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Compact X-ray source using electron linac and multilayer target with ultra-short period

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Abstract

Resonant Transition Radiation (RTR) is one the candidates for compact and tunable light sources in the region from VUV to X-ray. However, the single-mode RTR, which provides a fine tunability, has not been observed because of the difficulty of manufacturing stacked targets with narrow spacings. In this work, by using a multilayer target with submicrometer period, X-rays of single-mode RTR were generated and measured successfully. The measured X-ray spectra agree well with the theoretical estimations. This success in generating single-mode RTR shows a promising feasibility of RTR as a next-generation compact X-ray source.

1 Introduction

Transition radiation (TR) is emitted when high-energy electrons pass through the interface between materials with different dielectric constants [1]. The radiation has potential as a compact X-ray source because the electron energy necessary to emit X-rays in TR is far lower than that in synchrotron radiation (SR) and the photon yield of TR per electron is far larger than that of SR. The forward collimation within an radiation cone of $1/\gamma$ radians, where γ is the Lorentz factor, is also an advantage of TR.

TR from only one interface, however, does not have sufficient characteristics in terms of monochromaticity, intensity and tunability, which are necessary for a future X-ray source. These characteristics can be improved by using a periodic interface structure, which gives a strong resonance effect[2, 3, 4]. Such a resonated TR is called resonant transition radiation (RTR). The schematic of RTR is shown in Fig. 1

Especially, single-mode resonance of TR (SMRTR) shows superior monochromaticity and tunability[5, 6]. In most of the conventional experiments, however, SMRTR was not observed well because of the difficulty in manufacturing a stacked target with very narrow spacings.

In this work, therefore, we propose a multilayer Ni/C target with submicron periodicity and confirm the generation of SMRTR. We also show, in this work, some proposals and estimations for compact X-ray sources using SMRTR.

2 Experiment

2.1 Multilayer target

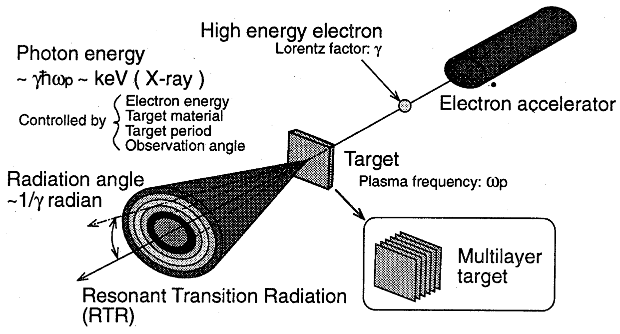

Fig. 1 Schematic of RTR.

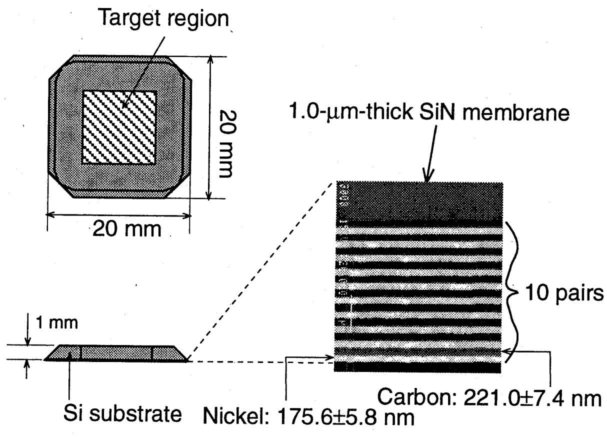

Fig. 2 Ni/C multilayer target.

To realize a target with submicron spacings, we make use of a technique for multilayer structure. The target consists of 180-nm-thick Ni radiator layers and 220-nm-thick carbon spacer layers. These are alternately deposited by RF magnetron sputtering on a SiN membrane. The structure of the target is shown in Fig. 2. We selected Ni for the radiator material because of its high TR yield and its transparency to keV-region X-rays. We selected carbon for the spacers because of its high X-ray transparency. The thickness of these layers are such that 15-MeV electrons emit photons with an energy of a few keV. Calculated X-ray spectra for various observation angles are shown in Fig. 3.

2.2 Apparatus

The experimental system is located at the NTT SR facility. The electron source is the 15-MeV LINAC for the SR injector [7]. A schematic of the system is shown in Fig. 4.

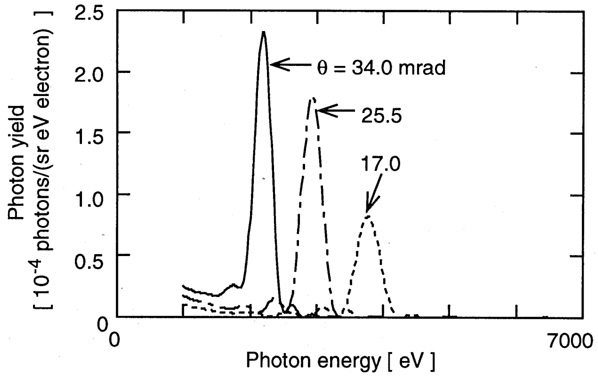

Fig. 3 Calculated RTR spectra for various observation angles.

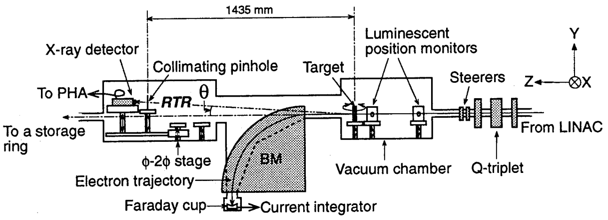

Fig. 4 Apparatus for RTR measurement.

The electron beams are focused by the Q-triplet, and are guided to the target. Since the electrons pass through the membrane before reaching the Ni/C part, the membrane has a negligible effect on the radiation. The electrons that pass through the target are bent by the bending magnet, and guided to the Faraday cup for beam charge measurement. The RTR passes through a 1 mmϕ collimating pinhole, and is detected by a Si photodiode detector connected to a pulse-height analyzer [8]. The distance from the target to the pinhole is 1435 mm. For soft X-ray and VUV measurement, all pieces of equipment except the magnets are placed in a vacuum. To eliminate pile-up, the electron charge per beam pulse should be low, i.e., 0.5 pC. The beam divergence and size are set so as to allow the measurement of the resonant effect.

2.3 Results

A target with ten pairs of Ni/C layers was normally bombarded by 15-MeV electrons. Figures 5(a) and 5(b) show the measured X-ray spectra for observation angles of 17, 25.5 mrads with respect to the beam trajectory. These angles coincide with $0.5/\gamma$ and $0.75/\gamma$, respectively. The dotted lines are calculated yields, which include the effects of the degradation of RTR spectra. The degradation originates from the effects of the divergence and size of the electron beam, measurement geometry, absorption in the detector window, and the energy resolution of the detector.

Each measured spectrum has a single peak between 2 and 4 keV, and the peak energy varies with observation angles. Theoretical simulations show a good agreement with the measured spectra. The difference in the absolute yield between the calculation and measurement is mainly due to pile-up. This is confirmed by the fact that an experiment performed with lower charge pulses resulted in an increase in the absolute yield.

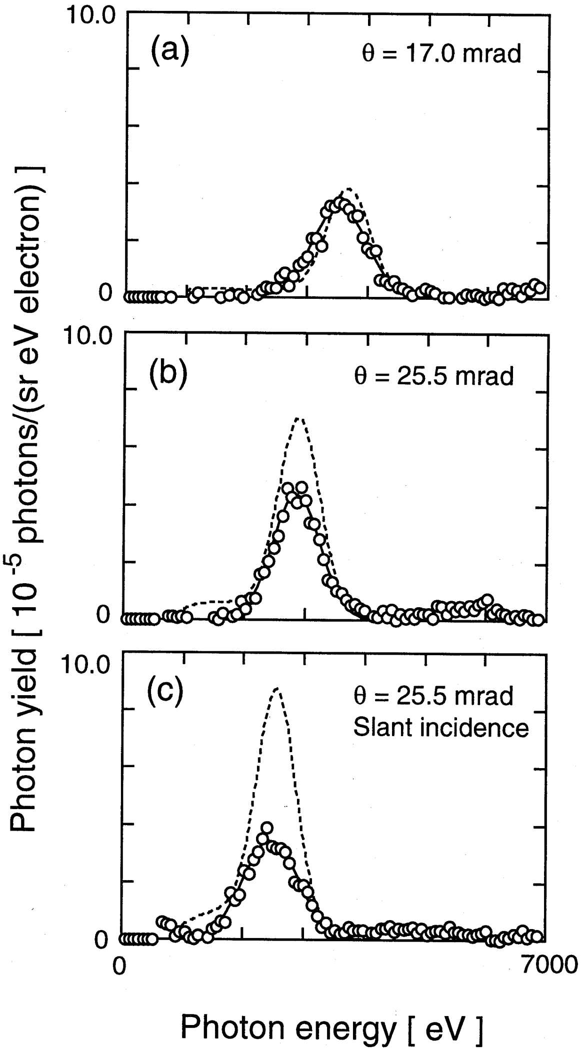

Fig. 5 Measured RTR spectra.

We also observed the spectrum at an incident angle of 65 degrees by rotating the target stage at the observation angle of 25.5 mrad. In this case, electrons see the period of target thicker than in the normal incidence; therefore, the peak energy of X-ray should be reduced. The measured spectrum is shown in Fig. 5(c). The peak energy of spectrum at slant incidence is lower than that in normal incidence. The peak shift of about 390 eV is close to the theoretical estimation.

3 Applications as compact X-ray sources

3.1 Short pulse X-ray source

The pulse length of RTR X-ray is mainly determined by the length of electron beams, and not sensitive to the target thickness because the emission is the result of the interference effect. Therefore, recently-developed sub-pico second electron beams can generate ultra-short X-ray pulses. LINAC-based Compton back-scattering using short-pulse LASERs can also generate such short X-ray pulses; however, the method has serious difficulties in jitters and alignments. On the contrary, RTR X-ray source is free from these problems; therefore, RTR is the most simple and practical method giving short pulse X-rays.

3.2 Tunable X-ray source

One of the advantage of SMRTR X-ray source is the tunability. The schematic of a tunable light source is shown in Fig. 6. Rotating the target and changing the incident angle are the most simple method giving tunability. Extracting a certain emission angle by using a cylindrical mirror and a pin-hole can also change X-ray energy. For fine monochromaticity, it is noticed that the divergence of the electron beams should be far smaller than the angle of radiation cone; $1/\gamma$.

3.3 Hard X-ray source

It is also an great advantage of RTR that the electron energy necessary to emit hard X-rays in RTR is far lower than that in SR. An example of calculated hard X-ray yield per unit beam current within a 10-mrad observation angle is shown in Fig. 7. In this calculation, 150-MeV electrons and Ni/C target are assumed. As shown in this figure, photon yield of RTR is far larger than that of SR from 1.5-GeV electrons and is comparable to that of SR from 3-GeV electrons.

4 Summary

By using Ni/C multilayer target, the single-mode RTR in soft X-ray region was successfully generated, and the spectra of this radiation were precisely measured. We also confirmed the monochromaticity and tunability of RTR. These results show a promising feasibility of RTR as a next-generation compact X-ray source.

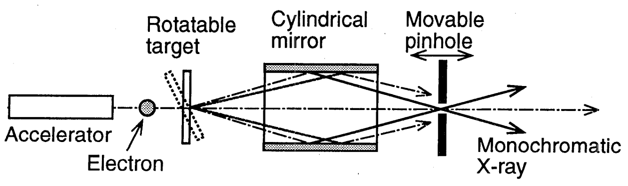

Fig. 6 An example of tunable X-ray source.

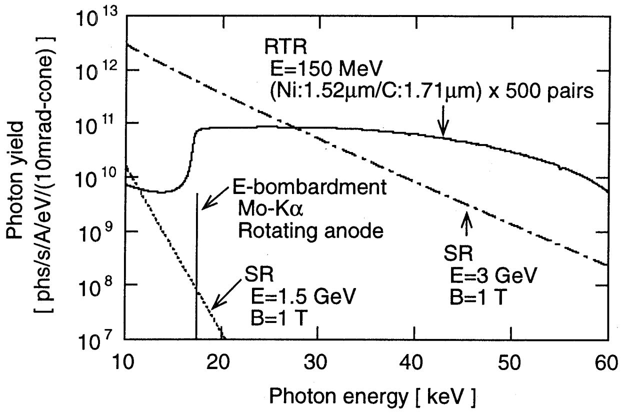

Fig. 7 Hard X-ray emission of RTR.

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