{eo}, \\ \gamma r, & 0 < r < r_{ro} \end{cases} \quad (5)$$

式中: γ 表示与 η 不同的径向偏移常数, 它们都大于 0;

下角标 i 和 o 分别代表内部和外部, s 代表螺旋, e 代表等相位, r 代表径向。图 2(a4) 展示了所构建的环形子相位, 其调控光场如图 2(b4) 所示。因 γr 作用, 环带周围杂散光强度明显降低, 能量更好地控制在环带中的扭曲波瓣上。上述模拟中拓扑荷数 $l = 5$ 。此外, 本文中所有的数值模拟除特殊说明外, 各参数分别为 $\eta = 0.13\pi, \beta = 0, \gamma = 2.5\pi$ 。

图 3 展示了拓扑荷数分别为 $\pm 2, \pm 3, \pm 6, \pm 7$ 的环形手性光场。通过控制拓扑荷数的大小可以控制扭曲波瓣的数量, 而控制拓扑荷数的符号可以操控扭曲波瓣的手性方向。

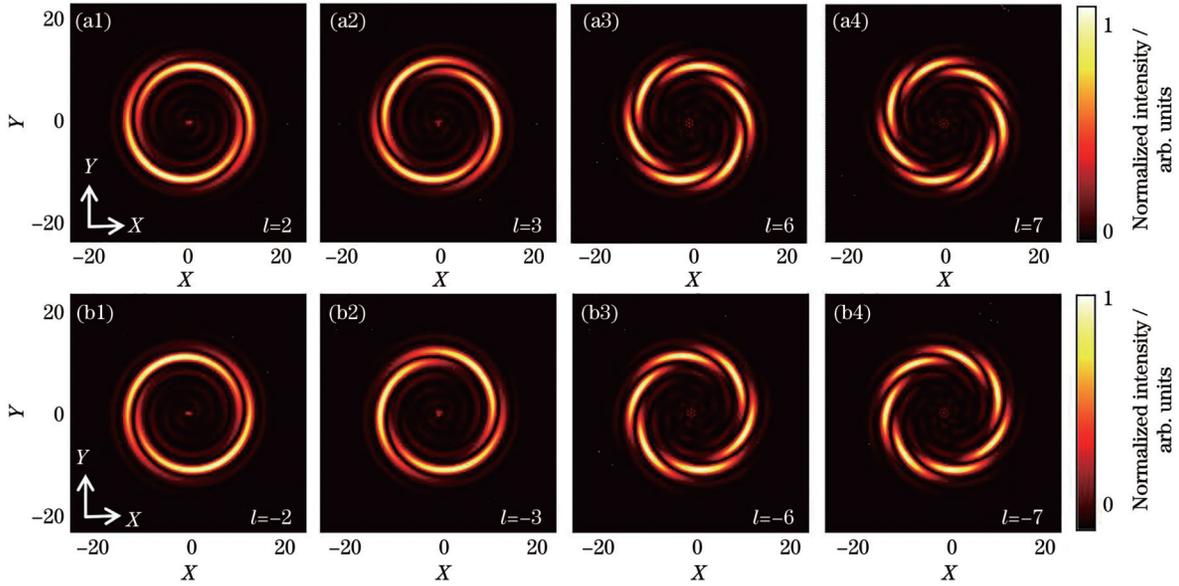


图 3 不同拓扑荷数下的手性结构光场。(a1)~(a4) 拓扑荷数 l 分别为 2、3、6、7; (b1)~(b4) 拓扑荷数 l 分别为 -2、-3、-6、-7
Fig. 3 Chiral structured beams under different topological charges. (a1)~(a4) $l=2, 3, 6,$ and 7 ; (b1)~(b4) $l=-2, -3, -6,$ and -7

为了产生更加灵活可调的手性光场, 构建了多环形相位。多环形相位由多个环形子相位叠加而成, 构建过程如图 4 所示, 可表达为

$$\phi(r, \theta) = \sum_{j=1}^n t_j(r, \theta) \phi_j(r, \theta), \quad (6)$$

式中: j 表示环形子相位序号; n 表示环形子相位个数; $t_j(r, \theta)$ 为透过率函数。

$$t_j(r, \theta) = \begin{cases} 1, & r_{ni}^j < r < r_{so}^j, 0 < \theta < 2\pi \\ 0, & \text{other} \end{cases}, \quad (7)$$

式中: $r_{ni}^n = 0; r_{so}^1 = r_{\max}$ 。第 j 个环形子相位 $\phi_j(r, \theta)$ 可表示为

$$\phi_j(r, \theta) = \begin{cases} l_j \theta + \eta r, & r_{si}^j < r < r_{so}^j \\ \beta, & r_{ei}^j < r < r_{eo}^j, \\ \gamma r, & r_{ri}^j < r < r_{ro}^j \end{cases} \quad (8)$$

式中: $r_{so}^j, r_{eo}^j, r_{ro}^j$ 分别表示径向环形涡旋相位、等相位、径向相位的外径; $r_{si}^j, r_{ei}^j, r_{ri}^j$ 为所对应的内径。各层涡旋相位紧密相连接, 即 $r_{so}^n = r_{ri}^{n-1}$ 。

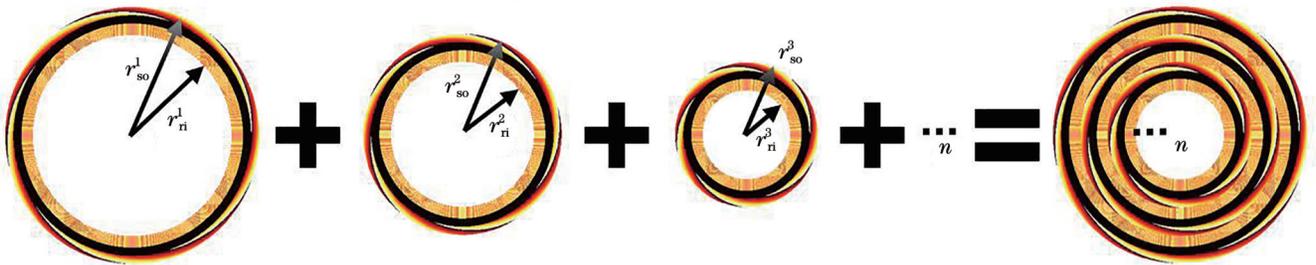


图 4 多环形相位的构建
Fig. 4 Construction of multi-ring phase

3 实验结果与讨论

实验装置如图 5 所示, 波长为 632.8 nm 的激光经针孔滤波器 (PF) 和透镜 L1 扩束准直, 通过分束器

(BS) 后垂直投射到已经加载相位图的反射式空间光调制器 (SLM; Holoeye, Pluto, 1920×1080, 8 μm), 经反射后通过透镜 L2, 在 CCD (Microvision, MV-EM200C, 1600×1200, 4.4 μm) 形成手性光场。

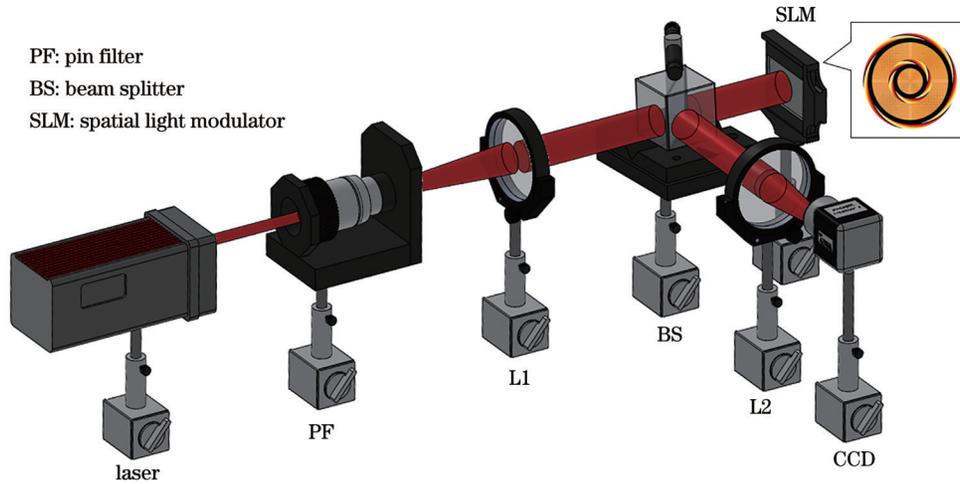


图 5 实验装置
Fig. 5 Experimental setup

图 6 (a1) 展示了内、外拓扑荷数 $l_1 = 5, l_2 = 5$ 的双环形相位分布, 图 6 (b1) 为经该相位调制后产生的

手性结构光场在归一化距离 $Z=20$ 处的光场分布, 其呈现明显的双层结构, 且扭曲的环瓣间因等相位 β 的

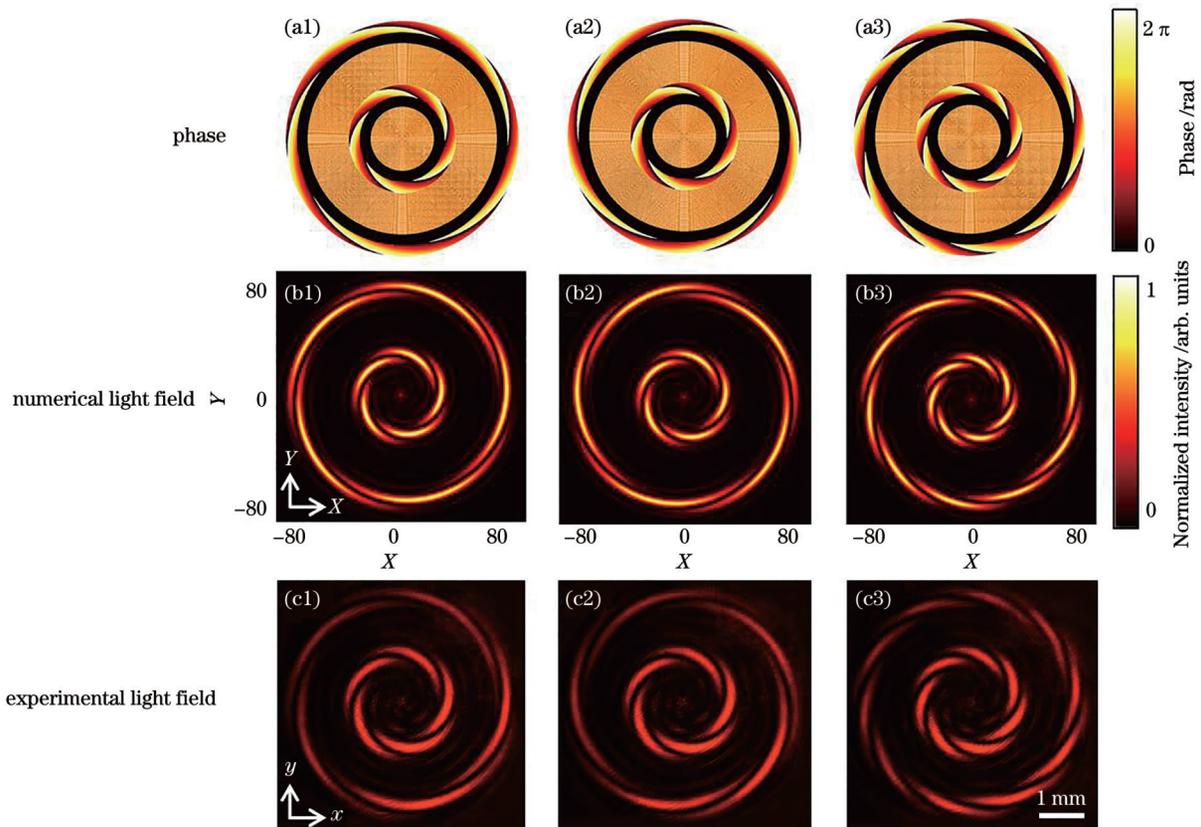


图 6 双环手性结构光场。(a1)~(c1) $l_1=l_2=5$ 时的双环形相位及光场; (a2)~(c2) $l_1=-5, l_2=5$ 时的双环形相位及光场; (a3)~(c3) $l_1=10, l_2=7$ 时的双环形相位及光场
Fig. 6 Double annular chiral structured light fields. Double annular phase and light fields for (a1)~(c1) $l_1=l_2=5$; (a2)~(c2) $l_1=-5, l_2=5$; (a3)~(c3) $l_1=10, l_2=7$

作用有明显的暗隙,拓扑荷数与其波瓣数量一致。图 6(c1)为对应的 $z=50$ mm 处的光场实验结果,其与仿真结果吻合很好。图 6(a2)~(c2)展现了拓扑荷数 $l_1=-5, l_2=5$ 时相应的结果,图 6(a3)~(c3)为 $l_1=10, l_2=7$ 条件下的相应结果,这些实验结果与预期完全吻合,证明所构建光场的手性方向和扭曲波瓣分别与拓扑荷数的正负和大小有关。因此,通过调控拓扑荷数能灵活控制光场结构。模拟中环形子相位间距 $\Delta r = r_{ro}^1 - r_{ri}^1 = 0.25$,最大半径 $r_{max} = 1$ 。

图 7(a1)~(a3)分别展示了 $l_1=l_2=10, \beta=0$ 时的双层手性结构光场在归一化传播距离 $Z=16, 20, 24$ 的数值结果。可以看到,在传播过程中光场形态保持不变。受紧贴空间光调制器的薄凸透镜的作用,相邻层间距随着传播距离的增加而减小。图 7(b1)~(b3)展示了归一化强度分布截面,其光强集中在环带位置。图 7(c1)~(c3)展示了传播距离 $z=40, 50, 60$ mm 处的实验光场分布,与仿真结果一致。计算中以紧贴透镜 L2 后球面的光场为初始光场。

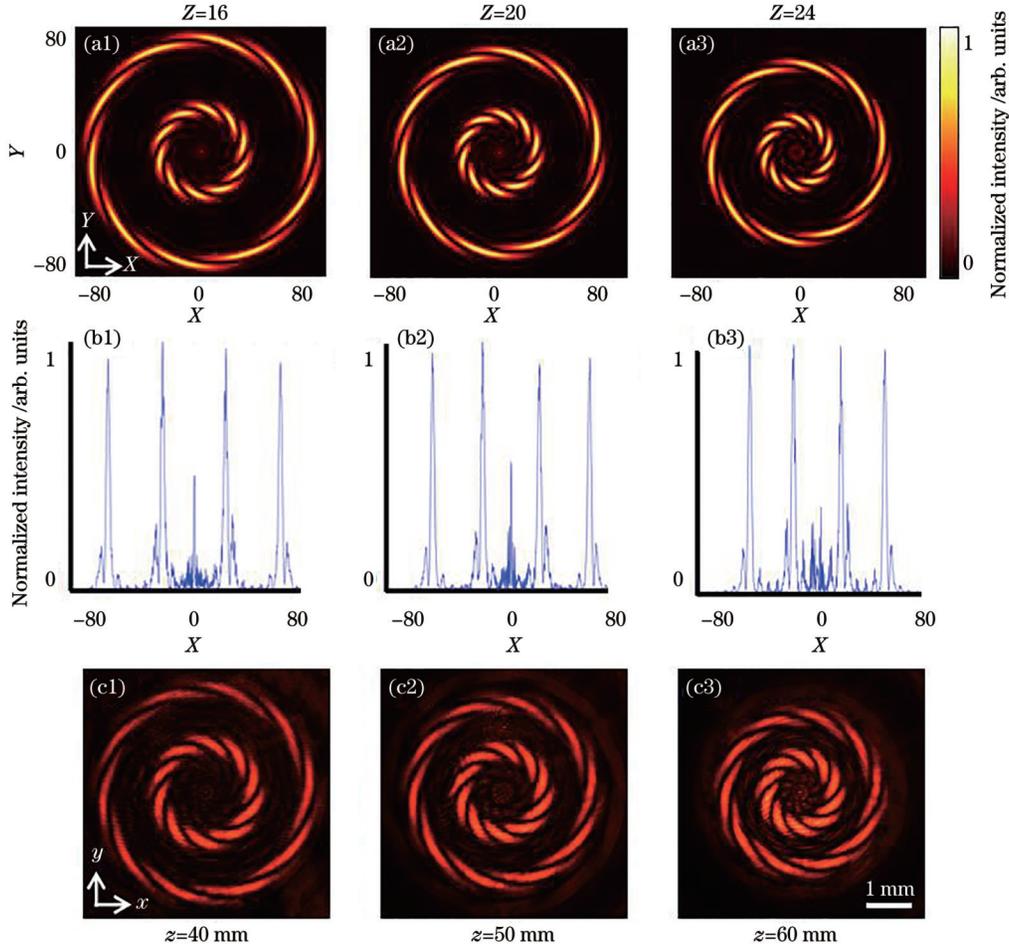


图 7 传播特性。(a1)~(a3)距离 $Z=16, 20, 24$ 时的模拟光场;(b1)~(b3)强度截面;(c1)~(c3) $z=40, 50,$ and 60 mm 时的实验光场

Fig. 7 Propagation characteristics. (a1)~(a3) Numerical chiral light fields for $Z=16, 20,$ and 24 ; (b1)~(b3) normalized intensity profiles; (c1)~(c3) experimental light fields for $z=40, 50,$ and 60 mm

为产生更加灵活复杂的手性结构光场,构建了多环形结构光场,图 8(a1)所示为三环相位,图 8(b1)展示了其数值模拟的光场分布,其呈现出预期的三环扭曲波瓣结构,图 8(c1)展示了相应的实验结果,其与数值模拟结果吻合,此时环间距 $\Delta r = 0.16, l_1 = l_2 = l_3 = 7$ 。图 8(a2)~(c2)所示为四环手性结构光场的结果,环间距 $\Delta r = 0.08, l_1 = -7, l_2 = l_3 = l_4 = 7$ 。这种复杂又灵活的手性结构为手性结构微加工提供了更多选择。

为了实现上述手性结构光场的旋转,在等相位 β

中引入相位梯度 $\Delta\beta$ 形成新的等相位,可以表示为 $\beta_{m+1} = \beta_m + \Delta\beta$,其中 β_m 表示序号为 $m (m \geq 1)$ 的等相位因子。图 9(a1)~(a3)所示为 3 个具有等相位梯度的环形子相位,此时 $\beta_1 = 0, \Delta\beta = 0.8\pi$ 且 $l_1 = l_2 = 5$ 。当引入等相位梯度时,环形子相位发生明显的变化。图 9(b1)~(b3)展示了相应的数值模拟光场分布,白色箭头标出同一扭曲波瓣。在引入相位梯度 $\Delta\beta$ 后,相邻扭曲光瓣之间旋转了一个角度。该偏转角 θ 可以表示为 $\theta = \Delta\beta / l$ 。图 9(c1)~(c3)所示为相应的光场实验结果,其手性结构分布与数值模拟结果完全吻合。

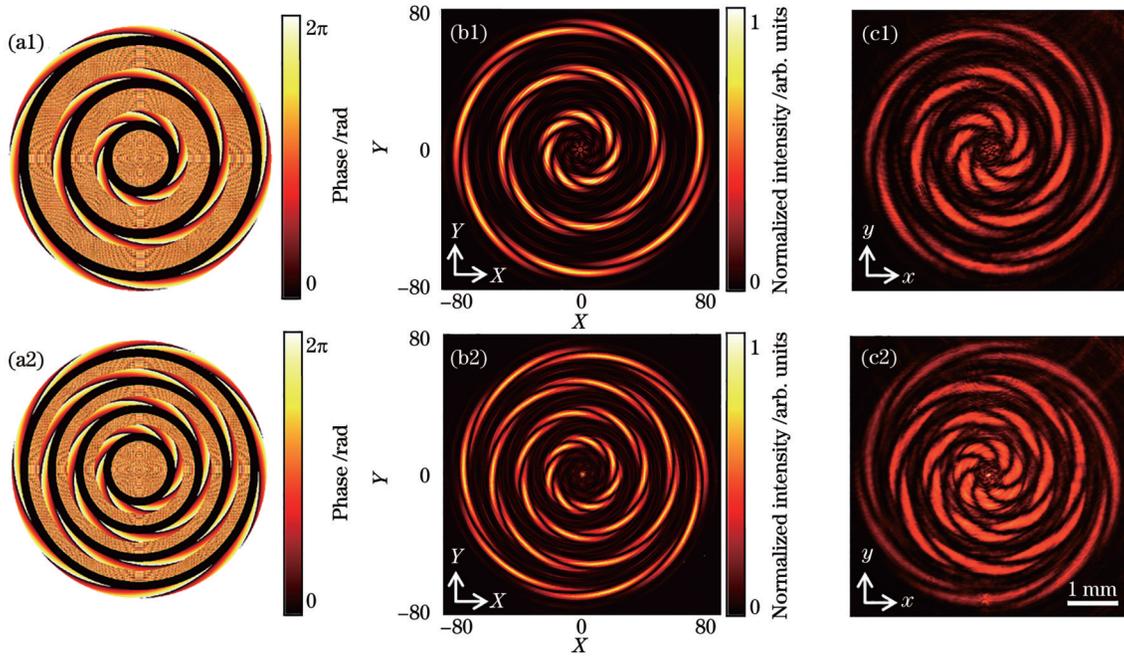


图 8 多环形手性结构光场。(a1)~(c1)三环形相位及光场;(a2)~(c2)四环形相位及光场
 Fig. 8 Multi-ring chiral structured light fields. (a1)–(c1) Three-ring phase and light fields; (a2)–(c2) four-ring phase and light fields

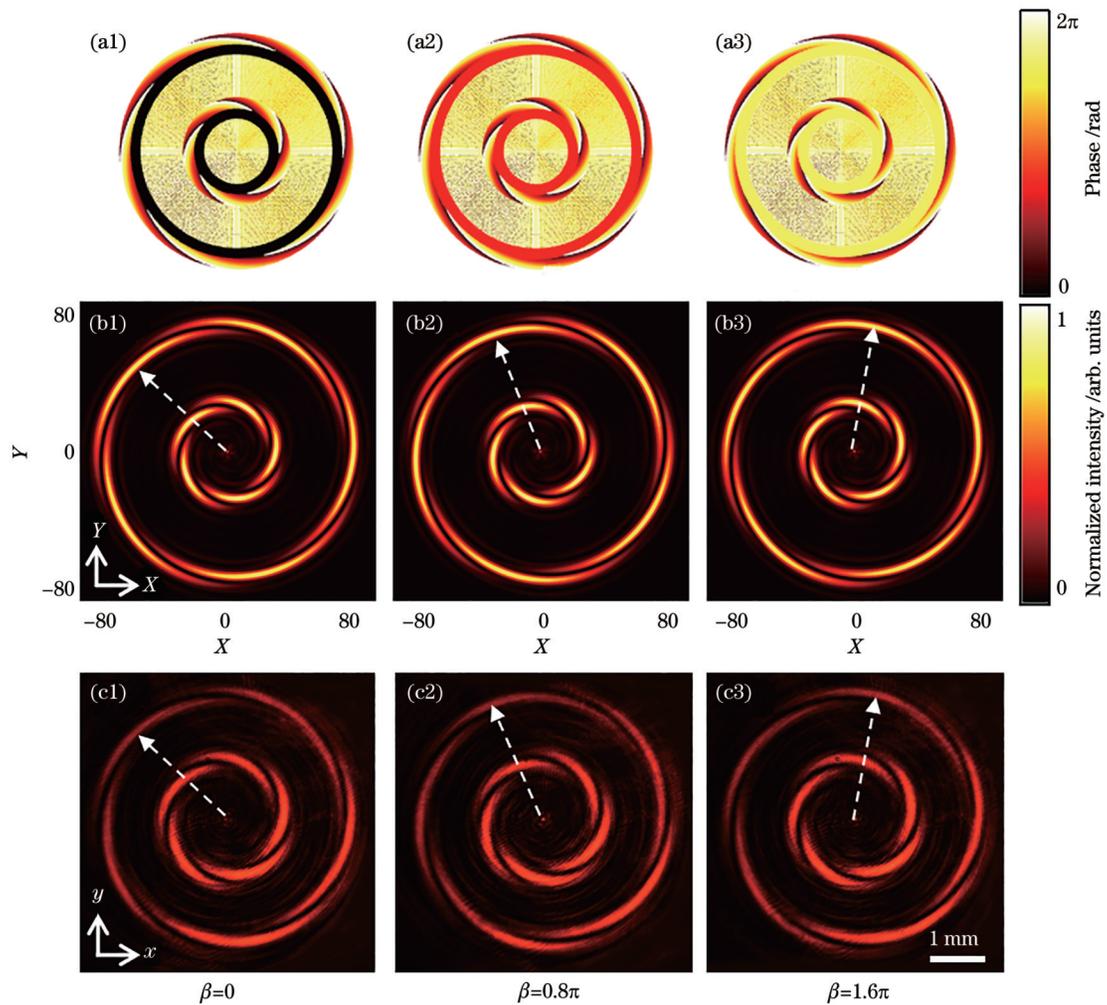


图 9 $\beta = 0, 0.8\pi, 1.6\pi$ 时的旋转特性。(a1)~(a3)双环形相位;(b1)~(b3)数值模拟光场;(c1)~(c3)实验光场
 Fig. 9 Rotating characteristics when $\beta = 0, 0.8\pi, 1.6\pi$. (a1)–(a3) Double annular phase; (b1)–(b3) numerical light fields; (c1)–(c3) experimental light fields

上述结果表明,通过改变等相梯度可以很容易地控制扭曲波瓣方向,而不是通过机械转动相位。在动态实验中,将具有相位梯度的环形子相位序列连续加载在 SLM 上,可以动态旋转该手性结构光场。动画 1 (https://www.opticsjournal.net/richHtml/gxxb/2024/44/8/0826002/SupplementalData/0826002_01.mp4) 模拟展现了动态加载环形相位序列实现手性结构光场旋转,等相相位梯度 $\Delta\beta = 0.1\pi$,初始等相相位 $\beta_1 = 0$,最大等相相位 $\beta_{20} = 1.9\pi$,拓扑荷数 $l_1 = l_2 = 5$ 。可以看出,内、外双环扭曲波瓣同向旋转,环形相位序列加载速度为 60 frame/s。动画 2 (https://www.opticsjournal.net/richHtml/gxxb/2024/44/8/0826002/SupplementalData/0826002_02.mp4) 展现了 $l_1 = -5$ 、 $l_2 = 5$ 的结果,其内、外两个扭曲波瓣的旋向相反,这为操纵手性结构光场提供了更高的自由度,这种旋转的优势也使得手性光束像光学扳手一样旋转和分选多粒子。

4 结 论

提出一种通过环形相位调制产生可调谐手性结构光场的方法。通过分别改变拓扑荷数大小、符号和等相相位梯度,可以灵活地控制手性结构光场的扭曲波瓣数量与扭曲方向以及旋转。除此之外,这种光场还可以通过连续改变等相相位梯度来旋转,而连续旋转的特性也为旋转粒子提供了可能。这些结构可控的手性光场为加工灵活的手性结构提供了可能,在光学微操纵及光通信领域也有较大的潜在应用价值。

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Generation and Manipulation of Tunable Chiral Structured Light Beams

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Abstract

Objective Vortex beam (VB) has attracted great attention due to its unique optical properties including a helical wavefront, phase singularity, and ability to carry orbital angular momentum (OAM) of $l\hbar$ per photon, where l is the topological charge, and \hbar is the reduced Planck constant. VBs have been widely used in super-resolution imaging, laser microfabrication, optical manipulation, and ultra-large capacity optical communication. Especially, OAM can twist molten material and can be used for chiral nanostructure microfabrication. In recent years, chiral structured light fields with twisted intensity distribution and OAM have attracted great research interest due to their advantages in optical microfabrication. Alonzo *et al.* constructed a spiral cone phase using the product of the spiral phase and cone phase and generated a spiral cone light field with chiral intensity distribution. Subsequently, Li *et al.* proposed a spiral light field with an automatic focusing effect by a power-exponential phase. However, these structures of chiral optical fields are simple. Therefore, generating a flexible and tunable chiral structured light field becomes important. However, the generation of flexible chiral light fields remains challenging. In this paper, we proposed a simple and efficient approach for generating tunable chiral structured beams (TCSB), which exhibited flexible adjustability and multi-ring chiral structures. Such light fields would be beneficial to flexible chiral structure micromachining, optical manipulation, and optical communications.

Methods We proposed and generated a TCSB by constructing an annular phase (AP) which consisted of multiple annular sub-phases (ASPs). Specifically, every sub-phase was constructed by introducing an equiphase and radial phase based on a classical spiral phase, and then a monocyclic TCSB was generated by imposing such ASP on an incident Gaussian beam. The number and direction of the twisted intensity lobes were flexibly and individually controlled by manipulating the topological charge, equiphase, and radial phase. Moreover, we used multiple ASPs to generate multi-ring chiral optical fields, which could be more flexible in practical applications. Experimentally, chiral light fields could be generated by phase modulation and observed via the CCD, as described in Fig. 5.

Results and Discussions The structures of the tunable chiral beams can be flexibly manipulated by controlling the topological charge (Fig. 6). The number and direction of the twisted intensity lobes are determined by the number and sign of the topological charge. By controlling the equal phase, the twisted lobe direction can be arbitrarily controlled (Fig. 9). More complex chiral structured beams with three-ring and four-ring structures are constructed, and this validates the effectiveness of our proposed approach. Additionally, the equal phase gradient is employed to control dynamically the rotation of the light fields (Video 1). The advantage of this rotation also makes this chiral beam beneficial for twisting transiently molten matter, machining complex chiral nanostructures, and sorting multiple particles.

Conclusions In summary, we have developed an effective method to generate TCSBs by multiple ASPs. The properties of the twisting lobes, including the twisting directions, lobe orientations, and lobe number can be freely manipulated by controlling the topological charge sign, magnitude, and equiphase, respectively. Our findings offer a novel promising technology to manufacture chiral microstructures. Moreover, the flexible TCSBs also provide an innovative method for optical manipulation and optical communications.

Key words physical optics; optical field manipulation; phase modulation; structured light field; chiral light field