Radiation-Induced Optical Fibre Loss in the Far IR

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Abstract

It was observed that the loss of a Ge-doped graded index (GI) fibre during gamma irradiation grows stronger at a longer wavelength (about 1300 nm) than at a shorter one (830 nm). The same is known from Ge-doped and undoped single mode (SM) fibres at about 1550 and 1300 nm.

During longer irradiations (≤ 2 d) it was found that the loss of the GI fibre at 830 nm was reduced by photobleaching, leading to approximately the same loss at 830 and 1300 nm during irradiation with higher light powers (≥ 10 μW). The stronger loss increase at 1550 nm of a Ge-doped SM fibre continued for more than 70 days, leading to an about 1.5 times higher loss at 1550 nm than at 1300 nm. The reason seems to be a long-lived absorption peak in the far IR.

I. Introduction

As discussed in [1] , the predominant opinion was that the radiation-induced loss of optical fibres at 1550 nm wavelength is distinctly lower than at about 1300 nm, as it is known from the "initial" attenuation (of unirradiated fibres). 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.

Some few experimentalists, however, reported very early on higher loss increase at 1550 nm during irradiations of longer duration [2-4]. Kyoto et al. [3] showed spectral measurements between about 800 and 1800 nm where the loss measured about 2 weeks after irradiation with a γ-dose of about 2×10^5 Gy decreased with increasing wavelength only up to a minimum around 1100 nm (undoped single mode fibre = SMF) or 1200 nm (Ge-doped SMF), respectively, and then began to increase again. They explained this behaviour by the existence of three short-lived defects with absorption maximum in the UV (causing "dose rate dependent loss") and one long-lived defect with maximum attenuation in the far IR (causing "dose dependent loss"). With increasing irradiation time the radiation-induced loss at longer wavelengths will thus continue to increase, whereas the loss at shorter wavelengths should show some saturation.

In [1] we demonstrated that the ratio of the loss induced by gamma irradiation at 1300 and 1550 nm increases within an irradiation time of about 10 s to a maximum value of about 2 (Ge-doped SMF) or about 2.7 (undoped SMF), respectively. After about 100 s (Ge-doped fibre) or about 1000 s (undoped fibre) the ratio begins to decrease and reaches a value of 1 after about 10^5 s (about one day), with a tendency to fall further. This behaviour was approximately the same for dose rates from about 0.01 to 2 Gy/s.

For the present paper we irradiated a Ge-doped SMF nearly two years (680 d) with ^{60}Co gammas of low dose rate up to a total dose of only 450 Gy (= 45 krad) in order to see whether loss increase at 1550 nm continued to increase faster than at 1300 nm.

Furthermore we measured simultaneously the loss increase of Ge-doped graded index (GI) fibres at 830 and 1310 nm with different dose rates. 830 nm lies closer to the UV peak, so that the loss ratio between 830 and 1310 nm could change even stronger with time than between 1300 and 1550 nm.

To find out whether different colour centre lifetimes in the UV absorption band and in an absorption peak in the far IR could be responsible for the temporal change of the loss increase ratio between the three usual communication wavelengths, we also made spectral loss measurements during and after irradiation.

II. Experimental

For the present investigations we only used SM and GI fibres with Ge-doped core and pure silica cladding. The 9/125/250 μm SM fibre with the designation SMF 1528 was drawn by Siecor (Neustadt/Coburg, Germany). It is identical with Corning's SMF 28. The 50/125/250 μm and 62.5/125/250 μm GI fibres were made in 1999 by Plasma Optical Fibre B.V. (= POF; Eindhoven, Netherlands).

During shorter tests (up to several days) the radiation-induced loss at discrete wavelengths was measured by the "transmission loss method", i.e., the light of a stabilized LED or laser diode source was coupled into one end of the fibre under tests, and at the other end the light power was measured continuously before, during and after irradiation. A block diagram of this measuring system is shown, e.g., in [5]. Loss measurements at discrete wavelengths during several months or even years lasting irradiations were made, from time to time, with an Optical Time Domain Reflectometer = OTDR (ADVANTEST Q8460).

Spectral loss measurements were made in two ways. After the end of irradiations during which the loss was measured at discrete wavelengths, the spectral loss was measured by the "cutback method". I.e., a longer fibre sample (usually about 5 m up to 2 km, dependent on radiation dose and wavelength region of interest) was connected between "white light source" (Halogen Lamp) and monochromator (BENTHAM TM300F). After the measurement the test fibre spool was cutted off at the lamp side, and a residual length of only about 2 m was introduced into the monochromator. The sensitive light input coupling remained thus unchanged. The difference between the two measured spectra is the attenuation in the cutted spool length. The difference of irradiated and nonirradiated samples

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(of same length) is equal to the radiation-induced loss. In order to extend the measurements to wavelengths up to about 2.5 µm a PbS detector was used. Below 1 µm we used a silicon detector.

We also made on-line spectral loss measurements during and after irradiation in order to study the spectral dependence of growth and annealing of loss. These measurements are identical with the "transmission loss method" at discrete wavelengths described above. Radiation-induced loss is calculated from the difference of the spectra measured during (or after) irradiation and before irradiation. The test fibre length has to be adjusted to the expected loss in the wavelength region of interest.

All irraditions were made with ^{60}Co gammas. The source activity was about 500 Ci for measurements with higher dose rates and about 80 mCi for the long time irradiations. All measurements were made at room temperature.

III. Results

A. Single Mode Fibre Loss at 1310 and 1550 nm

In [1] we have shown that the ratio of the radiation-induced loss at 1310 and 1550 nm decreases from about 2 after 10 - 100 s down to 0.75 after about 5 days, independent of dose rate and with still falling tendency. We therefore started a long time irradiation with a 3.5 km spool of the same SM fibre. At the beginning the dose rate was about 0.75 Gy/d. Fig. 1 shows the loss increase at 1310 and 1550 nm (solid lines) during a period of 454 days. The loss difference between both wavelengths still increased, whereas the ratio of the loss at 1310 and 1550 nm (dotted line) decreased to a minimum of about 0.64 after 75 days and then increased again, reaching values around 0.72 after about 400 days.

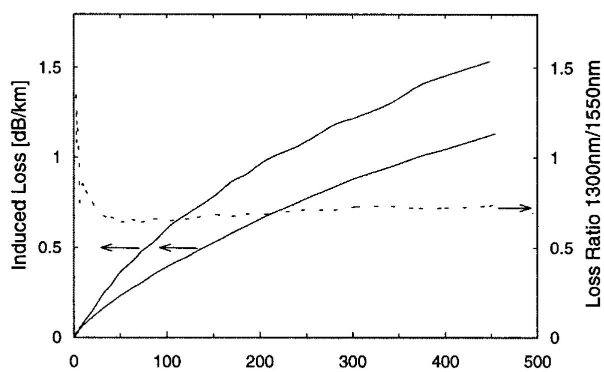

Fig. 1: Increase of radiation-induced loss at 1300 and 1550 nm with irradiation time (solid lines) and change of the loss ratio (dotted line). Fibre: Siecor SMF 1528 (single mode, Ge-doped core). OTDR-measurements. Mean dose rate: 0.69 Gy/d.

The accuracy of these measurements, however, is relatively limited because the radiation-induced loss reached values of only about 1.13 and 1.52 dB/km at 1310 and 1550 nm, respectively. We therefore stopped the OTDR measurements and tried a spectral loss measurement after an irradiation time of 680 days, when the dose had reached a value of about 450 Gy. The dose after 454 days was 314 Gy.

B. Graded Index Fibre Loss at 829 and 1310 nm

At the beginning we made some shorter irradiations with different dose rates (1.54 and 0.048 Gy/s). The loss increase at 829 and 1310 nm was measured continuously by the "transmission loss method". The loss ratio at 829 and 1310 nm of both fibre types (50/125 as well as 62.5/125 µm fibres) decreased with both dose rates from values around 10 after 10 s to nearly 2 after about 3 days (curves no. 1, 2 in Fig. 2). If this tendency would hold, one should expect that after some months the loss increase at 830 nm could be lower than at 1310 nm.

We therefore started a long time measurement with 2.5 km of the POF 50/125 µm GI fibre. The dose rate was about 3.8 Gy/d. Fibre attenuation was measured only from time to time with the OTDR. Even after 25 days the loss ratio still had

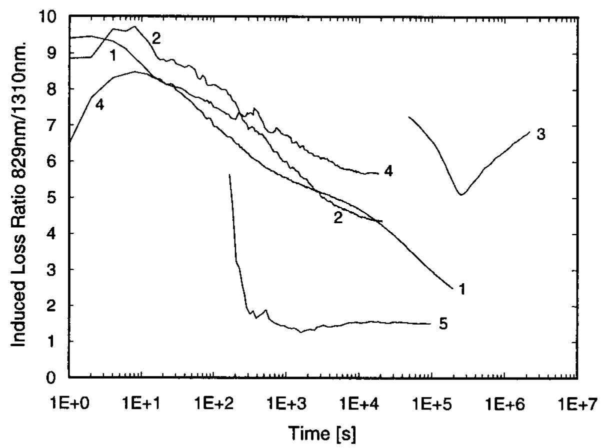

Fig. 2: Ratio of the radiation-induced loss at about 830 and 1300 nm as a function of irradiation time for different dose rates and light powers. Fibre: POF 50/125 µm GI GD18545D. Curve 1: 1.54 Gy/s, 10 µW; 2: 0.048 Gy/s, 10 µW; 3: 3.8 Gy/d, OTDR; 4: 0.047 Gy/s, 0.1 µW; 5: 0.047 Gy/s, 800 µW.

a value of about 6 (curve 3 of Fig. 2). One reason could be photobleaching: During the long time tests with only few OTDR measurements the 2.5 km spool remains unilluminated during most of the time, whereas during the shorter tests two separate fibres where permanently illuminated by 10 µW of 829 nm and 1310 nm, respectively. We therefore made another shorter test where the light intensity in both fibre samples was reduced to 0.1 µW. The results is shown as curve no. 4 in Fig. 2. Actually the loss ratio remained at higher values, not far below curve 3 measured with the OTDR at still lower (mean) light power.

If change to lower light powers reduces possible photobleaching and thus increases the loss ratio, then a change to distinctly higher light powers should lead to a lower loss ratio. The results of a measurement made with about 800 µW (at both wavelengths) is shown as curve 5 in fig. 2. Now the loss ratio decreased to a value of about 1.5 within less than 10 minutes and remained constant. This seems to be the lowest loss ratio obtainable with that light power.

Fig. 3 compares the loss increase at 829 and 1310 nm measured with 0.048 Gy/s at the three light powers. The 829 nm light caused distinct photobleaching (= loss reduction at higher light power), whereas an increase of the 1310 nm light intensity had no effect, at least in Ge-doped fibres. This would all the more be valid for 1550 nm light with its still lower quantum energy.

We therefore conclude: The decrease of the loss ratio at 1310 and 1550 nm with irradiation time could actually be caused by the increasing influence of the absorption band in the far IR, as stated in [3], whereas the decrease of the ratio at 830 and 1310 nm that is especially pronounced at higher dose rates and higher (829 nm) light powers is mainly caused by photobleaching by the 830 nm light.

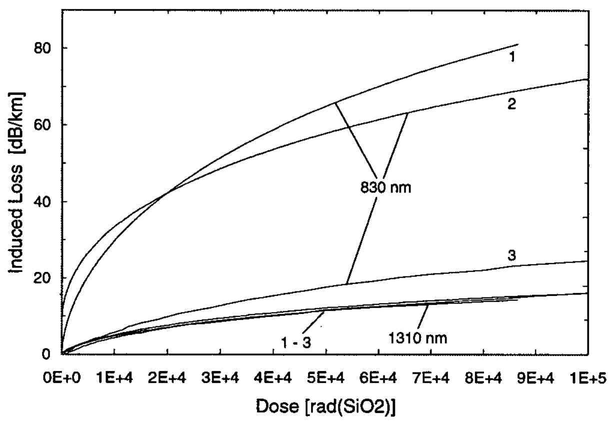

Fig. 3: Increase of the radiation-induced loss at about 830 and 1310 nm with dose for different light powers. Fibre: POF 50/125 µm GI GD18545D. Curve no. 1: 0.1 µW, 2: 10 µW, 3: 800 µW.

Nevertheless it seems to be promising to use 829 nm light of high intensity. The radiation-induced loss is of equal size as at 1310 nm, whereas the costs could be distinctly lower.

C. Spectral Loss Measurements with GI Fibres

In order to study the gradual change of the wavelength dependence of loss increase and annealing, we made with both GI fibre types (on-line) spectral transmission measurements before irradiation (reference value), at certain times during irradiation (after about 10^3 s, 3×10^3 s, 10^4 s, 3×10^4 s, and 10^5 s) and at certain times after the end of irradiation (after about 10^3 s, 3×10^3 s, 10^4 s, 3×10^4 s and 10^5 s). Irradiation was stopped immediately after the 10^5 s measurement, so that this result can be used as reference for calculation of the loss annealing. Irradiated fibre length was 200 m and 130 m for the 62.6/125 and 50/125 µm fibre, respectively. These lengths allowed measurements between about 750 and 2100 nm. With the 62.5/125 µm fibre we also made some additional measurements with only 1.56 m irradiated fibre length in order to get an impression of the wavelength dependence between about 500 and 770 nm. The dose rate was about 0.21 Gy/s, so that the dose at the end of irradiation was about 22 kGy.

Fig. 4 shows radiation-induced loss as a function of wavelength for the 62.5/125 µm fibre after the five irradiation times (or dose values). It can be clearly seen that loss increase towards greater wavelength becomes stronger with increasing irradiation time. This change of wavelength dependence with irradiation time can be expressed more distinctly by dividing the loss curves measured at later times by the curve measured after about 1000 s. Figs. 5, 6 (measurements between 3×10^3 s and 10^5 s) show these results for the 62.5/125 µm and 50/125 µm fibre, respectively. The 2.26 d and 11.7 d lines are the results from off-line measurements made after the end of some of the measurements of section III B. The absolute values are not really comparable since there were annealing periods between the end of the irradiation and the (off-line) spectral loss measurement. Figs. 5 and 6 evidence the following tendencies:

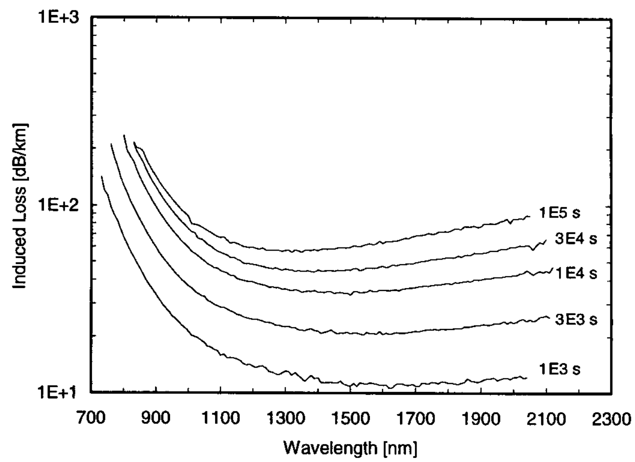

Fig. 4: Change of the wavelength dependence of the radiation-induced loss with irradiation time. Fibre: POF 62.5/125 µm GI CP02057H. Dose rate: 0.21 Gy/s.

- (Relative) increase of loss with irradiation time is stronger towards higher wavelengths ("far IR"), but also (with less intensity) towards shorter wavelengths, i.e., towards the loss maximum in the UV with "dose rate dependent loss" (Kyoto et al., [3]). These regions are separated by a broad minimum between about 850 and 1150 nm.
- Loss increase in the far IR (≥ 1800 nm) is far from being linear, or only "dose dependent", as outlined in [3]. There is still saturation. Saturation seems to be most pronounced around the minimum.
- As a consequence, the minimum of the radiation-induced loss shifts from around 1620 nm after 1000 s to around 1100 nm after 10^5 s (Fig. 4). After irradiation times of several days it is situated around 900 nm.

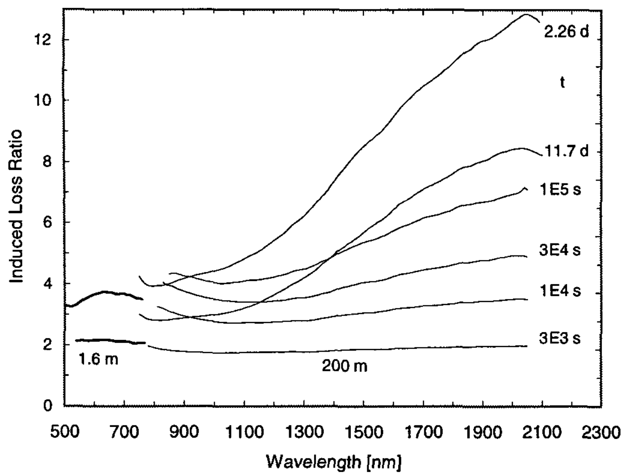

Fig. 5: Change of the wavelength dependence of the ratio of the loss measured at time t and after 1000 s. Fibre: POF 62.5/125 µm GI CP02057H. Measurements between 3×10^3 s and 10^5 s (thin or fat): on-line, $\dot{D}_\gamma = 0.21$ Gy/s. 2.26 d curve: off-line measurement after irradiation with 1.54 Gy/s up to 300 kGy. 11.7 d curve: off-line measurement after irradiation with 0.048 Gy/s up to 48 kGy.

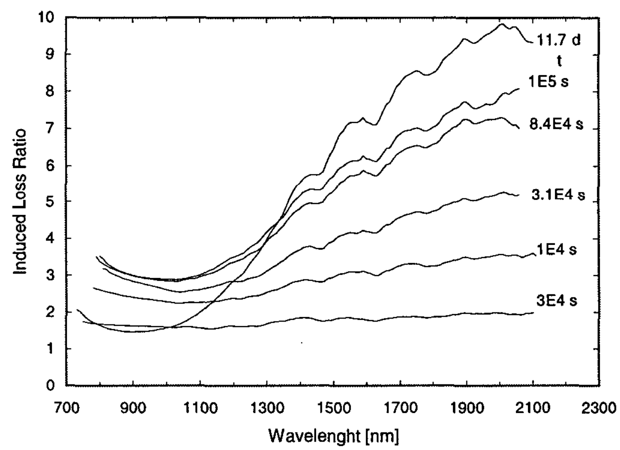

Fig. 6: Change of the wavelength dependence of the ratio of the loss measured at time t and after 1000 s. Fibre: POF 50/125 µm GI GD18545 D. Measurements between 3×10^3 s and 10^5 s: on-line, $\dot{D}_\gamma = 0.21$ Gy/s. 11.7 d curve: off-line measurement after irradiation with 0.048 Gy/s up to 48 kGy.

Loss annealing is expressed as the (spectral) loss measured at a certain time after the end of irradiation divided by the loss curve measured immediately before stopping the irradiation. Figs. 7 and 8 show the results obtained with the two GI fibre types. Loss annealing shows the same spectral dependence as growth: strongest and fastest annealing occurs around 1100 nm. This is not surprising, since the faster the loss anneals the earlier saturation sets in, or the more linear is the loss increase, the slower it anneals (no annealing = linear increase of loss with irradiation time or dose).

In [6] we show that even photobleaching shows the same spectral dependence, i.e., strongest loss reduction around 1100 nm, reduced influence around 650 nm and smallest influence in the far IR.

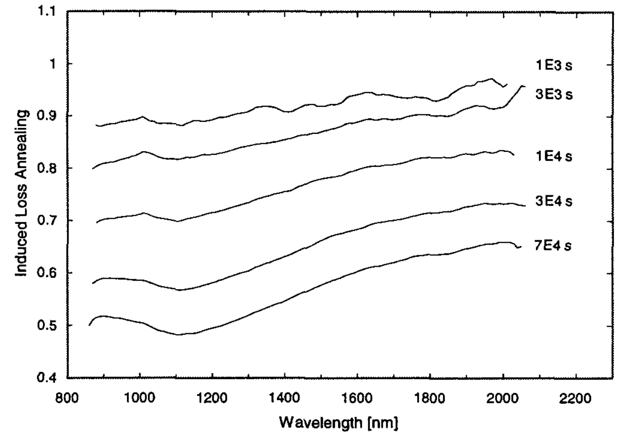

Fig. 7: Wavelength dependence of the residual loss at certain times after irradiation, relative to the loss at the end of irradiation. Fibre: 62.5 µm GI CP02057H. After irradiation with 0.21 Gy/s up to 22 kGy.

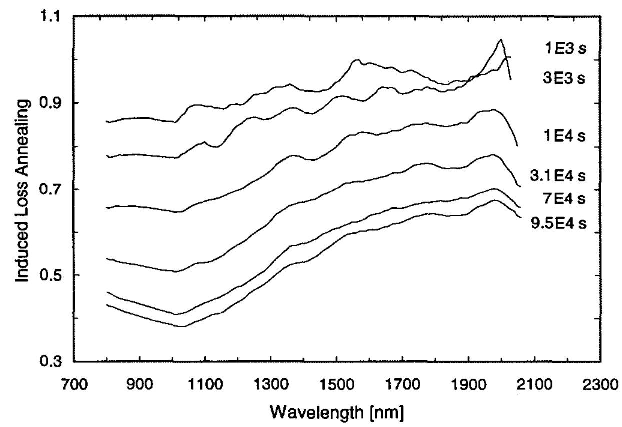

Fig. 8: Wavelength dependence of the residual loss at certain times after irradiation, relative to the loss at the end of irradiation. Fibre: POF 50/125 µm GI GD18545D. After irradiation with 0.21 Gy/s up to 21 kGy.

D. Spectral Loss Measurements with SM Fibres

With the SM fibre Siecor SMF1528 we measured the loss increase after 680 d of irradiation up to about 450 Gy by the cut back method as well as, in order to compare the result with that of shorter irradiations, on-line during an irradiation with a dose rate of 0.21 Gy/s. The procedure was the same as in section III.C.

Spectral loss measurements of SM fibres with our BENTHAM system were relatively uncertain. The light intensity that can be coupled into the fibre is very low, so that the signal-to-noise ratio is quite low. At relatively low dose values as after our 680 d irradiation or at the beginning of an on-line measurement the loss difference between irradiated and unirradiated samples is small, so that two noisy data sets of nearly equal size have to be subtracted. Results were only obtained after several smoothing and averaging procedures, as also discussed in [6].

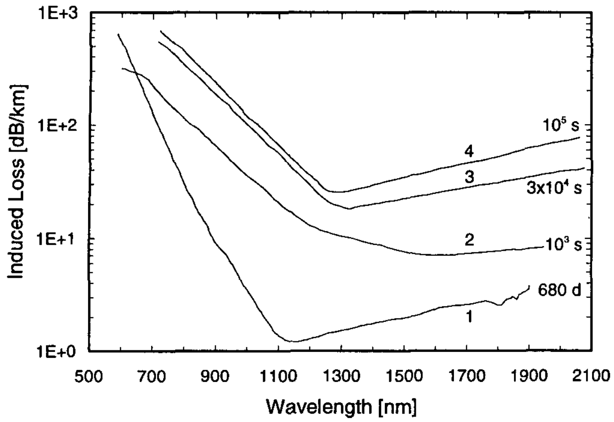

Fig. 9: Change of the wavelength dependence of the radiation-induced loss with irradiation time. Fibre: Ge-doped SM fibre Siecor SMF1528. 1: Off-line measurement after a 680 d irradiation up to 450 Gy. 2 - 4: On-line measurement during irradiation with a dose rate of 0.21 Gy/s

In Fig. 9 we see the results of both types of measurements. The lowest curve (no.1) was obtained with the sample that was irradiated for 680 d. The upper curves were measured during irradiation of a 130 m spool. The tendency is the same as that observed with the GI fibres. At the very beginning of an irradiation the minimum of the radiation-induced loss lies around 1600 nm. With increasing irradition time this minimum is shifted towards shorter wavelengths, and the slope of the curve section above the minimum increases. After 680 d the minimum lies slightly above 1100 nm. The loss values at 1300 and 1550 nm are 1.53 and 2.11 dB/km, respectively, and their ratio is 0.73. These values agree well with the results of Fig. 1.

IV. SUMMARY

Our investigations clearly confirm the results of [3] that there is an absorption peak in the far IR that dominates the radiation-induced loss above 1100 nm with increasing irradiation time.

It is difficult to determine the maximum of this peak because the initial fibre attenuation at wavelengths > 2000 nm is high compared with the additional radiation-induced loss. Some of the curves of Figs. 5, 6 (especially those measured at later times) indicate a maximum at about 2050 nm, whereas the earlier ones (and some of the curves shown in [6]) would favour a maximum at ≥ 2500 nm. The reason might be the finding of [7] that this peak "evolves with time: its maximum shifts to shorter wavelengths ...".

As a consequence, radiation-induced loss above 1100 nm increases with wavelength up to at least 2050 or 2500 nm, and the loss at 1550 nm is lower than at 1300 nm only for irradiation times < 1 d.

Wavelengths around 830 nm could yield comparable low loss increase as around 1300 nm when using one of the meanwhile cheap high power laser diodes (≥ 1 mW into GI fibres).

For long-term applications of optical fibres in all radiation environments wavelengths from about 900 to 1100 nm should be preferred for longer distances. Here we have minimal loss increase as well as fastest annealing. The latter, however, is the reason for the relatively low loss increase since saturation sets in earlier and is more pronounced than in the residual wavelength regions. The investigations of [6] show that also exactly between about 850 and 1150 nm photobleaching (by light of shorter wavelengths) leads to the strongest loss reduction.

V. ACKNOWLEDGEMENTS

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