Development of a 5 kHz Ultra-Line-Narrowed F_2 Laser for Dioptric Projection Systems

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ABSTRACT

The roadmap of semiconductor fabrication predicts that the semiconductor market will demand 65 nm node devices from 2004/2005. Therefore, an Ultra-Line-Narrowed F_2 laser for dioptric projection systems is currently being developed under the ASET project of "The F_2 Laser Lithography Development Project". The target of this project is to achieve a F_2 laser spectral bandwidth below 0.2 pm (FWHM) and an average power of 25 W at a repetition rate of 5 kHz. The energy stability (3-sigma) target is less than 10%.

An Oscillator-Amplifier arrangement at 2 kHz was developed as a first step of an Ultra-Line-Narrowed F_2 laser system. With this laser system, we did the basic study of the synchronization technology for line narrowing operation using two system arrangements: MOPA (Master Oscillator / Power Amplifier) and Injection Locking. Based on this experience we have developed the 5 kHz system. With the 5 kHz Line-Narrowed Injection Locking system, we have achieved a spectral bandwidth of < 0.2 pm with an output energy of > 5 mJ and an energy pulse to pulse stability of 10%. The feasibility of a 5 kHz Ultra-Line-Narrowed F_2 Laser for Dioptric Projection Systems has been demonstrated.

Keywords: F_2 laser, 157 nm microlithography, line-narrowing, injection locking, spectral bandwidth , dioptric

1. OUTLINE OF THE DEVELOPMENT

Basically two optical designs exist for 157 nm exposure tools that will be used for 65 nm devices: Dioptric and Catadioptric. Contrary to the Catadioptric design the dioptric design is a very common design for microlithography systems. Dioptric is therefore the "state of the art" design of current exposure tools and this is certainly a "driving force" for stepper suppliers to prepare Dioptric F_2 laser microlithography systems for the market within the given time frame.

[Fig.1] shows the relation between the laser spectral bandwidth and the laser output power necessary for the two lens designs. For the Dioptric design the chromatic aberration has to be corrected by applying at least two different lens materials: for example CaF2 and BaF2. Or, alternatively, a very narrow spectral light source at 157 nm has to be used. The Catadioptric design uses mirrors, which avoids wavelength dispersion. Therefore, the Catadioptric design has a much larger margin for the spectral bandwidth of the light source. The Catadioptric design requires a bandwidth (FWHM) of 0.8 ~ 1.2 pm at 157 nm, whereas the Dioptric design requires a FWHM below 0.2 pm. Dioptric design exposure tools also require more than 20 W of laser output power. Technically, however, it is very difficult to generate high output power and ultra-narrow bandwidth with a single laser unit because the Amplified Spontaneous Emission (ASE) increases with increasing F2 laser output power. And due to its nature the broadband ASE emitted by the laser cannot be spectrally narrowed by the line narrowing module. We developed therefore a 2-stage Injection Locked laser system: an oscillator laser emits the ultra-narrow seed laser beam and an amplifier laser amplifies the seed laser beam to the required output energy.

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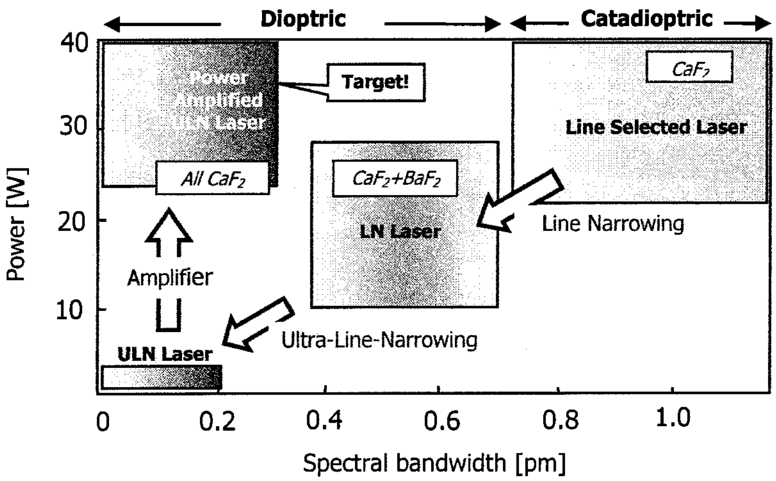
Our target specifications for the laser development are shown in [Table.1].



[Fig.1] Laser Type, Spectral Bandwidth and Lens Design

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

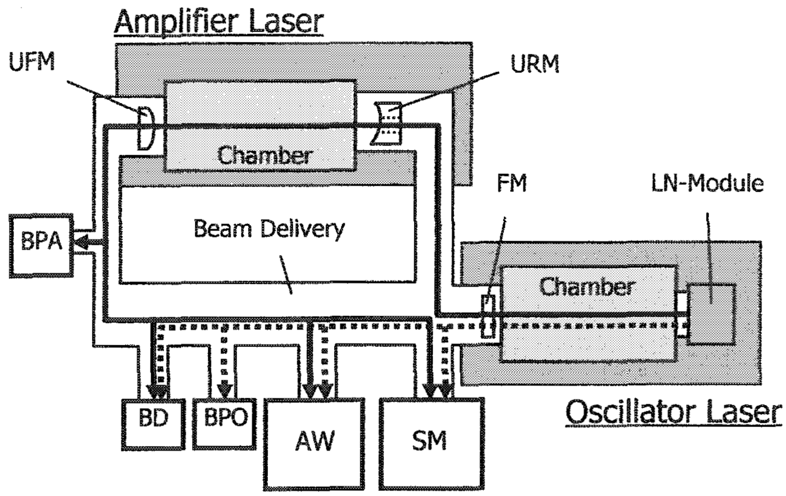
[Table.1] F_2 Laser target specifications

2. SYSTEM CONFIGURATION

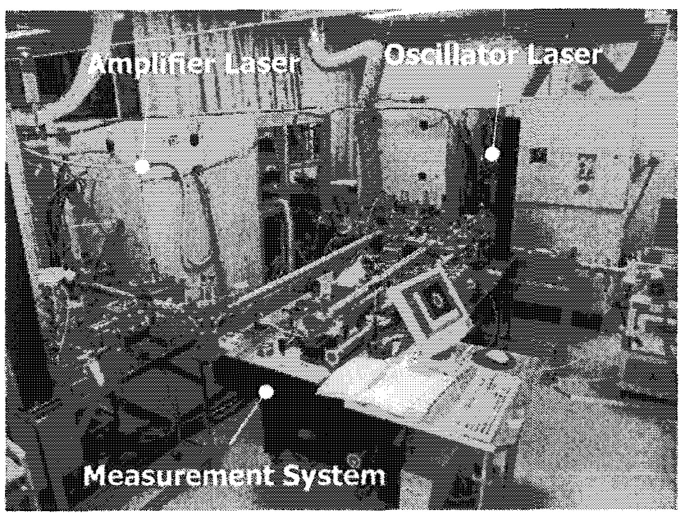
[Fig.2] shows a diagram of the Ultra-Line-Narrowed F_2 Laser System and a photograph of the system is shown in [Fig.3]. The 5 kHz system was developed based on our experience with a 2 kHz system[1, 2, 3, 4)]. The oscillator and amplifier laser and the laser performance measuring tools are interconnected with a N_2 purged beam delivery unit to avoid oxygen and other gas contamination.

A Prism-Grating Arrangement is used for Line-Narrowing in the Oscillator Laser. The front mirror (FM) of the Oscillator Laser is a flat mirror with 10 % reflectance. An unstable resonator of magnification 5 is used for the Amplifier Laser. The rear mirror (URM) of the unstable resonator has a hole in the center to pass the seed laser beam of the oscillator. The front mirror (UFM) has a HR coating in the center region and an AR coating in the outer region that transmits the amplified laser.

A high-resolution spectrometer (SM) and a high-resolution absolute wavelength meter (AW) were used to measure the spectral performance[5, 6, 7)]. The instrument function of the SM was measured with a 157 nm Coherent Light Source[8)] and the FWHM was about 0.1 pm. The AW uses a bromine lamp[9)] as a wavelength standard. 2-dimensional Beam Profiler (Star Tech Instruments/ BIP-5100) were used to measure the Beam Profile (oscillator: BPO, amplifier: BPA) and the Beam Divergence (oscillator and amplifier: BD). The laser output power was measured with a gentec power meter (PS-330-VUV) and Monitor DUO.



[Fig.2] The 5 kHz Ultra-Line-Narrowed F_2 Laser System

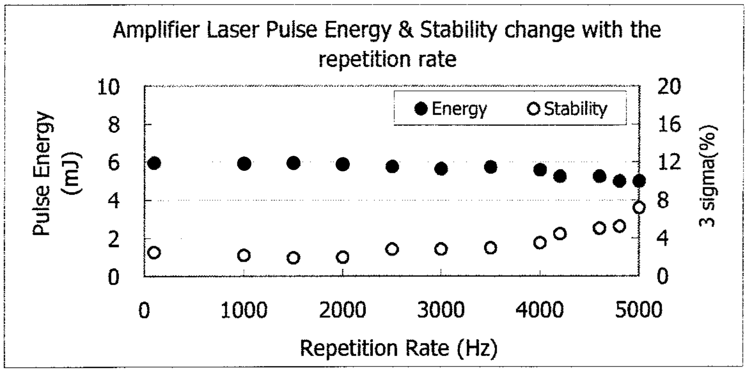


[Fig.3] Photograph of the 5 kHz Ultra-Line-Narrowed F_2 Laser

3. AMPLIFIER LASER PERFORMANCE

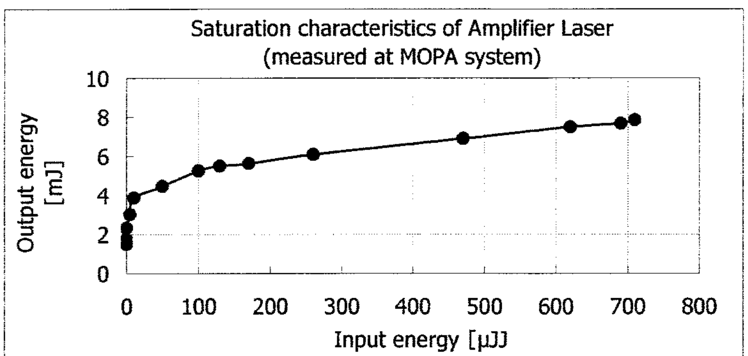
We use the same laser design for the oscillator and the amplifier laser. The oscillator and the amplifier laser energy are therefore identical when they are operated under the same conditions.

Power supply, discharge circuit, electrode design (width, length and gap distance) and gas condition were optimized for 5000 Hz operation. Especially, a sufficient laser gas velocity is important for a stable discharge at 5000 Hz. Accordingly, knife-edge type electrodes and a low total gas pressure were adapted for the laser. [Fig.4] shows the amplifier energy versus repetition rate for 300 kPa total gas pressure with a helium-rich-buffer. A laser pulse energy of 6 mJ with less than 3 % 3-sigma deviation was achieved below 3500 Hz repetition rate. Above 3500 Hz repetition rate, the laser energy and stability decreased. Measured values at 5000Hz were 5 mJ and 7.5%, respectively, which are, however, still within the development target.



[Fig.4] Amplification Laser Performance versus laser repetition rate

Saturation characteristics of the Amplifier Laser are shown in [Fig.5]. A Master Oscillator Power Amplifier (MOPA) system was set up and the saturation characteristics were measured. The Amplifier Laser was operated under the same condition as mentioned above; 300 kPa total gas pressure with a helium-rich-buffer. A 100 uJ seed beam was sufficient to achieve 5 mJ of output energy. The same energy was obtained for a single laser unit. The small signal gain was 15 ~ 16 %/cm for this operation condition.



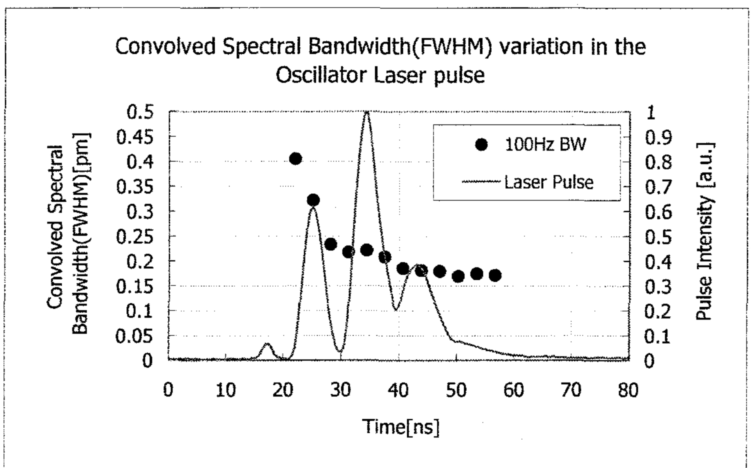
[Fig.5] Saturation characteristics of the Amplifier Laser at 5 kHz repetition rate

4. OSCILLATOR LASER PERFORMANCE

The oscillator laser was developed to obtain a spectral bandwidth of < 0.2 pm during the laser pulse. The gas condition of the oscillator laser was optimized for this purpose. The total gas pressure was below 300 kPa and helium was mainly used as oscillator buffer gas.

A typical oscillator laser pulse and its time-resolved spectral bandwidth are shown in [Fig.6]. The spectral bandwidth change was measured at 100 Hz with a Spectrometer [SM] equipped with a streak camera. As shown in [Fig.6], the spectral bandwidth decreases with increasing photon round-trips in the line-narrowing resonator. For the laser pulse shown, the initial bandwidth was 0.4 pm which then narrowed to about 0.17 pm. The time interval with a bandwidth below 0.2 pm was about 20ns ranging from 40ns to 60ns.

The integrated spectral bandwidth for this laser pulse was measured with the same spectrometer [SM] equipped with a CCD. The integrated bandwidth was about 0.24 pm. The integrated oscillator laser spectral bandwidth, however, does not have to be < 0.2 pm. It is sufficient to achieve < 0.2 pm during the oscillator laser pulse because the amplifier laser can be delayed accordingly.



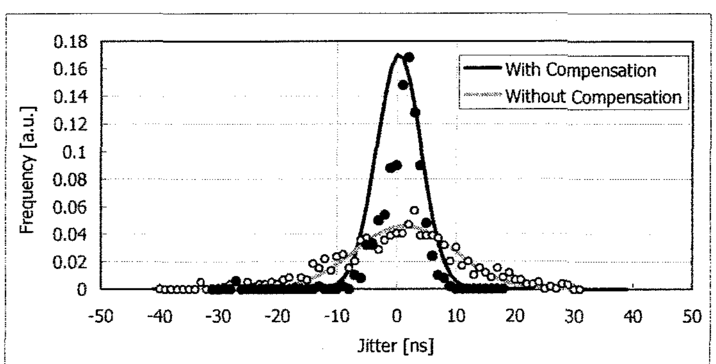
[Fig.6] Peak-normalized Oscillator laser pulse and spectral variation during the laser pulse

The prisms used for the line-narrowing module are all AR-coated in order to reduce surface reflections. The line-narrowing efficiency was about 25 %. This efficiency is defined as [Line Narrowed Energy] / [Free Running Energy]. The definitions of Free Running and Line Narrowed Energy are, respectively, the laser energy with "Front - Rear Mirror resonator" and with "Front Mirror - Line Narrowing Module" resonator. For a Free Running Energy of 1.9 mJ, we obtained 0.45 mJ with the Line Narrowing Module.

5. SYSTEM PERFORMANCE

Delay time fluctuation

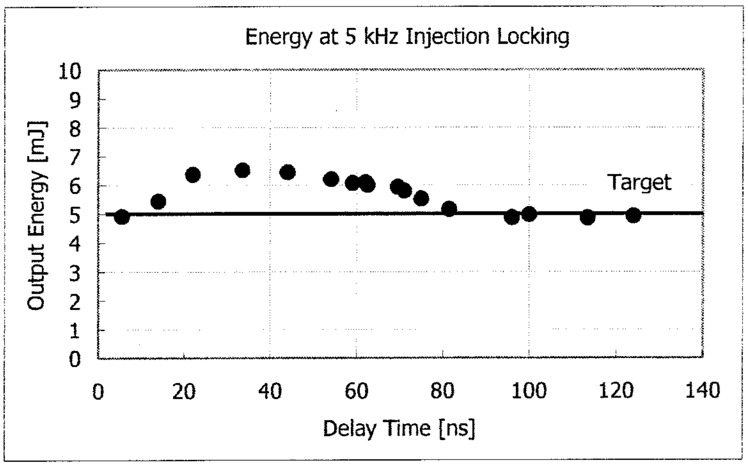
[Fig.7] shows the delay time fluctuation between the Oscillator and the Amplifier Laser. Distributions with and without jitter compensation for each laser unit are shown. Each sample contains 500 laser pulses. The jitter of each laser is mainly due to the charging voltage stability of the power supply. For example, if the power supply has a charging stability of about 0.5 %, the discharge fluctuation will be around 20 ns for a single laser. Without the jitter controller the 3-sigma fluctuation of the delay-time was about +- 30 ns. But using the controller, the fluctuation was reduced to about +- 10 ns.



[Fig.7] Delay time fluctuation between Oscillator and Amplifier Laser (sample: 500 pulses)

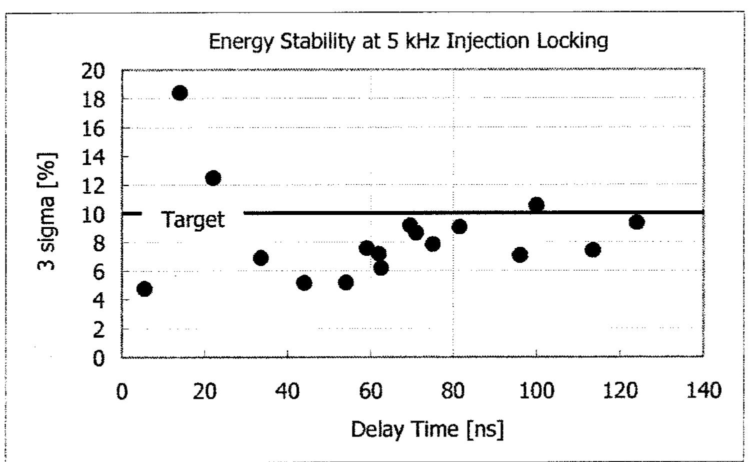
Energy Performance

The output energy of the Injection Locking system depends on the delay time between the oscillator and the amplifier laser [Fig.8]. For a small delay time, the side-light rising edges of the Oscillator Laser and the Amplifier Laser occur at the same time. With increasing delay time, the side-light emission of the amplifier emission occurs later than the oscillator laser. Therefore, only the tale of the oscillator laser pulse will be amplified.



[Fig.8] Relation between system output energy and delay time

An output energy of > 5 mJ with a maximum energy of 6.5 mJ was obtained within a 70 ns time range. For a delay time above 50ns the output energy decreased due to the decrease of the peak power of the Oscillator Laser pulse. [Fig.9] shows the energy deviation (3-sigma). The deviation was < 10 % for a time range of about 60 ns with a minimum energy deviation of 5.1 %.

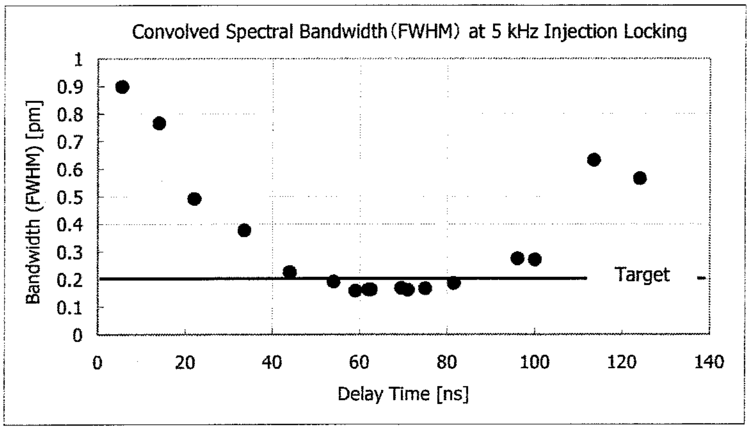


[Fig.9] Relation between system output energy stability (3- sigma) and delay time

Spectral Performance

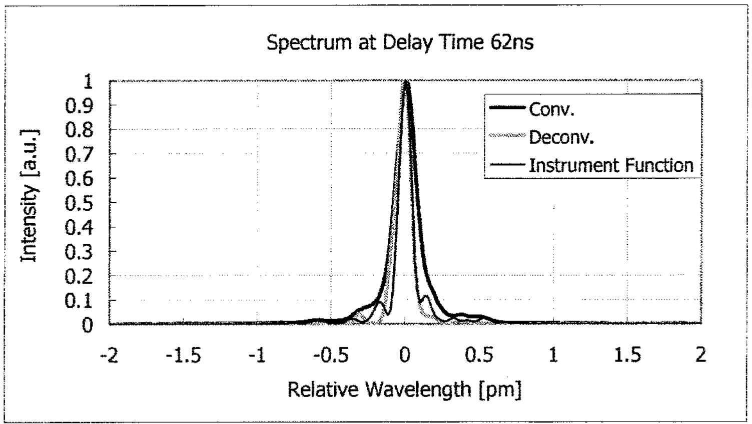
[Fig.10] shows the convolved integrated spectral bandwidth versus delay time. The convolved spectral bandwidth includes the instrument function of the spectrometer. The true spectral bandwidth is therefore smaller than the convolved spectral bandwidth. The bandwidth of the instrument function of the spectrometer is about 0.1 pm and the minimum measured spectral bandwidth is < 0.2 pm. Hence, the true laser bandwidth is < 0.2 pm.

The spectral bandwidth change of the laser system versus delay time matches well with the time dependence of the spectral bandwidth of the Oscillator Laser. The spectral bandwidth decreases to about 0.2pm until 40 ns. The bandwidth is then < 0.2 pm for about 30 ns (from 50 ns to 80 ns). The Oscillator Laser pulse intensity is not high enough to narrow the Amplifier Laser spectral bandwidth after 80 ns and the bandwidth increases again. It is therefore very important to achieve a narrow oscillator bandwidth during the Oscillator Laser pulse for a Ultra-Line-Narrowed Injection Locked Laser System.



[Fig.10] Relation between spectral bandwidth and delay time

The spectral shape at a delay time of 62 ns is shown in [Fig.11]. Convolved and deconvolved spectral shapes are shown together with the Instrument Function of the spectrometer. Convolved and deconvolved spectral bandwidths were, respectively; 0.16 pm and 0.12 pm. And the deconvolved spectral purity (E95%) was 0.45 pm.



[Fig.11] Convolved and Deconvolved Spectra at 62ns with Spectrometer Instrument Function

6. CONCLUSION

A 5 kHz Ultra-Line-Narrowed Injection Locked F_2 laser system has been developed. Power supply, discharge circuit, electrode design (width, length and gap distance) and gas condition were optimized for 5 kHz operation. We found that it is very important to achieve an oscillator bandwidth of < 0.2 pm during the oscillator laser pulse. The integrated bandwidth of the Oscillator Laser, on the other hand, does not have to be < 0.2 pm.

We succeeded in decreasing the delay time fluctuation to +- 10 ns. For a delay time between 50ns and 80ns, a Maximum Energy of > 5 mJ and a 3-sigma energy fluctuation < 10 % was obtained. The measured spectral bandwidth (convolved; FWHM) was < 0.2 pm. We deconvolved the spectral bandwidth with the instrument function of the spectrometer and we evaluated that the purity was < 0.5pm. The system has a delay time range of 30ns that satisfies the target energy and spectral performance data. We conclude that the key technologies for an Ultra-Line-Narrowed Injection Locked F_2 Laser System have been developed and that the system is a promising light source candidate for 157nm Dioptric Projection Systems.

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