Photography on the Femtosecond Scale

Visualizing Ultrafast Dynamics in a Single Shot

High-speed optical imaging is widely used for exploring and understanding fast dynamics, but the temporal resolution of conventional high-speed cameras is limited to about 1 ns due to their technical limitations. Here we introduce a high-speed imaging method called sequentially timed all-optical mapping photography (STAMP) which enables motion-picture femtophotography at a frame rate of more than a trillion frames per second.

Introduction

High-speed optical imaging is a powerful tool for studying dynamic phenomena in scientific research and inspecting parts and devices in industrial settings [1]. Unfortunately conventional high-speed cameras are not fast enough to reach the sub-nanosecond regime due to fundamental limitations in their mechanical or electrical operation [2, 3]. While the pump-probe method [4] can provide time-resolved images of faster events, it falls short for imaging difficult-to-reproduce events owing to its requirement for repetitive measurements. A new type of fast imaging methods is clearly needed to fill the gap between time-resolved imaging and high-speed cameras and hence explore the uncharted area of nature which is mostly found in complex physical, chemical, and biological systems.

In this article, we introduce a unique ultrafast optical imaging method, known as sequentially timed all-optical mapping photography (STAMP) [5], which is capable of achieving motion-picture photography on the femtosecond-to-picosecond time scales. STAMP’s all-optical operation circumvents the mechanical and electrical limitations of the conventional high-speed cameras and hence provides approximately 1000 times higher frame rates than them. Since STAMP does not require repetitive measurements for movie acquisition, it allows us to observe fast difficult-to-reproduce processes in a single shot.

Principles of STAMP

STAMP is based on the projection of the target’s time-varying spatial profile onto the spatial domain. This is made possible by employing spatial and temporal dispersion to spatially and temporally separate the time-varying event, respectively. Since the spatial and temporal dispersion is an optical effect, it eliminates the
speed bottleneck that exists due to the conventional camera’s mechanical and electrical operation in its movie acquisition process.

A specific embodiment of this concept is schematically shown in figure 1.

The STAMP camera is composed of five components: (1) ultrashort laser source, (2) temporal mapping device (TMD), (3) spatial mapping device (SMD), (4) image sensor, and (5) computer. First, an ultrashort laser pulse emitted from the laser source is temporally stretched and shaped by the TMD into several daughter pulses of different spectral bands. The daughter pulses are incident onto the time-varying target for sequential image recording. The image-encoded daughter pulses are spectrally separated by the SMD without causing image deformation so that they are detected on different areas of the image sensor. Based on the pre-calibrated relation between time and the optical wavelength and between the optical wavelength and the spatial coordinates on the detector, a sequential motion picture can be constructed from the recorded images.

To experimentally demonstrate motion-picture photography with STAMP, we developed the STAMP camera that can record six sequential images with variable temporal resolution. The laser source is a Ti:Sapphire femtosecond pulse laser with a chirped pulse amplifier that emits a pulse train with a repetition rate of 1 kHz, a center wavelength of 810 nm, and a pulse width of 70 fs. An optical chopper and mechanical shutter are used to pick a single pulse. The single pulse is split into a pulse for STAMP imaging and an excitation pulse for triggering an ultrafast event. The TMD consists of a pulse stretcher (e.g., a grating pair and glass rod) and a pulse shaper (e.g., a 4f lens system with a spatial light modulator) and tailors the temporal shape and intensity of each daughter pulse to be identical such that the successive “flashes” are the same except for the timing of their arrival at the target. The image-encoded daughter pulses are spatially separated by the SMD that consists a diffraction grating, periscope array, and a cylindrical lens while satisfying the requirement for image formation on the image sensor without image
deformation. The recorded images on the image sensor are digitally processed and recombined, but in the time domain, for producing a motion picture out of the temporally stacked image frames. The frame rate and exposure time of the STAMP camera can be determined by tuning the temporal dispersion in the TMD.

**Motion-Picture Photography with STAMP**

To show STAMP’s utility on the picosecond scale, we used it to monitor the early-stage plasma dynamics of a femtosecond-laser-induced ablation process. Here an excitation pulse with a pulse energy of 100 µJ and pulse duration of 70 fs was focused on the surface of a glass plate for ablating it (fig. 2 (A)). As shown in figure (B), plasma dynamics was visualized with the STAMP camera in a shadowgraph mode with a frame interval of 15.3 ps (corresponding to 65.4 x 10^9 frames/s) and exposure time of 13.8 ps. As shown in the image sequence or movie, the plasma plume generated by femtosecond laser expands rapidly in the radial direction. From the movie, the speed of the plume front was found to be approximately 105 m/s.

To further show STAMP’s movie-shooting capability on the femtosecond scale, we observed phonon dynamics in a crystal with STAMP. Here an excitation pulse with a pulse energy of 40 µJ and pulse duration of 70 fs was line-focused into a LiNbO_3 wafer to produce a phonon-polariton pulse via impulsive stimulated Raman scattering (fig. 3 (A)). The pulse formation was visualized in a polarization-gating mode and captured with a frame interval of 812 fs (corresponding to 1.23 x 10^12 frames/s) and exposure time of 1020 fs. A STAMP movie of the phonon dynamics is shown in figure 3 (B). It indicates that the intense electromagnetic field of the laser pulse excites lattice vibrations in the crystal and then a phonon-polariton wave-packet is formed from a seemingly random response of the crystal and propagates away from the excitation region. Figure 3 (C) shows the wave-packet propagation with a finer frame interval of 229 fs (corresponding to 4.37 x 10^12 frames/s). The speed of the phonon-polariton wave-packet was determined from acquired images to be 4.6 x 10^7 m/s (one sixth of the speed of light).

**Conclusion**

By overcoming the fundamental limitations that exist in the conventional high-speed cameras, STAMP enables motion-picture photography of ultrafast events on the femtosecond-to-picosecond time scales. By virtue of its ability to perform sequential image acquisition, STAMP can help us visualize fast dynamical processes of complex physical, chemical, and biological systems. We expect STAMP to be of use in a diverse range of applications including nuclear fusion, quantum chemistry, microfluidic biotechnology, shockwave therapy, and laser surgery.

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References

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