EPJ Web of Conferences **307**, 04030 (2024) https://doi.org/10.1051/epjconf/202430704030
EUROPHOTON 2024

Transient Analysis of Pump-induced Lensing Effects in Alexandrite Lasers Using Pump-Probe Technique

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Abstract: A novel transient pump-probe method is used to differentiate thermal and population pump-induced lensing mechanisms. In diode-pumped Alexandrite lasers, excellent agreement is found between theory and experiment and the population lens is found to be dominant in non-lasing amplifier.

1. Introduction

The pump-induced lensing effects in a laser gain medium limit the power scaling and lead to lower efficiency and a decrease both in beam quality and the resonator stability. The pump-induced lens is considered as the combination of the thermally induced lens due to the heat deposit in the gain medium and inversion induced lens due to the polarizability difference of the excited and ground state ions. Alexandrite has excellent thermal-mechanical properties, and while some work has been done to investigate the lensing effects in CW-diode-pumped Alexandrite lasers [1] it is difficult to distinguish the two mechanisms.

In this work, we produce a time-resolved transient pump-probe system to measure the temporal growth and decay of the pump-induced lens in an Alexandrite laser system and distinguish the two effects by the faster response of the inversion mechanism and the slower thermal response time. Alongside, the measurements we have developed a theoretical analytical model of the transient pump-induced lensing to quantitively interpret the experimental results.

2. Methods

2.1. Theoretical analysis of transient pump-induced lensing in a laser amplifier

We consider an 'ideal' four-level laser amplifier end-pumped by a Gaussian pump pulse. Its transient pump-induced lensing has a dioptric power that is the combination of a thermal lens $D_T(t)$ and a population lens $D_P(t)$, $D(t) = 1/f(t) = D_T(t) + D_P(t)$. The generation of pump-induced lens from the start of the pump pulse and the decay from the end of the pump pulse are considered separately [2].

For short pump pulse with time $t \ll t_0$ where $t_0 = w_p^2/8\alpha$ is the thermal diffusion response time for Gaussian pump size w_p,

$$D(t) = D_{T,SS}\frac{\left[t-(1-\beta)\tau\left(1-e^{-t/\tau}\right)\right]}{t_0} + D_{P,SS}\left[1-e^{-t/\tau}\right] \quad (1)$$

where $D_{T,SS} = \left(\frac{dn}{dT}\right)\frac{\eta_H P_a}{\kappa\pi w_p^2}$ and $D_{P,SS} = \frac{8CP_a}{\alpha_p \pi w_p^4 I_S}$. β is the partial fraction of the quantum defect that occurs immediately from the pump level to the upper laser level due to the fast non-radiative relaxation in the ideal four-level system.

The decay of combined dioptric power from the termination of the pump pulse is given by

$$D(t) = \frac{D_T(0)}{[1+(t/t_T)^2]} + D_P(0)e^{-t/\tau} \quad (2)$$

where $D_T(0)$ and $D_P(0) = D_{P,SS}\left[1-e^{-t_p/\tau}\right]$ are the thermal and population lenses at end of pump pulse with duration t_p. τ is upper-state lifetime and is 260 μs for Alexandrite at 25°C and we redefine t=0 is the end of the pump pulse.

2.2. Experimental setup

Fig. 1 illustrates the experimental method of the transient pump-probe measurement. The pump ($\lambda_p = 634nm$) is a repetitively pulsed beam with duration t_p and has Gaussian spatial distribution $I_p(\underline{r})$ at the laser crystal (Alexandrite). The green pulsed probe ($\lambda_{pr} = 532nm$) has about 11ns pulse width and can be set with delay in time relative to the pump. A Shack-Hartmann wavefront sensor (SH-WFS) is used to directly measure the radius of curvature (RoC) of the wavefront for each individual probe pulse which is relay-imaged onto the sensor with a pair of lens and magnification $m = -f_2/f_1$. The transient lens dioptric power can be calculated by $D(t) = -\frac{1}{f(t)} = -\frac{m^2}{RoC(t)}$. Lensing could be measured under non-lasing and lasing conditions.

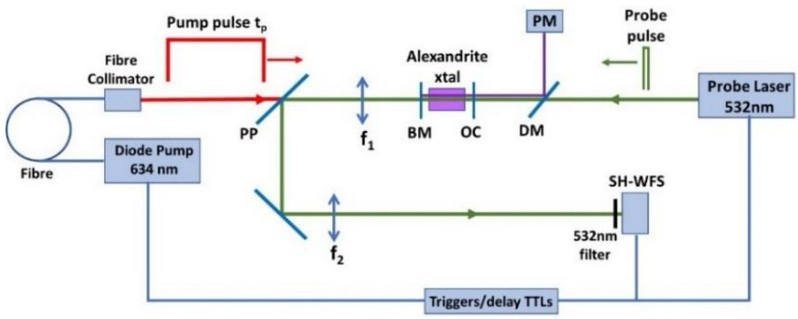

Fig. 1. Schematic of experimental system of the pump-probe measurement system.

3. Results and Discussions

In initial work, the steady-state dioptric power was measured by using a CW diode pump with effective pump waist size $w_{p,e} = 0.167$ mm. Fig. 2a shows the non-lasing dioptric power was near-linear with the absorbed power while under lasing condition it had a significant reduction in lens strength after the onset of lasing.

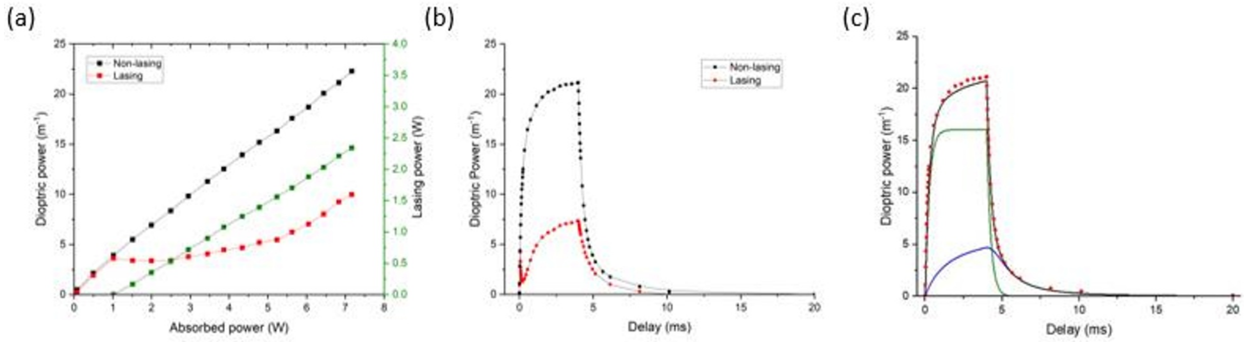

Fig. 2. (a) Steady-state dioptric power versus absorbed power under lasing (red) and non-lasing (black) condition and lasing power (green). (b) Transient dioptric power versus probe delay for a 4ms pump pulse under lasing (red) and non-lasing (black) condition. (c) Modelled transient dioptric power versus probe delay for a 4ms pump pulse of thermal lens (blue), population lens (green), combined theoretical lens (black) and combined experimental lens (red points) under non-lasing condition.

Fig. 2b shows the transient dioptric power for relative long pulse duration of 4ms, 50Hz pump pulse with same absorbed pump power (during the pulse on-time) and pump waist. Under non-lasing condition, the pump-induced lens approaches to quasi-steady state and is ~ $21\ \mathrm{m}^{-1}$ which is agree with the steady state in Figure 2a. Under lasing condition, the quasi-steady state dioptric power is ~ $7\ \mathrm{m}^{-1}$. The decrease of the dioptric power indicates the population lens is the main contribution to pump-induced lensing under non-lasing condition due to the slow thermal mechanism.

Fig. 2c shows the modeled transient pump-induced lensing under non-lasing condition. Excellent agreement is found between the model and the experiment transient results and we can discriminate that the modelled steady-state population lens $D_{P,SS} = 16.1\mathrm{m}^{-1}$, steady-state thermal lens $D_{T,SS} = 6.5\mathrm{m}^{-1}$ and the combined steady-state lens $D_{SS} = 22.6\mathrm{m}^{-1}$ and agree with the dioptric power at same pump absorbed power $P_a = 7.47W$ in Figure 2a. The population lens is dominant in the pump-induced lensing for Alexandrite. The inversion refractive index coefficient $C = 4.5\ 10^{-5}$ from modelling is consistent with the calculated value $C = 4.75\ 10^{-5}$ in linear fitting of steady-state condition [1].

4. Conclusion

An effective transient pump-probe analysis has been developed to help to distinguish the thermal and population components in pump-induced lensing. The results indicate the population lens in diode-pumped Alexandrite is considerably stronger than thermal component in the non-lasing amplifier. Under lasing, the population lens is clamped to a lower level. The pump-probe method and theoretical model of this work can also be applied to other gain media.

References

[1] Tawy, G., Wang, J. and Damzen, M.J. "Pump-induced lensing effects in diode pumped Alexandrite lasers,". Opt. Express 27, 35865-35883 (2019)

[2] Xiao, H., Jiang, X. and Damzen, M.J., "Transient pump-probe analysis of pump-induced lensing in laser amplifiers," Opt. Express 32, 12783-12799 (2024)