Development of Optical Diagnostic System for Burning Plasma Machine

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Abstract. A possibility of applying a compact optical diagnostics to nuclear systems, such as detecting high energy neutrons, ions and gamma-rays with a wide dynamic range_at elevated temperatures in a nuclear fusion system, has been studied, utilizing radiation resistant optical fibers and radioluminescence (radiation-induced luminescence) materials. Appropriate radioluminescence materials were found for dosimetry of each radiation field, namely, gamma-rays and ions, and neutrons. Especially, a high-energy neutron detection system utilizing optical fibers and radioluminescence materials will have several advantages, such as compact and robust, and can be a strong candidate for diagnostics of fusion neutrons in a burning plasma machine.

1. Introduction

Detailed diagnostics of radiation environments is vital for effective and safe operations of ITER. Up to now, major radiation dosimetry systems are utilizing electrical technologies, such as an ionizing chamber, and a fission chamber. However, in general, electrical technologies need to have high voltage power supply into high radiation-flux regions, which strongly demands a robust electrical insulating system. Electrical insulating materials are susceptible to a phenomenon called radiation induced electrical conductivity (RIC) [1] and they decrease their electrical resistivity (increase their electrical conductivity) under an electronic excitation radiation. Resultantly, a system tends to be voluminous and it sometimes cannot be deployed in a limited space, though steady efforts to miniaturizing a system are under way, such as a development of micro-fission chamber. Furthermore, the electrical insulators increase their electrical conductivity with increase of the temperature. As a rough evaluation, their electrical conductivity will be larger than 10^{-6}S/m above 600C and they cannot work properly as electrical insulators for an extended period.

Also, a heavy radiation environment generates electrical noises. For example, in light water reactors (LWRs), their core regions, in general, have a biased voltage up to 10V to the ground voltage and an electrical wires inserted there have electrical currents of about a few nano A, which will vary depending on variation of a local intensity of radiation. Especially, in case of a nuclear fusion reactor, the system itself will generate strong electrical noises caused by an electromagnetic field as well as by high temperature plasmas. For electrical diagnostics, appropriate signal intensity must be ensured against these strong electrical noises.

Optical radiation detection systems will solve these problems described above. However, until recently, there was no way to extract optical signal out of heavy radiation environments. In general, optical materials are vulnerable to heavy irradiation effects and they lose their optical transmissivity easily under irradiation. In the last decade, efforts were made to improve radiation resistance of fused-silica (SiO_2) core optical fibers (hereafter simply denoted as optical fibers), especially under the ITER-EDA (Engineering Design Activity) framework [2]. Several radiation-resistant optical fibers were developed [3] and are still under development. With the radiation-resistant optical fibers, a simple-structured, compact and robust radiation detection system can be established. For that purpose, a development of sensor-materials is vital.

Several radioluminescence materials (scintillator) have been already developed, but most of them are not refractory and cannot be used at elevated temperatures, such as sodium iodine (NaI). Even refractory scintillators such as ruby (chromium doped aluminum oxide; Al_2O_3-Cr) do not work as a scintillator at elevated temperatures, because their radioluminescence will decrease its intensity substantially above 300C, due to a phenomenon called "thermal quenching".

In the present study, radioluminescence materials were surveyed for diagnostics of radiation environments. Potential candidates were found for high-energy neutrons, ions and gamma-rays, some of which work even at elevated temperatures. The paper will describe radioluminescence behaviors of candidate materials under high-energy neutrons, ions and gamma-rays, sometimes as a function of temperatures. The present results indicate that an optical radiation detection system can be constructed, which will be compact and robust and can be applied to ITER and burning plasma machines.

2. Experimental setups

A candidate radioluminescence material was attached at one end of a radiation resistant optical fiber and was exposed to radiation. The radiation sources used in the present study were, a fission reactor of Japan Materials Testing Reactor (JMTR) of Oarai Research Establishment in Japan Atomic Energy Research Institute (JAERI), with a fast (E>1MeV) and a thermal (E<0.68eV) neutron flux in the range of 10^{15}-10^{17} n/m^{2}s and 10^{15}-10^{18}n/cm^{2}s, respectively in the temperature range of 100-800C. The associated gamma-ray dose rate was in the range of 0.1-1 kGy/s. For the fusion neutron irradiation (14MeV neutrons), the facility of Fast Neutron Source (FNS) in JAERI-Tokai was used, with a neutron flux of $10^{10\text{-}13}$n/m^{2}s in the temperature range of 20-150C. The associated gamma-ray dose rate was marginal and less than 10^{-2}Gy/s. The Cobalt-60 irradiation facilities in JAERI-Takasaki and in the faculty of quantum science in Tohoku University were used for the gamma-ray irradiation, whose dose rate was about 5Gy/s and about 10^{-2} Gy/s, respectively, in the temperature range of 20-400C. For ions, a tandem type accelerator in Institute for Materials Research of Tohoku University was used with hydrogen and helium ions of energies of 0.8-1.6MeV. Radioluminescence from a specimen was guided through the optical fiber to a measuring system. Detailed experimental setups are described elsewhere [3-9]. In the present paper, results on the gamma-rays and fusion neutrons are mainly described, emphasizing possibility of detecting high energy neutrons by an optical detection system.

3. Experimental results and discussions

3-1. Ions and gamma-rays irradiations

For measuring a gamma-ray flux, several radioluminescence materials are now available, such as chromium doped alumina (ruby) (Al_2O_3-Cr), europium oxide (EuO_2), and gadolinium oxide (GdO_2), which are insensitive to neutrons. Figures 1-3 show radioluminescence spectra under the gamma-ray irradiation. Here, it should be noted that the silica core optical fiber itself also generate radiation induced luminescence, which is composed of a peak at 450nm and a Cerenkov radiation in the case of gamma-irradiation. [3,4] However, superimposed radioluminescence from the optical fiber can be easily subtracted from the obtained spectra as shown in Fig 4 for the case of ruby. The ruby is well-known radioluminescence material and it can work as a gamma-ray detector with a wide dynamic range from 10^{-3}Gy/s to 10^{3}Gy/s. However, the intensity of its peak at 690nm decreases rapidly with increase of a displacement irradiation dose and with increase of the irradiation dose and with rise of the temperature as shown in Fig. 5. The ruby is a dopant-activated luminescent material and the +3 chromium ions tend to agglomerate at elevated temperatures in the alumina matrix. Also, the optical transition bands responsible for the radioluminescence will be susceptible to a so-called thermal quenching effect in its alumina matrix. [7,10]

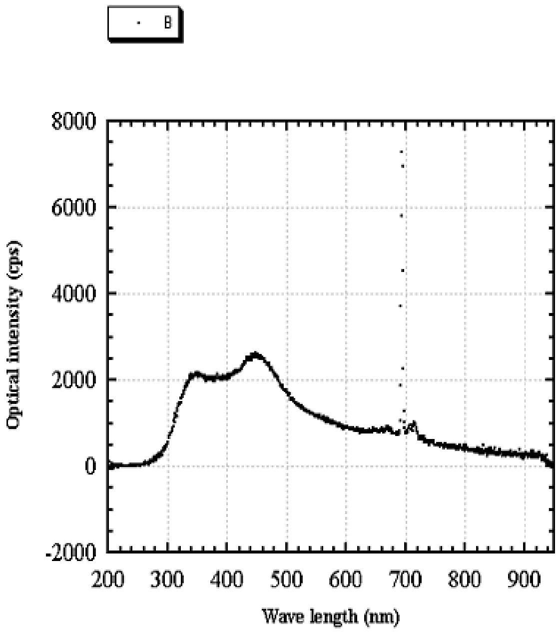


Figure 1 Radioluminescence spectrum of ruby (Al_2O_3-Cr) at about 690nm along with radioluminescence and Cerenkov from silica optical fiber under gamma-ray irradiation.

In the meantime, intensity of the radioluminescence peaks from the europium oxide and the gadolinium oxide showed more stable behavior with increase of the displacement dose at elevated temperatures. Figure 6 shows intensity of the radioluminescence of europium oxide at 613nm under the gamma-ray irradiation as a function of the temperature. The europium oxide was found to be an intrinsic luminescent material. In the meantime, some impurities are responsible for the radioluminescence in the gadolinium oxide. It is assumed that the gadolinium oxide has good electronic structures as a matrix for evolving radioluminescence of impurities in it. Probable impurities will be rare-earth elements nearby the gadolinium in the periodic table.

Figure 2
Radioluminescence spectrum from europium oxide (Eu_2O_3) under gamma-ray irradiation.

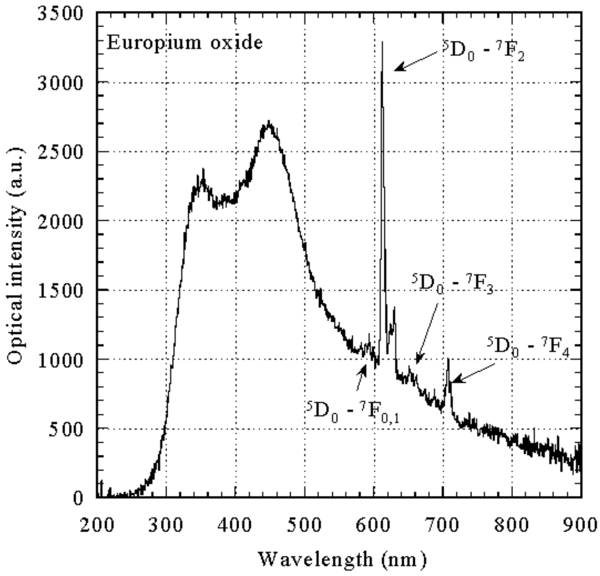


Figure 3
Radioluminescence spectrum from gadolinium oxide (Gd_2O_3) under gamma-ray irradiation.

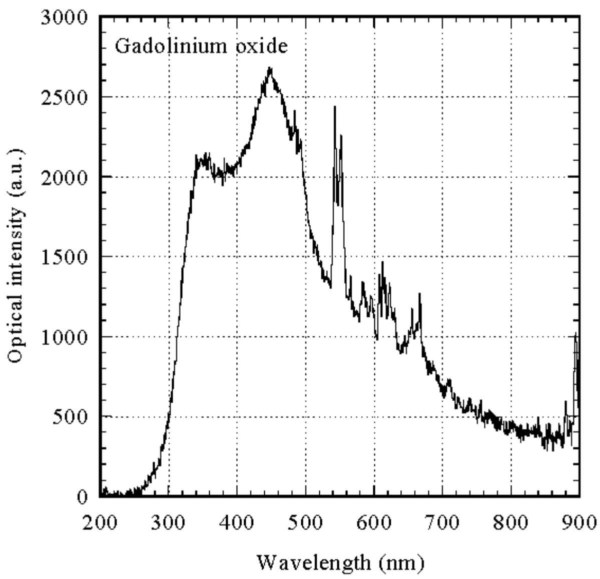
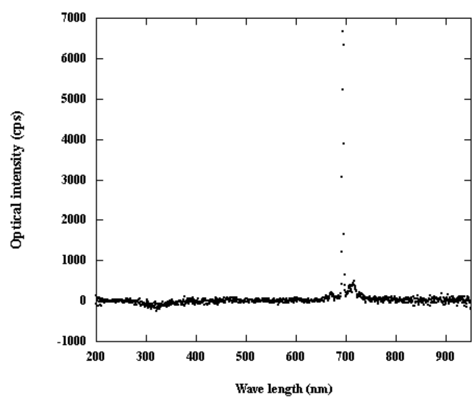


Figure 4
Spectrum obtained by subtracting radioluminescence of fused silica from radioluminescence of ruby shown in Fig. 1, under gamma-ray irradiation.



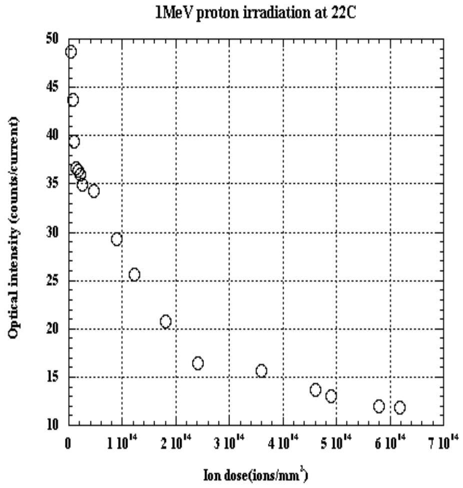


Figure 5 Optical intensity of radioluminescence peak at 690nm from ruby under proton irradiation. [7,10]

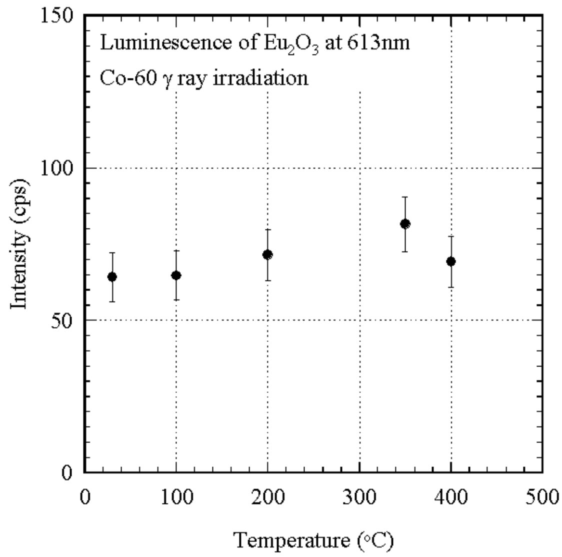


Figure 6 Temperature dependence of radioluminescence of europium oxide under gamma-ray irradiation.

A gamma-ray and ions measuring system with a dynamic range of 10^{-3}- 10^{5}Gy/s could be realized with the europium and gadolinium oxides in a temperature range of room temperature to 300C. The system could be applied not only to a post-irradiation facilities and remote maintenance systems but also to a near plasma region. Ion-probings at burning plasma edge will be also possible with the present system.

3-2. high-energy neutrons

A development of reliable diagnostics of high-energy neutrons is one among most important scientific and engineering topics for successful operation of a burning-plasma machine such as International Thermonuclear Experimental Reactor (ITER). Several techniques have been under consideration and some of them were demonstrated their possible feasibility in current machines, but with very low neutron flux&fluence and an associated low gamma-ray flux. A fusion-neutron diagnostic system should operate reliably with a neutron flux up to 10^{13}n/m^{2}s and an associated gamma-ray dose rate up to 1Gy/s, in an ITER-like machine. To be compatible with a realistic and expensive maintenance scenario, a system would better to survive a neutron fluence of 10^{21}n/m^2.

Several materials, which were expected to radiate luminescence, were attached at an end of a radiation resistant optical fiber whose core-diameter was 0.2mm and were exposed to high energy neutrons generated in FNS. The fast neutron flux was in the range of 10^{10-13}n/m^{2}s in the FNS and the gamma-ray dose rate was bout 5Gy/s in the JAERI-Takasaki gamma-ray facility. An optical signal was guided through a 30 m long radiation resistant optical fiber to a measuring instrument composed of an optical grating and a CCD, the PMA-11 made by Hamamatsu Photonics Co. Ltd.

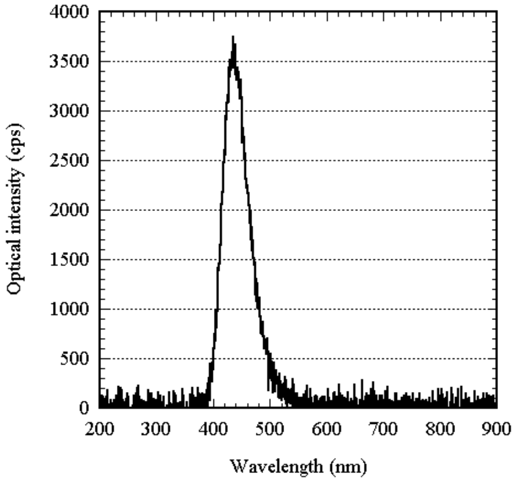


Figure 7 Radioluminescence spectrum of ZnS-Ag under 14MeV neutron irradiation.

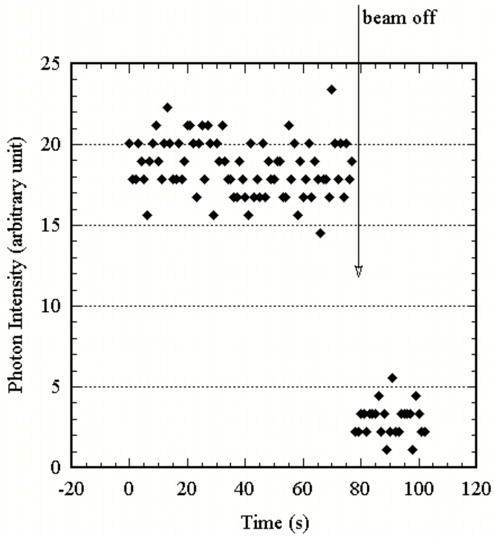


Figure 8 Change of radioluminescence intensity of ZnS-Cu at FNS shutdown.

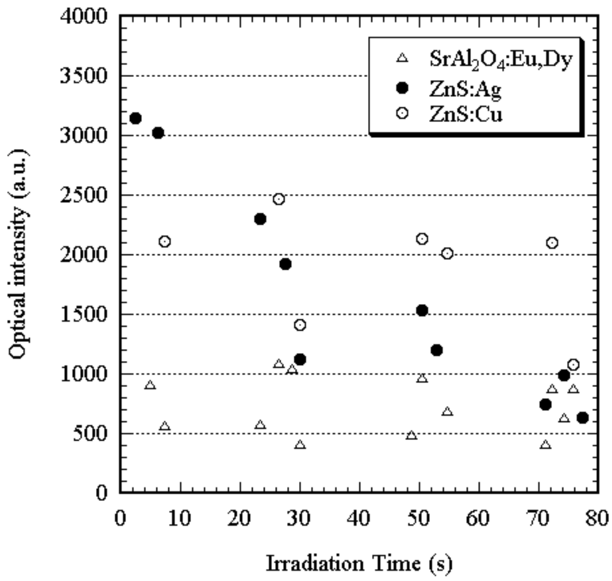


Figure 9
Change of intensity of main radioluminescence peaks under 14MeV irradiation.

Three materials, silver activated zinc sulfide (ZnS-Ag), copper activated zinc sulfide (ZnS-Cu), and a strontium aluminate doped with europium and dysprosium ($SrAl_xO_y$-EuDy), were found to be radioluminescent, being sensitive to high energy neutrons with a peak position at 450nm, 570nm, and 500nm, respectively, having a half width of 75-150nm. Figure 7 shows a luminescent spectrum from the ZnS-Ag under a fast neutron flux of about 10^{12}n/m^{2}s. Intensity change of the radioluminescence of ZnS-Cu was shown at the FNS shutdown in Fig. 8. With the 14MeV neutron-beam off, the radioluminescence suddenly disappeared. The time resolution is less than a few seconds. So, the radioluminescence was not caused by radioactivity induced by nuclear transmutations. The ZnS-Ag behaved similarly, but in the case of $SrAl_xO_y$-EuDy, the radioluminescence kept its intensity more than a few hours after the 14MeV neutron-beam off. This will be due to so-called long-lasting phosphorescence of the $SrAl_xO_y$-EuDy.

The ZnS-Ag had the strongest luminescence among three but its intensity decreased with the increase of neutron fluence, in the meantime, the other two, the ZnS-Cu and the $SrAl_xO_y$-EuDy had relatively weak luminescent intensity but their peak intensity did not change substantially with the fast neutron fluence up to 10^{20}n/m^2. Changes of the luminescent peak intensities are shown in Fig 9 as a function of irradiation time. For a high sensitivity, the ZnS-Ag is the best among three, but for a long-term stability and being free from frequent re-calibration or replacement, the ZnS-Cu and the $SrAl_xO_y$-EuDy are preferable.

Under the gamma-ray irradiation, three materials show_weak radioluminescence. Contribution from the gamma-ray is negligible under the 14MeV neutron irradiation as can be seen in Fig. 8. There, the gamma-ray dose rate to the radioluminescence material was mainly from stainless steel structures around it and it kept its intensity even after the 14MeV neutron beam-off. Also, it should be noted that the wavelength of the main radioluminescence spectrum is different between the gamma-ray and the 14MeV neutron irradiations. Discrimination between radioluminescence caused by the gamma-ray and the 14MeV neutrons is possible by detailed spectrum analysis.

The present system can detect the fast neutron flux down to 10^{11}n/m^{2}s with an integration time of 10 s. However, it is estimated that the system can detect a fast neutron flux down to 10^9n/m^{2}s with an integration time less than 1 s, with a photomultiplier system working at a fixed optical wavelength region. A dimension of a sensing element will be in the order of 0.1mm in diameter. Thus, the present results showed that the optical fast neutron detecting system with a high space resolution can be composed with a radiation resistant optical fiber and a neutron sensitive ZnS-Cu element, which is compact and easy to install and dismantle in a limited space in a burning plasma machine such as the ITER.

4. Summaries

Compact, simple and robust optical radiation-detection systems were proposed, with radioluminescence materials attached at one edge of a radiation resistant optical fiber. The system has sensitivity to gamma-rays, ions, and 14MeV neutrons. Some of radioluminescence materials can work at elevated temperatures. The proposed system can be applied to heavy irradiation environments in various nuclear systems, such as in-core region in advanced fission reactors and in near-plasma regions in a nuclear fusion reactor.

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