Distributed Rayleigh backscattering based optical fibre temperature measurements under ionising radiation exposure

A. Faustov,[1,2] A. Gusarov, *Member IEEE,*[1] M. Wuilpart, *Member IEEE,*[2]
P. Mégret, *Member IEEE*[2]

[1] SCK•CEN, Boeretang 200, 2400 Mol, Belgium
[2] University of Mons, place du Parc 20, 7000 Mons, Belgium

In-situ on-line monitoring of environmental conditions in nuclear facilities is an important but uneasy-to-solve problem. In particular, the presence of radiation is a serious complication. Fibre optics offers several crucial advantages over conventional electrical technologies and is promising to be used for sensing in such an environment. Our aim is to examine effects of high-dose irradiation on distributed temperature measurements using OFDR, which operation is based on Rayleigh backscattering spectra modification. Analysis of measurements of optical fibres exposed to intense gamma-radiation shows that despite the presence of radiation the temperature induced spectra shifts remain linearly dependent on temperature changes.

Introduction

On-line monitoring of environmental conditions in nuclear facilities has always been an important problem. Ordinary electronic sensors usually cannot survive harsh radiation environment, while those based on optical fibres are expected to sustain it. It is one of the main reasons for using fibre optics. Another important advantage is that optical fibre technologies allow distributed monitoring of external perturbations. Thus there is no need in multiple local sensors, which are replaceable by just one measuring fibre.

An important application of using distributed optical fibre sensors is cable ageing monitoring, which is an inevitable problem at nuclear facilities. After a long-term exploitation in a harsh radiation environment electrical cable coating becomes aged and fragile due to radiation and oscillations of temperature. This ageing can result in the loss of electrical isolation and consequently in short-circuiting with subsequent fire risks increases. Therefore cables have to be replaced when the prescribed operational time has elapsed. Such replacement procedures are expensive to carry out. Therefore, it has always been searched for any opportunity to predict accurately the cable life-time, which is strongly dependent on the environmental conditions. However, actual operational conditions quite often are not well-known, which can lead to two opposite types of mis-predictions. The first one takes place when harshness of the environment is over estimated. The cables, which could have been exploited more, are supposed to be replaced. It is obviously economically unreasonable. The second type of mis-prediction leads to potentially more severe consequences. When radiation- and temperature-related ageing is underestimated belated replacement can result in electrical circuit failures due to short cuts. Thus, the constant monitoring of the operational environment conditions can both delay replacement procedures and improve the safety.

Temperature monitoring is also important for the optical fibre dosimetry. Ionizing radiation generates point defects in the optical fibre core (see for example [1]), which results in increase of radiation induced attenuation (RIA) [2]. This effect can be used for fibre dosimetry. Unfortunately RIA is not stable in time due to temperature-induced changes. While the temporal instability of RIA of a particular fibre at a given temperature can be taken into account by performing irradiation screening experiments, taking into account thermo-induced instability in real situation is a much more difficult task which requires development of modelling tools together with temperature monitoring techniques.

The aim of this paper is to assess the feasibility of temperature measurements based on Rayleigh backscattering under high radiation doses. We show that thermo-induced spectra shift remains linear which allows reconstruction of temperature distribution in radiation fields.

Experiment Setup

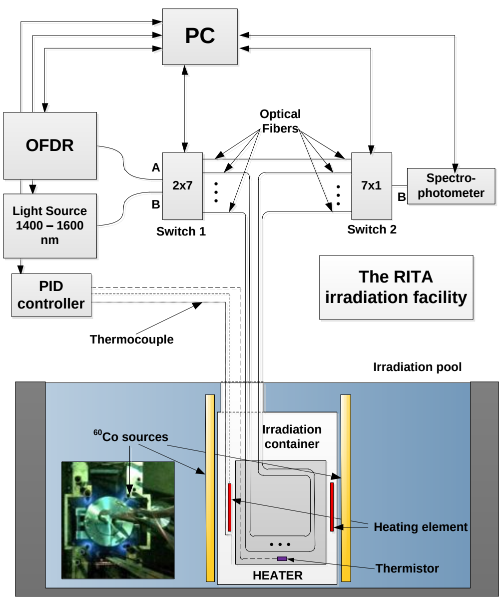

Fig. 1 The setup for the distributed temperature radiation-induced absorption measurements under intense gamma-radiation.

The experiment setup is shown in Fig.1. The irradiation experiment was performed at the RITA gamma-irradiation facility (^{60}Co source) at SCK•CEN, Mol, Belgium. We used six different fibres to conduct temperature measurements to see if different dopants could influence the results. There were three radiation hard samples from a manufacturer A (the name cannot be disclosed), one pure silica core fibre (SMPS 1550-125 P) from Oxford-Electronics, one Corning SMF-28 fibre, and a PM1550-HP fibre (Polarisation Maintaining). Fibres were irradiated during seven days. The dose rate was about 700 Gy/h and the total dose was approximately 110 kGy. The data-acquisition was automated and controlled remotely on a PC. To measure the temperature sensitivity coefficient in situ the temperature of the fibres was raised from 35°C to 75°C in five 10°C steps and then left to cool down to 30°C. At every step the temperature was allowed to stabilise within 0.2°C and the optical measurements were performed. Heating and cooling sequence took about 8 hours and was performed once each day. The optical measurements included acquisition of the Rayleigh-backscattering profiles using OFDR, and also spectral transmission assessment in a range from 1400 1600 nm. Unfortunately, due to a mistake in the program the spectra were measured only at the points of stabilisation.

Results

Temperature distribution along the fibres under radiation was measured with a commercially available optical frequency domain reflectometer (OFDR). Its operation is based on analysis of thermo-induced changes of the Rayleigh backscattering spectra. It is assumed that Rayleigh scatters inside the fibre core can be represented as a long, weak Fibre Bragg Grating (FBG) with a random period. External perturbations, such as temperature or strain, change the grating period and therefore the reflection spectrum [3].

As it is well known from the studies of FBGs thermo-induced spectra shift is linear proportional to temperature change

$$\Delta T = -K_T \Delta \nu, \qquad (1)$$

where $\Delta\nu$ is the frequency shift, ΔT – is temperature change, K_T - is the thermal sensitivity coefficient.

Table 1 Sensitivity coefficient measured before irradiation.

Manufacture	Fiber type	$K_T, °C/GHz$
Manufacture A	Type 1	-0,774±0,006
	Type 2	-0,790±0,006
	Type 3	-0,766±0,004
Oxford Electronics Ltd.	Pure SiO_2	-0,798±0,010
Corning	SMF-28	-0,764±0,004
Nufern	PM-fiber	-0,764±0,004

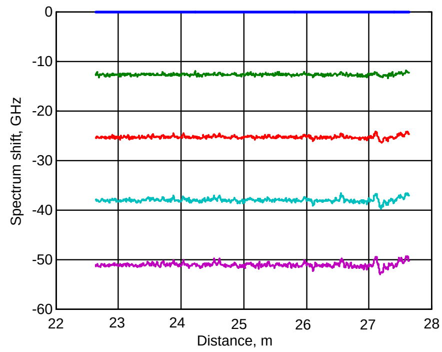

Fig. 2 Rayleigh spectra shift distribution along a 5 m SMF-28 fiber section measured at temperatures from 35 (top) to 75 °C (bottom) with a 10°C step.

The coefficients were measured before the irradiation, using the same set-up and the temperature profile, as during irradiation Tab. 1. For all the fibres the dependence of the spectrum shift on applied temperature was very close to linear. From each fibre trace a section of about five meters was chosen. For every section there were five spectral shift distributions measured at every temperature stability point, Fig.2. One of the sections was taken as a reference (measured at 35°C). In Fig. 2 this trace is shown as the zero line. Coefficient K_T was calculated for every position along the fiber and then the average was taken as the fiber thermal sensitivity coefficient. The standard deviation was also estimated.

Table 2 Temperature sensitivity coefficients before, during and after irradiation

Fiber type	$K_T, °C/GHz$ - Temperature sensitivity coefficient										
	0th day	Gamma irradiation								8th day afternoon	9th day morning
		1st day afternoon	2nd day afternoon	3rd day afte noon	4th day afternoon	5th day afternoon	6th day afternoon	7th day afternoon	8th day morning		
Type 1	-0,774	-0,770	-0,771	-0,772	-0,773	-0,769	-0,770	-0,769	-0,768	-0,753	-0,768
Type 2	-0,790	-0,794	-0,795	-0,789	-0,790	-0,787	-0,788	-0,788	-0,788	-0,770	-0,780
Type 3	-0,766	-0,760	-0,764	-0,765	-0,762	-0,763	-0,764	-0,763	-0,762	-0,748	-0,756
Pure SiO_2	-0,798	-0,804	-0,810	-0,832	-0,820	-0,808	-0,807	-0,809	-0,803	-0,805	-0,804
SMF-28	-0,764	-0,773	-0,786	-0,787	-0,784	-0,783	-0,780	-0,781	-0,780	-0,770	-0,769

The same algorithm of the coefficient calculation was used to estimate K_T for the fibres under γ-radiation. Results are listed in the Table 2. Measurements on the PM fibre are not usable due to high noise in the data. From the table it can be seen that irradiation didn't influence K_T. However, when the irradiation was terminated the absolute values of the coefficients for all the fibres except for the Pure SiO_2 had slightly decreased. This fact could be explained by annealing effect which took place when the irradiation was stopped. For the radiation hard pure silica core fibre no noticeable change was observed after the irradiation end. However, the magnitude of the decrease was <1% of the temperature coefficient and we believe that the result could also be a measurement error. The test environment was hostile not only to the fibres but also to the measurement equipment. All the variations of the coefficients during irradiation are inside the error band (for example see Fig.3). For most of the fibres standard deviation was within one per cent of the value of K_T. Results of the Pure silica fibre were much noisier than those of the others. The reason for that is not completely understood. The noise manifested itself in the temperature distribution calculations, so that sometimes correlation between heated and reference segments was lost and the measured frequency shift was unreasonably too high or too low (see Fig.4). For more information about correlation between heated and reference segments see [4].

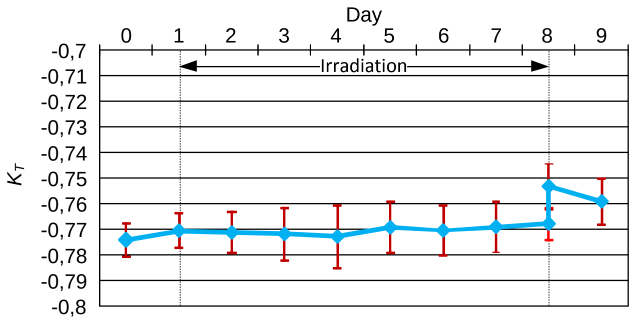

Fig. 3 K_T – coefficient change due to γ-radiation for the fibre Type 1

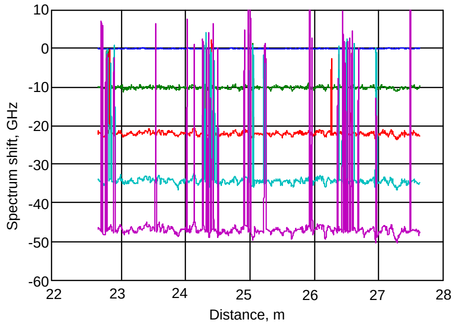

Fig. 4 A segment of noisy spectrum shift distributions along pure silica-core fiber

Those unreliable points were not taken into account when the K_T was calculated. Although there are many such points with apparently wrong values the spectra shift trends is still well discernible. Before irradiation such noisy points were not observed. Therefore, we can suppose that γ-radiation alters the Rayleigh backscattering of light by generating point defects in the fiber core, which results in the loss of correlation between two compared segments with different absorbed doses. Another possible reason might be a decrease of signal-to-noise ratio due to RIA.

Conclusion

We have examined the influence of high ionizing radiation doses up to 110 kGy on the distributed measurements based on the OFDR technique. We have found that during irradiation thermo-induced backscattering frequency spectra shift remains linearly proportional to temperature change for all examined optical fibres. Also it is observed that irradiation of optical fibres leads to losses of the correlation and unrealistically high or low thermo-induced spectra shift estimations. In most of situations it was nevertheless possible to retrieve temperature value from the noisy data.

References

[1] G. Pacchioni, L. Skuja, and D.L. Griscom, Defects in SiO_2 and Related Dielectrics: Science and Technology, Dordrecht: Kluwer Academic, 2000.

[2] H. Henschel, O. Köhn, H.U. Schmidt, E. Bawirzanski, A. Landers, "Optical Fibres for High Radiation Dose Environments", IEEE Trans. Nucl. Sci., vol. 41, pp. 510-516, 1994.

[3] M. Froggatt, and J. Moore, "High resolution strain measurement in optical fiber with Rayleigh scatter," Appl. Opt., 37, 1735, 1998.

[4] D. K. Gifford, B. J. Soller, M. S. Wolfe, M. E. Froggatt, "Distributed fiber-optic temperature sensing using Rayleigh backscatter," Proc. ECOC 2005.