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Effect of cavity length on low-energy single longitudinal mode pre-lase Q-switched laser

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In this paper, the effect of cavity length on a low-energy single longitudinal mode (SLM) pre-lase Q-switched laser is analyzed and demonstrated. Taking a Pr:YLF laser as an example, the basic output characteristics under pre-lase technology are shown. The SLM is degraded when the cavity length is as large as 25 mm. Further, for cavity lengths of 15 or 20 mm, SLM is achieved with different output characteristics. Compared with a long cavity (20 mm), the short-cavity case (15 mm) is indeed helpful for obtaining an SLM laser; however, the single-pulse energy, pulse width, and energy extraction efficiency are decreased by 4.7, 48, and 6.7%, respectively. The results of this analysis show that the cavity length influences the output characteristics and determines the realization of SLM in a pre-lase Q-switched laser. This is because the short cavity induces a relatively strong gain identification for the seed signal. Then, the time cost of the mode competition decreases and SLM can be achieved easily. However, a long cavity is conducive to mode competition, which generates superior output characteristics.

1. Introduction

Improvement of single longitudinal mode (SLM) laser efficiency, especially for low-energy lasers, is a longstanding and significant research problem. SLM lasers are often obtained via one of two methods. The first involves introduction of a loss among different modes, ensuring that the central mode obtains the minimum loss [1–3]; then, the central mode survives and the other modes can be filtered after oscillation and amplification. The advantage of this approach is that the device design is simple and easily implemented. However, an obvious disadvantage also exists, i.e., the threshold value increases and the SLM laser efficiency is low [4]. The second approach involves adjustment of the gain among different modes to ensure that the central mode obtains the maximum gain [5–8]. In that case, the central mode acquires more energy than the other modes after oscillation and amplification. When the power ratio between the central and other modes reaches a specific value, the state can be defined as SLM [9]. The advantage of this method is that no additional loss is introduced to the device; thus, the threshold value remains unchanged and the SLM efficiency can be greatly increased. However, the disadvantage is that it is not feasible for a high-energy laser to achieve SLM using this technique. When the injected energy increases, more modes are generated, which compete strongly for the energy. As a result, the energy is distributed by the different modes equally. When the injected energy exceeds a specific value, the power ratio among the different modes is reduced and the SLM fails. Thus, it is preferable to employ the second method to realize an SLM laser when the injected energy is limited by the existing technology.

Pre-lasing is a technology associated with the second method, which is realized by switching the loss in different stages and adjusting the time cost of the mode competition. The principles behind pre-lasing can be described as follows. First, the loss is switched to a fixed value and energy is injected into the laser. Then, the inversion population accumulates onto the upper level. The loss is then reduced slightly and part of the inversion population drops to a lower level. Hence, a regular seed signal is produced, in which the central mode has the greatest gain compared with the other modes. The mode competition time period is extended, and the central mode obtains the most energy. Finally, the loss is reduced to zero and the central mode achieves the maximum amplification. Hence, a SLM laser can be obtained. Throughout the entire process, two parameters must be considered for calculation and optimization. One is the loss in the different stages, while the other is the time cost of the mode competition. Both parameters are greatly influenced by the cavity length; thus, research on the cavity length is necessary.

The Pr:YLF laser has abundant wavelengths, which attract considerable research attention: 479, 522, 607, 639, and 747 nm can

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be acquired directly, and wavelengths of 304 and 374 nm can be efficiently obtained utilizing the double frequency [10–15]. In this study, we investigate the influence of the cavity length on a 639-nm Pr:YLF SLM laser realized using a 445-nm pump laser. The optimized parameters and output characteristics obtained when the cavity length is set to 15, 20, and 25 mm are shown in this paper. Following analysis, it is found that the cavity length influences the output characteristics and determines the achievement of SLM via pre-lase. Compared with a long cavity, the short cavity is indeed helpful as regards realization of the SLM; however, the output characteristics are weakened slightly compared to the longer-cavity case.

2. Effect of cavity length on seed signal

There are three processes that must be considered in pre-lase. The first is seed signal generation, for which the intensity and gain identification of the seed signal must be confirmed. The second process is mode competition, in which the inversion population distributed to the central mode should be optimized. Finally, the third process is the output stage, and the output characteristics (single pulse energy, pulse width, energy extraction efficiency) must be confirmed and compared under the different cavity length.

2.1. Seed-signal intensity

Here, the seed-signal intensity is discussed and analyzed. Firstly, the threshold inversion population Δn_t and threshold energy E_t can be obtained from the four-level rate equation [16], such that

$$\Delta n_t = \frac{L}{2\sigma l_0}, \tag{1}$$

$$E_t = \frac{h\upsilon \Delta n_t \pi r^2 l_0}{\eta_0}, \tag{2}$$

where $L = 0.04$ is the round-trip optical loss, $\sigma = 1.4 \times 10^{-19}$ cm^2 is the stimulated emission cross-section of the central mode (639 nm) in a Pr:YLF laser, $l_0 = 5$ mm is the medium length, $\upsilon = 6.76 \times 10^{14}$ Hz is the central-mode frequency, $r = 300$ μm is the radius of the oscillating beam cross section, $\eta_0 = 1$ is the pump efficiency, and $h = 6.62617 \times 10^{-34}$ J s.

The Q-switched loss and the competition loss are set to $L_x = xL$ and $L_k = kL$, respectively. Then, the inversion populations at the Q-switching and competition can be defined as $n_x = x\Delta n_t$ and $n_k = k\Delta n_t$, respectively. When the loss changes slightly, a seed signal is produced. The seed-signal inversion population can be described as $\Delta n_0 = (x - k)\Delta n_t$, which is the seed-signal intensity (X and K are positive dimensionless quantities).

2.2. Seed-signal gain identification

Switching the loss to L_x and determining the pump energy injected into the laser, the full width at half maximum (FWHM) of the seed signal can be expressed as

$$\frac{n_0}{\left(\frac{\Delta\upsilon_s}{2}\right)^2 + \left(\frac{\Delta\upsilon_D}{2}\right)^2} = \frac{\Delta n_t}{\left(\frac{\Delta\upsilon_D}{2}\right)^2}. \tag{3}$$

Further, solving Eq. (3) and simplifying the result yields

$$\Delta\upsilon_s = \sqrt{x-1}\,\Delta\upsilon_D. \tag{4}$$

The spacing of the two adjacent longitudinal modes $\Delta\upsilon$, which is determined by the specified cavity length, can also be obtained:

$$\Delta\upsilon = \frac{c}{2[l_0 \cdot n + (l - l_0)]}. \tag{5}$$

Here, $\Delta\upsilon_D = 100$ GHz is the FWHM of the Pr:YLF spontaneous radiation, $\Delta\upsilon_s$ is the FWHM of the seed signal when the system is in the Q-switched state, the number of longitudinal modes can be described as $N = \Delta\upsilon_s/\Delta\upsilon$ (N should be a positive integer), $n = 1.45$ is the refractive index of the Pr:YLF crystal, and l is the cavity length.

A Pr:YLF laser is a solid laser that exhibits homogeneous broadening. The atomic linear function of homogeneous broadening can be expressed as

$$\tilde{g}(\upsilon) = \frac{\Delta\upsilon_D}{2\pi}\left[(\upsilon - \upsilon_0)^2 + \left(\frac{\Delta\upsilon_s}{2}\right)^2\right]^{-1}, \tag{6}$$

where $\tilde{g}(\upsilon)$ is the gain of different mode. The center and adjacent modes occupy significantly more gain than the other modes at the competition stage; therefore, the gains of the other modes can be ignored. Hence, the gain difference ratio between adjacent mode υ_1 (there are two symmetrical modes near the central mode, and one can be taken as an example) and the central mode υ_0 is the gain identification, which can be obtained from Eq. (6), such that

$$\frac{g_0 - g_1}{g_0} = \frac{(\upsilon_1 - \upsilon_0)^2}{(\upsilon_1 - \upsilon_0)^2 + \left(\frac{\Delta\upsilon_s}{2}\right)^2}. \tag{7}$$

Eqs. (4) and (5) are substituted into Eq. (7), with the following expression showing the relationship between the injected energy and obtained gain identification:

$$\frac{g_0 - g_1}{g_0} = \frac{1}{1 + (x-1)\left[\frac{\Delta\upsilon_D(l + nl_0 - l_0)}{c}\right]^2}. \tag{8}$$

It is apparent that the gain identification becomes weaker in accordance with increased injected energy. This is the root cause of the SLM failure that occurs when higher energy is injected into the laser. If the gain identification becomes weak, the time cost of the competition is extended. When this time period spans the spontaneous radiation lifetime, the spontaneous radiation becomes dominant. It is known that the uncertainty of the spontaneous radiation renders the central mode gain less than the adjacent mode, causing failure of the SLM. It can also be found that the gain identification becomes strong when the cavity length decreases. This is because the spacing between two adjacent longitudinal modes increases and the number of modes decreases. As a result, the gain identification also increases. According to the above analysis, a short cavity strengthens the gain identification and reduces the time cost of the mode competition. Thus, we can conclude that the short-cavity case is indeed helpful for obtaining the SLM (see Fig. 1).

3. Effect of cavity length on mode competition

Following generation of the seed signal, the next process is mode competition. The entire inversion population is allocated in three directions: one part is consumed when gaining the central mode, another part is consumed when gaining the other modes, and the remainder is consumed when overcoming the round trip loss. The SLM precondition is that the power ratio between the central and adjacent modes must achieve a specific value (often set to 10). The power ratio between these two modes can be expressed as

$$\frac{P_0}{P_1} = \left[\frac{e^{2\sigma_0 n_k l_0}}{e^{2\sigma_1 n_k l_0}}\right]^q \left[\frac{L_0}{L_1}\right]^q, \tag{9}$$

where p_0 and p_1 are the central and adjacent mode powers, the first term on the right hand side is the gain ratio between the central and adjacent modes, the second is the loss ratio between the central and