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Radiophotoluminescence light scope for high-dose dosimetry

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HIGHLIGHTS

- A radiophotoluminescence (RPL) light scope was developed for high-dose dosimetry.
- The RPL light scope has high sensitivity and accuracy in high-dose dosimetry.
- Two-dimensional radiation dose distribution was obtained by the RPL light scope.

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ABSTRACT

A radiophotoluminescence (RPL) light scope is a remote-sensing technique for measuring in situ the radiation dose in an RPL detector placed at a distance. The RPL light scope is mainly composed of an ultraviolet (UV) pulse laser, telescopic lenses, a photomultiplier tube, and camera modules. In a performance test, some RPL detectors were placed at distances up to 30 m and were illuminated with a pulsed UV laser beam. The photoluminescence responses of the RPL detectors were analyzed using this scope. Their radiation doses were determined from the amplitude of the given component of the photoluminescence responses. The RPL readout could be repeated without fading, and its amplitude exhibited good linearity at a dose ranging from 0.1 to 60 Gy. Furthermore, a two-dimensional distribution of radiation dose was obtained by laser scanning on an RPL detector. It was confirmed that the RPL light scope was a useful remote-sensing tool for high-dose dosimetry.

1. Introduction

On 11 March 2011, an earthquake of 9.0 magnitude and the subsequent tsunami caused serious damages to the Fukushima Daiichi nuclear power plant (1F). Large amounts of radioactive particles were released from the 1F into the natural environment. The high levels of radioactivity prevented workers from approaching the broken nuclear reactors in the 1F. The spatial distribution of the radioactivity in the 1F is intricate due to the hydrogen explosions and the leakage of radioactively contaminated water. Radiation monitoring in the 1F is important at the primary decommissioning stage for the 1F. Appropriate radiation detection systems for the 1F need to be developed. The aim of this study is to develop a remote radiation-detecting system with a passive radiation dosimeter.

Silver-activated metaphosphate glass is widely used as an accumulation-type radiation dosimeter (Piesch and Burgkhardt, 1994; Ranogajec-Komor et al., 2008; Yamamoto et al., 2011). When ionizing radiations produce electron–hole pairs in the glass, radiophotoluminescence (RPL) centers are formed by the trapping of electrons (or holes) at the Ag^{+} centers (Yokota and Imagawa, 1967). The RPL centers emit light of wavelength 635 nm upon exposure to ultraviolet (UV) light. The RPL response exhibits high sensitivity and excellent linearity over a wide dose range. The RPL readout can be repeated without fading. In this respect, RPL glass dosimeters are superior to other passive radiation dosimeters such as thermoluminescent detectors and optically stimulated luminescence detectors (Knežević et al., 2013).

In our previous works (Sato et al., 2014; Zushi et al., 2014), we proposed an RPL photographing technique for visualizing high-level radiation fields. A number of RPL glass detectors were placed in a high-level radiation field. The RPL glass detectors were

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brightened with a UV-light-emitting diode (LED)-assembled illuminator, and an RPL photograph was taken with a digital camera. The spatial dose distribution was obtained through the digital image processing of the RPL photograph. This RPL photographing technique can be easily applied for high-level radioactivity. However, this was not suitable for remote sensing, because the radiation dose readout depended on the lighting condition. In this study, a new RPL light scope was developed. The RPL light scope employs a remote-sensing technique to measure in situ the radiation dose of an RPL detector placed at a distance. The operating principle of the RPL light scope is based on the analysis of the decay time components of the photoluminescence (PL) (Piesch et al., 1986).

Fig. 1 shows a photograph of a performance test of the RPL light scope. The scope is mainly composed of a UV pulse laser, telescopic lenses, a photomultiplier tube (PMT), and a camera module. An RPL detector is set at a distance from the scope. A pulsed UV laser beam is emitted from the scope to the RPL detector. Fast-response PL light from the RPL detector is measured through the telescopic lenses by the PMT. The distance between the scope and the RPL detector is obtained from the time duration between the laser triggering and PL signals. The radiation dose is measured in situ from the amplitude of the given component after the fast-response PL light. Furthermore, the direction of the laser beam is controlled by two mirror galvanometers (MGs) in the RPL light scope. Laser scanning and data processing can provide a two-dimensional (2-D) radiation dose distribution.

As for the other remote radiation-monitoring technique (Watanabe et al., 2013; Teichmann et al., 2013), the scintillation photons were transmitted via the optical fibers to one central reader. The detectors could be placed regardless of the light path. For an RPL light scope to operate suitably, a light path for the target and an appropriate dark environment are necessary.

2. Methods

Silver-activated metaphosphate glass was produced from reagent-grade powders using a melting method (Lee et al., 2011; Sato et al., 2013). $NaPO_3$, $Al(PO_3)_3$ and AgCl powders were mixed in a mullite crucible. The mullite crucible was placed in an electrical furnace, and its temperature was gradually raised to 1200 °C over the course of 10 h. The melting glass was maintained at this temperature for 5 h for homogenization. After the homogenization, the melting glass was slowly cooled to room temperature over 10 h. The atomic composition by weight in the RPL glass was as follows: O (51%), P (32%), Na (11%), Al (6%), Ag (0.1%), and Cl (<0.01%). The cooled glass rod was cut into pieces with a rotating diamond saw blade. The glass pieces were pulverized by a jet mill, and the pulverized particles were classified using 75- and 150-μm sieves. The pulverized particles were solidified with a polyurethane resin (Nissin Resin Co. Ltd) to fabricate RPL detectors of 3-mm thickness.

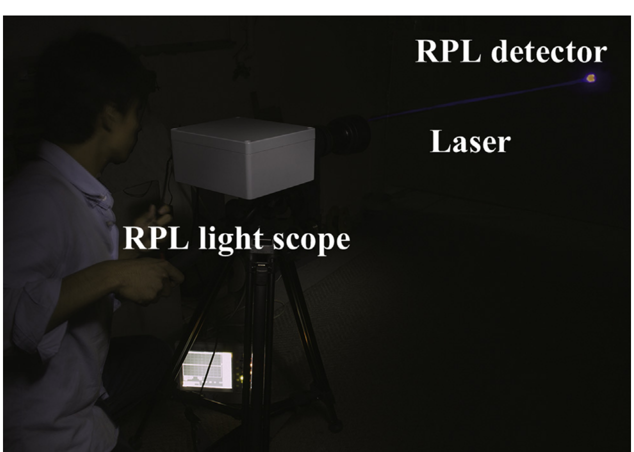

Fig. 1. Photograph of RPL light scope. An RPL detector is placed at a distance from the RPL light scope. The radiation dose of the detector and the objective distance are measured in situ by analyzing the PL and RPL responses.

Fig. 2 shows examples of the time-resolved PL spectra of RPL glass. The PL induced by 355-nm laser pulses was detected with a PMT through a scanning monochromator. Then such PL data were organized into the time-resolved PL spectra. The dose-dependent RPL had a broad peak with a wavelength of approximately 635 nm (Kurobori and Nakamura, 2012). However, the PL around 635 nm included some dose-independent intrinsic components. PL has been reported to have at least three different decay time components: the short-term component (<2 μs), the RPL component (2–10 μs), and the long-term component (>20 μs) (Piesch et al., 1986). The short- and long-term components are dose independent and are called “predose” in the RPL readout process.

Fig. 3 shows the experimental setup of the RPL light scope, which is mainly composed of a 355-nm pulse laser, telescopic lenses, a camera module, a PMT, and a PC-based digital storage oscilloscope (DSO). The UV pulse laser (FTSS 355-50, CryLaS) was operated at a pulse duration of 1 ns and a repetition rate of 1000 Hz. The pulse energy was 30 μJ. An electrical beam blocker was set to control the ON/OFF of a laser beam. The laser beam was directed using the two MGs. The 355-nm light was invisible to the naked eye. The telescope lens (TL2) was used for adjusting the laser beam spot size. However, the laser beam caused blue PL from the polyurethane resin of the RPL detector. The intensity of the blue PL was dose independent. Then, the laser spot could be easily confirmed with the naked eye. The beam splitter (BS1) split the beam and produced two focal points. The focal point on the image sensor of the charge-coupled device (CCD) was manually adjusted on the telescope lens (TL1, EF70-300 mm F4-5.6 IS USM, Canon). The RPL detector was clearly observed by the CCD with an exposure time of 1 s. The laser beam spot was generally focused in the field of view of the CCD. After this focus for the CCD, another focal point was roughly focused on the light-receiving face of the PMT, which was 8 mm in diameter. Even if it was a little out of focus, the RPL photons certainly entered the light-receiving face.

The RPL photons were effectively detected using the PMT (R9880U-20, Hamamatsu Photonics) with 635-nm band-pass interference filters. The resulting signals were stored in the DSO (HDO6104, Teledyne LeCroy). Their waveforms were analyzed with a homemade program for analyzing the decay time components as shown in Fig. 4 (Maki et al., 2011). The distance between the RPL light scope and the RPL detector was accurately determined from the time duration between the laser triggering and PL signals. The integrated value P of the PL at times ranging from 2 to 10 μs was calculated. In addition, the integrated value Q for the long-term component was evaluated by interpolating the decay curve of the long-term component over 40 μs. In our previous research (Ihara et al., 2008; Maki et al., 2011), the integrated value $P-Q$ was found to be precisely proportional to the radiation dose. This process is reasonably effective for improving the signal-to-noise ratio at a low dose level.

An RPL detector was placed in front of a 40-kV X-ray tube. During and after X-ray irradiation, the RPL responses were measured in situ by the RPL light scope at a distance of 3 m. In the other test, an intense ^{60}Co gamma ray source was shielded by lead blocks with a 10 × 20 mm window. An RPL detector plate of dimensions 110 × 120 × 3 mm was used to monitor the radiation dose. The laser scanning and data processing provided the 2-D radiation dose distribution.