# Evaluation of the performance of high phosphorous with germanium co-doped multimode optical fiber for use as radiation sensor at low dose rates

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**Abstract:** $GeO_2+P_2O_5$ co-doped step index multimode (SIMM) fiber having core diameter around 50 micron with numerical aperture around 0.21-0.22 proposed for the first time shows an excellent linear radiation response behaviour with sensitivity around 0.69 – 0.97 dB/m/100 rad at 505nm wavelength within the dose rates of 10-100 rad/hr as well as very low recovery at room temperature using $^{60}Co$ gamma radiation source. This enables its practical application in fiber optic personal dosimeter for measurement of low dose gamma radiation.

**OCIS codes:** (280.0280) Remote sensing and sensors; (060.0060) Fiber optics and optical communications; (060.2290) Fiber materials; (160.2220) Defect-center materials.

## 1. Introduction

The detection and measurement of gamma radiation using materials that are sensitive to such radiation has been a subject of intense investigation [1-6]. Optical fiber is found to be a good choice in this regard due to greater sensitivity at different dose levels compared to bulk glass dosimeters. The major advantage in using the fiber is that the radiation sensitivity can be adjusted to the dose or dose rate by selecting suitable fiber design, composition and operating wavelength. Under the action of nuclear radiation, point defects (colour centers) [7-9] arise in the glass network. As a consequence, the absorption of light propagating in the fiber increases. Hence, the possibility exists of measuring the dose of radiation by measuring the optical loss in the fiber. In general radiation induced loss of optical fibers [10,11] is largely dependent on the dopants used in the preform from which the fiber is manufactured as well as other parameters such as host glass composition, numerical aperture (NA), fiber design along with the type of radiation source and surrounding parameters.

There are requirements for remote monitoring of hazardous [12] or difficult-to-access areas such as nuclear reactors [13,14] and waste storage facilities. A fiber optical radiation dosimeter that can be permanently incorporated into these facilities and optically addressed from a central monitoring station. These sensors reduce costs and improve safety by eliminating the need to send personnel into hazardous areas to collect and analyze samples. In the last decades, extreme work have been carried out to study the radiation effects on optical fibers to use them as radiation sensors [12-19] under various radiation environments such as nuclear waste tanks, nuclear reactors, etc.

The radiation effects on P doped [20-21] bulk silica and fibers have been reported earlier. Some work on radiation sensitivity of P-doped fibers have been done at high dose rates to find out their suitability for use as fiber optic dosimeter in medical purpose [22-23]. Recently M. C. Paul et al. have reported the data of low dose radiation induced attenuation at infrared wavelengths for P-doped SIMM fiber [24]. The P doped SIMM fiber containing 12 mol% phosphorous shows sensitivity 0.55 dB/m/100 rad in dose rate range 1.0–100 rad/hr using Cobalt-60 emitting gamma rays with average photon energy of 1.25MeV. The high phosphorous doped SIMM fiber shows high sensitivity with much dose rate dependency at low dose rates below 100 rad/hr.

Remembering this problem, we have incorporated $GeO_2$ as co-dopant in the core of high phosphorous doped SIMM optical fibers for use as radiation sensor in dosimetry application at low dose rates. At low dose rate, below 50 rad/hr P doped fiber without co-doping of $GeO_2$ shows highly dose rate dependence behavior. However high phosphorous with $GeO_2$ co-doped SIMM fiber under suitable composition may improve such dose rate dependence behavior at low dose rates. We have examined the radiation response behavior at very low dose rates within 10-100 rad/hr using Cobalt-60 emitting gamma rays with average photon energy 1.25 MeV. The dependence of their sensitivities on dose rates and transmission wavelength along with their recovery nature have been studied on the basis of their radiation induced attenuation for evaluation of their feasibility to use as radiation sensor in fiber optic personal dosimeter.

## 2. Experimental

### *2.1 Fiber sample fabrication*

$P_2O_5$ co-doped SIMM optical fiber with and without $GeO_2$ in the core was fabricated by the modified chemical vapour deposition (MCVD) [25] process. The pure silica glass tube of OD/ID:14/11 mm dimension was taken for deposition of $SiO_2$-$GeO_2$, $SiO_2$-$GeO_2$-$P_2O_5$ and $SiO_2$-$P_2O_5$ soot layers to make different preform samples maintaining suitable deposition temperature around 1500-1550$^0$C with the help of single-wavelength online IR Pyrometer ( Model: PRO 44-50C-FOV15in/100-21-SB-AP-40C, Williamson Corp, USA ) with an accuracy of ± 5$^0$C. The details of fiber parameters are given in Table 1. The modified chemical vapor deposition (MCVD) [25] process was followed to fabricate P-doped SIMM optical fiber preforms containing different proportions of $P_2O_5$ in the core. The doping level of $P_2O_5$ in the deposited layer was increased by suitably modifying the process parameters. To increase the incorporation efficiency of $P_2O_5$, deposition temperature of $SiO_2$–$P_2O_5$ soot layer was optimized for minimization of the evaporation of $P_2O_5$. To increase the doping region, number of soot layers was increased up to a certain label without distortion of the deposited tube. The refractive index profile of the preform was measured by the preform analyzer (Vertical Model: PKL 2600, Photon Kinetics made, USA) shown in Fig. 1.

## *2.2 Induced loss measurement.*

The experimental setup for measurement of the radiation response behavior of $P_2O_5$ doped SIMM optical fiber was described in earlier work [24]. In our setup four meter length of each radiation sensitive fiber was wrapped around a test reel of 2.5 cm diameter and placed at the centre of the radiation field. Dose rate of the radiation source was varied by changing the distance between the fiber reel and the cobalt-60 source to measure the effect of dose rates on the fiber. Total dose was controlled by varying the exposure times for different dose rates. The light source was Quartz (100 W) halogen lamp and it's light stability is ±0.1% over 8 hour. To detect the light coming out from the fiber within 400-1100 nm wavelength range silicon detector was used in our experiment. The $^{60}$Co-gamma radiation source was taken with constant energy 1.25MeV to measure the radiation induced loss along with its sensitivity and recovery nature with different dose rates at 505nm and 560nm wavelengths. The dose rates of $^{60}$Co-gamma radiation source performed on each fiber are 10, 25, 50, 75 and 100 rad/hr with the total accumulated dose less than 100 rad.

### *2.3 Material characterization.*

Study of the surface morphology of high $P_2O_5$ doped preform samples was done through scanning electron microscope (SEM) shown in Fig. 2. The core of $GeO_2$+$P_2O_5$ doped SIMM optical fiber shows phase-separated regions. The cross sectional image of high $P_2O_5$ doped SIMM fiber NM-182 was given in Fig. 2. The electron probe micro analysis (EPMA) was performed to understand the distribution of different dopants into the whole core of two fiber preform samples NM-182 and PS-283 shown in Fig. 3.

## 3. Results and discussions

The radiation induced absorption spectra of two different P-doped SIMM fibers (NM-182 and PS-283) irradiated at dose rate of 100rad/hr are given in Fig. 4 to evaluate the suitable transmission wavelength at which the fiber shows the maximum radiation sensitivity. We have selected 505nm and 560nm transmission wavelengths from their radiation induced loss curves for study of radiation response behaviour. The radiation induced loss as well as sensitivity of two different fibers (NM-182 and PS-283) were measured at two different wavelengths 505 and 560nm because at these wavelengths high induced loss and also high sensitivity observed. Linearity measurements of fibers are taken up to a total dose of 100 rad at dose rate of 10 to 100 rad/hr. Both fibers shows well linear response behavior under such low dose rates. The effect of dose rates on the radiation response behavior of optical fiber is the most important factor to study their suitability as radiation sensor in fiber optic dosimeter. The results of the effect of dose rates on $GeO_2$, $P_2O_5$ and $GeO_2$+$P_2O_5$ doped fibers at 560nm transmission wavelength are given in Fig. 5 which shows well dose rates independent response behavior of $GeO_2$+$P_2O_5$ co-doped SIMM fiber (NM-182) under such low dose rates. We have studied the effect of core diameter on the radiation response behavior of $GeO_2$+$P_2O_5$ co-doped (NM-182) and P doped (PS-283) SIMM fibers. Such two P-doped fibers (NM-182 and PS-283) having core diameter of 50.0 and 40.0 µm shows the radiation sensitivities of 0.970dB/m/100rad and 0.6631 dB/m/100rad, respectively. Whereas Ge doped fiber containing 10 mol% $GeO_2$ and core diameter around 42µm shows the radiation sensitivity of 0.16dB/m/100Rad which becomes very much lower than that of $P_2O_5$ and $GeO_2$+$P_2O_5$ doped fibers as shown in Fig. 5. The results on the radiation response behavior of $GeO_2$+$P_2O_5$ co-doped SIMM fiber (NM-182) containing 16 mol% $P_2O_5$ and 6 mol% $GeO_2$ at two different wavelengths such as 560 and 505 nm under fixed dose rate of 100 rad/hr up to a total cumulative dose of 100 rad was shown in Fig. 6. The effects of dose rates on the sensitivity in the range 10 to 100 rad/hr with total dose up to 100 rad at 560nm transmission wavelength in the fibers NM-182 and PS-283 are shown in Fig. 7. The Ge+P co-doped SIMM fiber (NM-182) shows higher sensitivity than $P_2O_5$ doped SIMM (PS-283) fiber. Sensitivity of the fiber also depends on the transmission wavelength shown in Fig. 8. The radiation response behaviour of such type of high phosphorous with germanium co-doped optical fibers containing 16 and 14 mol% $P_2O_5$ can be explained based on the formation of P-related and Ge-related defect centres as well as their effects on the dose rates of radiation source. The defect centres mainly formed in $P_2O_5$ doped and $GeO_2$+$P_2O_5$ co-doped fibers are $POHC^s$ and $POHC^m$ (where's' and 'm' represent the ‘stable’ and ‘metastable’, respectively) [26-28] along with GeE$^{/}$ [29-30] defect. Fiber with larger core diameter (NM-182) shows higher sensitivity than lower core diameter fiber (PS-283) because of the formation of larger number of phosphorous oxygen hole centres (POHC) within the core region which is mainly responsible for high radiation induced loss of the fiber. $P_2O_5$+$GeO_2$ co-doped fiber (NM-182) with larger core diameter shows excellent linear radiation response behaviour with dose rates independency within 10-100 rad/hr than $P_2O_5$ doped fiber (PS-283). The presence of $GeO_2$ may prevent the rate of formation of POHC in a controlled way with increasing dose rates. The sensitivity of two different fibers (NM-182 and PS-283) varies at different wavelengths due to their different radiation induced absorption behavior. The result shows that the radiation induced loss at 560nm is greater than 505nm wavelength. The recovery nature of high P-doped SIMM fibers are evaluated at room temperature. The recovery nature of one $P_2O_5$-$GeO_2$ co-doped fiber (NM-182) containing 16 mol% $P_2O_5$ was described after irradiation up to a cumulative dose of 100 rad irradiated at dose rates of 10-100 rad/hr under 560 nm transmission wavelength shown in Fig. 9. Such recovery of the irradiated fiber was taken up to one hour after irradiation and shows very low fading behavior. Such slow recovery reveals that P-related defects does not anneal very much at room temperature and yield no permanent change up to a total cumulative dose of 100 rad in presence of Ge-related defect centers. During gamma-irradiation the interaction occurs between the germanium defects located in their core region and the electrons released by the phosphorous-oxygen double bond. The possible explanation about influence of $GeO_2$ co-doping in the core of phospho-silicate fibers on their radiation response behaviour will be based on the following reaction mechanism [31].

$$\equiv P=O \xrightarrow{h\nu} \equiv P-O^{\cdot} + e^{-} \longrightarrow \equiv P-O$$

$$\equiv Si\text{-}Ge\equiv \xrightarrow{h\nu} \equiv Si + GeE^{/} \longrightarrow \equiv Si\text{-}Ge\equiv$$

At high dose rates most of the POHC related defects transforms to the P1 related defect centers which are responsible for high sensitivity of such $P_2O_5$ doped SIMM fiber at low dose rates [24]. Germanium codoping will create the germanium defects ($GeE^{/}$) which are induced by the rupture of Ge-Si or Ge-Ge wrong bonds [31]. Such formation of $GeE^{/}$ centers will prevent the transformation of POHC related defect centers to the $P_1$ related centers at low dose rates. As a result of it, $P_2O_5$+$GeO_2$ doped SIMM fibers shows almost dose rate independent behaviour within the dose rates of 10-100 rad/h.

## 4. Conclusions

We are able to make 50.0 micron core diameter fiber having 16.0 mole% doping levels of $P_2O_5$ and 6.0 mole% of $GeO_2$ for study of radiation response behavior at room temperature. The radiation sensitivity of high phosphorous with germanium oxide co-doped optical fiber was found to be 0.69 – 0.97dB/m/100 rad with varying the dose rates from 10 to 100 rad/hr at 505nm wavelength and shows very low recovery at room temperature using $^{60}Co$ gamma radiation source. The sensitivity of the fiber is found to be very much related to the doping core region as well as the doping levels. Such type of large core high $P_2O_5$ with $GeO_2$ co-doped fiber shows good linearity in radiation response behavior as well as dose rate independency followed by low recovery in nature with high sensitivity which enables its practical application in fiber optic personal dosimeter for measurement of low dose gamma radiation .

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Lightwave Technol **11** 1793-1801 (1993)

## Tables

Table 1: Different parameters of the tested fibers

| Fibers | Core composition | Core diameter (µm) | NA | $P_2O_5$ content (mol%) | $GeO_2$ content (mol%) |
|---|---|---|---|---|---|
| NM-182 | $GeO_2$+$P_2O_5$ | 50 | 0.21-0.22 | 16 | 6 |
| PS-283 | $P_2O_5$ | 40 | 0.17-0.18 | 16 | 0 |
| PS-234 | $GeO_2$ | 42 | 0.17-0.18 | 0 | 10 |

**Figure captions**

Fig. 1: RI profile of high $P_2O_5$ doped SIMM preform (NM-182).

Fig. 2: SEM image of (A) high $P_2O_5$ doped NM-182 preform sample and (B) cross section image of the same fiber.

Fig. 3: The distribution of dopants of (A) high $P_2O_5$ doped (NM-182) and (B) high $P_2O_5$ with $GeO_2$ co-doped (PS-283) preforms.

Fig. 4: Radiation induced loss of different P-doped SIMM fibers (NM-182 and PS-283) after 1 hour radiation at the dose rate of 100 rad/hr (total dose 100 rad).

Fig. 5: Radiation response behavior of (A) $GeO_2$+$P_2O_5$ (NM-182) ; (B) $P_2O_5$ (PS-283); and (C) $GeO_2$ (PS-234) doped fibres.

Fig. 6: Wavelength dependence of the radiation induced loss of high $P_2O_5$ doped with $GeO_2$ co-doped SIMM fiber (NM-182) against dose rate of 100rad/hr.

Fig. 7: Radiation sensitivity of high $P_2O_5$ doped (NM-182) and high $P_2O_5$ with $GeO_2$ co-doped fiber (PS-283) at 560nm.

Fig. 8: The radiation sensitivity of $GeO_2$+$P_2O_5$ co-doped SIMM fiber (NM-182) at different wavelengths.

Fig. 9: Recovery nature of $GeO_2$+$P_2O_5$ co-doped SIMM fiber (NM-182) containing 16 mol% $P_2O_5$ and 6 mol% $GeO_2$ at 505 nm transmission wavelength with different dose rates.

**Figures**

**Figure 1**

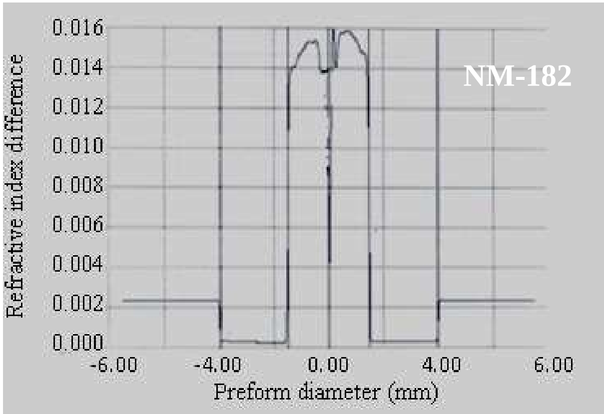


**Figure 2**

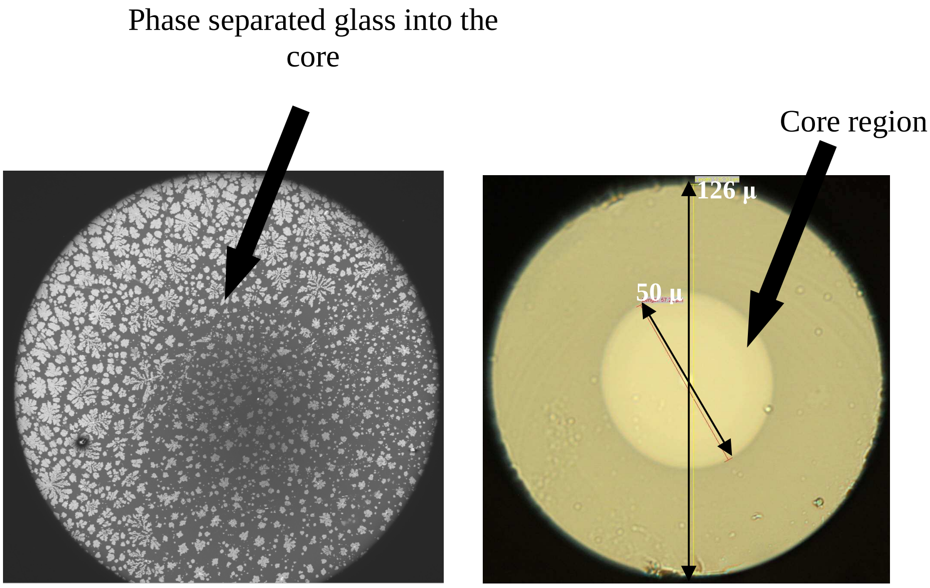


**Figure 3**

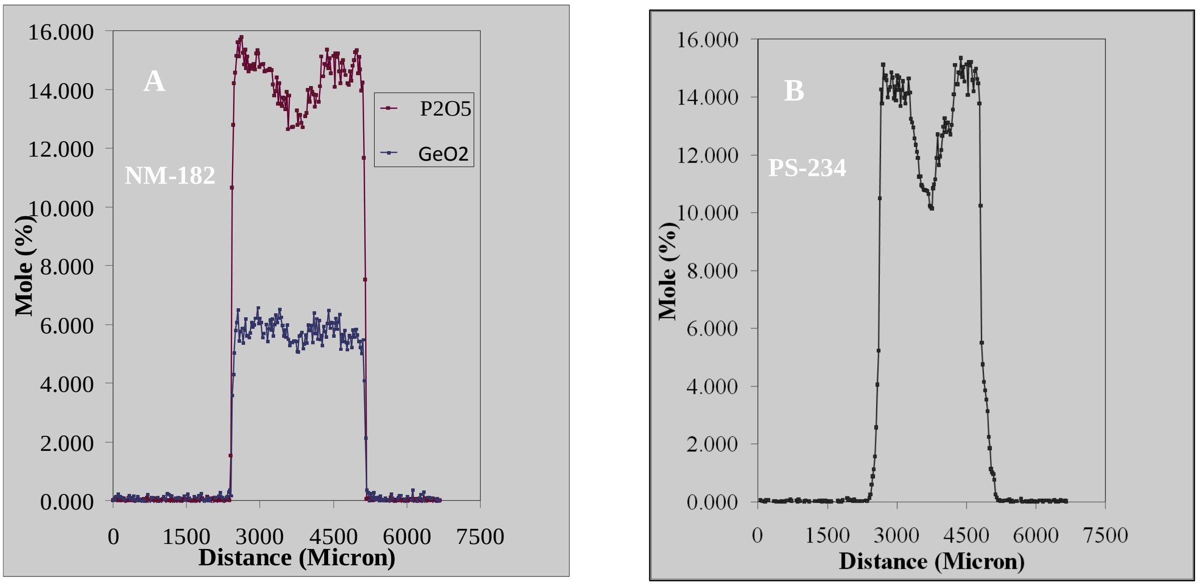
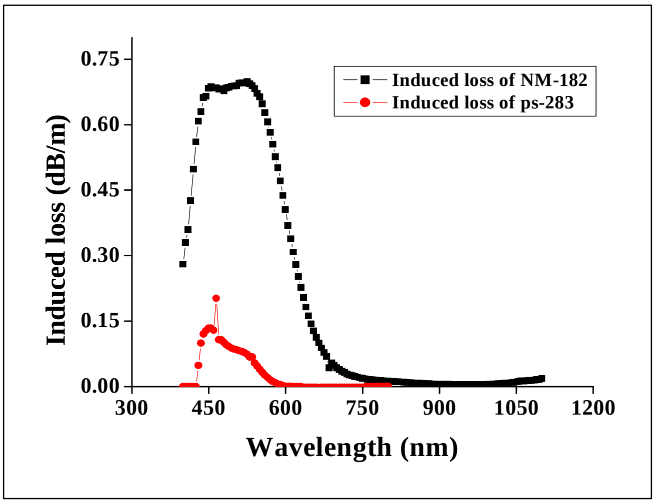
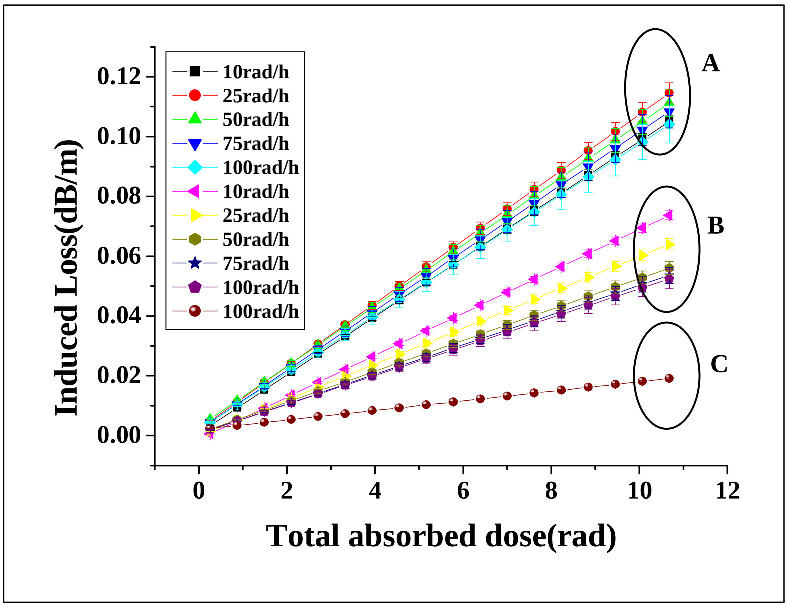

A
NM-182
P2O5
GeO2
Mole (%)
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
0
1500
3000
4500
6000
7500
Distance (Micron)
B
PS-234
Mole (%)
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
0
1500
3000
4500
6000
7500
Distance (Micron)

**Figure 4**



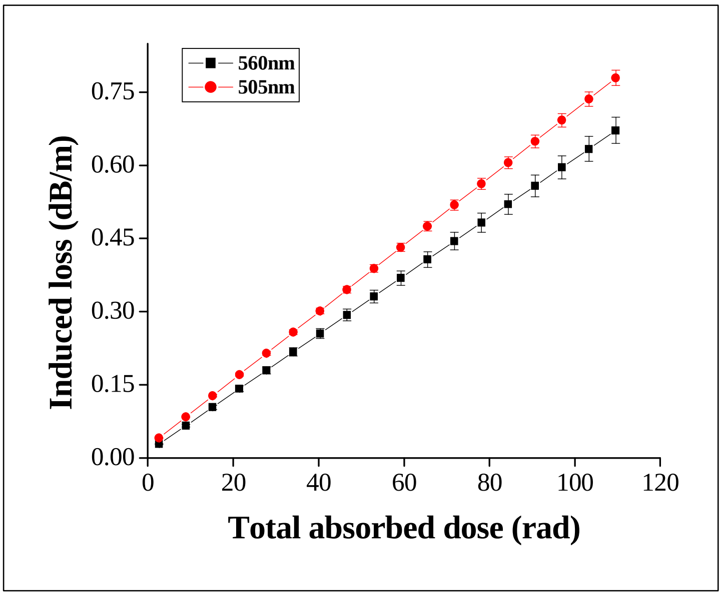
Induced loss of NM-182
Induced loss of ps-283
Induced loss (dB/m)
0.75
0.60
0.45
0.30
0.15
0.00
300
450
600
750
900
1050
1200
Wavelength (nm)

**Figure 5**



10rad/h
25rad/h
50rad/h
75rad/h
100rad/h
10rad/h
25rad/h
50rad/h
75rad/h
100rad/h
100rad/h
A
B
C
Induced Loss(dB/m)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0
2
4
6
8
10
12
Total absorbed dose(rad)

**Figure 6**



560nm
505nm
0.00
0.15
0.30
0.45
0.60
0.75
Induced loss (dB/m)
0
20
40
60
80
100
120
Total absorbed dose (rad)

**Figure 7**

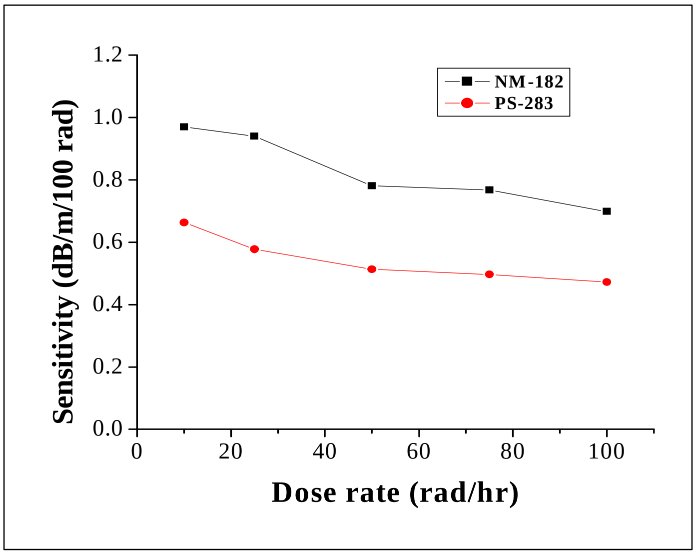
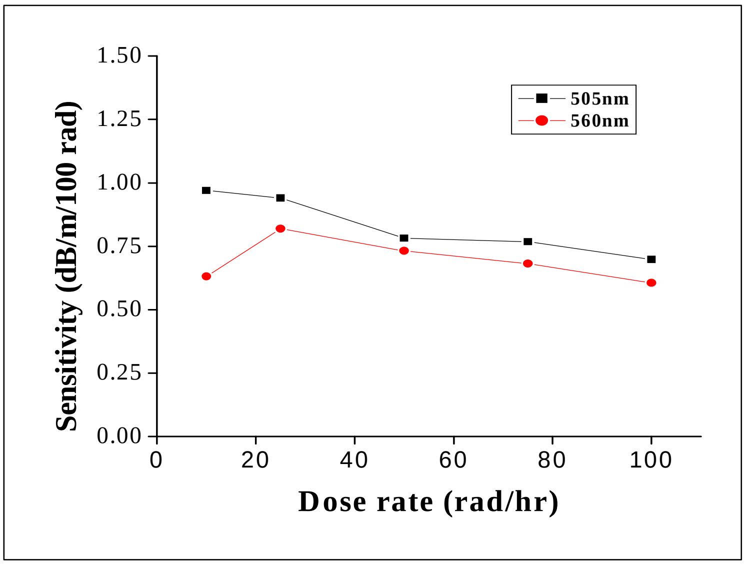
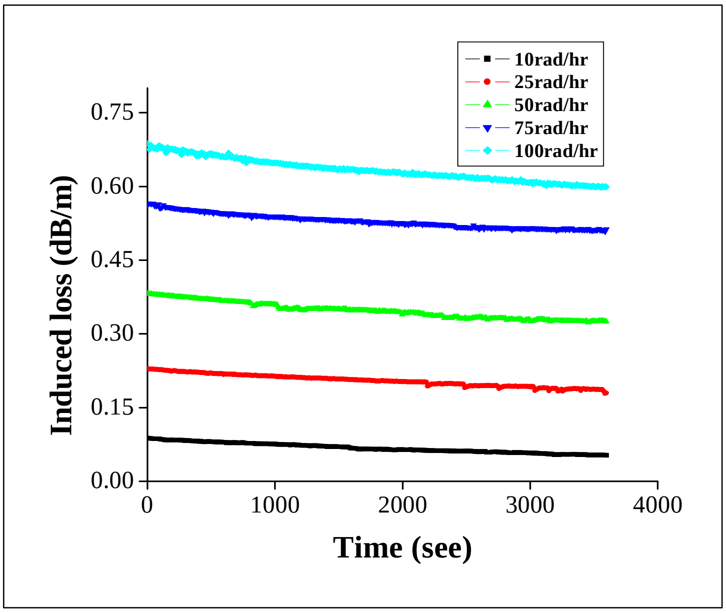

NM-182
PS-283
Sensitivity (dB/m/100 rad)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Dose rate (rad/hr)

**Figure 8**



1.50
1.25
1.00
0.75
0.50
0.25
0.00
Sensitivity (dB/m/100 rad)
0
20
40
60
80
100
Dose rate (rad/hr)
505nm
560nm

**Figure 9**



10rad/hr
25rad/hr
50rad/hr
75rad/hr
100rad/hr
Induced loss (dB/m)
0.75
0.60
0.45
0.30
0.15
0.00
0
1000
2000
3000
4000
Time (see)