

# Performance Improvement of Flashlamp-Pumped Ti: sapphire Laser

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Experimental study is performed on flashlamp-pumped Ti: sapphire lasers with single, double, and four-partial-ellipse-pump cavities aiming at improving the performance of the lasers. The output energy of 604 mJ per pulse with a width of 25  $\mu$ s at a total laser efficiency of 0.13% is achieved in the laser pumped by a light pulse of 45  $\mu$ s without a fluorescent converter. The laser output energy versus its Ti: sapphire rod length, pumping-light pulse duration, and electrical input energy are discussed with or without using a fluorescent converter. The result shows that much more output energy is obtained in a longer Ti: sapphire-rod laser pumped by a shorter light pulse when its output coupler has an optimized transmittance. In addition, an enhancement of output energy by a factor of 7 is achieved in the laser using a fluorescent converter LD490.

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## I. INTRODUCTION

Most Ti: sapphire lasers commercially available are pumped with other lasers such as argon ion lasers, copper vapor lasers, or frequency doubled Nd:YAG and Nd:YLF lasers, of which the wavelengths match the absorption band of Ti:Al<sub>2</sub>O<sub>3</sub>. [1] Laser pumping Ti: sapphire makes the laser more complex. In contrast, direct flashlamp-pumping of Ti: sapphire can offer the capability to obtain high energy and high average power while maintaining a relatively compact system. However, it is difficult to achieve high efficiency. Many investigations have been undertaken to improve the laser performance. [2]- [5] Boquillon and Muset [6] achieved a higher efficiency using a very high quality Ti: sapphire rod with a figure of merit of 800. The figure of merit is the absorption coefficient at 490 nm divided by the absorption coefficient at 820 nm. Brown and Fisher [7] used Stilbene 420 and Coumarin 450 as fluorescent converters with concentration ranging from 1 to 6  $\times 10^{-4}$  molar diluted in an ethanol-water solution to shift a part of UV flashlamp emission into the blue-green absorption band of Ti: Al<sub>2</sub>O<sub>3</sub> to make an improvement greater than 40% in optical stored energy in the Ti: Al<sub>2</sub>O<sub>3</sub> rod. The optimization of the flashlamp reflector can also result in improved performance of this laser. The optimal reflector directs the maximum pump light toward the rod while minimizing re-absorption by shielding the flashlamps from each other. [8]

Our efforts are directed to obtaining high energy and high power in a Ti: sapphire laser pumped by xenon flashlamps. We designed three types of pump cavities to perform the experiment on the flashlamp-pumped Ti: sapphire lasers. One is a single-ellipse-pump cavity. One is a double-partial-ellipse-pump cavity. The other one is a four-partial-ellipse-pump cavity. The output characteristics of the lasers are studied with or without a fluorescent converter LD490 dye. The influence of the pulse width of pump light on the laser output energy is also discussed. To do so, we carried out our experiment with three kinds of discharge circuits in which the pulse widths are 10, 45 and 65  $\mu$ s, independently. In addition, the effect of the transmittance of the output coupler on laser output energy is investigated.

## II. EXPERIMENTAL SETUP

### 1. Pump cavities

Pump cavity determines the efficiency in the transfer of radiation from pump source to laser element and it influences the overall efficiency of the laser system. The pump cavities of the flashlamp-pumped Ti: sapphire lasers in our experiment are elliptical cylinders with laser rods and pump lamps at focus points as shown in Figs. 1(a), (b), and (c). The elliptical configuration is based on the geometrical theorem that

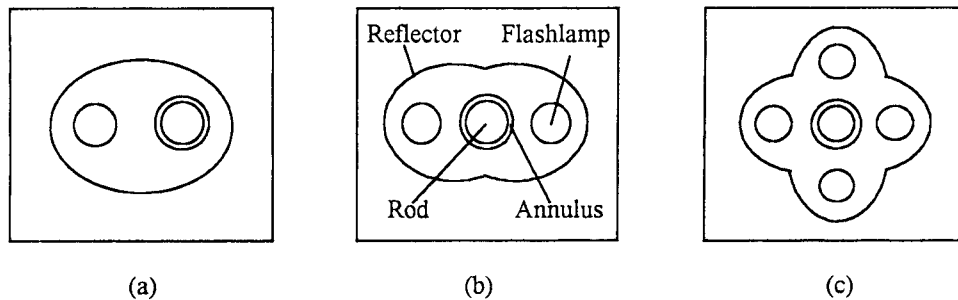


FIG. 1. Cross sections of elliptical pump cavities. (a) Single ellipse, (b) Double ellipse, (c) Four ellipse.

rays originating from one focus of an ellipse are reflected into the other focus. Therefore, it provides a good coupling between the pump lamps and the absorbing active material. The inner surfaces of the elliptical cylinders are coated with silver. All of the elliptical cylinder pump cavities have the same eccentricity, the equal radius of major axis and the identical radius of minor axis. The eccentricity is 0.4, defined as the ratio of half separation of the focal points to the radius of the major axis of the ellipse. The radius of the major axis of the elliptical cylinder is 30 mm, the radius of the minor axis is 27.5 mm, and the separation of the focal points is 24 mm. The geometrical parameters of the cavities are listed in Table 1. The detailed introduction is as follows:

Fig. 1(a) is the schematic of the single-ellipse-pump cavity. The Ti: sapphire rod is 10.2 cm long by 6.4 mm in diameter and has a concentration of 0.1 wt% Ti<sup>3+</sup>. A fluorescent converter can flow through a 1.8-mm-thick annulus around the rod. A xenon-filled linear flashlamp with 10.2-cm arc length and 5-mm bore size is located at one of the focal points in the elliptical cylinder while the Ti: sapphire rod is placed at the other focal point.

Fig. 1(b) is the cross section of the double-ellipse-pump cavity of the flashlamp-pumped Ti: sapphire laser. The Ti: sapphire rod is 15 cm long by 6.4 mm in diameter, and has a concentration of 0.1 wt% Ti<sup>3+</sup>. A fluorescent converter can flow through a 2.8-mm-thick annulus around the rod. Two xenon-filled linear flashlamps, each with 15.2 cm arc length and 7 mm bore size, are arranged in the double-partial-ellipse cylinders having one common axis at which the Ti: sapphire rod is placed.

Fig. 1(c) shows the cross section of a four-ellipse-pump cavity of the flashlamp-pumped Ti: sapphire laser. It has the same geometrical parameters of the Ti: sapphire rod and the flashlamps as Fig. 1(a). The Ti: sapphire rod is 10.2 cm long by 6.4 mm in diameter, and has a concentration of 0.1 wt% Ti<sup>3+</sup>. A fluorescent converter can flow through a 1.8 mm thick annulus around the rod. Four xenon-filled linear flashlamps are arranged in the four-partial-ellipse cylinders having one common axis at which the Ti: sapphire rod is placed.

## 2. Electrical driving circuit

The electrical driving circuit is shown as Fig. 2. The highest voltage that can be supplied is 25 kV. Resistors  $R$  in the circuit are 100 k $\Omega$ . Capacitors  $C$  are 2.4  $\mu$ F or 50  $\mu$ F, depending on the pulse duration of flashlamp emitting light. The light pulse durations from the flashlamps are 10, 45 and 65  $\mu$ s (FWHM) corresponding to the capacitors of 2.4, 50 and 50  $\mu$ F, respectively. An extra coil of 24  $\mu$ H is added for the light pulse of 65  $\mu$ s in the circuit. An external trigger is employed or not employed, depending on the charging voltage of the capacitors in the circuit. If the charging voltage of the capacitors is lower than the breakdown voltage of the flashlamps, the external trigger is indispensable. Otherwise, it is not necessary. For the convenience of measurement, especially for the measurement of the electrical input energy per pulse, the flashlamp is not triggered repetitively in our laser systems. In other words, the flashlamp is triggered once after the capacitor in the circuit is charged to a

TABLE 1. Structure parameters of the pump cavities.

Cavity type	Single ellipse	Double ellipse	Four ellipse
Rod length (cm)	10.2	15	10.2
Rod diameter (mm)	6.4	6.4	6.4
Annulus thickness (mm)	1.8	2.8	1.8
Arc length (cm)	10.2	15.2	10.2

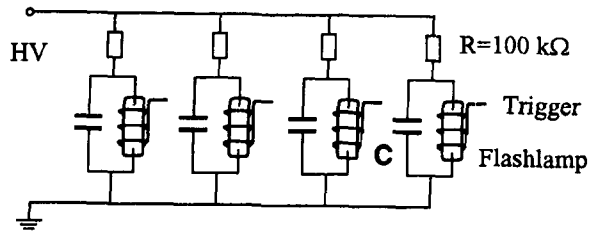


FIG. 2. Electrical driving circuit for the flashlamp-pumped Ti: sapphire laser.

designed energy, and it pumps Ti: sapphire during the lamp flash. Then, the capacitor is charged again and another experiment is started.

### III. EXPERIMENTAL RESULT

Typical oscillograms of laser pulse, energy, and pump light are shown in Fig. 3. The curves were obtained for the laser with four-partial-ellipse-pump cavity at 2-kV charging voltage of the capacitors in the driving circuit. The pulse durations of the flashlamps are  $45 \mu\text{s}$ . The Ti: sapphire laser pulse propagated into a power meter and was converted into an electrical signal. The electrical signal was transferred into an oscilloscope and shown by the oscilloscope. Then the shape of the laser pulse was tracked. The pulse energy value was measured by an energy meter in which the energy was obtained by the integration of electrical signal that was generated by the laser pulse irradiating on the optoelectronic converter in the meter. In Fig. 3, the time evolution of the integration of pulse signal for the energy was shown. The pulse of pump light was measured in such a way as follows: a part of the pumping light from the flashlamps was transfer-

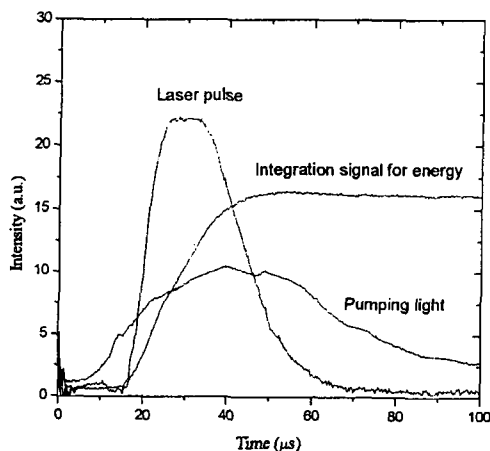


FIG. 3. Oscillograms of laser pulse, energy and pump light.

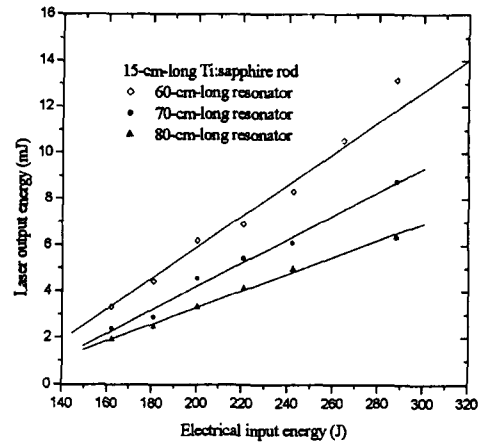


FIG. 4. The output energy as a function of electrical input energy for the laser with double-partial-ellipse cavity and 5% transmittance of the output coupler.

red into a photodiode through a fiber, the output signal of the photodiode was delivered into an oscilloscope, then the pulse shape was shown by the oscilloscope.

As mentioned above, our efforts are directed to obtain high power and high energy from the laser. To do so, we emphasize on examining the effect of the length of Ti: sapphire rod, the transmittance of the output coupler of the resonator, and the pulse duration of the flashlamp with or without a fluorescent converter on laser performance.

#### 1. Ti: sapphire rod length

First, we examine the effect of the length of the active material on the output laser energy. We give our results in Figs. 4 and 5. Fig. 4 shows the laser output energy versus the electrical input energy in the Ti: sapphire laser with a double-partial-ellipse-pump cavity at the pulse width of pumping light of  $45 \mu\text{s}$ . The resonator consists of a flat mirror and a concave output coupler of which the radius of curvature is 10 m and the transmittance is 5%. The length of laser resonator changes from 60 to 80 cm. The result shows that the laser output energy increases linearly with the electrical input energy. Fig. 5 demonstrates that the laser output energy versus the electrical input energy in the Ti: sapphire laser with a four-partial-ellipse-pump cavity at the pulse width of pumping light of  $45 \mu\text{s}$ . The parameters of the mirror and the output coupler are the same as those in Fig. 4. The length of resonator ranges from 50 to 60 cm. The figure shows the same characteristics of laser output energy as those

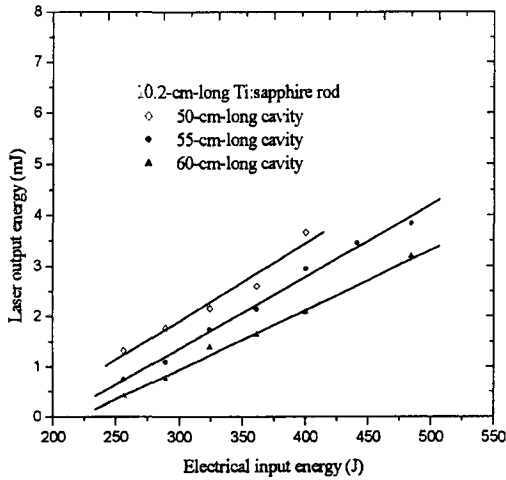


FIG. 5. The output energy as a function of electrical input energy for the laser with four-partial-ellipse cavity and 5% transmittance of the output coupler.

in Fig. 4. However, the laser output energy and the efficiency are reduced/. The output energy/4z+ versus the electrical input energy for the double-partial-ellipse-pump-cavity laser is  $E_{out} = 0.0067\%(E_{in} - 111.9)$ , whereas the output energy versus the electrical input energy for the four-partial-ellipse-pump-cavity laser is  $E_{out} = 0.0012\%(E_{in} - 220.2)$ . Under the same condition, the double-partial-ellipse-pump-cavity laser outputs much more energy. For example, at the same electrical input energy of 260 J and the same resonator length of 60 cm, the double-partial-ellipse-pump-cavity laser outputs a pulse in 10.5 mJ and it produces 20 times the pulse output energy of the four-ellipse-pump-cavity laser which outputs an pulse of 0.5 mJ. And the slope efficiency of the former is about 5 times higher than the value of the latter.

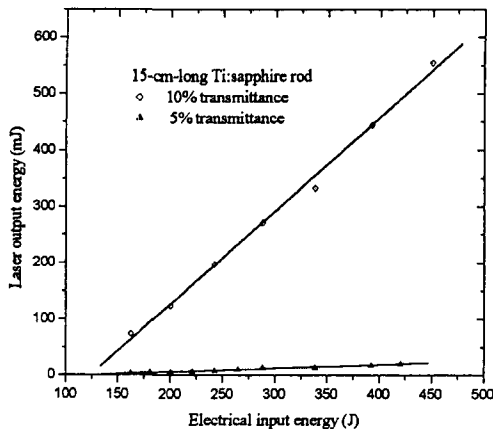


FIG. 6. Laser output energy dependent on the electrical input energy and the different transmittance of the output coupler in a double-ellipse-pump-cavity laser.

Comparing the double-partial-ellipse-pump-cavity laser with the four-partial-ellipse-pump-cavity laser, we know that the diameters of their Ti: sapphire rods, lamps, and eccentricities of pump cavities are same. Hence, both of them should have almost the same coupling efficiency between the flashlamps and the Ti: sapphire rods. This demonstrates that much more output energy can be achieved in the flashlamp-pumped Ti: sapphire laser with a longer Ti: sapphire rod when the other geometric parameters are the same. However, the length of Ti: sapphire rod is limited by the thermal lensing and the self-focusing effect in the laser. The thermal lensing effect leads to optical distortion. The self-focusing can catastrophically damage the Ti: sapphire rod. Therefore, an optimal rod length exists in the laser, depending on its application purpose.

## 2. Transmittance of output coupler

The laser output energy versus its transmittance of output coupler in a double-partial-ellipse-pump-cavity laser is shown in Fig. 6. The laser resonator is composed of a concave mirror in the radius of the curvature of 10 m, and a flat output coupler in the transmittance of 5% or 10%. The output energy of the laser with 10% transmittance of the output coupler increases linearly from 74 mJ to 0.55 J, and it is much more than the output of the laser with 5% transmittance of the output coupler of which the output energy varies from 3.3 to 20 mJ in the same range of electrical input energy from 162 to 450 J. We also used the output coupler with 20% transmittance to perform the experiment, but the output energy of the laser with the coupler is lower than the output of the lasers with the output couplers of 5% and 10% transmittance at the same electrical input energy and under the same other conditions. This indicates that there is an optimal transmittance located between 5% and 20%. Therefore, a suitable transmittance of the output coupler will result in more output energy and higher excitation efficiency of the laser. Because a high transmittance of the output coupler yields a great external loss in a laser, it leads to a decrease in intracavity laser power. A low transmittance of the output coupler results in lower output power. This makes an increase in the intracavity laser power. However, the intracavity loss of the laser increases. The internal loss leads to a decrease in the intracavity power. Therefore, an optimized transmittance of the output coupler exhibits. For the laser with the optimized transmittance of the output coupler, the most output energy can be obtained. Otherwise, the laser output energy decreases.

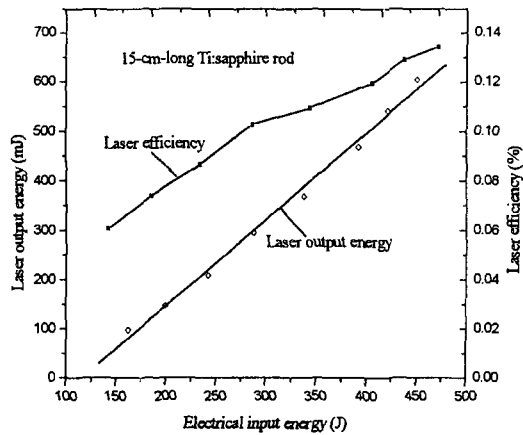


FIG. 7. Laser output energy and efficiency dependent on the electrical input energy in the double-ellipse-pump-cavity laser with 10% transmittance of the output coupler.

An important parameter to evaluate the laser performance is the electrical-to-optical efficiency of a laser. Here we give the electrical-to-optical efficiency versus the electrical input energy in our double-partial-ellipse-pump-cavity laser. It is shown in Fig. 7. The resonator consists of the same mirror and the flat output coupler of 10% transmittance as those in Fig. 6. The mirror and the output coupler are separated by 50 cm. The pulse width of pumping light is 45  $\mu$ s. The result shows that the laser efficiency and laser output energy increases with increasing the electrical input energy. At the electrical input energy of 450 J, the laser efficiency reaches 0.13% and the laser output energy reaches 604 mJ per pulse with a width (FWHM) of 25  $\mu$ s. At that time the peak output laser power is about 15 kW. As a result, the output energy versus the electrical input energy in this laser can be described as  $E_{out} = 0.175\%(E_{in} - 116.5)$ .

### 3. Fluorescent converter

Note that all of the results above are obtained without using a fluorescent converter for the flashlamp-pumped Ti: sapphire lasers, and the geometrical parameters of pumping cavities are not optimal. Fig. 8 shows the laser output energy versus the electrical input energy of the four-partial-ellipse-pump-cavity laser with or without LD490 fluorescent converter. The resonator is 50 cm long. LD490 dye diluted in an ethanol-water solution and in a concentration of  $4.5 \times 10^{-4}$  mol/l is used as a fluorescent converter. The experimental result shows that the output laser energy also increases linearly with the electrical

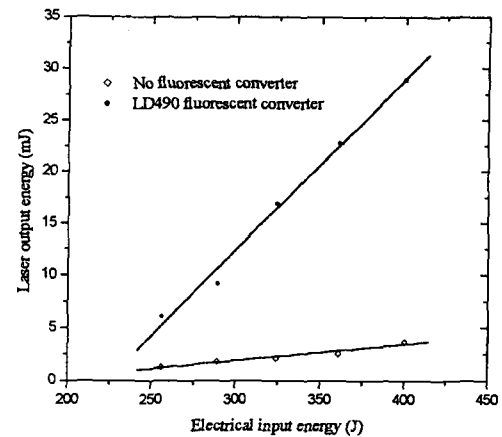


FIG. 8. Laser output energy as a function of electrical input energy of the four-partial-ellipse-pump-cavity laser with fluorescent converter and without fluorescent converter.

input energy. And the laser output energy is much higher than the value without using the converter under otherwise identical conditions. The figure shows that the laser output energy increases about 7 times with the fluorescent converter. The output energy changes from 6.1 to 28.9 mJ while the output energy changes from 1.33 to 3.88 mJ without the fluorescent converter at the same input electrical energy from 256 to 400 J. This indicates that LD490 dye is an effective converter to change the flashlamp emission into the absorption band of Ti: sapphire, resulting in more laser energy extraction.

### 4. Pulse duration of flashlamp

The laser output energy as a function of the electrical input energy in various pumping-light pulse widths is illustrated in Fig. 9. LD490 dye diluted in an ethanol-water solution and in a concentration of  $1 \times 10^{-3}$  mol/l is used as a fluorescent converter. The mirror and the output coupler are separated by 45 cm. The laser employs a single-ellipse-pump cavity. It can be seen that the output energy of the laser pumped by a 10- $\mu$ s-width light pulse from the flashlamp is higher than that pumped by a 45- $\mu$ s-width light pulse at the same electrical input energy. The output energy of the laser pumped by 45- $\mu$ s-width light pulse is higher than that pumped by a 65- $\mu$ s-width light pulse. This reveals that more laser energy can be achieved if the Ti: sapphire is pumped by shorter pulse of flashlamp emission.

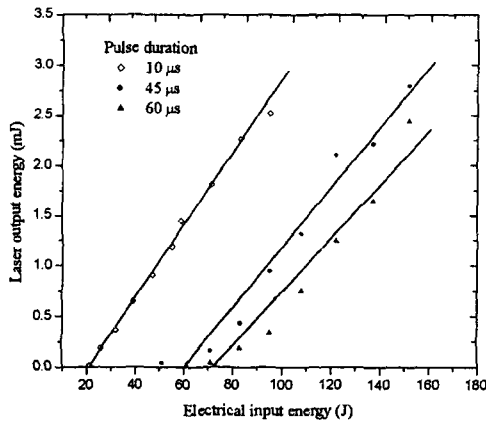


FIG. 9. Laser output energy dependent on the electrical input energy of the single-ellipse-pump-cavity laser for various pumping-light pulse durations.

#### IV. CONCLUSION

We carried out an experimental study on the flashlamp-pumped Ti: sapphire lasers with single, double, four- partial-ellipse-pump cavities. Our results showed that a 15-cm-long Ti: sapphire laser delivered up to 20 times the energy and the efficiency of a 10.2-cm-long Ti: sapphire laser on the conditions of the same lengths of resonators ranging from 50 to 80 cm and the equal electrical input energy lower than 450 J per pulse. In other words, much more laser output energy will be achieved if a longer Ti: sapphire rod is used instead of a shorter rod. However, the length of Ti: sapphire rod is limited by the thermal lensing and self-focusing effect that takes place in the laser. The thermal lensing effect leads to optical distortion. The self-focusing can catastrophically damage the Ti: sapphire rod. Therefore, an optimal rod length exists in the laser, depending on its application purpose. A suitable fluorescent converter also increases the laser output. We used dye LD490 as a fluorescent converter to make the output energy increase 7 times in a four-ellipse-pump-cavity laser. Unfortunately, the dye lifetime limits its wide application

in a practical laser. But, we achieved the laser output energy of 604 mJ for a single pulse with a width of 25  $\mu$ s in a double-ellipse-pump-cavity laser without fluorescent converter at the electrical input energy of 450 J and the pumping-light pulse of 45  $\mu$ s. If we use LD490 as a fluorescent converter in the laser, we can obtain much higher energy. In addition, our results showed that a shorter flashlamp pulse results in more laser output energy and higher laser efficiency. And an optimal transmittance of the output coupler will make a great increment of laser output. We performed the experiment on the laser with 5%, 10% and 20% transmittance of the output coupler. The experimental result revealed that the most output laser energy and the highest laser efficiency were achieved at the transmittance of the output coupler of 10%. Further optimization of the transmittance of the output coupler will deliver more energy and efficiency.

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