Thermal regime of femtosecond writing for a phosphate glass

(Student Paper)

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ABSTRACT

We report on peculiarities of femtosecond writing in phosphate glass at a thermal regime in the sense of two different types of written tracks demonstrated. The operation diagram is shown for a wide range of laser repetition rates (< 2 MHz) and pulse energies (< 400 nJ). In addition, we explain the mechanism of formation of periodic bubble-like structures and present some discussions for a thermal regime in other materials.

Keywords: Femtosecond-laser writing, refractive index, thermal regime, phosphate glass.

INTRODUCTION

Femtosecond (fs) writing is a technology where a refractive index is modified inside optical materials by fs laser pulses that enables technologists to create different kinds of both passive and active photonic devices based on waveguides or grating [1]. There are two regimes of writing [2] - a non-thermal regime, where the material cools down after each pulse and that occurs at low (< 200 kHz) repetition rates (RR), and a thermal regime (TR), where local heat accumulation occurs each pulse at high RR (> 200 kHz), correspondingly. The TR has several advantages [3], which are: (i) transverse section of tracks becomes more circular and larger, (ii) structure of tracks becomes smooth and so provides written waveguides with low losses, and (iii) lower pulse energy (PE) and higher scan speeds can be exploited at TR.

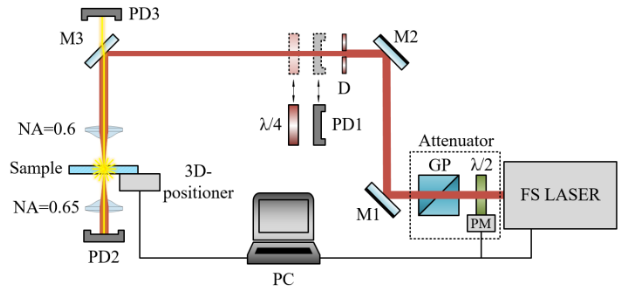

Figure 1. The experimental setup for femtosecond writing and measurement of transmitted laser and plasma glow radiation power

The TR is found experimentally for many materials, including silicate [4, 5], borosilicate [4, 6, and 7], phosphate [4, 8] and chalcogenide [9] glasses, and lithium niobate crystal [10, 11]. The research is limited to the specific RRs and PEs of available lasers. Besides, it is not clear a prior at what value RR it should be aimed. The TR is believed to happen at the RR about 1 MHz [7, 8, 9]. Sometimes it has been achieved it by making use of high-RR (25 MHz) lasers [4, 9] and ultrahigh-RR (80 MHz) oscillators [6]. However, void- or bubbles-like structures have been observed in some materials with increasing the RR instead of usual growth of the transverse section of tracks [4]. The reason for this phenomenon as well as overall picture of the TR is still not fully understood.

In this report, we demonstrate two different types of fs written tracks at TR in phosphate glass for first time to the best of our knowledge. We manage to distinguish tracks without and with internal structure as tracks type A and type B, respectively. The fundamental difference in physical processes is described in terms of operation diagram of the types A and B for a wide range of laser RR (< 2 MHz) and PE (< 400 nJ). A mechanism for the formation of bubble-like structures is proposed as a cyclic transition between the types. Finally, we provide recommendations for an experiment where the RR pertinent to the TR should be found in borosilicate glass, $LiNbO_3$ and Yb:KGW crystals.

1. EXPERIMENTAL DESIGN AND METHODS

The experimental setup for a fs writing is shown in Fig. 1. Yb-fiber laser (Avesta) provided 350-fs pulses at 1040-nm wavelength with a M^2 < 1.2 beam quality. The fundamental RR of the oscillator (2.11 MHz) was divided by a multiple built-up output acousto-optic modulator to lower the RR. The power of laser radiation was attenuated by a system of a half-wave plate on piezo-motor, Glan prism and photodiode PD1. Laser pulses were focused inside a phosphate glass sample (30x15x2 mm) by an aspherical lens (Thorlabs C610TME-C) with a numerical aperture (NA) of 0.6 and compensation of spherical aberrations at a depth of 850 μm. The sample was placed on a three-dimensional automated stage and moved relatively to the focus of the optical system with speed 50 μm/s. The laser polarization was parallel to the scanning direction. The transmitted laser beam was collected by a lens with NA = 0.65 and a photodiode PD2 measured continuously its power. During the experiment, the photodiode PD3 also measured the power of the plasma glow discharge through the lens with NA = 0.6 and dichroic mirror M3.

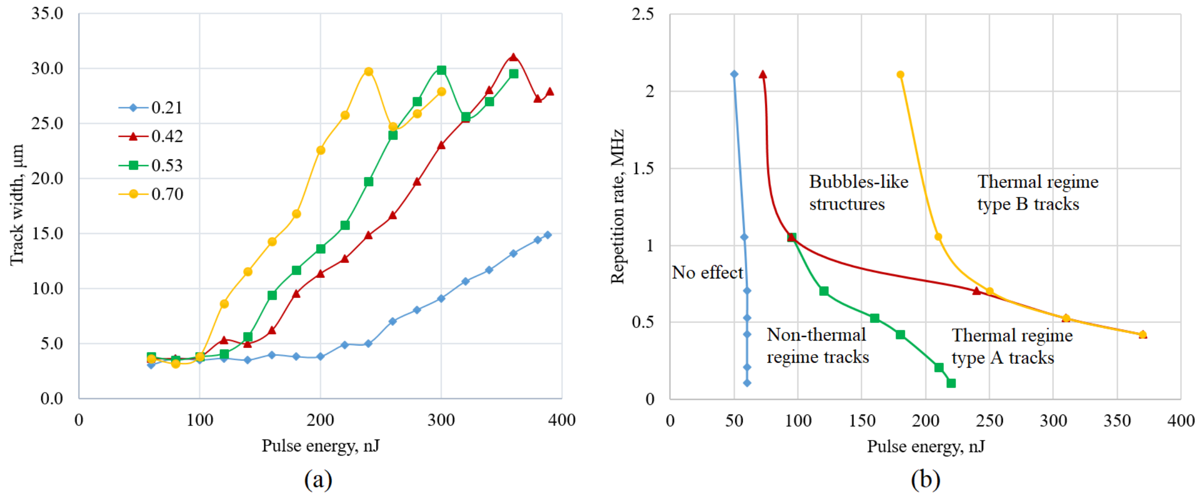

Figure 2. (a) The PE dependence of the track width measured from microscopy images at 0.21, 0.42, 0.53 and 0.70 MHz laser RR; (b) The characteristic diagram of the transition to the TR.

2. RESULTS AND DISCUSSION

For a wide range of the RR (0.11 – 2.11 MHz), series of tracks are produced with the PE ranging from 60 nJ to a maximum of 400 nJ. At a relatively low RR 0.21 - 0.70 MHz, a fracture of monotonic broadening of the track size with a grow in PE is observed. The dependence of the track width on the PE and RR is shown in the plot (Fig. 2a). The fracture can be associated with formation of the secondary structure (not shown here) inside the track, i.e. at a certain frequency, starting with a specific PE, the internal structure of the track changes, and the track size decreases. We distinguish tracks without and with internal structure as tracks type A and type B respectively. There also is a second inner layer observed as the type B. At higher RR 1.06 - 2.11 MHz, the situation looks different. Starting with some energy, void- or bubbles-like structures appear and then change to tracks of the type B. The characteristic diagram of the transition to the TR is shown in Fig. 2b.

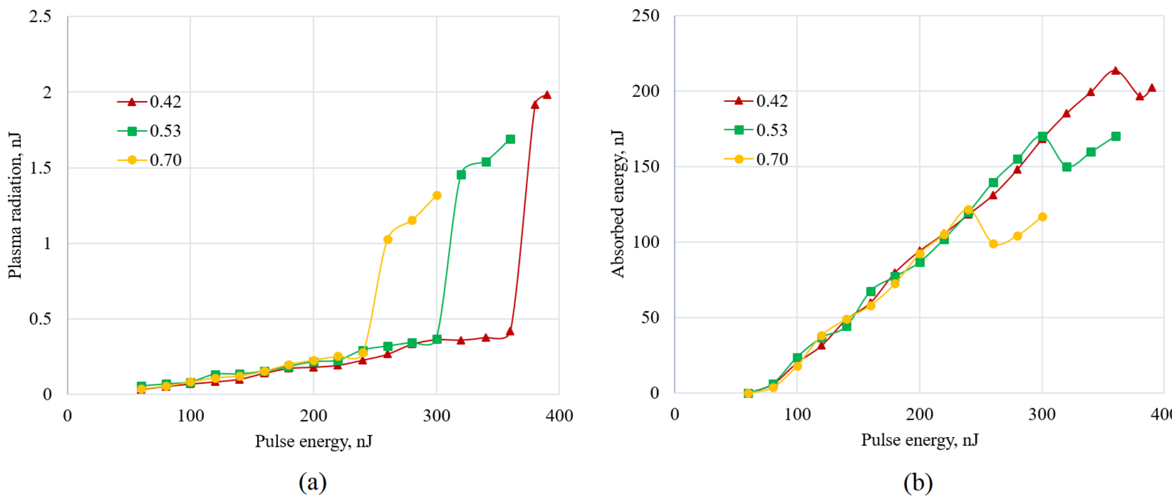

Figure 3. (a) The PE dependence of plasma glow radiation energy (b) and incident PE dependence of absorbed energy at 0.42, 0.53, 0.70 MHz laser frequencies

In order to study and distinguish different types of tracks, we determine the absorbed laser radiation by measuring the transmitted laser radiation during the writing. Since there is also a plasma glow in the focus, we also its radiation power is also measured. It turned out that during the writing tracks of type B, the plasma radiation is sharply increased by about 4 times (Fig. 3a). Totally, this radiation does not exceed 1% of the absorbed energy. The experimental dependence of absorbed energy on initial PE are shown in Fig. 3b, where there are clearly visible signatures in the transition from the type A to type B, i.e. the energy absorption drops drastically when the track type B is being written. That is, it is tempting to suggest from the data observed that the formation of the bubble-like structure is caused by a local temperature grow. It is also tempting to declare that there are three different mechanisms of material heating: (a) simple heating without melting, (b) melting after each laser pulse followed by rapid solidification, (c) a molten state in the focal region, so the energy of the pulse is absorbed in the liquid phase of the material.

The reasons for the absorption energy signature are not fully understood, but we assume it relates to the transition to the TR with a molten state in the focus where the liquid phase absorbs fewer laser power. It may be the case of a plasma defocusing or a change in the width of the band gap. However, the fact that the absorption has a signature, gives a qualitative explanation for the formation of the bubble-like structure. We believe that there is a periodic variation near the phase transition, and the track is obtained between types A and B. Therefore, the material absorbs the laser radiation and heats up, and when the magnitude of the lower temperature curve starts to exceed the melting temperature, the absorption in the liquid phase goes down; the material turns into the solid and starts absorbing more energy, etc. Besides, it is known that the thermal conductivity of the material also increases as the temperature rises up, which leads to faster cooling at higher temperatures.

As we show, there is no stable TR at any randomly chosen frequency. Each material has a convenient RR and PE band for it. For phosphate glass, we determined type A the convenient RR to be 0.4-0.7 MHz. In a similar way, we found for borosilicate glass a band of convenient RR to be 0.5-1.0 MHz. Type A tracks should be sought at the frequency “under” the bubbles-like structures formation RR. For example, in Yb:KGW at a RR of 2 MHz, bubbles start appearing at energy of 150-200 nJ, while at RR of 1 MHz there are no bubbles at the energies up to 400 nJ. Therefore, the TR should be searched around at frequencies around 1.5 MHz. For lithium niobate the broadening of tracks begins at 2 MHz, so the search of the TR should be in the range of RR 3-5 MHz. We noted that there is a correlation between the coefficient of thermal conductivity and RR [12].

The TR writing is extremely important for some applications. It is necessary to clearly define the boundaries of ranges A and B tracks types in order to operate at particular one. Type A tracks show itself as a low loss single- or multimode waveguides [4]. Type B tracks, despite of its inner structure, are useful for the fast writing of high NA depressed cladding waveguides with large mode area, which are used as hybrid laser amplifiers [13].

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