Optical fibres in radiation environments

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ABSTRACT

Means, and their limitations, for calculating the potential induced loss in an optical fibre, when subjected to long term exposure to radiation where dose rates and fibre temperature can vary, are considered.

1. INTRODUCTION

The performance of fibre optic based systems will degrade if they are exposed to ionizing radiation, as they could be in Space, in the vicinity of nuclear reactors, at waste processing facilities, particle accelerators, or radiation sterilization plants. All elements of the system could be at risk, but often the dominant effect will be the transmission loss induced in the fibre itself.

Measurements of the effect have been made since the early 70s, and the factors affecting the magnitude of the loss are now well known[1-4]. The effect is largely, and , in some cases, possibly entirely, related to the degree of ionization in the core material, and , thus, on the radiation dose. However, because of the effects of recovery mechanisms, acting over wide time scales, the loss actually observed will depend on the dose rate involved. Recovery can be thermally or optically driven. Then the loss at any point during irradiation, or after, will differ according to the fibre temperature or the optical power density in the fibre core. Regardless of the duration of the exposure, subsequent recovery may take place on time scales ranging from $\sim 10^{-12}$s to $>10^{8}$s. Many of the earlier workers studying these effects were interested in the consequences of exposure to the radiation output of nuclear weapons. Those concerned with tactical effects concentrate on times from 10^{-3}s to 10^{3}s; if involved with weapon testing, 1ns- 100ns. Even for degradation of major communication networks due to fallout, interest would not have extended beyond about 10^{5}s.

Fortunately, their upper time requirements come within the range for which adequate stability can be maintained in the optical transmission arrangements widely used in the measurements. The stability consideration is recognised in the inter-laboratory tests[5,6] which led to the development of radiation test standards[7]. An upper limit of 10^{4}-10^{5}s is sensible, particularly when such measurements are undertaken at other than ambient temperature. Where potential exposures are longer, as in the applications listed earlier, the use of an optical time domain reflectometer (OTDR) is recommended[8]. The test protocols are directed towards obtaining a good comparison of the behaviour of different fibres under irradiation, and thus define specific test conditions. They involve either a brief radiation pulse or continuous irradiation at a fixed rate. Transmitted light levels are kept low to avoid strong photobleaching, and measurements are obtained at a fixed fibre temperature. Particularly for OTDR results, the range of wavelengths covered is limited. In real applications, dose rates may vary, high light levels may be present, and the fibre temperature may differ from those at which test measurements have been made. The main aim of this paper is to establish the extent to which prediction of the eventual behaviour in these more variable environments can be made on the basis of the simpler test measurements.

2. TYPES OF FIBRES AND RADIATION RESPONSES

In categorising the various types of fibres, we limit ourselves to silica/glass versions. Generalization of the radiation response of all polymer fibres is difficult. It appears to be related to residual monomer, solvents, and other chemicals which have been used to control/accelerate polymerization. Also, relatively few measurements have been published for any given type. This is also the case for other non-silica fibres used at longer IR wavelengths, where behaviour seems to be dominated by impurity effects also. The classification should reflect whether the fibre response is linear or non-linear, since this is particularly relevant to the possibility of prediction.

The principal fibre categories are those with undoped silica, Ge doped, or Ge:P/P doped cores. Additionally, there are fibres utilising compound glasses, also special fibres, either by virtue of composition. e.g. Er - doped, or of structure e.g.

polarization maintaining. The classification assumes that, as far as fibre composition is concerned, the radiation response is predominantly determined by that of the core. Broadly this is the case.

If the response is linear, prediction of potential behaviour under irradiation is relatively straightforward. If non linear, it is practically impossible; the best to be expected is the setting of performance bounds. There is some confusion about linearity in the literature concerning fibres. For present purposes linear response is related to the generation of loss producing centres, and not necessarily with the growth of loss observed under steady irradiation. As indicated earlier, the latter can be modified by recovery processes. The test of linearity is whether the radiation impulse response (RIR, which, practically, is the induced loss behaviour recorded after a radiation at times much greater than the length of the pulse) is a universal function when scaled as loss/unit dose. Given this, the response may be obtained, as for any linear system, for any time variation of the disturbing factor, by convolution of that history with the impulse response (i.e. here, between dose rate variation and the RIR).

3. Ge DOPED CORE FIBRES

Fibres with Ge core doping exhibit relatively simple linear behaviour (Fig.1). The first term in the RIR expression dominates behaviour during irradiation typically for doses $<10^3$Gy, dose rates >0.00005Gy/s, and in the RIR itself, for a dose of 30Gy, at times $<$few x 10^4s. The model is justified elsewhere[9,10], and, in respect of the first term, is in good accord with available experimental data[11]. Essentially the behaviour is related to a recovery process involving hopping in a disordered (fractal) structure with a wide distribution of waiting times. Examples of calculations using the first term only are shown in Fig. 1. It is in coping with variable temperatures during irradiation or subsequent recovery that the model is at its weakest. This is, firstly, because it ignores any details of individual hopping and centre annihilation events, which might modify overall response near rapid temperature changes; secondly, because there is virtually no experimental evidence on which to base the model in this respect. Otherwise, the RIR expression permits calculation of the response to arbitrary dose rate histories (Fig. 2).

The second term in the RIR expression is essentially a "stand-in". It was introduced[11] to account for that part of the induced loss that shows no sign of recovery over times $\sim 10^8$s. The exponent was chosen on the basis of the simplest physical model for this component i.e. that it results from the modification of a proportion of the normal (first term) centres by, for example, structural relaxation. The proportion would have to be small to avoid significant alteration to the dynamics of the primary processes, and in fact it is. Experimental data is too patchy to confirm the chosen exponent; values in the range 0.5 - 0.8 could serve as well. Some calculations, which may be compared with experimental values[12] are presented in Fig. 3.

A number of unresolved factors that could influence the extent and variation of the long term loss include the following:
   a) more than one type of centre with different dose and dose rate dependencies may contribute.
   b) new trap sites may be created by the radiation itself.
   c) given that this loss component is usually obscured at early times, or, otherwise are too small to be measured, the effect could be related to the primary recovery process
   d) dependent on launch conditions and fibre length, some of the light power will be in the cladding; its composition will affect results, particularly for single mode fibres[13].
   e) hydrogen, generated by radiolytic action in fibre or coating materials, can diffuse, over the long times involved in observing the long term loss component, to create and modify attenuation sites[14].
   f) some phosphorus, possibly undeclared, could be present, also fluorine
   g) some photo bleaching[15].

The inherent variability in most of these factors suggests that it may not be possible to generalize about long term losses. Notice should be taken of an alternative approach[16,17]. This study employs data reduction techniques in analysing extensive in-house experimental results, to identify the dependence of induced loss on details of construction, composition, and manufacturing techniques with some success. Whether the process can be reversed, even given accurate details of all relevant features, is less certain. However, even at the highest doses, $\sim 10^6$Gy, provided the dose rate is low enough throughout (i.e. so that the power law term is unimportant), the loss in good Ge fibres does not exceed 50dB/km at 1300nm. Given that the length of fibre at risk from such levels of exposure would normally be relatively small, there should not be any problems for digital transmission.
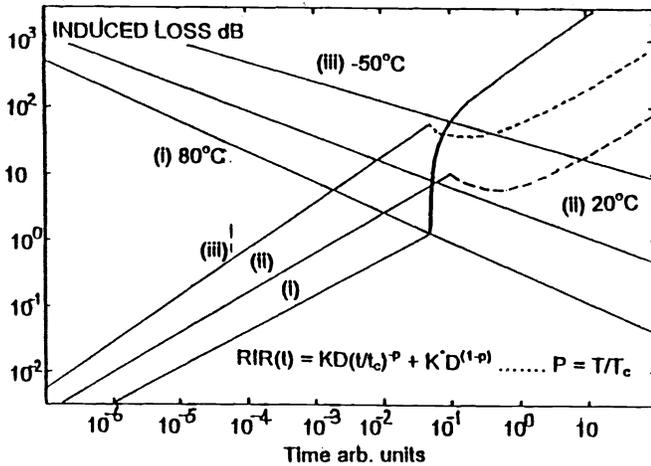
Figure 1. Shows, top to bottom, RIRs for -50, 20, 80°C in dB/unit dose; also growth under irradiation at 10x unit dose rate, for -50 and 80°C, to 0.05 time units, and for 20°c to 0.1 time units. Subsequently, abrupt temperature changes are assumed from 80 to -50°C and from -50 to 20°C for further growth, while at 20°C, the dose rate(R) suddenly becomes unit rate. Strictly speaking , arbitrary units apply only at one temperature. If the time unit is 1s, the RIR in dB/km/krad, and the loss growth is dB/km, the figures apply to a generic Ge fibre at 1300nm.
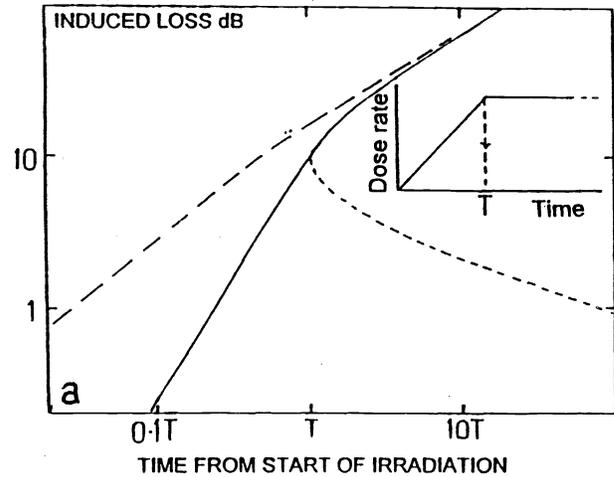

TIME FROM START OF IRRADIATION
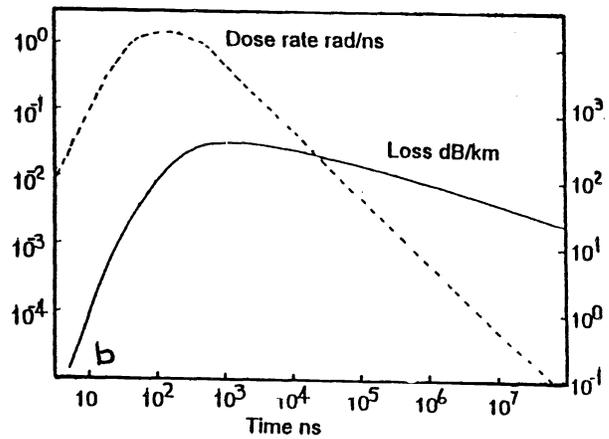
Figure 2a. Solid line depicts the induced loss v. time resulting from an irradiation of the form shown in the inset. Long dashes are loss v. dose. Short dashes indicate the recovery when the exposure terminates at T.

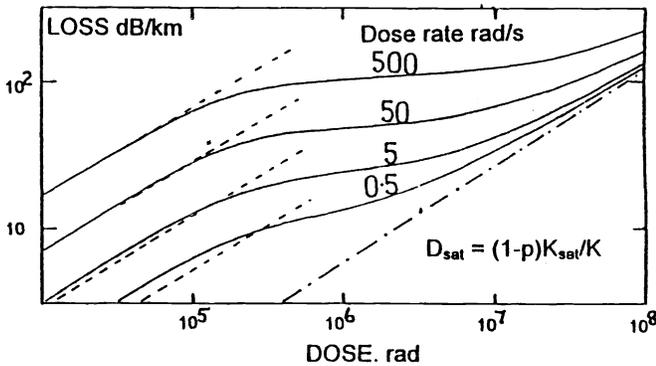Figure 2b. Calculation of the response of a Ge fibre (1300nm, 23°C) to the dose rate profile shown.

$D_{sat} = (1-p)K_{sat}/K$

Figure 3. Losses in a Ge fibre (1300nm, 23°C) during constant rate, R , exposure to higher doses (R = 0.5, 5, 50, 500 rad/s up from the lowest). Dotted lines show extrapolations of the low dose, high rate, power law limit; dot/dash is the long term, low dose rate limit, assumed not to recover.

4. Ge:P/P DOPED FIBRES

In a key paper[18], concerning centres responsible for induced loss in fibres containing phosphorus, the authors state "radiation induced losses in fibres containing both Ge and P in the core are virtually permanent, *decaying negligibly in a period of hours*" (my italics). The statement must be viewed in the light of their intent to contrast the behaviour of these fibres with that of those containing Ge only, and also, from the time aspect, of their interest in the tactical effects of nuclear weapons. It is true though that the general impression is that, because induced losses are relatively high as well as "permanent", phosphorus is an unacceptable dopant for fibres at risk from exposure to ionizing radiation. In many respects the view is correct, but not in all.

A small proportion of P in a Ge doped fibre eliminates much of the early transient loss associated with the Ge, without itself leading to unacceptable long term loss in tactical applications. The bonus is that it is possible to pick a Ge:P ratio leading to induced losses which are essentially constant over the tactical time scale, nearly independent of fibre

temperature, and with very similar values at the three wavelengths, 850nm, 1300nm, and 1600nm[19]. Alternatively, the relatively high losses occurring in fibres with elevated phosphorus content may be exploited to measure radiation exposure. Ideally, no recovery of the losses (fading of the reading) should occur. That some does is discussed elsewhere[20].

5. UNDOPED CORE FIBRES

Details of the behaviour of these fibres are to be found in the reviews and references therein[1-4]. They reveal a number of properties fatal to prediction, including non-linearity, strong photobleaching, and that the response can be affected by earlier exposures. One factor strongly affecting the degree of non-linearity is the proportion of -OH in the core. At doses <10s Gy, the value of the RIR, taken at a fixed time after irradiation, at the same temperature, and for the same core light power density, depends on dose ,D, approximately as $D^{0.25}$ - $D^{0.6}$, the exponent increasing as the -OH content decreases[21]. At higher doses, as well as saturation effects, radiation hardening can take place, typically revealed as a reduction in induced loss during constant rate exposure (Fig. 4). The hardening process is permanent. The sensitivity to subsequent exposures is then reduced, while residual losses from the hardening process are minimal. However, at some combinations of temperature, light power, and dose rate[22] the sensitivity can be increased. It does seem though that the losses eventually tend to the same independent of "hardening" history and even of light power.

Attempts have been made to find expressions to represent the behaviour (e.g.[23]). An expression for the RIR of this type of fibre has been suggested[24], which applies principally to the window around 850nm, extending to the longest visible wavelengths, but also fairly well at 1300nm for low -OH versions (Fig. 5). It is unlike that for Ge fibres in that, except at very short times, both terms tend to contribute significantly to the overall loss, making it more difficult to unambiguously fix the values of A, B, and q. Under the proper conditions, hardening removes the loss component quantified by the term B, which is also that susceptible to photobleaching. This is probably the explanation of the high dose trend described previously. Despite the qualitative success of the modelling, itself less apparent in coping with temperature dependence, non-linearity precludes its use in quantitative predictions.

Another complication arises when there are significant induced losses reduced by photobleaching[25]. There can be a positive feedback effect, in that bleaching increases its own effectiveness. Further, it will proceed more rapidly near the light launch end rather than at some distance down the fibre.

At high doses, loss around 850nm, at low dose rates, is few dB/km for 10^5 Gy to ~20dB/km for 10^6Gy. Induced loss characteristics in the visible region strongly depend on the presence and relative concentrations of chlorine and -OH[26]. Though losses are relatively high, these are the fibres to turn to if transmission in the visible is required; the different types offer choices according to the radiation environment, and whether low loss at a specific wavelength or a flat response

6. GLASS FIBRES / MULTICORE FIBRES.

A range of glasses have been used in optical fibres, which offer ease of production (by virtue of lower drawing temperatures than for silica) and lower costs at the expense of lower transmission, restricting their use to shorter links in most cases. Some versions, though, produced by the double crucible process, can approach silica in this respect. However, all exhibit greater radiation induced losses. Because of these, available radiation test results, especially recent ones, are too few and scattered to permit generalizing about their behaviour, but some are quoted to establish general levels of response.

Losses tend to be highest in lead silicate fibres. Sigel[27] recorded the recovery, at 1050nm, of such a fibre, at times from 1ms to 10^5s after a brief radiation pulse. This can be fitted very closely with a power law, $4200t^{-0.115}$dB/km for a dose of 1krad. Schneider's[28] results for a Siemens $Na_2O.K_2O.PbO$. silicate fibre at 850nm showed loss growth ~15000 dB/km/krad, while Buker[29] quotes ~20000 dB/km/krad at 660nm, and 10000dB/ km /krad at 850nm for "Schott PbO fibre". Although there are different dose rates in these two sets, the results are broadly compatible. Shrivenham values for a PbO multicore fibre range from 20000dB/km/krad at 600nm to ~3700 dB/km/krad at900nm (Fig. 6). The units quoted imply no recovery. Some does occur; over times seconds to hours it follows $7800t^{-0.096}$ dB/km/krad at 850nm. This empirical fit is not good enough to indicate full power law behaviour, as in Ge fibres, but, assuming that it does, a calculation was made of the expected ratio of losses after growth at 23 and 56.8°C in Buker's experiments, yielding 1.31. The experimental value was 1.25.
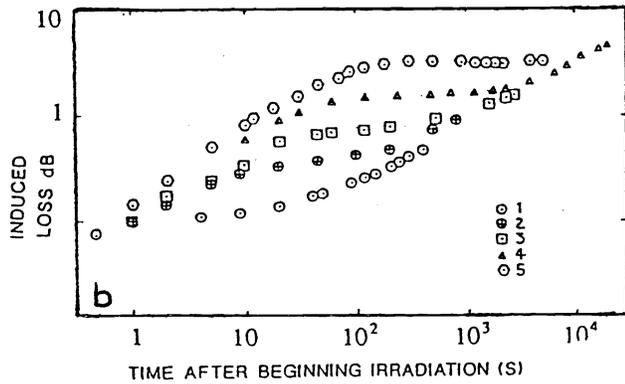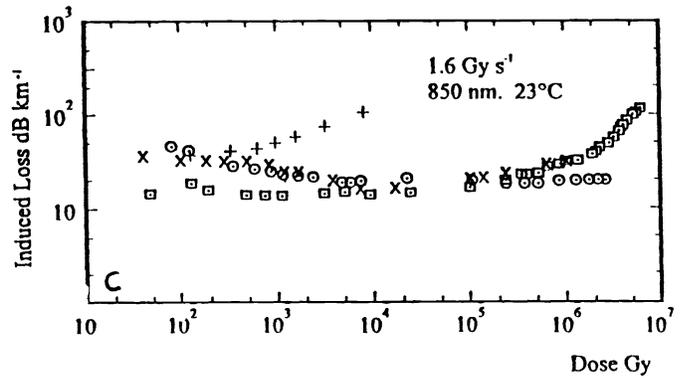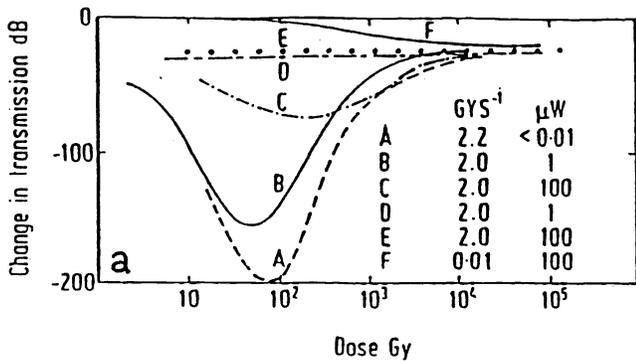
Figure 4a. Change in transmission induced, under the dose rate and light level conditions shown, for a number of samples of the same PCS fibre. Additionally, D and E had previously been irradiated. Note the tendency to the same loss value at high doses.

Figure 4b. Losses for successive exposures of the same sample of an undoped SMF (allowed to recover between exposures). This illustrates sensitization by pre-irradiation and the high dose tendency.

Figure 4c. Continuous irradiation of : + HCS fibre, which fails due to release of fluorine from the cladding; x and □ two Suprasil (~150ppm - OH). Hytrel clad, which had different radiation histories prior to these exposures. Both show evidence of radiation damage in the silicone cladding; o high -OH PCS.
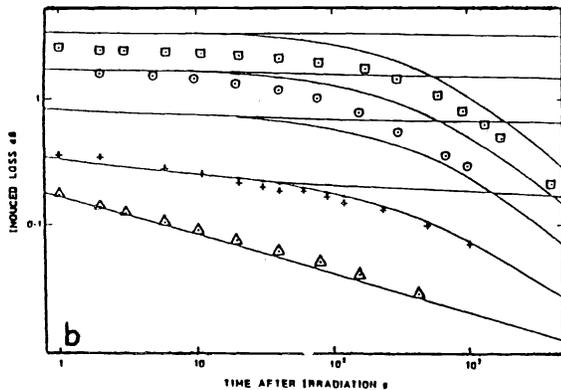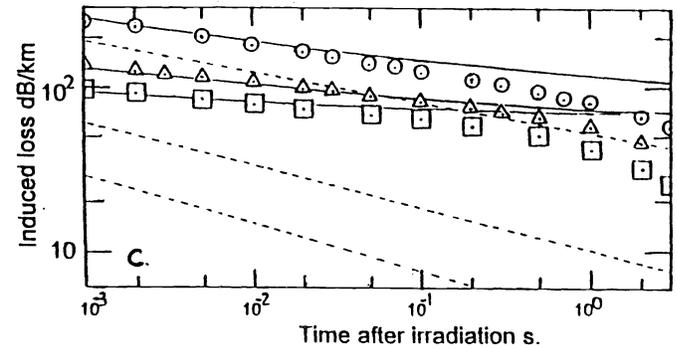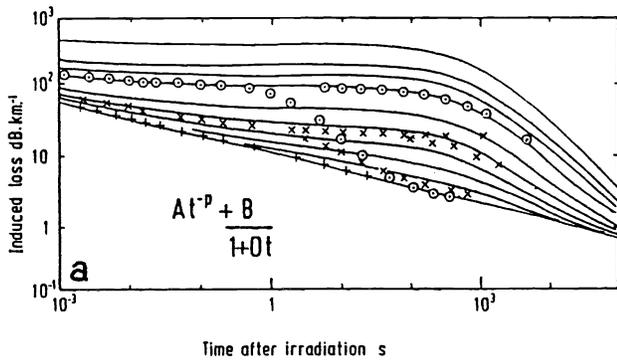
Figure 5a.Curves derived from the inset expression used to describe the RIR for undoped core fibres. Those shown are for A = 10 (at 1s), D = 0.00133 (light level 100nW), and for B from 0 to 400. Results (o) are for an all silica fibre at 100nW and 30μW; for an HCS fibre (x) for thermal annealing and two light levels; the remainder (+) for a hardened PCS.

Figure 5b. Responses to 400rad radiation pulses on equal lengths from the same pure silica fibre pull. Those as (o) are for the fibre as pulled. The others show either hardening or increased sensitivity due to different degrees of pre-irradiation and conditions under which it was performed.

Figure 5c. Effect of temperature on the RIR of an all-silica fibre (□ 75°C, Δ 25°C, O -60°C). The solid lines are an attempted model fit assuming that the effect is expressed in variation of the exponent q, with B (and A) unchanged. Also no account is taken of photobleaching (D = 0). Lines - - - show the contribution of the A term

Lower losses are found for some multicomponent fibres, though, in the nature of things, they will vary considerably with composition. One single core sample tested could be fitted with $1400t^{-0.35} +620$, and $1760t^{-0.32} +1680$, in dB/km/krad for 850nm and 660nm respectively, valid from ~1s to $>10^4$s. Another Na. Ba. Ge. borosilicate fibre from the double crucible process showed early losses of $710t^{-0.151}$ dB/km/krad at 850nm.

Multicore fibres have the complication that light will be launched into cladding, and where appropriate, support materials, with fibre lengths such that this component could form a significant proportion of the transmitted light. This would then affect radiation performance even if the cores are of high quality synthetic silica. Over the longer lengths then possible, the non-core fraction may be lost. However, if relatively impure material is used for the matrix, it is possible that that some impurities could transfer to the core during the production processes. One method used to improve the radiation performance of glass multicore fibres is Ce doping. With the correct valency, the cerium interacts with the impurity sites to shift associated induced loss from the near IR to the UV. There is a penalty of reduced transmission at the shorter visible wavelengths in the unirradiated fibre. Radiation test results for one of these fibres are shown in Figs.6,7. The classic power law response encourages the thought that effects at other temperatures may be calculated, despite lack of experimental confirmation.

7. SPECIALIST FIBRES

7.1 Fibre amplifiers.
Fibres, doped to provide lasing transitions, have been radiation tested, mostly for straightforward transmission loss, but, with Er doping, also while acting as amplifiers. Provided then that the amplifier is being worked in saturation, the gain loss is due to the transmission loss alone. Some values for the loss induced in various Er doped fibres are shown in Fig. 8. Loss/unit length differs firstly because the doping levels vary. High concentrations lead to amplifiers requiring just metres of fibre, the lowest, 100s+ metres. Principally the losses appear to be associated mainly with the aluminium codopant, the proportion of which also varies. Results for other lasing dopants have been obtained by Henschel et al[30].

7.2 Polarization maintaining fibres (PMF)
The combination of single mode operation and structural features responsible for their PM capability can make these fibres extreme exceptions to the rule of core material dominance of the radiation effects. They lead to losses which are generally higher than might be expected for the core composition[31](Fig. 9).

8. CONSEQUENCES OF INDUCED LOSS FOR FO SENSORS.

Some simpler FO sensors depend on fibre transmission. The most important are microbend sensors. They may incorporate techniques to reduce loss variation due to factors other than that being targeted. They may involve compensating fibres, which could cope with radiation effects, or measurements at different wavelengths, which may not. Any lossy or high order skew modes, which are often excessively sensitive to radiation, must be eliminated before reaching the bend unit.

In reflective sensors dependent on surface colour change and in fluorescence sensors, wavelength dependent, induced losses could be a problem. In temperature sensing, exploiting the ratio of Stokes : Anti-Stokes Raman scattering intensities, the two wavelengths are relatively close, but the technique could still suffer, the more so the shorter the central wavelength.

Michaelson/Mach-Zehnder interferometric sensors could be unbalanced by different radiation effects in the sensing and reference arms. High dose rates/high doses may cause leakage from one of the orthogonal modes to the other. Effects on FO gyroscopes have been described[32]; here there is a case where a relatively long length of fibre, in the coil(s), is at equally high risk throughout. High dose related changes in fibre Bragg gratings have been carefully detailed[33].

Conversely the induced loss may be used to detect and measure the radiation itself. Note that other radiation effects may be employed. They include thermoluminescence and radiophotoluminescence for total dose, and, for dose rate, various types of radioluminescence (Cerenkov, fluorescence, scintillation).
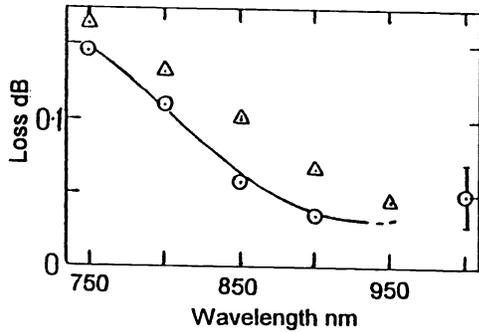
Figure 6. Losses after 150rad at 110 rad/s in 2m multicore fibres a) △ - lead glass, b) o - Ce doped glass. The line is to guide the eye. The lead glass experimental figures have been reduced by a factor of 25 before plotting. Thus, in this wavelength region, Ce doping can reduce losses by up to a factor of 50.
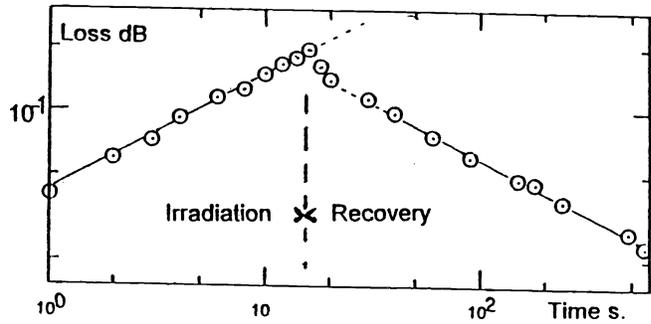

Figure 7. Loss during exposure at 100 rad/s, and subsequent recovery, for a 2m long, multicore fibre of Ce doped glass. It closely follows power law behaviour with an RIR $\propto t^{-0.5}$.
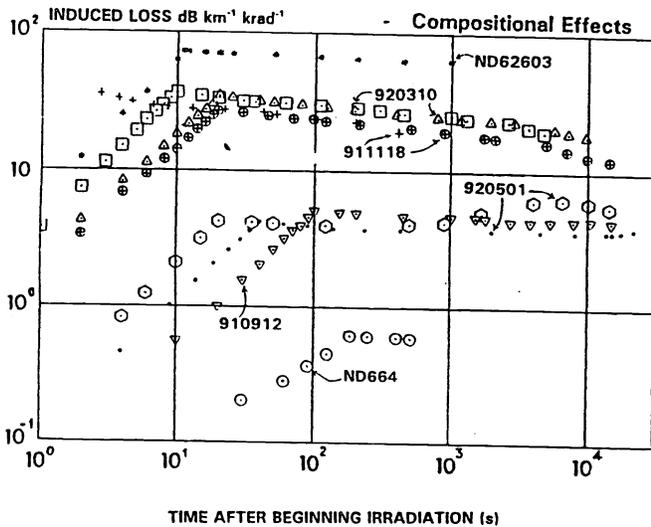

TIME AFTER BEGINNING IRRADIATION (s)

Figure 8. Losses during irradiation and recovery for a selection of Er doped fibres from a variety of sources and having different compositions. The same dose rate was used for all. In order to compare them the results have been scaled so that the recoveries (which tend to the corresponding RIRs at longer times)can be expressed in dB/km/krad..
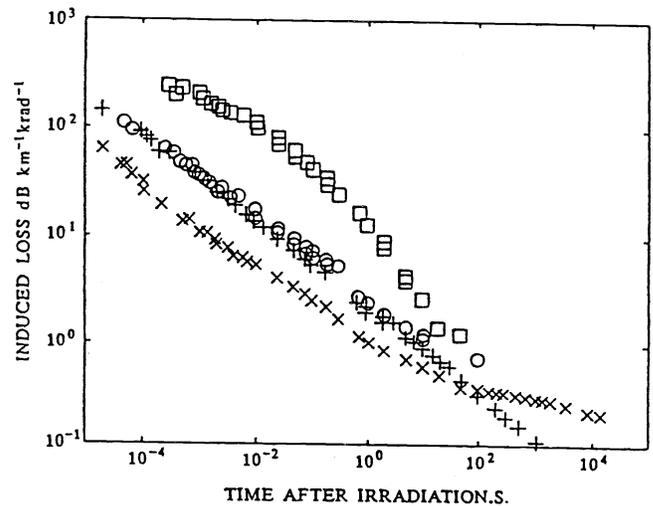

TIME AFTER IRRADIATION.S.

Figure 9. Recovery after pulsed irradiation for (+) Corning MM, (o) Philips MM, (x) Philips SM, and (□) 3M PMF, all at 23°C and for 1300nm, showing the greater sensitivity of the PM fibre, in this case at short times.

9. CHEMICAL CHANGES

Two major chemical effects on fibres due to radiation have been identified. The more important is where the cladding, coating, or both are fluoropolymers. Fluorine and hydrogen released by radiation combine to attack the glass of the core, generating scattering and reflective facets and, eventually cleaving sites. In silicone clad fibres, hydrogen might attack the glass, but more significantly structural changes in the polymer, like shrinkage, reduce the effectiveness of the cladding. Both effects are illustrated in OTDR traces (Fig. 10). Hydrogen released radiolytically from any part of a fibre cable could diffuse to generate new, or modify existing attenuation centres in the core.

10. CONCLUSIONS

It has been shown that, under conditions where power law recovery dominates, the behaviour of Ge doped fibres is predictable on the basis of a well determined RIR plus a spot result at another temperature. The spread in responses from fibre to fibre is relatively small, so that for most purposes the generic fibre behaviour will adequately predict the viability
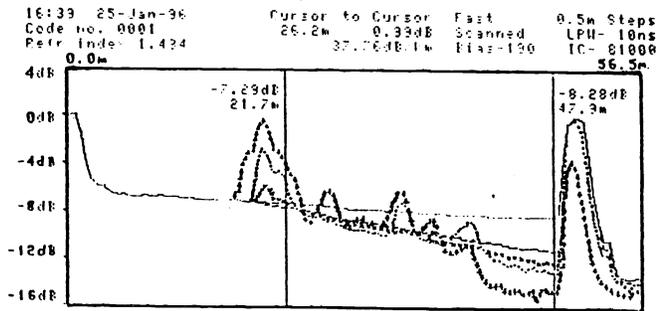
Figure 10a. Optical time domain reflectometer (OTDR) traces showing the development of non-uniform loss (slope of curve) related to core damage from the action of HF.
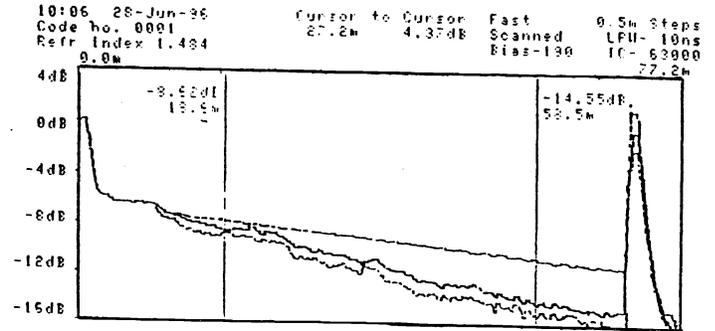
Figure 10b. OTDR trace for one of the Suprasil fibres of Fig. 4c. showing the development, above 10^7 rad of non-uniform loss, despite uniform irradiation, indicative of cladding failure.

in any projected applications. Saturation effects are reasonably predictable and at higher doses increase in loss is small. The "permanent" losses evident at low dose rates are poorly characterised and lead to unreliable prediction. However, these losses are likely to be small, either because the dose is low, or because the length of fibre under threat is not great. The message then is that for digital transmission at communication wavelengths potential changes due to radiation can be adequately predicted in Ge fibres, provided that there is no other interfering dopant present. Where the latter is phosphorus acceptable prediction is possible.

Losses in undoped core fibres are not predictable for arbitrary radiation environments. Additionally there tends to be a bigger range in their responses than is the case for Ge fibres. This is largely because they should be treated for irradiation situations as having different dopant levels of -OH, H, Cl, and, for use in the IR, alkalis. At ~850nm, for high doses broad loss limits may be set for good quality fibres, but, on the way to these levels, higher losses can occur which could vary considerably according to fibre type and measurement conditions

Lack of information about general behaviour inhibits prediction for other fibre types, though the apparent widespread applicability of power law expressions possibly point to the way forward.

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