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Novel fast-arrayed CCD X-ray detector using interline transfer-type CCD for time-resolved X-ray diffraction measurements

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Abstract

A novel fast-arrayed fiber-optic taper (FOT) coupled with a charge-coupled device (CCD) X-ray detector was developed. The interline transfer-type CCDs are used as image sensor. The detector was developed for the simultaneous time-resolved small- and wide-angle X-ray diffraction measurement at SPring-8 BL45XU. The detector consists of an array of two identical units, each comprising a phosphor, a demagnifying FOT, and a large format interline transfer-type CCD as an image sensor. The image stored in the CCD can be read out through the dual readout channels with 12 bits ADC within 220 ms (4.5 fps) without binning and within 65 ms (15 fps) with 8×8 binning. Moreover, this detector does not need to stop the incoming X-rays during the CCD readout and can simultaneously execute both exposure and readout on the CCD with a small dead time of $\sim$1 μs so that a duty-cycle ratio of almost 100% is achieved. Therefore, it allows the continuous rotation method. The basic performance characteristics of the detector are described.

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Keywords: Fiber-optic taper (FOT); Charge-coupled device (CCD); X-ray detector; Calibration; Time-resolved measurement; Wide-angle X-ray diffraction (WAXD)

1. Introduction

The arrayed fiber-optic taper (FOT) coupled with a charge-coupled device (CCD) X-ray detector (FOT-CCD X-ray detector) is widely used in both synchrotron macromolecular crystallography and X-ray scattering experiments [1]. In such applications, the FOT-CCD X-ray detector should have a large size of active area, a high resolution, a high rate of duty cycle, capability for time-resolved measurement, and high sensitivity. In particular, the time-resolved measurement capability is indispensable for applications to soft condensed matters such as polymers, surfactants, lipids, and liquid crystals. While designing an FOT-CCD X-ray detector, there are several points that should be considered.

First, the size of the active area and sensitivity are important in the detector design. Several research groups [2,3] and companies [4] have developed the detectors comprising arrays of FOTs and CCDs. Since the CCD size is typically limited to 10–50 mm per side, it is not easy for us to build a FOT-CCD X-ray detector that provides both a large active area and high sensitivity.

Second, with regard to the duty-cycle ratio and time-resolved measurement capability, the readout time of the CCD is also one of the important factors. There are three types of readout schemes available for full-frame transfer, frame transfer, and interline transfer. The full-frame transfer-type CCD (FFT-type CCD) is widely used in FOT-CCD X-ray detectors such as in the commercially available ones [4]. However, the FOT-CCD X-ray

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detectors, that use the FFT-type CCD must stop the incident X-rays during the CCD readout. Therefore, the duty-cycle ratio, defined as the ratio of the exposure time to the readout time, is below 100%. On the other hand, the FOT-CCD X-ray detectors that comprise the frame transfer-type CCD [5] or the framing-mode CCD [6,7] have a duty-cycle ratio of almost 100% due to the small dead time between recorded frames, and need to reduce the spatial resolution and active area size for faster readout. As the third choice, the interline transfer-type CCD (IL-type CCD) can be considered. This is widely used in commercial products such as digital video cameras and in machine vision applications; however, a FOT-CCD X-ray detector using an IL-type CCD has not yet been manufactured. In general, the surface structure of an IL-type CCD is more complicated than that of the FFT-CCD. Therefore, it is difficult to attach the FOT to an IL-type CCD. Moreover, the sizes of IL-type CCDs are reduced in commercial products. At the beginning of the 21st century, the development of large-format IL-type CCD, with over 10 million pixels had commenced for a high-performance digital still camera. Therefore, large-format CCDs became commercially available. The increase in the CCD size can reduce the demagnification ratio of the FOT, which also results in an increase in the sensitivity.

Our primary aim was to design a detector for measuring weak X-ray intensities, particularly for time-resolved wide-angle X-ray diffraction (WAXD) measurements from soft condensed matters [8]. Moreover, we attempted to increase the data collection efficiency and eliminate the need to control the incident X-rays during the CCD readout. In this paper, a brief design of novel fast arrayed FOT-CCD X-ray detector with a large-format IL-type CCD is described. The basic performance characteristics of the detector and verification experiments using a crystalline biodegradable polymer film are presented. We also demonstrate the continuous rotation method for a lysozyme crystal by using this detector to illustrate the small dead time for the CCD readout as a type of time-resolved experiment.

2. Detector design

The design goal of this detector is to achieve the capability of the time-resolved measurement with a time resolution of few tens of milliseconds and high sensitivity in order to discriminate the signals originating due to a few X-ray photons from the system noise. Moreover, a spatial resolution of 100 μm and a wide-azimuthal coverage of the diffraction pattern are required. In order to satisfy these design goals, an array of the low demagnification ratio FOTs and the large format IL-type CCDs are adopted. The detailed descriptions of each component are written in the following sections.

The detector is composed of a detector head, camera control unit, and data-acquisition system with a data processing software. The schematic diagram of the detector system is shown in Fig. 1. The detector system has been developed in collaboration with Hamamatsu Photonics K.K. in Japan.

An incoming X-ray photon is absorbed in the phosphor. The absorbed X-ray photon is converted into a visible-light photon and transferred through a fiber-optic faceplate (FOP), which holds the phosphor to the FOT. The FOT provides a larger active area, which is reduced in size to

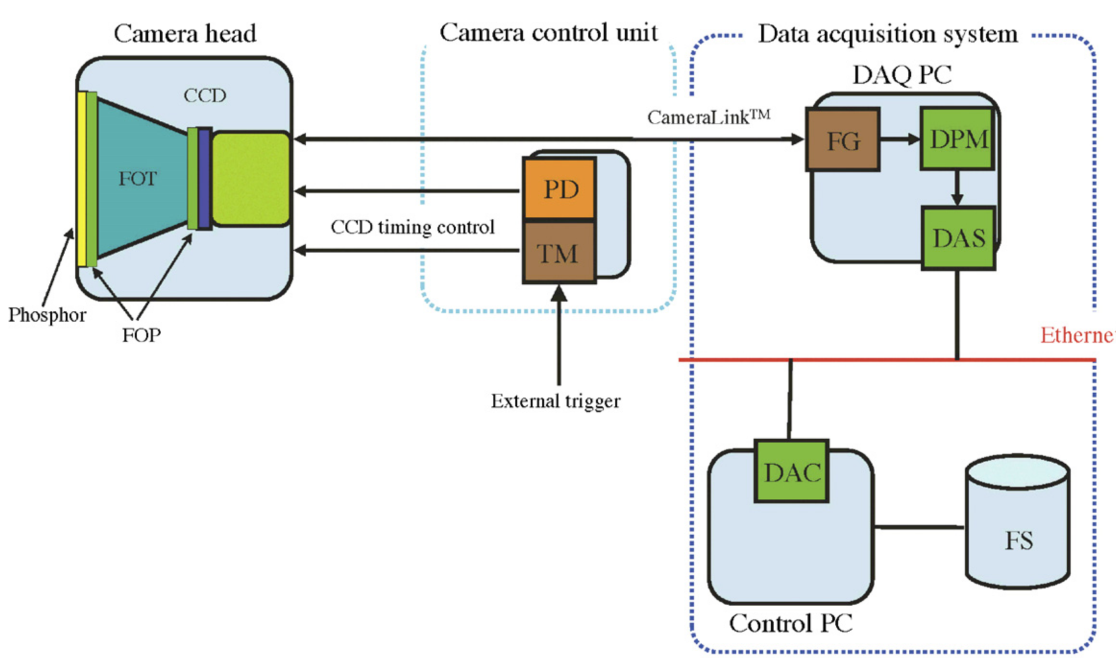

Fig. 1. Schematic diagram of the FOT-CCD X-ray detector system that comprises a camera head, camera control unit, and data-acquisition system including DAQ and control PCs. Acronyms: PD: Peltier driver, TM: timing module, FG: frame grabber, DPM: data processing module, DAS: data acquisition server, DAC: data acquisition client.