Micromachining of bulk glass with bursts of femtosecond laser pulses at variable repetition rates

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Abstract: Oscillator-only femtosecond laser micromachining enables the manufacturing of integrated optical components with circular transverse profiles in transparent materials. The circular profile is due to diffusion of heat accumulating at the focus. We control the heat diffusion by focusing bursts of femtosecond laser pulses at various repetition rates into sodalime glass. We investigate the effect the repetition rate and number of pulses have on the size of the resulting structures. We identify the combinations of burst repetition rate and number of pulses within a burst for which accumulation of heat occurs. The threshold for heat accumulation depends on the number of pulses within a burst. The burst repetition rate and the number of pulses within a burst provide convenient control of the morphology of structures generated with high repetition rate femtosecond micromachining.

OCIS codes: (350.3390) Laser processing of materials; (230.7370) Waveguides; (320.7090) Ultrafast lasers.

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1. Introduction

Femtosecond micromachining permits the fabrication of waveguides in three-dimensions inside a material without damaging its surface [1]. A long list of waveguide-based photonic devices have already been demonstrated including waveguide couplers, beam shapers, amplifiers, interferometers and resonators [2-12]. In 2001, high-speed writing of round waveguides was achieved through oscillator-only micromachining, reducing manufacturing times by three orders of magnitude [6].

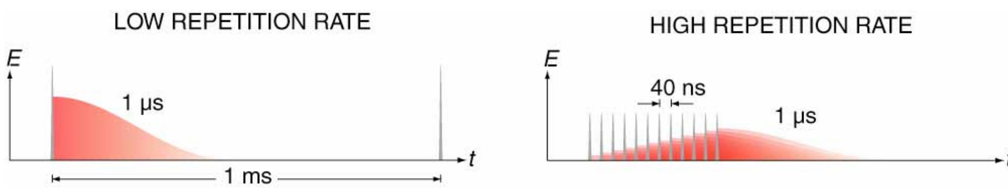

Fig. 1. At low repetition rate, the energy deposited by each laser pulse diffuses out of the focal volume before the next pulse arrives. At high repetition rate, energy accumulates in the focal volume making it possible to achieve very high temperatures around the focal volume with pulse energies of just a few nanojoules. Yellow: laser pulses; red: deposited energy.

Oscillator-only micromachining is fundamentally different from micromachining with an amplified laser system. The pulses from an amplified femtosecond laser system typically are separated by milliseconds, which far exceeds the time required for heat to diffuse out of the focal volume for a typical glass (1 µs for a 1 μm^3 volume in fused silica) [13]. The focal volume thus returns to room temperature before the next pulse arrives (see Fig. 1(*a*)). Consequently, the structural change caused by an amplified laser is confined to the focal volume, regardless of the number of pulses that strike the sample. The time interval between the pulses emitted by a femtosecond laser oscillator, on the other hand, is on the order of tens of nanoseconds, which is significantly shorter than the time required for heat to diffuse out of the focal volume (see Fig. 1(*b*)). Over time, the energy from successive pulses accumulates in and around the focal volume, producing structural changes. The train of oscillator pulses constitutes a “point source of heat” at the focal volume within the bulk of the material. The longer the material is exposed to the train of pulses from an oscillator, the higher the temperature at the focus and the larger the region that is heated. If the temperature exceeds the material’s melting point, structural changes can occur. Melting and resolidification of material up to a radius of 50 µm from a 1 µm focal spot has been demonstrated [6, 14], showing that micromachined features are controllable by simply varying the number of irradiating pulses.

The laser repetition rate also has an influence on maximum feature size [15]. For example, with 10^7 pulses at 0.2 MHz an 8-µm diameter feature is achieved, whereas with 10^3 pulses at 1 MHz a feature with about 18-µm diameter is formed [15]. Hence, a 10^4 increase in the number of pulses cannot account for the 1/5 decrease in repetition rate required for achieving large diameter features, showing that a small deviation in the laser repetition rate from the heat diffusion rate has a drastic effect on feature size.

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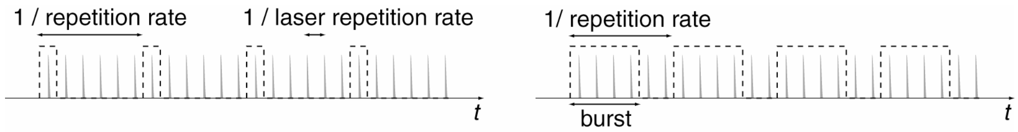

Fig. 2. Changing the laser repetition rate using an acousto-optically driven gate (dashed line). Left: The repetition rate is reduced to 1/6 of the pulse repetition rate. Right: burst of 4 pulses at 1/6 of the pulse repetition rate.

Past work focused on the relationship between single pulse repetition rate and feature size and established the threshold repetition rate for heat accumulation in the focal volume. In this letter, we present data on the heat accumulation caused by bursts of pulses from a laser oscillator at different burst repetition rates. Given the short time interval between the oscillator pulses, we expect a burst of N pulses with energy E per pulse to deposit the same amount of thermal energy as a single pulse of energy NE. However, the energy in a burst of pulses is not delivered in the same manner as a single more energetic pulse. The number of pulses in each burst has a pronounced effect on the minimum repetition rate for which energy accumulates.

Throughout this letter we will call the rate at which the bursts of pulses repeat the ‘repetition rate’ and the intrinsic rate of the laser pulse emission from the oscillator the ‘laser repetition rate’. We report on the dependence of the size of structures in soda lime glass on the repetition rate of bursts of 800-nm, 5.5-nJ femtosecond pulses. From the size of the structures, we infer the combination of repetition rate and number of pulses within a burst for which heat accumulation occurs. We find that the repetition rate threshold for heat accumulation depends on the number of pulses within a burst. We relate this threshold repetition rate to the time interval between bursts for which there is still a sizeable temperature increase (150 ± 50 K) from one burst to another. The repetition rate and the number of pulses within a burst are two additional parameters that can be used to control the size of structures generated with high repetition rate femtosecond laser micromachining.

2. Experimental

A 25-MHz Ti:Sapphire laser oscillator generates the 20-nJ, 60-fs output pulses for the micromachining experiments described below. The laser pulses are focused into the sample using a 1.4 numerical aperture (NA) oil-immersion microscope objective. To deliver a short pulse at the sample, we use a prism compressor to compensate for the dispersion introduced by the microscope objective and other optical elements in the beam path.

We created bursts at various repetition rates by inserting an acousto-optic pulse picker in the beam path. The pulse picker is synchronized with the laser oscillator and gated to select pulses at an externally set repetition rate. Figure 2 illustrates the pulse picking process and defines the repetition rate and laser repetition rate. In Fig. 2(a), one out of six pulses is selected by the electronic gate signal (dashed line), generating a 1-pulse ‘burst’ at 1/6 of the laser repetition rate. Figure 2(b) shows a 4-pulse burst at 1/6 of the laser repetition rate. The repetition rate and the number of pulses within a burst are varied in the experiment while the time between pulses in the burst (40 ns) is determined by the 25-MHz laser repetition rate.

Figure 2 also illustrates the limitation on the maximum number of pulses that can be selected at a given repetition rate. The pulse picker can select n pulses every N pulses, that is, transmit a burst of n pulses at integer divisions of the laser repetition rate: 25/N MHz. Hence the maximum number of pulses within a burst must be smaller than N–1, otherwise all pulses in the original pulse train are transmitted. For example, for bursts at 3.125 MHz (25/8 MHz), the maximum number of pulses inside the burst is 7.

We focused the laser into soda lime glass (72.2% SiO_2, 14.3% Na_2O, 4.3% CaO, 1.2% Al_2O_3 and K_2O and 0.3% S_2O_3), which has a 4-nJ energy threshold for damage at 1.4 NA. We produced arrays of dots with increasing number of bursts at each repetition rate, with each pulse within a burst having an energy of 5.5 nJ. The resulting structures were imaged by transmission optical microscopy to determine their size and shape.

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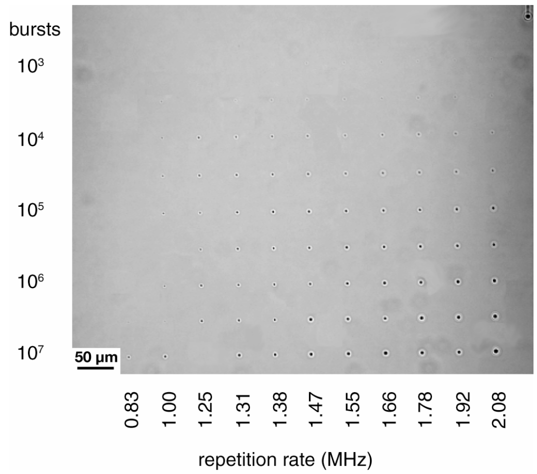

Fig. 3. Transmission optical microscopy image of sodalime glass irradiated with trains of femtosecond pulses, varying the number of bursts per spot and the repetition rate. The number of pulses within a burst is held fixed at 10. At low repetition rate and low number of bursts, the structures created in the sample are of too low contrast to be seen in transmission microscopy. The missing spots at 10^3 and 10^7 bursts, and 1.25 MHz repetition rate are due to an experimental malfunction.

We also generated continuous structures by translating the sample at a constant speed of 1 mm/s with respect to the laser beam, as is done during device fabrication. The speed was maintained by a computer controlled three-axis translation stage. After exposure, the sample was cut and polished, and the end view of the continuous structure was imaged using an optical microscope.

3. Results

Figure 3 shows an optical microscope image illustrating the effect of varying the repetition rate and the number of incident bursts for a 10-pulse burst. The highest repetition rate shown, 2.08 MHz, is very close to the maximum achievable repetition rate for a 10-pulse burst. To image all the features simultaneously, we used a low magnification objective. Under the low magnification used in Fig. 3, the features at low repetition rates and small number of incident bursts are barely visible. Higher magnification optical microscopy, however, confirms that the irradiation alters the structure of the sample.

The structures in Fig. 3 grow sharply in size with increasing number of incident bursts at the higher repetition rates, but the size increase is less pronounced at the lower repetition rates. Below 1.00 MHz, we observe no growth with increasing number of incident bursts.We repeated the procedure used to produce Fig. 3 with 3- and 5-pulse bursts. In each case, we observe a large increase in size with the increasing number of incident bursts at the higher repetition rates. The repetition rate for which growth becomes negligible, however, is different for 3-, 5- and 10-pulse bursts. We quantified our observations by averaging the measured diameter of 10 structures for each repetition rate. Figure 4 shows how the diameter of the structures obtained with a 5-pulse burst depends on repetition rate and number of bursts.

Figure 5 shows the dependence of the diameter of a continuous structure, obtained at a translation speed of 1 mm/s, on the number of pulses in a burst and repetition rate. Note that the same diameter can be obtained with more than one combination of repetition rate and number of pulses inside a burst. For example, both a 10-pulse burst at 1.8 MHz and a 4-pulse burst at 4.2 MHz yield a structure with a 6.5-µm diameter.

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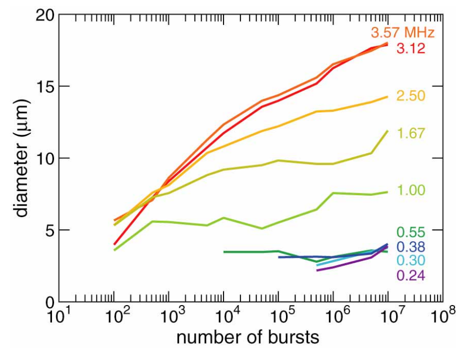

Fig. 4. Diameter of the structures generated at different repetition rates and number of 5-pulse bursts.

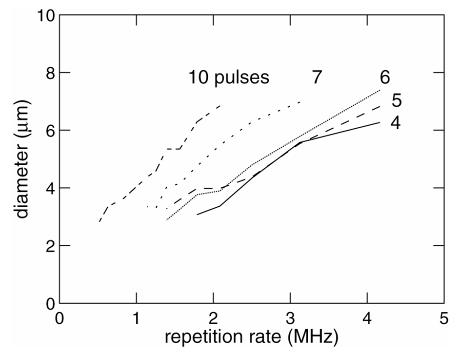

Fig. 5. Diameter of structures generated at a constant translation speed of 1 mm/s for different repetition rates and number of pulses inside a burst. The pulse energy is 5.5 nJ (at the sample).

4. Discussion

As illustrated in Fig. 1, when the time between pulses is short enough, heat accumulates from one pulse to another and the laser acts as a point source of heat within the material. Longer exposure of the sample to the heat source generates a larger affected region. Experimentally heat accumulation manifests itself by the growth of the observed structures with increasing number of incident bursts. We can therefore identify the occurrence of heat accumulation by observing the rate at which the structures grow with increasing number of incidents burst.

For every burst and repetition rate, we determined the rate of growth from plots such as the one shown in Fig. 4. Although the diameter grows at all repetition rates, the small growth observed at the lower repetition rates can be attributed to our measurement technique, which relies on an index contrast observed in an optical microscope. As the number of pulses is increased, a greater fraction of the affected region becomes detectable even though the size of the structure remains the same. For this reason we define the threshold for growth as the repetition rate for which the diameter grows by 1.5 µm over 10^5 bursts.

Each point in Fig. 6 corresponds to a combination of repetition rate and number of pulses inside a burst. The filled circles represent the combinations for which we observe significant growth with increasing incident bursts (*i.e.*, heat accumulation), while the hollow circles represent no growth (i.e., no accumulation).

We modeled the heat diffusion caused by *N*-pulse bursts with a simple expression for thermal diffusion [13-15]. Using room temperature values for the heat capacity, density and heat conductivity, we calculated the temperature increase between consecutive *N*-pulse bursts for various repetition rates assuming 30% absorption [14] of each 5.5-nJ laser pulse. In Fig. 6, the region where there is a temperature rise greater than 200 K is shown in grey and regions with a temperature rise smaller than 100 K in white. The transition between the two regions coincides reasonably well with the observed transition in growth rate indicating that accumulation of heat occurs when the temperature increases by about 150 K between each burst.

Figure 6 shows that the repetition rate above which heat accumulates depends on the number of pulses inside a burst. Previous authors have related the heat accumulation time to the heat diffusion time, which is defined by the time for the heat to be reduced to $1/e$ of its maximum value (1 µs for the glass system in question) [13, 14]. Such a relation, however, would lead to a straight threshold line at 1 MHz, not the curved threshold we observe in Fig. 6. The reason for the curved threshold is that an increase in the number of pulses inside a burst leads to a higher temperature increase after each burst. Consequently, more time is needed for the heat to diffuse out completely, and thus the threshold repetition rate decreases.

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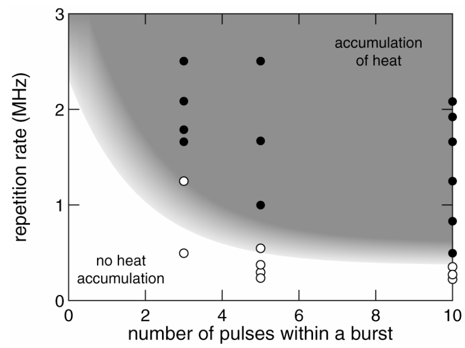

Fig. 6. Boundary between the regions of repetition-rate/pulse-number parameter space where the energy accumulates from pulse to pulse and where pulses act individually. Each 60-fs pulse delivers an energy of 5.5 nJ. Filled circles: the diameter of the structure grows by more than 1.5 μm in 10^5 bursts; open circles: no growth observed. The shaded area delineates the regions where calculations indicate that the temperature at the focus is raised by more then 150 ± 50 K between successive bursts.

Our results for a 1-pulse burst suggest that a repetition rate of at least 1.5 MHz is needed for heat to accumulate, which is not in agreement with the cumulative heating observed with 166-kHz, 1040-nm, 300-fs and 200-kHz, 1040-nm, 375-fs laser systems [15-17]. However, the pulse energies used in those experiments are 270 nJ and 520 nJ, respectively, and the deposited energy (assuming 40% absorption [15]) is significantly higher than in our experiment. When more energy is deposited, heat accumulation occurs at a lower repetition rate, explaining the difference between our results and the observations for amplified systems.

Another interesting feature of micromachining with burst of pulses is shown in Fig. 5. The same waveguide diameter can be achieved with multiple combinations of repetition rate and pulse number. For a set translation speed, the effective number of pulses irradiating a focal spot varies with the repetition rate and the number of pulses within a burst. Reducing the repetition rate by a factor of 2 and doubling the number of pulses within a burst amounts to the same total irradiated fluence. Although these conditions maintain the same total fluence, the sample undergoes a different thermal cycling, which can result in different physical properties, such as the index of refraction. Therefore varying the repetition rate/pulse number combination may provide a means to control the refractive index along the length of a waveguide, while maintaining a constant waveguide diameter.

5. Conclusion

The data on femtosecond laser micromachining in soda lime glass with bursts of pulses at variable repetition rates presented in this paper permit us to identify the combination of repetition rate and number of pulses within a burst for which heat accumulation occurs. The repetition rate threshold for heat accumulation depends on the number of pulses within a burst. We find that this threshold corresponds to the time interval for which the temperature at the focus increases by 150 ± 50 K between successive bursts. The repetition rate and the number of pulses within a burst thus make it possible to control the morphology of structures generated with high repetition-rate femtosecond laser micromachining.

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