DESIGN OF A RESONANT TRANSITION RADIATION SOURCE IN THE SOFT X-RAY RANGE

P. Wang, K. C. Leou, Department of Engineering and System Science, NTHU, Hsinchu, Taiwan
N.Y. Huang, W.K. Lau, A.P. Lee, NSRRC, Hsinchu, Taiwan

Abstract

Resonant transition radiation (RTR) can be generated from multi-layer structures when they are driven by relativistic electron beams. In consideration of using the NSRRC 90 MeV photoinjector as driver, we examined the feasibility of generating narrow-band soft x-rays from various multi-layer structures. Based on analytical theory, the expected angular-spectral distribution and photon yield of these radiators are calculated and compared.

INTRODUCTION

The feasibility of using multi-layer structures for generation of RTR in soft x-ray range is being investigated. We tentatively targeted the radiation energy of these structures centred at 2 keV and 620 eV. Radiation near this photon energy ranges found to be useful in research areas such as imaging of biomolecules, atom and molecular physics. The low-emittance NSRRC photoinjector system will be used to drive such RTR sources. In this system, the MeV electron beam from the laser driven photo-cathode rf gun are accelerated to its maximum energy of 90 MeV. The nominal parameters of the drive beam used in this study are listed in Table 1.

Table 1: Parameters of the Electron Beam Generated From the NSRRC Photoinjector

Beam energy	90 MeV
Emittance	0.8 mm-mrad
Bunch length	2.2 psec
Bunch Charge	100 pC

RESONANT TRANSITION RADIATION

The existence of transition radiation (TR) was predicted by Ginzburg and Frank in 1949[2]. For a charged particle traveling across the boundary between two media of different dielectric constants, the radiation fields can be calculated with classical electromagnetic theory. In the x-ray range, the dielectric constant can be described by Drude model adequately. The angular-spectral distribution of transition radiation from the boundary of two media being excited by a single electron at normal incidence is [3]:

$$\frac{d^2W_{TR}}{d\Omega d\omega} = \frac{e^2}{4\pi^2 c^3}\omega^2 \sin^2(Z_1 - Z_2)^2 \quad (1)$$

where

$$Z_{1(2)} = \frac{4c}{\omega[\gamma^{-2} + \theta^2 + (\omega_{p1(2)}^2 / \omega^2)]} \quad (2)$$

$\omega_{p1(2)}$ is the plasma frequency of material 1 (or 2).

For an N-layer structure which is fabricated by interleaved stacking of material 1 with thickness l_1 and material 2 with thickness l_2, the angular-spectral distribution of RTR can be calculated from the following equation with the phase shift as well as absorption in materials are considered[3, 4]:

$$\left(\frac{d^2W_{TR}}{d\Omega d\omega}\right)_N = \left(\frac{d^2W_{TR}}{d\omega d\Omega}\right)F_1 F_N \quad (3)$$

where the factor F_1 describes the inner-foil resonance such that

$$F_1 = 1 + \exp(-\sigma_1) - 2\exp(-\sigma_1/2)\cos(2\varphi_1) \quad (4)$$

and F_N describes the inter-foil resonance as

$$F_N = \frac{F_{Nn}}{F_{Nd}} \quad (5)$$

$$F_{Nn} = 1 + \exp(-N\sigma) - 2\exp(-N\sigma/2)$$
$$\times \cos[N(2\varphi_1 + 2\varphi_2)]$$

$$F_{Nd} = 1 + \exp(-\sigma) - 2\exp(-\sigma/2)$$
$$\times \cos(2\varphi_1 + 2\varphi_2)$$

where

$$\varphi_{1(2)} = l_{1(2)} / Z_{1(2)},$$

$$\sigma_{1(2)} = \mu_{1(2)}l_{1(2)}, \quad \sigma = \sigma_1 + \sigma_2.$$

$\mu_{1(2)}$ is the x-ray absorption coefficient of material 1(2). From the equations of F_1 and F_N, the resonance conditions of RTR can be obtained.

$$\varphi_1 = (2n-1)\pi/2 \quad (6)$$

$$\varphi_1 + \varphi_2 = m\pi \quad (7)$$

where n and m are integers. F_1 and F_N reach their maximum values when Eq. (6) and (7) are satisfied respectively.

DESIGN OF SOFT X-RAY RADIATORS

Effects of Beam Energy

For an incident electron at a fixed energy, broadband TR with wavelengths ranging from far infrared to hard x-ray is emitted from the interface between different media. Consider the case that material 2 is absent (vacuum), integration of Eq. (1) through 2π solid angle leads to the following equation:

$$\frac{dW}{\hbar d\omega} = \frac{\alpha}{\pi}\left\{\left[1 + 2\left(\frac{\hbar\omega}{\gamma\hbar\omega_p}\right)^2\right]\ln\left[1 + \left(\frac{\gamma\hbar\omega_p}{\hbar\omega}\right)^2\right] - 2\right\}$$

where α is the fine structure constant. One can easily observe from the above expression that the photon flux drops significantly with frequency goes beyond $\hbar\omega/\gamma\hbar\omega_p \approx 1$. Electronic plasma frequencies $\hbar\omega_p$ of common solid materials are about few tens of eV. For example, the plasma frequency of aluminum is 32.8 eV. To generate radiation at 2 keV photon energy, the Lorentz factor γ of the incident beam have to be greater than ~60. On the other hand, the emission angle is of the order of γ^{-1} which is also determined by the beam energy. This can be verified also by Eq. (1).

Selection of Materials

When the electron beam energy is chosen, the emission characteristics of RTR is determined by the geometry of the multi-layer structure and the materials to be used. Two types of radiator structures are considered for evaluation. Namely, structures with interleaved stack of foils with two different materials (Type A) as well as structures that made of equally spaced thin foils in vacuum (Type B).

Angular distributions of TR from a single boundary of the two types are compared and shown in Fig. 1. Beam parameters listed Table 1 is assumed in these calculations. As shown in Fig. 1 (a), angular distributions of radiation from a single boundary of Type B radiator (Mo-vacuum in this case) at 620 eV and 2 keV photon energies are very similar and both peaked at ~5 mrad as expected. However, for Type A boundary that consist of two different materials (Mo-C), emission angles are shifted outward and the angular distributions of radiation spread out. It is especially severe at low photon energy. As can be seen from Fig. 1(b), the 620 eV curve (blue line) spreads much wider than the case at 2 keV (red curve). Large angular spread is unfavorable because photon flux into a specific solid angle is very much reduced. In the 2 keV case of Fig. 1(b), the angular spread is still larger than the case of Type B boundary. The angular spreads are originated from the difference term of Z_1 and Z_2 in Eq. (1)

which is frequency dependent. Although Type B radiators have better emission characteristics than Type A, fabrication of these radiators is more complicated. It is found that a Type A structure formed by two materials having large discrepancy in density generate more TR photons from the boundary than those with little difference in density. However, higher density materials usually have higher x-ray absorption.
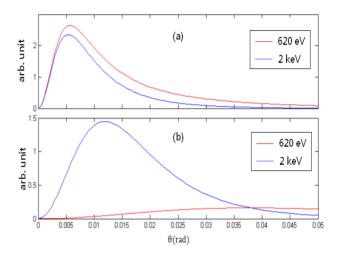

Figure 1: Angular distribution of TR when a 90 MeV electron normally incident unto (a) a Type B structure (Mo-vacuum), (b) a Type A structure (Mo-C).

Thickness of Layers

The angular-spectral distribution of RTR described in Eq. (3) is a product of the angular-spectral distribution of TR from a single layer, the inner-foil resonance function F_1 and the inter-foil resonance function F_N. Fig. 2 depicts the single-layer TR spectrum, F_1, F_N and multi-layer RTR spectrum at 5 mrad when the radiator is designed to have centre photon energy at 2 keV. When there is only one boundary, the TR spectrum shown in Fig. 2(a) is broad. The RTR radiator in this case has 11 periods such that each of these periods is formed by a 626 nm thick molybdenum film and 2.34 μm carbon film. The functions F_1 and F_N in Fig. 2(b) and (c) have resonance peaks at 2 keV with this geometry and $F_1 \times F_N$ represents constructive interference at 2keV. As a result, the spectrum of RTR shown in Fig. 2 (d) has narrow-band spectrum centred at 2 keV. Integration of angular-spectral distribution of radiation power (normalized to photon energy) from 0 to 10 mrad and from 1 to 3 keV and gives photon yield of about 0.05 photons per electron. This means that we can have $\sim 3 \times 10^7$ photons per 100 pC bunch from the 90 MeV NSRRC photoinjector.

Fig. 3 shows the spectral distribution of RTR centred at 620 eV and at 5 mrad. The radiator is composed of 12 equally spaced 218 nm Ni films in vacuum and the space between films is 34.92 μm. Photon yield in this case is about 1 photon per electron in the energy range from 320 eV to 920 eV.
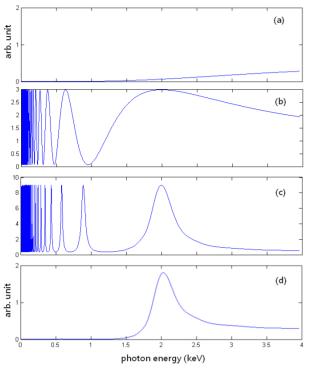
Figure 2: Spectral distribution of (a) single-layer TR. (b) F_1 (c) F_N (d) RTR from radiator.
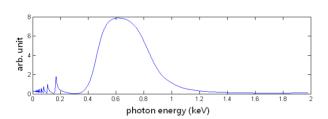

Figure 3: Spectral distribution of RTR centreed at 620 eV (2 nm in wavelength).

Number of Periods

Fig. 4 plots the photon yield as a function of period number N for the Type A radiator in Fig. 2. The photon yield will not increase with number of periods N indefinitely because of the x-ray absorption in materials.
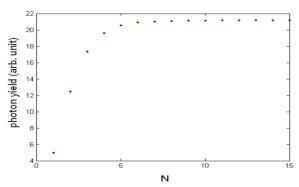

Figure 4: Photon yield with different number of periods N.

Number of Periods vs. Bandwidth

If absorption in materials is neglected, the bandwidth of resonant peak is inversely proportional to N. However, x-ray absorption in materials limits the reduction of radiation bandwidth at larger N. Fig. 5 shows the difference in radiation spectra with and without the absorption for the Type A radiator described in Fig. 2.
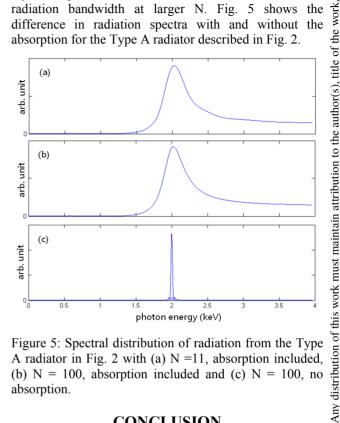

Figure 5: Spectral distribution of radiation from the Type A radiator in Fig. 2 with (a) N =11, absorption included, (b) N = 100, absorption included and (c) N = 100, no absorption.

CONCLUSION

Multi-layer structures for generation of narrow-band soft x-ray RTR at 2 keV as well as 620 eV are studied. Angular-spectral distribution of radiation and photon yield from various radiator configurations when excited by a single electron are calculated. It is found the photon yield will in general be saturated as the number of periods increases when x-ray absorption in materials is taken into account. Bandwidth of the radiation does not improve as the number of periods increases. Type B radiators have higher photon yields and smaller radiation divergence angles. The fabrication process for multi-layer radiators and the effect of beam emittance on emission characteristic will also be studied in the near future.

REFERENCES

[1] Yamada, K., Hosokawa, T., Takenaka, H., et al. Phys. Rev. A 59,3673 (1999)

[2] V.L. Ginzburg and I.M. Frank, Sov. Phys. JETP 16, 15 (1946)

[3] Alexander Petrovish Potylitsyn, "*Electromagnetic Radiation of Electrons in Periodic Structures*", Springer (2011)

[4] M. J. Moran, B. A. Dahling, P. J. Ebert, M. A. Piestrup, B. L. Berman, and J. O. Kephart, Phys. Rev. Lett. 57, 1223 (1986).