Development of high-repetition-rate X-ray chopper system for time-resolved measurements with synchrotron radiation

Hitoshi Osawa*, Togo Kudo, and Shigeru Kimura

Japan Synchrotron Radiation Research Institute, Sayo, Hyogo 679-5198, Japan

*E-mail: hitoshio@spring8.or.jp

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A high-repetition-rate X-ray chopper system has been developed for pump–probe time-resolved measurements with synchrotron radiation. This system has a rotating disc with 108 or 54 grooves (X-ray path on the disc) that provides an opening time of 1.17 or 0.52 µs with a rotating speed of 28,997 rpm. Also, this system could select single-pulse X-rays every 4 or 8 periods of the several-bunch structure operated at SPring-8, corresponding to an X-ray pulse frequency of 52.2 or 26.1 kHz, respectively, and is suitable for pump–probe studies of electronic devices such as next-generation memory devices. © 2017 The Japan Society of Applied Physics

A pump–probe time-resolved measurement uses pulses of synchrotron radiation (SR) as a measurement technique that can achieve time resolutions equal to the single-pulse width of SR. To perform pump–probe time-resolved measurements, it is necessary to match the frequency of pump (stimulation to the sample) pulses and that of probe pulses. Because the frequency of SR pulses is usually much higher than that of pump pulses, it is necessary to take out the required pulses from whole SR pulses. As a means of taking out X-ray pulses, X-ray choppers have been adopted at many SR facilities.1–8 Using X-ray choppers, there is the advantage that a good time resolution is not necessary for the detector in experiments. However, the repetition frequency of the X-ray single pulse obtained using an X-ray chopper is not very high, e.g., that installed in SPring-8 was limited to 3 kHz.2,3 On the other hand, for studies of electronic devices, e.g., next-generation memory, ferroelectric, and power electronic devices, electrical stimulation at rates of more than several 10 kHz is preferred. To meet this demand, we have developed such a high-repetition-rate X-ray chopper.

High-repetition-rate X-ray choppers can be realized by X-ray diffraction.8 However, this results in changes in the X-ray direction and position. By contrast, blocking the X-rays except at specific times does not affect these properties and is the approach used here. Figure 1 shows three typical types of X-ray chopper.1–2,4,8 Type A, with a rotating slotted disc, is similar to standard optical choppers. The motor axis is parallel to the X-ray beam and this type is referred to as the “parallel type”. In contrast, the triangular chopper B rotates about an axis perpendicular to the beam, and is referred to as the “perpendicular type”. For both A and B, each slit transmits one X-ray pulse each revolution. The perpendicular type blocks the X-rays at both the entrance and the exit; thus, for the same rotational speed and radius, it offers half the temporal width of the parallel type.

The chopping method that we adopted for our high-repetition-rate X-ray choppers described here is of type C. Similar to type B, the axis of rotation is perpendicular to the beam, offering the advantage of short opening time. The chopper is disc-shaped, similar to type A, but rather than using slits, the X-rays pass through grooves cut along radial lines on the surface of the disc. Since the X-rays pass through the center of the disc, this design offers twice the chopping repetition rate of types A and B for the same rotating speed. Furthermore, the grooved design has a low fabrication cost, and is well-suited to high chopping frequency applications that require a large number of grooves.

Figure 2(a) shows a photograph of the chopper apparatus that we developed. The upper part is the chopper disc housing that maintains a vacuum condition to reduce the friction of the chopper disc, and the lower part is the motor housing. The air-spindle motor system based on a brushless frameless DC servomotor (ShinMaywa Industries SPM30) is employed for rotating the chopper disc. The speed and phase of the motor rotation are controlled by a phase-locked loop circuit and a linear amplifier synchronizes the SPring-8 master RF signal as shown in Fig. 3.

Figure 2(b) shows a photograph of the chopper disc. The X-rays pass through grooves in the 140-mm-diameter disc. To allow high rotation speeds the disc must be light; thus, suitable materials for it are aluminum and titanium. To allow the use of the disc at X-ray energies of up to 30 keV, titanium was chosen. Figure 4(a) shows groove structures on the disc. We fabricated two types of groove with different widths and depth structures, labeled A and B. 54 pairs of grooves A and B are alternately installed in the circumference of the chopper.

Fig. 1. (Color online) Three typical X-ray chopping methods.
A precise design of each groove is shown in Fig. 4(b). Groove A has a single depth structure with a width of 250 µm and a depth of 500 µm. In contrast, groove B has a two-step depth structure; upper grooves are 250 µm wide and 1 mm deep, and bottom grooves are 110 µm wide and 500 µm deep, as shown in Fig. 4(b). When the disc is rotated at a speed of 28,997 rpm, which is synchronized to the SPring-8 master RF frequency, the 250-µm-wide grooves open an opening time of 1.17 µs, and the 110-µm-wide grooves open an opening time of 0.52 µs. These opening times allow the selection of single bunches in the “1 bunch + 1/7 filling”, “5 bunches + 1/7 filling”, and “12 bunches + 1/14 filling” modes, which are three of the electron filling modes usually operated at SPring-8. The different depths provide two different chopping frequencies. Using the upper 500-µm-deep zone [zone 1 in Fig. 4(b)], both grooves A and B transmit X-rays, giving a chopping frequency of 52.2 kHz (once every four full passes of the SPring-8 bunch structure). Using zones deeper than 500 µm (zones 2 and 3), only groove B transmits X-rays, giving a chopping frequency of 26.1 kHz (once every eight full passes of the bunch structure).

The performance of the developed chopper system was investigated at the BL13XU of SPring-8, using a 12.4 keV X-ray beam with a size of 250 µm (horizontal) × 400 µm (vertical). The transmitted X-ray beam from the chopper was irradiated onto a copper plate, and scattered and fluorescence X-rays were detected using an avalanche photodiode system (Scientex APD210X). Figure 5 shows the results of operating the chopper in the “5 bunches + 1/7 filling” mode. The time spectrum was collected by the mulch channel scaler (Ortec 9353). Figure 5(a) shows the time structure of X-ray pulses obtained without using the chopper. The bunch structure consists of five isolated single bunches (3 mA), and a multibunch portion increases the total stored current to 100 mA. Figure 5(b) shows the results obtained using zone 1 [Fig. 4(b)] of the chopper to select single-bunch X-rays every four periods. It is clear that all other pulses are effectively blocked by the chopper. Figure 5(c) shows the results of using zone 2; single bunch X-rays are transmitted every 8 periods. The ratio of the selected pulses to the
suppressed pulses is around 1 : 5,000,000, which is sufficient for many time-resolved measurement techniques.

Figure 6 shows the results of operating the chopper in the “12 bunches + 1/14 filling” mode. Figure 6(a) shows the time structure of X-ray pulses obtained without the chopper, and Figs. 6(b) and 6(c) show the results of chopping using zones 2 and 3 [Fig. 4(b)]. In this bunch mode, only using zone 3 can isolate one single bunch from SPring-8, because the groove width of zone 3 is below half of those of the other zones.

We developed an X-ray beam chopper suitable for pump–probe studies of electronic devices. It can select a single pulse every four or eight periods of the bunch structure operated at SPring-8. A high-repetition-rate chopper can increase the utilization efficiency of SR pulses. This enables time-resolved measurements using bending-magnet beamlines, with a flux density much lower than that of an undulator beamline.10,11)

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