Challenge of the F2 Laser for Dioptric Projection System

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ABSTRACT

It is predicted that the semiconductor market will demand 70nm devices from 2004 or 2005. Hence, F2 laser microlithography systems have to be developed according to this time frame. At ASET, "The F2 Laser Lithography Development Project" started in March 2000, as a 2-year project to fulfill this market requirement. The final target of this project is to achieve a F2 laser spectral bandwidth of 0.2pm (FWHM) at a repetition rate of 5000Hz and an average power of 25W. These specifications meet the demand of dioptric projection system.

We have done a feasibility study for a high efficiency line narrowing design to achieve the ultra narrow spectral bandwidth and the high output power. In addition, we have developed an intermediate engineering laser system consisting of an oscillator laser and an amplifier. With this laser system we have performed the line-narrowed operation using two arrangements: Master Oscillator Power Amplifier (MOPA) and Injection Locking.

With this Oscillator-Amplifier system and have achieved a spectral bandwidth (convoluted) of FWHM <0.2pm with both systems: MOPA and Injection Locking. The maximum output energy was >20mJ for MOPA and >15mJ for Injection Locked operation.

Keywords: F2 Laser, 157nm microlithography, line-narrowing, injection locking, MOPA, dioptric

1. INTRODUCTION

There are basically two optical designs to realize 70nm devices with 157nm microlithography: Dioptric and Catadioptric. The required spectral specifications for the F2 laser are different for the two optical designs and are shown in [Table. 1].

Dioptric design: This design is very common for present microlithography systems. For the exposure tool, only refractive optics (lens) are used in this design.

Catadioptric design: For the exposure tool, reflective optics (mirrors) are used in this design.

Using Dioptric design means that chromatic aberration has to be canceled by applying at least two different lens materials: CaF2 and BaF2. Or, alternatively, it is necessary to use a very narrow spectral light source for 157nm. Catadioptric design uses mirrors, which do not have wavelength dispersion as lenses. Therefore, the Catadioptric design has a much larger margin for the spectral bandwidth. Catadioptric design requires a Full-Width-At-Half-Maximum (FWHM) of 0.6 ~ 1.0pm at 157nm, but Dioptric design requires a FWHM below 0.2pm.

Dioptric is the "state of the art" design of current exposure tools and this is certainly a "driving force" for stepper suppliers to prepare Dioptric F2 laser microlithography systems for the market within the given time frame. Therefore there is a demand for Ultra Line-Narrowed F2 lasers to reduce the risks for developing the stepper system

[Table. 1] F2 Laser Bandwidth Requirement for Catadioptric and Dioptric Systems

Lens Design	Catadioptric	Dioptric	
Lens Material	CaF2	CaF2 + (BaF2)	CaF2
Bandwidth (FWHM)	<1.0pm	<0.5pm	<0.2pm
Laser System	Line Selection	Partial L/N	Ultra L/N

2. OSCILLATOR AND AMPLIFIER PERFORMANCE AS A SINGLE LASER

An important issue of the laser cavity is the transmittance of the optical components. Optical coatings for the F2 laser are stages still in the middle of development, therefore it is difficult to obtain high transmittance optics for the Ultra Line-Narrowing module. High loss optics of the Ultra Line-Narrowing module, however, cause a very low Ultra Line-Narrowing efficiency [(Narrow Running Energy) / (Free Running Energy)], and it is, therefore very difficult to develop a high power single-stage Ultra Line-Narrowed laser.

The presented F2 Laser R&D project will develop the Ultra Line-Narrowed F2 laser for microlithography with a FWHM bandwidth less than 0.2pm at 5000Hz, 5mJ output energy. ASET target specifications of the project are shown in [Table. 2].

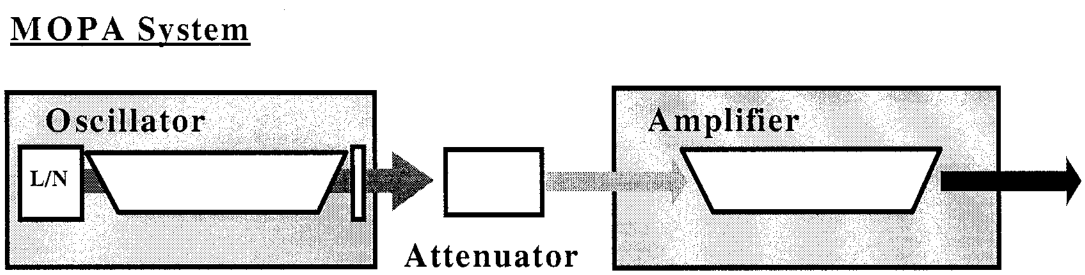


Fig. 1-1

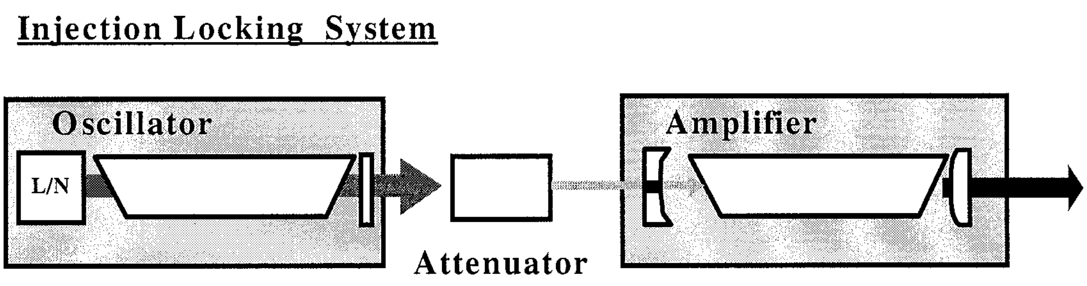


Fig. 1-2

[Fig. 1] Arrangement for MOPA and Injection Locking

[Table.2] ASET target specification of F2 Laser R&D Project

Specifications	Target
Repetition Rate	5000 Hz
Pulse energy	5 mJ
Average Power	25 W
Energy Stability	10 % (3 σ)
Spectral Bandwidth	0.2 pm
Spectral Purity (95%)	0.5 pm
Wavelength Stability	+/-0.05 pm

An intermediate Oscillator-Amplifier F2 laser configuration has been developed as a first step within this F2 laser R&D project to evaluate the possibility of an Ultra Line-Narrowed F2 Laser. For this system one F2 laser was used as an ultra line-narrowed oscillator, and a second one was used as the amplifier. We tested two arrangements: Master Oscillator Power Amplifier (MOPA) and Injection Locking. Schematics of the arrangements for MOPA and Injection Locking are shown in [Fig. 1].

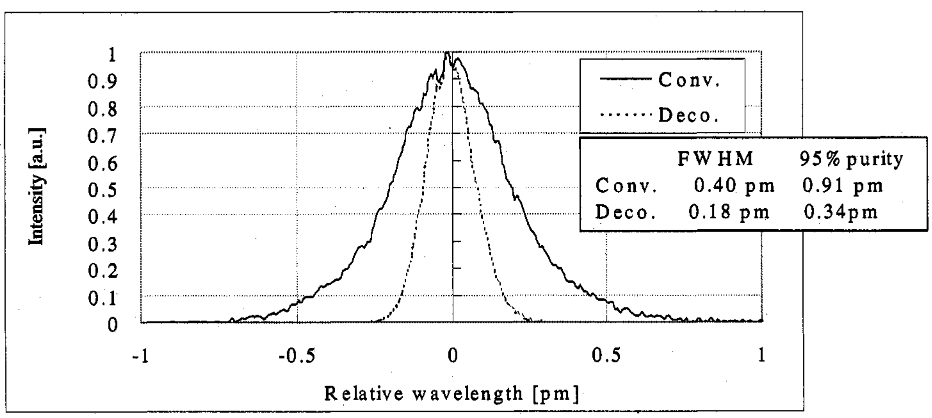
The FWHM bandwidth target of the oscillator is set to be < 0.2pm with an output energy of > 0.1mJ and the output energy target of the amplifier is set to be > 5mJ. The reason is that the bandwidth characteristic mainly depends on the oscillator whereas the output energy depends on the amplifier.

a. Oscillator Performance

The oscillator used a Prism-Grating Arrangement Line-Narrowing Cavity. In addition, the newly developed Long Pulse Discharge 4) was used for the Ultra Line-Narrowing operation. The pulse length of the oscillator at free running operation was more than 40ns integral square (Tis). Under Ultra Line –Narrowing operation, the Tis reduced to about 20ns. This decrease of the Tis is due to the optical loss of the Line-Narrowing cavity. Additionally the Ultra Line-Narrowing efficiency "[Ultra Line-Narrowed energy] / [Free Running energy]" is about 5~10% for the Ultra Line-Narrowed oscillator and depends on the discharge input power. To obtain a much higher efficiency, higher transmittance AR coatings are required for the optics.

However, this experimental oscillator satisfied the target specifications: output energy > 0.1mJ and FWHM <0.2pm. When the spectrum is deconvolved with the instrument function of the spectrometer 1), 5), the FWHM was 0.18pm and the 95% purity was 0.34pm as shown in [Fig. 2]. The oscillator output energy of the displayed spectrum was 0.1mJ.

A performance summary of the Ultra Line-Narrowed F2 Laser is shown in [Table. 3].



[Fig. 2] Spectrum for the oscillator

[Table. 3] Ultra Line-Narrowed F2 Oscillator Performance

Pulse Duration	**22.0 ns**	
Free Running Energy	**4mJ**	
Line Narrowing Energy	**0.2 mJ**	
[LN]/[FR] Rate	**5%**	
Spectrum [FWHM]	**0.40 pm [Conv.]**	**0.18 pm [Deco.]**
[95% Purity]	**0.91 pm [Conv.]**	**0.34 pm [Deco.]**

b. Amplifier Performance

The maximum output energy of the amplifier was 15mJ with a Flat-Flat stable optical resonator using a 10% reflection output coupler. Additionally the pulse duration Tis was 13ns. The amplifier was operated at a gas pressure between 350kPa and 400kPa using He as buffer gas. The maximum repetition rate of the amplifier was 2000Hz.

c. MOPA System

A schematic of the MOPA system is shown in [Fig. 1-1]. A beam delivery module that includes an attenuator connects the Ultra line-Narrowed Oscillator and the Amplifier. The beam delivery module was nitrogen purged to avoid laser absorption by oxygen gas. The attenuator was used to vary the seed energy of the amplifier.
In the MOPA configuration the amplifier was used as a one-pass gain media of the seed energy. Therefore no cavity mirrors were used.

Behind the oscillator-amplifier system a laser beam inspection system was set including an energy meter, two CCD beam profiler (one for the beam profile and another for the divergence measurement) and a spectrometer.

d. Injection Locking System

A schematic of the Injection Locking system is shown in [Fig. 1-2]. A beam delivery module connects the Ultra Line-Narrowed F2 Laser Oscillator and the Amplifier as described for the MOPA arrangement. Also in this case, an attenuator was used to vary the seed energy of the amplifier.

The amplifier is used as a laser oscillator having an unstable optical cavity. The rear mirror has a hole to pass the oscillator laser beam into the amplifier. The front mirror has a small center HR region with the outer region emitting the laser.

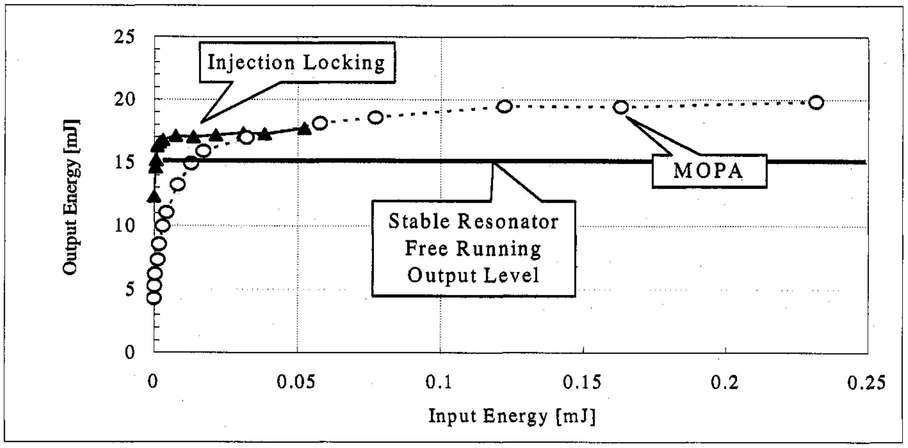
3. SYSTEM PERFORMANCE

a. Output Energy

a-1. Output energy vs. Input energy [2]:

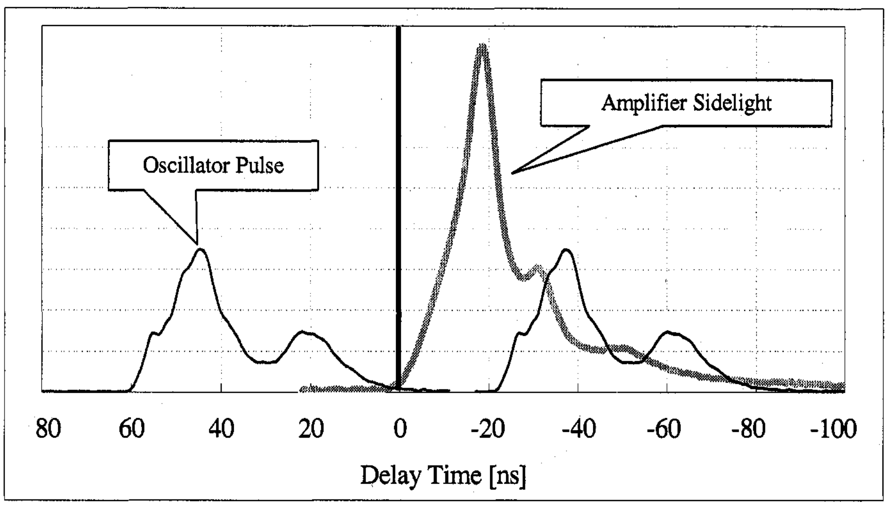
The output energy performance of both Oscillator-Amplifier systems (MOPA and Injection Locking) is shown in [Fig. 3]. The amplifier was operated under He buffer gas condition. For Injection Locking, the maximum output power was 17mJ, and the output energy saturates at about 0.005~0.010mJ oscillator seed energy. In the case of MOPA, the amplifier output energy increases rapidly until 0.03mJ oscillator seed energy. Above 0.03mJ seed energy, the output energy of the amplifier increases slightly and saturates. 20mJ maximum output energy was obtained in the case of MOPA with 0.23mJ oscillator input energy.

The amplifier of free running configuration with a Flat-Flat stable resonator emits the maximum output energy of 15mJ under the same gas condition for the MOPA and Injection Locking experiment At Injection Locking, 0.01~0.02mJ is sufficient to saturate the system output energy. Therefore, there is a possibility to use lower power and smaller Ultra Line-Narrowed oscillator, compared to our pleasant intermediate system.



[Fig. 3] Input-Output Energy performance of the Amplifier for MOPA and Injection Locking

a-2. Synchronized time delay between Oscillator and Amplifier vs. Output Energy:
The Oscillator-Amplifier output energy dependence on the delay time between oscillator and amplifier is shown in [Fig. 5].



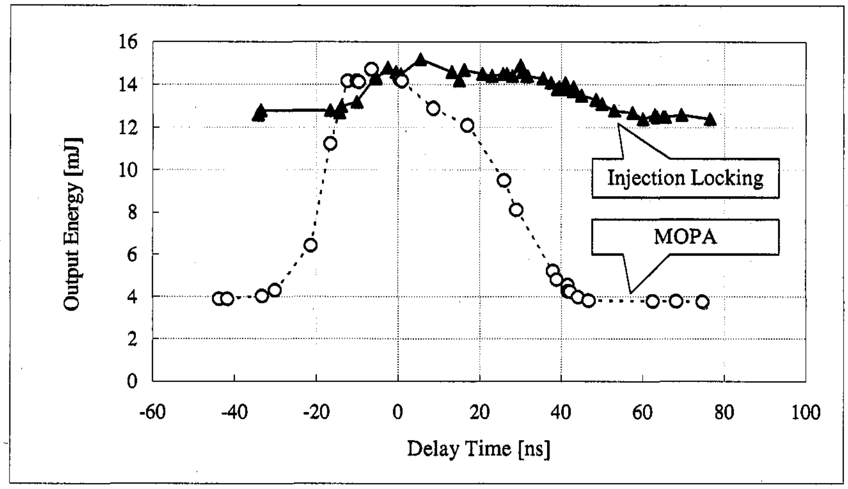
[Fig. 4] Definition of the Delay time between Oscillator Laser Pulse and Amplifier Sidelight

The amplifier was operated with He buffer. MOPA and Injection Locking "Output Energy vs. Delay Time" characteristics are shown in [Fig. 5]. As shown in [Fig. 4], a "negative" delay time means that the light emission of the discharge pulse (Sidelight) of the amplifier occurs earlier than the input seed laser pulse from the oscillator. A "zero" delay time means that the emission of the discharge pulse of the amplifier and the oscillator laser pulse occur at the same time. "Positive" delay time means that the oscillator laser pulse occurs earlier than the emission of the amplifier.

For the delay time and output characteristics experiment, about 0.002mJ of oscillator laser energy was seeded and the amplifier was operated to emit 14mJ under free running condition. As shown in [Fig. 5] 15mJ was obtained in this case for the MOPA and Injection Locking system. The output power of the Injection Locking system is stable for more than about 50ns at 15mJ. This means that for this operation condition, the oscillator laser energy and the pulse length are sufficient to saturate the output energy. The MOPA output energy is not as stable as the Injection Locking output energy and shows a peak.

Usually, the power supply and the controller of the laser systems have a jitter causing a varying the synchronization between oscillator and amplifier. Hence, a low jitter is required for the Oscillator Amplifier Configuration System.

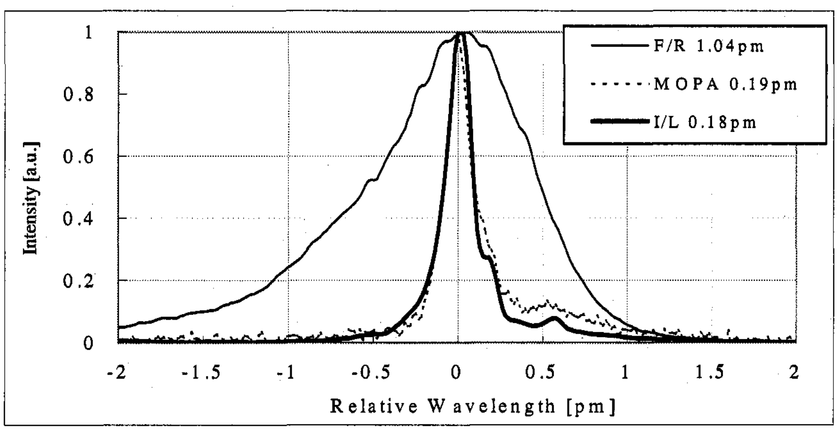
As can be seen from [Fig. 5] the Injection Locking system, however, has a higher margin for jitter than the MOPA system.



[Fig. 5] Output Energy vs. Delay time between Oscillator and Amplifier pulse

b. Spectral Bandwidth

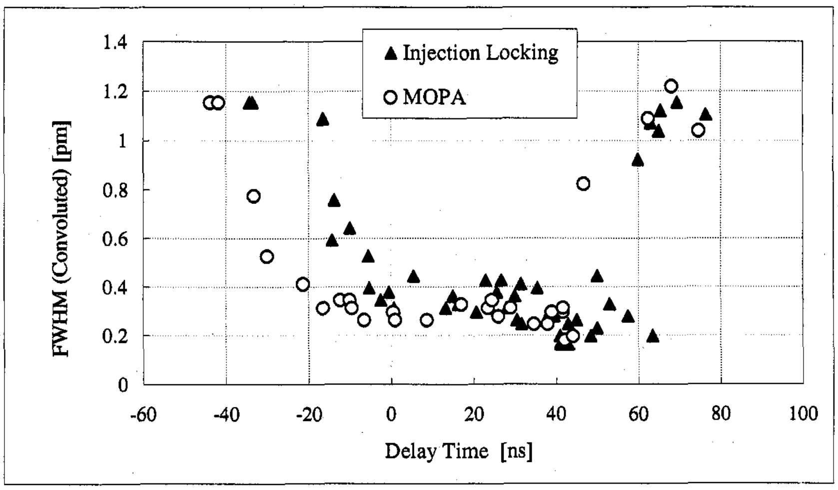
b-1. Sample of Bandwidth below 0.2pm:
A FWHM below 0.2pm has been obtained for both MOPA and Injection Locking System. The spectral bandwidths of the amplifier (free running), MOPA and Injection Locking system are shown in [Fig. 6]. Convoluted FWHM for free running, MOPA and Injection Locking were: 1.04pm, 0.19pm and 0.18pm, respectively.



[Fig. 6] Bandwidth of Amplifier (free running), Ultra Line-Narrowed MOPA & Injection Locking

b-2. Spectrum FWHM vs. Synchronized timing between Oscillator and Amplifier [3]:
The FWHM as a function of the delay time is shown in [Fig. 7]. The amplifier is operated under He buffer gas. The definition of the delay time is described before [Fig. 4]. Oscillator and amplifier are operated under the same condition as the Injection Locking experiment.

The change of the FWHM related to the delay time looks similar between MOPA and Injection Locking. However, for Injection Locking, when the delay time is below 0ns the FWHM increases faster compared to MOPA. For this case, free running oscillation of the amplifier will be the main laser source and this will make the Injection Locked FWHM broad compared to the MOPA FWHM. For Injection Locking the output energy is stable between 0~50ns delay time and this also the range for which the FWHM is minimal and below 0.3pm. The minimum FWHM below 0.2pm was obtained between 40~50ns.

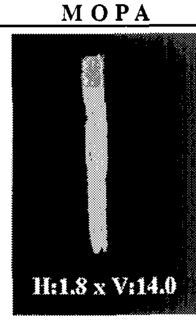
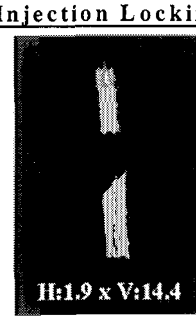
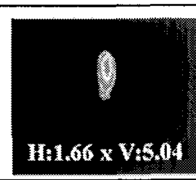


[Fig. 7] Spectrum FWHM vs. Delay time between Oscillator pulse and Amplifier pulse

c. Beam Performance

The beam profiles and the beam divergences for MOPA and Injection Locking are shown in [Fig. 8]. The beam size for MOPA and Injection Locking were: Horizontal 1.8mm x Vertical 14.0mm and Horizontal 1.9mm x Vertical 14.4mm, respectively. Note for the Injection Locking there is a hole in the center, due to the use of an unstable resonator for the amplifier cavity.

Beam divergence for MOPA and Injection Locking were: Horizontal 1.66mrad x Vertical 5.04mrad and Horizontal 0.98mrad x Vertical 1.05mrad, respectively. Injection Locking has a smaller divergence compared to MOPA. The vertical divergence for Injection Locking is less than 1/5 of the MOPA for our system design.

	MOPA	Injection Locking
Beam Profile @ $1/e^2$ [mm]		
Beam Divergence @ $1/e^2$ [mrad]		

[Fig. 8] Beam Profile and Beam Divergence for MOPA and Injection Locking

4. CONCLUSION

An intermediate Oscillator-Amplifier F2 laser configuration has been developed as a first step for this F2 laser R&D project to evaluate the possibility of the Ultra Line-Narrowed F2 Laser. We tested two Oscillator-Amplifier configurations: MOPA and Injection Locking, at a repetition rate of 10~100Hz.

The Maximum Energy was >20mJ for MOPA and >15mJ for Injection Locking operation. We achieved a spectral bandwidth (convoluted) of FWHM <0.2pm with both systems. The output energy for a bandwidth below 0.2pm are about 4mJ and 14~16mJ for MOPA and Injection Locking, respectively. Summarized performance of both systems is shown in [Table. 4].

From our study, we conclude that the Injection Locked Line-Narrowed F2 Laser System is a promising light source candidate for the 157nm Dioptric Projection System.

[Table. 4] Ultra Line-Narrowed F2 Oscillator-Amplifier Laser System Performance

Performance Items		Master Oscillator Power Amplifier	Injection Locking
Spectrum	FWHM [pm]	<0.2	<0.2
Power	[mJ]	4	14~16
Oscillator Power	[μJ]	60	10
Divergence	H [mrad]	1.66	0.98
	V [mrad]	5.04	1.05
Profile	H [mm]	1.8	1.9
	V [mm]	14	14.4

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REFERENCES

1. T. Kumazaki, T. Ariga, K. Sasano, R. Nohdomi and H. Mizoguchi, "Ultra-line-narrowed F2 laser for lithography (I)", The Japan Society of Applied Physics, The 61st Autumn meeting, 4p-X-3, 2000, Hokkaido, Japan
2. H. Mizoguchi, K. Hotta, H. Watanabe, T. Kumazaki, Y. Ueno, N. Kitatochi, M. Nakano, K. Sasano, R. Nohdomi, T. Nishisaka, T. Ariga and K. Nakao, "High Power High Repetition Rate Ultra-Line-Narrowed F2 laser for Microlithography", 157nm Technical data Review, 2000.11.14-16, San Diego, USA
3. Y. Ueno, T. Kumazaki, T. Ariga, T. Nishisaka, H. Watanabe, N. Kitatochi and R. Nohdomi, "Ultra-Line-narrowed F2 laser for Lithography (I)", 21st Annual meeting of The Laser Society of Japan, 30aVII7, 2001, Tokyo, Japan
4. H. Watanabe, N. Kitatochi, K. Kakizaki, A. Tada, J. Sakuma, T. Ariga and K. Hotta, "Long Pulse Duration of F_2 Laser for 157nm Lithography", SPIE Microlithography, ML4346-109, 2001, Santa Clara, CA, USA
5. O. Wakabayashi, J. Sakuma, T. Suzuki, H. Kubo, N. Kitatochi, T. Suganuma, T. Nakaike, T. Kumazaki, K. Hotta, H. Mizoguchi, K. Nakao, T. Togashi, Y. Nabekawa and S. Watanabe, "Spectral Measurement of Ultra Line-Narrowed F_2 Laser", SPIE Microlithography, ML4346-108, 2001, Santa Clara, CA, USA