Abstract. We report two types of plasma photonic devices using complex refractive index around an absorption edge. Cherenkov radiation using ultra-high intensity laser-produced relativistic electron beam having a Maxwellian distribution is evaluated by theoretical calculation. In the calculation result, this Cherenkov radiation is monochromatic in spite of energy distribution. This monochromaticity is due to characteristic of real part of complex refractive index around an absorption edge. Nonlinear transmission in metal using EUV light pulse is also reported. Transmission becomes nonlinearly higher with increase in energy density of EUV light from 6 J/cm². This nonlinear phenomenon is caused by change of absorption coefficient, that is, imaginary part of complex refractive index.

1. Introduction

Novel plasma photonic devices [1] have been developed to generate and control high energy density particles and radiation. These high energy density beams are expected for applications such as inertial fusion, x-ray generation and laboratory astrophysics. By using characteristics of complex refractive index, novel plasma photonic devices to generate and control x rays and/or EUV light can be realized. Complex refractive index $N$ is described by

$$N = n + i \cdot k.$$  

Here, $n$ and $k$ are real part and imaginary part of complex refractive index. In EUV region, real part $n$ only around absorption edge exceeds 1. Imaginary part $k$ has large difference between shorter wavelength side and longer wavelength side of absorption edge, and absorption coefficient also has large difference.

In this paper, we report extensive study of plasma photonic devices using complex refractive index in EUV region. Two types of plasma photonic device are reported. One is the monochromatic EUV radiation source based on Cherenkov radiation using ultra-high intensity laser-produced relativistic electron beam. For this radiation source, real part of refractive index $n$ exceeding 1 around absorption edge was used. Previously Cherenkov radiation in this region was generated by using monochromatic electron beam provided from an accelerator [2]. We show possibility of use of laser-produced electron beam having an energy distribution. The other is nonlinear transmission in metal.
using focused EUV-FEL (Free Electron Laser) pulse. Observed nonlinear phenomenon indicates that imaginary part of complex refractive index \( k \) around absorption edge is drastically changed. This phenomenon can be applied to novel optics in EUV region such as auto-correlator and x-ray pulse slicer.

2. Monochromatic EUV radiation source

Generally, in x-ray and EUV region, real part of complex refractive index \( n \) is smaller than 1. However, \( n \) exceeds 1 around the absorption edge for some matters. In this area, Cherenkov radiation can be emitted. This radiation is called “X-ray Cherenkov Radiation (XCR)” hereafter. XCR is monochromatic because refractive index exceeding 1 is in a very narrow region. Moreover, XCR has adjustability of wavelength by changing material of emitter.

In the case that an electron propagates linearly in a matter having a real part of complex refractive index \( n \), emission angle \( \theta \) and photon number \( N \) taking into account relativistic effects and absorption in the matter [3] are shown in

\[
\cos \theta = \frac{\gamma}{n \sqrt{\gamma^2 - 1}}
\]

\[
\frac{dN}{d\varepsilon} = \frac{2\pi \alpha}{hc} \left[ 1 - \frac{\left(1 + \frac{E}{E_0}\right)^2}{n^2\left(1 + \frac{E}{E_0}\right)^2 - 1} \right] \int_0^z \exp \left( - \frac{z}{l_{ab} \cos \theta} \right) dz
\]

where \( \gamma \) is Lorentz factor, \( c \) is light speed in vacuum. \( \varepsilon \) and \( \alpha \) are photon energy of XCR and fine structure constant of the matter, respectively. \( z \) is propagation length of electron in the matter. \( E \) is electron energy and \( E_0=0.511 \text{ MeV}, l_{ab} = \frac{hc}{4\pi \alpha k} \) is absorption length. Emitter thickness \( d \) of 10 \( \mu \text{m} \) was used, because absorption length of this XCR is much shorter than 10 \( \mu \text{m} \). High energy density electron beam produced by ultra-high intensity laser has energy distribution. In the calculation, electron slope temperature of 2 MeV, which was derived by using a plasma photonic device [1], is assumed. Divergence angle of electron beam is assumed to be 5°. This divergence angle is realized by

![Figure 1](image-url)

**Figure 1.** Calculation results of XCR emitted from Al. (a) Spectrum. (b) Angular distribution. This XCR has emission peak at 8.0° and 72.2 eV.
using a plasma photonic devices [1].

Figures 1 show calculation result of XCR emitted from aluminium (Al) emitter. This XCR has intensity peak at 72.2 eV and 8.0°. Although photon energy of peak of n at Al L absorption edge is 72.7 eV [4], emission peak shifts to 72.2 eV due to absorption in Al emitter. Figure 1(a) shows spectra dependent on emission angles. In spite of energy distribution of electron beam, XCR is highly monochromatic. Spectral width at peak of angular distribution (8.0°) is 1.2 eV, this corresponds to 1.7% bandwidth. Figure 1(b) shows angular distribution. This XCR has cone-like angular distribution dependent on photon energy.

Luminescence and efficiency of XCR was evaluated. Laser energy of 1 J is assumed, conversion efficiency from laser to electron beam assumed to be 10%. Calculated luminescence is 5x10^{22} photons/mm² mrad² see 0.1% b.w. Efficiency from laser energy to XCR is about 6x10^{-4}. This luminescence is higher than the case with electron beam produced by an accelerator. This XCR can be a compact monochromatic EUV radiation source, because generation of electron slope temperature of 2 MeV is possible with table-top laser system.

3. Nonlinear transmission using focused FEL

Development of free electron lasers (FEL) producing high energy photons are expected to open many new possibilities for science and engineering. One of the interesting studies with these FEL is nonlinear effect in this wavelength region. In the previous study, nonlinear transmission in Al was investigated with 13.5 nm-EUV light pulse [5], and focal spot was evaluated by ex situ observation of irradiated PMMA target [6]. We reported nonlinear transmission in tin. In the experiment we used a new method a using fluorescent material for in situ observation of EUV-FEL focal spot and transmission. This method is very convenient due to use of visible fluorescence.

EUV-FEL provided from XFEL prototype accelerator SCSS in SPring-8 [7] are used. Wavelength was 51 nm with bandwidth of < 1%. Pulse duration is <100 fs. Typical energy at entrance of experimental chamber was 10 μJ/pulse. This EUV pulse was focused by using two same cylindrical mirrors as a Kirkpatrick-Baez (K-B) optics [8]. Tin (Sn) was used as a target material for the saturable absorber. According to reference data [4], Sn has an N-shell edge at 52 nm. A three-layered target was used. The front side of Sn is coated by a thin Au film (thickness: 5 nm) in order to prevent a

Figure 2. (a) Focal spot of EUV-FEL observed with cooled CCD camera. Spot size is 5.6 μm x 4.9 μm. (b) Measured transmission of EUV-FEL in Sn layer (thickness: 80 nm).
contamination oxidation layer. The rear side is attached to a fluorescent material. A fused silica glass (SiO$_2$) was used as a fluorescent material. The band gap energy of the SiO$_2$ is 9.6eV so that in the wavelength range of this study, single photon absorption fluorescence occurs. Intensity and spot image of visible fluorescence were observed with a photomultiplier and a cooled CCD camera, respectively. Incident laser energy was monitored by surface scattered light with an electron multiplier calibrated with pyroelectric detector. The target was moved so that the EUV pulse always hits a fresh surface of the target.

Figure 2(a) shows focal spot of EUV-FEL observed with cooled CCD camera. Spot size of 5.6 $\mu$m x 4.9 $\mu$m was measured by in situ observation of fluorescent image. This focal spot size was kept during the experiment. Incident laser energy density was changed by using a gas attenuator. Before measurement of transmission in Sn layer, an experiment with two-layered target (Au / SiO$_2$) was performed, and it was confirmed that intensity of transmitted VUV light in Au layer is linearly proportional to incident laser energy density. Transmission in Sn layer (thickness: 80 nm) was derived from comparison with fluorescent intensity of two-layered target and that of three-layered target. Figure 3 shows transmission of EUV-FEL in Sn layer dependent on incident laser energy density. When the laser energy density is low, EUV light almost does not transmit in Sn layer. However, transmission becomes nonlinearly higher with increase in laser energy density from 6 J/cm$^2$. Measured transmission is much lower than reference data [4] in which transmission of 51-nm EUV light is 0.15 and that of longer wavelength region is around 0.5. This reason is seemed to be oxidation contamination in target fabrication. Measured transmission at > 6 J/cm$^2$ is 100 times higher than that at < 6 J/cm$^2$. This increase is more drastic than that in reference data. Additional investigation such as pump-probe experiments and calculation of atomic process will clarify details of this nonlinear effect.

4. Summary

We report two types of plasma photonic devices using complex refractive index around an absorption edge. X-ray Cherenkov radiation is an attractive radiation source. Especially, in spite of laser-produced electron having energy distribution, this radiation is monochromatic. Nonlinear transmission in Sn layer was realized using focused EUV-FEL. Fluorescent material was used for in situ measurements. This phenomenon can be applied for auto-correlator and x-ray pulse slicer and so on.

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