

# Low-loss Type II waveguide writing in fused silica with single picosecond laser pulses

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**Abstract:** A new domain of rapid waveguide writing with non-overlapping pulses of a 1-kHz ultrashort laser is demonstrated to produce low loss waveguides in fused silica glass. This new regime is distinguishable in two ways from traditional approaches in laser waveguide writing. First, an examination of a wide 50-fs to 5-ps range of pulse duration shows the lowest loss waveguides to form in a narrow  $1.0 \pm 0.2$  ps window that significantly exceeds the 50 - 200 fs duration reported as optimal in other studies. Second, an unusually high scan speed of  $1.0 \pm 0.2$  mm/s points to a novel Type-II photosensitivity mechanism for generating low-loss refractive index structures. The waveguides comprise of an array of nearly isolated single-pulse interaction volumes that sharply contrast with the high exposures of tens to thousands of overlapping laser pulses typically applied along a slowly moving focal volume. A minimum propagation loss of  $\sim 0.2$  dB/cm and a slightly asymmetric mode diameter of  $\sim 9$   $\mu\text{m}$  is reported for 633-nm light. The low loss waveguides fabricated with picosecond pulses enables 3-D photonics circuit fabrication with simpler and lower cost picosecond laser systems.

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**OCIS codes:** (230.7370) Waveguides; (350.3390) Laser materials processing; (320.2250) Femtosecond phenomena; (320.5390) Picosecond phenomena

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## 1. Introduction

Femtosecond laser direct writing of three-dimensional (3-D) photonic devices has opened new directions in fabricating compact telecom, sensing and biomedical systems by inducing permanent refractive index changes locally within the focal volume of a scanning laser beam [1-3]. The formation of low-loss waveguides can be divided into low (~1 kHz) and high (~MHz) repetition rate domains. High repetition rate lasers typically apply low pulse energy (10 to 100 nJ) to generate cylindrically symmetric waveguides by thermal diffusion and local heat accumulation effects [4-7]. In kHz systems, higher pulse energies (~1 μJ) generate refractive index structures defined by the focal volume of the laser and lead to asymmetric waveguide modes [8, 9]. With such diverse lasers, optimal waveguide scanning speeds have been reported from tens of microns per second for kHz systems to tens of millimeters per second for >100 kHz systems, depositing anywhere from tens to many thousands of overlapping laser pulses within the spot size of the laser. In this way, fluence doses ranging from 100 to 10<sup>6</sup> J/cm<sup>2</sup> yield smooth, continuous, and moderately strong refractive index changes of  $\Delta n = 10^{-4}$  to 10<sup>-2</sup> [3, 5, 10].

Recently, Mihailov and coworkers [11] demonstrated an extension of Type II ultraviolet laser photosensitivity [12] to ultrashort lasers by writing fiber Bragg gratings (FBGs) with a single high-fluence 120-fs pulse. While Type II modification is attractive for rapid fabrication, structural damage to the glass typically causes scattering and other deleterious optical losses. Mihailov *et al.* [11] attributed a 0.57-dB component of their FBG loss to such a Type-II phenomenon. Nevertheless, there appears evidence that Type II photosensitivity may be applicable to writing of low-loss waveguides. Will *et al.* [8] reported the formation of low loss waveguides (<1 dB/cm) for 514-nm light across a wide scanning speed range of 25-μm/s to 1-mm/s when using a 1-kHz 120-fs laser. The 1-mm/s scan speed marks the onset of a new low-loss Type-II photosensitivity mechanism we report here.

A new single-pulse domain of Type-II photosensitivity is identified for 1-kHz ultrashort laser writing of low loss waveguides in fused silica glasses. The lowest loss waveguides consist of a closely-spaced array of isolated laser-modification volumes—with each volume

formed by a single pulse. In this way, much higher (10 to 100 fold) writing speeds become possible for 1-kHz laser systems than the 10 to 125  $\mu\text{m/s}$  speeds previously reported [2, 3, 8, 9]. Furthermore, in contrast to widespread reports that waveguides are best formed with  $< 200\text{-fs}$  pulses [13], we note the lowest waveguide losses to be formed at 1.0-ps duration. This paper examines pulse duration, laser energy and scan velocity across a wide parameter space of 50 fs to 5 ps, 0.1 to 10  $\mu\text{J}$ , and 0.5 to 10 mm/s, respectively, and reports their effects on the quality, mode profile, and propagation loss of optical waveguides for 633-nm light.

## 2. Experiments

Waveguides were written with a regeneratively amplified Ti:Sapphire laser system (Spectra-Physics Spitfire Pro) delivering 800-nm pulses with 2.4-mJ maximum energy at 1-kHz repetition rate. The pulse duration was varied from 50 fs to 5 ps by tuning the compressor grating position while monitoring the positively chirped pulse duration with an autocorrelator (APE Pulse-Check). The laser pulse energy was varied from 0.1 to 10  $\mu\text{J}$  with a half wave plate and linear polarizer. A 0.25-NA aspherical lens focused the laser beam to  $\sim 1.2\text{-}\mu\text{m}$  diameter (full-width half maximum, FWHM) and  $\sim 12\text{-}\mu\text{m}$  depth of focus at a position  $\sim 200\text{ }\mu\text{m}$  below the surface of fused silica samples (Corning 7980,  $50\times 50\times 1\text{ mm}^3$ ). The sample was mounted on 3-D motion stages (Aerotech ABL1000) and scanned perpendicular to the laser beam direction with velocities of 0.5 to 10 mm/s, as illustrated in Fig. 1(a). During the scan, the laser polarization was held parallel to the sample travel direction. Waveguides were formed along the full 50-mm sample length.

At high scan speeds ( $\geq 1\text{ mm/s}$ ), the ellipsoid-like focal volume, shown enlarged in Fig. 1(b), separates into isolated interaction volumes, spaced by the travel distance,  $d$ , between successive laser pulses. At a repetition rate of  $R = 1\text{ kHz}$  and a scan speed of  $v = 1\text{ mm/s}$ , the spacing ( $d = v / R = 1\text{ }\mu\text{m}$ ) matches the beam spot size ( $w_0 = 1.0\text{ }\mu\text{m}$ ) to demark scanning zones of partial overlapping ( $v < 1\text{ mm/s}$ ) and nonoverlapping ( $v > 1\text{ mm/s}$ ) foci. Figure 1(c) shows an optical microscope image of a waveguide formed ( $d = 1.25\text{ }\mu\text{m}$ ) near this demarcation. We choose scan speeds of  $v < 0.7\text{ mm/s}$  to define the high overlapping zone where 50% or more of the beam diameter (FWHM) overlaps adjacent pulses.

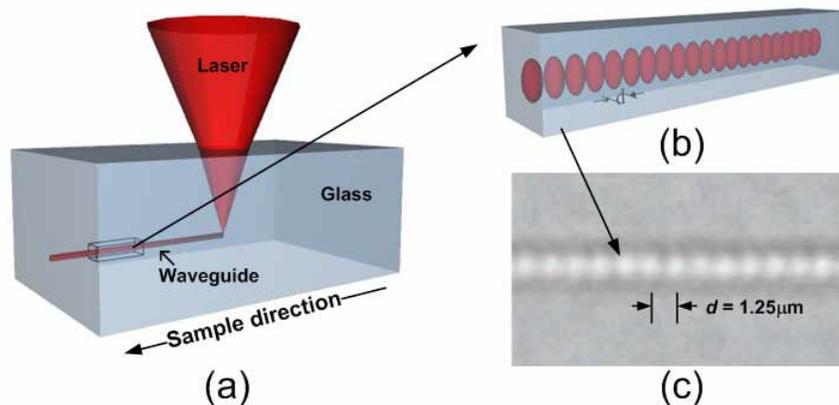


Fig. 1. Schematic illustration (a) of the waveguide fabrication process with the sample translated perpendicularly to the focused laser beam direction, and leading to an array of isolated focal volumes (b) under high ( $>1\text{ mm/s}$ ) scan velocities. A transverse microscope image (c) of a waveguide showing the isolated modification volumes written with 1-ps duration, 0.6- $\mu\text{J}$  energy, and 1.25 mm/s scan speed.

After waveguide writing, the fused silica samples were polished at both end facets. Unpolarized 633-nm light from a HeNe laser was coupled into a single mode fiber (Thorlabs SM600) and then butt-coupled into the waveguides. Near-field profiles of the guided modes

were obtained by imaging the output facets with a 100X microscope objective and a CCD camera (Spiricon SP-1550M). Waveguide propagation losses were assessed by imaging the exponential fall-off of the scattered waveguide light with a CCD camera (Panasonic KR222) positioned transversely to the sample as described by Okamura *et al.* [14].

### 3. Results and discussion

For the 0.5 to 10 mm/s range of scan velocities tested here, continuous and homogenous waveguides were observed only within a narrow pulse energy window of  $0.6 \pm 0.2 \mu\text{J}$ , with almost no variation across all pulse durations in the 50 fs to 1.5 ps range. Laser tracks appeared faint, discontinuous, or invisible under an optical microscope for pulse energy  $< 0.4 \mu\text{J}$ , or consisted of inhomogeneous damage lines above  $0.8 \mu\text{J}$ . No waveguiding was observed outside this  $0.6 \pm 0.2 \mu\text{J}$  range.

#### 3.1 Pulse-overlap (scan speed) effects

The top row of Fig. 2 shows the overhead optical microscope images of the laser exposed waveguide tracks inscribed with 1-ps pulse duration, 0.6- $\mu\text{J}$  pulse energy, and various scan velocities from 0.6 to 1.5 mm/s. Three zones of beam spot overlap are identified: high overlapping ( $> 50\%$  overlap) for  $v < 0.6 \text{ mm/s}$ , partial overlapping for  $0.7 < v < 0.9 \text{ mm/s}$  and non-overlapping for  $v > 1 \text{ mm/s}$ . For the scan speeds of 1.25 and 1.5 mm/s, isolated modification zones of 1.2- $\mu\text{m}$  diameter, each formed by a single laser pulse, are identifiable along the translation path. Such structures guide 633-nm light, possibly as a linear array of micro-lenses. However, guiding was not observed for larger spacing of  $d > 2 \mu\text{m}$  ( $v > 2 \text{ mm/s}$ ), perhaps due to scattering loss or insufficient focusing from the micro-lenses. For speeds of  $v < 0.8 \text{ mm/s}$ , inhomogeneous modification tracks appear that have larger waveguide losses and suggest overexposure. The most uniform and contiguous waveguides are noted only in a narrow range of scan speeds of 0.9 to 1.0 mm/s. This range defines the optimum pulse-to-pulse step size of  $d \approx 1 \mu\text{m}$  in which the lowest-loss waveguides were found.

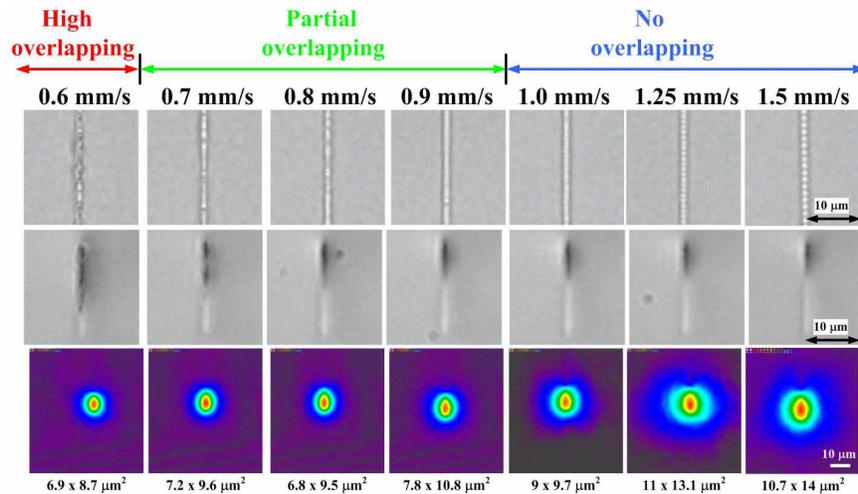


Fig. 2. Microscope images in top view (top row) and the side view (middle row) together with the near-field mode profiles of 633-nm light (bottom row) of waveguides written with 1-ps duration and 0.6- $\mu\text{J}$  pulse energy. Scan velocities are show above the top row and the mode sizes (FWHM) are given below the bottom row. The 1-ps laser is incident from the top in the side view microscope images and the mode field images.

The center row of microscope images in Fig. 2 shows the backlit cross sections of the waveguides, where the laser radiation was incident from the top. The bright elliptical shapes

indicate the region of positive refractive index change responsible for 633-nm waveguiding. Its shape closely matches the 1.2- $\mu\text{m}$  focus diameter and the 12- $\mu\text{m}$  depth-of-focus for the 0.25-NA lens. This relatively close correspondence contrasts with the observation by Luo *et al.* [15] of a 3.5 $\times$  increase of the vertical modification dimension as the laser pulse duration was reduced from 500 to 150 fs while using a similar ( $\sim 0.6\text{-}\mu\text{J}$ ) pulse energy in fused silica. The discrepancy may result from their tighter focusing geometry (NA 0.65). The mode profile asymmetry can be improved with higher NA lenses, cylindrical lenses [16], rectangular masks [17] or multi-pass laser scanning [18], but are not systematically explored in the present paper. The dark elliptical region above the bright one arises from light refracted out of a lower refractive index volume (i.e. negative index change) or scattered by waveguide inhomogeneities. As total exposure increases (right to left in Fig. 2), the dark volume extends into and overtakes the bright modification volume, suggesting higher waveguide loss at lower scan speed. In contrast, only positive refractive index changes were reported for 1-kHz waveguide writing in fused silica with slow scanning speeds of  $< 200\text{ }\mu\text{m/s}$  [3, 10].

The guided mode profiles for 633-nm light, shown in the bottom row of Fig. 2, can be represented by a Gaussian profile vertically and evanescent profile laterally that match expectations for an asymmetric 1.2- $\mu\text{m} \times 12\text{-}\mu\text{m}$  guiding cross-section. The mode diameter (average of  $x$  and  $y$ ) increases from 8 to 12  $\mu\text{m}$  (FWHM) as the scan speed increases, indicating an expected decrease in refractive index change with increasing scanning speed. The mode eccentricity varies from 0.4 to 0.7. All waveguides in Fig. 2 were single mode at 633 nm. Mode profiles could not be observed for scanning speeds of  $v < 0.4\text{ mm/s}$  or  $v > 2\text{ mm/s}$ . By separately matching the observed 9- $\mu\text{m}$  by 9.7- $\mu\text{m}$  (FWHM) mode profiles to one-dimensional step-index waveguide models of 1.2- $\mu\text{m}$  and 12- $\mu\text{m}$  width, we infer laser-induced refractive index change of  $\sim 5 \times 10^{-4}$  and  $\sim 4 \times 10^{-4}$ , respectively, for the 1-ps case of 1-mm/s scan speed. These values are at the low end of other reports [3, 10] that range from  $\Delta n = 10^{-3}$  to  $10^{-2}$  for kHz waveguide writing.

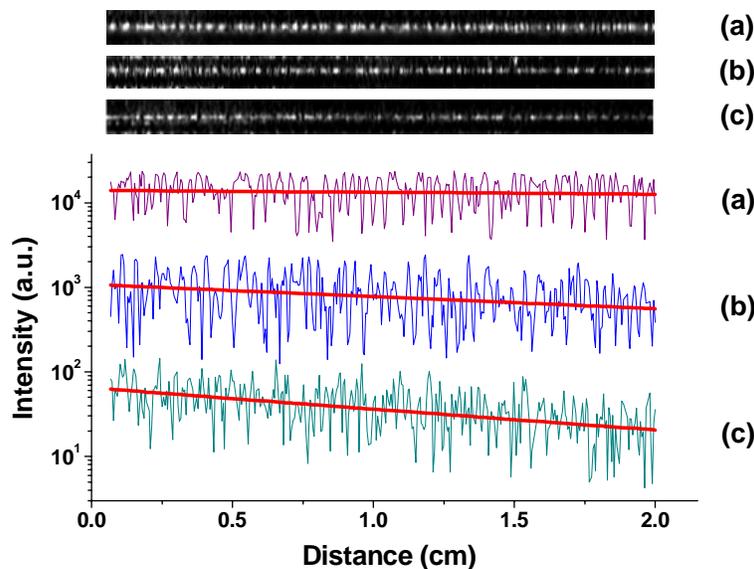


Fig. 3. Overhead CCD-camera images of scattered waveguide light (top) and log plot scattered intensity versus distance along waveguide for waveguides written with 1mm/s speed and pulse durations of (a) 1 ps, (b) 1.5 ps, and (c) 100 fs. The solid red lines mark the fitted exponential decay with slopes of (a) 0.2 dB/cm, (b) 1.2 dB/cm, and (c) 2.3 dB/cm.

Figure 3 shows the scattered light CCD images recorded from three waveguides fabricated with 1-mm/s scan speed and pulse durations of 100 fs, 1 ps, and 1.5 ps. The semi-log intensity plots show an exponential fall off along a 2-cm long waveguide section from which propagation losses may be inferred from the solid curve data fits. Data set (a) yields a surprisingly low  $\sim 0.2$  dB/cm loss. Propagation losses for the waveguide writing conditions of Fig. 2 are plotted in Fig. 4 as a function of the scan speed. Modest waveguide losses of  $< 1$  dB/cm are noted only in a narrow processing window of 0.8 to 1.25 mm/s scanning speed, with a minimum of  $\sim 0.2$  dB/cm at 1 mm/s. Much larger losses ( $> 1$  dB/cm) or the complete absence of waveguiding were noted outside this speed range. The lowest loss condition (for  $\sim 1$  mm/s) corresponds to the most homogeneous modification tracks in the top view of Fig. 2, that on close inspection appear as contiguous 1- $\mu\text{m}$  demarcations formed by single-pulse interactions.

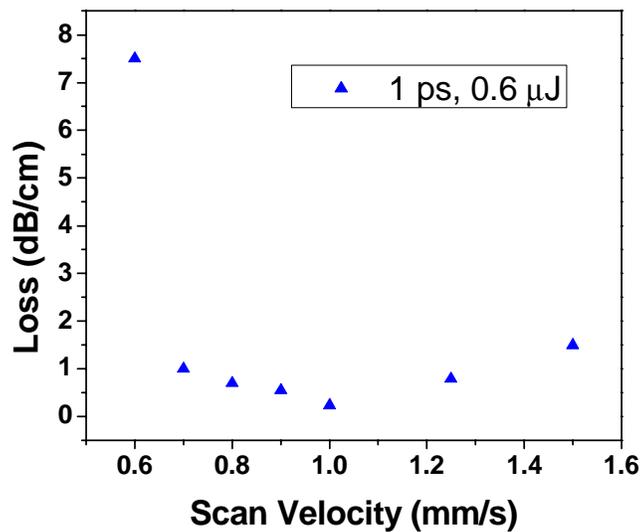


Fig. 4. Waveguide propagation loss as a function of scan velocity for 1-ps duration and 0.6- $\mu\text{J}$  pulse energy.

### 3.2 Pulse duration optimization

The effect of pulse duration on the waveguide properties was also examined across a wide parameter space of exposure conditions. Figure 5 shows the transverse (top row) and cross sectional (center row) microscope images together with the near-field mode profiles (bottom row) for 633-nm light in waveguides formed at an optimal 1-mm/s scan speed and various pulse durations. Pulse energy was optimized for lowest waveguide loss at each pulse duration, yielding 0.5  $\mu\text{J}$  for 50 fs, 0.6  $\mu\text{J}$  for 100 fs to 1 ps, and 0.7  $\mu\text{J}$  for 1.5 ps. Pulses longer than 2 ps generated inhomogeneous waveguides that did not guide 633-nm light.

Surprisingly, there is little variation in the waveguide appearance in either transverse or cross-sectional microscope views, or in the mode diameters, even though a large 30-fold variation of peak intensity has been applied by the 50-fs to 1.5-ps change in duration. The average mode diameter decreases slightly from 10.3  $\mu\text{m}$  at 50 fs to a minimum of 9.5  $\mu\text{m}$  at 1 ps, and then increases to 10.4  $\mu\text{m}$  at 1.5 ps. The waveguides are all single mode and asymmetric with eccentricities of 0.1 to 0.7. The waveguides written with 50-fs and 1.5-ps pulses are less homogeneous, but have slightly shorter cross-sectional length than the intermediate pulse duration (0.1 – 1 ps) that possibly accounts for their more symmetric mode

profiles. Overall, similar mode structures and nearly identical values of optimized pulse energy suggest the nonlinear absorption in fused silica and induced change in refractive index are only weakly dependent on the pulse duration in this 50 fs to 1.5 ps range in this waveguide writing scheme.

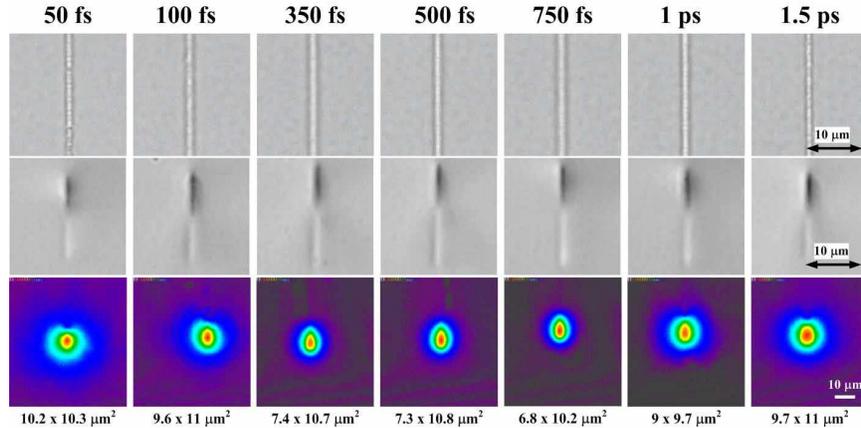


Fig. 5. Microscope images in transverse (top row) and end view (middle row) together with the near-field mode profiles of 633-nm light (bottom row) of waveguides written with 1-mm/s scan speed. Pulse energies are 0.5  $\mu\text{J}$  for 50 fs, 0.6  $\mu\text{J}$  for 100 fs to 1 ps, and 0.7  $\mu\text{J}$  for 1.5 ps. The mode sizes (FWHM) are given below the bottom row. The laser pulses are incident from the top in the end view and mode field images.

Although the waveguide images in Fig. 5 are similar, there is a strong dependence of propagation loss on pulse duration as shown in Fig. 3 and Fig. 6. Waveguides were written with pulse energy (see Fig. 5) and scan speeds (0.9 and 1.0 mm/s) optimized for the lowest loss for each pulse duration. Surprisingly, the minimum propagation loss of  $\sim 0.2$  dB/cm was observed for a relatively long 1.0-ps duration in sharp contrast to the much shorter pulses preferred by other groups using both either low or high repetition rate lasers. Hnatovsky *et al.* [13] identified a narrow processing window of 40 to 185 fs and 50 to 200 nJ/pulse with a 100-kHz laser as optimal for low-loss waveguide writing in fused silica under high pulse overlapping conditions ( $\sim 1500$  pulses per focal diameter). Fukuda and coworkers [19] reported a 5-fold increase in propagation loss for guiding 1550-nm light, also in the high-overlapping regime ( $\sim 1200$  pulses per focal diameter), as pulse duration increased from 150 to 600 fs for a 200 kHz laser. Several other groups [2-5, 8, 9, 20] are consistent in favoring short ( $< 200$  fs) pulses for low-loss waveguide writing. One common element in this other work is a slower scan speed that delivers anywhere from 5 to  $> 10^4$  overlapping pulses per focal diameter. In contrast, our waveguides were fabricated by non-overlapping laser pulses, which preclude any significant role for incubation effects that arise from accumulative damage of many overlapping pulses. Incubation effects dramatically alter the fluence threshold for surface and collateral damage in ablation of transparent dielectrics [21-24] and may drive similar damage mechanisms internally in the waveguides to explain the high propagation losses observed here for slow scanning speeds ( $< 0.5$  mm/s) where two or more pulses are effectively overlapped. Losses at higher scan speed are also anticipated as the high refractive-index voxels physically separate at scan speeds  $> 2$  mm/s and classical waveguiding by total internal reflection breaks down.

The effect of pulse duration on waveguide loss is more difficult to establish. If a low surface ablation threshold is commensurate with low loss waveguides, then it is instructive to consider again the damage threshold of transparent dielectrics. Most groups concur that the damage threshold fluence deviates from the thermal diffusion scaling of  $\sqrt{\tau}$  when the laser pulse duration,  $\tau$ , is shorter than 10 ps. Mourou and coworkers [23] accounted for a distinct minimum in the single-pulse ablation threshold of fused silica observed at around 1-ps

duration by combining the effects of photoionization and impact ionization with a high initial electron density of  $>10^{12} \text{ cm}^{-3}$ . Such high densities may arise from impurities in the glass, defects generated by neighboring pulse interactions, and pre-pulse interactions from the laser pedestal. Alternatively, the femtosecond-to-picosecond time dynamics of Joule heating, electron-phonon coupling, shock-induced damage and radiation shielding by a critical electron density front are equally important factors that may explain the optimal 1-ps pulse duration found here for writing low loss waveguides. In addition, by selecting appropriately high scan speed, the present work reveals a new processing window where non-overlapping interaction volumes are key to forming low-loss waveguides. Such isolated single-pulse interactions fall into the Type II class of laser photosensitivity, but with the unique advantage of being damage-free—unlike other Type II observations with ultrafast [11] or ultraviolet [12] lasers.

The present results are to our best knowledge, the first account of using picosecond pulses to inscribe buried waveguides in glasses. The observed minimization of waveguide loss at 1.0-ps duration was unanticipated, and opens new directions for 3-D waveguide writing in glasses. Although the estimated refractive index change of  $5 \times 10^{-4}$  is relatively small, the  $\sim 10\text{-}\mu\text{m}$  diameter mode profiles closely match the mode size of standard optical fiber for low-insertion loss coupling. We were unable to observe guiding of 1550-nm light in the present waveguides, possibly due to low refractive index contrast. However, 1550-nm guiding was definitively observed when approximately a dozen waveguide tracks were written side-by-side with  $\sim 1\text{-}\mu\text{m}$  spacing. Waveguide writing with negative chirped pulses were also applied for the same range of pulse durations, and yielded similar properties as the positively chirped pulses presented above.

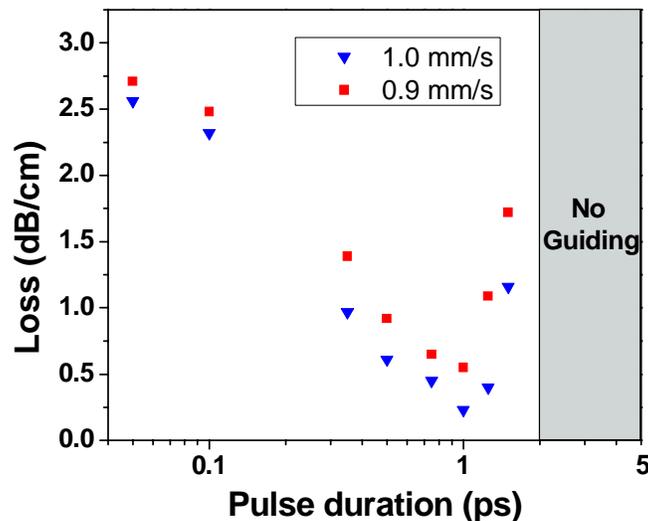


Fig. 6. Waveguide propagation losses as a function to the laser pulse duration for 1.0 and 0.9 mm/s scan speeds.

#### 4. Conclusion

A new approach to waveguide writing with non-overlapped pulses was demonstrated for the first time to produce low-loss waveguides in fused silica glasses with 1-kHz ultrashort laser pulses. This non-overlapping method offers the highest possible scan speed at a given repetition rate, and therefore promises much higher writing speeds ( $>1 \text{ cm/s}$ ) should the method be extensible to higher repetition rate  $>10 \text{ kHz}$ . The unexpected long pulse duration

of 1.0 ps—found to minimize the waveguide propagation loss—is to our best knowledge the first demonstration of picosecond waveguide fabrication in glasses. This result is significant in opening lower cost and more reliable picosecond lasers, as a more practical direction than femtosecond lasers, in manufacturing the first generation of 3-D photonics circuits.

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