Frequency-Domain Streak Camera for Ultrafast Imaging of Evolving Light-Velocity Objects

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We demonstrate a frequency-domain streak camera (FDSC) that captures the picosecond time evolution of luminal-velocity refractive index structures in a single shot. In our prototype FDSC, a probe-reference pulse pair propagates obliquely to a sub-picosecond pump pulse that creates an evolving nonlinear index structure in glass, supplementing a conventional frequency-domain holographic (FDH) probe-reference pair that co-propagates with the pump. A single spectrometer acquires data from both pairs via spatial or time-domain multiplexing, demonstrating the feasibility of a compact frequency-domain tomographic (FDT) system in which a single spectrometer processes data from multiple probing angles. © 2010 Optical Society of America

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Intense laser pulses propagating through matter create complex micrometer-scale, luminal-velocity structures such as ionization fronts, nonlinear index envelopes or laser wakefields [1] that are challenging to image in the laboratory, and thus are often known in detail only through intensive computer simulations. Accurate single-shot visualization can improve fundamental understanding of the generation and evolution of such structures, and improve the function of devices (e.g. laser wakefield accelerators) based on them. Recently Matlis et al. [2] captured “snapshots” of laser wakefield accelerator structures using frequency-domain holography (FDH) [3]. FDH uses a probe-reference (P-R) pair that co-propagates with an intense pump pulse and plasma structures it creates (see Fig. 1a). A temporally stretched probe pulse (wavelength \( \lambda_{pr} \)) covers the whole “object”, accumulating phase shift \( \Delta \phi_{pr}(r, \zeta, z) \) as a result of co-propagating with pump-induced refractive index structure \( \eta(r, \zeta, z) \) over distance \( z \). Here \( r \) denotes transverse distance from the pump propagation axis, \( \zeta \) longitudinal distance behind the pump. \( \Delta \phi_{pr} \) is reconstructed by interfering the probe with a temporally advanced “reference” pulse in a spectrometer, and Fourier analyzing the resulting frequency-domain hologram [2–4]. If, however, \( \eta \) evolves with \( z \), the reconstructed phase shift

\[
\Delta \phi_{pr}(r, \zeta) = \frac{2\pi}{\lambda_{pr}} \int_{0}^{L} [1 - \eta(r, \zeta, z)] dz
\]

averages over its variations. For a wakefield accelerator, such evolution can be critical to its function [5].

In this Letter we generalize FDH by including a frequency-domain streak camera (FDSC), which uses a P-R pair that propagates at angle \( \theta \) to the pump (see Fig. 1b). In the probe pulse frame, the evolving object sweeps across the probe profile with velocity

\[
\vec{v} = \frac{v_p \cos \theta - v_{pr}}{1 - v_p v_{pr} \cos \theta / c^2} \hat{e}_l + \frac{v_p \sin \theta \sqrt{1 - v_{pr}^2 / c^2}}{1 - v_p v_{pr} \cos \theta / c^2} \hat{e}_\perp,
\]

imprinting a phase shift “streak” that records information about the object’s evolution. Here \( \hat{e}_l \) and \( \hat{e}_\perp \) are parallel and perpendicular, respectively, to the probe propagation direction, while \( v_p = 0.68c \) and \( v_{pr} = 0.66c \) denote lab frame group velocities of pump and probe pulses, respectively, in the medium. For the geometry shown in Fig. 1b, the object sweeps along a streak axis \( \hat{v} \) that is approximately perpendicular to its propagation direction \( v_{pr} \). Thus for sub-picosecond long refractive index structure, line-outs perpendicular to the streak axis \( \hat{v} \) yield a temporal sequence of its longitudinal refractive index profiles \( \eta(0, \zeta, z) \) as a function of \( z \).

Fig. 1. Schematic probe-reference pulse configurations for a. frequency-domain holography (FDH) and b. frequency-domain streak camera (FDSC) after pump has just entered (\( z \approx 0 \)), is about to exit (\( z \approx L \)), and has exited (\( z > L \)) the medium (grey). Arrows denote propagation directions of pump-induced index perturbation \( \eta(r, \zeta, z) \) (red) and chirped probe-reference pulses (blue). The latter are imaged from \( z = L \) to the entrance slit of a spectrometer.
with time resolution \( d_\perp/v \), where \( d_\perp \) is the object’s dimension perpendicular to its propagation direction. For different \( \theta \), similar line-outs yield the temporal history of the object’s transverse profile \( \eta(r, 0, z) \). Thus by probing the object simultaneously at multiple angles, it is possible in principle to reconstruct the temporal evolution of its entire two-dimensional profile \( \eta(r, \zeta, z) \) using tomographic algorithms. For such frequency-domain tomography (FDT) to be practical, however, it is important to demonstrate the ability to record cross-talk-free data from multiple probes simultaneously using a single spectrometer, just as multiple conventional holographic images can be stored in a single recording medium \[6\].

Here, as a proof of concept, we created an evolving refractive index structure by focusing a pump pulse (wavelength \( \lambda_{pu} = 800 \) nm, bandwidth \( \Delta \nu = 30 \) nm FWHM) of 600 fs duration inside a fused silica plate of thickness \( L = 3 \) mm. The pump induces refractive index \( \eta(r, \zeta, z) = n_2 I(r, \zeta, z) \), where \( n_2 \sim 3 \times 10^{-16} \) cm\(^2\)/W is the nonlinear index of glass \[7\], and \( I(r, \zeta, z) \) is the pump intensity profile. Thus \( \eta(r, \zeta, z) \) evolves as the pump pulse diffracts, self-focuses, etc. Two linearly chirped, 1 ps, second harmonic \( (\lambda_{pr} = 400 \) nm) pulse pairs P1-R1 and P2-R2 probed \( \eta(r, \zeta, z) \) simultaneously at \( \theta = 0^\circ \) (FDH) and \( 14^\circ \) (FDSC), respectively. At \( 14^\circ \), the streak sweeps nearly transversely across the probe profile.

The two pairs, each with probe and reference separated by \( \Delta t_{PR} = 3.3 \) ps, were imaged from the sample exit plane \( (z = L) \) to the entrance slit of a single spectrometer using either spatial or temporal multiplexing. For spatial multiplexing (SM), they were imaged independently to spatially offset locations along the slit (which selected a lineout of each profile), P1-R1 with magnification 12 to resolve the micron-size index “bubble” optimally, and P2-R2 with magnification 2.3 to resolve the millimeter-long “streak”. The length of the slit limits the number of P-R pairs that can be imaged simultaneously. In our case, two nearly filled the slit. Temporal multiplexing (TM) is described later.

Figure 2(a) shows reconstructed images from the spatially multiplexed FDH (top row) and FDSC (2nd row) probes, and the spectrum (3rd row) and spatial profile (3rd row inset) of the pump at \( z = L \), as initial peak intensity \( I \) of the pump (focused here to spot radius \( w_0 \sim 20 \) \( \mu \)m at \( z = 0 \)) increased from 0.04 (left) to 1.5 (right) TW/cm\(^2\). In the upper end of this intensity range, \( n_2 I L \gg \lambda_{pu} \), so pump propagation becomes nonlinear. The FDH images show the longitudinally-averaged \( \eta(r, \zeta, L) \). Indirect signs of evolution are evident. For example at larger \( I \), \( \Delta \phi_{pr} \) exceeds \( 2\pi \) near \( r = 0 \) (creating complicated phase wrapping artifacts), indicating that self-focusing occurred. Moreover, the longitudinal extent \( \sim 1 \) ps) of the index “bubble” exceeds the pump pulse duration \( \sim 600 \) fs) measured from a transverse line-out of the FDSC streak. This discrepancy is explained by 450 fs group velocity walk-off between 800 nm pump and 400 nm probe, which elongates the pump-induced index profile into a longitudinal phase streak even in the FDH line. These complications in interpreting FDH data underscore the importance of FDSC.

The FDSC images (Fig.2(a), middle row) show a distinct phase streak that increases in amplitude with \( I \). Line-outs along the streak axis, plotted in Fig.2(b), reveal intensity-dependent evolution of the axial phase shift. To help interpret this evolution, we modeled propagation of Gaussian pump pulses using the Nonlinear Schrödinger Equation (NLSE), including multi-photon absorption (MPA) and plasma formation \[8\]. Fig.2(c) shows the calculated peak pump intensity \( I(z) \) for various initial \( I \). For \( I = 0.04 \) TW/cm\(^2\), nonlinearities are negligible, \( I(z) \) decreases monotonically by linear diffraction over Rayleigh range \( z_R \approx \pi n_0 w_0^2/\lambda_{pu} \). The transmitted pump spectrum is barely perturbed from the incident spectrum (Fig.2(a), 3rd row, left). For \( I = 0.47 \) TW/cm\(^2\), peak pump power (3 MW) reaches critical power \( P_{cr} = \pi (0.61)^2 \lambda_{pu}^2/8n_0n_2 = 2.15 \) MW, and the pump propagates with nearly constant intensity, indicating a balance between self-focusing and diffraction with MPA still weak. Simultaneously, we begin to observe pump frequency broadening to \( \Delta \nu \sim 50 \) nm (Fig. 2(a) 3rd row, 2nd panel), a signature of self-phase modulation. As pump intensity increases further (\( I = 0.70 \) to
Fig. 3. Frequency-domain streak camera using temporal multiplexing. 
(a) Frequency domain hologram. 
(b) Fourier transform of a horizontal line-out of frequency domain hologram, and the arrangement of the pulse train (inset). 
(c) 0° and 14° phase shift profiles at $I \sim 1$ TW/cm² recorded in a single shot. 
(d) Optimized TM pulse train with 4 probes, 1 reference and its Fourier transform.

1.47 TW/cm², NLSE calculations show: (i) the pump self-focuses closer and closer to the glass entrance, initially increasing its intensity, then decreases monotonically in intensity (see Fig. 2(c)); (ii) direct MPA is the primary cause of the monotonic intensity decrease (the MPA-produced electron-hole plasma does not significantly defocus the pump, but stabilizes its transverse profile); (iii) the pump converges to a nearly intensity-independent transverse Townes profile [9] with FWHM 16 μm, in good agreement with the exit profiles shown in the insets of the last two panels, 3rd row of Fig. 2(a). Meanwhile the transmitted pump spectrum further broadens (Fig. 2(a) 3rd row, last 2 panels), indicating stronger self-phase-modulation. The transverse FWHM of the FDH phase profiles (Fig.2(a), top row) agree well with the exit pump profiles and NLSE calculations (their apparent broadening with increasing $I$ results from increased visibility of the wings as total $\Delta \phi_{pr}$ increases). The initial self-focusing accounts for the large $\Delta \phi_{pr}$ near the center of the FDH images at high $I$. The example illustrates how combining information from FDH and FDSC improves accuracy of interpretation.

To demonstrate additional data storage capability, we temporarily multiplexed FDH and FDSC by imaging P1-R1 and P2-R2 to the same spot on the spectrometer slit, but with a temporal shift $\Delta t_{P1P2} = 400$ fs between P1-R1 and P2-R2 as shown at the top of Fig. 3(b). This 4-pulse sequence produces 4 fringe frequencies $\Delta t_{P1Ri}$ ($i = 1, 2, j = 1, 2$) in the raw frequency-domain hologram (see Fig. 3(a)) and 9 distinct peaks (four of them redundant) in the Fourier-transformed (FT) data (Fig. 3(b)). Central peak 0 corresponds to the autocorrelation of each pulse [4]. Remaining peaks arise from interference of (1) P1-P2 and R1-R2 ($\Delta t_{P1P2} = \Delta t_{R1R2} = 400$ fs); (2) P2-R1 ($\Delta t_{P2R1} = 2.9$ ps); (3) P1-R1 and P2-R2 ($\Delta t_{P1R1} = \Delta t_{P2R2} = 3.3$ ps); (4) P1-R2 ($\Delta t_{P1R2} = 3.7$ ps). FDH and FDSC phase shift profiles shown in Fig. 3(c) were recovered from peaks 4 and 2, respectively. Here, for simplicity, we focused the pump loosely ($w_0 \approx 100$ μm), rendering pump propagation nearly linear, so that both FDH and FDSC lines could be imaged with the same magnification. We found a minimum shift $\Delta t_{P1P2} \sim 400$ fs was needed to avoid overlap between neighboring peaks in the FT data (Fig. 3(b)), and thus to avoid cross-talk between FDH and FDSC. This is greater than the ideal $\Delta t_{P1P2}^{(min)}$ set by the coherence time ($\tau = \lambda^2/c\Delta \lambda_{pr} \sim 50$ fs) of unperturbed probes of bandwidth $\Delta \lambda_{pr}$. By interfering all probes $P_i$ with a single reference pulse $R_1$, as shown at the top of Fig. 3(d), extraneous peaks (such as 3 in Fig. 3(b)) can be eliminated, allowing maximum data storage density. In this optimum TM configuration, the maximum number of probe lines is on the order of $\Delta t_{P1P2}^{(max)}$/$\Delta t_{P1P2}^{(min)}$, where $\Delta t_{P1P2}^{(max)}$ is the maximum probe-reference separation for which FD fringes are resolvable by the spectrometer’s array detector (typically $\sim 10$ pixels/ fringe needed). For our apparatus $\Delta t_{P1P2}^{(max)} \sim 3.3$ ps, indicating 7 to 8 probes can be temporally multiplexed in each of 2 SM lines, demonstrating the feasibility of recording FDT data from $\sim 15$ angles in a single shot with one spectrometer, without cross-talk.

In summary, we combined FDH with FDSC to observe the longitudinally-averaged structure and evolution of a microscopic light-speed object simultaneously. Moreover, using both spatial and temporal multiplexing, we demonstrated the feasibility of processing data from multiple probes with a single spectrometer. This is a critical step towards FDT, which can potentially reconstruct a time sequence of a quasi-static snapshots, like frames of a movie, of evolving light-velocity objects. This work was supported by U.S. DoE grants DE-FG02-07ER54945 and DE-FG03-96ER40954 and NSF grant PHY-0936283.

References