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Self-guided glass drilling by femtosecond laser pulses

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Abstract Straight through-holes of high aspect ratio have been fabricated in glass by femtosecond laser pulses, utilizing unique characteristics of ultrafast lasers such as volumetric multi-photon absorption and nonlinear self-focusing. In this study, interestingly, the drilling process was initiated and progressed in a self-regulated manner, while the laser focus was fixed through the specimen at the neighborhood of the rear surface that was in contact with liquid during the entire drilling process. The deposition of laser energy along the nonlinearly extended focal range and the guided drilling along the pre-defined region are explained based on time-resolved optical transmission and emission measurements.

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Much attention has been paid on fabricating three-dimensional microstructures in transparent materials by ultrashort pulse laser radiation. When ultrashort laser pulses are focused inside a transparent material, only a very limited region near the focal volume absorbs laser energy by nonlinear multi-photon process [1]. Hence, a variety of interesting applications have been pursued, including optical waveguides [2], microchannels [3], and recently hybrid opto-fluidic devices [4] inside glass. Although glass offers optical transparency as well as thermal, mechanical and chemical stability, the fabrication of high-aspect ratio features is challenging by conventional techniques.

Among abundant efforts in this field, direct-ablation based three-dimensional microchannel fabrication has been demonstrated [3, 5]. In these studies, glass drilling was performed by focusing an ultra-short laser beam on the rear surface through the transparent sample and scanning the laser focus towards the front surface by taking advantage of the volumetric multi-photon absorption process in order to achieve more stable absorption and facilitate removal of the machined material debris. The debris removal efficiency was further improved by maintaining the machined spot in contact with liquid. Compared with the subsequent etching based approach [4], direct-ablation methods provide single step fabrication with relatively faster processing speed that may be ideal for precise via-hole fabrication.

In this study, liquid-assisted glass drilling is performed by femtosecond laser pulses of 800 nm wavelength. However, in contrast to previous investigations, the laser focus is fixed in the neighborhood of the rear surface of the glass without scanning the laser focus throughout the drilling process, thus enabling simple and stable processing conditions. The results are also interesting in respect to fundamental aspects of the nonlinear femtosecond laser beam propagation through transparent materials.

Figure 1(a) shows a schematic diagram of the femtosecond laser glass drilling and Fig. 1(b) the in situ monitoring system. Detailed description of the experimental apparatus is found elsewhere [3]. Briefly, femtosecond laser

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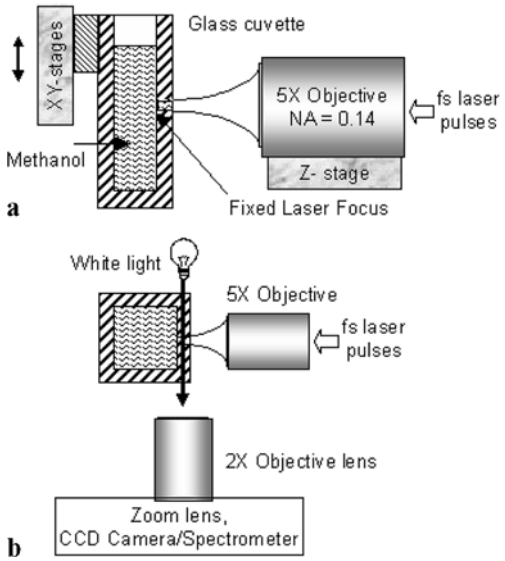

Fig. 1 Schematic diagrams of (**a**) femtosecond laser glass drilling system, and (**b**) in situ monitoring setup

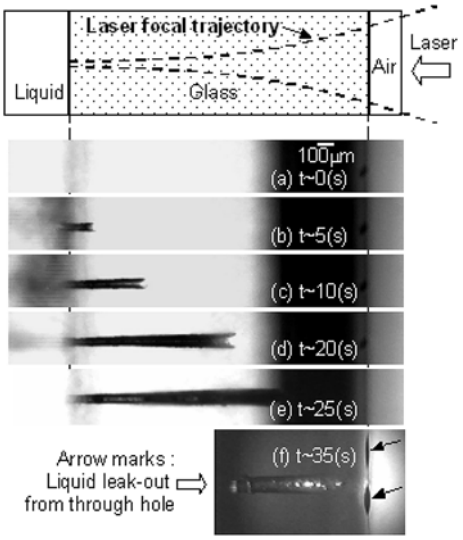

Fig. 2 Snapshots of in situ transmission microscope image of drilling process. Laser focusing path is displayed on the *top figure* (not in real scale). (**a**) Initial energy deposition stage, (**b**) actual drilling initiated from rear surface, (**c**)–(**e**) continuous guided drilling process along pre-defined region, machined debris ejection motions are inspected from the machined hole, and (**f**) liquid leaks out from the other-side of completed through-hole (arrow marks indicate liquid leak-out)

pulses with temporal width of about 100 fs full-width-half-maximum, 800 nm wavelength, and 1 kHz repetition rate are focused near the rear surface of glass sample that is in contact with methanol through a long working distance objective lens of ∼0.14 numerical aperture. Side view transmission (under white light illumination) and emission images were taken to monitor the process in situ via a 2X objective lens coupled with 12X zoom lens. For detailed investigation of the drilling mechanism, the spectrum of the collected laser-induced emission was analyzed by a gated spectrometer (Princeton Instruments). Since the applied pulse energy level (∼157 μJ, measured after the objective lens) was substantially higher than the respective ablation threshold of bulk glass, the laser focus was intentionally shifted towards the liquid (∼100 μm for the specific case of chosen focusing lens and glass material) from the geometrical focus, in order to avoid direct initiation of the rear surface ablation. Under the adjusted focal condition, glass drilling begins after irradiation of a series of laser pulses (typically ∼1000–2000 pulses).

Figure 2 shows in situ side view transmission images of the drilling process by white light illumination. Without noticeable change in optical image in the early stage ($t < \sim 1$ (s), Fig. 2(a), where t is elapsed time after turning on the laser beam), the actual drilling began at $t \sim 1$ (s) from the liquid–glass interface (Fig.2(b)). The drilling then continued accompanied by vigorous debris ejection till complete through-holes were fabricated at $t \sim 35$ (s) across the 1.25 mm thick glass, as confirmed by liquid transfer through the machined channel and the wetting of the front surface (Fig. 2(f)). The average diameter of the drilled channel was ∼120 μm (∼80 μm at rear surface and ∼160 μm at the front surface) at a mean aspect ratio of ∼10:1. It is reminded that the current drilling process does not involve relative scanning motion of the laser focus with respect to the sample. The average processing speed of ∼36 μm/s achieved by the present fixed laser focus scheme is significantly faster than the achieved by scanning (∼1–30 μm/s). Furthermore, it avoids undesirable termination of the drilling process that occurs at non-optimum scanning speed in the case of scanning configuration [3, 5]. Channels of similar length were machined by fixing the laser focus at the front surface of glass material in a vacuum environment although severe cracks observed near the machined holes [6]. The greatly extended channel length compared to the small depth of focus (DOF) of the lens (∼14 μm) has to be attributed to the nonlinear self-focusing driven by ultra-short pulsed laser. When the laser is focused on the rear surface, a higher portion of the applied laser pulse energy is absorbed inside the glass bulk [7]. Since the laser fluence was set at a level near the ablation threshold at the rear surface, the extended zone inside glass upstream of the laser focus experienced the type of local structural modification encountered in optical waveguide fabrication [2].

Similar side-view imaging performed without white light illumination (Fig. 3) elucidates the drilling mechanism by visualizing laser-induced plasma emission. A bright region was observed almost instantaneously after turning on the laser (Fig. 3(e)) and persisted for ∼1 (s) before the actual initiation of the drilling process at the rear glass specimen surface (Fig. 3(f)) based on imaging at ∼30 frames per second (fps). Imaging at 250 fps (i.e., capturing every

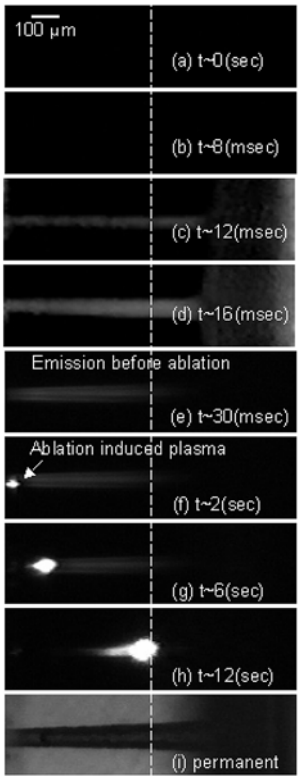

Fig. 3 A visualization of laser-induced plasma emission during the drilling process. (**a**)–(**e**) initial energy deposition stage, wide spectrum plasma emission inspected through the whole thickness of the glass, (**f**) actual drilling (ablation) initiated at rear surface of the glass and ablation induced plasma visualized, (**g**)–(**h**) continuous material removal along energy pre-deposition region, and (**i**) permanent image of drilled hole. No white light illumination was applied for the emission images in (**a**)–(**h**). High speed camera (operated at 250 Hz capturing rate) was used to acquire images (**a**)–(**d**)

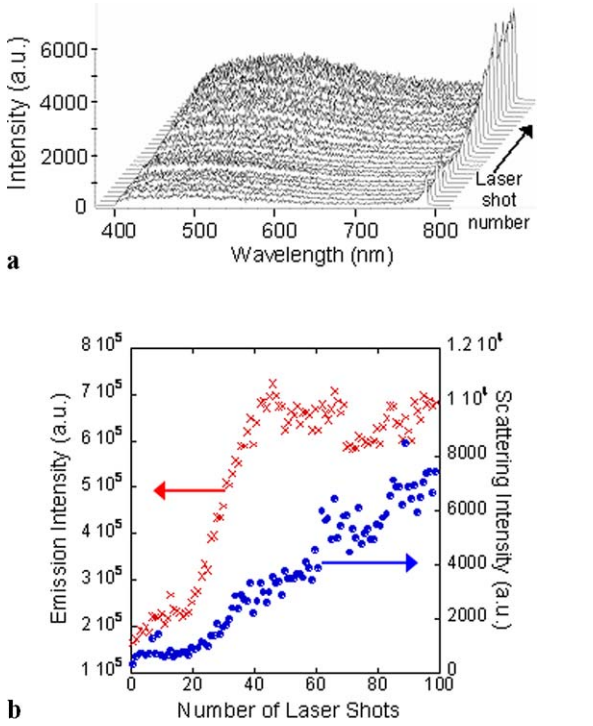

Fig. 4 (**a**) Measured emission spectra in the early stage of glass drilling process, and (**b**) a plot of intensities of both the broadband visible emission (integrated valued in the wavelength range of 400–700 nm) and scattered laser light (measured value ∼790 nm wavelength) with respect to the number of laser shots

four laser pulses, Fig. 3(a)–(d)), could not detect emission upon the initial few laser shots (∼8 shots, Fig. 3(a), (b)). Emission appeared after ∼12–16 laser shots (Fig. 3(c), (d)), clearly showing accumulated pulse effects along the nonlinear self-focusing zone formed inside the glass medium. Actual drilling was initiated from the rear surface (Fig. 3(f)) since that was subjected to the highest laser intensity and surface material removal was easier. Extremely bright emission light induced by laser ablation was visible on the ablated spot. It should be noted that the final shape of the drilled hole approximately followed the envelope of the earlier observed bright emission region (compare Fig. 3(e) with Fig. 3(i)). Time-resolved spectroscopic analysis was performed to clarify the laser-induced emission. Due to the limited sampling rate of the intensified charge coupled device (ICCD) camera in the gated spectrometer, the repetition rate of the femtosecond laser was reduced to ∼50 Hz. Figure 4(a) displays emission spectra taken every two pulses. The intensities of both the broadband visible emission and scattered laser light (∼800 nm wavelength) increased with the number of laser shots, as plotted in Fig. 4(b). Care was paid to collecting emission light from the entire region of the drilled zone by a 2X objective lens. In comparison to measurements done in the absence of liquid, the emission from the glass bulk side collected by a higher magnification lens showed discrete peaks near ∼545 and ∼365 nm, possibly due to the optical breakdown and/or filamentation, as explained by several groups [8]. Strong atomic transition peaks as typically observed in laser induced breakdown spectroscopy [9] from impurity elements (Na and Ba in B270 glass material used in this experiment [10]) were dominant near the ablation spots. However, when the collection was adjusted to encompass the entire drilling region, the contribution of the aforementioned discrete peaks was significantly reduced and a wideband spectrum became prominent. Even though additional wideband spectral components from liquid breakdown cannot be excluded, the increasing trend both in emission and scattering proves that measurements acquired at early timings of Figs. 3 and 4 are effectively associated to the bulk glass modification process. It is inferred that the reinforcement of the bright emission and the growing scattering signal signify accumulated structural change incurred before the actual ablative material removal process. Therefore, once ablation was initiated at the rear surface, the structurally modified region that was defined by the preceding laser pulses experienced preferential ablation, leading to self-guided drilling.

In summary, liquid-assisted drilling of high aspect ratio holes in glass was successfully demonstrated by femtosecond laser pulses with the laser focus fixed near the rear liquid–glass interface so that the actual drilling process could be retarded. Visualization and spectral measurement of laser-induced emission revealed that laser energy was deposited inside the glass bulk, pre-defining a modified structure region via the contribution of nonlinear self-focusing.

This volumetric structural modification took place before the commencement of the actual material removal, thereby enabling a self-guided drilling process.

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