# Ultra-high-repetition-rate ArF excimer laser with long pulse duration for 193-nm lithography

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## ABSTRACT

High-repetition-rate ArF excimer lasers are needed to enable high throughput and energy-dose stability in 193-nm scanner systems. Last year we described a 4-kHz ArF excimer laser with long pulse duration, which can narrow the spectral bandwidth by increasing the number of round trips and reduce optical damage from low-peak power. The design of the 4-kHz ArF excimer laser has been improved for mass production. Operating rates exceeding 4 kHz are needed to optimize lasers for next-generation technologies that can enable high NA and the development of high-throughput scanners. We have analyzed the possibilities of achieving repetition rates higher than 4 kHz.

The discharge width was reduced by about 25 % with a variation of the electric field at the discharge section, and the gas flow and gas-mixture conditions were improved. As a result, we obtained the following performance characteristics: 42-W average power, 3.5 % pulse-to-pulse energy stability of sigma, and a 44-ns integral-square pulse width at 6 kHz with a bandwidth of below 0.45 pm in FWHM. We concluded that developing 6-kHz ArF excimer lasers for next-generation 193-nm lithography is feasible.

**Keywords:** excimer laser, ArF, 193-nm lithography, line-narrowing, high repetition rate, long pulse duration

## 1. INTRODUCTION

Much progress has been made in ArF excimer lithography as a result of a joint effort of semiconductor manufacturers and equipment makers. ArF excimer lasers are now viewed as a light source in the next-generation lithography that can be used for 4-Gbit DRAM production at 130 – 100-nm or below design rules. There has been a shift in excimer laser lithography from experiments to production.

Earlier, we described a narrow-bandwidth 4-kHz ArF excimer laser.[1.] One of its features is its ability to oscillate with long laser pulse duration that can narrow the spectral bandwidth by increasing the number of round trips and reduce optical damage from low-peak power. The 4-kHz ArF excimer laser, G40A, is already ready to be put into mass production. Development of new fine-node design rules is accelerating in recent semiconductor-device technology. Main target characteristics that we want to achieve in stepper/scanner and laser performance are summarized in Table 1. To optimize lasers for next-generation technologies that can enable high NA and the development of high-throughput scanners, not only narrower spectral bandwidths but also higher operating rates that exceed 4 kHz are required. So far, only ArF excimer lasers that operate at 4.5 to 5 kHz have been described.[2,3.]

In Gigaphoton, we are developing a next-generation 6-kHz ArF excimer laser, G60A. First, we tried to reconstruct a 4-kHz excimer laser prototype to analyze the possibilities of achieving higher repetition rates of operation. Then we focused not only on pulse-energy stability but also on the pulse width, because it tends to decrease because of the discharge instability at high repetition rates.

In this paper, we present output characteristics of repetition rates of up to 6 kHz in improved-prototype narrow-band ArF excimer lasers as a function of laser-gas-mixture conditions.

**Table 1 Main target characteristics in stepper/scanner and laser performance**

| Target stepper/scanner characteristics | Target laser characteristics |
|---|---|
| High resolution | Narrow bandwidth<br>Wavelength stability |
| High throughput | High average power<br>High repetition rate |
| High CD control | Energy stability<br>High repetition rate<br>Wavelength stability |
| Low operating cost | Long lifetime<br>High durability |

## 2. FEATURES OF ArF LASERS

We developed new devices to improve the performance of high-repetition-rate ArF excimer lasers. The following devices were used in our 6-kHz prototype laser:

(1) A high-efficiency discharge circuit based on a short rise time of the discharge current

Floating inductance of the discharge-current circuit was reduced as much as possible. Because the value of inductance is determined by the cross-sectional area in the discharge-current circuit, we rearranged the discharge components. As a result, laser-oscillation efficiency was enhanced, and the discharge input decreased.

(2) A uniquely designed discharge-electrode section that enables reduction of the discharge width and allows us to keep it reduced for a long time

We improved the design of the cathode, anode, preionizer, and assist electrode in terms of the electric field distribution to reduce the discharge width and to keep it reduced for a long time. Reducing the discharge width enables operating at higher repetition rates, while keeping the discharge width reduced enables extending the chamber lifetime.

(3) A low-input homogeneous preionizer with a high-intensity surface corona discharge

The electrode design of the preionizer was improved to allow for a high-intensity surface corona discharge. Preionizer input was reduced as much as possible by increasing generation efficiency and utilization rates of ultra-violet rays.

(4) A magnetic pulse-compression circuit (MPC) with a high compression ratio to enable generating an over-voltage across the electrodes

The voltage applied across the main electrodes must be set so that it can rise rapidly because the breakdown voltage depends on the rise time of the voltage applied to the electrodes. When the rise time is rapid, the breakdown voltage increases improving laser performance.[4.] We designed a lower residual inductance for the final stage of the MPC and improved the MPC connection to the laser chamber to reduce the voltage rise time.

(5) An IGBT switching unit capable of operating at up to 8 kHz
We developed a new switching unit for the pulse power modulator with solid-state switch elements, IGBT. Our switching unit can be operated at repetition rates of up to 8 kHz.

(6) A high-speed uniform gas-circulation system capable of detecting gas flows on electrode surfaces.
The most important requirement for high-repetition-rate operation is optimization of the gas flow in the discharge section. We developed a new gas-circulation system for high-average velocity and high uniformity at all discharge volumes capable of detecting gas flows on electrode surfaces.

(7) A laser chamber that minimized impurity generation, with a laser gas added to enable impurity control.
Impurity in laser gases affects ArF laser performance. We added a Xe gas into the laser gas to stabilize and enhance the ArF laser performance. We analyzed in detail impurity effects on the laser performance. The results show that it is important to reduce possible contamination in the laser chamber to stabilize the laser performance. [5.]

As a result of integrating the devices described above, the discharge stability improved significantly, and the laser-pulse duration stretched beyond 40 ns even when operating at high repetition rates. The use of the devices prevents spatial discharge constriction, which occurs in the later half-segment of the laser pulse, allowing for the discharge exciting the ArF excimer to be maintained for periods as long as 100 ns. Component lifetime can also increase. This type of a chamber-life test has been going on now for over 6 billion pulses at a repetition rate of 4 kHz.
Figure 1 shows the shape of the temporal pulse as a variation of the laser pulse duration in our narrow-band ArF excimer laser. The laser pulse duration varied with the discharge circuit constant and the gas-mixture conditions. A full width at half maximum (FWHM) of about 45 ns and a time-integral-squared (Tis) pulse width of about 50 ns were given as maximum values. 'Tis' can be defined as follows.

$$\mathrm{Tis} = \int [\, I(t)dt \,]^2 / \int I(t)^2 dt,$$

where I(t) is the time-dependent power of the laser pulse. [6.] Pulses of all shapes can operate at a laser energy of 5 mJ. Such long pulse duration can narrow the bandwidth by increasing the number of round trips in laser cavity and reduce optical damage. We obtained a convolved spectral bandwidth with a FWHM of about 0.6-, 0.4-, and 0.35-pm for the Tis of 16-, 34-, and 50-ns, respectively.

## 3. RESULTS AND DISCUSSION

### 3.1 Performance after reducing the discharge width

The discharge width of the gas flow was reduced from about 45 to about 35 mm by improving the design of the cathode, anode, preionizer, and assist electrode in terms of the electric field distribution. Figure 2 shows the maximum repetition rate without an arc-like discharge at the downstream versus an average gas velocity at the center of the discharge section. In Fig. 2, the solid line shows the reduced discharge width, and the dashed line shows a normal discharge width. As a result of reducing the discharge width, the operating rate increased to 5 kHz at the same gas velocity required for an operating rate of 4 kHz with a normal discharge width. The following equation for clearing ratio CR can explain this result.

$$\mathrm{CR} = v / (f_m \boldsymbol{w})$$

where $v$ is the inter-electrode gas velocity, $f_m$ is the maximum repetition rate, and $\boldsymbol{w}$ is the discharge width.[7.] Low gas velocity, when discharge products cannot be flowed out, causes an arc-like discharge at the downstream degrading energy stability. For our ArF excimer laser, the CR should be about 2.5.

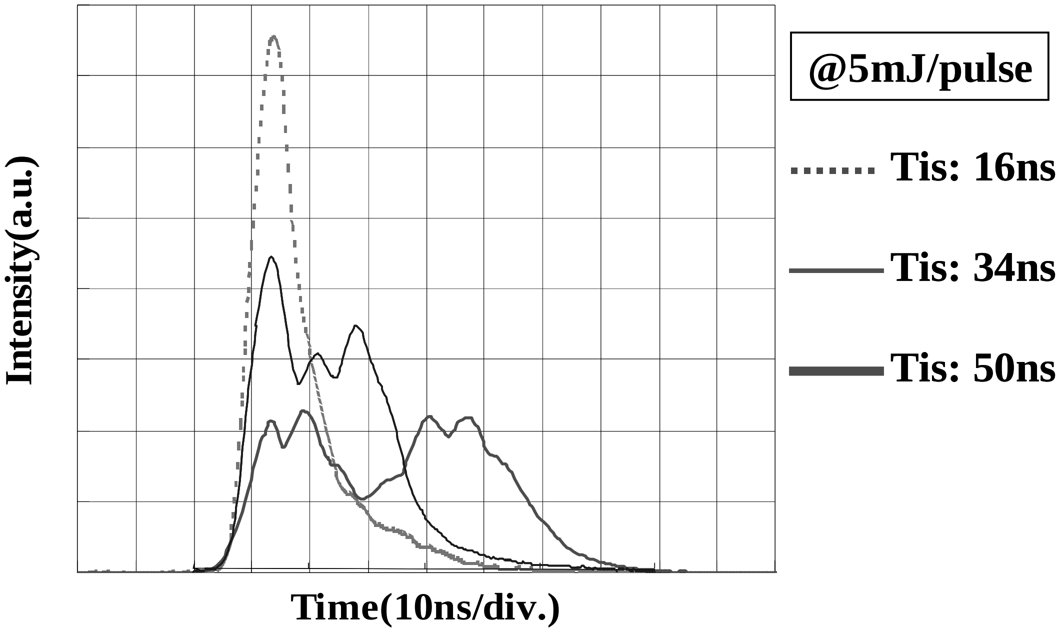

Fig. 1 Temporal pulse shape as a variation of laser pulse duration

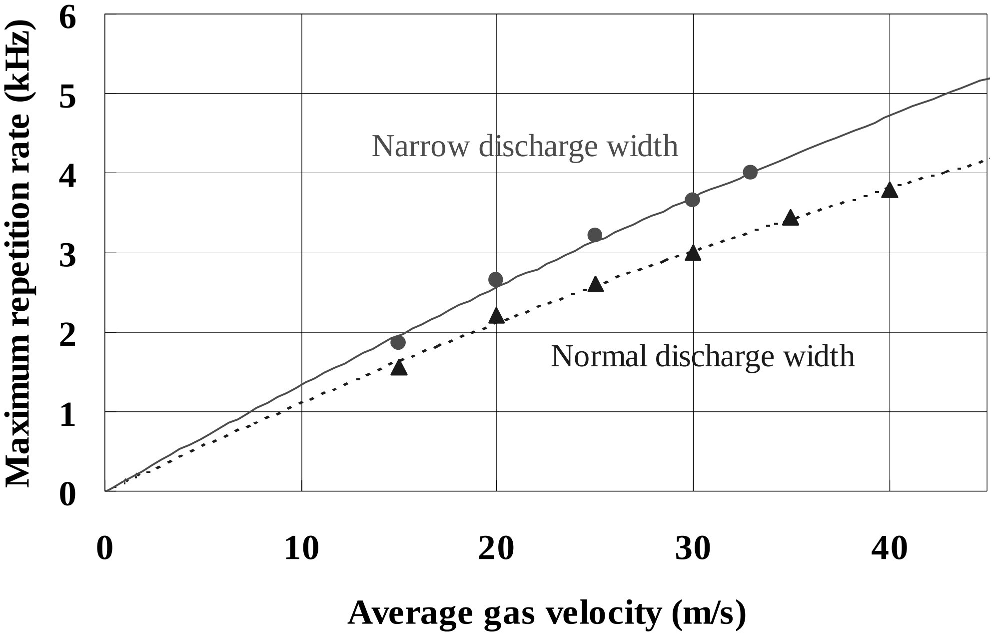

Fig. 2 Maximum repetition rate versus average gas velocity

Figures 3, 4, and 5 show the narrow-bandwidth laser energy, pulse-to-pulse energy stability of sigma, and pulse width Tis versus the repetition rate as a parameter of an Ar concentration, respectively. In all Ar concentrations, the FWHM of the spectral bandwidth was below 0.45 pm. In Fig. 4, we can see that the energy stability deteriorates at rates higher than 5 kHz because of the low gas velocity. The laser pulse duration was set at about 40 ns of Tis by changing the discharge circuit constant and gas-mixture conditions. We found that high Ar concentrations reduce the pulse width at higher repetition rates, even though high laser energy is generated. In the 2.5 % Ar concentration, the pulse width was hardly reduced. In higher for example, 3.5 % Ar concentrations, a discharge constriction occurred in the later half-segment of the laser pulse. Figure 6 shows the pulse shape as a variation of the Ar concentrations at 6 kHz. As we can see, the later half-time intensity decreased in the 3.5 % Ar concentration.

### 3.2 Performance after improving gas flow velocity and distribution

We developed a new gas-circulation system. To improve pulse-to-pulse energy stability at rates of over 5 kHz, we increased an average gas velocity from 45 to 50 m/s in the discharge section by increasing the blower rotation speed. We designed gas flow guides to prevent gas flows on both the anode and cathode surfaces from decreasing at all discharge volumes. Figure 7 shows gas flow velocity between the cathode and anode before and after the gas flow was improved. The vertical axis represents the space between the electrodes, and the horizontal axis represents the gas flow velocity. As we can see, the gas flow on the electrode surfaces increased after the improvements described in Fig. 7.

Figures 8, 9, and 10 show the narrow-bandwidth laser energy, pulse-to-pulse energy stability of sigma, and pulse width Tis versus the repetition rate as a parameter of an F2 concentration, respectively, with an Ar concentration of 3 %. The FWHM of the spectral bandwidth was below 0.45 pm in all F2 concentrations. In Fig. 9, we can see that energy stability at rates higher than 5 kHz improved with lower F2 concentrations. The pulse width was hardly reduced in the 0.07 % F2 concentration, as shown in Fig.10. Figure 11 shows the pulse shape as a variation of the F2 concentrations at 6 kHz. As we can see, the first half-time intensity decreased, but the later half-time intensity increased with low F2 concentrations. Our results at 6 kHz and expected specifications for the newest line-narrow module are summarized in Table 2.

**Table 2 Results and expected specifications at 6 kHz**

| **Features** | **Results** | **Expected specifications** |
|---|---|---|
| Average power | 42 W | 30 W |
| Pulse energy | 7 mJ | 5 mJ |
| Pulse-to-pulse energy stability | 3.5 % (Sigma) | < 3.0 % (Sigma) |
| Spectral bandwidth | < 0.45 pm (FWHM) | < 0.3 pm (FWHM) |
| Pulse duration | 44 ns (Tis) | > 40 ns (Tis) |

## 4. SUMMARY

The discharge width was reduced by about 25 % with a variation of the electric field at the discharge section. Gas flow and gas-mixture conditions were improved. As a result, we achieved the following performance characteristics: 42-W average power, 3.5 % pulse-to-pulse energy stability of sigma, and a 44-ns integral-square pulse width at 6 kHz with the bandwidth of below 0.45 pm in FWHM. We concluded that developing 6-kHz ArF excimer lasers for next-generation 193-nm lithography is feasible.

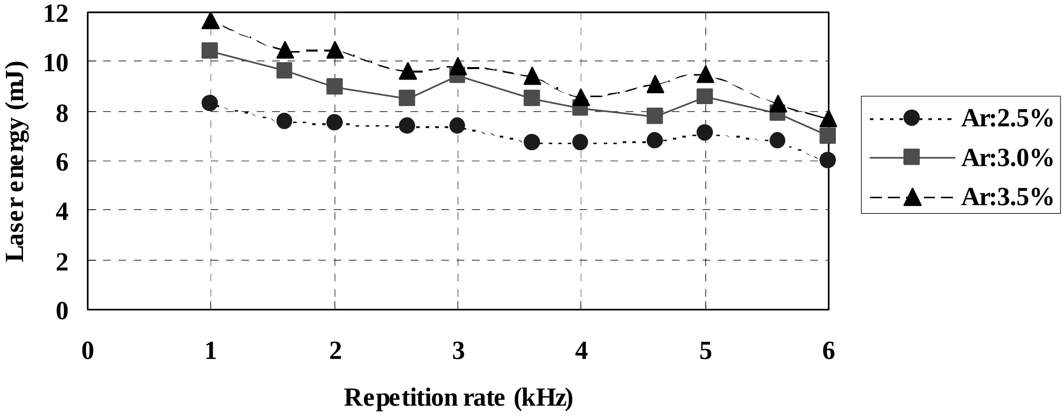

Fig. 3 Narrow-bandwidth energy versus repetition rate as a parameter of Ar concentration

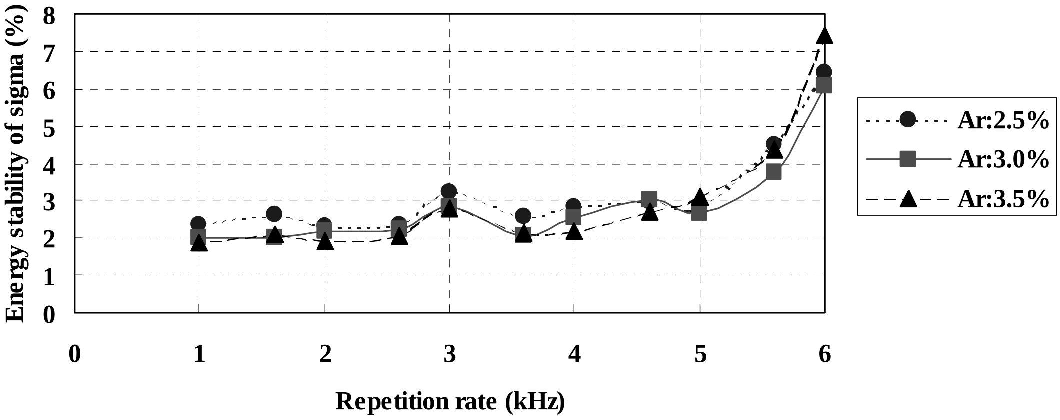

Fig. 4 Energy stability versus repetition rate as a parameter of Ar concentration

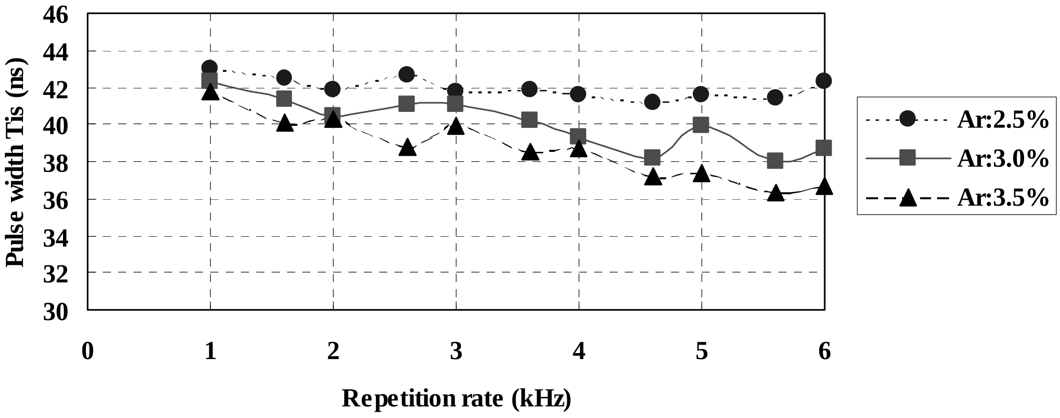

Fig. 5 Pulse width Tis versus repetition rate as a parameter of Ar concentration

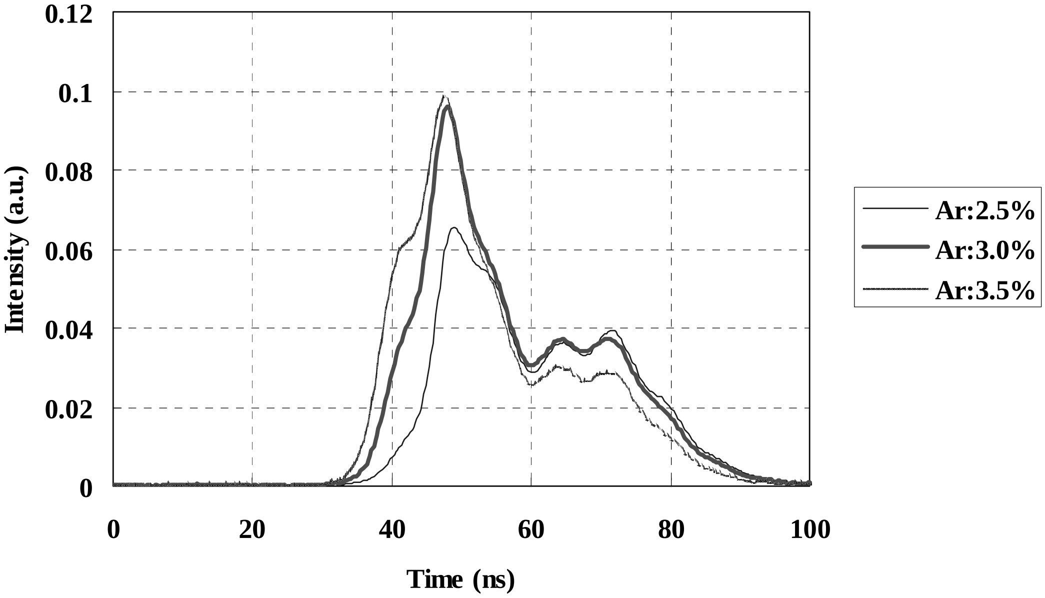

Fig. 6 Pulse shape as a parameter of Ar concentrations

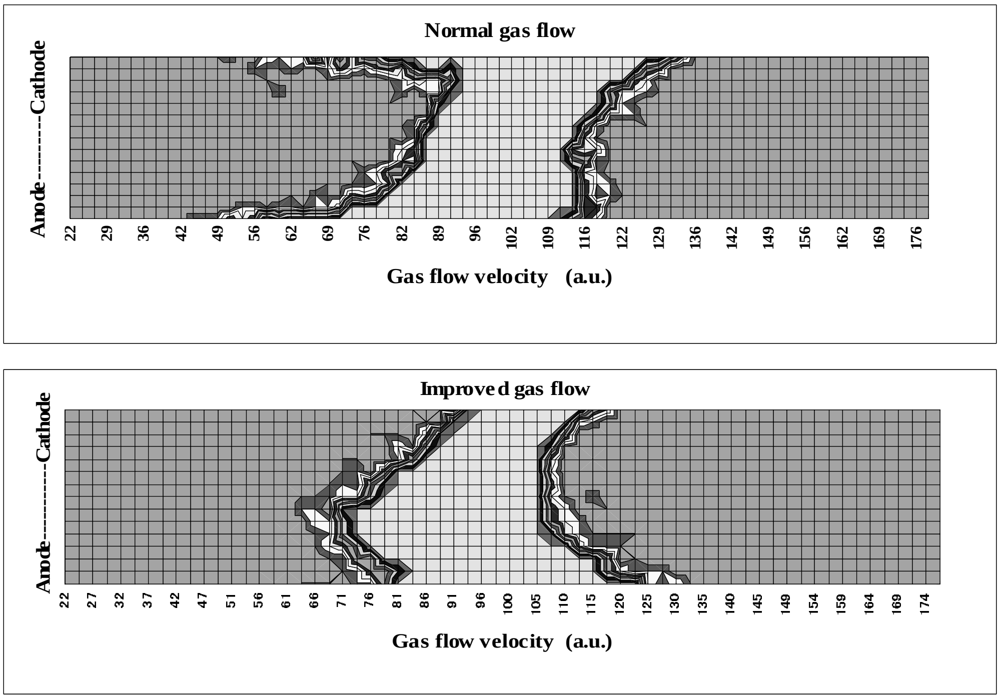

Fig. 7 Gas flow velocity between cathode and anode

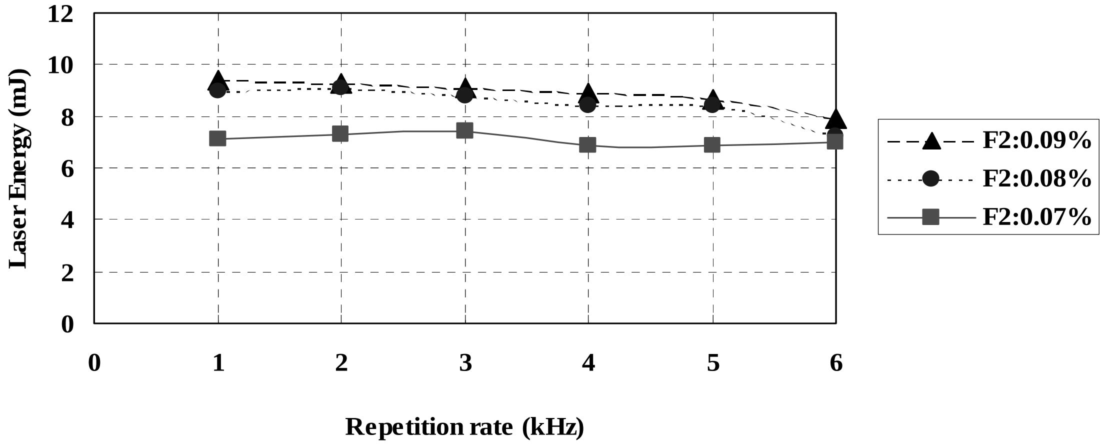

**Fig. 8 Narrow-bandwidth energy versus repetition rate as a parameter of F2 concentration**

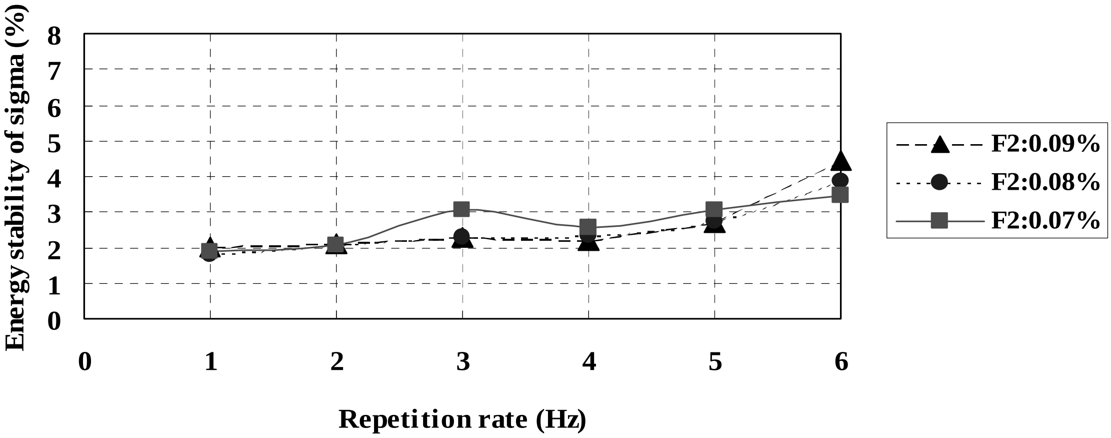

**Fig. 9 Energy stability versus repetition rate as a parameter of F2 concentration**

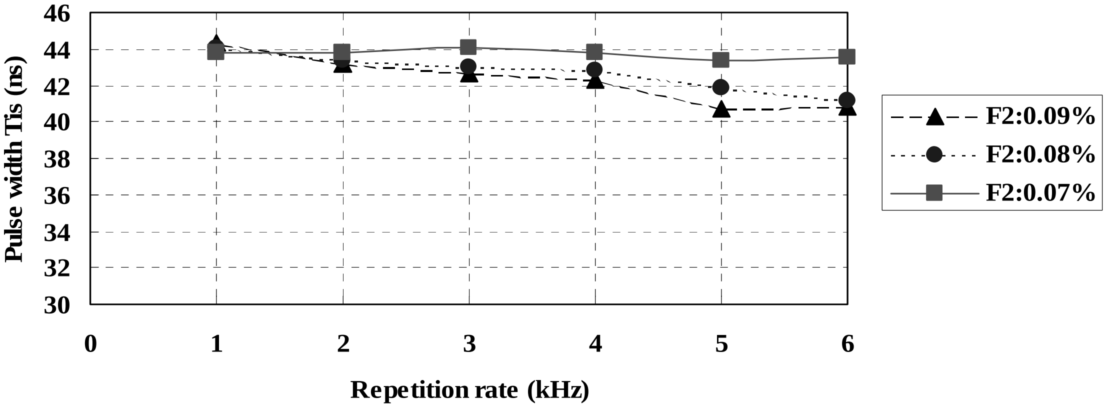

**Fig. 10 Pulse width Tis versus repetition rate as a parameter of F2 concentration**

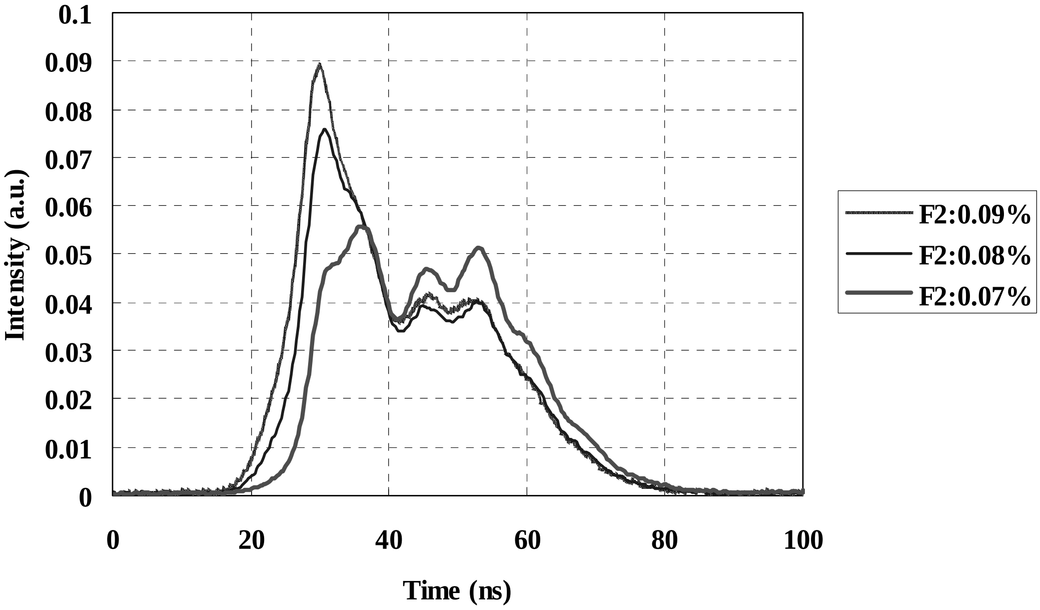

**Fig. 11 Pulse shape as a parameter of F2 concentration**

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