Study of silica optical fibers for real-time dosimetry of pulsed radiotherapy

Marjorie Grandvillain, Marie Vidal, Mohamed Bouazaoui, Hicham El Hamzaoui, Bruno Capoen, Joël Herault, Mourad Benabdesselam, Franck Mady

Marjorie Grandvillain, Marie Vidal, Mohamed Bouazaoui, Hicham El Hamzaoui, Bruno Capoen, et al.. Study of silica optical fibers for real-time dosimetry of pulsed radiotherapy. 14th International Conference on SiO2, Dielectrics and Related Devices, Jun 2023, Palermo, Italy. hal-04584732

HAL Id: hal-04584732

https://hal.univ-cotedazur.fr/hal-04584732

Submitted on 23 May 2024

Study of silica optical fibers for real-time dosimetry of pulsed radiotherapy

Marjorie Grandvillain[1,2], Marie Vidal[2], Mohamed Bouazaoui[3], Hicham El Hamzaoui[3], Bruno Capoen[3], Joël Herault[2], Mourad Benabdesselam[1], Franck Mady[1]

[1] Université Côte d'Azur, Fédération de recherche Claude Lalanne, Institut de Physique de Nice, CNRS UMR7010, 17 rue Julien Lauprêtre, 06200 Nice, France marjorie.grandvillain@univ-cotedazur.fr
[2] Centre Antoine Lacassagne, Fédération de recherche Claude Lalanne, 227 avenue de la Lanterne, 06200 Nice, France
[3] Université Lille, CNRS, UMR8523 - PhLAM – Physique des Lasers, Atomes et Molécules, CERLA/IRCICA, F-59000 Lille, France

Keywords: Dosimetry, silica glass, radioluminescence, optical fiber

INTRODUCTION

Silica optical fibers offer many advantages for the dosimetry of ionizing radiations in medical applications, particularly in radiotherapy (RT). Advances in patient irradiation techniques require ever-increasing spatial and temporal accuracy in dose measurement. Current dosimeters, which are mainly based on radioelectric conversion (ion chambers or semiconducting diodes), have become ill-adapted to innovative treatment modalities: (*i*) they are not compliant with MRI-guided radiotherapy, (*ii*) they are too large in size to allow a sufficient spatial resolution in the highly-modulated irradiation fields of stereotactic irradiations, (*iii*) their efficiency is lowered at high dose rates, notably those encountered in "flash" radiotherapy and high-energy proton-therapy pulses [1]. By contrast, radioluminescent dosimeters exploit a radio-optical conversion which is insensitive to magnetic fields and well suited to high dose rate operation. When they are cast into the form of optical fibers with a sensitive volume that can be as small as 50 microns in diameter, they also meet the important need for miniaturization

Compared to other inorganic scintillators, silica glass has the great advantage of being almost "tissue equivalent" for the particle energies in clinical applications (photons and protons). By doping silica with luminescent ions, it is possible to obtain a scintillating fiber probe whose sensitive volume is contained in the fiber itself. The steady-state intensity of the radioluminescence (RL) produced under permanent irradiation of silica rods and fibers is significant and has been widely demonstrated to increase linearly with dose rate over at least 6 decades
[2], [3], [4].

The ANR FIDELIO project (2021-2025) aims to develop a real-time silica fiber RL dosimeter specifically optimized for pulsed radiotherapy beams and microbeams. Two types of dosimeters are discussed here, which were showed best potential for the targeted applications [5] : a Gd^{3+}- and a Ce^{3+}-doped silica RL probes. Beyond the well-established proportionality of the steady-state RL to the dose rate, our basic investigations first aimed at characterizing the kinetics of the RL responses (raise and fall), as well as the repeatability and reproducibility of the RL kinetics and levels. We propose to present the main results of this important study.

MATERIALS AND METHODS

Uniformly doped $Gd^{+\,3}$ or $Ce^{+\,3}$-doped silica glasses were prepared by the PhLAM laboratory of Lille using the sol-gel technique. The sensor consists of a 1 cm-long rod of this glasses spliced to an iXblue silica radiation-resistant fiber which ensures the luminescence transport from the probe to the photodetector. The diameter of the probes used in this study is 0.22 mm.

The signal is collected with the Hamamatsu H7421-40 photomultiplier tube associated with a C8855-01 counting unit from the same manufacturer. When a rapid acquisition is required, we use the Hamamatsu HPD R11322U connected to the amplifier C5594 and the related C13182-01 counting unit.

Irradiations were performed under a 30kV X-Ray beam of a copper anode x-ray tube (Inel XRG3D). Dose rate were varied from 0.8 Gy/s to 11.3 Gy/s. A series of measurements has also been carried out under proton irradiations at the 65 MeV R&D beam line of the medical cyclotron of the Centre Antoine Lacassagne, the anti-cancer center of Nice (France).

RESULTS AND DISCUSSION

For both samples, and not surprisingly, our measurements again demonstrate a very good linearity of the RL steady-state level with the particle flux, both under photon and proton beams (not illustrated here). To study the effect of the exposure time on the RL kinetics, 1 to 10 s exposures were sequentially applied at a constant dose rate, separated by rest periods of about 8-10 s. The typical results of such experiments are shown in figure 1 (left part, at a dose rate D’ = 11,3 Gy s-1). Obviously, raise and fall times are not identical. As the exposure time increases along successive irradiations runs, the rise time of the RL is not significantly changed but an increasing phosphorescence signal can be observed for both Ce and Gd-doped silica probes. The intensity plateau, determined by the dose rate, well remains the same across the runs, but the phosphorescence is found to decay more and more slowly. Clearly, the RL decay kinetics strongly depends on the prior irradiation time (hence dose), even for rather short exposure times and doses. After its clear increase, the RL decay time seems to stabilize from a certain time (and cumulated dose) which is about 120 s (and 400 Gy). This threshold is however (far) beyond typical pulse and total exposure durations whether in the case of flash RT or high-energy proton therapy. This finding has strong consequences, because the RL fall time will determine the capability of the dosimeter to discriminate between successive irradiation pulses (the fall time should be smaller than the pulse repetition time).

To investigate this effect and its physical origins, we simulated the RL response for distributions of trapping levels identical to those reported by our team in [6] (the model is not detailed in this short extended abstract but will be introduced during the conference presentation). The RL simulated when using the same parameters as in the experiment (notably the temporal sequence) is displayed in the right part of figure 1. The experimental behavior (increase and stabilization of the decay time) is well reproduced by a standard RL model using an extended distribution of traps, demonstrating the role of shallow traps in the process. The simulation was carried out with two different densities of traps (inset), emphasizing the increase of phosphorescence with the density of shallow traps.

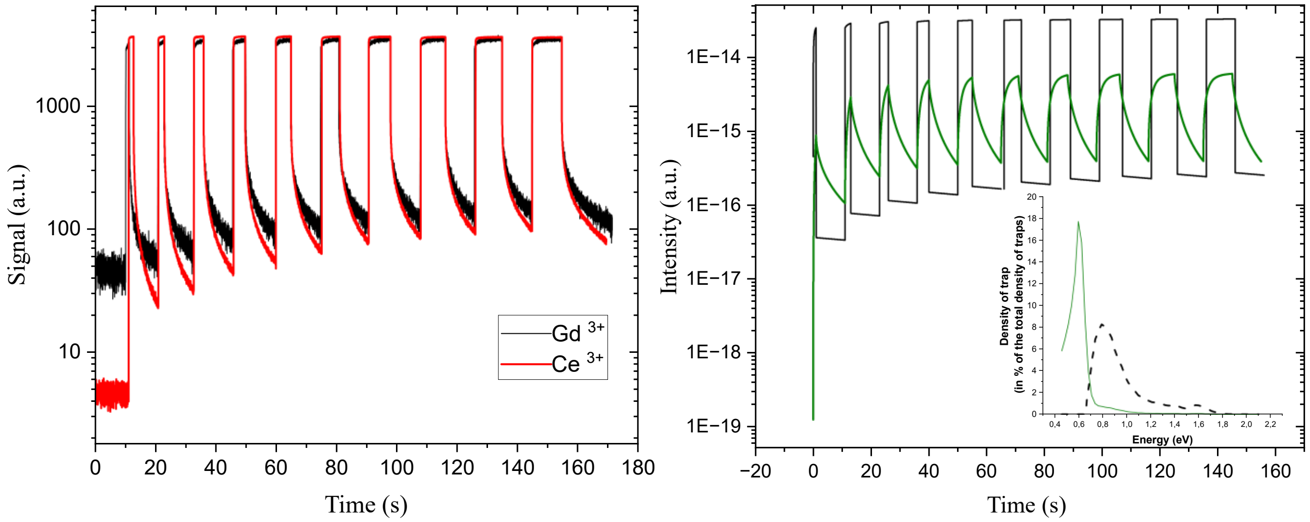

Figure 1 - (Left) RL graph for SiO2:Gd and SiO2:Ce at increasing exposure time, constant dose rate; (Right) RL modelization for increasing exposure time with two different densities of trap. The inset represents the two used densities of traps, with the same color code as the intensity.

The repeatability was verified under short exposure (of the order of one second) and a 10 min-exposure. For each doping, a series of exposure was made on the same probe and attention was paid to the time between two successive irradiations.

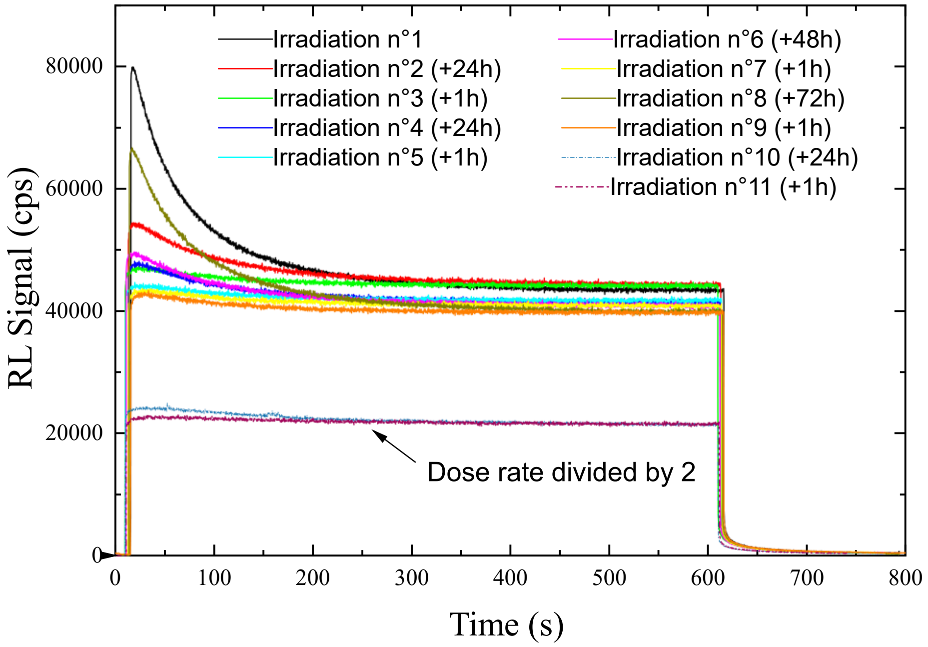

Figure 2 – Repeatability for Gd3$^+$ probes - Irradiations are reproduced at different time delays from the previous irradiation (336h, 72h, 48h, 24h and 1h).

Time since previous radiation (h)	Oversignal (ratio)
336	1,83
72	1,66
48	1,21
48	1,17
24	1,21
24	1,15
24	1,16
24	1,13
1	1,06
1	1,05
1	1,06
1	1,07
1	1,07
1	1,05

Table 1 - Ratio of oversignal at the beginning of the irradiation.

Gd-doped glass show a good repeatability after a 10-min exposure but we measured an oversignal at the beginning of the exposure. This oversignal is only dependent on the time interval between two exposures. The longer the interval, the higher the oversignal. It is independent of the cumulative dose and of the dose rate. This implies that the fiber must be irradiated not long before the measurement. However, Ce^{3+} probes do not show this history-dependent phenomenon and the signal is reproducible regardless of the duration of the exposure and the time elapsed since the previous exposure.

CONCLUSIONS

Gd^{3+} or Ce^{3+} -doped silica probes show good linearity of RL response with dose rate. Cerium doping is encouraging for measurements under clinical beams, providing high sensitivity and good short- and long-term repeatability. The radiative history of the Gadolinium probe has a strong impact on the repeatability of the signal. This phenomenon should be considered for the future.

REFERENCES

[1] F. Romano, C. Bailat, P. G. Jorge, M. L. F. Lerch, and A. Darafsheh, ‘Ultra-high dose rate dosimetry: Challenges and opportunities for FLASH radiation therapy’, *Med. Phys.*, vol. 49, no. 7, pp. 4912–4932, 2022, doi: 10.1002/mp.15649.

[2] H. El Hamzaoui *et al.*, ‘Cerium-activated sol–gel silica glasses for radiation dosimetry in harsh environment’, *Mater. Res. Express*, vol. 3, no. 4, p. 046201, Apr. 2016, doi: 10.1088/2053-1591/3/4/046201.

[3] S. Girard *et al.*, ‘Potential of Copper- and Cerium-Doped Optical Fiber Materials for Proton Beam Monitoring’, *IEEE Trans. Nucl. Sci.*, vol. 64, no. 1, pp. 567–573, Jan. 2017, doi: 10.1109/TNS.2016.2606622.

[4] J. Vidalot *et al.*, ‘Monitoring of Ultra-High Dose Rate Pulsed X-ray Facilities with Radioluminescent Nitrogen-Doped Optical Fiber’, *Sensors*, vol. 22, no. 9, Art. no. 9, Jan. 2022, doi: 10.3390/s22093192.

[5] C. Hoehr *et al.*, ‘Novel Gd3+-doped silica-based optical fiber material for dosimetry in proton therapy’, *Sci. Rep.*, vol. 9, p. 16376, Nov. 2019, doi: 10.1038/s41598-019-52608-5.

[6] F. Mady *et al.*, ‘Optical fibers under irradiation: quantitative assessment of the energy distribution of radiation-induced trapped states’, in *Fiber Lasers and Glass Photonics: Materials through Applications II*, Online Only, France, Apr. 2020, p. 48. doi: 10.1117/12.2557834.