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Femtosecond-induced micostructures in Magnesium- doped Lithium Niobate crystals with high repetition rate

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ABSTRACT

In this paper, heat accumulation effect of MgO: LN crystal irradiated by femtosecond pulses was analyzed by a developed thermal conduction model in terms of the spatial and temporal distribution of the absorbed laser energy. Using the focused femtosecond pulses about 61 fs at 1040 nm with a repetition rate of 52 MHz, ablation morphologies under different exposure time and average power were obtained experimentally. The measured laser-induced damage threshold of X-, Y- and Z-cut MgO: LN crystals are 0.82 mJ/cm^2, 0.74 mJ/cm^2 and 0.76 mJ/cm^2, respectively, and based on the measurement achieved in the Lab the differences in the ablation morphologies were analyzed in detail.

1. Introduction

Femtosecond laser micromachining has recently emerged as one of the most efficient techniques for direct three-dimensional (3D) microfabrication of transparent optical materials [1–5]. Lithium Niobate (LN) crystal is notoriously difficult to etch, some micro-structure fabricating technologies have been proposed, such as focused ion beam milling (FIB) [6], electric field overpoling (EFO) [7]. The benefits of femtosecond laser micromachining are especially pronounced for brittle materials like LN crystal. High repetition rate ultrashort laser pulses cause the heat accumulation effects that mitigate defect-induced damage and avoid collateral damage such as micro crack formation during laser material processing [8]. Heat accumulation effects allow the formation of microstructure in transparent optical materials while a femtosecond laser beam is focused and scanned by controlling the laser beam direction [9–12]. Such internal laser modification of transparent optical materials is highly attractive for fabricating integrated micro-optical devices in novel 3D architectures.

Among a number of transparent optical materials, MgO doped Lithium Niobate (MgO: LN) crystal is one of the most important materials for fabrication of integrated photonic devices such as waveguides, electro-optic and acousto-optic modulators, optical switches, couplers, and second harmonic convertors [13–17]. Because of its large effective nonlinear coefficient and wide transmission range, it allows effective conversion with relatively short structures, which is important for group-velocity-mismatch (GVD) concerns of short-duration pulses. A femtosecond laser as a novel tool for optical processing has been applied extensively. There are unique advantages in favour of femtosecond laser micromachining over other photonic-device fabrication techniques. Unfortunately, this micromachining approach is vulnerable to precise control of the cross-sections. Therefore, a study of characteristics of femtosecond laser-induced microstructure is of great value to micromachining of MgO: LN crystal.

In this paper, an explicit thermal diffusion model to describe the thermal effect of femtosecond laser interaction with MgO: LN crystal was presented, and thermal distribution with spatial and temporal dependence was numerically simulated. The damage areas as a function with increased exposure time and average power were obtained experimentally by using focused femtosecond pulses of 61 fs at 1040 nm with a repetition rate of 52 MHz. The LIDT of X-, Y- and Z-cut MgO: LN crystals were measured, and the differences in the ablation morphologies were analyzed accordingly.

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2. Simulation of thermal effect

Many recent works [18–20] have demonstrated that there are two major regimes of femtosecond pulse laser ablation: non-thermal ablation and thermal ablation. The ablation using low fluence and short pulse width is based on nonthermal ablation, and the long pulse width or high laser fluence is based on thermal ablation. There is a transition between the two regimes influenced by laser fluence associated with the pulse width, and the higher the laser fluence, the shorter the critical pulse width. While the laser fluence is very high, the thermal ablation mechanism will be dominant and the heat effect will be evident. In our experiment, most probable source of the free electrons other than multiphoton ionization for seeding avalanche ionization is the thermally excited free electrons in conduction band, since higher temperature can be attained due to heat accumulation at higher pulse repetition rates [21]. For evaluating the density of the thermally excited free electrons, it is essential to simulate the temperature distribution in the MgO: LN ablation. For this purpose, in terms of the spatial and temporal distribution of the absorbed laser energy, a thermal conduction model was developed.

Assuming the instantaneous heat source $q(x', y', z')$ appears at a repetition rate of f in an infinite solid moving at a constant speed of ν along x-axis, the heat conduction Eq. (1) is established by taking a laser pulse energy as an initial heat source, and initial temperature distribution is given by Eqs. (2) [22]

$$\frac{\partial T}{\partial t} - D\nabla^2 T = 0 \tag{1}$$

$$T(x, y, z, if^{-1}) = \delta\left(t - \frac{i}{f}\right)\frac{A}{c_p\rho}q\left[\left(x + \nu\frac{i}{f}\right), y, z\right] \tag{2}$$

where D is thermal diffusivity, c_p is the specific heat capacity, ρ is the volume mass density, A is the absorptivity of laser energy, i is the number of pulse, and T is the temperature distribution at time t after ablation of i-th pulse. For simplicity, the thermal properties of MgO: LN crystal are assumed to be independent of temperature. The heat diffusion time out of the absorption volume in the MgO: LN crystal is about 1 μs [23]. Therefore, it is reasonable to assume that the absorbed laser energy before 1 μs does not spread out, and all the pulse energy within 1 μs is the initial heat source, and assuming the heat source size is a cube with a side length of 3 μm in the simulation. Assuming the instantaneous heat q is subjected to Gaussian distribution, therefore, the heat source for the i-th pulse can be expressed as follows:

$$q_{i_{th}}(x + v \times if^{-1}, y, z) = q_0 \exp\left[-\frac{2[(x - x' - v \times if^{-1})^2 + (y - y')^2 + (z - z')^2]}{L^2}\right] \tag{3}$$

where q_0 is the maximum absorbed energy. After the irradiation of i-th pulse, the total thermal energy can be expressed by Eq. (4):

$$q(x, y, z) = \sum_{i-1}^{n} \iiint_{\substack{heat\\source}} q_{i_{th}}(x + v \times if^{-1}, y, z)dx'dy'dz' \tag{4}$$

By solving Eqs. (1)–(4), the temperature distribution can be obtained and written as Eq. (5)

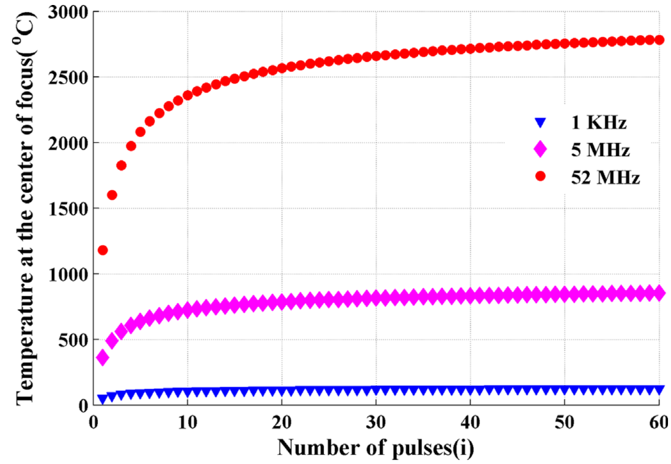

Fig. 1. Relationship between the number of pulses and temperature.

$$T(x, y, z, if^{-1}) = \frac{A}{8c_p\rho}\sum_{i-1}^{n}\iiint_{\substack{heat\\source}} \frac{q_{i_{th}}(x + v \times if^{-1}, y, z)}{(\pi D \times if^{-1})^{3/2}} \exp\left\{\frac{(x - x' - v \times if^{-1})^2 + (y - y')^2 + (z - z')^2}{4D \times if^{-1}}\right\}dx'dy'dz' \tag{5}$$

when $x=y=z=0$ and $\nu=0$, from Eq.(5), the relationship between the temperature at the center of focus and the number of pulses was obtained. The simulation is based on the pulse duration 61 fs, absorptivity $A=65\%$, and single pulse energy 2.5 nJ, which corresponds to the experimental conditions. Fig. 1 shows the thermal effect of femtosecond laser with repetition rates 1 kHz, 5 MHz and 52 MHz, respectively.

From Fig. 1, the temperature at the center of focus increases with the number of pulses, and when the number of pulses increases, the temperature will reach a saturation temperature. However, the value of the equilibrium temperature is determined by the repetition rates. In the case of low repetition rates, such as 1 kHz and 5 MHz, the temperature relaxes to below the working point before the next pulse arrives, which results in a minimal accumulation of heat and the equilibrium temperature are, respectively, 120 °C and 850 °C respectively. However, in the case of 52 MHz repetition rates, the heat accumulation becomes remarkable, and the value of the saturation temperature is higher than 2700 °C. The thermal accumulation leads to a melted volume dependent on the increased pulse number and repetition rate.

3. Experimental configuration

The samples were X-, Y- and Z-cut MgO: LN wafers with a dimension of 10 mm × 10 mm and a thickness of 5 mm, and the surfaces were optically polished and uncoated. The experimental configuration is shown in Fig. 2. The femtosecond laser pulses (1040 nm, 61 fs, 52 MHz) were generated by a large-mode-area photonic-crystal-fiber laser oscillator. A half-wave plate and a PBS

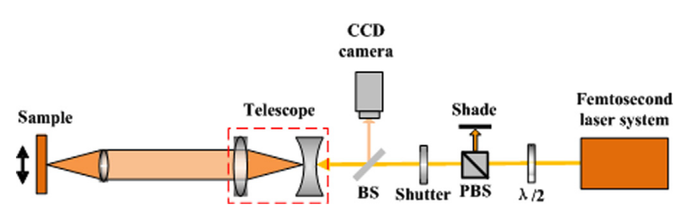

Fig. 2. Experimental setup. BS: beam splitter with a split ratio of 1:9, PBS: polarization beam splitter.