Ultrafast observation of intense light-matter interactions in flexible glass via single-shot frequency domain holography

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Abstract: We use frequency domain holography (FDH) to spatio-temporally visualize the laser-matter interaction caused by the optical Kerr effect and plasma in flexible Corning® Willow® Glass in a single-shot

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Flexible glass has recently been the focus of much research due to various applications such as wearable devices, microfluidics, biosensors, and 3-D photonics. Femtosecond laser micromachining [1, 2] is an excellent tool to fabricate these devices due to the negligible thermal effects, enabling fabrication of clean and fine 3-D structures without post-processing. Ultrathin borosilicate glass Corning® Willow® Glass [3], has been shown to be a viable substrate for flexible waveguides fabricated by femtosecond laser micromachining with low propagation losses [4]. To understand and control the fundamental dynamics of femtosecond laser micromachining and also laser matter interactions, visualization of material modification including plasma creation and recombination is vital. Here we use the state-of-the-art single-shot frequency domain holography (FDH) [5, 6] to spatio-temporally visualize the optical nonlinearities when thin flexible glass is irradiated by a femtosecond laser pulse. In particular, the single-shot capability of FDH provides a robust visualization tool when permanent material change is involved during laser matter interactions.

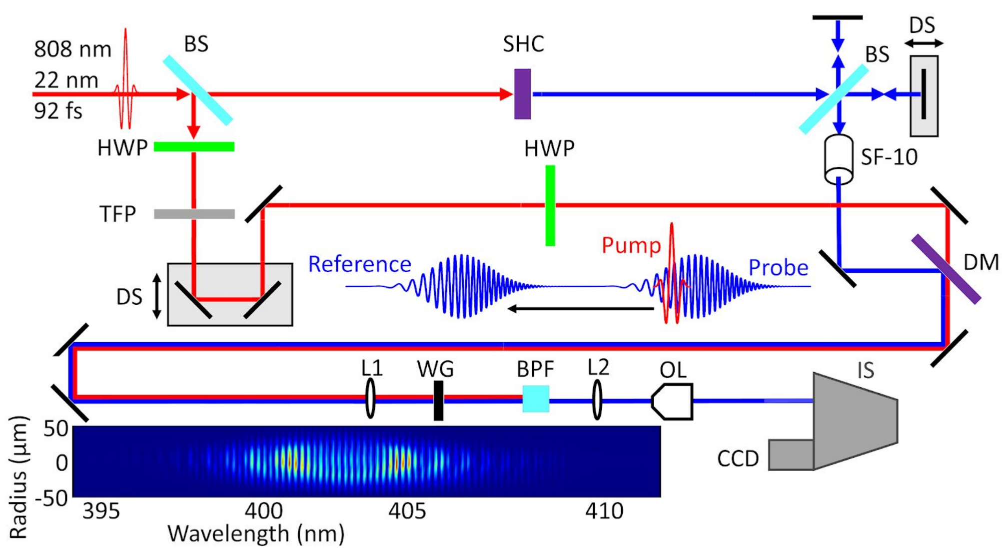

Fig. 1. Schematic explaining the frequency domain holography (FDH) experiment. BS: beam splitter, SHC: second harmonic (KDP) crystal, DS: delay stage, SF-10: dispersive glass, HWP: half waveplate, TFP: thin film polarizer, DM: dichroic mirror, L1:f= 40 cm focusing lens, WG: Wil-low Glass sample, BPF: optical bandpass filter, L2:f= 5 cm relaying lens, OL: objective lens, IS:imaging spectrometer, CCD: charge coupled device camera. An example single-shot spatio-spectral interferogram is shown at bottom.

In our experiment [Fig. 1], a 808 nm central wavelength, 92 femtosecond (fs) Ti:Sapphire pulse is split into two arms, denoted by the pump arm and the reference/probe arm. The pump arm includes a half waveplate and a thin-film polarizer to change the pulse energy, and a delay stage to control the temporal delay. In the other arm, denoted by the reference/probe arm, the pulse is sent first through a second harmonic crystal that frequency doubles the 808-nm pulse and is then sent to a Michelson interferometer. This creates two identical 404- nm pulses called the reference and the probe separated by 2.5 ps. Both pulses are then sent through a 2 cm long SF10 glass sample in order to chirp the pulses to ~1 ps. Finally, the pump and the reference/probe are spatially recombined by a dichroic mirror and propagate colinearly. The chirped reference pulse traverses the flexible glass sample first acting as a phase reference to the later probe. After the reference pulse, the intense fs pump pulse induces the time evolution of the optical Kerr effect and/or plasma in glass, which is measured by the probe pulse. After the sample, the 808 nm pump is spectrally filtered out and the reference and probe are imaged onto an imaging spectrometer. The reference and probe pulses generate spatio-spectral interferograms [Fig. 1] measured by a charge coupled device (CCD) camera. To fully reconstruct the spatio-temporal phase, it is required to measure the spectral amplitude and phase both with and without the pump as well as the chirp of the probe/reference pulses using a combination of Fourier method and chirp characterization [7–9]. The pulse chirping is critical for single-shot measurements since different wavelengths in the chirped probe represent different time delays between pump and probe as shown in Fig. 1.

We first measure the nonlinear index of refraction (n_2) of Willow Glass using FDH. The spatio-temporal phases are measured with input intensities ranging from 3.7×10^{11}W/cm^2 to 3.0×10^{12} W/cm^2. By linearly fitting the accumulated phase as a function of intensity [Fig. 2(a)], n_2 can be calculated through the cross-phase modulation given by $\varphi=(2\pi/\lambda_{pr})(2n_2I)d$, where λ_{pr} is the probe wavelength of 404 nm, I is the intensity of the pump pulse, and d is the sample thickness (100 μm) [10]. Second, we visualize the plasma dynamics with the pump intensity of 1.8×10^{13}W/cm^2. We can clearly see the transition from the positive phase via Kerr effect to the negative phase via plasma generation as the intensity increases in time and subsequent plasma decay/recombination [Fig. 2(c)].

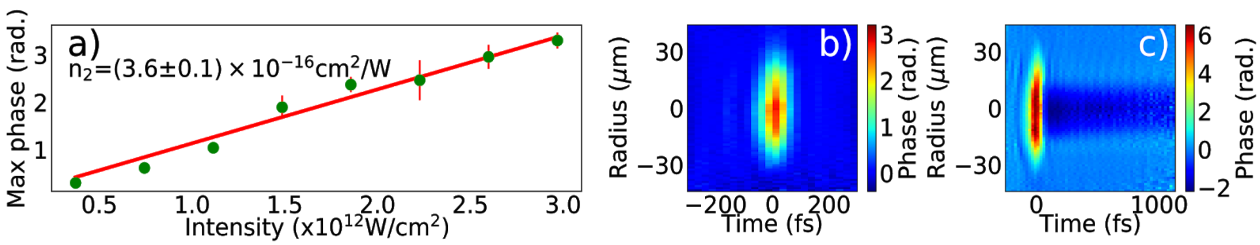

Fig. 2. (a) Experimental results of the average maximum phase over 8 single shots per intensity. (b) An example single-shot spatio-temporal phase due to optical Kerr effect extracted from FDH with pump intensity of 2.6×10^{12}W/cm^2. (c) An example spatio-temporal phase profile taken with pump intensity of 1.8×10^{13}W/cm^2 showing plasma generation and recombination.

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References

[1] R. R. Gattass and E. Mazur, "Femtosecond laser micromachining in transparent materials," Nature Photonics, **2**, 219–225, 2008.
[2] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," Opt. Lett., **21**,1729–1731, 1996.
[3] S. M. Garner, Flexible Glass: Enabling Thin, Lightweight, and Flexible Electronics. Wiley-Scrivener, 2017.
[4] S. Huang, M. Li, S. M. Garner, M.-J. Li, and K. P. Chen, "Flexible photonic components in glass substrates," Opt. Express, **23**, 22532–22543, 2015.
[5] S. P. Le Blanc, E. W. Gaul, N. H. Matlis, A. Rundquist, and M. C. Downer, "Single-shot measurement of temporal phase shifts by frequency-domain holography," Opt. Lett., **25**, 764–766, 2000.
[6] D. Dempsey, G. C. Nagar, C. K. Renskers, R. I. Grynko, J. S. Sutherland, and B. Shim, "Single-shot ul-trafast visualization and measurement of laser–matter interactions in flexible glass using frequency domain holography," Opt. Lett., **45**, 1252–1255, 2020.
[7] M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," J. Opt. Soc. Am, 72, **1**,156–160, 1982.
[8] K. Y. Kim, I. Alexeev, and H. M. Milchberg, "Single-shot supercontinuum spectral interferometry," Applied Physics Letters, **81**, 22, 4124–4126, 2002.
[9] X. Gao, X. Wang, B. Shim, A. V. Arefiev, R. Korzekwa, and M. C. Downer, "Characterization of clus-ter/monomer ratio in pulsed supersonic gas jets," Applied Physics Letters, **100**, 6, 064101, 2012.
[10] R. W. Boyd, Nonlinear Optics. Elsevier, Acad. Press, 2011.