High-resolution Multi Grating Spectrometer for High Quality Deep UV Light Source Production

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1. ABSTRACT

Deep UV lithography using ArF excimer laser requires very narrower spectral properties. However, spectrometers that have sufficient resolution to evaluate the ArF excimer laser are commercially not available. High-resolution multi-grating spectrometers for measuring spectral bandwidth at full width at half maximum (FWHM) and spectral purity of ArF excimer lasers are introduced. To achieve high resolution, a special grating arrangement called HEXA (Holographic and Echelle Gratings Expander Arrangement) is designed. A holographic grating and an echelle grating are used so that the input light is expanded and diffracted several times. The resolution of the HEXA spectrometer is more than two million. To evaluate the resolution and the stability of the spectrometer, we measured the instrument function by a coherent light source whose wavelength is same as ArF excimer laser. The experimentally obtained resolution of the spectrometer is 0.09pm or 0.05pm that is selectable. The measured dispersion has a good agreement with the theoretical value. To evaluate the spectral properties of excimer lasers, the instrument function must be very stable. This high-resolution spectrometer enables high quality control of line-narrowed ArF excimer laser mass production.

Keywords: metrology, spectral width, spectrometers, KrF excimer laser, ArF excimer laser

2. INTRODUCTION

Deep UV lithography with KrF/ArF excimer lasers requires extremely narrow laser bandwidths in order to reduce the chromatic aberration of lithography projection lenses. Last year we reported the DEGA spectrometer, which has a resolution of 0.11pm.[1)] The DEGA spectrometer is a large size instrument and placed in a separate temperature controlled chamber. It is mainly used for the KrF excimer laser production. For the ArF excimer laser production, smaller sized and transportable spectrometers without reduced the resolution are required. This paper presents a newly developed high-resolution multi-grating spectrometer for measuring the spectral bandwidth at full width at half maximum (FWHM) and spectral purities of ArF excimer lasers. (The purity is defined as the spectral width containing 95% of the total laser energy (E95).)

3. REQUIREMENT OF HIGH RESOLUTION SPECTROMETER FOR ARF EXCIMER LASER PRODUCTION

As small features of integrated circuits are required, the specifications for the light source of optical lithography steppers become more difficult. When the design rule drops below 0.13 micron, a spectral bandwidth of less than 0.35pm will be required. For the development of narrower light source, precise measurement systems are indispensable. The resolution of the instrument must be at least 1/5 to 1/10 of the spectral bandwidth. However, there is no instrument with this specification right now. From the standpoint of the restrictions for size and stability of the instrument, it is very difficult to accomplish a resolution as 0.03pm. Therefore we are using deconvolution to obtain accurate measurements with instruments whose resolution is 0.1 to 0.2pm. When the deconvolution method is used, FWHM of the instruments function must be smaller than the spectral bandwidth of the lasers to be measured, and a very precise measurement of the instrument function is indispensable. [1)] In the case of KrF excimer laser wavelength (248nm), a single mode frequency doubled Ar ion laser, which has very narrow spectral bandwidth, is commercially available and it can be used to measure the instrument function. On the other hand, for the ArF excimer laser wavelength (193nm), there is no coherent light source available.

Another problem for the spectrum measurement for the ArF excimer laser production is the size of the instrument. The excimer laser is a very large sized gas laser and fixed equipment. Therefore the optical properties of the laser are measured by guiding the laser light through the optical fibers or by setting the spectrometer near the laser. For the ArF wavelength (193nm) long optical fibers cannot be used due to transmission losses. For example, the transmission of 10m fibers at 193nm is less than 1/100. Since more than several ten meters of fiber are required, it is impossible to get sufficient light intensity. The only solution is to make a small and transportable instrument, which can be placed besides the laser. We have made a high resolution spectrometer called DEGA and used it for the KrF excimer laser production line. The DEGA spectrometer has a very high-resolution and is very stable. However, the size is very large, W2000 x D1000m, and it cannot be used for ArF laser production. As the result, we must develop a small sized high-resolution spectrometer.

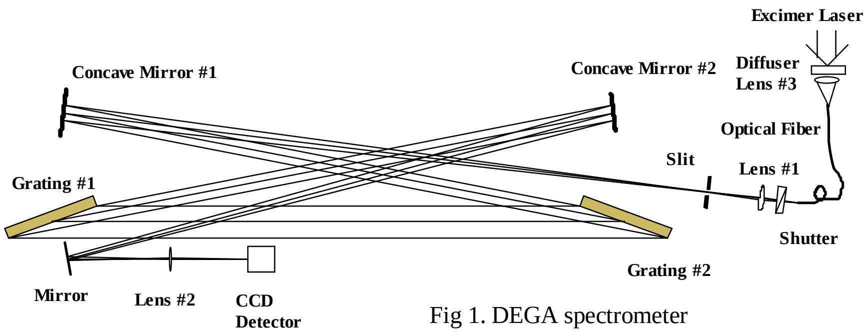

Fig 1. DEGA spectrometer

To characterize the spectral property of the light source for the lithography, full-width-half-maximum (FWHM) is commonly used. To evaluate the imaging contrast for high NA lens, we must use not only FWHM but also use the spectrum purity E95 (bandwidth enclosing 95% of the energy). The measured value of E95 is very sensitive to the noise level of the instrument. Fig 2 shows the measured E95 for different S/N ratio. For this calculation, an ideal spectrum profile of E95 1.0pm, FWHM 0.3pm is assumed and white noise is superimposed. The vertical scale means the percentage of the error of E95. Suppose a spectrum has S/N ratio of 1000, calculated E95 becomes 1.05pm. This means that a S/N ratio of more than 1000 is required to reduce the calculation error below 5%.

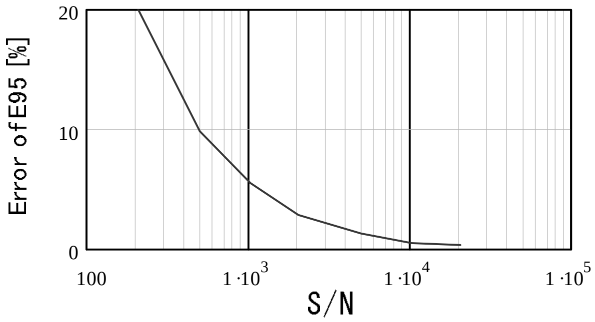

Fig 2:

E95 calculation error due to noise

Instrument Function: FWHM 0.1pm E95 1.0pm

Laser Spectrum: FWHM 0.3pm E95 1.0pm

E95 is calculated after deconvolution

Fig 3 shows the error of E95 caused by the number of quantization levels for the spectrum intensity signal. For lower quantization levels, there is a possibility to have a smaller E95 value than true value. This graph implies, at least more than 12 bits quantization level is a must.

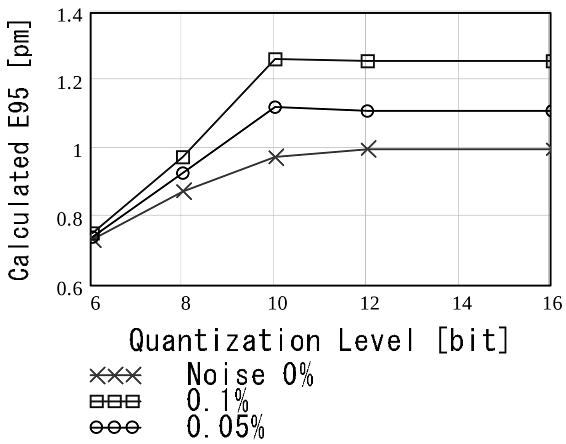

Fig 3:

E95 calculation error due to quantization level

Laser Spectrum: FWHM 0.3pm E95 1.0pm

Summarizing the above discussion; we set the following target specifications for the spectrometer.

FWHM of Instrument function	< 0.1pm
S/N ratio	> 1000
Quantization level	> 12 bits
Instrument size	Transportable

4. PRINCIPLE OF HEXA SPECTROMETER

To accomplish the target resolution, the resolution of one grating is insufficient. A multiple diffraction arrangement with plural gratings is necessary. At the same time, we must increase the angular dispersion. Usually longer focal length collimators are used to have a large angular dispersion. The longer focal length collimators not only require a large sized instrument but also make the spectrometer dark. Although the excimer laser is powerful enough to measure the spectrum, the coherent light source to measure the instrument function doesn't have enough power. Reducing the light loss caused by

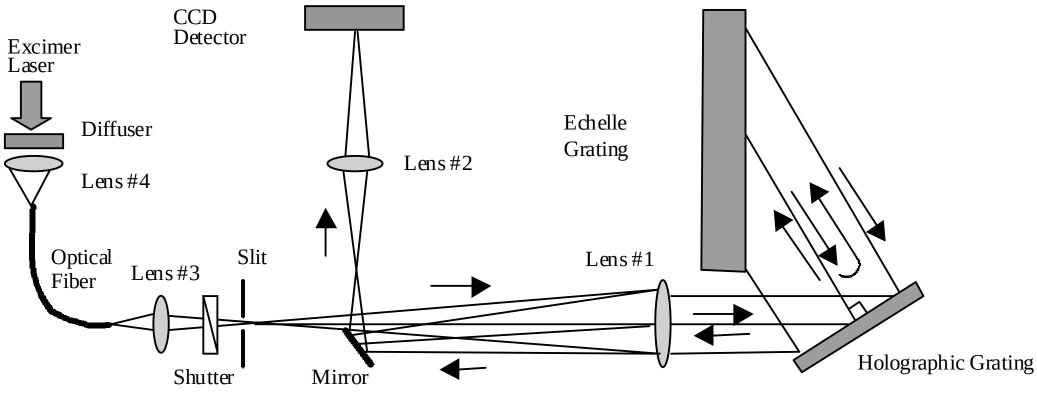

Fig. 4 Layout of the HEXA spectrometer

the spectrometer as much as possible is therefore also important. With these restrictions, we designed a spectrometer with a new grating arrangement that can achieve a high-resolution in spite of the small instrument size. Fig 4 shows the basic idea. The laser to be measured is fiber coupled and imaged onto the entrance slit by lens #3. The light passing the slit is collimated by lens #1. The light is diffracted by Holographic grating toward an Echelle grating. The diffraction angle of the Holographic grating is set to zero degree. (Perpendicular to the surface of Holographic grating) Because of the Echelle grating is set to the Littrow angle, the incident light is diffracted back into the same direction as the incident light. The light re-entered to the Holographic grating is diffracted again and goes back to the lens #1. The collimator lens #1 creates the slit image onto the slit. If the Echelle grating is slightly rotated into the clockwise direction, the slit image is reflected by the mirror and imaged onto the CCD through lens #2. The lens #2 is used to magnify the slit image. The magnification also increases the angular dispersion. With this arrangement, the laser to be measured is diffracted three times, two times by the Holographic grating and one time by the Echelle grating, and the spectral resolution is increased. If the diffraction angle by the Holographic grating is large, the collimated beam is expanded and the angular dispersion is also increased.

On the other hand, because the entrance angle of the Holographic grating is zero degree, the reflected light goes to the Echelle grating. The light is diffracted by the Echelle grating and returns to the Holographic grating. If the rotation angle of the Echelle grating is adequately adjusted, the diffracted light is guided to the CCD direction. In this case, the laser to be measured is diffracted four times and a higher resolution can be achieved. We call this configuration Double Pass (DP), because of the light is diffracted by the Echelle grating two times, while the former case is diffracted once. (Single Pass (SP)) Besides, it is possible to diffract three times, Tipple Pass (TP) and more by the Echelle grating. As the number of diffraction increase, the resolution is enhanced, however the light intensity decreased by the each diffraction and signal to noise ration (S/N) decreases. By means of this new arrangement, the resolution is not only high but also selectable with the same configuration. We call this new type spectrometer, HEXA (Holographic and Echelle gratings Expander Arrangement) spectrometer.

5. DESIGN OF HEXA SPECTROMETER

The important parameters to design the HEXA spectrometer are

Focal length of collimator lens:	f
Numerical aperture of collimator lens:	NA
Groove spacing of Gratings:	d1, d2
Diffraction angle of Holographic grating:	ϕ
Diffraction order of gratings:	m1, m2
Total number of pass:	SP, DP or TP

The focal length of collimator should be long to obtain a large dispersion. However, the size of spectrometer will become large and the numerical aperture (NA) of the collimator will decrease. When the NA increases, the spectrometer can collect more light and has a better S/N. At the same time, the diffraction limit is reduced and the resolution improved. On the other hand, this will require large size optical components such as lens and gratings. Especially for the gratings, there is a strong restriction for the size by the manufacturing process and the selection of gratings is limited. The diffraction angle and diffraction order of the Holographic grating strongly affect the resolution of the spectrometer. If the diffraction angle is large, the beam expansion ratio will increase and the dispersion will be improved. Another point to consider is diffraction efficiency that is affected by the diffraction angle and the properties of gratings such as blazed angle. Because there are many restrictions, careful attention must be paid to optimize these parameters.
The angular dispersion of the HEXA spectrometer for the double pass is defined by the following equation (1),

$$\frac{d}{d\lambda}\beta_o = \frac{m1}{d1 \cdot \cos(\beta 3)} + \frac{2 \cdot m2}{d2 \cdot \cos(\beta 2)} \cdot \frac{\cos(\alpha 3)}{\cos(\beta 3)} + \frac{m1}{d1 \cdot \cos(\beta 1)} \cdot \frac{\cos(\alpha 3) \cdot \cos(\alpha 2)}{\cos(\beta 3) \cdot \cos(\beta 2)} \qquad \text{----}(1)$$

where;
the suffix number 1 denotes the input light to the Holographic grating, the number 2 denotes Echelle grating and the number 3 denotes the output light from the Holographic grating. βo is the output angle from the collimator lens, λ is the wavelength, m, d, alpha, beta are the diffraction order, the groove spacing of the gratings, input and output light angle to the gratings respectively. The table 1 shows an example of calculation. In this table, the focal length of 1500mm, CCD detector's pixel size of 24 micron whose quantization level is 16bit and the magnification ratio of lens #2 of five times are assumed. The calculated resolution shows, the SP and DP has enough performance for our objective.

	Dispersion [pm/ch]	**Resolution [pm]**	**Relative Efficiency**
SP	**0.024**	**0.050**	**1**
DP	**0.013**	**0.025**	**0.45**
TP	**0.009**	**0.017**	**0.20**

Table 1: example of calculation for the HEXA spectrometer
SP: Single Pass, DP: Double Pass, TP: Triple Pass

The performance of a spectrometer is generally described by the instrument function. The shape of the instrument function is defined by the optical performance of collimator and magnification lenses, the wave-front distortion of gratings, the diffraction performance of gratings, the width of slit and the performance of CCD detector array. The most important part is the collimator. Usually the collimator system of spectrometers is designed by concave mirrors to eliminate chromatic aberration. However, it has a defect to create astigmatism. Because spectrometers for the excimer laser production are required only for a narrow spectral range, a wide range achromatic system is not needed. Therefore a lens system, which is superior to mirrors for aberration, is appropriate to the HEXA spectrometer. A new diffraction limited lens system at both ArF wavelengths (193nm) and KrF wavelength (248nm) is designed.
The actual size of the HEXA spectrometer is only W1200 x H1023 x D700mm even though it has very high-resolution performances that correspond to a more than 15m length spectrometer. It has casters and only one operator can easily move it. The equipment is separated into two sections, upper and lower. The body of spectrometer is installed on the upper part that is temperature controlled within +/- 0.1 degree. To maintain the high stability of the measurement, the spectrometer is perfectly sealed and purged. Even when an operator moves the HEXA spectrometer from one laser to another, no adjustments are required.

6. CALIBRATION OF HEXA SPECTROMETER

All the parts of the HEXA spectrometer, are strictly inspected for their performances and then assembled. Although the total performance of spectrometer can be estimated by the results of the inspection, some sort of error might be included. For our objective these errors are not negligible. The total performance of the spectrometer must be calibrated.
There are two important categories to calibrate a spectrometer. One is the dispersion that decides the unit of wavelength axis and the other is the instrument function that describes the resolution of the spectrometer. The instrument function is a must

for the precise measurement of the spectral profile by the deconvolution method. In this section, the coherent light source that is necessary to measure the instrumentfunction and the dispersion calibration scheme are introduced.

6.1 193nm coherent light source

To measure the instrument function of the HEXA spectrometer, a light source that has very narrow spectral bandwidth compared to the excimer laser is required. Usually this kind of light source is called coherent light source. Also, periodical inspection of the instrument function is necessary to reconfirm the long-term stabilities or to detect the malfunction of the spectrometer. As for the KrF wavelength (248nm), single mode frequency doubled Argon ion lasers are commercially available, however, there is no coherent light source for the ArF wavelength (193nm). Last year Komatsu developed a 193nm coherent light source (193CLS) in cooperation with the University of Tokyo.[2)] Recently, we modified the 193CLS to an all solid type laser system in order to use it at the excimer laser plant. Fig 5 shows the schematic diagram of new 193CLS.

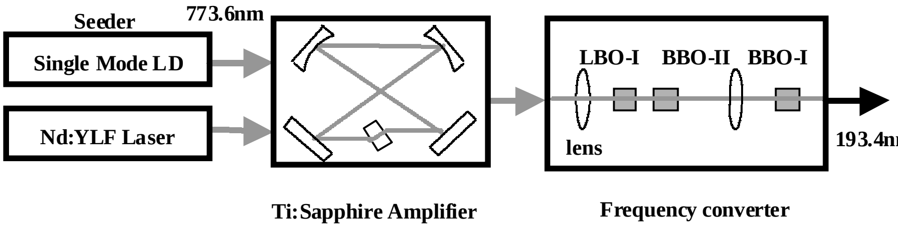

Fig 5 Schematic diagram of new 193CLS

The 193CLS consists of a seeder, an amplifier, and a frequency converter. The seeder is a tunable single mode CW diode laser (LD) whose wavelength is 773.6nm. The pulsed amplifier is a Ti:sapphire ring laser pumped by an Nd:YLF laser. The amplified light passes through a frequency converter generating the fourth harmonic of 193.4nm. To improve the power stability a new injection control system, a temperature control and a purge system are appended.

We have measured the spectral bandwidth of the 193CLS with the Michelson interferometer. As the optical path difference of the interferometer increases, the visibility of interference fringes decrease. The 193CLS has a coherent length of 4m at 50% visibility. If the spectral profile is a gauss function, the spectral bandwidth is calculated as 4fm (33MHz). The result obtained suggests that the 193CLS has sufficient spectral performance to measure the instrument function of the HEXA spectrometer.

6.2 Calibration of the dispersion of HEXA spectrometer

The output wavelength of the 193CLS is easily changed by tuning the wavelength of the seeder LD. The seeder LD is CW laser whose wavelength can be easily measured by the interferometer type wave-meter. The dispersion calibration was made by the following system. (Fig 6)

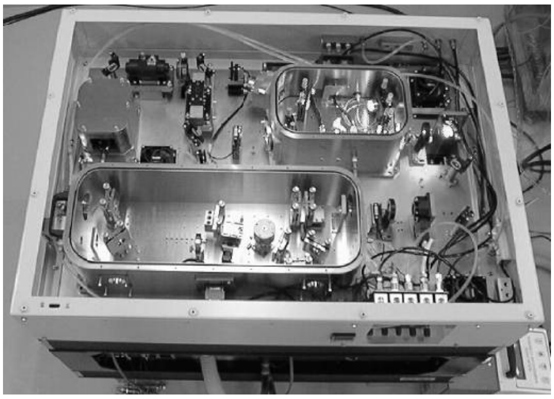
Photo 1: 193CLS system

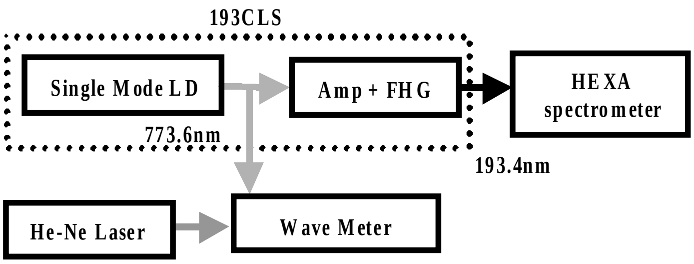

Fig 6 Schematic diagram of dispersion calibration system

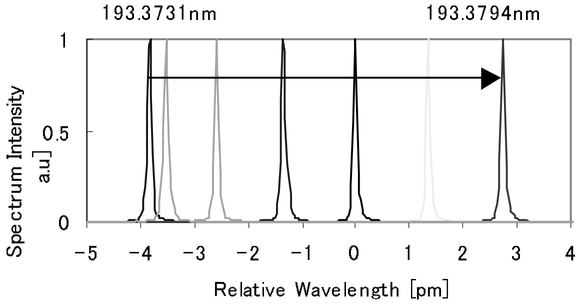

Fig 7a Dispersion Calibration
Movement of spectrum prfile

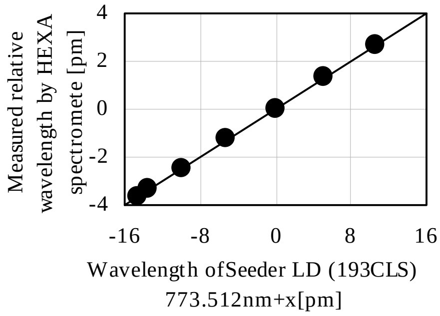

Fig 7b Dispersion Calibration results

The wavelength of the seeder LD is precisely measured by comparing it with the wavelength of a Zeeman stabilized reference He-Ne. The output wavelength of the 193CLS is calculated from the seeder wavelength by the relationship that the fourth harmonic wavelength is strictly a quarter of seeder wavelength. The output of the 193CLS is measured by the HEXA spectrometer and the spectrum location on the CCD channel is checked. Next, we change the wavelength of the seeder LD and measure the wavelength again. The spectral dispersion is the value of the wavelength difference divided by the channel difference on the CCD. Fig 7 shows the result of the measurements. The obtained dispersion is 0.024pm, which is in good agreement with the calculated value of 0.024pm/ch. We also calibrated the dispersion for DP and TP cased and confirmed the good agreement with the theoretical values. This confirms that the HEXA spectrometer is assembled and adjusted as designed.

7. EVALUATION OF HEXA SPECTROMETER

The optical properties of the high-resolution spectrometer depend on the characteristic of collimator system. Because the collimator lens of the HEXA spectrometer is newly designed, the performances are experimentally confirmed. A reflection mirror having super flat surface is placed between the Holographic grating and the collimator lens, and the slit image is observed by the CCD. Fig 8 shows the result that the lens has a very good performance being diffraction limited.

The next important factors for a spectrometer, which affect the profile of the instrument function, are the wave front aberration of gratings and stray light. These factors become very large, since the HEXA spectrometer uses two gratings and has multiple diffraction. Therefore, we checked the diffraction performance for each grating. Fig 9 shows the instrument function when only the Holographic

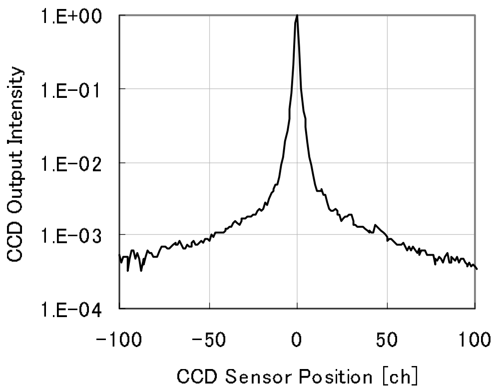

Fig 8 Evaluation of Collimator Lens

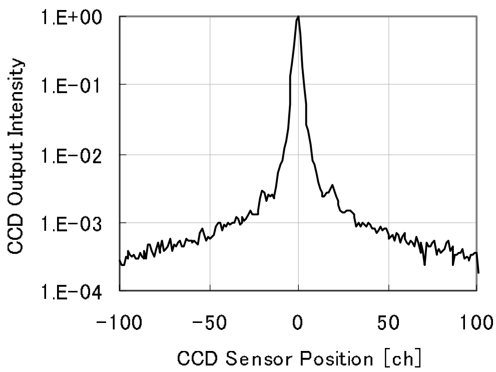

Fig 10 Evaluation of Echelle Grating

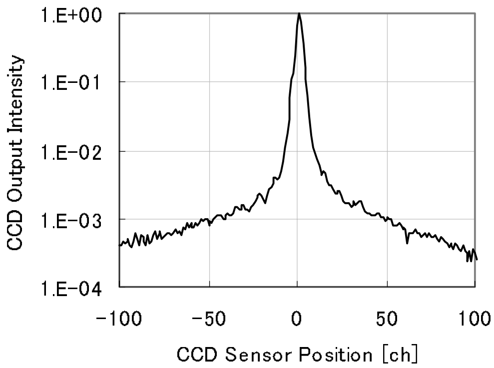

Fig 9 Evaluation of Holographic Grating

grating is arranged at the Littrow angle. Fig 10 is the instrument function when the Echelle grating is arranged at the Littrow angle. In this case, a reflection mirror is used instead of the Holographic grating. The instrument function of Echelle grating is inferior to that of the Holographic grating. It is mainly caused by the defect of surface flatness of the grating that is somewhat wave shaped. However, the order of flatness is not so big as to seriously affect the total performance of the HEXA spectrometer. As for the stray light, although there are small asymmetries at the wing, they are very small levels for both gratings.

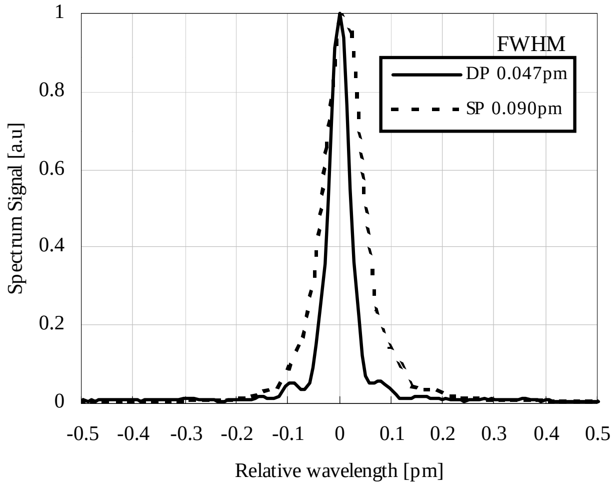

Fig 11 Instrument function of HEXA spectrometer

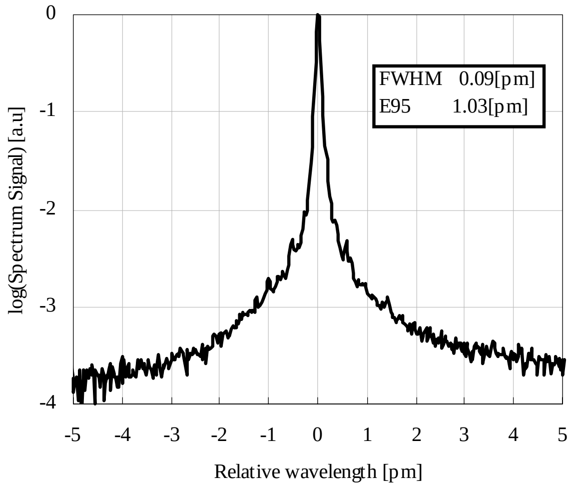

Fig 12 Instrument function of HEXA spectrometer (SP) in log scale

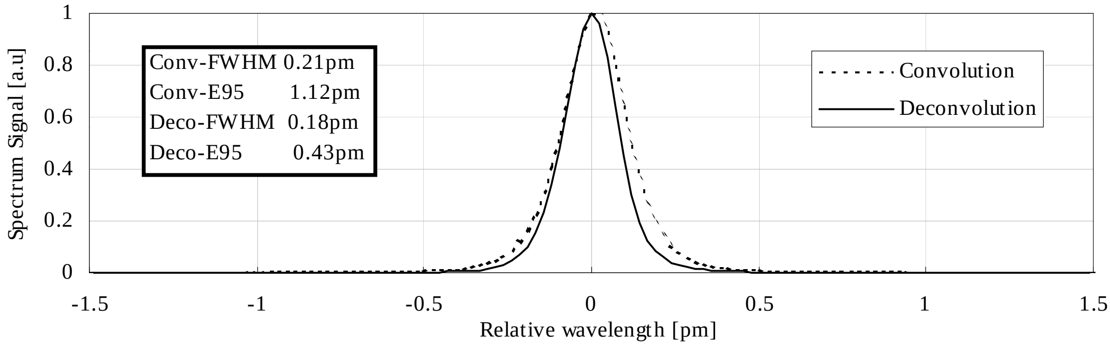

Fig 13 ArF excimer laser spectrum profile measured by HEXA spectrometer

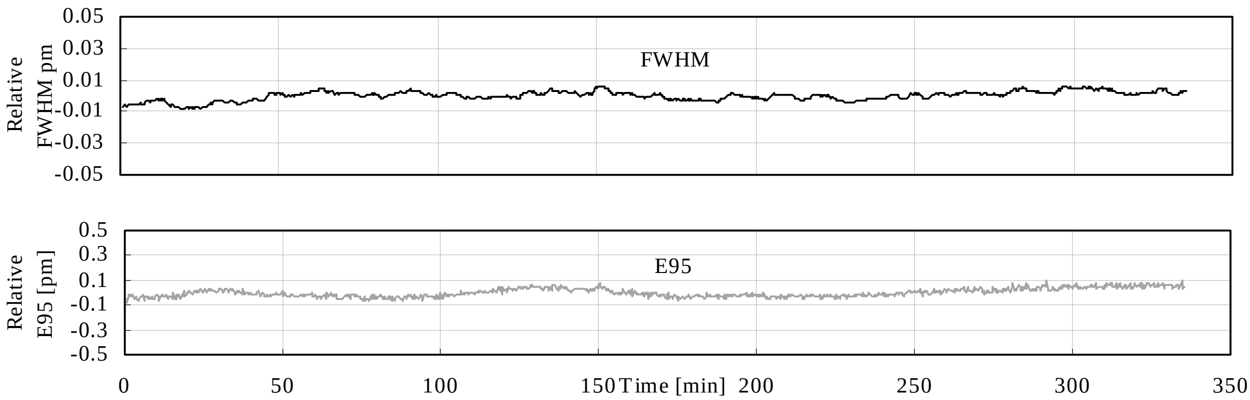

Fig 14 Long-term stability test of the HEXA spectrometer

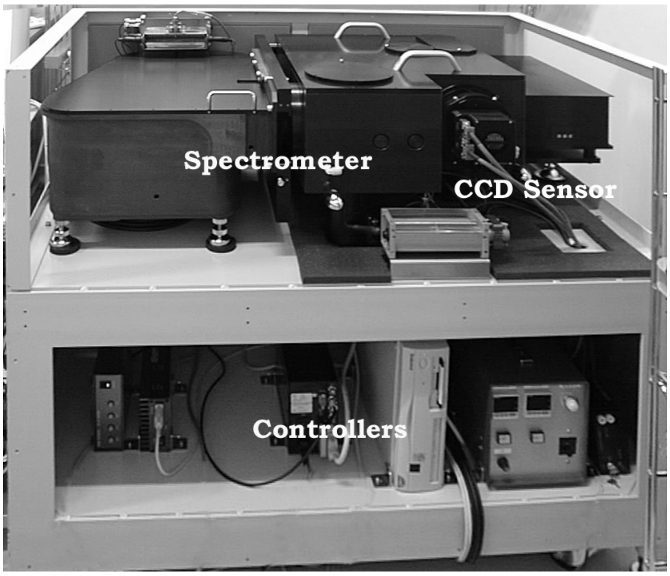

Photo 2: HEXA Spectrometer

As the final performance check of the HEXA spectrometer, the total instrument function of SP and DP are measured. (Fig 11) The FWHM of instrument function are 0.090pm (SP) and 0.047pm (DP), which correspond to the resolution of $2x10^6$ (SP) and $4x10^6$ (DP). These results are larger than the theoretical resolutions (table 1) that do not include factors other than the grating resolution. If these additional factors such as optical properties of the collimator lens, slit width and the cross talk of CCD sensors are considered, the experimental results are very reasonable values. Although the DP arrangement has very high resolution, the light loss is very large and the profile is not so smooth as for SP. The smoothness of the instrument function profile is also important for the deconvolution. Another drawback of the DP is stability. The DP is very sensitive to the change of the environment. In order to have a stable instrument function, very precise environment controls such as temperature, vibration and pressure are required. For the practical inspection of the excimer laser, the SP arrangement is better than the DP. Fig 12 shows the instrument function of SP in log scale. The graph indicates that the HEXA spectrometer has very good S/N of more than $5x10^3$ to measure the excimer laser. Fig 13 finally shows the result of a measured ArF excimer laser profile by the HEXA spectrometer (SP). The doted line is the convolution spectrum and the solid line is the deconvolved spectrum.
Fig 14 shows the result of a long-term stability test of the HEXA spectrometer (relative movement of FWHM and E95 of the instrument function). The 193CLS is used and the E95 & FWHM values are monitored for more than five hours. Although the E95 value is very sensitive to a change of the spectrometer, measured results show that the HEXA spectrometer is a very stable instrument.

8. SUMMARY

We designed and evaluated a high-resolution spectrometer with compact size for ArF excimer lasers. Results show that the resolution and the dispersion are sufficiently high to measure FWHM and E95 of excimer lasers with the necessary precision. The high stability obtained allows usage of the spectrometer for the mass production line and will guarantee the high spectral quality of our ArF excimer lasers for deep UV lithography.
In a next step, we will extend the spectral range to the F2 laser wavelength.

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