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チタンサファイア増幅部の利得測定

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チタンサファイア共振器からのレーザーパルスをヤグレーザーの第二高調波により励起することにより増幅し、出力レーザーパワーを測定した。ポンプレーザーによる励起がある場合とない場合のレーザー出力強度比を、取り出しエネルギーゼロの領域まで外挿することにより、シングルパスとダブルパスの小信号利得を、励起レーザー光密度の関数として測定した。シングルパスの利得を2準位のレート方程式により計算した。得られた計算結果は実験結果をよく再現した。この結果に基づき、共振器出力を多段階増幅部を用いて増幅した。

東海研究所：〒３１９－１１９５茨城県那珂郡東海村白方白根２－４
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Gain Measurements of Ti:sapphire Amplifier

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Ti:sapphire laser pulses from an oscillator were amplified by the pumping of a second harmonics of Nd:YAG laser, and output laser power was measured. By extrapolating the laser power ratio with and without pump laser to extracted power of zero, single-pass and double-pass small-signal gains as a function of incident pump energy density were obtained. The single-pass small signal gain was calculated by means of two level rate equation, which reproduced experimental results well. Based on these results, the oscillator output was amplified in a series of amplifier chain.

Keywords: Ti:sapphire Laser, Amplifier, Small-signal Gain, Nd:YAG Laser, Single Pass, Double Pass

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1. Introduction

Several advantageous features of Ti:sapphire laser (TSL) such as broad gain region, easy handling of solid state brick, and stable operation without vibration by dye circulation, make TSL potentially useful light source for high resolution spectroscopy and laser isotope separation[1]. As a light source for laser isotope separation, broad tunability, narrow linewidth with a single-longitudinal mode and stable operation are desirable, which are attainable with a TSL oscillator. For the isotope separation on a large scale or frequency conversion of the fundamental output with a nonlinear crystal to obtain shorter wavelengths, high laser pulse energy is required. The laser pulse can be amplified by a master-oscillator power-amplifier (MOPA) chain in series.[2]

In this study, single-pass and double-pass small-signal gains of a Ti:sapphire crystal pumped by the second harmonics of Nd:YAG laser were measured. Based on the results, the TSL oscillator pulse was amplified in a series of amplifier.

2. Experimental method

Figure 1 shows the schematics of the experimental setup for single-pass (a) and double-pass (b) gain measurements. The Ti:sapphire crystal (18mm length) was obtained from Union Carbide Co. The titanium concentration was 0.15% by weight. The absorption coefficients for π-polarization at 532 nm and 800 nm were 1.9 cm^{-1} and 0.05 cm^{-1}, respectively. It was mounted at Brewster's angle on a holder at room temperature.

The crystal was longitudinally pumped by the second harmonics of Q-switched Nd:YAG laser (Lumonics HY1200) operated at 10 Hz. The pump laser was focused with a lens and injected from an end of the crystal. The temporal duration of the pump laser was 10nsec. The polarization of the pump laser was parallel to the c-axis of the crystal (π-polarization).

As a signal laser, TSL oscillator was used. The oscillator consisted of a Ti:sapphire crystal, a grating (1800 line/mm), a tuning mirror, and a total reflector. By grazing-incidence configuration and cavity length control, single-longitudinal mode operation with linewidth less than 500 MHz was possible. The intensity of the signal laser was attenuated with ND filters. The signal laser was introduced almost collinearly with the pump laser into the crystal 25 nsec after the pump laser pulse. Figure 2 shows the temporal profile of the pump laser and the probe laser at the entrance of the crystal. For single-pass gain measurement shown in figure 1(a), the introduced signal laser was amplified by the pumped crystal, and the laser output was detected with a power meter. The signal was detected as an average of ten pump pulses. For double-pass configuration shown in figure 1(b), the amplified laser was reflected with a back mirror, and amplified in the crystal again. The overlap of the pump laser and the signal laser was optimized to give highest output power.

3. Results and discussion

Figure 3 shows the output laser power measured with (I) and without (I_0) YAG laser pumping at the laser wavelength of 808 nm. Figure 4 shows the relation between the observed signal gain (I/I_0) and the incident pump energy density at the introduced probe laser power between 110 μJ (a) and 770 μJ (c). The results show that the gain increased with the pump energy density, and it decreased with the signal laser power. Figure 5 shows the relations between the gain (I/I_0) and the extracted power (I-I_0) obtained at the pump energy density of 4.3 J/cm^2. By extrapolating the relation to the extracted power of zero, small-signal gain g_0 averaged over the crystal length L at each pump energy was determined. Figure 6 summarizes the obtained small-signal gain for single-pass (a) and double-pass (b) as a function of incident pump energy density. The results show that small-signal gain increased linearly with the pump energy density and the gain for double-pass was about twice that of single-pass.

Figure 7 shows the wavelength dependence of double-pass small signal gain at the pump energy density of 4.3 J/cm^2. The results show that the gain was largest at about 780 nm.

The single-pass gain of the laser pulse was calculated based on a two level rate equation formulation.

$$\frac{\partial N_1(x,t)}{\partial t} = \sigma_{ap} I_p(x) N_0(x,t) - N_1(x,t)\sigma_e I_l(x,t) + N_0(x,t)\sigma_a I_l(x,t) - N_1(x,t)/\tau \quad (1)$$

$$\frac{\partial I_l(x,t)}{\partial x} = N_1(x,t)\sigma_e I_l(x,t) - N_0(x,t)\sigma_a I_l(x,t) \quad (2)$$

where $N_1(x,t)$ and $N_0(x,t)$ are the concentration of titanium ions in excited level and ground level, respectively, $I_p(x)$ and $I_l(x,t)$ are the internal photon intensities of pump laser and signal laser, σ_{ap} is the absorption cross-section of pump laser, σ_e is the cross-section for stimulated emission from excited level to ground level, σ_a is the absorption cross-section of signal laser from ground level to excited level, and τ is the radiative decay time of the excited level. Considering that the pump laser was introduced before the signal laser and that the fluorescence time is long enough compared with the travel time of laser pulse in the crystal, equation (2) is approximated by,

$$\frac{dI_l(x)}{dx} = [(\sigma_e + \sigma_a)\sigma_{ap} I_p(x)\exp(-\alpha_p(L-x))\exp(-\Delta t/\tau) - \sigma_a] N I_l(x) \quad (3)$$

where L is the length of the crystal, N is the concentration of Ti^{3+} ions ($=N_1+N_0$), α_p is the absorption coefficient of the pump laser, and Δt is delay time of signal laser to pump laser.

Figure 8 shows the horizontal spatial profile of pump laser (a) and probe laser (b).

From the experimental observation, the spatial profile of the pump laser was assumed to be a circular beam. Before injection to the crystal, the pump laser was focused, and the increase of pump laser cross-section in the crystal during the propagation was considered. The number of photon of the pump laser at the distance of x from the crystal end was given by,

$$I_p = \frac{E_p}{h\nu_p}\frac{1}{S(x)}$$

where E_p is the introduced pump energy, $h\nu_p$ is the photon energy of the pump laser, and $S(x)$ is the cross section of the pump laser at a distance of x from the end of the crystal. The spatial profile of the signal laser was assumed to be Gussian as shown in figure 8(b). The number of photon of the signal laser $I(r)$ was given by,

$$I(r) = I_0 \exp[-2(r/r_0)^2]$$

$$I_0 = \frac{2P_t}{\pi r_0^2 h\nu_l}$$

where P_t is the energy of signal laser, r is the distance from the center of the laser beam, r_0 is the radius of the signal laser, and $h\nu_l$ is the photon energy of the signal laser. Equations (1) and (3) were solved numerically, and from the laser intensity ratio at the entrance and the exit of the crystal, signal gain was obtained. In this calculation, the radiative decay time of the excited level τ (=3.15×10^{-6} sec)[3], the cross-section for stimulated emission σ_e (=2.7×10^{-19} cm^2)[3], the absorption cross-section of pump laser σ_{ap} (=9.3×10^{-20} cm^2)[4] were obtained from references. The delay time of the signal laser from the pump laser Δt was 25 nsec, and the crystal length L was 18 mm. The concentration of titanium ions N(=2.0×10^{19} /cm^3), the absorption cross-section of pump laser σ_{ap} (=9.3×10^{-20} sec^2), and the absorption cross-section of signal laser σ_a (=2.2×10^{-21} cm^2) were determined from the absorption coefficient of the crystal.[5] The solid line in figure 6 denoted by Cal shows the calculated results of the small signal gain. The experimental results for single-pass were well reproduced by the calculations.

The oscillator output was amplified in a series of amplifiers. The oscillator output of 0.62 mJ by the pump input of 66 mJ was amplified at the initial stage amplifier (AMP 1, double pass), and output energy of 63 mJ by the pump power of 137 mJ was obtained. Considering the damage of the back mirror, single pass amplifier was used in the following stages. The output from AMP 1 was amplified by AMP 2 (single pass), and output of 88 mJ was obtained by the pump input of 43 mJ. It was then amplified by AMP 3 (single pass) where output of 154 mJ was obtained by the pump input of 68 mJ, and by AMP 4 (single pass) where output of 186 mJ was obtained by the pump input of 140 mJ. The gain at each stage was also shown in figure 6 by AMP1~AMP 4.

4. Conclusion

Ti:sapphire laser pulses from an oscillator were amplified by the pumping of a second harmonics of Nd:YAG laser, and single-pass and double-pass small-signal gains as a function of incident pump energy density were obtained. The single-pass small signal gain was calculated by two level rate equation, which reproduced the experimental results well. Based on these results, the oscillator output was amplified in a series of amplifier chain.

Acknowledgement

The authors are grateful to Mr. T. Shimizu for his assistance in this study.

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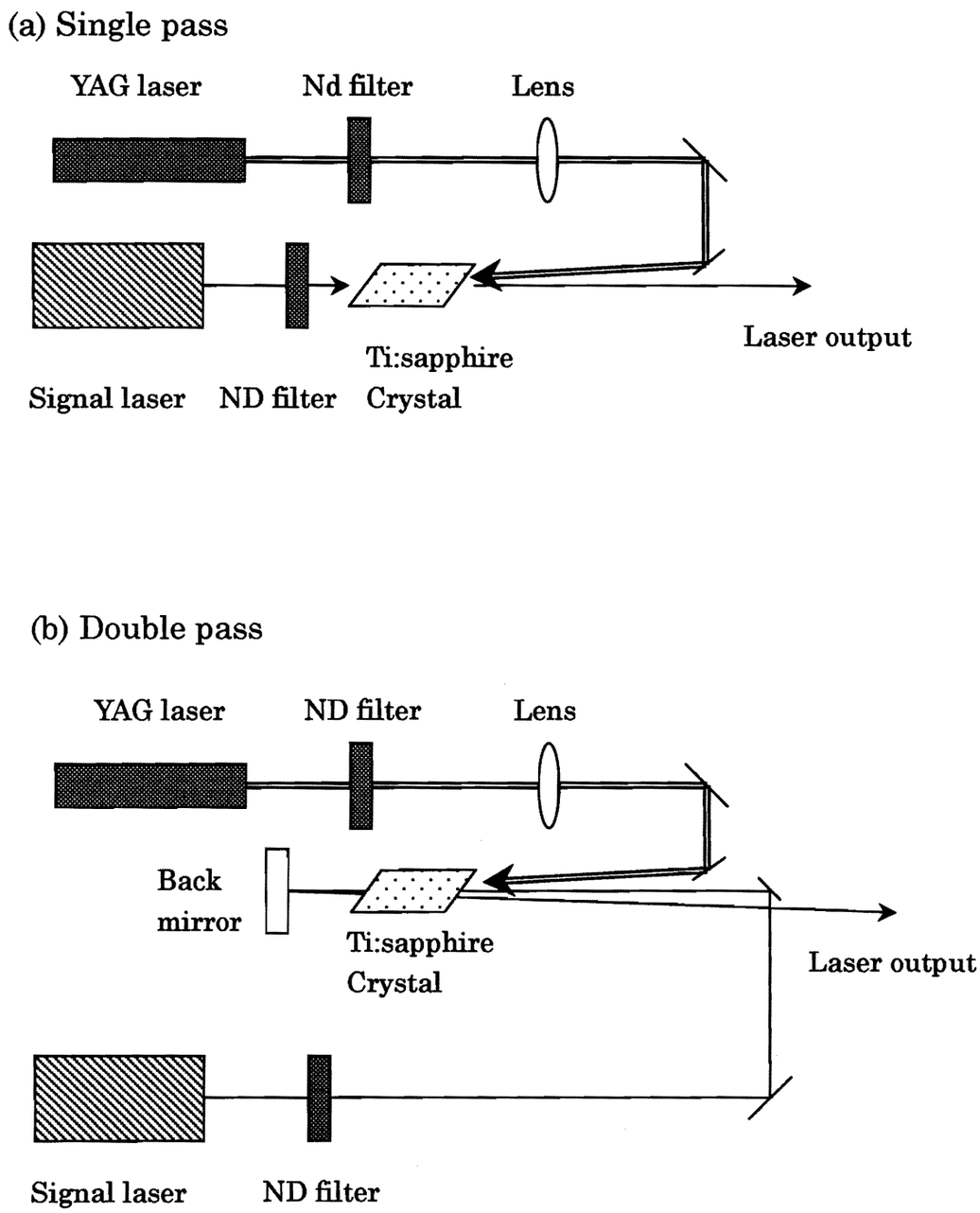


Fig. 1 Schematics of the experimental setup for the measurements of single-pass (a) and double-pass (b) small-signal gain in a Ti:sapphire amplifier.

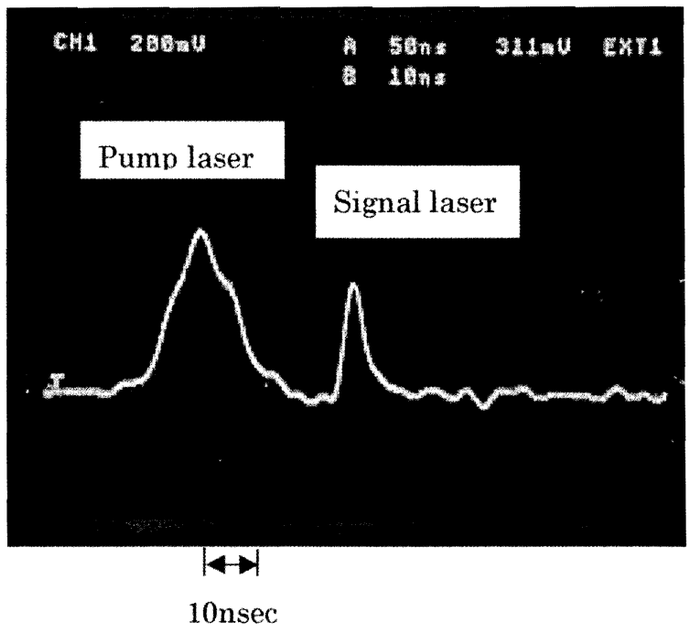


Fig. 2 Temporal pulse shape of pump laser and signal laser at the entrance of crystal.

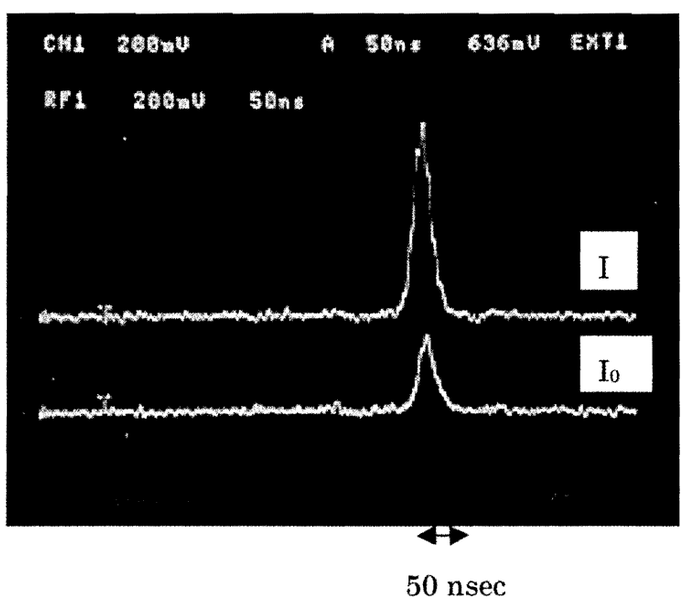


Fig. 3 Temporal pulse shape of output laser from Ti:sapphire amplifier crystal with (I) and without (I_0) YAG laser pumping.

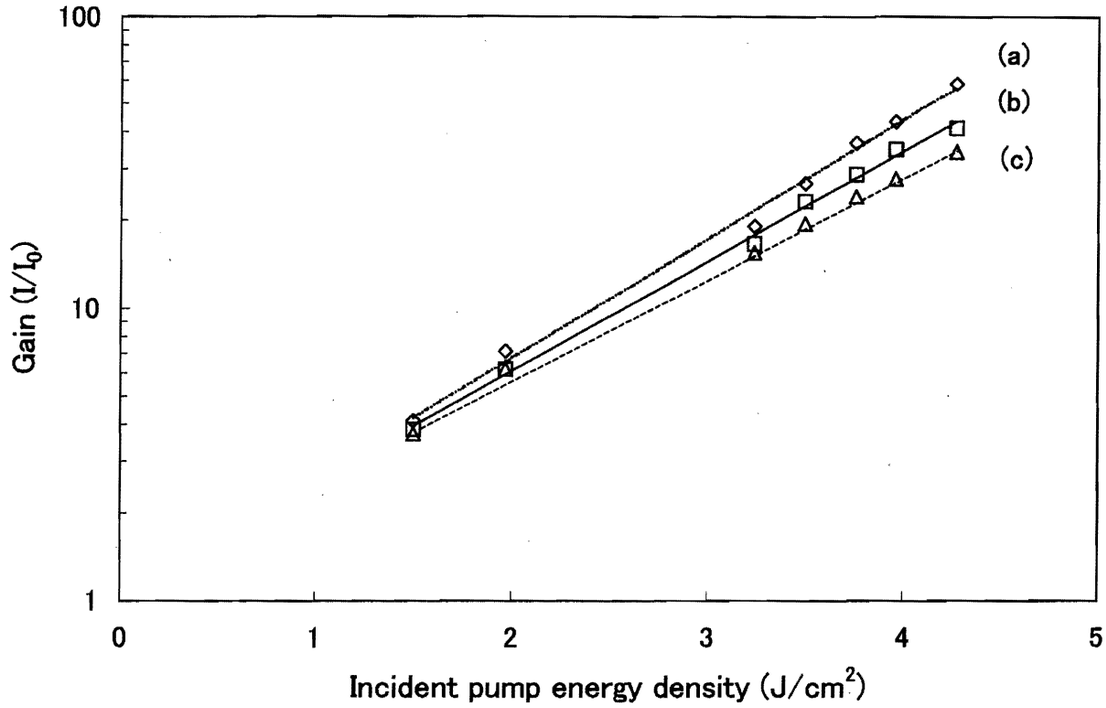


Fig. 4 The obtained gain (the ratio of the output laser intensity with (I) and without (I_0) pump laser) as a function of pump laser density. The incident signal laser power was 110 μJ (a), 420 μJ (b) and 770μJ (c).

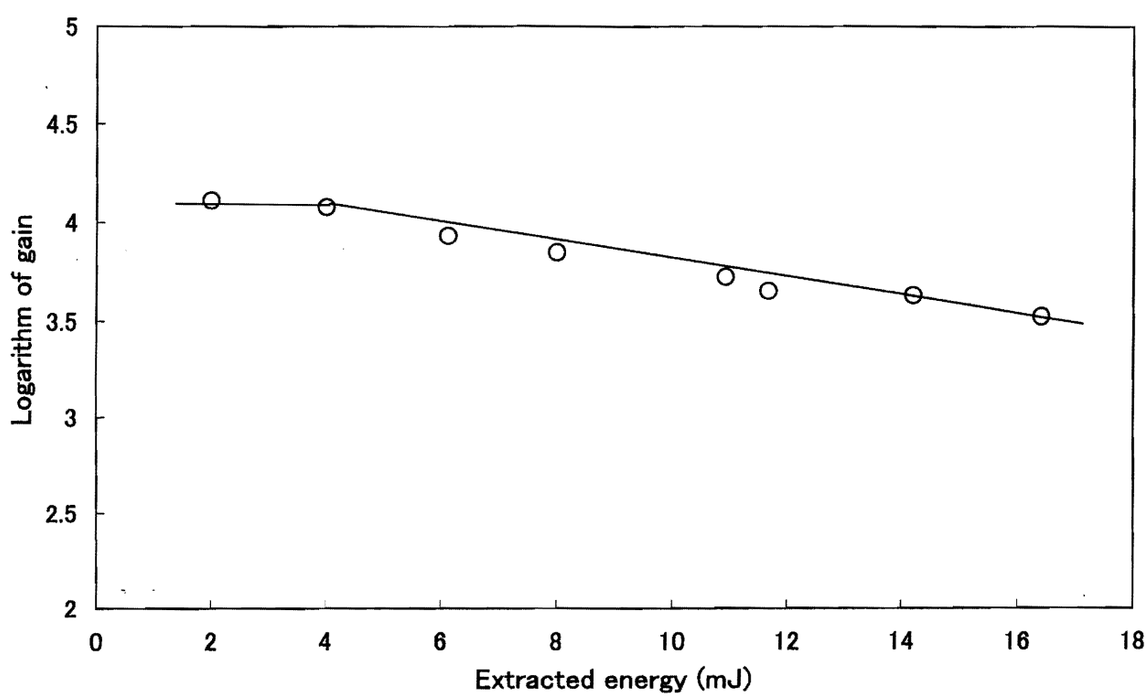


Fig. 5 The relation of logarithm of gain (I/I_0) and extracted power ($I-I_0$) at the pump energy density of 4.3 J/cm^2.

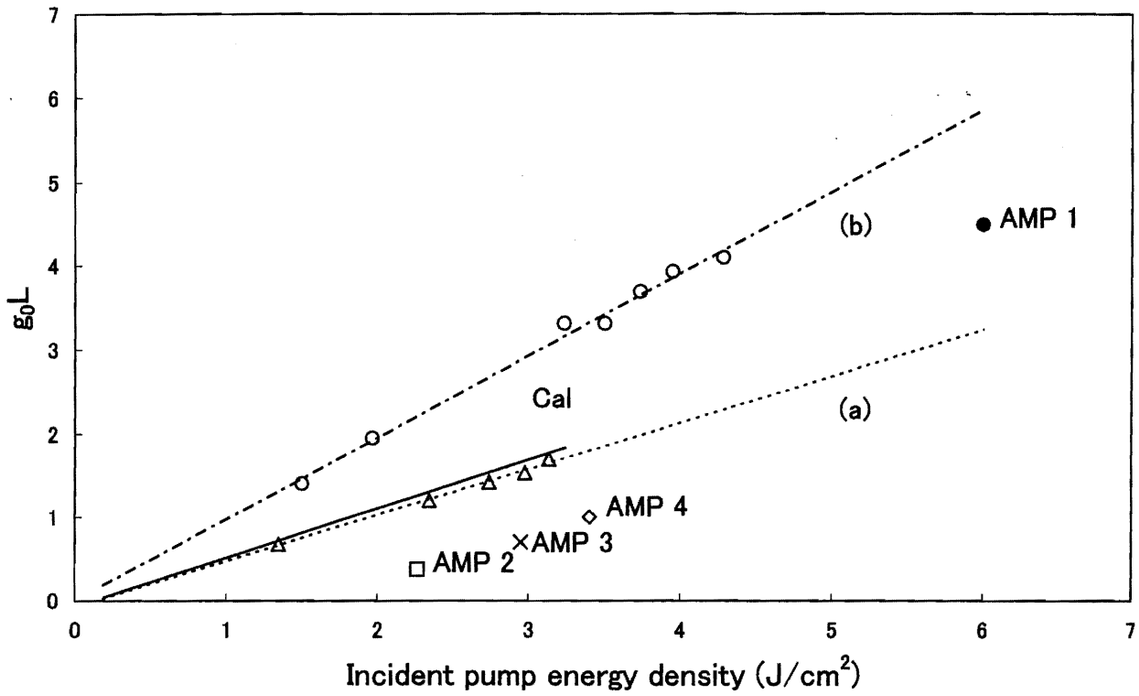


Fig. 6 The exponential gain g_0L for single-pass (a) and double-pass (b) as a function of pump energy density. The results of calculation are also shown by solid line denoted by Cal. The gain for each stage of amplifier is denoted by AMP 1 – AMP 4.

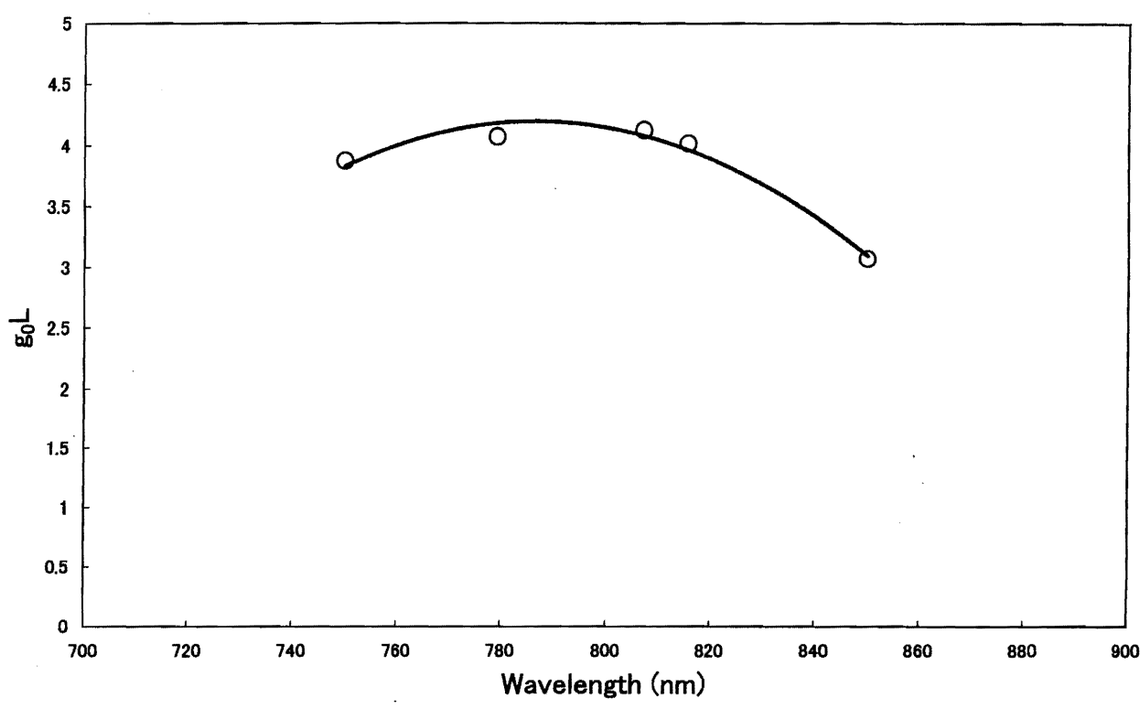
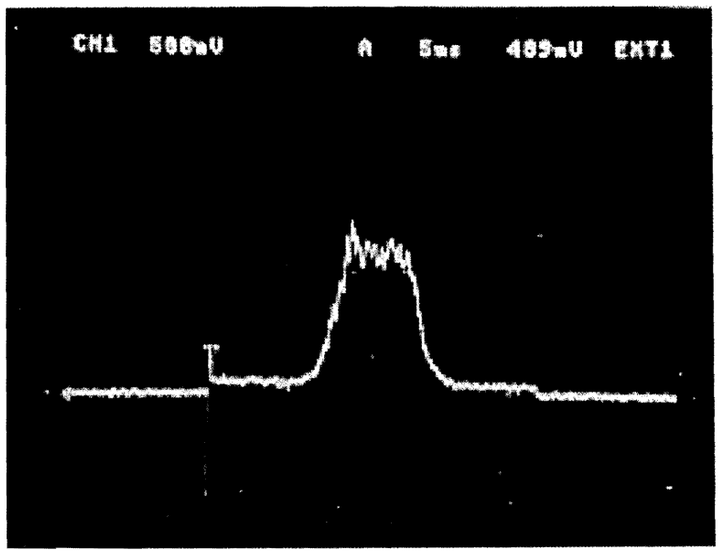


Fig. 7 Experimental double-pass small-signal gain as a function of wavelength of the output laser at the pump energy density of 4.3 J/cm^2.

(a) Pump laser



(b) Signal laser

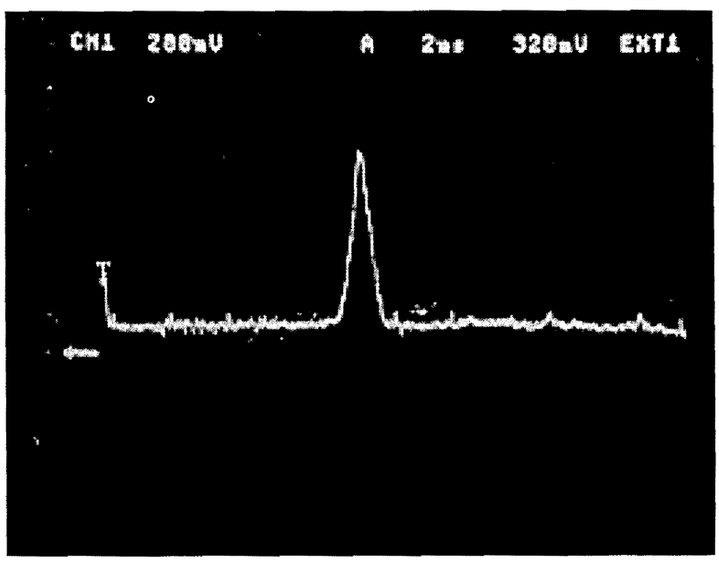


Fig. 8 Horizontal spatial profiles of pump laser (a) and signal laser (b).