Beam quality of a new-type MOPO laser system for VUV laser lithography

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ABSTRACT

ArF-dry microlithography is currently switching from pre-production to mass-production and the target node is shifted from 90 nm to 65 nm. ArF-wet or F_2 laser lithography will then be an important player for the next generation node below 45 nm. Therefore, high throughput and high-resolution exposure tools for VUV lithography require VUV light sources (ArF and F_2 lasers) with high power and narrow bandwidth. In this paper, we describe the beam quality of the new- type injection lock (MOPO, master oscillator power oscillator) ArF laser system we developed and compare it with the beam quality of a master oscillator power amplifier (MOPA) ArF laser system.

A high power and narrow bandwidth ArF laser can be achieved with twin laser chambers in a MOPA or an injection lock laser configuration. Compared to the MOPA system, the injection lock laser system has an excellent performance (e.g. high efficiency, long pulse duration and narrow spectrum). On the other hand, the injection lock system has some disadvantages in beam quality showing high spatial coherence, broadband emission and having a beam profile with a hole.

These technical issues have been solved, however, with the following two new breakthrough-technologies: (1) a new-type injection lock system having low spatial coherence and a beam profile with no hole and (2) the optimization of the injection seed energy and discharge timing between the twin chambers for low broadband emission. The spatial coherence, the broadband spectrum and the beam profile of the new-type injection lock system were measured with a Young's interferometer, a wide range spectrometer with etalons and a 2-dimensional beam profiler, respectively. The new-type injection lock ArF laser system had a lower spatial coherence than a conventional injection lock system, a very low broadband emission level thus preventing deterioration of exposure tools resolution, and a beam profile with no hole. Moreover, we reconfirmed that the new-type injection lock system has the same excellent performance as the conventional injection lock system.

Keywords: ArF laser, Broadband emission, Spatial coherence, Injection lock, Lithography, MOPA

1. INTRODUCTION

ArF-dry exposure tools for the 90-65nm node(1, 2) require ArF lasers with a spectral (FWHM) width below about 0.2 pm and an output power of more than 40 to 60 W in order to achieve high throughput and high-resolution. Moreover, ArF-wet exposure tools for the 45nm node(1, 2) require ArF lasers with still narrower bandwidth and higher output power. Only twin chamber laser systems can meet these requirements simultaneously. MOPA(3) and injection lock(4) methods are used in twin chamber systems(5). Compared to the MOPA system, the injection lock system has some advantages: high efficiency, long pulse duration and a narrow spectrum. However, the injection lock laser system has some important issues in beam quality including high spatial coherence, broadband emission and a beam profile with a hole(5). We developed a new-type injection lock system that solves these technical issues. The purpose of this paper is to report the beam quality of the new-type injection lock ArF laser system compared to a MOPA ArF laser system.

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Chapter 2 explains the system configurations of the MOPA system and the injection lock system, and illustrates the experimental setup of the twin chambers system and the measurement system used to measure laser beam parameters: spectral bandwidth, broadband spectrum, spatial coherence, beam profile and pulse duration. Chapter 3 compares energy efficiency, pulse duration and spectral bandwidth between the MOPA system and the new-type injection lock system. Chapter 4 illustrates the Young's interferometer used to measure the spatial coherence, and compares the spatial coherences of the MOPA system, the conventional and the new-type injection lock systems. Chapter 5 describes a wide range spectrometer with etalons to measure broadband emissions, and evaluates the broadband emission in the new-type injection lock system. Chapter 6 discusses the beam profiles of the MOPA system, the conventional and new-type injection lock systems. Finally, we conclude in chapter 7.

2. TWIN CHAMBER SYSTEM CONFIGURATION

We tested three arrangements: a MOPA system, a conventional injection lock system and a new type injection lock system. The twin chamber systems need to be adopted to achieve narrow bandwidth and high power at the same time. The first chamber is called seed laser in case of the injection lock system and master oscillator for the MOPA system. Both the seed laser and the master oscillator have the same configuration as a conventional single chamber system. A prism-grating arrangement was used for line narrowing in the seed laser. Therefore, the seed laser emits an ultra line narrowed spectrum at low pulse energy. The second chamber, called the power amplifier for the MOPA system or the power laser for the injection lock system, amplifies the seed laser beam while keeping the optical property of seed laser. The power amplifier only consists of the second chamber. The function of the power amplifier is to amplify the seed light passing through the second chamber. On the other hand, the power laser may include an optical resonator. The function of the power laser is to amplify and to oscillate simultaneously the injected seed light. This new-type injection locked system is patent pending. Hence, the arrangement of the new-type injection locked system is not illustrated.

Fig. 1 shows the experimental setup of the twin chamber system and the system to measure the beam parameters of the MOPA and the injection lock system. The twin chamber system consisted of a seed laser with a line-narrowing module, a power amplifier or a power laser with an optical resonator. The laser beam quality measurement system included a beam profiler, biplanar phototubes, a Young's interferometer, a wide range spectrometer with etalons and a high-resolution spectrometer. All units were interconnected with a purged beam delivery unit to avoid oxygen and other gas contamination. This MOPA system was a single pass-MOPA system. The second chamber had the same chamber design as the first chamber. Both, the first chamber and the second chamber were operated at a repetition rate between 100 to 1000 Hz. The resonator was placed inside the power laser only for the injection lock systems tests. A synchronization system allowed the jitter between the first and the second chamber discharge to be maintained to within ± 2 ns.

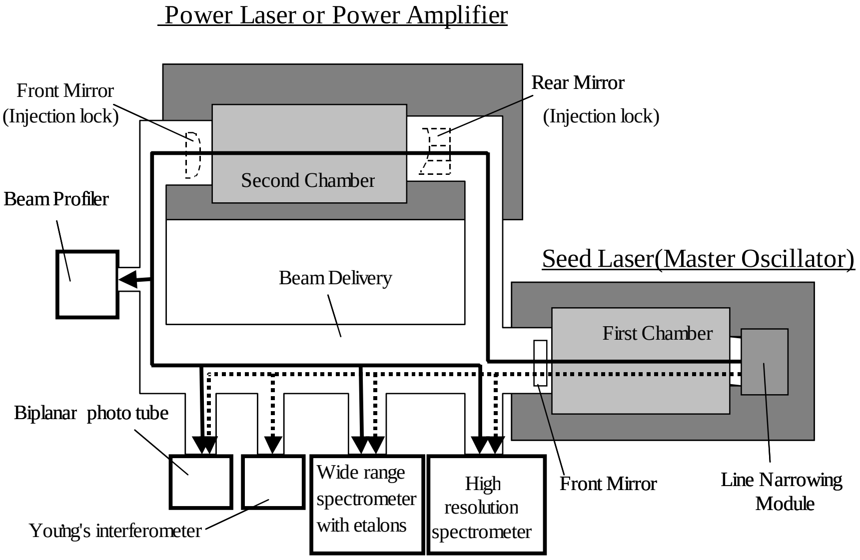

Fig. 1. Experimental setup of the twin chamber system and the system to measure beam qualities

The high-resolution spectrometer was used to measure the spectral laser profiles within ± 5 pm. The wide range spectrometer with the etalons was used to measure broadband emission of the new-type injection lock system. These spectrometers were calibrated with a 193nm coherent light source[6)] (193CLS). A 2-dimensional Beam Profiler (Star Tech Instruments/ BIP-5100) was used to measure the beam profiles. The output power and pulse energy of these systems were measured with a gentec power meter (PS-330-VUV) and the pulse energy monitors embedded in the laser systems, respectively. The pulse duration was measured with biplanar phototubes (R1193U-55, HAMAMATSU PHOTONICS).

3. COMPARISON BETWEEN MOPA AND NEW-TYPE INJECTION LOCK SYSTEM

This section summarizes some previously known advantages[5)] of the new-type injection lock system compared to the MOPA system. Amplified energy characteristics, temporal pulse shapes and spectral profiles are compared between the MOPA system and the new-type injection lock system. It has been shown that the new-type injection lock system has some advantages: higher efficiency, longer pulse duration, and a narrower bandwidth than the MOPA system.

3.1. Relation between output energy and seed energy

Fig.2 shows the relation between output energy and seed energy in the single pass MOPA system and the new-type injection lock system. Operation conditions of the amplifier chamber were kept constant; only the seed energy was changed. The output energy of the new-type injection lock system increased from 18 to 36 mJ increasing the seed energy from 0 to 1.64 mJ and saturated at a seed energy of about 0.1 mJ. On the contrary, the output energy of the single pass-MOPA system increased from 3.0 to 18 mJ increasing the injection seed energy from 0.06 to 1.6 mJ. The output energy of the new-type injection lock system was greater than that of the single pass MOPA system operated under the same second chamber condition. A double pass MOPA system was not tested, but a double pass MOPA is expected to have an output energy between the single pass MOPA system and the new-type injection lock system. Therefore, the new-type injection lock system has higher efficiency than a MOPA system.

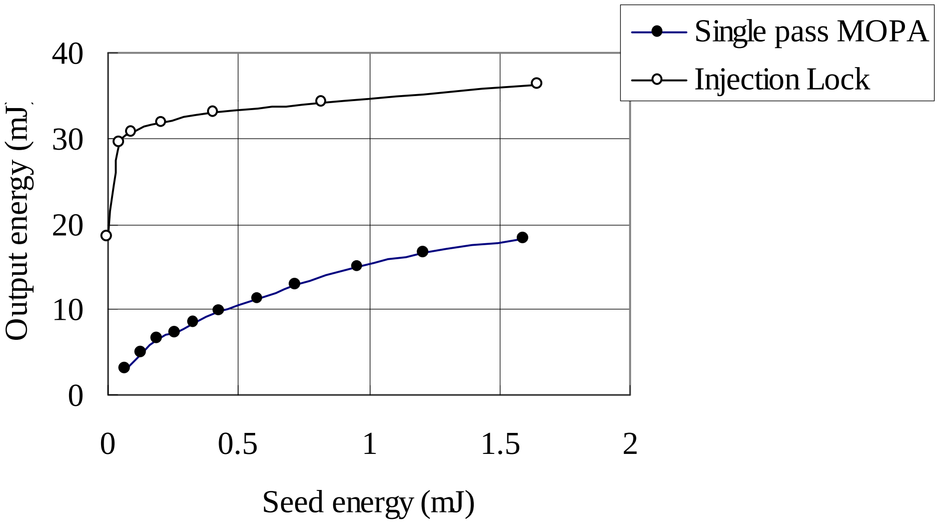

Fig.2. Relations between output energy and seed energy in the single pass MOPA system and the new-type injection lock system

3.2. Pulse durations of MOPA system and new-type injection lock system

Fig. 3 shows the temporal pulse shapes of the MOPA system and the new-type injection lock system. Temporal pulse widths defined by the integral square (TIS) were 21 ns for the MOPA system, and 44 ns for the new-type injection lock system. In addition, the new-type injection lock system had about the half peak intensity of the MOPA system The new-type injection lock system pulse duration is longer and an optical pulse stretcher can therefore be made smaller than for a MOPA system

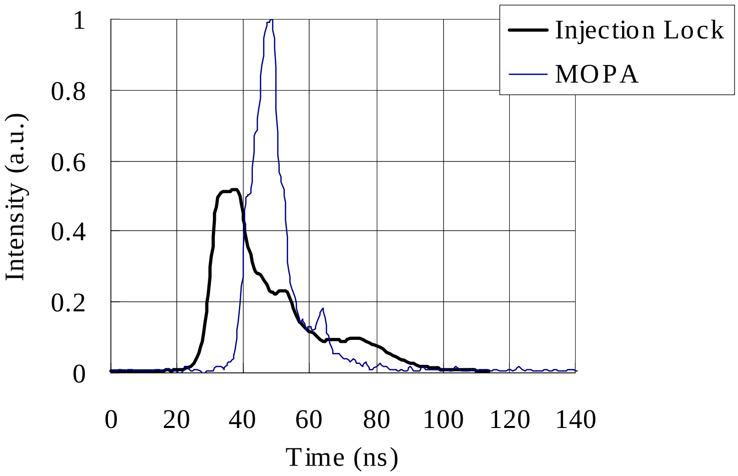

Fig.3. Temporal pulse shapes of the MOPA system and the new-type injection lock system

3.3. Spectral profiles of MOPA system and new-type injection lock system

Fig.4 shows the spectral laser profiles of the MOPA system and the new-type injection lock system. The MOPA system had a spectral FWHM of 0.21 pm and a spectral purity (defined by the bandwidth containing 95% of the total integrated energy) of 0.47 pm. The new-type injection lock system had a FWHM of 0.13 pm and a spectral purity of 0.32 pm. The new-type injection lock system had a narrower spectral bandwidth than the MOPA system.

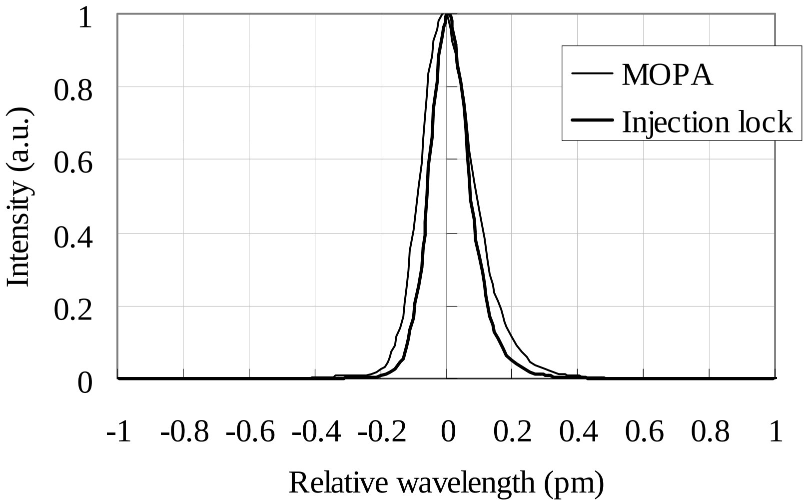

Fig.4. Spectral profiles of the MOPA system and the new-type injection lock system

4. SPATIAL COHERENCE

Exposure tools require laser with low spatial coherence to suppress speckle patterns formed on the mask and on the wafer. The section illustrates the Young's interferometer for spatial coherence measurement and indicates the results of the spatial coherences of the MOPA system, the conventional and the new-type injection lock systems.

4.1. Young's interferometer

Fig. 5 shows the optical arrangement of the Young's interferometer used for the spatial coherence measurements. The ArF laser beam illuminates the double pinhole. The double pinhole then divides the laser beam into two wave fronts. Mirror #1 and mirror #2 reflect the two wave fronts. A fringe pattern is finally formed on the CCD. With increasing pinhole distance, the visibility of the fringe pattern decreases. With decreasing spatial coherence, the visibility decreases for constant pinhole distance, or the pinhole distance decreases for constant visibility. The spatial coherences of the laser beam can be evaluated by plotting the visibility of the fringe pattern vs. the pinhole distance. The visibility is given by

$$\text{Visibility} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \qquad (1)$$

where I_{max} and I_{min} are the maximum and minimum intensity of the fringe pattern, respectively.

Both double pinholes had diameters of 20 μm. The distance between the double pinhole and the CCD was 2.5m. The distance between the pinholes was changed in the range of 0.1mm to 2mm.

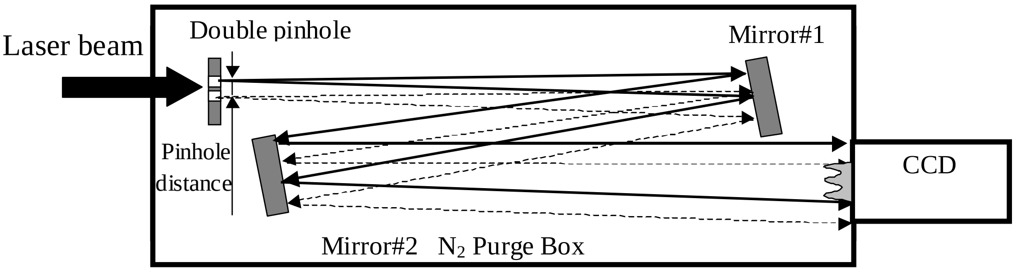

Fig.5. Optical arrangement of the Young's interferometer

4.2. Spatial coherence of the MOPA system, the conventional and the new-type injection lock systems

Fig. 6 and 7 show the spatial coherences of the MOPA system, the conventional and the new-type injection lock systems in vertical and horizontal direction, respectively. In vertical direction, the new-type injection lock system had almost the same spatial coherence as the MOPA system but had lower spatial coherence than the conventional injection lock system. In horizontal direction, the new-type injection lock system had a similar spatial coherence as the MOPA system and had a slightly lower spatial coherence than the conventional injection lock system. It has been shown that the spatial coherence of the new-type injection lock system is about the same as for the MOPA system.

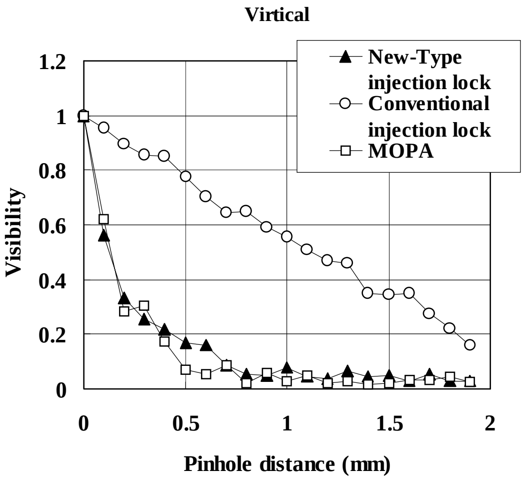

Fig. 6. Spatial coherences in vertical direction

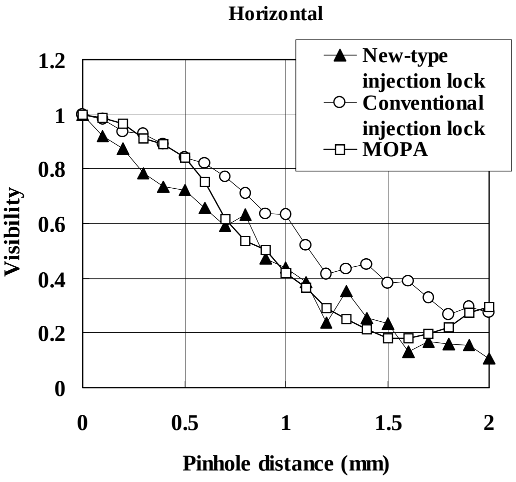

Fig. 7. Spatial coherences in horizontal direction

5. BROADBAND EMISSION

The broadband emission of the injection lock system may deteriorate the resolution of exposure tools and therefore has to be measured. The spectrum of the injection lock system at non-optimal operating conditions contains a free running spectrum and a line-narrowed spectrum. The broadband emission is a component of the free running spectrum. Free running ArF lasers have a spectral (FWHM) width of about 450 pm. Therefore, it is impossible to measure the broadband emission of ArF lasers using the high-resolution spectrometer with a narrow range of about ± 5 pm. This section illustrates the wide range spectrometer with etalons for measuring broadband emission, and presents the results of the broadband emission in the new-type injection lock system.

5.1. Broadband emission measurement system

Fig. 8 shows the optical arrangement of the broadband emission measurement system. This system consists of two etalons and a wide range spectrometer. The etalons were used to improve the signal-to-noise ratio. Both etalons had a free spectral range of 300 pm and a finesse of F=8.5. The spectrometer was a modified-Czerny-Turner spectrometer in combination with a magnifying concave-convex mirror configuration. The output focal length was 1890mm, the dispersion was 2.2 pm/ch, and the wavelength range was about 2250pm. The ArF laser beam, sampled from the main ArF laser beam, passes through the etalons and enters the spectrometer. The absolute wavelength of the spectrometer was calibrated with the natural emission lines of an As lamp at 193.0035nm, 193.7594nm, and 193.8827nm. The instrumental function of the spectrometer was measured with a 193 nm coherent light source6) (193CLS). Wavelength selection by one etalon requires an adjustment of the wavelength of the second etalon. As a consequence, the contrast of this modulation was about 1000. We used the etalons to selectively stop the central spectral peak. The broadband emission of the new-type injection lock system was evaluated with the followings profiles: the measured instrumental function of the spectrometer, the free running spectrum of the ArF laser, the spectral profile measured by the spectrometer combined with the etalons, and the transmission spectrum of the etalons. The broadband ratio is defined by the ratio of the integrated energy of the broadband spectrum to the total energy. This broadband emission measurement system had an accuracy of the broadband ratio within about 10^{-4}.

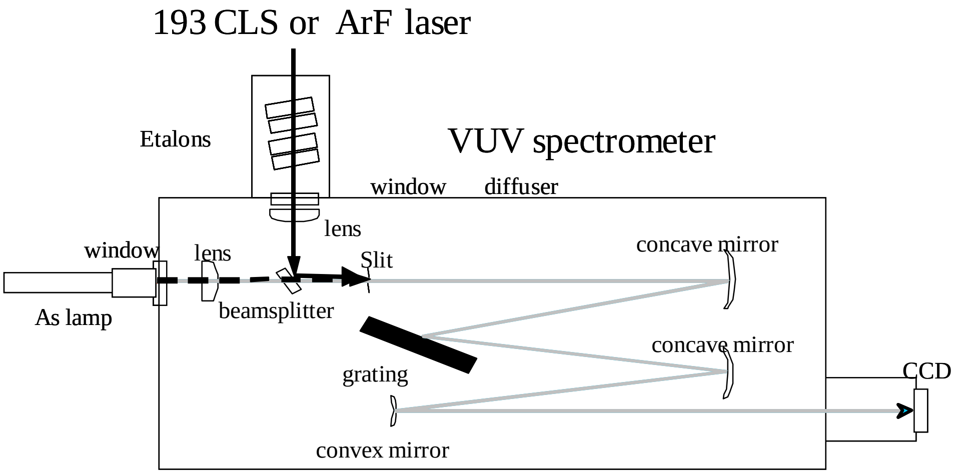

Fig.8. Optical arrangement of the broadband emission measurement system.

5.2. Broadband spectra and broadband ratio of the new-type injection lock system

Fig. 9 shows the broadband spectra of the new-type injection lock system with and without the etalons and the instrumental function of the spectrometer. The thick line shows the spectrum of the new-type injection lock system at low injection seed energy measured without etalons. The solid line shows the spectrum of the new-type injection lock system at high injection seed energy measured with the etalons. The broadband emission at the low injection seeding energy was estimated to be about 1000 times as much as that at the high injection seeding energy, because the modulation contrast of the etalons was about 1000. The thin line shows the instrumental function measured by the 193CLS.

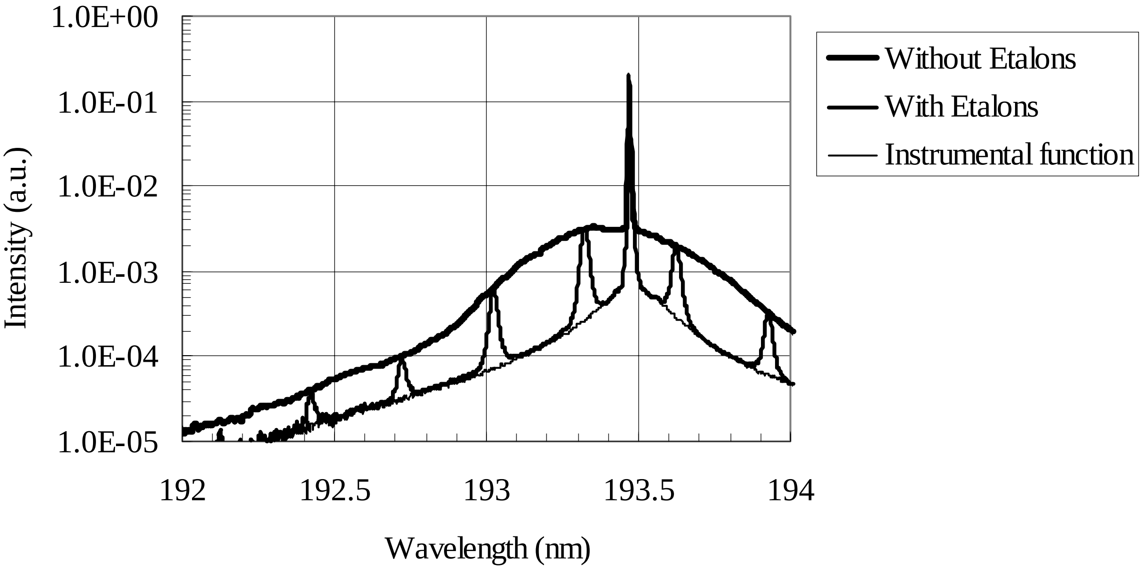

Fig.9. Broadband spectra of the new-type injection lock system with and without the etalons and the instrumental function.

Fig. 10 shows the dependence of the broadband ratio, pulse energy and energy stability of the new-type injection lock system on the delay time (defined by the relative discharge delay between the first chamber and the second chamber). The seed laser was operated at a pulse energy of about 0.4 mJ. The broadband ratio reached a minimum at 35 ns and was below $3X10^{-4}$ in the range from 25 ns to 35 ns. This very low broadband emission level of the new-type injection lock system prevents deterioration of the exposure tool projection lens resolution. The pulse energy remained stable in the range from 20 to 40 ns with a pulse energy of about 20 mJ. The energy stability was less than 6 % in the range from 15 ns to 40 ns.

These results indicate that broadband emission can be suppressed by optimizing the injection seed energy and the discharge timing between the twin chambers. In addition, the new-type injection lock system has a potential to achieve an output power of more than 60 W and an energy stability of less than 6 %.

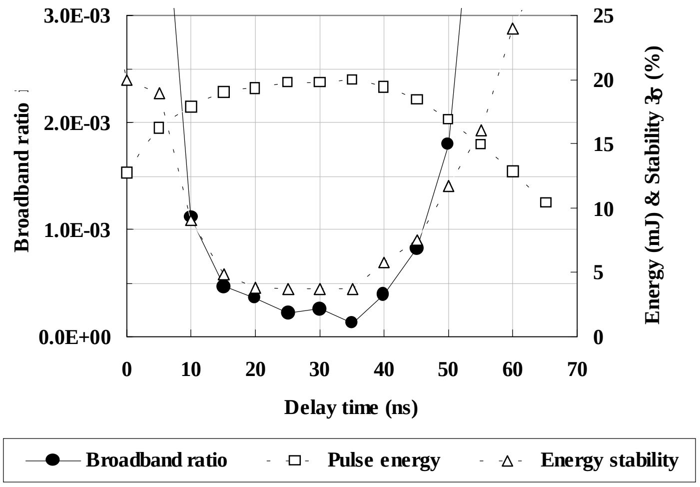

Fig.10. Dependence of the broadband ratio, pulse energy and energy stability of the new-type injection lock system on the delay time

6. BEAM PROFILE

Fig.11. shows 2-dimensional beam profiles of the MOPA system, the conventional and the new-type injection lock systems. The conventional injection lock system had the disadvantage of a beam profile with a hole in the center. On the contrary, the new-type injection lock system has a beam profile with no hole as in case of the MOPA system.

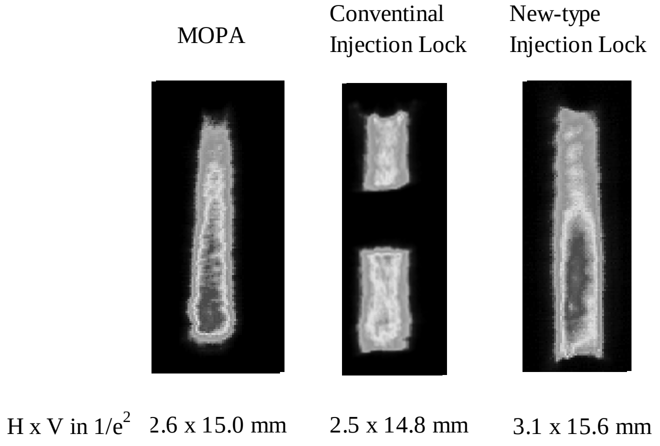

Fig.11. Beam profiles of the MOPA system, the conventional and the new-type injection lock laser systems

7. CONCLUSION

We have developed a new-type injection lock technology with the following breakthrough characteristics: low spatial coherence, low broadband emission and a beam profile with no hole. Moreover, we reconfirmed that the new-type injection lock system had some advantages compared to the MOPA system: higher efficiency, longer pulse duration, and a narrower bandwidth.

As a result of our study, we have already started to develop a 60 W ArF laser7) (GT40A) equipped with this new-type injection lock technology. This technology is expected to be applied in high power laser light sources for ArF and F_2 lithography.

ACKOWLEDGMENTS

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