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Upper-limit resolving power of semiconductor X-ray detector materials: A cascaded-systems model of interaction-specific MTFs

The modulation transfer function (MTF) is a critical metric for quantitatively assessing the contrast-transfer capability of X-ray imaging devices, particularly in terms of their ability to resolve fine details. Photon-counting detectors (PCDs), which use semiconductor sensor materials, typically exhibit superior MTF performance compared to scintillator-coupled detectors [1]. This is primarily because the diffusion of charge carriers in semiconductors is much smaller than that of light in scintillators. To mitigate the effects of lateral light diffusion, structured designs of scintillators have developed.

The upper limit of spatial resolution in X-ray detectors is determined by the spatial distribution of absorbed energy resulting from X-ray interactions. In a recent study [2], we demonstrated that when the MTF induced by X-ray interactions is combined with a charge-sharing compensation scheme in PCD operation, the overall MTF of the detector can be significantly reduced, as illustrated in Fig. 1(a). Thus, it is essential to understand the contribution of each type of interaction to the upper-limit MTF in a given detector material to improve PCD imaging performance. While numerous studies have explored detector materials in terms of detection efficiency, research into the spatial-resolution effects caused by X-ray interactions remains relatively limited.

In this study, we present a cascaded-systems model to describe the MTF induced by X-ray interactions, as depicted in Fig. 1(b). This model categorizes interactions such as the photoelectric effect, Rayleigh scattering, and Compton scattering, and takes into account energy absorption at both local and remote sites, as well as energy escape. It enables a modular and traceable analysis of how various photon events contribute to signal spreading or resolution loss [3]. We implement the model using the Monte Carlo technique, and we analyze the impact of each interaction mechanism on the total MTF by tracking energy-absorption events through each interaction history. For this purpose, we utilize the pTrac output from MCNP (Version 5, RSICC, Oak Ridge, TN), which provides photon energy and spatial coordinates at each interaction site.

Fig. 1(c) presents the interaction-specific transfer functions in the Fourier domain for a CdTe detector. Each curve corresponds to a specific X-ray interaction pathway, including the photoelectric interaction (T_{PKL}, T_{PK}, T_{PL}), scattering event (T_{CL}, T_{CPKL}, T_{CPK}, T_{CPL}), and multiple scattering (T_{MC}). This detailed decomposition facilitates an in-depth analysis of how each type of interaction affects spatial resolution. The proposed model offers a systematic approach for isolating and quantifying the individual contributions of various X-ray interactions to the overall MTF. We apply this model to investigate the upper-limit MTF for different detector materials, such as CsI, Si, CdTe, GaAs, HgI_2, and PbO.

Reference
[1] J. Lee, S. Yoo, S. Oh, S. Park, C. H. Lim, J-W. Park, J. Tanguay, and H. K. Kim, "Analysis of the detective quantum efficiency of a dual-energy photon-counting X-ray detector", NDT & E International. In publication.
[2] H. K. Kim, "Development of Energy-Integrating Detectors for Large-Area X-Ray Imaging", in Radiation Detection Systems, K. Iniewski and J. S. Iwanczyk eds. CRC Press, pp. 163-224, 2021.
[3] S. Yun, J. Tanguay, H. K. Kim, and I. A. Cunningham, "Cascaded-systems analyses and the detective quantum efficiency of single-Z x-ray detectors including photoelectric, coherent and incoherent interactions", Medical physics, Vol. 40, No. 04, pp. 041916, 2013.

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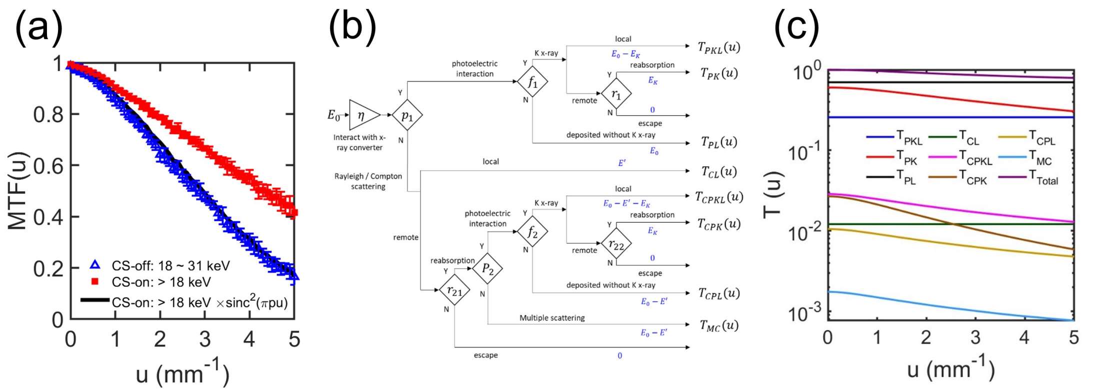

Figure 1: (a) Measured MTFs of a 2 mm-thick CdTe PCD with a 100-µm pixel pitch. The difference between the two measurements and the fitted curve suggests that the fluorescence X-ray photon range corresponds to the pixel dimension. (b) The proposed sascaded-systems model for describing X-ray interaction-induced MTFs. (c) Interaction-specific transfer functions derived from applying the cascaded-systems model to Monte Carlo data.

Workshop topics

Applications

Authors: LEE, Junho (Computational X-ray Imaging Laboratory, School of Mechanical Engineering, Pusan National University); KIM, Ho Kyung (Computational X-ray Imaging Laboratory, School of Mechanical Engineering, Pusan National University)

Co-authors: OH, Seokwon (Computational X-ray Imaging Laboratory, School of Mechanical Engineering, Pusan National University); PARK, Seongbon (Computational X-ray Imaging Laboratory, School of Mechanical Engineering, Pusan National University); YOO, Seungjun (Computational X-ray Imaging Laboratory, School of Mechanical Engineering, Pusan National University)

Presenter: LEE, Junho (Computational X-ray Imaging Laboratory, School of Mechanical Engineering, Pusan National University)