Kinetic models and spectral dependencies of the radiation induced attenuation in pure silica and phosphorous doped fibres: from basic physics to distributed fibre optic dosimetry

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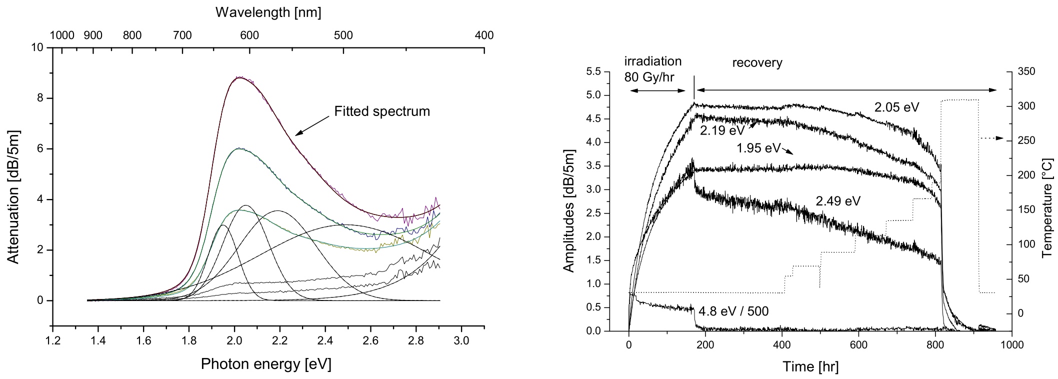
We present the results of a study on the radiation induced attenuation in pure silica and phosphorous doped fibres where both the spectral and kinetic behaviour are explored during and after irradiation in spent fuel gamma facilities. Basic kinetic models and their fractal transformed counterparts are considered. Since the radiation induced attenuation is in general the sum of contributions from different absorption bands — related to underlying radiation induced defects — the spectral dependencies are also tackled by Gaussian resolution into absorption bands of which the individual kinetics are studied as well. The potential for distributed fibre optic dosimetry is assessed too.

1 Introduction

Radiation-induced attenuation (RIA, or A for formulas) in optical fibres has been extensively studied [1] during the past decades as they offer distinct advantages over their classical counterparts for telecommunication applications and as sensors for a wide range of measurands. Most of the efforts with respect to radiation effects, were devoted to assess their radiation hardness in nuclear or space applications, but their potential for dosimetry has been investigated too. In all these studies, the optical fibre acts as a sensing medium for radiation through induced changes of the optical absorption in the fibre waveguide. In this paper, the results of irradiation experiments with two different fibre types are presented and their potential for dosimetry discussed. A custom made pure silica fibre may be of interest for high dose applications (up to 100 kGy) while the Phosphorous for doses from a few Gy up to several kGy.

Dynamic response The dynamic response for a given interrogating wavelength is the sum of different contributions from the underlying absorption bands kinetics. A number of papers treated the modelling of the combined ("envelope") kinetic behaviour of the RIA at one or a few wavelengths during irradiation and the recovery after irradiation. Obviously, a simple model for this is of interest for dosimetry applications where the dose is measured on-line during irradiation. The recovery or "fading" dynamics are important for off-line dosimetry or varying dose-rate regimes.

The annealing behaviour is governed by temperature and radiation driven relaxation kinetics, which also influence the attenuation growth and contribute to dose-rate dependencies. For general dosimetry, it is desirable to have long relaxation times, or at least one of them in the more common case where the relaxation process consists of several subcomponents.



(a) Decomposition of the absorption spectra into 5 Gaussian shaped absorption bands

(b) Evolution of the amplitutes of the absorption bands during the experiment

Figure 1: Decomposition of the absorption spectra into different absorption bands of the high OH, low Cl pure silica sample.

Basic approach for radiation dosimetry with optical fibres For the approach followed in this paper, the radiation induced absorption can be formally represented by the simplified expression Eq. Eq. (1). In this expression the wavelength is replaced by the corresponding photon energy, $E\,[\mathrm{eV}] = 1240/\lambda\,[\mathrm{nm}]$, which is a fundamental parameter for the absorption band position and shape.

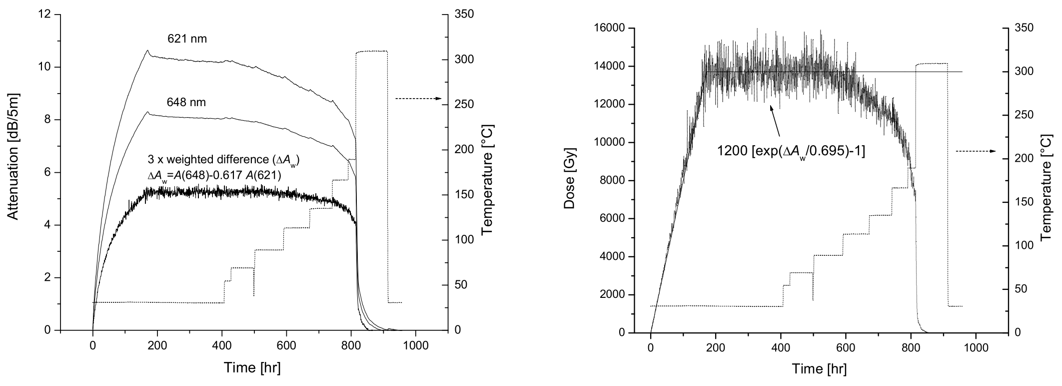
$$A(E,t) = \sum_i k_i(t)\,\psi_i(E) \tag{1}$$

In Eq. Eq. (1) the absorption bands are supposed to be time-invariant with respect to their shape $\psi_i(E)$ and position, and the corresponding amplitudes $k_i(t)$ to contain all time related dependencies. The factors $k_i(t)$ therefore incorporate all the effects of temperature, photo-bleaching, dose-rate, dose and annealing — in general the irradiation and environmental history. For pure silica and P-doped fibres, these absorption bands have been partly identified, however, since most of them are rather broad, it is difficult to resolve each of them.

2 Irradiation of pure silica samples and dose-reconstruction

The pure silica samples were irradiated at a dose-rate of 80 Gy/h up to a total dose of 14 kGy. The temperature was kept constant at 30°C during irradiation and a recovery period of nine days. After this initial recovery phase, the temperature was risen in steps, lasting a few hours to a few days, to assess the temperature effects on the annealing rate. The final phase of this experiment consisted of a steep rise in temperature (300°C) to anneal all remaining radiation induced attenuation.

Identification of absorption bands Around 600 nm, the RIA is dominated by two well known radiation induced defects [2]. A 5-band model for the RIA in the range from 430 nm to 900 nm was derived (see Fig. 1a), which resulted in perfect fits (within the noise limits) for the duration of the experiment. Although the 5-band model "explains" the absorption spectra for the wavelength interval showed here, there may be more unidentified bands present. Once the positions and widths were



(a) An annealing free dose estimator

(b) Calibration with exponential growth

Figure 2: Dose reconstruction in a two-phase process.

determined, the amplitude of each absorption band was calculated for all recorded spectra, and the resulting evolution is depicted in Fig. 1b.

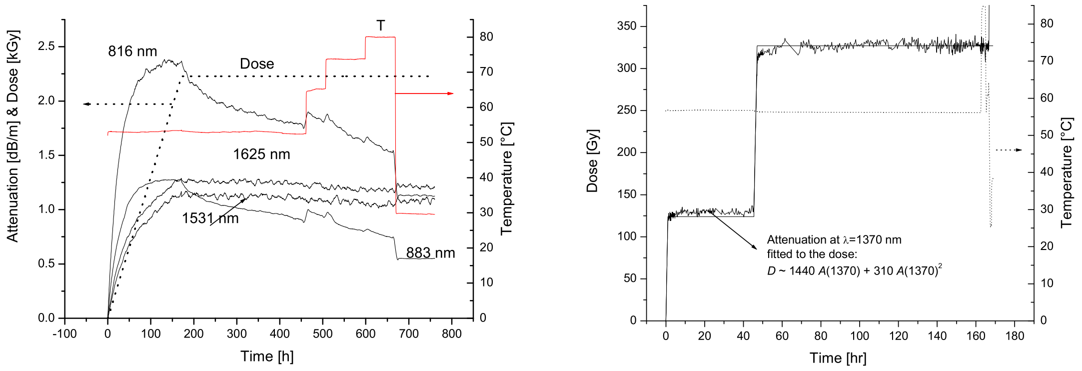
Dose reconstruction Two useful features of the absorption band at 1.95 eV are apparent from Fig. 1b. The room temperature annealing just after the irradiation is absent and this remains the case during the heating up to 90 °C. Higher temperatures induce the annealing of this band.

In any case, the stability of this band at elevated temperatures after irradiation offers the potential for more robust dosimetry with respect to temperature effects. Indeed, considering Eq. Eq. (1) and the extent of the absorption bands, an annealing free (up to 70 °C) RIA based dose estimator can be derived by solving the system of equations at three wavelengths in the 550 nm to 650 nm region (neglecting the contribution from the 4.8 eV band). However, due to noise considerations, an even simpler (heuristic) model was tried with success: a two-wavelength weighted difference in the region from 600 nm to 650 nm, and a calibration function for the dose response during irradiation. In Fig. 2a, the result for such a weighted difference for the RIA at 621 nm and 648 nm is shown which proves to be stable for temperatures up to at least 70 °C. This means that the weighted difference is also a measure for the stable absorption bands (mainly POR) in Fig. 1b.

In a second step, the response of this alternative expression is calibrated through non-linear estimation with an exponential growth curve (see Fig. 2b) to the applied dose during the experiment. Inevitably, these calculations also amplify the noise present in the base signals. However, with optimised light sources, detectors and signal de-noising, this problem should be easy to overcome.

3 Irradiation of phosphorous doped samples and dose-reconstruction

Kinetic response In the recorded spectral interval, the region from 500 nm to 1000 nm exhibits a significant annealing, attributed to mostly the Phosphorous-Oxygen-Hole-Centre (POHC) which is linked to several absorption bands(9). Further in the infrared (> 1400 nm), a weaker so-called P1 defect type is essentially annealing free. Also, the P1 type defect is almost insensitive to temperature variations (as well during and after irradiation) which implies increased robustness with respect to environmental factors. This is shown in Figure 3(a)



(a) Kinetic response at several wavelengths

(b) Dose reconstruction with P-doped sample

Figure 3: Irradiation at 52 °C of the phosphorous doped sample

Dose reconstruction Figure 3(b) shows the results of a second degree polynomial calibration function which is capable of reproducing the dose within 10 % accuracy. Power-law and stretched saturating exponentials could also easily be fitted to the response, but due to the minor sub-linear response, the parameters obtained with these fits did not have numerical or physical significance.

4 Conclusion

The use of optical fibres as intrinsic dosemeters certainly offers potential for applications like nuclear incident monitoring. For dosimetry systems requiring more accuracy, the approach and techniques presented with the pure silica fibre samples, provide a solution to eliminate the annealing effects after irradiation for temperatures up to at least 90°C. The phosphorous doped fibres are useful for distributed measurements by employing the independence of the radiation induced attenuation with respect to temperature effects and the absence of annealing for specific wavelengths, with an optimum near 1550 nm.

References

[1] E. J. Friebele, K. Long, C. Askins, G. M.E., M. Marrone, and D. Griscom, "Overview of radiation effects in fiber optics," in *Optical Fibre Sensing and Systems in Nuclear Environments*, vol. 541 of *SPIE Proceedings*, pp. 70–88, 1985.

[2] D. L. Griscom, "The natures of point defects in amorphous silicon dioxide," in *Defects in* SiO_2 *and Related Dielectrics: Science and Technology* (G. Pacchioni, L. Skuja, and D. Griscom, eds.), vol. 2 of *Nato Science Series II: Mathematical and Physical Chemistry*, pp. 117–159, Kluwer Academic Publishers, 2000.