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Development of an electromagnetic phase shifter using a pair of cut-core coils for a cross undulator

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ABSTRACT

This paper describes the development of a phase shifter that can be used in cross undulators for fast polarization switching. The phase shifter is composed of a pair of cut-core coils and a thin-walled stainless steel duct. Evaluation of the magnetic fields of the phase shifter indicates that the switching frequency of this simple and low-cost device can exceed 30 Hz.

Soft X-ray experiments based on light polarization properties, such as circular dichroism or ellipsometry, have played a significant role in probing of the electronic and magnetic states of matter. Recently, there has been growing worldwide interest in, and demand for, polarization-controlled soft X-ray sources. The cross or crossed undulator, which was proposed by Kim [1], is one such synchrotron radiation light source, but it differs from the well-known APPLE-II-type undulator and the elliptically polarized undulator, which regulate the light polarization directly via the trajectory of the electron beam [2,3]. Polarization control in a cross undulator is based on the interference of the horizontal and vertical linear radiation fields generated by two adjacent undulators set in a crossed configuration [1,4]. A phase shifter located between the undulators is used to delay the electron motion and thus control the final polarization state, which can take the form of circular, elliptical or tilted linear polarization. The performance of a cross undulator using two undulator segments was examined by BESSY [5]. User operation of an advanced cross undulator, the segmented cross undulator, which is composed of eight segments [6,7], has recently been carried out at the SPring-8 beamline BL07LSU. Installation of a cross undulator in a newly constructed synchrotron radiation facility [8] is also being considered. Additionally, Kim [9] has also proposed the use of the cross undulator to generate arbitrarily polarized light in X-ray free electron laser (XFEL) sources, and a number of researchers have already investigated the performance of the cross undulator and have considered possible upgrades [10–15].

The most important technical element in a cross undulator is the phase shifter, which creates a well-defined magnetic field to regulate the motion of passing electrons. Phase shifters using permanent magnets have already been used for cross undulators at synchrotron radiation facilities [16,6]. However, a cross undulator works most effectively when the polarization control is associated with fast switching. This feature has led to extensive application of the lock-in amplifier technique to existing soft X-ray polarization experiments and guarantees high sensitivity signal detection for use in the study of, for example, extremely diluted elements in a material. The magnetic field in a phase shifter should therefore be produced using an electromagnetic coil [17]. While Kim [1] proposed that the switching frequency could ideally be as high as 1 kHz, the switching frequency of the actual device depends on a number of factors, including the performance of the accelerators, device stability, and cost. There is therefore strong demand for the development of an AC-switching phase shifter to establish fast polarization switching for synchrotron radiation and free-electron laser sources.

In this research, we have constructed a phase shifter for a cross undulator by combining a pair of cut-core coils with a thin-walled vacuum duct. Because the integrated magnetic field of the phase shifter must be zero, the adoption of a cut-core coil is completely rational. This is because a cut-core coil generates a completely closed magnetic circuit, meaning that the integrated magnetic field

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applied to the passing electron is, in principle, zero. Additionally, cut-core magnets can be found cheaply, and the construction cost can thus be low. From the results of performance tests based on inductive voltage measurements, it is likely that cross undulator switching can be performed at frequencies of more than 30 Hz in the SPring-8 storage ring. This frequency exceeds the polarization switching frequency of the kicker-type soft X-ray undulator or the electromagnetic variably polarizing undulator for synchrotron radiation [18–24] and is almost equivalent to the frequency of the XFEL pulses [25–31].

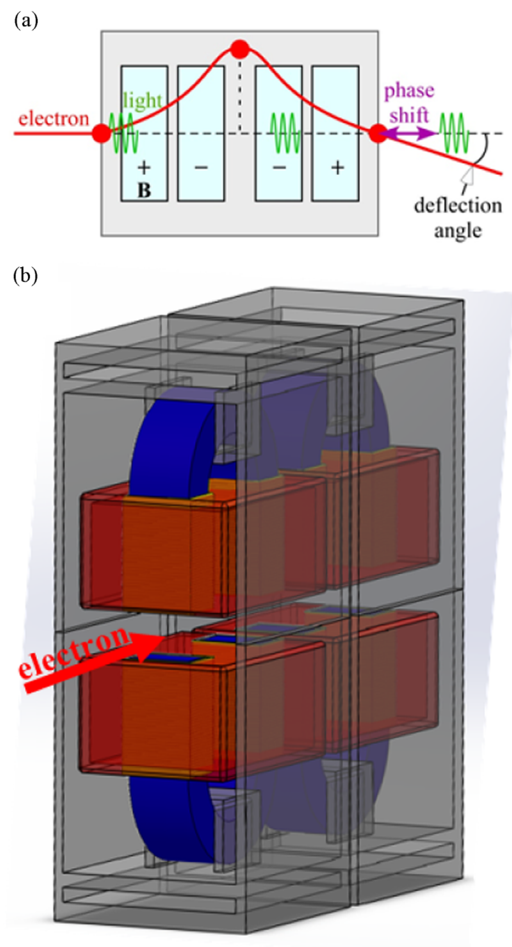

Fig. 1. (a) The principle of the phase shifter using the cut-core coil pair. (b) Three-dimensional image of the mechanical design.

Fig. 1(a) shows a schematic drawing of the principle of the proposed phase shifter. The magnetic circuit is constructed using a pair of cut-core coils. In the figure, the relative directions of the magnetic fields generated by the cross section surfaces of the magnets are indicated. The two pairs of cut-core magnets have field directions that are opposite to each other and the integral magnetic field applied to passing electrons is thus fundamentally zero. Using the light wave as the reference in the figure, a passing electron is delayed by following the additional path induced by the magnetic field, and the difference corresponds to a "phase shift". In the ideal case, the electron motion when it exits the phase shifter must be the same as that before it enters the phase shifter. However, in reality, the magnetic field in a phase shifter may not be fully compensated because of structural misalignment of the magnets or the different variabilities of the individual magnet components. Consequently, the electron trajectory after passing through a phase shifter can be accompanied by a deflection angle. Thus, mechanical optimization and evaluation of the magnetic field are required before phase shifter installation in the accelerator system to ensure that the disturbance of the electron beam is negligible. Fig. 1(b) shows a transparent three-dimensional image of the phase shifter that was designed during the present research. As described above, the phase shifter is composed of two cut-core magnets. Each cut-core magnet is composed of a U-shaped magnetic yoke rolled with an electromagnetic coil, and the magnet assembly is mechanically fixed at the support. The complementary section is placed at a different height and the cross-sections of the pair face each other.

Fig. 2 shows photographs of the phase shifter constructed using a pair of cut-core coils in the present research. The iron yoke is rolled with 25-micron-thick amorphous iron foil. This thin foil ensures good performance at high operating frequencies. Taking the stacking factor due to the interlayer plastic into account, the

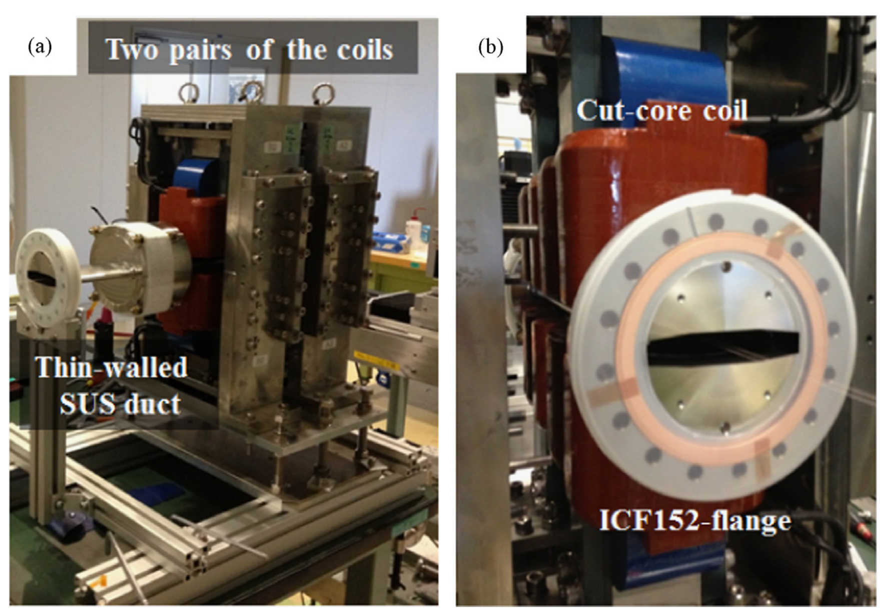

Fig. 2. Photographs of the phase shifter installation for SPring-8 BL07LSU. (a) Photograph of the thin-walled stainless steel duct that is set between pairs of cut-core coils. The duct is also combined with an ultra-high vacuum (UHV) flange (ICF152 flange), a straight duct section for the permanent magnet phase shifter, and a bellows duct section. (b) Photograph showing the area around the UHV flange, taken on the opposite side from (a).