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# Characteristics of Plastic Scintillators Fabricated by DLP 3D Printer

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## 1. Introduction

Plastic scintillators have been extensively used in medical health physics dosimetry as in-vivo probes during radiation treatment and therapy [1]. It has various characteristics such as water equivalence over the megavoltage energy range, temperature and pressure independence, and flexibility to manufacture in different sizes and shapes. Various techniques have been used to fabricate plastic scintillation detectors, and the most common technique is a thermal polymerization technique, but it requires a long time of more than two weeks.

In this research, the 3D printer whose method is Digital Light Processing (DLP) was used to make plastic scintillators in an innovatively short time (20 minutes to 2 hours). Three kinds of acrylic monomers were used in the fabrication to see the effect on the detector performance depending on the monomer material. For the monomer which showed the highest light yield, we observed the changes in the performance as a function of the concentration of fluorescent dye and wavelength shifter. In addition, the effect of addition of naphthalene as a diluent was investigated.

## 2. Methods and Results

### *2.1 Digital Light Processing (DLP) 3D printer*

Digital Light Processing (DLP) is a lamp-based process with photopolymer resins which react with the light source and cure to form a solid in a very precise way [2]. A light from the lamp is applied to the entire surface of the vat of photopolymer resin according to the 3D data supplied to the machine (the .stl file), whereby the resin hardens precisely where the light hits the surface. Once the layer is completed, the platform within the vat rises upward by a layer thickness and the process is repeated for the subsequent layer. Figure 1 shows a basic concept of DLP 3D printer. In this research, M-one DLP 3D printer (MAKEX TECHNOLOGY) was used to fabricate plastic scintillators.

### *2.2 Resin Components and Fabrication*

In order to fabricate plastic scintillators by the DLP 3D printer, we prepared resins composed of UV-polymerizable formulations. They are based on an acrylic monomer and doped with a photoinitiator which plays a major role of UV-polymerization. In addition, a fluorescent dye and a wavelength shifter are added so that the wavelength of a scintillation light emitted by the monomer matches the sensitive wavelength region of PMT.

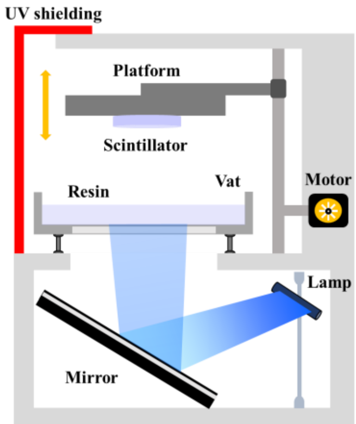


Figure 1. Basic concept of DLP 3D printer.

Table I shows different formulations in this study. The monomers used in the formulations were Isodecyl acrylate (Sigma-Aldrich), Ethoxylated (15 EO) trimethylolpropane triacrylate (Sigma-Aldrich), and Ethoxylated 30 BPA dimethacrylate (Sigma-Aldrich). Hereafter we call the three monomers “M-1”, “M-2” and “M-3”, respectively. Diphenyl(2,4,6-trimethylbenzoyl) phosphineoxide (TPO, aladdin) was used as the photoinitiator. 2,5-Diphenyloxazole (PPO, aladdin) and 1,4-Bis(5-phenyl-2-oxazolyl)benzene (POPOP, aladdin) were added at various concentrations as the fluorescent dye and the wavelength shifter, respectively. Each resin was stirred for 4 hours in a water bath at 70℃. In case of naphthalene addition, the resins were stirred for 2.5 hours.

The size of the fabricated scintillators was 10 × 10 × 5 $mm^3$. The 3D printer should be set as follows: z-axis resolution of 120 μm, burn-in exposure time of 15 sec, modeling exposure time of 15 sec and waiting time of 5 sec.

### *2.3 Estimation of Light Output*

To evaluate the performance of the prepared scintillators, the gamma-ray spectrum of each scintillator was measured. Figure 2 shows the experimental schematic for the measurement.

The $^{137}Cs$ gamma source (full energy peak of 661.7 keV, Compton edge of 477.3 keV) was used. The light yield was determined by the number of photoelectrons per energy unit ($N_{phe}$) which is given by the following equation [3].

$$N_{phe} = \frac{PP_E}{K_E}\frac{K_{1phe}}{PP_{1phe}}\frac{1}{0.477334} \text{ [phe/MeV]} \qquad (1)$$

Table I: Concentration of chemicals in each resin recipe. (PPO, POPOP, TPO and Naphthalene are the fractions based on monomers.)

| Sample Number | Monomer (%) | PPO (%) | POPOP (%) | TPO (%) | Naphth-alene (%) |
|---|---|---|---|---|---|
| 1 | M-1 (100) | 1.5 | 0.08 | 0.5 | - |
| 2 | M-2 (100) | 1.5 | 0.08 | 0.5 | - |
| 3 | M-3 (100) | 1.5 | 0.08 | 0.5 | - |
| 4 | M-3 (100) | 1.5 | 0.03 | 0.5 | - |
| 5 | M-3 (100) | 1.5 | 0.07 | 0.5 | - |
| 6 | M-3 (100) | 1.5 | 0.11 | 0.5 | - |
| 7 | M-3 (100) | 1.5 | 0.2 | 0.5 | - |
| 8 | M-3 (100) | 1.5 | 0.03 | 0.5 | 15 |
| 9 | M-3 (100) | 1.5 | 0.07 | 0.5 | 15 |
| 10 | M-3 (100) | 1.5 | 0.11 | 0.5 | 15 |
| 11 | M-3 (100) | 1.5 | 0.2 | 0.5 | 15 |
| 12 | M-3 (99) | 0.5 | 0.2 | 0.5 | - |
| 13 | M-3 (100) | 1.5 | 0.2 | 0.5 | - |
| 14 | M-3 (98) | 2.5 | 0.2 | 0.5 | - |

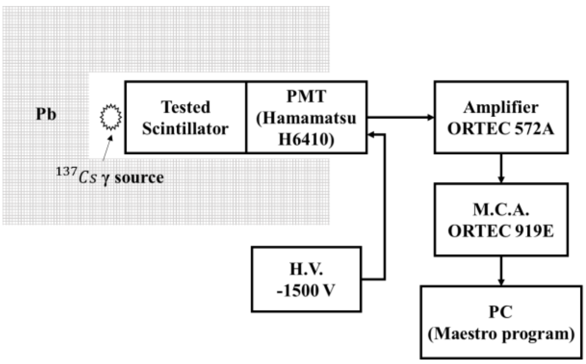


Figure 2. Schematic view of gamma-ray measurement.

This can be achieved through a comparison between the peak position of a single photoelectron spectrum ($PP_{1phe}$) and the specific point of energy spectrum e.g., Compton edge ($PP_E$). $PP_{1phe}$ and $PP_E$ are measured under amplifier's gain $K_E$ and $K_{1phe}$, respectively.

Effective quantum efficiency of PMT ($Q.E._{eff}$) should be considered when calculating the light output because there is a difference in emission intensity spectra of scintillation light from each scintillator. Effective quantum efficiency is the number of photoelectrons emitted from the photocathode and given by the following equation [4].

$$Q.E.(\lambda) = \frac{S \times 1240}{\lambda} \times 100\ [\%] \quad (2)$$

$$Q.E._{eff} = \frac{\int I(\lambda) \times Q.E.(\lambda)\, d\lambda}{\int I(\lambda)\, d\lambda}\ [\%] \quad (3)$$

S is a radiant sensitivity [A/W] of PMT's photocathode (Hamamatsu H6410) and $\lambda$ is an emission wavelength [nm] of plastic scintillator. The emission intensity spectra $I(\lambda)$ [a.u] were measured using Cary Eclipse Fluorescence Spectrophotometer (Agilent). Using the light yield and $Q.E._{eff}$ of each scintillator, light output is calculated by the following equation. The results are summarized in Figure 3.

$$\text{Light output} = \frac{\text{Light Yield}}{Q.E._{eff}}\ [\text{ph/MeV}] \quad (4)$$

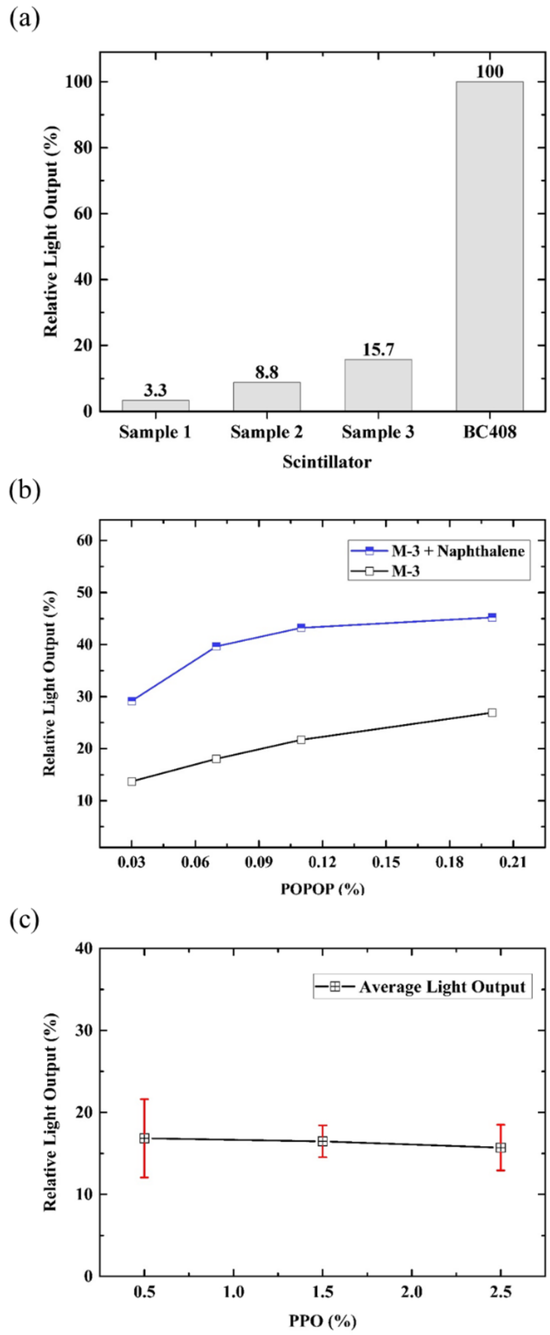


Figure 3. Relative light output (a) with respect to monomers M-1, M-2, M-3 and BC408, (b) POPOP concentrations and addition of naphthalene and (c) PPO concentrations. Relative light output is based on that of the commercial plastic scintillator (BC408).

In Figure 3(a), Sample 3 based on M-3 showed the highest light output (15.7%). It is found that the number of benzene rings in the resin affects scintillation light output. In Figure 3(b), it was shown that the increase of wavelength shifter POPOP up to 0.2% and the addition with naphthalene 15% improve scintillator light output. In Figure 3(c), there was no significant change in the performance with respect to the increase of fluorescent dye PPO. It should be noted that the reproducibility of the result was the range from 10 to 30% in terms of standard deviation.

## 3. Conclusions

In this study, three types of tests were carried out. The light output relative to that of BC408 commercial plastic scintillator was estimated and compared. The highest light output was 45.2% for Sample 11. As a next task, we will investigate the performance of scintillators based on non-acrylic monomers fabricated by 3D printer.

## REFERENCES

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