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Article

High Spatial Resolution Single-Shot Femto-Second Raster Framing Imaging Using Wavelength/Polarization-Time Encoding

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Abstract: We present a single-shot ultrafast imaging technique named wavelength /polarization-time encoded ultrafast raster imaging (WP-URI). This innovative method harnesses the principles of raster imaging in conjunction with wavelength and polarization time encoding to achieve high frame rate, high spatial resolution imaging at the atomic time scale (10 femtoseconds to 1 picosecond). The WP-URI system employs four femtosecond laser pulses, each with distinct wavelengths and polarizations, to illuminate and capture ultrafast events. These events are subsequently sampled by a spatial sampling mask and imaged to record the wavelength/polarization-encoded raster images in a single exposure. Through numerical simulations, we demonstrate the system's capability to image uniformly moving objects and rotating sector-shaped objects at an unprecedented frame rate of 25 trillion frames per second (Tfps), with an intrinsic spatial resolution of 50 line-pairs per millimeter(lp/mm), capturing four frames in a single exposure on a femtosecond timescale, and accommodating a large imaging area. With the advantages of both high spatio-temporal resolution and high frame rate, the WP-URI system has become a powerful tool for studying the interactions of matter and carrier dynamics in plasma physics, femtosecond lasers, and semiconductor devices.

Keywords: ultrafast raster imaging; spatial resolution; frame rate; wavelength/polarization-time encoding

1. Introduction

Ultrafast optical imaging with high spatial resolution on atomic timescales (from picoseconds to femtoseconds) has emerged as a powerful tool to capture transient phenomena in various fields such as ultrafast physics, chemistry, and biology [1–5]. This capability allows the visualization of dynamic processes such as carrier dynamics in semiconductors [6], ultrafast optical responses in quantum well microstructures [7], femtosecond soliton molecules [8], laser-induced plasma formation [9], and bond formation and breakage in chemical reactions [10–12]. Such insights are crucial for advancing fundamental understanding and driving technological innovation. The most widely used technique in this area is pump-probe imaging, which achieves temporal resolutions down to femtoseconds and even attoseconds [13–15]. Although powerful, pump-probe methods require repeated measurements and are ineffective for capturing stochastic or non-repeatable events due to their reliance on multiple exposures and temporal scanning. To address this limitation, various single-shot ultrafast imaging techniques have been developed. Among these techniques, compressed ultrafast photography (CUP) and its variants, such as T-CUP, CUST, and CUSP [16–24] have attracted significant attention. This type of technology utilizes electron beam scanning or all-optical scanning devices combined with compressed sensing algorithms to capture dynamic scenes, achieving higher frame rate and larger

numbers of frames—currently up to 219 trillion frames per second (Tfps) and nearly 1,000 frames. However, it often suffers from limited spatial resolution due to inherent trade-off between temporal resolution and spatial precision, as well as the computational complexity of image reconstruction. Another category of ultrafast imaging techniques involves spectral time-coding methods such as STAMP, SF-STAMP, OPR, and SS-AUOI [25–31]. These techniques utilize wavelength division multiplexing to encode temporal information into different spectral components. For example, SF-STAMP has achieved an imaging frame rate of 7.5Tfps with 25 frames and a temporal resolution as low as 465 fs [26]. While these methods have enabled high frame rates, they are constrained by the uncertainty principle, which limits the achievable effective frame rate and temporal resolution. Spatial frequency division techniques [32,33] utilize spatial dispersion to encode temporal information at different spatial frequencies, e.g. [32] can obtain four frames at a frame rate of 5Tfps and an exposure time of 200 fs, achieving a spatial resolution of 15lp/mm. However, the method they employ results in a trade-off between the number of frames and the spatial resolution. Increasing the number of frames can degrade spatial resolution, thus limiting its effective improvement. Non-collinear optical parametric amplification (NOPA) techniques [34–37] is based on Noncollinear optical frequency conversion, has also achieved a frame rate of up to 15Tfps with a spatial resolution of 30lp/mm without the use of microscopy. However, due to the complexity of the system, the number of frames is primarily limited to four. It can be seen that these techniques can achieve single-shot ultrafast imaging with frame rates reaching the terahertz frames per second (Tfps) level and temporal resolutions in the picosecond to femtosecond range. However, due to limitations inherent in their respective imaging principles and technologies, developing a single-shot ultrafast imaging system that simultaneously offers high spatiotemporal resolution, ultrahigh frame rates (exceeding 25Tfps), high spatial resolution (over 30lp/mm), and a simple, practical setup remains a significant challenge.

In this paper, we introduce a novel single-shot ultrafast imaging scheme based on the raster scanning principle combined with wavelength and polarization time encoding, termed wavelength/polarization-time encoded ultrafast raster imaging (WP-URI). Using the proposed WP-URI system, we demonstrate the imaging of transient scenes at a frame rate of 25Tfps with an intrinsic spatial resolution of 50lp/mm. The system also offers a large imaging area and a relatively simple optical configuration compared to existing methods. The high temporal and spatial resolutions, coupled with the single-shot capability, make our system a powerful tool for in-depth studies of ultrafast dynamics in materials science, photonics, and chemical processes, such as femtosecond laser interactions with matter and carrier dynamics in semiconductor devices.

2. Principle and System

2.1. Principle of WP- URI

The methodology of wavelength/polarization-time encoded ultrafast raster imaging (WP-URI) is graphically illustrated in Figure 1. This approach combines the raster imaging principle with wavelength and polarization time-coding techniques. Figure 1a shows a schematic of the raster imaging principle. The signal from a two-dimensional object is sampled by a spatially periodic sampling mask, resulting in a raster image. The object's signal is then reconstructed using a Fourier algorithm. According to the Nyquist-Shannon sampling theory, the signal of an object can be accurately reconstructed from the raster image if the sampling rate of the raster image is twice the highest spatial frequency of the band-limited signal of the object. However, in practical high-speed raster-based imaging systems, however, the raster image is typically under-sampled. In addition, to achieve framing imaging, there must be an appropriate proportional relationship between the pitch of the sampling points and their size in the raster image. The principle of WP-URI is shown in Figure 1b. A scene of an ultrafast process can be represented by a discrete of time-ordered frames $O(x, y, t_n)$ where $n=1, 2, \dots, N$. In this method, four femtosecond laser pulses $I(x, y, t_n)$ of equal intensity and equal time delay (Δt) are marked with different wavelengths and polarizations. After illuminating the object, the information of the object at different times was encoded by these four femtosecond

laser pulses with distinct wavelengths and polarizations and sampled by an array of micro-wavelength/polarized samplers $S(x, y)$. The system captures this information in a single-shot exposure, and the detector plane records an accumulation of wavelength/polarization-encoded raster images $R(x, y)$, where the sampling points of different raster images are located at different pixel addresses on the detector plane. The recorded image can be expressed as:

$$R(x, y) = \sum_{n=0}^3 R_n(x, y, t_n) = \sum_{n=0}^3 P_n W_n I(x, y, t - n\Delta t) O(x, y, t - n\Delta t) S(x, y) \quad (1)$$

where P and W denote polarization and wavelength coding, respectively, (with $P_0 = P_1, P_2 = P_3, W_0 = W_2, W_1 = W_3$), and $S(x, y)$ is the sampled pattern of the sampler.

In the data reconstruction process, each wavelength/polarization time-encoded raster image $R_n(x, y, t_n)$ is extracted from $R(x, y)$ through system calibration. A Fourier transform is then performed on each $R_n(x, y, t_n)$, and the reconstructed transient scene for each time frame is given by:

$$O(x, y, t_n) = F^{-1}(H[F(R_n(x, y, t_n))]), n = 1, 2, 3, 4 \quad (2)$$

Here, F and H represent the operations of Fourier transformation and filtering, respectively. The spatial resolution of the two-dimensional reconstructed images primarily depends on the sampling point pitch in the sampling mask. The number of image frames is determined by the number of probe pulses encoded by wavelength and polarization, and the size of each image frame is identical to the detector area. The imaging frame rate is determined by the time difference Δt between adjacent encoded sub-pulses, the maximum effective imaging frame rate is the reciprocal of the pulse width.

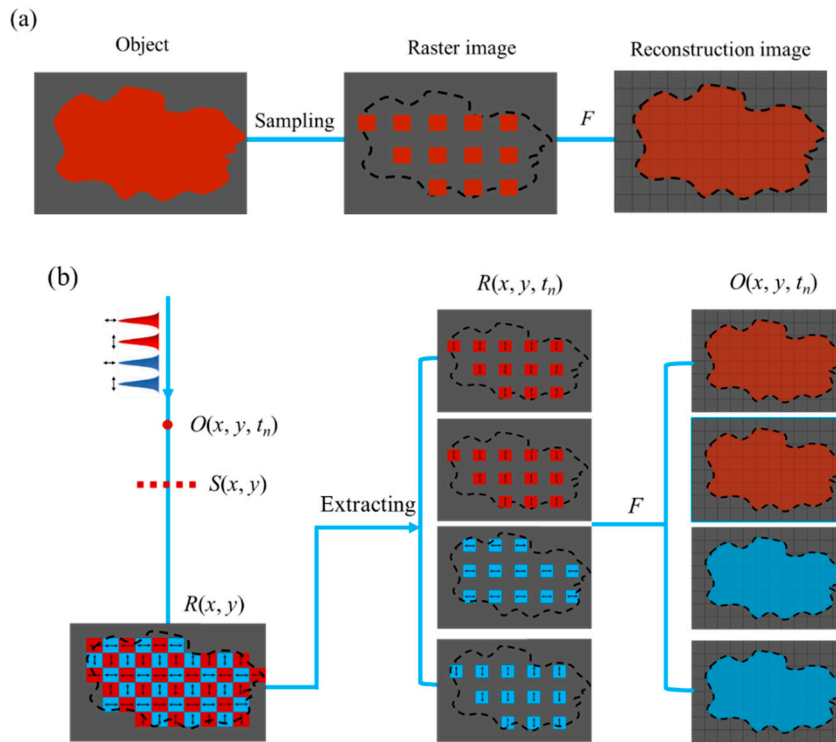


Figure 1. The operating principle of WP-URI. (a) Schematic of the raster imaging principle based on sampling theory. (b) Schematic illustration of the proposed WP-URI.

2.2. System of WP- URI

The experimental setup for the WP-URI system is shown in Figure 2. A femtosecond laser pulse (800 nm, 35 fs), generated by a Ti:Sapphire femtosecond laser amplifier, is used as the probe pulse. The pulse passes through a wavelength-polarization (W-P) time encoder, as indicated by the dashed box in the figure. Within the W-P time encoder, the femtosecond laser pulse passes through a second harmonic generator (SHG), where a small fraction of its energy is converted into its second harmonic

(400 nm, 35 fs). The pulse then passes through an optical wedge with a transmission-to-reflection energy ratio of 1:10. The transmitted part is used as the probe pulse, while the reflected part is used as a pump pulse to excite ultrafast events. A filter is used to equalize the intensities of the 800 nm and 400 nm pulses. The pulses then pass sequentially through a 50:50 beam splitter (BS₁), polarizers P₁ and P₂ with orthogonal polarization directions, time delay units DL₁ and DL₂, and a delay stage.

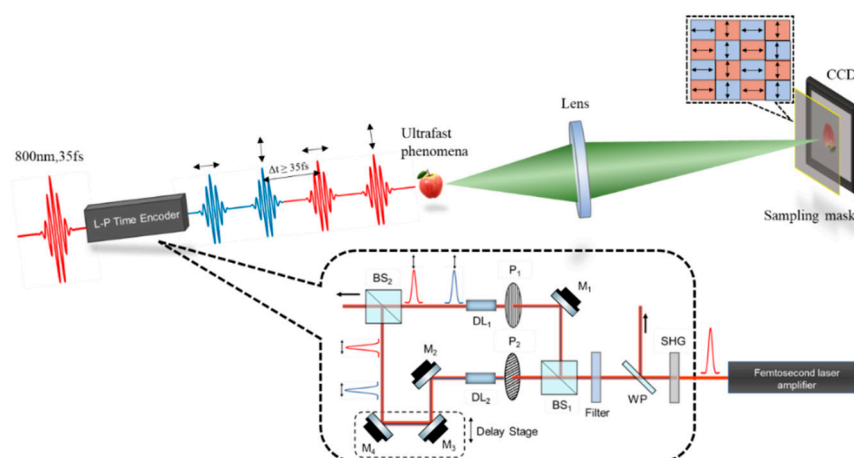


Figure 2. System configuration of WP-URI for the single-shot ultrafast imaging. SHG, second harmonic generator; WP, wedge plate; BS₁ and BS₂, beam splitters; P₁ and P₂, polarizers; DL₁ and DL₂, delay lines; M₁-M₄, Mirrors; W-P time encoder, Wavelength and Polarization time encoder.

Finally, they are recombined by the 50:50 beam splitter (BS₂) to generate four coaxial femtosecond laser pulse trains of equal intensity and equal time intervals (with time intervals greater than or equal to the pulse width of the femtosecond laser pulse), each labelled with different wavelengths and polarizations. These pulse trains then illuminate the ultrafast event. The ultrafast event is sampled and imaged by a spatial sampling mask. As shown in the enlarged diagram, the light red and light blue units represent filter pixels for the central wavelengths of 800 nm and 400 nm, respectively. The horizontal and vertical double-headed arrows indicate the transmission directions of the probe light. The sampling mask is placed in close proximity to the CCD detection plane and an imaging lens captures the scene in a single-shot exposure. Finally, the recorded data are processed using Fourier reconstruction algorithms to retrieve high-resolution images of the transient ultrafast event.

3. Results and Discussions

3.1. Characterization of the Spatial-Temporal Resolution

Temporal resolution and spatial resolution are two of the most critical parameters in high-speed imaging systems. In the WP-URI system, the temporal resolution is determined by the pulse width of the Fourier-transform limited pulses emitted by the femtosecond laser amplifier (800 nm, 35 fs, 1 kHz), while the intrinsic spatial resolution is defined as half the reciprocal of the pitch of the sampling points in the sampling mask. Figure 3 shows results of the numerical simulation using the USAF-1951 test chart as the target as the test target, with a size of 512×512 pixels, each pixel being $5\mu\text{m} \times 5\mu\text{m}$ and a spatial resolution of 100lp/mm. The imaging system used a lens with a focal length of 100 mm and an aperture diameter of 25 mm. A sampling mask matching the dimensions of the target consisted of 512×512 sampling points, each measuring $5\mu\text{m} \times 5\mu\text{m}$. The CCD detector also had 512×512 pixels with the same pixel size of $5\mu\text{m} \times 5\mu\text{m}$. The random white noise intensity of the system was set to 0.6, with an additional random white noise level of 0.2 introduced by the sampling mask. Figure 3a shows the raster image obtained after imaging the target illuminated by the (800 nm, P)-encoded pulse, and Figure 3b shows the corresponding reconstructed image, Figure 3c,d show

the intensity distribution scanned along line a and b in Figure 3b, respectively. It can be seen from these figures that the spatial period of the fringes is approximately four pixels in size, i.e., $20\mu\text{m}$. Therefore, the intrinsic (unit magnification) spatial resolution is approximately 50lp/mm, which is in good agreement with the theoretical calculation results. Figure 3e shows the four two-dimensional images reconstructed using wavelength/ polarization encoding, where 'P' and 'S' denote horizontal and vertical polarizations, respectively. These images demonstrate that the intrinsic spatial resolution is not less than 50lp/mm. and the dimensions of the reconstructed images are equal to those of the CCD detector plane, confirming accurate spatial representation across the entire imaging area.

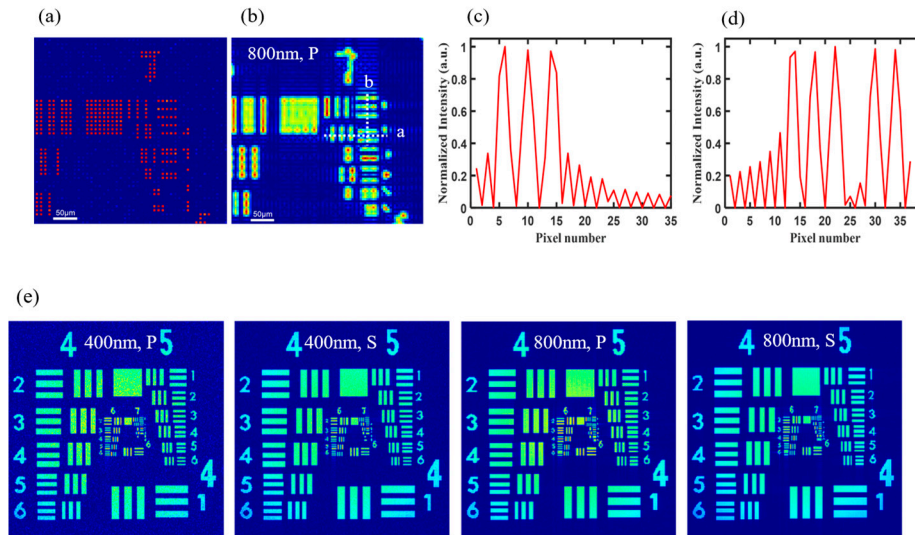


Figure 3. (a) Raster image of a USAF-1951 test target obtained using the (800 nm, P)-encoded pulse, (b) reconstructed image of the test target from the raster image in Figure 3(a), (c) intensity distribution scanned along line a in Figure 3(b), (d) intensity distribution scanned along line b in Figure 3(b), (e) four reconstructed images of the test target obtained by the WP-URI system using wavelength/polarization-coded laser pulse trains.

In addition, the spatial resolution of the system can be further improved by reducing the size of the sampling points on the sampling mask. The current maximum spatial resolution can reach 62.5lp/mm when the sampling point size on the sampling mask is reduced to $4\mu\text{m}$, which is the diffraction limit of the imaging lens. This improvement demonstrates that by optimizing the sampling mask design, the WP-URI system can achieve spatial resolutions approaching the theoretical limits of the imaging optics, making it highly suitable for applications requiring ultra-high-resolution imaging.

3.2. Single- Shot Imaging of an Object's Uniform Motion

To validate the reliability and accuracy of the WP-URI system's single-shot multi-frame imaging capability, we performed numerical simulations of imaging a uniformly moving object. The simulation parameters were as follows: four illumination pulses encoded with different wavelengths/polarizations, each with a pulse width of 35 fs and the time difference a time difference of 1ps between adjacent pulses. The object consisted of the letters 'A', 'B' and 'C' moving horizontally from right to left at a speed of $0.64\mu\text{m}/\text{ps}$ over a time window of 4 ps. Figure 4a shows the data recorded on the CCD detector plane after a single exposure, representing an accumulation of raster images encoded with different wavelengths/polarizations over time. Figure 4b is an enlarged view of the section indicated by the yellow line in Figure 4a. By calibrating the system, we extracted and reconstructed the different raster images separately. Figure 4c shows the four sequential time images obtained from the data reconstruction, clearly showing the uniform horizontal motion of the object from right to left. Under unit amplification conditions, the spatial resolution of each image is

approximately 50lp/mm. The system achieved a frame rate of 1 trillion frames per second (Tfps) with a frame interval of 1ps and an exposure time of 35 fs. These simulation results verify the system's framing capability of the system and its performance in single-shot multi-frame imaging.

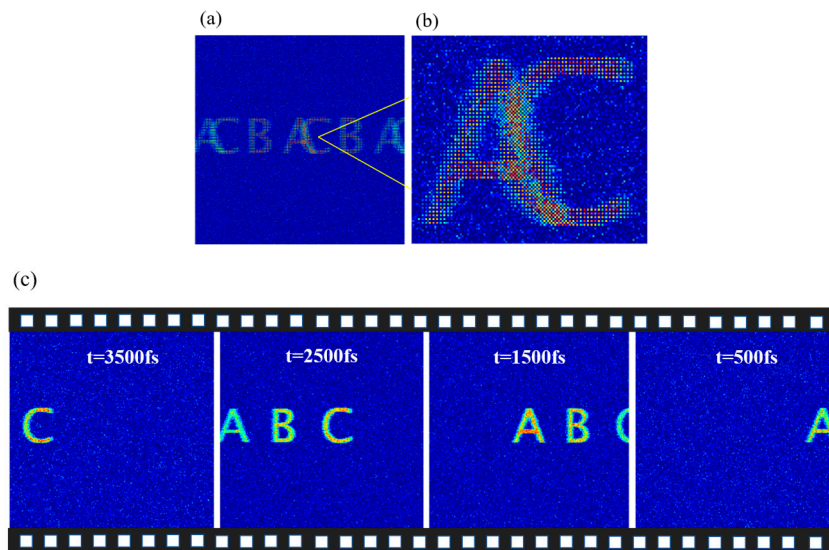


Figure 4. (a) Data recorded on the CCD detection plane after a single exposure, (b) enlarged view of the area indicated by the yellow solid line in Figure 4 (a), (c) four sequential time images of the object in uniform motion obtained by data reconstruction.

3.3. Single- Shot Imaging of the Uniform Rotation Object

To demonstrate the exceptional performance of our WP-URI system in single-shot multi-frame imaging with ultrahigh temporal resolution, we performed numerical simulations of a rotating sector-shaped object. The system uses four illumination pulses, each uniquely encoded by different wavelengths and polarizations, with a pulse width of 35 fs. We set the time intervals between adjacent pulses to 40 fs and 100 fs, effectively capturing sequences of four images within each interval. Considering that the object completes a full 360-degree rotation in 1ps, these time intervals allow us to sample its rotational motion with high precision. Figure 5 shows the simulation results. In Figure 5a, four reconstructed images under a single exposure correspond to time interval of 40 fs, taken at times $t=0$ fs, 40 fs, 80 fs, and 120 fs, with rotation angles of approximately 90° , 76° , 61° , and 46° , respectively. Similarly, Figure 5b shows the results with a time interval of 100 fs, obtained at times $t=100$ fs, 200 fs, 300 fs, and 400 fs, with rotation angles of approximately 54° , 18° , 342° , and 306° , respectively. These results clearly illustrate the uniform rotation of the sector-shaped object. These results clearly illustrate the uniform rotation of the sector-shaped object. The sequence captured with a frame rate of 25Tfps (time interval of 40 fs) provides fine temporal sampling of the rotational motion, capturing subtle positional changes between frames. In contrast, the 10Tfps (100 fs) frame rate provides a broader view of the overall rotational progression, highlighting more significant changes in orientation over time.

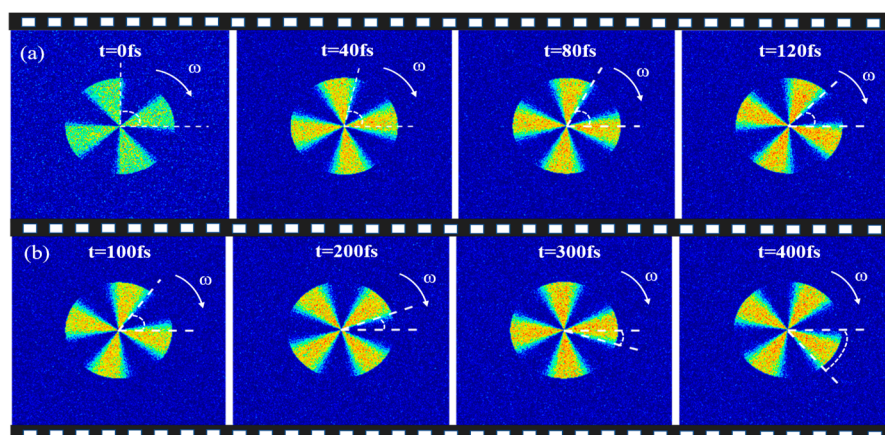


Figure 5. Simulated images of a sector-shaped uniformly rotating object captured using the WP-URI system with single-shot multi-frame imaging. Where ω denote the angular velocity. **(a)** Images of a sector-shaped uniform rotating object with a time interval of 40 fs, with rotation angles of approximately 90°, 76°, 61°, and 46°, respectively. **(b)** Images of a sector-shaped uniform rotating object with a time interval of 100 fs, with rotation angles of approximately 54°, 18°, 342°, and 306°, respectively.

4. Conclusion

This paper presents the system, designed for capturing the transient events with high frame rate and high spatio-temporal resolution at the atomic time scale. Our numerical simulations validate the system's performance in imaging uniformly moving objects and rotating sector-shaped objects. It achieves a frame rate of 25 trillion frames per second (Tfps) and a spatial resolution of 50lp/mm, capturing four frames in a single-shot exposure. A key feature of this system is that several main parameters are independent of each other and will not interfere with each other: the spatial resolution is determined by the sampling interval of the raster plate, while the frame rate depends on the fixed time difference between the probe laser pulses; the temporal resolution is only limited by the width of the probe light pulse, so the use of femtosecond laser sources with shorter pulse widths allows us to achieve higher temporal resolution and higher frame rate; the number of frames is determined by the number of wavelength/polarization-encoded femtosecond laser pulses. Furthermore, the WP-URI system's expansive imaging area is particularly advantageous for documenting large-scale phenomena. These collective strengths position the WP-URI system as an invaluable research instrument, with broad applications spanning plasma physics, materials science, and semiconductor dynamics, among other cutting-edge fields.

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