Analysis on the damage threshold of MgO:LiNbO₃ crystals under multiple femtosecond laser pulses

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Abstract

An improved theoretical model of the interaction between multiple femtosecond laser pulses and MgO:LiNbO₃ crystals with different doping concentrations has been established based on the classical two-temperature model. The evolutions of electron and lattice temperature with the duration, the repetition frequency and the numbers of multiple femtosecond laser pulses in MgO:LiNbO₃ crystals have been simulated numerically by the Crank-Nicholson implicit finite-difference method. Furthermore, the variations of the damage threshold of MgO:LiNbO₃ crystals with the parameters of multiple femtosecond laser pulses at different doping concentrations, as well as the influence of doping concentration on damage threshold have also been analyzed. The results show that, the damage threshold of MgO:LiNbO₃ crystals increases with the increasing of the duration of the femtosecond laser pulse. The damage threshold of MgO:LiNbO₃ crystals first decreases with the increasing of the numbers and the pulse repetition frequency of the laser pulses and then tends to be a constant. The damage threshold of a small amount of MgO-doped LiNbO₃ crystals is higher than that of undoped LiNbO₃ crystals. Consequently, the resist damage capability of LiNbO₃ crystals can be enhanced by doping appropriate MgO in many practical applications.

1. Introduction

Because of excellent performance of LiNbO₃ crystals, it has been widely used and become one of the most important multifunctional materials in optical area [1]. However, due to the relatively low damage threshold of LiNbO₃ crystals, it is likely to be damaged under high power laser irradiation. Therefore, the research on the damage mechanism induced by high power laser has become an important subject in the field of laser technology.

On the one hand, in order to explore the damage process of optical materials under laser pulse irradiation, a lot of models studying the interaction between laser pulse and materials such as the two temperature model (TTM) [2], the dual-phase-lag model (DPL) [3], and the hyperbolic two-step radiation heating model [4] have been proposed. By far, although a large number of experimental studies have been performed to determine the damage for multiple laser pulses with high repetition frequency [5–7], the prediction of the damage threshold of LiNbO₃ crystals is still lack of effective theoretical and experimental researches [8–11]. It is thus necessary to study theoretically the interaction between multiple femtosecond laser pulses and LiNbO₃ crystals and analyze the variations of damage threshold of crystals with the femtosecond laser parameters.

On the other hand, it has been widely concerned on how to improve the resist damage capability of LiNbO₃ crystals. In recent years, it has been discovered that the resist damage capability of LiNbO₃ crystals can be improved by doping small amounts of Mg²⁺, Zn²⁺, In³⁺ or other impurity ions into LiNbO₃ crystals [12,13] resulting in expanding the application range of LiNbO₃ crystals in the field of high power laser field. Thus, it is also necessary to research the influences of doping on the damage threshold of LiNbO₃ crystals.

In this paper, based on the classical two-temperature model and taking the effects of electron excitation, carrier absorption, as well as other ionizing procession into account, an improved theoretical model has been built up to study the damage threshold of MgO:LiNbO₃ crystals at different doping concentrations under multiple femtosecond laser pulses. The evolutions of electron and lattice temperature of undoped LiNbO₃ crystals with the damage threshold, the repetition frequency and the numbers of multiple femtosecond pulses.
lasers have been simulated numerically. Moreover, the variations of the damage threshold of MgO:LiNbO3 crystals at different doping concentrations with the parameters of the femtosecond laser pulses have also been analyzed.

2. Theoretical model

2.1. The interaction between femtosecond laser pulse and the crystals

A large number of carriers will be generated by the means of multi-photon and avalanche ionization inside the crystals irradiated by the femtosecond laser pulse in a very short time. Then the carriers’ temperature rises sharply due to the absorption of the photon energy. Because the action of the femtosecond laser pulse is very short, the carriers are unable to transfer photon energy to the lattice timely, which leads to higher electron temperature, whereas the lattice temperature is still relatively low. Then, the electron energy is transferred to the lattice by coupling at the end of pulse, which leads to the rising of the lattice temperature and the dropping of the electron temperature, and the temperature of the electron and lattice eventually reaches at the thermal equilibrium state.

The irreversible damage in the crystals will be caused by the physical processes such as melting, gasification when the thermal equilibrium temperature is higher than the melting point of the crystals. In this paper, it is assumed to the crystal damage criterion that the lattice temperature reaches the melting point T of the crystals. This corresponds to a physical process of interaction between the femtosecond laser pulse and the crystals.

According to the above analysis, the two-temperature coupled equations [14–16] can be used to describe the physical process of the interaction between the femtosecond laser pulse and the crystals, i.e.,

\[
C_e \frac{\partial T_e}{\partial t} = \kappa_e \nabla(\nabla T_e) - \varphi(T_e - T_l) + S
\]

\[
C_l \frac{\partial T_l}{\partial t} = \kappa_l \nabla(\nabla T_l) + \varphi(T_e - T_l)
\]

where \(C_e = 3K_Bn_t/2\) and \(C_l = \rho c_p\) are the heat capacity of the electron and lattice system, respectively. Here \(K_B\) is the Boltzmann constant, \(n_t\) is the free carrier density in crystals, \(\rho\) is the density of material, \(c_p\) is specific heat capacity of unit volume in lattice system. \(T_e\) and \(T_l\) represent electron and lattice temperature, \(\kappa_e\) is the electron heat conductivity, which is given by \(\kappa_e = \frac{3K_B\mu}{2e n_t}\). Here \(\mu\) is the mobility of carrier, \(e\) is the electron charge. \(\kappa_l\) is the lattice heat conductivity. \(\varphi(T_e - T_l)\) is the energy dissipation per unit time per unit volume in electron system and \(\varphi = 3K_Bn_t/2\tau_x\) is the electron-lattice coupling coefficient. Where \(\tau_x\) is the relaxation time constant of the interaction between electron and lattice. \(S\) is the laser source term.

The free carriers in the crystals are produced through ionization process, which can be described by the general expression [17,18],

\[
\frac{\partial n_t}{\partial t} = \frac{\partial n_t}{\partial t}_{mp} + \eta_{ava} n_t - \eta_{rec} n_t^2
\]

where \(\eta_{ava}\) and \(\eta_{rec}\) are avalanche ionization rate, diffusion rate and recombination rate, respectively. The first term on the right side comes from the multiphoton ionization mechanism. The second term is from the avalanche ionization mechanism. The remaining terms account for the diffusion of electrons out of the focal volume and for the recombination losses of electrons and lattice.

For the multiphoton ionization rate in Eq. (3), we use an expression based on Keldysh’s model [19].

\[
\left( \frac{\partial n_t}{\partial t} \right)_{mp} = \frac{2\omega}{9\pi} \left( \frac{\omega m^*}{\hbar} \right)^{1/2} \left[ 16\pi e^2 \omega^2 C_0 n_t \right]^k \exp(2k) \Phi \left( \sqrt{2k - \frac{2E_g}{\hbar\omega}} \right)
\]

where \(\omega\) is the laser frequency, \(m^*\) is the effective reduced electron-hole mass, \(\hbar\) is Planck constant, \(E_g\) is the band gap energy, \(c\) and \(v_0\) are the speed of light and absolute dielectric constant in vacuum, respectively. \(n_t\) is the refractivity, \(I\) is the intensity of laser pulse, \(k = (E_g/(\hbar\omega)+1)\) with \((x+1)\) denoting the integer part of the number \(x+1\). In addition, \(I\) and \(\Phi(z)\) are given by

\[
\begin{aligned}
I &= I_0 \exp \left[ -4 \log(2) \left( \frac{t - 1.5\tau}{\tau} \right)^2 \right] \\
\Phi(z) &= \int_0^z \exp \left( y^2 - z^2 \right) dy
\end{aligned}
\]

where \(I_0\) is the peak intensity of Gaussian pulse, \(\tau\) is the duration of the femtosecond laser pulse, \(\Phi(z)\) is Dawson integral.

The avalanche ionization rate \(\eta_{ava}\) in Eq. (3) can be expressed by

\[
\eta_{ava} = \frac{1}{\omega^2 \tau_x^2 + 1} \left( \frac{e^2 \tau_x I}{\epsilon n_t m^* E_g} - \frac{m^* \omega^2 \tau_x^2}{M} \right)
\]

where \(M\) is the molecular mass.

The diffusion rate \(g\) is given by the following expression

\[
g = \frac{\tau_x E_g}{3m^*} \left[ \left( \frac{2.4}{w_0^2} \right)^2 + \left( \frac{1}{z_r} \right)^2 \right]
\]

where \(w_0\) is the radius of beam waist, \(z_r = \pi w_0^2/(\lambda/n)\) is the Rayleigh length with \(\lambda\) denoting the center wavelength of incident laser.

The recombination rate \(\eta_{rec}\) is taken to be \(2 \times 10^{-9}\, \text{cm}^3/\text{s}\) [17].

The laser source term \(S\) can be expressed by

\[
S = (1 - R) \alpha \exp(-\alpha z) I
\]

where \(R\) is the surface reflectance of crystal materials, \(z\) is the direction of the incident laser, \(\alpha\) is the free carrier absorption coefficient in crystals and can be given by the following equation [20].

\[
\alpha = \frac{e^2 \tau_x n_t}{4\pi^2 \epsilon_0 c \tau^2 \lambda^2 \mu}
\]

where \(\mu\) is the mobility of carrier.

For simplicity, we assumed that the crystals are irradiated by vertically incident femtosecond laser pulse along the x direction, and there is no other magnetic field effect. Consequently, Eqs. (1) and (2) can be simplified into a one-dimensional two-temperature equation, i.e.,

\[
C_e \frac{\partial T_e}{\partial x} = \kappa_e \frac{\partial}{\partial x} \left( \frac{\partial T_e}{\partial x} \right) + S - \varphi(T_e - T_l)
\]

\[
C_l \frac{\partial T_l}{\partial x} = \kappa_l \frac{\partial}{\partial x} \left( \frac{\partial T_l}{\partial x} \right) + \varphi(T_e - T_l)
\]
The one-dimensional two-temperature equations are solved numerically by the Crank-Nicholson implicit finite-difference method [21] with initial and boundary conditions. The difference scheme is given by

\[
\frac{T_{e,j}^n - T_{e,j-1}^n}{\Delta t} = k_e \left( \frac{T_{e,j+1}^n - 2T_{e,j}^n + T_{e,j-1}^n}{\Delta x^2} + \alpha(t)\Delta x \exp[-4 \log(2) (\frac{j-1}{\Delta t} - 1.5 \tau)^2] \right)
\]

\[
\frac{T_{l,j}^n - T_{l,j-1}^n}{\Delta t} = k_l \left( \frac{T_{l,j+1}^n - 2T_{l,j}^n + T_{l,j-1}^n}{\Delta x^2} \right)
\]

(12)

(13)

where \(\Delta x\) and \(\Delta t\) refer to the step of space and time, respectively, \(i\) and \(j\) denote the \(i\)th space and the \(j\)th time. For clarity, the equations can be further written as

\[
\left(\frac{2}{r_e + 2}\right)T_{e,j}^n - T_{e,j-1}^n + T_{e,j-1}^n = \left(\frac{2}{r_e + 2}\right)T_{e,j}^n + T_{e,j+1}^n + T_{e,j-1}^n
\]

\[
2\Delta t\alpha(1-R)\exp(-\alpha(i-1)\Delta x)\exp[-4 \log(2) (\frac{j-1}{\Delta t} - 1.5 \tau)^2] r_eC_e
\]

\[
+ \frac{2\Delta t\alpha(1-R)\exp(-\alpha(i-1)\Delta x)\exp[-4 \log(2) (\frac{j-1}{\Delta t} - 1.5 \tau)^2]}{r_eC_e}
\]

(14)

\[
\left(\frac{2}{r_l + 2}\right)T_{l,j}^n - T_{l,j-1}^n + T_{l,j-1}^n = \left(\frac{2}{r_l + 2}\right)T_{l,j}^n + T_{l,j+1}^n + T_{l,j-1}^n
\]

\[
+ \left(\frac{2\Delta t\alpha}{r_lC_l}\right) \left(\frac{T_{l,j}^n - T_{l,j-1}^n}{\Delta x} \right)
\]

(15)

where \(r_e = k_e \Delta t/(C_e \Delta x^2)\) and \(r_l = k_l \Delta t/(C_l \Delta x^2)\).

Additionally, the initial temperature of the crystal surface is assumed to be the ambient temperature \(T_0\), the space and time are divided into \(N\) and \(NN\) points, respectively.

Initial conditions: \(T_{e,1}^0 = T_0, \ T_{l,1}^0 = T_0\ i = (1, 2, 3, \cdots N)\)

(16)

Initial boundary conditions: \(\frac{C}{\Delta x} (T_{e,j}^n - T_{e,j+1}^n) = 0, \ \frac{C}{\Delta x} (T_{l,j}^n - T_{l,j+1}^n) = 0\ j = (1, 2, 3, \cdots NN)\)

(17)

Terminal boundary conditions: \(T_{e,NN}^n = T_0, \ T_{l,NN}^n = T_0\)

(18)

2.2. The interaction between multiple femtosecond laser pulses and the crystals

The interaction between multiple femtosecond laser pulses and the crystals is not a simple repetition for laser pulse. The carrier density and electron and lattice temperature at the end of the previous pulse cycle is used as that at the beginning of the next pulse cycle and so on. The whole process can be expressed by

\[n_i(n_{\text{pulse}}(j = 1) = n_i(n_{\text{pulse}} - 1)(j = NN)\]

(19)

\[T_{e,\text{pulse}}(x = i, j = 1) = T_{e,\text{pulse}}(x = i, j = NN)\]

(20)

\[T_{l,\text{pulse}}(x = i, j = 1) = T_{l,\text{pulse}}(x = i, j = NN)\]

(21)

where \(n_{\text{pulse}}\) represents the \(n\)th laser pulse.

3. Results and discussion

Based on the above theoretical model, the damage threshold of the MgO:LiNbO₃ crystals with different doping concentrations has been studied theoretically. The center wavelength of the incident laser is 800 nm and the main physical parameters of the MgO:-

LiNbO₃ crystals are listed in Table 1.

Fig. 1 shows the electron and lattice temperature distributions of the undoped LiNbO₃ crystals under the femtosecond laser pulse. The incident laser intensity is 1.5 J/cm² and the duration of laser pulse is 100 fs. In order to clearly reveal the distributions of the electron and the lattice temperature, we just show the temperature distribution in 20 ps (shorter than the cycle of laser pulses).

It is shown from Fig. 1 that the temperature of the electron and lattice in the LiNbO₃ crystals decreases gradually with the increasing of the depth. As a result, the temperature of the electron and lattice is the highest on the surface of the crystals (Depth = 0). Thus, it is regarded as the damage criterion that the lattice temperature on the surface of the crystals reaches the melting point of the crystals.

Because the improved two-temperature model takes into account the effects of electron excitation, carrier absorption, as well as other ionizing processes, we further present the variations of the carrier density (a) as well as electron and lattice temperature (b) in undoped LiNbO₃ crystals under femtosecond laser pulse with the time in Fig. 2. The duration of femtosecond laser pulse is 100fs and the incident laser intensity is 1.5 J/cm².

We can see from Fig. 2 (a) that, the carrier density in undoped LiNbO₃ crystals initially increases slowly and then sharply increases when it reaches above \(-10^{17}\) cm⁻³. Meanwhile, the evolutions of electron temperature are similar to that of carrier density in Fig. 2 (b), indicating that the electron temperature is directly affected by the carrier density due to the connection of the electron heat capacity \(C_e\) and the electron heat conductivity \(k_e\) to the carrier density according to Eq. (1). However, the lattice temperature almost remains unchanged firstly because the electron can hardly transfer energy to the lattice in very short time and then it starts to rise because the electron energy is transferred to the lattice by coupling. Therefore, the improved two-temperature model well describes the dynamic process of evolutions of the carrier density and temperature in LiNbO₃ crystals and it can be used for MgO: LiNbO₃ crystal with the increasing of the carrier density.

3.1. The effect of pulse duration on damage threshold

Fig. 3 presents the evolutions of the temperatures of the electron and the lattice in undoped LiNbO₃ crystals under multiple femtosecond laser pulses with different pulse durations. The incident laser intensity is 0.8 J/cm². The numbers and the repetition frequency of the laser pulse are 5 and 1 kHz, respectively.

As shown in Fig. 3 (a) and (c), the maximum values of the electron and lattice temperature for each laser pulses at 40fs are
larger than that at 200 fs. The reason is that, the peak intensity of the laser pulse increases with the decreasing laser pulse duration for a given laser intensity. Thus, the temperature can rise when the duration of the incident laser decreases. The evolutions of the electron and lattice temperature with time under the first femtosecond laser pulse are also shown in Fig. 3(b) and (d) in order to more clearly analyze the variations of the electron and lattice temperature. We can see that the electron temperature rises sharply whereas the lattice temperature changes slightly at first, and then the electron temperature drops rapidly whereas the lattice temperature rises slowly due to the electron-lattice coupling. Finally, the temperature of the electron and lattice reaches the thermal equilibrium state and drops gradually when the time further increases.

Fig. 4 further gives the variations of the damage threshold of the MgO:LiNbO3 crystals at different doping concentrations with the duration of the multiple femtosecond laser pulses. Fig. 4 indicates that the damage threshold of the MgO:LiNbO3 crystals at the different doping concentrations almost linearly increases with the increasing of the duration of multiple femtosecond laser pulses. Moreover, the damage threshold of the MgO(0.5 mol %): LiNbO3 crystals is significantly higher than that of the MgO(0 mol %): LiNbO3 crystals under multiple femtosecond laser pulses for a given laser pulse duration. For example, the damage threshold of the MgO(0.5 mol %): LiNbO3 crystals is 1.63 J/cm² for the pulse duration at 40 fs. The reason is that the carrier mobility in the crystals increases after doping a small amount of MgO into the LiNbO3 crystals and the free carrier absorption coefficient in the crystals decreases with the increasing of the carrier mobility according to Eq. (9), which leads to weakness of the absorption ability of the crystals for the energy of the incident laser pulses. Consequently, the MgO(0.5 mol %): LiNbO3 crystals require higher laser energy to reach the melting point of the crystal than the undoped LiNbO3 crystals at the same pulse duration.

### Table 1

<table>
<thead>
<tr>
<th>Crystals</th>
<th>cp (J Kg⁻¹ K⁻¹)</th>
<th>ρ (Kg m⁻³)</th>
<th>κ (W m⁻¹ K⁻¹)</th>
<th>τ (ps)</th>
<th>T (K)</th>
<th>n</th>
<th>R</th>
<th>μ (cm² V⁻¹ s⁻¹)</th>
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<tbody>
<tr>
<td>MgO (0 mol%): LiNbO3</td>
<td>648</td>
<td>4630</td>
<td>4.6</td>
<td>1</td>
<td>1530</td>
<td>2.257</td>
<td>0.149</td>
<td>0.8</td>
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<tr>
<td>MgO (0.5 mol%): LiNbO3</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30.6</td>
</tr>
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</table>

**Fig. 1.** The electron (a) and lattice (b) temperature distributions in space-time domain of undoped the LiNbO3 crystals under the femtosecond laser pulse.

**Fig. 2.** Variations of the carrier density (a) and electron and lattice temperature (b) in undoped LiNbO3 crystals under femtosecond laser pulse with the time.

3.2. The effect of pulse repetition frequency on damage threshold

Fig. 5 depicts the variations of the electron and lattice temperature in the undoped LiNbO3 crystals with the repetition frequency of the incident laser pulse. The laser energy intensity is 0.8 J/cm². The numbers and the duration of the laser pulse are 5 and 40 fs, respectively.

It can be seen from Fig. 5 that the maximum of the lattice temperature in the undoped LiNbO3 crystals increases with the increasing of the pulse repetition frequency during each laser pulse cycle starting with the second pulse, whereas the maximum of the electron temperature is almost the same. For example, the maxima of the electron and lattice temperature in the second laser pulse cycle in Fig. 5 are 7.68 x 10⁵ K and 3204 K when the pulse repetition...
frequency is 1 kHz, whereas the maxima of electron and lattice temperature are 7.68 × 10^5 K and 3223 K when it is 2 kHz. The cycle of laser pulses decreases with the increasing repetition frequency of laser pulses, which leads to weakness of the lattice temperature attenuation for the repetitive laser pulses with relatively short cycle. Thus, the temperature of the lattice increases with the increasing of the pulse repetition frequency when the crystals are irradiated by the next pulse. Additionally, it is worth noting in Fig. 5(b) that, the maximal lattice temperature of the next pulse is higher than that of the previous pulse. The reason is that there exists the energy accumulation effect in the crystals irradiated by multiple femtosecond laser pulses. Moreover, the energy cumulative effect becomes more obvious with the increasing of the pulse repetition frequency.

The damage threshold of the crystals is related to the maximal lattice temperature, but the maximal lattice temperature varies frequency is 1 kHz, whereas the maxima of electron and lattice temperature are 7.68 × 10^5 K and 3223 K when it is 2 kHz. The cycle of laser pulses decreases with the increasing repetition frequency of laser pulses, which leads to weakness of the lattice temperature attenuation for the repetitive laser pulses with relatively short cycle. Thus, the temperature of the lattice increases with the increasing of the pulse repetition frequency when the crystals are irradiated by the next pulse. Additionally, it is worth noting in Fig. 5(b) that, the maximal lattice temperature of the next pulse is higher than that of the previous pulse. The reason is that there exists the energy accumulation effect in the crystals irradiated by multiple femtosecond laser pulses. Moreover, the energy cumulative effect becomes more obvious with the increasing of the pulse repetition frequency.

The damage threshold of the crystals is related to the maximal lattice temperature, but the maximal lattice temperature varies
with the repetition frequency of laser pulse. Thus, the variations of the damage threshold of MgO:LiNbO3 crystals at different doping concentrations with the repetition frequency of femtosecond laser pulse are further given in Fig. 6.

As shown in Fig. 6, the damage threshold of the MgO:LiNbO3 crystals at different doping concentrations firstly decreases with the increasing of the pulse repetition frequency and then almost tends to a constant with the further increasing of the pulse repetition frequency. The main reason is that the cycle of the laser pulses decreases with the increasing of the repetition frequency, which leads to the increase of the lattice temperature at the end of the each laser pulse. Consequently, the lattice temperature of the next pulse will increase on the basis of the lattice temperature at the end of the previous pulse and it is easy to reach the melting point of the crystals. Therefore, the higher repetitive laser pulses require less incident laser energy when lattice temperature reaches the melting point of the crystals.

3.3. The effect of pulse number on damage threshold

The energy accumulation effect of multiple laser pulses is not only related to the repetition frequency of the incident laser pulses, but also to the numbers of laser pulses. Fig. 7 gives the evolutions of the electron and lattice temperature in undoped LiNbO3 crystals with the numbers of the incident femtosecond laser pulses. The incident laser energy intensity is 0.8 J/cm², the pulse repetition frequency is 1 kHz and the pulse duration is 40 fs.

We can see from Fig. 7 (a) that, the maximal electron temperature keeps almost the same with the increasing of the numbers of the laser pulses, whereas the maximal lattice temperature rises rapidly and then approaches almost a constant with the increasing

of the pulse numbers in Fig. 7 (b).

Furthermore, the variations of the damage threshold of the MgO:LiNbO3 crystals at different doping concentrations with the numbers of multiple femtosecond laser pulses are plotted in Fig. 8.

It can be described in terms of two major processes in Fig. 8: (i) firstly, the damage threshold of the MgO:LiNbO3 crystals at different doping concentrations sharply declines with the increasing of the pulse numbers because of the energy cumulative effect of multiple laser pulses; (ii) then, it slowly drops and eventually almost tends to be a constant with the further increasing of the pulse numbers. For example, the damage threshold of the undoped LiNbO3 crystals under about 30 femtosecond laser pulses is 0.48 J/cm² for the pulse duration at 40 fs, which is in agreement with the experimental results and theoretical data in Ref. [9]. And the damage threshold of the MgO(0.5 mol%):LiNbO3 crystals under about 30 femtosecond laser pulses is 1.46 J/cm². The reason for the two major processes is that the heat conduction is strengthened with the increasing of the total duration of laser pulses, whereas the energy cumulative effect is weakened, which inhibits the further decline of damage threshold.

4. Summary

A theoretical model of the interaction between multiple femtosecond laser pulses and the MgO:LiNbO3 crystals at different doping concentrations has been established, in which the effects of electron excitation, carrier absorption and other ionizing process are coupled into the classical two-temperature model. The effects of multiple femtosecond laser pulses parameters on the damage threshold have been analyzed numerically by the Crank-Nicholson implicit finite-difference method based on damage criterion. The
main conclusions are obtained as following: (i) The damage threshold of the MgO:LiNbO3 crystals at different doping concentrations increases with the increasing of the duration of the multiple femtosecond laser pulses; (ii) The damage threshold of MgO:LiNbO3 crystals declines rapidly with the increasing of the repetition frequency and the numbers of the multiple femtosecond laser pulses at first, then decreases slowly and finally tends to a constant; (iii) The damage threshold of MgO-doped LiNbO3 crystals is higher than undoped LiNbO3 crystals.

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References