Multi-shot and single-shot time-resolved visualization of material modification during laser micromachining with flexible glass

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Abstract: We visualize material modification during laser micromachining, in particular, laser waveguide fabrication in flexible Corning® Willow® Glass via time-resolved interferometry, and single-shot frequency-domain holography which is a robust technique for studying permanent material change/damage.
OCIS codes: (350.3390) Laser materials processing; (130.2755) Glass waveguides; (320.7100) Ultrafast measurements.

Femtosecond laser micromachining (FLM) is a rapidly-developing field that has many advantages over long-pulse laser manufacturing techniques such as small spot sizes mainly due to minimal thermal effects (even down to the diffraction limit) as well as complete 3-D manufacturing capabilities [1]. As FLM gains popularity, the study of the underlying dynamics of femtosecond laser modification is becoming a field of active investigation [2–4]. Recently, flexible devices including photonic devices have been receiving significant attention and FLM of flexible materials can provide a robust tool for fabricating waveguides [5], and photonic sensors in biological tissues [6], because heat should be avoided in flexible materials. Our group was able to successfully fabricate waveguides in flexible Corning® Willow® Glass and visualize plasma formation using time-resolved interferometry [7]. In this paper, we report on measuring femtosecond time-resolved phase changes including not only plasma generation but also waveguide formation via plasma recombination through multi-shot time-resolved interferometry (TRI) and also single-shot frequency-domain holography (FDH) [8]. In particular, FDH is a robust single-shot technique for studying laser-induced permanent material change and damage.

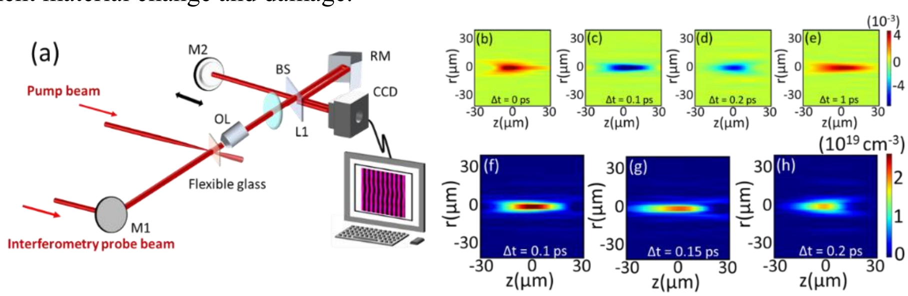

Fig. 1. (color online) Time-resolved interferometry experimental setup is shown in (a). M1, M2: mirrors; L1: f = 20-cm lens; OL1: 10x objective lens; RM: rooftop mirror; CCD: charge-coupled device camera communicating with computer. Change in refractive index after single-shot exposure are shown with (b) $\Delta t = 0$ ps, (c) 0.1 ps, (d) 0.2 ps and (e) 1ps. Measured plasma densities are shown with (f) $\Delta t = 0.1$ ps, (g) 0.15 ps and (h) 0.2 ps, in cm^{-3}.

First, TRI is used to perform time-resolved studies of waveguide fabrication. The experimental setup is shown in Fig. 1(a). A 45-fs, 800-nm pump beam is focused by a 10x objective lens (NA = 0.25) at a depth of 100 μm inside the 200-μm thick flexible Willow Glass sample, which is similar to our waveguide fabrication experiment [7], and a 45-fs, 800-nm probe beam intersects the pump-affected region at 90°. The time delay Δt between pump and probe is controlled by a translational stage. The probe beam is relayed using a 10x objective lens and a 20-cm focal length lens (4-f system) to an interferometer, in which a rooftop mirror is used to invert the embedded perturbation of one arm relative to the other. Phase is extracted from the interference fringe shift using the Fourier technique [9], and the Abel inversion assuming axial symmetry is used to retrieve the refractive index change (Δn). The change in the refractive index for various delays are shown in Figs. 1(b - e). Near $\Delta t = 0$ ps [Fig. 1(b)], the probe beam experiences cross-phase modulation (XPM) (positive phase, $\Delta n > 0$) due to the intense pump beam. For $\Delta t = 0.1$ and 0.2 ps [Figs. 1(c) and (d)], the negative phase change ($\Delta n < 0$) is due to presence of plasma. For later delays from $\Delta t \sim 0.5$ ps to 10 ns, the positive phase change occurs [Fig. 1(e)] due to plasma recombination and subsequent permanent material change (here waveguide formation). Extracted plasma densities for various delays are shown in Figs. 1(f - h) and the decrease in plasma densities from $\Delta t = 0.1$ to 0.2 ps indicates recombination of plasma, which agrees with the plasma recombination time (150 fs) in solids [10]. Note that we have improved our TRI sensitivity via better imaging so that we can see small positive phase shifts more clearly compared with the previous report [7].

Although TRI is an excellent technique, we should move the sample after measurement at each delay to find undamaged regions. Therefore, we perform frequency-domain holography (FDH) [8], which enables visualizing nonlinear laser-matter interactions in a single shot. The experimental schematic is shown in Fig. 2(a). A 45fs, 800-nm beam is split in two arms by a beamsplitter. In one arm, the beam is sent to a KDP crystal for second harmonic generation (SHG) and then to a Michelson interferometer that generates reference and probe pulses separated by 1.5 ps. The reference and probe are chirped to ~ 1 ps by a 2-cm long SF10 glass sample and are recombined with the 800-nm pump beam from another arm using a dichroic beamsplitter. The time delay Δt between pump and probe is controlled by a translational stage. Then, the three collinear pulses are focused by a curved mirror into a 200-μm thick flexible Willow Glass sample. First, the 400-nm reference travels unaffected and second, the 800-nm pump perturbs (i.e., ionizes) the medium. Third, the 400-nm probe is modulated by the pump-affected region, acquiring a temporally-evolving phase. After the 800-nm pump is filtered out, both the reference and probe enter an imaging spectrometer generating an interferogram. For single-shot measurements, it is critical to generate chirp in the reference and probe so that different wavelengths in the interferogram represent different time delays between the pump and the probe. Spatio-temporal phase profiles are retrieved using a Fourier method [9]. As shown is Fig. 2(b), we observe the positive phase change near zero delay due to XPM, negative phase change due to plasma generation until Δt ~300 fs, and at later delays, positive phase change due to plasma recombination and subsequent permanent material change (i.e., waveguide formation). This observation is in very good agreement with that via multi-shot TRI (see Fig. 1).

This work is supported by the National Science Foundation (NSF) (Grant No. PHY-1707237), the U.S. Air Force Office of Scientific Research (AFOSR) (Grant No. FA9950-18-1- 0223) and IEEC of Binghamton University.

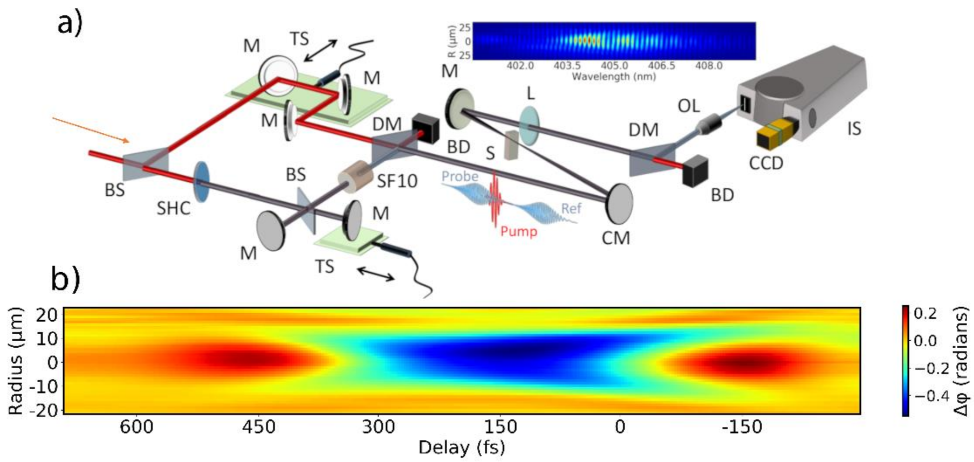

Fig. 2. (color online) Frequency-Domain Holography experiment to extract spatio-temporal phase change (a). M: mirror; CM: curved mirror; DM: dichroic mirror; BS: beamsplitter; S: glass sample; BD: beam dump; SHC: second harmonic crystal; L: lens; IS: imaging spectrometer; SF10 (for chirping the 400nm pulses); OL: objective lens. Phase collected as functions of radial coordinate and delay with pump modification (b). Note the positive phase in earlier times followed by negative phase associated with plasma generation and then positive phase associated with plasma recombination and waveguide formation.

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