Long run-time performance characteristics of a line-selected 2kHz F_2-laser for optical microlithography

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ABSTRACT

Driving optical lithography below the 100nm node is very demanding for optical materials due to the deep ultra-violet radiation to be used. Light sources enabling detailed material studies in the wavelength range of interest are therefore indispensable. For this purpose Gigaphoton Inc. developed a line-selected F_2 laser operating at 2kHz which is based on the well proven technology of its KrF and ArF lasers. The F_2 laser uses a line-selecting module in order to oscillate at the stronger (157.63nm) of the two F2 transition lines emitted under free running conditions (157.52nm and 157.63nm). The laser transition is not line-narrowed resulting in a deconvoluted bandwidth of 0.92pm (FWHM) with a 95% integrated energy width of 2.95pm. The F_2 laser delivers 7.5mJ pulses at 2000Hz with a fluctuation sigma of 3% (50 pulse window). Laser characteristics important for industrial applications and results of durability tests (> 2.5Bpls) will be presented. Discussed laser performance data include laser beam characteristics, especially beam profile and divergence, wavelength and pulse energy stability during gas lifetime cycles as well as the overall laser performance and reliability during a laser-chamber lifetime cycle.

Keywords: fluorine molecular laser, F_2,157nm, line-narrowing, microlithography

1. INTRODUCTION

Recently, the interest in molecular fluorine laser (F_2-laser) has strongly increased due to its potential to drive optical microlithography below the 100nm node down to 50nm device structures [1]. Preparations are already under way to start from 2003 on the replacement of current KrF and ArF lithographic light sources at 248 and 193nm, respectively, with 157nm F_2-lasers. Depending on the imaging system of the exposure tool to be used, two spectral F_2-laser bandwidths are currently discussed and developed. First, a bandwidth below 0.6nm (fwhm) for catadioptric and, second, below 0.2nm for refractive exposure tool optics. In order to design the corresponding laser resonators, appropriate optical materials having an acceptable transmission at the laser wavelength of 157nm are indispensable and include for example CaF_2 [2]. Evidently, for the heavy-duty operation of light sources for optical microlithography, laser resonator and additional optical laser components including coatings have to be optimized concerning "radiation inertness" against the F_2-laser 7.9eV laser photons. In order to provide a reliable light source for corresponding optical material testing, Gigaphoton developed a 2kHz F_2-laser and tested its long-run time performance characteristics thoroughly. The experimental set-up, performed measurements and detailed discussions will be presented in this paper.

2. LASER SYSTEM

The F_2-laser design is based on Gigaphoton's well-proven KrF and ArF technology and includes RF pre-ionization and an all solid-state pulse power module (PPM) using gate turn-on thyristors (GTO) [3,4]. The high GTO current switching stability results in a lower laser energy fluctuation compared to conventionally used thyratrons. In addition, since switching is not provided by a discharge, the GTO lifetime is basically semi-permanent. A maximum energy of 6.0J/pulse, generated by the PPM, is fed into the F_2-laser discharge whose RF-preionization system has been optimized. Other optimized parameters

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include the peaking capacitance of the discharge circuit and the electrode gap. In order to reduce gas impurities and contamination, materials exposed to F_2-laser gas have been carefully selected. Experiments showed that contaminations are more critical for the F_2-laser compared to the ArF laser. Related to our previously published results[5], the line-selecting resonator module has an improved efficiency. Note that the F2-laser mainly oscillates at two wavelengths in free-running mode, 157.52nm and 157.63nm, while KrF and ArF lasers emit broadband radiation. Resonator design parameters are therefore different for both systems. Due to the vacuum ultraviolett (VUV) radiation emitted by the F_2-laser and its strong absorption in air, the laser beam propagates in vacuum tight ducts purged with oxygen free nitrogen.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In order to test the long run-time performance of the developed F_2 laser (Gigaphoton G20F), the system has been operated at our research facilities over a current total of 2.5 billion laser pulses (Bpls). Main test results are presented in the following:

3.1 Laser resonator and line selecting resonator module

A schematic of the F_2-laser resonator is shown in figure 1. CaF_2 substrates form the laser cavity. The output coupler is wedged (10') and the side facing the cavity is 10% reflection, the other side AR-coated. The high-reflection mirror has a multi-layer dielectric coating with a reflectivity of about 93% at 157nm. Prisms are used to select the stronger (157.63nm) of the two F_2 transition lines emitted under free running conditions (157.52nm and 157.63nm). The laser is operated with about 0.1% fluorine in a helium buffer.

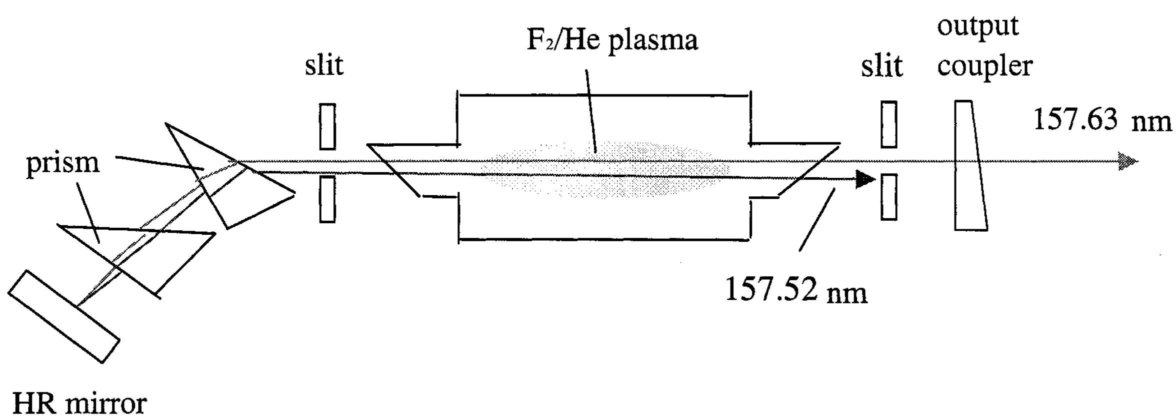

Figure 1: Single line laser resonator.

The effect of the line selecting resonator module consisting of prisms is displayed in figure 2. Under free running condition two laser transitions are observed whereas line-selection enables the laser to oscillate on the stronger transition line. A VUV spectrometer with a high resolution (Shimadzu Corp.) was used to measure all fluorine laser spectra. Compared to our previously reported line selecting resonator module[5] the single-line efficiency of the redesigned new module increased to 75%; the single-line efficiency is defined as the ratio of single-line to free running laser output energy. Currently, further improvement of the single-line efficiency is under investigation.

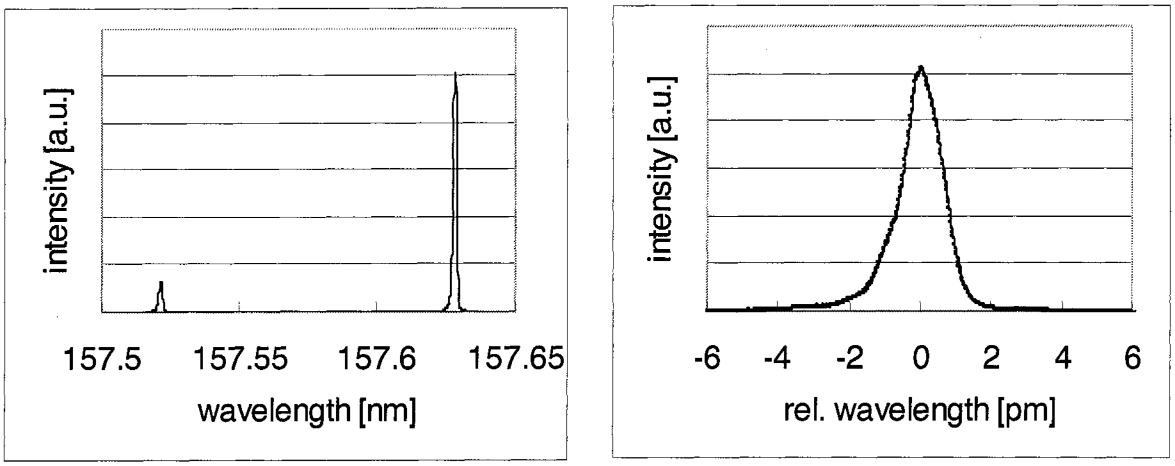

Figure 2: Measured free run F_2 laser spectrum (left) and single-line F_2 spectrum at 157.63nm (right).

3.2 Energy and dose stability

Figure 3 shows the energy stability after 2 Bpls during a laser pulse interval of 100Mpls. During this period, about 2 gaslife cycles, the duty cycle of the laser was changed according to figure 4 operating the laser at 2000Hz, 5mJ locked output energy. The pulse to pulse stability for a window of 50 pulses varies slightly for the different duty cycles but the overall maximum fluctuation is as low as 1.2% (sigma). Figure 5 shows the dose stability distribution taken from samples of 50 consecutive bursts. The dose stability for each burst sample has been calculated using a 50 pulse moving average. Again, a low value has been obtained resulting in a dose stability of the F_2-laser below +/- 0.37%.

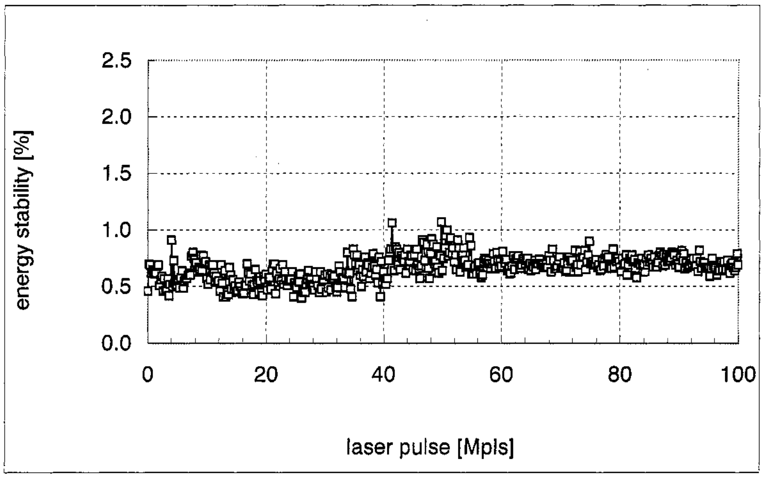

Figure 3: Energy stability; moving average of 50 pulses.

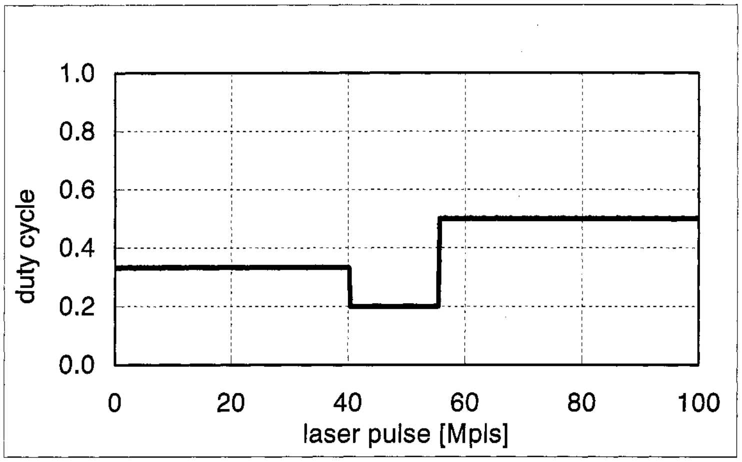

Figure 4: Laser duty cycle for presented sample.

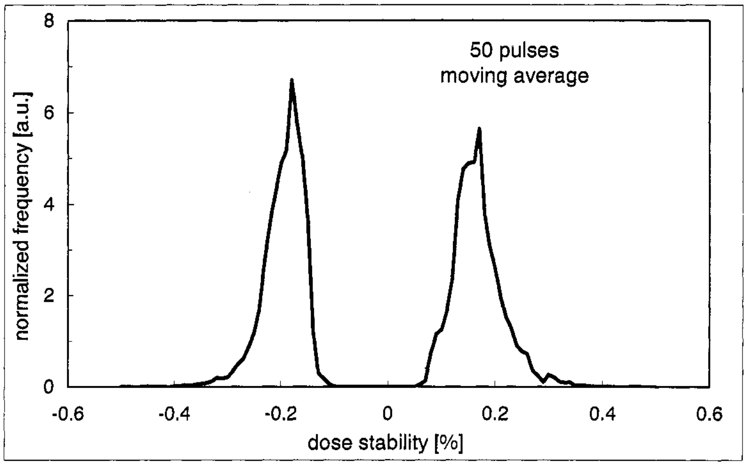

Figure 5: Dose stability (DS) distribution; the plot displays the DS of 50 bursts sampling and 50 pulses moving average during 100Mpls.

3.3 Spectral bandwidth and purity

The deconvoluted spectral profile of the line selected molecular fluorine laser is shown in figure 6 for a total gas pressure of 350kPa at 2kHz, 5mJ in energy locked operation. The full width at half maximum (fwhm) is 0.92pm and the corresponding 95% integrated energy width is 2.9pm as shown in figure 7. Since the selected F_2 laser transition is not line-narrowed by the laser resonator, both, the central wavelength and the bandwidth, depend on the total gas pressure of the laser discharge due to pressure broadening effects. Values of 0.003pm/kPa and 0.002pm/kPa have been measured for central wavelength and bandwidth changes, respectively.

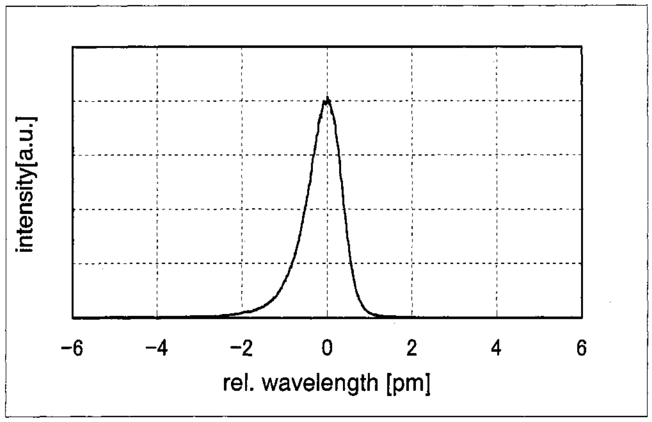

Figure 6: Laser spectral profile; 0.92pm deconvoluted fwhm.

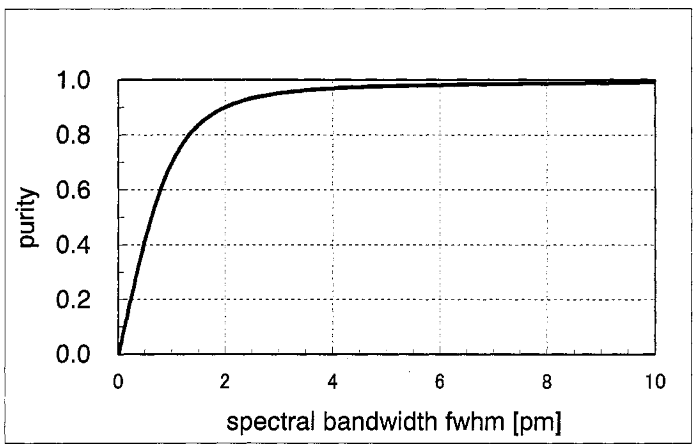

Figure 7: Laser spectral purity; 2.95pm for P95.

3.4 Laser beam size and beam divergence

The laser beam size and the laser beam divergence are shown in figure 8 and 9, respectively, for the above mentioned sample of 100Mpls after 2 Bpls including three different duty cycles (see figure 4). Measured vertical and horizontal beam sizes are about 16.0 and 3.2 mm respectively ($1/e^2$; full width) and vertical and horizontal divergences 5.7mrad and 1.1mrad, respectively.

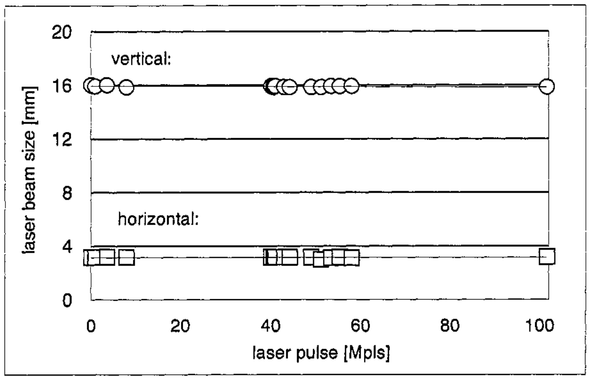

Figure 8: Laser beam size at $1/e^2$ full width

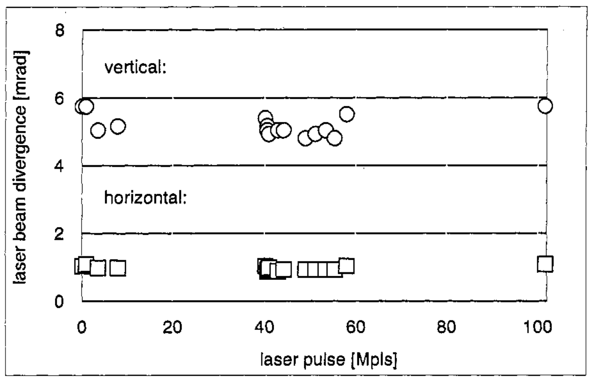

Figure 9: Laser beam divergence at $1/e^2$ full width

3.5 Laser beam polarization

A Rochon prism has been used to determine the laser beam polarization for free running and line selected operation. First results of the transmitted laser intensity as a function of the prism rotation angle are shown in figure 10. A linear polarization of 82.0% and 88.0% has been measured for free running and line selected operation, respectively. The F_2 laser polarization is, probably due to the higher gain, smaller than the linear polarization of KrF and ArF laser which is about 99%.

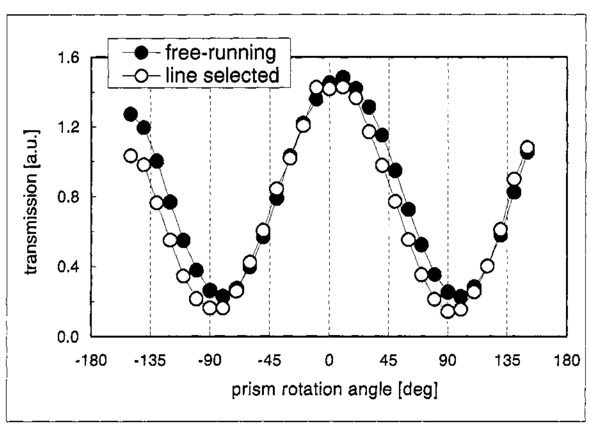

Figure 10: Laser beam polarization

3.6 Lifetime of optical components

Figure 11 and figure 12 show results of the measured initial transmission and reflection of laser chamber windows and output couplers, respectively, compared to the sample transmission and reflection measured after 2.5Bpls. As can be seen, changes are minimal such that lifetimes of optical components are at least the current 2.5Bpls.

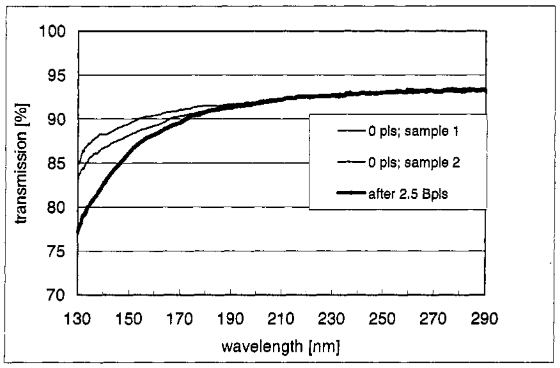

Figure 11: Laser chamber window transmission before and after 2.5Bpls.

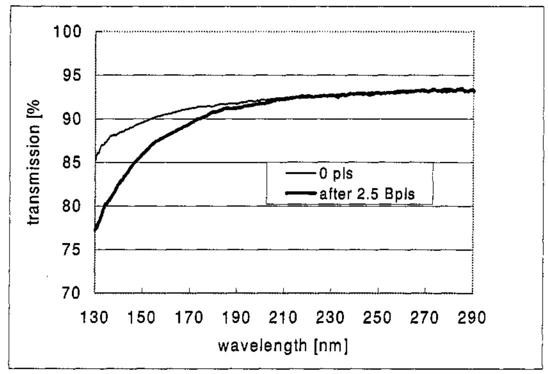

Figure 12: Output coupler transmission before and after 2.5Bpls.

3.7 Performance summary

Lon-run time performance parameters of the developed molecular fluorine laser G20F are summarized in table 1.

laser parameter	value	unit	remark
wavelength	159.63	nm	single-line
bandwidth	1.0	pm	fwhm
spectral purity	< 3.0	pm	95% integrated energy
pulse length	14	ns	Tis
max. repetition rate	2	kHz	
output power	10	W	at 2 kHz
pulse energy	5	mJ	at 2 kHz
dose stability	± 0.5	%	50pls mavg
beam size	3.0	mm	horizontal, fw $1/e^2$
	16.0	mm	vertical, fw $1/e^2$
beam divergence	1.0	mrad	horizontal, fw $1/e^2$
	5.7	mrad	vertical, fw $1/e^2$
laser lifetime			
laser gas	> 50	Mpls	
optical components	> 2.5	Bpls	
laser chamber	> 1.5	Bpls	

Table 1: Long run-time characteristics of G20F

4. CONCLUSION

We performed long run-time durability tests (> 2.5Bpls) of our 2kHz line-selected fluorine laser G20F. This laser delivers 10W at the maximum repetition frequency of 2kHz. The laser wavelength is line-selected at 157.63 nm having a bandwidth of about 1pm (FWHM). The durability test included continuous measurements of laser beam parameters, e.g. energy, wavelength, beam profile and divergence, as well as the evaluation of the overall laser system performance, e.g. lifetimes of laser gas, optical components and laser chamber. Based on the test results the G20F laser characteristics can be summarized as follows:

The laser emits a single line at 157.63 nm with a spectral purity of about 2.9pm and a bandwidth of 1pm (FWHM). The pulse duration is 6ns (FWHM) or 14ns (Tis). The maximum pulse energy is 7.5mJ. The pulse energy fluctuation (sigma) is 3.3% and the energy dose stability 0.5% for a moving average of 50 pulses and for duty cycles between 30% and 50%. The beam profile size is about 3.0 x 16.0 mm^2 ($1/e^2$), and the beam divergence is 1.0mrad and 5.7mrad, horizontal and vertical respectively. The gas lifetime is 50Mpls, which is equivalent to 72hrs (3 days) operation. Lifetimes of main optical components and the laser chamber are above 2.5 and 1.5 Bpls, respectively.

In conclusion, the durability test of our F_2-laser G20F proved that this line-selected 2kHz laser has the industrial performance necessary to be used for optical microlithography applications.

ACKNOWLEDGMENTS

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