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Optimization of a Passively Q-switched Yb:YAG Laser Ignitor Pumped by a Laser Diode with Low Power and Long Pulse Width

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We successfully constructed a passively Q-switched Yb:YAG laser ignitor pumped by a diode laser with low power and long pulse width. To the best of our knowledge, this is the first study to achieve a quasi-MW output power from an optimized Q-switch Yb:YAG laser ignitor by using a pumping diode laser module emitting at under a power of 23 W. The output pulse energy of our optimized laser is 0.98 mJ enclosed in a 1.06 ns pulse width, corresponding to a peak power of 0.92 MW.

Keywords : Laser ignitor, Q-switching, Yb:YAG laser, Air breakdown
OCIS codes : (140.3540) Lasers, Q-switched; (140.3615) Lasers, ytterbium; (140.3440) Laser-induced breakdown; (140.3410) Laser resonators

I. INTRODUCTION

Recently, laser ignitors have been studied as potential replacements for electric spark plugs in internal combustion engines because laser ignition offers a number of potential benefits, such as no quenching of the combustion flame kernel, ability to deliver laser energy to any location of interest in the combustion chamber, possibility of delivering the beam simultaneously to different positions, and temporal control of ignition [1]. The differences between the combustion chamber structures for conventional and laser ignition are depicted in Fig. 1. As a laser ignitor can efficiently deliver laser energy to any location of interest in the combustion chamber with no quenching by plug electrodes, it can therefore ignite leaner or higher-pressure burnable mixtures that are more difficult to ignite [2].

Hence, in this field over the last few decades the laser ignitor has become recognized as an attractive method to improve the combustion process. Due to these advantages, many scientists have been expecting laser ignition to be utilized in stationary gas engines for energy cogeneration; in ground-based turbines, aero turbines, and rocket engines; in scramjet engines; or in reciprocating engines [1, 3].

The laser intensity required for breakdown must be of the order of 100 GW/cm^2 [4]. To achieve such a high-intensity laser pulse, a Q-switching technique is usually utilized when a pulse laser is designed. A laser ignitor must be designed to be as compact as a spark ignitor for installation in a commercial combustion engine. A longitudinal pumping method is one way to construct a compact laser [5]. Hence, a laser ignitor has been designed in the style of a Q-switching laser longitudinally pumped by a laser diode (LD). Yb:YAG is one of the preferred laser mediums for designing a laser ignitor operated by a low-pump-power source, because it can store a high amount of excitation energy due to its long fluorescence time of ~1 ms [5].

However, most reported laser ignitors have operated by using a high-power LD of over 100 W to achieve a 1 MW laser output [6, 10]. This method of using a high-pump-power LD with a short pulse width has the advantage of the overall efficiency increase of a Q-switch laser [5]. However, a shorter pump pulse results in an extra burden on the pump source, because the pump is required to operate at a higher peak power to deliver the same amount of energy to the laser medium. Additionally, an electric power supplier must have high power capability, and this supply system needs a heavy chiller to cool the high-power LD. This implies that the laser ignition system is not

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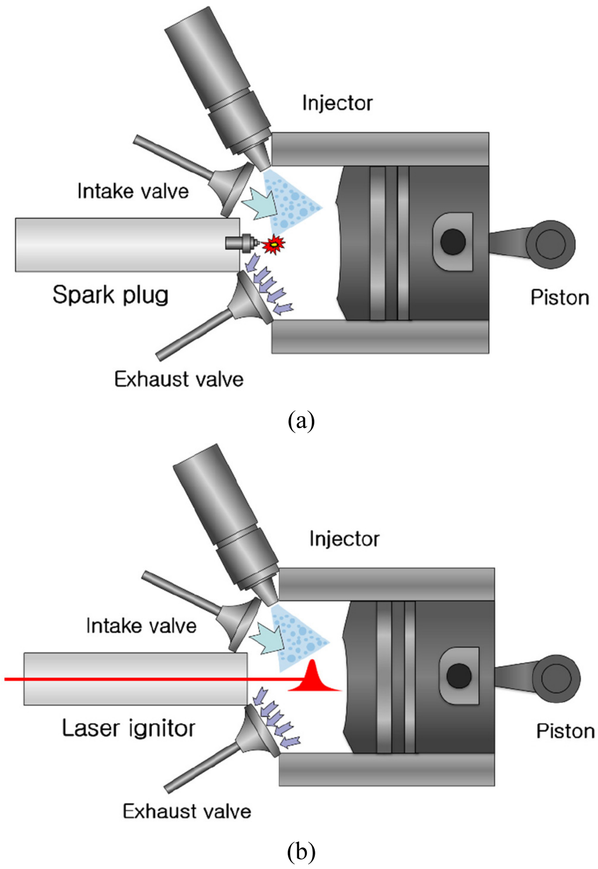


FIG. 1. Internal combustion engine ignition chamber structures with (a) an electric spark plug and (b) a laser ignitor.

compact. Hence, to design a compact laser ignition system, it is necessary to pump Yb:YAG using a low-peak-power LD with a long pulse width larger than the laser medium fluorescence time. To obtain sufficient stored energy inside the laser medium using a low power pump, lasing must be prevented during the laser medium fluorescence time. However, it is not easy to determine the conditions to attain sufficient stored energy. Hence, to obtain a giant Q-switch pulse with a low-power LD module, we need to experimentally determine the optimal conditions for the main design parameters, such as an initial transmittance of Q-switcher (Cr:YAG), cavity length, output coupler reflectance, and pump beam size. These conditions can be obtained by conducting various experiments for a number of combinations of cases for all design parameters.

In this study, we perform experiments to determine the optimal conditions for the design parameters of the laser ignitor pumped by a low-power LD. Then, we experimentally analyze the dependence of the designed laser ignitor on the laser design parameters of initial transmittance of the Q-switcher (Cr:YAG), cavity length, output coupler reflectance, and pump beam size under the condition of a pump power of less than 30 W. With the help of our analysis results, we demonstrate a quasi-megawatt-power laser ignitor pumped by a low-peak-power LD of less than 23 W. The final optimized results are compared with the simulation results based on rate equations.

II. EQUATIONS USED FOR Q-SWITCHED Yb:YAG LASER OUTPUT ANALYSIS

The following equations from Eq. (1) to Eq. (9) are derived from laser rate equations to analyze the output of a Q-switched Yb:YAG laser with a Cr:YAG saturable absorber [7-11]:

$$N_i = \frac{2\sigma_g N_{s0} l_s + \ln\left(\frac{1}{R}\right) + L}{2\sigma l}, \tag{1}$$

$$N_{th} \cong \frac{2\sigma_e N_{s0} l_s + \ln\left(\frac{1}{R}\right) + L}{2\sigma l}, \tag{2}$$

$$N_i - N_f - N_{th} \ln\left(\frac{N_i}{N_f}\right) = 0, \tag{3}$$

$$E = \frac{h\nu A}{2\sigma\gamma} \times \ln\left(\frac{1}{R}\right) \times \ln\left(\frac{N_i}{N_f}\right), \tag{4}$$

$$P = \frac{h\nu A l}{\gamma t_r} \times \ln\left(\frac{1}{R}\right) \times \left[N_i - N_{th} - N_{th}\ln\left(\frac{N_i}{N_{th}}\right)\right], \tag{5}$$

$$\tau_P \approx \frac{E}{P}, \tag{6}$$

$$N_g + N_e = N_{s0}, \tag{7}$$

$$2\sigma_g N_{s0} l_s = \ln\left(\frac{1}{T_0{}^2}\right), \tag{8}$$

$$2\sigma_e N_{s0} l_s = \ln\left(\frac{1}{T_{\max}^2}\right). \tag{9}$$

Here, N_i is the initial inversion density when a Q-switching process is initiated, σ_g is the ground absorption cross-section of a Cr:YAG crystal, and N_g, N_e, and N_{s0} are the absorber ground, excited state, and total population densities, respectively. l_s is the Cr:YAG length, and l and σ are the length and emission cross-section of the laser gain medium, respectively. R is the reflectivity of the output coupler and L is the round-trip dissipative loss. N_{th} is the inversion density at a Q-switching pulse peak and σ_e is the excited-state absorption cross-section of a Cr:YAG crystal.

When a Q-switching process is initiated, we can assume $N_g \approx N_{s0}$ because the photon density inside a cavity is extremely small. Using this assumption, we can derive Eq. (8) for an initial absorber transmittance (T_0). If there are sufficient photons inside a cavity to saturate an absorber, we can assume $N_e \approx N_{s0}$. Using this assumption, we can derive Eq. (9) for maximum absorber transmittance ($T_{\max}$). Due to excited-state absorber absorption, $T_{\max}$ is lower than 100%. In Eq. (3), N_f is the final inversion density when a Q-switching process is completed. N_f can be obtained by substituting N_i and N_{th} into Eq. (3). Using N_i, N_{th}, and N_f, we can calculate a Q-switching pulse energy (*E*). In Eq. (5) and Eq. (6), A and γ are the effective beam cross-section and the inversion reduction factor of the laser gain medium, respectively, and t_r is the cavity round-trip time. The Q-switching pulse width (τ_P) can be obtained by dividing the output energy (*E*) of Eq. (5) by the output power (*P*) of Eq. (6). To obtain the theoretical results for the output energy and power of a Q-switched laser, we need to measure the parameter values of L and A. In section IV, we explain how to measure these values. The following table (Table 1) presents the material properties of the laser medium Yb:YAG, saturable absorber Cr:YAG, and other laser parameters.

III. DEPENDENCE OF THE OUTPUT CHARACTERISTICS OF A Q-SWITCHED Yb:YAG LASER FOR A LASER IGNITOR ON LASER CAVITY PARAMETERS

Figure 2 illustrates a photograph and scheme of our Q-switched Yb:YAG laser used for a laser ignitor. We used a Cr:YAG crystal as a passive Q-switcher.

A pig-tailed 30 W LD module emitting at a wavelength of 940 nm was used to longitudinally pump the Yb:YAG laser medium. The pump LD fiber had a core diameter of

TABLE 1. Material properties and laser parameters

Parameter	Value (unit)	Explanation
l	4 mm	Thickness of Yb:YAG
l_s	1.85 mm	Thickness of Cr:YAG
σ	2.1×10^{-20} cm^2	Emission cross-section of Yb:YAG [5]
σ_g	4.6×10^{-18} cm^2	Ground absorption cross-section of Cr:YAG [12-14]
σ_e	8.2×10^{-19} cm^2	Excited-state absorption cross-section of Cr:YAG [14]
$h\nu$	1.93×10^{-19} J	Laser photon energy
A	0.051 mm^2	Effective laser beam area in the laser medium
γ	1	Reduction factor [10]
L	0.97	Round-trip loss at 9 mm cavity length

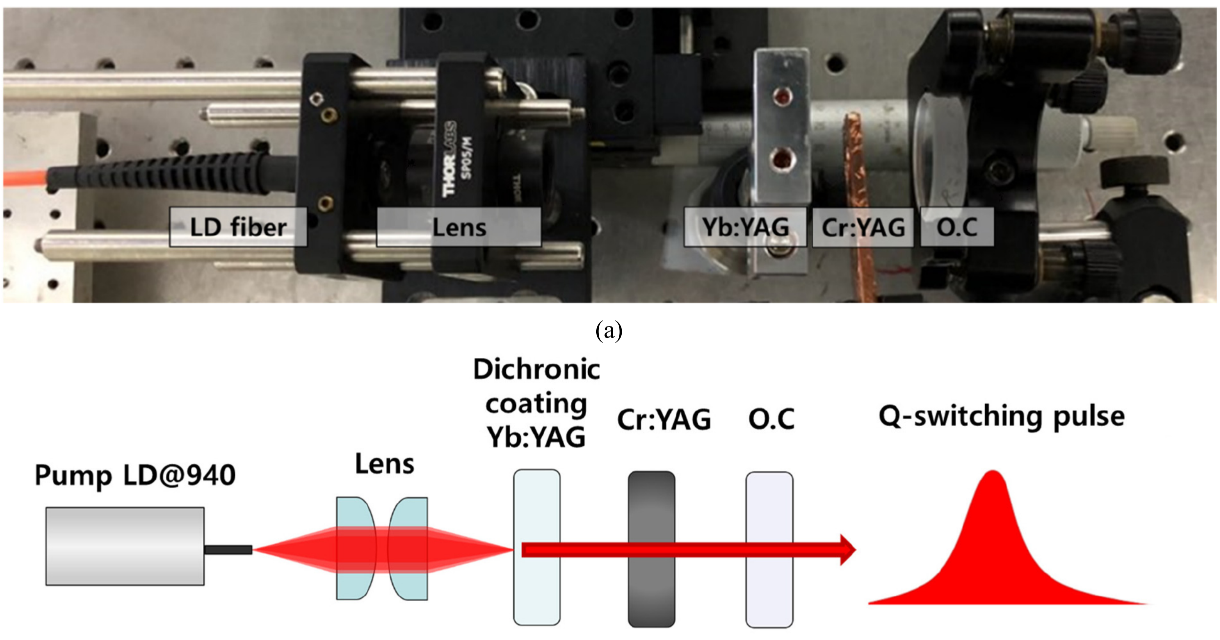


FIG. 2. (a) Photograph and (b) scheme of our Q-switched Yb:YAG laser.

105 mm and 0.22 NA. The fiber output beam was focused onto the Yb:YAG by two lenses. The focal length of the front lens at the end of the pump fiber was 15 mm and fixed, and the focal length of the next lens was varied between 25 mm and 50 mm to control the pump beam size on the laser medium. The pump beam pulse width was set to 1.2 ms, slightly larger than the Yb:YAG fluorescence lifetime. To minimize accumulated heat inside the Yb:YAG, the repetition rate of the pump beam was set to 1 Hz. If the laser crystal mount is equipped with a cooling system, the maximum repetition rate of this type of a Yb:YAG laser can be about 800 Hz which is limited by a pump beam pulse width. As the purpose of our study is to demonstrate the operation of the laser ignitor for a low-peak-power LD, we did not improve the cooling system for our Q-switching laser. The Yb:YAG crystal used had a thickness of 4 mm and a doping rate of 5 at.%. One side of the Yb:YAG was HR- and AR-coated at 1030 nm and 940 nm wavelength, respectively, and the other side was AR- and HR-coated at 1030 nm and 940 nm wavelength, respectively. Additionally, both sides of the Cr:YAG were AR-coated at 1030 nm wavelength. The reason for the HR-coating of Yb:YAG at 940 nm is for reabsorption of the transmitted pump beam after one pass through the Yb:YAG.

Firstly, we investigated the laser output characteristics with varying cavity length and initial transmittance of Cr:YAG, with the pump beam diameter on the Yb:YAG surface set to 210 mm and output coupler reflectance set to 30%. The chosen values for diameter and reflectance are the parameter values used in the next experiment, which demonstrate the effects of pump beam diameter and output coupler reflectance on the laser output. The results are depicted in Fig. 3.

Figure 3 depicts that a pulse width decreases while the output energy increases as an initial transmittance of Cr:YAG decreases. As predicted by Eq. (1) and Eq. (8), this result is caused by the increased initial inversion density due to cavity loss increase from the increased initial transmittance of Cr:YAG [8]. The results demonstrate that the pulse width is proportional to the cavity length, whereas the output energy is almost independent of the cavity length. The dependence of a pulse width on a cavity length is due to the round-trip time t_p described in Eq. (5) [7]. From these results, we can predict that the lower the initial transmittance of Cr:YAG and the shorter the laser cavity length, the narrower the laser pulse width and, subsequently, the higher the laser output peak power.

Figure 4 depicts the dependence of the laser output energy and pulse width on the pump beam diameter (w_p) and output coupler reflectance (R) when the cavity length is set to 60 mm. The experimental results demonstrate that the pump beam size has a more significant effect than the output coupler reflectance on our designed laser output. The pulse width was not explicitly changed by the output coupler reflectance, as depicted in Fig. 4(b), whereas it

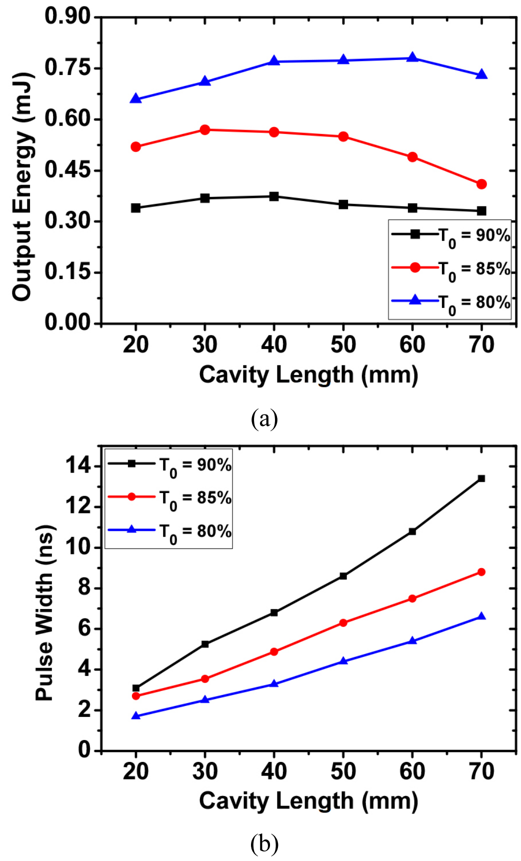
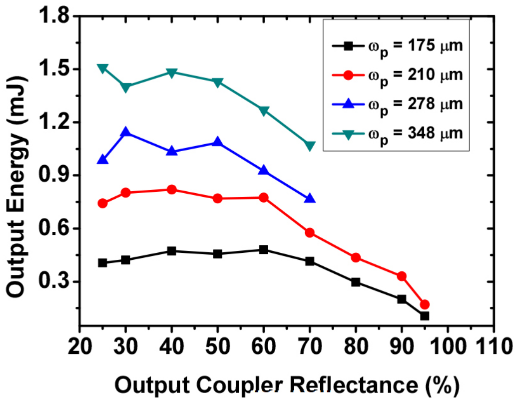


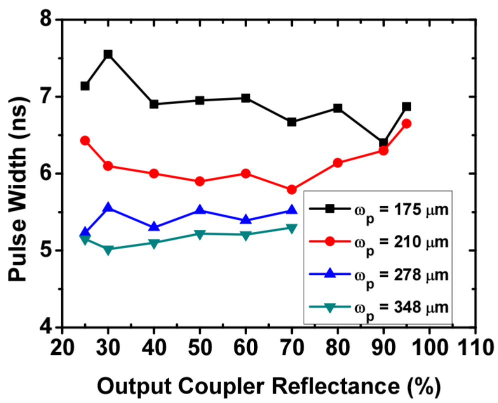
FIG. 3. Dependence of (a) laser output energy and (b) laser pulse width on cavity length and initial transmittance of Cr:YAG.

explicitly decreased as the pump beam diameter was increased. Moreover, the output energy explicitly increased as the pump beam diameter was increased. In addition, we found that the lasing threshold increased as the pump beam diameter was increased.

Additionally, Fig. 4 depicts that the output energy decreases when R increases. With the simulation using Eq. (1) to Eq. (4), we can prove that the output energy decreases with increasing R. But the pulse widths weakly depends on R as shown in Fig. 4(b). So the output peak power calculated by the pulse energy divided by the pulse width has the similar tendency to the output energy. From this result, we can suppose that the internal laser power can be significantly increased by increasing R. This implies that optical damage to the laser's optical components can more easily occur at a high reflectance R. Hence, in our experiments, we cannot obtain the output energy for over 80% of R due to optical damage when the pump beam size is set to 278 mm or 348 mm. Figure 4(a) also depicts that the output energy for $w_p = 348$ mm is four times larger than that for $w_p = 175$ mm at $R = 25\%$. From these results, we presume that under the conditions of $T_0 = 80\%$, $w_p = 348$ mm and $R = 25\%$, our laser can emit a high energy pulse.

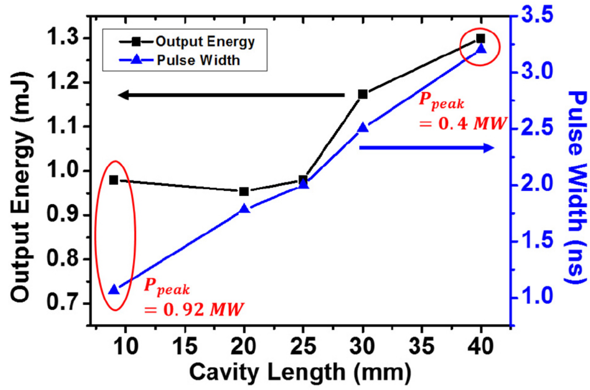


(a)

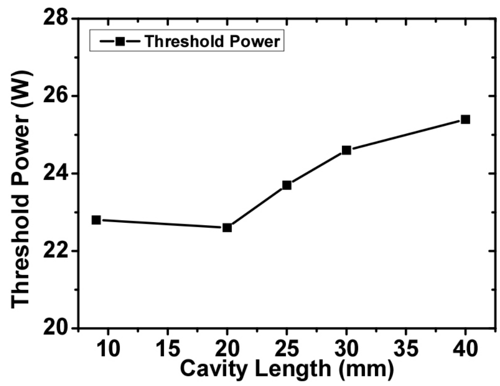


(b)

FIG. 4. Dependence of (a) laser output energy and (b) laser pulse width on pump beam diameter and output coupler reflectance.



(a)



(b)

FIG. 5. (a) Laser output energy and (b) threshold pump power when cavity length is varied from 9 mm to 40 mm.

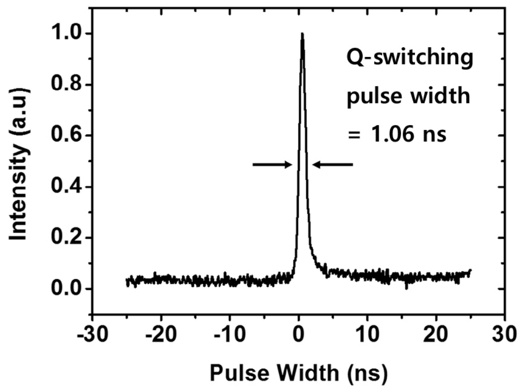
IV. OPTIMIZED OUTPUT OF A Q-SWITCHED Yb:YAG LASER IGNITOR

On the basis of the results of the previous section, we re-investigated the effect of cavity length on laser output to obtain an optimized laser power. We set $T_0 = 80\%$, $w_p =$ 348 mm and $R = 25\%$, which gave the best results in the previous section. Figure 5 depicts the laser output energy and the threshold pump power when the cavity length was varied from 9 mm to 40 mm.

The results demonstrate that the output energy and output pulse width decreased with decreasing cavity length. However, the output peak power increases, as depicted in Fig. 5(a). Figure 5(b) illustrates that the threshold pump power (P_{th}) decreases with a decrease in the cavity length. As the output energy was sensitive to alignment conditions at a short cavity length, we performed a precise alignment of the optical components. We reduced the cavity length as much as possible in our laser structure to obtain the shortest possible pulse width. The aligned shortest cavity length was 9 mm. Next, we realigned the position of the focal point of the pump beam to obtain a perfect mode match between the laser mode and the pump beam. After this alignment process, we were able to obtain an output energy of 0.98 mJ and an output pulse width of 1.06 ns. This corresponded to a peak power of 0.92 MW. The measured pulse shape is depicted in Fig. 6(a). To demonstrate laser ignition by our Q-switched laser, we performed an air breakdown experiment by focusing the optimized laser output beam using a lens with 2.54 cm focal length. The focal spot diameter was measured to be 16.6 μm. Hence, the intensity was 107 GW/cm^2 at the focal point. Air breakdown was observed, as depicted in Fig. 6(b), and M^2 of the beam used was measured as 2.

As mentioned in the previous section, a Q-switched pulse should not be generated until after the Yb:YAG fluorescence lifetime for low-pump-power LD usage. Hence, to confirm that there was sufficient energy storage time for the Yb:YAG in our experiment, we measured the delay time of a Q-switching pulse from a pump beam starting time by monitoring the scattering signal from the Yb:YAG surface. The measured delay time was approximately 1 ms, as depicted in Fig. 7. The result demonstrates why a high-power pulse for laser ignition occurs at a low pump power of less than 23 W.

We measured the effective laser cross-sectional area (A) and cavity round-trip loss (L) to compare the experimental results to ones obtained by the Q-switching theory. Using



(a)

(b)

FIG. 6. (a) Output pulse shape after precise alignment, and (b) photograph of air breakdown.

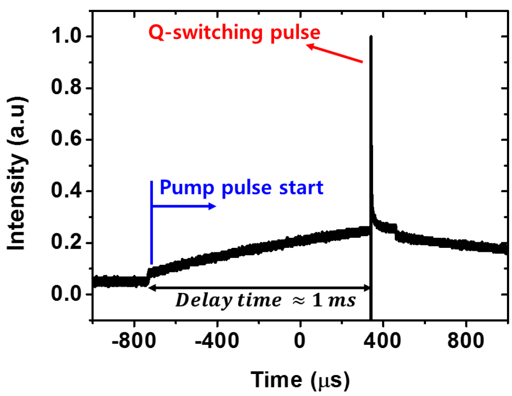


FIG. 7. Measured delay time of Q-switching pulse from pump beam starting time.

an optical image relay system and a CCD camera, we measured an effective laser cross-sectional area of 0.051 mm^2. In addition, we obtained the cavity round-trip loss using the Findlay and Clay method as shown in Fig. 8 [5]. Figure 9 illustrates the relationship of -ln(R) and the pump power threshold (P_{th}). Using the Findlay and Clay method, the cavity round-trip loss corresponds to the vertical-axis intercept of L, as depicted in Fig. 9, and L was measured as 0.97.

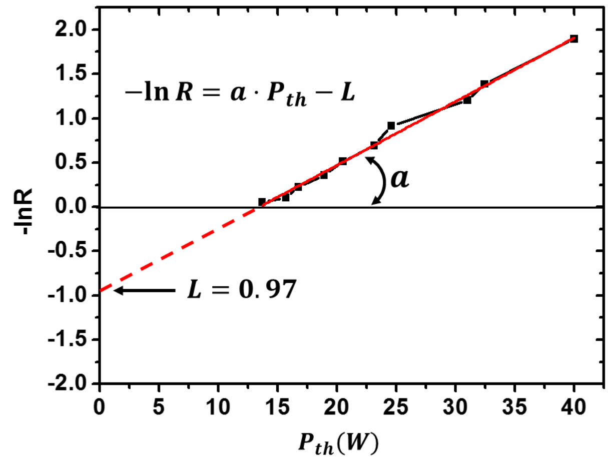


FIG. 8. Cavity round-trip loss measurement by the Findlay and Clay method.

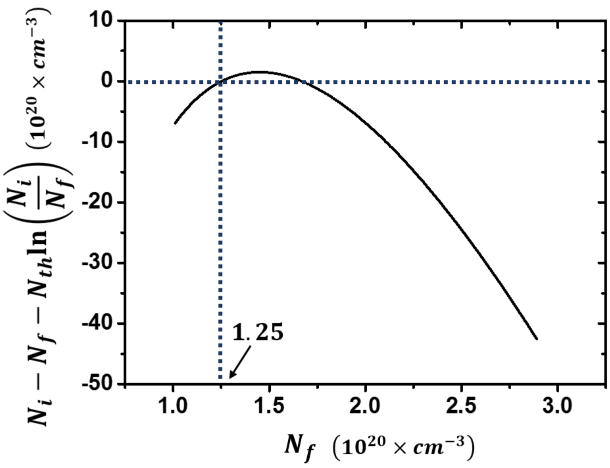


FIG. 9. Calculation of final inversion density N_f.

Using the measured value of L, the final inversion density N_f can be calculated using Eq. (3). To solve Eq. (3), we used the values of N_i and N_{th} calculated using Eq. (1) and Eq. (2), which are 1.668×10^{20} cm^{-3} and 1.45×10^{20} cm^{-3}, respectively. The final inversion density N_f was obtained using the graph depicted in Fig. (10). The calculated N_f is 1.25×10^{20} cm^{-3}.

With these values of N_i, N_{th}, and N_f, we can obtain the theoretical results of 0.946 mJ energy, 1.134 ns pulse width, and 0.834 MW power. These results almost agree with the experimental results of 0.98 mJ energy, 1.06 ns pulse width, and 0.92 MW power.

V. CONCLUSION

We successfully constructed a passive Q-switched laser for a laser ignitor, which can operate under the condition of low-power LD pumping of less than 23 W. To achieve this, we experimentally investigated the dependence of the laser output on cavity length, initial transmittance of Cr:YAG, pump beam size, and output coupler reflectance. On the basis of the experimental analysis, we determined the design parameter values for our laser ignitor. With the optimized parameter values, the laser designed for our laser ignitor has an output of 0.98 mJ energy, 1.06 ns pulse width, and 0.92 MW power. We found that these results approximately agree with the theoretical results. If we can coat the optical component using ion-beam sputtering, we can design our Q-switched laser to achieve stronger output pulse energy.

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