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Simple and Downsized Amplification System of a Femtosecond Laser Pulse using Dye Gain Media

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Abstract : A femtosecond laser pulse of a fiber laser is amplified in dye gain media. To evaluate the conditions for the amplification of a femtosecond laser pulse, the time-resolved measurements of gains in OXAZINE 750, DOTC, and LDS 821 dye solutions are carried out by using a TEA N_2 laser (λ= 337.1 nm, FWHM= 0.6 ns), a TE N_2 laser (λ= 337.1 nm, FWHM= 6 ns) and the second harmonic of a Nd:YAG laser (λ= 532 nm, FWHM= 5 ns), as the pump sources. The amplified output energy of the fs laser pulse is 1 μJ, and the pulse width is 180 fs (FWHM). These output energy and pulse width are comparable to those of a typical CPA laser system, and the cost performance is very high.

Key words: femtosecond laser, dye gain media, time-resolved gain measurements

１. Introduction

In recent years, with the development of ultra-short laser pulse generation and its amplification techniques, femtosecond (fs) lasers have been widely used in the field of laser processing [1-3]. Because of their ultra-narrow pulse duration, fs lasers enable ultra-precision processing with a marginal heating effect or processing with nonlinear processes such as multi-photon absorption and multi-photon ionization. Furthermore, these lasers have become important light sources in fields such as time-resolved X-ray diffraction, time-resolved absorption spectroscopy, multi-photon microscope, and generation of terahertz (THz) electromagnetic waves.

Thus far, the generation of fs laser pulses has been performed using solid-state lasers such as titanium sapphire lasers or dye lasers. Moreover, passive mode-locked ultra-short pulse fiber lasers using rare-earth elements, such as Er-doped optical fiber amplifiers [4], have been developed and widely used.

At present, the chirped pulse amplification (CPA) method has been used for the amplification of fs laser pulses [5-6]. According to this technique, first, the duration of a seed laser pulse is extended to lower the peak power; second, the low-peak-power laser pulse is amplified using amplifiers. Finally, the amplified laser pulse is compressed to reduce the pulse duration. However, it is difficult to achieve higher stability and lower costs because of the complicated structure of the CPA system.

In this work, in order to simplify and downsize the amplification system, the fs laser pulse of the fiber laser was amplified in dye gain media pumped by three types of pump sources; the obtained output energy was 1 μJ/pulse.

2. Experimental Setup

Figure 1 shows the conceptual experimental setup in this work. A mode-locked fiber laser (IMRA, Femtolite) can simultaneously radiate fs laser pulses at a fundamental wavelength of 1560 nm (FWHM = 100 fs, pulse repetition rate = 50 MHz, pulse energy = 0.6 nJ) and a second harmonic wavelength of 780 nm (FWHM = 100 fs, pulse repetition rate = 50 MHz, pulse energy = 0.4 nJ). The second harmonic pulse is focused into a dye cell by using a lens. The fundamental laser pulse is reflected by a dichroic mirror and received by a detector, where it is converted into 50-MHz electric signals. The signals are divided into 1-10 Hz electric signals by means of a frequency divider. These divided signals are delayed by using a delay generator and then fed to a pump source with a time delay of τ. The delay between the fs laser pulse and the pump laser pulse in the dye cell can be adjusted by varying the value of τ; in this manner, the fs laser pulse gets amplified.

The time-resolved gains are measured by using a TEA N_2 laser (USHO, λ= 337.1 nm, FWHM = 0.6 ns, pulse energy = 200μJ) with a sub-nanosecond pulse width, a TE N_2 laser (USHO, λ= 337.1 nm, FWHM= 6 ns, pulse energy= 3 mJ) with a nanosecond pulse width and the second harmonic of a Nd:YAG laser (NEW WAVE RESEARCH, λ= 532 nm, FWHM= 5 ns, pulse energy = 5 mJ) as the pump sources and OXAZINE 750, DOTC, and LDS 821 as the dye solutions. The second harmonic generation (λ= 780 nm) of fiber laser can be amplified when the theses three dyes are excited. These three dyes can be excited by a YAG laser or N_2 laser. The optical gain is calculated by comparing the amplified fs laser pulse energy with the input fs laser pulse energy. The amplified fs laser pulse energy is measured by using a detector (Gentec, ED-100A), and the pulse duration is measured by means of an autocorrelation method by using a homemade Michelson's interferometer with second harmonic generation crystal.

3. Results and Discussion

Figure 2 shows the results of a time-resolved

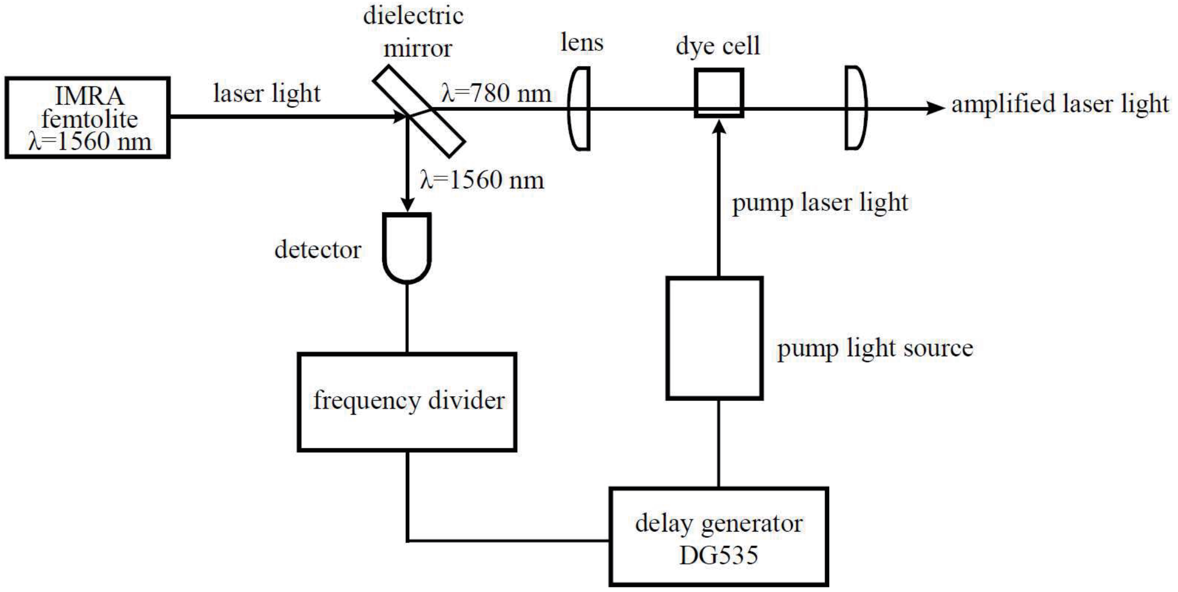

Figure 1: Schematic diagram of the experimental setup for the amplification system of a femtosecond laser.

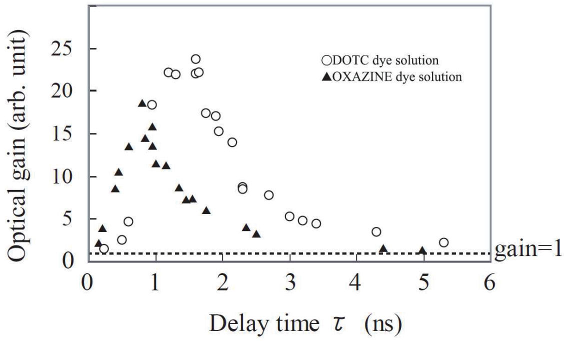

Figure 2: Temporal behavior of the optical gain when a TEA N_2 laser with a sub-nanosecond pulse width was used as a pump source.

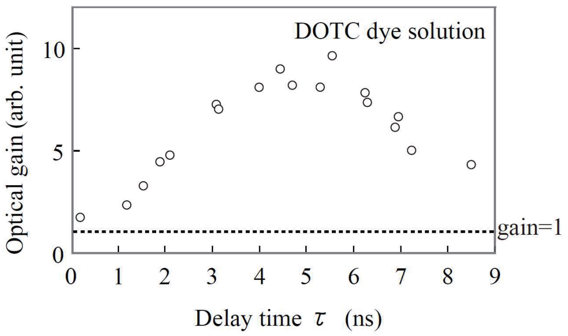

Figure 3: Temporal behavior of the optical gain when a TE N_2 laser with a long pulse width (6 ns) was used as a pump source.

gain measurement using a TEA N_2 laser. The horizontal axis represents the delay time τ from when the excitation laser light was incident on the dye solution to when the fs laser light was incident. The vertical axis represents the optical gain. A positive gain was defined as being greater than 1. Figure 2 shows the results of the time-resolved gain measurement for OXAZINE 750 dye solution and DOTC dye solution. The gain for OXAZINE 750 increased with the delay time τ, and the peak of the gain was approximately 18 at τ = 0.8 ns and then decreased. The gain for DOTC solution also increased with time, peaked at approximately τ = 1.5 ns, and then gradually decreased. These results revealed that when a TEA N_2 laser with a sub-nanosecond pulse width was used, a larger laser output could be obtained by using DOTC dye solution with a large gain.

Figure 3 shows the results of the time-resolved gain measurement using a TE N_2 laser with a long pulse width. When the DOTC dye solution was used, the gain increased with time, reached a maximum value of 9 at τ = 5.5 ns and gradually decreased. A comparison with Fig.2 reveals that the peak value of the gain was low, but the time domain in which the gain was positive was long.

When an N_2 laser was used as the excitation light source of the dye, the output of the amplified fs laser was quite unstable. This was because of the high voltage switch used in the N_2 laser. A gap switch was employed for the high-voltage switch of the N_2 laser used in this experiment. The time jitter of the gap switch was approximately < ± 30 ns. Therefore, it is considered that the fluctuation of the delay time τ was approximately the same, and the laser output became unstable.

To obtain a stable laser output, an amplification experiments were carried out by using an Nd:YAG laser (NEWWAVE RESEARCH, λ= 532 nm, FWHM= 5 ns, pulse energy = 5 mJ) laser with a short time jitter (<±1 ns).

Figure 4 shows the results of the time-resolved gain measurement when three types of dyes were used. The gain for LDS 821, DOTC, and OXAZINE 750 dyes solution increased with the delay time τ, reached a maximum at τ = 5.5 ns, 6.5 ns, and 6.5 ns, respectively, and then decreased. In the amplification experiment using the three dyes in Fig.4, it was observed

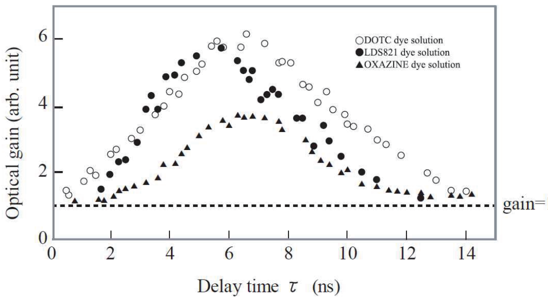

Figure 4: Temporal behavior of the optical gain when an Nd:YAG laser with a long pulse width (5 ns) was used as a pump source.

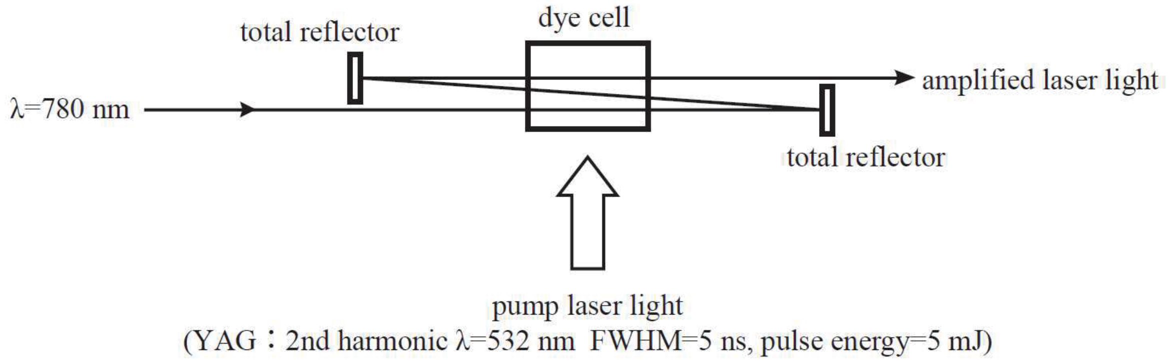

Figure 5: Schematic of three path amplification system.

that the gain was the largest when DOTC was used. In addition, a stable laser output could be obtained by using a YAG laser with a short time jitter. The output stability of the amplified fs laser by using a YAG laser was ± 3% (at 1σ).

Additional amplification experiments were performed using a YAG laser and a DOTC dye solution. Fig. 5 is a schematic of a three-path amplification. A three-path amplification experiment of an fs laser was conducted by installing reflection mirrors before and after the dye cell, and the experiment succeeded in obtaining a laser output of approximately 1 μJ/pulse.

Figure 6 shows an autocorrelation trace of the amplified fs laser pulse measured using the Michelson's interferometer with second harmonic generation crystal. In this measurement, we used the second harmonic of the Nd:YAG laser with a pulse duration of 5 ns and the DOTC dye solution. A duration of approximately 280 fs (FWHM) was obtained from the autocorrelation trace in Fig. 6. Assuming a sech^2 laser pulse shape, the pulse duration was calculated by multiplying the FWHM of the autocorrelation trace by a factor of 0.648. Therefore, the duration of the fs laser pulse was 180 fs (FWHM).

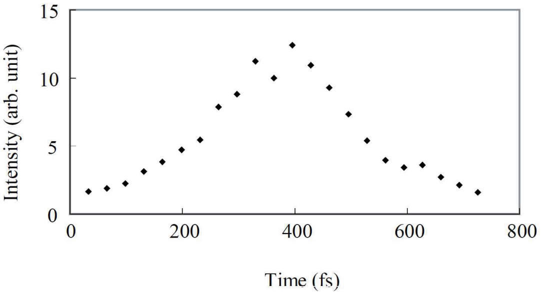

Figure 6: Autocorrelation trace of the amplified laser light pulse using Michelson's interferometer with second harmonic generation crystal. The duration of the fs laser pulse is 180 fs (FWHM).

The experimental results shown in Fig. 2-4 show that the gain was higher when the TEA N_2 laser with a sub-nanosecond pulse width was used as the excitation light source of the dye instead of the second harmonic of the YAG laser. However, the amplified laser output became unstable because of the gap switch used in the nitrogen laser. It is considered that a stable laser output could be obtained using a thyratron switch for the high voltage switch of the nitrogen laser. Although, compared to the gap switch, the thyratron switch is considerably more expensive and complicated to handle.

4. Conclusion

A fs laser pulse of the fiber laser was amplified in dye gain media, and the time-resolved gains were measured by using pulsed lasers as the pump sources. The maximum gain has been obtained by using the TEA N_2 laser as a pump source and DOTC as a dye solution. When the second harmonic of the Nd:YAG laser with a time jitter (<±1 ns) was used as a pump source, the stability of the amplified output power has been improved since the time domain for obtaining a positive gain value was greater than the timing jitter of the pump source. The amplified pulse energy was 1 μJ, and the pulse duration 180 fs (FWHM). These output energy and pulse width are comparable to those of a typical CPA laser system, and the cost performance is very high.

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