第 52 卷第 8 期　　红外与激光工程　　2023 年 8 月
Vol.52 No.8　　Infrared and Laser Engineering　　Aug. 2023

液晶几何相位技术实现光场空间结构全维度调控

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摘　要：几何相位平面光学元件由于高效、紧凑及易集成等优点已被广泛用于光场空间结构调控。但以 q-plate 为代表的此类元件只提供自旋相关的波前控制能力，振幅调控能力的缺失导致无法利用光场的全部空间维度，严重阻碍了相关领域研究的进一步深化。笔者团队在国家自然科学基金等项目资助下，以液晶人工微结构中的几何相位为物理基础设计并论证一系列新型几何相位元件，解锁了平面光学技术对近轴结构光场的全维度调控能力，为高维经典及量子信息等需要依托光场调控技术的实验研究提供了重要工具。

关键词：几何位相；　液晶；　平面光学；　光场调控
中图分类号：O439　　**文献标志码：**A　　**DOI：**10.3788/IRLA20230396

随着现代光学的迅速发展，光学自旋-轨道耦合(Spin-Orbit Coupling, SOC)效应的揭示与研究深入使其在光场调控、显微成像、量子通信、光与物质相互作用等领域受到广泛关注。无论对于量子还是经典应用，目标 SOC 态与标量偏振态间的互易转换接口是实现该类结构光子态产生、调控及表征的重要物理途径。SOC 互易接口的物理实现需要自旋相关的空间光调制，目前有两种可行的技术路线：一种是包含空间光调制器，如硅基液晶或数字微镜的偏振干涉仪，这种装置虽然可以动态、灵活地操控光场矢量空间结构，但价格昂贵、装置复杂不便于集成；另一种则是基于空间变取向液晶或介电超表面几何位相原理的二元平面光学元件[1−2]，特点是易于低成本实现可嵌套的多功能集成，使其成为光场调控与微纳光子学研究的共焦点。然而，目前以 q-plate、J-plate 为代表的二元光学元件只能提供偏振自旋相关的波前调控[3−4]，无法精确控制光束的空间振幅。因此无法构建面向任意傍轴矢量本征模式的 SOC 互易接口，导致现有几何相位元件无法用于需要全维度调控光场空间结构的研究中。

为了解决上述问题，笔者课题组及合作团队基于液晶光控取向技术论证了一种能够对入射光场实施任意自旋共轭空间复振幅控制的几何相位元件。因该新型平面元件具有空间变化的光栅周期、深度和液晶取向等特征，故称之为结构几何位相光栅 (Structured Geometric Phase Grating, SGPG)[5−6]。图 1 为以 SGPG 为核心元件构建的 SOC 互易接口原理图，其中的 SGPG 被设计为将入射基模高斯模式转换为一对共轭正交拉盖尔-高斯模式 (携带径向模式)。与偏振光栅搭配使用即可实现任意目标 SOC 态与对应标量偏振基模态间的高效互易转换：即该自锁相装置可将任意标量偏振模式转换为对应高阶矢量模式，也可将产生的 SOC 态再次精确转换回能够高效耦合进单模光纤的标量偏振态。这一关键技术的论证为基于高阶 SOC 态的高维经典及量子光场制备、调控及接口技术研究提供了重要支撑。

此外，笔者联合团队还揭示并论证了基于液晶几何相位原理的矢量波前调控技术，开发出一系列具备光场空间结构全维度调控能力可商用的液晶几何相位元件。图 2(a) 和 (b) 分别展示了一种开发中

收稿日期：2023−07−03；　**修订日期：**2023−07−10

基金项目：国家自然科学基金项目 (62075050, 11934013, 61975047)

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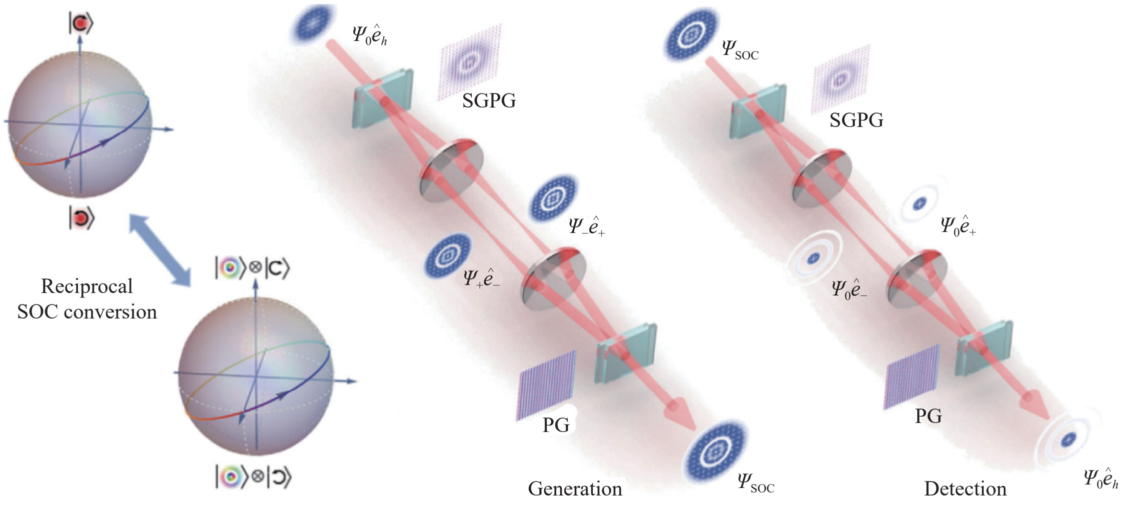

图 1 基于 SGPG 构建的任意 SOC 互易接口 (SGPG: 几何相位光栅, PG: 偏振光栅)

Fig.1 Schematic of reciprocal SOC interface based on SGPGs(SGPG: Structured geometric phase grating, PG: Polarizing grating)

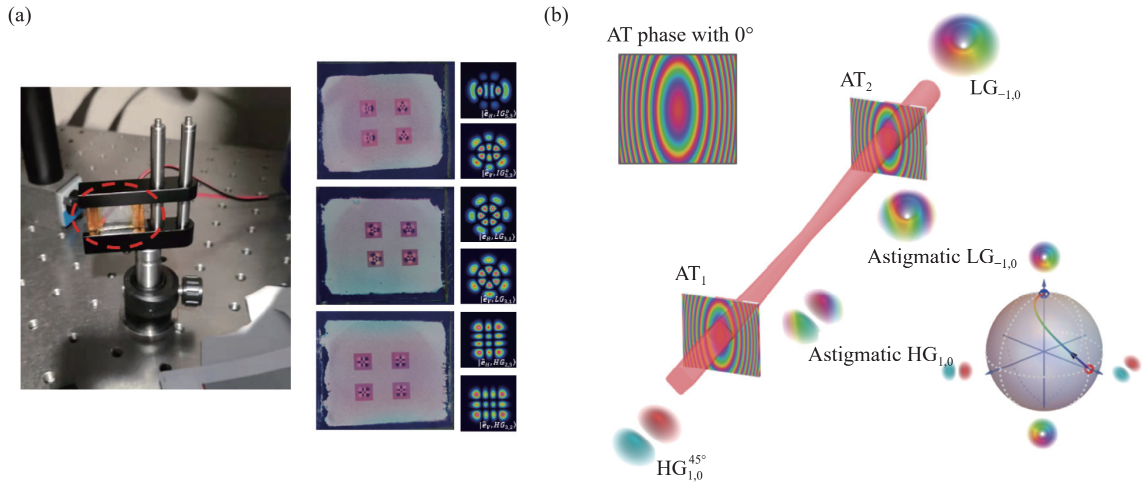

图 2 基于液晶几何相位原理的 (a) 高阶空间模式产生器与 (b) 空间模式转换器

Fig.2 (a) High-order spatial mode generator and (b) true zero-order convertor enabled by liquid-crystal geometric phase

的液晶高阶模式产生器和空间模式转换器[7–8]。其中液晶高阶空间模式产生器仅需单次通过该元件即可将入射光场精确转换为携带目标空间复振幅的高阶模式；而空间模式转换器则是用于高阶空间模式变换的“真零级波片”，可实现同阶数 Laguerre–Hermite–Gaussian 模式群内的无相差转换[9]。上述系列技术成果为全维度光场空间结构调控基础及应用研究提供了新的便捷途径。

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Full control of structured light with liquid-crystal geometric phase

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Abstract:

Significance Flat optics elements based on geometric phase, owing to their low cost, integrability, and versatility, have been widely used in shaping of light's spatial structure. Notably, current SOC (spin-orbit coupling) devices, such as the best-known q-plates, provide only spatial phase modulation with SoP (state of polarization)-switchable behavior. The absence of amplitude control prevents research scholars from accessing light's full spatial degrees of freedom, thus limiting their application in corresponding studies. This team demonstrates a series of novel flat optics elements with liquid-crystal geometric phase, which unlocks the full-field control of paraxial structured light, providing a powerful toolbox for relevant experimental studies and especially for high-dimensional classical/quantum information.

Progress To control a paraxial SOC state in all its spatial degrees of freedom, spin-dependent complex amplitude modulation provides an essential alternative. But up to now, it has remained elusive with flat optics. This paper fills this gap by putting forward a new type of geometric phase element termed structured geometric-phase grating (SGPG), featuring a spatially-varying grating cycle, depth and orientation (Fig.1). In addition, the joint team also demonstrated the vector wavefront control technology based on the geometric phase of liquid crystals, and developed a series of liquid crystal geometric phase elements (e.g., mode convertor (Fig.2(a)) and high-order spatial mode generator (Fig.2(b)) with the full dimensional control ability.

Conclusions and Prospects Such a crucial advance, compared with the present geometric phase elements, unlocks the control of paraxial structured light in all spatial dimensions, and paves the way for arbitrary SOC conversion via flat optics. This capability makes it a key extra-/intracavity component to build a structured laser that has greater tunability in beam structure, compared with reported systems based on q-plate and metasurface. For quantum optics, the proposed reciprocal SOC interface allows to implement a Bell measurement for arbitrary SOC states, which is the basis for the teleportation scheme for SOC photon pairs. Moreover, owing to the capability of full-field spatial mode control, the device also paves the way for quantum control of high-dimension photonic skyrmions. Beyond single-beam vector mode control, this principle can further realize multiple vector mode control through the addition of a Dammann grating structure. This represents a promising way to develop information exchange and processing units working for photonic SOC states, that is, vector-mode multiplexers and demultiplexers.

Key words: geometric phase; liquid crystal; flat optics; light field shaping

Funding projects: National Natural Science Foundation of China (62075050, 11934013, 61975047)