Feasibility study of flexible flat-panel X-ray detectors for digital radiography

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1. Introduction

Flexible flat-panel detectors (FPDs), which utilize both organic photodiode (OPD) and organic thin-film transistor (OTFT) technologies, are recently concerned in digital radiography [1]. The flexible FPD has several potential advantages, such as high accessibility to patient, avoidance of geometrical burr due to the oblique angle incidence of X-ray, great reduction in manufacturing cost due to jet-printing. At once, The OPD/OTFT arrays were fabricated by jet-printing [2] techniques, mechanical robustness due to plastic substrates, and so on.

In this study, we have investigated the feasibility of flexible FPD by comparing theoretical detective quantum efficiency (DQE) with that of the conventional amorphous silicon-based FPD. We chose copper phthalocyanine-fullerene (CuPc-C_{60}) organic materials for the construction of the flexible FPD. DQE was calculated by the linear-systems transfer theory.

2. Methods and Results

2.1 Metrics of system performance

Contrast, spatial resolution and noise are important parameters characterizing the performance of an imaging system. Since these parameters are closely interrelated each other, we require metrics which consider those factors overall. DQE is representative metric to quantify the imaging performance and describes how many incident X-ray photons are used to form an image. Spatial-frequency-dependent DQE incorporates the modulation transfer function (MTF) and noise power spectrum (NPS) characteristics of an imaging system [3].

2.2 Linear-systems transfer theory

We have applied the linear-systems transfer theory [4] to estimate the signal and noise transfer in FPDs and thus the DQE performances. Fig. 1 shows the cascade models describing the signal and noise transfer in FPDs based on the linear-systems transfer theory. In this study, seven physical-process stages are considered to model FPDs.

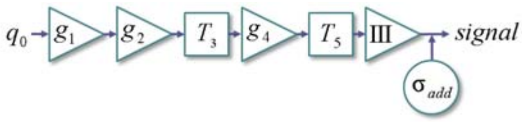

Fig. 1. A schematic describing the cascaded linear-systems model of a FPD.

Table I: The parameters and symbols used for cascaded linear-system model of FPDs in this study.

Stage	Description	Symbol	Process
1	Quantum detection	$g_1 = A_Q$	Binomial selection
2	Quantum amplification	$g_2 = A_M$	Binomial selection
3	Quantum scatter	T_3	Stochastic relocation
4	Quantum conversion	$g_4 = A_D$	Binomial selection
5	Aperture integration	T_5	Deterministic blurring
6	Sampling	III	Deterministic process
7	Additive noise	σ_{add}	Deterministic process

Table I summarizes the detailed description of each process of an interacting stage.

From the definition of DQE as the ratio of the squared output SNR to the squared input SNR, we can write down the analytical DQE like

$$\mathbf{DQE}(\boldsymbol{\rho}) = \frac{\overline{q}_0 \times \overline{G}^2 \times \mathbf{MTF}^2_{out}(\boldsymbol{\rho})}{\mathbf{NPS}_{out}(\boldsymbol{\rho})} = \frac{\overline{q}_0 (a^2 A_Q A_M A_D)^2 T_3^2(\boldsymbol{\rho}) T_5^2(\boldsymbol{\rho})}{S_5(\boldsymbol{\rho}) ** \mathbf{III}(\boldsymbol{\rho}) + \sigma_{add}} \quad (1)$$

To verify our cascaded-model-analysis approach, we have applied this approach to the detector, which is installed in our laboratory, and compared the theoretical results with the experimental measurements. The detector consists of RadEye100EV (Rad-icon imaging Corp., USA) CMOS photodiode arrays and Min-R2190 (Carestream Health Inc., USA) granular phosphor screen. Physical parameters describing each stage were obtained from Monte Carlo method. MCNPX™ (Version 2.5.0., ORNL, USA) and DETECT2000™ (Laval University, Quebec, Canada) codes were used to simulate the X-ray photon and optical photon transports,

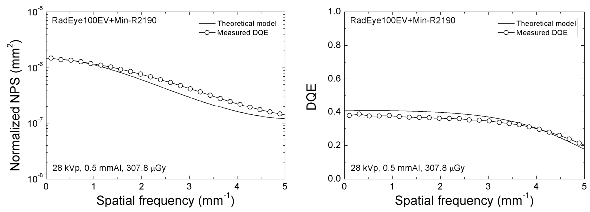

Fig. 2. The measured normalized NPS and DQE for the CMOS flat-panel detector with Gd_2O_2S:Tb scintillator are well described by the cascaded model analysis.

respectively. In this study, A_Q is 0.6257, A_S is 0.6676, A_M is 405 and A_D is 0.4. As demonstrated in Fig. 2, the theoretical model results are greatly agreed with the measurements.

2.3 Additive electronic noise

The total additive noise of an imaging system can be estimated by the sum of each noise component in quadratues. Eq. (2) describes the total additive noise:

$$\sigma_{add} = \sqrt{\sigma_{pix}^2 + \sigma_{amp}^2 + \sigma_{data}^2 + \sigma_{ext}^2 + \sigma_{dig}^2} = \sqrt{\sigma_{pix}^2 + \sigma_{base}^2} \qquad (2)$$

σ_{amp} is preamplifier noise, σ_{data} is data line noise, σ_{ext} is external noise, σ_{dig} is ADC noise and σ_{base} is baseline system noise excluding pixel noise. Therefore σ_{base} becomes to

$$\sigma_{base} = \sqrt{\sigma_{amp}^2 + \sigma_{data}^2 + \sigma_{ext}^2 + \sigma_{dig}^2} \qquad (3)$$

We assumed that σ_{base} of OPD/OTFT detector the same as *a*-Si:H system because we have assumed that the preamplifier and ADC could be shared. Therefore, the total additive noise of OPD/OTFT detector is mainly determined by pixel noise, and it is further expressed as

$$\sigma_{pix} = \sqrt{\sigma_{theraml}^2 + \sigma_{pd-on}^2 + \sigma_{pd-off}^2} \qquad (4)$$

Table Ⅱ. Physical parameters for calculating electronic noise properties of CuPc-C_{60} and *a*-Si:H

Photodiode type	CuPc-C_{60}	*a*-Si
ε_r	3	11.4
C_{pd}	1.19 fF	20 pF
$I_{pd\text{-}leak}$	448 pA/mm^2	110 fA/mm^2
$\sigma_{TFT\text{-}theraml}$	19 e^-	2519 e^-
σ_{pix}	2355 e^-	2716 e^-

Table II shows the electrical properties of CuPc-C_{60} and *a*-Si:H. Under 10-V bias voltage, the dynamic range of CuPc-C_{60} and *a*-Si:H are 29.98 dB and 113.25 dB, respectively. If we can achieve the dark current level of OPD under 0.1 pA, σ_{pix} of OPD decreases and the dynamic range of OPD system would dramatically be enhanced.

2.4 Detective quantum efficiency

CuPc-C_{60} OPD has maximum quantum efficiency (QE) of 30% at 650 nm. The calculated QE of CuPc-C_{60} considering the spectral matching with $Gd_2O_2Si{:}Tb$ emission spectrum is 14.18%. Fig. 3 shows the estimated DQE performances with various input parameters. The overall performances of organic-material-based detectors are poorer than the conventional detectors because of the inherent low external QE.

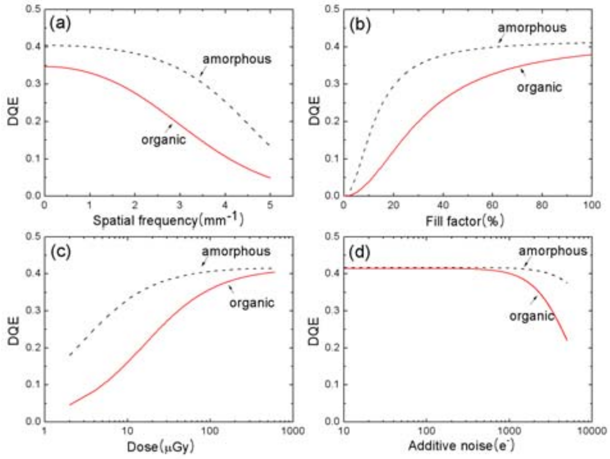

Fig. 3. Theoretically estimated DQE results for CuPc-C_{60} and *a*-Si:H based FPDs using the cascaded model analysis. (a) DQEs as a function of spatial frequency, (b) DQEs as a function of fill factor, (c) DQEs as a function of input dose, (d) DQEs as a function of additive electronic noise.

3. Conclusions

We have considered CuPc-C_{60} for OPD/OTFT for flexible FPDs and compared the estimated performance with the conventional *a*-Si:H based FPD. As CuPc-C_{60} has lower QE and higher additive noise, DQE of the flexible detector is lower than that of the conventional one. Because dark current of OPD dominates pixel noise, it is necessary to manufacture OPD having lower dark current less than 0.1 pA for higher DQE performance. DQE of OPD/OTFT-based detector is more sensitive to additive noise larger than 1000 e^- than *a*-Si:H-based detector. If OPD would be manufactured to have fill factor larger than 80% or have additive noise less than 1000 e^-, DQE performance comparable to the conventional detector would be expected.

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