GAMMA AND NEUTRON RADIATION DAMAGE STUDIES OF OPTICAL FIBRES

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Abstract

An optical data link is under development at CERN for readout of the tracking detectors in the future compact muon solenoid experiment (CMS) at the CERN large hadron collider (LHC). Radiation doses inside the experiment will be ~20Mrad and ~10^{14}neutrons/cm^2 over a 10 year period of operation. The effects of neutron and gamma irradiation on the attenuation at 1550nm wavelength have been studied in both germanium-doped and pure-silica core single-mode optical fibres. The induced attenuation was greater in the Ge-doped fibre than in the pure-silica core fibres for both neutron and gamma damage. Pure-silica core fibres will be therefore be used in the CMS tracker. The gamma induced attenuation in the pure-silica core fibres was dependent on total dose, allowing a prediction to be made for the transmission losses during LHC operation.

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1. Introduction

Experiments are currently being designed to exploit the future CERN large hadron collider (LHC), where two high luminosity 7TeV proton beams will be collided at a rate of 40MHz. Optical links will be used for data transfer and this work forms part of the development of a 55,000 channel analogue optical link for readout of 15 million microstrip detectors in the tracker of the compact muon solenoid experiment (CMS)[1]. The initial development work on the CMS optical link[2] has closely followed the activities of the RD23 collaboration[3,4] that has developed a bi-directional analogue optical link based on the use of radiation-hard arrays of reflective multi-quantum well modulators optimised for 1550nm operation. The use of optical links is preferable in the CMS tracker analogue readout scheme, in order to minimise noise and benefit from the smaller space requirement, and smaller mass of fibres, compared to the alternative copper cable.

The large collision rate and LHC beam energy will lead to a large flux of particles in the CMS tracking volume. Total radiation levels over a ten year operational period are expected to be up to 20Mrad and 10^{14}neutrons/cm^2[1]. The dose-rate and neutron flux will be approximately 600rad/hr and 10^{10}neutrons/cm^2/hr, as the LHC beams will be operated for only 5 months per year. Due to induced radioactivity inside the CMS experiment, plus the overall complexity of the apparatus, it will not be possible to replace easily any damaged or degraded elements of the optical link during the lifetime of the experiment. All the link components must therefore be both reliable and radiation resistant. The motivation for this work was to determine the suitability of candidate single mode optical fibres for use in the CMS experiment by irradiating fibre samples under realistic LHC conditions (room temperature, ~100µW incident light power, and total doses similar to 10 years of LHC operation).

It is well established that radiation damage in SiO_2 optical fibres leads to a degradation of optical transmission[5]. Optically active defects can be introduced by ionisation[6,7] or atomic displacement mechanisms[6,7], or via the activation of pre-existing defects[6]. The presence of impurities in the fibre, such as chlorine[8] and phosphorus[9,10], increases the radiation induced transmission losses at infrared wavelengths. These losses can be both permanent and temporary[5] and mechanisms such as optical bleaching[11,12,13] can affect the rate of recovery during and after irradiation. The induced attenuation is determined by the competing rates of creation and annealing (plus activation and de-activation) of absorption centres[6,14,15]. Transmission losses due to radiation damage can therefore be sensitive to both total dose and dose-rate, in addition to factors such as transmission wavelength[5], injected light power[11,12,13] and temperature[5,16,17]. Pure silica core fibres are generally accepted to be more radiation hard than germanium doped fibres[10] although a similar degree of radiation resistance was observed in a recent study[18].

2. Experimental procedure

In this investigation the radiation induced attenuation was measured, at a wavelength of 1550nm, for three different single mode fibre types considered for use in the CMS experiment. The fibres included a germanium-doped fibre, manufactured by Lycom[19], and two types of pure silica core fibres with fluorine-doped cladding, manufactured by Lycom[20] (referred to as PSCF-A) and Sumitomo[21] (referred to as PSCF-B). The geometry of each fibre was identical: ~9µm diameter core, 125µm diameter cladding, and 250µm diameter acrylate coating. The pure silica core fibres were made by vapour-phase axial deposition and the OH impurity content was <ppb.

The schematic arrangement of the apparatus during irradiation is illustrated in figure 1, with details of the irradiation tests listed in Table 1. The fibre samples were wound on a 6cm diameter spool. No connectors or splices were exposed to radiation. The irradiations were carried out at room temperature; the temperature in the irradiation cell was monitored but not controlled. For the neutron irradiation, nickel dosimetry foils were used to measure the total integrated flux. A calibrated silicon photodiode was used to measure the dose-rate in the gamma irradiations. All gamma doses and dose-rate units correspond to damage in silicon, i.e. rad(Si). The exposure time was then used to calculate the total dose. Alanine dosimeters were also used to verify the total gamma dose; good agreement was observed with the photodiode. Light of 1550nm wavelength was continuously injected into the fibre samples (~100µW per fibre) during the irradiations and monitored recovery periods. A fourth, unirradiated fibre was used to record any variations in the laser power allowing normalisation of the power level injected into the irradiated fibres. The light output from each fibre was measured and stored at intervals of between 1 and 20 minutes depending upon the dose-rate. The radiation induced attenuation loss A was then calculated for each fibre according to,

$$A(t) = -10\log\left(\frac{V(t)}{V(0)}\frac{V_n(0)}{V_n(t)}\right)$$

where V(t) is the output signal amplitude at time t (irradiation started at time t=0), and $V_n(t)$ is the output signal amplitude from the unirradiated fibre used to monitor the laser power. The attenuation in the unirradiated parts of each fibre, the splitter, and the spliced optical connections are therefore subtracted and it was assumed that these loss contributions remained constant throughout the test.

3. 6MeV neutron damage (Test A)

The fibres were irradiated with neutrons using the SARA facility[22] at the Institut des Sciences Nucleaires, Grenoble, France. At this facility, neutrons with an average energy of 6MeV are obtained by bombarding a beryllium target with a deuteron beam. Over a period of 43 hours the 100m long fibre samples received a total integrated flux between $2x10^{13}n/cm^2$ and $8x10^{13}n/cm^2$, depending upon the position of the fibre spool relative to the source. These doses are equivalent to several years of LHC operation. The power level of the continuously injected laser light (1550nm) was 150µW, a similar value to that expected in the CMS optical link.

The radiation induced attenuation results are shown in figure 2. The induced losses in the Ge-doped fibre sample were 1.8dB, compared to ~0.1dB in the pure-silica core fibre samples. These results are consistent with those in a similar experiment[23] though the losses we measured were generally less, possibly due to the smaller neutron energy in our test compared to 14MeV in Ref. [23]. During the 200hr period of monitoring after the irradiation, a recovery of ~10% of the radiation induced losses was observed in the Ge-doped fibres. No recovery, greater than the measurement uncertainty, was observed in the pure-silica core fibres. In contrast, the results of Ref. [23] show ~60% recovery of the induced loss in the pure silica core fibre in one hour after irradiation. This apparent discrepancy can be explained by the difference in the neutron flux, which was ~20 times greater in Ref. [23]. Induced losses that recover over the time scale of one hour will have been suppressed in our experiment due to the smaller neutron flux and longer irradiation period.

4. ^{60}Co gamma damage

4.1) Test B-1

The gamma irradiations were carried out using the ^{60}Co source at Imperial College, London. The first exposure had a dose-rate of 50 to 74rad/s to see quickly the effects of an accumulated dose of ~30Mrad, similar to that expected in LHC applications. Light of 1550nm wavelength was continuously injected with a power level of 60μW. The radiation induced attenuation results are shown in figure 3. It was noted that despite a fast initial increase in attenuation which quickly saturated, the Ge-doped fibres appeared to be just as radiation resistant as the pure silica core fibres at the final dose of ~30Mrad, similar to results obtained in Ref. [18].

4.2) Tests B-2 and B-3

Irradiation B-2 was done with a smaller dose-rate (~0.22rad/s) to simulate LHC conditions more realistically. This test was divided into two exposures: B-2.1 and B-2.2. The total dose was ~0.4Mrad and ~0.9Mrad in each part respectively. A further irradiation (Test B-3) was then carried out with the same fibres, using a higher dose-rate of ~25rad/s, with a total dose ~20Mrad to enable a cross-check with the results from test B-1. Longer samples of fibre were irradiated (300m), for increased sensitivity, and the injected power level was 150μW per fibre. The Lycom fibres (Ge-doped and PSCF-A) used in this test (and the neutron irradiation) were from a different batch to those irradiated in test B-1. The Sumitomo fibre (PSCF-B) was taken from the same spool as in the other tests.

The data set for these irradiations is shown in figure 4. In contrast to the results from B-1, the Ge-doped fibre was observed to have larger losses than the pure-silica core fibres. This is consistent with results reported previously in a similar investigation[16,23]. In the final, high dose-rate, irradiation (B-3) the loss in the Ge-doped fibre was greater than the range of the measurement (~35dB).

5) Discussion of ^{60}Co gamma damage

The gamma irradiation results are shown as a function of dose for the Ge-doped fibre in figure 5. The small dose-rate exposure (B-2) induced greater losses per unit length than the larger dose-rate exposure (B-1), which is in contrast to other findings[16,23]. However, the irradiated fibre length in the B-2/B-3 tests was 300m compared to 88m in B-1. This unusual behaviour could occur as a result of optical bleaching[11,12,13], which would be lessened in the longer fibre sample. The discussion of the Ge-doped fibre results is limited since differences could be due simply to the Ge-doped fibre in test B-1 not being from the same batch as the fibre sample used in the other irradiations.

The induced loss in the pure-silica core fibres is shown in figure 6 as a function of gamma dose. The attenuation is observed to be more dependent upon total dose than dose-rate, allowing a prediction to be made for the radiation induced attenuation for pure-silica core fibres used in the CMS experiment. Despite the relatively large level of injected light power (~100µW) in our gamma tests, the results for the pure-silica core fibres are in agreement with data from a similar experiment[16] on single mode fibres where an injected power of 20nW was used to monitor the gamma induced losses at 1300nm. (The induced loss is expected to be ~2 times greater at 1550nm than at 1300nm in pure-silica core fibres[16].) Optical bleaching is therefore unlikely to have had a major influence over the induced losses in the pure-silica core fibres investigated in our experiment.

The recovery in the pure-silica core fibres during the period between tests B2-1 and B2-2, and B2-2 and B3, was found to be temporary in nature. Temporary recovery has been observed in other radiation damage experiments on optical fibres[24] and SiO_2 films[25], where it was attributed to optical[24] or thermal[24,25] bleaching that de-activated the absorption centres. The passivated absorption centres could be re-activated[24,25] by exposing the samples again to ionising radiation. Figure 7 shows results from tests B2-1 and B2-2 where the gamma exposure was interrupted and the recovery monitored for $2x10^6$s. About 40% of the damage from irradiation B2-1 recovered by the time irradiation B2-2 was started. However, within $1.5x10^5$s of re-starting the irradiation, the induced attenuation had returned to the value at the end of the previous gamma exposure. Temporary recovery was also observed after the B2-2 irradiation, where the attenuation at the start of the B3 large dose-rate test also returned to the value measured at the end of the B2-2 irradiation period. Since there was no similar fast increase in the attenuation at the very beginning of the gamma exposures of the pure silica core fibres, these defects were not already present in the initial material and were therefore introduced by radiation damage.

6. Conclusions

Neutron irradiation increased the attenuation in a 100m sample of Ge-doped single-mode fibre by 0.018dB/m after an integrated flux of $4x10^{13}n/cm^2$. This loss was ~20 times greater than the induced attenuation in the neutron damaged pure-silica core fibre samples. Gamma irradiation also induced greater losses overall in the Ge-doped fibre, between 0.06dB/m and 0.09dB/m after 1Mrad, compared to 0.015dB/m in the pure-silica core fibres. The gamma induced attenuation for the Ge-doped fibres depended upon the dose-rate, whereas the results for the pure-silica core fibres were independent of dose-rate. The observed recovery of the gamma induced attenuation in the pure-silica core fibres was only temporary in nature and the previously induced losses were re-established when irradiation was re-started. In summary, pure-silica core fibres were found to be more suitable for use within the CMS tracker than the Ge-doped fibres. The pure-silica core fibres should survive the whole lifetime of the CMS experiment with radiation induced losses at 1550nm of ~1dB in the 10m length of each fibre link contained within the tracker.

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Table caption

Table 1: Irradiation parameters for the neutron and gamma tests. Dose-rates or neutron flux are accurate to ~10%.

Figure captions

Figure 1: Schematic set-up of the irradiation experiments.

Figure 2: Radiation induced attenuation during 6MeV neutron test. Exposure took place between $2.2x10^5$s and $3.9x10^5$s (43 hour duration) with a flux of $\sim 3x10^8 n/cm^2/s$.

Figure 3: Radiation induced attenuation during first gamma test (B-1). The dose-rates were 55, 50 and 74 rad/s for the Ge-doped, PSCF-A and PSCF-B fibres respectively.

Figure 4: Radiation induced attenuation in second series of gamma tests (B-2.1, B-2.2, B-3). Dose-rates of around 0.22 rad/s were used in Tests B-2.1 and B-2.2, and around 25 rad/s for test B-3. Missing blocks of data were due to technical problems. The attenuation for the Ge-doped fibre went beyond the sensitivity of the measurement in irradiation B-3.

Figure 5: Results of all gamma irradiations on Ge-doped fibres plotted as a function of dose. For comparison the results from fibre PSCF-B, irradiation B-1 are also shown.

Figure 6: Results of all gamma irradiations on pure-silica core, F-doped cladding fibres plotted as a function of dose.

Figure 7: Results of B2-1 and part of B2-2 gamma irradiations on pure-silica core, F-doped cladding fibres, illustrating the temporary nature of the observed recovery. Lines have been drawn to indicate the time required to return to the attenuation value reached in B2-1.

	Test A	Test B-1	Test B-2.1	Test B-2.2	Test B-3
radiation source	6 MeV neutrons	^{60}Co - γ			
irradiated fibre length (m)	100	88	300		
injected laser power (µW)	150	60	150		
wavelength (nm)	1550				
Ge-doped fibre Dose-rate (rad / s) or flux (n / cm^{2} / s)	2.6x10^{8}	55	0.22	0.22	25
PSCF-A Dose-rate (rad / s) or flux (n / cm^{2} / s)	1.3x10^{8}	50	0.23	0.23	31
PSCF-B Dose-rate (rad / s) or flux (n / cm^{2} / s)	5.2x10^{8}	74	0.20	0.20	21
Duration of exposure (s)	1.6x10^{5}	5.0x10^{5}	1.9x10^{6}	4.4x10^{6}	6.8x10^{5}
Duration of monitored recovery (s)	7.0x10^{5}	1.0x10^{5}	2.0x10^{6}	3.5x10^{6}	1.5x10^{6}

Table 1

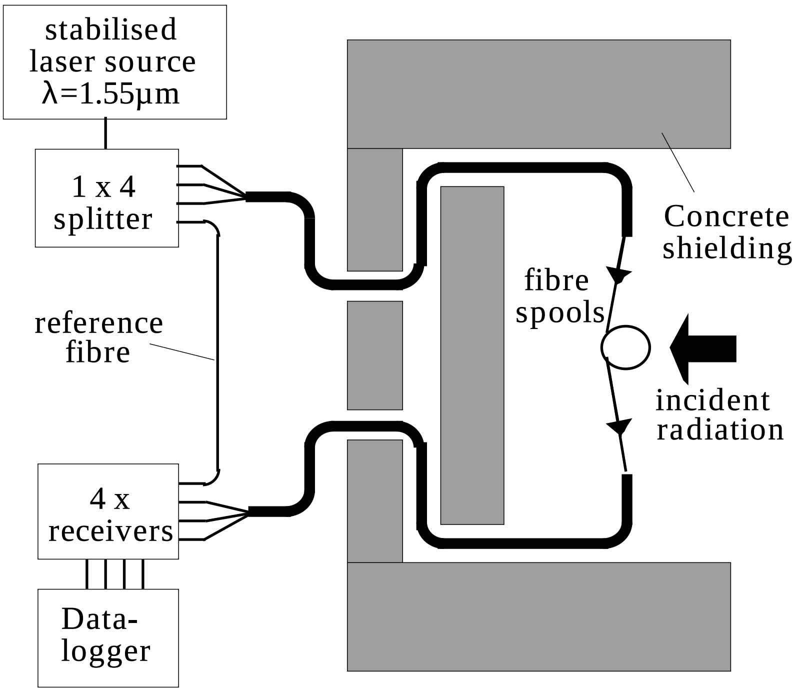

stabilised
laser source
λ=1.55μm
1 x 4
splitter
reference
fibre
4 x
receivers
Data-
logger
Concrete
shielding
fibre
spools
incident
radiation

Figure 1

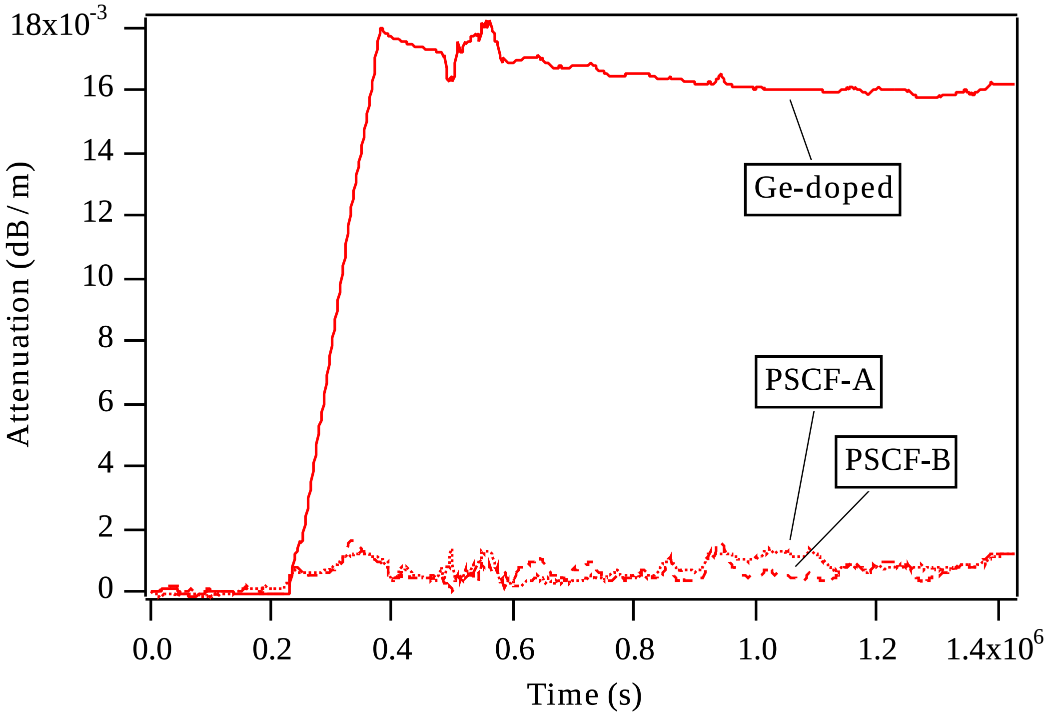
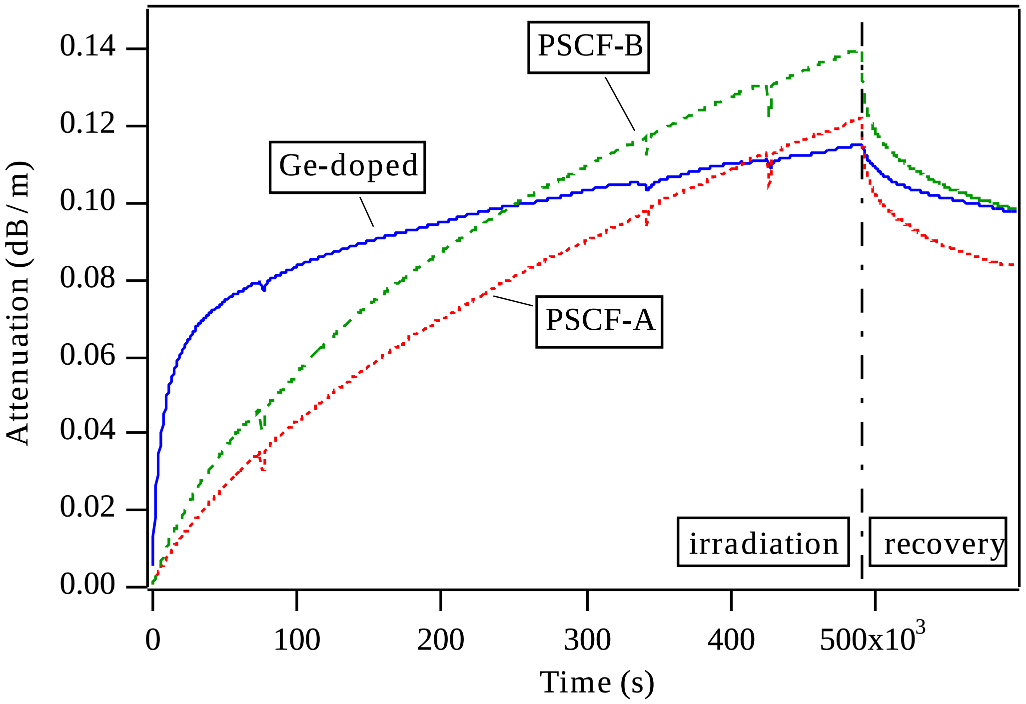

18x10^{-3}
16
14
12
10
8
6
4
2
0
Attenuation (dB / m)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4x10^{6}
Time (s)
Ge-doped
PSCF-A
PSCF-B

Figure 2


PSCF-B
Ge-doped
PSCF-A
irradiation
recovery
Attenuation (dB/m)
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0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
500×10^3
Time (s)

Figure 3

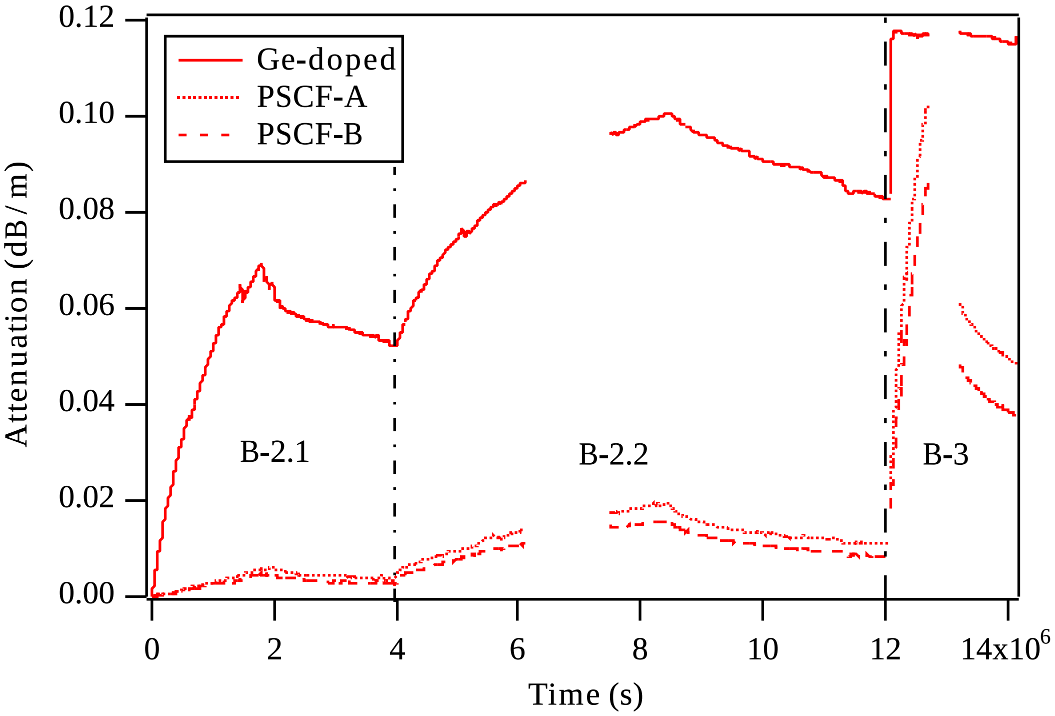
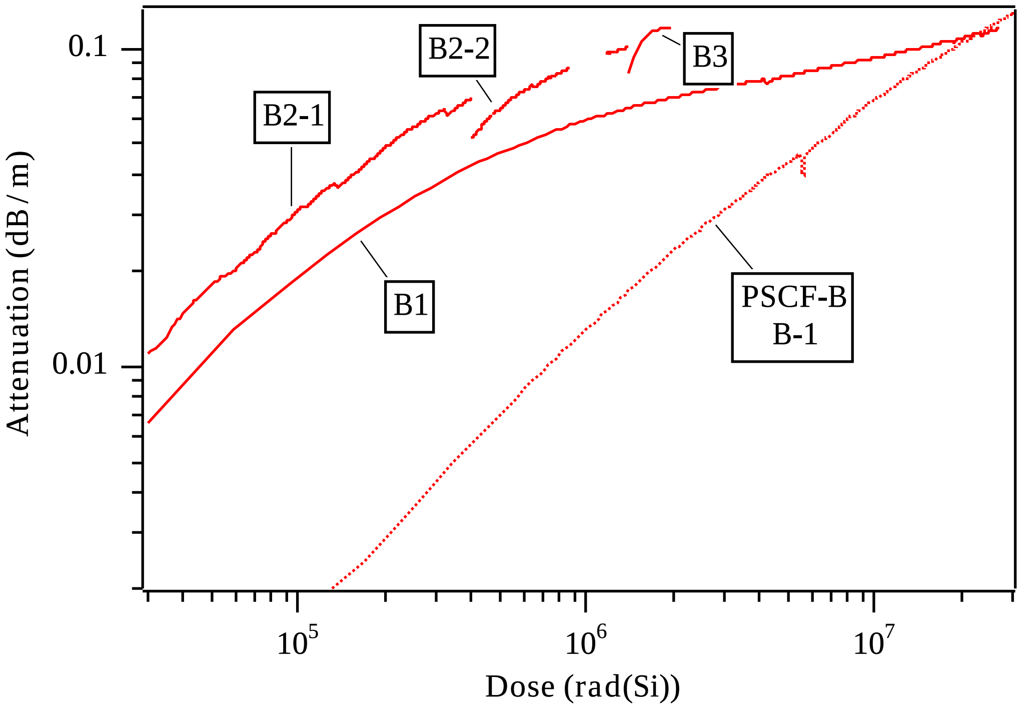

0.12
0.10
0.08
0.06
0.04
0.02
0.00
Attenuation (dB/ m)
Ge-doped
PSCF-A
PSCF-B
B-2.1
B-2.2
B-3
0
2
4
6
8
10
12
14x10^6
Time (s)

Figure 4


B2-2
B3
B2-1
B1
PSCF-B
B-1
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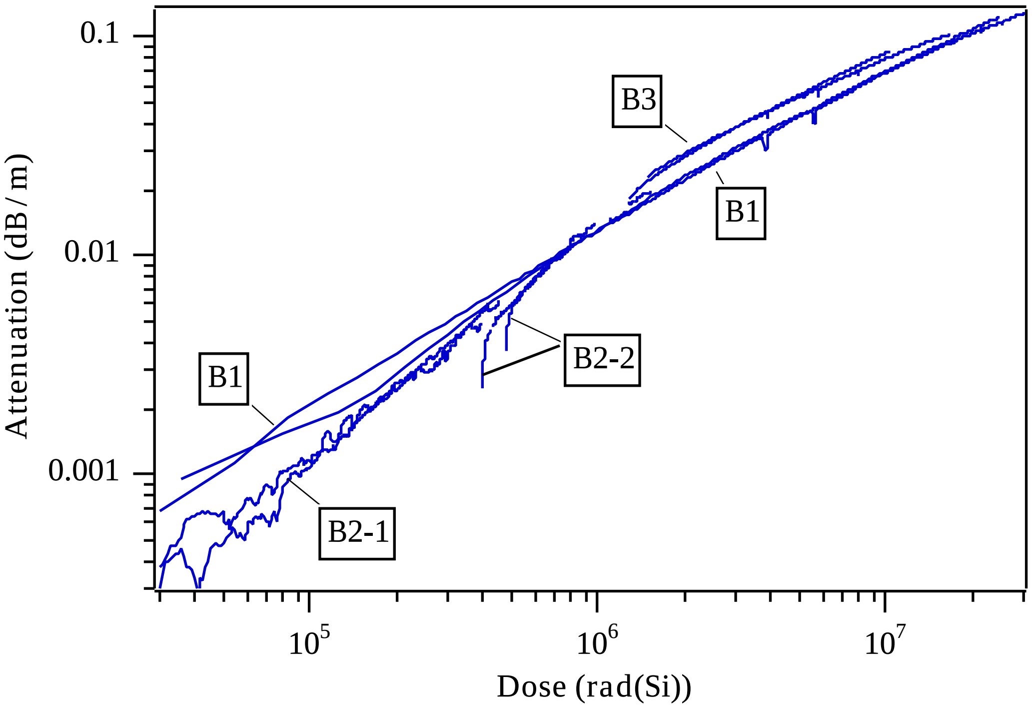
0.01
Attenuation (dB/ m)
10^5
10^6
10^7
Dose (rad(Si))

Figure 5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0.01
0.001
Attenuation (dB/ m)
10^5
10^6
10^7
Dose (rad(Si))
B3
B1
B1
B2-2
B2-1

Figure 6

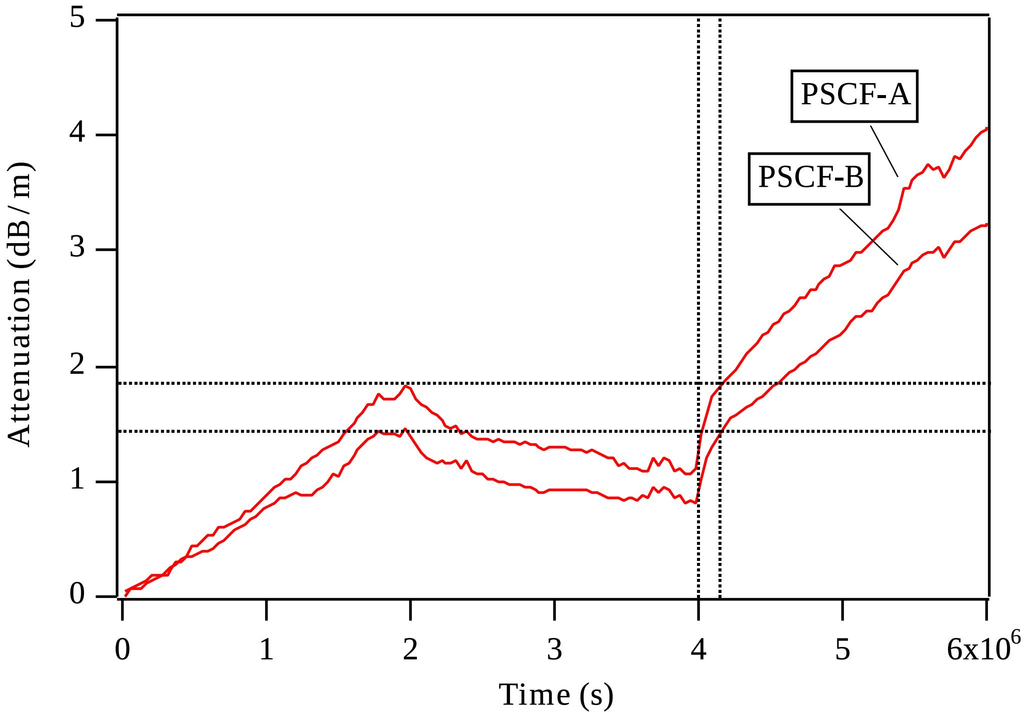

Figure 7