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※封底论文※

时空光场调控以及时空光涡旋波包的研究进展（特邀）

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摘　要：综述了时空耦合光场，包括时空光场的理论背景，产生时空光场的实验方法，以及时空光涡旋波包的研究现状。由于时空光场的生成涉及色散与衍射效应之间微妙的相互作用，尽管用于产生时空耦合光场的实验装置与现有的4f脉冲整形器实验装置几乎相同的，但与传统的脉冲整形或光束整形技术相比，时空光场的生成过程更为丰富。新型时空光场具有独特的光子学特性，如携带具有纯横向轨道角动量的光子，在传播过程中不发生衍射，或以可控的群速度传播，使其成为量子光学、纳米光子学、自旋光子学和光与物质相互作用等研究领域的重要工具。

关键词：光场调控；超快光学；时空光场；光子角动量

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0 Introduction

The development of ultrafast laser has opened new avenues for physicists and scientists. Differed from Continuous Wave (CW) laser, ultrafast laser emits output in the form of optical pulses whose pulse duration is at 10～100 femtosecond scale ($1\ \mathrm{fs} = 10^{-15}\ \mathrm{s}$)[1-2]. Thanks to its short pulse duration, high pulse energy, high peak intensity, and a broadband spectral coverage, ultrafast laser has become an enabling tool in the research fields for probing ultrafast events[3], strong field physics[4], nonlinear optics[5-6], and spectroscopic applications[7-8].

In recent years, there is a growing research interest in studying complex Spatiotemporal coupled (STc) optical fields generated by ultrafast lasers. These complex STc optical fields exhibit unique photonic properties that are previously unavailable. For example, Spatiotemporal Optical Vortices (STOV) wavepackets that have a spiral phase in ST domain can carry photons with a pure transverse Orbital Angular Momentum (OAM)[9-19]. Space-time light sheets with a modulated field distribution in the spatial frequency and spectral domain (k-ω space) can possess an arbitrary group velocity[20-25], achieve negative refraction on interfaces[26], propagate with self-accelerating in space-time[27] or propagate without spread in space[28-37]. These newly published research works have pushed the frontier of photonic researches and created new opportunities in the photonics research field, and hence we feel it is necessary to review the state-of-art research status of STc optical fields, especially for research works published in the last decade.

In this paper, we review the research progress of novel STc optical fields with a particular emphasis on the

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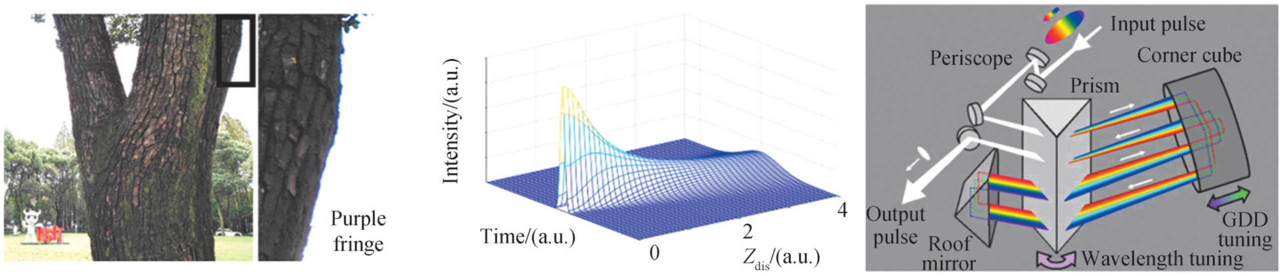
newly discovered STOV wavepackets. We review the origin and early study of STc optical fields. Then we introduce the theoretical model for describing STc optical field. It covers the mathematical equations for simulating STc optical field and provides an example of the evolution of STOV wavepackets under dispersive and non-dispersive propagation. Thirdly, we discuss the experimental realization of STc optical fields. In generating STc optical fields, the interplay between dispersion and diffraction is more subtle compared with conventional pulse shaping or beam shaping techniques. These will be discussed in this section. Finally, we give a detailed review of the newly discovered STOV wavepackets in the fourth section. We hope this review can serve as a mini guide book for more photonics researchers in studying novel STc optical fields.

1 Origin and early study of STc optical fields

Due to the time-frequency uncertainty principle, ultrafast laser has a significantly broader spectrum compared with CW laser and can be thus affected by chromatism. A typical source for chromatism is material dispersion, i.e., broadband light propagating in bulky optical elements such as lenses and prisms. A simple example of chromatism is the purple fringes found in the high contrast boundary areas of a smartphone photo (see Fig. 1(a)). Those purple fringes are caused by a radially varying dispersion of the imaging system that results in a color-dependent lateral shift at the image plane[38]. Such chromatic effect is considered detrimental to the image quality and optics scientists have invented achromatic lenses to prevent it.

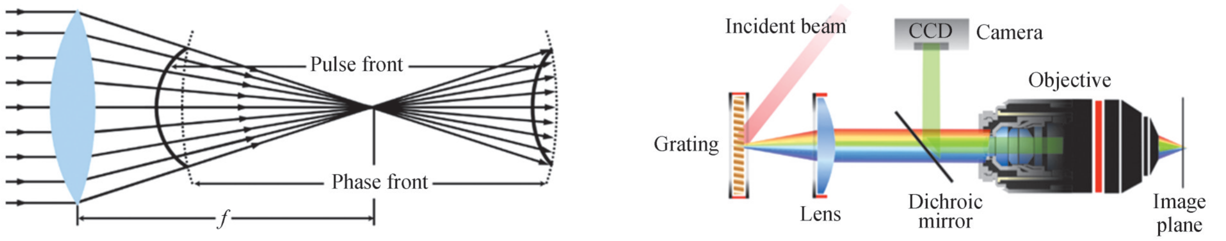
It is noteworthy that smartphone photos are images illuminated by incoherent light sources, and, therefore, chromatism only affects the light propagation geometrically. For an ultrafast laser, the output pulse profile in the time domain is the result of constructive and destructive interference between a phase-coherent broadband spectrum in the frequency domain. In this case, chromatism leads to a spectrally varying phase and it can severely distort the temporal pulse profile. Fig.1 illustrates two examples for the influence of chromatism for an ultrafast laser, including pulse broadening[2] as shown in Fig. 1(b) and pulse compression[39-42] as shown in Fig. 1(c). For almost any ultrafast laser oscillator, the dispersion management is of great importance[43-44]. External to the laser cavity, a proper management of dispersion has been widely used in Chirped Pulse Amplification (CPA) technique[45], facilitating the construction of super-intense lasers[46].



(a) Purple fringe caused by chromatism in high contrast boundary area of a smartphone photo

(b) Temporal pulse broadening due to propagation in dispersive medium

(c) Pulse compression using material dispersion in the prism of a prism pulse compressor[42]



(d) ST optical field has an offset between its pulse front and phase front after it propagates through a thick lens[47]

(e) Temporal focusing of a spatially linear dispersed field in nonlinear microscopic applications can achieve higher axial resolution[69]

Fig. 1 Chromatism on optical beams, pulses, and Spatiotemporal (ST) optical fields

Consider chromatism in both spatial domain and temporal domain, ultrafast lasers, especially lasers with a broadband spectrum, are affected by chromatism in a Spatiotemporal (ST) manner. The optical field under chromatism can evolve into a Spatiotemporally Coupled (STc) field[47-51]. Fig. 1(d) shows a typical example of

STc optical field whose pulse front and phase front are not overlapping with each other due the group velocity and phase velocity difference in a thick lens. Since one major application of ultrafast laser is to use its intense light field to drive physical process or to use its tight ST confinement for probing physical phenomena with high precision, STc optical field is considered to be detrimental as it has a large spread in ST domain with a reduced peak intensity[52-54]. Therefore, early study on STc optical field mainly focuses on eliminating STc effects. Later, it was discovered that a properly engineered STc optical field can facilitate certain physical process. For example, pulse-front-tilted STc field can have both phase matching and group velocity matching in a nonlinear crystal and it can boost the conversion efficiency in nonlinear optical processes[55-64]. A spatial dispersive light field can be temporally focused (see Fig. 1(e)) when it passes objective lenses and it can benefit nonlinear microscopic applications[65-69] and 3D fabrication processes[70] with a higher axial resolution and a faster scanning speed.

There are already several review articles published on the theory, measurement technique and application for those STc optical fields[71-74] that mainly have a first-or second-order coupling between the spatial (or angular) and temporal (or spectral) coordinates. In recent years, there are more research works on studying STc optical field with a much more complex field structure. In the next section, we are to introduce the theoretical model for these complex STc optical fields, which provides the theoretical background for studying these fields.

2 Theoretical model for STc optical field

Spatiotemporal (ST) optical field is characterized in a three-dimensional (x, y, t) space. For a spatiotemporally uncoupled field, the field can be written as the product of its transverse field (beam) and its temporal field (pulse), $E(x, y, t) = E(x, y) \cdot E(t)$. Therefore, the ST field can be analytically or experimentally studied separately in the spatial domain and time domain[75-77]. For Spatiotemporally Coupled (STc) optical field, it cannot be written as the space-time field product and it is thus mandatory to use a theoretical model that accounts physical effects in the spatial domain and time domain simultaneously. In this section, we will introduce the theoretical model used for studying STc optical fields and how to use the model to simulate the evolution of STc optical fields under dispersive or non-dispersive propagation.

In most scenarios, STc optical fields are investigated in the paraxial regime, meaning the dimension of the STc fields in the transverse domain is much larger than the optical wavelength, $w_b \gg \lambda_0$. This assumption can greatly simplify the calculation process for propagation a STc optical field. Another assumption that is always taken is the Slowly Varying Envelope Approximation (SVEA). It equivalently means the spectral bandwidth of the field is much smaller than the optical center frequency, $w_\Omega \ll \omega_0$. Besides, we assume the field is linearly polarized at this stage. The field can be thus written in a scalar form as $E(x, y, t) = A(x, y, t) \cdot e^{i\phi(x, y, t)} \cdot e^{-i\omega_0 t}$, where $A(x, y, t)$ is the field amplitude and $\phi(x, y, t)$ is the field phase. STc optical field can be thus related to its spatial frequency and spectral counterparts using the following Fourier transformations,

$$\tilde{E}(k_x, k_y, \omega) = \iint E(x, y, t) e^{-i(k_x x + k_y y - \omega t)} \mathrm{d}x\mathrm{d}y\mathrm{d}t \tag{1}$$

$$E(x, y, t) = \iint \tilde{E}(k_x, k_y, \omega) e^{+i(k_x x + k_y y - \omega t)} \mathrm{d}k_x\mathrm{d}k_y\mathrm{d}\omega \tag{2}$$

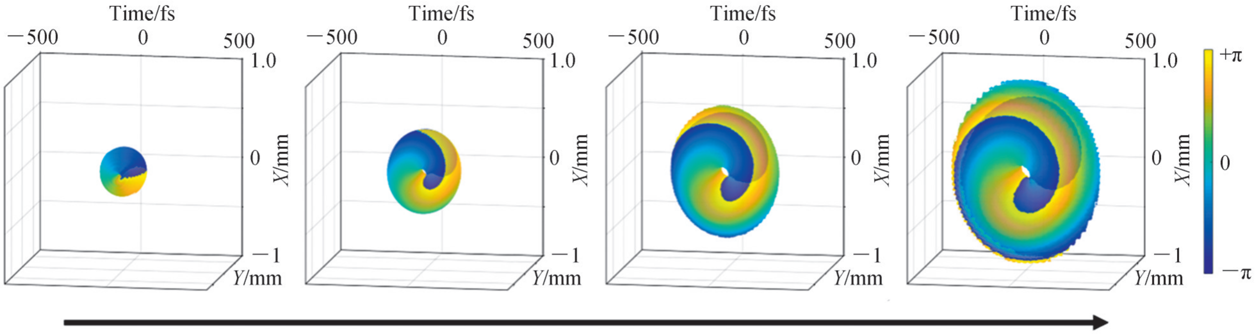
here, (k_x, k_y, ω) is the spatial frequency and spectral coordinate which is reciprocal to (x, y, t). In this Fourier transformation expression, normalization factors are neglected because we are more interested in the relative distribution of the STc field. Using these equations, the propagation of a STc optical field in a dispersive medium can be written as

Fig. 2 Evolution of STOV wavepacket with a topological charge of $l = +1$

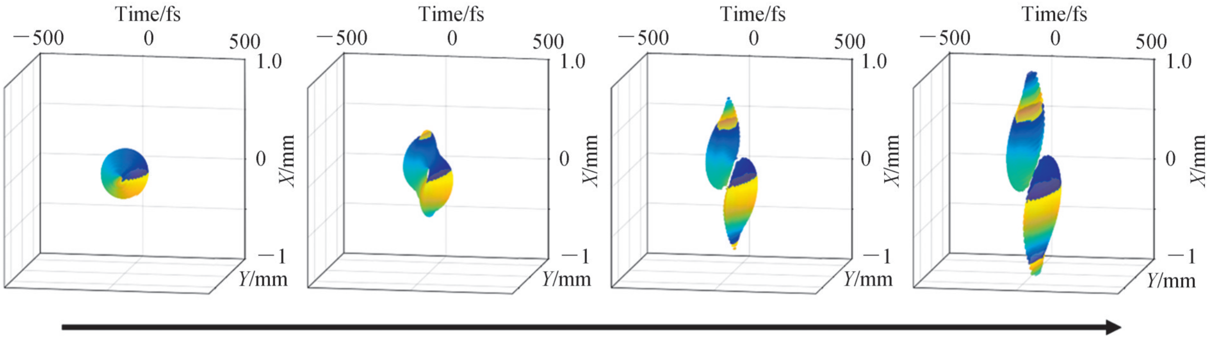
$$\tilde{E}_{z=L}(k_x, k_y, \omega) = \tilde{E}_{z=0}(k_x, k_y, \omega) \cdot e^{i\left(\frac{k_x^2 + k_y^2}{2k_0} + \frac{\beta_2 \Omega^2}{2}\right)L} \tag{3}$$

where k_0 is the averaged propagation constant of the field, β_2 is the Group Velocity Dispersion (GVD) coefficient of the medium, $\Omega = \omega - \omega_0$ is the relative optical angular frequency, and L is the propagation distance. For a non-dispersive propagation, β_2 is set as zero.

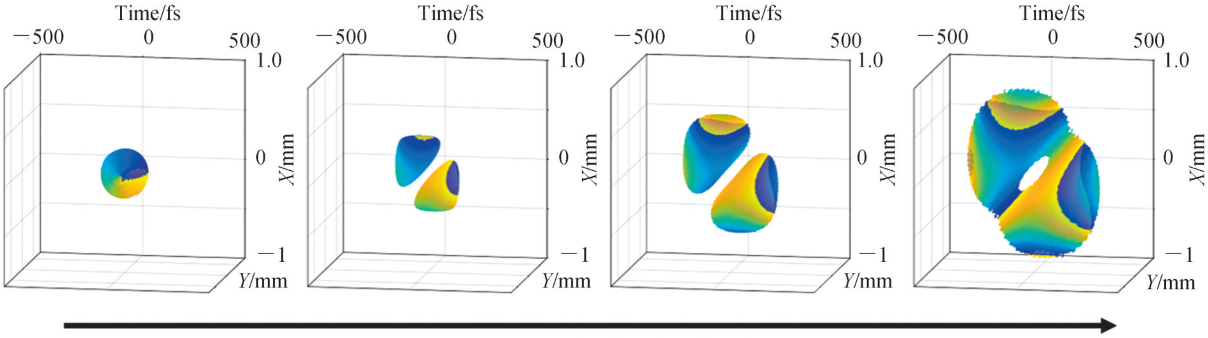
Using Eq. (3), the evolution of STc optical fields can be both analytically and numerically calculated. To give an example, Fig. 2 shows the evolution of a Spatiotemporal Optical Vortices (STOV) wavepacket[9,10,18] under dispersive and non-dispersive propagation. The 3D plots show the iso-surface shell of the wavepacket where the localized intensity of the field drops to 10% of the peak intensity and the surface color is registered to the phase of the wavepacket. The initial STOV wavepacket shown in the leftmost figure has a spiral phase of $\exp(\mathrm{i}l\theta_{x-t})$, where l stands for the topological charge and θ_{x-t} is the polar angle in (x, t) space. The topological charge l is $+1$.



(a) Evolution of STOV wavepackets under normal dispersive propagation



(b) Evolution of STOV wavepackets under non-dispersive propagation



(c) Evolution of STOV wavepackets under anomalous propagation

Fig. 2 Evolution of STOV wavepacket with a topological charge of $l=+1$

During dispersive propagation, STc optical fields such as STOV wavepacket will spread in all directions in (x, y, t) space. During non-dispersive propagation, STc fields only spread in the spatial domain. Consider the x-direction diffractive phase term and the dispersive phase term in Eq. (3), it can be noticed that the evolution of STc fields under normal dispersion resembles an optical beam propagation process except that the y-coordinate in beam propagation is now replaced by t-coordinate. Therefore, STOV wavepacket can maintain its ring-like shape under normal dispersive propagation while it splits into a diagonal shape under anomalous dispersive propagation due to a strong astigmatism between the accumulated dispersive phase and diffractive phase[18]. Meanwhile, it is also noteworthy that STOV wavepacket has a spiral phase reversal during anomalous dispersive propagation (see the rightmost figure in Fig. 2(c)). It means the photon within the STOV field now carries a transverse OAM with a topological charge of -1 instead of $+1$.

3 Experimental realization of STc optical field

The experimental realization of STc optical field is normally achieved by a phase and/or amplitude modulation in the spatial and spectral domain of the input optical field. One typical setup for generating STc optical field has the same configuration as a zero-dispersion 4-f pulse shaper[78-80]. Fig.3 illustrates the schematic of a STc field generator. The generator has the same configuration as a standard zero-dispersion 4-f pulse shaper[78-80] except that the 1D Liquid-Crystal Spatial Light Modulator (LC-SLM) in a pulse shaper is now replaced by a 2D SLM so that it can modulate the spatial and spectral phase of the input field[9,17]. The generator constitutes a pair of diffraction gratings, a pair of cylindrical lenses, and a transmissive 2D LC-SLM. In the setup, each component is separated by the focal length of the cylindrical lens. In this way, the spatial-spectral (x-ω) component of the input field can be projected at the LC-SLM plane. The spatial-spectral field at LC-SLM plane $E_{\mathrm{SLM}}(x,\Omega)$ can be related with the input field $E_{\mathrm{in}}(x',t)$ via a one-dimensional Fourier transformation over t which can be written as

$$E_{\mathrm{SLM}}(x,\Omega)\Big|_{x=x'}=\iint E_{\mathrm{in}}(x',t)\mathrm{e}^{\mathrm{i}\Omega t}\mathrm{d}t \tag{4}$$

where $\Omega=\omega-\omega_0$. In the setup, the gratings disperse or re-collimate the light field along y'-direction (see Fig. 3 for the exact geometry) and we assume the field is uniformly distributed along y'-direction. Using Eq. (4), STc optical field after the generator $E_{\mathrm{out}}(x',t)$ can be expressed as

$$E_{\mathrm{out}}(x',t)\Big|_{x'=x}=\iint E_{\mathrm{SLM}}(x,\Omega)\cdot\exp\left(\mathrm{i}\cdot\phi_{\mathrm{SLM}}(x,\Omega)\right)\mathrm{e}^{-\mathrm{i}\Omega t}\mathrm{d}\Omega \tag{5}$$

where $\phi_{\mathrm{SLM}}(x,\Omega)$ stands for the 2D phase applied on LC-SLM and we assume there is negligible diffraction effect along x-direction when the light field propagates inside the generator.

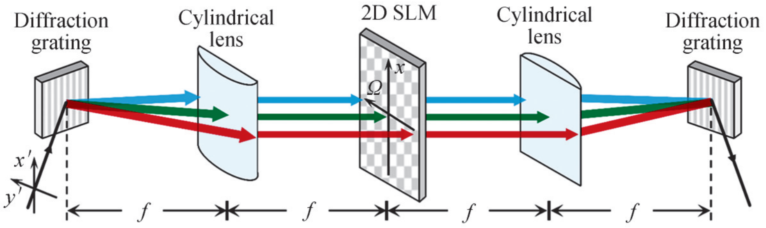


Fig. 3 Schematic of a spatiotemporal coupled (STc) optical field generator

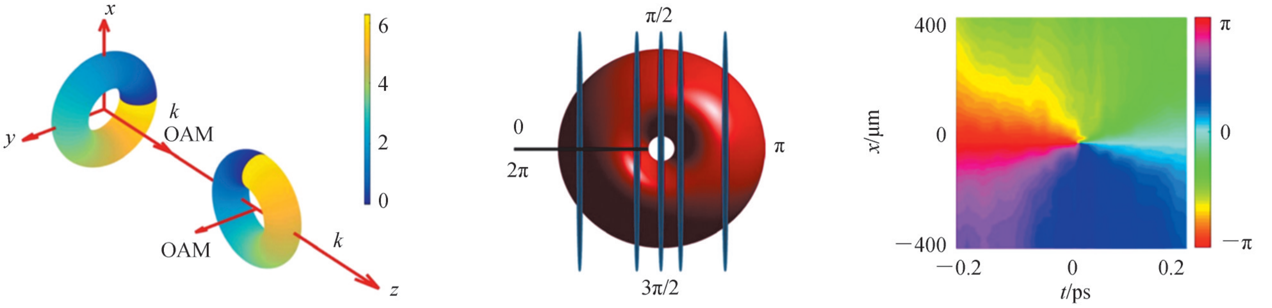
STc field generator has been extensively used for generating and studying STc optical fields such as STOV wavepackets[9], self-accelerating ST Airy wavepacket[27], and space-time light sheets[31]. Besides, it is also possible to replace the programmable LC-SLM device in the setup with a transmission optical mask so that the spatial-spectral transmittance is modulated. Some specific STc optical fields such as ST Bessel wavepackets can be generated using this non-programmable setup[81].

4 Regimes of STc optical field generation

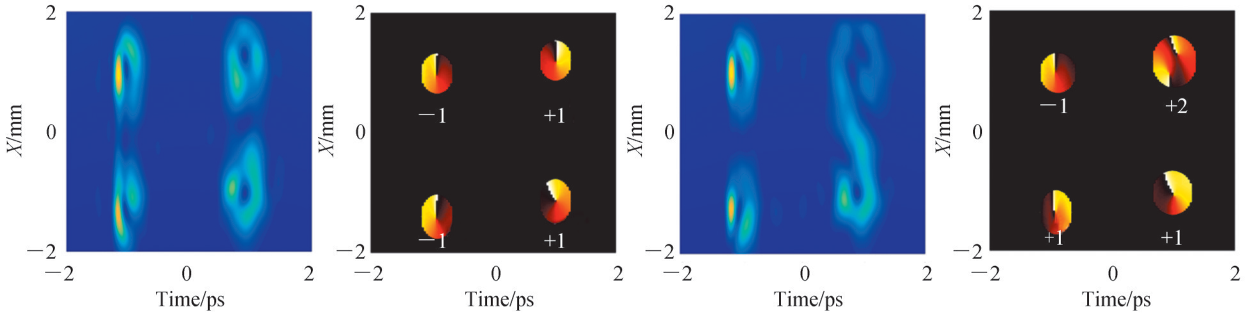
It should be noted that although 4-f pulse shaper setup for STc optical field generation appear to be simple, the subtle interplay between dispersion and diffraction during the process makes the generation of STc optical fields more sophisticated. Among the research works that utilize STc field generator, there are distinct differences in those realizations according to the distance between the exit plane of the generator and the observation plane. Here we can roughly categorize them into three main different operation regimes:

1) The "far-field" regime. In this approach, the observation plane is set at several Rayleigh ranges after the generator[9,14], or, alternatively, an additional lens or an additional imaging system can be inserted after the generator so that the "far-field" position is now relocated to the back focal plane of the lens or the imaging

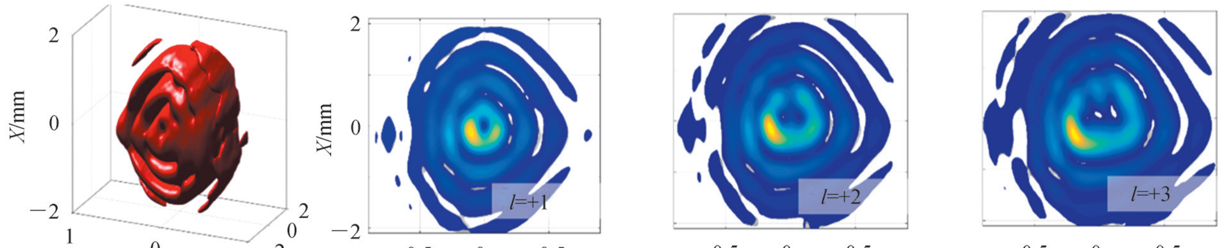
system[31][81]. In both scenarios, the observed STc optical field $E_{\mathrm{ob}}(x,t)$ becomes mathematically the Fourier transform of the STc field at the exit plane of the generator, which transform between the x'-direction coordinate of the exiting STc field and x-direction coordinate of the observed STc field[82]. That is equivalent to say, the generator now modulates spatial frequency and spectral phase $\phi(k_x,\omega)$ of the observed field, or it changes the spatial frequency and spectral field distribution $\tilde{E}(k_x,\omega)$ of the observed field. To give an example, in the experimental realization of STOV wavepacket with a controllable transverse Orbital Angular Momentum (OAM) (see Fig. 4(a) for the visualization of a simulated STOV wavepacket), a spiral phase of $\mathrm{e}^{-\mathrm{i}l\theta}$ is applied on the LC-SLM in the generator. The observation plane is set at several Rayleigh ranges after the generator, and, therefore, a 2D Fourier transform can give the observed STc optical field in x-t space via[83]



(a) 3D profile of a standard pulse vortex beam (left one) and a STOV wavepacket (right one)
(b) ST intensity profile of a STOV wavepacket with a topological charge l of +1
(c) Measured ST phase of a STOV wavepacket generated using the “far-field” regime operation[9]



(d) Measured ST intensity and phase profiles of STOV lattices. This complex field is generated by exploiting the “near-field” operation[18]



(e) Bessel STOV wavepacket with l of +1. Generated using the “intermediate” regime[17]
(f) ST intensity profiles of Bessel STOV wavepackets. The topological charge l of these wavepackets is +1, +2, and +3, respectively[17]

Fig. 4 STOV wavepackets generation using different operation regime of the spatiotemporal coupled optical field generator[9,17,18]

$$G(\rho,\phi)=\mathrm{FT}\left\{g_R(r)\,\mathrm{e}^{-\mathrm{i}l\theta}\right\}=2\pi(-\mathrm{i})^{l}\mathrm{e}^{-\mathrm{i}l\phi}H_l\left\{g_R(r)\right\} \tag{6}$$

here, (ρ,ϕ) is the polar coordinate in (x,t) space defined by $\rho=\sqrt{x^2+t^2}$ and $\phi=\arctan(x/t)$, FT is the Fourier transform, and H_l is the Hankel transform of order l. In a Fourier transformation, the spiral phase and its related optical OAM are conserved. Fig. 4(b) plots the theoretical prediction of a generated STOV wavepacket and Fig. 4(c) shows the measured ST phase, indicating a STOV wavepacket can be generated by applying a spiral phase in its (k_x,ω) space[9].

2) The “near-field” regime. In contrast to the “far-field” regime, the “near-field” regime means the

observation plane is placed within the Rayleigh range after the generator. In this case, there is negligible diffraction and the observed optical field can be expressed by Eq. (5). One interesting application of this "near-field" approach is to use a linearly chirped pulse as the input to seed the generator. Since for a linearly chirped pulse, its instantaneous frequency is linearly dispersed in time, the spatial phase modulation applied on the LC-SLM inside the generator now translates to a direct ST phase modulation for the generated field. This allows a direct sculpturing of the STc optical field in the ST domain, permitting the generation and manipulation of more complicated STc optical fields in an intuitive fashion. Fig. 4(d) plots the measurement results for the ST intensity and phase of two STOV lattices[18]. Each lattice contains four STOV wavepackets with different topological charge. Using this "near-field" operation of the generator, STOV collision and STOV annihilation experiments are demonstrated.

3) The "intermediate" regime. In this operation regime, the interplay between dispersion and diffraction for STc field propagation is more subtle. Once the dispersive phase and the diffractive phase are perfectly balanced, the evolution of a STc optical field has the exact same mathematical expression of a Fresnel diffraction integral, except that the y-direction coordinate in a Fresnel diffraction is now replaced by time[17]. It is well known that an optical axicon can be used to generate a Bessel beam[84]. The STc field generator can also apply a spatial-spectral conical phase for generating a ST Bessel wavepacket. If an additional helical phase is also applied, the generator can generate Bessel STOV (BeSTOV) wavepackets with a higher-order Bessel function distribution in ST domain. The results for BeSTOV wavepackets with a charge of $+1$, $+2$ and $+3$ are shown in Fig. 4(e) and Fig. 4(f).

5 Recent developments in STOV wavepackets

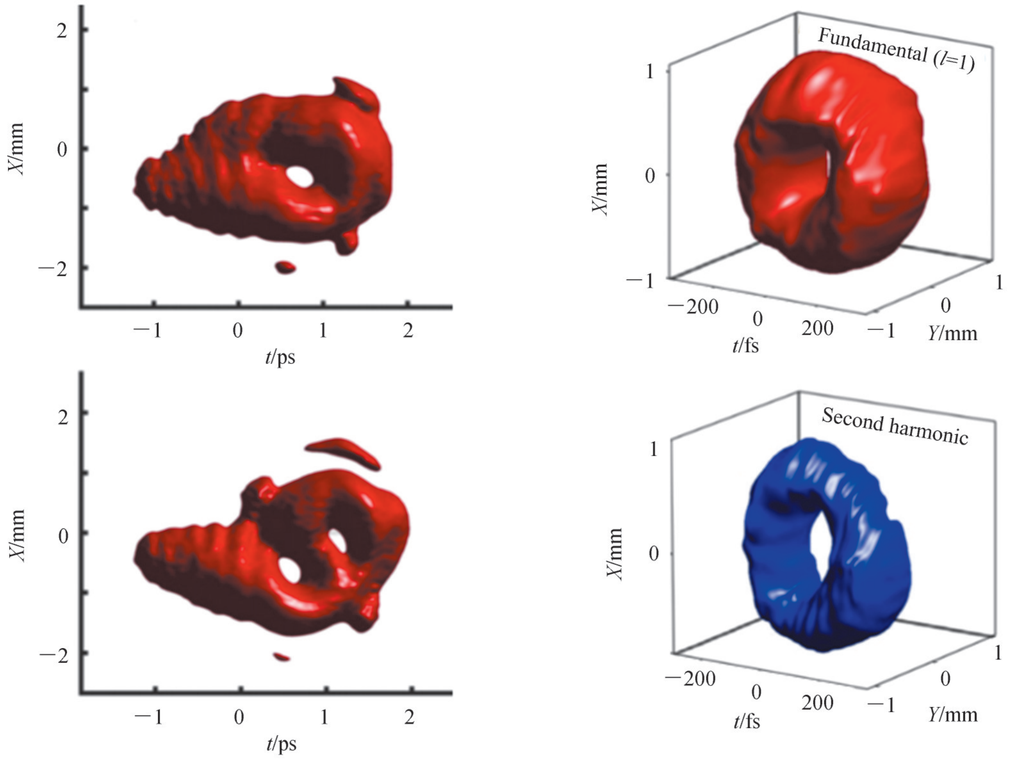
One of the most recent examples of STc optical fields that attracted significant attention is the Spatiotemporal Optical Vortices (STOV) wavepacket. The STOV wavepackets have unique photonic property that the wavepacket can carry pure transverse Orbital Angular Momentum (OAM). Over the last three decades, photonics research community has been extensively studying optical fields that carry a longitudinal OAM[85] or a longitudinal Spin

Angular Momentum (SAM)[86], i.e., vortex beam or left/right circular polarized (LCP/RCP) beam. The angular momentum such field carries has an orientation that is in parallel with the propagation direction of the light field. It was later discovered that transverse SAM can occur in special cases such as a tightly focused beam[87]and evanescent waves from waveguides[88]. On the other hand, only limited research works have theoretically predicted the possibility of photonic transverse OAM in the form of a STOV wavepacket[89-90]. The first demonstration of STOV wavepacket is achieved using the nonlinear collapse and self-arrest of an extremely intense optical pulse in air[91]. The resulting STOV wavepacket has limited pulse energy and this realization approach lacks the control over STOV.

Recently, scientists have successfully generated a STOV wavepacket using a STc optical field generator setup (see Fig. 3) based on a 2D phase modulation device[9-10]. The generated STOV wavepacket can have a controllable ST field structure with a spiral phase of $\exp(il\theta_{x-t})$ in the spatiotemporal domain (see Fig. 5(a) for the experimental results of STOV wavepackets with a topological charge l of $+1$ and $+2$). The creation of a controllable photonic transverse OAM has granted scientists a new degree of freedom for manipulating the photons. It also means the control over photonic OAM is extended from previous 1D to 3D.

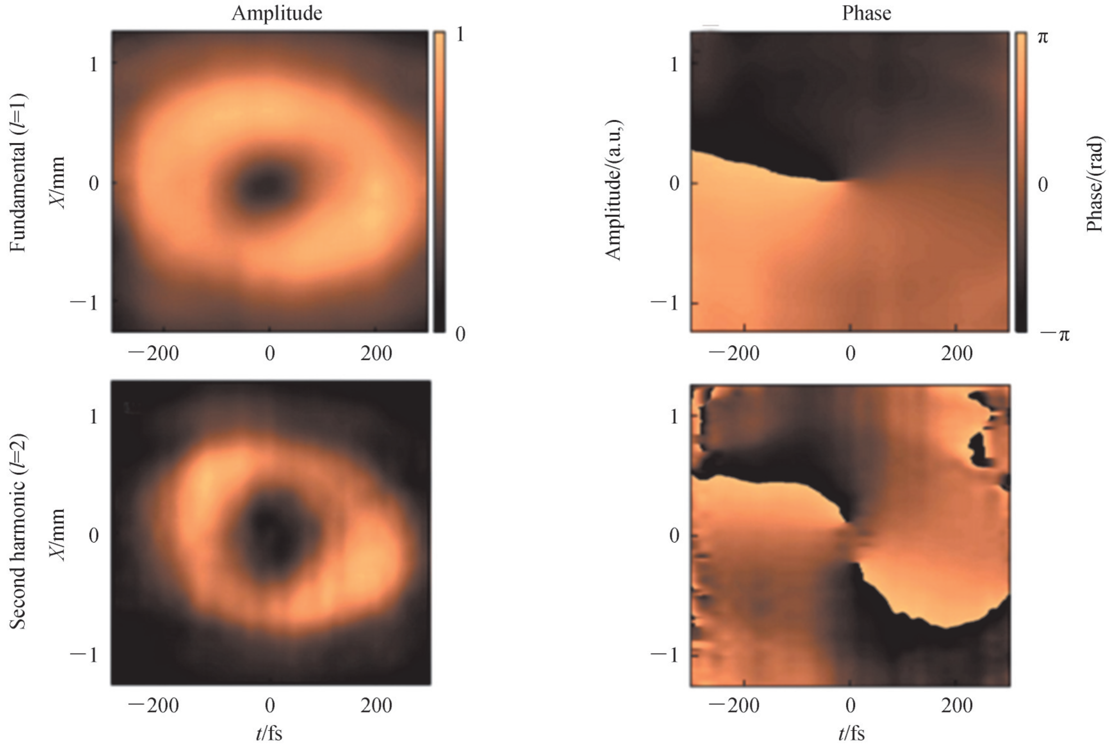
Since the first experimental demonstration of generating STOV wavepackets[9-10], many research groups have studied STOV-related physical experiments. In a nonlinear optical experiment of a second harmonic generation (SHG) process, fundamental STOV wavepackets are converted into SHG STOV wavepackets[12-13]. The resulting SHG STOV wavepacket can maintain its ring-like field distribution in ST domain (see Fig. 5(b) for the iso-surface plot for the measurement results). Besides, the ST phase measurement has verified the conservation of transverse OAM during nonlinear optical processes (see Fig. 5(c) for the ST phase measurement results). Besides, STOV wavepacket can combined with spatial vortices whose OAM is in the longitudinal direction. The resulting STOV wavepacket can have a photonic OAM with a controllable orientation[16] (see Fig. 6(a) for the 3D intensity measurement results for wavepackets whose photonic OAM has a controllable orientation). Furthermore, if polarization control is introduced to modulate a

STOV wavepacket, it was found that a ST phase singularity can co-exist with a spatial polarization singularity[19] (see Fig. 6(b) for the 3D intensity measurement for a cylindrical vector STOV wavepackets). The resulting complex STc optical field can possess a complex local density of photonic angular momentum in space and time, which is of great interest for researchers who study the Spin-Orbit Interaction (SOI) of light[15,95].



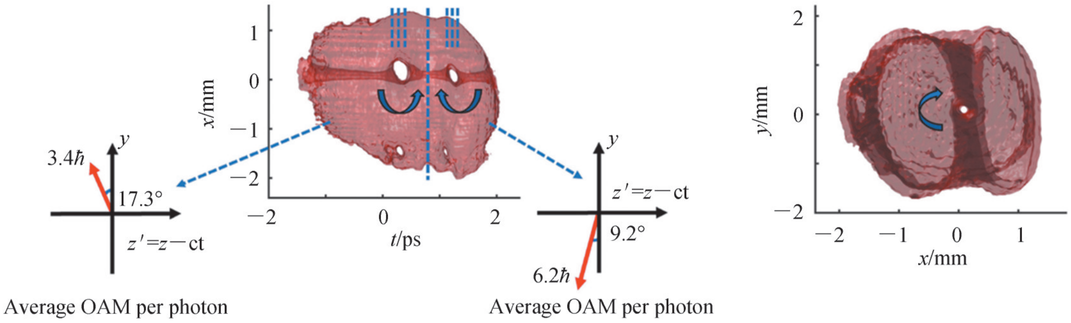
(a) Iso-surface plot for STOV wavepackets with a topological charge l of +1 and +2[9]

(b) Fundamental STOV wavepacket (l=+1) and second harmonic STOV wavepacket (l=+2)[12]

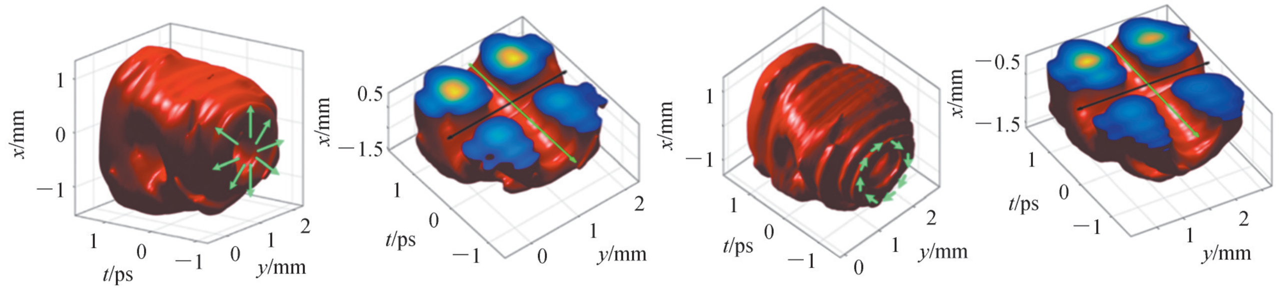


(c) ST amplitude and phase of fundamental STOV (l=+1) and SHG STOV (l=+2)[12]

Fig. 5 STOV wavepacket and SHG STOV wavepacket



(a) STOVs with $l=-1$ and $l=+1$ superposed with a spatial vortex of topological charge -1[16]



(b) STOV wavepackets embedded with a spatial polarization singularity[19]

Fig. 6 STOV wavepackets superposed with additional photonic singularities

6 Summary and future perspectives

In the past decade or so, there have been a dramatic increase in research interests in Spatiotemporal Coupled (STc) optical fields. These fields feature unique photonic properties that are previously unavailable from conventional optical fields. Considering the rapid developing nature, it is inevitable that such a brief review will leave many other important aspects and seminal works out. A special focus is given to the recent example of Spatiotemporal Optical Vortices (STOV) wavepackets that carry photonic transverse Orbital Angular Momentum (OAM). The use of 4-f pulse shaper as an STc optical field generator offers great flexibility to create a wide variety of novel fields. Although the realization of these novel STc optical fields utilizes an experimental setup that is almost exact the same as a standard 4-f pulse shaper, the subtle interplay between dispersion and diffraction during the process makes the generation of STc optical fields more complicated compared with pulse shaping or beam shaping. Meanwhile, it is exactly such a complexity that will offer much richer physics deserving future explorations. During the formation of complicated STc optical field, there are also new physical phenomena yet to be investigated in the future, for example, the reversal of STOV polarity during a dispersive propagation of STOV wavepackets.

The pulse shaper based STc optical field generation method has seen great success and received tremendous interests. It should be pointed out that the current experimental setup can be easily modified to simultaneous modulate multiple parameters over the input light field so that the device can generate much more ST vectorial field. In addition, the generated STc optical fields can be further structured in the spatial domain using the very mature spatial modulation techniques to produce much more sophisticated STc fields such as photonic toroidal vortex[96]. It is fairly certain to conclude that unprecedented level of control for photons is now already on the horizon.

Despite the great success already achieved, there are much more need to be studied, understood and developed in STc optical fields. For example, new generation methods that utilize metasurfaces or other nanophotonic structures are highly desirable in order to miniaturize the generation system and incorporate multiple parameters modulation into the system. With multiple parameters modulated STc fields, new characterization method will be needed. Consequently, a more complete set of toolboxes for the generation and characterization of complex STc optical fields shall be developed. With such a toolbox available, many other STc fields that are highly interesting but was not possible to generate, such as those localized waves[29] will become feasible. Another important future direction for STc optical fields is to study novel light matter interaction phenomena with the generated STc fields. And finally, how to transfer the current STc optical field technique to super-intense and ultrafast high-power laser deserves special attention as it may hold the key to unlock the full potential of these large laser facilities. It is never wise to predict exactly what would come out from a nascent research field such as STc optical field. However, with the unprecedented level of control of the spatiotemporal degree of freedoms of light, it is safe to say that spatiotemporally sculptured optical fields purposefully will significantly enrich the photonics arsenal for scientists in broad research fields ranging from quantum optics, nanophotonics, spin-photonics and spintronics, optical information transmission and processing, optical spectroscopy, laser driven particle acceleration, and much more beyond.

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Spatiotemporal Sculpturing of Light and Recent Development in Spatiotemporal Optical Vortices Wavepackets (Invited)

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Abstract: This paper reviews Spatiotemporal Coupled (STc) optical fields including their theoretical background, the experimental configuration for generating STc optical fields, and the current research status of the newly-discovered Spataiotemporal Optical Vortices (STOV) wavepackets. Firstly, we review the origin and early study of STc optical fields, and introduce the theoretical model for describing STc optical fields. To give an example, we show the spatiotemporal evolution of a STOV wavepacket under normal dispersive, anomalous dispersive, and non-dispersive propagation. Under normal dispersive propagation, the STOV wavepacket maintains its ring-like field structure in the spatiotemporal domain. Under non-dispersive propagation, the STOV wavepacket evolves into a diagonal shape. Under anomalous dispersive propagation, the STOV wavepacket has the polarity reversal during the process. Secondly, we describe the typical experimental setup for generating STc optical fields. Although the experimental configuration for realizing STc optical fields shares almost exact the same experimental setup of a standard 4-f pulse shaper, the generating process is more complicated compared with conventional pulse shaping or beam shaping techniques as it involves a subtle interplay between the dispersion and diffraction effects for the generated STc optical fields. We categorize the operation of a STc optical field generator into three different regimes bythe distance between the exit plane of the generator and the observation plane for the generated STc optical fields：1）the “far-field regime” where the observation plane is at several Rayleigh range after the generator；2）the “near-field” regime where the observation plane is within one Rayleigh range；and 3）the “intermediate” regime where the observation plane is placed between “far-field” and “near-field”. For each operation regime，we give an example of the experimentally generated STOV wavepacket，namely，the first experimental realization of STOV wavepackets，STOV lattices，and Bessel STOV wavepackets. Thirdly，we give a detailed review about the state-of-art research status of the newly discovered STOV wavepackets including introducingwhy STOV wavepacket has become an interesting research topic for scientists，the demonstration of the conservation of transverse photonic Orbital Angular Momentum（OAM）proved by a nonlinear Second Harmonic Generation（SHG）experiment，and STOV wavepackets superposed with additional spatial photonic singularities. Compared with conventional vortex beam，the spatiotemporal spiral phase carried by a STOV wavepacket enables the photon within the wavepacket to have a pure transverse OAM，which makes STOV wavepacket an interesting tool in many research fields. Besides STOV wavepackets，other STc optical fields generated by this STc optical field generator setup also feature unique photonic properties such as achieving negative refraction，propagating free of diffraction，and propagation in a controllable group velocity. So far，the pulse shaper based STc optical field generation method has seen great success and received tremendous interests by the research community. Despite the great success already achieved，there are much more need to be studied，understood and developed in STc optical fields. With the unprecedented level of control of the spatiotemporal degree of freedoms of light，spatiotemporally sculptured optical fields will significantly enrich the photonics arsenal for scientistsin broad research fields ranging from quantum optics，nanophotonics，spin-photonics and spintronics，optical information transmission and processing，optical spectroscopy，laser driven particle acceleration，and much more beyond.

Key words：Optical field manipulation；Ultrafast optics；Spatiotemporal optical fields；Photonic angular momentum

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