Influence of dose rate on radiation induced loss in optical fibres

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ABSTRACT

The magnitude of the radiation induced loss in optical fibres depends strongly on the dose rate, i.e., whether a certain dose is reached, e.g., within about 10^{-7} s ("prompt pulse" of a nuclear explosion), within one minute ("initial radiation" of a nuclear explosion), within some hours (e.g. accident in a nuclear power plant), or within many years (space environments, normal operation of nuclear power plants, undersea cables).

We exposed four different fibres to dose rates between 0.05 rd/s and 180 rd/s (= 1.8 Gy/s) of a ^{60}Co source as well as to the pulsed radiation of a flash X-ray facility (> 10^{11} rd/s) in order to find out systematic trends that possibly allow interpolation between continuous and pulsed irradiation or extrapolation of the results of continuous irradiations to even lower dose rates.

In some cases extrapolation of the induced losses measured between 0.05 and 180 rd/s to higher dose rates yields nearly exactly the results of pulsed irradiations with about 10^{11} to $3 \cdot 10^{12}$ rd/s, so that extrapolation down to values of, e.g., 10^{-5} rd/s seems to be allowed, too.

The investigations also give interesting informations about existence and influence of different colour centres in one fibre type.

1. INTRODUCTION

At most of the usual ^{60}Co radiation effects test facilities, dose rates of 10^5 rd/h (= 27.8 rd/s; 100 rd = 1 Gy) are an upper limit, when larger test objects like spools with fibre lengths between 50 m and 500 m have to be irradiated with sufficient homogeneous dose distribution.

A lower limit are dose rates $\lesssim$ 0.01 rd/s. This holds for two reasons: Firstly, the tests become too time consuming (e.g. 10^4 rd in more than 11 days). Secondly are most of the test arrangements not stable enough during such long times. The stability problem is often still worsened by limited available test fibre lengths (i.e. ratio of drifts to increase of loss is too high).

Therefore we tried to find out whether the variation of the radiation induceds loss with dose rate measured in the range 0.05 rd/s $\lesssim \dot{D}_\gamma \lesssim$ 200 rd/s at our ^{60}Co facility shows such a clear tendency, that the results can be extrapolated to lower or higher dose rates by at least two or three decades. As a test for the practicability of such extrapolations, we irradiated the same fibres at our flash X-ray facility (Febetron 705) with electron dose values between $3 \cdot 10^3$ and 10^5 rd. That corresponds to dose rates > 10^{11} rd/s. In case extrapolation of the results of continuous irradiations to such high dose rates (over more than 9 decades!) will lead to nearly the same results as pulsed irradiations (within one order of magnitude or better), extrapolation to lower dose rates over two or three decades seems to be justified, too.

An increase of induced loss with dose rate is expected for fibres that show distinct annealing of that loss after pulsed or continuous irradiations. An increase of dose rate will here lead to an increase of the ratio of colour centre formation rate and decay rate, i.e. to a higher concentration of colour centres. Or: A certain dose is reached in a shorter time, so that fewer colour centres can already decay during irradiation.

On the other hand it is well known that fibres that are co-doped with phosphorus (P) show no annealing of the induced loss (see, e.g., refs. 1,2). With these fibres the induced loss should be (nearly) independent of dose rate. This property makes them, e.g., very interesting for dosimetry purposes. That is the reason why we choose such a fibre, too, for our present investigations.

As far as we know it is the first time that such a quantitative investigation of the dose rate dependence of the radiation induced loss is performed. In the available publications (e.g. ref. 3) it is only shown in a qualitative manner that the induced loss also depends on dose rate (or not, with P-doped fibres).

2. EXPERIMENTAL

For our present investigations we choose one fibre each of the three most important fibre types, i.e., a single mode (SM) fibre, a graded index (GI) fibre and a mulitmode step index (MM SI) fibre with pure SiO_2 core (see Table 1).

Table 1: Investigated Fibres

	Type	Diameter [μm] Core	Cladding	Coating	Core Material	Cladding Material	Water Content [ppm]
Philips SM FL 1048C	SM	6/7 [a]	123	245	SiO_2(Ge,F)	SiO_2(Ge,F)	< 0.01
AT&T Rad Hard 3A	GI	49.1	124.5	250.8	SiO_2(Ge)	SiO_2	
Optical Fibres M10	GI	50.5	125	250	SiO_2(Ge,P)	SiO_2	
Heraeus SS 1.2 152/90	MM SI	100	120	245	SiO_2	SiO_2(F)	≥ 800

a: Mode field diameter at 1310/1550 nm

The SM fibre can be used at 1300 nm as well as at 1550 nm ("dispersion flattened") and shows fairly low radiation sensitivity. The AT&T fibre is the best GI fibre (with respect to radiation hardness) we ever tested. The MM SI fibre has a high OH content (about 1000 ppm), so that it can only be used at wavelengths $\lesssim$ 850 nm (OH absorption bands!). Nevertheless show these OH rich fibres the lowest radiation induced losses. The reason seem to be fast annealing mechanisms caused by hydrogen (H) diffusion.

Finally we choose another GI fibre whose core is co-doped with P. The reason was already mentioned above.

The experimental equipment used for induced loss measurements at the ^{60}Co source as well as at the flash X-ray source is nearly identical with that described in ref. 1.

The ^{60}Co source (present activity 285 Ci) can be pushed out of a shielding container into a narrow tube (Ø = 18 mm), so that very high dose rates (up to 200 rd/s) can be achieved by placing narrow wounded fibre spools around the source. Low dose rates are choosen by placing larger diameter spools (with fibre lengths between 200 and 600 m) far away from the source extension tube.

Preliminary tests yielded that fibre winding diameter had no influence on measured induced losses with SM fibres.

Table 2: Influence of fibre winding diameter (D)
(Dose rate ≈ 21 rd/s, Fibre temperature ≈ 22°C)

Fibre	Wavelength [nm]	Induced Loss [dB/km] at $D_\gamma = 10^4$ rd and with $D \geq 5$ cm	$D \geq 12$ cm
AT&T Rad Hard 3A	1308	3.0	2.6
Optical Fibres M 10	1308	158.4	150,7
Heraeus SS 1.2 152/90	865	3.7 [a]	4.6 [b]

a/b: Mean values of 2/4 measurements

With the GI fibres and the MM SI fibre, however, this influence is obvious (Table 2). Nevertheless we did not correct for this effect because at the two neighbouring measuring points with the largest fibre winding diameter difference (at about 160 rd/s and 21 rd/s with winding diameters ≥ 4 cm and ≥ 12 cm, respectively) the induced losses differed by factors of about 2 (AT&T GI) and about 2.5 (Heraeus MM SI), respectively, whereas the influence of the winding diameter is only of the order of 10 - 20%.

The source extraction time ($\lesssim$ 0.4 s) is small compared to the irradiation time for the lowest dose taken into consideration (300 rd).

Electron pulse risetime and effective pulse length of the Febetron 705 are about 10^{-8} s and $3 \cdot 10^{-8}$ s, respectively. The dose values of $3 \cdot 10^3$ rd, 10^4 rd and 10^5 rd we choose for our comparison of continuous and pulsed irradiation are therefore achieved with dose rates of about 10^{11} rd/s, $3\cdot10^{11}$ rd/s and $3\cdot10^{12}$ rd/s, respectively.

Fibre cooling at our pulsed source was not so effective than at the ^{60}Co source, so that we reached only about -50°C instead of -60°C during the continuous irradiations.

Because of the relatively large size of our fibre cooling flange, the present maximum achievable dose rate for the -60°C measurements at the ^{60}Co source was about 4.6 rd/s.

3. RESULTS AND DISCUSSION

3.1 Fibre "Philips SM FL 1048C"

Figure 1 shows the increase of the induced loss with accumulated dose during a ^{60}Co irradiation for six different dose rates. The result is typical for fibres whose colour centres show distinct annealing (condition for dose rate dependence) and whose loss increases continuously with dose. At lower dose rates irradiations were only performed up to lower dose values. The reasons (long irradiation times, limited stability) were already discussed.

In order to get quantitative informations about the dose rate dependence, we prepared curves of the induced loss as a function of dose rate for eight different dose values (i.e., vertical cuts through the set of curves of Fig. 1 at given dose values).

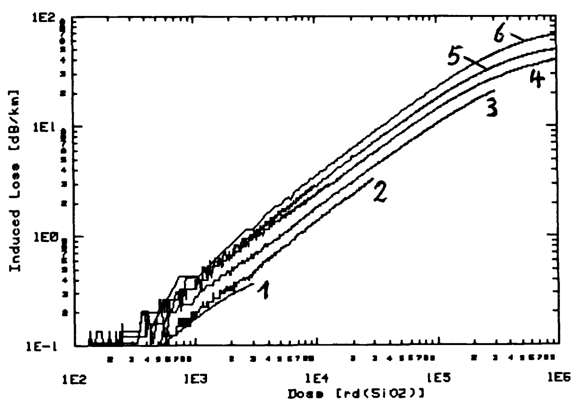
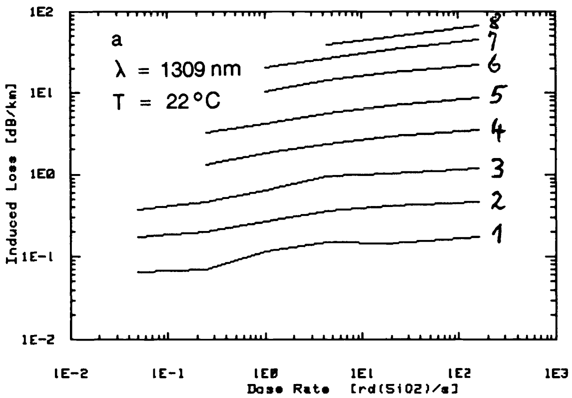
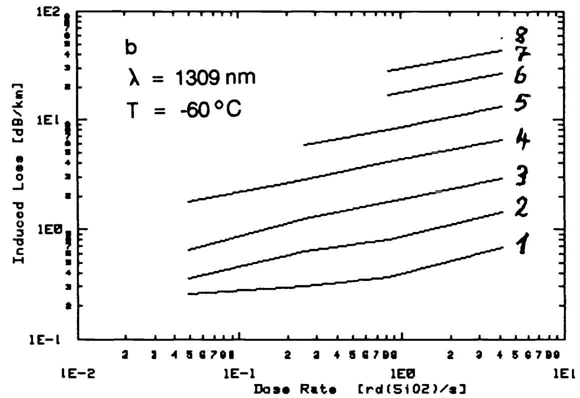
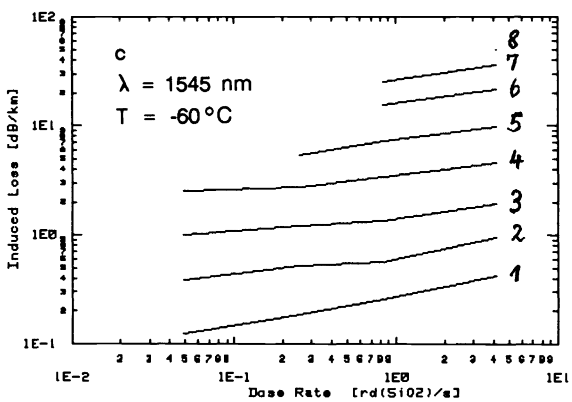


Figure 1: Induced loss as a function of dose for six different dose rates. λ = 1309 nm, P = 20 μW, T = 22°C. $\dot{D}_\gamma$ = 0.05 rd/s (1), 0.25 rd/s (2), 1 rd/s (3), 4.4 rd/s (4), 19.8 rd/s (5), and 161 rd/s (6).

The results are shown in Figs. 2a - 2c. At wavelength λ = 1545 nm we only made measurements at -60°C because the induced loss at this wavelength is only about half of that at 1300 nm. Therefore measurements at room temperature and 1545 nm would be of insufficient accuracy.





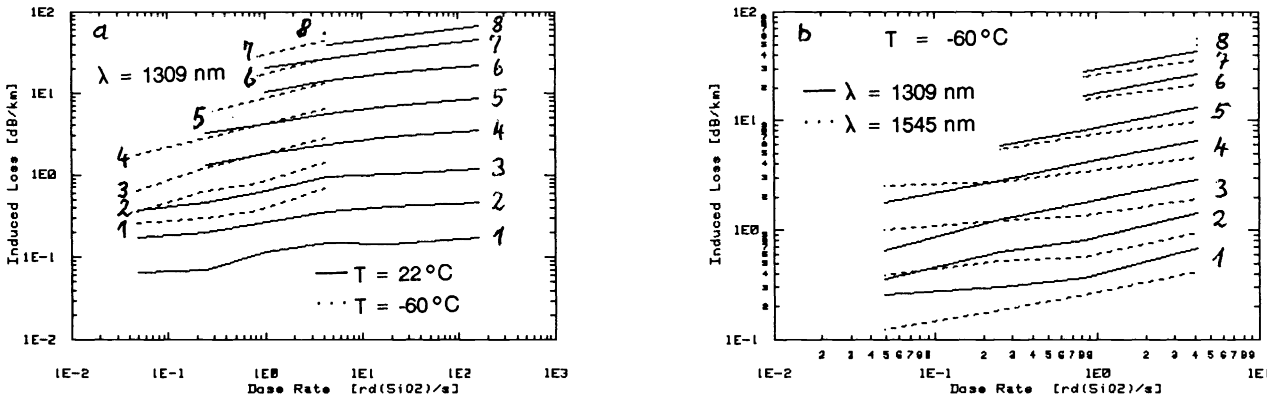


Figures 2a-c: Induced loss as a function of dose rate; P = 20 μW. D_γ = 300 rd (1), 10^3 rd (2), $3 \cdot 10^3$ rd(3), 10^4 rd (4), $3 \cdot 10^4$ rd (5), 10^5 rd (6), $3 \cdot 10^5$ rd (7), 10^6 rd (8).

Figs. 3a,b compare the results we got for $\lambda = 1309$ nm at both temperatures (a) and at T = -60°C for both wavelengths (b), respectively.

The five figures show a lot of interesting details: The dose rate dependence is nearly constant within the whole investigated range and nearly the same at all dose values. So it is obvious that, e.g., the induced loss for a dose of 10^6 rd achieved with lower dose rates can easily be determind in cases where it was only measured with one higher dose rate (points in figs. 2b,c) by drawing a line through that point parallel to the lines below.

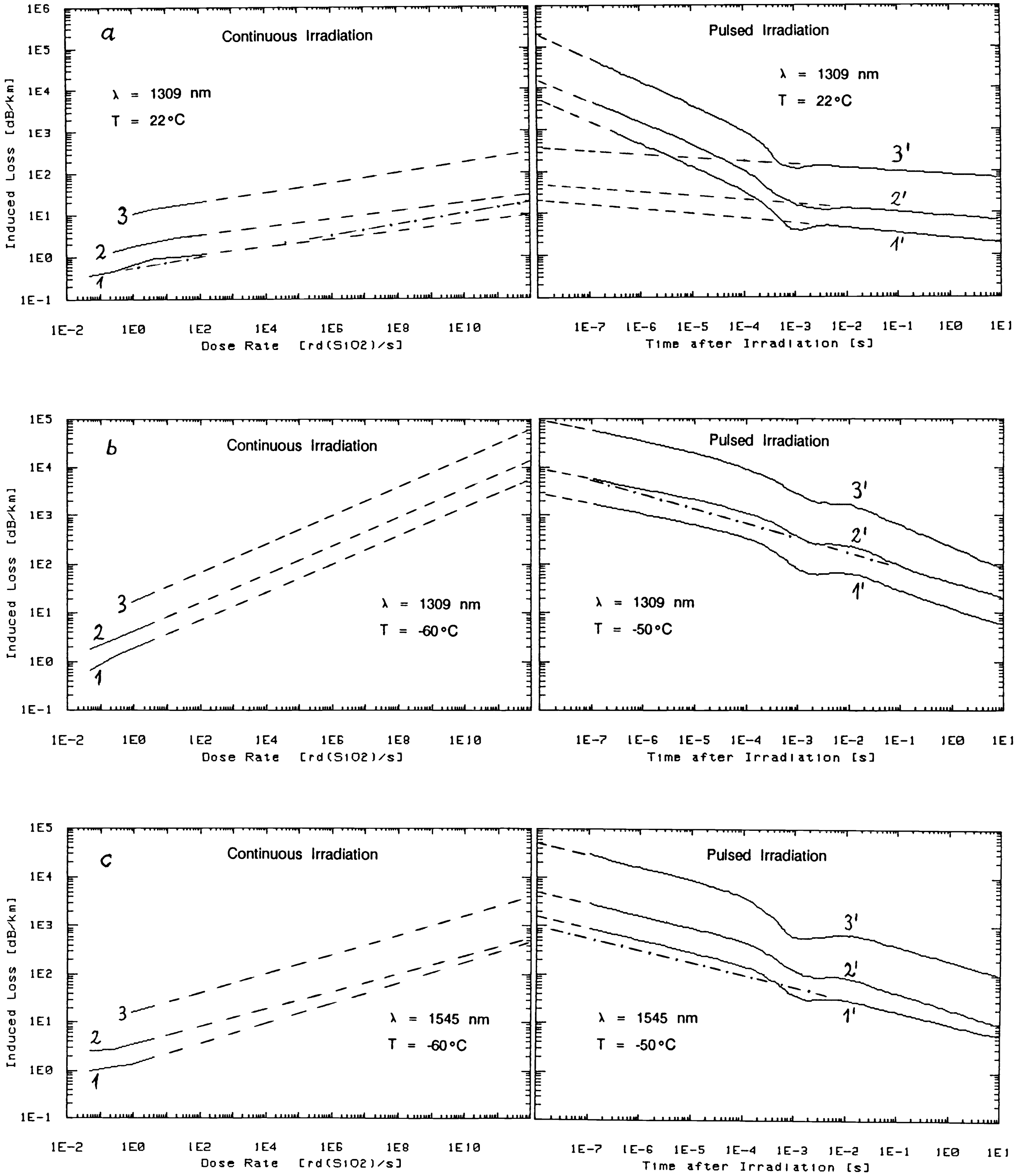
The dose rate dependence is stronger at -60°C than at room temperature (Fig. 3a) and at 1309 nm than at 1545 nm (Fig. 3b), respectively. An explanation for the temperature dependence of the slope (Fig. 3a) could be that at low temperatures another, shorter living type of colour centres contributes to the induced loss. The influence of wavelength on the slope of the curves (Fig. 3b) could also be explained by two types of colour centres (with different live times) that contribute with different magnitude to the absorption at 1309 nm and 1545 nm, respectively.



Figures 3a,b: Induced loss as a function of dose rate; Influence of temperature (a) and wavelength (b); P = 20 μW.
D_{γ} = 300 rd (1), 10^3 rd (2), $3 \cdot 10^3$ rd (3), 10^4 rd (4), $3 \cdot 10^4$ rd (5), 10^5 rd (6), $3 \cdot 10^5$ rd (7), 10^6 rd (8).

The nearly linear course of the induced loss with dose rate at all dose values in the log-log presentation suggests to try an extrapolation to extremely high dose rates as they occur at pulsed irradiations, in order to compare the results of both types of measurements.

Figures 4a-c show the results. The annealing curves after pulsed irradiation exhibit at room temperature two time regions with different slopes. From that one can conclude that two types of colour centres exist in this type of fibre: a shorter living one that dominates at times < 10^{-3} s and a longer living one that dominates at times > 10^{-3} s. It is reasonable to assume that this longer living type is mainly responsible for the induced loss during continuous irradiations with low dose rates. Extrapolation of this later part of the curves back to the time of colour centre formation (10^{-8} to $3 \cdot 10^{-8}$ s; see section 2.) and extrapolation of the results of the continuous irradiations to the corresponding high dose rates of the pulsed irradiations (10^{11} to 10^{12} rd/s; see section 2.) really leads to nearly identical results (Fig. 4a). If one would be able to increase the dose rate of the ^{60}Co irradiations continuously up to such high values, however, the slope would begin to increase when the short living colour centres begin to contribute significantly to the induced loss.



Figures 4a-c: Comparison of continuous and pulsed irradiation. D = $3\cdot10^3$ (rd) (1,1'), 10^4 rd (2,2'), and 10^5 rd (3,3'). Corresponding dose rates of the pulsed irradiations: $\dot{D}_e = 10^{11}$ rd/s (1'), $3\cdot10^{11}$ rd/s (2'), and $3\cdot10^{12}$ rd/s (3').

Fig. 5 shows that at low temperatures the decay rate of the shorter living colour centres decreased so drastically that they dominate in the whole investigated time range. Therefore they should also be mainly responsible for the induced loss during continuous irradiations.

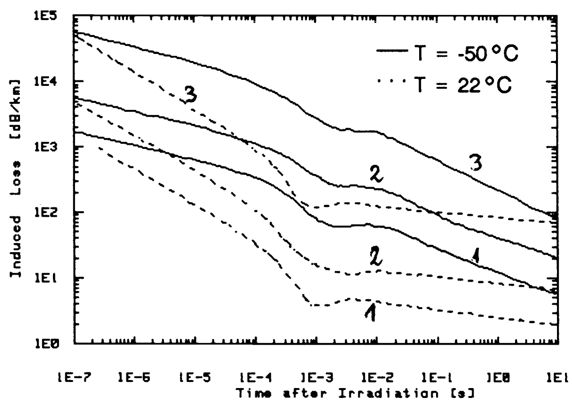


Figure 5: Induced loss after pulsed irradiation. P = 20 μW. $D_{es} = 3 \cdot 10^3$ rd (1), 10^4 rd (2), and 10^5 rd (3).

The extrapolations to short times and high dose rates, respectively, confirm this assumption (Fig. 4b).

The same extrapolations of the results measured at λ = 1545 nm and low temperatures (Fig. 4c) do not lead to that astonishing agreement between pulsed and continuous irradiations. The reason might be that at λ = 1545 nm the shorter living colour centres contribute significantly to the induced loss only at higher dose rates ($\gg$ 5 rd/s, our maximum dose rate at low temperatures.)

3.2 Fibre "AT&T MM Rad Hard 3A"

With this fibre we only made measurements at room temperature and one wavelength.

Figure 6 presents the increase of the induced loss with dose for 6 different dose rates. The distance between neighbouring curves is a little bit greater than with the previous SM fibre (Fig. 1), indicating a stronger dose rate dependence of the induced loss.

Figure 7 shows directly the dose rate dependence for the same eight different dose values as before (Fig. 2). Again we see a systematic trend of the set of curves so that it seems to be justified, e.g., to extrapolate the upper high dose curves (4 to 8) to lower dose rates.

Figure 8 compares pulsed and continuous irradiations. The slope of the annealing curves after pulsed irradiation (right side) remains unchanged in the whole investigated time range, so that one can expect that there dominates only one colour centre and that this centre might be responsible, too, for the induced loss during continuous irradiations. Extrapolations to short times and high dose rates, respectively, leed indeed to the same induced losses for the dose values $3 \cdot 10^3$ and 10^4 rd. The discrepancy at 10^5 rd may be explained by the long irradiation time necessary to reach such a high dose: in the course of long irradiation times eventually existing longer living colour centres begin to dominate.

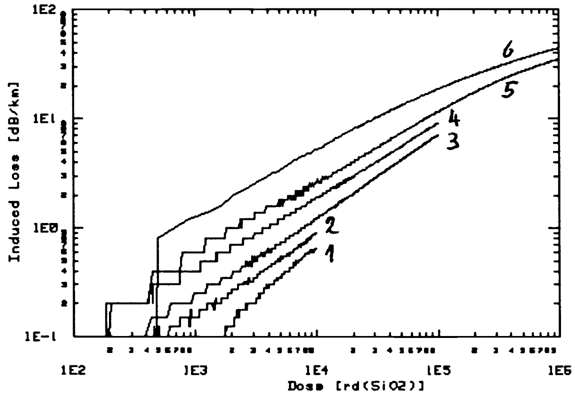


Figure 6: Induced loss as a function of dose for six different dose rates. λ = 1308 nm, P $\approx$ 10 μW, T = 22°C. $\dot{D}_\gamma$ = 0.05 rd/s (1), 0.25 rd/s (2), 1 rd/s (3), 5 rd/s (4), 21.7 rd/s (5), and 189 rd/s (6).

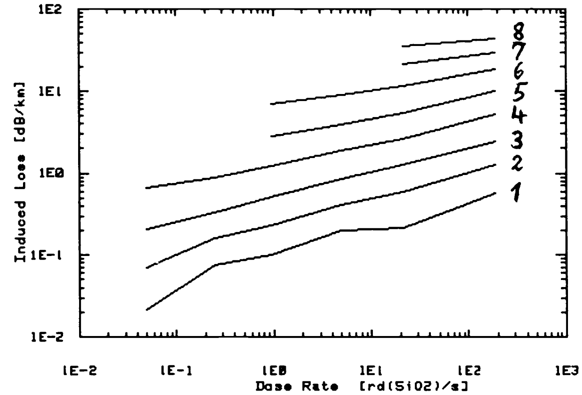


Figure 7: Induced loss as a function of dose rate. λ = 1308 nm, P $\approx$ 10 μW, T = 22°C. D_γ = 300 rd (1), 10^3 rd (2), $3\cdot10^3$ rd (3), 10^4 rd (4), $3\cdot10^4$ rd (5), 10^5 rd (6), $3\cdot10^5$ rd (7), and 10^6 rd (8).

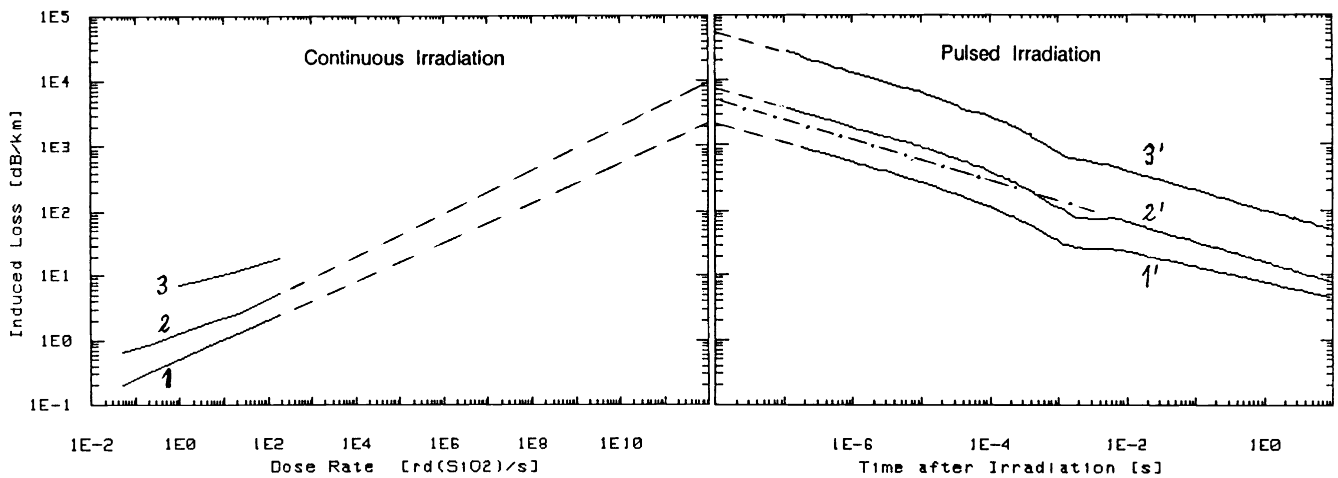


Figure 8: Comparison of continuous and pulsed irradiation. λ = 1308 nm, P $\approx$ 10 μW, T = 22°C. $D = 3\cdot10^3$ rd (1,1'), 10^4 rd (2,2'), and 10^5 rd (3,3'). Corresponding dose rates of the pulsed irradiations: $\dot{D}_e = 10^{11}$ rd/s (1'), $3\cdot10^{11}$ rd/s (2'), and $3\cdot10^{12}$ rd/s (3').

3.3 Fibre "Optical Fibres M10"

This is the GI fibre with a concentration of 0.13 % P in the core material. From these P containing fibres it is known that radiation induced losses do not anneal even within extremely long times. As a consequence they should show a linear increase of induced loss with dose and independence of the induced loss of dose rate.

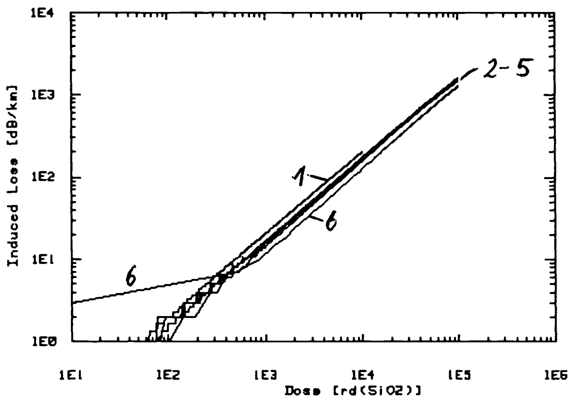


Figure 9: Induced loss as a function of dose for six different dose rates. λ = 1308 nm, P $\approx$ 10 μW, T = 22°C. $\dot{D}_\gamma$ = 0.05 rd/s (1), 0.25 rd/s (2), 1 rd/s (3), 5 rd/s (4), 21.7 rd/s (5), and 189 rd/s (6).

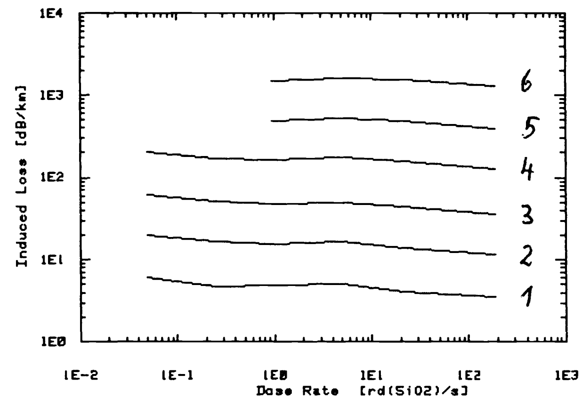


Figure 10: Induced loss as a function of dose rate. λ = 1308 nm, P $\approx$ 10 μW, T = 22°C. D_γ = 300 rd (1), 10^3 rd (2), $3\cdot10^3$ rd (3), 10^4 rd (4), $3\cdot10^4$ rd (5), and 10^5 rd (6).

Figures 9 and 10 do confirm this behaviour. In both pictures, however, we find a little increase of the loss at very low dose rates as well as a decrease at the highest dose rate. An explanation of this behaviour can be found in the right side of Figure 11 (pulsed irradiation): Immediately after irradiation exist large numbers of short living colour centres. After about 10^{-4} s, however, their contribution to the induced loss is fallen below that of the P containing colour centres. The charge carriers released during the further decay of the short living centres seem to be trapped by

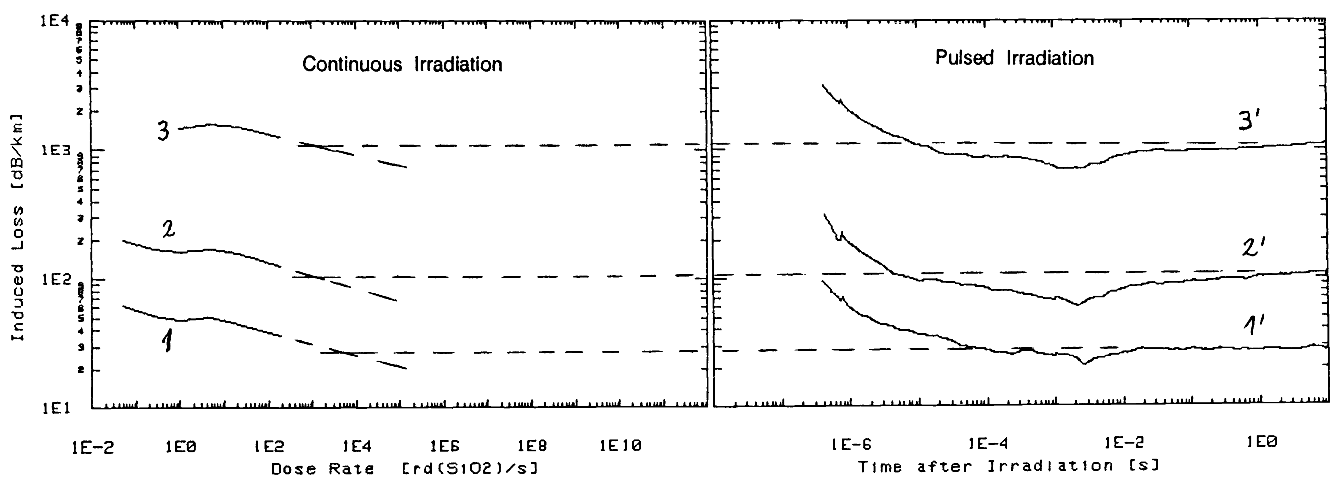


Figure 11: Comparison of continuous and pulsed irradiation. λ = 1308 nm, P $\approx$ 10 μW, T = 22°C. D = $3\cdot10^3$ rd (1,1'), 10^4 rd (2,2'), and 10^5 rd (3,3'). Corresponding dose rates of the pulsed irradiations: $\dot{D}_e$ = 10^{11} rd/s (1'), $3\cdot10^{11}$ rd/s (2'), and $3\cdot10^{12}$ rd/s (3').

precursors of the P containing centres, so that the induced loss begins to increase again after times $\gtrsim 3 \cdot 10^{-3}$ s.

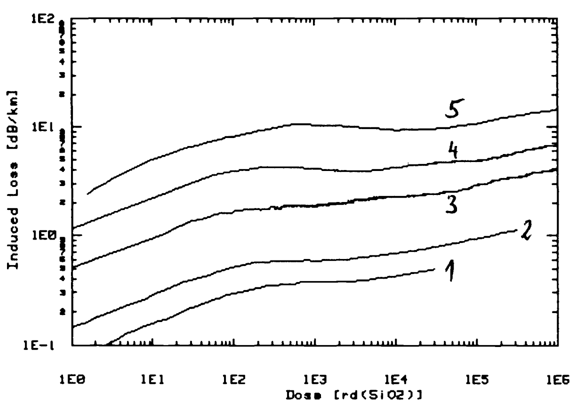
The same conversion of short living into P containing colour centres should take place during continuous irradiations. The lower the dose rate, the higher the degree of conversion and, thus, the induced loss.

The induced loss 10 s after a pulsed irradiation is about of the same size than that during a continuous irradiation with a dose rate of about 10^3 rd/s, i.e., the induced loss is independent of dose rate over more than 10 decades, and over more than 14 decades it varies only by at most a factor of two.

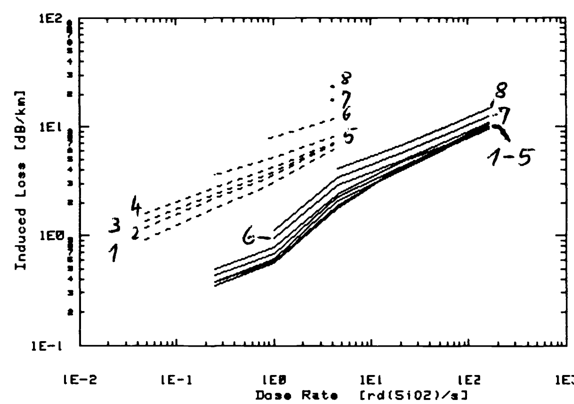
<u>3.4 Fibre "Heraeus SS 1.2 152/90"</u>

With this fibre we made measurements at room temperature as well as at -60°C (^{60}Co) and -50°C (pulsed), respectively.

Fig. 12 shows the increase of the induced loss with dose during a ^{60}Co irradiation at room temperature. The space between the different curves is relatively large, i.e., the dose rate dependence of the induced loss is relatively strong. This was to be expected because of the very fast annealing these fibres exhibit after continuous irradiations.



<u>Figure 12:</u> Induced loss as a function of dose for five different dose rates. λ = 865 nm, P = 10 μW, T = 22°C. $\dot{D}_\gamma$ = 0.25 rd/s (1), 1 rd/s (2), 4.6 rd/s (3), 20.4 rd/s (4), and 162 rd/s (5).



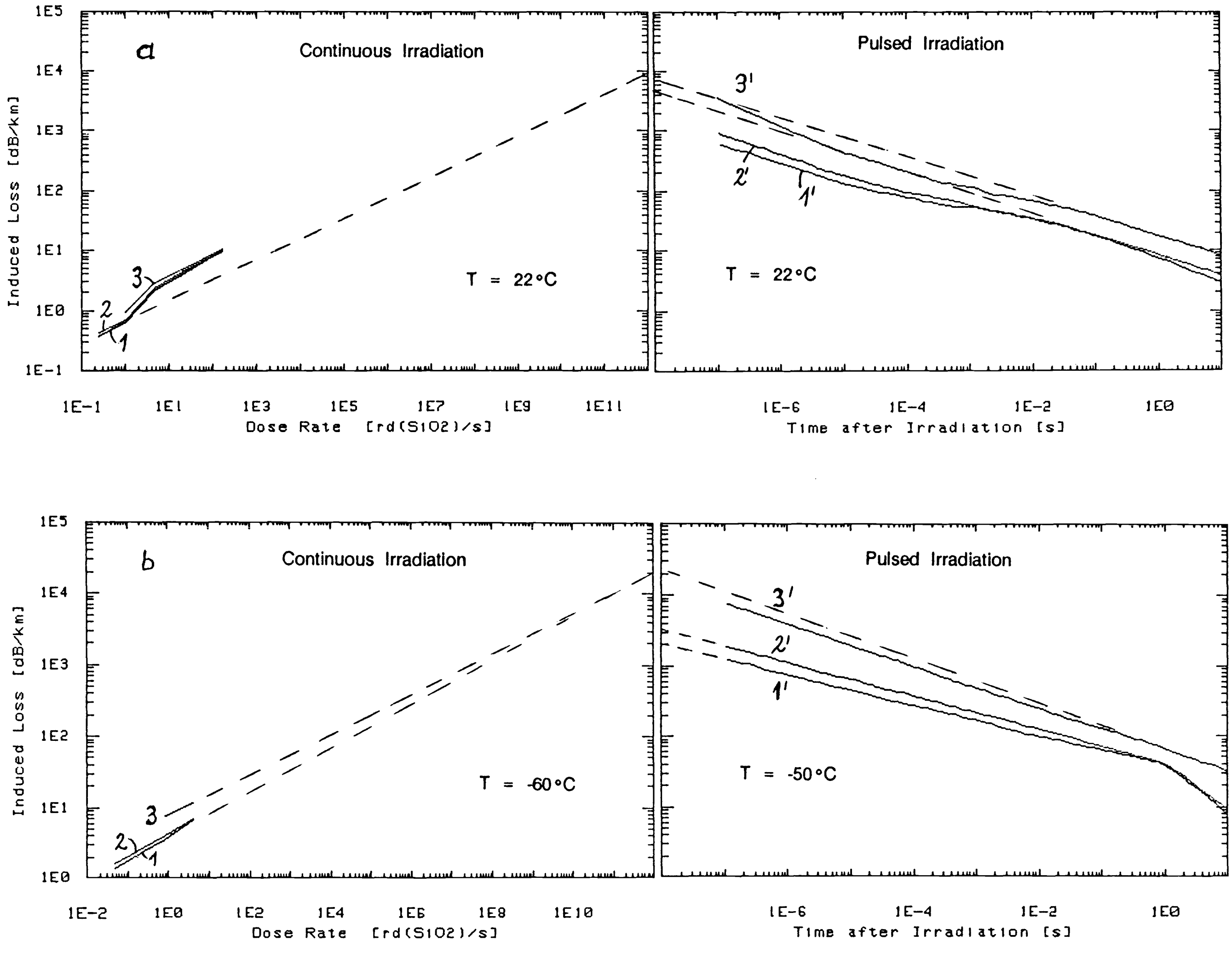
<u>Figure 13:</u> Induced loss as a function of dose rate. λ = 865 nm, P = 10 μW, D_γ = 300 rd (1), 10^3 rd (2), $3 \cdot 10^3$ rd (3), 10^4 rd (4), $3 \cdot 10^4$ rd (5), 10^5 rd (6), $3 \cdot 10^5$ rd (7), and 10^6 rd (8).

Between about 100 and 10^5 rd, however, the increase of loss with dose is only very moderate. This behaviour can be explained by an equilibrium that is reached when the rates of colour centre formation and annealing became equal. With short annealing times this equilibrium is reached at low levels of dose as well as induced loss.

The higher the dose rate, the higher the equilibrium level of the induced loss.

Figure 13 compares dose and dose rate dependence of the induced loss for the two fibre temperatures. We can see that at low temperatures the induced loss is more dose dependent than at room temperature.

Furthermore one observes with the room temperature results a change of the dose rate dependence between about 1 and 10 rd/s. This change suggests that at higher dose rates another, shorter living colour centre becomes effective. For a comparison of pulsed and continuous irradiations (Figs. 14a,b) at room temperature, best agreement is to



Figures 14a,b: Comparison of continuous and pulsed irradiation. $D = 3\cdot10^3$ rd (1,1'), 10^4 rd (2,2'), and 10^5 rd (3,3'). Corresponding dose rates of the pulsed irradiations: $\dot{D}_e = 10^{11}$ rd/s (1'), $3\cdot10^{11}$ rd/s (2'), and $3\cdot10^{12}$ rd/s (3').

be expected when comparing the lower left part of the dose rate dependence curves with the later results (> 10^{-2} s) of the annealing curves after pulsed irradiations (see Fig. 14a). The agreement is indeed relatively good.

At -60°C the whole dose rate dependence curves (Fig. 14b) can be extrapolated to high values. With the annealing curves after pulsed irradiation it seems to be recommendable to choose again the later parts. The 100 krd curve exhibits nearly the same slope within the whole time range, and the agreement is indeed a little bit better when considering only the results at late times. With the 3 krd and 10 krd curves, however, the results at late times seem to be spoiled by drifts of the receiver. Extrapolation of the results measured at early times (< 0.1 s) leads to induced losses that are about a factor of 10 lower than the results one gets by extrapolation of the ^{60}Co measurements to high dose rates.

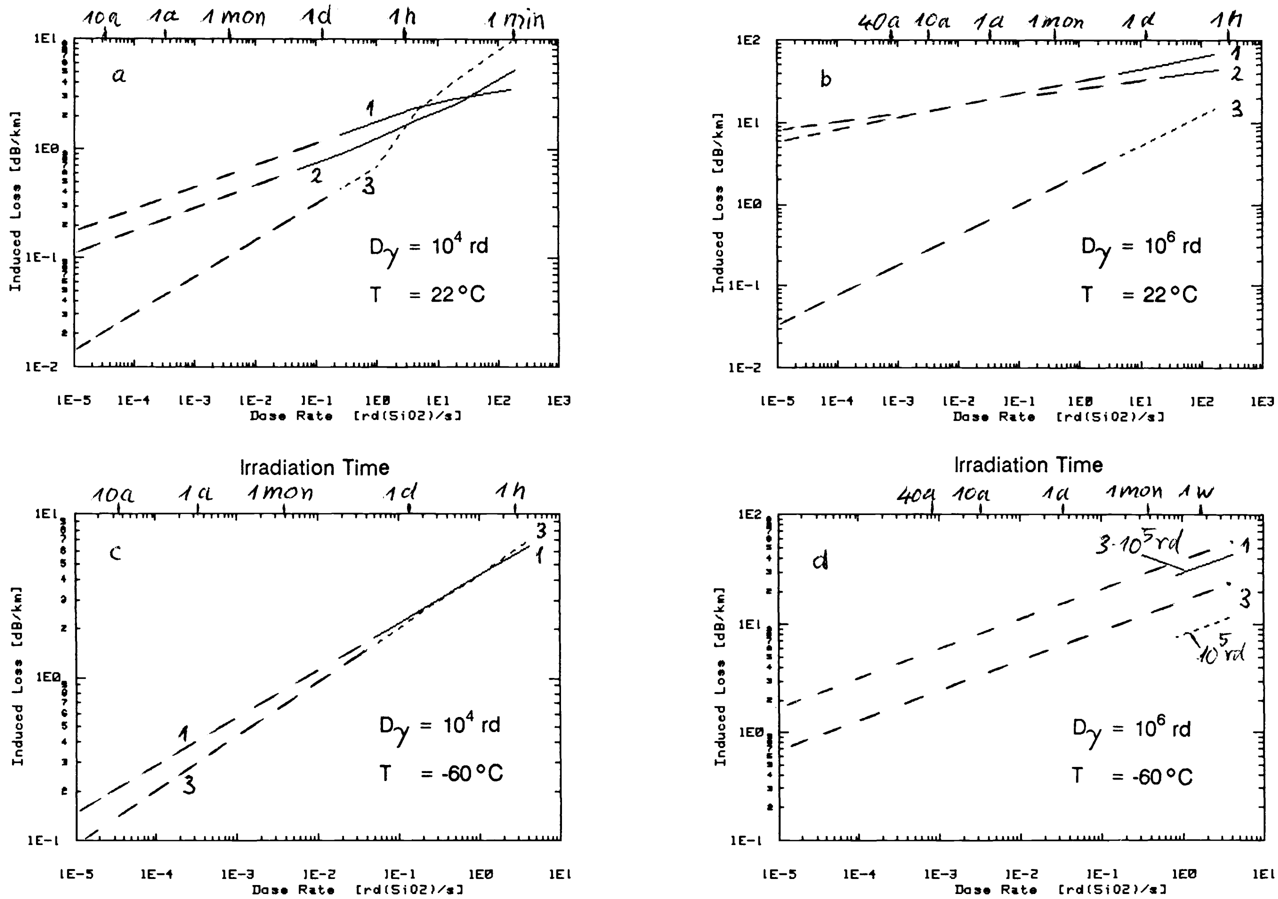
Despite of this latter discrepancy, it seems to be justified with this fibre, too, to extrapolate the results of the ^{60}Co measurements down to dose rates of 10^{-4} to 10^{-5} rd/s in order to get fairly good estimates for the expected losses at extemely low dose rates.

4. CONCLUSIONS

Extrapolation of the results of continuous irradiations over about 10 decades up to the extremely high dose rates of pulsed irradiations led to an astonishingly good agreement of the induced losses. It seems to be justified, therefore, to extrapolate the results of the ^{60}Co irradiations also over about 3 decades down to the lowest dose rates that are to be expected in nuclear engineering and space environments. When an optical fibre inside a TV satellite receives, e.g., a dose of 10^4 rd within one year, the corresponding dose rate would be about $3 \cdot 10^{-4}$ rd/s.

Figures 15a-d show these extrapolations for the dose values 10^4 and 10^6 rd and both applied fibre temperatures. The room temperature results lead to nearly identical results for the both Ge doped fibres (1,2), as to be expected. The results of the undoped fibre with its rapid annealing behaviour after continuous irradiations at room temperature, however, decrease much faster, so that radiation induced losses of such fibres become negligible below dose rates of 0.1 to 0.01 rd/s, compared with an initial loss of about 8 dB/km ($\lambda \approx 850$ nm).

In contrast to this, the losses of Ge doped fibres and undoped fibres decrease at -60°C with indentical slope and lead, therefore, to nearly the same results at very low dose rates. The reason might be that at these low temperatures the colour centres that exist in all SiO_2 glasses with relatively high precursor concentrations can be populated to such a high degree that their contribution to the induced loss exceeds that of the Ge containing colour centres.



Figures 15a-d: Extrapolation of measured radiation induced losses to extemely low dose rates.
1: Fibre Philips SM FL 1048C, λ = 1309 nm, P = 20 μW; 2: Fibre AT&T MM Rad Hard 3A, λ = 1308 nm, P = 10 μW; 3: Fibre Heraeus SS 1.2 152/90, λ = 865 nm, P = 10 μW.

This explanation is supported by Fig. 16: At room temperature, both fibres show a distinctly different annealing behaviour, especially at later times that are more relevant for comparisons with continuous irradiations. At -50°C, however, the fibre with the pure SiO_2 core (3) maintains the same slope than at room temperature, whereas the slope of the Ge doped fibre changed significantly and is now very similar to that of the undoped fibre.

Despite of the apparently convincing results we found for the dose rate behaviour of radiation induced losses, it would be important to make some reliable measurements at dose rates < 10^{-3} rd/s in order to confirm our predictions. A method that could overcome the stability problems should be measurements with an OTDR. Up to now, however, it seems not be proved that conventional transmission loss measurements and OTDR measurements yield the same results for radiation induced losses. We could show (for the first time, as far as we know) that both methods lead to exactly the same results (Fig. 17). The comparison was made, however, at a fairly high dose rate (20 rd/s).

We hope that we will be able in the near future to make an OTDR measurement with the fibre Philips SM FL 1048C at about 10^{-3} rd/s in order to find a first proof for the validity of our method of getting relatively fast estimates for radiation induced losses at very low dose rates.

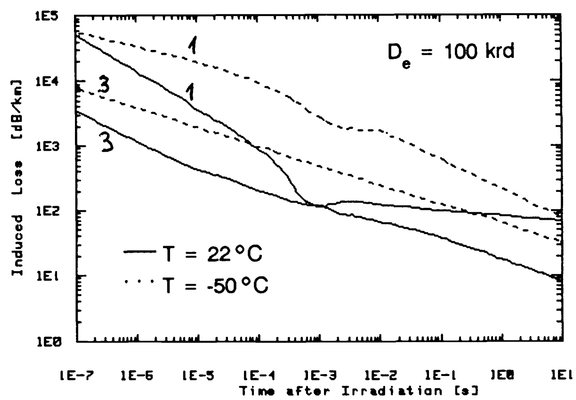


Figure. 16: Change of the induced loss after pulsed irradiation with temperature. 1: Fibre Philips SM FL 1048C, λ = 1309 nm, P = 20 μW; 3: Fibre Heraeus SS 1.2 152/90, λ = 840 nm, P = 10 μW.

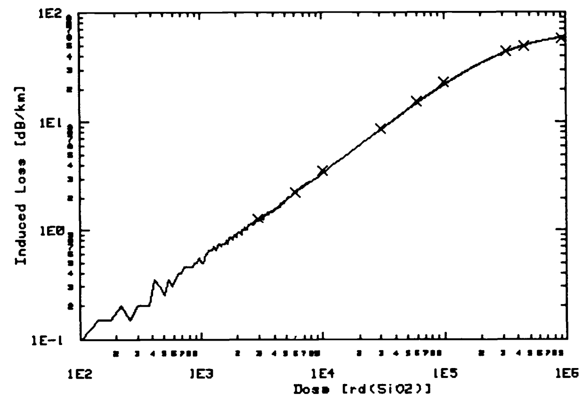


Figure 17: Comparison of the induced losses during continuous irradiation measured by conventional transmission loss measurement (——) and OTDR (xxx). Fibre: Philips SM SA 4015C; $\dot{D}_\gamma$ = 1200 rd/min, $\lambda \approx$ 1300 nm, P $\approx$ 0.1 μW, T = 22°C.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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