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Effects of Fiber-optic Plates on Image Quality of CMOS X-ray Detectors

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1. Introduction

Complementary metal-oxide-semiconductor (CMOS) active-pixel sensor has lately attracted for digital radiography due to its intrinsic low electronics noise, high fill factor, and dynamic imaging capability [1,2]. However, radiation damage and its effects on image quality of CMOS devices have also been reported by previous studies [3-6]. In this regard, most CMOS sensor manufacturers usually employ a fiber-optic plate (FOP) bonded to the CMOS photodiode array. In this configuration, the FOP layer absorbs un-attenuated x-ray photons through an overlaid scintillator; otherwise the un-attenuated photons might be absorbed within the CMOS photodiode array directly. Therefore, it is important to select an optimal thickness of an FOP layer for the long-term use of CMOS sensors providing high-quality images. We are constructing a micro computed tomography (micro-CT) system with a CMOS sensor. In this study, we have investigated the effects of FOP on x-ray image qualities of a CMOS sensor in terms of sensitivity, modulation transfer function (MTF), noise power spectrum (NPS), and detective quantum efficiency (DQE).

2. Methods and Results

2.1 Detector Preparation

The CMOS detector consisted of a two-dimensional array of CMOS photodiodes and an overlying scintillator to detect x-ray photons that are converted into light photons in a scintillator layer as shown in Fig. 1(a). The CMOS photodiode array (RadEye, Teledyne Rad-icon Imaging., USA) had a 512×1024 pixel format with a pitch of 0.048 mm, which provides an active area of about 25×50 mm^2 [7]. We employed a commercial Gd_2O_2S:Tb scintillator (Min-R2000, Carestream Health Care Inc., USA). The thickness and density of the scintillator were 0.084 mm and 4.04 g/cm^3, respectively. The CMOS detector was placed in a dedicated light-tight box with 1-mm-thick graphite window.

In order to investigate the effects of FOP on image quality, we inserted a commercial FOP (Incom Inc., USA) between the scintillator and CMOS photodiode layers. The FOP was mostly based on SiO_2 (70%), and had a thickness of 3 mm. According to the manufacturer, fiber diameters ranged from 6 to 10 μm, and the physical density was about 4 g/cm^3. The scintillator and FOP were coupled directly onto the CMOS photodiode array using a thin polyurethane form layer for compression between the scintillator and graphite.

The role of an FOP layer in the CMOS detector is schematically depicted in Figs. 1(b) and (c).

2.2 Imaging Conditions

To mimic micro-CT imaging conditions, we used 40 to 70 kVp tungsten-target spectra (UltraBright™, Oxford Instruments X-ray Technology, Inc., USA) with additional filtration that was determined to have similar pixel values at the maximum exposure of each spectrum peak energy setup. The aluminum thickness used for additional filtration and the measured half-value layers (HVLs) are summarized in Table I. The source-to-detector distance of 700 mm was used and the integration time of the CMOS detector was 1 sec.

Table I: X-ray spectra used in this study

Peak energy (kVp)	Fixed filter (mmAl)	Measured HVL (mmAl)
40	0.5	1.49
50	3.0	2.46
60	6.5	4.12
70	10.5	5.53

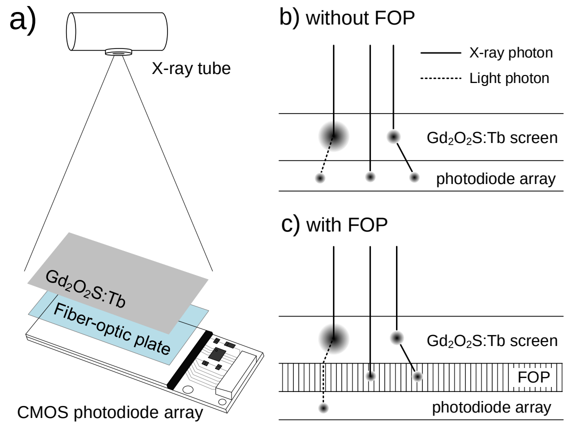

Fig. 1. Sketch describing (a) an experimental setup of the CMOS detector (b) without and (c) with an FOP layout to characterize the effects of FOP on image quality. Possible interactions and transports of x-ray and light photons in the CMOS detector are depicted.

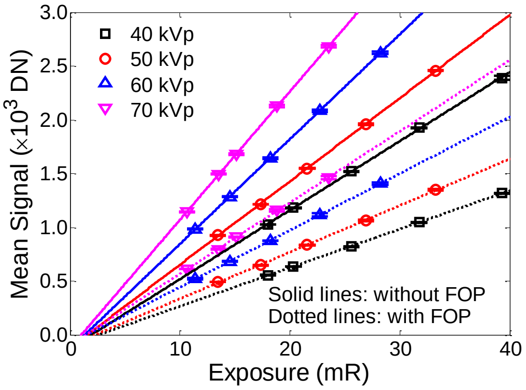

Fig. 2. Mean pixel values of the detector as a function of exposure with respect to various spectra. Solid and dotted lines denote the least-squares regression analyses without and with FOP layout, respectively.

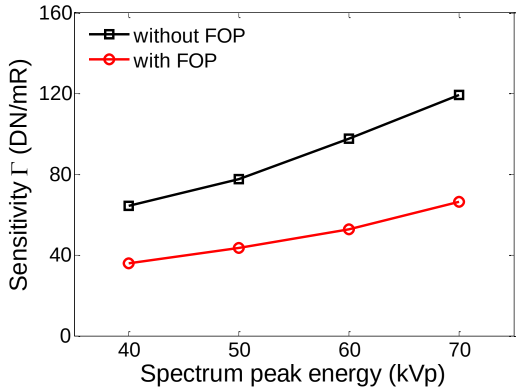

Fig. 3. Measured x-ray sensitivities as a function of spectrum peak energy.

2.3 Imaging Quality Characterization

The x-ray image qualities of the CMOS detector without and with the FOP layout were investigated in terms of sensitivity, MTF, NPS, and DQE. For various exposure levels, the detector response was calculated using a 256×256 sized region of interest (ROI) taken from 10 images. For a quantitative measurement, we followed the standard protocol to obtain the MTF and NPS, which are introduced by the IEC 62220-1 report [8]. From our measurement results, the discrepancy between two perpendicular directions (i. e., the readout and gate line directions) were negligible for both MTF and NPS; hence we report only the readout directional results for a brevity. The DQE was calculated by using the measured MTF, NPS and the estimated photon fluence $\bar{q}$ as follows [8]:

$$\mathrm{DQE}(f)=\frac{\mathrm{SNR}_{out}^{2}}{\mathrm{SNR}_{in}^{2}}=\frac{\bar{S}^{2}\mathrm{MTF}^{2}(f)}{\bar{q}\mathrm{NPS}(f)} \qquad (1)$$

where $\bar{S}$ is the mean pixel value in digital number (DN). The typical gain-offset correction algorithm was applied to all images prior to the analyses [7].

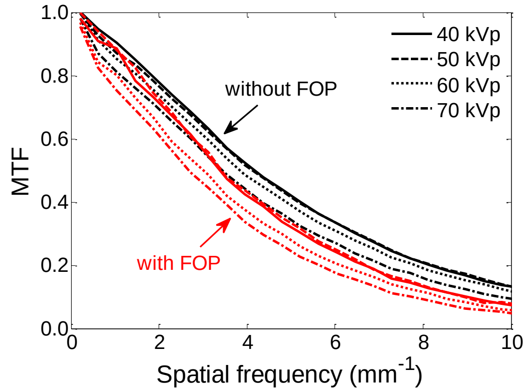

Fig. 4. MTFs measured without and with the 3-mm-thick FOP for various x-ray spectra.

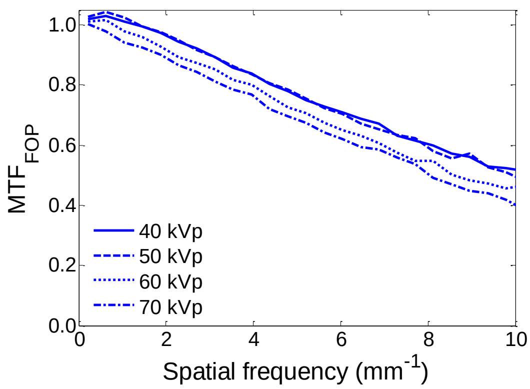

Fig. 5. Estimated MTFs due to the FOP layer itself.

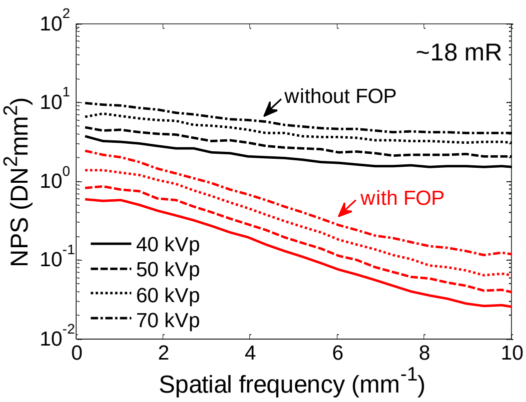

Fig. 6. Measured NPSs of the CMOS detector without and with the FOP layer for various x-ray spectra.

2.4 X-ray Response and Sensitivity

Figure 2 shows the measured pixel values of the detector as a function of x-ray exposure for various incident spectra. Least squares analysis using a first-order polynomial showed that the detector response was quite linear as a function of exposure. We note slight negative offsets in the regression analyses. From the response results, it is shown that the use of FOP reduces the x-ray response of detector due to the loss of light photons through the FOP layer. The x-ray sensitivity, which can described by a pixel value per unit exposure, is shown in Fig. 3. The average light photon transmittance of FOP was determined to be 55.4±0.9% by taking ratios of sensitivities measured without and

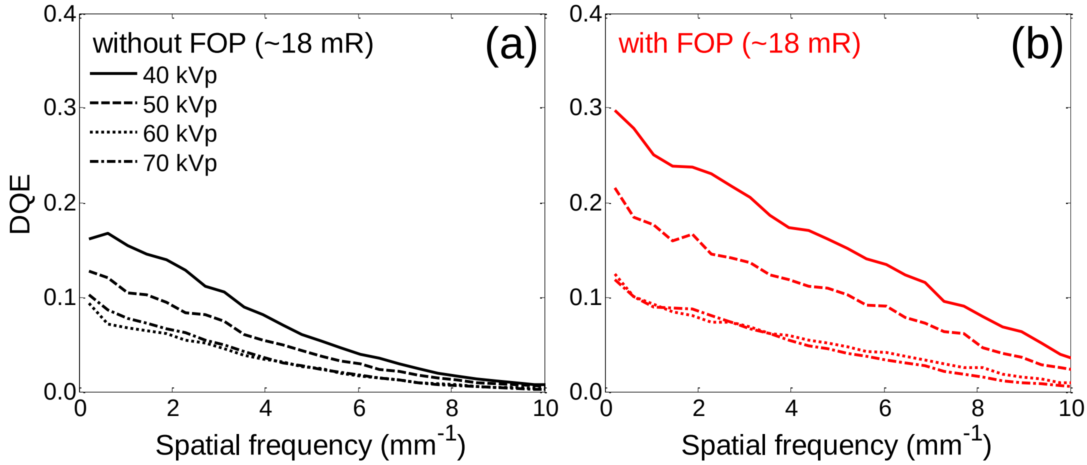

Fig. 7. Measured DQEs of the CMOS detector (a) without and (b) with the FOP lay at a similar exposure level (~18 mR) for various x-ray spectra.

with the FOP layer. The determined value agrees well with the transmittance provided by the manufacturer (> 50%).

2.5 Modulation Transfer Function

Figure 4 shows the MTFs of the CMOS detector without and with FOP. For all x-ray spectra, it is shown that the use of FOP degrades the MTF performance over all the spatial frequency ranges, and which implies an additional blurring due to the FOP layer. The MTF decreased with increasing photon energies because of the generation of characteristic x-rays and more probable Compton scattering events in the scintillator layer. From the measured MTFs, as shown in Fig. 5, the MTFs of the FOP layer itself were estimated by dividing the measured MTF with the FOP layer by that without the FOP layer. Energy dependency of MTF_{FOP} is shown.

2.6 Noise Power Spectrum

The NPSs measured without and with FOP were plotted in Fig. 6. Although the x-ray exposure for each spectrum was similar, the discrepancies in NPS between the NPSs without and with FOP were significant. From a previous work from our group [6], it was shown that a direct absorption of x-ray photons unattenuated from a scintillator in the CMOS photodiode array induced an uncorrelated noise which could result in a severe degradation in noise performances. By inserting the 3-mm-thick FOP, the effects of uncorrelated noise induced by the direct absorption of x-ray photons were significantly reduced particularly at a high spatial frequency region.

2.7 Detective Quantum Efficiency

Figure 7(a) and (b) show the DQEs measured without and with FOP, respectively. The DQEs with FOP show are much larger than the DQEs without FOP, particularly for low-energy spectra. Although the use of FOP degrades the sensitivity and MTF, it greatly enhances NPS performance. Therefore, we obtained much improved DQE performance with the FOP layer for micro-CT imaging conditions.

3. Conclusions

By comparing the image qualities of the CMOS detector measured without and with FOP, the effects of FOP on the imaging system have been investigated for various x-ray spectra. Measurements showed that the FOP degraded the x-ray sensitivity and resolving power, whereas it enhanced noise properties by absorbing un-attenuated x-ray photons. As a result, the use of FOP enhances the DQE performance which mainly governs x-ray image quality. However, for a low exposure imaging, the use of FOP may not be appropriate because it reduces the light photon transmittance by ~55% which implies that the image quality could be easily affected by additional electronics noise rather than quantum noise. In this regard, the use of FOP may be more appropriate for industrial applications in which irradiation condition is harsh. In this study, it is shown that the design of FOP such as thickness, transmittance and density should be selected with respect to a detector design and imaging conditions to obtain an optimized image quality.

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