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A high output energy (5J) and high repetition rate (100Hz) laser system is required for the edge Thomson scattering system in ITER. A YAG laser (Nd:YAG laser) is a first candidate for the laser system satisfying the requirements. It is important to develop a high beam quality and single longitudinal mode (SLM) laser oscillator in order to realize this high power laser system. In this design work, following activities relating to the SLM laser oscillator have been carried out: design of the laser head and the resonator, estimation of the output power for the SLM laser oscillator, consideration of the feedback control scheme and consideration of interface for amplification system to achieve required performance (5J, 100Hz). It is expected that the designed laser diode (LD) pumped SLM laser oscillator realizes: 100 Hz of repetition rate, 10 mJ of output energy, 10 ns of pulse width, single longitudinal mode, TEM_{00} of transversal mode, divergence less than 4 times of the diffraction limit, energy stability within 5%.

Keywords: ITER, Thomson Scattering, YAG Laser, Single Longitudinal Mode, Stimulated Brillouin Scattering, Phase Conjugate Mirror, Laser Diode (LD) Pump

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*Hamamatsu photonics K.K

ITER 周辺トムソン散乱計測装置用単一縦モードレーザー発振器の設計

日本原子力研究開発機構　核融合研究開発部門
ITER プロジェクトユニット
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ITER の周辺トムソン散乱計測装置では、高い出力エネルギー（5J）で高繰り返し（100Hz）のレーザーシステムが求められている。YAG レーザー（Nd:YAG レーザー）は、これらの性能を満たすレーザーシステムの第一候補である。このような高出力レーザーを実現するためには、高いビーム品質と単一縦モードのレーザー発振器の開発が重要である。そのため、レーザーヘッドと共振器の設計、単一縦モードレーザーの出力パワーの評価、単一縦モード発振のための制御の検討、最終性能（5J, 100Hz）を達成するための増幅器などのインターフェース、の検討を行った。ここで設計した半導体励起の単一縦モードレーザーシステムが、繰り返し 100Hz、出力エネルギー10mJ、パルス幅 10ns、単一縦モード、TEM_{00} の横モード、発散角は回折限界の４倍以下、エネルギー安定度は５％以内の性能を実現できる見通しを得た。

本研究は、ITER 移行措置活動の一環として実施した、タスク(ITA 55-10)に基づくものである。

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1. Introduction

A high output energy (5J) and high repetition rate (100Hz) laser system is required for the Thomson scattering system for measurement at the edge region of ITER plasmas. A YAG laser (Nd:YAG laser) is a first candidate for the laser system satisfying the requirement. Taking into account long distance propagation of the laser beam on ITER, high beam quality is required. However, it is very difficult to produce the high-power and the high-quality laser beam from a laser oscillator simultaneously. A general technique is that a low-power laser beam, which is generated by high-beam-quality laser oscillator, is amplified by laser amplifiers to obtain a required high-power and high-quality laser beam. This technique is called the Master Oscillator Power Amplifier (MOPA). In the case of the solid-state laser such as a YAG laser, it is effective to compensate the wavefront distortion appeared in the high-power amplifier (amplifying rod of the YAG laser) using a phase conjugate mirror.[1-4] A stimulated-Brillouin-scattering-based phase conjugate mirror is commonly used for this purpose, and the laser of the single-longitudinal-mode is required in order to operate the phase conjugate mirror. Therefore, the laser oscillator needs to maintain the single-longitudinal-mode oscillation throughout the long time (> 10 min.).

Design of the single-longitudinal-mode (SLM) laser oscillator, in which long-time high stability operation is possible, is reported in this report. Following items are included in this design work.

- Design of the laser head and the resonator (see section 2)
- Estimation of the output power for the SLM laser oscillator (see section 2)
- Consideration of the feedback control scheme to obtain SLM (see section 3)
- Consideration of the Interface for amplification system to achieve final performance (5J, 100Hz) (see section 4)

Note that designs of the high-power amplifier and the total laser system are out of scope in this design work. Designs of the high-power amplifier and the total laser system will be carried out in a near future.

2. Design of Single-longitudinal-mode (SLM) Laser Oscillator

2.1 Specifications for the design

The target specifications of the single-longitudinal-mode (SLM) laser oscillator are summarized in Table 1.

Table 1. Required specifications of the single-longitudinal-mode (SLM) laser oscillator

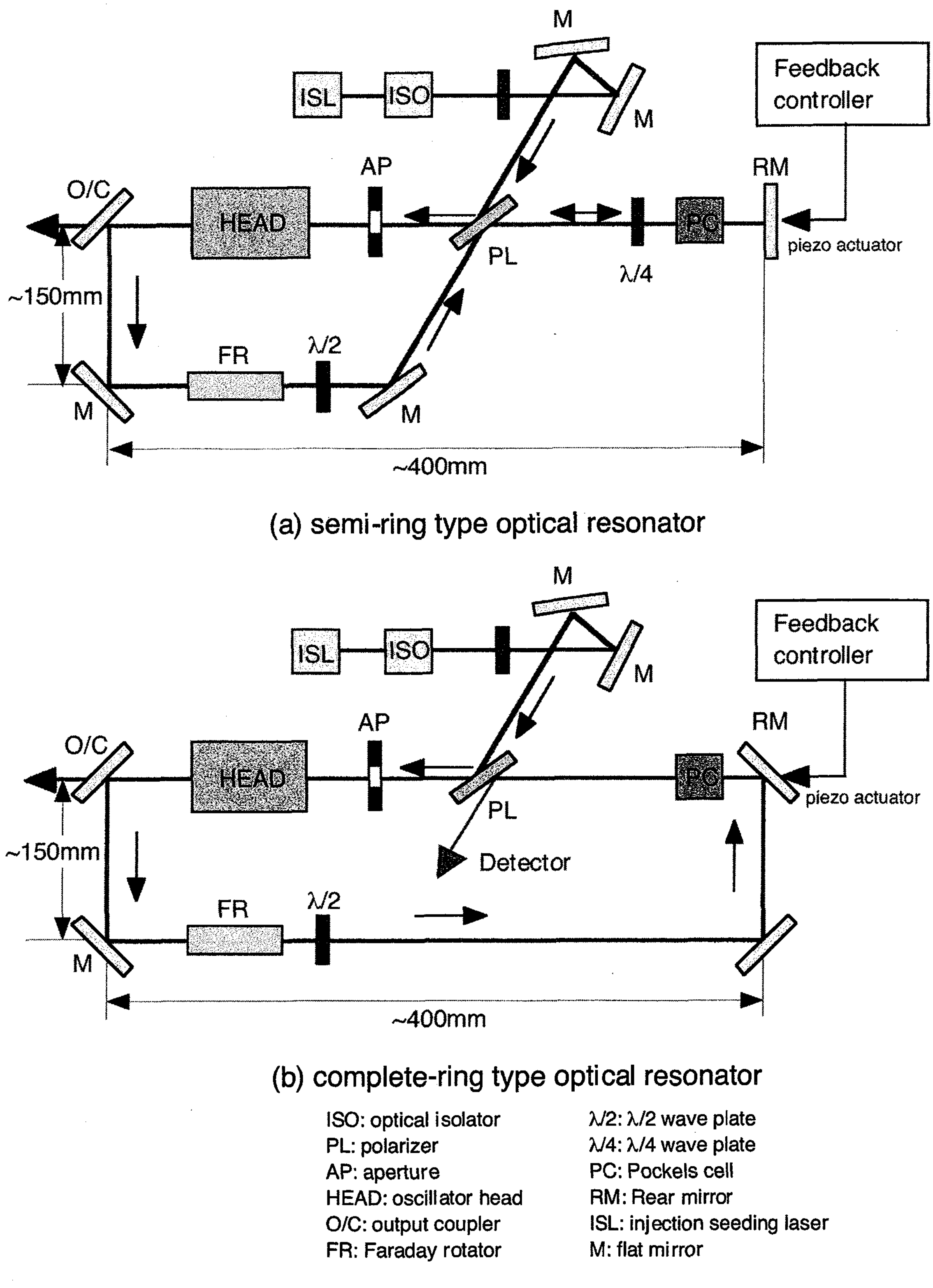
Item	Specification (target)
Operation mode	Pulse oscillation
Wavelength	1064 nm
Repetition rate	100 Hz
Output energy	10 mJ
Pulse width	10 ns
Divergence	< 4 times of the diffraction limit
Pumping method	Laser diode (LD) pumping
Longitudinal mode	Single
Transverse mode	TEM_{00}
Linear polarization	100:1
Stability of the output energy	$\sigma/E < \pm 5$ % (10 min.)
Jitter of output pulse	< 1 ns

2.2 Configuration of optical resonator for the SLM laser oscillator

To generate the SLM laser beam, the configuration of optical resonator of a ring type rather than the Fabry-Perot type is generally used. Since standing wave of electric field rises in the optical resonator of the Fabry-Perot type, the spatial hole burning effect of the gain arises in the laser medium. Therefore, the standing wave profile of the electric field changes every moment, and the laser wavelength fluctuates. On the other hand, since the laser beam propagates unidirectionally in optical resonator of the ring type, the standing wave does not arise. The wavelength of noise level light which contributes to the laser oscillation is maintained, and can go round in the optical resonator, because the standing wave does not arise. Accordingly, the emission wavelength is easily stabilized in the ring optical resonator, and the ring optical resonator is suitable for the SLM oscillation. Two types of optical configuration for ring resonator have been considered in this design work. Figure 1 shows basic configurations of optical resonator for the SLM laser oscillator, (a) "semi-ring type" and (b) "complete-ring type", respectively. The semi-ring configuration has been adopted in the JT-60 Thomson scattering system.[2-4] This configuration has few advantages. For example, a hold-off voltage of the Q switch can be lowered, and the oscillation threshold can be lowered. This configuration is often used for cost reduction due to these advantages. However, the semi-ring type is rather inferior to the complete-ring type in obtaining the SLM since there is a path where the laser beam goes back and forth on an identical path between a polarizer and a rear mirror. This path is indicated as "↔" in Figure 1(a). Therefore, in order to design the stabilized SLM oscillator, the complete-ring type resonator has been considered. Laser diode (LD) pumping method has been adopted in order to reduce the fluctuation of the thermal load of laser medium.

Furthermore, reliability of the stable SLM oscillation is guaranteed by using an injection seeding technique. The injection seeding is accomplished by introducing radiation from a low power, CW, stable single-frequency laser (seeder) into the Q-switched laser cavity during a pulse buildup period. Both the injected SLM laser light (seed light) and spontaneous emission from the master oscillator (slave laser) will be regeneratively amplified in the slave cavity. If the injected signal has enough power on a slave cavity resonance, corresponding single axial mode eventually saturates the homogeneously broadened gain medium, and prevents development of any other axial modes from spontaneous emission in the absence of spatial hole burning.[5)] In this design, a $Nd:YVO_4$ laser (CW), which is pumped by laser diodes, has been adopted as the injection seeder. Spectral band width of the injection seeder is about 10 MHz.

Specifications of optical components used in the ring oscillator (Fig.1(b)) is summarized in Table 2.



(a) semi-ring type optical resonator

(b) complete-ring type optical resonator

ISO: optical isolator	λ/2: λ/2 wave plate
PL: polarizer	λ/4: λ/4 wave plate
AP: aperture	PC: Pockels cell
HEAD: oscillator head	RM: Rear mirror
O/C: output coupler	ISL: injection seeding laser
FR: Faraday rotator	M: flat mirror

Figure 1. Configuration of optical resonator: (a) semi-ring type, (b) complete-ring type.

Table 2. Specifications of optical components for the ring oscillator

Symbol	Name	Specifications	Note
ISO	optical isolator	TGG crystal, magnetic field by permanent magnet, 5 mm diameter, 45 deg Faraday rotation	with polarizers
PL	polarizer	plate type or air-gaped prism polarizer	
AP	aperture	1~2 mm diameter	
HEAD	oscillator head	3 mm diameter of YAG rod	LD pump
O/C	output coupler	surface A: transmissivity 50% @1064nm, surface B: AR coat	
FR	Faraday rotator	TGG crystal, magnetic field by permanent magnet, 5 mm diameter, 45 deg Faraday rotation	
$\lambda/2$	$\lambda/2$ wave plate	10 mm diameter	
$\lambda/4$	$\lambda/4$ wave plate	10 mm diameter	for semi-ring resonator
PC	Pockels cell	KD*P or BBO crystal	
RM	Rear mirror	surface A: Reflectivity > 99.8% @1064nm, surface B: AR coat	
ISL	injection seeding laser	Nd:YVO_4 laser, SLM, CW, spectral band width ~10MHz	
M	flat mirror	surface A: Reflectivity > 99.8% @1064nm, surface B: AR coat	

2.3 Estimation of output power for the SLM laser oscillator

From Table 1, laser output energy of 10 mJ is required. Generally, about 20% of light-light transformation efficiency is expected for a YAG laser which oscillates with longitudinal and transversal multimode. In this case, about 50 mJ is sufficient for pumping energy of laser diode.

The single transversal mode is also necessary, when the SLM oscillates. In order to obtain single transversal mode (TEM_{00}), an aperture is inserted in the resonator, and diffraction loss is compulsorily applied to the higher mode. The output energy is reduced to less than a half by the opening restriction to the aperture. The TEM_{00} oscillation of about 15 mJ has been obtained in the 360 mJ pumping in the test at Hamamatsu Corporation (4% of light-light transformation efficiency) without any longitudinal mode control. Note that the configuration of the laser cavity was not ring type, but the configuration was Fabry-Perot resonator in this test. In case of the SLM oscillation, typical output energy obtained from an oscillator is 10 mJ or less. In order to obtain output energy more than 10 mJ as designed value of the SLM oscillator, the pumping energy of LD is set 360 mJ, and calculations of the output performance are carried out. It is the appropriate setting to obtain 10 mJ of output energy from the SLM oscillator as possible output energy

The Q-switching is necessary for realizing the SLM laser oscillator that satisfies the specification shown in Table 1. Here, the complete-ring type resonator shown in Figure 1(b) is modeled, and expected Q-switched output energy and pulse width are evaluated.

In this model, switching time is set zero, and output energy E_{out} and laser pulse duration τ are calculated with following analytical equations,

$$E_{out} = n_i\left(1-\frac{n_f}{n_i}\right)Vn_0 h\nu \frac{\ln R_1}{\ln R_1 + \ln(1-L)}, \tag{1}$$

$$\tau = \frac{\ell_C}{c(L-\ln R_1)} \frac{n_i\left(1-\frac{n_f}{n_i}\right)}{n_i - n_t\left(1+\ln\frac{n_i}{n_t}\right)}, \tag{2}$$

where,

n_i: initial population inversion per unit volume normalized by n_0,

n_f: final population inversion per unit volume normalized by n_0,

n_t: threshold population inversion per unit volume normalized by n_0,

n_0: Nd ion density [cm^{-3}].

V: excited volume of laser medium [cm^3],

h: Plank constant [Js],

ν: laser frequency [s^{-1}],

R_1: Transmissivity of output coupler,

L: loss in laser cavity per one turn,

ℓ_C: length of laser cavity [cm],

c: light speed [cm/s].

Parameters of n_i, n_t are calculated with following equations,

$$n_i = \eta \frac{E_{in}}{n_0 h \nu V}, \tag{3}$$

$$n_t = \frac{\ln\left(R_1(1-L)\right)^{-1}}{\sigma \ell_p n_0}, \tag{4}$$

where,

η: efficiency of pumping,

E_{in}: pumping energy,

σ: cross section for stimulated emission,

ℓ_p: length of pumping.

Parameter of n_f is calculated from n_i, n_t with the following relation,

$$\frac{n_f}{n_i} = e^{\left(\frac{n_f}{n_t} - \frac{n_i}{n_t}\right)}. \tag{5}$$

Since the target of output energy is 10 mJ as shown in Table 1, dependences of Q-switched pulse energy and pulse width on the transmissivity of output coupler R_1 have been evaluated. In the evaluation, the energy loss in the laser cavity per one turn L is a variable parameter, L=5%, 10%, 15% were calculated respectively. Conditions of the evaluation are as follows,

E_{in}= 360 [mJ] (=1.8 kW×200 μs),

$\eta = \eta_T \eta_S \eta_q \eta_a \eta_{rep} = 0.37$,

where,

η_T=0.9: radiation transfer efficiency,

η_S=0.759: Stokes factor,

η_q=0.9: quantum defect,

η_a=0.9: absorption efficiency,

η_{rep}=0.67: relaxation in pumping duration,

V=4.24×10^{-1} [cm^3] (=ϕ3mm×ℓ6cm),

σ=2.8×10^{-19} [cm^2],

n_0=2.1×10^{20} [cm^{-3}],

ℓ_C=100 [cm].

Evaluated results were shown in Figures 2 and 3. It has been found that optimum transmissivity of output coupler is around 50 % under conditions above. Although the target output energy is 10 mJ, Fig. 2 shows that the expected energy exceeds 15 mJ and the present design has a margin of 1.5 times. From Fig. 3, the expected pulse width is evaluated to be 11 ns, which is almost the same as the target value of 10 ns. It is possible to make the pulse duration in the calculation to be 10 ns if the cavity length is 80~90 cm. Note that actual output energy is lower than the evaluated value and actual pulse width tends to be long, since the switching time is assumed to be the zero ideally.

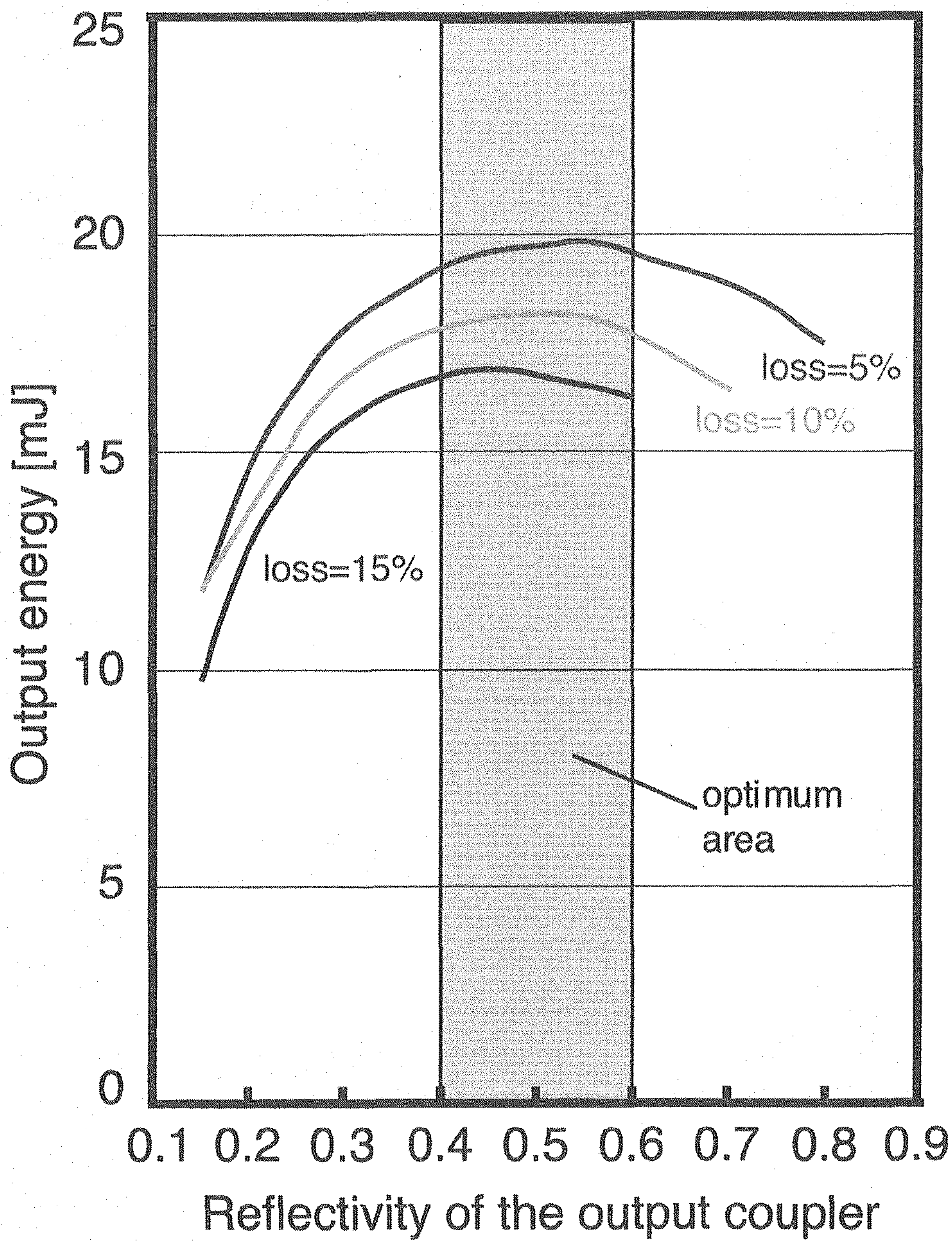


Figure 2. Dependence of output coupling for output energy

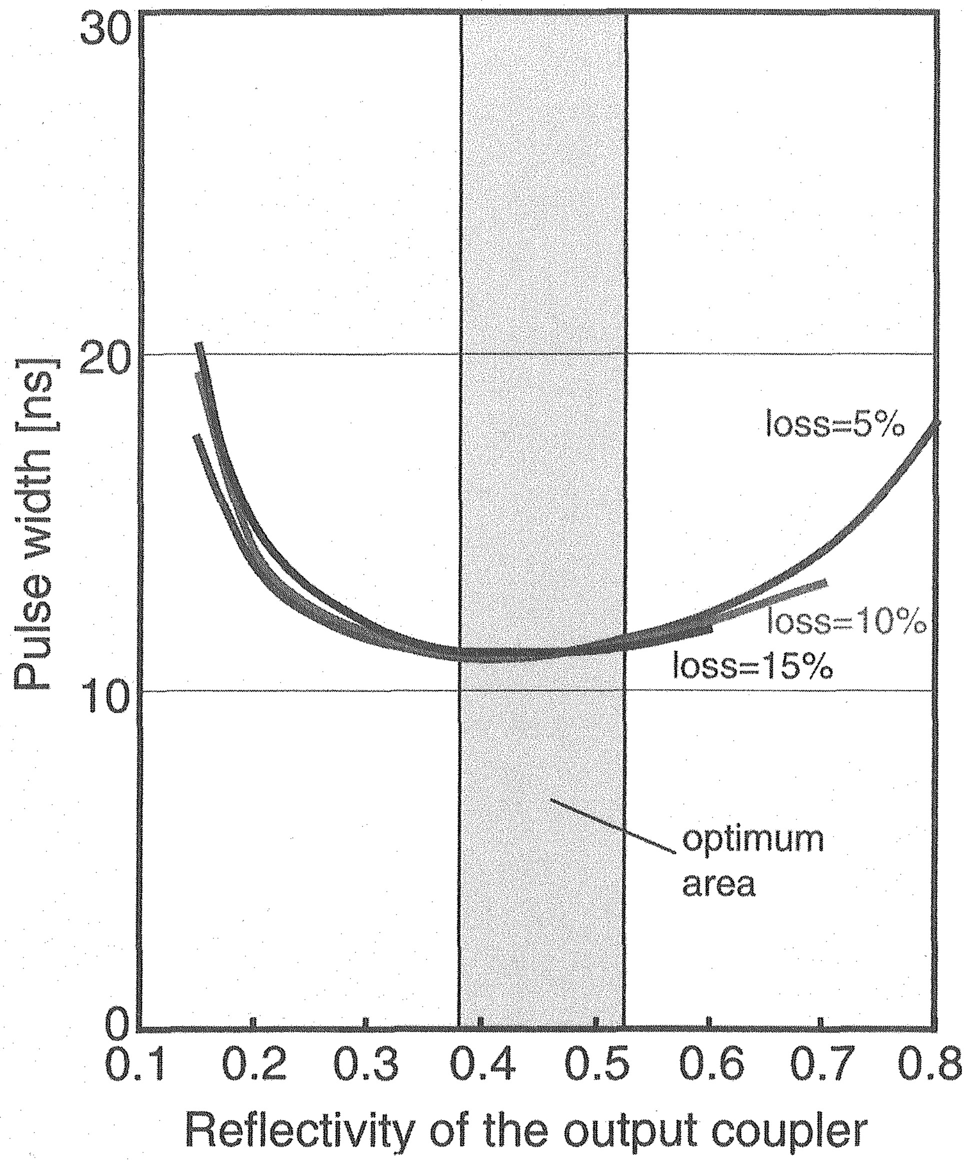


Figure 3. Dependence of output coupling for Q switched pulse width

2.4 Estimation of other performances

The beam divergence, linear polarization, energy stability and the jitter of the output pulse have been confirmed by the similar laser system developed at JAEA until now.

The beam divergence is specified as "less than 4 times of the diffraction limit" in Table 1. It is possible to obtain the beam divergence which is close to the diffraction limit in theory, because the transverse mode has been made fundamental mode (TEM_{00}) in order to get the SLM. An example of the beam profile, which has been observed using the similar SLM laser [6], is shown in Fig. 4. In case of the example, the beam profile is a Gaussian profile, and the beam divergence is less than 2 times of the diffraction limit.

The linear polarization is specified as "100:1" in Table 1. In the resonator model of the Q-switched laser for the design calculation, a single direction of large polarized loss is applied by polarizer placed in the laser resonator. Therefore, performance of the linear polarization of oscillating laser beam in theory is very high. The linear polarization better than 100:1 has been obtained actually in the typical Q-switched oscillation of laser beam, so far.

The energy stability and the jitter of output pulse are specified as "$\sigma / E < \pm 5\%$ (10 minutes)" and "< 1ns", respectively. Typical waveforms of the Q-switched pulse from an injection-seeded SLM oscillator are shown in Fig. 5. It shows waveforms of (a) a single shot and (b) 500 Hz Q-switched pulses superimposed for 10 seconds on the oscilloscope. The fluctuation of the energy is within $3\sigma / E < \pm 2.5\%$, which sufficiently satisfies the required specification of $\sigma / E < \pm 5\%$. However, the number of superimposed shots is only 5,000, which is an order of magnitude smaller than 60,000 shots corresponding to 100 Hz pulses for 10 minutes. It has been confirmed that the stability of output energy is ensured while the external feedback control is in operation in the test. Figure 5 shows that the jitter has been settled within the line width (under 1ns) of the oscilloscope.

Therefore, it can be expected for the development of laser systems so far that required specifications are promissingly achieved.

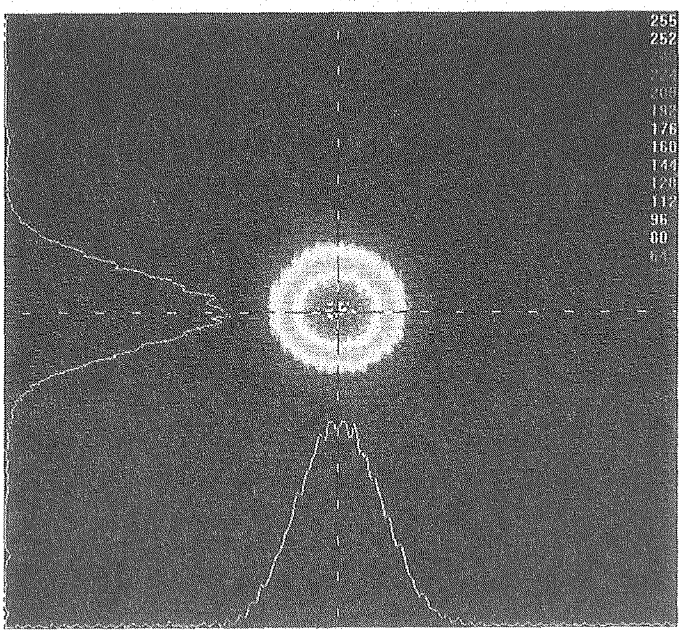


Figure 4. Example of beam profile in SLM oscillation

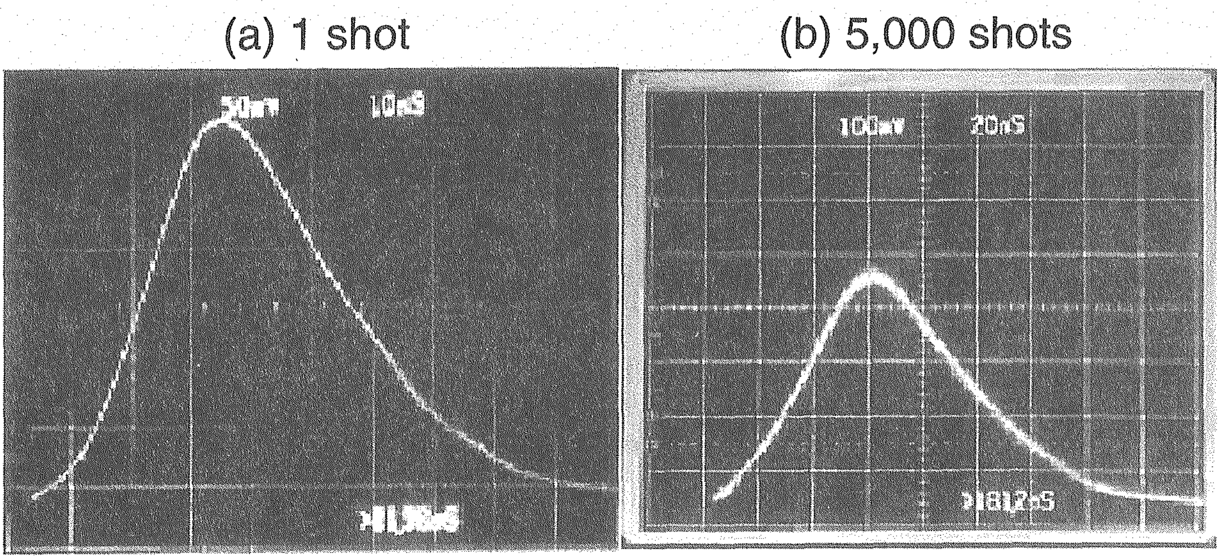


Figure 5. Examples of wave forms of Q-switched pulse in SLM oscillation. (a) single shot wave form, (b) stored wave form for 5000 shots

2.5 Design of laser head

Typical peak power of QCW (quasi-continuous-wave) pulse of the laser diode for pumping is 100 W per unit module (1 cm LD bar). In this design, the pumping pulse width is assumed to be 200 μs, taking the fluorescence lifetime of the Nd:YAG medium into account.

From the LD module (1 cm LD bar) for pumping, the light energy of 20 mJ per pulse is emitted. Since 360 mJ is necessary as total pumping energy as described in previous sections, it is necessary to pump the Nd:YAG crystal using 18 LD modules. Taking into account the uniformity of the pumping, the configuration in which the laser medium can be pumped from the multiple directions as much as possible is desirable. However, the 3-way pumping is generally carried out due to the mechanical restriction. Schematic of the 3-way pumping is shown in Fig. 6(a). The pumping energy of the basic configuration of 3-way pumping (3 LD arrays) is 60 mJ, and the pumping of 180 mJ is possible by joining the 3 basic configurations (9 LD arrays). When another pumping head using 9 LD arrays, which rotates 60 degree against anterior pumping head, is placed coaxially as shown in Fig. 6(b), the uniformity of pumping profile in the rod can be more improved, and total 360 mJ of pumping energy is achievable.

For example, 3-way × 3-sets LD (9 LD arrays) pumped single laser head produced by Hamamatsu Corporation is shown in Fig. 7. Two LD pumped heads is necessary in order to obtain the pumping energy of 360 mJ in total. The size of this laser head is 70 mm wide × 80 mm height × 75 mm long, approximately. The diameter of the laser rod is 3 mm as considered in Section 4.2.3. For the LD bars for pumping, three sets of HAMAMATSU LA0238-808QCW1x3 are used. The driving voltage and current is 6 V and 100 A, respectively. In the case of operation at a pulse width of 200 μs and a repetition rate of 100 Hz, the total power consumption per laser head is 36 W. The cooling methods for LD and the laser rod are water-cooling. Lifetime of the LD is about 10^9 shots. In the case of 100 Hz operation, it can be used for one year even if it is operated for 8 hours continuously every day.

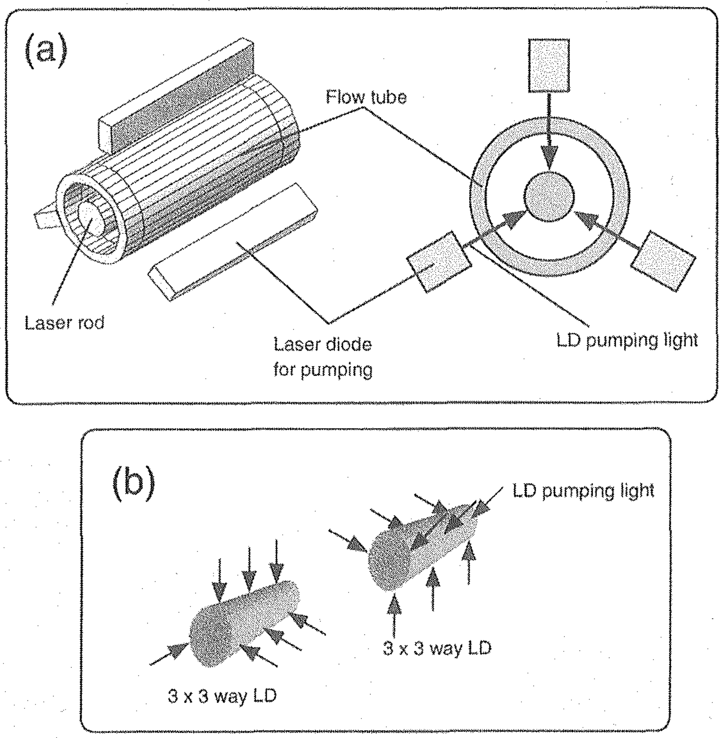


Figure 6 (a) schematic of the 3-way pumping head, (b) schematic of the two heads in series (9x2 LD arrays)

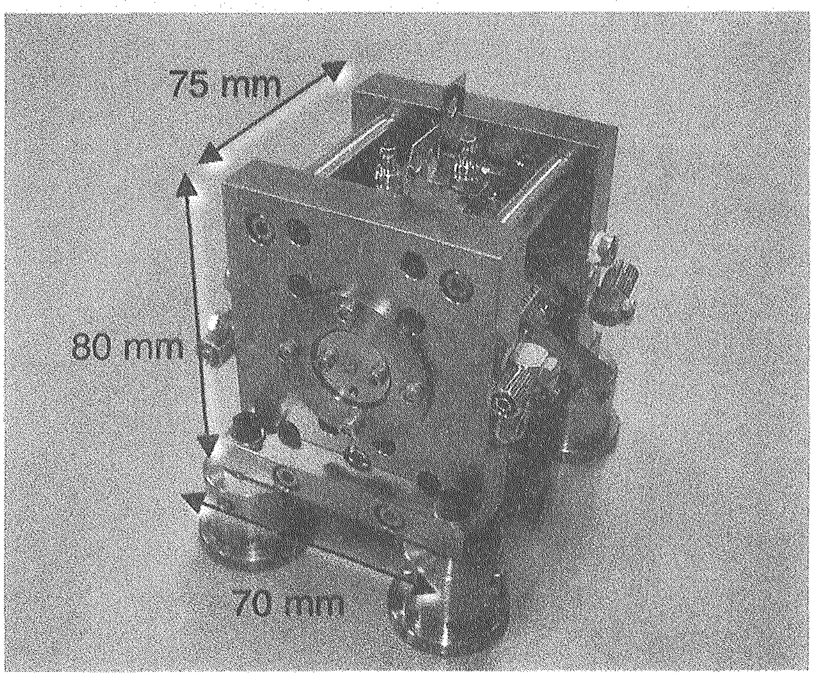


Figure 7 3-way LD pumped laser head

3. Design of Feedback Control Scheme for SLM Oscillation

3.1 Factors of laser wavelength fluctuation and elimination method

The fluctuation of the laser wavelength originates from optical components, refractive index variation of the air and change in the resonator length. These fluctuation factors are due to the change in the pressure, humidity and temperature of the air. It is important to remove these factors as much as possible. In this section, techniques that can eliminate the fluctuation factors are considered.

Typical oscillating band width of Q-switched Nd:YAG laser of which pulse width is 10 ns is about 44 MHz, and the stability of the center wavelength is required to be approximately ±5 MHz. The frequency at the laser wavelength is 283 THz, and the stability of the wavelength requires $\Delta\lambda/\lambda \sim \pm 5\text{MHz}/283\text{THz} \sim \pm 1.7\times10^{-8}$. On the basis of the requirement of this stability, the main fluctuation factors are analyzed without the error allocation. Followings are conditions for maintaining the SLM oscillation.

(1) Laser medium

- Requirement for the refractive index stability ($\Delta n/\Delta T \sim 7.3\times10^{-6}$)

  From $\Delta\lambda/\lambda \sim \Delta n < 1.7\times10^{-8}$, required temperature stability is calculated to be $\Delta T = \pm 0.0023$ K, when the temperature is T=300 K.

- Requirement for the change in the crystal length ($\alpha \sim 7.5\times10^{-6}$)

  From $\Delta\lambda/\lambda \sim \Delta\ell/\ell \sim \alpha\cdot\Delta T/\ell < 1.7\times10^{-8}$, required temperature stability is calculated to be $\Delta T = \pm 0.0023$ K, when the temperature is T=300 K.

(2) Structure of optical resonator

- Requirement for the change in the cavity length

  Main mechanism components used for the resonator is assumed to be stainless steel. Since the coefficient of linear expansion α is 10×10^{-6}, required temperature stability is $\Delta T = \pm$ 0.0017 K.

- Requirement of the mechanical vibration of the resonator

  In case of the cavity length is 1 m, the slippage on the optical axis must be $\Delta L <$ 17 nm in order to satisfy $\lambda \sim \Delta\ell/\ell < 1.7\times10^{-8}$.

(3) Influence of the air

Requirements for the stability of the temperature, humidity and pressure of the air are calculated with the equation of the refractive index of the standard air, $n_r - 1 = 10^{-6}\{103.82(P_S/T) + (P_W/T)\}$. Where, P_S, P_W and T are partial pressure of the air [mmHg], partial pressure of the vapor [mmHg] and temperature [K], respectively. Requirements for the stability of the temperature, humidity and pressure are calculated independently,

temperature: $\Delta T < \pm 0.02$ K,

humidity : $\Delta E < \pm 1$ % RH,

pressure : $\Delta P < \pm 0.05$ Torr.

It is important to eliminate these disturbing factors in order to maintain the long-time stability of SLM oscillation. However, it is not realistic to ideally maintain the stabilities of temperature, humidity, pressure of the air and to eliminate the mechanical vibration. Adding the stable feedback control system with a fast response is a candidate method for eliminating disturbance factors. Concretely, following schemes have been considered.

- The cooling system in which highly precise temperature control is possible is used.
- The appropriate material is chosen for mechanical components.
- The oscillator is isolated from the external environment using an appropriate case.
- The laser system is installed in the air-conditioned clean room.

Fluctuation factors of laser wavelength and approaching the stabilization are summarized in Fig. 8.

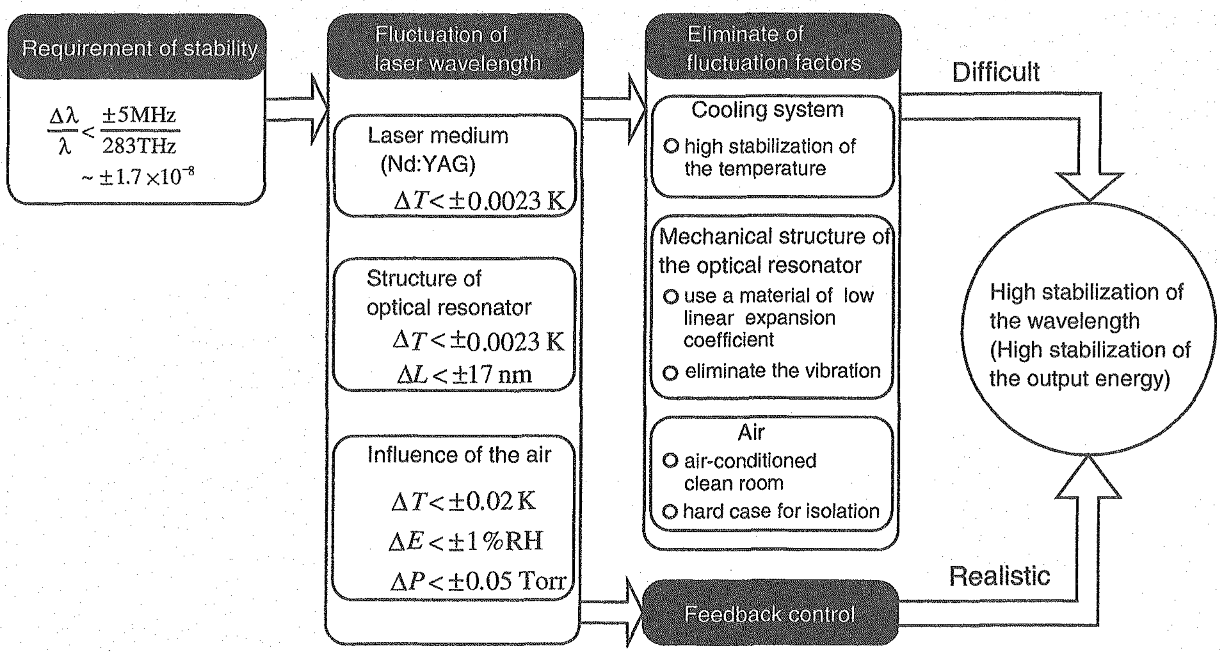


Figure 8. Schematic of the fluctuation factor of laser wavelength and approaching the stabilization

3.2 Design of feedback control scheme for SLM oscillation

From the consideration in the previous section, the cavity length must be controlled with the accuracy under several tens nanometers in order to maintain stably the SLM oscillation for a long time. The frequency of the longitudinal mode in the resonator must be adjusted to the frequency of the injection seeder. By performing this feedback control, the weak SLM oscillation light introduced from the seeder can be confined as seed light in the resonator. Since the frequency of laser light is determined by that of the injection seeder, the

SLM oscillation is ensured by the feedback control.

An example of the composition of the cavity length control system is shown in Fig. 9. The system consists of followings.

(1) Detector: biplaner phototube, e.g. HAMAMATSU R1193U
(2) Universal frequency counter: e.g. Agilent technologies 53132A
(3) Computer: e.g. personal computer which can use GPIB interface
(4) Piezo-electric actuator with the controller: e.g. piezo-electric actuator: Piezomechanik GmbH, HPSt 150/14-10/12 VS22 (uniaxial drive), controller: Piezomechanik GmbH, PisiCon 150-1

The piezo-actuator mounted on the resonator mirror can change the cavity length. The universal frequency counter measures a time difference between a trigger signal of Q-switch and a rise of the laser pulse. The computer controls the changing of the cavity length in order to minimize the time difference measured by the universal frequency counter.

The time difference between the trigger signal of Q-switch and the rise of laser pulse is minimized during the SLM oscillation as shown in Fig.9(lower). The universal frequency counter measures a time difference between the trigger signal of Q-switch and the rise of the laser pulse in a time interval of about 20 ms and the result is sent to the computer. The control of the laser cavity length starts when a time difference measured by the universal frequency counter exceeds the preset value. In case that the time difference is less than the preset value, the voltage for the piezo-actuator is retained.

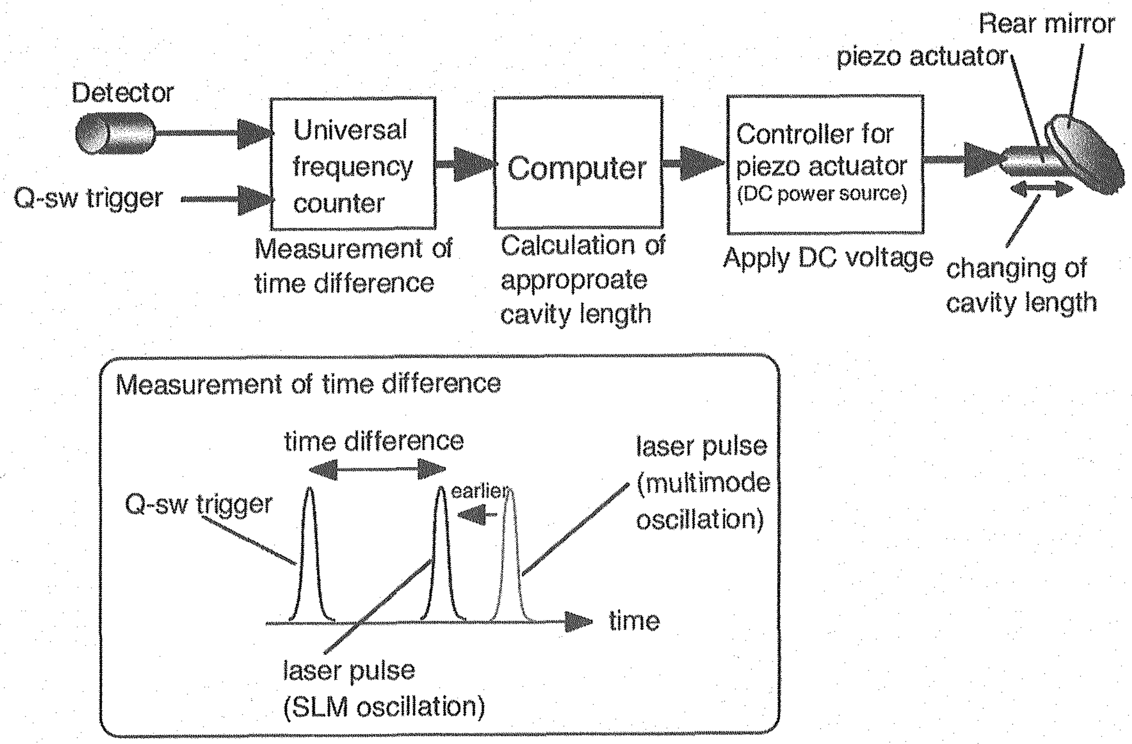


Figure 9 Schematic of cavity length control system

3.3 Feedback control sequence

The time difference between the trigger signal of Q-switch and the rise of laser pulse is minimized during the SLM oscillation. The reasons are as follows. In case there is no injection seeding, the laser oscillation starts from the light of the noise level. In the case of the injection seeding, since the SLM oscillation light from the seeder becomes the seed light, the number of photons, which contribute to the oscillation, predominates over that of the noise level. Therefore, the build-up timing of the laser oscillation becomes faster. However, if the longitudinal mode frequency of the Q-switched oscillator as the host does not agree with that of seeder, the seeder light becomes the noise, and the Q-switched oscillator changes to the multimode oscillation condition. The rising time of the laser oscillation does not become faster in this case. Using this characteristic, the basic control procedure for maintaining the SLM oscillation has been designed as follows.

(1) The applied voltage to the piezo-actuator is swung.

(2) The relationship between applied voltage and time difference from the trigger signal of Q-switch to the rise of laser pulse is confirmed.

(3) The build up time of laser pulse is roughly adjusted to be shortest.

(4) The applied voltage to the piezo-actuator is slightly vibrated, and the build up time of laser pulse is adjusted to be shortest.

(5) If the buildup time exceeds the preset value, the buildup time is adjusted again by the procedure (1)-(4).

The conceptual control scheme by the basic control procedure mentioned above is shown in Fig. 10. The similar laser system with the feedback control scheme based on the approach of this basic control procedure has already been developed and the long-term stabilization of the SLM oscillation has been successfully achieved.[6] The repetition rate of this laser is 500 Hz.

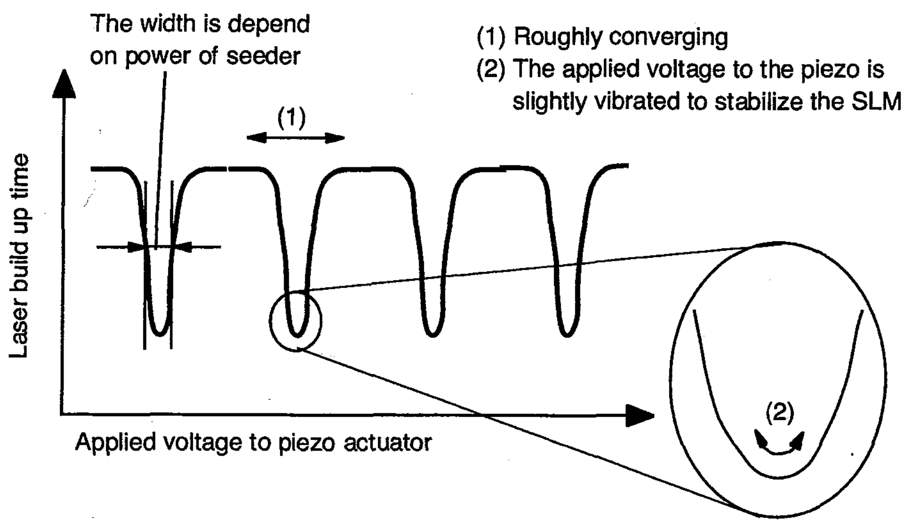


Figure 10 Conceptual scheme of the control by basic control procedure

4. Interface for Amplification System to Achieve Final Performance

In the laser system of the edge Thomson scattering system in ITER, the output energy of 5 J and repetition rate of 100 Hz is required as the final performance. To obtain the final performance, following design has been carried out. First, pumping methods (LD pumping and flash lamp pumping) have been considered individually and the flash lamp pumping method has been chosen for the amplifier system. Secondly, we have designed the optics configuration for the amplification system using the chosen pumping method, considering the relay-imaging.

4.1 Pumping method for the amplifiers

4.1.1 Laser diode pumped amplifier

The necessary pumping energy is estimated in order to design the amplifier system using the LD pumped amplifier. When 60% of extraction efficiency of the Nd:YAG amplifier and 40% of the upper-level storage efficiency is assumed, the necessary pumping energy is estimated to be 20 J at the minimum because approximately 24% of pumping energy corresponds to 5 J of laser output energy.

In order to extract large output energy of 5 J, the rod diameter more than 12 mm is required because the rod diameter depends on damage threshold of the AR coat on the rod surface. In order to obtain the uniform pumping profile, it is important that pumping light reaches the rod center. In the case of the LD pumping of large diameter rod (> ~10 mm), it is difficult to obtain the uniform pumping profile since the absorption coefficient is so large that the pumping light is generally absorbed at the periphery of the rod.

Recently, Hamamatsu Corppration. has obtained the uniform pumping profile for large diameter rod (12 mm in diameter) by the special pumping technique in the side LD pumping. The performance of the amplifier head is 0.5 J of pumping energy and ~1.3 of small signal gain. The amplifier system with the total output energy of 20 J can be achieved by using 40 heads. However, it is a very large-scale and expensive system.

4.1.2 Flash lamp pumped amplifier

The necessary pumping energy is estimated for the amplifier system using flash lamp pumped amplifier. In the case of Nd:YAG laser, about 3% of the input energy to the flash lamp is stored in the laser medium. Due to the spontaneous emission loss and extraction efficiency, it is possible to extract 1 % of pumping energy as the laser output energy. Therefore, necessary total pumping energy is about 500 J in order to obtain 5 J of the laser output energy.

A flash lamp pumped, large rod diameter amplifier head (14 mm in diameter) being used in the Thomson scattering system in JT-60 has 90 - 100 J of pumping energy at the 50 Hz operation and a small signal gain of 6.4 - 7. The small signal gain of the amplifier heads in the JT-60 system is shown in Fig. 11. The pumping energy over 500J is possible using these six amplifiers. The design using 10-12 heads as a 50 J pump has been also considered so that the thermal load per head is about 5 kW.

At the present time, more compact amplification system can be composed by using the flash lamp pumping at low cost compared to the LD pumping. Therefore, the flash-lamp-pumped amplifier system is chosen in this design. However, the adoption of the LD-pumping method should be considered, if the cost of the LD approaches to that of flash lamp in the near future.

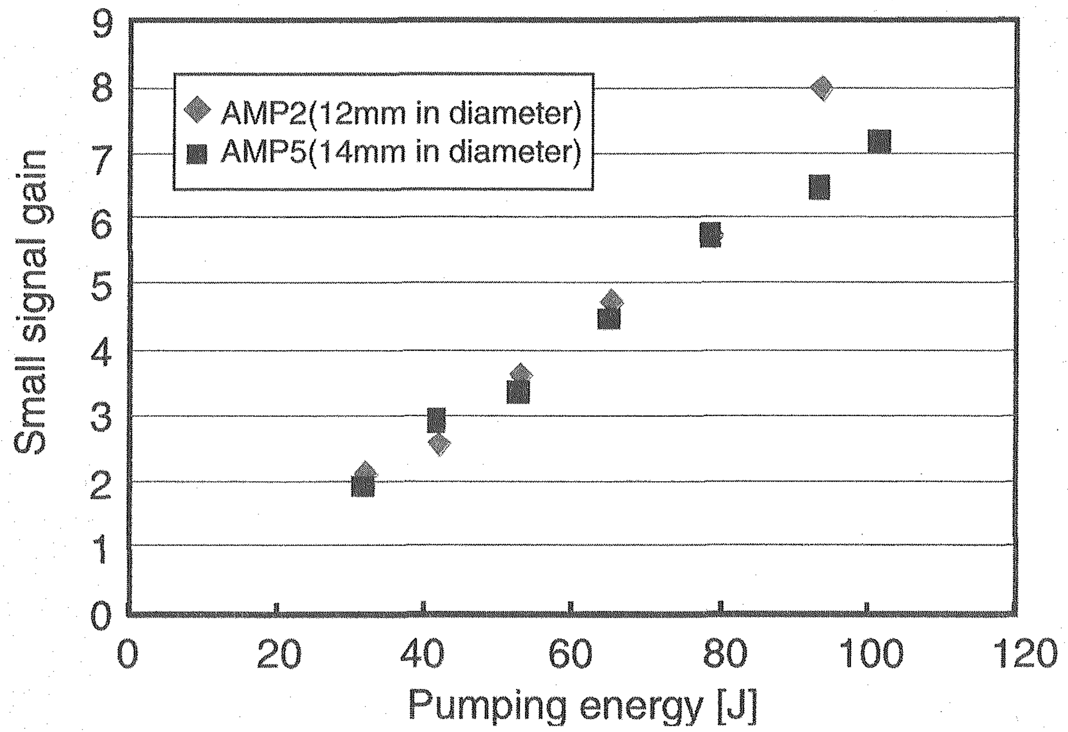


Figure 11 Small signal gain of amplifier heads in the JT-60 laser system

4.2 Optical layout of amplification system

The optical layout, which has double-pass configuration using the flash-lamp-pumped amplifier head (14 mm in diameter), has been considered. For the double-pass configuration, the phase conjugate mirror by stimulated Brillouin scattering is used for the turning mirror. Only one phase conjugate mirror is used for the double-pass configuration, considering the output waveform. The laser beam passes through 6 power amplifiers in series, and is amplified in the double-pass configuration. In order to compensate the depolarization, two amplifiers are made to a pair, and the 90-degree rotating plate is placed between two amplifiers.

In the relay-imaging, the image point must be located in the center of laser rod in order to prevent the appearance of the hot spot by the amplification of the diffraction pattern. It is necessary to place a vacuum cell because the beam converges between 2 convex lenses used in the relay-imaging. Beam propagation taken into account the relay-imaging has been simulated and the beam diameter and divergence has been calculated at each optical component. In the simulation, ABCD matrix method was used. The beam diameter and divergence of the master oscillator are assumed 1.5 mm and 1.293 mrad, respectively. The focal length by the thermal lens effect at the amplifier is assumed 1.5 m. The focal length of the lens for the relay-imaging is 20 cm. Results are shown in Fig. 12 and Table 3.

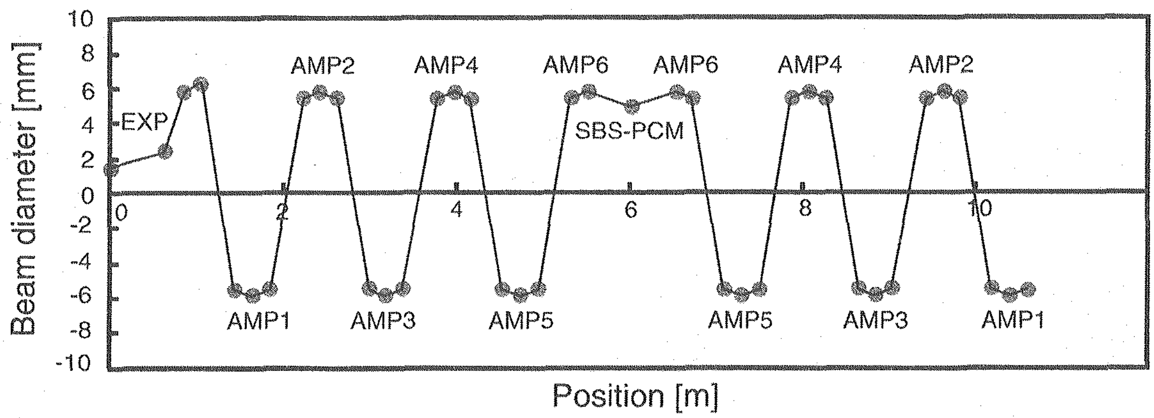


Figure 12 Simulation result of beam propagation with the relay-imaging technique

Table 3 Simulation result of beam propagation with the relay-imaging technique

Optics	Thick-ness	Focal length [m]	Position [m]	Optical matrix				Product of optical matrix				x_0[m]	θ_0[rad]	x[m]	θ[mrad]
				A	B	C	D	A	B	C	D				
OSC-FM	0.000		0					10000	0.0000	0.0000	1.0000	0002	0.00129	150	1.29
	0.636		0.636	1	0.6360	00000	1	10000	0.6360	0.0000	1.0000	0002	0.00129	232	1.29
Lens 1	0.000	-0.15	0.636	1	0.0000	66667	1	10000	0.6360	6.6667	5.2400	0002	0.00129	232	16.78
	0.210		0.846	1	0.2100	00000	1	24000	1.7364	6.6667	5.2400	0002	0.00129	585	16.78
Lens 2	0.000	04	0.846	1	0.0000	-25000	1	24000	1.7364	0.6667	0.8990	0002	0.00129	585	2.16
	0.200		1.046	1	0.2000	00000	1	25333	1.9162	0.6667	0.8990	0002	0.00129	628	2.16
SF1 IN	0.000	02	1.046	1	0.0000	-50000	1	25333	1.9162	-120000	-8.6820	0002	0.00129	628	-29.23
	0.400		1.446	1	0.4000	00000	1	-22667	-1.5566	-120000	-8.6820	0002	0.00129	-541	-29.23
SF1 OUT	0.000	02	1.446	1	0.0000	-50000	1	-22667	-1.5566	-0.6667	-0.8990	0002	0.00129	-541	-2.16
	0.200		1.646	1	0.2000	00000	1	-24000	-1.7364	-0.6667	-0.8990	0002	0.00129	-585	-2.16
AMP1	0.000	15	1.646	1	0.0000	-06667	1	-24000	-1.7364	0.9333	0.2586	0002	0.00129	-585	1.73
	0.200		1.846	1	0.2000	00000	1	-22133	-1.6847	0.9333	0.2586	0002	0.00129	-550	1.73
SF2 IN	0.000	02	1.846	1	0.0000	-50000	1	-22133	-1.6847	12.0000	8.6820	0002	0.00129	-550	29.23
	0.375		22208	1	0.3748	00000	1	22843	1.5693	12.0000	8.6820	0002	0.00129	546	29.23
SF2 OUT	0.000	02	22208	1	0.0000	-50000	1	22843	1.5693	0.5787	0.8353	0002	0.00129	546	1.95
	0.200		24208	1	0.2000	00000	1	24000	1.7364	0.5787	0.8353	0002	0.00129	585	1.95
AMP2	0.000	15	24208	1	0.0000	-06667	1	24000	1.7364	-1.0213	-0.3223	0002	0.00129	585	-1.95
	0.200		26208	1	0.2000	00000	1	21957	1.6719	-1.0213	-0.3223	0002	0.00129	546	-1.95
SF3 IN	0.000	02	26208	1	0.0000	-50000	1	21957	1.6719	-120000	-8.6820	0002	0.00129	546	-29.23
	0.373		29942	1	0.3734	00000	1	-22851	-1.5700	-120000	-8.6820	0002	0.00129	-546	-29.23
SF3 OUT	0.000	02	29942	1	0.0000	-50000	1	-22851	-1.5700	-0.5744	-0.8322	0002	0.00129	-546	-1.94
	0.200		31942	1	0.2000	00000	1	-24000	-1.7364	-0.5744	-0.8322	0002	0.00129	-585	-1.94
AMP3	0.000	15	31942	1	0.0000	-06667	1	-24000	-1.7364	1.0256	0.3254	0002	0.00129	-585	1.96
	0.200		33942	1	0.2000	00000	1	-21949	-1.6713	1.0256	0.3254	0002	0.00129	-545	1.96
SF4 IN	0.000	02	33942	1	0.0000	-50000	1	-21949	-1.6713	12.0000	8.6820	0002	0.00129	-545	29.23
	0.373		37674	1	0.3732	00000	1	22840	1.5691	12.0000	8.6820	0002	0.00129	546	29.23
SF4 OUT	0.000	02	37674	1	0.0000	-50000	1	22840	1.5691	0.5800	0.8363	0002	0.00129	546	1.95
	0.200		39674	1	0.2000	00000	1	24000	1.7364	0.5800	0.8363	0002	0.00129	585	1.95
AMP4	0.000	15	39674	1	0.0000	-06667	1	24000	1.7364	-1.0200	-0.3213	0002	0.00129	585	-1.95
	0.200		41674	1	0.2000	00000	1	21960	1.6721	-1.0200	-0.3213	0002	0.00129	546	-1.95
SF5 IN	0.000	02	41674	1	0.0000	-50000	1	21960	1.6721	-120000	-8.6820	0002	0.00129	546	-29.23
	0.373		45407	1	0.3733	00000	1	-22836	-1.5689	-120000	-8.6820	0002	0.00129	-545	-29.23
SF5 OUT	0.000	02	45407	1	0.0000	-50000	1	-22836	-1.5689	-0.5820	-0.8377	0002	0.00129	-545	-1.96
	0.200		47407	1	0.2000	00000	1	-24000	-1.7364	-0.5820	-0.8377	0002	0.00129	-585	-1.96
AMP5	0.000	15	47407	1	0.0000	-06667	1	-24000	-1.7364	1.0180	0.3199	0002	0.00129	-585	1.94
	0.200		49407	1	0.2000	00000	1	-21964	-1.6724	1.0180	0.3199	0002	0.00129	-546	1.94
SF6 IN	0.000	02	49407	1	0.0000	-50000	1	-21964	-1.6724	12.0000	8.6820	0002	0.00129	-546	29.23
	0.373		5.314	1	0.3733	00000	1	22832	1.5686	12.0000	8.6820	0002	0.00129	545	29.23
SF6 OUT	0.000	02	5.314	1	0.0000	-50000	1	22832	1.5686	0.5840	0.8392	0002	0.00129	545	1.96
	0.200		5.514	1	0.2000	00000	1	24000	1.7364	0.5840	0.8392	0002	0.00129	585	1.96
AMP6	0.000	15	5.514	1	0.0000	-06667	1	24000	1.7364	-1.0160	-0.3184	0002	0.00129	585	-1.94
	0.500		6.014	1	0.5000	00000	1	18920	1.5772	-1.0160	-0.3184	0002	0.00129	488	-1.94
PCM	0.000	-1.26	6.014	1	0.0000	07937	1	18920	1.5772	0.4855	0.9333	0002	0.00129	488	1.94
	0.500		6.514	1	0.5000	00000	1	21348	2.0438	0.4855	0.9333	0002	0.00129	585	1.94
AMP6	0.000	15	6.514	1	0.0000	-06667	1	21348	2.0438	-0.9376	-0.4293	0002	0.00129	585	-1.96
	0.200		6.714	1	0.2000	00000	1	19472	1.9580	-0.9376	-0.4293	0002	0.00129	545	-1.96
SF6 IN	0.000	02	6.714	1	0.0000	-50000	1	19472	1.9580	-106738	-10.2192	0002	0.00129	545	-29.23
	0.373		70873	1	0.3733	00000	1	-20373	-1.8568	-106738	-10.2192	0002	0.00129	-546	-29.23
SF6 OUT	0.000	02	70873	1	0.0000	-50000	1	-20373	-1.8568	-0.4873	-0.9350	0002	0.00129	-546	-1.94
	0.200		72873	1	0.2000	00000	1	-21348	-2.0438	-0.4873	-0.9350	0002	0.00129	-585	-1.94
AMP5	0.000	15	72873	1	0.0000	-06667	1	-21348	-2.0438	0.9358	0.4276	0002	0.00129	-585	1.96
	0.200		74873	1	0.2000	00000	1	-19476	-1.9583	0.9358	0.4276	0002	0.00129	-545	1.96
SF5 OUT	0.000	02	74873	1	0.0000	-50000	1	-19476	-1.9583	10.6738	10.2192	0002	0.00129	-545	29.23
	0.373		78606	1	0.3733	00000	1	20369	1.8565	10.6738	10.2192	0002	0.00129	546	29.23
SF5 IN	0.000	02	78606	1	0.0000	-50000	1	20369	1.8565	0.4891	0.9367	0002	0.00129	546	1.94
	0.200		80606	1	0.2000	00000	1	21348	2.0438	0.4891	0.9367	0002	0.00129	585	1.94
AMP4	0.000	15	80606	1	0.0000	-06667	1	21348	2.0438	-0.9341	-0.4258	0002	0.00129	585	-1.95
	0.200		82606	1	0.2000	00000	1	19479	1.9587	-0.9341	-0.4258	0002	0.00129	545	-1.95
SF4 OUT	0.000	02	82606	1	0.0000	-50000	1	19479	1.9587	-106738	-10.2192	0002	0.00129	545	-29.23
	0.373		86339	1	0.3732	00000	1	-20359	-1.8555	-106738	-10.2192	0002	0.00129	-545	-29.23
SF4 IN	0.000	02	86339	1	0.0000	-50000	1	-20359	-1.8555	-0.4941	-0.9415	0002	0.00129	-545	-1.96
	0.200		88339	1	0.2000	00000	1	-21348	-2.0438	-0.4941	-0.9415	0002	0.00129	-585	-1.96
AMP3	0.000	15	88339	1	0.0000	-06667	1	-21348	-2.0438	0.9291	0.4211	0002	0.00129	-585	1.94
	0.200		90339	1	0.2000	00000	1	-19489	-1.9596	0.9291	0.4211	0002	0.00129	-546	1.94
SF3 OUT	0.000	02	90339	1	0.0000	-50000	1	-19489	-1.9596	10.6738	10.2192	0002	0.00129	-546	29.23
	0.373		94073	1	0.3734	00000	1	20367	1.8563	10.6738	10.2192	0002	0.00129	546	29.23
SF3 IN	0.000	02	94073	1	0.0000	-50000	1	20367	1.8563	0.4903	0.9378	0002	0.00129	546	1.95
	0.200		96073	1	0.2000	00000	1	21348	2.0438	0.4903	0.9378	0002	0.00129	585	1.95
AMP2	0.000	15	96073	1	0.0000	-06667	1	21348	2.0438	-0.9329	-0.4247	0002	0.00129	585	-1.95
	0.200		98073	1	0.2000	00000	1	19482	1.9589	-0.9329	-0.4247	0002	0.00129	546	-1.95
SF2 OUT	0.000	02	98073	1	0.0000	-50000	1	19482	1.9589	-106738	-10.2192	0002	0.00129	546	-29.23
	0.375		10.182	1	0.3748	00000	1	-20524	-1.8713	-106738	-10.2192	0002	0.00129	-550	-29.23
SF2 IN	0.000	02	10.182	1	0.0000	-50000	1	-20524	-1.8713	-0.4120	-0.8629	0002	0.00129	-550	-1.73
	0.200		10.382	1	0.2000	00000	1	-21348	-2.0438	-0.4120	-0.8629	0002	0.00129	-585	-1.73
AMP1	0.000	15	10.382	1	0.0000	-06667	1	-21348	-2.0438	1.0112	0.4997	0002	0.00129	-585	2.16
	0.200		10.582	1	0.2000	00000	1	-19325	-1.9439	1.0112	0.4997	0002	0.00129	-541	2.16

5. Summary

A SLM laser oscillator for the high performance laser system (5J, 100Hz) has been designed for the edge Thomson scattering system in ITER. As for the configuration of resonator, a ring type has been adopted for the high quality SLM. A LD pumped oscillator head has been also designed. In order to obtain the stable SLM, a feedback control system has been designed. The LD pumped SLM laser oscillator which has the following performance has been designed: 100 Hz of repetition rate, 10 mJ of output energy, 10-15 ns of pulse width, single longitudinal mode, TEM_{00} of transversal mode, less than 4 times of the diffraction limit for divergence, within 5% of energy stability. This performance is summarized in Table 1. Furthermore, an interface for amplification system to achieve final performance (5J, 100Hz) has been considered.

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m-1
密度（質量密度）	キログラム毎立法メートル	kg/m^3
質量体積（比体積）	立法メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
（物質量の）濃度	モル毎立方メートル	mol/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率	（数の） 1	1

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表３．固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(a)	rad		$m \cdot m^{-1}=1$(b)
立体角	ステラジアン(a)	sr(c)		$m^2 \cdot m^{-2}=1$(b)
周波数	ヘルツ	Hz		s^{-1}
力	ニュートン	N		$m \cdot kg \cdot s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
エネルギー，仕事，熱量	ジュール	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
工率，放射束	ワット	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
電荷，電気量	クーロン	C		$s \cdot A$
電位差（電圧），起電力	ボルト	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
電気抵抗	オーム	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
磁束	ウエーバ	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
セルシウス温度	セルシウス度(d)	℃		K
光束	ルーメン	lm	$cd \cdot sr$(c)	$m^2 \cdot m^{-2} \cdot cd=cd$
照度	ルクス	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd=m^{-2} \cdot cd$
（放射性核種の）放射能	ベクレル	Bq		s^{-1}
吸収線量，質量エネルギー分与，カーマ	グレイ	Gy	J/kg	$m^2 \cdot s^{-2}$
線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当	シーベルト	Sv	J/kg	$m^2 \cdot s^{-2}$

(a)ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。

(b)実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“１”は明示されない。

(c)測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。

(d)この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	$Pa \cdot s$	$m^{-1} \cdot kg \cdot s^{-1}$
力のモーメント	ニュートンメートル	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg \cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m \cdot m^{-1} \cdot s^{-1}=s^{-1}$
角加速度	ラジアン毎平方秒	rad/s^2	$m \cdot m^{-1} \cdot s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg \cdot s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
質量熱容量（比熱容量），質量エントロピー	ジュール毎キログラム毎ケルビン	$J/(kg \cdot K)$	$m^2 \cdot s^{-2} \cdot K^{-1}$
質量エネルギー（比エネルギー）	ジュール毎キログラム	J/kg	$m^2 \cdot s^{-2} \cdot K^{-1}$
熱伝導率	ワット毎メートル毎ケルビン	$W/(m \cdot K)$	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
体積電荷	クーロン毎立方メートル	C/m^3	$m^{-3} \cdot s \cdot A$
電気変位	クーロン毎平方メートル	C/m^2	$m^{-2} \cdot s \cdot A$
誘電率	ファラド毎メートル	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
透磁率	ヘンリー毎メートル	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	$J/(mol \cdot K)$	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1} \cdot s \cdot A$
吸収線量率	グレイ毎秒	Gy/s	$m^2 \cdot s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3}=m^2 \cdot kg \cdot s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2 \cdot sr)$	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3}=kg \cdot s^{-3}$

表６．国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	1° =(π/180) rad
分	’	1’ =(1/60)° =(π/10800) rad
秒	”	1” =(1/60)’ =(π/648000) rad
リットル	l、L	1l=1 $dm^3=10^{-3}m^3$
トン	t	1t=10^3 kg
ネーパ	Np	1Np=1
ベル	B	1B=(1/2)ln10(Np)

表７．国際単位系と併用されこれに属さない単位でSI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	1eV=1.60217733(49)×10^{-19}J
統一原子質量単位	u	1u=1.6605402(10)×10^{-27}kg
天文単位	ua	1ua=1.49597870691(30)×10^{11}m

表８．国際単位系に属さないが国際単位系と併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里		1海里=1852m
ノット		1ノット=1海里毎時=(1852/3600)m/s
アール	a	1 a=1 $dam^2=10^2m^2$
ヘクタール	ha	1 ha=1 $hm^2=10^4m^2$
バール	bar	1 bar=0.1MPa=100kPa=1000hPa=10^5Pa
オングストローム	Å	1 Å=0.1nm=10^{-10}m
バーン	b	1 b=100$fm^2=10^{-28}m^2$

表９．固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn・s/cm^2=0.1Pa・s
ストークス	St	1 St =1$cm^2/s=10^{-4}m^2/s$
ガウス	G	1 G ≙10^{-4}T
エルステッド	Oe	1 Oe ≙(1000/4π)A/m
マクスウェル	Mx	1 Mx ≙10^{-8}Wb
スチルブ	sb	1 sb =1$cd/cm^2=10^4cd/m^2$
ホト	ph	1 ph=10^4lx
ガル	Gal	1 Gal =1$cm/s^2=10^{-2}m/s^2$

表10．国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
X線単位		1X unit=1.002×10^{-4}nm
ガンマ	γ	1γ=1 nT=10^{-9}T
ジャンスキー	Jy	1 Jy=$10^{-26}W \cdot m^{-2} \cdot Hz^{-1}$
フェルミ		1 fermi=1 fm=10^{-15}m
メートル系カラット		1 metric carat = 200 mg = 2×10^{-4}kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	
ミクロン	μ	1 μ =1μm=10^{-6}m

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