Dark Signal Consideration in Spatial Resolution for Scintillator Coupled CMOS Sensor

Kwang Hyun Kim, Yong-Kyun Kim, Seung Jin Lee, Gyuseong Cho, Young Soo Kim, and Jeon Sung Chae

Abstract—The spatial resolution of scintillator coupled CMOS sensor has been investigated for the conditions of the digital radiography by using unified MTF. The scintillator was FOP CsI with high resolution and the CMOS sensor has a pixel pitch of 48 \( \mu \text{m} \). The effects of initial dark signal of the sensor on the unified MTF were newly modeled considering different radiography conditions. This model showed well the contribution of the dark signal on the degradation of the spatial resolution, and it compared to the measured spatial resolution.

I. Introduction

In the digital radiography, the sensor having high resolution as well as sensitivity makes clear distinction for the small object. Especially, digital mammography and nano-scale radiography need small pixel size, with the pixel pitch of 10 \( \sim \) 50 \( \mu \text{m} \), of the sensor to get high spatial resolution.

For the spatial resolution, the modulation transfer function (MTF) is a convenient factor to assess the image resolution and is expressed in terms of the resolving power of the imaging system [1]. As one of the methods to estimate the resolution of the scintillator coupled sensor, the system MTF, \( MTF_{\text{sys}} \), has been considered as

\[
MTF_{\text{sys}} = MTF_{\text{sci}} \cdot MTF_{\text{sen}}
\]

The intrinsic scintillator resolution, \( MTF_{\text{sci}} \), reflects the blurring of scintillation light in the scintillator and the sensor resolution, \( MTF_{\text{sen}} \), for the intrinsic sensor spatial resolution, respectively. Therefore, the system MTF, \( MTF_{\text{sys}} \), covers detector resolution in digital radiography system.

Especially, to evaluate the spatial resolution of the sensor, many researchers have used sinc function as an intrinsic sensor resolution in the field of digital radiography. However, this sinc function gives the information of the spatial resolution based on only the pixel pitch. In case that CMOS vision sensor is used, the unified MTF model has been applied for more detail explanation of the sensor resolution as functions of the lateral diffusion length in the pixel, the fillfactor of the pixel sensor, and the incident wavelength on to the sensor [2,3]. In their research, they used small pixel pitch of 6 \( \mu \text{m} \) to 8 \( \mu \text{m} \) and general visible light as incident photons, and from their results the fill factor as well as carrier diffusion in the pixel influenced on the sensor intrinsic resolution.

In this paper, the unified MTF has been investigated for the conditions of the digital radiography, and the influence of unified MTF on the system MTF also considering scintillator resolution. Pixel pitch, fill factor, and incident scintillation light have been used as variable parameters since these parameters are highly dependent on the design process of the digital radiography detector. In addition, the effect of the dark signal in the sensor and the detector on the sensor resolution has been analyzed by calculation and experiments.

II. Modulation Transfer Function

A. Evaluation of Unified MTF in Digital Radiography Condition

The unified MTF starts from the concept that the CMOS sensor does not have 100 \% fill factor since the sensor contains metal lines and transistors, and these reduce fill factor of the sensor. Besides, the diffusion and crosstalk of minority carriers between pixel and pixel, which are generated in the solid-state sensor array by incident wavelength, are considered in the estimation of the sensor intrinsic spatial resolution.

So as to verify the unified MTF model in the digital radiography condition, we calculated the unified MTF by [2] and compared it to the geometric MTF based on sinc function. The sensors of small pixel size and low fill factor were applied to both the unified MTF and the geometric MTF based on sinc function for each incident wavelength. Fill factors of 30 \% and 40 \% for the pixel pitch of 10 \( \mu \text{m} \) at the wavelength of 550 nm and 40 \% and 50 \% for the pixel pitch of 15 \( \mu \text{m} \) at the wavelength of 610 nm were used and the results are shown in Fig. 1. and Fig. 2.

In Fig. 1-a and 1-b, even at small pixel pitch, the effect of the lateral diffusion of the minority carrier has not been revealed at the wavelength of 550 nm. However, at the wavelength of 610 nm, the higher frequency have shown the more effect of diffusion, and degraded spatial resolution as shown in Fig. 2-a and 2-b.

For larger pixel size, it is assumed that the sensor has the pixel pitch of 50 \( \mu \text{m} \), but varying fill factor of 80 \%, 85 \%, 90 \%, and 100 \%, and incident wavelengths of 550 nm. Fig. 3.

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shows one of the calculated examples for the unified MTF (uMTF) and the geometric MTF (gMTF).

As a result, there was no difference between the unified MTF and the geometric MTF. The wavelength of 610 nm also follows that trend even it did not show here.

By using the unified MTF in consideration of the system spatial resolution, \( MTF_{sys} \), the equation (1) can be changed as

\[
MTF_{sys} = MTF_{sci} \cdot MTF_{uni}
\]

(2)

where \( MTF_{uni} \) is the unified MTF of the sensor. In this equation, it has been known that the worst among the scintillator intrinsic resolution and sensor intrinsic resolution governs the system resolution as a rule of thumb.

Fig. 1. Comparison of geometric MTF and unified MTF by changing fill factors of 30\% and 40\% for the pixel pitch of 10\,\mu m (Fig.1-a.), and 40\% and 50\% for the pixel pitch of 15\,\mu m (Fig.1-b.) at the wavelength of 550\,nm.

Fig. 2. Comparison of geometric MTF and unified MTF by changing fill factors of 30\% and 40\% for the pixel pitch of 10\,\mu m (Fig.2-a.), and 40\% and 50\% for the pixel pitch of 15\,\mu m (Fig.2-b.) at the wavelength of 610\,nm.

Fig. 3. Comparison of geometric MTF and unified MTF by changing fill factors of 80\% to 100\% for the pixel pitch of 50\,\mu m. In the calculation of the unified MTF the incident wavelength was 550\,nm.

Fig. 4. The effect of the unified MTF on the system MTF at the large pixel size of 48\,\mu m by changing fill factors of 80\% to 100\%.
B. Consideration of Dark Signal in Unified MTF Model

Dark signal generated without any incident light comes mainly from leakage current in the sensor, and the leakage current influences on the dynamic range as well as sensor contrast transfer function or modulation transfer function.

However, the following equation which used in calculation of unified MTF model does not reflect the dark signal and correlate any parameter.

\[
MTF(f) = \frac{S_{o_{\text{max}}}(f) - S_{o_{\text{min}}}(f)}{S_{o_{\text{max}}}(f) + S_{o_{\text{min}}}(f)}
\]

(3)

where \(S_{o_{\text{max}}}(f)\) and \(S_{o_{\text{min}}}(f)\) are each signal from maximum signal generated in open aperture and minimum signal generated in opaque aperture at the given pixel geometry, respectively.

In this equation, signal output \(S(f)\) is given by

\[
S_{o}(f) = \alpha Na e^{\sigma_y} [K_1(f)] + \frac{Na(1-e^{-\sigma_y})}{2} [K_2(f)]
\]

(4)

where \(\alpha\) is the absorption coefficient, \(N\) is incident photons, \(a\) is pixel pitch, and \(y\) is depletion depth. \(K_1(f)\) and \(K_2(f)\) are frequency dependent parameters in pixel to pixel. This equation was calculated by integrating current density considering charge generation in the depletion and diffusion from the bulk region.

In our previous research result, it was shown and analyzed that the resolution of the scintillator coupled CMOS sensor was degraded by the direct detection of X-ray and consequently increasing dark signal in ADC unit [6]. And now, the influence of initial intrinsic dark signal on spatial resolution also can be modeled by the basic semiconductor physics and the unified MTF.

The signals of \(S_{o_{\text{max}}}(f)\) and \(S_{o_{\text{min}}}(f)\) in equation (3) are the calculated values by charge generated in the depletion region and diffusion from the bulk, and using the assumption that the dark signal comes partially from the diffusion from bulk substrate [7]. Therefore, to relate the dark signal to equation (3), it is modeled for output signal as

\[
S'_{o_{\text{max}}}(f) = \alpha Na(S_{o_{\text{max}} \cdot F}) e^{\sigma_y} [K_1(f)] + \frac{Na(S_{o_{\text{max}} \cdot F})(1-e^{-\sigma_y})}{2} [K_2(f)]
\]

(5)

and

\[
S'_{o_{\text{min}}}(f) = \alpha Na(S_{o_{\text{min}} \cdot F}) e^{\sigma_y} [K_1(f)] + \frac{Na(S_{o_{\text{min}} \cdot F})(1-e^{-\sigma_y})}{2} [K_2(f)] + (S_{o_{\text{min}} \cdot F})
\]

(6)

In both equations, \(F\) is the weighted percentage of a dark signal in an output signal, which contributes the signal and is measured value in the sensor. Therefore, equation (3) finally leads to the following equation as functions of frequency and dark signal.

\[
MTF(f, F) = \frac{S'_{o_{\text{max}}}(f, F) - S'_{o_{\text{min}}}(f, F)}{S'_{o_{\text{max}}}(f, F) + S'_{o_{\text{min}}}(f, F)}
\]

(7)

By using equations of (3) and (7), we compared each other considering the effect of the dark signal, weighted \(F\) value, on the modulation transfer function. The parameters in Table 1. were used in these calculations based on AMIS generic 0.8 µm nwell CMOS process and digital radiography conditions.

<table>
<thead>
<tr>
<th>CMOS parameters</th>
<th>Psubstrate</th>
<th>nwell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impurity concentrations (1/cm³)</td>
<td>10¹⁵</td>
<td>10¹⁶</td>
</tr>
<tr>
<td>Intrinsic carrier concentration (1/cm³)</td>
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<tr>
<td>Excess Carrier Lifetimes (μs)</td>
<td>psub 100</td>
<td>nwell 10</td>
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<tr>
<td>Diffusion constant (cm²/s)</td>
<td>psub 34.8</td>
<td>nwell 11.2</td>
</tr>
<tr>
<td>Digital radiography condition</td>
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<td></td>
</tr>
<tr>
<td>Incident wavelength from scintillator (nm)</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>Incident photons (1/μm²)</td>
<td>300</td>
<td></td>
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<tr>
<td>Pixel geometry</td>
<td>Pixel pitch: 48 µm</td>
<td>Fill factor: 0.85</td>
</tr>
<tr>
<td>Weighted F values</td>
<td>0.17 and 0.5</td>
<td></td>
</tr>
</tbody>
</table>

Especially, the weighted \(F\) values were calculated from the measured data which were the ratio of the dark signal and the output signal in ADC unit, and will be discussed in later section of experiments set-up and results.

As shown in Fig. 5., the calculated MTF were all fitted by the Lorentz equation to show full range of frequencies, and the greater the value of \(F\) influences on the more degradation of modulation transfer function. While the MTF without \(F\) value reflects only the aperture size of the sensor, considering \(F\) value makes clear distinction in dark signal contribution.

We also evaluated the effects of the wavelength on the calculated MTF with or without \(F\) value. By using two wavelengths of 550 nm and 610 nm at the fill factors of 80 % and 90 %. The variation of the MTF was investigated. Fig. 6. shows that no changes were happened by changing wavelengths without considering dark signal, however, the shorter wavelength degraded the MTF than the longer wavelength at the higher frequency with dark signal contribution.

By assuming that the incident wavelengths and photons are same, the effect of fill factor on the MTF was also revealed as shown in Fig. 7. Considering dark signal in MTF degraded it more sever at the full range of frequency.
In this study, we fixed two sets of conditions of mammography and general diagnostic radiography. The X-ray sources of 28 kVp-16 mAs and 80 kVp-4.83 mAs were entered into the RadEye1™ CMOS APS imager, which were coupled to the FOP CsI-HR™ of HAMAMATSU, and set to the SID of 750 mm and 650 mm for each condition. The CMOS sensor has an active area of 25 mm by 50 mm with the pixel size of 48 µm.

The presampling modulation transfer function was measured by the recommended procedure of others [8]. From the acquired line spread-function (LSF) by using a Tantalum phantom, 1.5 mm of thickness, with a 10 µm width slit, the MTF was calculated by Fourier transform.

In this procedure, the measured output signals in ADC unit (ADU) were 90 and 276 for mammography and diagnostic radiography. And the initial dark signals were 45 and 47 before measuring the MTFs for both conditions. Therefore, the calculated $F$ values were 0.5 and 0.17, respectively.

As a result shown in Fig. 8, we plotted the measured system MTFs and compared these to the calculated system MTFs without and with $F$ value. The data of the calculated sys MTF were calculated by using parameters mentioned in Table. 1. The equations of (3) and 4 were used for without considering dark signal and the equations of (5), (6), and (7) in considering dark signal, respectively.

In this figure, the differences were slightly revealed between the measured and the calculated although $F$ value was considered. This may be caused by the coupling the FOP CsI-HR scintillator to the sensor leading to light spreading between their gaps. However, without $F$ value, the calculated sys MTF did not predicted well the measured sys MTF, especially at low energy of mammography condition.
IV. DISCUSSION AND CONCLUSION

We investigated the unified MTF model in the digital radiography system. Basically, the unified MTF is influenced by mainly aperture size, not by the amount of carrier diffusion at large pixel sensor, and especially, it was meaningless for the scintillator having the worst resolution than the sensor resolution.

However, in the analytical approach such as cascaded system analysis [9], the unified model at the stage of presampling pixel resolution should be applied in more definite engineering calculation. And if the scintillator structure follows the pixellated on the sensor itself, the unified MTF gives more detail spatial resolution than the geometric MTF based on only sinc function.

In this paper, we showed the relation the contribution of the dark signal on the unified MTF and newly modeled the unified MTF as a function of $F$ value which considers output signal and dark signal. Therefore, newly modeled unified MTF can explain that noise level of the sensor influences on the dynamic range as well as sensor modulation transfer function. This model also covers the incident radiography condition considering the degradation of the MTF, which depends highly on the ratio of maximum output signal to dark signal.

V. REFERENCES