Radiation hardening of optical fibre links by photobleaching with light of shorter wavelength

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Abstract

The influence of additionally injected short-wavelength photobleaching light on the radiation hardness of Ge-doped graded index fibres working at 1300 nm wavelength is investigated. Predictions are complicated by the fact that more efficient shortwave bleaching light experiences higher radiation-induced loss.
Promising results are found for low fibre temperatures ($\lesssim$ -50°C) and bleaching light of about 835 nm wavelength.

I. INTRODUCTION

It is well known that an increase of light power conducted in irradiated fibres can reduce the radiation-induced attenuation of some fibre types significantly. This effect is usually designated as photobleaching and was investigated by a variety of laboratories, e.g. [1 - 22]. Most of the authors used multimode step index (MM SI) fibres with undoped SiO_2 core of low or high OH-content, but only very few papers (e.g. [17 - 22]) present photobleaching measurements with Ge-doped fibres.

The highest photobleaching of all fibres investigated so far by Fraunhofer-INT was observed with pure silica core fibres of low OH-content fabricated by Schott Glaswerke, Germany, by their PICVD process (plasma impulse chemical vapour deposition). An increase of light power in the single mode (SM) fibre Schott P 926/20 E from 0.001 μW to 355 μW reduced the loss induced after ^{60}Co irradiation up to 100 Gy from about 220 dB/km to about 0.9 dB/km (see. e.g. [23]). These fibres, however, never attained practical importance and are no longer produced.

The highest radiation hardness is shown by fibres with pure silica core of high OH-content [23, 24]. Such fibres, however, are only produced as MM SI fibres with typical core diameters of 100 or 200 μm, so that their bandwidth usually is $\lesssim$ 25 MHz×km.

Higher bandwidths can be obtained with graded index (GI) fibres ($\gtrsim$ 500 MHz×km) and SM fibres (> 10 GHz×km). Nearly all GI fibres and also most of the SM fibres have a Ge-doped silica core. Such fibres are used for telecommunication purposes. The continuing efforts to increase the repeaterless transmission distance, i.e. to improve fibre quality, led to the result that most of these fibres can also be used in certain radiation environments as outlined in [23, 24]. Ge-doped fibres, however, have the disadvantage that their radiation-induced loss increases considerably with decreasing temperature (see e.g. [23]). This can be explained by an increased lifetime (i.e. reduced thermal bleaching) of colour centres already effective at room temperature as well as by the fact that other colour centres which are very unstable at room temperature (i.e. of extremely short lifetime) can become efficient at lower temperatures.

SM fibres with pure silica core are considered to be more radiation resistant, but in [23] it is shown that this might only be valid within a restricted dose range.

Since the radiation-induced loss (similar to the initial attenuation) decreases with increasing wavelength (see e.g. [23]), transmission wavelengths around 1300 nm (or 1550 nm) should be applied. It is known from literature that with these wavelengths photobleaching in Ge-doped fibres is only very weak at room temperature [16, 19-22]. In [16] it was shown that also the SM fibre with undoped silica core whose good radiation hardness is described in [23, 24] shows nearly no photobleaching at 1300 nm. At low temperatures, however, even Ge-doped fibres can show reduced radiation sensitivity at higher light powers [17 - 22].

II. PREVIOUS WORK, OBJECTIVES OF PRESENT WORK

Gilbert [18] has already demonstrated that the radiation-induced loss Ge-doped fibres show after pulsed irradiation at -195 °C can be bleached more efficiently by light of 456 nm wavelength than by 956 nm light. He concluded therefrom that also the induced loss after pulsed irradiation at room temperature can be reduced more effectively by light of shorter wavelength. He suggests to use light of an argon laser (450 - 550 nm) for bleaching and to insert filters to separate the long-wavelength transmission light from the bleaching light. Gilbert used only short fibre pieces so that wavelength-dependent loss could not disturb his systematic investigations.

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Similar systematic investigations with one of the undoped SM fibres made by Schott are described in [21]. The continuous irradiations at a ^{60}Co source were also performed at different temperatures in order to develop an equation for simultaneous description of thermal bleaching and photobleaching.

The present investigations should serve a more practical purpose. We intended to find out whether the good radiation hardness of modern high bandwidth Ge-doped fibres of certain application-specific lengths working at 1300 nm can be further improved by additional injection of shortwave light, especially at low temperatures. Suitable light sources are the now available cheap high power laser diodes with wavelengths around 670 nm, 780 nm, and 830 nm, respectively. We made continuous irradiations (at a ^{60}Co source), but the results should also be valid, to a certain degree, for pulsed irradiations, at least at later times. Friebele et al. [25] postulate that short irradiation with high dose rate should lead to the same final loss than long-term irradiation with low dose rate up to the same dose. This should hold since growth and recovery of colour centres are independent processes.

The problem with real communication systems of certain fibre length is that the radiation-induced loss increases with decreasing wavelength, so that the most effective light with the shortest wavelength might not reach the fibre end even after relatively low radiation doses. Since predictions would only be possible with precise knowledge of wavelength-dependent loss as well as of bleaching efficiency (for each temperature of interest), we simply tried to find out whether there exist optimal conditions for a certain situation (fibre length, temperature).

We used a GI fibre since they are easier to handle than SM fibres with their small core diameter. Similar (but never identical) results are to be expected with all other Ge-doped GI and SM fibres.

III. EXPERIMENTAL

Fig. 1 shows a block diagram of the experimental equipment. Transmission measuring light and shortwave bleaching light were mixed with a Gould "Multimode Fused Bidirectional Coupler". The receiver (HP8153A Lightwave Multimeter with HP81532A Power Sensor (InGaAs)) was protected from the high intensity bleaching light by up to three "Long Wave Pass Filters" (LPF) blocking light with wavelength ≤ 1100 nm.

The measuring light intensity (from a 1288 nm LED source) was about 5 µW, whereas bleaching light intensity was about 320 µW at all wavelengths

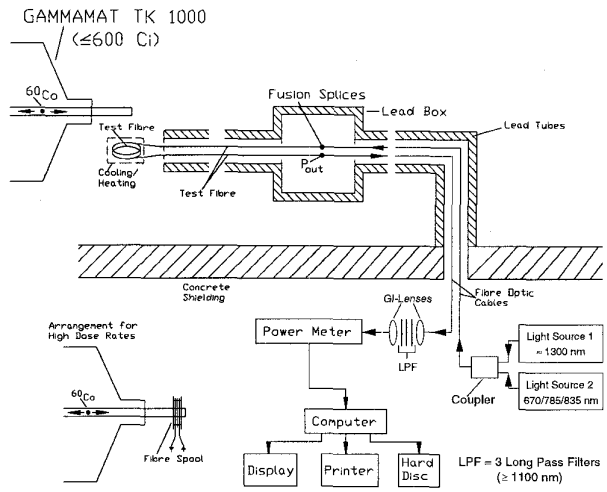

Fig. 1: Block diagram of the experimental equipment.

(from laser diodes with wavelengths of about 670, 785, 835, and 1300 nm). With the 1300 nm laser source, however, bleaching and measuring light were identical.

The investigations were made with 50/125 µm Ge-doped GI fibres drawn by KWO Kabel GmbH (Berlin, Germany) from a set of (nearly) identical preforms made by FiberCore Jena GmbH (under different name) before 1990. Details about this fibre type can be found in [20], together with results of systematic variations of wavelength, light power, temperature, and dose rate during ^{60}Co gamma irradiation of fibre sample KWO G2.2./1380. These early tests yielded that this fibre type shows weak photobleaching at room temperature and even more at -50 °C.

Results of high-dose irradiations (up to 10^6 Gy) of fibre samples KWO G2.2./1380 and KWO G41/007 at temperatures around 33 °C can be found in [23, 24].

The present investigations began with fibre sample KWO G41/0067. We irradiated 50 m and 1000 m long pieces at room temperature and made only one test with a 9 m piece at -55 °C. The results were already presented in [22]. Systematic measurements at -55 °C had to be continued with 50 m and 400 m long pieces as well as with two about 1 km long pieces of the (nearly) identical fibre KWO G41/0042/32 because we only had about 4.5 km of each fibre sample.

With the latter fibre we also made spectral loss measurements. Our analyzer system (Advantest Q8381 Optical Spectrum Analyzer with TQ8111 White Light Source) can be used in the wavelength range 600 nm ≤ λ ≤ 1700 nm. 50 m fibre pieces were irradiated with a dose rate of 0.22 Gy/s up to a final dose of 10^4 Gy, and measurements were made at intermediate

dose values of 30 Gy, 60 Gy, 100 Gy, 300 Gy, etc. We compared three different situations:

- fibre at room temperature, illumination with white light source;
- fibre at -55 °C, illumination with white light source;
- fibre at -55 °C, illumination with white light source plus 670 nm laser source.

These light conditions were maintained during the whole irradiation phase.

Thus we can, e.g., compare the effect of an increase of temperature from -55 °C to room temperature with the effect of additional injection of 670 nm light at -55 °C.

IV. RESULTS

Results of radiation-induced loss measurements made with fibre pieces of different length should not be compared by calculating, e.g., a loss in dB/km when the fibre shows noticeable photobleaching. We therefore always show the loss per test fibre length that mostly differs from figure to figure.

Long fibre pieces had to be coiled up on spools with larger diameter. We therefore had to increase the distance between fibre spool and ^{60}Co source. As a consequence the dose rate decreased from about 0.22 Gy/s to 0.05 Gy/s. This has to be considered, too, when comparing results of different measurements since the radiation-induced loss (mostly) increases with dose rate.

A. Fibre Sample KWO G 41/0067

Fig. 2 shows the results of 50 m pieces irradiated at room temperature with a dose rate of 0.21 Gy/s up to a final dose of 10^4 Gy(SiO_2). The fibres were continuously illuminated during irradiation with light of 1300 nm wavelength (P = 310 μW) or with light of λ = 1288 nm (P = 5.5 μW, for transmission loss measurement) plus photobleaching light with an intensity of 310 μW and a wavelength of 835 nm, 785 nm, or 670 nm, respectively. One can see that at low dose values (around 10 Gy) photobleaching with 670 nm light (curve 4) leads to less than half of the loss as 1300 nm light of the same intensity (curve 1). At higher dose values, however ($\geq 10^3$ Gy), light of shorter wavelength has greater attenuation and doesn't lead to radiation hardening of this configuration (i.e. 50 m fibre length, 10^4 Gy, room temperature).

A similar situation exists for the configuration 1 km fibre length, 100 Gy, and room temperature (Fig. 3). The loss of 1 km pieces after only 100 Gy without short wavelength bleaching light (solid line) is still tolerable

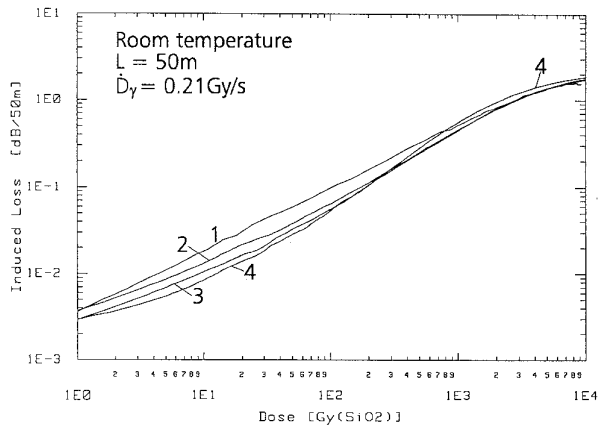

Fig. 2: Photobleaching caused by light of different wavelength in fibre KWO G 41/0067.
1: λ = 1300 nm (LD; 310 μW)
2: λ = 1288 nm (LED; 5.5 μW) + λ = 835 nm (LD; 310 μW)
3: λ = 1288 nm (LED; 5.5 μW) + λ = 785 nm (LD;310 μW)
4: λ = 1288 nm (LED; 5.5 μW) + λ = 670 nm (LD; 310 μW)

(1.3 dB). For longer fibre pieces or higher dose values 670 nm and 785 nm light will loose its bleaching efficiency. Only 835 nm light seems to preserve its efficiency up to higher dose levels (or longer fibre pieces).

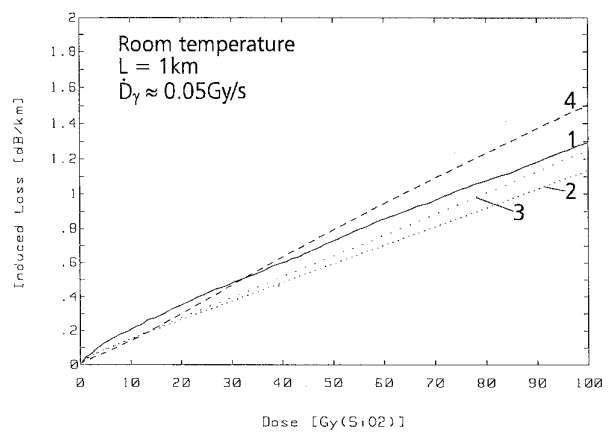

Fig. 3: Photobleaching caused by light of different wavelength in fibre KWO G 41/0067.
1: λ = 1300 nm (LD; 310 μW)
2: λ = 1288 nm (LED; 4.7 μW) + λ = 835 nm (LD; 310 μW)
3: λ = 1288 nm (LED; 4.4 μW) + λ = 785 nm (LD; 310 μW)
4: λ = 1288 nm (LED; 4.5 μW) + λ = 670 nm (LD; 310 μW)

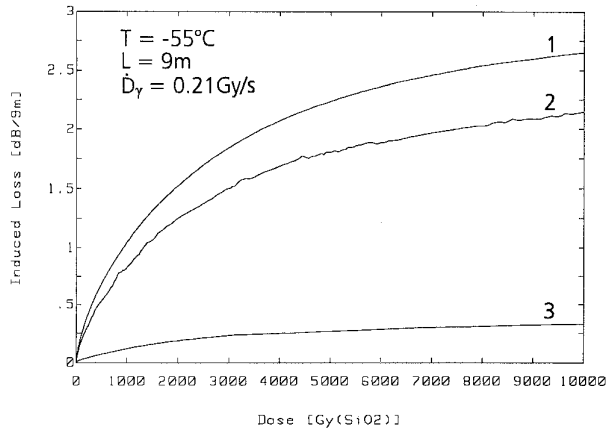

Fig. 4: Photobleaching caused by light of different wavelength in fibre KWO G 41/0067.
1: λ = 1288 nm (LED; 5 μW)
2: λ = 1300 nm (LD; 310 μW)
3: λ = 1288 nm (LED; 5 μW) +
λ = 785 nm (LD; 310 μW)

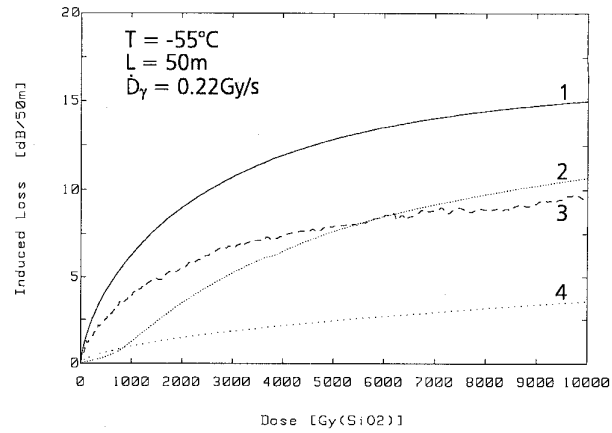

Fig. 5: Photobleaching caused by light of different wavelength in fibre KWO G 41/0042/32.
1: λ = 1288 nm (LED; 3.2 μW)
2: λ = 1288 nm (LED; 3.0 μW) +
λ = 670 nm (LD; 330 μW)
3: λ = 1300 nm (LD; 330 μW)
4: λ = 1288 nm (LED; 3.0 μW) +
λ = 835 nm (LD; 330 μW)

First measurements at -55°C fibre temperature were made with only 9 m fibre length (Fig. 4). One can see that increasing the 1300 nm light intensity from 5 to 310 μW only leads to slight reduction of radiation-induced attenuation, whereas additional injection of 785 nm light leads to strong loss decrease.

The results at -55°C are so promising that the tests were continued with another, approximately identical KWO GI fibre sample (section IV B.).

B. Fibre Sample KWO G 41/0042/32

Fig. 5 shows similar measurements as Fig. 4, but with 50 m fibre length and bleaching light of 670 and 835 nm. 670 nm light (curve 2) loses its superiority already after dose values $\gtrsim$ 5000 Gy, whereas an end of the radiation hardening capability of 835 nm light (curve 4) is not noticeable up to dose values of 10^4 Gy. The situation will be even more promising if the 835 nm light is added to a high intensity of 1300 nm light and/or if 835 nm light is injected from both ends of an irradiated optical fibre. With such measures data transmission over distances of about 50 m at temperatures $\lesssim$ -50°C would be possible up to dose values of at least 10^5 Gy.

The situation of longer transmission lines (400 to 1000 m) in medium dose environments (about 100 Gy) is presented in Figs. 6, 7. From Fig. 6 one can estimate that injection of 835 nm light (in contrast to 670 nm light) will be advantageous up to even higher dose values or longer fibre pieces. Again the situation would be still better if 835 nm light is injected at both fibre ends and/or added to a high intensity of 1300 nm light.

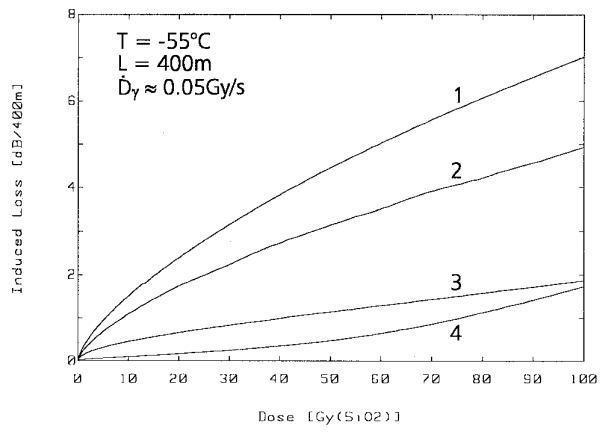

Fig. 6: Photobleaching caused by light of different wavelength in fibre KWO G 41/0042/32.
1: λ = 1288 nm (LED; 5.2 μW)
2: λ = 1300 nm (LD; 330 μW)
3: λ = 1288 nm (LED; 3.1 μW) +
λ = 835 nm (LD; 304 μW)
4: λ = 1288 nm (LED; 2.4 μW) +
λ = 670 nm (LD; 304 μW)

The latter case is shown in Fig. 7 for a fibre length of nearly 1 km. The result indicates that still higher dose levels or longer transmission lengths would be possible, especially if 835 nm light is injected from both fibre ends.

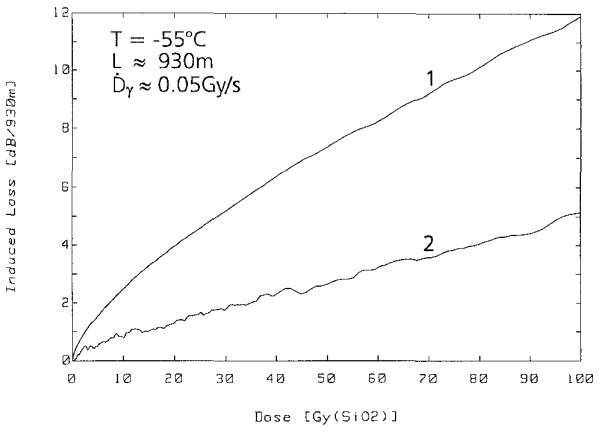

Fig. 7: Photobleaching caused by light of different wavelength in fibre KWO G 41/0042/32.
1: λ = 1300 nm (LD; 330 μW)
2: λ = 1300 nm (LD; 330 μW) +
λ = 835 nm (LD; 330 μW)

Fig. 8 presents the results of spectral attenuation measurements made at an intermediate dose of 1000 Gy (see end of section III). Increase of temperature from -55 °C to room temperature begins to be effective only above about 700 nm (extrapolation of measured curves) and shows increasing efficiency with increasing wavelength, whereas additional injection of 670 nm light at -55 °C is more effective than the increase of temperature only below about 1100 nm. At wavelengths $\gtrsim$ 1300 nm shortwave ligth becomes more and more

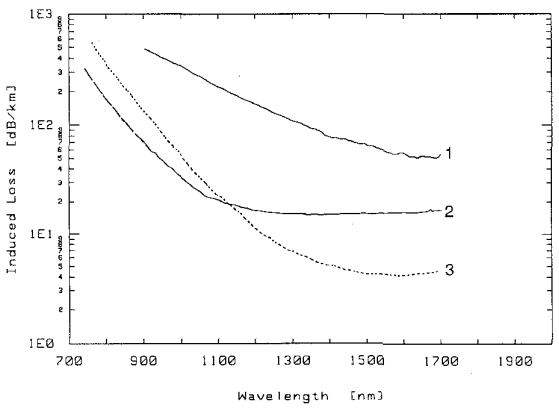

Fig. 8: Influence of temperature and shortwave bleaching light on the loss induced by a gamma dose of 1000 Gy in the fibre KWO G 41/0042/32; L = 50 m, $\dot{D}_\gamma$ = 0.22 Gy/s.
1: -55 °C, white light source
2: -55 °C, white light source + 670 nm laser light
3: room temperature, white light source

ineffective. The reason might be that radiation-induced loss at these wavelengths is dominated by colour centres with maximal absorption in the far infrared and that these colour centres are relatively insensitive against shortwave light. The existence and increasing efficiency with increasing irradition time of colour centres in the far IR was already demonstrated for Ge-doped SM fibres in [23, 24].

Gilbert [18] stated that his 456 nm light had the highest bleaching efficiency over his entire measuring band, but this ended at about 970 nm where our 670 nm light, too, is very effective.

V. SUMMARY

Our investigations have shown that injection of photobleaching light of about 835 nm wavelength can distinctly increase the radiation hardness of Ge-doped optical fibres at low temperatures ($\lesssim$ -50°C). The tolerable radiation dose of 50 m fibre links can be increased to values $\gtrsim 10^5$ Gy, and the repeaterless transmission length in medium dose environments (about 100 Gy) to values far above 1 km. This situation can be still improved by bleaching light injection from both fibre ends.

Since shortwave laser diodes as well as 1×2 couplers and long wave pass filters are relatively cheap, radiation hardening by photobleaching with shortwave light should be taken into consideration when high bandwidth fibre links have to be employed at low temperatures.

Principally it should be possible to find optimal bleaching conditions with shortwave light also for the Ge-doped GI fibres of other manufacturers as well as for Ge-doped SM fibres. Since, however, the optimal conditions for a certain fibre length and fibre temperature depend very strongly on the spectral course of radiation-induced loss and on the bleaching efficiency of the respective fibre, it will be necessary to repeat our tests with the desired fibre.

Up to a certain (fibre-dependent?) wavelength (see Fig. 8) injection of shortwave bleaching light can be more efficient than increasing fibre temperature (if possible).

It should be investigated whether the loss induced at wavelengths $\gtrsim$1300 nm can be bleached more effectively by light of longer wavelength, e.g. $\lambda \approx$ 1550 nm.

VI. ACKNOWLEDGEMENT

We grateful acknowledge the generous supply of GI fibres by Mr. M. Emmerich, KWO Kabel GmbH, D-12532 Berlin, Germany.

VII. REFERENCES

[1] C.E. Barnes, "Irradiation and photobleaching of all-silica, pure silica core fibers at low temperatures", SPIE vol. 404: Optical Fibers in Adverse Environments, pp. 47-54, 1983.

[2] G. Breuzé, J. Serre, A. Friant, "Selective photobleaching of steady-state gamma irradiated silica fibers-application to the hardening of a digital optical link", SPIE vol. 867: Optical Devices in Adverse Environments, pp. 32-39, 1987.

[3] E.M. Dianow, L.S. Kornienko, E.P. Nikitin, A.O. Rybaltovskii, P.V. Chernov, "Reversible optical bleaching of the induced absorption in fiber-optic waveguides", Sov. J. Quant. Electron., vol. 9, no. 5, pp. 636-637, 1979.

[4] E.M. Dianov, L.S. Kornienko, E.P. Nikitin, A.O. Rybaltovskii, P.V.Chernov, "Influence of the temperature and optical power level on induced absorption in fiber-optic waveguides of pure quartz glass", Sov. J. Quant. Electron., vol. 11, no. 9, pp. 1171-1177, 1981.

[5] B.D. Evans, "Thresholds for photoenhanced radiation resistance in optical fibers", SPIE vol. 1174: Fiber Optic Reliability: Benign and Adverse Environments III, pp. 20-26, 1989.

[6] B.D. Evans, "Correlation of the absence of the 630-nm band with the intensity of photobleaching of ionizing radiation-induced loss in undoped silica fibers at -55 °C", Journ. of Lightw. Techn., vol. 8, no. 9, pp. 1248-1288, 1990.

[7] A.H. Johnston, B.D. Evans, M.P. Baze, R.A. Greenwell, "Photobleaching effects in step index pure silica optical fibers during in-situ irradiation at low temperatures", SPIE vol. 867: Optical Devices in Adverse Environments, pp. 25-31, 1987.

[8] G.H. Sigel, E.J. Friebele, M.J. Marrone, M.E. Gingerich, "Analysis of photobleaching techniques for the radiation hardening of fiber optic data links", IEEE Trans. Nucl. Sci., vol. NS-28, no. 6, pp. 4095-4101, 1981.

[9] E.J. Friebele, M.E. Gingerich, "Radiation-induced optical absorption bands in low loss optical fiber waveguides", Journ. of Non-Cryst. Solids, vol. 38&39, pp. 245-250, 1980.

[10] E.J. Friebele, M.E. Gingerich, "Photobleaching effects in optical fiber waveguides", Appl. Optics, vol. 20, no. 19, pp. 3448-3452, 1981.

[11] S. Okamoto, T. Ohnishi, T. Suzuki, T. Hayashi, T. Gozen, H. Tanaka, T. Shintani, "Radiation resistivity of pure silica core fibers: photobleaching effects and temperature dependence", Ann. Rep. of the Radiation Center of Osaka Prefecture, vol. 27, pp. 83-87, 1986.

[12] A. Robinson, "Ionising radiation effects on doped silica and pure silica core fibres", SPIE vol. 721: Fiber Optics in Adverse Environments III, pp. 63-73, 1986.

[13] T. Suzuki, T. Hayashi, T. Gozen, H. Tanaka, S. Okamoto, "Radiation resistivity of pure silica core fibers", SPIE vol. 721:Fiber Optics in Adverse Environments III, pp. 44-49, 1986.

[14] J.G. Titchmarsh, "Signal-level dependence in the recovery rate of irradiated plastic-clad silica fibre", Electr. Lett., vol. 15, no. 4, pp. 111-112, 1979.

[15] R.H. West, A.P. Lenham, "Characteristics of light induced annealing in irradiated optical fibres", Electr. Lett., vol. 18, no. 11, pp. 483-484, 1982.

[16] H. Henschel, O. Köhn, "Investigation of the radiation sensitivity of five single mode fibres", Internal Report 5/90 of the Fraunhofer-INT (in German).

[17] C.E. Barnes, "Laser diode-induced photobleaching at low temperatures in Co-60 irradiated fibers", IEEE Trans. Nucl. Sci., vol. NS-29, no. 6, 1479-1483, 1982.

[18] R.M. Gilbert, "Photobleaching of radiation-induced color centers in a germania-doped glass fiber", IEEE Trans. Nucl. Sci., vol. 29, no. 6, pp. 1484-1488, 1982.

[19] R.H. West, "Radiation effects on fibre optics", SPIE vol. 867: Optical Devices in Adverse Environments, pp. 2-9, 1987.

[20] H. Henschel, O. Köhn, "Investigation of the radiation sensitivity of graded index fibre KWO G2.2./1380", Internal Report 2/92 of the Fraunhofer-INT (in German).

[21] F. Sonnenberg, "The photobleaching effect in optical fibres", Diploma Thesis, 1993; Internal Report 3/93 of the Fraunhofer-INT (in German).

[22] H. Henschel, O. Köhn, "Reduction of the radiation sensitivity of graded index fibre KWO G41/0067 by photobleaching with light of shorter wavelength", Internal Report 4/93 of the Fraunhofer-INT (in German).

[23] H. Henschel, "Radiation hardness of present optical fibres", SPIE vol. 2425: Optical Fibre Sensing and Systems in Nuclear Environments, pp. 21-31, 1994.

[24] H. Henschel, O. Köhn, H. U. Schmidt, E. Bawirzanski, A. Landers, "Optical fibres for high radiation dose environments", IEEE Trans. Nucl. Sci., vol. 41, no. 3/1, pp. 510-516, 1994.

[25] E.J. Friebele, M.E. Gingerich, D.L. Griscom, "Survivability of optical fibers in space", SPIE vol. 1791: Optical Materials Reliability and Testing, pp. 177-188, 1992.