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PROTON IRRADIATION EFFECTS ON OPTICAL ATTENUATION IN DOPED – AND PURE – SILICA FIBERS

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Proton Irradiation Effects on Optical Attenuation in Doped- and Pure-silica Fibers

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Optical attenuation in doped- and pure-silica fibers was measured at wavelengths of 470 nm, 660 nm, and 850 nm during and after 20 MeV proton irradiation. In the experiment the fibers were arranged on a holder to make "one layer" so that uniform proton irradiation can be achieved to them. The induced loss of the doped-silica fiber increased strongly at the beginning of the first irradiation, and decreased slowly after stopping of the beam. In the second irradiation, however, the developed loss was not so large. On the other hand, the loss of the pure-silica fiber increased gradually in the first irradiation, and decreased very quickly after the beam stopped. The loss increased stepwise at the very beginning of the second irradiation. Small luminescence from the fibers during irradiation was observed also. The luminescence of the pure-silica fiber was slightly larger than that of the doped-silica fiber. The induced loss of HCP fibers was also measured when a SiO_2 plate was set in front of the fibers. It may be possible to estimate the proton dose in materials using fiber-optic technique. Proton sensitivities of doped- and pure-silica fibers were, respectively, 1.0×10^{-10} at 660 nm and 5.5×10^{-12} at 470 nm in units of (dB/m)/(protons/cm^2), where the values were estimated from the slope of the loss growth curves at the beginning of the first irradiation.

Keywords: Irradiation Effect, Proton, Optical Fiber, Optical Attenuation, Silica, Doped, Induced Loss, Step-index, Graded-index, Sensitivity, Dosimeter

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純粋及びドープト石英ファイバーの陽子照射効果

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（1999年4月13日受理）

純粋及びドープト石英ファイバーに20MeV陽子を照射し、波長470nm、660nm及び850nmにおける光学損失を測定した。実験ではファイバーに対して一様に陽子線が照射されるように、ファイバーを「一層」に配置した。ドープトファイバーの損失は最初の照射の初期に大きく増大し、陽子ビームを止めると損失はゆっくりと減少した。再度の照射では損失の増加はそれほど大きくなかった。一方、純粋ファイバーの場合、最初の照射では損失はゆっくりと増加していくが、ビームを止めると損失は非常に速く減少した。再度照射すると、損失は照射初期の非常に短い時間にステップ状に増加した。照射中にファイバーからの小さな発光を確認した。発光の大きさは純粋ファイバーの方が幾分大きめであった。また、石英ファイバーの前面に厚さの異なる石英の板を置いて陽子線を照射し光学損失を測定した。損失増加曲線の初期の傾きから陽子線による線量が評価可能であることがわかった。さらに、陽子線に対するファイバーの感度は、最初の照射の損失増加特性の曲線の傾きから評価すると、ドープトファイバーが660nmで1.0×10^{-10} (dB/m)/(protons/cm^2)、純粋ファイバーが470nmで5.5×10^{-12} (dB/m)/(protons/cm^2)であった。

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1. Introduction

The optical fiber is one of the most promising candidates for signal transmission in future communication systems because it has ideal properties such as broad bandwidth, low attenuation, light weight, and being free from sensitivity to electromagnetic interference. They are also expected to be used in nuclear power plants or accelerator facilities where high energy photons or charged particles exist. It is well known that such radiation on optical fibers strongly influences their optical properties and the effects of radiation on optical fibers have been widely studied1)-11). In particular the effects by gamma rays are well investigated1)-5). The degradation of the properties by the irradiation is thought to be caused by formation of some color centers such as E' centers, GeX centers, and non-bridging oxygen hole centers (NBOHCs). The E' center consists of an unpaired electron on a silicon bond to three oxygen atoms, and the NBOHC a hole trapped on a non-bridging oxygen. In general, color centers are formed from precursors by capturing electrons and/or holes. Such degradation by the irradiation, however, can be also used as a principle for an attenuation-based fiber optic dosimeter12)-14). Hence the authors have started to investigate the feasibility of applying the principle to a proton dosimeter, since the flexibility and the small diameter of fibers meet the better adaptability to monitoring of local doses, especially in a tumor of a patient during proton therapy.

As concerned with the effects by proton irradiation, Ray et al.15) studied the effects by 20 MeV proton irradiation and concluded that reversible and irreversible increase in the attenuation of optical fibers occur at doses below and above certain critical levels. On the other hand, Boucher et al.16) used 90 MeV protons and investigated degradation in interferometric fiber optic gyroscopes including optical fibers. In experiments of proton irradiation on optical fibers, however, it should be noted that a proton with a certain energy has a finite penetration depth (range) in the fibers by losing its energy due to interactions with atoms in fiber materials. According to our calculation using some stopping power functions17), a proton with an initial energy of 20 MeV loses its energy and stops after traveling about 2.4 mm in SiO_2. Therefore, if we irradiate a bundle of fibers (which has "several layers") with 20 MeV proton beam as shown Fig. 1(b), only the first layer can be irradiated with 20 MeV proton but not other layers. This means the fibers cannot be irradiated uniformly. In other words, some parts of fibers are irradiated with 20 MeV protons but others with energies less than 20 MeV. In this report, we present some experimental results of proton irradiation effects on the optical attenuation in optical fibers, where the fibers are arranged as "one layer" as shown in Fig. 1(a). Hence a uniform proton irradiation on fibers, being necessary to estimate the sensitivity, is successfully implemented.

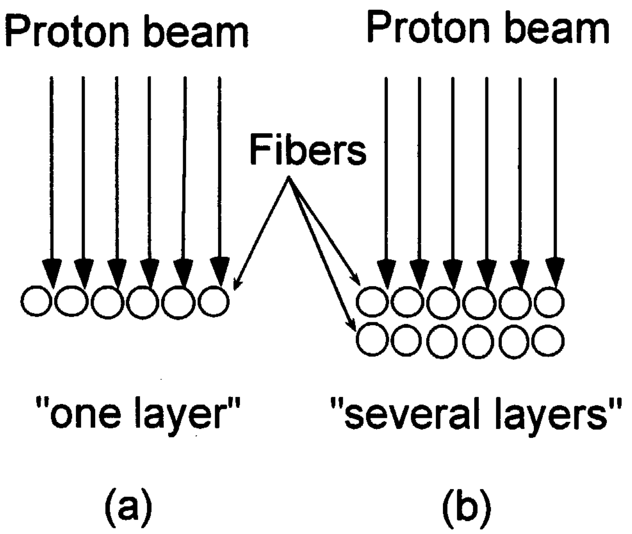


Fig.1 Proton irradiation on fibers with (a) one layer and (b) several layers.

2. Experiment

Sample optical fibers to be irradiated with protons are of Corning 50/125 CPC3 type manufactured by Siecor, and HCP type by SpecTran. The CPC3 type fiber is a graded-index type one and is doped with Ge and P to have a non-linear refractive index profile in the core. The HCP type fiber is a step-index type and contains low OH^-. Table I lists the specifications of the fibers. Both ends of each sample fiber are connected with pigtails which are made of HCS fibers by using a splicing method. The HCS fibers are also manufactured by SpecTran and have almost the same optical properties as HCP fibers do. The samples were set with glue on a "donuts-shaped" sample holder. Figure 2 shows the experimental arrangement. The irradiation part of each sample fiber was mounted on the corresponding holder. The irradiation part was a set of 4 fiber strings arrayed in one layer. The total irradiation length was about 2 cm since the diameter of the proton beam is 5 mm as explained below. The samples were also connected with a transmission fiber which length is about 20 m. The experiments were carried out at the Multi Purpose Compact Cyclotron at Jülich of Forschungszentrum Jülich GmbH, Germany. The proton energy is about 20 MeV and the beam diameter is 5 mm. In the experiments the optical attenuation in the fibers during proton irradiation was measured at wavelengths of 470 nm, 660 nm, and 850 nm with the FADOS system which was developed by the fiber-optic sensor development group at Forschungszentrum Jülich GmbH. The FADOS system mainly consists of an optical transmitter, a receiver unit and a data acquisition system. The transmitter unit guides the input light from LEDs with different wavelengths into the sample fibers. The LEDs are activated so that only one LED works during recording of the data at the corresponding wavelength. The details have been already presented the published papers[12)-14)].

Table I Specifications of irradiated fibers.

fiber	type	Diameter (μm)			Other feature
		Core	Clad	Buffer	
CPC 3	GI	50	125	250	Doped with Ge and P
HCP	SI	110	125	250	Low OH^-

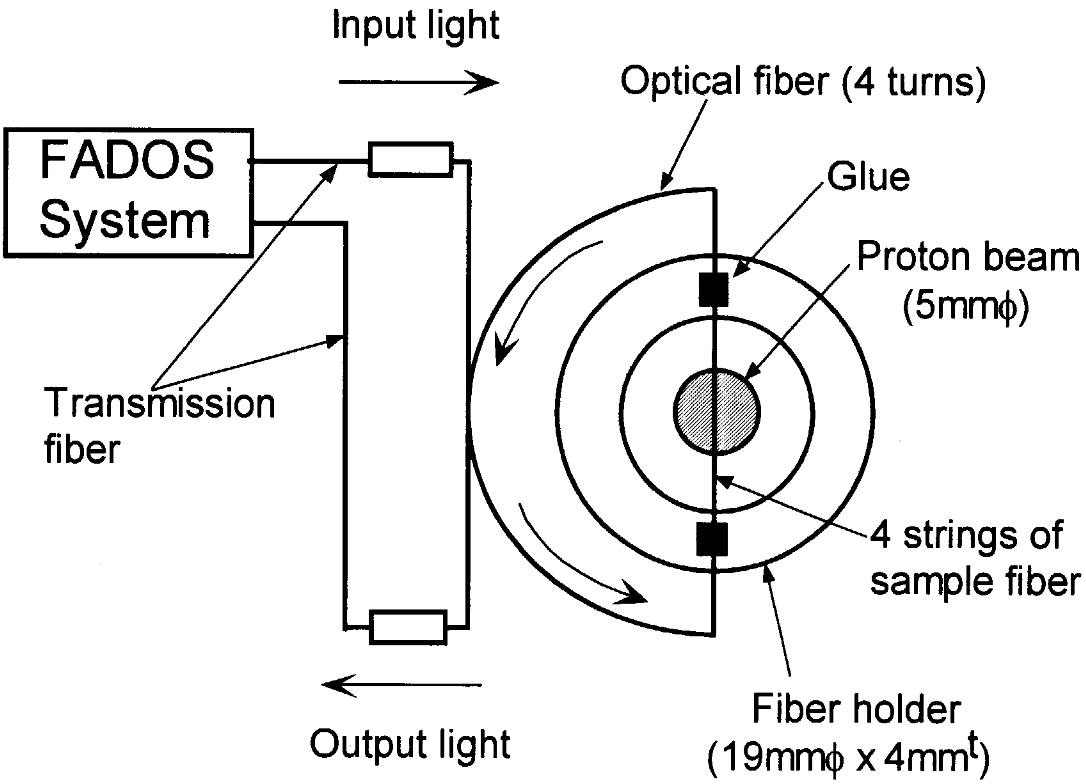


Fig.2 Experimental arrangement.

3. Results and discussion

3.1 Induced loss

The induced loss by the proton irradiation, Q(dB/m), is written as

$$Q(dB/m) = -\frac{10}{L}\log_{10}\left(\frac{V_{fiber}(LED-on) - V_{fiber}(LED-off)}{V_{reference}(LED-on) - V_{reference}(LED-off)}\right), \tag{1}$$

where L is the irradiation length in meters; $V_{fiber}(LED\text{-}on)$ and $V_{fiber}(LED\text{-}off)$ are, respectively, the outputs of irradiated fibers in case that the LED is on and off; $V_{reference}(LED\text{-}on)$ and $V_{reference}(LED\text{-}off)$ are, respectively, the outputs of a reference channel in case that the LED is on and off. Here, one must notice that $V_{fiber}(LED\text{-}on)$ and $V_{fiber}(LED\text{-}off)$ include the influence of luminescence from fiber materials by the irradiation. The influence can be cancelled by subtracting $V_{fiber}(LED\text{-}off)$ from $V_{fiber}(LED\text{-}on)$, as explained later.

Figure 3 shows the induced loss of the CPC3 fiber during proton irradiation. Since the transparency of the fiber at 470 nm was completely destroyed immediately after the irradiation, the losses at 660 nm and 850 nm are shown in the figure. In the first irradiation the proton current was 16.67 nA which corresponds to a proton flux of 5.3 ×

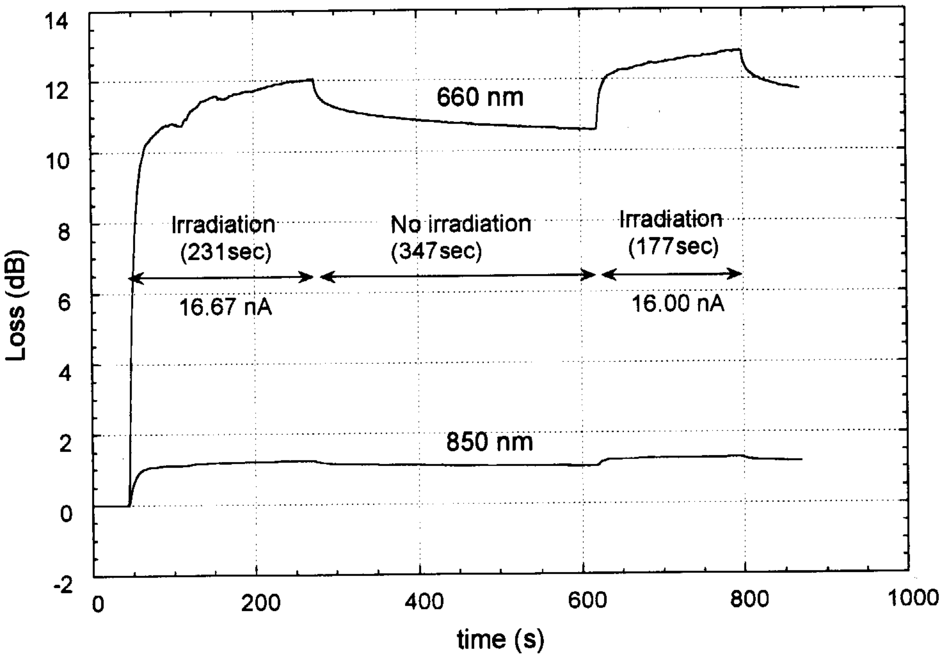


Fig.3 The induced loss of the CPC3 fiber during proton irradiation.

10^{11} protons/cm^2/s while the irradiation time was 231 seconds. During the first 20 seconds in the first irradiation, the losses at 660 nm and 850 nm were increased strongly. For example, the loss at 660 nm was about 10 dB at that time. The loss of 10 dB was about 80 % of the total loss in the first irradiation. After that, the loss at 660 nm increased slowly and reached 12 dB at the end of the first irradiation. When the proton beam stopped, the relaxation phenomenon was observed but its time constant was large, i.e., the loss decreased slowly. Even 347 sec after stopping of the proton beam, the loss was 10.6 dB and still remained 88 % of its maximum value (12 dB) at 660 nm in the first irradiation. This means that the loss of the CPC 3 fiber at 660 nm was governed by permanent loss or irreversible loss by the proton irradiation. In the second irradiation with a proton current of 16.0 nA corresponding to a proton flux of 5.1 $\times 10^{11}$ protons/cm^2/s, the loss at 660 nm sharply increased but its quantity was smaller than that in the first irradiation. At the end of the second irradiation the loss at 660 nm was 12.8 dB. The induced loss in the second irradiation was only 2.2 dB, which is very small compared to that in the first irradiation (12 dB) even if the difference of proton dose in both irradiation is taken into account.

Figure 4 shows the results of the HCP fiber. One can see in the figure that the loss induced by the proton irradiation was very small compared to that of the CPC 3 fiber. This may come from the fact that the HCP fiber is a step-index fiber and contains very small impurities in SiO_2, while the CPC 3 fiber is a graded-index fiber and is doped with

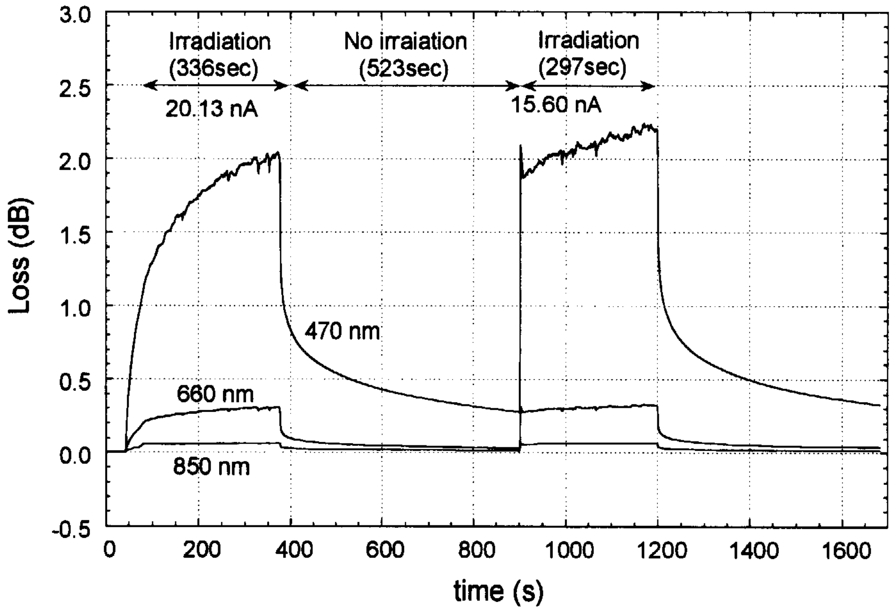


Fig.4 The induced loss of the HCP fiber during proton irradiation.

Ge and P to have a non-homogeneous refractive index profile in the core. Impurities in SiO_2 should cause some precursors and they should be the origin of color centers created by the irradiation. In the first irradiation with a proton current of 20.13 nA which corresponds to a proton flux of 6.4×10^{11} protons/cm^2/s, the losses at all measured wavelengths increased gradually. The loss at 470 nm was 2.0 dB at the end of the first irradiation. When the irradiation stopped, the losses decreased very quickly, i.e., the time constant is very small. The loss at 470 nm, for example, decreased from 2.0 dB to 1.0 dB in only 10 seconds and reached 0.28 dB in 523 seconds, which was 14 % of the value at the end of the first irradiation. This suggests that the permanent loss of HCP fiber was very small. In the second irradiation, the losses increased stepwise at the very beginning of the irradiation. This phenomenon is quite different from that in the first irradiation. The loss at 470 nm increased by 1.3 dB only in one second. After the sharp increase at the beginning, the loss increased almost linearly. When the beam stopped again, the losses decreased quickly in the same manner of the first irradiation.

3.2 Luminescence from the fibers

It is quite reasonable for us to assume that some luminescence exists in the fiber by the proton irradiation. In eq. (1), $V_{fiber}(LED\text{-}on)$ and $V_{fiber}(LED\text{-}off)$ can be considered as

$$V_{fiber}(LED\text{-}on) = V_{luminescence} + V_{signal} + V_C \tag{2}$$

and

$$V_{fiber}(LED\text{-}off) = V_{luminescence} + V_C, \tag{3}$$

where $V_{luminescence}$ represents the output due to luminescence from fibers by the irradiation; V_{signal} is the output of transmission light; V_C represents contributions to the output except the luminescence and the transmission signal. Therefore, the output of the transmission signal can be obtained by subtracting $V_{fiber}(LED\text{-}off)$ from $V_{fiber}(LED\text{-}on)$. Figure 5 shows $V_{fiber}(LED\text{-}off)$ of both fibers. Clear luminescence depending on the proton beam operation is recognized in the HCP fiber but not in the CPC3 fiber. Since V_C during irradiation is not measurable, it is difficult to estimate $V_{luminescence}$ accurately. However, if we regard V_C as constant throughout the experiment and adopt an average of V_C without irradiation as an estimate of V_C, $V_{luminescence}$ can be obtained by

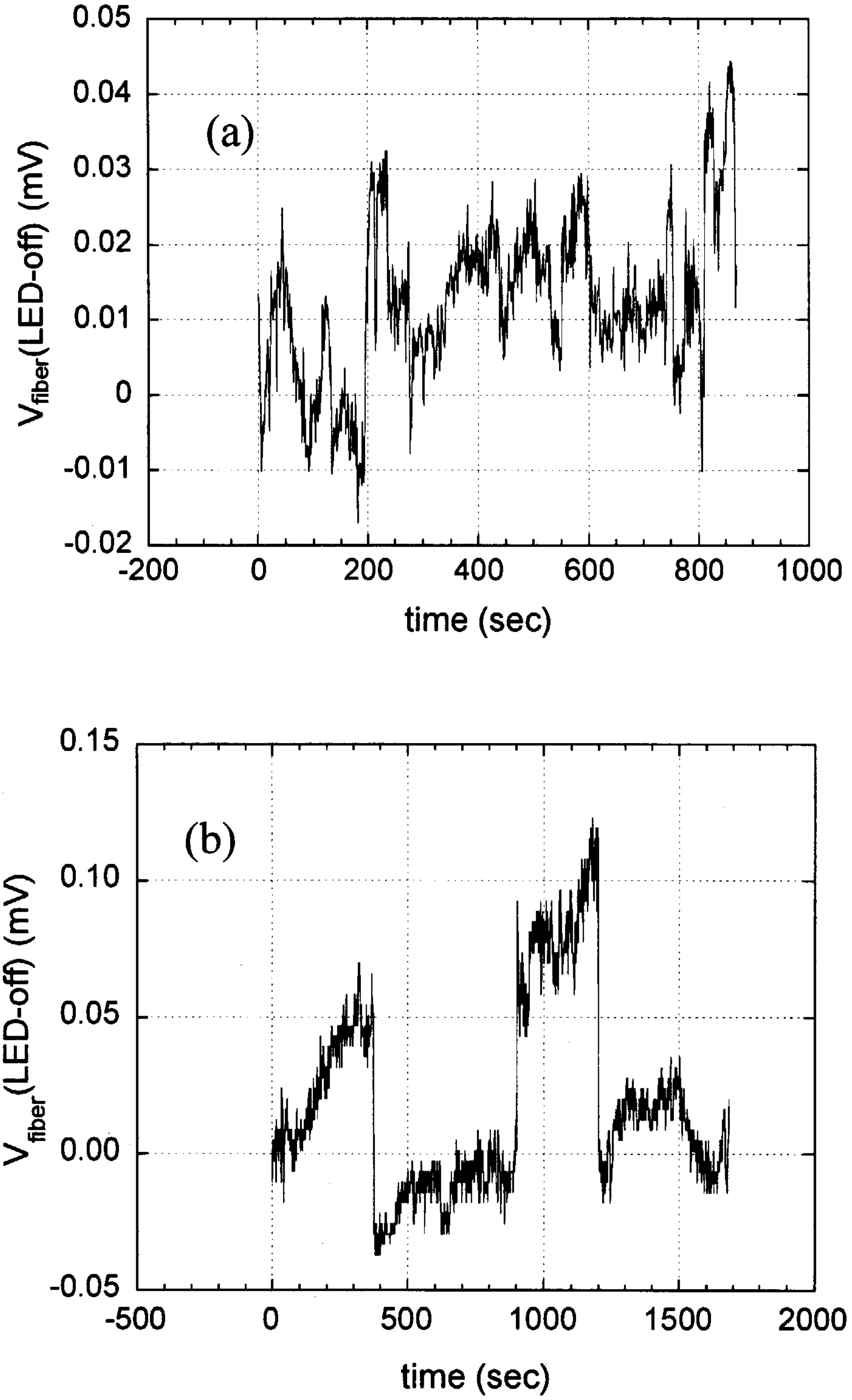
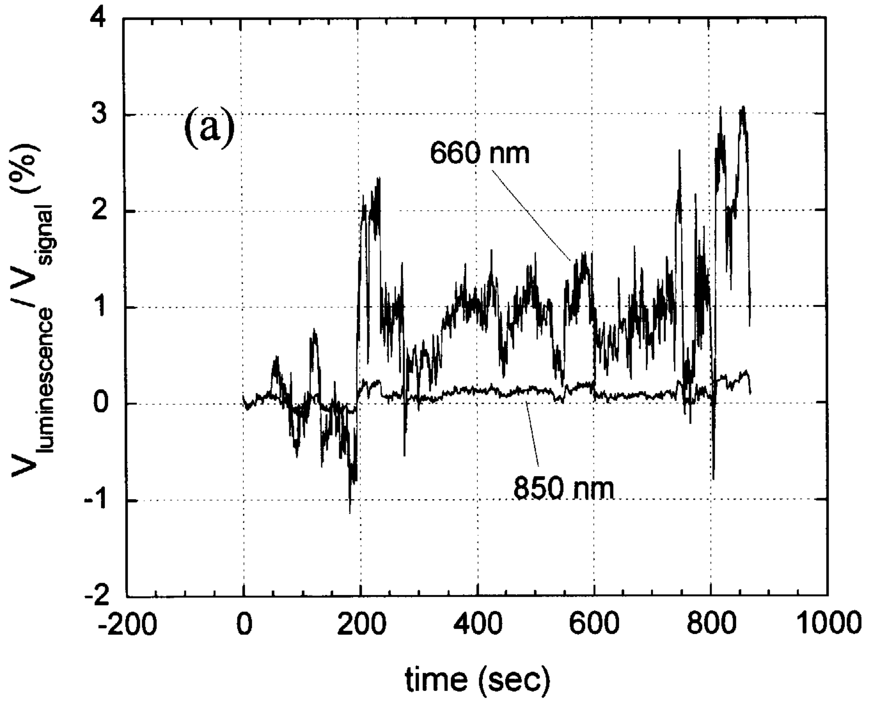


Fig.5 V_{fiber}*(LED-off)* of (a) CPC3 fiber (660 nm) and (b) HCP fiber (470 nm).



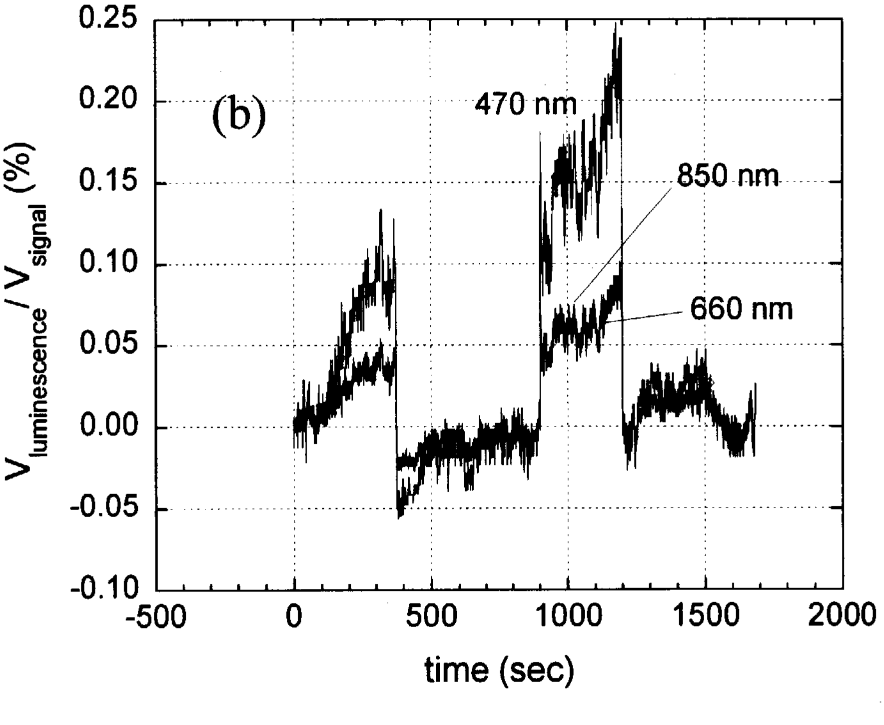


Fig.6 $V_{luminescence}/V_{signal}$ of (a) CPC3 fiber and (b) HCP fiber.

$$V_{luminescence} = V_{fiber}(LED\text{-}off) - \overline{V}_C , \tag{4}$$

where $\overline{V}_C$ is an average of V_C without irradiation. Since large $V_{luminescence}$ should be origins of noises in measurement of the transmission signal, the $V_{luminescence}/V_{signal}$ value was estimated in both fibers. The results are shown in Fig.6. The $V_{luminescence}/V_{signal}$ values of the CPC3 and HCP fibers are less than 3.1% and 0.25 %, respectively. The reason of relatively large $V_{luminescence}/V_{signal}$ values of the CPC3 fiber at 660 nm is that the transmission signal at 660 nm is small due to the large induced loss of the fiber as shown in Fig. 3. The small $V_{luminescence}/V_{signal}$ values are also preferable for application of optical fibers to an attenuation-based dosimeter.

The detailed mechanism of growth and relaxation of the loss is not clear but we can explain phenomenologically as below. In case of the CPC 3 fiber, there may exist a large amount of precursors even before the irradiation because the fiber is doped with Ge and P. In the first irradiation, therefore, the precursors became color centers and the loss increased in a relatively short time. After the pre-existed precursors converted to color centers by capturing electrons and /or holes, the increase of the loss is mainly caused by newly developed precursors by the proton irradiation. It can be considered that a relatively high energy is necessary to make precursors from normal SiO_2 bonds and the rate of loss increase is relative low compared to that in the beginning of the irradiation. In the second irradiation, the loss reached almost the same value at the end of the first irradiation in a short time because there existed relaxed color centers (i.e., precursors) which had been converted to color centers in the first irradiation and they were again converted by the irradiation. It is noted that the rate of loss increase is almost the same in both first and second irradiations except their beginnings. It shows that the mechanism of loss increase is also the same and is governed by new precursors created by the proton irradiation during both periods. In case of the HCP fiber, very small amount of precursors existed before the irradiation and the loss in the first irradiation was caused by color centers formed from newly developed precursors. This may be the reason that the loss increased gradually in the first irradiation. At the beginning of the second irradiation, there existed a large amount of precursors which had been converted to color centers during the first irradiation and then relaxed after the beam stopped. These precursors were again converted to color centers by the second irradiation. This conversion occurred in a very short time and the loss increased stepwise. It is clear that the loss growth and relaxation strongly depend on the irradiation history of the fiber.

3.3 Proton dose in SiO_2

Next we have carried out another experiment to estimate proton dose in SiO_2 using the HCP fibers. It is well known that the dose by protons has a large value when they stop by losing their energies in materials. Figure 7 shows an example of simple calculation of the dose by 20 MeV protons in pure SiO_2 using stopping power functions. One can see that the curve has a sharp peak at the end of the proton range. In the experiment, a SiO_2 plate with a thickness of t was set in front of the fibers. Consequently, the fibers were irradiated by protons which had traveled a distance of t in SiO_2. The induced loss was measured changing the thickness of t. The proton energy was 19 MeV. Figure 8 shows the results when t = 0.62 mm, 1.030 mm, 1.540 mm, 2.004 mm, 2.104 mm, and 2.185 mm.

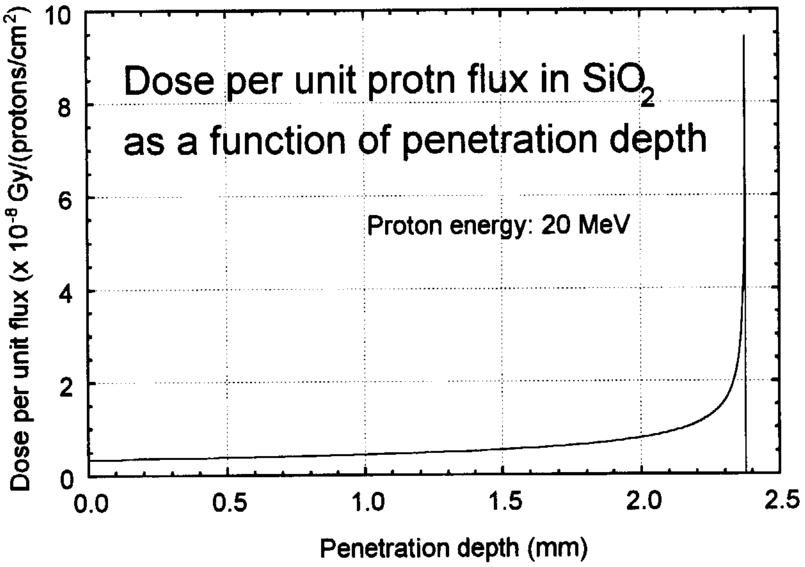
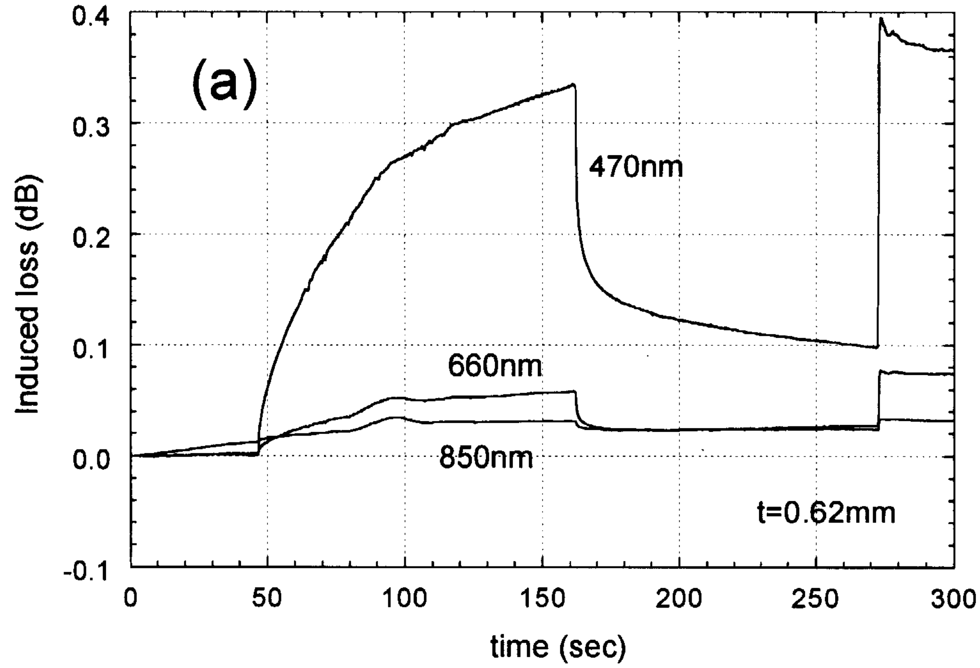


Fig.7 Dose per unit proton flux in SiO_2 as a function of penetration depth.



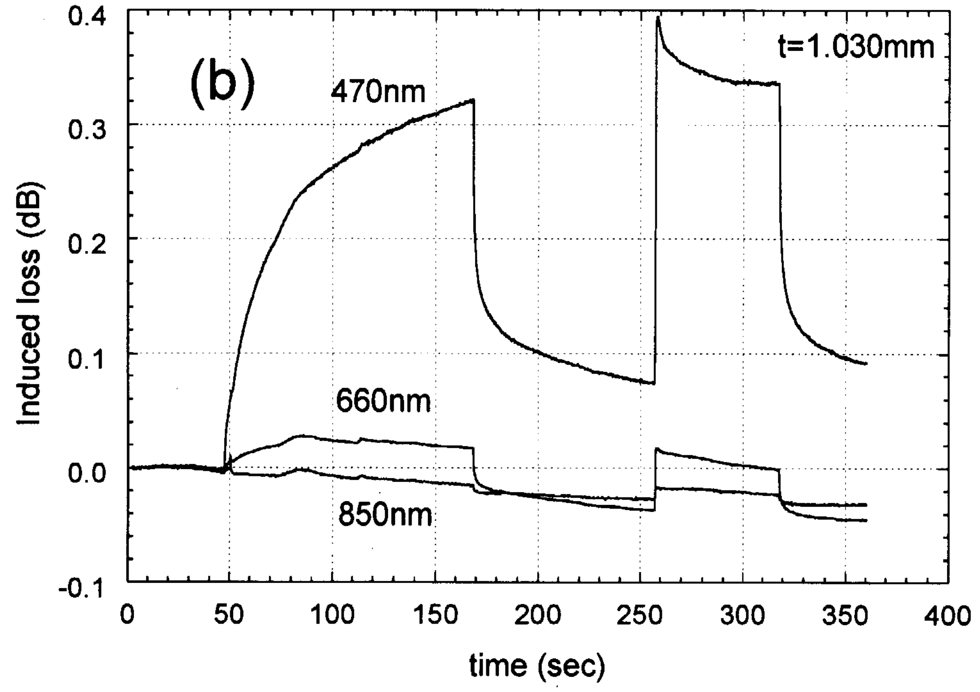
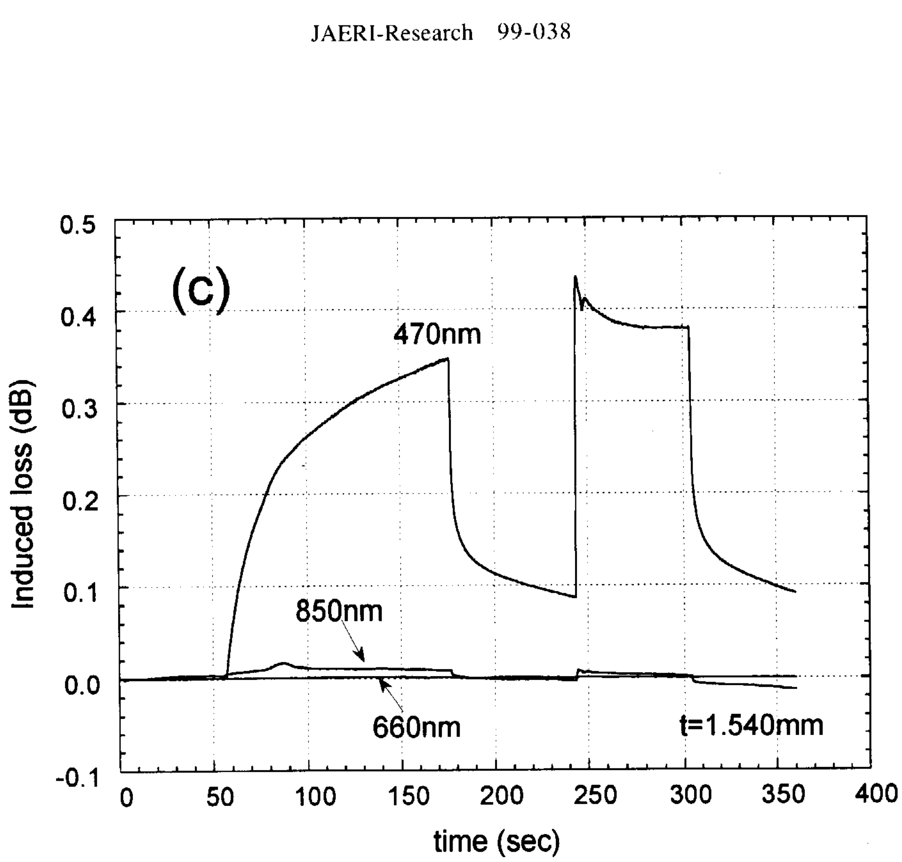


Fig.8 Experimental results. (a) t=0.62 mm and (b) t=1.030 mm.



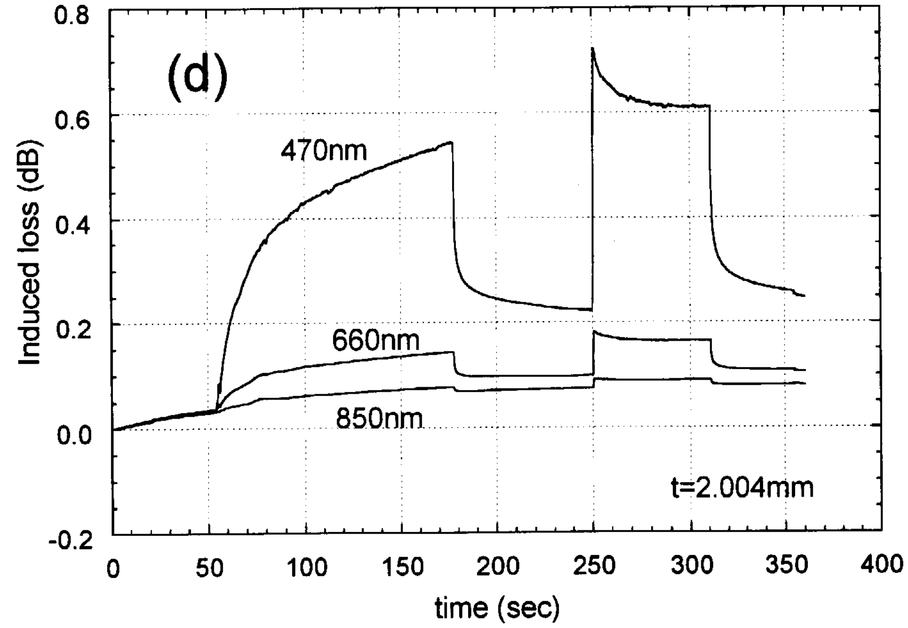


Fig.8 Experimental results. (c) t=1.540 mm and (b) t=2.004 mm. *(continued)*

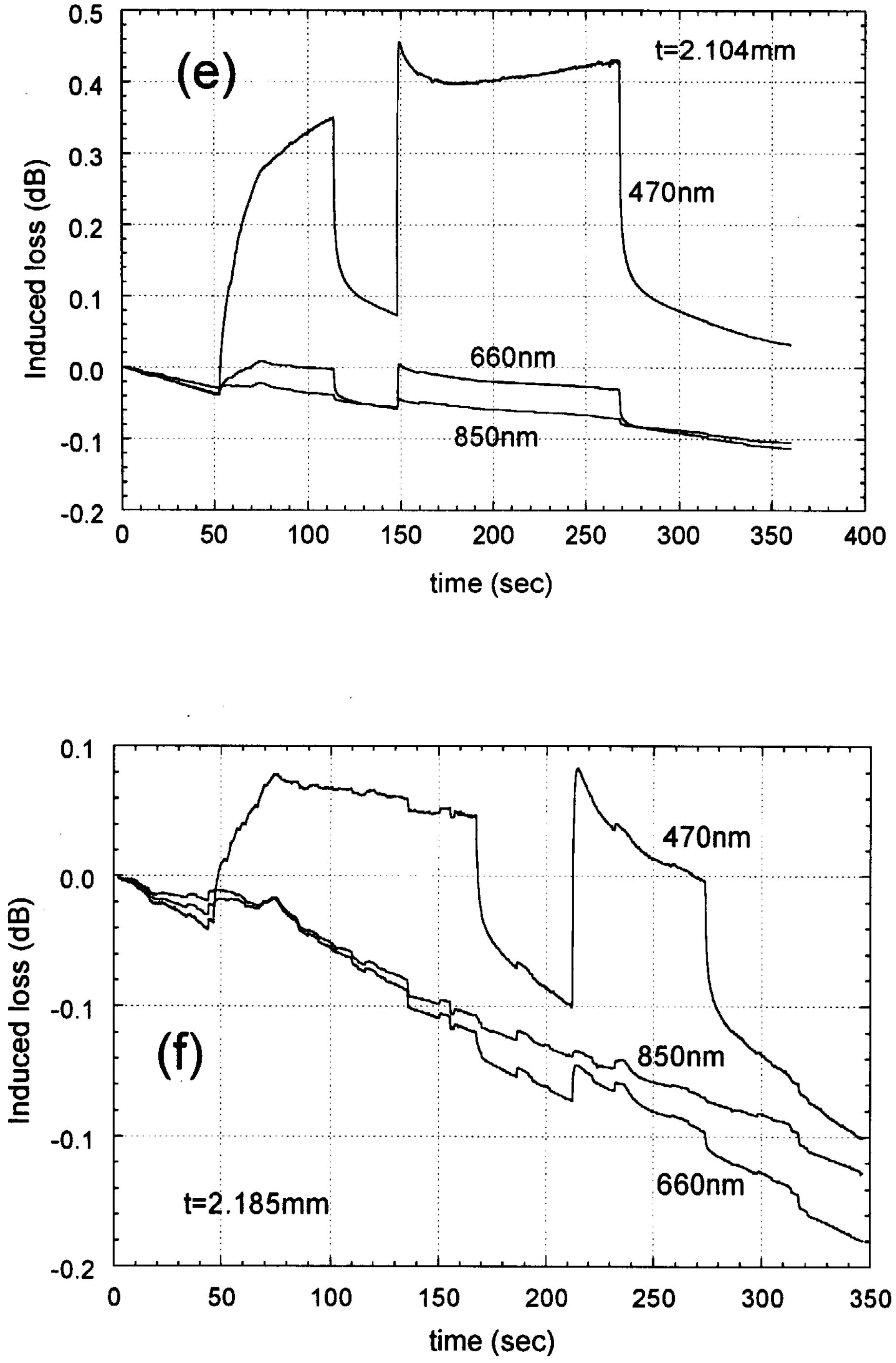


Fig.8 Experimental results. (e) t=2.104 mm and (f) t=2.185 mm. *(continued)*

One can see that the slope at the beginning of the first irradiation in each figure of Fig.8 has a maximum value at about t = 2 mm. The same experiment with t > 2.3 mm showed that the loss were not observed and that the fibers were not irradiated by protons. Although the loss increased non-linearly, we can adopt the slope as an estimation of the dose by protons. Figure 9 shows the slope as a function of the SiO_2 plate thickness. It clearly shows the dose distribution which corresponds to Fig. 7, where the curve has a sharp peak at the end of the proton range. Hence one can say that the estimation of the proton dose in materials may be possible by using fiber-optic technique. The reason why the peak is not sharp compared to that of Fig.7 is that the fiber has a finite diameter and the dose is averaged over the fiber materials.

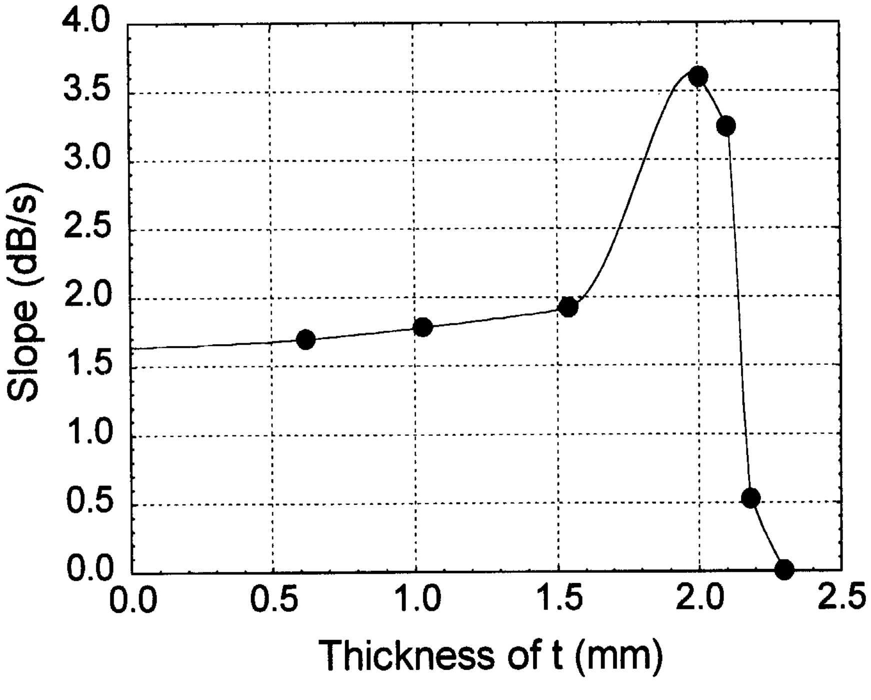


Fig.9 The loss increasing slope as a function of the SiO_2 plate thickness.

3.4 Proton Sensitivity of the fiber

Finally, we estimated the proton sensitivities in both fibers. Since the loss increased non-linearly, we used the slope at the beginning of the first irradiation in Figs. 3 and 4 for the calculation. The calculation results are listed in Table II. Proton sensitivities of the CPC3 and HCP fibers were, respectively, 1.0×10^{-10} at 660 nm and 5.5×10^{-12} at 470 nm in units of (dB/m)/(protons/cm^2). The sensitivities listed in the table may contain errors as large as 10 % because of unstability of the proton beam. The sensitivity of the CPC 3 fiber is much greater than that of the HCP fiber. In both fibers the sensitivities are high for a short wavelength.

Table II Estimated proton sensitivities.

fiber	Proton flux (protons/cm^2/s)	Sensitivities [(dB/m)/(protons/cm^2)]		
		470 nm	660 nm	850 nm
CPC3	5.3×10^{11}	-	1.0×10^{-10}	9.6×10^{-12}
HCP	6.4×10^{11}	5.5×10^{-12}	9.2×10^{-13}	2.3×10^{-13}

4. Conclusions

Optical attenuation in doped- and pure-silica fibers (CPC3 fibers by Siecor and HCP fibers by SpecTran, respectively) was measured at wavelengths of 470 nm, 660 nm, and 850 nm during and after 20 MeV proton irradiation. The results obtained in the experiments are summarized as follows.

(1) The induced loss of the CPC3 fiber increased strongly at the beginning of the first irradiation, and decreased slowly after stopping of the beam. In the second irradiation, however, the developed loss was not so large. The developed loss was governed by the permanent or irreversible loss.

(2) The loss of the HCP fiber increased gradually in the first irradiation, and decreased very quickly after the beam stopped. The loss increased stepwise at the very beginning of the second irradiation. The permanent loss of the HCP fiber was small.

(3) Small luminescence was observed in both fibers during irradiation. The luminescence was slightly larger in the HCP fiber than in the CPC fiber. The $V_{luminescence}/V_{signal}$ value was, however, very small in both fibers, where $V_{luminescence}$ represents the output due to luminescence from fibers by the irradiation and V_{signal} is the output of transmission light.

(4) The induced loss of HCP fibers was also measured when a SiO_2 plate was set in front of the fibers. It may be possible to estimate the proton dose in materials using fiber-optic technique.

(5) Proton sensitivities of the CPC and HCP fibers were, respectively, 1.0×10^{-10} at 660 nm and 5.5×10^{-12} at 470 nm in units of (dB/m)/(protons/cm^2), where the values were estimated from the slope of the loss growth curves at the beginning of the first irradiation.

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国際単位系（SI）と換算表

表1　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2　SIと併用される単位

名称	記号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19}J

1 u=1.66054×10^{-27}kg

表5　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1nm=10^{-10}m

1 b=100fm^2=10^{-28}m^2

1 bar=0.1MPa=10^5Pa

1 Gal=1cm/s^2=10^{-2}m/s^2

1 Ci=3.7×10^{10}Bq

1 R=2.58×10^{-4}C/kg

1 rad=1cGy=10^{-2}Gy

1 rem=1cSv=10^{-2}Sv

（注）

1．表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。

2．表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。

3．barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。

4．EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m^2)=10 P(ポアズ)(g/(cm·s))

動粘度　1m^2/s=10^4St(ストークス)(cm^2/s)

圧力	MPa(=10bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^{6}	3.67098×10^{5}	1	8.59999×10^{5}	3412.13	2.65522×10^{6}	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605J（計量法）

= 4.184J（熱化学）

= 4.1855J（15℃）

= 4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)

= 75 kgf·m/s

= 735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

PROTON IRRADIATION EFFECTS ON OPTICAL ATTENUATION IN DOPED–AND PURE–SILICA FIBERS