High-dimensional orbital angular momentum comb

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Orbital angular momentum (OAM) of photons offers an additional degree of freedom by accessing the spatial structure of light beams. The most attractive property of OAM is its infinite number of eigen states. These OAM states constitute an infinite dimensional Hilbert space, contributing to a series of high-dimensional scenarios which could not be realized before.

Since its first introduction for light beams 30 years ago,[1] OAM has benefited many advanced applications ranging from classical to quantum physics.[2–6] Much effort has been made for OAM generation. Stable OAM sources, including those on chips have been demonstrated, and the focus of OAM study has turned gradually from academic research to practical applications. Despite advances, there still exist challenges that have not yet been well addressed, for example, in the generation of multiple OAM components in one beam simultaneously.

Reporting in *Advanced Photonics Nexus*,[7] Shiyao Fu, Chunqing Gao, and colleagues from Beijing Institute of Technology, propose a simple azimuthal binary phase modulation scheme that can transform a Gaussian beam into a structured light beam containing multiple OAM components with equal spacing and uniform power. This structured light beam presents a comb distribution in the OAM domain, so it is termed an "OAM comb." Their approach provides a convenient way to simultaneously tailor multiple OAM channels, with the potential to impact many fields, including optical information technology.

Rigorous mathematical derivation has already proved that one cannot produce multiple OAM components on-demand simultaneously through a single phase-only element.[8] This is because a complex modulation function, including both amplitude and phase modulation, is required. At the same time, for practical applications, a simple configuration with reduced complexity (e.g., single phase-only element) is always preferable. Considering the high efficiency of phase-only modulation, achieving multiple OAM generation from a single phase-only element becomes an attainable goal. An original way is to use an iterative algorithm (e.g., spontaneous optimization algorithm) to find the phase-only approximate function for generating multiple OAM components, which is easy to converge to a local optimum.[6] Afterwards, an improved pattern search assisted iterative algorithm is proposed to tackle this issue, showing favorable performance for the simultaneous generation of multiple OAM components.[9,10]

Although various iterative algorithms have been successful in the generation of multiple OAM components with a single phase-only element, they usually pay the price of increased complexity, and they are time-consuming due to the iterative process. This may limit some practical applications that require a fast response such as the multistate OAM shift keying in optical communications.[11] The highlight, and also the contribution of the work,[7] is achieving noniterative generation of multiple OAM components—namely, the high-dimensional OAM comb, with a simple procedure free of iterative process. The work presented by Fu et al. is inspired by the idea of Dammann grating,[12] which can produce multiple diffraction orders with identical intensity.

The common Dammann grating is a binary 0-π phase element and operates in Cartesian coordinates. It linearly extends the incident light beam spatially in the far-field, as shown in Fig. 1(a). Fu et al. map the Dammann grating from Cartesian to polar coordinates (i.e., from "x-space" to "φ-space" with φ the azimuthal angle), and thus construct an azimuthal binary phase grating. Such azimuthal phase distribution can extend the incident light beam along the azimuthal direction, forming a series of helical harmonic modes in the far-field, as shown in Fig. 1(b). Through finding proper azimuthal transition points, one can obtain multiple helical harmonic modes with equal intensity weights—that is, a kind of OAM comb.

Based on the above idea, a high-dimensional OAM comb that consists of 64 OAM components ranging from -63 to +63, with an OAM spacing of 2, was generated in the proof-of-principle experiment. It is worth noting that a given OAM comb usually corresponds to a specific set of azimuthal transition points. Flexible OAM comb generation with tailored OAM distribution is available by properly adjusting the number and value of azimuthal transition points.

Because of the high-dimensional orthogonality of OAM states, the ability of generating multiple OAM components in a simple way is of great significance for OAM-enabled advanced applications. Now, Fu and colleagues have proposed an effective toolkit for high-dimensional OAM comb generation. Their work paves the way for a variety of advanced application scenarios such as high-security encryption holography, high-dimensional data information transfer, high-dimensional photon entanglement, etc.

Towards future work developing an OAM comb and beyond, several prospects can be envisioned, as follows (Fig. 2). First, in most reported works on OAM comb generation, discrete bulky optical elements are commonly used. It is attractive to develop all-fiber OAM comb and integrated OAM comb. The former can be fully compatible with fiber-based wide applications,[13] and the latter can facilitate chip-enabled applications by photonic integrated circuits with compactness and stability.[14] Second, OAM light beams with the helical phase structure are just one kind of structured light beams. In general, structured light is characterized by spatially variant amplitude, phase, and polarization distribution. There are many examples of structured light beams, including Laguerre-Gaussian (LG), Hermite-Gaussian (HG), Bessel, vector beams, etc.[15,16] The concept of an OAM comb can be also extended to LG comb, HG comb, Bessel comb, vector comb, and more general structured light comb (optical spatial comb). Third, remarkably, the comb concept is previously used in the frequency domain, i.e., optical frequency comb.[17,18] The OAM comb or the extended optical spatial comb might be further combined with the optical frequency comb, i.e., implementing the comb in hybrid physical dimensions of light waves, which may inspire more interesting applications.

In summary, the proposed high-dimensional OAM comb extends the idea of optical frequency comb from the conventional frequency domain to the spatial domain. Despite the significant progress achieved in the OAM comb generation, it is still in its infancy. In the future, there will be increasing opportunities in the fundamentals and applications of high-dimensional OAM comb, and beyond.

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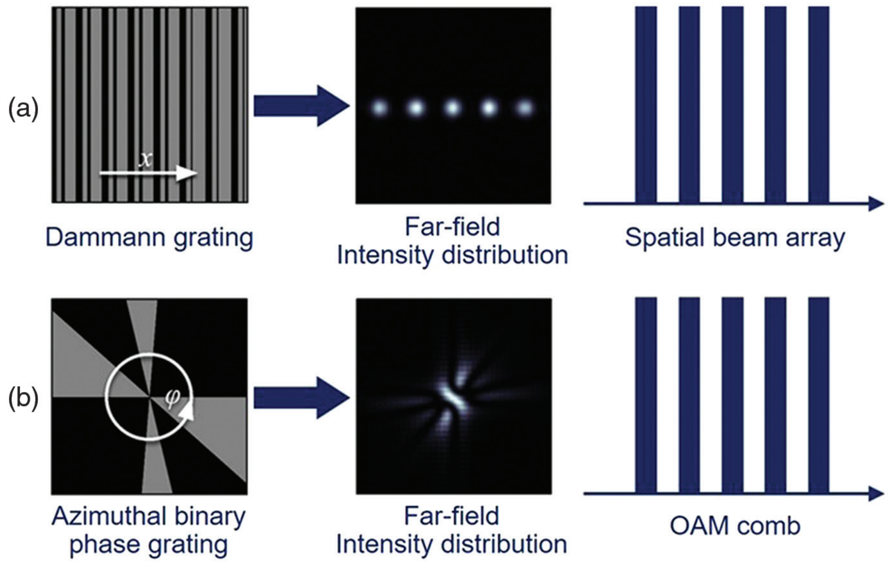

Fig. 1 Analogy between the Dammann grating and the azimuthal binary phase grating (OAM comb). (a) Dammann grating and spatial beam array. (b) Azimuthal binary phase grating and OAM comb.

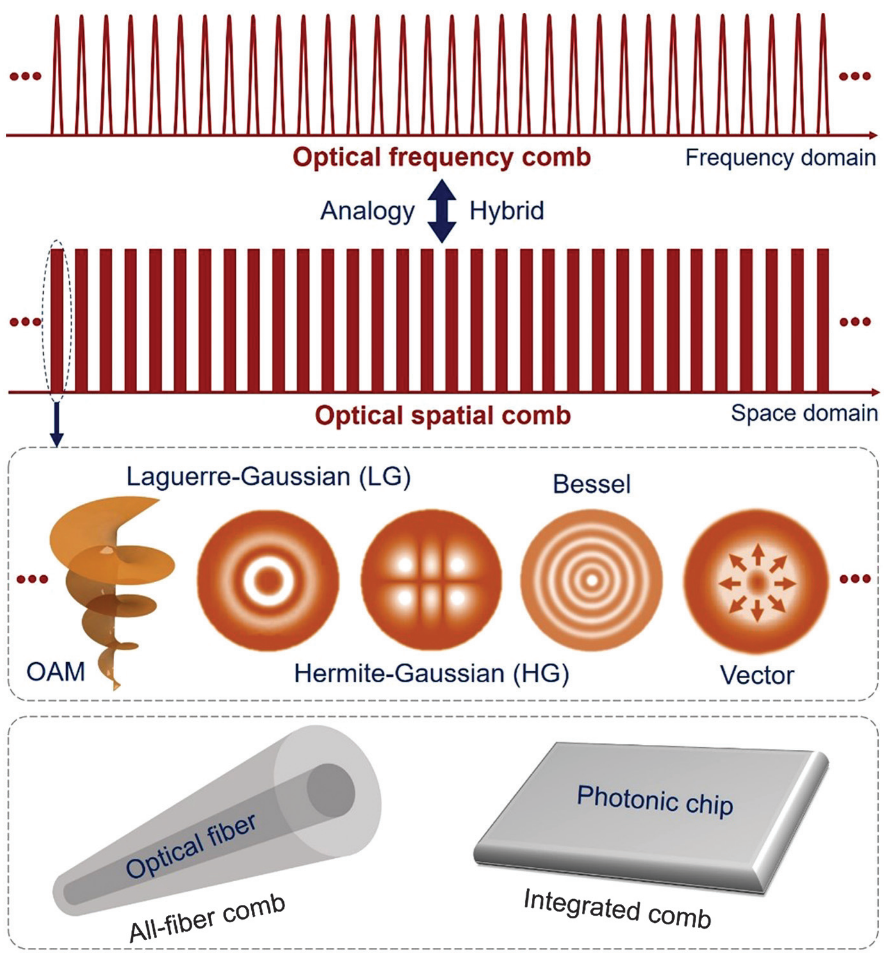

Fig. 2 Prospects towards future grooming OAM comb and beyond (optical spatial comb).

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