COMPACT EUV SOURCE BASED ON LASER COMPTON SCATTERING BETWEEN MICRO-BUNCH ELECTRON BEAM AND CO_2 LASER PULSE

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Abstract

High-power extreme ultra-violet (EUV) sources are required for next generation semiconductor lithography. We start developing a compact EUV source in the spectral range of 13-14 nm, which is based on laser Compton scattering between a 7 MeV micro-bucnhed electron beam and a high intensity CO_2 laser pulse. The electron beam extracted from a DC photocathode gun is micro-bunched using laser modulation techinque with the Compton wavelength at a harmonic of the seeding laser [1] before the main laser Compton scattering for EUV radiation. A considerating scheme for the compact EUV source based on laser Compton scattering with micro-bunched electron beam and the anaritical study of micro-bunch generation are described in this papar. A plan of test experiment generating micro-bunched electron beam will be also introduced in this conference.

INTRODUCTION

The developments of EUV light sources using both laser produced plasma (LPP) and discharge produced plasma (DPP) are currently under way in the world [2]. Using the LPP or the DPP, the EUV light is obtained from high-temperature and high-density plasma. In these EUV sources, the debris problem is most critical issue and it results in reduced lifetime of expensive components and collector mirrors.

As an EUV source based on electron beam, a self-amplified spontaneous emission (SASE) free electron laser (FEL) using superconducting linear accelerators also had been demonstrated in the DUV and EUV spectral range with GW power at DESY[3]. Similarly as a light source that used FEL, various schemes of a seeding FEL such as HGHG have also proposed and demonstrated [4,5]. T. Shintake has proposed laser optical modulation and wavelength compression to generate fully coherent radiation at x-ray wavelength [6,7] However, the SASE and seeding FEL scheme requires large scale (GeV scale) accelerator and a long undulator. On the other hand, one of the promising approaches to intense and short-pulse EUV generation in the spectral range 13-14 nm is the use of a laser synchrotron source (LSS), which is based on laser Compton scattering. Laser Compton scattering between an electron beam and a high-intense laser beam has been investigated as an effective technique for high-brightness short wavelength light generation [8-10]. As other proposal of EUV source, Intel Corp. (M. Goldstein et al.) had proposed a scheme of EUV source using a hybrid optical klystron for micro-bunching and high-gain harmonic generation FEL with laser seeding [1]. This scheme is a combination of pre-bunching and coherent radiation. As other scheme to generate short-wavelength radiation with small equipments, R. Bonifacio have performed theoretical and numerical studies about quantum effect in SASE FEL with laser wiggler and the experimental parameters were specified for both the quantum and the classical regimes [11]. In this paper, we describe the preliminary studies about laser Compton scattering with coherent effect using pre-bunched beam and an experimental plan will be briefly introduced.

EUV SOURCE BASED ON LASER COMPTON SCATTERING

The LSS possesses several advantages, a compactness of instruments, wide energy tunability, a good directivity of the beam and a narrow spectrum, which can be obtained by selecting the scattered angles. The total number of produced photons can be estimated using the product of the cross section (σ_{Comp}) and luminosity (L) which is determined by the scattering geometry of the electron beam and laser pulse. It is difficult to use the laser Compton configuration for a high-power EUV source directly, because of the small cross section of Compton scattering and a small number of photons generated by one collision. We considered to applying a combination of a laser-stacking cavity using CO_2 laser pulse and a low energy ERL for EUV source. In numerical estimation, the photon flux of 10^{14} [photons/2%B.W./sec] in the EUV spectral range can be achieved using this scheme [12]. Huang and Ruth also proposed a compact laser-electron storage ring for x-ray generation in 1997 [13].

Optical Undulator

In laser Compton configuration, an optical undulator is used instead of a magnetic undulator used in the usual configuration of the SASE experiments. For an optical undulator, the radiation wavelength λ_r is

$$\lambda_r = \frac{\lambda_L \cdot (1+a_0{}^2)}{4\gamma^2} \qquad (1)$$

where a_0 is a normalized vector potential, which can be written by $a_0 = 0.85\times\lambda_L[\mu m]\sqrt{I}[W/cm^2]$ (I: laser intensity

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($I = P/(\pi w_0^2)$, P: laser power, w_0: beam radius at waist). The wavelength λ_r differs from the resonance wavelength of conventional FEL by a factor two, since the magnetic undulator period λ_W is replaced by $\lambda_L/2$. We apply a high-power CO_2 laser for laser Compton scattering to generate EUV light and the resonance energy of electron beam is approximately 7MeV. In the optical undulator, the number of photons which one electron emits by an undulator radiation is given by $N_{ph} = (2/3)\pi\alpha N_W K^2(1+K^2)$, where α, N_W, and K are the fine structure constant (1/137), the number of undulator periods and undulator parameter (a_0), respectively [14]. Assuming that K = 0.5 and N_W = 100, one electron approximately radiates 0.5 photons. In order to realize the EUV light source of the 100W output, which corresponds to the EUV flux of 7 x 10^{18} photons/sec, it is estimated that an average beam current of 2 amperes is required. This thing suggests it is difficult to generate enough number of photon for the high power EUV source using the conventional undulator radiation process.

SASE-FEL Process Using Optical Undulator

The essential feature of the high-gain FEL including SASE is that a large number of electrons radiate coherently. In that case, the intensity of the radiation field grows quadratically with the number of electrons: $I_n = n^2 I_1$. A possibility of high-gain FEL using the optical undulator examined as following. FEL parameter (ρ) in one-dimensional model of SASE-FEL is calculated from the parameters of electron beam and laser pulse shown in Table 1. The number of optical undulator periods (N_W) to reach the high-gain regime is in the order of $1/\rho$ and the required length of the optical undulator is $L_W = \lambda_L/\rho$. In the case of radiation wavelength at 13.5 nm, ρ ~9×10^{-6} and L_W ~0.6 m, then a_0 ~0.72 with 500GW of the laser power. The FEL parameter is quite small and L_w is much longer than the Rayleigh range (3mm) of the CO_2 laser. In addition, it is necessary to satisfy the following conditions in 1D SASE-FEL model. There are (a) $\varepsilon < \lambda/4\pi$, (b) $\lambda L_g/4\pi\beta < \varepsilon$ (the gain length smaller than Rayleigh of the radiation), (c) $\sigma_\gamma/\gamma < \rho$, and the condition of the emittance is extremely severe. The condition (a) requires 10^{-8} order of the normalized emittance. A more realistic parameter search will be necessary to apply the high-gain FEL process to laser Compton scheme directly.

LASER COMPTON SCATTERING USING PRE-BUNCHED BEAM

In SASE process, the train of micro-bunches is ultimately formed with a bunch-spacing equal to the wavelength of radiation. The particles within a micro-bunch radiate coherently. We apply a pre-bunched beam for laser Compton scattering in order to enhance the radiation power and to shorten the optical undulator length (Fig. 1). In the case of EUV source, it is necessary to form the micro-bunch with bunch spacing of 13.5 nm or its harmonics. The electron beam is pre-bunched by a seeding laser pulse with bunch spacing at harmonics of the EUV wavelength before the main laser Compton scattering for EUV radiation. A high power laser will be an effective beam density modulation source for the low energy electron beam in order to realize the micro-bunch.

Table 1: Parameters of electron beam and CO_2 laser

Electron beam	
Beam energy	7.2 MeV
Peak current	1 kA
Beam size	50 μm
CO_2 laser	
Wavelength	10.6 μm
Peak power	500GW
Beam size	50 μm

Thermal Energy Spread in Micro-Bunching

The initial energy spread (thermal energy) of electron bunch near a cathode is should be smaller than the modulation energy by the laser, otherwise there is no effect of the laser bunching due to a diffusion in longitudinal direction by the energy spread. A photocathode is better than a thermal cathode, since the thermal energy spread is decided by the cathode temperature. As discussed in Ref. 6, it is not converted into density modulation of electron beam even if we apply the laser modulation on the cathode directly. The diffusion length of electrons having the thermal energy spread on the photocathode is larger than the modulation laser wavelength. For example, we assume the photocathode temperature: 300 K, thermal energy ($E_{th} = kT/2$): 13 meV, a field gradient of DC gun: 10 MV/m (= 200kV/2cm). As for the electrons which have the zero and the thermal energies are extracted from cathode at the same time, only about 11.5μm are different in a longitudinal position around an anode. This thermal diffusion length is longer than the wavelength of IR laser such as CO_2 laser, therefore the effect of energy modulation is disappeared by the thermal diffusion of electrons.

During the energies γ and $\gamma+\Delta\gamma$ of electrons travel in the drift space (L), the longitudinal position of the electrons shifts only Δz, which can be expressed as

$$\Delta z = \frac{L \cdot \Delta\gamma}{\gamma^3 \sqrt{1 - 1/\gamma^2}} . \qquad (2)$$

For the low kinetic energy of electron (small β), there is a possibility that the longitudinal positions of the electrons change due to the small energy difference. Here, we consider about the electron beam extracted from the 100kV DC gun with photocathode. The electron beam

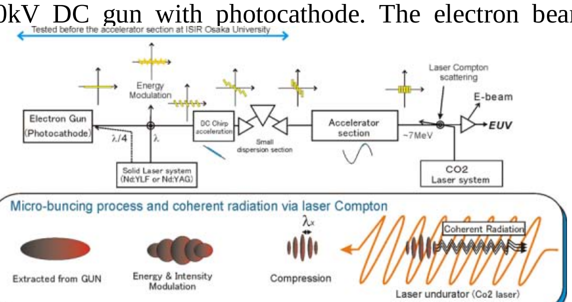

Fig. 1: Schematic drawing of considerating scheme and laser Compton scattering with pre-bunched electron beam.

with thermal energy spread $\Delta\gamma$ (13meV) passing through 1.0m drift space, the Δz is $2.7\mathrm{x}10^{-8}$ m. This value is much shorter than the laser wavelength.

Laser Modulation

Energy of the electron beam is modulated by the electric fields of laser pulse. Energy modulation converts to a charge density modulation passing through drift space or dispersion section. To put the energy modulation on the electron beam efficiently by small laser power, we thought the modulation is applied for the low energy electron beam. Two methods are being examined as the energy modulation. One is a method of using an optical resonator [12,15] and the other using z-direction polarized laser pulse [16]. Here, we examine about the case (A) in Fig. 2. In this scheme, by crossing two laser pulses a standing wave is made at overlap region and electric filed is generated on a parallel with the propagation axis of electron beam. This energy modulation scheme use the same configuration of beam size monitor [15]. We consider using the optical resonator and the pulse stacking technique [17] to realize the high peak field and stable interaction between electron beam and the laser electric field. But mirror alignment and control will be severe since short focusing mirrors are used to make a small waist in the resonator. The laser profile at the waist point is assumed a Gaussian distribution and the electric filed of laser is expressed as

$$E_z(z,t) \;=\; E_z(z,0)\cdot e^{-z^2/2\sigma_W{}^2}\cdot\cos\omega t\,. \qquad (3)$$

The modulation efficiency (M_{ef}) depends on the waste size of the laser, it is given by

$$M_{ef} \;\propto\; e^{-k^2\cdot\sigma_w{}^2/2\beta^2} \qquad (4)$$

where k, σ_w and β are wave number, waist size of the laser and the velocity of electron, respectively. The field gradient generated by the laser can be expressed by $E\,[TV/m] \cong 2.7\times10^{-9}\sqrt{I}$, where I [W/cm^2] is laser intensity at waist. From the Eq. 4, very small beam size of laser is required ($\sigma_W < \lambda_L$) and the large numerical aperture (NA) will be necessary for the focusing (ex. 0.5). It is difficult to satisfy the condition to make small laser waist. The electron beam can be modulated only to partial in this method, because the size of the electron beam is larger than the laser waist ($\sigma_W < \sigma_e$). Besides, the Δz is caused by the laser modulation have to be smaller than $\lambda\beta/2$, which is bunching period of laser modulation. Further study is required for laser modulation.

Beam Test of Laser Modulation at ISIR

We will perform the beam test of the laser modulation to generate the micro-bunch electron beam using 100kV DC gun with Cu photocathode and Nd:YLF laser system as shown in Fig.1 (arrow part). The electron beam with 10 ps (FWHM) is generated using the DC photocathode gun with 4th harmonics of a Nd:YLF laser, and the fundamental laser pulse is used as a seeding laser for the energy modulation. Now, two schemes are considered to be the laser modulation for the micro-bunch generation.

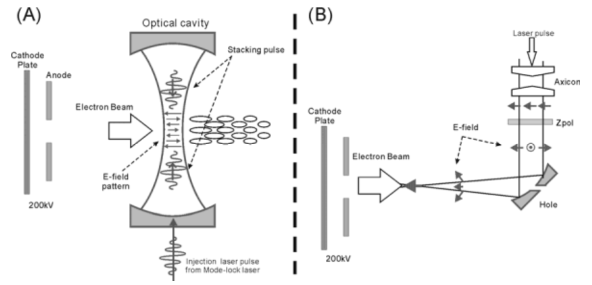

Fig.2: Schematic drawings of laser modulation using (A) optical resonator with focal waist and (B) z-direction polarized laser pulse.

Firstly we will try the method (B) in Fig. 2 using z-direction polarized laser. Diagnostic of micro-bunch beam is important and delicate. We will use a high frequency rf deflector and image intensifier screen. The electron beam is sliced out using metal slit in transverse direction and streaked by transverse magnetic field of the rf deflector. The transverse profile of beam measured using intensifier screen with high resolution. We study about laser modulation using our electron gun system in detail.

SUMMARY

We start to develop the EUV source based on laser Compton scattering. In the preliminary consideration, there were very severe condition for the average current and the emittance of electron beam. In order to enhance the intensity of radiation to use coherent effect, the pre-bunched beam is applied to the laser Compton scheme. The experiment of micro-bunching will be tested using the 100kV DC photocathode gun and Nd:YLF laser. We will continue the numerical study about the micro-bunch generation including space charge in the electron beam and the micro-bunching effect for the laser Compton scattering.

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