High power light source for future extreme ultraviolet lithography based on energy-recovery linac free-electron laser

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Abstract. The development of ways to increase the intensity of extreme ultraviolet (EUV) light sources for future EUV lithography is important to realize high throughput fine patterning. The energy-recovery linac (ERL) free-electron laser (FEL), which is an accelerator based light source, is a candidate for this. We clarify the design concept of the ERL-FEL for EUV light sources for future lithography, delivery systems of the FEL light to multiscanners, and future development items of the accelerator technologies and a possibility of the beyond EUV. [DOI: 10.1117/1.JMM.21.2.021210]

Keywords: high power source of extreme ultraviolet; future lithography; free-electron laser; light; accelerator; energy recovery linac.

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1 Introduction

For the microfabrication of silicon semiconductors, many technological developments have been carried out over many years in consideration of Moore's law. The ArF excimer laser is a light source with a wavelength of 193 nm. To ensure high-resolution patterning, the technology of exposure in liquid (immersion exposure) is used to increase the value of the open aperture (NA), and multiple exposure systems are used to realize a mass production system for 22/20 nm to 10 nm nodes. In 2018, the extreme ultraviolet (EUV) lithography system, with a wavelength of 13.5 nm, reached high volume manufacturing (HVM) production.[1] To realize HVM production, great efforts have been made on the exposure systems, including an illumination optical system, a reflection mask, and a projection optical system, which is based on a reduction optical system using Mo/Si multilayer mirrors. The system consists of a total of 12 multilayer mirrors.

The EUV light source intensity in the HVM system was required to be 250 W at the beginning. Currently, the light source system uses the laser-produced-plasma (LPP) method, in which a high-intensity CO_2 laser irradiates Sn droplets to put Sn atoms into a plasma state, so the high-intense EUV light, with a wavelength of 13.5 nm, is produced from that transition state in Sn plasma. For this purpose, many developments have been made such as increasing the output of the CO_2 laser to excite the plasma state (up to 20 kW or more) and improving the conversion efficiency by shaping the Sn droplet by irradiation by a prepulse laser, so the stable 250 W EUV source is realized in a real HVM system. However, it is necessary to solve some problems to further increase the intensity, such as the debris problem of Sn on a collective optical multilayer mirror, and these developments are progressing now.

Even though mass production has started by means of EUV lithography based on the LPP light source, for the next frontier, the "stochastic effect" has become an important issue in semiconductor fine patterning.[2] This "stochastic effect" is due to the shot noise in exposure on the resist, and further enhancement of the light source intensity and appropriate resist is required to

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proceed to finer scale processing. The current logic 7-nm node micromachining has started mass production at 250 W, but it is expected that a much higher power of EUV source will be needed to avoid the shot noise effect for high throughput systems. The intensity of the required EUV light source is estimated to be, e.g., higher than 1 kW at the 3-nm node and about 3 kW at the 2-nm node fine patterning, as described by Soichi Inoue of KIOXIA at the fourth EUV-free-electron laser (FEL) Workshop.[3] To this end, one of the promising candidates for high-power EUV light sources is a SASE-FEL light source based on an energy recovery linac (ERL). The intensity is expected to exceed 10 kW, and it is a clean light source with no problem with debris.

In the following sections, the concept of the ERL-FEL (Sec. 2), design of ERL-FEL (Sec. 3), design concept of the optics from ERL-FEL to the EUV scanner (Sec. 4), efforts to apply to industry (Sec. 5), beyond EUV (Sec. 6), and a summary (Sec. 7) are described.

2 Concept of an ERL-FEL

An FEL is a device based on a high-energy electron accelerator to generate coherent electromagnetic radiation.[4] Figure 1 depicts a schematic view of the FEL consisting of an electron accelerator and an undulator, a periodically alternating magnetic field. The radiation wavelength, λ, is a function of the electron beam energy and the undulator configuration:

$$\lambda = \frac{1 + a_w^2}{2\gamma^2}\lambda_u, \tag{1}$$

$$a_w = \frac{eB_{\mathrm{rms}}\lambda_u}{2\pi m_e c}, \tag{2}$$

where $\gamma = E/(m_e c^2)$ is the normalized electron energy, a_w is the rms undulator parameter, B_{rms} is the on-axis rms magnetic field, λ_u is the undulator period, m_e and e are the electron mass and charge, respectively, and c is the vacuum speed of light.

Equations (1) and (2) suggest that the radiation wavelength can be tuned by changing the electron energy and the undulator design. For a radiation wavelength of 13.5 nm, we can use an electron beam with an energy of 800 MeV and an undulator with a period of 28 mm and the on-axis rms field of 0.45 T.

The energy conversion efficiency from the electron beam to the radiation is typically <0.1% in FELs operated in the EUV wavelength. To compensate for the small efficiency and achieve high-power radiation from an FEL, the ERL was proposed.[5] Figure 2 shows the principle of the ERL. An electron beam from an injector is accelerated by a superconducting (SC) linear accelerator, by which a bunch of electrons is accelerated by a time-varying radiofrequency (RF) electromagnetic wave and then transported to a recirculation loop. An undulator is installed in the recirculation loop to drive the FEL. The spent electron beam is again injected into the SC accelerator at the RF phase opposite the acceleration, so the electrons are decelerated. Therefore, the energy of the accelerated electrons is converted back into the RF energy and recovered to accelerate the succeeding electrons.

For the operation of an FEL, a high-quality electron beam with a small energy spread and a small divergence (emittance) is necessary. The ERL is able to provide such a high-quality electron beam because an electron beam in the ERL goes to a beam dump after deceleration and another fresh electron bunch is accelerated every turn. In addition, the ERL has another practical

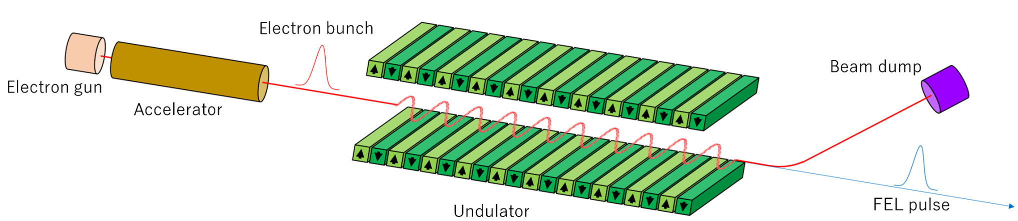

Fig. 1 Schematic view of the FEL.

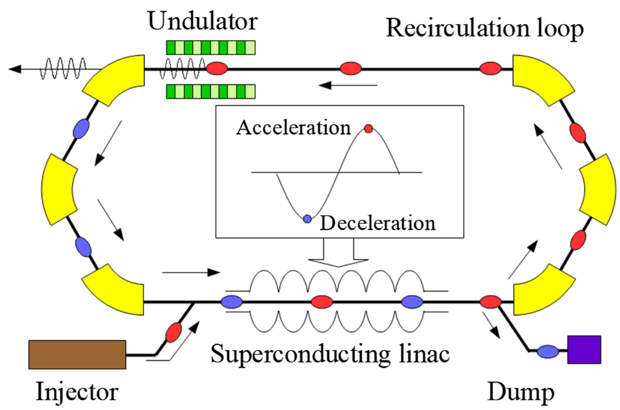

Fig. 2 Energy-recovery linac free-electron laser.

advantage in there being small electron energy at the beam dump to reduce the production of radioactive material.

High-power FELs have been realized by ERLs in infrared wavelengths.[6–8] The highest power so far demonstrated in an ERL-FEL was 14.3 kW at a wavelength of 1.6 μm driven by an electron beam of 115 MeV and 8 mA. The FEL was a multipass oscillator type, and the FEL pulse repetition rate was 75 MHz.[6] A single-pass FEL driven by an ERL is also under development, in which the growth of infrared radiation was recently demonstrated.[9]

The coherent radiation in the FEL can be established in various emission architectures, including multipass and single-pass configurations, as shown in Fig. 3. For a high-power FEL operated in the EUV wavelength for industrial lithography applications, practical emission architectures are (1) single-pass self-amplified spontaneous emission (SASE), (2) single-pass self-seeding FEL, and (3) multipass regenerative amplifier FEL. Once the requirement of the FEL performance for a specific application and the available technology are given, a quantitative comparison of these emission architectures can be performed by running numerical simulations to ascertain the feasible FEL power and examine the robustness and redundancy of the system.[10] In this study, we chose the ERL SASE-FEL because the ERL has been proven to be a high-power FEL driver and the combination of ERL and SASE-FEL has also been demonstrated. In the

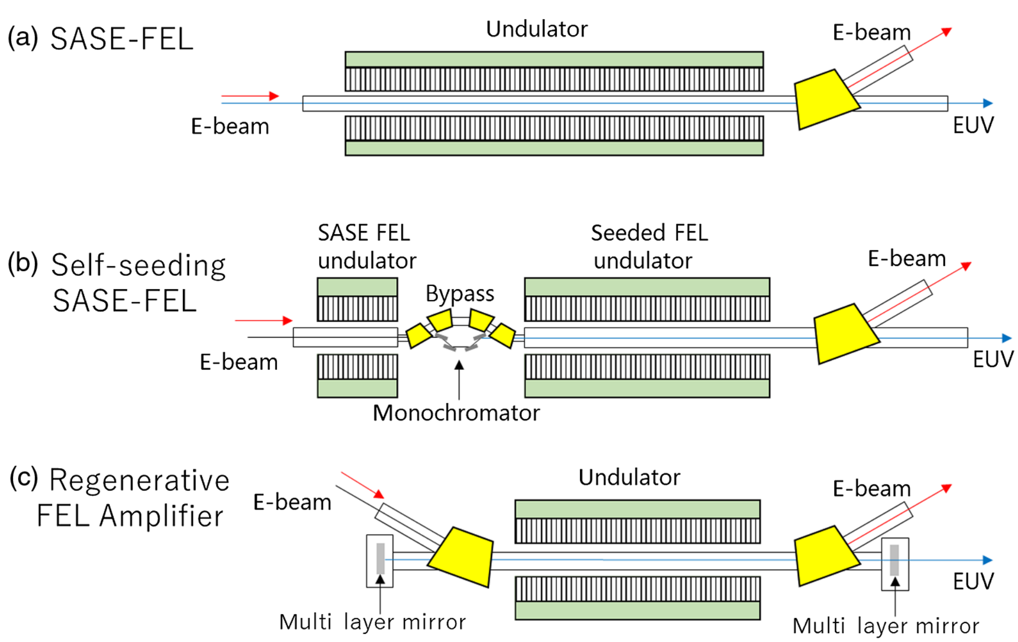

Fig. 3 Emission architectures for the EUV-FEL: (a) SASE-FEL, (b) self-seeding SASE-FEL, and (c) regenerative amplifier FEL (RAFEL).

following sections, we describe an example of a high-power ERL-FEL based on the proposed conceptual design.

3 Design of an ERL-FEL

An ERL-FEL was designed and studied to provide >1 kW EUV power for multiple scanners.[11,12] An image of the design is illustrated in Fig. 4, and the design parameter values are listed in Table 1. The ERL-FEL consists mainly of an injector, a main linac, a recirculation loop including two arc sections and an undulator system for FEL, and a dump line. The injector diagnostic beamline is used for measuring the injection beam parameters.

In the ERL-FEL, electron bunches generated in the electron gun at 162.5 MHz are accelerated by a SC injector linac up to 10.5 MeV and injected into the SC main linac via the merger. The electron bunches are then accelerated by the main linac up to 800 MeV and magnetically compressed in the first arc section to increase the peak current. The electron beam passes through the undulators to generate 13.5-nm EUV light via the SASE-FEL process. After light emission, the electron beam is decompressed in the second arc section and returned back to the main linac

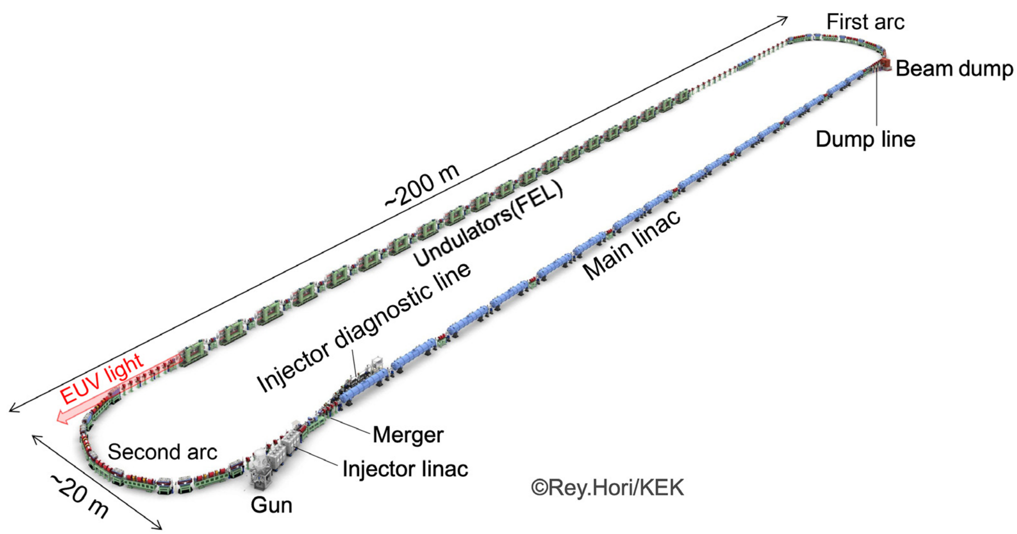

Fig. 4 Illustration of an ERL-FEL designed for EUV lithography.

Table 1 Nominal design parameter list of the ERL-FEL for EUV lithography.

Parameter	Design value
Beam energy	800 MeV
Injection energy	10.5 MeV
Bunch charge	60 pC
Bunch repetition frequency	162.5 MHz
Average beam current	10 mA
RF frequency	1.3 GHz
Undulator period	28 mm
Undulator parameter	1.168
EUV wavelength	13.5 nm

in the deceleration phase for energy recovery. Finally, it is decelerated down to almost the same energy as the injection energy and extracted to the dump line with a beam dump.

The ERL-FEL requires a high-current electron beam with low longitudinal and transverse emittances. A dc photocathode gun is one of the most promising candidates for such electron guns because a high-current beam of 9 mA was routinely provided from the dc gun at the Jefferson Lab ERL-FEL,[6] whereas the Cornell photoinjector operates with an average current of 65 mA,[13] the highest record to date. The Cornell photoinjector furthermore demonstrated a low-emittance beam satisfying the requirements of the high-repetition-rate XFEL[14] as a 400 kV dc photocathode gun. Moreover, a 500 kV dc photocathode gun[15] at High Energy Accelerator Research Organization (KEK) has stably operated with a maximum average current of 1 mA.[16]

Two cERL-injector cryomodules,[17] each of which has three 2-cell SC cavities,[18] are used for the ERL-FEL design. The 2-cell SC cavities have a TESLA-like cell shape and a larger beam pipe aperture of 88 mm. Each of them is equipped with two input couplers and five higher-order-mode (HOM) couplers. The main linac must accelerate the electron beam with an average current of 10 mA without strong field emission and without serious beam breakup and cavity heating due to the HOMs induced by the beam. The cavity model used for this ERL-FEL design is a Tesla-type 9-cell cavity with a large-aperture HOM-damped beam pipe.[19–21]

Two arc sections are needed in the ERL-FEL to recirculate the electron beam for energy recovery and to control the bunch length magnetically using a bunch compression and decompression scheme. In bending magnets of such arc sections, a short electron bunch radiates strong coherent synchrotron radiation (CSR). The strong CSR field emitted from the back of the bunch catches up with and affects the front of the bunch, and as a result, it degrades the beam quality. The optics design of the first arc for suppressing the CSR effects in bunch compression is one of the key tasks for increasing the FEL output. A double-bend achromat lattice is adopted in the first arc section to suppress CSR effects in bunch compression,[12,22] and a triple-bend achromat lattice is used in the second arc section for bunch decompression to avoid serious cavity heating due to the short bunch length and to obtain efficient energy recovery without serious beam loss.

The undulator system of the ERL-FEL consists of 18 circular-polarizing (helical) undulators of about 5-m length because a circular-polarizing undulator has a larger FEL-parameter (Pierce parameter) value than a linear-polarizing undulator. If variably-polarizing undulators such as an Apple-II type[23] undulator are used for the last several undulators, the ERL-FEL can also produce various polarization states including linear and circular polarizations. The intersection between the undulators is about 1 m in length, and a phase shifter and a focusing quadrupole magnet are placed in the intersection. The phase shifter controls the path length of the electron bunch by a magnetic chicane to correct the phase difference between the undulator radiation and the electron bunch. The focusing strength of the quadrupole magnets between the undulators should also be optimized to maximize the FEL output power.

A start-to-end (S2E) simulation using particle tracking and FEL codes can estimate the performance of the designed ERL-FEL.[12] Figure 5(a) shows the FEL pulse energy as a function of the undulator section length. Microbunching grows in the electron beam, and as a result, the FEL pulse energy continues to drastically increase until it is saturated at more than about 60 m, as shown in Fig. 5(a). The FEL pulse energy is 79.5 μJ at the end of the undulator section without tapering and 88.5 μJ with linear undulator tapering of 2%. For the bunch repetition frequency of 162.5 MHz, the FEL power of 14.4 kW is achieved at 9.75 mA with the 2% tapering. The calculated spectrum of the EUV-FEL light and the reflectivity curve of Mo/Si multilayer are shown in Fig. 5(b). As shown in this figure, the spectral width is narrow enough for the reflection bandwidth of Mo/Si multilayer. After the FEL lasing, the momentum spread of the electron beam is increased; however, the beam is well transported without serious beam loss with appropriate beam-pipe apertures, providing >10 kW power at <10 mA.

4 Design Concept of the Optics from ERL-FEL to EUV Scanner

An accelerator-based ERL-FEL will produce the high-power EUV light source, with >10 kW. It is, however, expected that the initial cost will be almost one order-of-magnitude higher than that of the present 250 W LPP EUV light source. Therefore, it is important to reduce the cost per one

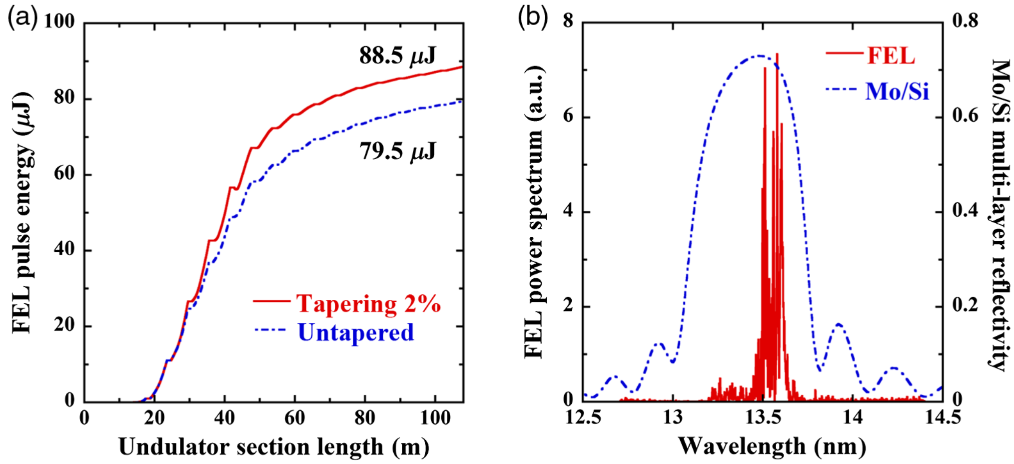

Fig. 5 (a) The calculated FEL pulse energy without and with tapering as a function of the undulator section length and (b) the calculated FEL power spectrum for 2% linear undulator tapering at the FEL exit with the Mo/Si multilayer reflectivity curve.

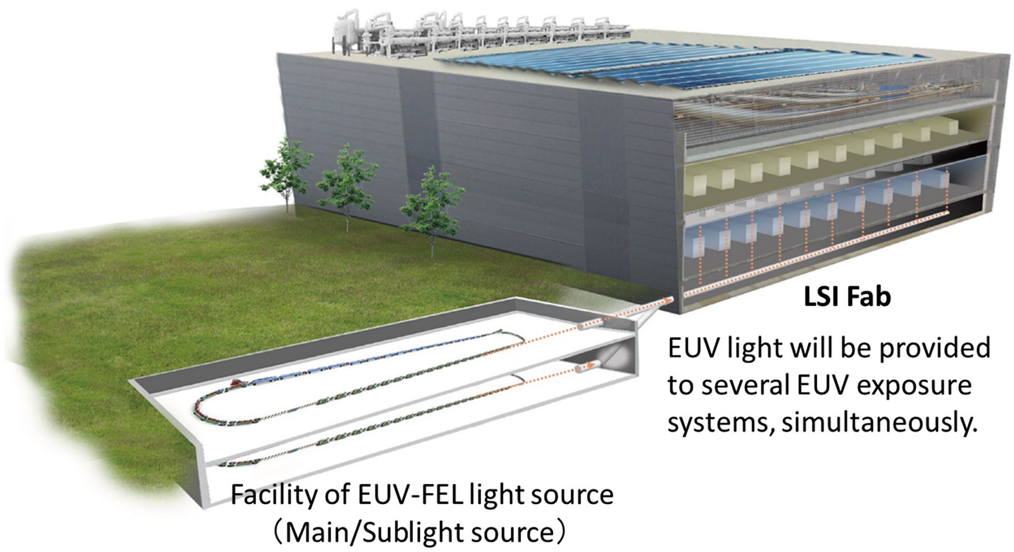

Fig. 6 Schematic view of the LSI Fab based on the EUV-FEL light source. FEL light is distributed into 10 scanner systems using a guide beamline.

scanner system. Figure 6 shows a schematic view of the future large-scale integration (LSI) Fab based on ERL-FEL light source as described by several authors.[24–26] To reduce the cost per scanner, the FEL light must be delivered to 10 scanners by means of an arrangement of grazing incidence curved mirrors system without any radiation damage to the optical components. The most serious problem is expected to be an ablation effect at the high peak intensity of the ERL-FEL. In the case of grazing incident mirrors for the EUV energy region with a grazing incident angle of about 3 deg, there is no ablation damage at several existing FEL beamlines because the footprint of the irradiation light is elongated by the geometry and the high reflectivity mirrors (as much as 98%). The threshold of the ablation on several materials such as Mo/Si multilayer mirrors, Si, and Al by the irradiation of the EUV-FEL light has been reported by M. Nishikino[27] as about 20 $\mathrm{mJ/cm^2/pulse}$, when the pulse width is <10 psec.

On the other hand, the estimated EUV-FEL light source power is about 10 $\mu\mathrm{J/pulse}$ with 1 mm in diameter size at 3 m far from the undulator. At that position, the energy density of the normal incidence is about 10 $\mathrm{mJ/cm^2/pulse}$. This energy density is almost comparable to the threshold value.

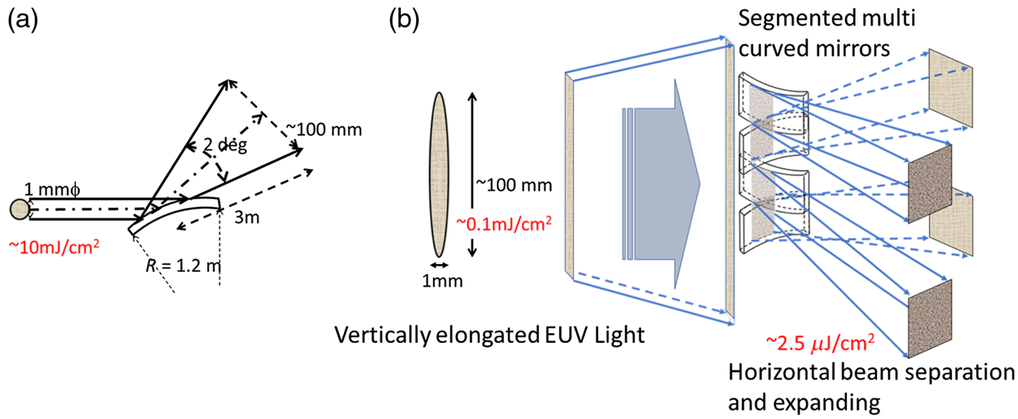

Fig. 7 (a) Horizontal beam expanding using curved grazing mirror, with a bending radius of about 1.2 m, is set as the central glancing angle that is 2.5 deg. (b) Horizontal beam separation and beam expanding are based on an alternative arrangement of the horizontally curved mirrors. Consequently, the original normal incident power density is about 10 $\mathrm{mJ/cm^2}$; however, the final power density can be reduced to about 2.5 $\mu\mathrm{J/cm^2}$.

A preliminary design concept for the optical beamline from the ERL-FEL to the multiscanners is proposed as follows. The concept is based on the two-dimensional beam expanding using horizontal and vertical curved grazing mirror systems. For example, when the curved mirror with a bending radius of about 1.2 m is set as the central glancing angle that is 2.5 deg, it is possible to expand the FEL light up to ~100 mm at the position 3 m away from the mirror as shown in Fig. 7(a). Then the horizontal beam separation and beam expansion can be realized using segmented multicurved mirror systems as shown in Fig. 7(b), which shows a schematic three-dimensional bird's-eye view of the beam separation and expansion. Consequently, the power density of the normal incidence is about 2.5 $\mathrm{mJ/cm^2/pulse}$, which is almost four orders of magnitude smaller than the threshold value of the ablation. After the expansion system of FEL light, collimation mirror systems for both directions will be installed in the beamline to keep the beam size, so these segmented and expanded FEL light beams will lead to the first multilayer mirrors to introduce the light to the corresponding scanners. A similar curved grazing mirror system to distribute FEL light to multiscanners was proposed by Erik Hosler and his group.[28]

5 Effort to Apply to Industry

For industrialization, it is important to make some efforts for cost reduction. In particular, the reduction of construction and operation costs of the accelerator is essential. In this section, we briefly introduce the latest accelerator technologies to be effective for EUV-FEL.

First, we briefly explain why we use an SC RF accelerator and what kind of emerging technologies will be applicable for operational cost-reduction from the viewpoint of cryogenic loss. To accelerate the beam, we need to store the power in the RF cavity. However, stored power is dissipated by the cavity wall. This wall loss (called power loss) is proportional to the surface resistance. We normally use the Q-value, which is inversely proportional to the residual resistance of the cavity surface, to evaluate the cavity performance. An SC RF accelerator of Nb will keep the Q-value to about $>1\times10^{10}$ at 2 K using a normal surface treatment,[29] which reduces the power loss by a factor of 1/1,000,000 at 2 K. Even though we consider the cryogenic efficiency from 2 K to room temperature of about 1000, power consumption due to the surface loss of the SC RF accelerator was reduced by a factor of 1/1000. This is the advantage of using a SC RF cavity to operate in CW mode with a high current beam. Therefore, various large-scale SC accelerators have been constructed and operated especially for x-ray FEL use. The surface treatment technique of the Nb SC cavity has shown drastic progress in the last decade. The reduction of the residual resistance was achieved by a nitrogen-doping (N-doping) treatment, which is one of the cavity surface treatments. The cavity was annealed up to 800°C in the vacuum furnace for heat treatment in the normal surface treatment. On the other hand, for N-doping treatment, nitrogen was injected at 800°C for up to 20 min at 3 Pa vacuum pressure and followed by annealing 800°C for around 30 min. After this N-doping procedure, the N-rich Nb cavity surface was obtained, and the Q-value was increased at least by a factor of 2 at 2 K at a medium field of 15 MV/m.[30–32] Using this technique, we obtained a few times higher Q-value than that of the normal surface treatment. This technique has become well established in recent years.[30–32] Furthermore, another surface treatment, called Mid-T baking, was recently established.[33] This treatment also obtains a few times higher Q-values than usual. These N-doping and Mid-T baking techniques are applicable for our EUV-FEL and reduce the cryogenic operational cost during beam operation to at least half of the original operational cost using the normal surface treatment technique. The Q-values of both N-doping and Mid-T baking around the 12.5 MV/m accelerating field are at least twice as high as that of the normal surface treatment. The new SC cavity made by another alternative material of Nb_3Sn with a higher Tc of 18 K than Nb was developed.[34] The Nb_3Sn cavity gives the same Q-values of 1×10^{10} at 4.2 K with >10 MV/m accelerating gradient. Unfortunately, this is not used for real accelerators now. However, this development has great potential for reducing the cryogenic efficiency and results in the use of a small cryogenic refrigerator, which is beneficial for industrial applications.

Second, the development of an undulator with a simple structure is another candidate for cost reduction. Conventional undulators have a variable mechanism of the magnet array gap to change the radiation wavelength. For the undulators, a strong support mechanism is required to suppress a large mechanical strain caused by changing the gap against the magnetic attraction force between the upper and lower magnet arrays. EUV-FEL does not require the mechanism because it aims to emit light with a single wavelength of 13.5 nm. However, tapering of the undulator magnetic field is required to maximize the FEL output power. To achieve optimal tapering in a simple way, we decided to use a fixed gap undulator with an adjustable phase of the magnet array. The adjustable phase undulator (APU) changes the magnetic field on the beam axis by sliding the magnet array of one side longitudinally while keeping the gap.[35] The change in magnetic force due to the sliding of the magnet array is much smaller than that due to changing the magnet gap. Therefore, it is possible to make an undulator with a simpler mechanical support. The prototype APUs with a fixed gap were already installed in the cERL and successfully operated.[9] An APU helps create a simpler and more cost-effective undulator for industrialization.

Finally, we review the idea of multiturn energy recovery linac. The multiturn energy recovery reduces the length of the main-linac section and results in the reduction of the size of EUV-FEL. The beam is accelerated twice by the same main-linac cavities and the length of the main-linac is reduced by half, which reduces the cost reduction of ERL construction and operational cost of cryogenic loss due to the reduction of SRF accelerators by half. The effort of multiturn energy recovery recently was developed at Cornell University to demonstrate the multiturn energy recovery linac.[36] The beam was accelerated four times and decelerated four times in the same cavities. The commissioning just started with a small beam current of a few nA. However, if the multipass ERL beam operation can be established, and the beam current is successfully increased up to 10 mA, this multipass ERL scheme will reduce the construction size of an EUV-FEL in the future.

6 Beyond EUV

Another important development for much finer patterning is the so-called "beyond EUV" for developing lithography systems based on much shorter wavelengths such as 6.75-nm wavelength or even shorter.[37]

As shown in Eqs. (1) and (2), the wavelength of an FEL light is proportional to $1/E^2$, where E is the energy of the electron beam at the accelerator. Therefore, it is possible to achieve the short wavelength by installing additional SC cavities to get the higher energy of the accelerator. On the other hand, assuming that the quality and current of the electron beam do not change even if the energy increases, the FEL parameter representing the power conversion efficiency from the electron beam to the FEL light decreases in proportional to $1/E$, and the gain length and beam power increase in proportion to E. Although the length of the undulator system required for FEL in beyond EUV increases in proportional to E, the FEL power of beyond EUV can be expected to be equivalent to that of EUV.

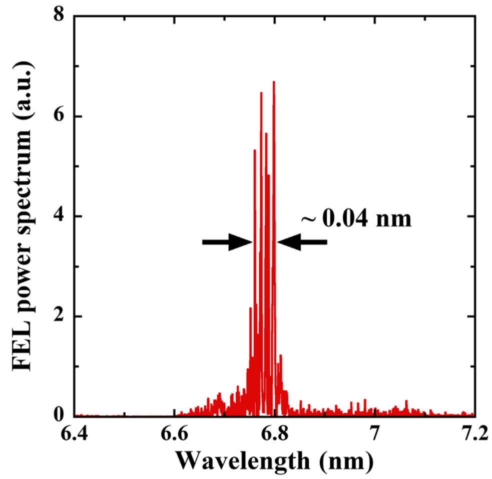

Fig. 8 Wavelength spread of the FEL spectrum at 6.75-nm wavelength. The FWHM is ∼0.04 nm, which is narrow enough to match the acceptance of the multilayer mirror.

Figure 8 shows the FEL spectrum of the wavelength: 6.75 nm when the accelerator energy is $E = 1131\ \text{MeV} = (800 \times \sqrt{2})\text{MeV}$ and the other accelerator parameters are the same as those in Table 1 and Ref. 38. As shown in this figure, the wavelength spread is about 0.04 nm, and this value is slightly less than the width of the acceptance bandwidth of the multilayer reflectivity curve in this wavelength.[39] The expected intensities of the FEL light are 12.7/25.4 kW @ 9.75/19.5 mA (162.5/325 MHz), respectively. Therefore, ERL-FEL is one of the strong candidates for a light source of the beyond EUV lithography systems.

7 Summary

To avoid the stochastic noise, which comes from the shot-noise effect, developing more powerful EUV sources for further fine patterning such as the 3- and 2-nm nodes is necessary. In this article, we described the following subjects. An ERL-FEL design gives us an EUV light source with a high repetition rate (> 100 MHz) and a high-intensity > 10 kW power, so this is one of the most promising candidates for future EUV lithography. If the FEL light is distributed to 10 scanners or more, the initial and running costs of the light source for one scanner will be of the same order or less than that of the presently operated LPP light sources. And the preliminary design concept is presented to distribute the FEL light to multiscanners without any problem of the ablation effect on the optical components. It is important to develop a cost effective and smaller accelerator system for industrial applications. Therefore, the development of a high Q SC cavity to reduce the running cost and a multipass system to minimize the accelerator size has been described. Another further development is the so-called "beyond EUV" system using a much shorter wavelength to achieve much finer patterning. The light source based on the ERL-FEL system is very suitable for this purpose, not only because of the high intense light source but also because of the FEL spectral width, which is narrow enough to match the multilayer optics.

Even though the ERL-FEL is regarded as one of the most suitable candidates for a future high power light source for EUV lithography, there is no such high energy SASE-FEL based on an ERL system. Fortunately, KEK has a test ERL facility called cERL that has started the operation of the midinfrared FEL,[9] and the midinfrared FEL light was observed. This result can be regarded as a principle of concept for EUV-FEL. The other remaining accelerator technologies are a demonstration of a double-pass layout to scale down the accelerator system and the final design of the superconducting cavity for the ERL-FEL machine with electron beam operation.

Another remaining subject is checking the performance of EUV lithography with the coherent light source. Fortunately, this test can be done using operating FEL machines or high brilliant synchrotron radiation facilities. This effort is necessary to get the solutions to solve the problems such as speckle. The full detail of the present article will be included in a book from SPIE Press.[40]

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