THE EFFECT OF SURFACE ROUGHNESS OF CSI(TL) MICRO-COLUMNS ON THE RESOLUTION OF THE X-RAY IMAGE; OPTICAL SIMULATION STUDY

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Micro-columnar CsI(Tl) is the most popular scintillator material which is used for many indirect digital X-ray imaging detectors. The light scattering at the surface of micro-columnar CsI(Tl) scintillator was studied to find the correlation between the surface roughness and the resultant image resolution of indirect X-ray imaging detectors. Using a commercially available optical simulation program, Light Tools, MTF (Modulation Transfer Function) curves of the CsI(Tl) film thermally evaporated on glass substrate with different thickness were calculated and compared with the experimental estimation of MTF values by the edge X-ray image method and CCD camera. It was found that the standard deviation value of Gaussian scattering model which is determined by the surface roughness of micro-columns could certainly change the MTF value of image sensors. This model and calculation methodology will be beneficial to estimate the overall performance of indirect X-ray imaging system with CsI(Tl) scintillator film for optimum design depending on its application.

Keywords : Micro-columnar, CsI(Tl), Scintillator, X-ray Detector, Surface Roughness, Simulation

1. INTRODUCTION

A CsI(Tl) scintillator film with a micro-columnar structure has been widely used in indirect X-ray imaging detectors for digital radiography (DR) and X-ray telescope. The attributes of the scintillator considerably affects an X-ray image although its original function is to convert X-ray into visible light. Spatial resolution, the ability to distinguish between two closely spaced objects on an image, is one of the most important factors that can be influenced by the properties of the scintillator. In order to enhance the spatial resolution of the indirect X-ray imaging detectors, prior efforts focused on the pixelated CsI(Tl) scintillator, for example, deposited on a patterned photo-resist layer with a few tens of micrometer scale [1]. Besides many researches for better spatial resolution, there have been a few attempts to model and simulate the transport of scintillation light in the complicated structure of micro-columnar CsI(Tl) scintillators [2].

In this research, a new simulation study of the light transport in micro-columnar CsI(Tl) scintillators was carried out by using a commercially-available optical simulation program, ‘Light Tools’ and a general software, ‘MATLAB’. This approach makes it possible to simulate the light transport in geometrically complex models such as a 2-D array of cylindrical columns with a hemisphere top or pixelated scintillators coupled with a micro-lens. Finally, we found out the relationship between the spatial resolution of image and the surface roughness of CsI(Tl) scintillator columns using this simulation method.

2. SIMULATION METHOD

Modeling and simulating the light transport in a micro-columnar CsI(Tl) scintillator using ‘Light Tools’ requires some assumptions on the scintillation light distribution, surface properties, and bulk properties [3]. The background of these assumptions is described in the following three

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subsections. Finally, in the last subsection, the evaluation of the roughness of column surfaces is presented for verification of the simulation.

2.1 Scintillation Light Distribution

An X-ray beam radiated from an X-ray tube which is operated even at a fixed high voltage has a wide energy spectrum. In general, this X-ray beam is filtered so that the intensity of the low energy region can be reduced. Fig. 1 shows a result of an MCNP simulation on an X-ray tube with a tungsten anode operated at 80 kVp. According to the Lambert-Beer's law, the X-ray beam incident into a scintillator film is absorbed and loses its energy or intensity following the equation (1) [4].

$$E = \sum_i E_i \mathrm{I}_{0,i} \exp\left[\left(-\frac{\mu_i}{\rho}\right)\rho\chi\right] \qquad (1)$$

where E is the energy of X-ray beam at the distance *x* from the surface in kVpcm^{-2}, $\mathrm{I}_{0,i}$ is the intensity of the incident beam in the *i*th energy bin in #cm^{-2}, E_i is the average energy of the *i*th energy bin of X-ray beam in kVp, ρ is the density of CsI(Tl) in gcm^{-3}, and $\mu_i\rho^{-1}$ is the mass attenuation coefficient at the *i*th energy bin. Because CsI(Tl) is a mixture of CsI and Tl, the mass attenuation coefficient of CsI(Tl) should be calculated by using both coefficients. However, the contribution of Tl for the coefficient is negligible since its concentration is only about 0.2%. Therefore, we can use only the mass attenuation coefficient of CsI [4].

Assuming that the energy of scintillation light is proportional to the absorbed x-ray energy into the scintillator, we estimated the distribution of visible light sources. The first step was to discretize the results of MCNP simulation with 5keV bins. Next, applying Lambert-Beer's law with the initial average photon value of each energy bin and the corresponding mass attenuation coefficient, we plotted the X-ray energy distribution according to the depth of the scintillator which has a thickness of 50 μm. It is shown in Fig. 2 that the energy of x-ray beam decreases linearly along the absorption depth. This result is well coincident with the fact that the derivative of the first-order exponential curve is approximately constant in the vicinity of the zero; in this case, the coefficient in the order of a few cm^{-1} and the depth in a few tens of μm take the exponential function near the zero. Since the energy of X-ray beam falls in a constant rate, it was assumed that the amount of X-ray energy absorbed in a constant width of the scintillator is fixed. Therefore, a scintillation light distribution was set to be uniform according to the depth of CsI(Tl).

2.2 Surface Properties

When scintillation light hits a surface of the scintillator, it can be transmitted or reflected following Fresnel's equation and Snell's law. First, we applied Fresnel's equation to the simulation using 'Fresnel Loss Mode'. Furthermore, we used the unpolarized mode in this simulation because scintillation light has no particular polarization. The explanation of 'Fresnel Loss Mode' in 'Light Tools' is summarized as follows [3]:

"When the Fresnel Loss option is checked, the defined values for reflectance and transmittance are substituted with the Fresnel reflectance and transmittance values. If the Fresnel calculations indicate that the angle of incidence is beyond the critical angle, then a transmittance value of zero is applied to all rays."

Second, we assumed scattering types of surface as a specular scatterer when the surface is ideally polished and as a Gaussian scatterer when the surface roughness is unknown. That's because the standard deviation σ of

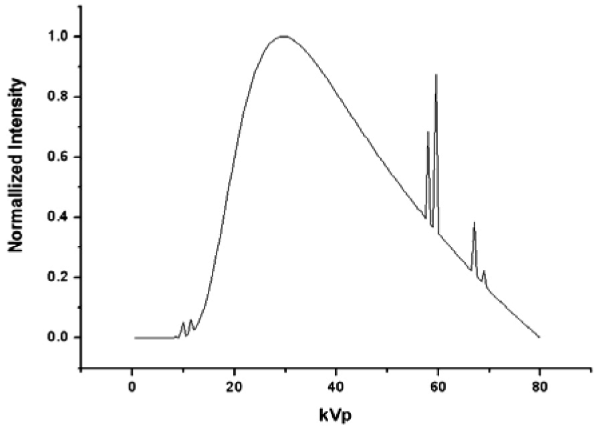

Fig. 1. Normalized X-ray intensity distribution from an X-ray tube operated at 80kVp from the MCNP simulation.

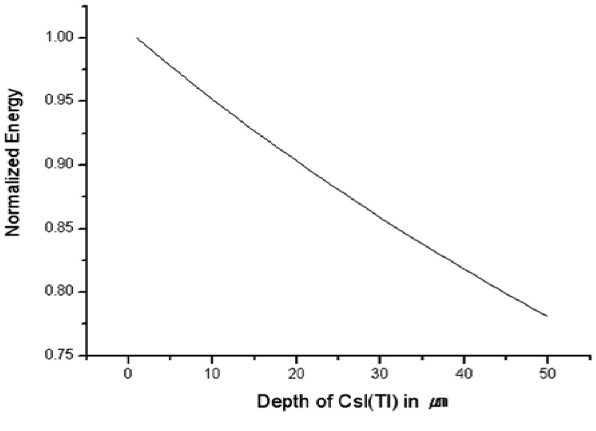

Fig. 2. Normalized X-ray energy distribution in a CsI(Tl) scintillator which has the depth of 50 μm.

Gaussian scatterer varies with the degree of surface roughness so that it can describe various scattering situation at a surface [5]. The Gaussian scatterer is illustrated in Fig. 3, and its intensity distribution follows the equation (2).

$$\mathrm{P}(\theta) = \mathrm{P}_0 \exp\left[\left(-\frac{1}{2}\right)\left(\frac{\theta}{\sigma}\right)^2\right] \qquad (2)$$

where P(θ) is the intensity or radiance in the θ direction, P_0 is the intensity or radiance in the specular direction, and σ is the standard deviation of the Gaussian distribution in degree.

2.3 Bulk Properties

As visible photons pass through the bulk of CsI(Tl), they undergo collisions that may change their direction of motion. After the visible photons interact with the atoms of CsI(Tl) at the point determined by the mean free path, they can be absorbed or scattered in their preferred directions. Since the mean free path of CsI(Tl) is approximately 1000mm for a single crystal microstructure, the probability of absorption is very small so the amount of the absorbed photons in the bulk of CsI(Tl) can be neglected [2]. In case that visible light reaches a interaction point, the scattering angle distribution is assumed to be isotropic following the assumption of the other widely used simulation program DETECT2000 [6].

Depending on the microstructure CsI(Tl) scintillator film such as a columnar structured film or a single crystal plate, light propagation in this film is totally different. When visible light propagates in a single crystal structure, its propagation direction does not change. However light propagation direction in a CsI(Tl) film with the micro-columnar structures is not preserved because of the interaction with surfaces of each CsI(Tl) columns. Therefore each columns in the CsI(Tl) scintillator film as shown in Fig.4 was treated as a single crystal in the simulation [2]. This assumption has been justified from the research of the X-ray diffraction pattern of micro-columnar structured CsI(Tl) [7]. The geometry of the CsI(Tl) column was assumed to be a cylinder with a hemisphere on the top which has a diameter of 5μm. By closely packing these cylinders which is illustrated in Fig.5, the uniformity of the azimuth distribution of the scintillated light is satisfied.

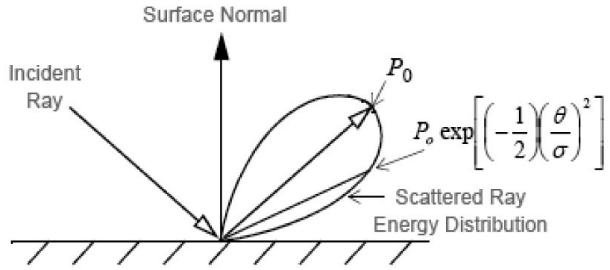

Fig. 3. The Gaussian scatterer in ‘Light Tools’.

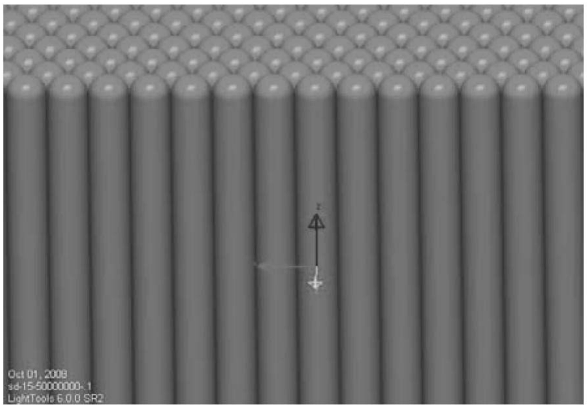

Fig. 5. Simulation model of micro-columnar CsI(Tl) used in Light Tools.

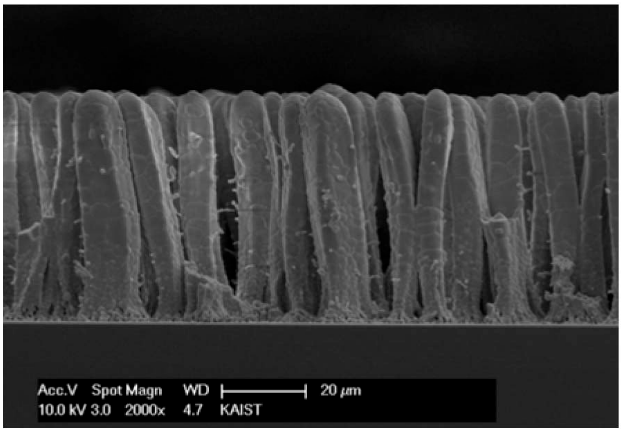

Fig. 4. A SEM image of a micro-columnar structured CsI(Tl) film.

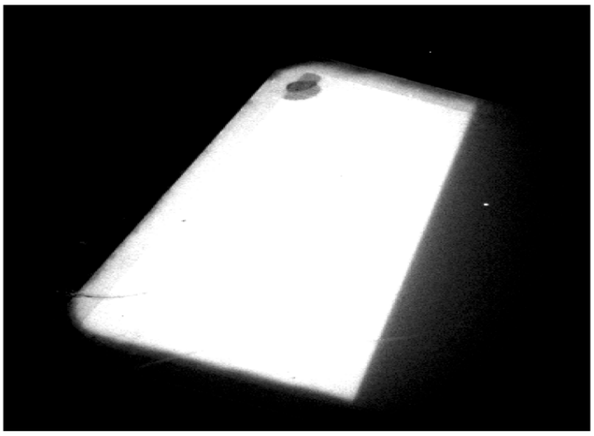

Fig. 6. An edge image of a CsI(Tl) scintillator irradiated by 80kvp X-ray.

2.4 Verification and Evaluation of Surface Roughness

To verify this simulation method, the results from the Light Tools simulation and the results from experiments were compared.

In the experiment, we irradiated CsI(Tl) scintillator samples with an 80kVp X-ray beam to get an edge image. The samples were fabricated using a PVD(Physical Vaporized Deposition) process on a slide glass with the thicknesses of 50 µm and 25 µm. The conditions of the fabrication of the PVD process are the chamber pressure of 0.01 torr and the substrate temperature of 31°C in the thermal evaporator shown in Fig.10. The X-ray edge image taken from this CsI(Tl) sample is shown in Fig.6 and its MTF curve is calculated as shown in Fig.7. The MTF curve was obtained to find out the standard deviation of the Gaussian scatterer.

In order to follow the experimental setup in simulation, the scintillator film was modeled as an array of CsI(Tl) cylinders on the slide glass and receiver plane was set as the bottom surface of the slide glass because the focal plane of the optical lens was set on that position. From the result of this simulation, an MTF curve was obtained by using an MATLAB program which converts the simulation results to an edge image as shown in Fig. 8. In order to assure the simulation, the spatial resolution change of X-ray images with the different thickness of micro-columnar CsI(Tl) films was estimated.

For the matching of the spatial frequency at the MTF value of 0.5 in both measurement and simulation MTF curves, we firstly founded that the standard deviation value of Gaussian scatter angle for the CsI(Tl) of 50 µm height should be 22° in this simulation. With this condition, the 0.5 MTF value was matched to be 1.31 in both experiment and simulation. Using another sample which is fabricated to have the height of micro-columnar CsI(Tl) to be 25 µm in the same conditions with previous sample, the MTF curve of edge image were also calculated. The result was that the 0.5 MTF value of CsI(Tl) which has 25 µm height

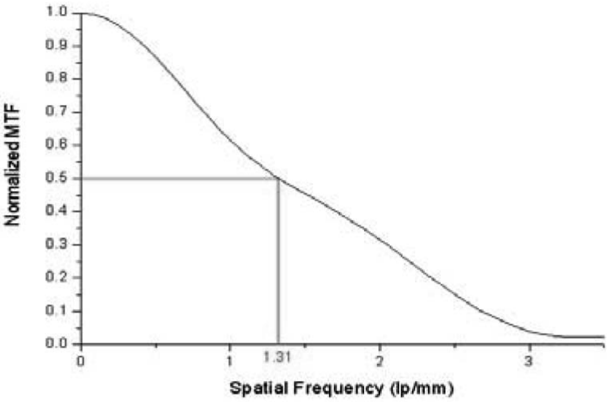

Fig. 7. An experimental MTF curve and 0.5 MTF value from the X-ray image of CsI(Tl) scintillator.

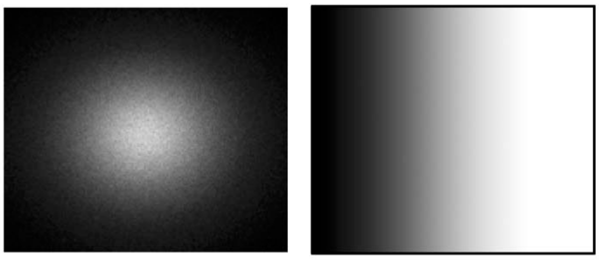

Fig. 8. A point image of simulation result(left) and an edge image (right) converted from the point image using an MATLAB program.

Fig. 9. The CCD image sensor with an optical lens set.

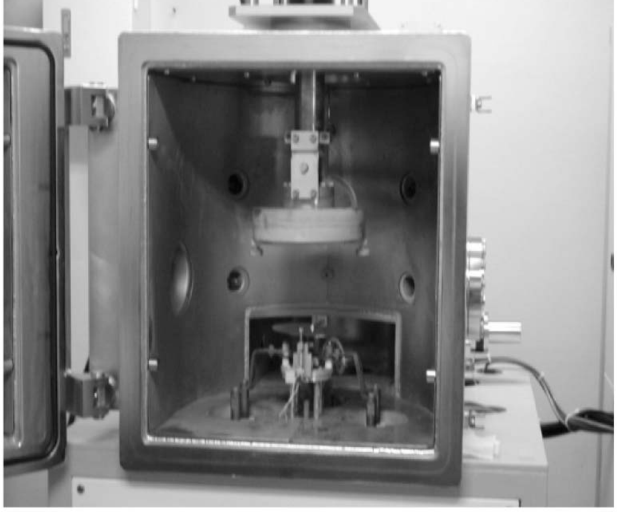

Fig. 10. The thermal evaporator for PVD process.

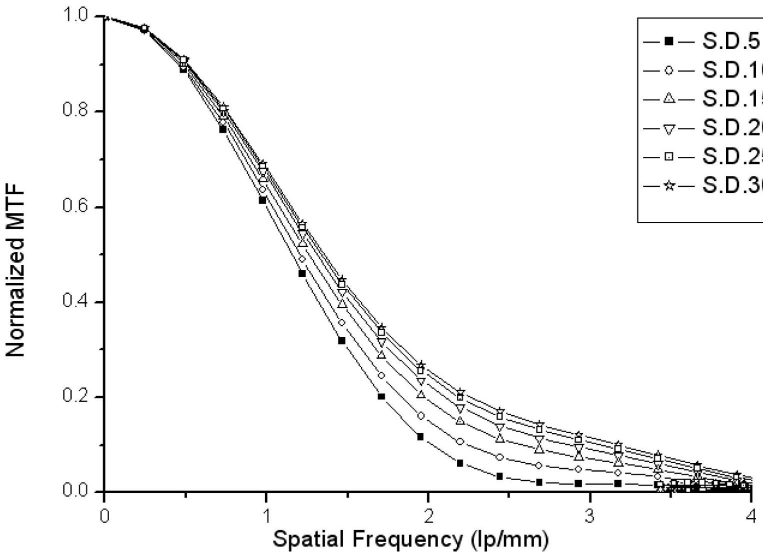

Fig. 11. MTF curves obtained from the edge image of the simulation result varying with standard deviation.

was 1.344. Also, the 0.5 MTF value of simulation result was found to be 1.341 by having percent difference of variation as 8.8%. This tendency satisfies the fact that 0.5 MTF increases as decreasing the height of micro-columnar CsI(Tl) [8]. Therefore it is concluded that the simulation in the CsI(Tl) sample which was fabricated under this condition have high degree of accuracy to predict the light transport.

3. RESULTS AND DISCUSSION

The simulation with the standard deviation of 22° is well coincident with the experiment result of micro-columnar CsI(Tl) film fabricated in the pressure of 0.01 torr and substrate temperature of 31°C. By comparing the MTF curve of another CsI(Tl) which has different height of column with the MTF curve of its simulation, the reliability of this simulation method has been achieved.

Another result of this simulation is that increasing the standard deviation of Gaussian scatterer in the simulation, 0.5 MTF values are elevated from 1.15 to 1.35. It was evaluated that the standard deviation of Gaussian function increased with increasing surface roughness in light scattering experiment [5]. Therefore it is concluded that by increasing the roughness of the each column surfaces, the higher resolution of X-ray image should be obtained. The MTF curves of simulation results are shown in Fig. 11.

4. CONCLUSION

In this research, there were two achievements. Firstly, a new approach to simulate the light transport in scintillator for X-ray imaging was conducted using Light Tools and verified with experiments. And secondly, increasing the roughness of micro-column boundaries of CsI(Tl) in this simulation, the MTF curves are enhanced to have higher resolution of image. As a further research, a method to control and optimize the surface roughness of micro-columns in CsI(Tl) will be performed.

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