Probing solid-state laser characteristics through polarization behavior

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Abruptly changing pump-beam polarization provides an effective probe of the physical mechanisms controlling solid-state laser polarization transition, and can help estimate some key laser properties.

It is difficult to accurately describe the polarization state of light emitted by lasers. Generally, laser polarization behavior is often probed by changing a single parameter, such as pump current, to see what happens. This kind of experiment can be used to formulate and validate theoretical models of the phenomenon. Detailed studies have found that many physical mechanisms contribute to the complex polarization behavior of semiconductor lasers. However, similar studies have yet to be performed on optically-pumped solid-state lasers. Here, we describe our efforts to remedy this situation.

Under some conditions, the polarization of solid-state lasers is known to depend on the pump-beam polarization and the stress-induced birefringence that determines the laser cavity polarization. While models have been developed that accurately describe the steady-state behavior, the dynamic evolution predicted by these models had not been compared to experiments.

We have been found that abruptly changing the pump beam polarization switches the laser’s polarization state. However, contrary to the behavior seen in semiconductor lasers, the switching occurs after a significant delay. Further investigation has allowed us to accurately model the delay as due to three physical parameters.

In our experiments, an electro-optic modulator adjusted the polarization of the pump beam, which was applied to a Nd:YAG laser. The laser’s polarization response to abruptly changing the pump beam’s polarization by 90°, but keeping its power constant, appeared after a delay of several tens of microseconds (see Figure 1). The delay strongly increased as the pump amplitude approached the threshold pump strength. During this turn-on period, the output polarization angle was unchanged, although the intensity showed relaxation oscillations. After the delay, the angle evolved to its new steady-state value on a time scale much smaller than the relaxation period, followed by large fluctuations in the total intensity similar to those during turn-on.

The experimental results are well represented with the rate-equation model proposed by Bouwmans et al., which indicates that the slow recovery of the laser population inversion causes the delay. When the pump polarization changes, the existing laser steady-state condition does not immediately lose its stability because the population reservoirs relax toward their new steady-state values on a microsecond time-scale.

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Figure 2. The polarization response delay calculated from Equation (1) (black line) compares very well with the measured delay (black circles) as a function of pump strength above threshold J (the ratio of pump strength to threshold pump strength). Parameter values used for the calculated delay: $\gamma = 3.3 \times 10^{-5}$, $\beta_L = 0.62$, $\beta_P = 0.75$.

However, this model does not clearly identify the key laser parameters that influence the delay. We deduced these with an asymptotic analysis of the laser equations, taking advantage of the different time scales available on our system. The result was an expression for the delay that depends only on the medium decay rate $\gamma$, the gain anisotropy $\beta_L$, and the pump absorption anisotropy $\beta_P$:

$$\text{Delay} \sim \frac{1}{\gamma (1 + \frac{1}{2}E_a^2 (1 + \beta_L))}$$  \hspace{1cm} (1)

where $E_a^2$ is proportional to the intensity of the polarization mode that is lasing before the switch. $E_a^2$ changes linearly with the pump strength, and depends on the parameters $\beta_L$ and $\beta_P$. The delay calculated with Equation (1) is in excellent agreement with the measured delay (see Figure 2). We can therefore use equation (1) to estimate the gain and absorption anisotropy, quantities that are difficult to measure.

We have shown that polarization can be a useful probe of solid-state laser properties. The dynamic-switching experiments, combined with an analysis of the laser rate equations, provided valuable insight on the physical mechanisms that control the polarization switching transition. Solid state lasers are Class B lasers characterized by the slow recovery of the population inversion, so our results are relevant to all Class B lasers exhibiting polarization dynamics.

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References