JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 28, NO. 11, NOVEMBER, 1989, pp. 2354-2356

Pressure-Controlled Wavelength Stabilization of a KrF Excimer Laser with Narrowed Bandwidth

Yasuhiro SHIMADA, Koichi WANI and Yoshiro OGATA

Electronics Research Laboratory, Matsushita Electronics Corporation, Takatsuki, Osaka 569

(Received August 1, 1989; accepted for publication September 16, 1989)

A spectrally narrowed and wavelength-stabilized KrF excimer laser has been developed. The spectral bandwidth of the laser output was narrowed to 3 pm FWHM using a set of two intracavity air-spaced etalons. An air pressure control system for providing automatic feedback to the intracavity etalons is described. The center wavelength was stabilized to within ±0.5 pm under feedback control both in a continuous running mode and in an intermittent burst mode.

KEYWORDS: KrF, excimer laser, lithography, wavelength stabilization, spectral narrowing, pressure control

§1. Introduction

The KrF excimer laser oscillating at 248 nm is expected to be a powerful light source for VLSI exposure systems with application to 0.5-micrometer design rules. Because an all-quartz lens system is not prepared for chromatic aberration, the laser as an illuminator is required to have a spectral purity of less than 5 pm FWHM and a wavelength stability of within a fraction of the narrowed bandwidth.[1]

For spectral narrowing of excimer lasers, intracavity dispersive or interferometric optics have been commonly used.[2-5] In tuning the wavelength, mechanical tuning for tilting the intracavity spectral narrowing elements is not reliable for continuous scanning. We have developed a spectrally narrowed KrF excimer laser with an air pressure control system for wavelength stabilization, which provides a smooth and precise tuning.[6] The laser wavelength is tuned by pressure scanning of air-spaced etalons. In the present paper, we discuss the behavior of the laser wavelength stability both in a continuous running mode and in an intermittent burst mode.

§2. Experimental Procedure

A schematic diagram of the laser system is shown in Fig. 1. A UV-preionized transverse discharge KrF laser with a $2\times0.8\times45$ cm^3 discharge volume was used. The laser was operated at 100 Hz in a mixture of 5% Kr and 0.25% F_2 in He at 1400 Torr.

As spectral-narrowing elements, we used a set of two air-spaced etalons. One is a fine etalon with a free spectral range of 43 pm. Another is a coarse etalon with a free spectral range of 430 pm. These etalons are mounted in a sealed chamber and inserted in the laser cavity.

A small portion of the laser output is introduced into a wavelength monitoring unit for detecting the output wavelength. A block diagram of the wavelength monitoring unit is shown in Fig. 2. An external monitoring etalon is installed in this unit. The laser beam introduced onto the monitoring etalon forms concentric fringe circles on a linear image sensor. The change in the fringe diameter corresponds to the fluctuation of the wavelength and is detected by monitoring the positions of the symmetric peaks of the intensity distribution on the linear image sensor. The difference from the specific position of the fringe is transformed to a dc signal as the output of a difference amplifier. For an optimum wavelength, the difference signal is adjusted to zero. When the fringe circles contract or expand due to fluctuation of the wavelength, the difference signal becomes positive or

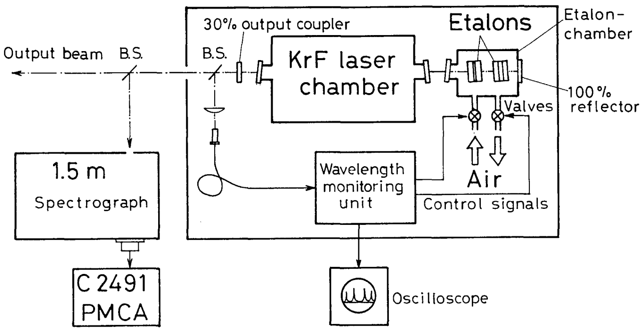

Fig. 1. Schematic diagram of the spectrally narrowed and wavelength-stabilized KrF excimer laser and the experimental setup.

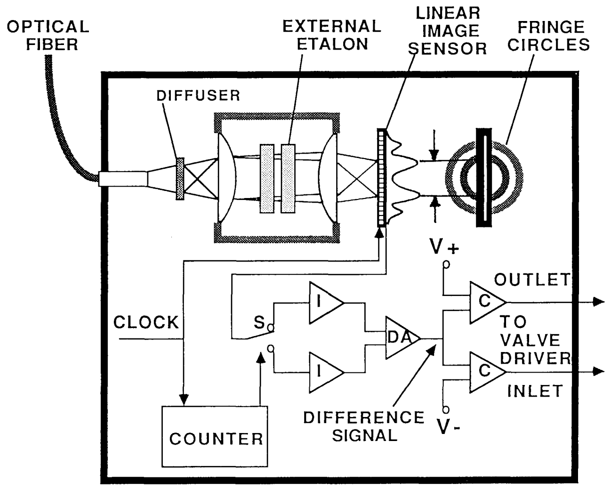

Fig. 2. Block diagram of the wavelength monitoring unit with an external etalon. S: analog switch, I: integrator, DA: difference amplifier, C: comparator, V_+, and V_-: reference voltages.

negative, respectively. This signal is used to correct the center wavelength by controlling the air pressure in the sealed chamber. By this sequence, the feedback loop is closed.

The center wavelength and bandwidth are also monitored by a high-resolution spectrograph beside the laser system. A quick wavelength shift is observed with an oscilloscope trace of the fringe pattern signal extracted from the wavelength monitoring unit.

§3. Results and Discussion

A narrowed spectral bandwidth of 3 pm FWHM was obtained as shown in Fig. 3. The output energy with the narrowed bandwidth was 10 mJ.

We have examined the temporal behavior of the center wavelength for the following four cases: (a) continuous running mode without wavelength control, (b) intermittent burst mode without wavelength control, (c) continuous running mode applying feedback control, and (d) intermittent burst mode applying feedback control.

In case (a), shown in Fig. 4(a), the center wavelength decreases exponentially within a few minutes of commencing and then approaches a constant value. The initial decrease in wavelength is caused by thermal strain of the etalons due to absorption of the laser power. Because the refractive index of a gas is determined only by its number density,7) the refractive index in the sealed chamber remains constant. As a result, once the etalons reach thermal equilibrium, the center wavelength settles down to a steady-state value.

In case (b), the intermittent burst mode, the laser is interrupted by off-cycles with arbitrary periods. We selected the off-cycle periods to be much longer than the rest period of exposure of a wafer stepper. Each period of on-cycle is fixed at 2 minutes. In this operation, the initial decrease in wavelength appears at the beginning of every on-cycle, as shown in Fig. 4(b). Since the intracavity etalons turn back towards the initial state due to thermal recovery during the off-cycles, the wavelength at the beginning of every on-cycle deviates from the steady-state value. The maximum wavelength deviation from the steady-state value depends on the period of the preceding off-cycle concerned with thermal recovery time. For example, at restart after the off-cycle of 15 seconds, the center wavelength has drifted away from the

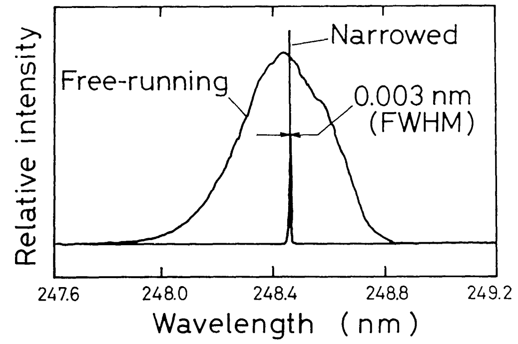

Fig. 3. Spectral profiles of free-running and narrowed band. Bandwidths of free-running and narrowed band are 0.4 nm FWHM and 0.003 nm FWHM, respectively.

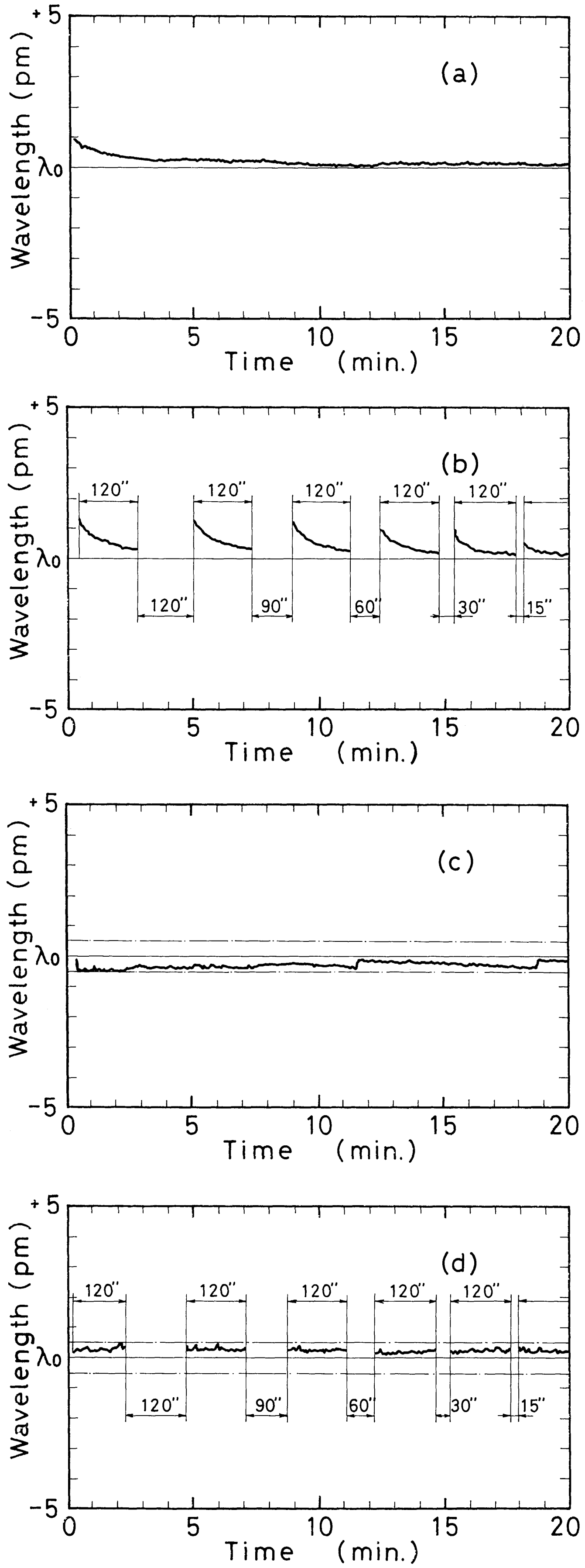

Fig. 4. Temporal behavior of the center wavelength after a cold start operating at 100 Hz: (a) continuous running mode without wavelength control, (b) intermittent burst mode without wavelength control, (c) continuous running mode applying feedback control, and (d) intermittent burst mode applying feedback control.

steady-state value by 0.5 pm.

In case (c), shown in Fig. 4(c), where feedback control is applied in a continuous operation, the initial decrease in wavelength at the beginning was suppressed to within a few seconds; then, the center wavelength was fixed in the stabilizing range of ±0.5 pm. The maximum wavelength deviation at the very beginning was estimated to be equal to that in case (a).

In case (d), shown in Fig. 4(d), the initial decrease in wavelength at the beginning of each on-cycle was improved compared to that in case (b), while the maximum wavelength deviations at the very beginnings of each on-cycle were estimated to be the same as those in case (b).

Because the drift in wavelength during the off-cycles is caused by thermal recovery of the etalons, the center wavelength turns back towards the initial wavelength as the off-cycle period increases. When the laser is operated synchronizing with a wafer stepper, the off-cycle period of the laser is within a few seconds or less, which is short enough to avoid the drift in wavelength due to the thermal recovery of the etalons. We observed wavelength deviation in the order of 0.5 pm after the off-cycle of 15 seconds. This feature ensures that the center wavelength remains in the stabilizing range when the laser is used as a light source for the wafer stepper.

§4. Conclusion

We have developed a new system for wavelength stabilization of a spectrally narrowed KrF excimer laser, using a feedback loop for controlling the air pressure. The lasing bandwidth was reduced to 3 pm FWHM by the intracavity etalons. The center wavelength was stabilized to within ±0.5 pm with a sufficient margin even in an intermittent burst mode with an actual off-cycle of the wafer stepper. This technique for wavelength stabilization will assist the development of excimer-laser-based lithography.

Acknowledgments

We would like to thank Dr. Miyata, T. and the staff of Matsushita Research Institute Tokyo, Inc. for their technical cooperation and valuable advice.

References

1) V. Pol, J. H. Bennewitz, T. E. Jewell and D. W. Peters: Opt. Eng. **26** (1987) 311.
2) T. J. MaCkee: Can. J. Phys. **63** (1985) 214.
3) T. R. Loree, K. B. Butterfield and D. L. Barker: Appl. Phys. Lett. **32** (1978) 171.
4) E. Armandillo and G. Giuliani: Opt. Lett. **8** (1983) 274.
5) T. J. Pacala, I. S. McDermid and J. B. Laudenslager: Appl. Phys. Lett. **40** (1982) 1.
6) K. Wani, Y. Ogata, Y. Watarai, T. Ono, T. Miyata, R. Sano and Y. Terui: *Proc. SPIE. Excimer Beam Applications, Boston, 1988* (SPIE, Washington D. C., 1988) Vol. 998, p. 2.
7) M. Born and E. Wolf: *Principles of Optics* (Pergamon, Oxford, 1980) 6th ed., p. 88.