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Refractive index engineering inside silicon by infrared laser pulses of different pulse durations in the picosecond regime

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Abstract: We report on the refractive index engineering inside silicon bulk by picosecond infrared lasers. Different responses are observed depending on the pulse durations. This represents a critical step for prototyping 3D silicon photonics microdevices. © 2019 The Author(s)
OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3390) Laser materials processing; (040.6040) Silicon.

1. Introduction

One of the challenges in silicon photonics is to extend the architectures of the microdevices from 2D to 3D. Infrared laser can penetrate inside bulk silicon, therefore offering a promising tool for 3D refractive index engineering and silicon photonics devices prototyping. Of all the laser parameters, the pulse duration was found to have a great impact on the laser modification. Recently, successful modification inside the silicon were reported by using nanosecond laser pulses [1-4]. Despite the easy success of modification by nanosecond laser, the types of modification are very limited, and the written waveguides exhibit high losses. Femtosecond lasers were found to be very difficult for bulk modification due to nonlinear propagation and ionization effects. The success of modification deep inside silicon was not achieved until we recently introduced the solid-immersion focusing [5], but the flexibility is limited due to the contact nature of solid-immersion focusing. Picosecond laser is accompanied with less nonlinear effects compared to femtosecond laser, while offering more possibilities of modification types compared with nanosecond laser. However, the modification of silicon using picosecond laser with different pulse durations remains poorly investigated. In this work, picosecond laser with different pulse durations were used for modification inside the silicon.

2. Results and discussion

The experimental setup used in this research is shown in Fig. 1. The laser source (Pharos, Light-conversion) generates infrared laser pulses at 1030 nm central wavelength. The wavelength of the laser pulses is converted to 1550 nm by using an optical parametric amplifier and the pulse duration is measured at 174 fs. The energy is controlled by the combination of a half-wave plate and a broadband polarized beam splitter (PBS). Then the beam is injected in a stretcher arrangement consisting of two Littrow gratings (Thorlabs) to introduce negative group velocity dispersion to the original laser pulses. The incident angle is 10° away from the Littrow angle. The pulse duration of the laser pulses can be tuned by changing the distance between the gratings. The pulse duration is checked by using a long-range auto-correlator implemented next to the irradiation setup. Afterwards, the pulses are focused 300 μm inside the Si samples by Micro-objective lens (N.A. 0.85, Olympus LCPLN-IR 100x), which has a correction collar to compensate the spherical aberration induced by the pre-foci silicon material. The Si samples are 1 mm thick intrinsic silicon crystals with $100(\pm 5^\circ)$ orientation. They are prepared by cleaving a wafer (Siltronix). After irradiation, the phase change of the samples will be measured by an infrared phase microscopy [6] (as shown in Fig. 1(b)).

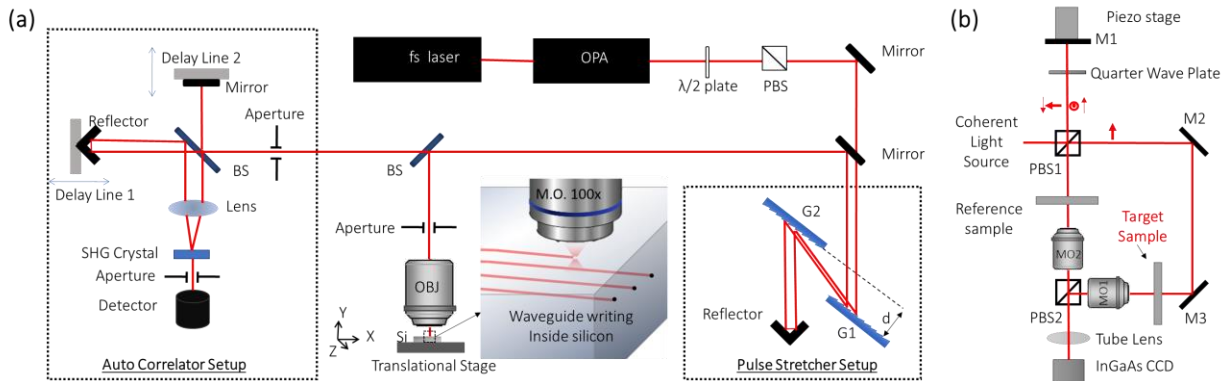


Fig. 1 (a) The schematic of the experimental setup for silicon modification with stretched pulse; (b) The schematic of the phase microscopy for detection of the phase change.

Before irradiation experiments, the pulse durations of different grating distance were measured, as shown in Fig. 2(a). The experimental results fitted very well with theoretical predicts based on the dispersion theory. Then, the stretched laser with different pulse durations were used for irradiation. For each different pulse duration, totally 10 different energy levels from 10% to 100% were used. The incident pulse energy before the pulse stretcher setup was kept the same. At each spot, 1000 pulses were used for modification, with the laser repetition rate of 1 kHz. The modification inside the silicon varies with different pulse duration is shown in Fig. 2(b). When the pulse duration decreases, the area of the modification tends to become smaller, and the energy range of modification also becomes smaller. Fig. 2(c) shows the map of fabrication results under different pulse duration and threshold. In Zone A, the pulse energy doesn't exceed the damage threshold so that no modification is obtained; Zone B represents the combinations of pulse duration and pulse energy which may lead to modification; in Zone C, the pulse energy is very high, but no modification occurred. The existence of Zone C implies that, at some pulse durations, high incident pulse energy doesn't guarantee higher absorbed energy by the material and higher modification possibilities. This interesting phenomenon proves the high nonlinearity in the laser propagation inside the bulk silicon.

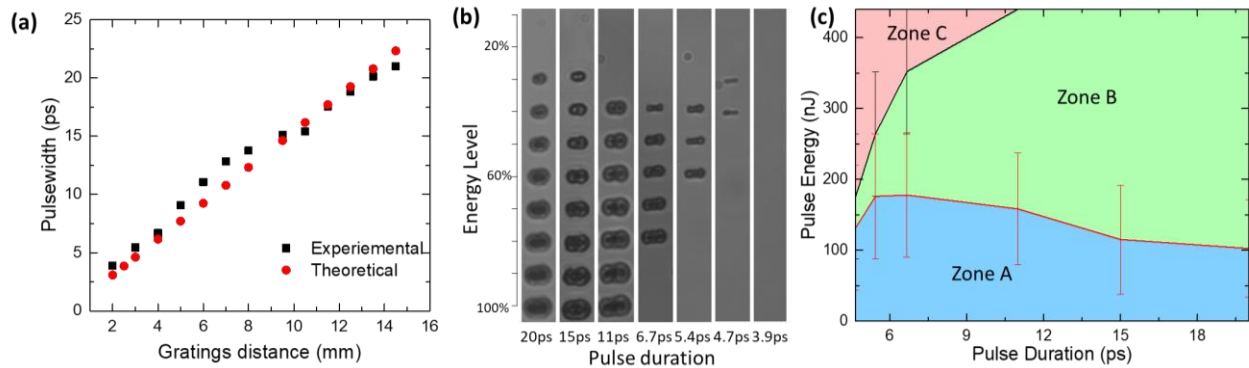


Fig. 2 (a) Experimental measurement and theoretical predictions of pulse width changes v.s. the grating distance; (b) The modification results of different pulse duration and energy level; (c) The map of fabrication results under different pulse duration and pulse energy.

3. Conclusion

Modifications inside silicon by different durations in picosecond range were investigated, which shows that the energy range when modifications occur are highly related to the pulse duration. The pulse duration may also influence the refractive index changes, which needs further characterization by the infrared phase microscopy. This research can offer more understanding for the optimization of pulse duration for the refractive index engineering by infrared laser.

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