

# Study of the dynamics of transformation of point defects in phosphosilicate fibres by the induced refraction index

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**Abstract.** A method for studying the dynamics of transformation of defects in optical fibres, exposed to UV radiation, by the dose dependence of the induced refractive index is proposed. The processes of transformation of defects in a low-loss phosphosilicate fibre, loaded with molecular hydrogen, irradiated at the 193-nm wavelength are investigated using this method. It is assumed that such a fibre has at least two types of defects, responsible for the induction of the refractive index.

**Keywords:** phosphosilicate fibre, photosensitivity, point defects of glass, induced refractive index, excimer laser.

## 1. Introduction

It is known that the increase in the induced refractive index in germanosilicate fibres (GSFs) and phosphosilicate fibres (PSFs) under UV exposure is intensified when the fibres are loaded with hydrogen. It was shown in Ref. [1] that photochemical reactions, leading to the increase in the induced refractive index under these conditions, have two stages. At the first stage, under exposure to UV radiation hydrogen is embedded into the glass network, the initial defects of glasses are destroyed and new, ‘intermediate’ defects are formed. During the further exposure, at the second stage, intermediate defects are destroyed and ‘final’ defects of the third type, determining the variation in the refractive index of glass, are formed. Both stages of this photochemical reaction proceed under exposure concurrently, thus complicating investigation of each of them. Principally, it is possible to separate photochemical reactions of the second stage from those of the first stage by removing hydrogen, contained in a fibre, at a certain stage. Due to accumulation of intermediate defects in the glass network in the initial time period, the photochemical reactions of the second stage can continue when the exposure is resumed. At this time the accumulated

intermediate defects are transformed into the final defects with the induction of the refractive index. By the variation of the induced refractive index, the dynamics of the photochemical reaction of the second stage of the process can be investigated [2].

By the present moment, the two-stage photochemical reactions, involving different defects, are revealed at least in two types of fibres (GSFs and PSFs), loaded with molecular hydrogen [3]. Thus, this kind of the reaction of the refractive-index induction can prove to be universal for hydrogen-loaded fibres. An attempt of theoretical description of the dynamics of defects of the photochemical reaction in such fibres was made [2]. The conjectures concerning reagents (i.e., the specific form of the defects) involved at each stage of the reactions, which take place in GSFs [2] and PSFs [4], were made. It is proposed to use the described phenomenon of the two-stage process of the refractive-index induction in hydrogen-loaded fibres as a basis for the technology of changing the refractive index, which is called the pre-exposure. This technology may have a number of advantages as compared to the traditional technology, wherein the stages of the refractive-index variation under exposure are not separated [2].

The universality of the appearance of the considered process seems to require a deeper insight on a phenomenological level even without binding to its concrete realisation on the level of photochemical reactions in different materials. In particular, it is necessary to reveal whether this process is the main or, perhaps, even the only one during the induction of refractive index in optical fibres.

The aim of this work is investigation of the role of the two-stage photochemical reaction in the induction of the refractive index in PSFs based on the analysis of the dynamics of defect transformation under UV exposure.

## 2. Theory

For mathematical expression of variations in the defect concentration in the fibre core under UV exposure, the author of Ref. [2] proposed equations used to describe the kinetics of chemical processes. Variations in concentrations of the primary A, intermediate B, and final C defects in the two-stage process of the exposure of fibres can be represented in the differential form as:

$$\dot{A} = -v_1 A, \quad (1a)$$

$$\dot{B} = v_1 A - v_2 B, \quad (1b)$$

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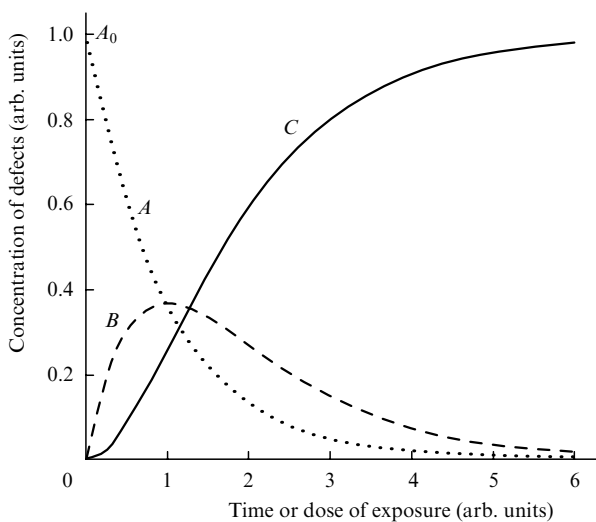
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$$\dot{C} = v_2 B, \quad (1c)$$

where  $v_1$  and  $v_2$  are the rates of photochemical reactions at the first and second stages. The solutions of these differential equations have the form

$$\begin{aligned} A &= A_0 e^{-v_1 t}, \\ B &= v_1 A_0 \left( \frac{e^{-v_1 t} - e^{-v_2 t}}{v_2 - v_1} \right), \\ C &= A_0 \left[ 1 + \left( \frac{v_1 e^{-v_2 t} - v_2 e^{-v_1 t}}{v_2 - v_1} \right) \right], \end{aligned} \quad (2)$$

where  $A_0$  is the initial concentration of primary defects;  $t$  is the time or dose of exposure. The dependences of concentrations of each kind of defects on the time or dose of exposure are demonstrated in Fig. 1.



**Figure 1.** Time or dose dependences of concentration of defects of types  $A$ ,  $B$ ,  $C$  for  $v_1 = v_2$ .

The analysis of expressions (2) shows that for every ratio of the rates of processes at stages 1 and 2 the function  $B(D)$  ( $D$  is the exposure dose) has its maximum. This maximum appears due to the fact that the increase in the concentration of intermediate defects (in case of the decreased concentration of primary defects) becomes, at a certain dose  $D$ , so small as to be equal to the consumption of these defects in the second process [see Eqn (1b)]. From the existence of the maximum of function  $B$  follows that the function  $C(D)$  for the same value of  $D$  should have an inflection, i.e., it should be S-shaped: the starting portion of a curve with a limited growth of the function, an increased growth in the intermediate portion and a reduction of the growth in the final portion. The term ‘S-shaped form’ was first introduced in Ref. [5] to denote the typical form of the dose dependence observed in an experiment. The presence of the maximum of the function  $B(D)$  and S-shaped form of the function  $C(D)$  is demonstrated in Fig. 1, where the ratio  $v_1/v_2 = 1$ . Note an important particularity of the function  $C(D)$ . It follows from Eqn (1c) that its derivative is, accurate to the coefficient, equal to the function  $B(D)$ , therefore the forms of their curves should be identical.

Consider the change of the form of functions  $C(D)$  and  $B(D)$  for different ratios of rates  $v_1$  and  $v_2$ . In the case of  $v_1 \gg v_2$ , the maximum of the function  $B(D)$  increases and approaches the ordinate axis. The inflection of the curve of the function  $C(D)$  lies closer to the ordinate axis as well, and the S-shaped form of the dependence becomes practically unnoticeable. The drop of the function  $B(D)$  and growth of  $C(D)$  in almost the entire range of doses is determined in this case by the slowest process with the rate  $v_2$ . When  $v_2$  is increased up to  $v_2 \gg v_1$ , the value of the maximum of the function  $B(D)$  noticeably decreases, the maximum as itself shifts to the coordinate origin, the S-shaped form of the dependence  $C(D)$  practically disappears as in the previous case, and the process of the defect transformation has for the observer also a single stage with the rate  $v_1$ . The S-shaped form of the dependence is the most noticeable in the case when  $v_1 = v_2$  (Fig. 1).

Thus, the S-shaped form of the dependence  $C(D)$  and, respectively, of the dependence of the induced refractive index on the exposure dose can serve as an indication of the two-stage process, and the position of the maximum in the dose dependence  $B(D)$  can point to the ratio of rates  $v_1$  and  $v_2$ . In the case of  $v_1 \gg v_2$  and  $v_2 \gg v_1$ , an experimental detection of the S-shaped form of the induced refractive-index dependence may become difficult. Another practically important conclusion is that the derivative of the dose dependence of the induced refractive index is able to represent the dynamics of the concentration of intermediate defects in the two-stage process of their transformation.

The dependence of the concentration of defects and, respectively, induced refractive index on the exposure dose  $D$  can be expressed in a more complete form according to the law presented, for example, in Ref. [6]:

$$\Delta N \sim cD^f, \quad (3)$$

where  $c$  and  $f$  ( $f < 1$ ) are empirical constants.

We, however, will use Eqns (2), because they, in particular, allow for the explanation of the appearance of the S-shaped form in the dose dependence of the induced refractive index.

### 3. Experiment and analysis of results

For the experimental investigation of the dynamics of photochemical reactions, taking place in the fibre core under UV exposure, we should follow variations in concentrations of all three types of the defects. These variations can affect dose dependences of such parameters as the induced refractive index and induced absorption, luminescence intensity, intensity of bands in the Raman scattering spectrum or intensity of ESR-signal. It seems that for all these parameters the presence of the S-shaped form of the dose dependence can indicate the presence of the two-stage process, while variations in the derivative of the dose dependence can represent the dynamics of the concentration of the defects at the preceding stage of the photochemical process.

A number of works has been published by now, considering the correspondence between the exposure dose dependences of the above-mentioned experimentally detected magnitudes and the dynamics of the concentration of defects in fibres. The possibility of registration of the dynamics of initial and intermediate defects  $A$  and  $B$  by the

luminescence intensity was demonstrated in Ref. [7]. In Ref. [8], the dose dependence of the induced refractive index, obtained from the results of writing the Bragg grating in a fibre, is compared with the dynamics of concentration of defects, obtained from the ESR data. In our opinion, the method using interferometric technique is the most accurate for registering dose dependences of the induced refractive index.

Let us presume, as in Ref. [2], that the concentration  $C$  of final defects is linearly dependent on the induced refractive index, which allows experimental registering of its variations. In our opinion, the change in concentration of intermediate defects can also be experimentally observed by using the procedure of pre-exposure. Thereto, a number of samples of a hydrogen-loaded fibre are pre-exposed to different doses, at the next step hydrogen in samples is out-diffused by heating, and then all pre-exposed parts are further exposed to equal small doses of radiation. As a result, the dependence of the induced refractive index on the pre-exposure dose for the given value of  $D$  can be defined. Since the initial growth of the induced refractive index at the second stage of the process in pre-exposed samples depends on the cumulative concentration of intermediate defects  $B$  in different parts, variations in the induced refractive index will follow changes in concentrations of these defects depending on the pre-exposure dose.

It seems that in the similar experiment one can also register the dynamics of concentration of primary defects  $A$  as a function of the dose, if the process of the concentration change is a one-stage process.

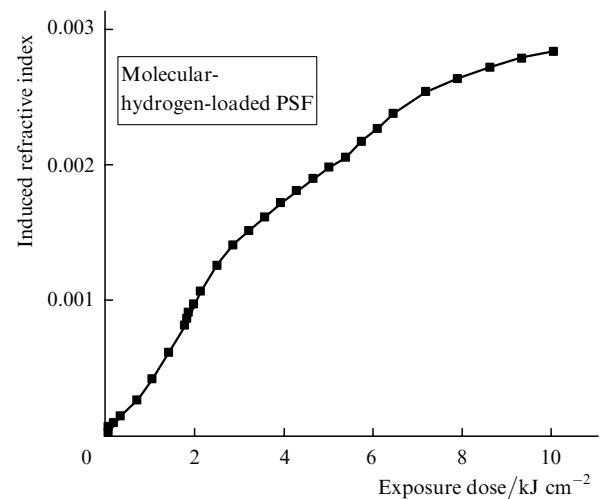
A great number of dose dependences of the induced refractive index obtained under different conditions of exposure of fibres of different kinds has been registered by now. According to our data, the S-shaped form of the dose dependence is detected at least for two kinds of fibres: phosphorous-doped fibres [9] and a germanium-doped fibre (SMF28 [5]). In most of other experiments with germano-silicate fibres, the S-shaped form of the dose dependence seems not to be observed, therefore we can suppose that for these fibres either  $v_1 \gg v_2$  or  $v_1 \ll v_2$ . In this work, however, we will make an analysis of data only for PSFs, wherein the S-shaped form of the dose dependence appears reproducibly in fibres with different concentrations of phosphorous oxide.

The S-shaped form of the dose dependence was revealed right in the first exposure of PSFs [9]. Authors of Ref. [4] made a conjecture that this form of the dependence is determined by two different photochemical reactions, proceeding sequentially in the fibre core under increase in the dose  $D$ . In that very work, the dependence of the induced refractive index in the PSF on the pre-exposure dose was for the first time presented. That dependence, just as the similar dependence in the GSF, had the maximum, though it was reached not at the dose  $\sim 100 \text{ J cm}^{-2}$  as in the GSF [2], but at the dose  $\sim 1.5 - 2 \text{ kJ cm}^{-2}$ . It was also shown in Ref. [4] that under exposure of the pre-exposed sample the S-shaped dose-dependence typical for PSF is absent, which points to the one-stage process of the defect transformation.

Our experimental investigations were made for the PSF with low optical losses [10]. The molar concentration of phosphorous oxide in the PSF was about 12%, the difference of the refractive indices in the core and the cladding was equal to 0.01, the cutoff wavelength  $\lambda_c = 1.1 \mu\text{m}$ . The fibres were loaded with molecular hydrogen under an ambient pressure of 100 atm at a temperature of  $100^\circ\text{C}$ .

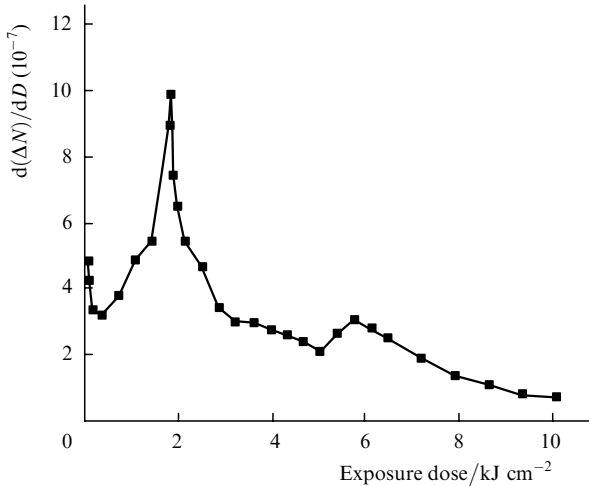
The exposure was realised by CL-7000 and Lumonics-520 ( $\lambda = 193 \text{ nm}$ ) excimer lasers with pulses of a  $100 - 300 \text{ mJ cm}^{-2}$  power density. The laser pulse repetition rate was 10 Hz in all experiments. The dose dependences of the induced refractive index were measured by means of Mach-Zehnder interferometers, created in the studied fibre [11], for which the two long-period gratings were formed inside the fibre at a certain distance from each other. When the light propagated through the first grating, the cladding mode was excited, and after the propagation through the second grating the cladding and fundamental modes interfered with each other. The first grating was written so as to make losses in the grating to be approximately equal to 3 dB, which allowed us to divide the power of light, propagated through the grating, into two approximately equal parts and provided high visibility of the interference pattern (15–20 dB) after writing the second grating. The induction of the refractive index in the fibre core changed the phase only in one arm of the interferometer. The induced refractive index was measured, as a rule, at a wavelength of about  $1.5 \mu\text{m}$ . The changes of the positions of peaks of the interference pattern were registered by the AQ6317 optical spectrum analyser with the accuracy of  $\pm 0.05 \text{ nm}$ .

Figures 2 and 3 demonstrate the characteristic dose dependence of the refractive index and its derivative with respect to the dose obtained for one of the PSF samples. The curve in Fig. 2 is S-shaped within the  $0 - 4$  and  $4 - 10 \text{ kJ cm}^{-2}$  ranges of doses, the curve in Fig. 3 has two maxima and two minima, respectively.

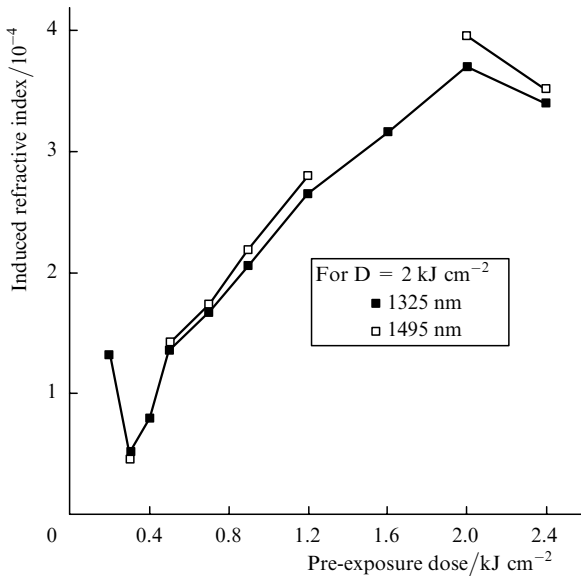


**Figure 2.** Dose dependence of the induced refractive index obtained for one of the studied PSF samples.

For the same fibre the experiment with the pre-exposure was realised. For this purpose, an interferometer was formed in a piece of a fibre, loaded with molecular hydrogen. The interval between two long-period gratings of the interferometer was divided into several sections each being pre-exposed to one of the doses in the range of  $0.2 - 2.4 \text{ kJ cm}^{-2}$ , within which the S-shaped dependence of the induced refractive index was observed (Fig. 2). Then, hydrogen was out-diffused from the interferometer and each of the pre-exposed sections was once again exposed to the dose of  $2 \text{ kJ cm}^{-2}$ . The values of the induced refractive index for



**Figure 3.** Derivative of the induced refractive index as a function of dose obtained for the dose dependence given in Fig. 2.



**Figure 4.** The induced refractive index as a function of pre-exposure dose at the wavelengths of 1325 and 1495 nm.

each of the pre-exposed sections are demonstrated in Fig. 4 as a function of the pre-exposure dose. The induced refractive index was measured at two wavelengths of light propagated through these sections. The results obtained in these two series of experiments are in good agreement with each other. The deviations from them provide an approximate estimate of the inaccuracy of measurements of the induced refractive index at exposure of the elementary section of the interferometer. As is seen from Fig. 4, this inaccuracy does not exceed 10% and is determined basically by the difference between the values of the induced refractive index measured at 1325 and 1495-nm wavelengths.

From the comparison of curves presented in Figs 3 and 4 we can see that the dependences correlate with each other within the mentioned range of doses. The values of doses, at which the minimum (about  $0.3 \text{ kJ cm}^{-2}$ ) and maximum ( $1.8\text{--}2 \text{ kJ cm}^{-2}$ ) are reached, are practically equal. Let us note also that the location of the first maximum testifies the

fact that the optimal pre-exposure dose is about  $2 \text{ kJ cm}^{-2}$ , which was for the first time reported in Ref. [4].

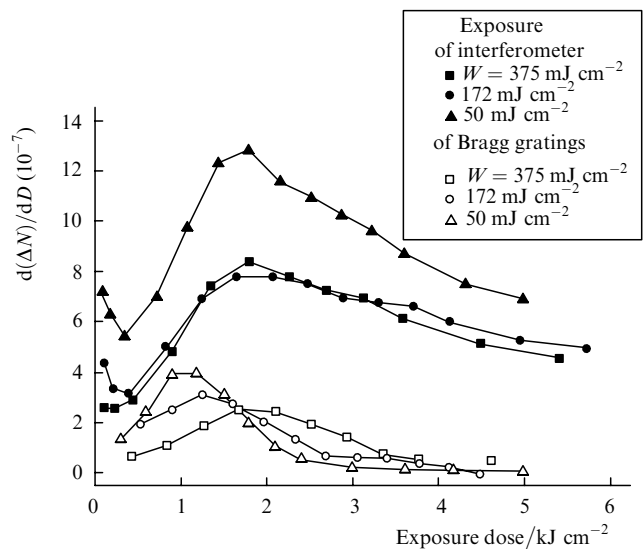
As appears from the comparison of curves, the dependence of the induced refractive index on the pre-exposure dose really represents the dynamics of the variation in concentration of intermediate defects in the process of its exposure. It follows also that the equations of chemical kinetics can be used to describe the dynamics of defects in the glass network, and the derivative of the dose dependence is able to represent the changes in concentration of intermediate defects.

An important peculiarity of the curve, given in Fig. 2, is the presence of the S-shaped characteristic within two ranges of doses, and the distinctive feature of Fig. 3 is the presence of two maxima divided by a minimum. The value of the dose of the second couple of extremums in Fig. 3 differs for different samples of interferometers. The detection of two extremums in the derivative of the dose dependence testifies that the dynamics of the process of defect transformation is more complicated and not determined by a single two-stage process, as was assumed in Ref. [2].

In addition, some principal remarks concerning the results of the above-illustrated experiment should be made.

1. The dose dependences of the induced refractive index can be recorded not only by means of interferometer but also by the results of writing the Bragg gratings in an optical fibre. For comparison, we wrote some Bragg gratings in the studied fibre using the phase mask with the period of  $1.06 \mu\text{m}$ . As a result, a peak of losses appeared in the spectrum of light transmission through the grating at a wavelength of  $1.48 \mu\text{m}$ . The depth of that peak was registered by increasing the exposure dose and then used to calculate the induced refractive index and to plot its dose dependence.

The comparative results of calculations of the derivative of the dose dependence of the induced refractive index in the PSF from the data on exposure of three sections of the interferometer and three Bragg gratings are given in Fig. 5. The power density of the excimer-laser pulse was varied in



**Figure 5.** Dose dependences of derivative of induced refractive index obtained from the data on exposure of three sections of interferometer and three Bragg gratings for the power density of the excimer laser pulse  $W = 375, 172, \text{ and } 50 \text{ mJ cm}^{-2}$ .

each case of the refractive index induction in the fibre. The set of power densities for each case of exposure was the same. It is seen that at the exposure of the interferometer the position of maxima in Fig. 5 practically does not change with the change in the pulse power density and the position of minimum is reproduced in the two of three results of the exposure. The exposure doses, at which minima ( $\sim 400 \text{ J cm}^{-2}$ ) and maxima ( $\sim 1700 - 1900 \text{ J cm}^{-2}$ ) are reached in the interferometric case, are close to the values given in Fig. 3. When the Bragg gratings are used, the detection of extremums in the dose dependence of the derivative of the induced refractive index is considerably poorer: the maxima shift depending on the dose value, while the minima disappear on the whole.

A bad reproducibility of the extremum positions obtained at the exposure of Bragg gratings can be determined by the difference between the dynamics of the process of the refractive index induction during writing of the periodic structure as a Bragg grating and the dynamics of the exposure to the homogeneous beam in the case of the interferometer, as well as by the potentially more accurate measurement of the induced refractive index in the interferometric method of detection [11].

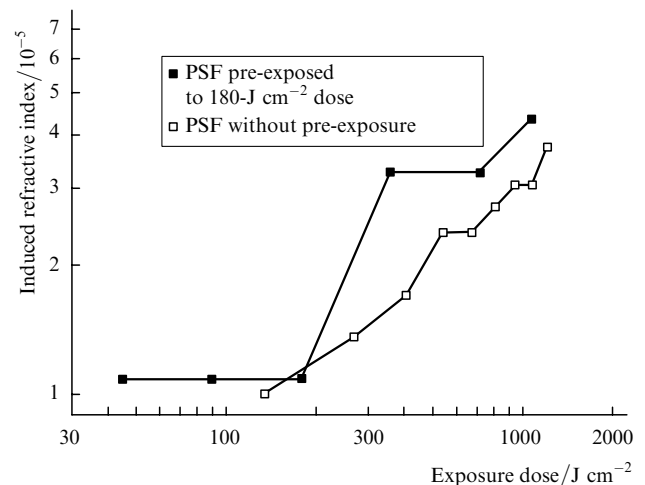
2. The form of the dose dependence of the induced refractive index obtained using the interferometer strongly depends on the hydrogen distribution in the fibre cladding. This distribution changes due to leaving of hydrogen from the cladding into the ambient space in the process of its diffusion. Therefore, to obtain better reproducibility of the values of the induced refractive index on doses in different sections of the interferometer, the measurements should be performed in equal time intervals after extracting the interferometer from the hydrogen camera.

3. The variations in concentration of intermediate defects in the fibre can be revealed from the results of the fibre exposure by means of two methods. However, it is preferable to use for this purpose the dose dependence of the induced refractive index and its derivative, since plotting the dependence on the pre-exposure dose is an enormously more complicated procedure.

Let us present the results of investigations, which can shed light on the origin of the first minimum of the dose dependence of the derivative of the induced refractive index. We can suppose that the presence of this minimum at the dose of about  $300 - 400 \text{ J cm}^{-2}$  in Figs 3–5 indicates the decrease in concentration of some other initial defects  $A_{01}$ , different from those, which are involved in the two-stage process of the refractive index induction. Further, we can suppose that their transformation under UV exposure has only one stage and leads to the appearance of the defects of the final type  $C_{01}$  and, consequently, to the refractive index induction within the range of doses up to  $\sim 500 \text{ J cm}^{-2}$ . The possibility to discover the dynamics of concentration of the initial defects by the analysis of dose dependences in a one-stage process of transformation was reported in the Section 2 of this paper.

The supposition of the presence of another type of defects in PSFs is justified, in our opinion, by the following results. Figure 6 demonstrates the data on the refractive-index induction in the two sections of the interferometer with the hydrogen-free fibre: in the section without pre-exposure and section pre-exposed to the  $180\text{-J cm}^{-2}$  dose. The result of the induction of the time-stable refractive index in the hydrogen-free PSF under exposure at

$\lambda = 193 \text{ nm}$  is obtained, in our opinion, for the first time. The fact of the refractive-index induction in the hydrogen-free PSF can indicate as itself the presence of the defects different from those, which take part in the two-stage process of the photochemical reaction. In both curves in Fig. 6 one can notice the growth of the induced refractive index up to the dose level of  $300 - 500 \text{ J cm}^{-2}$  (which approximately corresponds to the position of minima in Figs 3 and 4) and the slowing of the growth after this level. Possibly, the refractive index was also induced under doses lower than  $100 \text{ J cm}^{-2}$ , but this fact was not registered due to the insufficient sensitivity of the interferometer. The approximate coincidence of the exposure dose, at which the destruction of the supposed initial defects  $A_{01}$  (Figs 3, 4) takes place, and the dose ( $\sim 500 \text{ J cm}^{-2}$ ), at which the concentration of final defects  $C_{01}$  (Fig. 6) saturates, testifies the supposition that the same one-stage process of the defect transformation is registered in these experiments.



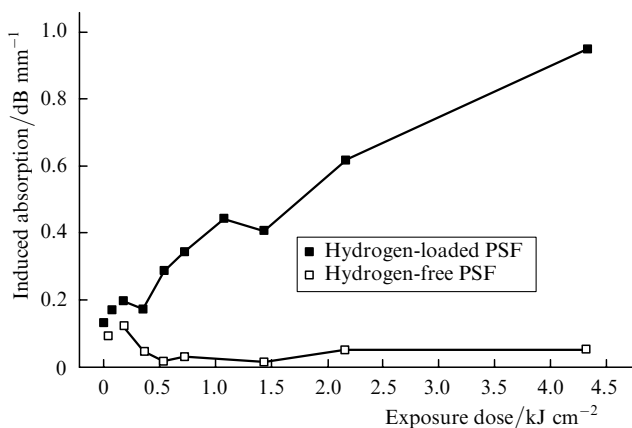
**Figure 6.** Dose dependences of the induced refractive index in two hydrogen-free samples: without pre-exposure, and pre-exposed to the dose of  $180 \text{ J cm}^{-2}$ .

The result of the exposure of the pre-exposed section of the interferometer (Fig. 6) indicates, in our opinion, that photochemical reactions involving the defects of two types take place. First, as a result of exposure the defects are destroyed and transformed in one stage into their final form. Their total destruction leads to the appearance of a 'shelf' in the growth of the induced refractive index. However, the main increase in the refractive index is caused, seemingly, by the two-stage transformation into the final form of intermediate defects, which appear in the fibre as a result of pre-exposure. The latter defects seem to be sufficient to make the dose dependence of the pre-exposed sample higher than that of the initial sample (Fig. 6).

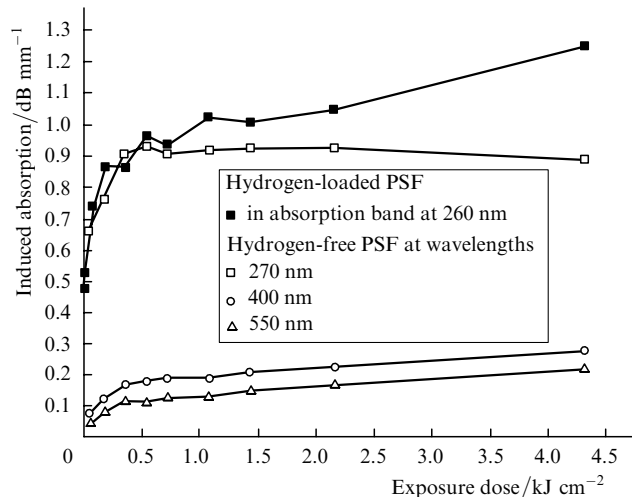
The conjecture of the presence of two types of initial defects in PSFs was verified also by the analysis of dose dependences of the induced absorption in the PSF. The induced absorption was studied using the Fourier spectrometer and Perkin–Elmer spectrophotometer in bulk samples, being cut from the preform similar to that, of which the studied fibres were drawn, with the molar concentration of phosphorous oxide of 12%. These samples were irradiated by the same excimer lasers and in the same regimes as at the refractive index induction. The induced

absorption was measured several days after the exposure, when the relaxation processes in fibres connected with the exposure were not any more detected experimentally in induced absorption.

Figure 7 shows the dose dependences of the induced absorption in the maximum of the absorption band at a 3050-nm wavelength, corresponding to the stretching vibrations of OH in silanol group hydrogen-bonded with the non-bridging atom of oxygen of phosphorous tetrahedrons of the glass network. The changes in the induced absorption at this wavelength are connected with the induction of the refractive index in the PSF [12]. Figure 8 demonstrates the change in the refractive index within the UV range in the absorption bands at 260, 270, 400, and 550 nm corresponding to the electronic transitions of phosphorous colour centres.



**Figure 7.** Induced absorption within the absorption band at  $\lambda = 3050$  nm for hydrogen-loaded and hydrogen-free PSFs.



**Figure 8.** Induced absorption for hydrogen-loaded PSF within the absorption band at 260 nm and for hydrogen-free PSF within absorption bands at 270, 400, and 550 nm.

In all curves, presented in Fig. 8, the character of the dose dependences of the induced absorption changes at a dose of about  $400 \text{ J cm}^{-2}$ : the value of induced absorption becomes stable within UV and visible wavelength ranges for the hydrogen-free samples and begins to rise slowly in the hydrogen-loaded sample. In the IR range the induced

absorption degrades at this dose in both samples, after which it begins to increase slowly in the hydrogen-loaded sample.

Looking for the correspondence between dose dependences of the induced absorption and the dynamics of the defect transformation, we can use the same ideas of the two-stage process and three types of defects as in the case of dose dependences of the induced refractive index.

It is reasonable to assume that the changes in the defects of the one-stage process of transformation can be easier revealed by the induced absorption in hydrogen-free fibres. In this case, the drop of the induced absorption in the IR range displays the change of concentration of initial defects, while the change of concentration of their final form is indicated by the growth and saturation of the induced absorption within UV and visible ranges. As is seen, the drop of the induced absorption in the IR range at exposure doses of up to  $400 \text{ J cm}^{-2}$  (Fig. 7) correlates either with the decrease in the refractive-index dose dependence in the pre-exposure experiment (Fig. 4) or with the decrease in derivatives of dose dependences in Figs 3 and 5. The growth and saturation of the induced absorption in UV and visible ranges at a dose of more than  $400 \text{ J cm}^{-2}$  (Fig. 8) correlate with the data on dynamics of the induced refractive index presented in Fig. 6.

It seems that in the case of hydrogen-loaded samples the variations in the induced absorption in the IR wavelength-range represent not only the dynamics of concentration of initial defects of the one-stage process but also the dynamics of concentration of intermediate defects of the two-stage process. This fact can be indicated by a sharp break of the dose dependence of the induced absorption in the hydrogen-loaded sample at a dose  $\sim 1.1 - 1.5 \text{ kJ cm}^{-2}$  (Fig. 7), which is somewhat lower than  $1.7 - 2 \text{ kJ cm}^{-2}$  value, at which the maximum of the concentration of intermediate defects is reached (Figs 3–5). The deviation of the exposure dose at this break of the induced absorption from the positions of maxima in the induced refractive index in Figs 3–5 can be explained by the low reproducibility of the estimate of the dose position of the small induced-absorption break in Fig. 7. The break of the dose dependence of the induced absorption in the hydrogen-loaded PSF sample in the range of exposure doses of up to  $500 \text{ J cm}^{-2}$  (Fig. 7) can be explained by overlapping of dose dependences of the induced absorption, connected with variations in concentration of the defects involved in one-stage and two-stage processes of transformation. The dose value at this break is close to that of minima in Figs 3–5 ( $\sim 400 \text{ J cm}^{-2}$ ).

#### 4. Conclusions

We have proposed a comparatively simple in realisation and informative method for studying the transformation of the defects in fibre cores under UV exposure. It implies the analysis of forms of the curves of the dose dependence of the induced refractive index and its derivative. The S-shaped form of the dose dependence of the refractive index induction can serve as an indication of the two-stage process of the defect transformation in the glass network. The derivative of the induced refractive index as a function of the dose represents the dynamics of the variation of concentration of intermediate defects.

The analysis of dose dependences of the induced refractive index and induced absorption in PSFs allows

us to make a conjecture that the PSF core has at least two types of initial defects, and there are two channels of their transformation into the final form, resulting in the change in refractive index. These are the defects with one-stage transformation in the absence of hydrogen and defects with two-stage transformation, for which photochemical reactions with hydrogen are required. These photochemical reactions proceed in different ranges of the exposure doses. Reactions of the first type cease at doses of about  $500 \text{ J cm}^{-2}$ , reactions of the second type (with the presence of hydrogen) cease at doses of about  $2000 \text{ J cm}^{-2}$ . Reactions of the first type lead to the increase in the refractive index of  $(3 - 4) \times 10^{-5}$ . The induction of the time-stable refractive index in the hydrogen-free PSF is obtained, in our opinion, for the first time and testifies the presence of two types of initial defects in such fibres. However, the two-stage process with the presence of hydrogen at the first stage is the main process, which leads to the induction of the refractive index  $\sim 10^{-3}$  in the PSF.

The presence of the two-stage photochemical reaction in PSFs explains the S-shaped form of the dose dependence of the induced refractive index. However, the real form of the dependence of the induced refractive index on the exposure dose is more complicated than the S-shaped. This fact can be connected with the concurrent proceeding of several photochemical reactions in the range of exposure doses of  $0 - 10 \text{ kJ cm}^{-2}$ .

The possibility of the description of the dynamics of photochemical reactions in PSFs by means of relatively simple equations of chemical kinetics is verified experimentally by the correlation of the curve of the derivative of the dose dependence, obtained by the interferometric method of measuring the induced refractive index, and the curve of the dependence on the pre-exposure dose.

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