Effects of prism beam expander and slits on excimer laser linewidth narrowing module

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Theoretical simulation and experiments based on a prism beam expander and an echelle grating are conducted to study the dependence of linewidth and pulse energy on incidence angle and slit width. With a larger prism incident angle or narrower slit width, the linewidth becomes narrower while the laser pulse energy becomes lower. However, the pulse energy can be improved by optimally designing the prism beam expander. In addition, a subpicometer linewidth ArF laser is obtained with a double-prism beam expander and an echelle grating.

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Deep ultraviolet radiation based on ArF excimer lasers is extensively used in ultralarge-scale integrated circuit lithography[1−3], stimulated Raman scattering[4−6], and fiber grating writing[7−9]. ArF excimer lasers that are characterized by short wavelengths and high photon energy can be precisely focused[10]. However, before the advantages of the lasers can be realized, a free running linewidth of approximately 500 pm should be substantially narrowed. The critical dimension and resolution of a projection system are determined by the linewidth of a lithography source. The chromatic aberration of exposure tools can be effectively mitigated by linewidth narrowing of laser sources. Thus, spectral linewidth narrowing of ArF excimer lasers significantly reduces the lithography node.

Effective optics used for linewidth narrowing include etalons, prisms, and gratings[11]. An ultranarrow linewidth can be obtained using narrow-band filtering etalons in excimer lasers. However, the output pulse energy of the laser is limited by the low damage threshold of etalons[12−17]. Obtaining an ultranarrow linewidth by separately using prisms or grating is difficult[18−20], and prism grating configurations characterize high cavity dispersion and high optical damage threshold[21−23]. Previous studies[24−27] reported that an ultranarrow linewidth laser could be demonstrated through a prism beam expander and a grating. Laser efficiency is low because of the limited diffraction efficiency of the grating working in extremely high orders and the reflective losses of prisms[28]. However, whether optimizing the prism beam expander could enhance the pulse energy of linewidth-narrowed lasers has yet to be determined. In addition, the relationship between the slit width and linewidth of excimer lasers remains unknown.

In this letter, the spectral linewidth narrowing of an ArF excimer laser based on a prism beam expander and an echelle grating is reported. Linewidth and pulse energy are sensitive to beam magnification and divergence angle. The magnification and divergence angle are determined primarily by the incident angle of the prism and slit width in the cavity, respectively. Thus, the dependence of linewidth and output energy on incident angle and slit width is investigated.

The cavity dispersion equation is extensively used to estimate the dispersive linewidth in high-gain pulsed lasers that incorporate multiple dispersive optical elements. The dispersion can be high in multiple-prism grating arrangements because grating dispersion is multiplied by the large beam magnification provided by the multiple-prism beam expander. For achromatic prism beam expanders[29], the total dispersion for line narrowing results mainly from grating. Therefore, the linewidth of a linewidth-narrowed laser can be expressed as[30,31]

$$\Delta\lambda_{\mathrm{FWHM}} = \frac{\theta_{\mathrm{div}}}{2M\sqrt{N_{\mathrm{R}}}\tan\alpha_{\mathrm{B}}}\lambda, \tag{1}$$

where θ_{div} and λ are the horizontal divergence angle and laser wavelength, respectively, M is the magnification of the prism beam expander, α_{B} denotes the blazed angle of the echelle grating, and N_{R} is the number of round trips in the laser cavity.

Based on Eq. (1), a narrower linewidth can be obtained by increasing the beam magnification of the prism beam expander, selecting an echelle grating with a large blazed angle, or increasing the number of round trips. However, the practical approach to linewidth narrowing is to enhance the magnification of the prism beam expander.

The total magnification of the N-prism beam expander can be expressed as

$$M = \prod_{k=1}^{N} \frac{\cos\phi_k \cos\nu_k}{\cos\theta_k \cos\mu_k}, \tag{2}$$

where θ_k and ϕ_k are the incidence and refraction angles on the incidence plane of the kth prism, respectively, and μ_k and ν_k are the incidence and refraction angles on the exit plane of the prisms, respectively.

The parameters in the simulation are the same as those used in the following experimental configurations. Considering fused silica right angle prisms with an apex angle

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of 37°, the dependence of magnification on the incidence angle of the prism beam expander is mathematically simulated (Fig. 1). The linewidth narrowing effect is marginal at a small magnification that arises from low incidence angles. A narrow linewidth can be realized by increasing the incidence angle of the prism beam expander. The output energy of the linewidth-narrowed pulse is limited because of high reflectivity losses at the incident plane caused by large incident angles. Therefore, an incident angle range from 55° to 80° is selected. Moreover, for the multiple-prism beam expander, the total magnification is more sensitive to changes in incident angle.

Theoretical simulation and experiments were conducted to study the dependence of linewidth-narrowed bandwidths and pulse energy on incidence angle and slit width.

Experiments were performed using a Gamlaser model EX100 ArF excimer laser (maximum pulse energy, 16.8 mJ at 20 Hz). The divergence angle in the beam-expanded horizontal direction is 1.5 mrad. A schematic of the standard oscillator with a line narrowing module (LNM) design is shown in Fig. 2. A 1.2-m-long discharge tube provides gain to the oscillator. A narrow linewidth is achieved using an echelle grating, a prism beam expander, and a 30% reflectivity output coupler (OC). The apex angle of the right angle-fused silica (n=1.5603@193.4 nm) prism is 37°. The rear reflector is an echelle grating with a blazed angle of 79° operated in Littrow configuration in the 108th order. The overall length of the oscillator cavity is approximately 1.5 m. For the 20-ns laser pulse, the number of round trips N_{R} in the cavity is approximately 2.

The theoretical analysis shows that beam magnification is determined by incident angle for a given prism beam expander. To study the dependence of linewidth on beam magnification, the relationship between the laser linewidth and incident angle of a single prism is systematically examined. Figure 3 shows the

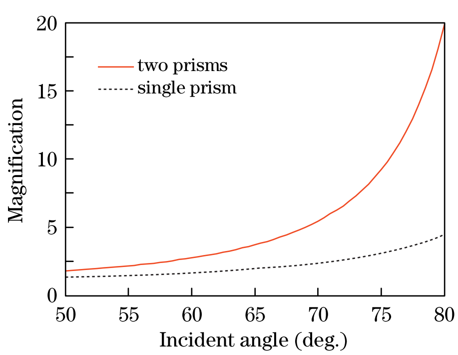

Fig. 1. Relationship between incident angles and magnifications of prisms with an apex angle of 37°.

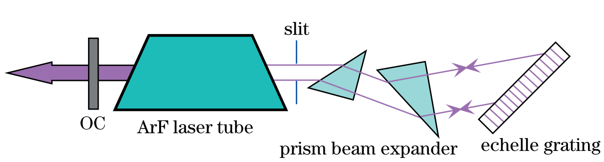

Fig. 2. Schematic of the ArF excimer laser with linewidth narrowing configuration.

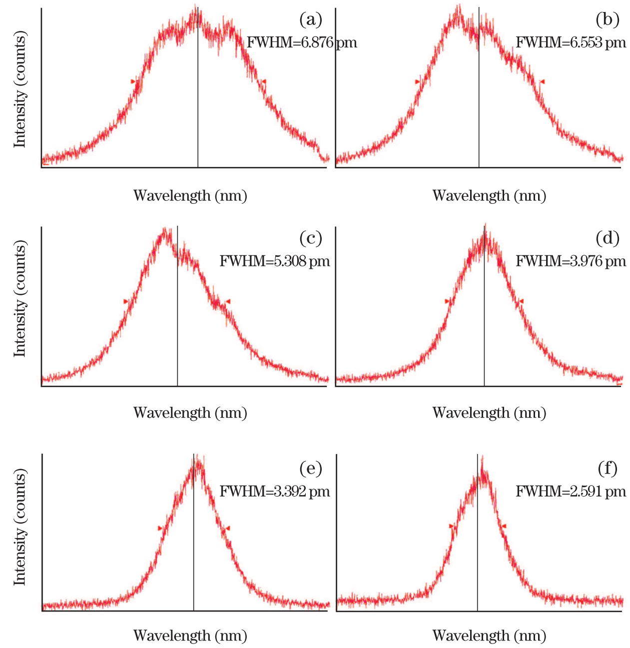

Fig. 3. Spectra of the linewidth-narrowed ArF laser with incident angles of (a) 55°, (b) 60°, (c) 65°, (d) 70°, (e) 75°, and (f) 80° of the single-prism beam expander. SNR: signal-to-noise rate; FWHM: full-width at half-maximum.

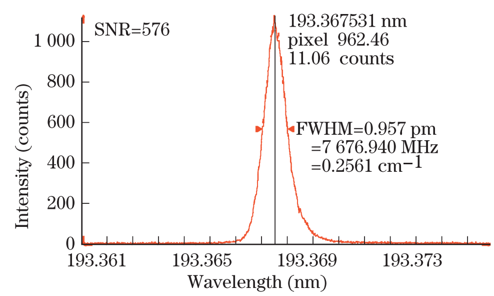

Fig. 4. Spectrum of the linewidth-narrowed laser using the double-prism beam expander and echelle grating (0.957 pm, 0.3 mJ).

spectra of the linewidth-narrowed ArF laser with different incident angles of the single-prism beam expander. Moreover, the linewidth of the output laser that uses the double-prism beam expander and echelle grating configurations is presented. The minimal linewidth 0.957 pm is obtained at an incident angle of 80° for both prisms. The spectrum detected using a high-resolution echelle grating spectrometer (ELIAS III, LTB Berlin, resolution 0.060 pm) is shown in Fig. 4.

The linewidth apparently narrows with increasing incident angle. The linewidth of the ArF excimer laser as a function of incident angle is plotted in Fig. 5 (dashed curve). For the given incident angle range, the linewidth of the output laser pulse almost linearly decreases with increasing incident angle.

The physical mechanism of the phenomenon can be illustrated as follows. Beam magnification enlarges as incident angle increases. The effective dispersion of the echelle grating is M times larger than that of the original grating. The spectrum bandwidth of the feedback laser from the dispersion of the grating becomes narrower with higher dispersion. Therefore, the effective cavity dispersion that arises from the increase in incident angle of the prism accounts for the dependence of linewidth narrowing on incident angle.

The theoretical simulation of the relationship between linewidth and incident angle is depicted in Fig. 5 (solid curve) according to Eq. (1) with a wavelength of 193.37 nm. A comparison of the two curves shows that the experimental results agree with the theoretical simulation.

The output pulse energy of the linewidth-narrowed laser versus the incident angle curve is shown in Fig. 5 (dotted curve). The pulse energy of the output laser is lower at a larger incident angle because the majority of the spectral band dispersion caused by the echelle grating cannot resonate in the laser cavity. As a result, linewidth narrowing is inevitably accompanied by a decrease in pulse energy.

However, the decrease in the slope of the pulse energy becomes noticeably slow at an incident angle of approximately 71°. The linewidth narrowing and the output pulse energy of the laser show improvements. This result can be explained as follows. For the designed prism, the beam can perpendicularly exit the prism at an incident angle of 71°. Consequently, the reflectivity at the exit plane of the prism causes minimal cavity losses. Moreover, the optical path in the linewidth narrowing module is the shortest at this incident angle. The losses that arise from oxygen absorption in the atmosphere become lower. Therefore, the improvement in pulse energy benefits from the decreased cavity losses that arise from the optimal prism design.

In addition, laser pulse energy decreases with linewidth narrowing. The pulse energy of the output laser becomes lower with a narrower linewidth. The pulse energy is nearly linear with the linewidth, except around an optimal incident angle of 71°, indicating that energy losses are high at deep linewidth narrowing. For high-energy and ultranarrow linewidth applications, two-stage laser systems that consist of an oscillator and an amplifier should be adopted to obtain ultranarrow linewidth and high pulse energy[8,19,21,32−34].

A laser linewidth can be narrowed by decreasing the slit width at the horizontal direction[35]. The fluorescence emitted by the laser tube is 8×4 (mm). The slit width can be varied from 0 to 5 mm.

The FWHM linewidth as a function of slit width is shown in Fig. 6 (solid curve). A narrow linewidth is

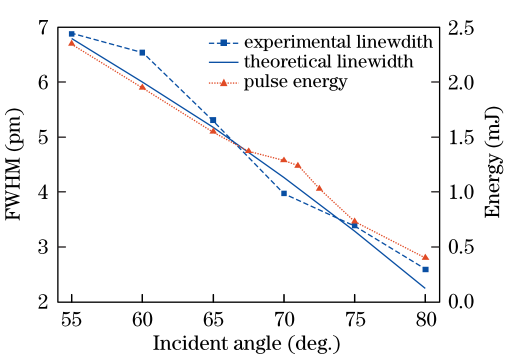

Fig. 5. Linewidth of the laser versus incident angle in the theoretical simulation (solid curve) and experiment (dashed curve). The relationship between pulse energy and incident angle is also shown (dotted curve).

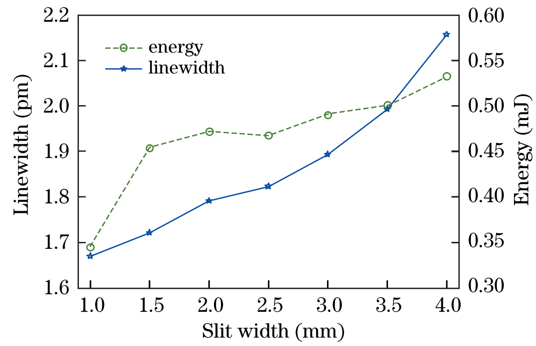

Fig. 6. Slit width versus linewidth (solid curve) and pulse energy (dashed curve) of the ArF laser (20 Hz, 13 kV).

obtained with a narrow slit width. Linewidth almost linearly decreases with decreasing slit width because the divergence angle of the incidence laser beam in the LNM is deduced as the decrease in slit width.

Aside from linewidth, laser pulse energy is related to slit width. Figure 6 (dashed curve) shows that the pulse energy rapidly decreases with decreasing slit width. Energy tremendously decreases at a slit width of 1 mm as a result of mass space filtering losses. Thus, balancing the pulse energy and linewidth narrowing by decreasing slit width is an important task.

In conclusion, the linewidth narrowing of an ArF excimer laser using a prism beam expander and an echelle grating configuration is theoretically and experimentally investigated. The experimental results show that linewidth decreases almost linearly with increasing beam magnification or decreasing slit width in the cavity. The pulse energy of the output laser is lower with a narrower linewidth. However, even at large incident angles, pulse energy improves when an optimally designed prism beam expander is used. In addition, a linewidth of 0.957 pm is obtained using a double-prism beam expander with an incident angle of 80° and an echelle grating.

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