SOME NEW OPTICAL TECHNIQUES FOR REACTOR INSTRUMENTATION

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Abstract

Fibre optics is expected to emerge as a new means of reactor instrumentation, not only for signal transmission, but also for distribution sensing of temperature and radiation dose level in and around the reactor plant. Recently, fluorine-doped fibre optics were shown to be radiation resistant up to 10^{19} n/cm^2. A micro-photo multiplier is being developed using a lithography technique for fibre optics of 100 μm diameter. Resonance ionisation spectroscopy through laser is applied to the detection of fission fragments. Preliminary experiments concerning Xe-isotope detection of the tag gas FFD system are considered, as is the sophisticated concept of reactor control by laser. Several topics currently being reviewed by our group are discussed.

Introduction

Currently, optical techniques are being widely applied in many industrial and scientific research fields. For example, fibre optics is essentially important in the modern community as the digital signal transmission line.

Distribution sensing through fibre optics is a very interesting technique, as temperature distribution can be measured simultaneously along the 1~2 km range of the fibre optics with an accuracy of 0.1°C.

The application of fibre optics to nuclear reactor instrumentations has, however, been limited in the area of low radiation dose level due to its radiation damage effects, while it has already been introduced in nuclear power plants as the signal cable and the image guide system.

The most important recent event is the development of fluorine-doped fibre optics, which can be made available in high radiation dose up to 10^9 Gy or 10^{19} n/cm^2 [1]. Using this fibre optic, a systematic development of research studies with regard to the application of distribution fibre sensing in nuclear power plants can be expected.

The research study on the distribution measurements of radiation level by the fibre optics are conducted in several ways. One approach is using plastic scintillating fibre optics, and another is the application of the Raleigh-Thompson scattering phenomena of laser light in the fibre optics.

Additionally, a micro-optional sensor to fit the diameter of the fibre optics is now under research using the lithography technique [2]. Its structure is similar to the well-known micro-channel plate (MCP), the electron multiplication of which is, however, the same as the photo multiplier. Therefore it is called the micro-photo multiplier.

Laser techniques are also interesting in the many fields of scientific and industrial measurement system. Here, we review various sophisticated applications of laser techniques to reactor instrumentations which are in progress at our laboratory.

One of these is the ultra high sensitive elemental analysis through Resonance Ionisation Spectroscopy (RIS) by laser, especially applied to the detection of fission product isotopes such as Xe. The main feature of this technique is the detectability of the small amount of the FP atoms lower than 10^6, without regard to their half-lives and radio-activities.

Another application is the development of the Nuclear Pumped Laser (NPL) as a self-powered neutron detector using the ^{3}He-Ne-Ar gas system. The idea of neutron spin orientation by laser is also discussed; this leads to the development of new concepts such as reactor control by laser and neutron spin oriented reactor.

Radiation distribution measurements by fibre optics

As is mentioned above, this has been realised in several ways. One typical approach is the utilisation of plastic scintillating fibre optics (PSF) in which the core part of the fibre optics is made by a plastic scintillator instead of silica glass. These PSF are already provided commercially by several companies.

A block diagram of the PSF measurement system is shown in Figure 1. The radiation incident position in the PSF is determined by the time of different method of the two signals from the photo multipliers attached to both ends of the PSF.

A typical result is shown in Figure 2, which is obtained from the PNC's fast experimental reactor JOYO. The spatial resolution is about 30 cm in these data; this will be improved by the numerical correction method and through the use of fast electronics with better time resolution.

Figure 1. Block diagram of PSF and typical MCA data

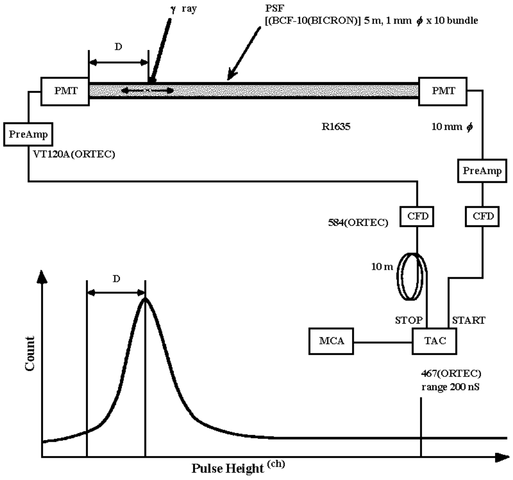
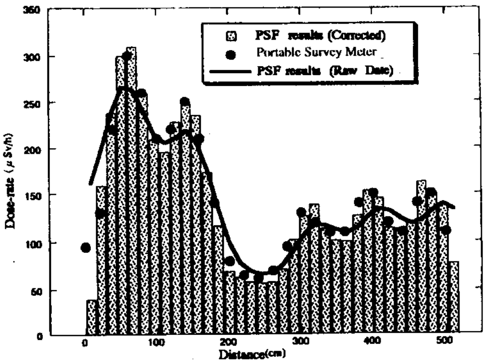


Figure 2. Radiation dose distributions measured by PSF compared to portable survey meter



As the diameter of each PSF is about 100 μm – sometimes too small to show enough detection efficiency – the bundle PSF is often used although the PSF flexibility is slightly reduced.

The effective length of the PSF is about 10 m depending on the scintillator photon numbers produced by radiation due to the scintillation light attenuation in PSF. Then the standard glass fibre can be attached to the PSF as the light guide.

Another approach for measuring radiation distribution is realised by practically combining the small scintillator with the light guide fibre optics, which has been successfully applied to the neutron flux measurement of the critical assembly of the Kyoto University Research Reactor Institute [3].

In the higher radiation level, the Thompson scattering effect is shown by the colour centre produced in the fibre optics. Therefore, the radiation induced attenuation rate of the fibre can be investigated by means of the so-called “Optical Time Domain Refractometry” (OTDR) method. The applicability of the OTDR method to radiation distribution sensing has been examined experimentally in our group.

Development of radiation-resistant fibre optics

It is well-known that commercial fibre optics are affected by the radiation irradiation that is known as the radiation-induced loss of fibre optics. Although a complete understanding of this mechanism of radiation-induced loss has not been obtained, the radiation-induced radical in fibre optics may produce the colour centre to absorb the light.

Currently, developments have been made with regard to radiation resistant fibre optics through the control of OH radical content in the fibre; under these circumstances, some improvement has been detected.

Recent dramatic improvements have been made using fluorine-doped fibre optics, in which radiation-induced radicals are thought to be stabilised through combining the fluorine atoms not to be colour centre [1].

In the manufacture of fluorine-doped fibre, great care has been taken not to produce any micro-cracks in the fibre through the control of procedures and environments; this is a comment of the manufacturer.

Fibre optics have been examined in the radiation environment of the core test region of Japan Material Testing Reactor (JMTR) at JAERI. Typical results are shown in Figures 3 and 4. It can be shown that this fibre is available up to neutron irradiation of 10^{19} n/cm^2 and 10^9 Gy of gamma ray irradiation at the temperature of 370K [1].

This radiation resistant fibre optics is expected to be utilised in many reactor instrumentations such as fibre scope observation in the reactor core, process measurements in and around the core and also the signal transmission line in these areas. In particular, the distributed sensing of the fibre optics is thought to improve the monitoring point density in the reactor. More research studies on fibre sensing are systematically required.

Temperature distribution sensing in radiation environment

A typical example of distribution fibre sensing is the temperature measurement based on the Raman Scattering Phenomena in the fibre. This is available as a commercial product. The applicability of this kind of fibre sensing is examined experimentally in radiation environments, the results of which are presented in the next paper [4].

Figure 3. Reactor radiation test of fluorine-doped fibre optics in JMTR [1]

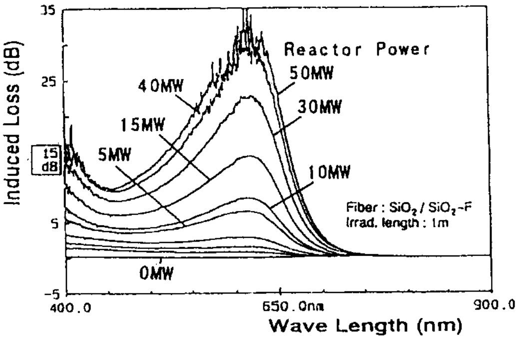
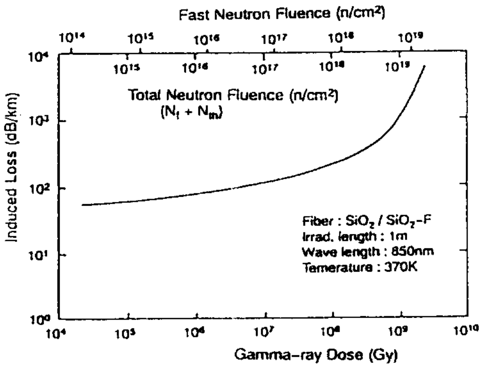


Figure 4. Radiation-induced loss of fluorine-doped fibre optics at 850 nm light [1]



Development of micro-photo-multiplier

The photonic signal from fibre optics is usually detected by the photo-multiplier or the photo-diode depending on the output photon intensities. These two light sensors are generally too large in diameter compared to fibre optics which possess a diameter of 100 μm.

A new concept of micro-photo multiplier has been proposed by researchers at the University of Tokyo, where the required electron multiplication processes are made in the small inner wall of the 100 μm diameter hole produced in the silicon plate utilising lithography techniques. The size and shape of the hole have been determined to show the expected electron multiplication phenomena.

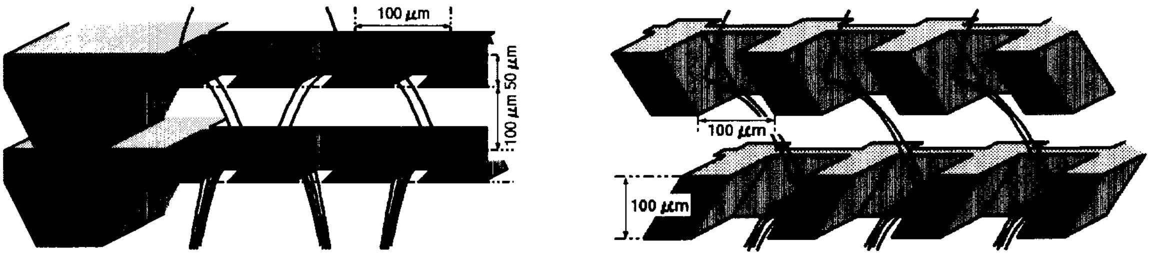
Two kinds of practical micro-photo multiplier elements have been manufactured by two different companies: Sumitomo Precision Products. Co. Ltd. and Sumitomo Electronic Industries Ltd. Models made by the respective manufacturers are shown in Figures 5 (A) and (B).

Preliminary examinations of these micro-electron multiplier plates have shown the possibility of practical applications. These test experiments show that each electron has a multiplier factor of 2~3 when the dynode voltage is applied to the plates at about 150~200 volts.

Figure 5. Two types of produced micro photo-multiplier

(A) Pyramid-shaped micro-PM

(B) Slanting hole micro-PM



Although the electron multiplication effects can also be obtained by the micro-channel plate (MCP), which has almost the same size hole as the present micro-photo multiplier, the proportionality to the incident electron numbers after multiplication is greatly differential. The micro-photo multiplier demonstrates the best proportionality as the standard size photo-multiplier, while the MCP shows the worst. The signal read-out system is now under development from the arrayed micro photo-multipliers. Thus, many fibre optics can be simultaneously connected to this device; this is a necessary measure, as the bundled fibre optics are required for the multi-purpose distribution measurements.

Laser RIS for fission products detection

The Resonance Ionisation Spectrometry (RIS) mechanism is well known for application to U-235 nuclear fuel enrichments by laser technique. Basically, the main feature of RIS is an ultra high-sensitive detection of each isotope atom in the specimen [5], and it is possibly applicable to medium atomic number atoms that have low ionisation potential energy. Therefore RIS can be easily applied to fission products detection when the FP has a long half-life or even if it has been disintegrated.

The RIS system has been experimentally examined for the measurement of the Xe-isotope ratio that is used as the tagging gas of the failed fuel detection and location (FFDL) of the fast breeder reactor.

The RIS system is shown in Figure 6, and Figure 7 shows the typical result for the Xe gas sample of the natural isotopic abundance. From this experiment, the Xe atom detection limit has been estimated to be about 500 atoms/8 $\times$ 10^{-5} cc at the laser intensity of 0.3 mJ/pulse, where the volume of 8 $\times$ 10^{-5} cc corresponds to the laser irradiated zone.

Further experiments are planned to measure the contamination map of Cs-137 in the reactor system using the RIS system, as this system is applicable for the detection of radio isotopes with longer half-lives.

Nuclear pumped laser and reactor control by laser

Experimental studies on Nuclear Pumped Laser (NPL) have a long history, and the most recent topic of interest is a mixed NPL gas cell of ^{3}He-Ne-Ar which has been lased experimentally under the neutron irradiation of 10^{12} or 10^{15} n/cm^2 sec [6].

Figure 6. Block diagram of laser RIS system with TOF mass spectrometer for Xe gas detection

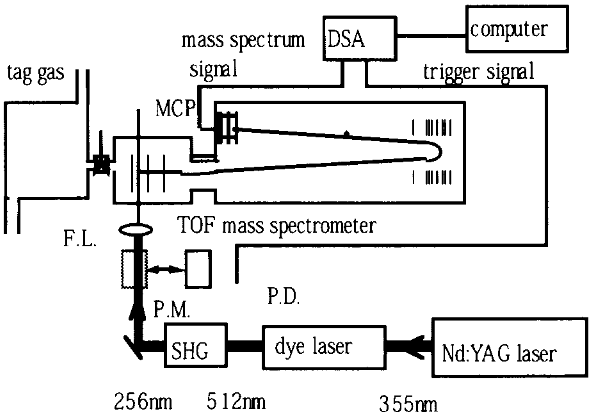
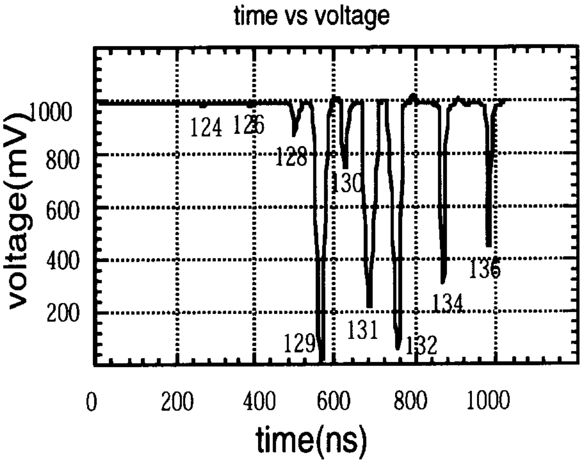


Figure 7. Typical output of laser RIS-mass spectrometer for Xe isotopic detection. The Xe isotopic number is written for each peak



Experimental testing in progress at JAERI [7] has not been extremely successful; the simulation study, however, predicts the lasing at a thermal neutron flux of about 10^{14} n/cm^{2} sec. A demonstration experiment is also planned.

The He-3 nuclear spin orientation by lasers is an interesting and sophisticated tool in reactor technology. The large neutron absorption cross-sections of the ^{3}He nucleus are decreased by half when the ^{3}He nuclear spin is oriented. Both spins of neutron and He-3 nucleus are 1/2 respectively, and the reaction of ^{3}He(n,p) t occurs when the two spins are antiparallel. If such is not the case, the reaction does not take place.

Therefore, this He-3 spin orientation technique can be utilised as a new reactor control rod system in which reactor control can be accomplished through laser irradiation. Another interesting application is neutron spin orientation in the nuclear power reactor especially around the He-3 gas cell under laser irradiation. This is a truly new concept , known as “Neutron Spin Oriented Reactor” [8].

Summary

Several new optical techniques are reviewed for application to reactor instrumentations, which are mainly based on research and development studies in our group. It is thought to be possible to exchange many parts of the reactor sensors with the equivalent optical devices, such as the fibre optics and the laser systems. In particular, the level of sensing will be greatly advanced, symbolically speaking from the current “point measurement” to “distribution measurement”. As this occurs, the degree of safety monitoring in nuclear power reactors is expected to increase in accuracy, especially as a result of the utilisation of new optical systems. More systematic research studies are expected in the domain of advanced reactor instrumentation based on optical techniques.

REFERENCES

[1] T. Kakuta *et al*., “Neutron Irradiation Effects on Optical Fibres,” Sci. Rep. RITU, A40, 153~157 (1994).

[2] J. Kawarabayashi *et al*., “New Array-type Electron Multiplier as a Two-dimensional Position Sensitive Detector,” Nucl. Instr. & Method, A353, 172~175 (1994).

[3] C. Mori *et al*., J. Nucl. Sci. Technol., 31 (3), 248 (1994).

[4] F. Jensen *et al*., “Development of a Distributed Monitoring System for Temperature and Coolant Leakage,” the next paper in this publication.

[5] E.G. See, H.J. Kluge *et al*., ed., Proc. Int. Symp. on Resonance Ionisation Spectroscopy, Bernkastelkues, Germany, 1994 (1995).

[6] Y.R. Shaban and G.N. Miley, Laser and Particle Beams, 11, 559-566 (1993).

[7] N. Yamanaka *et al*., “Analysis of Nuclear Pumped Lasing Mechanism for Application to Nuclear Radiation Measurements,” Nucl. Inst. & Method, to be published.

[8] K. Ishikawa, T. Iguchi and M. Nakazawa, “Polarised Thermal Neutron Field Around Polarised Helium-3 Gas Cells in a Nuclear Reactor,” JAERI-Conf.2 (JAERI-M-93-228) Vol. 2, p. 986~996 (1993).