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Journal of Nuclear Materials 329–333 (2004) 1490–1494
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Non-linear optical properties of silica-glass-core-fiber waveguides under intense pulsed reactor irradiation

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Abstract

The light emission and transient optical loss (TOL) of KU-1 (Russia) and K-3 (Japan) fibers during pulsed reactor irradiation (pulse duration 80 μs, dose rate $< 7\times10^{16}$ n/cm^2 s) have been measured in the visible region. The intensity of fast component of light emission obeys sub-linear dose rate dependence. The intensity of light emission and the TOL depend on the intensity of probing light. Lower intensity of the light emission is observed for higher intensity of probing light. The light emission quenching occurs for wavelengths shorter or longer than the wavelength of probing light. Probing with light enhances the TOL and shortens the decay time of TOL. A 'two-photon-flows' model has been introduced to analyze correlation between the effect of light emission quenching and the TOL enhanced by probing light. The effect of light emission quenching provides means to control the optical properties of fibers in radiation environments.

1. Introduction

The important issues for potential use of optical fibers in the diagnostic systems of fusion reactors [1] are (a) the acceptable level of radiation sensitivity and (b) the linear optical response. The radiation sensitivity of optical fibers shows up as interference by radiation-induced light emission (RLE), transient optical loss (TOL) and residual optical loss. At present, much attention is paid to the radiation sensitivity of silica fibers doped with OH groups or F [2,3]. As for optical response, two types of non-linear behaviors of optical fibers have been observed in the visible region. First, during pulsed reactor irradiation, a sub-linear dose rate dependence of the intensity of RLE was observed [4]. Second, it was found that radiation-induced optical properties depend on the light intensity in the fibers, during steady-state gamma or pulsed reactor irradiation [5–7].

The non-linear optical response of silica fibers during irradiation was first observed in experiments at a TRIGA pulsed fission reactor (pulse 40 ms, dose per pulse 8×10^{13} n/cm^2) [6]. Optical signals were integrated over time and measured with and without light probing. The radiation-induced light amplification in the wavelength range from 300 to 600 nm was reported. It was found that the sum of intensities of the RLE and the probing light measured separately was less than the intensity of simultaneous RLE and probing light.

During steady-state gamma irradiation (^{60}Co-sourse, dose rate 7 Gy/s), the RLE bands at 450 and 650 nm were observed for silica fibers of various grades [7]. At low doses (<100 Gy), the radiation-induced light amplification in the visible region was observed [7]. With increasing dose, the residual optical loss increased and diminished the effect, however, in the blue spectral range, where the RLE was the strongest, and the residual optical loss was relatively weak, the light amplification was observed up to a dose of about 10 MGy.

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doi:10.1016/j.jnucmat.2004.04.246

Usually, the RLE and optical loss are assumed to be independent of the light intensity in fibers (linear approximation). Accordingly, the efficiency of RLE and the TOL are calculated from two measurements: the light emission intensity only (no probing light) and the intensity of simultaneous light emission and probing light transmitted through a fiber [4]. The radiation-induced light amplification is a typical effect showing the dependence of optical properties on the light-intensity. By using the linear approximation, processing of the data on radiation-induced light amplification gives negative TOL.

The purpose of the present paper is to stress the importance of non-linear optical responses of optical fibers for diagnostics of fusion plasma. Known results on radiation-induced optical non-linearity of optical fibers under pulsed reactor irradiation are reviewed, and new data on the non-linear behavior during pulsed reactor irradiation are reported.

2. Experimental

Two types of silica fiber waveguides of KU-1 grade (Fiber Optic Research Center, Russia, OH content 1000 ppm, core diameter 100 μm, cladding thickness 10 μm) and K-3 grade (Fujikura Ltd., Japan, OH content 10 ppm, F doped, core diameter 200 μm, cladding thickness 25 μm) were used in experiments. Twenty meters of each fiber were exposed to reactor pulses. The initial optical absorption coefficients of these fibers in the range of 400–800 nm were presented elsewhere [8].

The techniques of optical measurements during pulsed irradiation of BARS-6 fission reactor (IPPE, pulse duration 80 μs, dose per pulse $<5.5\times10^{12}$ n/cm^2 (9 Gy), dose rate $<7\times10^{16}$ n/cm^2 s (1.1×10^5 Gy/s)) have been presented elsewhere [4,5]. The optical signals and the neutron flux were measured simultaneously.

To probe the fibers we used two continuous lasers: He–Ne-laser (wavelength 632 nm, power 1 mW) and AIG:Nd^{3+}-laser (second harmonic wavelength 532 nm, power 8 mW). The laser wavelength of 632 nm corresponds to the range where the absorption band ascribed to the non-bridging oxygen hole center [9] is observed for fibers of low OH concentration (K-3).

3. Light emission

The time dependencies of RLE of KU-1 fibers under pulsed reactor irradiation were measured in [4]. The effect of optical loss was eliminated, by using the linear approximation. The time dependence of light emission has two components: fast and slow [4].

$$I(t) = I_{\mathrm{fast}} + I_{\mathrm{slow}} = aD^{\delta}(t) + b\int_0^t (D(t')\cdot e^{\frac{t'-t}{\tau}})\,dt'. \quad (1)$$

The slow component (I_{slow}) was attributed to radioluminescence. To calculate the slow component, a relaxation behavior with characteristic time τ of 150 ± 50 μs [4] for the visible range was considered. It was plausible that the fast component (I_{fast}) was due to the Cherenkov radiation [4], as the RLE during pulsed electron irradiation [10]. Finding the intensity of Cherenkov radiation to be proportional to the dose rate $D(t)$ was anticipated. However, the fast component obeys sub-linear dose rate dependence with the exponent δ of ≈0.7. The exponent does not depend on the wavelength in the visible range.

To find the cause of the non-linear dose rate dependence, other experiments were done, aimed at determining whether the intensity of light emission or TOL depended on the intensity of probing light [5]. First, the intensity of probing light at a wavelength the same as that of RLE was changed several times, and the intensity of the light coupling out of the fiber during reactor pulses was measured [5]. When the probing light was switched off, only the RLE was observed. Under irradiation, the TOL affected the shape of the optical signals both during probing of the fiber and without the probing. In the range of the neutron pulse's maximum, the light emission without probing light showed an intensity higher than the intensity of simultaneous light emission and probing light. That is, on increasing the intensity of the light coupling the fibers, the intensity of the light coupling out of the fiber does not increase, but decreases. Therefore, the contributions from the RLE and probing light cannot be considered independent, and the linear approximation mentioned is not valid. For instance, a complex value of absorption coefficient, i.e. with real and imaginary parts, is obtained by using the linear approximation, which is unreasonable.

In the next experiment, the wavelength of the light coupling out of the fiber differed from the wavelength of the probing light. The probing light was eliminated by a monochromator, and the light coupling out of the fiber was due only to RLE. Switching on the probing light resulted in a decrease of the RLE in the visible range. It is shown in Fig. 1 that after switching on the probing light (wavelength 632 nm) the intensity of light emission of K-3 fiber at the wavelength from 450 to 650 nm decreases. At the highest intensity of the probing light ($\approx$100 mW/cm^2) the light emission intensity is 1.5 times lower. The light emission quenching occurs for wavelengths shorter or longer than the wavelength of the probing light. This effect was observed for both the OH-doped and F-doped fibers. Fig. 2 shows the dependence of RLE intensity measured for KU-1 fiber at the wavelength of 450 nm on the intensity of probing light (532 nm).

The non-linear behavior observed during pulsed reactor irradiation is evidence that the efficiency of RLE and/or the TOL depend on light intensity in the fibers. In the next section we will analyze the effects stemming

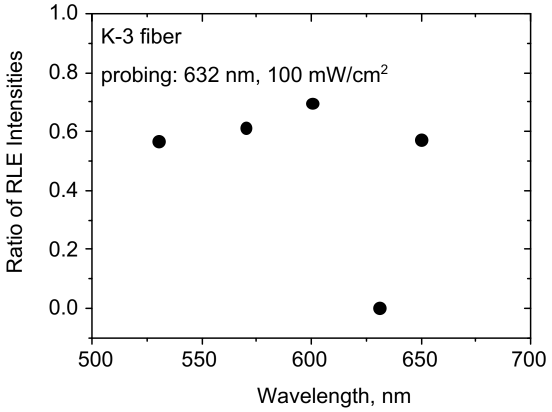

Fig. 1. Decrease of RLE intensity of K-3 fiber probed with He–Ne laser (632 nm). The intensity of RLE at probing normalized to the intensity of RLE without probing is plotted vs the wavelength of RLE. The intensities of RLE at maximums of the neutron pulses are compared.

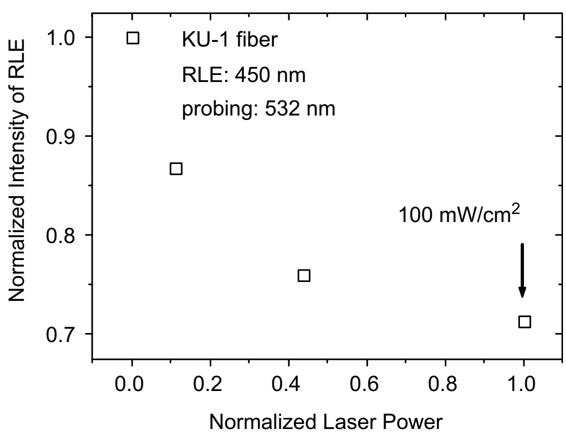

Fig. 2. Dependence of RLE intensity of KU-1 fiber at the wavelength of 450 nm on the intensity of probing with IAG laser (532 nm). The intensities of RLE at maximums of the neutron pulses are taken.

from the linear dependence of TOL on the light intensity in a fiber.

4. A 'two-photon-flows' model

Let us consider an optical fiber (Fig. 3) where the propagating light (intensity I), the RLE (power of light emission Q) and the optical losses $\alpha(I)$ linearly dependent on the light intensity in the fiber interact with each other

$$\alpha(I) = \alpha(1 + kI), \tag{2}$$

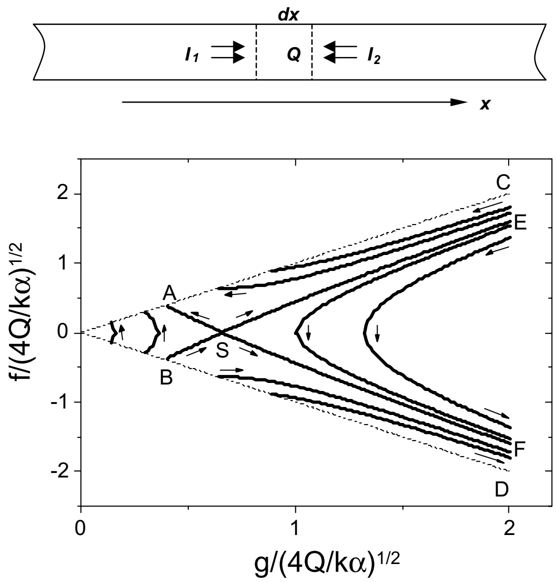

Fig. 3. Phase diagram calculated from Eq. (7) by varying the C parameter.

where k is an efficiency of photon-induced absorption.

The propagating light can be thought as two photon flows moving in opposite directions, with intensities I_1 and I_2. In a small piece of the fiber (length dx), the photon flows gain intensities owing to the light emission and weaken because of the optical losses

$$\frac{dI_1}{dx} = Q - \alpha I_1(1 + k(I_1 + I_2)), \tag{3}$$

$$\frac{dI_2}{dx} = -Q + \alpha I_2(1 + k(I_1 + I_2)). \tag{4}$$

Using the following substitution in Eqs. (3) and (4)

$$g = I_1 + I_2, \quad f = I_1 - I_2, \tag{5}$$

one can derive the equation

$$\frac{dg}{df} = \frac{f(1 + kg)}{g(1 + kg) - 2Q/\alpha}. \tag{6}$$

The general solution of Eq. (6) is the expression given below

$$f^2 = g^2 - \frac{4Q}{k\alpha} \ln\left(\frac{1 + kg}{C}\right), \tag{7}$$

where C is an integration constant depending on the boundary conditions and fiber length L.

The phase diagram calculated from Eq. (7) for various C is given in Fig. 3, lower section. The area of the phase diagram is limited by two lines, OC and OD, corresponding to the condition $g \geqslant |f|$. The saddle point S has coordinates $((2k)^{-1}(\sqrt{1+8Qk/\alpha}-1);0)$. The arrows near the phase trajectories show directions of the photon flow with intensity equal to I_1.

The phase diagram consists of several regions corresponding to different situations in the fiber. With no probing light, $I_1(0) = I_2(L) = 0$, all solutions fall in the region OASB. At relatively low intensity of probing light, the solutions are in the same region. The other regions correspond to cases of probing with the intensity of light exceeding a certain threshold. With no probing light, no solution is possible for these regions. The probing with one beam of light, $I_1(0) \neq 0$ or $I_2(L) \neq 0$, corresponds to the region ACES or FSBD respectively, whereas the region ESF corresponds to probing with two beams.

In the frame of the model, the non-linear dependence of the intensity of RLE on the dose rate [4] can be understood, assuming the power of light emission Q in the bulk of fibers is proportional to the dose rate. In the particular case of a long fiber, $L \gg (\alpha + 2Qk)^{-1}$, the intensity of light emission in the middle part of the fiber can be expressed symbolically as

$$g(L/2) \approx (2k)^{-1}\left(\sqrt{1+8Qk/\alpha}-1\right). \quad (8)$$

With increasing Q, the linear dependence of light emission changes to the square-root dependence. In experiments, the sub-linear dose rate dependence with an exponent of about 0.7 was measured [4].

The quenching of RLE during the optical probing of fibers can be explained in the frame of the model. At probing with one beam of light, for example $I_1(0) \neq 0$, the intensity of the light coupling out of the fiber is equal to $I_1(L) = g(L) = f(L)$, which correspond to a point at the line OC of the phase diagram. Calculations show, that the point always shifts to the region of high $g(L)$ on increasing the intensity of the probing light $I_1(0)$. However, the contribution from RLE decreases.

It should be noted that the RLE and TOL are observed in wide spectral ranges, whereas the probing light is a narrow laser line. That is, non-linear responses may depend on both the wavelength of TOL and the wavelength of the probing light, which could be a subject of a more sophisticated model.

5. Transient optical loss

The TOL was measured in the study [8]. The radiation intensities of the lasers used for probing were set much higher than the intensity of light emission. In general, slightly different kinetics of the TOL of the fibers of different OH concentration was observed. KU-1 fiber showed the TOL lower (up to 6.5×10^{-4} cm^{-1}) than that of K-3 fiber (up to 2×10^{-3} cm^{-1}). After the fast increase of TOL during neutron pulses, further slow recovery of transparency is observed, taking tens of seconds. The time dependencies of the TOL at different wavelengths are qualitatively similar for the same fiber, especially for the K-3 fiber. The TOL was high in the regions where the optical absorption before reactor pulses was high.

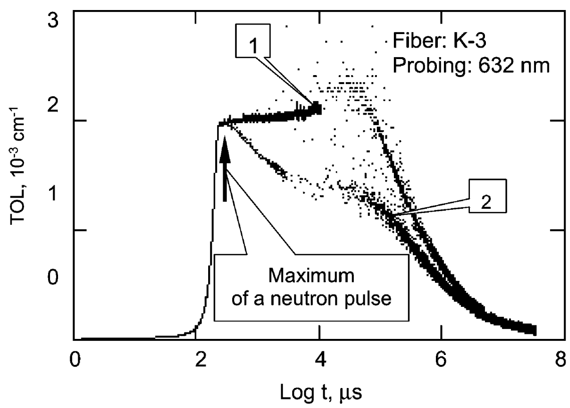

Fig. 4. Time dependencies of transient optical loss of K-3 fiber at the wavelength of 632 nm. The intensity of probing light is equal to 100 mW/cm^2 (1) and 6 mW/cm^2 (2).

The TOL measurements revealed a transient process at times from several milliseconds to several seconds (Fig. 4). The transient process shows up as a temporal increase of TOL. The relationship between the TOL and the evolution of radiation-induced charge carriers, including charge carrier trapping, trap diffusion and electric polarization, was discussed in [8]. After the transient process, the TOL shows the final decay of the trapped charge carriers. We suppose that laser irradiation may affect the TOL through stimulating the charge carrier diffusion on traps.

It was confirmed in experiments with lasers that the TOL depended on the intensity of probing light, namely, the TOL observed after the reactor pulses. On increasing the laser intensity, the transient process becomes more pronounced, and the TOL decays faster (Fig. 4). At present, it is difficult to confirm the effect of probing light on the TOL during reactor pulses. If the laser intensity is set much higher than the intensity of light emission the TOL does not depend on the laser intensity probably because of the same saturation behavior as that shown in Fig. 2.

6. Conclusion

The KU-1 and K-3 fibers showed non-linear optical response during intense pulsed reactor irradiation. The intensity of radiation-induced light emission and the transient optical loss depend on intensity of probing light. Lower intensity of the light emission is observed for higher intensity of probing light. The light emission quenching occurs for wavelengths shorter or longer than the wavelength of the probing light. The fast growth of TOL during a reactor pulse is followed by a slow (tens of seconds) recovery of transparency of the fibers. Probing with light enhances the TOL and shortens the decay time of TOL.

The non-linear optical responses measured in this study are very fast as compared to typical plasma pulses [1]. However, they might be important for transient regimes such as ignition of plasma, plasma disruptions, etc. Moreover, non-linear optical responses may occur during steady-state irradiation of fibers [7]. The effect of light emission quenching provides means to control the optical properties of fibers in radiation environments and can be used to improve the signal-to-noise ratio. Non-linear optical responses of optical fibers must be considered as an important issue for the plasma diagnostics of fusion reactors.

Acknowledgements

A part of this study was financially supported by the Budget for Nuclear Research of the MEXT, based on the screening and counseling by the Atomic Energy Commission.

References

[1] S. Yamamoto, T. Shikama, et al., J. Nucl. Mater. 283–287 (2000) 60.
[2] T. Shikama, T. Kakuta, M. Narui, T. Sagava, N. Shamoto, T. Uramoto, K. Sanada, H. Kayano, J. Nucl. Mater. 212–215 (1994) 421.
[3] S.F. Paul, J.L. Goldstein, R.D. Durst, R.J. Fonck, Rev. Sci. Instr. 66 (1995) 1252.
[4] P.V. Demenkov, O.A. Plaksin, V.A. Stepanov, P.A. Stepanov, V.M. Chernov, K.M. Golant, A.L. Tomashuk, J. Nucl. Mater. 297 (2001) 1.
[5] P.V. Demenkov, O.A. Plaksin, V.A. Stepanov, P.A. Stepanov, M.O. Zabezhailov, K.M. Golant, A.L. Tomashuk, Proc. SPIE 4547 (2001) 74.
[6] A.A. Boody, M.A. Prelas, Proc. Conf. Phys. Nucl. Induced Plasmas 3 (1993) 32.
[7] A.L. Tomashuk, D.V. Pavlov, K.M. Golant, Garching 17–19 (June) (1996).
[8] O.A. Plaksin, V.A. Stepanov, T. Shikama, J. Nucl. Mater. 307–311 (2002) 1242.
[9] D.L. Griscom, J. Ceram. Soc. Jpn. 99 (1991) 923.
[10] J.E. Golob, P.B. Lyons, L.D. Looney, IEEE Trans. Nucl. Sci. 24 (1977) 2154.