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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

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

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

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, $v = 6.76 \times 10^{14}$ 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

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

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

$$\Delta v_s = \sqrt{x-1}\,\Delta v_D. \tag{4}$$

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

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

Here, $\Delta v_D = 100$ GHz is the FWHM of the Pr:YLF spontaneous radiation, Δv_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 $N = \Delta v_s / \Delta v$ (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

$$\tilde{g}(v) = \frac{\Delta v_D}{2\pi}\left[(v - v_0)^2 + \left(\frac{\Delta v_s}{2}\right)^2\right]^{-1}, \tag{6}$$

where $\tilde{g}(v)$ 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 v_1 (there are two symmetrical modes near the central mode, and one can be taken as an example) and the central mode v_0 is the gain identification, which can be obtained from Eq. (6), such that

$$\frac{g_0 - g_1}{g_0} = \frac{(v_1 - v_0)^2}{(v_1 - v_0)^2 + \left(\frac{\Delta v_s}{2}\right)^2}. \tag{7}$$

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

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

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

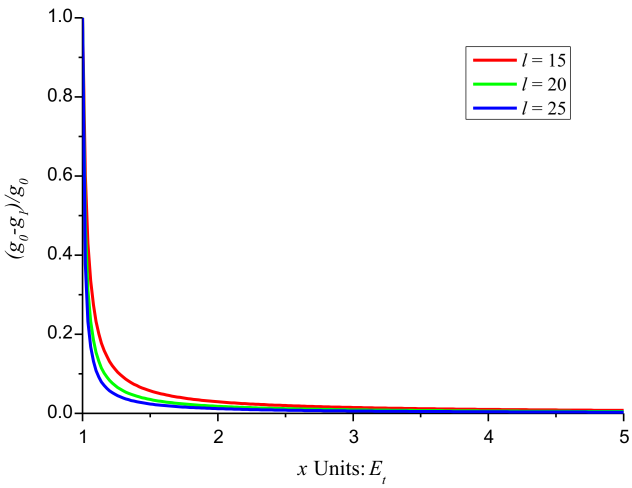

Fig. 1. Relationship between gain identification $(g_0 - g_1)/g_0$ and injected energy x for cavity lengths of 15, 20, and 25 mm (Units of injected energy: E_t).

adjacent modes, L_0 and L_1 are the central and adjacent mode losses, respectively, t is the competition time cost, and $q = (c \cdot t)/2l$ is the round trip. During pre-lase, the loss between different modes is almost identical and the loss ratio between different modes can be taken as 1. The stimulated emission cross-sections σ_0 and σ_1 are proportional to the gains g_0 and g_1, respectively. When the power ratio between the central and adjacent modes becomes 10, Eq. (9) can be reduced to

$$e^{\frac{(g_0-g_1)l_0 c\sigma_n K\Delta nt}{g_0 l}} = 10. \tag{10}$$

From Fig 2, it is apparent that the competition time cost decreases when the competition loss increases and the cavity length decreases. When the cavity length is overlong, the competition time cost is longer than the spontaneous emission lifetime and the SLM fails (taking $l = 25$ mm as an example). This is because a short cavity strengthens the gain identification and shortens the competition time cost. It can also be seen that, when the competition loss increases to the vicinity of the initial Q-switched loss, the inversion population of the competition increases and the seed-signal intensity is weakened; this strengthens the gain identification significantly. Therefore, the power ratio between the central and adjacent modes can be easily increased sufficiently to realize SLM. Based on the above, it can be concluded that reduction of the cavity length and an increase in the competition loss approaching the initial Q-switched loss are helpful for decreasing the competition time cost. Thus, SLM can be obtained easily.

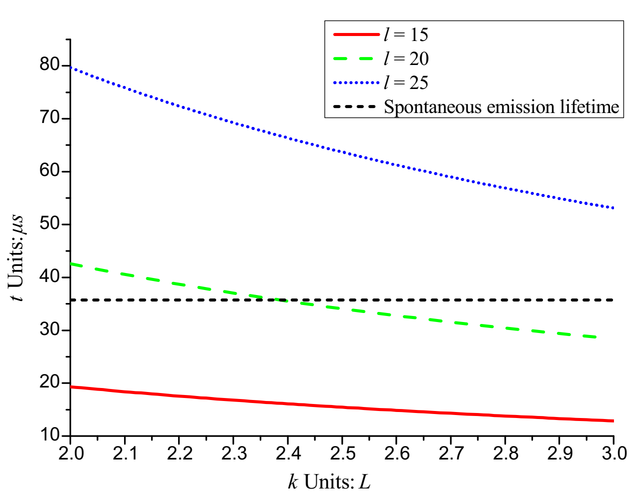

Fig. 2. Relationship between competition loss k and competition time cost t for different cavity lengths when SLM is achieved and the injected energy is triple the threshold value.

The competition time cost and loss set can be confirmed via the above analysis. However, the central mode gain, which is the inversion population cost of gaining the central mode, must also be assured. In fact, the central mode gain determines the SLM output characteristics. Optimization of the SLM requires that the central mode gain is optimized and reaches a maximum value.

Next, the competition model is established and SLM optimization is shown. The competition model is based on the precondition that SLM has been achieved. The central mode gain can then be discussed based on two conditions: (a) The central mode gain is generated by amplification of the seed signal. (b) The inversion population of entire system limits the central mode gain. There are also two moments at which the competition begins and finishes, and the possible equations can be expressed as follows.

In the initial competition stage, the gain of a single trip can be defined as

$$G = e^{2\sigma_n n_x l_0}. \tag{11}$$

Immediately after the competition has finished, the loss should be equal to the gain of the single trip, such that

$$L_k = G_k = e^{2\sigma_n n_k l_0}. \tag{12}$$

Condition (a) can be expressed as

$$n_1 = \frac{\Delta n_0}{N} \cdot \left[\left(\frac{G}{L_k}\right)^{\frac{1}{2}}\right]^q, \tag{13}$$

where n_1 is the central mode inversion population and is generated by the seed-signal amplification, $(G/L_k)^{1/2} = e^{\sigma_n (x-k)\Delta nl}$ is an approximation of the gain factor in a single trip, and $\Delta n_0/N$ is the inversion population of the central mode in the original seed signal.

Condition (b) can be described as

$$n_2 = n_k \cdot \left(\frac{p_0}{p_0 + 2p_1}\right)\left(\frac{1}{1+\left(\frac{L_k}{G}\right)^{\frac{q}{2}}}\right). \tag{14}$$

In Eq. (14), n_2 is the inversion population of the central mode provided by the entire system, n_k is the total gain inversion population of the entire system, $p_0/p_0 + 2p_1 = 5/6$ is the mode discrimination factor, and $(L_k/G)^{1/2}$ is an approximation of the loss factor for a single trip. The relationship between n_1 and n_2 corresponds to the effective gain efficiency $\eta = n_1/n_2$, which can be obtained from

$$\eta = \frac{6}{5 \cdot N} \frac{(x-k)(e^{\sigma_n \Delta nct(x-k)\frac{l}{l_0}} + 1)}{k}. \tag{15}$$

From Fig. 3, it is apparent that the intersection corresponds to $\eta = 1$ in Eq. (15). The intersection is the extreme value corresponding to the maximum gain of the central mode. This behavior can be explained as follows: When the extreme value is not reached, the inversion population consumed by the seed-signal amplification is greater than the inversion population offered by the entire system, and the actual gain is the inversion population provided by the entire system. If the extreme value is exceeded, the inversion population consumed by the seed-signal amplification is less than the inversion population provided by the entire system, and the actual gain is the inversion population consumed by the seed-signal amplification. It is easy to see that the ideal optimization of the central mode is realized when η reaches 1, and the actual gain is shown in Fig. 4.

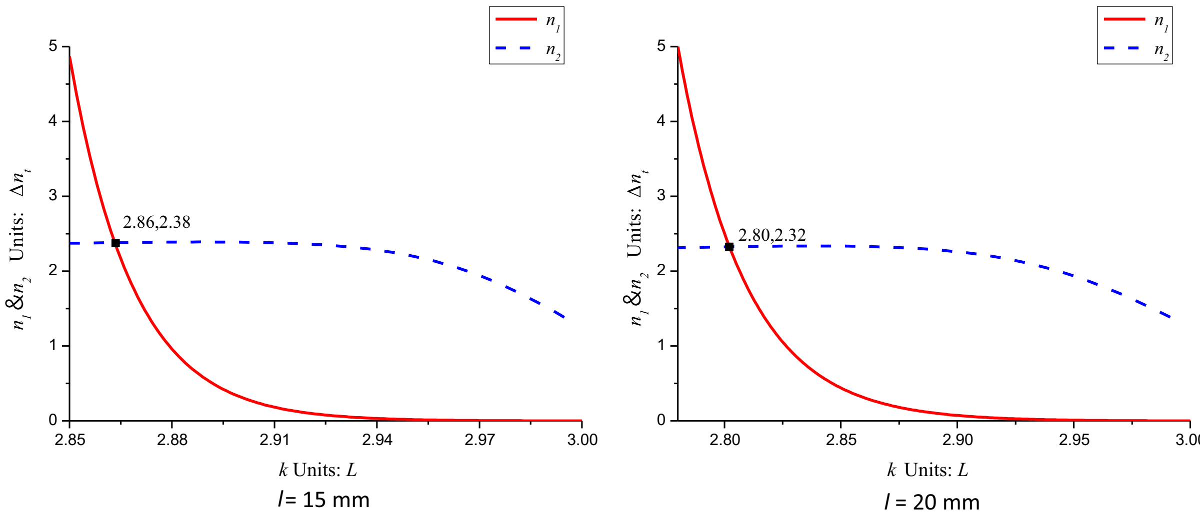

Fig. 3. SLM optimization when injected energy triples the threshold value and the cavity length increases.

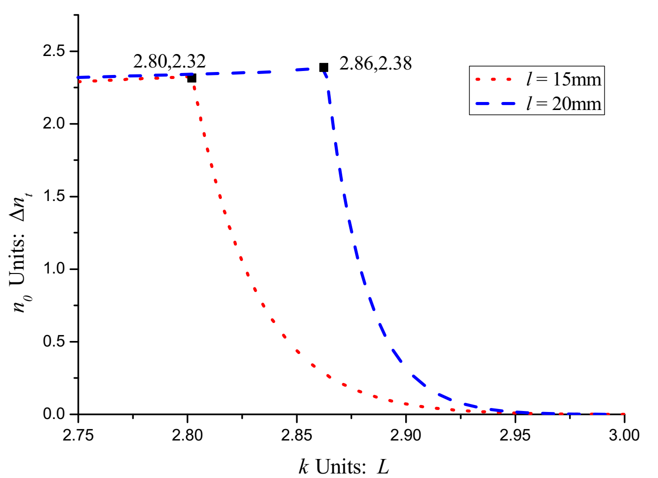

Fig. 4. Relationship between actual gain n_0 and competition loss k for different cavity lengths.

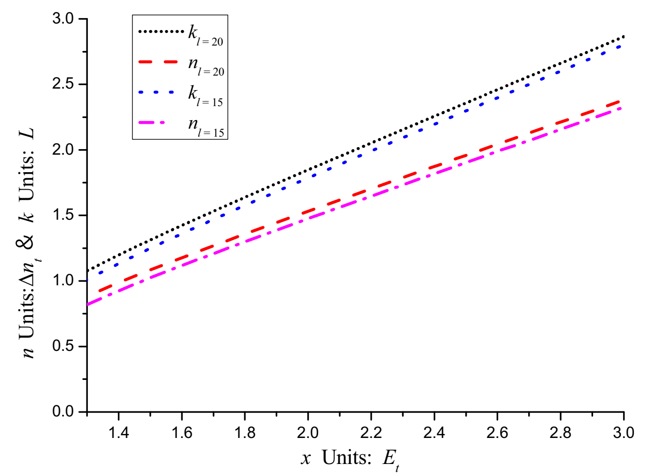

Fig. 5. Relationship between actual gain n_0, competition loss k, and injected energy x under different cavity lengths.

It is apparent that the long cavity is beneficial in driving the central mode to acquire a greater gain. Further, Fig. 4 indicates that it is necessary to set the competition loss closer to the Q-switching loss. This is because the long cavity causes the gain identification and the initial intensity of the seed signal to weaken. Then, the remainder of the inversion population becomes greater than that for the short cavity. When the mode competition is implemented adequately, the actual gain of the long cavity becomes greater than that obtained in the short-cavity case.

The relationship between the actual gain, competition loss, and injected energy is shown in Fig 5. Compared with the different cavity lengths, the long cavity provides a certain advantage. That is, the actual gain and efficiency are greater than those for the short cavity. Based on the above, we may safely conclude that SLM can easily be obtained in the short cavity. However, the long cavity is suitable for obtaining higher-efficiency SLM. Therefore, it is necessary to select a reasonable cavity length to obtain an SLM laser for a specific injected energy value.

4. Effect of cavity length on output characteristics

The output characteristics can be acquired using the theory presented by Degnan [17]:

$$T = 1 - \exp\left[-L\cdot\left(\frac{z-1-\ln z}{\ln z}\right)\right], \tag{16}$$

$$E = \frac{Ah\nu L}{2\sigma\gamma}(z-1-\ln z), \tag{17}$$

$$\tau_p = \frac{2l}{cL}\left[\frac{\ln z}{z\left(1-\frac{z-1}{z\ln z}\left(1-\ln\frac{z-1}{z\ln z}\right)\right)}\right], \tag{18}$$

$$\eta_0 = 1 - \frac{1+\ln z}{z}, \tag{19}$$

where the value of Z is the ratio of the roundtrip small-signal gain to the roundtrip dissipative loss, $A = \pi r^2$ is the laser beam cross section, $r = 300$ μm is the cross section radius, T is the optimum transmittance, E is the single pulse energy, τ_p is the pulse width, and η_0 is the energy extraction efficiency. Then, the output characteristics of the pre-lase Q-switched laser under different cavity lengths and normal Q-switching can be respectively computed, as shown in Fig. 6.

The output characteristics of the pre-lase Q-switched laser for different cavity lengths and those for normal Q-switching can be

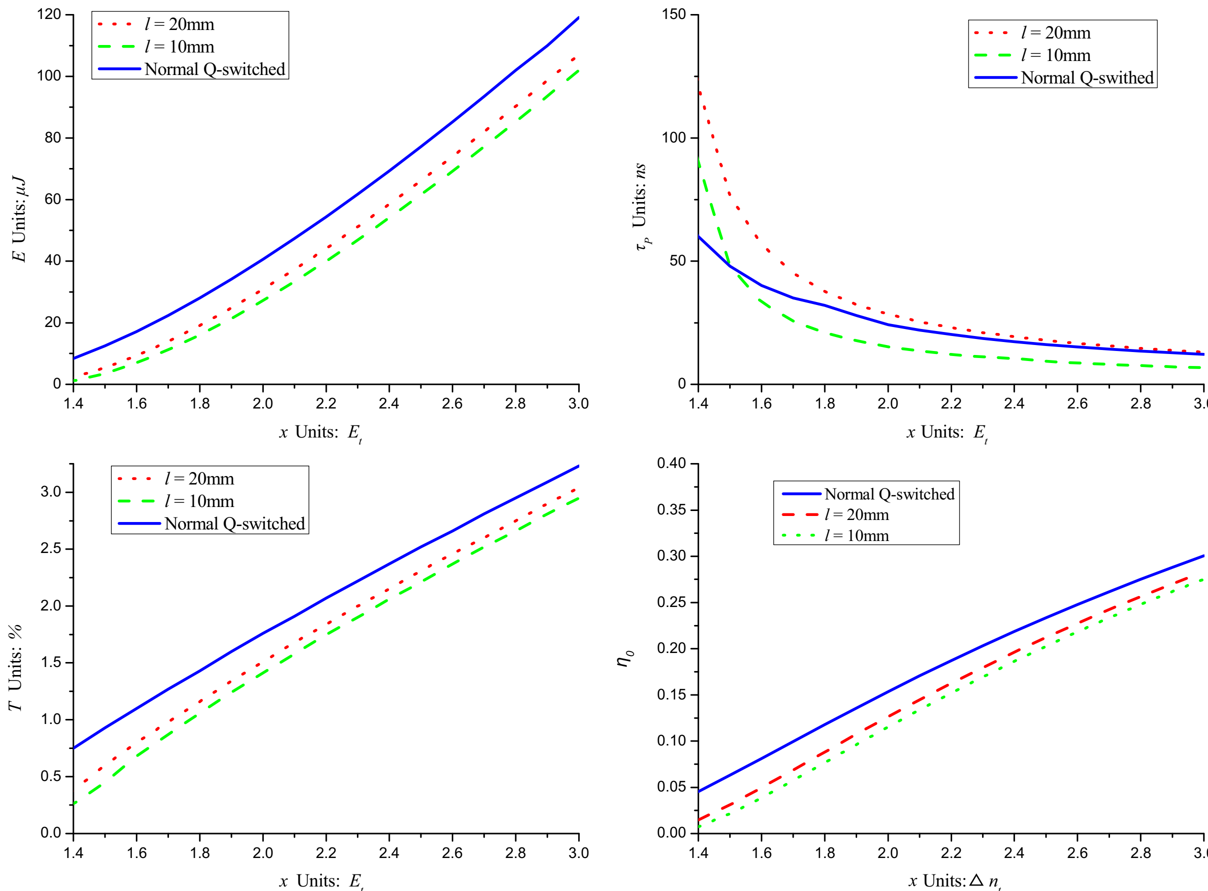

Fig. 6. Output characteristics of pre-lase Q-switched laser and normal Q-switched laser are shown under different conditions.

seen in Fig. 6. It is known that the output characteristics of a long cavity are closer to the normal Q-switched case and it is easier to obtain high-energy SLM with greater single pulse energy; however, the pulse width is wider than that for the short cavity. Because the single pulse energy is influenced by the parameter *Z*, which is affected by the cavity length, the pulse width is obviously influenced by the cavity length. The short cavity causes the pulse width to narrow and reduces the single pulse energy. We can conclude the following: If the injected energy is sufficiently large, it is preferable to choose a short cavity to obtain SLM. When the injected energy is small, it is preferable to choose a long cavity to obtain additional SLM.

5. Discussion and conclusion

In this paper, pre-lasing technology in a low-energy laser was analyzed and the effect of the cavity length was discussed. The specific pre-lase parameters and output characteristics were optimized and shown in detail. After the analysis, the optimized results were determined for different injected energies. In summary, SLM can easily be obtained with a short cavity, but the SLM laser efficiency is greater for a long cavity. Further, it was proven that the cavity length greatly influences the pre-lase and output characteristics. Finally, the most noteworthy conclusion is that the use of pre-lasing technology to obtain SLM in a low-energy laser is preferable, and the optimization method discussed herein can be used in most lasers to obtain high-efficiency SLM through simple control of the parameters.

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