Induced loss after pulsed and continuous irradiation of single mode and graded index fibres

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ABSTRACT

As part of a measuring program that should give us a survey of the radiation sensitivity of present commercial optical fibres we tested four more single mode (SM) and three graded index (GI) fibres at wavelengths of 850 nm (GI fibres only), 1300 nm and 1550 nm. All fibres were exposed to electron pulses of 500 rd, 3 krd, 10 krd and 100 krd as well as to the continuous gamma radiation of a Co-60 source up to 10 krd and 100 krd. At 10 krd additional measurements with fibre temperatures of +100°C and -50°C were made at both irradiation facilities.

After some brief comments on experimental details we present a small fraction of the results and refer to some interesting details we found till now, e.g. the enormous photo-bleaching in a SM fibre with pure SiO₂ core or the reverse temperature dependence of the induced loss after pulsed irradiation of a P containing fibre at very short and longer times after irradiation. Furthermore, induced losses after pulsed and continuous irradiation are compared, as well as their dependence upon wavelength and temperature.

1. INTRODUCTION

Measurements of the radiation induced loss in optical fibres are made since more than 15 years (see e.g. ref. 1 and the literature quoted in it). During this time nearly all relevant dependencies were investigated, e.g. induced loss as a function of radiation dose, time after irradiation, wavelength and temperature. The results of all these tests still can be used for theoretical interpretations of the phenomenon, but not for answering the question about the magnitude of the radiation induced loss in commercial fibres of today. The reasons therefore are numerous: improved preform manufacturing procedures, higher purity of the basic materials, clean rooms for both preform production and fibre drawing, improved cladding and, mainly, the efforts of many manufacturers to develop radiation hard fibres. Furthermore, most of the earlier measurements were made at wavelengths around 850 nm, only a small fraction at about 1300 nm and nearly none at 1550 nm.

This is the reason why we tried to test a larger number of present SM and GI fibres of different firms. As a first step (last fall) we tested a SM and a GI fibre from "Optical Fibres" (GB). The core of the GI fibre was doped with Ge (11.9 %) and P (0.13 %), that of the SM fibre with Ge only (3.8 %). The results are listed up in ref. 2. Than, this spring, in the course of our cooperation in the "Nuclear Effects Task Group", NATO Panel IV, RSG12, we irradiated a GI fibre from AT&T (AT&T MM Rad Hard 3A) and from Corning (Corning 1507 FOTS-LH) as well as two SM fibres from LTI (designated as "LTI 850 nm SM" and "LTI 1300 nm SM"). The results of our relatively extensive measurements can be found in ref. 3 and as

<table>
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<th>Fibre Type</th>
<th>Core Diameter (μm)</th>
<th>Cladding Diameter (μm)</th>
<th>Coating Diameter (μm)</th>
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<th>Loss [dB/km]</th>
<th>Loss [BW MHz·km]</th>
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<td>&lt;1/-</td>
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a: Mode field diameter at 1300 nm
b: Mean values

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contribution to ref. 4. However, because of the limited fibre length (300 m of each fibre), these investigations could not be so extensive than our present ones where we had about 2000 m from six fibres each and 1000 m from a seventh one.

All the (very poor) informations we got up to know about these fibres are listed in Table 1.

Within our contribution to this conference we can present only a small fraction of all the measurements described in the next chapter. The complete data can be found in ref. 5.

2. EXPERIMENTAL

Fig. 1 shows block diagrams of our measuring equipment for pulsed and continuous fibre irradiations. To reach the intended doses (500 rd to 100 krd) the flash X-ray facility (Febetron 705) is used in the electron mode. When the energy of the electrons is so high that their range in silica is large compared to the fibre thickness, they will cause the same induced loss than gamma radiation of the same dose, and determination of the dose at the fibre core is unproblematic. With single-layer fibre spools and our predominantly used mean electron energy of about 1.5 MeV this condition is fulfilled.

Most of the measurements were made at room temperature. To find out the radiation sensitivity of fibres in extreme environments we made additional measurements at fibre temperatures of +100°C (373 K) and -50°C (223 K), but only with one dose value (10 krd).

The irradiated fibre length varied between 15 m for all fibres at the lowest pulse dose (500 rd) and 8 cm up to 2 m at the highest dose, depending on the radiation sensitivity of the corresponding fibre.

For the Co-60-irradiations we chose a dose rate of 5 rd/s because this was the recommended value for most of the previous measurements within the NATO "Nuclear Effects Task Group". At this dose rate, however, the induced loss in some fibres was so low that we had to irradiate 100 m in order to be sure that the total induced loss is large compared to unavoidable drifts and to the resolution of our optical power meter (0.01 dB). Only for the GI fibre "AT&T Natural 1A" lengths between 5 m and 25 m were sufficient.

Table 2 gives a survey of the measurements we made with each of the seven fibres at the flash X-ray and the Co-60 facility, respectively. Especially with the doses 10 krd and 100 krd applied at both facilities we hoped to draw interesting comparisons between the different irradiation methods.
3. RESULTS

3.1 Pulsed Irradiation

Figs. 2a, b and 3a,b,c show the induced loss as a function of time after irradiation for the seven investigated fibres at all wavelengths, but only measured at room temperature, an electron dose of 10 krds and the light power 20 µW. Because of the relatively high noise of our fast receiver it isn't worth to show the loss at later times in separate diagrams with enlarged scale. There exist no significant differences between the losses of SM and GI fibres when compared at the same wavelength, aside from the P containing GI fibre "AT&T 98/11". 

Figures 2a, 2b. Induced loss after pulsed irradiation of four SM fibres.

D_e = 10 krds, P_out = 20 µW, T = 24°C. Left side (2a): λ = 1300 nm; right side (2b): λ = 1550 nm.

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Natural 1A". The loss of this fibre at early times ($10^{-5}$ s $\leq t \leq 10^{-4}$ s, $t$ depending on the wavelength) is significant lower than that of the other fibres, but it remains nearly constant for hours and days (beginning with $t \geq 10^{-2}$ s), so that this fibre is only of limited practical worth, aside, e.g., from radiation dosimetry purposes. The annealing behaviour of the three Ge doped SM fibres deviates from that of the fibre "Schott P928/11" having an undoped $\text{SiO}_2$ core.

![Graph 1](image1)

1. Philips MM GE 1257 B
2. AT&T MM Rad Hard 3A
3. AT&T MM Natural 1A

![Graph 2](image2)

1. Philips MM GE 1257 B
2. AT&T MM Rad Hard 3A
3. AT&T MM Natural 1A

**Figures 3a - 3c.** Induced loss after pulsed irradiation of three GI fibres. $D = 10$ krd, $P_{nm} = 20$ mW, $T = 24^\circ$C. Left side, above (3a): $\lambda = 840$ nm; right side, above (3b): $\lambda = 1300$ nm; left side (3c): $\lambda = 1550$ nm.

![Graph 3](image3)

**Figure 4.** Induced loss of the SM fibre "Philips SG 1679 C" for three different light powers (1 mW, 20 mW, 200 mW). $\lambda = 1300$ nm, $D_{nm} = 10$ krd, $T = 24^\circ$C.

![Graph 4](image4)

All fibres doped with Ge only show insignificant or none photobleaching, as shown in Fig. 4 for the SM fibre "Philips SG 1679 C". This also holds for the GI fibre "AT&T Natural 1A" at 840 nm, containing at least some P as co-dopant (Fig. 5a). At 1300 nm and 1550 nm, however, this fibre exhibits a decreased induced loss at higher light powers within the
time range $2 \cdot 10^{-5}$ s to $2 \cdot 10^{-2}$ s, as shown in Fig. 5b for 1300 nm. This (temporarily) photo-bleaching has nearly no (1300 nm) or exactly no (1550 nm) equivalent during the continuous irradiation of that P containing fibre, in contrast to the fibre we will speak about next.

Figures 5a, 5b. Influence of light power on the induced loss after pulsed irradiation of the GI fibre "AT&T Natural 1A" (core doped with Ge, P). $D_e = 10$ krđ, $T = 24$ °C. Left side (5a): $\lambda = 840$ nm, $P_{out} = 1, 20, 357$ μW; right side (5b): $\lambda = 1300$ nm.

Figs. 6a, b demonstrate the only significant photobleaching we have found. It appears with the SM fibre "Schott P928/11" having a pure SiO₂ core. At both wavelengths the influence of the light power becomes evident at times $\approx 10$ s and is meaningless after times

Figures 6a, 6b. Influence of the light power on the induced loss after pulsed irradiation of the SM fibre "Schott P928/11" (undoped core). $D_e = 10$ krđ, $T = 24$ °C. Left side (6a): $\lambda = 1300$ nm; right side (6b): $\lambda = 1550$ nm.

$\geq 1$ s where the induced loss completely annealed with all light powers $\geq 1$ μW. Because of the considerable size of the photobleaching we also varied the light power at $+100$ °C and $-50$ °C within the same limits. So we can investigate the temperature dependence of photobleaching as well as the dependence of the induced loss from temperature at three different light powers. These results are presented in ref. 5.

Fig. 7a shows the temperature dependence of the induced loss typical for all Ge doped SM and GI fibres. There is a strong increase of the loss with decreasing temperature. Qualitatively the same dependence is found for the SM fibre with pure SiO₂ core, but with lower temperature gradient, as shown later. Again the P containing fibres behaves completely different (Fig. 7b). Firstly, the variation of induced loss is relatively small. Secondly, it is opposite at short and long times after irradiation at all three wavelengths. Only at times $\leq 3 \cdot 10^{-5}$ s we have the order known from the Ge doped and undoped fibres, whereas, especially pronounced between $10^{-2}$ s and 1 s, the induced loss increases with increasing temperature. This behaviour is even more interesting and confusing at 1300 nm and 1550 nm.
Figure 7a, 7b. Induced loss as a function of time at three different fibre temperatures. D = 10 krd, \( P_{\text{out}} = 20 \, \mu \text{W} \). Left side (7a): SM fibre "Philips SG 1679 C", \( \lambda = 1300 \, \text{nm} \); right side (7b): GI fibre "AT&T Natural 1A", \( \lambda = 840 \, \text{nm} \).

wavelength, where we additionally varied the light power at all three temperatures. The results are to be found in ref. 5.

From our measurements of the induced loss with different electron pulse doses we attain diagrams for the induced loss after pulsed irradiation as a function of dose. Fig. 8a shows such results for the GI fibre "Philips GE 1257 B" and 840 nm wavelength. Curve parameter is the time after irradiation. Fig. 8b shows for the GI fibre "AT&T Rad Hard 3A" and

10^{-5}s after irradiation that this dose dependence is not influenced by the wavelength. This holds for all investigated fibres, within the limits of error.

Figs. 9a, b compare the dose dependence for the four SM fibres and the three GI fibres, respectively. All Ge doped fibres as well as the Ge+P doped fibre exhibit nearly the same linear increase. The deviation with the SM fibre "Fujikura 10/125 04" at low doses is eventually caused by an erroneous deviation of the lowest dose from the intended value (500 rd). We will repeat this measurement in the near future. Only the fibre with the undoped core ("Schott P928/11") shows a completely different dose dependence. The induced loss is relatively high at low doses and than increases only slowly even up to the highest dose values. The loss induced during continuous irradiation of this fibre has a similar course and its sharp increase at low dose values becomes more evident.
Figures 9a, 9b. Dependence of the induced loss from the electron pulse dose. $P_{\text{out}} = 20 \, \mu W$, $T = 24 \, ^\circ C$, $10^{-5} \, s$ after irradiation. Left side (9a): SM fibres, $\lambda = 1300 \, nm$; right side (9b): GI fibres, $\lambda = 840 \, nm$.

Fig. 10a contains the complete information about temperature dependence of the induced loss; we got for each of the Ge doped fibres, aside from the additionally measurements at $840 \, nm$ wavelength with the two GI fibres. It seems to be definite that the decrease of the induced loss with increasing temperature is more rapid at later times, with all wavelengths. For the undoped SM fibre and the Ge+P doped GI fibre we also can extract the influence of light power on the variation of induced loss with temperature at nearly all investigated wavelengths (see ref. 5).

Figures 10a, 10b. Temperature dependence of the induced loss after pulsed irradiation. $D = 10 \, krd, P_{\text{out}} = 20 \, \mu W$. Left side (10a): SM fibre "Fujikura 10/125 04", $t = 10^{-5} \, s$ (upper curve), $t = 10^{-4} \, s$ (middle), $t = 10^{-3} \, s$ (lower curve); right side (10b): all fibres, $\lambda = 1550 \, nm$, $10^{-3} \, s$ after irradiation. ——— AT&T SM 100A, ••••• Philips SM SG 1679 C, ——— Fujikura SM 10/125 04, ——— Schott SM P 928/11, ——— AT&T MM Natural 1A, ——— AT&T MM Rad Hard 3A, Δ——Δ Philips MM GE 1257 B.

This reverse temperature dependence of the induced loss of Ge+P doped fibres is already known from continuous irradiations (e.g. ref. 6).

Figs. 11a, b show the wavelength dependence of the induced loss. In Fig. 11a is to be seen that fibre temperature has no significant influence. Fig. 11b compares all seven fibres. The wavelength dependence is relatively similar for the five Ge doped fibres and the undoped fibre. With the Ge+P doped fibre, however, we found an increase of the induced loss with increasing wavelength above $1300 \, nm$. Again this deviating behaviour of Ge-P doped fi-
bres is known from continuous irradation at a Co-60 source (e.g. ref. 7).

Figures 11a, 11b. Variation of the induced loss after pulsed irradiation with wavelength. $D = 10 \text{ kr}d, P_{out} = 20 \mu \text{W}, 10^{-5} \text{s after irradiation. Left side (11a): GI fibre "AT&T Rad Hard 35" at three different temperatures; right side (11b): all fibres at $T = 24^\circ \text{C}, \cdots \cdots \cdots \text{AT&T SM 100 A, \cdots \cdots \cdots \text{Philips SM SG 1679 C, \cdots \cdots \cdots \text{Fujikura SM 10/125 04, \cdots \cdots \cdots \text{Schott SM P228/11, \cdots \cdots \cdots \text{AT&T MM Natural 1A, \cdots \cdots \cdots \text{AT&T MM Rad Hard 3A, \cdots \cdots \cdots \text{Philips MM GE 1257 B.}}}$

3.2 Continuous Irradiation (Co-60)

Figs. 12a - c and 13a - d give a survey of the results we got for the seven fibres at

Figures 12a - 12c. Induced loss during continuous irradiation of the SM fibres. $D = 5 \text{ rd/s}, P_{out} = 20 \mu \text{W}, \text{ room temperature.}$

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our standard test conditions ($D_y = 5 \text{ rd/s}$, $D_x = 10 \text{ krd}$, $P_{out} = 20 \mu\text{W}$, room temperature). Because of the limited length of this paper, only for one wavelength of each fibre group (SM and GI, respectively) annealing of the induced loss is shown. As mentioned before, the loss of the fibre with pure $\text{SiO}_2$ core (Schott) increases very fast at low dose values ($\leq 20 \text{ rd}$) and remains nearly constant thereafter ($\leq 2 \text{ dB/km}$ at 10 krd). The loss of the residual SM fibres at 10 krd ranges from 3.5 to 7 dB/km (1300 nm), whereas that of the Ge doped GI fibres reaches only 1.5 to 2.5 dB/km at that wavelength. At 1550 nm, too, the Ge doped GI fibres show slightly lower induced losses. In contrast to all these fibres the loss of the Ge$^+$P doped GI fibre is very high (about 200 dB/km at both wavelengths) because there occurs no annealing in the course of irradiation as is to be seen from the pulsed irradiation results (Figs. 3, 5, 7b).

Figs. 14a, b show the influence of light power on the induced loss during continuous irradiation. Whereas after pulsed irradiation of the SM fibre "Philips SG 1679 C" no photobleaching occurred (Fig. 4), we have a small decrease of the loss with increasing light power during continuous irradiation (Fig. 14a). The other Ge doped fibres show comparable or minor light power influence. With the Ge$^+$P doped GI fibre we observed exactly no influence at 1550 nm wavelength, a very small decrease with increasing light power at 1300 nm and a small increase at 850 nm when we raised the light power from 1 to 20 $\mu$W. Again the SM fibre with the pure $\text{SiO}_2$ core shows the greatest photobleaching. The strong acceleration of the annealing with increasing light power we observed after pulsed irradiation of that fibre (Figs. 6a, 6b) leads during continuous irradiation to a lower saturation value of the induced loss, i.e. the equilibrium where the numbers of produced and decayed colour centres (per time unit) are comparable, is reached at lower loss levels.

In Figs. 15a,b we compare the temperature dependence of the loss induced during continuous irradiation of one of the Ge doped SM fibres (15a) with that of the SM fibre with pure SiO\(_2\) core (15b). Comparable with the results we got for the pulsed irradiation of Ge doped fibres (Fig. 7a) there is a strong increase when the fibre is cooled down to \(-50^\circ\text{C}\) and a smaller decrease when it is heated up to 100 \(^\circ\text{C}\), whereas the loss of the fibre with pure SiO\(_2\) core again is relatively independent from fibre temperature (at higher dose values).

Figs. 16a,b give an impression of the wavelength dependence of the induced loss during continuous irradiation. As known from the pulsed irradiations there is a strong decrease when the wavelength is raised from about 850 nm to 1300 nm and a relatively small one from 1300 nm to 1550 nm. The relative difference of the losses between irradiations at 1300 nm and 1550 nm wavelength is mostly smaller than in Fig. 16a, depending on fibre type, dose (10 krd or 100 krd) and fibre temperature (see ref. 5). With the Ge+P doped GI fibre the loss measured with 1550 nm is at all temperatures higher than that measured with 1300 nm.
Figures 16a, 16b. Wavelength dependence of the induced loss during continuous irradiation. \( P_{\text{out}} = 20 \, \mu W, \beta = 5 \, \text{rd/s}, \) room temperature. Left side (16a): SM fibre "Philips SG 1679 C", right side (16b): GI fibre "AT&T Rad Hard 3A".

Figs. 17a,b show two examples of irradiations up to 100 krd. The linear increase of induced loss with dose (in the log-log-representation) goes on up to this dose with nearly all Ge doped fibres as well as with the Ge+P doped GI fibre, at all wavelengths. The GI fibre "AT&T Rad Hard 3A" (Fig. 17a) has the lowest loss of all Ge doped fibres (about 6.5 dB/km at 100 krd; \( \lambda = 1550 \, \text{nm} \)), whereas that of the Ge+P doped fibre increases to about 17 dB/km.

Figures 17a, 17b. Induced loss during continuous irradiations up to 100 krd. \( \lambda = 1550 \, \text{nm}, \beta = 5 \, \text{rd/s}, \) room temperature. Left side (17a): GI fibre "AT&T Rad Hard 3A", \( P_{\text{out}} = 20 \, \mu W; \) right side (17b): SM fibre "Schott P928/11".

1200 dB/km (1300 nm) and to about 2000 dB/km (1550 nm), respectively. In Fig. 17a we also compare the loss during a first irradiation up to 10 krd with that of a second one up to 100 krd. As with most of the other fibres there exist (when at all) only negligible differences between first and second irradiation. The lowest loss of all investigated fibres has again that with the pure \( \text{SiO}_2 \) core (Fig. 17b), but only when illuminated with high light power (\( \gtrsim 20 \, \mu W \)).

3.3 Comparison of pulsed and continuous irradiation

The next four figures (18a,b and 19a,b) compare the increase of the induced loss with radiation dose. For the pulsed irradiations residual losses at increasing times after irradiation are distinguished. The loss induced during continuous irradiation (with 5 rd/s!) is mostly far below that after pulsed irradiation with all fibres that exhibit a noticeable annealing after pulsed irradiation (i.e. all undoped and Ge doped fibres; Figs. 18a,b and 19a). In contrast to this, the losses of the Ge+P doped fibre after pulsed and during continuous irradiation (Fig. 19b) are nearly identical, as to be expected, because this fibre shows no annealing after pulsed irradiation (Figs. 3a-c; 5a,b; 7b) as well as after con-
continuous irradiation (Fig. 13d). With most of the Ge doped fibres the loss during continuous
irradiation increases with a slightly smaller slope than that after pulsed irradiation. Fig. 19a shows a typical example. The only clearly recognizable common result of the irradiations of the undoped fibre (Fig. 18b) is, that with both types of irradiation there is a relatively low increase of induced loss with dose. Not shown here are slight slope differences of some loss versus dose diagrams when fibres are (continuously) irradiated at different temperatures or light powers. We will look if there exist some correlations.

Figures 18a, 18b. Induced loss as a function of dose for pulsed and continuous irradiation of SM fibres. $\lambda = 1550\text{ nm}$, $P_{out} = 20\text{ mW}$, room temperature. Left side (18a): SM fibre "AT&T 100A"; right side (18b): SM fibre "Schott P928/11".

Figures 19a, 19b. Induced loss as a function of dose for pulsed and continuous irradiation of GI fibres. $P_{out} = 20\text{ mW}$, room temperature. Left side (19a): GI fibre "AT&T Rad Hard 3A", $\lambda = 850\text{ nm}$; right side (19b): GI fibre "AT&T Natural 1A", $\lambda = 1300\text{ nm}$.

Figs. 20a,b compare the temperature dependence of the loss induced after pulsed and continuous irradiation up to 10 krads. For the chosen fibres the losses of both irradiation methods have the same temperature dependence. Some of the Ge doped fibres, however, occasionally show a smaller decrease of the loss during continuous irradiation than after pulsed irradiation between 300 and 370 K. With the undoped fibre (Schott), the loss during continuous irradiation seems even to increase slightly with fibre temperature (measured at 1300 nm), whereas that after pulsed irradiation shows a slight decrease.
Figures 20a, 20b. Comparison of the temperature dependence of the loss after pulsed and continuous irradiation. \( D = 10 \text{ krd}, P_{\text{out}} = 20 \mu\text{W} \). Left side (20a): SM fibre "Fujikura 10/125 04", \( \lambda = 1300 \text{ nm} \); right side (20b): GI fibre "AT&T Natural 1A", \( \lambda = 850 \text{ nm} \).

The wavelength dependence of the loss is in principle the same for both irradiation methods, as shown in Figs. 21a, b. Only the SM fibres "AT&T 100 A" and "Fujikura 10/125 04" both seem to exhibit an increase with increasing wavelength at higher fibre temperatures (at 100°C and 24°C with the AT&T fibre and only at 100°C with the Fujikura fibre), whereas the corresponding losses after pulsed irradiation decrease.

### 4. SUMMARY

Our measurements have shown that there already exist several commercial Ge doped SM and GI fibres with very low induced losses during continuous irradiation and a relatively fast (<100 s), but not always complete annealing of the loss after pulsed irradiation.

P containing fibres are generally unsuited for applications in radiation environments because the induced losses do not anneal. Therefore, considerable losses can accumulate in the course of time.

SM fibres with pure SiO₂ core exhibit extremely low induced losses during continuous irradiation even up to 100 krd when the light power is high enough (several hundred \( \mu\text{W} \)), and their annealing time after pulsed irradiation is extremely short under these circumstances.

When changing from 1300 nm to 1550 nm wavelength on observes (when ever) a maximum decrease of the induced loss of about 50 %, whereas the loss of GI fibres can decrease to
less than $1/20$ when changing from 850 nm to 1300 nm.

The radiation sensitivity of Ge doped fibres decreases considerably with increasing temperature. Whereas the loss after pulsed irradiation changes with nearly constant gradient within the whole investigated temperature range (-50°C to +100°C), the loss during continuous irradiation mostly seems to decrease stronger in the interval from -50°C to +24°C than within that from +24°C to +100°C. The loss of the undoped fibre after pulsed irradiation decreases only slowly with increasing temperature, whereas that during continuous irradiation eventually slightly increases with temperature.

Pulsed and continuous irradiations show in principle the same dependence of induced loss on dose, temperature, and wavelength, but with some fibres and under some special circumstances (e.g. high temperature or light power) the gradients can differ or even be reverse.

5. REFERENCES

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