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Editorial of special issue on spatiotemporal optical fields and time-varying optical materials

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We give an introduction to the special issue on spatiotemporal optical fields and time-varying optical materials, composed of six articles.

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Optical science is currently witnessing a surge of interest in exploring complex optical fields with intricately tailored space-time characteristics. These spatiotemporal optical fields, carefully sculpted, are opening up new facets in both classical and quantum optics studies and paving the way for many novel applications. These include, but are not limited to, super-resolution imaging, nanofabrication, optical manipulation, high-dimensional communication, and quantum information processing. Simultaneously, there is a growing fascination surrounding time-varying optical materials. These dynamic materials, in stark contrast to their time-invariant counterparts, provide an innovative degree of freedom in orchestrating electromagnetic fields and light–matter interactions across time and space. Furthermore, these time-varying materials offer a promising avenue for generating and tailoring spatiotemporal optical fields.

In light of these rapidly advancing fields, *Chinese Optics Letters* publishes this special issue to highlight the most recent strides made in the realm of spatiotemporal optical fields and time-varying optical materials. The scope extends from fundamental theories to the discovery of novel physical properties and further includes some practical applications. This issue serves as a testament to the importance of these evolving fields and a celebration of their latest breakthroughs.

Since the demonstration of generating spatiotemporal optical vortex (STOV) wavepackets carrying transverse orbital angular momentum (OAM), much research has been conducted to study STOV-related wavepackets. However, most of the research has focused on coherent optical wavepackets with a well-defined phase singularity placed in the x–t plane. Gu *et al.* extend the dimension of spatiotemporal optical field study by exploring a new type of STOV wavepacket[1]. Different from conventional STOV wavepackets, the wavepacket investigated in this work has a multi-STOV structure embedded in multiple space–time. The study uses photonic OAM theory and numerical model to perform calculations. Two configurations of wavepackets are studied. For the first configuration, the spiral phase structure is set to be located in the x–t plane and the y–t plane, separately, with different ellipticities. As shown in Fig. 1, such configuration allows the wavepacket to possess a controllable transverse OAM. Both the magnitude and the orientation of the OAM can be continuously tuned by changing the ellipticity of the spiral phase.

In the second configuration, the additional spiral phase is set to be added in the x'–t plane, a spatiotemporal plane that has a tilted angle with respect to the x–t plane. This allows the multi-STOV wavepacket to have a stronger controlling capability over the transverse OAM by changing the tilted angle $\theta_{x-x'}$ between the x- and x'-axes. Figure 2 shows the spatiotemporal iso-intensity and phase profile of such multi-STOV wavepackets. The graphs in Fig. 2(c) clearly illustrate that the orientation of the OAM can be tuned in the x–y plane. The multi-STOV wavepacket studied in this work can be further combined with a spatial vortex phase so that the resulting wavepacket can carry a full-vectorial photonic OAM orientated in any space–time direction and may bring new opportunity in research fields such as novel optical communication, manipulating quantum systems, and many others.

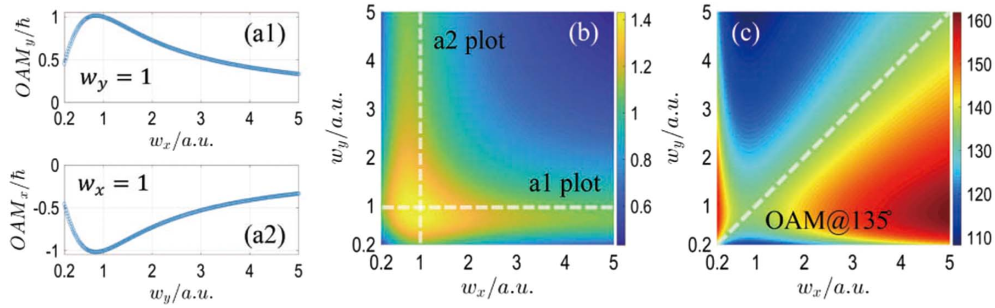

Fig. 1. OAM of a STOV wavepacket with phase singularities embedded in the x–z and y–z domains with varying scaling factors. (a) OAM projection in the y-direction and x-direction when w_y or w_x is fixed. (b) Magnitude of OAM with a changing w_x and w_y. The dashed lines correspond to results shown in (a1) and (a2). (c) Orientation of OAM in the x–y plane with varying w_x and w_y. Adapted from Ref. [1].

Adams and Chong bridge the spatiotemporal optical field to the partial temporal coherence by exploring a tilted STOV wavepacket with a partial temporal coherence[2]. Compared with a laser light source that is fully coherent, an incoherent light source has the benefit of having a cheaper and simpler setup, an improved signal-to-noise ratio in optical communication, and a reduced speckle pattern in imaging applications. In this work, they use another established technique that uses a pair of rotated cylindrical lenses to add a tilted angle to the partially coherent STOV wavepacket. The generated tilted optical vortices with partial temporal coherence may facilitate applications such as communication, particle manipulation with low-cost and simple-to-use sources.

Figure 3 shows the iso-intensity plot of the numerically simulated tilted STOV wavepacket with a partial temporal coherence. The partial coherence is added to the wavepacket by applying a random phase on the temporal frequency of a coherent wavepacket. The result clearly illustrates that the vortex angle of the wavepacket varies substantially in time. To verify the simulation results, a partially temporally coherent laser system is built based upon an amplified spontaneous emission (ASE) source with an output spectrum as shown in Fig. 4(c). A pulse shaper with a spiral phase is used to add transverse OAM to the source, and rotated cylindrical lenses are used to spatiotemporally tilt the vortices. The measurement results (Fig. 4) demonstrate that a tilted OAM is generated based on this ASE source (the lower

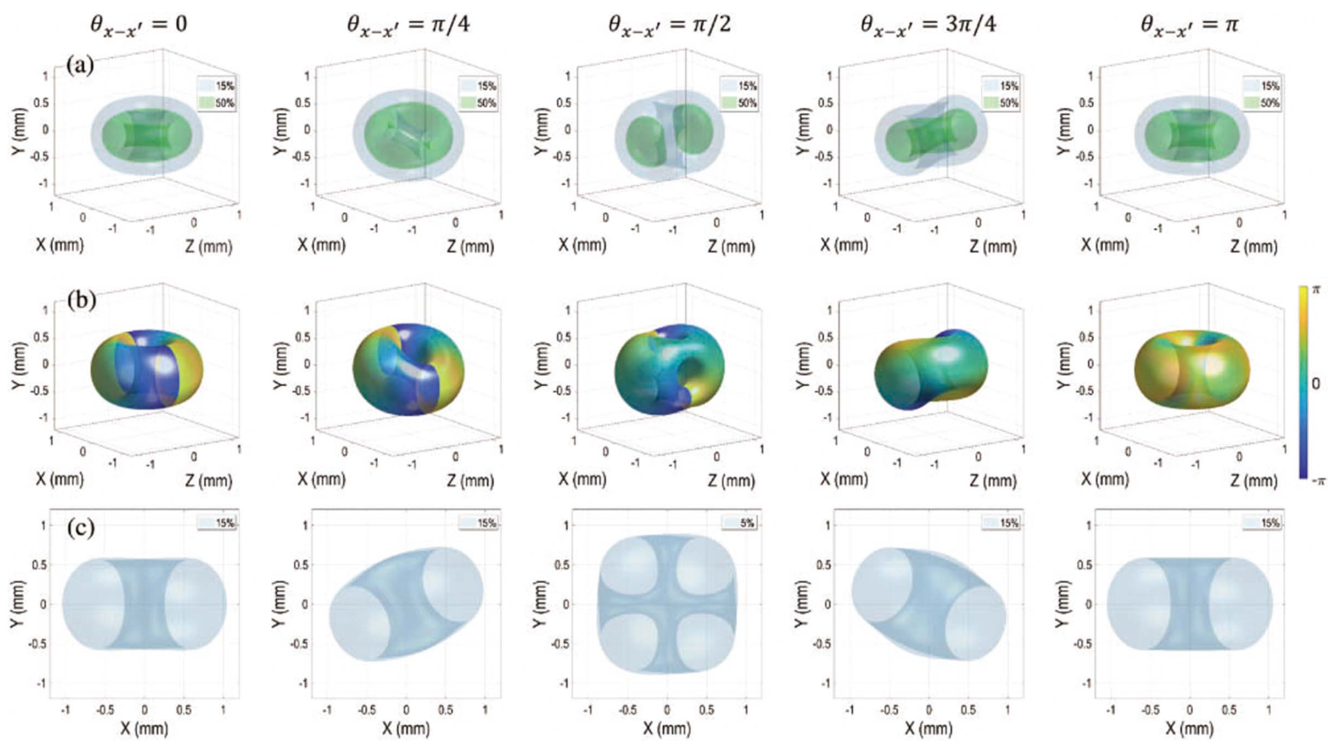

Fig. 2. Spatiotemporal intensity and phase profile of STOV wavepackets with phase singularities embedded in the x-t and x'-t domains. The angle difference between the x- and x'-axes changes from 0 to π in an interval of $\pi/4$ (from left to right). (a) Intensity isosurface plot at 15% and 50% of the intensity maximum. (b) Phase distribution on the 15% intensity isosurface plot. (c) Intensity isosurface plot (15%) in the x–y plane. Adapted from Ref. [1].

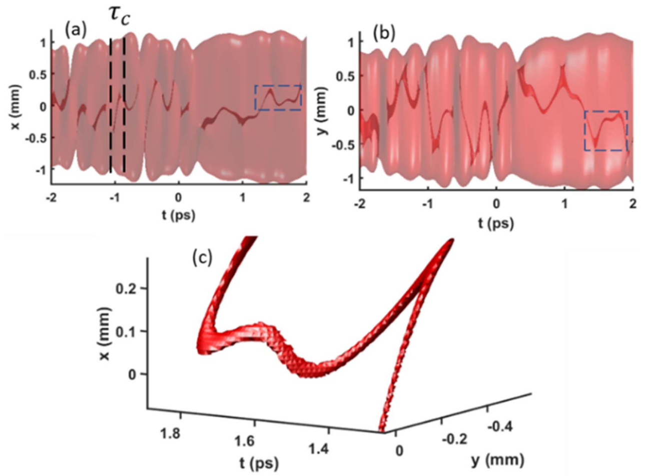

Fig. 3. Iso-intensity of simulated partially coherent tilted vortices in (a) the *x-t* view and (b) the *y-t* view. The coherence time, $\tau_C = 186$ fs, is overlayed in one section to highlight the typical length of the intensity fluctuations and vortices. (c) A small region of the same realization shown to highlight the random vortex tilt path. Adapted from Ref. [2].

right graphics shown in Fig. 4), and the experimental findings have a good agreement with theoretical predictions (the lower left graphics shown in Fig. 4). For the first time, to the best of our knowledge, a tilted STOV wavepacket with partial temporal coherence is demonstrated in this work. This new tool may encourage new research and applications in various fields, such as novel optical communications and partial manipulations.

STOV wave packets exhibit unique spatiotemporal characteristics. To enrich temporal features of such wave packets, additional temporal profiles can be combined with STOVs. Zang *et al.* demonstrate the combination of STOVs with Airy pulses and inherited non-dispersive, self-acceleration, and self-healing features[3]. The Airy-STOV wave packets with controllable phase singularity location can maintain its temporal profile for long-distance propagation and self-healing against external perturbation. To generate Airy-STOV packets, a third-order-dispersion (TOD) combined with a spiral phase is applied in the spatial frequency–frequency domain. Figure 5(a) shows the simulated intensity profile of an Airy-STOV wave packet with topological charge $l = 1$. Multiple spatiotemporal phase singularities exist, as shown in the phase profile [Fig. 5(b)].

If the group velocity dispersion (GVD) effect is much smaller than the TOD, then the GVD will not change the Airy-STOV structure significantly. On the other hand, a larger TOD leads to a smaller self-acceleration. The experimental setup for the generation and characterization of Airy-STOV is similar to that used in Ref. [4]. A spiral phase and a cubic frequency phase are applied in the spatial frequency–frequency domain. A spatial quadratic phase is applied to compensate for the positive chirp of the seed pulse and the diffraction effect of free-space propagation.

The experimental result verifies that the Airy-STOV has a dispersion-free propagation distance 3.7 times longer than a regular STOV. The self-acceleration effect enables the control of the temporal location of the spatiotemporal vortex. The temporal shift is proportional to the square of the propagation distance corresponding to a uniform acceleration motion. Figure 6 shows the temporal shift of the phase singularity in the main lobe of the Airy-STOV caused by the self-acceleration effect.

Gao *et al.* explore the generation of STOVs in the green and ultraviolet (UV) wavelength regions using frequency up-conversion techniques[5]. Their remarkable work not only presents the first demonstration of STOV generation in green and UV spectral bands but also provides the first observation of the sum-frequency generation (SFG) process involving STOVs (Fig. 7). The authors confirm the conservation of the topological charge in STOVs during these nonlinear processes. They also discover that degradation of the generated STOV pulse can occur when the nonlinear crystal is placed out of focus of the incoming light, similar to the degradation phenomenon of STOV studied in the linear optics region[4,6]. This discovery is crucial for understanding the limitations and practical applications of STOV-based systems and can be seen as its validation in the nonlinear realm.

Notably, this work introduces a novel method for controlling the topological charge of the nonlinear harmonic generation by adjusting the focusing position of the fundamental STOV. This approach not only offers a promising way to manipulate the transverse orbital angular momentum carried by STOVs but also provides valuable insights into the control and optimization of STOV-based systems. The advancements in this research can potentially lead to further developments and applications of STOVs across a wide range of disciplines, including STOV-based optical communications, quantum optics, and high-dimensional laser processing. The innovative work of Gao *et al.* sets a strong foundation for future research in the field of STOV generation and manipulation, opening new possibilities for practical implementations.

Qi *et al.* propose an innovative simultaneous wireless information and power transfer (SWIPT) transmitting architecture based on an asynchronous space-time-coding digital metasurface (ASTCM)[7]. This creative approach has the potential to significantly impact wireless communications and the Internet of Things (IoT). The authors present the design of a spatial-division multiplexing SWIPT transmitter based on ASTCM, which takes advantage of the unique properties of metasurfaces for the simultaneous and efficient transfer of information and power. The method employs a spatial-division multiplexing strategy on the metasurface, with a portion used for beamforming to achieve power transfer and the remaining meta-atoms used for information modulation and transmission (Fig. 8).

To demonstrate the effectiveness of the proposed method, Qi and colleagues carry out experimental verification using a simple 3-bit metasurface sample. The results showcase the ability to transmit information and energy simultaneously in different directions at different frequencies, highlighting the potential of the ASTCM-based SWIPT architecture for wireless communication and IoT applications. Additionally, the proposed ASTCM-based SWIPT architecture effectively addresses the challenges faced by traditional SWIPT transmitters, such as cross-talk distortion and reduced power amplifier efficiency.

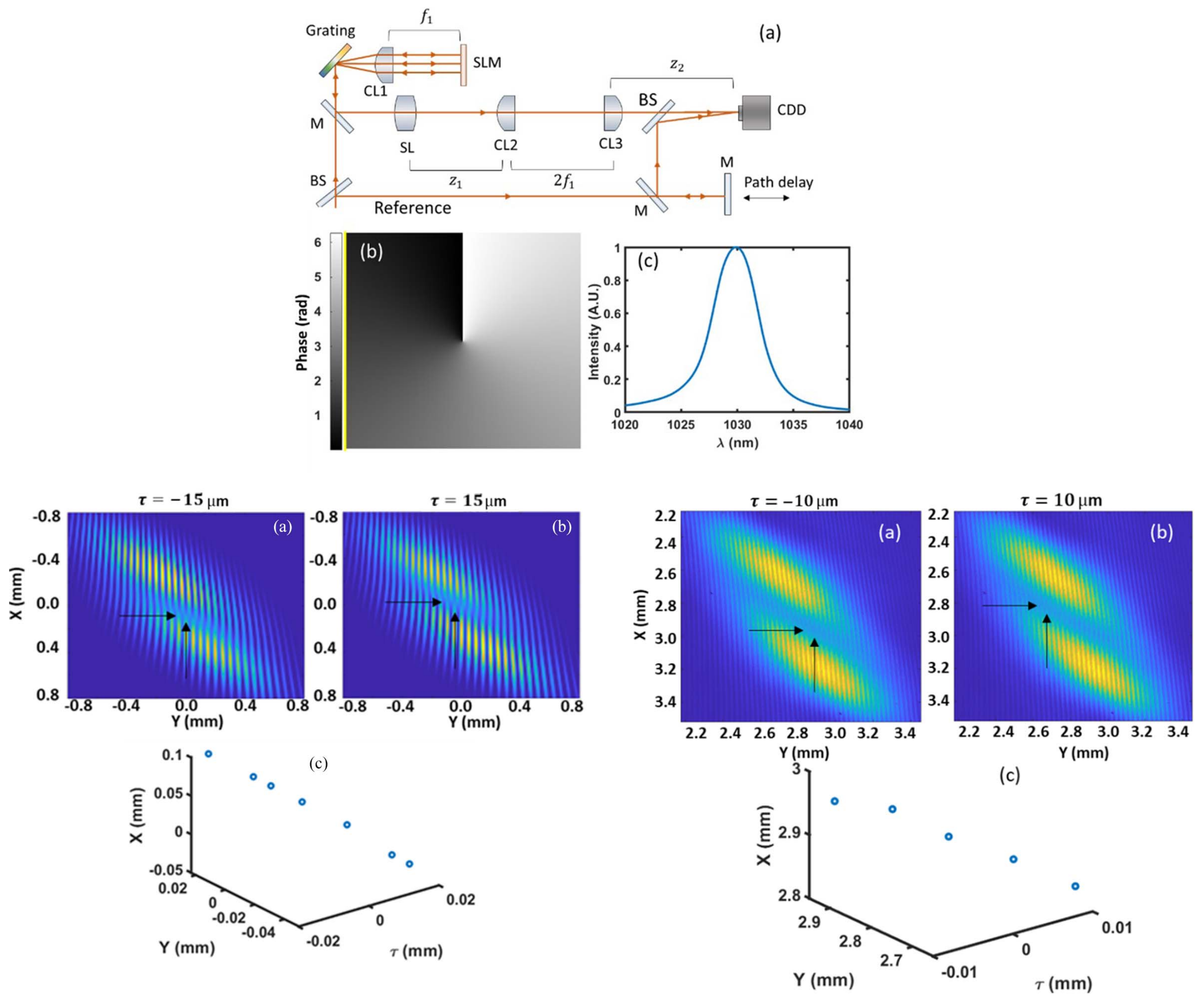

Fig. 4. (Upper) (a) Experimental setup. BS, beam splitter; CL, cylindrical len with focal length $f_1 = 100$ mm; SLM, spatial light modulator; M, mirror; SL, spherical lens with focal length $f = 300$ mm; distances $z_1 = 200$ mm and $z_2 = 200$ mm. (b) SLM spiral phase map. (c) Spectrum of ASE light source. (Lower left) (a), (b) Simulated interference patterns at two reference delays of 30 separations. (c) 3D trace of the singularity. (Lower right) (a), (b) Experimental interference patterns at two reference delays showing moving singularity indicated by arrows. (c) Plot of vortex singularity points position versus delay. Adapted from Ref. [2].

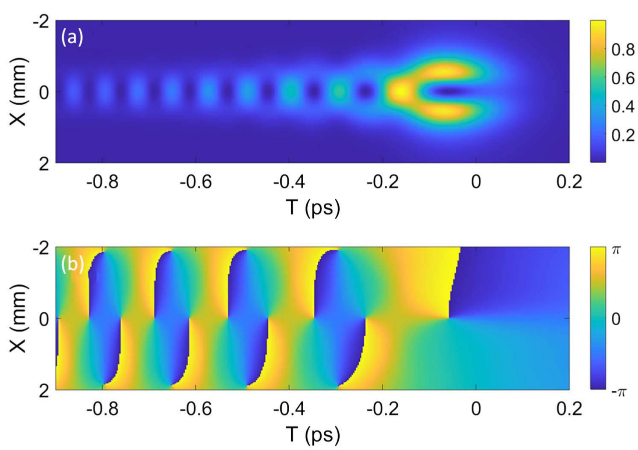

Fig. 5. Simulation of Airy-STOV wave packet of topological charge $l = 1$. (a) Normalized intensity profile and (b) phase profile. Adapted from Ref. [3].

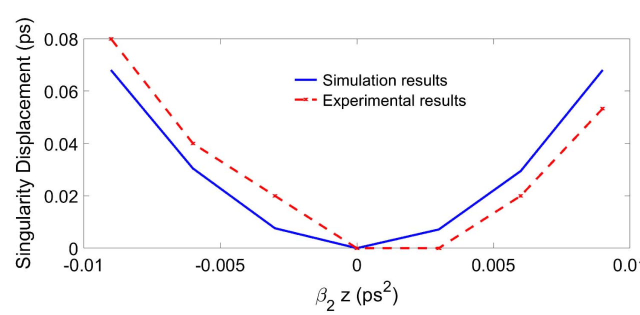

Fig. 6. Phase singularity temporal shift as a function of GVD. Adapted from Ref. [3].

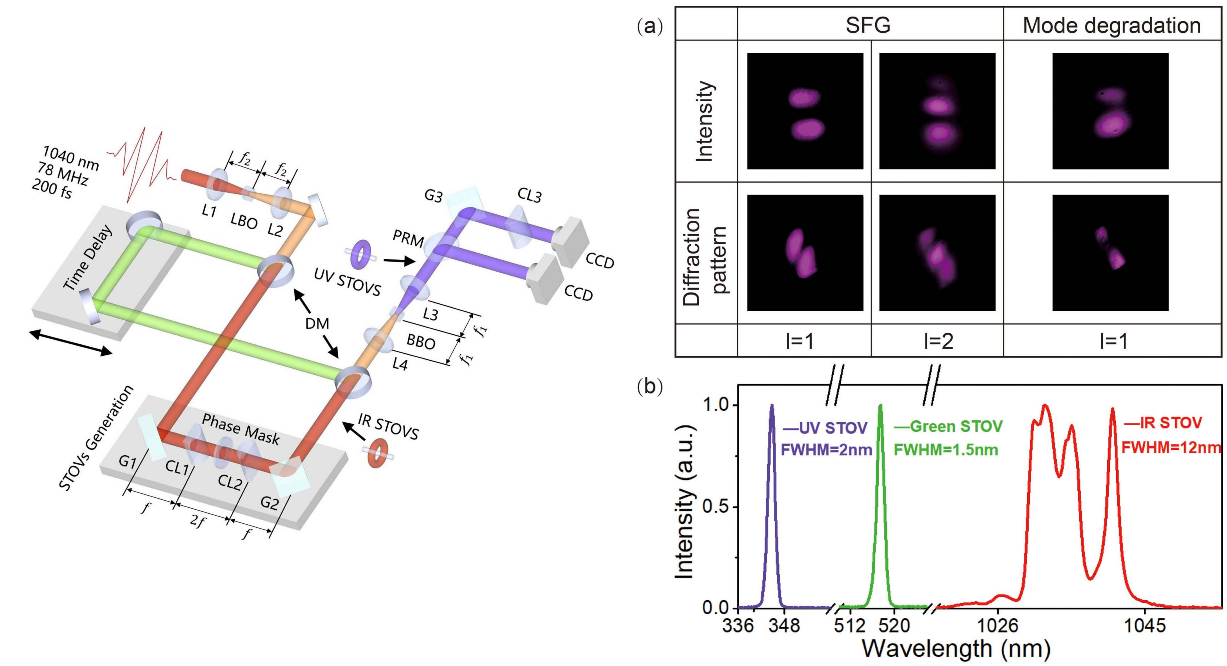

Fig. 7. Experimental setup and corresponding results for the generation and characterization of UV STOVs using the SFG process. Adapted from Ref. [5].

The study also suggests that additional modulation methods can be incorporated into the architecture, making it adaptable for a broader range of practical applications. This work has significant implications for developing advanced wireless communication systems and IoT devices, paving the way for future research and applications in this rapidly evolving field.

Liquid crystals (LCs), with their response to external stimuli and dynamically tunable characteristics, emerge as potential time-varying materials. Wang *et al.* introduce an innovative holographic iterative algorithm that enables the implementation of cascaded LC holography for optical encryption[8]. Each LC layer acts as a secret key, generating a unique holographic image. When two LC elements are cascaded, a new holographic image is produced, distinct from the images formed by each individual LC key. The work also demonstrates dynamic optical encryption by electrically switching LCs with combined electric keys, suggesting a high potential for applications requiring the transmission of different encrypted messages (ciphertexts) to multiple recipients.

Through experimental verification, the researchers showcase the potential of the proposed system in cascaded optical encryption with secret sharing and electrically dynamic optical encryption with enhanced encoding capabilities (Fig. 9). By utilizing more than one LC layer and the cascaded configuration, combined with producing high-quality holographic images, they offer enhanced security, flexibility, and potential applications in various fields. These include visual optical cryptography, optical communications, anti-counterfeiting measures, optical data storage, dynamic holographic display, all-optical computing, and diffractive neural networks. The tunable nature of LCs is

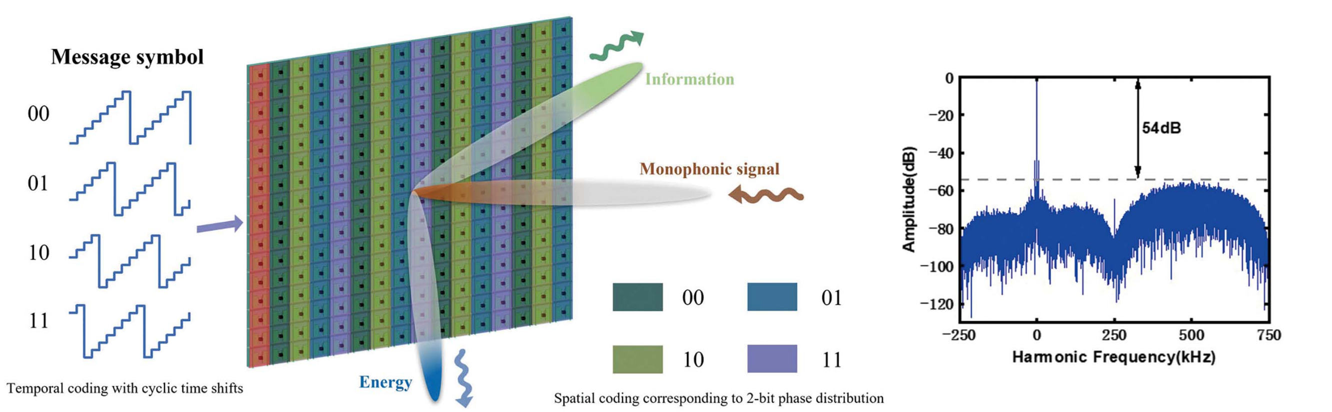

Fig. 8. Schematic of directional power transfer and omnidirectional information transmission based on the proposed ASTCM and the measured normalized spectrum distribution. Adapted from Ref. [7].

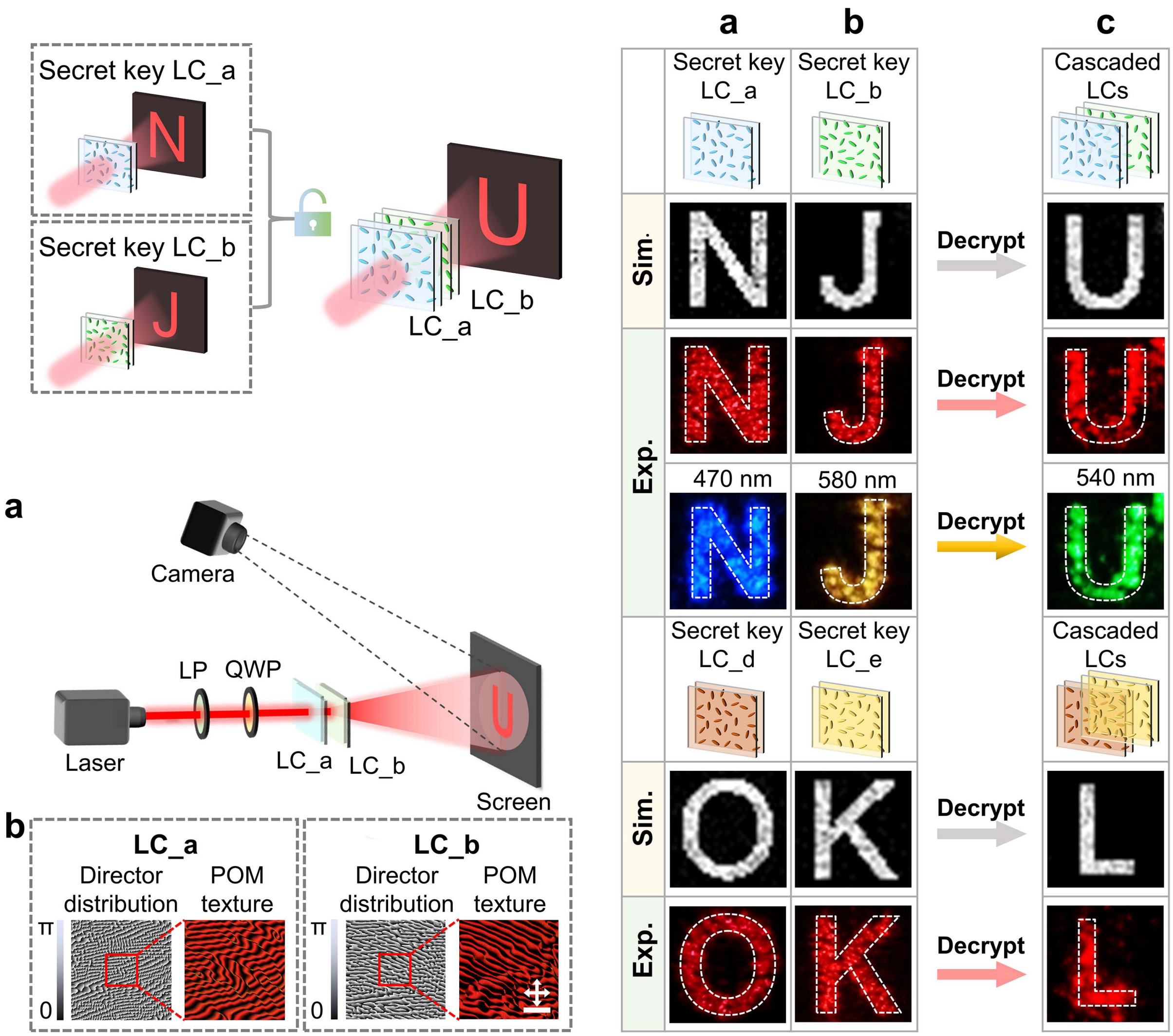

Fig. 9. Conceptual depiction of the implementation of the cascaded LC-holographic encryption, along with the corresponding experimental setup and results. Adapted from Ref. [8].

also highlighted, allowing for dynamic manipulation of holographic performances and establishing a dynamic secret-sharing platform. Consequently, this work has potential implications for the future of optical encryption.

In conclusion, this short review provides an overview of the recent contributions published in the special issue on spatiotemporal optical fields and time-varying optical materials in *Chinese Optics Letters*. These works each offer a distinct insight, enhancing our comprehension of these intricate fields. Collectively, they broaden our perspective on optical science and underscore the rich potential for further exploration. This special issue showcases the diversity of current research in these domains and paves the way for future investigations, hinting at promising developments in optical science.

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