Radiation-induced loss of optical fibres at 1300 nm and 1550 nm wavelength

Henning Henschel, Otmar Köhn, Hans Ulrich Schmidt
Fraunhofer-INT, D-53879 Euskirchen, Germany

ABSTRACT

The radiation-induced loss of single mode fibres with undoped and Ge-doped core material was measured at 1300 nm and 1550 nm in the time range from 0.1 s to $\lesssim$ 500000 s at room temperature (+25 °C). With the Ge-doped fibre, measurements were also made at -50 °C and +80 °C. The ratio of the losses at 1300 nm and 1550 nm increased at +25 °C with both fibre types within about 10 s to a maximum value of ≈ 2 (Ge-doped) or ≈ 2.7 (undoped). Then the ratio decreased continuously and became < 1 (= higher loss at 1550 nm) after about 35000 - 70000 s (Ge-doped) or $\gtrsim$ 350000 s (undoped). After ≈ 500000 s a value of ≈ 0.75 was reached with the Ge-doped fibre, with an observable tendency to fall further.

At -50 °C the ratio increased up to about 2.2 and remained constant (as if frozen) during the whole irradiation time of 500000 s. At +80° C, however, the radiation-induced loss at 1550 nm was higher at the beginning and became lower than the one at 1300 nm only after an irradiation time of $\gtrsim 10^4$ s.

Additionally the annealing time of loss was measured after the end of irradiation for varying irradiation times between about 3 s and 400000 s. The results can qualitatively explain the radiation-induced loss curves at 1300 nm and 1550 nm as well as their ratio.

Keywords: Optical fibres, gamma irradiation, radiation-induced loss, 1300 nm, 1550 nm, irradiation time variation, annealing time vs. irradiation time.

I. INTRODUCTION

The initial attenuation of optical fibres at 1550 nm is only about half as high as at 1300 nm, so that very long repeaterless fibre optic links should work at 1550 nm, unless a higher radiation-induced loss increase at 1550 nm could lead to a higher *total* attenuation (initial plus radiation-induced) at this wavelength.

The predominant opinion until now has been that optical fibres with undoped as well as with Ge-doped silica core show lower radiation-induced loss at 1550 nm than at 1300 nm wavelength. The reason is that the majority of the published measurements were irradiations of relatively short duration, and that most of the residual tests with longer irradiation times (≫ 10000 s) were often performed at only one of these two wavelengths.

Friebele et al.[1], however, reported on a continuous ^{60}Co gamma irradition with a dose rate of only 1 rad*/d of a Ge-doped graded index fibre ("Valtec prototype"). At the dose 100 rad (i.e. after an irradiation time of 100 days) the loss increase at 1.5 µm (0.021 dB/km) was about twice that at 1.3 µm (< 0.012 dB/km).

One of our spectral loss measurements of a Ge-doped graded index fibre made by AT&T[2] (^{60}Co gamma dose rate 1200 rad/min ≈ 22 rad/s) showed higher induced loss at 1300 nm up to a dose of 10^5 rad (irradiation time about 4550 s), but higher loss at 1550 nm already at a dose of 1.4×10^6 rad (≈ 64500 s).

Kyoto et al.[3,4] made some systematic investigations about dose rate dependence, wavelength dependence, and temperature dependence of radiation-induced loss as well as of its annealing time. They used undoped as well as Ge-doped single mode (SM) fibres. The undoped fibre showed about 3 times higher loss at 1300 nm than at 1550 nm after 1 h of irradiation with a

* 100 rad = 1 Gy. The material is always SiO_2, i.e. rad = rad(SiO_2).

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dose rate of about 10^5 rad/h, whereas irradiation of the same fibre with about 2 rad/h led to distinctly higher loss at 1550 nm at dose values $\gtrsim 10^3$ rad (irradiation time > 500 h $\approx 2 \times 10^6$ s) [4]. Spectral loss measurements with both fibre types [3] showed continuous increase of loss with wavelength, beginning from ≈ 1100 nm (undoped fibre) or ≈ 1250 nm (Ge-doped fibre), respectively. Irradiation time was 25 h (90000 s), and the spectral loss measurements were performed two weeks later. They explained their results by the existence of three short-lived defects ($0.02 \leq \tau < 3$ s), with maximum attenuation in the UV, leading to loss dependent on dose rate, and one long-lived defect ($\tau \approx 4 \times 10^5$ s), with maximum attenuation in the far IR (> 1800 nm), leading to loss independent of dose rate. They did not point out whether the ratio of the induced losses at 1300 and 1550 nm depends on dose or irradiation time, nor did they try to find out limits for a higher loss at 1300 nm.

In [5] we showed for the first time the crossover where the radiation-induced loss at 1550 nm becomes higher than that at 1300 nm. We irradiated (at room temperature) two Ge-doped SM fibres made by different manufacturers with a ^{60}Co gamma dose rate of about 140 rad/s ($\approx 5 \times 10^5$ rad/h) and measured continuously the increase of radiation-induced loss at 1300 and 1550 nm. The crossover took place at a dose of $(2\text{-}3) \times 10^6$ rad, i.e. after about 14000 to 20000 s. The two loss curves continued diverging up to the final dose of 10^8 rad (> 700000 s).

For the present paper we made similar measurements with an undoped and a Ge-doped SM fibre (at room temperature), but instead of comparing the loss increase at both wavelengths over three decades, we show the ratio of the losses at 1300 and 1550 nm which is restricted to values between 0 and 4. The dose rate was varied between about 1 and 200 rad/s in order to find out whether the crossover point mainly depends on irradiation time or on dose. Additionally we measured the annealing time of induced loss for irradiation times from about 3 to 400000 s, hoping to find an explanation for the observed loss ratio curves. With the Ge-doped fibre we repeated some of these measurements at temperatures of -50 °C and +80 °C in order to find out whether the previous results can be applied to environments with extreme temperature.

2. EXPERIMENTAL

Both investigated fibres were SM fibres with diameters of about 9/125/250 µm for core, cladding, and coating, respectively. The coating material of both fibres was UV curable arcylate.

The Ge-doped fibre had a pure silica cladding and was drawn by Siecor (Neustadt/Coburg, Germany). The Siecor product name is SMF 1528, and it is identical with Corning's SMF 28. The undoped fibre (F-doped cladding material) was supplied by Lightspec and should be very similar to the undoped fibres used by Kyoto et al.[3,4].

Irradiations were performed at a ^{60}Co source with a maximum activity of 500 Ci (= 18.5 TBq). The dose rate can be varied between about 0.05 rad/s and 250 rad/s simply by changing the distance between test fibre coil and point source.

Radiation-induced loss measurements were made by the "transmission loss method", i.e., the light of a stabilized laser diode was coupled into one end of the fibre under test, and at the other end the light power was measured continuously before (stability test), during, and after irradiation. Compensation of light source drifts was achieved by insertion of a reference branch. A block diagram of the measuring system is given, e.g., in [5].

At the beginning of each irradiation, measurements were made with a higher repetition rate so that the averaging time of our commercial light power meter (HP8153A) had to be reduced. As a consequence, the signal to noise ratio at times $\lesssim 40$ s can be relatively low, especially at higher and lower temperatures (rapid transmission loss fluctuations).

The light power inside the fibre core was 10 µW in all cases. Since both fibres show only negligible photobleaching, the results should be very similar at other light power values.

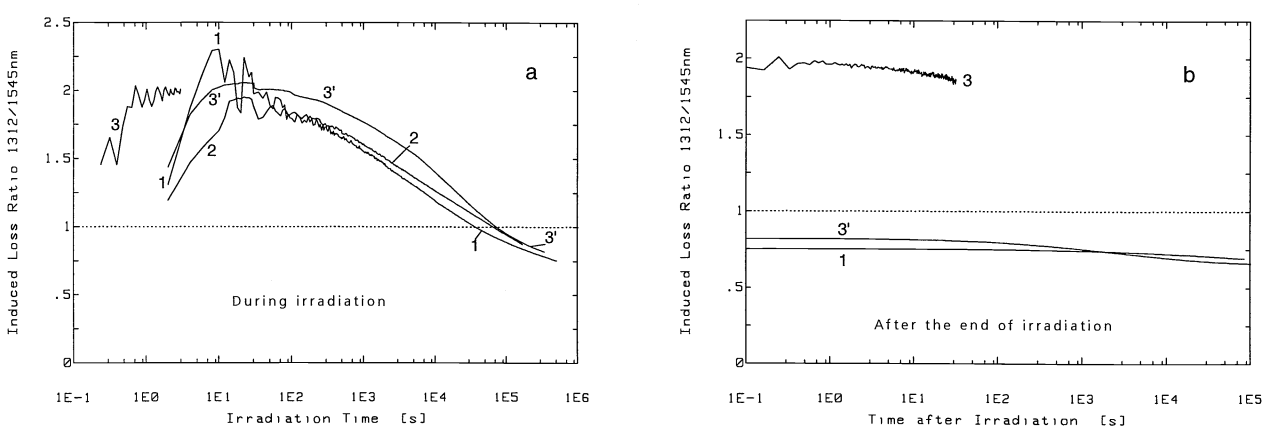
3. RESULTS

3.1. Measurements at room temperature

3.1.1. Ratio of induced loss at 1300 and 1550 nm

Instead of plotting the radiation-induced loss over three decades and looking for the crossover of the 1300 nm and 1550 nm curves[5], we only present the ratio of the losses at both wavelengths. This ratio is > 1 as long as the loss induced at 1300 nm exceeds that measured at 1550 nm.

Figs. 1a,b show the results obtained for the Siecor fibre (Ge-doped) with three different dose rates (about 1, 15, and 200 rad/s, respectively). The loss ratio increases from about 1 at times $\lesssim$ 1 s to a maximum value of about 2 within about 20 s (Fig. 1a). Then the ratio decreases continuously and falls below "1" after an irradation time between about 35000 s (1 rad/s) and 70000 s (15 and 200 rad/s). Thus the point of equal loss mainly depends on irradiation time rather than on dose (= dose rate $\times$ irradiation time).



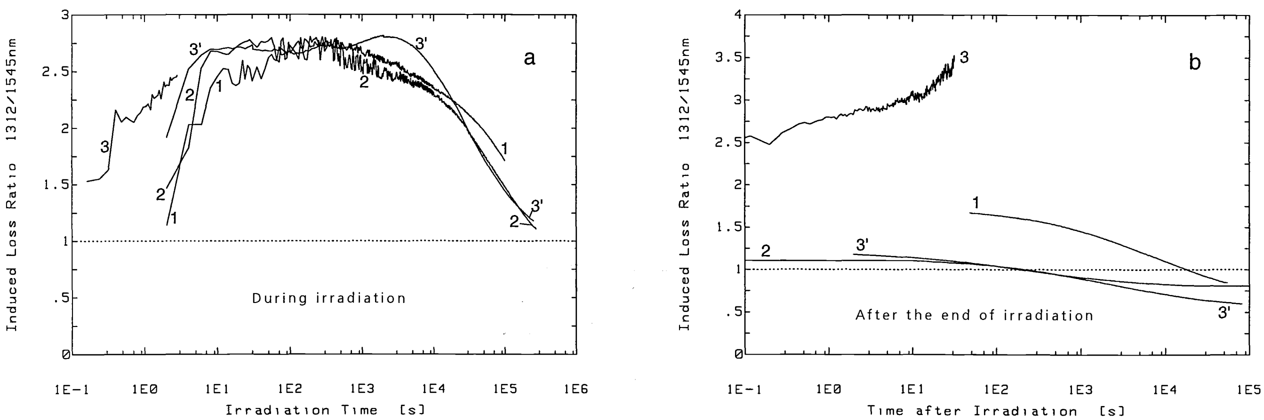
Figs. 1a,b: Ratio of radiation-induced losses at 1312 nm and 1545 nm as a function of irradiation time.
Fibre: Siecor SMF 1528 (single mode, Ge-doped core), light power: 10 µW, room temperature.
1: Dose rate $\dot{D}_\gamma \approx 1$ rad/s, 2: $\dot{D}_\gamma \approx 15$ rad/s, 3, 3': $\dot{D}_\gamma \approx 200$ rad/s.

Cuvres 1, 2 and 3' were measured with a minimal repetition rate of 2 s, so that the results at times < 4 s are unreliable. We therefore made some additional measurements with shorter repetition time (about 0.1 s) and irradiation time ($\approx$ 3 s.) The resulting curve 3 shows that the sharp decrease against short irradation times seems to be correct.

After the end of irradiation the loss ratio continues to decrease with approximately the same slope (Fig. 1b).

In Figs. 2a,b we see the same curves for the Lightspec fibre (undoped). Here the maximum reaches values of about 2.75 and is already obtained after about 10 s (Fig. 2a). The ratio remains nearly constant up to an irradiation time of about 4000 s and would have fallen below "1" after about 350000 s. Again the crossover is mainly dependent on irradiation time.

After the end of the long irradation periods (curves 1, 2, 3') the ratio decreases faster and becomes < 1 already after about 200 s (curves 2, 3') and 20000 s (curve 1), respectively (Fig. 2b). After the 3 s-irradiation the ratio continues to increase.



Figs. 2a,b: Ratio of radiation-induced losses at 1312 nm and 1545 nm as a function of irradiation time.
Fibre: Lightspec (single mode, undoped core), light power: 10 µW, room temperature.
1: Dose rate $\dot{D}_\gamma \approx 3.4$ rad/s, 2: $\dot{D}_\gamma \approx 15$ rad/s, 3, 3': $\dot{D}_\gamma \approx 200$ rad/s.

3.1.2. Annealing time as a function of irradiation time

It is well known that the growth of radiation-induced loss with dose (or irradiation time) is governed by the annealing behaviour of the colour centres involved. (Ge+P)-doped fibres, e.g., with nearly non-annealing loss show a (nearly) linear increase of loss with dose up to very high dose values (see e.g. [6]), whereas undoped fibres (with low as well as high OH-content) show (intermediate) saturation already at dose values around 10^3 rad since they (also) have very short-lived colour centres.

So we hoped that additional determination of annealing time as a function of irradation time could help us to explain our results. We typically irradiated fibre samples up to 3 s, 30 s, 300 s, 3000 s, 30000 s, and about 400000 s and measured the subsequent loss annealing up to times of 200000 s. We normalized the loss to the value at the end of irradation (= 1) and determined the time when the loss reached 1/2. We call this time "Annealing Time".

Fig. 3 shows the result obtained with the Siecor fibre (Ge-doped) at 1312 nm and room temperature. The annealing time determined by this procedure for the two fibres at 1312 and 1545 nm and room temperature is shown in Figs. 4a,b. The time to anneal to the value 1/e (instead of 1/2) shows exactly the same tendency.

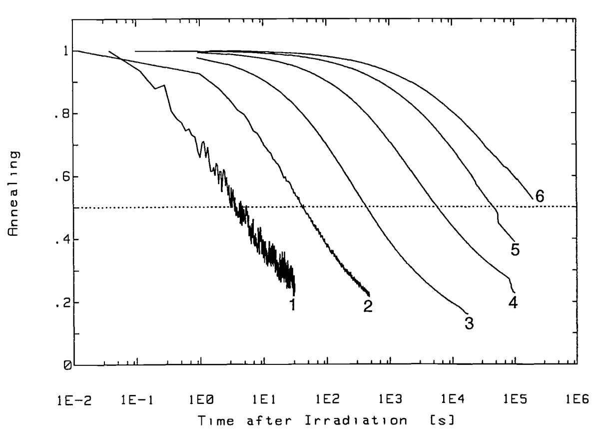
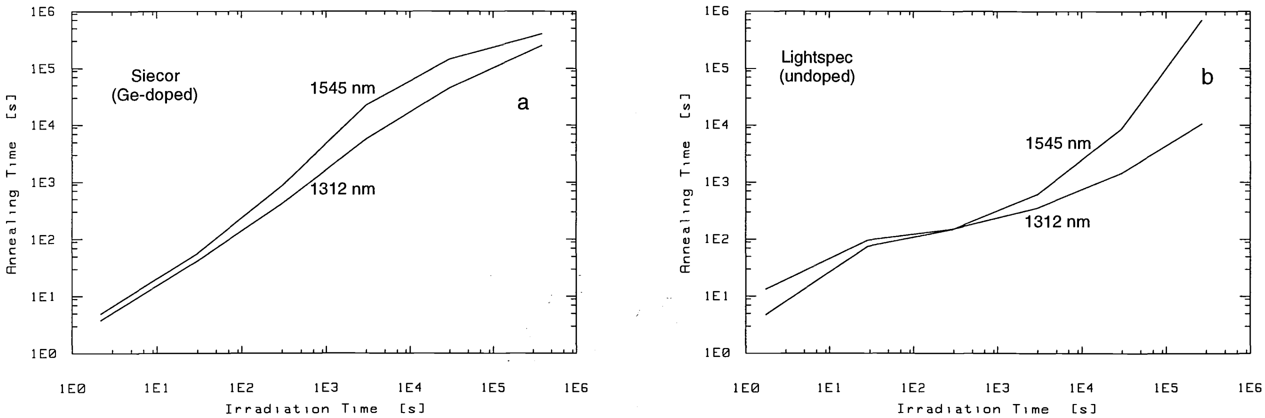


Fig. 3: Loss annealing as a function of time after the end of irradiation. Loss value at the end of irradiation is set at "1". Fibre: Siecor SMF 1528 (single mode, Ge-doped), wavelength: 1312 nm, light power: 10 µW, dose rate: ≈ 15 rad/s, room temperature.
1: Irradiation time $t_{irr.} \approx 2.2$ s, 2: $t_{irr.} = 30$ s, 3: $t_{irr.} = 300$ s, 4: $t_{irr.} = 3000$ s, 5: $t_{irr.} = 30000$ s, 6: $t_{irr.} \approx 386000$ s.

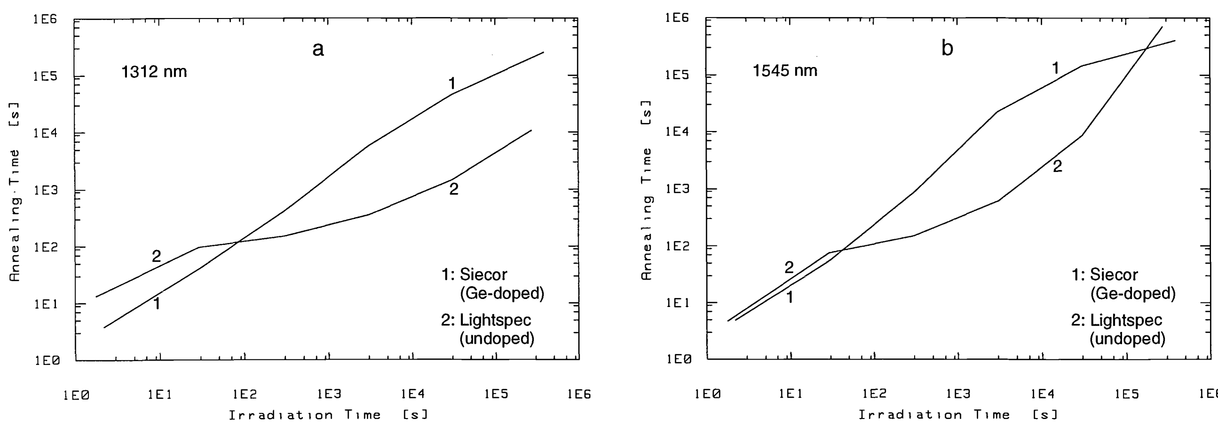


Figs. 4a,b: Annealing time as a function of irradiation time; comparison of results at 1312 nm and 1545 nm.
Light power: 10 μW, dose rate: ≈ 15 rad/s, room temperature.

These curves can indeed help to explain the loss ratio curves of Figs. 1a, 2a. With the Siecor fibre (Fig. 1a) the ratio remains constant (between about 1 to 30 s) as long as the annealing times are approximately equal. When the annealing time at 1545 nm begins to increase faster (> 30 s), the ratio begins to decrease. At very late times when the annealing times come closer again (≳ 100000 s) the slope of the ratio curves begins to decrease.

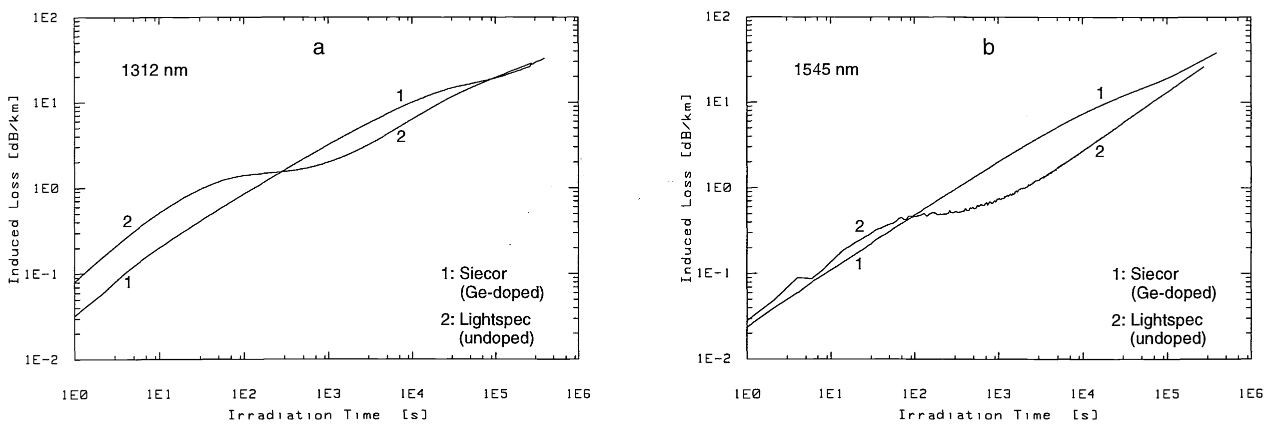
With the Lightspec fibre the loss ratio is approximately constant between 10 s and 1000 s (Fig. 2a). This is exactly the interval where the annealing times at both wavelengths are nearly equal. Again the ratio begins to decrease when the annealing time at 1545 nm begins to increase faster than at 1312 nm.

Figs. 5a,b compare the annealing times of both fibres at 1312 and 1545 nm, whereas Figs. 6a,b do the same with the respective induced losses. One can see that the loss curves (Figs. 6a,b) exactly reflect the behaviour of the annealing curves (Figs. 5a,b).



Figs. 5a,b: Annealing time as a function of irradiation time; comparison of results for Siecor and Lightspec fibre.
Light power: 10 μW, dose rate: ≈ 15 rad/s, room temperature.

The annealing curves of the Lightspec fibre (Fig. 4b) seem to support the results of Kyoto et al.[3,4] for this fibre type (undoped), i.e. that there exists a group of three short "relaxation times" (0.02 s, 0.15 s, 2.59 s) that are caused by the UV absorption peak and one long relaxation time (≈ 350000 s) that is caused by an absorption peak in the far IR. The Lightspec annealing times increase during about 30 s and then remain nearly constant, i.e. there seems to exist an upper value of a short annealing time group. This is the time range (up to about 1000 s) where the UV-tail (i.e. loss at 1312 nm) dominates. When the influence of the long-lived colour centre (IR-tail) begins to dominate ($\gtrsim$ 10000 s), the loss ratio begins to decrease sharply.



Figs. 6a,b: Radiation-induced loss as a function of irradiation time; comparison of results for Siecor and Lightspec fibre. Light power: 10 µW, dose rate: ≈ 15 rad/s, room temperature.

Our annealing results obtained with the Siecor fibre (Ge-doped), however (Fig. 4a), seem not to be consistent with the results of Kyoto et al.[3,4] or Sandhage et al.[7] ("Two-Colour-Center Model") since our annealing times increase continuously with irradation time, whereas Kyoto et al. found nearly identical "relaxation times" for undoped as well as for Ge-doped fibres.

Continuous increase of "decay time" with irradiation time for this fibre type is also stated by the authors of [8] and [9]. The physical reason for this steady increase in annealing time could be the existence of a set of colour centres with different half-life where, with increasing irradiation time, the longer-lived centres (with stronger absorption in the far IR) begin to dominate [9], or a gradual transformation of simple, short-lived centres into more and more complex and stable ones, with increasing absorption in the far IR.

3.2. Measurements at -50 °C and +80 °C

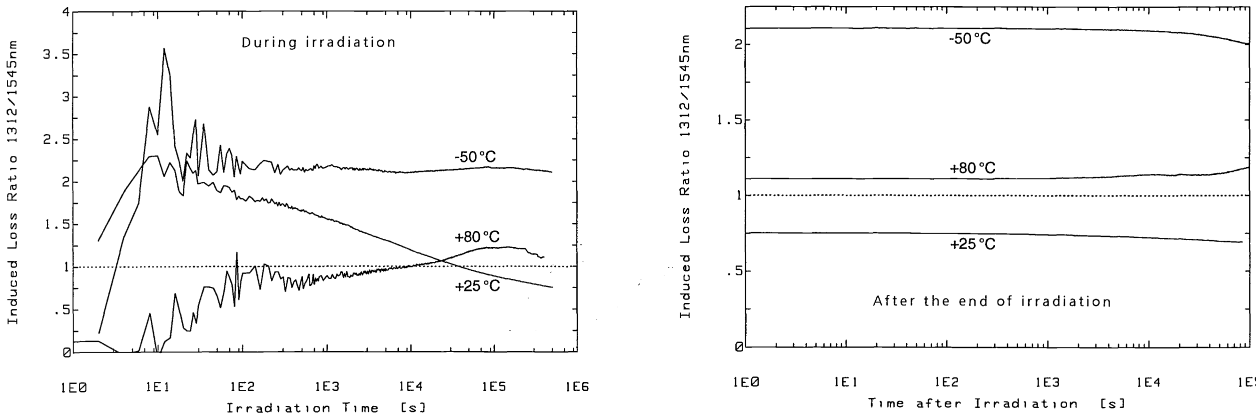
3.2.1. Ratio of induced loss at 1300 and 1550 nm

Measurements at -50 °C and +80 °C were only made with the Siecor fibre (Ge-doped). The dose rate at these two temperatures was about 3 rad/s.

In Figs. 7a,b the results are compared with that of a measurement made at room temperature (+25 °C) with a dose rate of about 1 rad/s. At +25 °C and -50 °C the loss ratio increases during about 10 s to a value of about 2.3 (Fig. 7a). At -50 °C the ratio then remains constant (as if frozen), whereas at +25 °C it decreases continuously to a value of about 0.75 within 500000 s (about 6 days).

At +80 °C the ratio increases during 100 s to about the same value (≈ 0.8) which is reached at +25 °C only after 6 days. It remains then nearly constant for about 400 s and begins to increase thereafter for 10^5 s, reaching a maximum value of 1.25. Then it begins to decrease again.

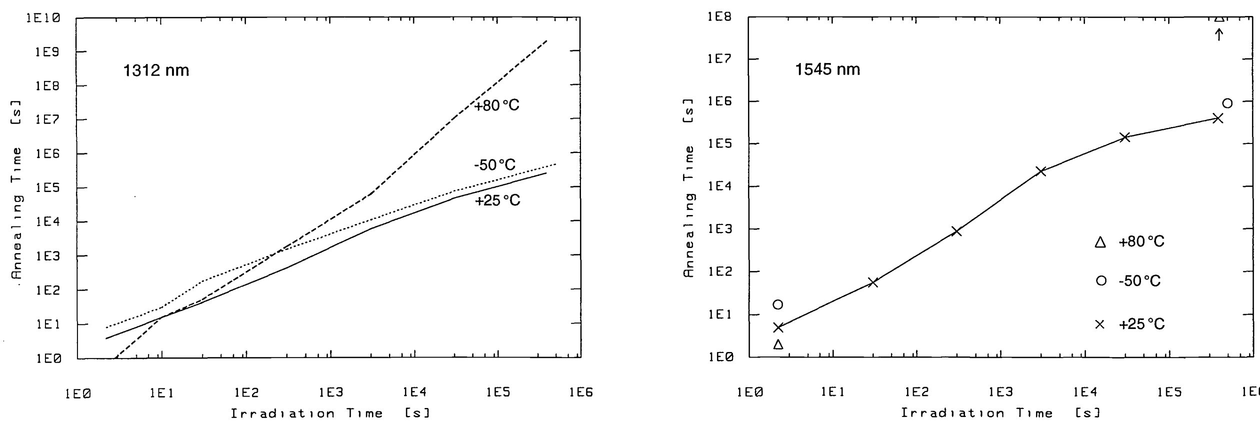
After the end of irradiation, however, there is again a slight increase of the loss ratio at +80 °C (Fig. 7b), whereas it decreases from about 2.1 to 2.0 at -50 °C during the observation time of 100000 s.



Figs. 7a,b: Ratio of radiation-induced loss at 1312 nm and 1545 nm as a function of irradiation time for fibre temperatures of -50 °C, +25 °C, and +80 °C. Fibre: Siecor SMF 1528 (single mode, Ge-doped), light power: 10 µW, dose rate: ≈ 3 rad/s (-50 °C, +80 °C) or ≈ 1 rad/s (+25 °C).

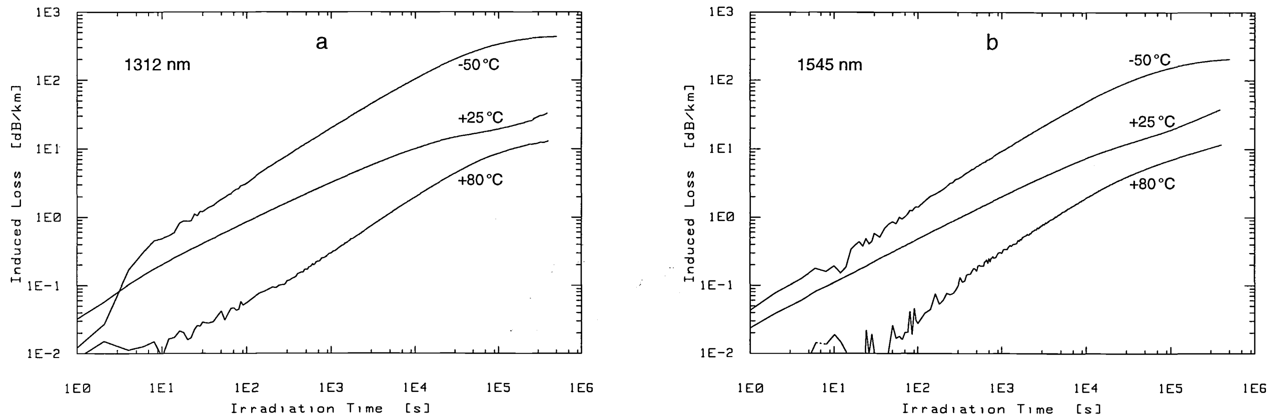
3.2.2. Annealing time as a function of irradiation time

Figs. 8a,b and 9a,b show the corresponding "annealing times" and "induced losses", respectively. With 1545 nm, annealing times at -50 °C and +80 °C were only measured for the shortest and longest irradiation time, but the tendency seems to be the same as with 1312 nm.



Figs. 8a,b: Annealing time as a function of irradiation time; comparison of results at -50 °C, +25 °C, and +80 °C.
Fibre: Siecor SMF 1528 (single mode, Ge-doped), light power: 10 µW, dose rate: ≈ 3 rad/s (-50 °C, +80 °C) or ≈ 15 rad/s (+25 °C).

The annealing times at -50 °C are higher than at +25 °C for all irradiation times (Fig. 8a). This can be the reason for the stronger increase of loss with irradiation time at -50 °C, compared with +25 °C (Figs. 9a,b). Above irradiation times of 100 s, the annealing times at +80 °C show a strong increase which could be the reason for the stronger increase of loss at times ≳ 300 s, compared with +25 °C (Fig. 9a; with -50 °C and +80 °C loss values measured at times ≲ 40 s are relatively unreliable, as already pointed out in section 2.).



Figs. 9a,b: Radiation-induced loss as a function of irradiation time; comparison of results at -50 °C, +25 °C, and +80 °C. Fibre: Siecor SMF 1528 (single mode, Ge-doped), light power: 10 µW, dose rate: ≈ 3 rad/s (-50 °C, +80 °C) or ≈ 15 rad/s (+25 °C).

Longer annealing times at +80 °C sound surprising at first, but one should take into consideration that some short-lived colour centres that can contribute to the loss at room temperature cannot exist at +80 °C, leading to a distinctly lower loss at this temperature (Figs. 9a,b).

4. CONCLUSION

Our investigations have shown that the ratio of the radiation-induced losses at 1300 nm and 1550 nm wavelength depends on irradation time as well as on temperature.

At room temperature, fibres with Ge-doped as well as with undoped silica core have about two (Ge-doped) to 2.7 times (undoped) higher loss at 1300 nm than at 1500 nm only during relatively short irradiation times ($\lesssim$ 100 s with Ge-doped fibres and $\lesssim$ 1000 s with undoped fibres). Then the loss ratio decreases continuously, reaching values < 1 after about 20000 s to 70000 s with Ge-doped fibres and after $\gtrsim$ 350000 s with undoped fibres. This behaviour is (nearly) independent of dose rate, i.e. the crossing time (from lower to higher loss at 1550 nm) depends predominantly on irradiation time and not on dose.

The same measurements with a Ge-doped fibre at -50 °C and +80 °C have shown that at -50 °C the loss ratio remains (nearly) constant (≈ 2.2) during the whole measuring time (nearly 6 days of irradiation). At +80 °C, however, the radiation-induced loss at 1550 nm was higher at the beginning of an irradiation and became lower than at 1300 nm only after an irradiation time of $\gtrsim 10^4$ s.

Kyoto et al.[3,4] explain this behaviour by the existence of absorption peaks in the UV, with shorter relaxation times, and in the far IR, with very long relaxation time. The tail of the first peak is more dominant at 1300 nm than at 1550 nm. The opposite is valid for the IR-peak. Thus, with increasing irradiation time, the loss at 1550 nm might grow faster than at 1300 nm.

Since fibres with undoped as well as with Ge-doped core material showed the same wavelength dependence of their loss in the far IR, Kyoto et al. concluded that the origin of the IR peaks is the same for both materials. They interprete it "as a change in vibration modes due to structural defects caused by gamma radiation". Nothing is to be found in any other literature about radiation-induced absorption bands at wavelengths > 1800 nm existing in fibres with undoped and Ge-doped core material of high purity at room temperature.

Measuring the annealing time of induced loss after the end of irradiation as a function of irradiation time (from about 3 s to 400000 s), we found a nearly constant increase for the Ge-doped fibre, whereas the undoped fibre showed saturation after about 30 s and a further increase after about 3000 s. The latter behaviour can be explained by a group of short-lived colour centres and (at least) one long-lived colour centre which Kyoto et al. believe to have identified for this undoped as well as for their Ge-doped fibres.

The different increase of loss with irradiation time (or dose) of Ge-doped and undoped fibres, as well as the change of the loss ratio at 1300 nm and 1550 nm with irradiation time, can qualitatively be explained by the respective annealing time curves.

5. REFERENCES

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