非线性光场调控实现12倍相位超分辨实时干涉测量

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摘　要：光学干涉仪是现代精密测量技术的核心支撑，但其分辨率受到光源波长的限制，无法通过无限减小波长提高分辨率，而“相位超分辨”即是指设法解决光源波长限制的技术手段。目前“相位超分辨”研究主要通过调控N光子纠缠态的途径实现，但是由于N光子纠缠态制备与调控的极高难度和符合计数的极低效率使得该途径无法用于实际测量。针对这一瓶颈，笔者联合团队利用轨道角动量 (OAM) 相干态在光学超晶格中的级联参量上转换过程高效构造、提取多光子复振幅信号。实现了$N=12$倍的相位超分辨干涉信号的实时测量，为发展可实际应用的高倍率相位超分辨干涉测量技术提供了一条全新的物理途径。

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随着科技水平的不断进步，超高测量精度技术及仪器逐渐成为了前沿科学必不可少的工具。在现代精密测量科学中，高测量精度的光学干涉仪计量技术及仪器扮演着核心支柱角色，从否定以太假说的初代迈克尔逊干涉仪到能够观测引力波事件的激光干涉仪引力波天文台[1−2]，干涉仪的性能伴随激光与光场调控技术已经实现了跨越多数量级的提升。任何干涉仪的性能很大程度上取决于其相位分辨率和灵敏度，二者分别受到了光源的德布罗意波长和散粒噪声极限的限制[3]，由于极短波长光场易被吸收且难以操控的特性，使得干涉仪无法通过缩短波长的方式无限提升其分辨率，而“相位超分辨”是指设法解决光源波长限制的技术手段。

目前，实现相位超分辨的主要途径是通过N光子纠缠态的制备和调控。这种方法基于以下原理：首先，N光子纠缠态的等效德布罗意波长取决于光子的波长λ和数量N，即λ/N；其次，散粒噪声极限来源于光场振幅 (即光子数) 与光场相位之间的不确定性关系，即$\Delta\varphi\Delta N\geqslant 1$。$N$光子纠缠态中，最大的不确定度是光子的数量，因此具有最小的相位不确定度，可以用海森堡极限$\Delta\varphi=1/N$表示，从而突破了散粒噪声极限$\Delta\varphi=1/\sqrt{N}$的限制；最后，可以通过统计N光子符合计数的方式提取和记录具有λ/N等效德布罗意波长的复振幅信号。

该途径的优势在于可以同时实现“相位超分辨”与“相位超敏感”。但多光子态的制备与调控难度随N呈指数增加，以及极低的符合测量效率 (如$N=10$时，干涉复振幅信号每个数据点的采集都需要数小时的符合测量且干涉可见度较差[4])，共同限制了该途径实现超分辨干涉测量的可实际应用。即使对于$N=2$的最简情况，在昂贵超导探测器与周期极化晶体技术加持下即便能够同时实现相位超分辨与超敏感[5]，但

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是低于皮瓦量级的信号光子流使其仍然难以具备实际应用潜力。值得注意的是，在 SU(2) 干涉仪中追求相位平衡位置附近无穷小区域的“相位超敏感”只有在完美的传输探测效率和足够的光功率条件下 (千瓦激光器) 才有意义。相比之下，利用低成本的探测器，特别是实现等效短德布罗意波长的实时干涉测量将更有意义。

为了解决上述问题，笔者联合团队基于非线性光场调控物理研究成果[6–7]，论证了一种低测量成本的“结构非线性光学”实时相位超分辨测量方案。利用轨道角动量 (OAM) 相干态在参量上转换过程中的模态结构演化模拟$N00N$态在 SU(2) 干涉仪中的光子数模态演化行为，以更加高效的主动手段制备了携带相位信息的多光子振幅信号。

如图 1(a) 所示，泵浦光是由正交偏振 ($|\hat{e}_+\rangle, |\hat{e}_-\rangle$) 的拉盖尔-高斯模式 ($LG^p_{\pm l}$) 叠加所形成的自旋轨道耦合 (SOC) 模态，将 SOC 模态$|\psi_{SOC}\rangle = \sqrt{1/2}(|\hat{e}_+, LG^0_{+l}\rangle + e^{i\varphi}|\hat{e}_-, LG^0_{-l}\rangle)$入射准周期光学超晶格中，利用其多重准相位匹配的特性，实现了$N(=2,3,4)$倍的携带位相超分辨信号的相干态产生。由于本方案是通过参量上转换过程来提升干涉仪分辨率，可知信号波长在级联上转换中会逐步减小，阻碍了分辨率的提升 (如携带$e^{i4\varphi}$的信号波长为 390 nm，已经接近紫外光谱的边缘)。但由于已获得的N倍超分辨的相位信息承载在 OAM 模态上，与光场纵模无关。因此，利用参量下转换降低超分辨信号频率后，再次级联参量上转换，最终实现了$N = 12$倍的相位超分辨干涉信号，且此时信号强度仍然肉眼可见，仅需低成本光电探测器即可实现实时记录 [8–9]。此外，与利用N光子纠缠态实现超分辨测量的方式类似，当$N > 2$时同样会出现除目标模态$N00N$以外的噪声模态。但可以通过现有成熟的空间模式投影技术提取出目标模态 (文中方案为共轭 OAM 模态，$\sqrt{1/2}\left(|LG^0_{+N}\rangle \pm e^{iN\varphi}|LG^0_{-N}\rangle\right) \overset{proj.}{\rightarrow} \sqrt{1/2}\left(1 \pm e^{iN\varphi}|LG^{p'}_0\rangle\right)$)。通过该技术，本方案在实验上实现了近乎完美 ($\approx 1$) 的干涉可见度，如图 1(b) 所示。

值得注意的是，在$N = 2$的相位超分辨干涉信号产生过程中，使用 II 型二次谐波产生 (SHG) 的 SOC 模态可以避免不必要的模态噪声生成，但此时相位超分辨干涉信号变成了纯标量模式，无法再实现 II 型 SHG 过程。这启发了笔者团队设计一种设备，可以将标量模式转换为相关的 SOC 模态，同时保证其所携带的位相信息不变。即$\sqrt{1/2}|\hat{e}_D\rangle\left(|LG^0_{+N}\rangle - e^{iN\varphi}|LG^0_{-N}\rangle\right) \overset{SOC}{\leftrightarrow} \sqrt{1/2}\left(|\hat{e}_+, LG^0_{+N}\rangle + e^{iN\varphi}|\hat{e}_-, LG^0_{-N}\rangle\right)$，其中$|\hat{e}_D\rangle = \sqrt{1/2}\cdot\left(|\hat{e}_+\rangle + |\hat{e}_-\rangle\right)$表示对角偏振态。通过该操作后，可以在

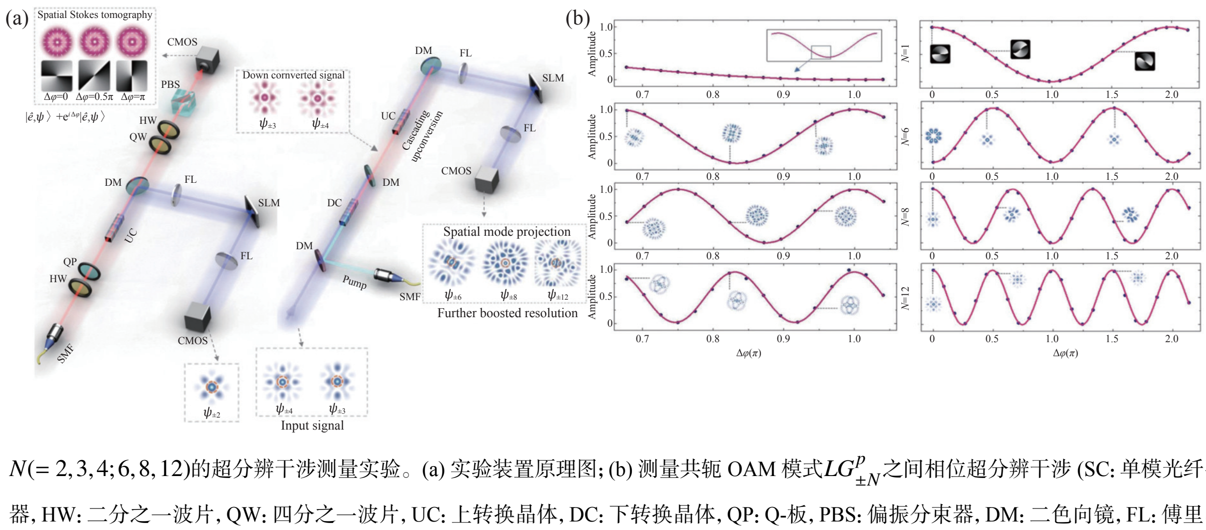

图 1 $N(=2,3,4;6,8,12)$的超分辨干涉测量实验。(a) 实验装置原理图；(b) 测量共轭 OAM 模式$LG^p_{\pm N}$之间相位超分辨干涉 (SC：单模光纤准直器，HW：二分之一波片，QW：四分之一波片，UC：上转换晶体，DC：下转换晶体，QP：Q-板，PBS：偏振分束器，DM：二色向镜，FL：傅里叶透镜，SLM：空间光调制器，CMOS：相机)

Fig.1 Experimental demonstration of superresolution interferometric measurements for $N(=2,3,4;6,8,12)$. (a) Schematic of the experimental setup; (b) Measured superresolved interference between conjugate OAM modes $LG^p_{\pm N}$(SC: single-mode fiber collimator, HW: half-wave plate, QW: quarter-wave plate, QP: Q-plate, UC: upconversion crystal, DC: downconversion crystal, PBS: polarizing beam splitter, DM: dichroic mirror, FL: Fourier lens, SLM: spatial light modulator, CMOS: camera)

后续的参量上转换过程中,完全消除不需要的噪声模态,从而极大提高最终干涉信号的可检测能量。

如图 2 所示,笔者联合团队基于液晶几何相位的零阶像散变换原理[10] 设计了一个几何相位元件,当标量模式的超分辨干涉信号通过该元件时,两条路径内的信号将会发生相对旋转,其中一路信号将会转换成另外一路信号的互补模式$\sqrt{1/2}|e_A\rangle(|LG^0_{+N}\rangle+e^{iN\varphi}|LG^0_{-N}\rangle)$,其中,$|e_A\rangle=\sqrt{1/2}(|e_+\rangle-|e_-\rangle)$表示反对角偏振态。因此,最后输出光束将被转换为可以在 II 型 SHG 过程中使用的 SOC 模态。在不久的将来,借助该设备和 mJ 脉冲激光器将有望实现$N>100$倍的超分辨率干涉测量。

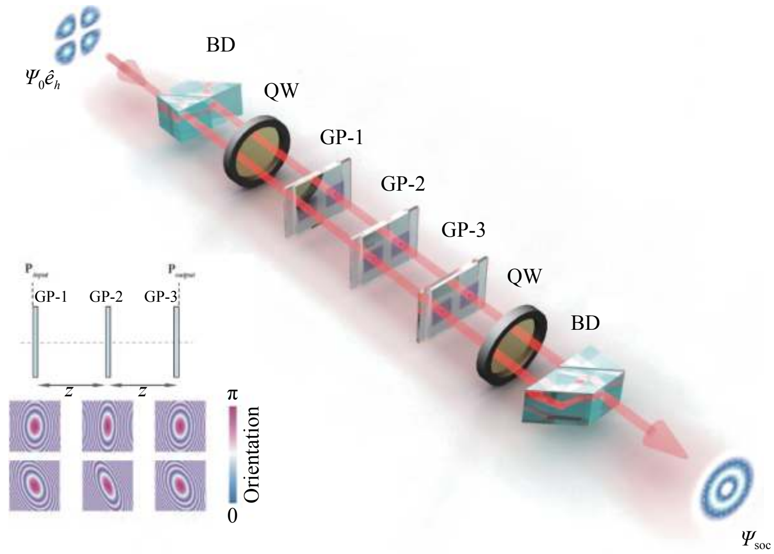

图 2 进行中的关键技术改进:基于液晶几何相位实现真零阶像象散变化 SOC 转换器原理图 (BD: 光束偏移棱镜, QW: 四分之一波片, GP: 几何相位元件)

Fig.2 Key technological improvement in the ongoing study, a SOC convertor based on true zero-order astigmatic transformation enabled by liquid-crystal geometric phase(BD: Polarizing beam displacing prism, QW: Quarter-wave plate, GP: Geometric phase elements)

文中研究将位相信息编码进泵浦光场轨道角动量自由度,利用受激光参量过程主动构造多光子振幅,使得系统实际应用上的绝对性能在相较传统途径有了质的飞跃,此外,由于光场具有众多可调控自由度,将位相信息编码到光场偏振自由度的同时利用高次谐波产生过程实现位相信息成倍增加同样也是一种可行的技术途径[11]。

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Twelvefold phase superresolution interferometric measurement in real time via nonlinear light field control

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Abstract:

Objective Optical interferometry metrology techniques and devices are pillars of modern precision metrology. With the development of laser and light field shaping technologies, their performance has achieved significant improvements across multiple orders of magnitude. However, they are still limited by the wavelength of the light source. Due to the easy absorption and difficult manipulation of extremely short-wavelength optical fields, the resolution of interferometers cannot be infinitely improved by simply reducing the wavelength. "Phase superresolution" refers to the technological means to overcome the limitation imposed by the light source wavelength. Currently, research on phase superresolution mainly focuses on manipulating N-photon entangled states to achieve this goal. However, the extremely high difficulty in preparing and controlling N-photon entangled states, as well as the low efficiency of coincidence counting, renders this approach impractical for actual measurements. Therefore, it is necessary to realize real-time phase superresolution measurements to meet practical application requirements.

Methods To overcome these aforementioned cutting-edge challenges, the collaborative team has taken a novel approach of utilizing the modal structure evolution of orbital angular momentum (OAM) coherent states during parametric conversion processes to simulate the behavior of N00N states in SU(2). Consequently, they have achieved a more efficient means of actively preparing multi-photon amplitude signals carrying interferometer arm phase information.

Results and Discussions Phase superresolution signal carried by coherent states with an N-fold enhancement (N=4) has been achieved in a single artificial metamaterial crystal using multiple quasi-phase matching in quasi-periodic optical superlattice (Fig.1(a)). By cascading parametric conversions of the superresolution signal, a phase superresolution interference signal with enhanced resolution of up to N=12 has been realized. Remarkably, the signal intensity remains visible to the naked eye, and real-time recording can be achieved with low-cost photodetectors. In the near future, using this scheme with appropriate technical improvement (Geometric phase elements) with N>100, corresponding to an extreme-ultrviolet de Broglie wavelength, is expected to be an attainable goal.

Conclusions The preparation of N-photon entangled states typically involves the use of spontaneous parametric down-conversion (SPDC) process to convert the short-wavelength pump light into a photon stream with extremely low efficiency. The target signal is then selected using inefficient photon coincidence counting systems. As a result, the performance of such systems is significantly lower compared to interferometers that directly utilize the pump light source for sensing. In the approach proposed by the collaborative team, spatial modes are employed to encode phase information into the pump light field. By actively constructing multiphoton amplitudes through a strong stimulated parametric process, the signal power loss incurred in cascaded nonlinearities can be regained through phase-sensitive amplification, leading to a significant improvement in system performance. Therefore, their result paves a promising way for the development of practical phase superresolution interferometry techniques and instruments for metrology.

Key words: phase superresolution; nonlinear optics; light field control

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