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Experimental demonstration of spatiotemporal analog computation in ultrafast optics

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Abstract

It is intractable to perform information processing and computation on single ultrafast optical pulses, within picoseconds or even femtoseconds. Here, we experimentally demonstrate an optical spatiotemporal differentiator, a mirror-symmetry-breaking dielectric metagrating, which performs analog computations of both spatial and temporal differentiations on single ultrafast optical wavepackets. The spatiotemporal differentiator is designed with a transfer function with linear dependence on spatial wavevector and temporal frequency and fabricated by using a double-exposure E-beam lithography process. We achieve the first-order spatiotemporal differentiation with experimental resolutions of approximately 14 μm (in space) and 260 fs (in time). Furthermore, we report a parabolic relationship between the transverse velocity of a front-tilted photonic wavepacket and the normalized intensity of its first-order spatiotemporal-differentiation wavepacket. This relationship allows direct measurement of the transverse velocity using only the normalized intensity, fundamentally simplifying velocity detection. These capabilities of optical spatiotemporal computation endow emerging space-time optics with fundamental computation blocks.

Introduction

Spatiotemporal structured light can provide new capabilities in controlling ultrafast optical pulses as required^{1–7}. Several studies have addressed the great opportunities for joint manipulation on both spatial and temporal degrees of freedom, where the space-time coupling effect enables novel phenomena, including optical space-time wavepackets^{8–11}, front-tilted pulses^{12,13}, full spatiotemporal light modulation^{14,15}, spatiotemporal optical vortices (STOVs)^{16–22}, and so on. More recently, spatiotemporal holograms^{14,23,24}, spatiotemporal images^{25–27}, and STOV arrays^{14,25} have been encoded in a single ultrafast optical pulse, with critical potential applications in

optical communication, high-resolution microscopy, high-harmonic generation, and laser micromachining.

Since spatiotemporal optical wavepackets are just within the time scale of picoseconds or even femtoseconds, high-speed information processing to these ultrafast optical pulses is far beyond the capability of state-of-the-art electronics. Recently, substantial interest has been sparked to explore nanophotonic structures with analog computation features, which outperform conventional digital processing to optical fields^{28,29}. Extensive studies show that optical differentiators enable parallel image processing to extract the boundary of objects, and achieve high computation efficiency without analog-to-digital conversion^{30–38}. In particular, special designed structures have been proposed to implement analog computation to spatiotemporal wavepackets^{39–43}. For example, with a mirror-symmetry-breaking metagrating, we proposed the nonlocal effect to enable optical spatiotemporal differentiation, which could be deployed to highlight the space-time variations of ultrafast optical pulses and generate the STOVs⁴⁰. By performing optical computation of high-order spatiotemporal differentiation, a very recent theoretical work discussed event-based image processing metasurfaces when the input image is evolving in time on subpicosecond

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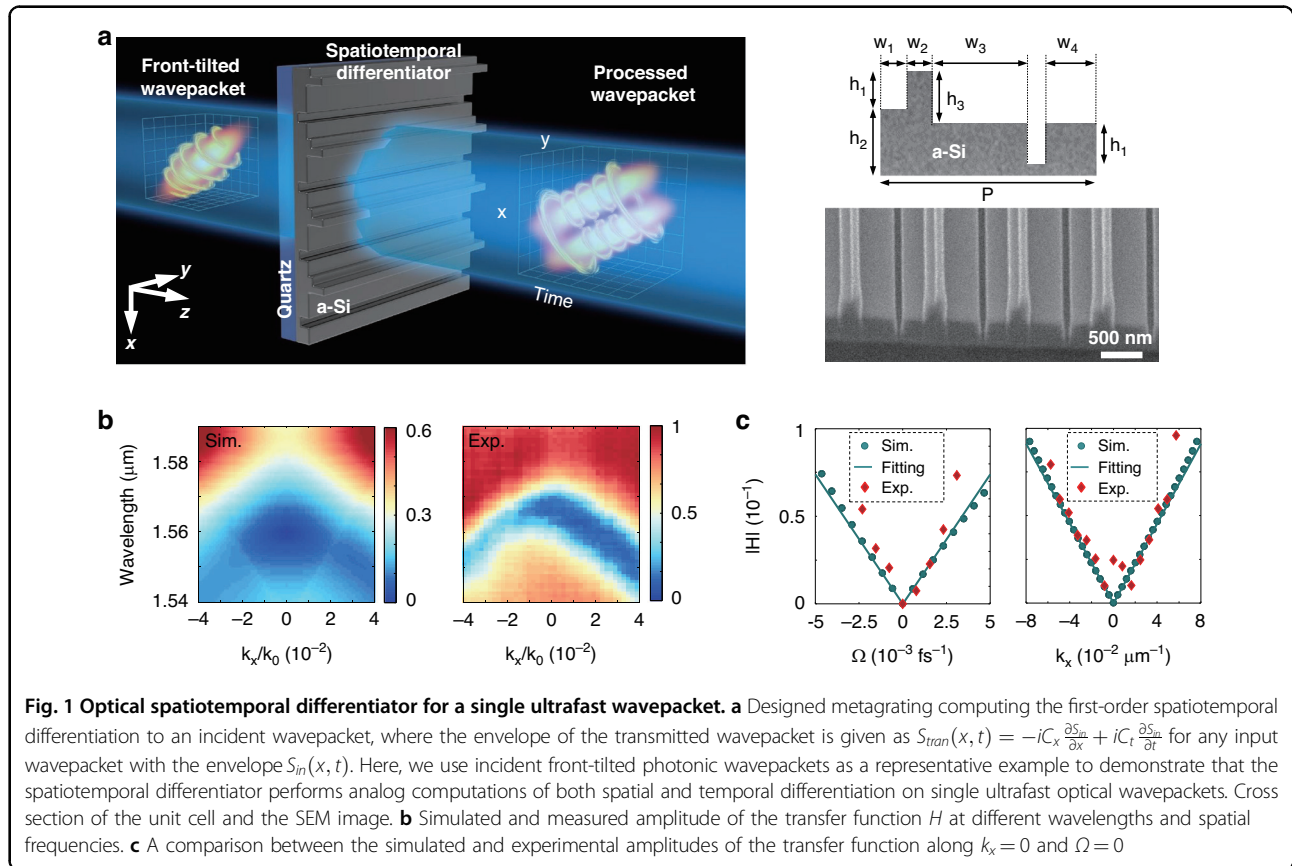
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timescales⁴⁴. A metallic meta-device was fabricated and used to demonstrate spatiotemporal differentiation for microwave signals⁴³. For spatiotemporal computation with intractable ultrafast pulses, none of these structures, however, has been demonstrated experimentally either.

Here, we experimentally demonstrate an optical spatiotemporal differentiator, a mirror-symmetry-breaking dielectric metagrating, which performs analog computations of both spatial and temporal differentiations to ultrafast optical wavepackets. The spatiotemporal differentiator is designed with a transfer function with linear dependence on spatial wavevector and temporal frequency, and fabricated by using a double-exposure E-beam lithography process. Generally, when a spatiotemporal wavepacket transmits through the metagrating, the output wavepacket exhibits an envelope proportional to the joint-differentiation profile of the incident pulse in both space and time. As an example, we generate front-tilted photonic wavepackets as the incident pulses and measure the spatiotemporal profile of the transmitted ones. Due to the presence of an out-of-phase delay between the spatial and temporal contributions, the metagrating creates spatiotemporal phase singularities with transverse orbital angular momentum of light. Furthermore, we report a parabolic relationship between the transverse velocity of a front-tilted

photonic wavepacket and the normalized intensity of its first-order spatiotemporal-differentiation wavepacket. This relationship allows direct measurement of the transverse velocity using only the normalized intensity, fundamentally simplifying velocity detection. Our experimental results demonstrate that compact nanostructures provide fundamental computation blocks for extreme spatiotemporal manipulation, paving the way towards integrated ultrafast optical computing.

Results

Design and experimental characterization of spatiotemporal joint manipulation

To demonstrate the first-order spatiotemporal differentiator, we design a metagrating with silicon nanostructures sitting on a quartz substrate (Fig. 1a). Based on the mirror-symmetry breaking⁴⁰, a spatiotemporal differentiation has a transfer function in frequency space $H = C_x k_x + C_t \Omega$, where k_x is the transverse wavevector, $\Omega = \omega - \omega_0$ denotes the sideband frequency with the center frequency ω_0 of the wavepacket, and C_x and C_t are the differentiation coefficients in space and time, respectively. As a result, for any input pulse with the envelope $S_{in}(x, t)$, the envelope of the transmitted pulse is given as $S_{tran}(x, t) = -iC_x \frac{\partial S_{in}}{\partial x} + iC_t \frac{\partial S_{in}}{\partial t}$.

To evaluate the space-time coupling, we define a complex parameter $A = C_t/C_x$. The magnitude of $|A|$ is related to the coupling strength, while space-time decoupling occurs if $|A| = 0$ or ∞ . Note that the phase $\Delta\varphi = \arg(A)$ determines the phase delay between the spatial and temporal contributions. By breaking the mirror symmetry of the metagrating, it has been shown that the contribution can be out of phase, i.e., $\Delta\varphi \neq 0$ or π (ref. ⁴⁰). For the out-of-phase case, the transfer function H has phase singularity and zero value at $k_x = 0$ and $\Omega = 0$. Thus, for a normal incident Gaussian-shaped pulse, the pulse transmitted through the metagrating will be a STOV with the phase singularity (where the zero-value intensity is located) in the spatiotemporal domain, as shown experimentally later.

By using the finite-element method, we design the metagrating on a quartz substrate, with the center operation wavelength at $\lambda_0 = 1560$ nm (see the design details in Materials and methods (MM) Sec. 1 and Supplementary Material (SM) Fig. S1). We fabricated experimentally with double-exposure E-beam lithography (EBL) by using two masks (MM Sec. 2). The metagrating with a subwavelength period of $p = 1005$ nm diffracts the normally incident light into only the zeroth order due to $p < \lambda_0$. For breaking mirror symmetry, the unit cell consists of different widths and heights for the gaps and pillars, where the geometric parameters are $w_1 = 128$ nm, $w_2 = 112$ nm, $w_3 = 429$ nm, $w_4 = 240$ nm, $h_1 = 235$ nm, $h_2 = 375$ nm, $h_3 = 320$ nm (Fig. 1a).

To measure its transfer function, we develop a homemade angle-resolved optical spectroscopy (MM Sec. 1). Figure 1b shows the transfer function H by simulation and experimental results. Approximately at a central operation wavelength of $\lambda_0 = 1560$ nm and $k_x = 0$, the linear dependence of H on the time and spatial frequencies reveals the required feature for a spatiotemporal differentiator (Fig. 1c), and the expected phase singularity is located. To evaluate the experimental C_x and C_t , both the measured and simulated transfer functions are compared at the temporal and spatial frequencies, where their good agreement confirms the required linear dependence in a first-order spatiotemporal differentiator. We fit the amplitude and phase of H along the lines $k_x = 0$ and $\Omega = 0$, respectively. This yields theoretical values of $C_x = 1.14e^{-1.49i}$ μm and $C_t = 14.8e^{-3.06i}$ fs, implying a nonzero space-time coupling strength of $A \approx -12.98i$ fs μm^{-1} . The phase delay between C_x and C_t is close to $\pi/2$, which indicates the out-of-phase contribution between the spatial and temporal differentiation computations.

Spatiotemporal differentiation and phase-singularity generation

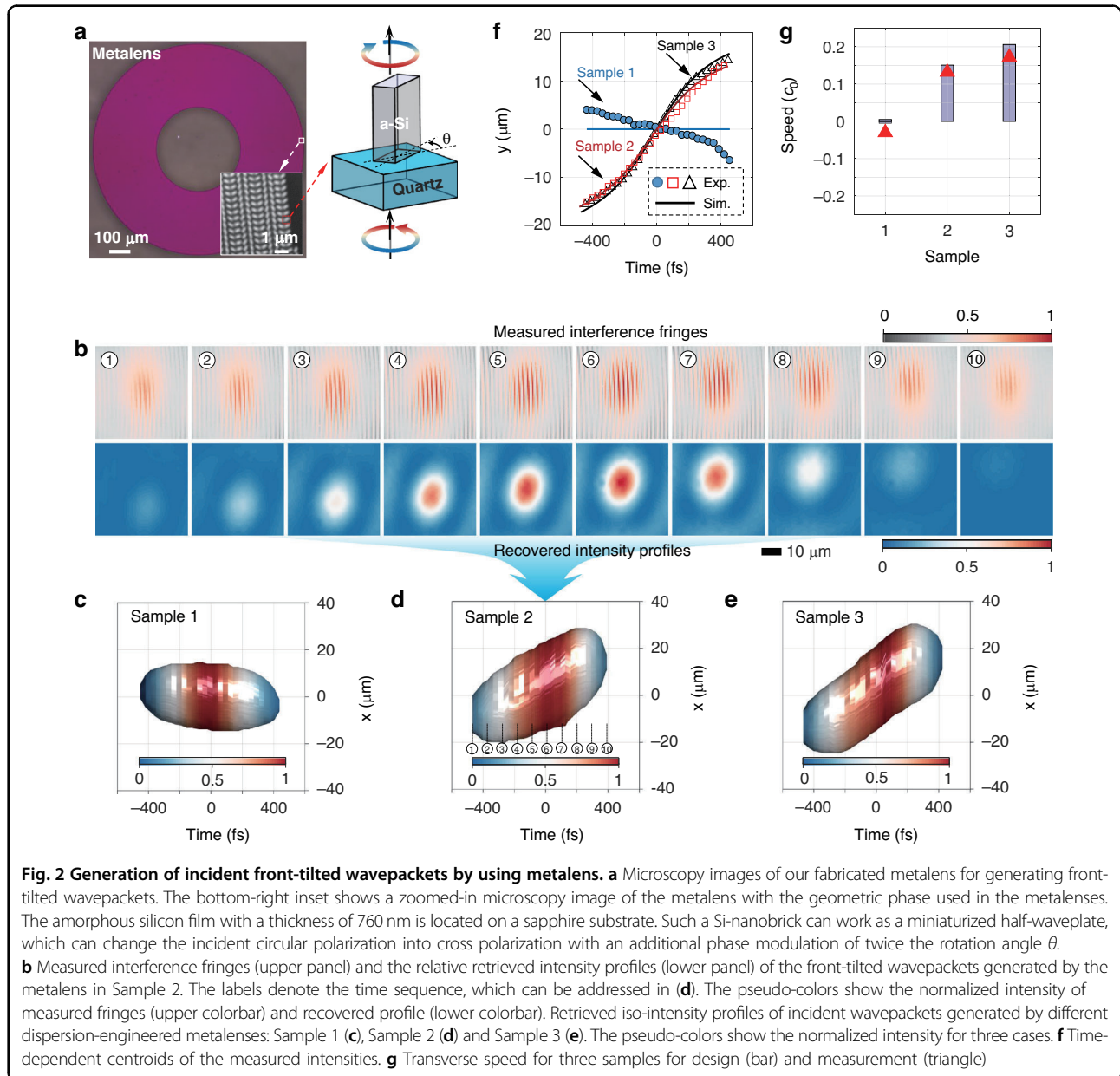
To show the first-order spatiotemporal differentiator performing analog computation, we generate three

different front-tilted photonic wavepackets by designing and fabricating high numerical aperture metalenses with off-centered phase profiles (see the design and fabrication details in MM Sec. 2). By controlling the propagation delay, the incident wavepacket at the radial position of the metalenses arrives at the focal plane in different sequential times so that the eccentric phase with x -coordinate dependence leads to a laterally moving focus with time, i.e., spatiotemporal front-tilted wavepackets. With different geometric phase distributions (chosen for their dispersion-less feature^{45,46}), three samples are designed and fabricated (see Sample 2 in Fig. 2a, and Samples 1 and 3 in SM Fig. S6).

The generated front-tilted wavepackets are characterized with a custom-made Mach–Zehnder interferometer (SM Fig. S7). By using a delay line to control the signal arm, the upper panel in Fig. 2b shows the measured fringes shift vertically for Sample 2, implying the transverse motion of the wavepackets (see the retrieved intensity profiles in the lower panel in Fig. 2b). The measured results for Samples 1 and 3 are shown in SM Fig. S8, 9, respectively. For a better observation of these transverse shifts, we show the iso-intensity profiles of these retrieved wavepackets with different transverse velocities in Fig. 2c, d, which reveal the expected shift of the intensity profiles with time. The time-dependent centroids of the measured intensities for these wavepackets are in good agreement with their theoretical values (Fig. 2f). By fitting these shifted centroids, we obtain the measured transverse velocities: $v_1 = -0.028c_0$ (Sample 1), $v_2 = 0.1318c_0$ (Sample 2) and $v_3 = 0.1752c_0$ (Sample 3), as observed in Fig. 2g, where c_0 is the speed of light in vacuum.

By inserting the metagrating into the signal arm of the Mach–Zehnder interferometer, we observe that the spatiotemporal wavepackets differentiated by the metagrating have interference fringes with two-lobe shapes. The upper panel in Fig. 3a shows the interference fringes when the incident wavepacket is generated by Sample 2 (see SM Fig. S8, 9 for the cases of Sample 1 and 3, respectively). The two lobes in the intensity profile of the transmitted wavepackets are key signatures of spatiotemporal differentiation applied to the incident front-tilted wavepackets, as a result of the differentiation computation performed on the envelope of the input wavepacket. Owing to the transverse velocities of the incident front-tilted wavepackets, the retrieved intensity profiles (the lower panel in Fig. 3a in the case of Sample 2) of the spatiotemporal differentiation wavepackets also shift with time. For a better observation, Fig. 3b–d show the iso-intensity profiles of the transmitted pulse for the incident wavepackets generated by all the three samples, respectively. As one of the features of spatiotemporal differentiation, the zero-intensity profiles in the spatiotemporal-differentiation wavepackets are observed experimentally near the spatial and



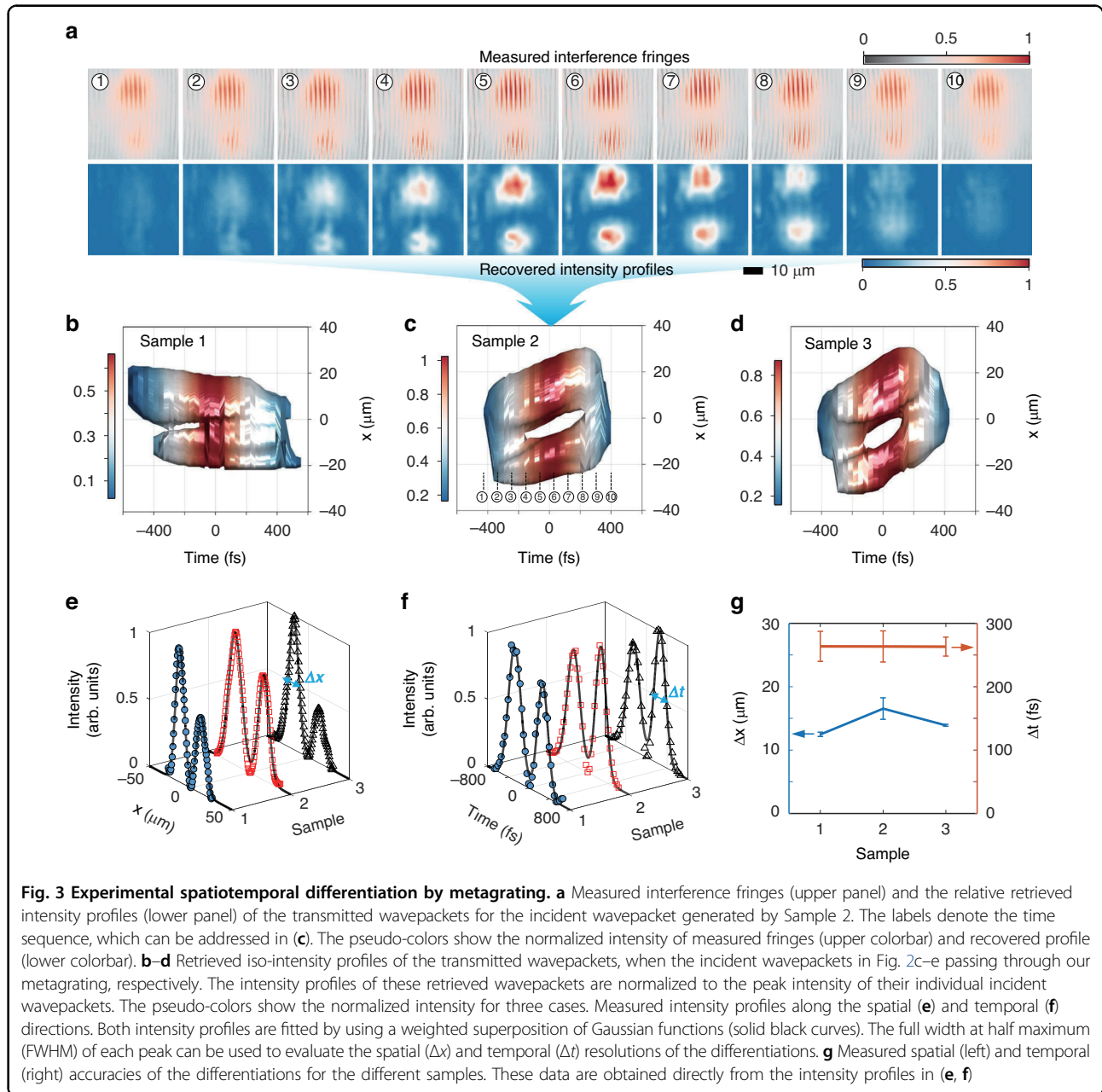


temporal centers (i.e., $x = 0$ and $t = 0$), where the incident wavepackets have the slowest spatiotemporal variation.

To elaborate such a differentiation operation, the measured x -directional (Fig. 3e) and temporal (Fig. 3f) intensity profiles across the zero-intensity position exhibit the expected saddle shapes with two peaks. The full width at half maximum (FWHM) of each peak is used to evaluate the resolution of both spatial and temporal differentiations. By using numerical fitting (see the solid black curves in Fig. 3e, f), we obtain the experimental resolutions Δx and Δt (Fig. 3g) for different samples. The average values are $\Delta t = 263.4$ fs and $\Delta x = 14.3$ μm , which coincide with the theoretical predictions $\Delta t = 200$ fs and $\Delta x = 12.5$ μm , derived from the linear-dependence ranges

in the temporal frequency and wavevector domains, approximately about $-0.005 \leq \Omega/\omega_0 \leq 0.005$ and $-0.08 \leq k_x/k_0 \leq 0.08$ (Fig. 1c). The experimental temporal resolution Δt is greater than the predicted Δt , which is caused by the temporal width of the reference probe in the interferometer. Note that the differentiation resolutions can be further enhanced by designing metagratings with the low Q-factor, which broadens the linear ranges in both the temporal and spatial frequency domains, according to spatiotemporal coupled-mode theory^{47–49}.

Such a spatiotemporal differentiation exhibits the advantage of optical analog computing, which can process with a few hundred femtoseconds without optical-to-electric and electric-to-optical signal conversion. As

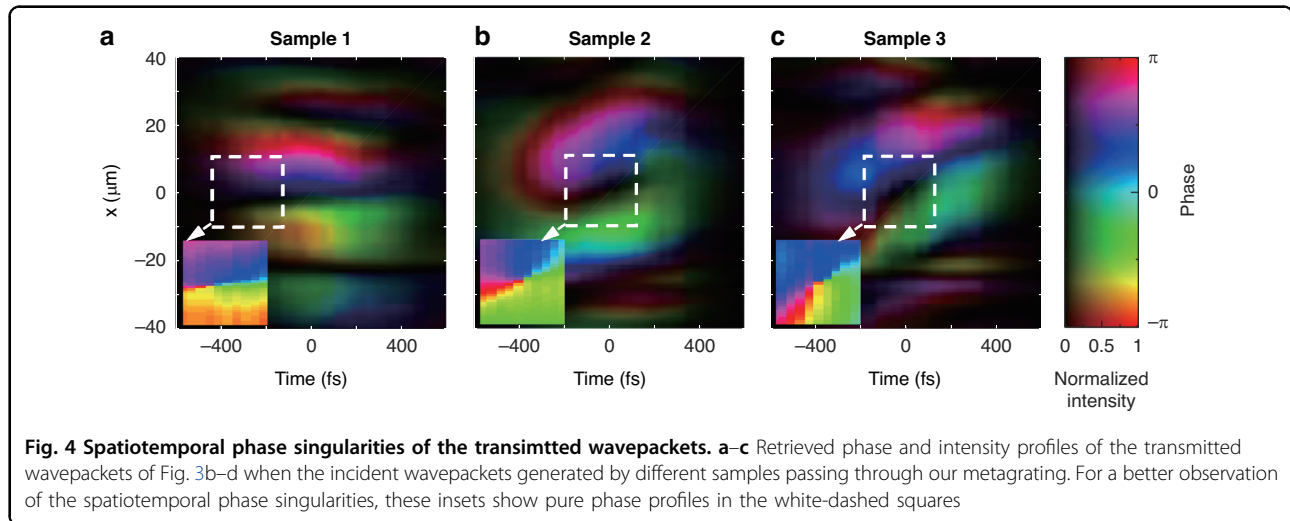


another feature of spatiotemporal differentiation, spatiotemporal phase singularities are also revealed experimentally by using the retrieved phase and intensity profiles (Fig. 4). Near the centers, we can observe the phase singularities with dark intensity profiles of the transmitted wavepackets, which originate fundamentally from the out-of-phase delay between the spatial and temporal differentiation. Correspondingly, across these phase singularities, the measured interference fringes have half-period dislocations between the upper and lower parts of the fringes, implying an expected phase jump of π over the singularities. These observations agree with the null intensities around the centers as depicted in the iso-

intensity contours (Fig. 3b–d). Thus, we have confirmed the validity of the proposed spatiotemporal differentiator to the incident front-tilted wavepackets. For general spatiotemporal wavepackets, the spatiotemporal computation can be verified by measuring the profiles of both the incident and transmitted pulses using an experimental setup similar to the Mach–Zehnder interferometer shown in SM Fig. S7.

Probing ultrafast transverse shifting velocity by spatiotemporal differentiation

Given that practical laser wavepackets have near-Gaussian spectra⁵⁰, we consider a front-tilted photonic



wavepacket with a Gaussian-type temporal distribution and a general transverse envelope transversely shifting

$$S_{in}(x, t; v_T) = f(x - v_T(t - t_0)) \cdot e^{-\left(\frac{t-t_0}{w_t}\right)^2} \quad (1)$$

where x is only the lateral coordinate to simplify the discussion, v_T is the transverse shifting velocity of the front-tilted wavepacket, and w_T and t_0 denotes the waist radius and the center of the Gaussian distribution in the temporal dimension, respectively. The general function $f(x)$ is the spatial distribution of the wavepacket at the time $t = t_0$. Note that v_T determines only the transverse velocity of the pulse with respect to the time axis, which reflects the inherent shape of the pulse. Therefore, the velocity v_T is independent of the propagation velocity of the pulse. The transmitted wavepacket is

$$S_{tran}(x, t; v_T) = -iC_x e^{-\left(\frac{t-t_0}{w_t}\right)^2} \cdot \left[(1 + Av_T) \cdot f'(\xi) + \frac{2A(t-t_0)}{w_t^2} f(\xi) \right] \quad (2)$$

where f' is the first-order differentiation of the function f , $\xi = x - v_T(t - t_0)$ and the coupling coefficient $A = C_t/C_x$. The magnitude $|A|$ is related to the coupling strength between space and time. Equation (2) expresses the dependence of the transmitted wavepacket on the transverse velocity v_T . To obtain a measurable parameter, the normalized intensity is given as

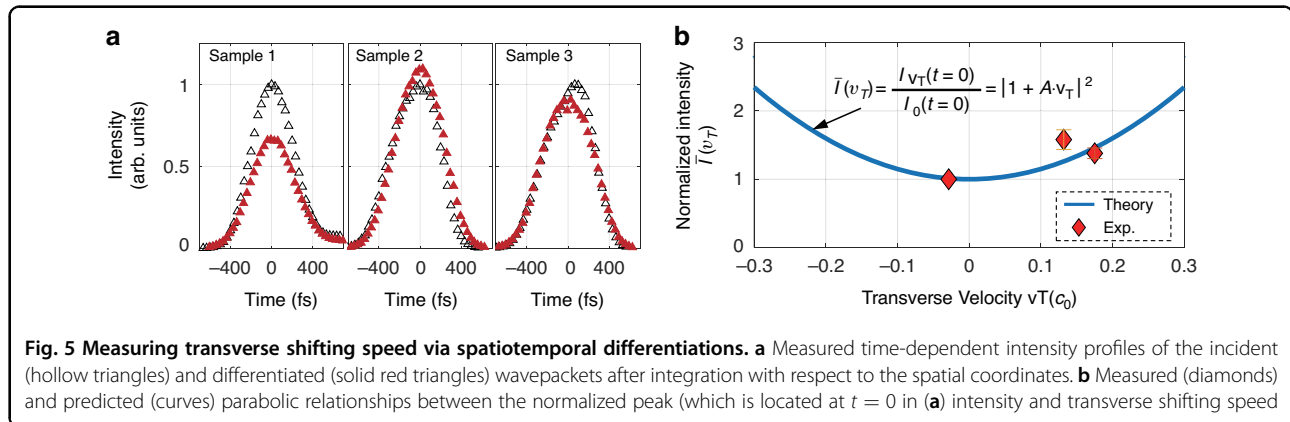
$$\bar{I}(v_T) = \frac{I(x, t_0; v_T)}{I(x, t_0; 0)} = |1 + Av_T|^2 \quad (3)$$

where the intensity of the transmitted wavepacket is $I(x, t; v_T) = |S_{tran}(x, t; v_T)|^2$. We note that at time $t = t_0$, the first-order derivative of the intensity for the

transmitted wavepacket is zero (see the details in SM Sec. 2), which means a maxima or minima of intensity, and this property can be utilized to determine the time t_0 .

Note that Eq. (3) indicates that the transverse velocity can be inferred by measuring the intensity at one moment, without the requirement for measurements of their whole temporal and spatial profiles. First, since the suggested $\bar{I}(v_T)$ is independent of the spatial coordinates x , we can use the integrated intensity $P(t; v_T) = \int I(x, t; v_T) dx$ in experiment, leaving one-dimensional temporal intensity and have that $\bar{I}(v_T) = P(t_0; v_T)/P(t_0; 0) = |1 + Av_T|^2$. Such an operation facilitates experimental implementation because it can suppress the errors of intensity from spatial deviation and inevitable environmental noise. Second, $\bar{I}(v_T)$ depends on only the transverse velocity v_T when the coupling coefficient A is fixed for a given spatiotemporal differentiator. Once the dimensionless parameter $\bar{I}(v_T)$ is obtained by measuring the integrated intensity P at time $t = t_0$, we can calculate the transverse velocity v_T directly via Eq. (3). Third, Eq. (3) shows that the coupling between spatial and temporal differentiations is significant for the proposed mapping, because when they are decoupled, i.e., $|A| = 0$ or ∞ , it will be invalid to measure v_T .

To demonstrate this effect, we verify the parabolic relationship in Eq. (3) by measuring the intensity values when the front-tilted wavepackets transmit through the spatiotemporal differentiator, with different transverse velocities. To eliminate the deviation from different powers in each incident laser wavepacket, the experimental $P(t; v_T)$ (solid red triangles in Fig. 5a) of each differentiated wavepacket is normalized to the peak intensity of the transmitted wavepacket through the silicon film on a quartz substrate (hollow triangles in Fig. 5a). We experimentally determine the time t_0 as the maximum intensity in Fig. 5a. By addressing their measured velocities, Fig. 5b shows, the experimental data



$\bar{I}(v_T)$ (red diamonds), which basically obey the predicted parabolic formula (solid curve). We notice that the solid curve in Fig. 5b is not a fitting one; rather, it is based on the experimentally determined parameter A , independently obtained from the measurement shown. For Sample 2, we observe a relatively large deviation, which might be caused mainly by the imperfect normal incidence of the wavepackets on the metagrating. Since the customization of arbitrarily shaped pulses is still an emerging research area, generating arbitrarily tilted pulses with specific transverse velocities remains challenging. Although a dispersion-controlled metalens is employed here to produce the tilted pulses, the current approach is still limited in generating pulses with arbitrary spatiotemporal dispersion. As a result, only limited experimental data based on three fabricated metalenses are presented in this work. Nevertheless, these results convincingly provide experimental verifications for the parabolic relationship between the normalized intensity and the transverse shifting velocity. Note that because the transverse shifted velocities are comparable to the speed of light, the parabolic relationship offered by the spatiotemporal differentiation suggests an indirect method to characterize the transverse movement of front-tilted photonic wavepackets.

Discussion

In conclusion, we experimentally demonstrate spatiotemporal differentiation computation on single ultrafast optical wavepackets using a mirror-symmetry-breaking metagrating. We achieve first-order spatiotemporal differentiation with experimental resolutions of approximately $14\ \mu\text{m}$ (in space) and $260\ \text{fs}$ (in time). This ultrafast information processing enables real-time computing computation on spatiotemporal structured wavepackets, surpassing the current capabilities of the state-of-the-art electronic instruments. As a result, spatiotemporal computing opens new avenues in the emerging field of space-time optics^{51–53}, with promising applications in optical communication and processing^{54–56}, high-harmonic generation^{57–59}, and optical tweezers^{60,61}.

Specifically, we have demonstrated that the spatiotemporal differentiator is beneficial for characterizing the transverse shifting speed of front-tilted optical pulses. This spatiotemporal differentiation effect enables the detection of transverse motion at extremely high speeds, approaching the speed of light. It complements traditional techniques such as the Doppler effect for detecting longitudinal velocities and the angular Doppler effect using structured light for measuring lateral velocities^{62,63}.

In comparison with conventional optical computing based on spatial differentiation^{28–38}, our experimental results demonstrate that spatiotemporal differentiators provide fundamental building blocks for spatiotemporal optical computation, incorporating both spatial and temporal processing^{64–66}. In the present work, we propose a metalens-based method to precisely modulate dispersion and generate spatiotemporally structured light. Recent advances have focused on encoding information in the spatiotemporal domain and on generating spatiotemporal holograms and images within a single ultrafast optical pulse using spatial light modulators (SLMs)^{14,23–26}. With the development of various cutting-edge SLMs capable of gigahertz modulation rates and low power consumption^{15,67,68}, spatiotemporal computing holds promise for enabling high-dimensional structured light as advanced information carriers, paving the way for ultrafast optical computing.

Materials and methods

Numerical simulation and characterizing the transfer function of the first-order spatiotemporal differentiator

We consider that the incident (transmitted) field is expressed as $E_{in(tran)}(x, t) = S_{in(tran)}(x, t)e^{-i\omega_0 t}$ and decompose $S_{in(tran)}(x, t)$ into a weighted superposition of plane waves via a Fourier transform: $S_{in(tran)}(x, t) = \iint \tilde{S}_{in(tran)}(k_x, \Omega) \exp(ik_x x - i\Omega t) dk_x d\Omega$, where $S_{in(tran)}$ and $\tilde{S}_{in(tran)}$ denote the envelope amplitude and envelope spectrum of the incident (transmitted) field, respectively. k_x is the transverse wavevector, and $\Omega = \omega - \omega_0$ denotes



the shifted temporal frequency with the center frequency ω_0 of the wavepacket. One can evaluate the wavepacket transformation from the incident to the transmitted light by using the transfer function $H \equiv \tilde{S}_{\text{tran}}(k_x, \Omega) / \tilde{S}_{\text{in}}(k_x, \Omega)$ in momentum space.

Here, we numerically simulate the transfer function H via the finite-element method via the commercial full-wave software package COMSOL (SM Fig. S1), where the periodic boundary along the x direction is used. In our simulation, the refractive indices of silicon refer to the experimental data⁶⁹. The design of the metagrating is implemented by scanning the structural parameters until the expected transfer function is obtained while considering the breaking of the mirror symmetry.

To characterize its transfer function, we develop homemade angle-resolved optical spectroscopy (see its optical setup in SM Fig. S2), which can output transmission at spatial and spectral frequencies. Owing to the broken mirror symmetry of our metagrating, the measured transfer function exhibits an asymmetric distribution of $k_x = 0$, which can also be observed in the simulated transfer function (Fig. 1b). The measured transfer function at $k_x = 0$ has a valley at a wavelength of ~ 1567 nm, which deviates slightly from the designed 1560 nm due to measurement uncertainty and fabrication errors. To evaluate the experimental C_x and C_t , both the measured and simulated transfer functions are compared at the temporal and spatial frequencies (Fig. 1c), where their good agreement confirms the required linear dependence in a first-order spatiotemporal differentiator. In addition, its ability to generate spatiotemporal phase singularity has also been validated experimentally by checking the intensity and phase profiles of the wavepackets transmitted through this metagrating (see the simulated and experimental results in SM Fig. S3).

Fabrication of metagrating and metalens

To fabricate the 3-dimensional metagrating with three-level heights, we use a double-exposure E-beam lithography process, which can be divided into three steps (SM Fig. S4). Step 1 is the generation of the mark for the next alignment. After the exposure and development of the photoresist (S1813), a 10 nm chromium film is deposited on the device via electron beam evaporation (Kurt J. Lesker, PVD75 Proline) to increase its adhesion, followed by the deposition of an 80 nm gold film. The cross-mark patterns are subsequently transferred into the Cr/Au film after lift-off in NMP (N-methylpyrrolidone) solvent. Step 2 is the generation of the first pattern layer. The positive electron-beam resist (AR-P 6200) is coated and baked. After alignment with cross-marks, the dried photoresist was patterned via electron beam lithography (JEOL, JBX 6300FS) and developed in AR600-546 for 60 s. The a-Si film without a photoresist is then etched to the designed

thickness via an inductively coupled plasma-reactive ion etching (ICP-RIE) system (Oxford, Plasma Pro System100 ICP380). Finally, the residual photoresist is removed by the NMP solvent. Step 3 is the generation of the second pattern layer, which is a repetition of step 2 via electron-beam lithography but with different patterns. Then, the device is etched, and the photoresist is removed, yielding 3-dimensional metagrating.

Note that the feature size of the device is ~ 100 nm. To obtain high-quality metagrating, the first and second pattern layers must align precisely for better performance. To solve this problem, we fabricate a series of arrays of the first pattern layer with a fixed period of 500 μm . However, in the fabrication of the second pattern layer, the fixed period of the arrays is 499.99 μm , which is 10 nm smaller than that of the first pattern layer. This design works via the same principle with a Vernier calliper. Even if there are errors in alignment during fabrication, we can always find a relatively precise sample, which greatly reduces the difficulty of alignment issues in fabrication.

In this work, metalenses are also used to generate dispersion-engineered laser wavepackets (SM Sec. 1). Its fabrication follows the standard lift-off electron beam lithography process. First, a positive electron-beam resist is patterned and developed, followed by deposition of a 10-nm-thick chromium film for hard masking. Thus, the nanobrick patterns are transferred into the ultrathin chromium film after lift-off. Then, the a-Si film without a hard mask is etched sufficiently by an ICP-RIE system. Finally, the residual chromium mask is removed by a chromium etchant, leaving the metalenses used in our experimental measurement.

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Author contributions

Z.R. and K.H. initiated the idea and the project. K.H. designed the experiment for this work. J.H. and Z.R. developed the metagrating design for spatiotemporal differentiation and performed numerical simulation. Z.R., J.H., H.Z. and S.Z. conducted theoretical analysis. J.S., K.H. Q.Z. and F.S. designed the metalenses. D.Z. fabricated the samples. J.S., H.W. and D.Z. carried out the experimental measurements. K. H. processed and visualized the data. Z.R. and K.H. supervised the project and wrote the manuscript. All authors discussed the results and commented on the paper.

Data availability

The data that support the findings of this study are available from the corresponding authors upon request.

Conflict of interest

The authors declare no competing interests.

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