



# Theoretical method for generating regular spatiotemporal pulsed-beam with controlled transverse-spatiotemporal dispersion

Zhaoyang Li<sup>\*</sup>, Noriaki Miyanaga

*Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*

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## ABSTRACT

Herein we theoretically report a method that generates a transverse-spatiotemporal dispersion, which is distinct from previous spatial, temporal, and longitudinal-spatiotemporal dispersions. By modulating the transverse-spatiotemporal dispersion, two not yet reported spatiotemporally structured beams, i.e., the honeycomb beam and the picket-fence beam, can be generated in the space–time domain. The generated spatiotemporally structured beams have novel and tunable periodic distributions. The transverse-spatiotemporal dispersion, spatiotemporally structured beams and their inner relationship are analyzed and introduced. We believe that this method might open a path towards new optical beams for potential applications, such as ultrafast optical fabrication and detection.

## 1. Introduction

Optical dispersion is one of the fundamental phenomena in polychromatic, broadband and short-pulse light sources in optics [1]. Spatial dispersion was the first observed form of dispersion and is dependent on the wave vector. For example, after a single refraction or diffraction process, spatial dispersion can easily be generated and is used as a basic tool in fields such as spectroscopy [2]. Temporal dispersion is generally relevant to the frequency-dependent phase velocity in optical media or systems, and is commonly used to shape or modulate optical pulses in time to produce pulses, such as chirped pulses and solitons, for a wide range of applications [3,4].

Recently, following the rapid developments in ultrashort optical pulse generation, some coupling effects were presented. Akturk et al. presented a general theory of first-order spatiotemporal coupling [5], i.e., coupling between the spatial (or spatial-frequency) and temporal (or frequency) coordinates of Gaussian pulses and beams. The electric field ( $E$ -field) of a first-order spatiotemporal coupling can be written in the form  $E(x, t) \propto \exp(Q_{xx}x^2 + 2Q_{xt}xt - Q_{tt}t^2)$ , and the cross-term  $Q_{xt}$  provides information about eight types of spatiotemporal couplings. In practical applications, wave-front rotation can be used in high-harmonic generation experiments to enable the production of isolated attosecond pulses [6]. Focusing of spatial dispersion beams with narrow initial beam apertures (i.e., frequency-dependent beams that are completely separated in the transverse direction), which is known as simultaneous space–time focusing, can be used to improve axial resolution for wide-field imaging applications [7–9]. Only very recently, with the help of the spatiotemporal coupling, the velocities of ultrashort light pulses

were controlled [10], diffraction-free space–time light sheets were generated [11,12], and a new focusing scheme of flying focus was demonstrated [13]. In general, the first-order spatiotemporal coupling and the related distortions show slow near-linear variations. However, cases involving higher-order spatiotemporal couplings would become more complex. For example, in the case of longitudinal-spatiotemporal dispersion involving second-order spatial and temporal terms in the nonlinear Schrödinger equation without the slowly-varying envelope approximation, the coefficients contain the spatial dispersion and group velocity dispersion information, which would then lead to wave envelopes with either relativistic or pseudo-relativistic characteristics [14]. Another example is the complex spatiotemporal distortion in recent ultra-intense femtosecond lasers [15].

In this paper, we describe a rarely researched optics dispersion of the transverse-spatiotemporal dispersion, which is generated in an improved 4- $f$  grating system, which is usually used for pulse-shaping. By modulating the transverse-spatiotemporal dispersion, two kinds of spatiotemporally structured beams (honeycomb-like and picket-fence-like beams) are theoretically produced in the space–time domain, respectively.

## 2. Method and results

Fig. 1 shows a short pulse signal is injected into a 4- $f$  grating system, and the initial beam aperture is expanded to a size that is relatively equivalent to the spatial separation induced by the angular dispersion. A phase spatial light modulator (P-SLM) is positioned just in front of the first lens (L1) instead of the Fourier plane (FP), and then a

<sup>\*</sup> Corresponding author.

E-mail address: [zhaoyang-li@ile.osaka-u.ac.jp](mailto:zhaoyang-li@ile.osaka-u.ac.jp) (Z. Li).

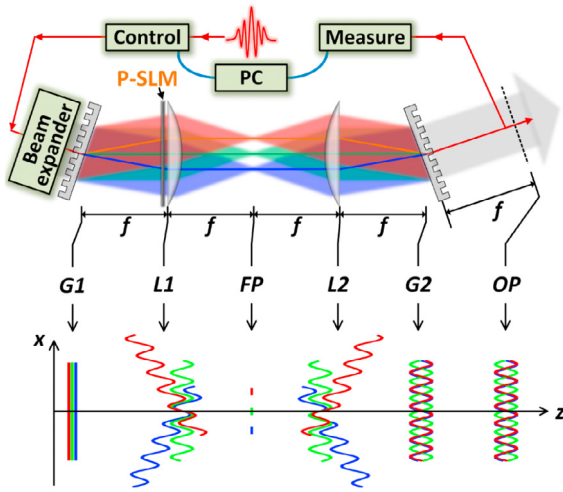


Fig. 1. The setup of the method, and the phase-fronts of three frequencies at different positions. G1: grating 1, L1: lens 1, FP: Fourier plane, L2: lens 2, G2: grating 2, and OP: output plane.

space-dependent phase modulation is introduced at this space–spectrum coupling plane. Before the first grating (G1), each frequency has a planar phase-front, however, at the P-SLM, a space-dependent phase modulation is overlaid on each phase-front, although the frequency-dependent beams are separated along the transverse direction ( $x$ -axis). Then, after the second grating (G2), where the angular dispersion is removed, the spectral phase (i.e., temporal dispersion) varies across the transverse direction, thereby the transverse-spatiotemporal dispersion is produced.

Here, we can find that the differences in the proposed method when compared with three kinds of previous methods are clear. In the traditional 4- $f$  grating system for pulse-shaping, the phase modulator is positioned at the Fourier plane (FP) (and not at the space–spectrum coupling plane), where the beam's spatial properties are completely removed. This is why this method is usually called Fourier transform pulse shaping [16]. In the simultaneous space–time focusing, the beam aperture is usually very narrow when compared with the spatial separation induced by the angular dispersion [7–9]. And, in the beam smoothing for high power lasers, there is usually zero or negligible spatial/angular dispersion, although the transverse phase modulation is applied to a large-aperture beam [17,18]. Consequently, the effect discussed in this paper were not found in previous simulations or experiments.

According to the setup in Fig. 1, we could simulate the complex amplitude of each frequency along the propagation path by using the Collins diffraction formula

$$U_2(x_2, z, \omega) = \frac{\exp(ikz)}{i\lambda B} \int U_1(x_1, \omega) \cdot \exp\left[\frac{ik}{2B}(Ax_1^2 - 2x_1x_2 + Dx_2^2)\right] dx_1, \quad (1)$$

where  $A$ ,  $B$  and  $D$  are elements of the ABCD propagation matrix.

The simulation in this paper is based on the following parameters: Gaussian spectrum/pulse with a center wavelength of 1030 nm and a bandwidth of 20 nm (Full width at half maximum, FWHM), super-Gaussian beam with an order of 10 and a diameter of  $\sim 3$  mm (Full width, FW), grating density of 200 g/mm, Littrow incident angle (i.e., same incident and diffracted angles for the center wavelength), focal length of 100 mm, and sine function phase modulation (from P-SLM) with initial modulation peak-to-valley (PV) value of  $0.9\pi$  and spatial period of 0.6 mm.

Along the propagation path in the setup, Fig. 2 shows the intensity spatial profiles of three frequencies (1022, 1030 and 1042 nm) at

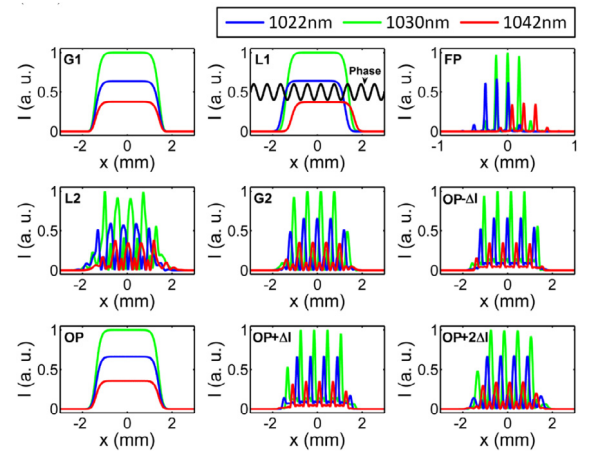


Fig. 2. Intensity spatial profiles of three frequencies (1022, 1030 and 1042 nm) at different positions. G1: grating 1, L1: lens 1, FP: Fourier plane, L2: lens 2, G2: grating 2, OP: output plane, and  $\Delta l$  is the offset length (50 mm here)

several key positions. At the first grating (G1), frequency-dependent beams have a same spatial location, however, at the first lens (L1), they are separated along the angular dispersion direction ( $x$ -axis). In this case, the space-dependent phase modulation (from P-SLM) would modulate the phase-fronts of different frequencies differently. Because of the phase-front modulation and the propagation diffraction, the intensity profiles at the Fourier plane (FP), the second lens (L2) and the second grating (G2) are distorted. However, at the output plane (OP), which is the image position of the P-SLM, the spatial distortion of the intensity profile disappears. Consequently, Fig. 2 shows that, at the output plane (OP), the amplitude/intensity distortion induced by the phase-front modulation and the propagation diffraction becomes negligible, however, for other positions with an offset length, it cannot be satisfied.

Meanwhile, for the ideal case, as a benefit of the use of the 4- $f$  system, if the P-SLM does not work, the spatial and temporal dispersions induced by the first grating (G1) could be compensated completely by the second grating (G2), and the output is then restored to match the input without additional spatial, temporal or spectral modulations. In this case, the generated transverse-spatiotemporal dispersion can be controlled well using the P-SLM.

According to the above, the amplitude/intensity distortion at the output plane (OP) is negligible, and the spatiotemporal distribution of the pulsed-beam is mainly determined by the transverse-spatiotemporal dispersion.

Using the above parameters, we simulate the propagation of each frequency by the Collins diffraction formula, and, after the coherent addition, the pulsed beam in both time and space is obtained by the Fourier transform at each spatial position. Fig. 3(a) shows the input pulsed beam (super-Gaussian in space and Gaussian in time) is changed into a honeycomb beam in the space–time domain, and the spatiotemporal distribution is in the  $x$ - $t$  plane. Fig. 3(b) shows the sine function phase modulation in space ( $x$ -axis) is tilted along the spectral frequency axis ( $\Delta f$ -axis).

Refer to Fig. 1, if an appropriate space-independent initial temporal dispersion (i.e., spectral phase) is loaded, for example the spectral phase of the center optical ray is measured and pre-compensated using commercial products Wizzler and Dazzler by Fastlite Inc. [19], the dispersion-free condition would occur at the beam center as well as some positions with certain periodic locations along the transverse direction ( $x$ -axis) [Fig. 4(b)], and then the Fourier transform-limited pulse would be achieved at these positions. However, at other positions, temporal dispersions and pulse distortions cannot be avoided. In this case, Fig. 4(a) shows the input pulsed beam is then changed into a

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