Spectral Measurement of Ultra Line-Narrowed F_2 Laser

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ABSTRACT

F_2 lasers are the light source of choice for microlithographic tools enabling structures below the 70nm technology node. Accurate measurements of the spectrum of F_2 lasers are therefore very important. We have succeeded in measuring the spectrum of an ultra line narrowed F_2 laser using a VUV grating spectrometer calibrated with a 153nm coherent light source (153CLS).

As a first step in the development of a 157nm coherent light source (157CLS), the less complex 153CLS has been built. Using resonant two-photon processes and four-wave mixing in Xe, this method provided a tunable laser system with high conversion efficiency and a very narrow linewidth, which can be approximated by a δ function. The 153CLS included a pulsed, single-mode tunable Ti:sapphire laser (768.0nm), a third harmonic generation unit (256.0nm) and a Xe gas cell. The153CLS had a linewidth of 0.007pm (FWHM) and a power of 0.05mW at 1000Hz.

The VUV grating spectrometer and a Michelson interferometer for F_2 lasers have also been developed. The instrument function of the spectrometer has been measured with the 153CLS. Experimental and theoretical instrument functions were in good agreement (FWHM: 0.30pm). The instrument function at 157nm was therefore estimated to have the theoretical FWHM of 0.31pm. The spectral linewidth of the line-selected F_2 laser has been measured under various laser conditions with the spectrometer as well as with the interferometer. Results show good agreement between both measurements.

The spectrum of the ultra line narrowed F_2 laser was measured with the VUV grating spectrometer calibrated using the 153CLS. The laser's FWHM of the deconvolved spectrum was 0.29pm. The deconvolved spectral purity containing 95% of the total laser energy is less than 0.84pm.

Keywords: F_2 Laser, metrology, linewidth, spectrometer, coherent VUV laser and Michelson interferometer

1. INTRODUCTION

The current technology of spectral measurements of ultra line-narrowed F_2 lasers for microlithography is described in this paper. Requirements of the F_2 laser linewidth evidently depend on the specific design of the microlithography projection system. For a catadioptric system design, for example, a single-line (1pm) F_2 laser is sufficient. A dioptric design, however, requires a laser linewidth of about 0.2pm (FWHM), which is due to the large dispersion of the refractive index of CaF_2 at 157nm. Up to now most exposure tools using KrF and ArF lasers have been equipped with dioptric lens systems[1)] but the final decision for F_2 laser exposure tools is still open. Hence, the metrology of the F_2 laser spectrum is an important issue, and we are therefore developing high-resolution spectrometers and the 157CLS in cooperation with The University of Tokyo, Japan, which can be used to calibrate the spectrometers.

High-resolution spectrometers for ultra line-narrowed excimer lasers have been developed[2,3,4,5)]. The spectrum of excimer lasers has been obtained by assuming that the laser spectrum corresponds to the measured convolved spectrum[2,3)] or by deconvolving the laser spectrum with the theoretical instrument function. However, accurate spectral profile measurements of ultra line-narrowed F_2 lasers have not been reported so far. We have succeeded in measuring the instrument function of the VUV grating spectrometer with the 153CLS for the first time in the world.

2. SPECTRAL MEASUREMENT TOOLS

2.1 Spectral measurement with coherent light source and spectrometer

The resolution of a spectrometer is limited by the instrument function of the spectrometer. Hence, to measure spectra more precisely, measurement of the instrument function and deconvolution of spectra are necessary[6)].

Figure 1 shows a schematic diagram of a very accurate method to measure the laser spectrum: The spectrum of the coherent light source can be approximated by a δ function if it is sufficiently narrow compared to the instrument function of the spectrometer. In this case, the measured laser spectrum corresponds to the instrument function, which can therefore be directly measured. When a laser spectral profile is measured with the same spectrometer, a convolved spectrum is obtained. The true laser spectrum can then be calculated by deconvolution using the measured instrument function of the spectrometer.

We have already precisely measured the spectra of KrF and ArF excimer lasers using our developed high-resolution spectrometers, which have calibrated with a single-mode Ar+SHG laser[4)] and our developed 193nm coherent light source[5)], respectively. In case of the F_2 laser, the VUV spectrometer needs to be calibrated at 157nm. Therefore, we are developing a high-resolution VUV spectrometer and the 157CLS in cooperation with the University of Tokyo.

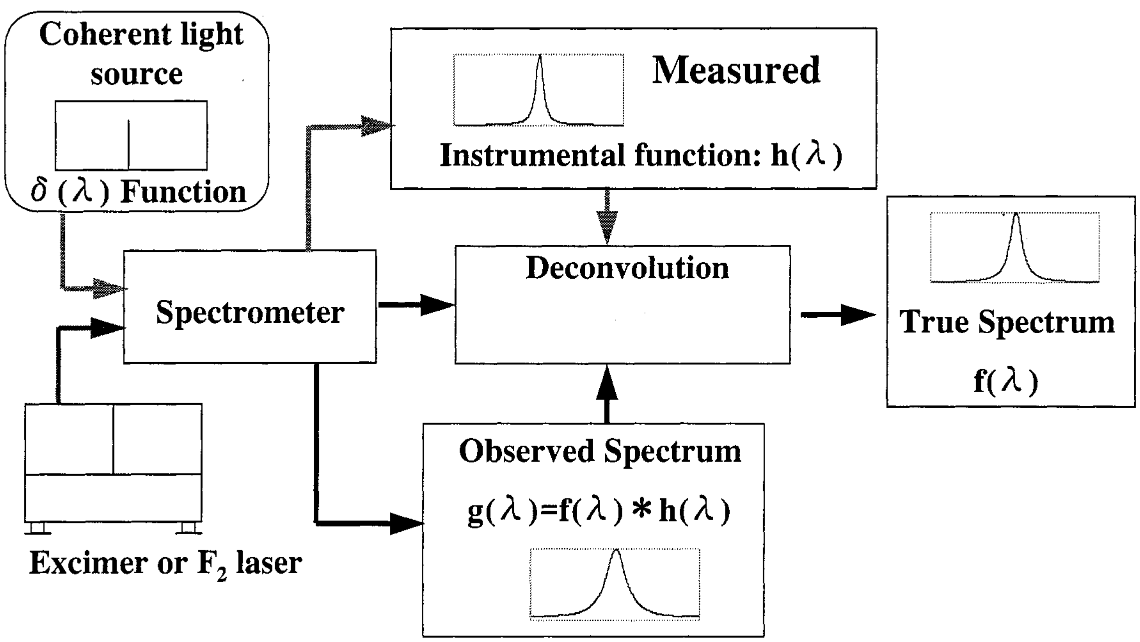

Figure 1 Schematic diagram of an accurate measurement method of laser spectra.

2.2 153nm coherent light source

A single-mode solid state laser generating 157nm has until now not been developed, because nonlinear crystals, which have high transmittance and durability at 157nm, are not available. Radiation generated by two-photon resonant frequency mixing in Xe was reported in the spectral region of the VUV[7)]. Features of this system are high efficiency, no degradation and no spectral broadening due to two-photon resonant frequency mixing in Xe. We have developed the 153CLS, which was based on these results.

The development of the 157CLS is done in two steps. First, the 153CLS has been developed to prove this system in principle. Figure 2 shows a schematic diagram of the 153CLS. The 153CLS contained a pulsed, single-mode Ti:Sapphire seed laser, a Ti:Sapphire amplifier, a frequency conversion unit and a two-photon resonant frequency conversion gas cell. Non-linear crystals and the Xe gas cell provided the frequency conversion and the two-photon resonant frequency conversion, respectively. The seed laser and the amplifier were pumped by a pulsed YLF SHG Laser. The pulsed Ti:Sapphire laser generated a single longitudinal mode at 768.046nm(ω). This light was amplified having the wavelength and the spectral profile of the seed light. The Ti:Sapphire laser system had an average power(P_{ω}) of 7 W at ω. The non-linear crystals generated the third harmonic of the amplified light at 256.015nm(3ω)which is the excitation wavelength of the two-photon transition($5p^1S_0 \rightarrow 6p[5/2,2]$) of Xe. The output power ($P_{3\omega}$) of third harmonic generation (3 ω) was 1 W. The unconverted power (P_{ω}) was 3 W. The third harmonic (3 ω) and the fundamental (ω) were mixed in the Xe gas cell. The VUV radiation was generated at 153.61nm, the fifth harmonic, by difference frequency mixing 2(3 ω)- ω=5 ω.

The153CLS had a power of 0.05mW at 1kHz and a pulse-duration of 10.4ns(FWHM) at 153nm. The spectral linewidth of the fundamental (ω) was measured with a scanning Fabry-Perot etalon and was less than 0.056pm(FWHM). The spectral linewidth of the fifth harmonic (5 ω) at 153nm was calculated from the spectral linewidth of the fundamental (ω) to be less than 0.007pm(FWHM). The time-linewidth product at 153.61nm was 0.52. The Fourier transform limit of a Gausssian pulse is 0.44. Therefore, it was estimated that the spectral linewidth of the 153CLS was even less than 0.007pm(FWHM). Since the spectral linewidth of the 153CLS is narrow compared to the instrument function (about 0.3pm), this 153CLS can be used as a calibration tool for the VUV spectrometer.

In the next step, we plan to develop the157CLS adding a pulsed, second single-mode Ti:Sapphire laser and a second amplifier. The second single-mode pulsed Ti:Sapphire laser generates 681.190nm(ω_2). This light is amplified. The third harmonic (3 ω)and the fundamental(ω_2)are mixed in the Xe gas cell. The VUV radiation is then generated at 157.629nm by difference frequency mixing $2(3\omega) - \omega_2 = \omega_{VUV}$.

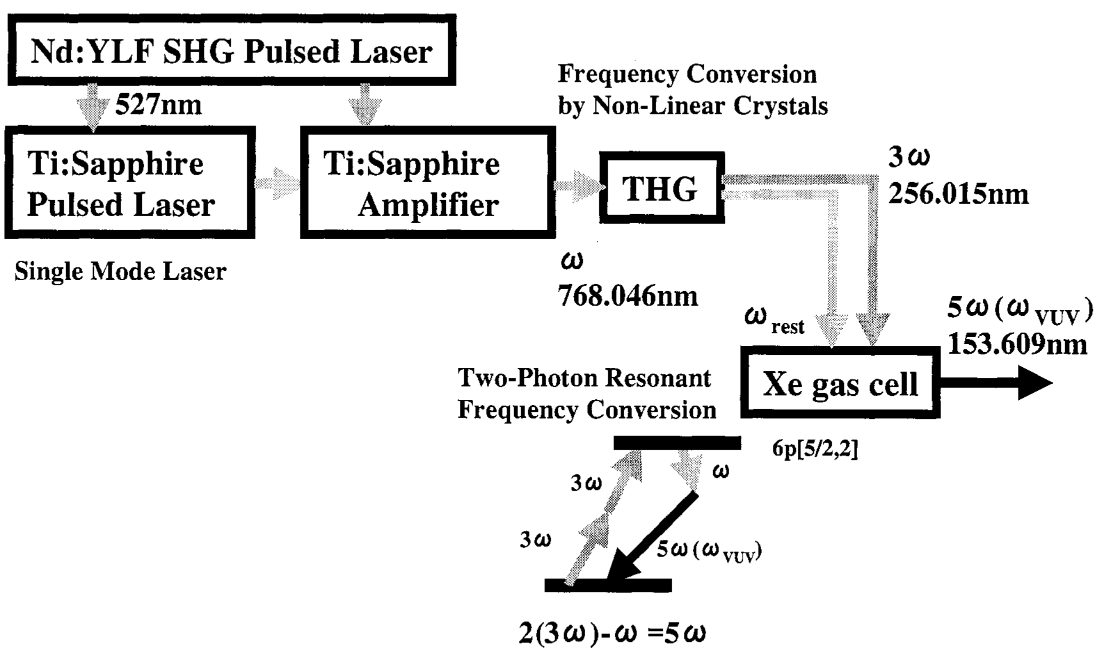

Figure 2 Schematic daiagram of the 153nm coherent light source system

2.3 VUV grating spectrometer

Grating spectrometers enable to measure spectral profiles of lasers precisely. However, there is need to measure precisely the instrument function of the grating spectrometer. Figure 3 shows the Czerny-Turner VUV grating spectrometer. The spectrometer has an entrance slit, two concave mirrors, a reflective grating and an exit slit. The 153CLS or the F_2 laser illuminates the entrance slit. The light passing the entrance slit is collimated by concave mirror #1. The grating diffracts the light and concave mirror #2 creates the slit image. The slit image is scanned by detecting the light intensity passing the moving exit slit with a photomultiplier tube.

The instrument function (I.F.) of this spectrometer is given [6] by the convolution of the resolution function (G) of the grating, the rectangular function (S_{en}) of the entrance slit width, the diffraction limit function (N) of the numerical aperture (N.A.), the rectangular function (S_{ex}) of the exit slit width and the aberration function (A):

$$\text{I.F.} = G * S_{en} * N * S_{ex} * A \quad (1)$$

$*$: convolution operation

We can calculate G, S_{en}, N and S_{ex} from the specifications of the spectrometer. However, the aberration function cannot be precisely calculated and the line spread function of this optical system at 157nm has to be accurately measured. Since the Czerny-Turner spectrometer is an all-reflective optical system, no chromatic aberration occurs. Therefore, if the instrument function of the spectrometer at 153nm can be measured, the instrument function at 157nm can be estimated because both of wavelengths was almost corresponding.

Both of mirrors had focal length of 1m. The Grating was an echelle grating, which had 79 groove/mm, a width of 51.4mm and a blaze angle of 74 degrees. The observed diffraction orders were 158 and 154 at 153nm and 157nm, respectively. The resolution of the echelle grating at 157nm was 6.26×10^5. Both the entrance slit and the exist slit had a slit width of 5µm. The linear dispersion was 0.11pm/step (16pm/mm). The N.A. was 0.005. The spectrometer was kept vacuum by a vacuum pump. Temperature of the spectrometer was controlled at 38.0℃ ±0.1℃. Neglecting aberration, the theoretical instrument function (FWHM), which was 0.31pm at 157nm and 0.30pm at 153nm, was calculated using equation (1).

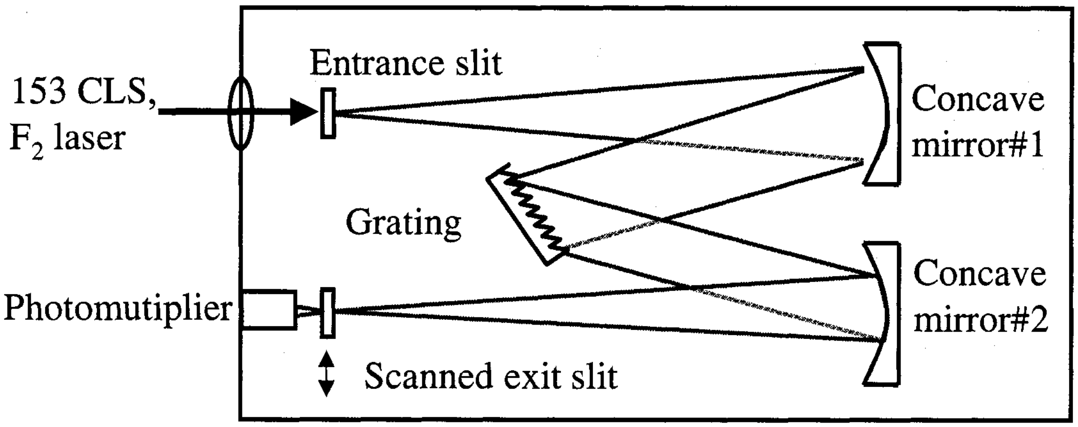

Figure 3 Czerny-Turner VUV grating spectrometer

The solid line in figure 4 shows the theoretical instrument function calculated by equation (1) at 153nm. The circles in figure 4 show the instrument function measured by the 153CLS. As the output power of the 153CLS was very low (0.05mW), the measured instrument function was relatively noisy. However, calculated and experimental results were almost corresponding. Both of the instrument functions have a FWHM of 0.30pm. Therefore, the instrument function at 157nm was estimated to be in agreement with the theoretical instrument function neglecting aberration at 157nm.

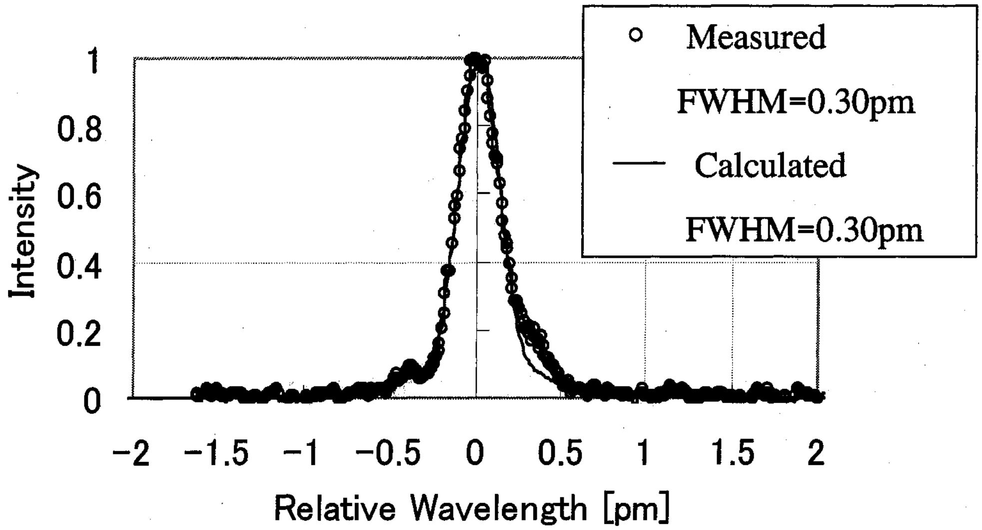

Figure 4 153nm coherent light source measured and calculated instrument functions of VUV spectrometer

2.4 Michelson interferometer[8)]

A Michelson interferometer for the F_2 laser has been developed. In case of the Michelson interferometer, the spectral linewidth can be calculated from the measured coherence length. An accurate measurement of the spectral profile, however, is impossible. Figure 5 shows the optical arrangement of the Michelson interferometer. The F_2 laser beam illuminates a diffuser. The diffused light is focused by lens#1 and, after passing a pinhole placed at the focal point is collimated by lens#2 in order to form plane wavefronts. A beam splitter then divides the wavefront. After reflection, light from both HR mirror#1

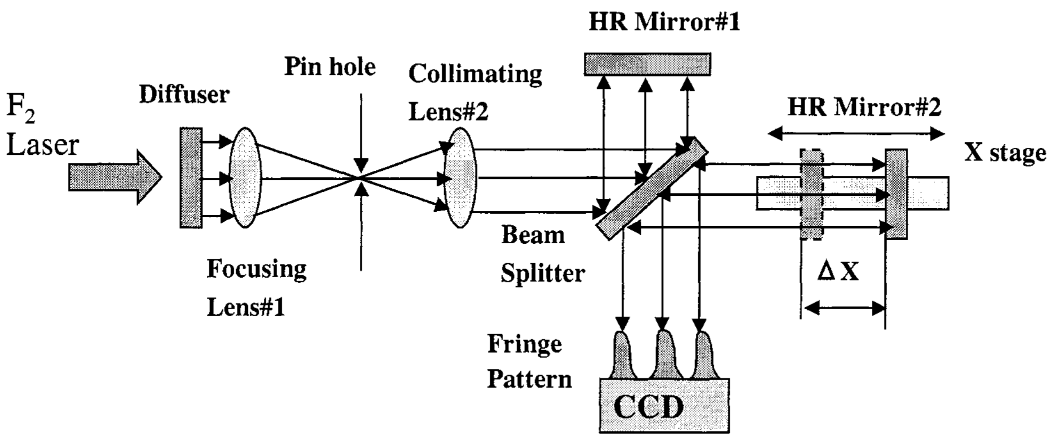

Figure 5 Optical arrangement of Michelson interferometer for F_2 laser

and HR mirror#2 impinges again on the beam splitter. Two interference patterns are the formed, one imaged onto a CCD and the other going back to the light source. The HR mirror#2 is placed on a X stage, which can be moved parallel to the optical axis. The Optical path difference(OPD) is twice in distance(ΔX) from OPD=0 to the actual position of the X stage. The CCD detects the fringe pattern and visibility of the fringe pattern at each OPD is measured. With increasing the OPD, the visibility of interference fringes decreases. If the spectral profile is a gauss function, the temporal coherence and linewidth of F_2 laser can be calculated from the plots of OPD vs. Visibility.

3. SPECTRAL MEASURMENT

We have measured the spectral linewidths of our developed 2kHz line-selected F_2-laser (G20F) with the Michelson interferometer and the VUV grating spectrometer. The spectral linewidth of F_2 laser depends on the total gas pressure. The more the total gas pressure increase, the broader the spectral linewidth becomes due to pressure broadening.

Dependence of the temporal coherence on total gas pressure is shown in figure 6. The coherence length of the G20F and the spectral linewidth was calculated by Gaussian-fits. The coherence length decreased with increasing total gas pressure. Coherence lengths at 50% visibility for 150kPa, 300kPa and 400kPa were $2.5*10^{-2}$m, $1.2*10^{-2}$m and $1*10^{-2}$m, respectively. The spectral linewidth broadened as the total gas pressure increased. Spectral linewidths estimated by Gaussian-fit at 150kPa, 300kPa and 400kpa were 0.43pm, 0.84pm and 1.05pm, respectively.

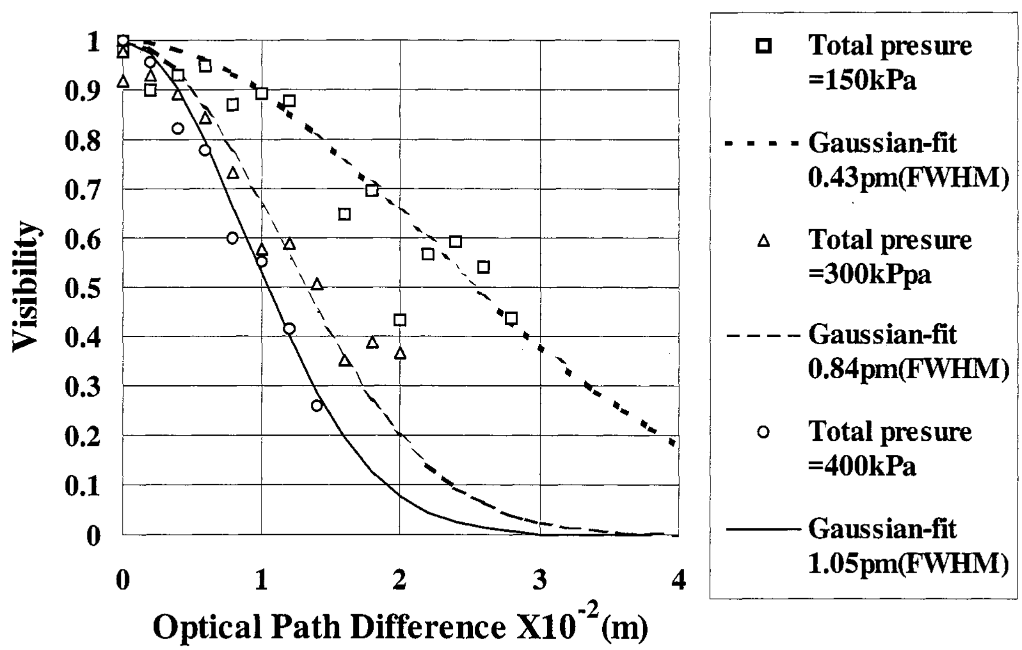

Figure 6 Dependence of the temporal coherence on the total gas pressure for the F_2 laser(G20F)

The spectral linewidth of the G20F has been measured under various conditions with the VUV grating spectrometer as well as with the Michelson interferometer. The deconvolved FWHM was obtained by deconvolution as described before. Figure 7 shows the Michelson interferometer data correlation with the VUV grating spectrometer data. Circles and Squares show deconvolved and convolved linewidth(FWHM), respectively. The results showed good agreement.

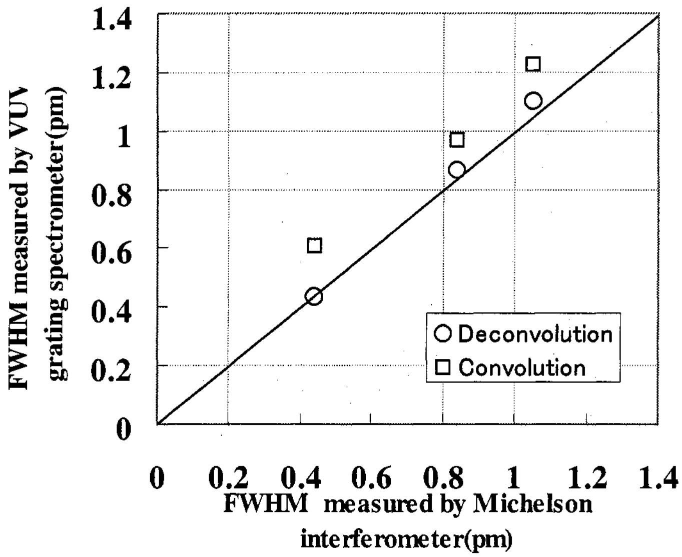

Figure 7 Michelson interferometer data correlation with VUV grating spectrometer data

Figure 8 shows the spectral profiles of the ultra narrowed F_2 laser G20F equipped with a line-narrowing module and the instrument function of the VUV grating spectrometer. Circles, Thin and thick solid lines show the convolved spectrum, the theoretical instrument function and the deconvolved spectrum, respectively. The FWHM of the instrument function was 0.31pm. The laser's FWHM of the convolved and deconvolved spectrum were 0.48pm and 0.29pm respectively. The deconvolved spectral linewidth(95%Energy) containing 95% of the total laser energy was less than 0.84pm.

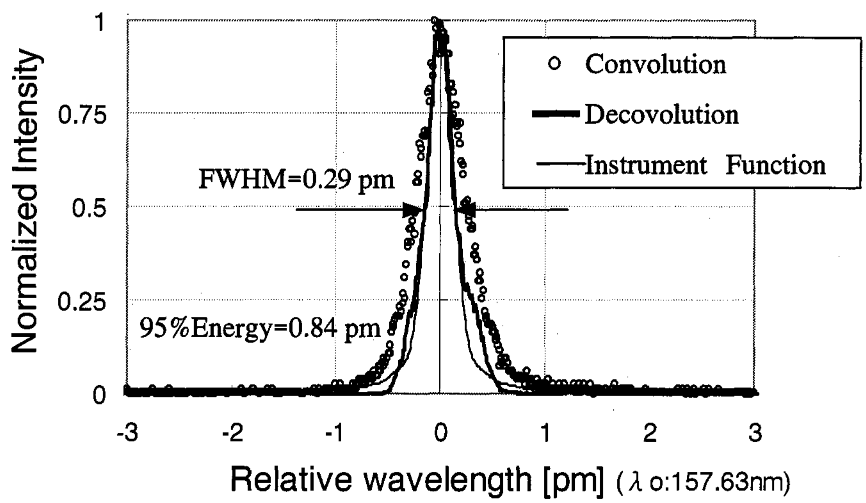

Figure 8 Spectral profiles of the ultra narrowed F_2 laser

CONCLUSIONS

We succeeded in developing accurate spectral measurement tools for ultra line-narrowed F_2 lasers. The instrument function at 153nm of the VUV grating spectrometer was measured for the first time in the world using our developed 153CLS. The spectral profile of the ultra line-narrowed F_2 laser was measured with the spectrometer calibrated using the 153CLS. In the near future, a 157CLS will be available to calibrate our high-resolution spectrometers at 157nm. This high precision spectral measurement technology will accelerate the development of ultra line-narrowed F_2 Laser.

ACKNOWLEDGMENTS

This work was performed under the management of Association of Super-Advanced Electronics Technologies (ASET) in the Ministry of Economy Trade and Industry (METI) Program supported by New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES

1) A. Kroyan, J. Bendik, O. Semprez, N. Farrar, C. Rowan: "Modeling the Effects of Excimer Laser Bandwidths on Lithographic Performance", SPIE Vol. 4000 (2000)pp658-664
2) A. I. Ershov, G.G. Padmabandu, J. Tyler, P. P. Das: "Novel metrology for measuring spectral purity of KrF lasers for deep UV lithography", SPIE Vol. 3677 (1999)pp611-620
3) A. I. Ershov, G.G. Padmabanbu, J. Tyler, P. P. Das: "Laser spectrum line shape metrology at 193nm", SPIE, 4000(2000) pp1405-1417.
4) Toru Suzuki, Takanori Nakaike, Osamu Wakabayashi and Hakaru Mizoiguchi, "High-resolution Multi Grating Spectrometer for High Quality Deep UV Light Source Production", SPIE, 4000(2000) pp1452-1460.
5) Osamu Wakabayashi, Tatsuo Enami, Takeshi Ohta, Hirokazu Tanaka, Hirokazu Kubo, Toru Suzuki, Katsumoto Terashima, Akira Sumitani and Hakaru mizoguchi: "Billion level durable ArF excimer laser with highly stable energy",Proc. SPIE,3679(1999)pp1058-1068.
6) Peter A. Jansson; "Deconvolution of Images and Spectra", Second Edition Academic Press, 1997
7) R. Hilbig and R. Wallensten; "Tunable VUV Radiation Generated by Two-Photon Resonant Frequency Mixing in Xenon ",IEEE J. Quantum Electron. , vol. QE-19, No.2(1983)pp194-201
8) Miles V. Kein and Thomas E. Furtak; "OPTICS", Second Edition John Wiley & Sons, 1986