Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Nuclear Materials 329–333 (2004) 1456–1460

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Radiation-hardening techniques of dedicated optical fibres used in plasma diagnostic systems in ITER

B. Brichard [a,*], A. Fernandez Fernandez [a], H. Ooms [a], F. Berghmans [a], M. Decréton [a], A. Tomashuk [b], S. Klyamkin [b], M. Zabezhailov [b], I. Nikolin [b], V. Bogatyrjov [b], E. Hodgson [c], T. Kakuta [e], T. Shikama [d], T. Nishitani [f], A. Costley [f], G. Vayakis [f]

[a] *SCKCEN, Belgian Nuclear Research Centre, Boeretang, 200, 2400 Mol, Belgium*
[b] *FORC, Fiber Optic Research Centre, 38-119991 Moscow, Russia*
[c] *Euratom-CIEMAT, 22-28040 Madrid, Spain*
[d] *Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[e] *Japan Atomic Energy Research Institute, Naka 311-0193, Japan*
[f] *ITER-JWS-Naka, Naka 311-0193, Japan*

Abstract

This paper addresses the particular need to develop suitable fabrication techniques of glasses to improve the radiation-resistance and extend the lifetime of optical fibres in high radiation background. Two radiation hardening techniques based on hydrogen and fluorine doping of glass have been applied on step index pure silica core optical fibres. The radiation-induced optical absorption and luminescence have been measured in gamma and fission reactor irradiation conditions at SCKCEN, Mol Belgium. The experimental results show that the lowest optical absorption is achieved in the hydrogen-treated fibre sample. However, the luminescence effect remains significant in any type of fibre and cannot be reduced by the investigated radiation hardening techniques.

1. Introduction

Optical plasma diagnostic systems are usually combinations of mirrors, lenses and windows to transport light emitted from the plasma edge to the remote diagnostic area. The optical path is generally complex and involves numerous components. The practical attractiveness of optical fibre to transport light contributes in reducing the complexity of the optical path design. Successful demonstrations of the application of the fibre technology in tokamak environment have been carried out in the early 90s at TFTR [1] and JET [2]. At that occasion, plasma diagnosticians used the optical fibres to transport the plasma emission to the diagnostic area where the light is spectrally dispersed to extract the plasma parameter information (e.g. charge exchange recombination spectroscopy).

In contrast to TFTR and JET, ITER plasma diagnostic systems [3] will have to face additional problems regarding radiation damage. Plasma pulse durations in ITER will last typically several hundred seconds. During this period, the plasma will be producing a significant amount of radiation, implying in the long term significant radiation damage for components installed close to the plasma vessel. Consequently, chemical and physical properties of the material will change and in turn may compromise the performances of the systems.

In the case of optical components such as silica based optical fibres, radiation affects the optical properties in

---

[*] Corresponding author. Tel.: +32-143 32640; fax: +32-143 11993.

E-mail address: bbrichar@sckcen.be (B. Brichard).

0022-3115/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2004.04.159

three ways. The first is the so-called radiation induced absorption. Radiation creates defects in the silica that in turn absorb light. As a general rule, the absorption is strong in the far UV and extends up to the wavelength regions (visible and NIR) where the optical plasma diagnostic systems operate. The second effect is the radiation-induced luminescence. Radiation can generate light inside the optical fibres. Some part of this light, uncorrelated with the plasma light emission, is guided together with the useful signal. Obviously, both effects are to be minimized to guarantee the reliability of the plasma parameter measurements.

The third effect is the radiation-induced refractive index change. Generally, this effect is weak and can be neglected as long as the optical plasma diagnostic system is based on an intensity measurement scheme.

2. Need for the development of radiation resistant glasses

Due to the particular radiation issue expected in ITER [3], an irradiation assessment program coordinated by the ITER central team was initiated using the irradiation facilities in the Japan [4], Russia [5] and Europe home-teams [6] in an attempt to develop a radiation resistant glass. In the past 10 years, a considerable expertise was gained from the different home teams. This paper presents the contribution of the European home-team in the development of a radiation optical fibre candidate for ITER. The experimental data were obtained from the gamma irradiation facilities and the fission reactor irradiation experiments conducted in the BR2 Material Testing Reactor of SCKCEN (Mol, Belgium). The present discussion focuses on both the radiation-induced absorption and luminescence effects in optical fibre candidates for ITER.

The key element to producing a radiation resistant glass relies on the reduction of the number of precursors of colour centres. This can be achieved in various ways. First, the raw material used in the fabrication of the silica fibre preform should be prepared as pure as possible since impurities tend to introduce additional defects. Second, the fabrication technology must be carefully controlled to minimize the number of drawing-induced defects as much as possible. Third, the use of well-defined dopants or special post-drawing glass treatments may be applied to improve the radiation-resistance of the fibres. In the present case, two possible techniques were evaluated: the treatment of the glass by molecular hydrogen and the fluorine doping of the core fibre.

Depending on the fabrication process, the core-doped fluorine fibres are generally more radiation sensitive and also suffer from excessive optical bending losses. From that point of view, the hydrogen treatment proved to be the most effective in term of improvement of the radiation resistance. Before discussing the results, it is useful to briefly review the importance of hydrogen treatment in irradiated silica glasses.

3. Role of hydrogen in irradiated silica glasses

The positive role of hydrogen in limiting radiation-induced optical degradation was first demonstrated on bulk silica glasses by Faile [7] and Shelby [8]. Later, Nagasawa [9] observed a similar effect in irradiated glass fibres. The author observed that the hydrogen treatment, carried out either prior to or following the irradiation, drastically suppressed the 2 eV optical absorption band that develops in silica due to the formation of non-bridging oxygen hole centres (NBOHC) and Peroxy radicals (POR). In 1992, Lyons and Looney [9] investigated the radiation-induced loss response at only one wavelength (850 nm) in different hydrogenated fibres. The authors explained that the combination of the pre-irradiation sequence at moderate total dose followed directly by the hydrogen loading phase contributes to reduce the number of preexisting defects and/or weak bonds that would otherwise act as precursors of colour centres during subsequent irradiation. Even if the total dose range reported was limited to small values, it became clear at that time that the processing technique can be optimized by a combination of loading and pre-irradiation phases.

However, the authors [10] did not comment on the type of defects involved. A possible mechanism explaining the radiation hardening at 2 eV results from the hydrogen cracking reaction on a NBOHC. In other word, the NBOHC defect responsible of the strong visible absorption (2 eV) is simply converted into an hydroxyl group. Recently, ab initio calculations confirmed that this conversion mechanism is exothermic by 0.4 eV whereas the hydrogen dissociation on NBOHC sites only requires 0.1 eV [11].

4. Optical fibre candidates for ITER

Five pure-silica core fibres coated with acrylate have been fabricated by various manufacturers. The KS4V, the KU1 and the KUH2G are fabricated by the Fibre Optic Research Centre in Moscow. The KU1 fibre is drawn from a glass preform synthesized with a vapour-phase deposition technology using $SiCl_4$ as raw material. The KU-H2G glass is similar to the KU1 but underwent a pre-irradiation followed by a molecular hydrogen treatment in high temperature (>80 °C) and pressure conditions (>100 bars). With the KS4V glass, the fabrication technology is based on a completely different process using repeated purification and consolidation procedures of a sol of polysilicon acid. The purity of the silica obtained by this technique (silica of type V) is extremely high. The total concentration of metal impurities does not exceed 10^{-4}% in weight.

The two remaining fibres, F1-doped and F2-doped are based on a fluorine-doped core technology developed by Mitsubishi and Fujikura companies respectively.

All fibres are characterized by a step refractive index profile, a core diameter of 200 μm and a core-cladding ratio between 1.1 and 1.2.

5. Evaluation of the optical performances

Following the fibre fabrication, one needs to assess the optical performances regarding the radiation-induced absorption and luminescence. Several irradiation experiments have been jointly conducted in the nuclear reactors and gamma irradiation facilities of the European Union, Japan and Russian Federation. Details of the experimental set-up developed by the Europeans for recording in situ the radiation-induced absorption and luminescence can be found in Ref. [6]. In the case of the fission reactor irradiation, the fast neutron flux reached 3.5×10^{13} n/cm^2 s and the ionising dose 1600 Gy/s at a reactor power operating at 60 MW.

5.1. Radiation-induced absorption

Figs. 1 and 2 compare the radiation-induced absorption measured in the five tested fibres irradiated with Co-60 sources or fission reactor irradiation conditions. The experimental results showed that the optical absorption of hydrogen treated optical fibres is reduced by a factor 5–10 compared to the untreated fibres. One of the fluorine-doped fibre (F2-doped) did not survive the reactor test and quickly degraded the optical transmission.

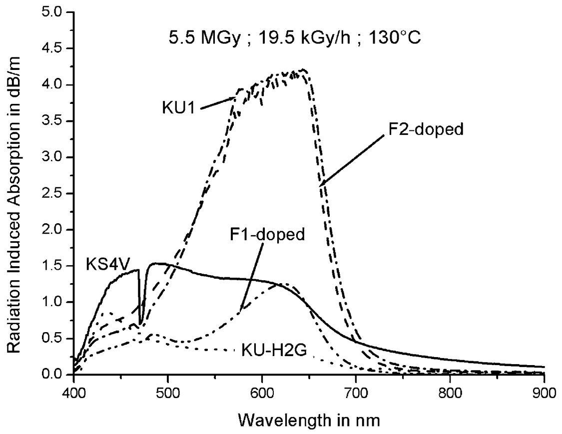

Fig. 1. Spectral comparison of the radiation-induced absorption response due to Co-60 irradiation. The lowest absorption is measured in the hydrogen treated glass (KU-H2G).

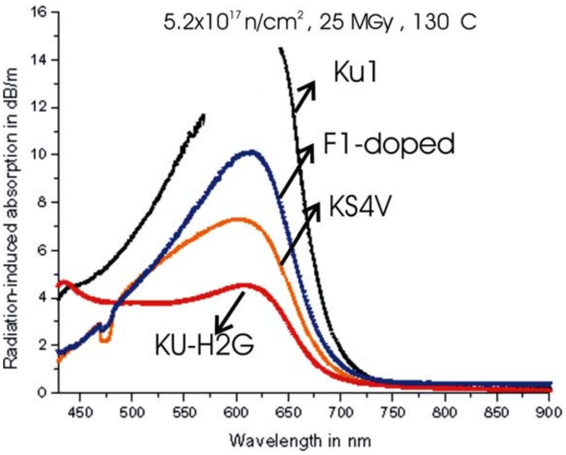

Fig. 2. Spectral comparison of the radiation-induced absorption response due to fission reactor irradiation. The lowest absorption is measured in the hydrogen treated glass (KU-H2G).

The presence of hydrogen retards the formation of NBOHC resulting in a better optical transmission in the visible region at equivalent irradiation dose. Actually, the optical absorption results from the combined formation of various defects, the NBOHC but also the POR. A more details analysis [12] based on a spectral deconvolution approach of the absorption band showed indeed that, in the case of KU1 type glass, the hydrogen tends to act primarily on the NBOHC sites as theoretically reported in paragraph 3. Fig. 3 shows that, at equivalent total ionising dose, the optical absorption due to NBOHC is greater in the hydrogen-treated KU1 glass than in the untreated KU1 glass, while the POR defect

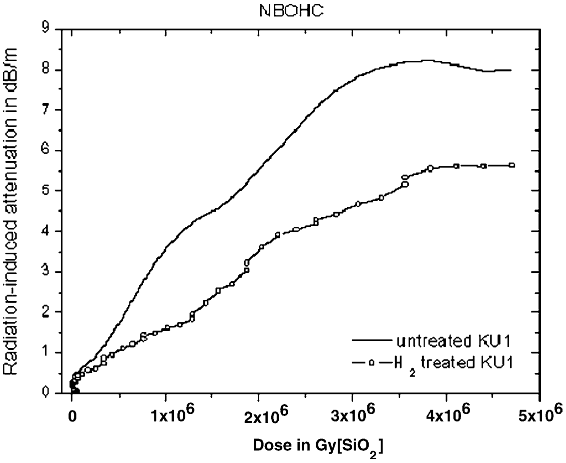

Fig. 3. NBOHC defect contribution to the radiation-induced absorption in hydrogen-treated and untreated KU1 fibre as a function of the ionising dose. Fission reactor irradiation.

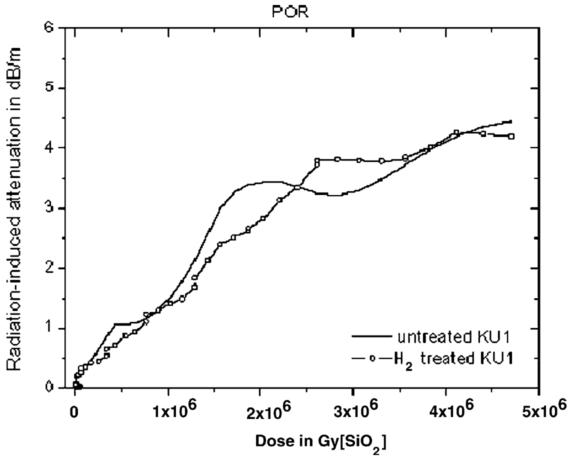

Fig. 4. POR defect contribution to the radiation-induced absorption in hydrogen-treated and untreated KU1 fibre as a function of the ionising dose. Fission reactor irradiation.

(Fig. 4) contributes to the absorption in the same way in both type of fibres.

5.2. Temperature dependencies of the radiation-induced absorption

As expected, a temperature increase contributes in reducing the optical absorption. Fig. 5 shows the evolution of the optical absorption in the hydrogen-treated fibre with respect to the time. Negative time corresponds to measurements carried out before the start of the reactor while the zero indicates the reactor start. At that moment, the temperature increases due to gamma heating and the temperature was arbitrary controlled at 300 °C. At this temperature, although the reactor operated at full power, the decrease of the optical absorption appeared clearly at high temperature.

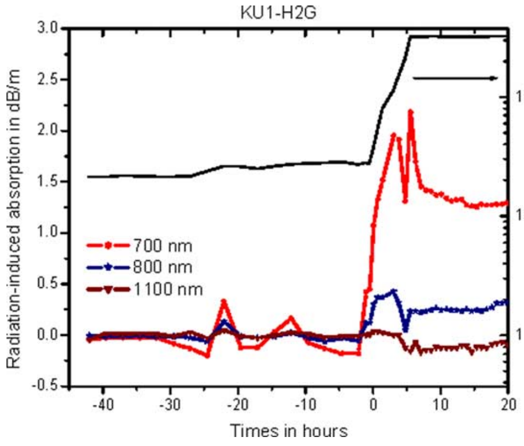

Fig. 5. Evolution of the radiation-induced absorption in hydrogen-treated KU1 glass fibre following a temperature increase. Zero on the *x*-axis indicates start of the reactor.

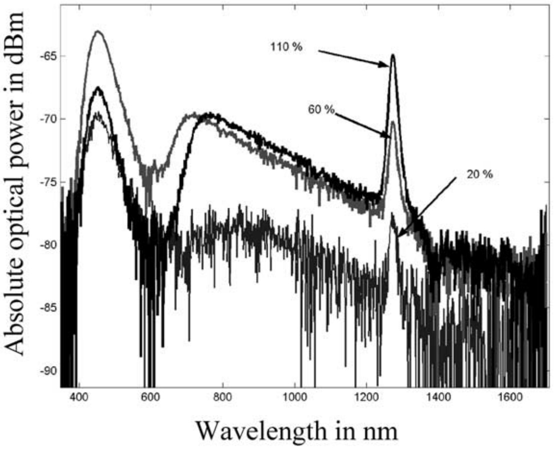

Fig. 6. Luminescence spectra measured in KS4V glass fibre as a function of the reactor power.

5.3. Radioluminescence

In the case of the reactor tests, strong luminescence was observed in all type of fibres. The main contributor to the luminescence comes from the Cherenkov emission induced by the gamma radiation. However, there also exist other contributors arising from the defect creations (450 nm) or the presence of oxygen (1240 nm). Fig. 6 gives the general structure of the luminescence spectrum coming out of the fibre. The luminescence level is roughly proportional to the reactor power in the infrared region.

Regarding the temperature dependence of the luminescence, the luminescence did not reduce, contrary to the expectation, when the temperature was increased. The luminescence tends to increase with the temperature as indicated in Figs. 7 and 8. This surprising result may be explained from the fact that the luminescence in the visible region is dominated by the Cherenkov effect. In first approximation, the Cherenkov effect is weakly temperature dependent, especially with a 100 °C temperature difference, while in the meantime the absorption is substantially reduced as shown previously. Consequently, a temperature rise improves the transmission of the Cherenkov light because of the absorption reduction, resulting in an apparent increase of luminescence at the detector side.

6. Application of the hydrogen loading technique to large core optical fibres

In practice, plasma diagnostic systems use large core optical fibres with a typical diameter as large as

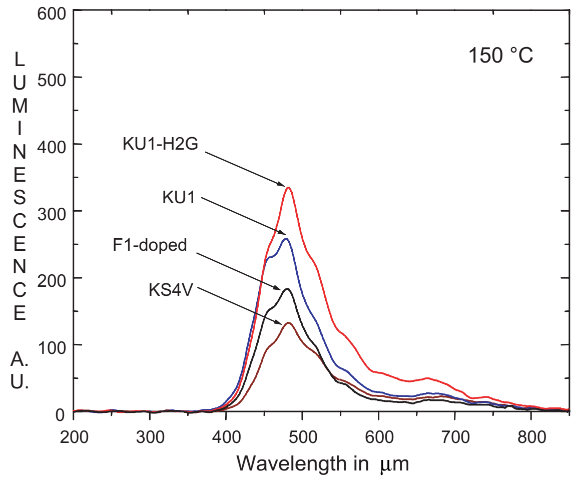

Fig. 7. Relative comparison of luminescence spectra measured at 150 °C.

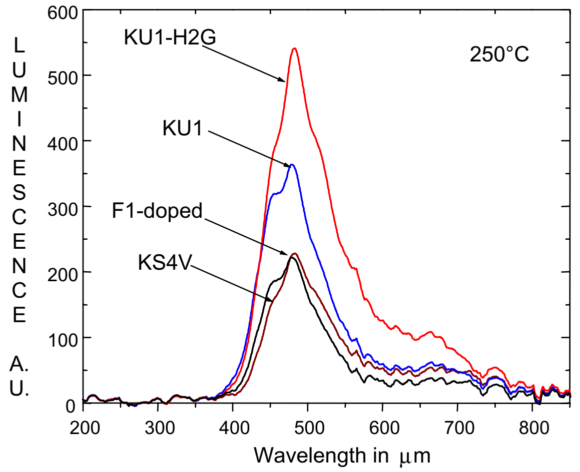

Fig. 8. Relative comparison of luminescence spectra measured at 250 °C.

600–1000 µm. While the hydrogen treatment proved to be efficient in small core optical fibres, the applicability of the method needs to be verified in large core fibres. The parameters controlling the hydrogen loading process, like time, pressure, temperature and pre-irradiation dose, must be optimized for the case of large core fibres. In 2003, a 600 µm optical fibre supplied by the European Heraeus-Tenevo company has been loaded with hydrogen and installed in the European EFDA-JET Tokamak (Culham, UK). This experiment aims to evaluate in the long term and in transient irradiation conditions, the optical transmission in a representative environment and operation conditions of a fusion reactor. Study of 14 MeV neutron effects will be possible during the Tritium campaigns of 2003 and will permit a study of the radiation effects in large-core hydrogen-loaded optical fibres. Additional work is currently on-going to develop metal-coated and hydrogen loaded large core optical fibres.

7. Conclusion

Due to the extensive effort in the development of radiation-hardening and radiation-testing, pure silica optical fibres are now becoming available for plasma diagnostic systems subjected to intense radiation background. The treatment of the glass by hydrogen proved to be an efficient technique in reducing the radiation-induced absorption in the visible spectrum. However, major difficulties remain in reducing the luminescence effect. Further experimental research is in-progress to successfully apply the hydrogen treatment to large core optical fibres.

References

[1] A.T. Ramsey, K.W. Hill, Rev. Sci. Instrum. 63 (1992) 4735.
[2] P.D. Morgan, in: Proceedings of the Symposium on Fusion Technology, September, 1992, p. 169.
[3] R. Aymar, J. Nucl. Mater. 307–311 (2002) 1.
[4] T. Kakuta, T. Shikama, T. Nishitani, B. Brichard, A. Krasilnikov, A. Thomasuk, S. Yamamoto, S. Kasai, J. Nucl. Mater. 307–311 (2002) 1277.
[5] A. Ivanov, S. Tugarinov, Yu. Kaschuck, A. Krasilnikov, S. Bender, Fus. Eng. Des. 51–52 (2000) 973.
[6] B. Brichard, A. Fernandez Fernandez, P. Borgermans, M. Van Uffelen, F. Berghmans, M. Decreton, E. Hodgson, T. Shikama, T. Kakuta, A. Tomashuk, K. Golant, A. Krasilnikov, Fus. Eng. Des. 56–57 (2001) 917.
[7] S. Faile, J. Schmidt, D. Roy, Science 156 (1967) 1593.
[8] J. Shelby, J. Appl. Phys. 50 (1979) 3702.
[9] K. Nagasawa, Y. Hoshi, Y. Ohki, K. Yahagi, Jap. J. Appl. Phys. 24 (1985) 1224.
[10] P. Lyons, L. Looney, SPIE, Ed. 1791 (1992) 286.
[11] N. Lopez, M. Vitiello, F. Illas, G. Pacchioni, J. Non-cryst. Solids 1 (2000) 56.
[12] B. Brichard, A.F. Fernandez, H. Ooms, P. Borgermans, F. Berghmans, IEEE Trans. Nucl. Sci. 50 (2003) 2024.