Front. Optoelectron. China 2011, 4(4): 387–392
DOI 10.1007/s12200-011-0213-2

RESEARCH ARTICLE

Threshold gain properties of lasing modes in ID disordered media optically pumped by femtosecond-lasing pulse

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Abstract By numerically solving Maxwell's equations and rate equations, a comprehensive calculation on spectrum intensity and spectral widths of three localized modes via different pumping rates in one-dimensional (1D) disordered medium is investigated, in which pumping rate is described by a time function with duration of 80 fs. The spectral intensities varying with the peak value of femtosecond (fs) pumping pulse are calculated in the same disordered medium, and the calculated spectral intensities are compared with those with fixed pumping (simulation time is 6 ps). These results show that excited modes with fs pulse pumping rates are only slightly different from those with fixed pumping (picosecond (ps) pulse), which suggests the excited modes largely depend on the medium rather than the pumping rate at least for those of which pumping rates are fs and ps. At last, lifetimes of three excited modes are calculated. It is found that there is a certain corresponding relation between the mode's lifetime and its threshold-pumping rate, which is the longer lifetime with lower threshold.

Keywords one-dimensional (1D) disordered medium, lasing pumping rates, localized modes

1 Introduction

Random lasers in various strongly and weakly scattering disordered medium with optical gain, were first theoretically predicted by Letokhov in the late 1960s [1] and were further experimentally observed by Lawandy et al. in 1994 [2], random lasers are well illustrated with a time dependent theory to perform a lasing numerical simulation in localized modes [1–11]. By this theory, many properties of random lasers have been investigated. Previous works had mainly focused on random lasers with a fixed pumping rate, in which all random lasers were pumped with a lasing pulse, while pumping rate was usually considered as a fixed value in the whole process of numerical simulations. Because the duration of the simulating time was usually a few picoseconds (pss), a fixed pumping rate may be available for the pumping pulse emitted from a nanosecond (ns) or ps laser, but it could be not adequate for the pumping pulse emitted from a femtosecond (fs) laser. Much information for random lasing could be lost in the simulations, especially in the case of fs pumping. Moreover, threshold gain behavior is very improtant subject for conventional lasers. Therefore, threshold gain properties of lasing modes in one-dimensional (1D) disordered media optically pumped by fs-lasing pulse are investigated here.

In this work, threshold gain behavior of random lasers is calculated in 1D random medium pumped by an 80 fs pulse. In order to be compared with fixed pumping, the spectral intensity varying with the peak value of fs pulse pumping is calculated at the same disordered medium structure, and the simulation time of the system is 6 ps. Therefore, the fixed pumping denotes ps pulse in our simulation. The calculated results show that the excited modes between the fs pulse and fixed pumping (ps pulse) are only slightly different, which suggest that excited modes cannot be determined by the duration of pumping. To further explore the physical nature of excited modes for random lasers, the modes' lifetimes have been calculated.

Received January 25, 2011; accepted March 26, 2011

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The results indicate that there exists a certain correspondence between the mode's threshold pumping rate and its lifetime, and the lower the threshold is with the longer lifetime. Our works enrich the knowledge in case of short pulse pumping, as well as offer more guidance for relevant experiments.

2 Theoretical model

Binary layers of the system are consisted of two dielectric materials, as shown in Fig. 1. White layer simulates the air, which is characterized by a random variable thickness a_n and a dielectric constant $\varepsilon_1 = \varepsilon_0$, while black layer with a fixed thickness b = 300 nm and a dielectric constant $\varepsilon_2 = 4\varepsilon_0$ simulates the scatters that are also a gain media with a four-level atomic system. The random variable a_n is described as $a_n = a(1 + w\gamma)$, where a = 180 nm, w is the strength of randomness, and γ is a random value in the range $[-0.5, 0.5]$.

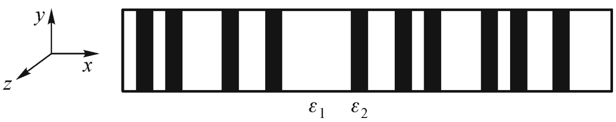

Fig. 1 Schematic illustration of 1D random medium

For the 1D time-dependent Maxwell equations and an active and non-magnetic medium, we have

$$\frac{\partial H_y}{\partial x} = \varepsilon_0 \varepsilon_i \frac{\partial E_z}{\partial t} + \frac{\partial P_z}{\partial t}, \quad (i = 1,2), \tag{1a}$$

$$\frac{\partial E_z}{\partial x} = \mu_0 \frac{\partial H_y}{\partial t}, \tag{1b}$$

where P_z is a polarization density component in z direction, ε_0 and μ_0 are the electric permittivity and the magnetic permeability of vacuum, respectively.

For the four-level atomic system, the rate equations read

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = \frac{N_2}{\tau_{21}} - W_\mathrm{p}(t)N_1, \tag{2a}$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - \frac{E_z}{\hbar\,\omega_l} \cdot \frac{\mathrm{d}P}{\mathrm{d}t}, \tag{2b}$$

$$\frac{\mathrm{d}N_3}{\mathrm{d}t} = \frac{N_4}{\tau_{43}} - \frac{N_3}{\tau_{32}} + \frac{E_z}{\hbar\,\omega_l} \cdot \frac{\mathrm{d}P}{\mathrm{d}t}, \tag{2c}$$

$$\frac{\mathrm{d}N_4}{\mathrm{d}t} = -\frac{N_4}{\tau_{43}} + W_\mathrm{p}(t)N_1. \tag{2d}$$

Set particle population in unit volume of each level is N_4, N_3, N_2 and N_1 individually. The pumping rate from E_1 to E_4 is W_p; the particles arrive and E_4 transfer to E_3 quickly in the form of radiationless transition, the factor of probability is $1/\tau_{43}$. Before the population inverse, E_3 transfer to E_2 quickly in the form of spontaneous activity emission, the factor of probability is $1/\tau_{32}$. E_2 transfer to E_1 mostly in the form of spontaneous activity emission, the factor of probability is $1/\tau_{21}$.

The polarization obeys the following equation:

$$\frac{\mathrm{d}^2 P}{\mathrm{d}t^2} + \Delta\omega_l \frac{\mathrm{d}P}{\mathrm{d}t} + \omega_l^2 P = \kappa \Delta N E_z. \tag{3}$$

This equation links Maxwell's equations with rate equations. $\Delta N = N_2 - N_3$ is the population difference density between the populations in the lower and upper levels of the atomic transition. Amplification takes place when external pumping mechanism produces population inversion $\Delta N < 0$. The linewidth of atomic transition is $\Delta\omega_l = 1/\tau_{32} + 2/T_2$ where collision time T_2 is usually much smaller than lifetime τ_{32}. The constant κ is given by $\kappa = 6\pi\varepsilon_0 c^3/(\omega_l^2 \tau_{32})$.

The pumping rate W_p(t) is

$$W_\mathrm{p}(t) = W_\mathrm{peak} \exp\left(-\frac{4(t-t_0)^2}{\tau^2}\right), \tag{4}$$

where W_peak is the peak value of the pumping, τ is the width of the pumping, t_0 is the time corresponding to the peak value, as shown in Fig. 2. In our simulations, τ and t_0 are set to 80 and 200 fs for all conditions, respectively.

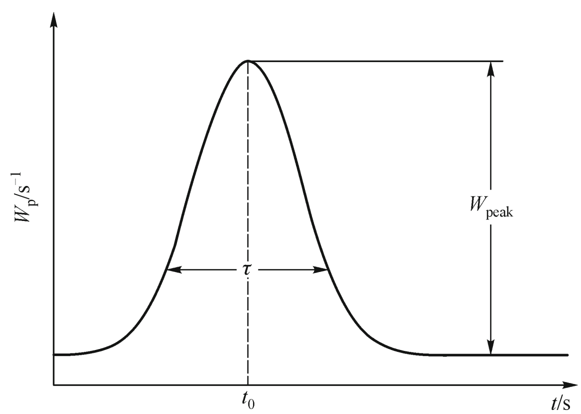

Fig. 2 Illustration of pumping process with time

The values of those parameters in the above equations that will be used in simulating the active part in the following numerical calculations, and they are respectively taken as:

$$T_2 = 2.18 \times 10^{-14}\ \mathrm{s},\ \tau_{32} = 1 \times 10^{-8}\ \mathrm{s},$$

$$\tau_{21} = 5 \times 10^{-12}\ \mathrm{s},\ \tau_{43} = 1 \times 10^{-13}\ \mathrm{s},$$

and

$$N_T = \sum_{i=1}^{4} N_i = 3.313 \times 10^{24}\mathrm{m}^{-3}.$$

When pumping is provided over the whole system, the electromagnetic fields can be calculated. In order to model such an open system, a Liao absorbing layer [11] is used to absorb outward wave. The space and time increments have been chosen to be $\Delta x = 1\times10^{-8}$ m and $\Delta t < \Delta x/(2c)$, where Δt is taken to be 1.67×10^{-17} s, respectively. The pulse response is recorded during a time window of length T_w = 6 ps at all nodes in the system and Fourier transform is used to obtain an intensity spectrum.

3 Calculation and discussion

Analysis with calculating the spectral intensity varying with the peak value of fs pulse pumping was carried out. Three long-life modes indicated by their central wavelengths λ_0, λ_1 and λ_2 are marked, respectively, while their spectral peak intensities are tracked and their threshold gain properties under different peak values of fs pumping pulse are analyzed. The duration of the pumping pulse is set to τ = 80 fs for all conditions. As seen from Fig. 3(a), when the peak value of the pumping rate is quite low ($W_p = 1\times10^{10}\ \mathrm{s}^{-1}$), there are many discrete peaks, peak intensity of each peak is weak and the ordering of peak intensity is as same as that of spectral intensity. Note that each peak corresponds to a lasing mode supported by the disordered medium. With the peak value of the pumping rate increasing to a special value ($W_p = 1\times10^{11}\ \mathrm{s}^{-1}$), the spectral intensity of mode λ_0 in Fig. 3(b) is stronger than that in Fig. 3(a) about two orders of magnitude, indicating that only the mode λ_0 is effectively amplified and dominates the

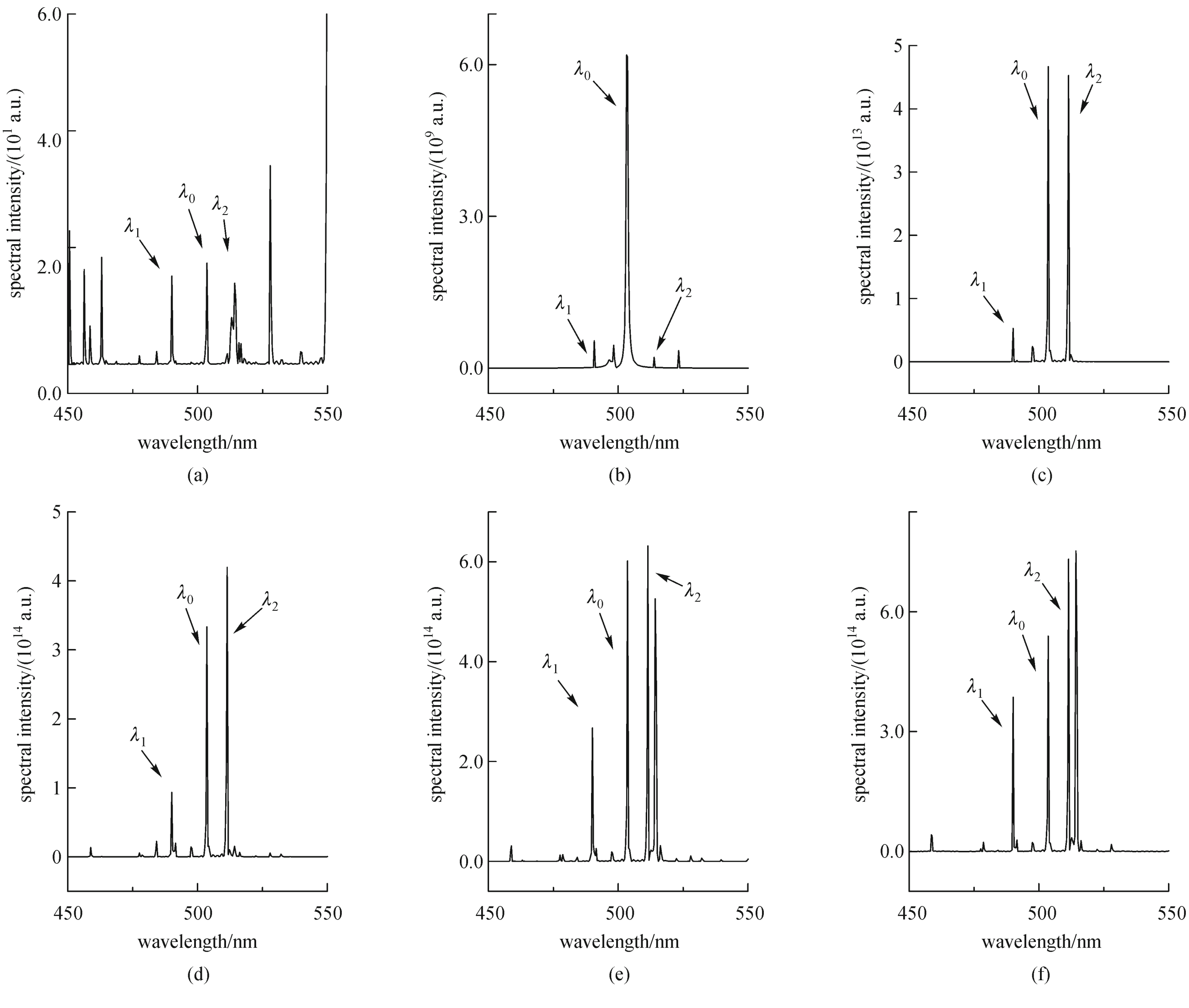

Fig. 3 Intensity spectrum in arbitrary units versus the wavelength for 1D disordered medium shown in Fig. 1 at (a) $W_p = 1\times10^{10}\ \mathrm{s}^{-1}$; (b) $W_p = 1\times10^{11}\ \mathrm{s}^{-1}$; (c) $W_p = 1\times10^{12}\ \mathrm{s}^{-1}$; (d) $W_p = 1\times10^{13}\ \mathrm{s}^{-1}$; (e) $W_p = 1\times10^{14}\ \mathrm{s}^{-1}$; (f) $W_p = 1\times10^{15}\ \mathrm{s}^{-1}$

whole spectrum. It is worth noticing that the spectral width of the mode λ_0 becomes quite larger at $W_p = 1\times10^{11}\ s^{-1}$ than that at lower W_p ($W_p = 1\times10^{10}\ s^{-1}$). When the pumping rate further increases, accompanied by the increase of the peak intensity and the decrease of the spectral width for the mode λ_0, but the spectral widths of the modes λ_1 and λ_2 become larger than those at lower W_p, as shown in Figs. 3(c) and 3(d). As the pumping rate increases farther, due to mode competition more modes are excited, as shown in Figs. 3(e) and 3(f). The intensities and widths of the three modes finally reach to their stable values as the pump rate increases greatly as well as another mode also is excited, as shown in Fig. 3(f).

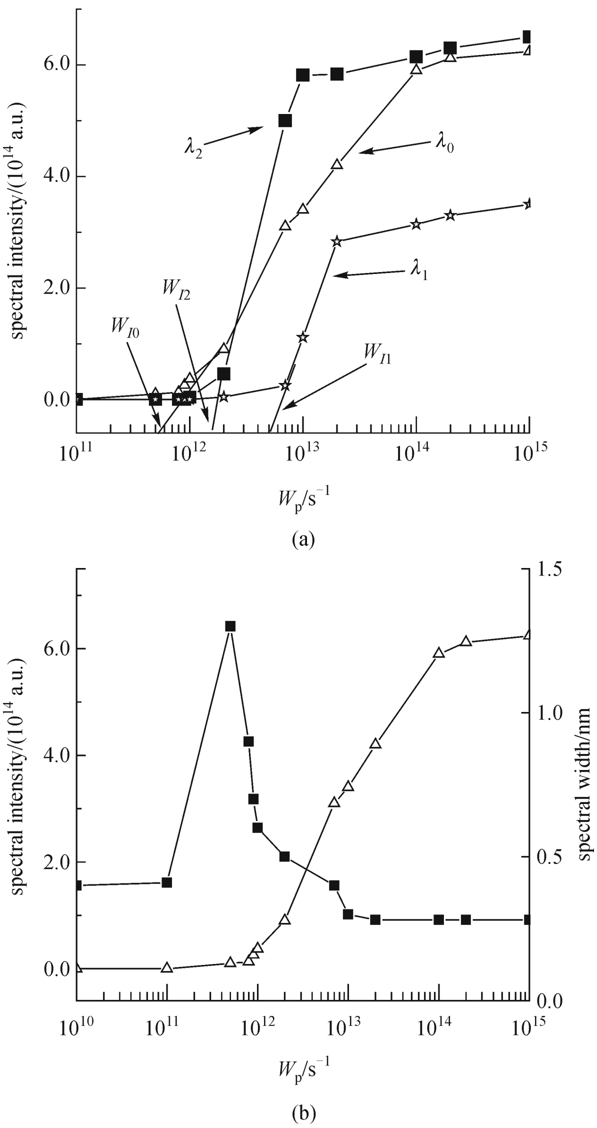

Fig. 4 Plots of the peak intensity and spectral width of the lasing modes versus the pump rate W_p under fs pulse pumping. (a) Peak intensities for the four indicated modes, and the lasing threshold measured from the plots are $W_{I0} = 5\times10^{-11}\ s^{-1}$, $W_{I1} = 3\times10^{-12}\ s^{-1}$ and $W_{I2} = 1.2\times10^{-12}\ s^{-1}$; (b) peak intensity and spectral width for the mode λ_0

To obtain more information about the threshold gain behavior for the modes, numerous calculations are performed at different pumping rates, and curves of the peak intensity and the spectral width versus the pumping rates for the three modes can be obtained, as shown in Fig. 4. According to traditional method, pumping thresholds for the three modes have been shown in Fig. 4(a) as $W_{I0} = 5\times10^{-11}\ s^{-1}$, $W_{I1} = 3\times10^{-12}\ s^{-1}$ and $W_{I2} = 1.2\times10^{-12}\ s^{-1}$ respectively, in which I denotes the threshold determined by intensity. For the mode λ_0, a jump for the spectral width within a pump regime near the pumping threshold has been observed. The peak value of the jump appears at the point that is close to the threshold of the mode (Fig. 4(b)).

For comparison, we calculated the spectral intensity varying with the fixed pumping rate using the same medium structure under 80 fs pulse pumping, as shown in Fig. 5. The calculated results show that there are only slightly differences under the fs pulse pumping among the excited modes. The sequence of the excited modes using the fixed ps pulse pumping is identical to that of using fs pulse pumping.

In order to further investigate intrinsic reason that makes the mode λ_0 be excited firstly, the rates of the energy decays for the modes λ_0, λ_1 and λ_2 at the same disordered structure described as above. Three models are separately excited by a monochromatic source. The monochromatic source has a Gaussian envelope with same amplitudes for the three modes. For each mode, the energy is recorded at all nodes and the total energy is obtained by summing the energy at all nodes. Figure 6 shows the evolution of the normalized total energy decay with time, from which we can obtain the mode's lifetime τ for each mode if we define τ to be the time that the total energy decreases from its maximal value E_{max} to E_{max}/e, in which e is approximately equal to 2.71828. The computed results show that the ordering of the three modes' lifetime τ is $\tau_1 < \tau_2 < \tau_0$. This indicates that there is a certain correspondence between the mode's threshold and its lifetime. Because the quality factor of a mode is directly proportional to τ, i.e., $Q = 2\pi c\tau/\lambda$, there exists a certain correspondence between the mode's threshold pumping rate and its Q-factor and a localized mode with a larger Q-factor has a lower threshold.

4 Conclusions

In conclusion, threshold gain behavior of random lasers is investigated in 1D random medium pumped by an 80 fs pulse. The results show that the excited modes are only slightly different between the fs pulses and fixed pumping (6 ps). This suggests the excited modes strongly depend on the medium structure instead of the duration of pumping, at lease for both fs and ps case.

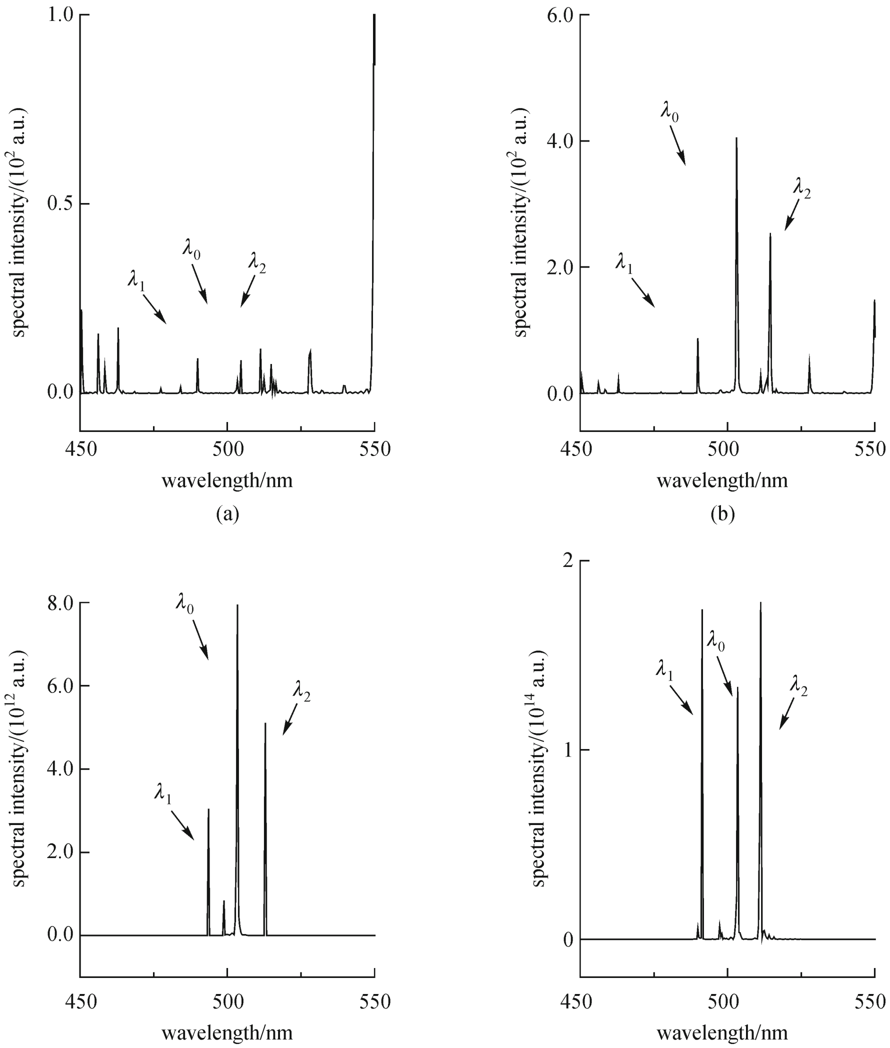

Fig. 5 Spectral intensity in arbitrary units versus the wavelength for 1D disordered medium pumped by a fixed pumping rate shown in Fig. 1 at (a) $W_p = 1\times10^8$ s^{-1}; (b) $W_p = 1\times10^9$ s^{-1}; (c) $W_p = 1\times10^{10}$ s^{-1}; (d) $W_p = 1\times10^{11}$ s^{-1}

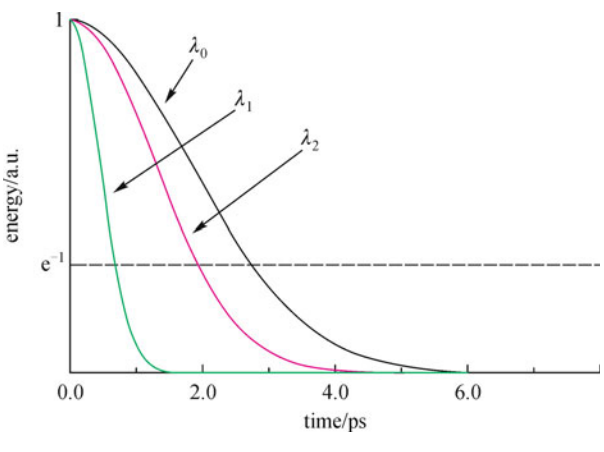

Fig. 6 Normalized total energy decays with time for each marked mode. Three lifetimes are τ_0= 2.84 ps, τ_1= 0.92 ps, and τ_2= 1.85 ps

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 60778003 and 60378001).

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