光场空间结构全维度非线性调控理论及应用

吴海俊[1]，于丙石[1]，姜嘉琪[1]，赵 波[1]，Carmelo Rosales-Guzmán[1]，白振旭[2]，朱智涵[1*]，史保森[3*]

(1. 哈尔滨理工大学 黑龙江省量子调控重点实验室 大珩协同创新中心，黑龙江 哈尔滨 150080；
2. 河北工业大学 先进激光技术研究中心，天津 300401；
3. 中国科学技术大学 中国科学院量子信息重点实验室，安徽 合肥 230026)

摘　要：得益于数字全息与几何相位平面光学技术的逐渐成熟，空间结构光场调控及应用研究已在线性光学领域取得蓬勃发展。与之相比，以非线性光学为物理途径的相关研究虽能实现许多关键功能(如光场间信息交互) 却仍处于起步阶段。笔者课题组在国家自然科学基金等项目的支持下，近期聚焦光场调控与非线性光学领域前沿问题“空间多模态经典及量子光场的非线性产生、变换及接口技术”，重点突破了空间全维度参量变换理论与相关技术瓶颈，取得了一系列理论及应用创新成果，为高维量子光学相关实验研究的开展打下坚实基础。

关键词：结构光场；　非线性光学；　光场调控

中图分类号：O437　　**文献标志码**：A　　**DOI**：10.3788/IRLA20230397

现代光学的发展始终与人们对光场自由度及相应维度的认知与应用升级保持同步。以操控光场模态结构为目标的光场调控研究也因此成为推动光学理论及应用前沿的核心手段，特别是近 30 年来对光场空间结构及其高维空间模态的开发与利用，使其逐步成为前沿热点[1–2]。光场调控许多关键功能 (诸如光场间信息交互与频率接口操作) 的实现都需要以非线性光学为物理手段[3]。因此，非线性光场调控的研究与发展对推动现代光学发展至关重要。非线性光场调控研究当下的核心任务是：探索如何利用光场间、光与物质间的非线性相互作用对目标调控光场在更多维度中 (特别是空间模态) 实现按需操控；并以新维度为牵引深化非线性光学理论研究，揭示多模态非线性相互作用中的新物理与新效应，推动、发展基于非线性光场调控技术的新概念与新应用。

笔者课题组在国家自然科学基金的支持下，近期聚焦光场调控与非线性光学领域前沿问题“空间多模态经典及量子光场的非线性产生、变换及接口技术”，重点突破了空间全维度参量变换理论与相关技术瓶颈，取得了一系列理论及应用创新成果。

1) 理论创新方面：任意空间结构光场的非线性产生与频率变换为基于空间模态编码的新型高容光通信、高维光学量子信息等应用基础研究提供了重要物理途径。其中，轨道角动量 (OAM) 模态的参量产生、调控与表征技术已被广泛研究。但 OAM 以外的冗余空间维度 (如径向模态及偏振矢量结构) 因非线性变换规律尚不明确，导致在实验研究中无法被重复利用且多被当做噪声维度避而远之，这严重阻碍了通过非线性调控手段对光场完整空间维度的开发与利用。为此，笔者团队系统性突破了相关理论瓶颈：首次给出小信号三波混频中的柱坐标系下空间模态全自由度参量变换理论[4](见图 1(a)) 以及非线性自旋-轨道耦合调制下的参量极化场模型[5](见图 1(b))。合并使用上述两项理论工具即可完备描述、预测光场矢量空间结构 (振幅、相位及偏振) 在任意旁轴二阶参量过程中的非线性传播变化规律[6]。以理论工具为牵引，笔

收稿日期：2023−06−10；　修订日期：2023−06−25

基金项目：国家自然科学基金项目 (62075050, 11934013, 61975047)；黑龙江省自然科学基金项目 (UNPYSCT-2020185, LH2022A016)

作者简介：吴海俊，男，博士生，主要从事非线性光学方面的研究。

导师(通讯作者)简介：朱智涵，男，教授，博士生导师，博士，主要从事非线性光学方面的研究。

通讯作者：史保森，男，教授，博士生导师，博士，主要量子信息与量子光学方面的研究。

者团队提出非线性像散频率接口技术概念 (见图 1(c)), 并揭示了像散参量过程中新物理效应“反常 OAM 守恒”, 深化了人们对非线性 OAM 守恒原理的认知[7], 相关成果受到国际权威学者团队高度认可并在近期领域综述中多次积极评价[1−3]。

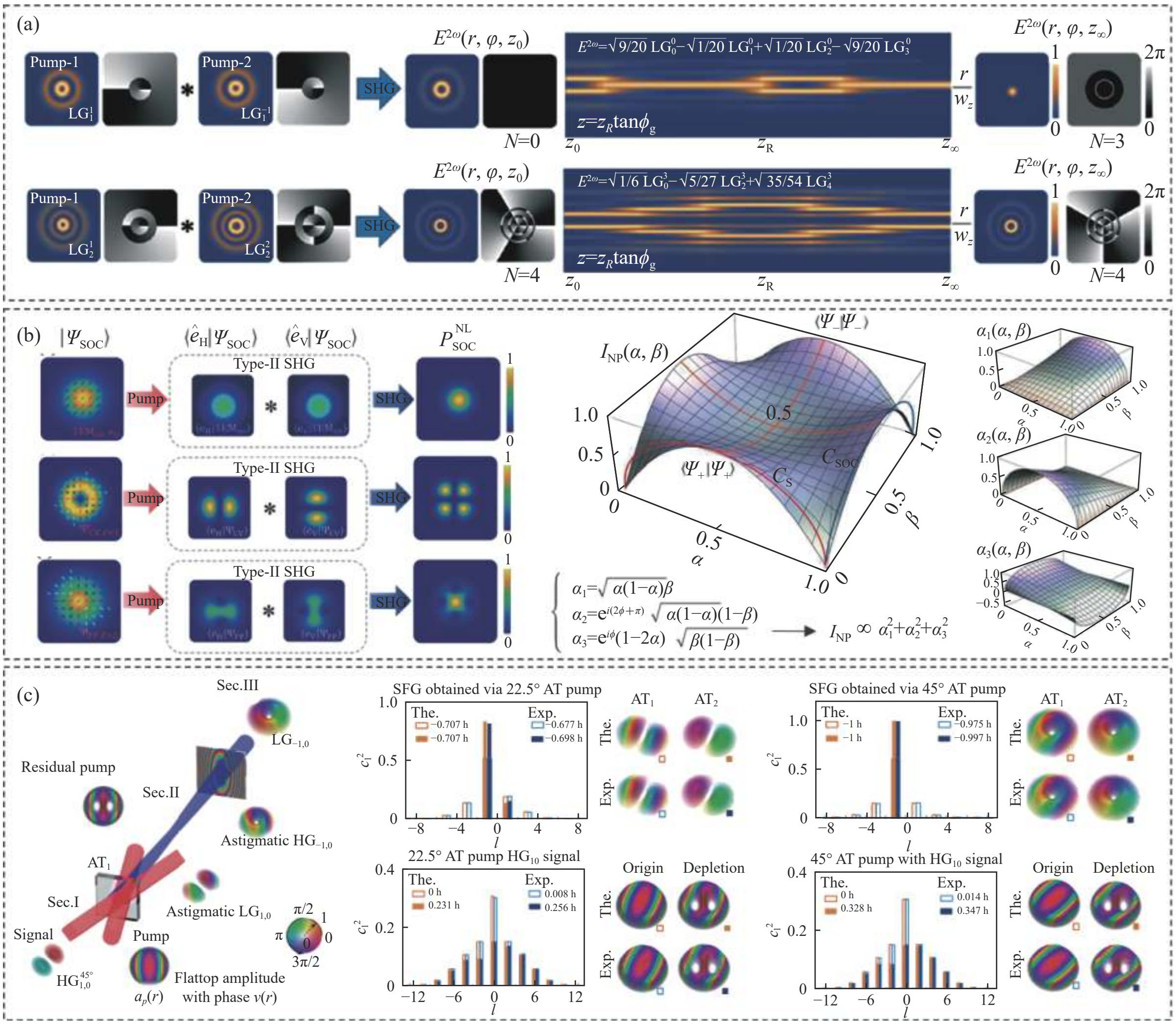

图 1 理论研究进展, 包括 (a) LG 模式空间模式全域选择定则与 (b) SOC 调制的非线性极化理论 (c) 像散参量过程中的反常 OAM 守恒

Fig.1 Theoretical advances in structured nonlinear optics, including (a) full field selection rules based on LG basis, (b) SOC-mediated nonlinear polarizations, and (c) anomalous OAM transfer in nonlinear astigmatic transformation

2) 应用创新方面: 基于受激参量过程的频率转换是应用最为广泛的非线性光场调控技术之一。其中“频率接口”技术既可实现不同频段信息光场间的交互, 还可将红外频率等不便于直接观测的信号转换至硅基探测器的优势探测频段[8]。然而, 非线性过程的增益 (或量子效率) 与相互作用光场的偏振及空间模态相关, 这会导致空间模态编码的高维光子态在非线性转换过程中失去原有模态结构。针对这一瓶颈问题, 笔者团队以上述理论为指导, 提出一种基于超高斯泵浦偏振 Sagnac 非线性干涉仪的频率变换技术, 在国际上首次实现了与信号空间模态及偏振结构无关的保形频率接口[9−10](见图 2(a))。该技术可将任意待转换信号的空间模态及所承载的自旋拓扑结构高保真相干传递到新的频率, 这一关键技术的突破为面向空间多模态编码的量子接口最终实现奠定重要基础。该光学系统的逆向使用还可实现具有特定空间模态及矢量偏振结构的高维纠缠态制备。在此基础上, 通过引入超高斯涡旋泵浦技术, 该装置还可在一

定范围内实现振幅结构无关 OAM 频率接口,在不影响信号光场径向动量模态的情况下实现频率与 OAM 的同步变换[11](见图 2(b))。新理论[4] 还启发了基于空间多模态非线性光学效应的新应用,笔者团队据此提出一种空间分辨自相关测量技术,首次实现超快光场的时域包络-空间模态联合表征[12](见图 2(c))。该技术中的模态间相位信息除用于空间模态识别外,还可用于电场复振幅表征,结合几何相位元件[13] 后有望以十分低廉的成本 (相较于 FROG 技术) 实现超快光场表征。

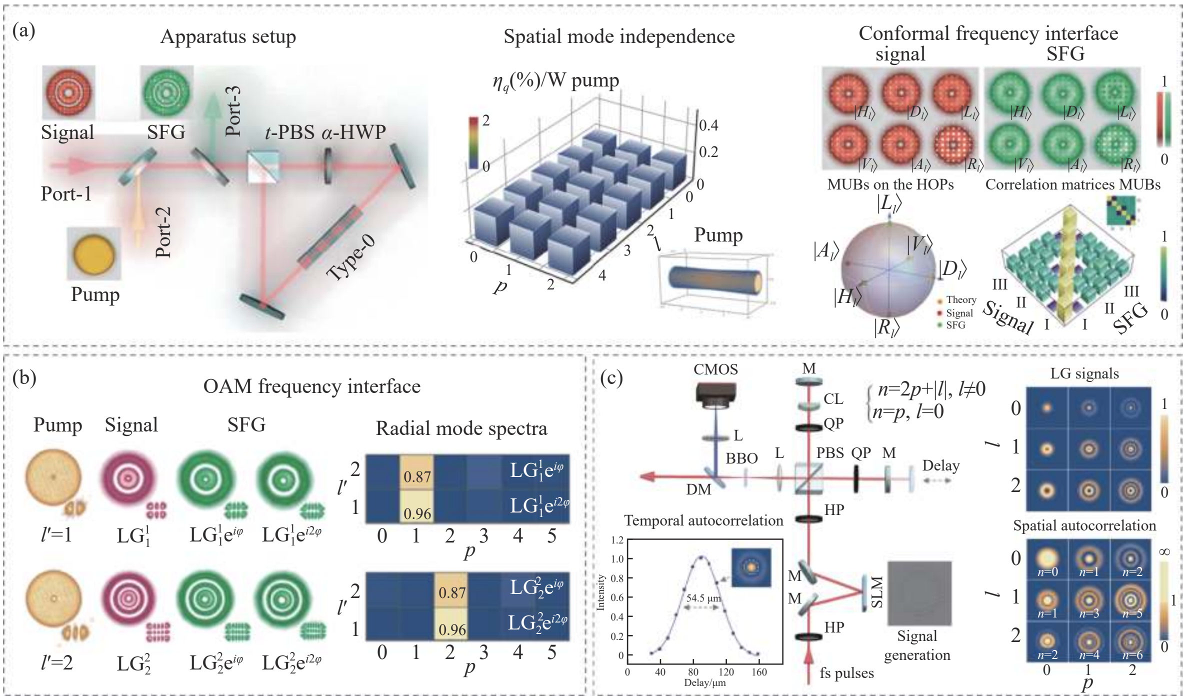

图 2 应用研究进展,包括 (a) 矢量空间结构保形频率接口,(b) 空间振幅无关的非线性 OAM 转换以及 (c) 空间模态分辨自相关测量技术

Fig.2 Application advances in structured nonlinear optics, including (a) conformal frequency interface for vectorial spatial modes, (b) nonlinear OAM conversion with spatial-amplitude independence, and (c) spatially-resolved autocorrelation measurement

上述系统性研究成果填补了非线空间结构光场全维度调控的关键理论空白,进一步拓展光场调控相关领域的研究思路,对结构激光技术、高维量子态调控、偏振分辨上转换成像等相关研究具有重要指导意义。

参考文献:

[1] Forbes A, de Oliveira M, Dennis M R. Structured light [J]. *Nature Photonics*, 2021, 15(4): 253-262.

[2] He C, Shen Y, Forbes A. Towards higher-dimensional structured light [J]. ***Light*: *Science & Applications***, 2022, 11(1): 205.

[3] Buono W T, Forbes A. Nonlinear optics with structured light [J]. *Opto-Electronic Advances*, 2022, 5(6): 210174.

[4] Wu H J, Mao L W, Yang Y J, et al. Radial modal transitions of Laguerre-Gauss modes during parametric up-conversion: Towards the full-field selection rule of spatial modes [J]. *Physical Review A*, 2020, 101(6): 063805.

[5] Wu H J, Yang H R, Rosales-guzmán C, et al. Vectorial nonlinear optics: Type-II second-harmonic generation driven by spin-orbit-coupled fields [J]. *Physical Review A*, 2019, 100(5): 053840.

[6] Yang H R, Wu H J, Gao W, et al. Parametric upconversion of Ince-Gaussian modes [J]. *Optics Letters*, 2020, 45(11): 3034-3037.

[7] Wu H J, Yu B S, Jiang J Q, et al. Observation of anomalous orbital angular momentum transfer in parametric nonlinearity [J]. *Physical Review Letters*, 2023, 130(15): 153803.

[8] Zhou Zhiyuan, Shi Baosen. Progresses in infrared detection based on spectrum transducing (invited) [J]. ***Infrared and Laser Engineering***, 2023, 52(5): 20230165. (in Chinese)

[9] Wu H J, Yu B S, Zhu Z H, et al. Conformal frequency conversion for arbitrary vectorial structured light [J]. *Optica*,

2022, 9(2): 187-196.

[10] Wu H J, Zhao B, Rosales-guzmán C, et al. Spatial-polarization-independent parametric up-conversion of vectorially structured light [J]. ***Physical Review Applied***, 2020, 13(6): 064041.

[11] Jiang J Q, Wu H J, Yu B S, et al. Nonlinear orbital angular momentum conversion with spatial-amplitude independence [J]. ***Journal of Optics***, 2022, 25(2): 024004.

[12] Yu B S, Li C Y, Yang Y, et al. Directly determining orbital angular momentum of ultrashort laguerre-Gauss pulses via spatially-resolved autocorrelation measurement [J]. ***Laser & Photonics Reviews***, 2022, 16(9): 2200260.

[13] Li C Y, Liu S J, Yu B S, et al. Toward arbitrary Spin-Orbit flat optics via structured geometric phase gratings [J]. ***Laser & Photonics Reviews***, 2023, 17(5): 2200800.

Nonlinear control of structured light in all spatial degrees of freedom

Wu Haijun[1], Yu Bingshi[1], Jiang Jiaqi[1], Zhao Bo[1], Carmelo Rosales-Guzmán[1], Bai Zhenxu[2], Zhu Zhihan[1*], Shi Baosen[3*]

(1. Wang Da-Heng Center, Heilongjiang Key Laboratory of Quantum Control, Harbin University of Science and Technology, Harbin 150080, China;
2. Center for Advanced Laser Technology, Hebei University of Technology, Tianjin 300401, China;
3. CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China)

Abstract:

Significance Driven by the recent gradual maturity of digital holography and flat optics with geometric phase, great advances have been made in shaping and application of structured light in the linear optics. In comparison, relevant study based on nonlinear optics, although enabling many crucial functions, such as information exchange between light fields or photons, is still in its infancy. Focusing on this frontier topic of structured nonlinear optics-i.e., nonlinear generation, transformation and interface of classical/quantum states encoded by complex spatial modes-some theoretical and technical bottlenecks to parametrically control all the spatial dimensions of light have been broken. These results lay a solid foundation for future relevant studies on high-dimensional quantum optics experiments.

Progress Advances in parametrically controlling all the spatial dimensions of light can be divided into theoretical and applied aspects. On the theoretical side, a parameter transformation theory for the full-field selection rule of spatial modes in cylindrical coordinates during small signal three-wave mixing (Fig.1(a)) and a theoretical model of spin-orbit-coupling-mediated nonlinear polarizations (Fig.1(b)) were first proposed. These two theoretical tools can be used together to describe and predict the nonlinear propagation of the vector spatial structure of light fields (amplitude, phase, and polarization) in any paraxial second-order parameter process. Guided by theoretical tools, a nonlinear astigmatism frequency interface has been proposed (Fig.1(c)). In this parametric astigmatism system, an unexpected new physical effect called anomalous orbital angular momentum conservation has been uncovered. This discovery renewed the perception of the nonlinear orbital angular momentum conservation. On the applied side, a frequency conversion technique based on a Sagnac nonlinear interferometer pumped by a super-Gauss mode was first proposed to achieve a spatial polarization independent conformal frequency interface (Fig.2(a)). On this basis, the apparatus can also act as a spatial-amplitude independent frequency interface for orbital angular momentum, which enables a simultaneous conversion of frequency and orbital angular momentum without impacting on the radial mode of signals, with the introduction of vortex super-Gaussian modes (Fig.2(b)). What's more, the new theory has also inspired a new application called spatially-resolved autocorrelation technique, which is based on spatially multimodal nonlinear optical

effects. This technique allows for the characterization of the temporal envelope and spatial modes of ultrafast light simultaneously (Fig.2(c)).

Conclusions and Prospects These systematic research results fill the key theoretical gaps in the field of nonlinear control of structured light in all spatial degrees of freedom. They also provide inspiration for new ideas in the field of light field shaping and have significant implications for related studies, such as structured laser technology, modulation of high-dimensional quantum states and polarization-resolved up-conversion imaging.

Key words: structured light; nonlinear optics; light field shaping

Funding projects: National Natural Science Foundation of China (62075050, 11934013, 61975047); Natural Science Foundation of Heilongjiang Province of China (UNPYSCT-202018, LH2022A016)