Photoinduced fiber gratings

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ABSTRACT

The paper presents the state of the art of glass photosensitivity and photoinduced fiber gratings. The techniques for fiber grating fabrication and the basic grating properties are reviewed. Photosensitive fiber glass compositions, techniques to enhance photosensitivity as well as the wavelengths at which gratings can be written are considered. The most important applications of Bragg and long-period gratings are discussed.

Keywords: photosensitivity, fiber Bragg and long-period grating, fiber laser, fiber sensor

1. INTRODUCTION

Photosensitivity of doped silica glass, namely its ability to change its refractive index under the action of an incident light, is now intensively studied and applied in telecommunication, material processing and fiber-optic sensor systems. Several hundreds of papers have been devoted to these topics. International meetings and workshops on fiber photosensitivity and gratings are continually held [1, 2], not to mention special journal issues [3] and monographs [4]. Nevertheless, in spite of the intensive investigations of the glass photosensitivity mechanisms, these mechanisms are not known with certainty.

The formation of permanent gratings in optical fibers was first observed by K.Hill et al. in 1978 [5]. In their experiments, an Ar-ion laser radiation was launched into the core of a Ge-doped-silica fiber. Strong reflection of the input light was observed after several minutes of irradiation. To explain this effect the authors supposed that an optical standing wave resulting from an interference of two counter-propagating beams in the fiber core produces a refractive index grating with a period equal to the wave period. Later, the two-photon nature of the index change became evident [6], and finally an ultraviolet irradiation in side-irradiation geometry was suggested to provide much more efficient single-photon photorefractivity mechanism [7]. The latter work stimulated strong development of the technology and applications of fiber gratings, because the side-writing technique allowed fabrication of gratings, whose resonance wavelengths, bandwidths, and other properties can be varied over wide limits.

2. CLASSIFICATION OF FIBER GRATINGS

The interaction of one mode of a fiber with other modes is commonly described with the help of coupled-mode theory [8] in which only two modes are supposed to be nearly phase matched and capable of resonant coupling. Based on the coupled-mode theory, a quantitative information about the coupling coefficients and spectral properties of fiber gratings can be obtained [9,10]. Two modes are coupled by a grating, if their propagation constants β_1 and β_2 satisfy the phase matching condition: $\beta_2 = \beta_1 + 2\pi/\Lambda$, where Λ is the grating period.

Fig.1 illustrates a variety of possible couplings of the HE_{11} (LP_{01}) mode with different copropagated (a - c) and counterpropagated (d – g) modes. This figure shows schematically the dispersion curves for the core-bounded ($n_{cl} < n_{eff} < n_{co}$) and cladding-bounded ($n_{coat} < n_{eff} < n_{cl}$) modes. The hatched region represents the continuum of radiation modes. Two dashed curves 1 and 2 give the value of $n_{eff} - \lambda/\Lambda$ for short-period and long-period gratings with periods Λ_{sp} and Λ_{lp}, respectively. Intersections of these curves with the dispersion curves of different modes (open circles in fig.1) show the wavelengths at which the phase-matching condition is satisfied. The grating can couple the fundamental mode to different modes at different wavelengths. For example, a strong short-period grating can excite cladding modes and radiation modes at shorter wavelengths, apart from the main reflection band.

The energy transfer efficiency is defined by the coupling coefficient, which is proportional to the mode overlap in the region of the fiber that contains the grating. In addition, if the grating is tilted or the induced refractive index distribution is axially nonuniform, interactions between the symmetric fundamental mode and asymmetric modes will occur.

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3. BRAGG GRATINGS

Bragg grating couples the fundamental mode of a single-mode fiber with the counterpropagating core mode. This means that at a certain wavelength the light propagating in the fundamental mode is reflected back. The properties of this reflection depend on the grating parameters. For a uniform Bragg grating of length L, reflectivity R at the resonance wavelength λ_{Br} can be expressed as $R = th^2(kL)$, where $k = \pi\Delta n_{mod}\eta/\lambda_{Br}$ is the coupling coefficient (Δn_{mod} is the amplitude of sinusoidal index modulation and $\eta = \int_0^a |E_{co}|^2 r dr \Big/ \int_0^\infty |E_{co}|^2 r dr$ is the portion of the fundamental mode power propagating in the fiber core of radius a).

The full bandwidth at the first zeros of the reflection spectrum is $\Delta\lambda = \lambda_{Br}^2 \sqrt{\pi^2 + (kL)^2} / 2n_{eff}L$.

Depending on the application, Bragg grating can be designed with a uniform or chirped period structure. The induced refractive index distribution along the grating length can be apodized to suppress the grating side-lobes. In addition, blazed gratings can be created, if the interference fringes are angled with respect to the fiber axis. The spectral properties of all these grating types are described in [4, 9].

Strain and temperature vary the modal index and grating period. The Bragg wavelength shift, in this case, can be expressed as:

$$\Delta\lambda = 2n\Lambda\left\{\left[1 - \frac{n^2}{2}\left(p_{12} - \nu(p_{11} + p_{12})\right)\right]\varepsilon + \left[\alpha + \frac{1}{n}\frac{dn}{dT}\right]\Delta T\right\}$$

where ε is the applied strain, p_{ij} are the stress-optic coefficients, ν is Poisson's ratio and α is the thermal expansion coefficient of silica, and ΔT is the temperature change. The temperature sensitivity of a Bragg grating is mainly due to the thermo-optic effect and is $\frac{1}{\lambda}\frac{\delta\lambda}{\delta T} = 6.7\times10^{-6}\,{}^\circ C^{-1}$. The strain induced Bragg wavelength shift results primarily from the change of the grating period and is $\frac{1}{\lambda}\frac{\delta\lambda}{\delta\varepsilon} = 0.78\times10^{-6}\,\mu strain^{-1}$ (Ref.[11]). Although the absolute wavelength shift in Bragg gratings is quite small, it can be significant in comparison with the grating bandwidth, which is typically ~0.1 nm. Therefore, Bragg grating based temperature and strain sensors feature a very high sensitivity: ~0.1 °C and ~1 μstrain, respectively. The possibility of cascading several gratings in one fiber makes them attractive for distributed point sensing. The main concepts of Bragg grating application in sensors and possible sensor schemes can be found in review [11].

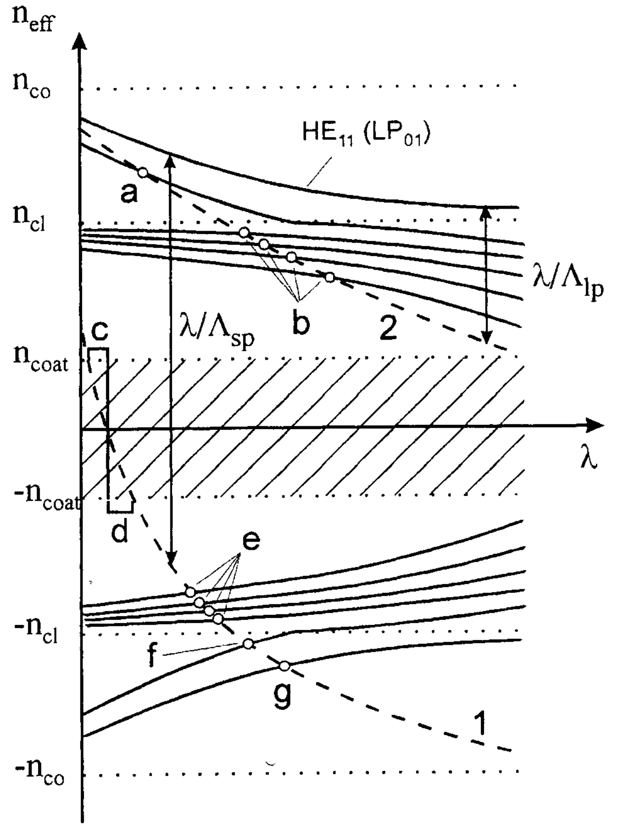

Fig.1. The diagram demonstrating the phase matching conditions for coupling of the lowest-order mode (HE_{11}/LP_{01}) with different copropagated (a - c) and counterpropagated (d - g) core (a, f, g), cladding (b, e) and radiation (c, d) modes of a fiber. n_{co}, n_{cl} and n_{coat} are the refractive indices of fiber core, cladding and coating, respectively

4. LONG-PERIOD GRATINGS

Photoinduced long-period cladding-mode-coupled gratings (LPG) have been proposed as a band-rejection filter [12]. This grating type has a large period $\Lambda = 100 \div 500$ µm and couples the core mode to a set of cladding modes propagating in the same direction. As a rule, the cladding modes are guided by the silica-air interface. The energy transferred to a cladding mode is then absorbed in the coating. As the result, an absorption band arises in the transmission spectrum. A large number of guided modes (~10^4) can propagate in the cladding, but only some of them (namely, HE_{lm} and EH_{ln} modes) have a sufficiently large overlap integral with the fundamental mode. The main feature of these modes is axial symmetry, the number of radial oscillations being equal to the radial mode number m [13].

The cladding mode intensity due to coupling with the fundamental mode can be represented as $S = sin^2(kL)$, where k is the coupling coefficient. As in the case of Bragg gratings, $k = \pi\Delta n\eta/\lambda_r$, where λ_r is the resonance wavelength and

$$\eta = \int_0^a E_{co} E_{cl}^* r dr \Big/ \sqrt{\int_0^\infty |E_{co}|^2 r dr \cdot \int_0^\infty |E_{cl}|^2 r dr} \cdot$$

The full bandwidth $\Delta\lambda$ at the first zeros of the absorption spectrum is $\Delta\lambda = 2\lambda_r^2 \sqrt{\pi^2 - (kL)^2} \Big/ \pi L(n_{eff}^{co} - n_{eff}^{cl})$.

A detailed theoretical consideration of cladding mode coupling in long-period gratings can be found in [10, 14].

The transmission spectrum of a long-period grating is rather sensitive to external influences, such as mechanical deformation, temperature, strain, and refractive index of the surrounding medium [15].

Temperature sensitivity of the LPG can be expressed by the following equation [16]:

$$\frac{d\lambda}{dT} = \frac{\Lambda\left[\dfrac{\partial n_{eff}^{co}}{\partial T} - \dfrac{\partial n_{eff}^{cl}}{\partial T}\right] + \dfrac{\lambda}{\Lambda}\dfrac{d\Lambda}{dT}}{1 - \Lambda\left[\dfrac{\partial n_{eff}^{co}}{\partial \lambda} - \dfrac{\partial n_{eff}^{cl}}{\partial \lambda}\right]}.$$

The second term in the nominator can be neglected, because the expansion coefficient of silica glass is small ($\lambda/\Lambda \cdot d\Lambda/dT \approx 6 \cdot 10^{-4}$ nm/°C). Therefore, $d\lambda/dT$ of LPG is defined by temperature sensitivity of the refractive index of silica and doped silica (the first term in the nominator) and the waveguiding properties of the fiber (denominator). It should be noted that the material term is positive and is large enough, because germanium-doped silica glass has dn/dT greater than that of pure silica ($1.1 \cdot 10^{-5}$ °C^{-1} (85%SiO_2/15%GeO_2) and $7.8 \cdot 10^{-6}$ °C^{-1} (SiO_2)) [17]. The temperature responses of two resonance bands of an LPG usually differ in magnitude, which can be explained by the difference of the index dispersions.

Strain sensitivity of LPGs was tested in several papers [18, 19]. It was found that depending on fiber type the strain sensitivity of the loss peak could be varied in a wide range from 15 to -7 nm/%ε [18]. It was supposed that the magnitude and sign of strain sensitivity are defined by the difference between the strain-optic coefficients of the core and cladding regions. Nevertheless, further investigations should be performed in order to clarify the features of strain sensitivity of LPGs.

Sensitivity of the resonance peak position of LPG with respect to the refractive index of the external medium n_{ext} is very high, when n_{ext} is slightly less than the cladding index. $d\lambda/dn_{ext}$ can be as high as ~ 10^4 nm. When $n_{ext} > n_{cl}$, the grating position becomes insensitive to n_{ext} [20].

The transmission spectrum of a LPG is highly sensitive to bending. On the one hand, this necessitates caution in handling gratings; on the other hand, opens up prospects for creation of sensitive optical fiber sensors of mechanical deformations. The bending sensitivity of a grating spectrum is so great that a curvature radius of more than 1 meter can be detected [21]. Grating bending leads to reduction of the resonance amplitude and its displacement to longer wavelengths [21, 22]. An exact theory of the bending effect is still to be developed. As follows from the experimental data, grating bending results in changes of the field distributions of the core and cladding modes, which reduces the overlap integral I. The resonance shift to longer wavelengths points to an increase of Δn_{eff}. In our earlier work [16], a bending-induced splitting of the initial grating peak was observed. This result was recently confirmed in ref.[23], where the resonance splitting was observed in a straight LPG written in a fiber with large core concentricity error (CCE). It was demonstrated that in such a fiber the bend-induced splitting has clear asymmetry with respect to rotation angle. Based on these experiments it can be suggested, that the resonance splitting is attributed to the excitation of EH_{1n} cladding modes (these are the even cladding modes in terms of the model proposed by Erdogan [10]). These modes have relatively small overlap integral I with the core mode in straight gratings written in the fibers with low CCE. Breaking of symmetry caused by CCE or/and grating bending leads to the increase of I for EH_{1n} modes and to appearance of additional loss peaks in the grating transmission spectrum.

Cladding mode propagation constant $\beta_{clad} = 2\pi n_{eff}^{clad}/\lambda$ depends on the cladding diameter. This fact permits irreversible alteration of the resonance wavelength of LPGs [24]. The cladding diameter can be easily decreased by etching the fiber section containing the grating in a HF acid solution. This will significantly shift the resonance wavelength to longer wavelengths without affecting the coupling efficiency. The resonance wavelength displacement increases with the cladding mode order and amounts to 100 nm and over for the highest cladding modes.

Besides the cladding-mode-coupling long-period gratings produce intermodal and polarisation mode coupling (intersection *a* in fig.1). In mode couplers [25] written in few-mode fibers the resonance coupling of two core modes takes place. The same effect occurs in polarisation couplers (rocking filters) [26], which are induced in birefringent fibers. In this case two modes with orthogonal polarisation states interact. The resonance energy transfer arises at the wavelength, at which the grating period is equal to the polarisation mode beatlength. Spectral properties of mode and polarisation couplers can be calculated with the help of copropagated coupling mode theory [4].

6. GRATING FABRICATION TECHNIQUES

Bragg gratings having a comparatively small period, they are written in a UV-light interference pattern. The formation of this pattern requires high spatial and temporal coherence of the UV-light source. The interference pattern should be highly stable, because the grating inscription procedure can last for several minutes. The interference pattern is usually created via intersection of two UV-beams on the plane of the fiber, the interference period being dependent on the angle between the beams. Several holographic techniques based on this principle have been proposed for the fabrication of fiber Bragg gratings with different parameters using various UV-sources (Ref. [4, 27, 28] and references therein].

One of the most widespread techniques of uniform Bragg grating fabrication is based on the application of Lloyd interferometer, which is schematically shown in fig.2. The advantages of this scheme include high mechanical stability, flexible variation of the grating length and resonance wavelength. At the same time, such a technique requires high spatial coherence of UV-light and, therefore, is usually used with a frequency-doubled Ar-ion laser.

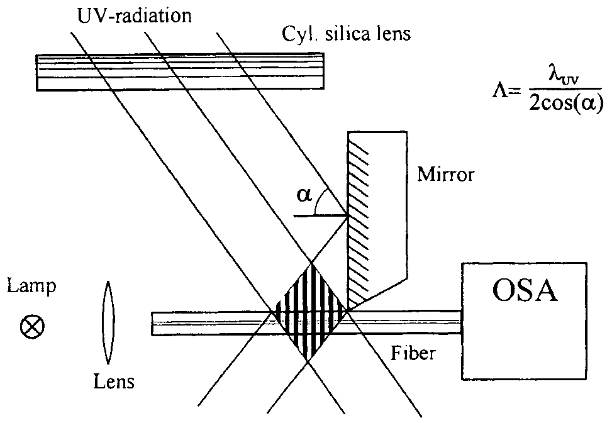

Рис.2. Lloyd interferometer scheme for uniform Bragg grating fabrication.

New approach for the grating fabrication was demonstrated in Ref.[29, 30], where it was suggested to use a silica phase mask with a certain relief on its surface (fig.3). The mask is usually designed to diffract the incident UV-beam mainly in the 1 and –1 orders. These two diffracted order beams interfere to produce a periodic pattern that photoimprints a corresponding grating in the fiber. The phase mask technique is less flexible in comparison with the holographic one, nevertheless it is more suitable to fabricate the fiber gratings with reproducible parameters. Moreover, it offers easier alignment of the optical scheme and lower coherence requirements on the UV-radiation. Therefore, excimer laser sources are suitable for the phase mask technique.

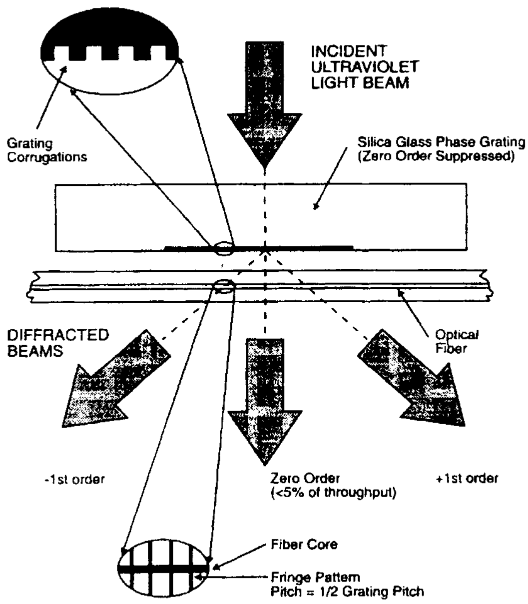

Fig.3. Phase mask technique for Bragg grating writing [29].

There are two most widespread ways of UV-writing of LPGs: 1) the amplitude mask technique [12, 15], in which the periodic structure is formed by a slot-hole mask (fig.4a), and 2) the step-by-step technique [31], in which the required index structure is formed via mechanical translation of the fiber relative to the focused laser beam (fig.4b). The amplitude mask technique, at which all elements of a grating are formed simultaneously, is more attractive, if a pulsed UV-source, such as an excimer laser, is used. Continuous sources, on the contrary, are preferable for local index formation, because an increase in the UV-power density results in a reduction of the irradiation time [32]. The step-by-step technique of LPG fabrication appears to be more flexible. It allows forming various grating shapes (apodization, chirp, etc), it is much easier as compared to the amplitude mask technique. For example, in ref.[33] such an opportunity was taken to suppress the grating side-lobes and resonance bands caused by high harmonics of the main grating period.

It should be mentioned that the requirements on the UV-source for LPG writing are less stringent than in the case of

Bragg grating writing. In particular, there are no basic restrictions on the coherence length of UV-radiation. Besides, owing to a rather large grating period, mechanical stability of the writing system may be sufficiently low.

The refractive index profile in a fiber can be changed by heating the fiber up to temperatures T > 1000 °C. As a result of such thermal treatment a profile variation can occur owing to a number of reasons:

1) mechanical deformation of the fiber, change of its size [34];

2) stress-optic effect due to redistribution of elastic stresses in the fiber [35, 36];

3) spatial redistribution of chemical composition of the glass due to thermo-induced diffusion of dopants [37, 38].

Local fiber heating can be produced by IR laser sources (CO_2-laser [39,40] or CO-laser [37,38,41]) or by localized electrical discharge [42,43]. Such grating type can be written in fibers insensitive to UV-light, for example, in pure-silica-core fibers [21]. Thanks to a large coupling coefficient which can be achieved by the methods pointed out, strong thermo-induced gratings consisting just of several pitches ($N \sim 20$) can be written. Being prepared by local fiber heating up to the temperature close to the melting point of silica glass, thermo-induced gratings have higher temperature stability in comparison with the photoinduced gratings and retain their spectral properties even at temperatures of about 1000°C [41].

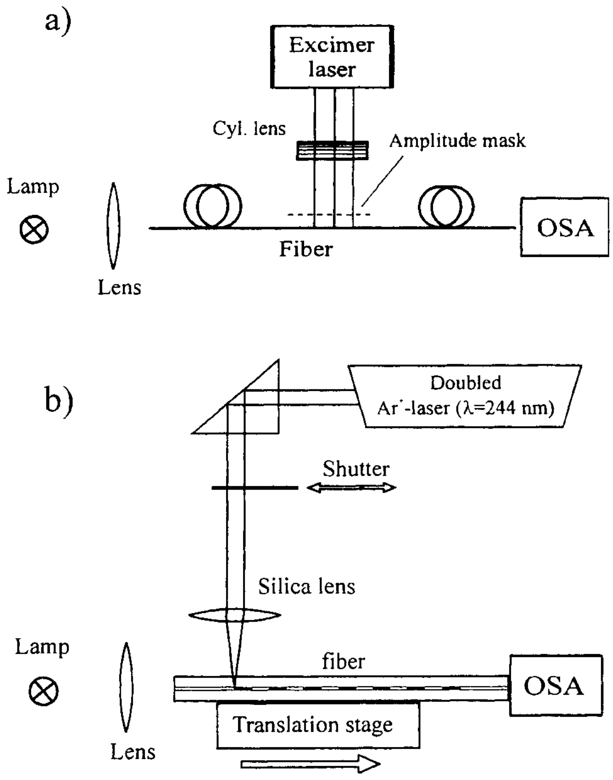

Fig.4. Amplitude mask (a) and step-by-step (b) techniques of the LPG fabrication.

7. MECHANISMS OF GE-DOPED FIBER PHOTOSENSITIVITY AND WRITING WAVELENGTHS

The microscopic mechanisms involved in photorefractivity phenomenon are still not completely understood even in the most investigated Ge-doped silica glass. Nevertheless it is well known that in germanosilicate fibers photoexcitation of germanium oxygen deficient centers (Ge-ODC) plays a key role in the transformation of the glass network and leads to a permanent index change.

Fig.5 represents a typical absorption spectrum of Ge-doped glass. It is clearly seen that this spectrum has two main absorption bands centered at 242 nm (5.1 eV) and 330 nm (3.75 eV) which are ascribed to singlet-to-singlet and singlet-to-triplet Ge-ODC absorption, respectively [44]. Visible lines of the Ar-ion laser (488 and 514 nm) have been used for internal grating writing by two-photon excitation of the singlet absorption band. Direct 242-nm band excitation can be realized with the help of a KrF-excimer laser (248 nm), a frequency-doubled Ar-ion laser (244, 257 nm), a frequency-quadrupled Nd^{3+}:YAG laser (266 nm) or a frequency-doubled XeCl-pumped dye laser. Spectral efficiency of index change corresponds to the Ge-ODC absorption spectrum, and pulsed irradiation appears to be more efficient than irradiation with cw lasers. This fact testifies to the role of local glass heating in the process of index induction. A typical maximum index induced via the

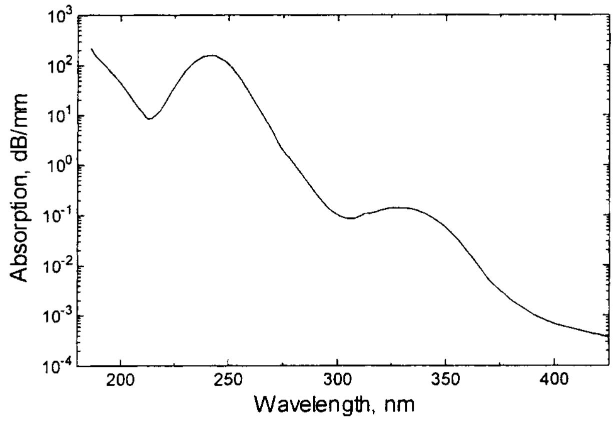

Fig.5. Absorption spectrum of 11 mol.% GeO_2-doped glass produced by the MCVD method [44].

excitation of the 242-nm band in lightly Ge-doped fibers is about 10^{-4}.

The triplet absorption band whose maximum is three orders of magnitude less than that of the singlet band can also be used to write permanent index gratings [31, 45]. In this case, near-UV CW radiation of an Ar-ion laser (333 - 364 nm) is used. A comparative analysis of the induced index dynamics for the singlet and triplet excitation of Ge-ODC (Fig.2) showed that the Ge-ODC transformation from the long-lived ($\tau \approx 100$ μs) excited triplet state is the dominant mechanism in Ge-doped glass photorefractivity [46].

Using ArF-laser radiation (193 nm) another photosensitive regime was achieved in which an induced index of about 10^{-3} can be reached in standard fibers [47, 48]. It was found in ref.[48] that at λ=193 nm a single-photon mechanism of index change (most likely, excitation of a defect band centered at $\lambda < 200$ nm) is dominant in fibers with a high germanium concentration, whereas in lightly doped fibers a second order process (conduction band excitation) prevails.

Finally, it was shown recently that the vacuum UV light of an F_2-laser (157 nm), which directly excites the conduction band of Ge-doped silica glass, gives the rate of index change greater than that under 193 nm irradiation [49]. In spite of the rapid index growth, the maximum index change induced in a SMF28 fiber was not very high ($\sim 10^{-4}$).

Several models have been suggested to explain the UV-induced index change. It was known that the singlet band irradiation of Ge-doped glass leads to bleaching of Ge-ODCs which are transformed into other defect centers with new absorption bands in the UV region [44]. Therefore, it was supposed that the changes in the absorption spectrum lead to the refractive index change owing to Kramers-Kronig relation [50]. Using this color center model, L.Dong et al. [51] obtained a good correlation between the photoinduced growth and thermally activated decay of the induced index and the 195-nm absorption band. An index change as high as 3×10^{-4} was calculated by the Kramers-Kronig relation in a fiber with 10 mol.% of GeO_2. It should be noted here that in accordance with the color center model the UV-induced transformation takes place only in the vicinity of a Ge-ODC, which is excited by radiation, while the glass network remains unaffected.

The color center model is not sufficient to explain the total index change, which can exceed 10^{-3} in Ge-doped fibers. Therefore, another model supposing compaction (all the glass network is involved in this process) of the glass under the action of UV-light was proposed and confirmed experimentally [52, 53]. In particularly the creation of the relief on the surface of a preform slice under the action of UV-light with a corresponding intensity profile was observed. This relief turned out to be temperature reversible: it disappeared after annealing at 600°C which is in a good agreement with annealing of photoinduced gratings. In ref.[54] it was shown that the fiber irradiation increases the axial tensile stress inside the fiber core independently of the initial stress sign. Such stress development can be a response of the silica cladding to the core glass compaction. An additional proof of UV-induced Ge-doped glass densification was obtained in ref.[55], where strong changes in the spectra of spontaneous Raman scattering have been observed after the fiber was exposed to a total dose of 41 kJ/cm^2 at 248 nm. The changes testify to a decrease of the order of the tetrahedron rings in the glass. The authors supposed that the UV-photons can break large (sixfold or larger) rings, which leads to the formation of low-fold rings. This process results in an increase in the glass density and, therefore, in an increase in its refractive index.

8. PHOTOSENSITIVE GLASS COMPOSITIONS AND PHOTOSENSITIZATION TECHNIQUES

The photosensitivity of fibers depends on many different factors such as the fiber preparation technique, dopant type and level, irradiation wavelength, irradiation power and type (pulsed or cw radiation), etc. Initially only Ge-doped fiber photosensitivity was discovered [5, 7]. Then it was found that phosphorus- [56] and nitrogen- [57] doped glasses exhibit a strong index change under 193 nm irradiation.

Photosensitivity of Ge-doped fibers can be increase by B- or Sn-codopings [58, 59]. The gratings written in boron-codoped fibers have a much poorer thermal stability, and boron gives an additional absorption at the 1.55-μm communication window. In contrast, Sn-codoping does not increase loss in the near-IR range, and gratings fabricated in such fibers have an improved thermal stability as compared to gratings in ordinary Ge-doped fibers.

As was mentioned above, the concentration of Ge-ODC defines the fiber sensitivity to 242-nm band irradiation. The defect concentration is found to be approximately proportional to the germanium content in the glass and depends on the glass fabrication procedure. In particular, the strength of the 242-nm band can be increased by collapsing a preform in reduced conditions [60].

Nitrogen codoping of germanosilicate glass prepared by plasmachemical technologies can also increase the strength of this band providing the increase of glass photorefractivity at 240 nm [61, 62]. In ref.[62] the measured amplitude of the Ge-ODC singlet absorption in Ge- (7 mol.%) and N- (0.1 at.%) codoped silica amounted to 670 dB/mm, which far exceeds the values commonly observed in germanosilicate glass with 7 mol.% GeO_2 fabricated by the MCVD process (~200 dB/mm) [63]. As a result, an induced refractive index change as high as 2.8×10^{-3} was observed in an unloaded fiber, and a change of $\sim10^{-2}$ was observed in a hydrogen-loaded fiber (cw 244-nm irradiation with a cumulated dose of about 300 kJ/cm²).

To increase the photosensitivity of fibers with a small germanium concentration in the core, two hydrogen techniques have been suggested: exposure of the glass to the flame an oxygen-hydrogen burner (flame brushing) [64] and high-pressure low-temperature hydrogen loading [65]. At present, the latter technique has become most widespread owing to its relative simplicity. H_2-loading allows increasing the UV-induced index change in Ge-doped fibers up to 10^{-2}. However, gratings written in H_2-loaded fibers feature poorer thermal stability and must be pre-annealed at elevated temperature. In addition, UV-irradiation of an H_2-loaded fiber leads to the formation of Ge-OH groups with an absorption band at 1.4 µm, which intensity can amount to 1 dB/mm [66].

Fig.6 illustrates dose dependencies of the index change measured in different fibers by the interferometric technique, described in ref.[67]. Most of them have the traditional power law behavior $\Delta n_{ind} \sim D^b$ (Ref.[32]). Fig.6 attests once again that:

- photosensitivity increases with increasing germanium concentration in the fiber core (curves 1, 4 and 5);
- a small amount of nitrogen strongly enhances photorefractivity of Ge-doped glass (curves 1 and 2);
- hydrogen loading improves photosensitivity by nearly one order of magnitude (curves 2 and 3).

In addition, we see that a phosphorus-doped H_2-loaded fiber exhibits the strongest sensitivity as compared to other fibers, although the absorption at 193 nm in P-doped glass is ~10 dB/mm [68], which is much less then that in Ge-doped glass at 242 or 193 nm (α ~ 200 dB/mm [44]).

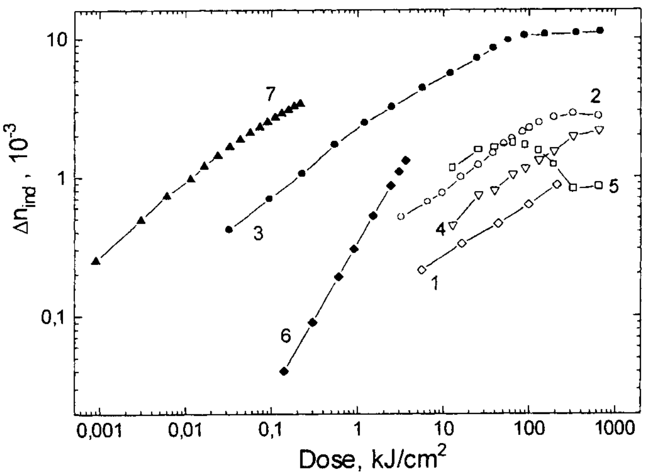

Fig.6. Dose dependencies of index change induced by 244 nm cw radiation (1 - 5) and 193 nm pulsed radiation (6 - 7) in fibers with the following core compositions: 1) 7 mol.% GeO_2 (244 nm); 2) 7 mol.% GeO_2, 0.1 at.% N; 3) 7 mol.% GeO_2, 0.1 at.% N (H_2-loaded); 4) 12 mol.% GeO_2; 5) 20 mol.% GeO_2; 6) 1.2 at.% N; 7) 7 mol.% P_2O_5 (H_2-loaded).

Several types of photosensitivity have been discovered in Ge-doped fibers depending on the fiber parameters and irradiation conditions. The first type was observed in fibers with a small germanium concentration (< 20 mol.% GeO_2) and is accompanied by a positive index change, monotonically growing with UV dose. (Type I photosensitivity). Thereafter, it was found that in fibers heavily doped with germanium the index growth is followed by index decreasing on reaching a certain dose (Type IIa photosensitivity) [69]. This negative index dynamics was not observed, when the gratings were written in bulk glass samples [70]. Type IIa photosensitivity can be promoted by stretching the fibers in the process of irradiation [71]. These facts testify to a stress-optic origin of type IIa photosensitivity.

If the power density is increased up to 1 J/cm², a strong grating can be written with only one excimer laser pulse [72]. This so called type II grating results from intense heating (several thousands of degrees) of the fiber core, which can produce local fusion at the core-cladding interface. Type II photosensitivity can be used for grating writing immediately in the process of fiber drawing, before coating application [73].

Thermal stability of fiber gratings is one of the most important issues, because we need to know the grating lifetime both under normal conditions and at elevated temperatures encountered in many sensor applications. It is well known that the temperature-activated decay of UV-induced index depends on the operation temperature and time. As a rule, isochronal annealing is used to estimate thermal resistance of gratings. Type I gratings written in Ge-doped fibers start to decay at 300 ÷ 400°C and disappear completely at 600 ÷ 700°C [71]. These values are in a good agreement with the data on stability of paramagnetic GeE'-centers [74] to suggest that these defects are involved in the photorefractive effect. It was shown, in addition, that gratings written in Ge-doped fibers by 248 and 193 nm pulsed light[48] as well as by 333-364 nm cw radiation[31] possess approximately the same thermal stability. Hence one can infer that the final state of a UV-irradiated glass network does not depend on the specific irradiation wavelength.

Type II gratings feature an extremely high thermal stability, which is in good agreement with the fusion mechanism mentioned above.

The semiempirical Erdogan model [75] which was proposed in 1994 to explain thermal decay of grating remains most frequently cited and adequately describes most of the experimental data. According to this model, the UV-induced defects responsible for the induced index decay, when they overcome a certain energy barrier, whose magnitude has a broad distribution. The main conclusion that can be drawn from this model is that the residual induced index after the temperature exposure is defined by the thermal prehistory of the fiber. The model provides quantitative estimations of temporal degradation of photoinduced gratings. In addition, it is concluded that grating stability at high temperatures can be improved by preannealing of the grating. It is possible to calculate the necessary preannealing temperature and duration.

9. GRATING APPLICATIONS

In-fiber Bragg and long-period gratings are finding increasing use in various areas of science and technology. Excellent reviews devoted to applications of gratings have been published [4, 76, 77, 78]. The specific applications include narrow- and broad-band-stop reflection and loss filters, rare-earth-doped and Raman fiber lasers, semiconductor external grating cavity lasers, fiber grating interferometers, dispersion compensation and pulse compression schemes, fiber sensors, gain spectrum flattening of Er-doped fiber amplifiers, etc.

9.1. Fiber Bragg grating sensors

Fiber gratings written in the fiber core by UV radiation are often used as sensing elements. The gratings provide an all-fiber design of the sensor. Multiplexing of several gratings written in the same fiber allows the creation of a distributed sensor capable of measuring the spatial profile of a physical quantity.

Fiber-optic sensors based on Bragg grating can be classified into several types. Sensors of the first type detect the grating spectrum with a spectrum analyzer or a similar device. The intrinsic temperature sensitivity of Bragg gratings, written in the core of a silica fiber, is about 0.01 nm/°C. To obtain the resolution of 0.1°C, the spectrum analyzer must resolve the shift of the reflected wavelength to an accuracy of about 0.001 nm. Such a resolution might be achieved with a bench-top device, such as grating-based monochromator; however, incorporation of a small-size spectrometer with the above resolution into a fiber sensor is a complicated task. Nevertheless, in ref.[11], a temperature sensor was reported with a bulk diffraction grating and a CCD array. After computer processing of the recorded spectrum, an accuracy of 0.1°C was provided. Apart from monochromators, scanning Fabry-Perot interferometers, both of fiber and bulk types, are used as spectral devices to measure the Bragg wavelength shift.

Another group of fiber sensors is based on a narrow-band tunable light source. A tunable DFB laser diode or a broadband LED connected to a Fabry-Perot interferometer can be used as the light source. The reflected signal consists of short light pulses, arising at the moment when the source wavelength coincides with the Bragg wavelength. A change in temperature or stress, applied to the grating, causes a change in the phase difference between the signal controlling the source wavelength and the reflected light signal [79].

Sensors of the third type utilize a broadband light source and a passive optical filter. The spectral characteristic of the filter is chosen in such a way that the light amplitude is linear with wavelength. In addition, the dependence of light amplitude on wavelength should be sufficiently steep near the Bragg wavelength. The filter converts a change in the reflected light wavelength into a change in the detected

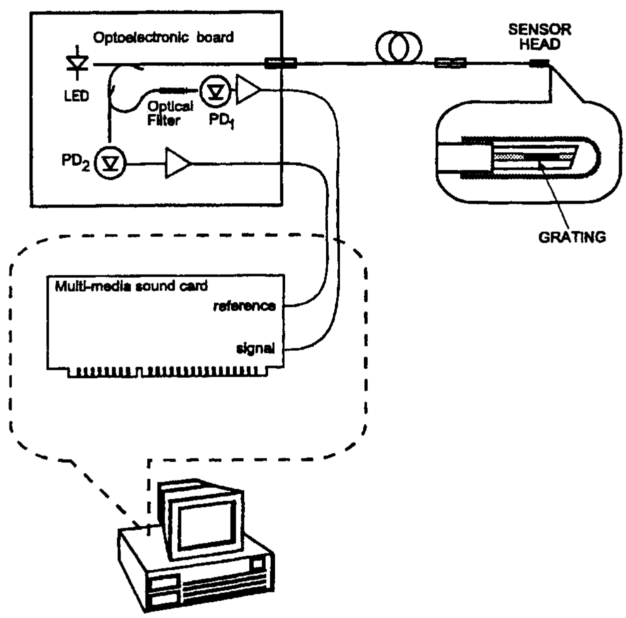

Fig.7. A scheme of the fiber optics temperature sensor [83].

signal amplitude. Selective fiber couplers [80], biconic filters [81], or long-period fiber gratings [82] have been proposed for use as a passive filter.

A simple scheme of temperature sensor, using a Bragg grating as a sensitive element, has been demonstrated in ref.[83] (fig.7). In this scheme a long-period grating is used to transform the temperature induced shift of the reflected light wavelength into the variation of amplitude of the detected signal. The sensor design provides insensitivity of the measured value to fluctuations of the optical source power and to fiber loss. The sensor is meant for measuring the temperature of remote objects at a distance of up to 1 km in the presence of strong electromagnetic fields and provides an accuracy of ± 1°C and a resolution of 0.1 - 0.2°C in the temperature range from −100 to +200 °C.

9.2. Long-period grating applications

As follows from the above consideration, LPGs can be used in various fiber devices, such as fiber sensors [15, 16, 21], narrow-band loss filters [12, 84], including tunable filters [85], modulators of optical radiation [86], etc.

One of the most important applications of LPGs in telecommunication systems is related to flattening gain spectrum of fiber amplifiers used in WDM/DWDM systems and to flattening spectra of broadband luminescence sources. The possibility of using LPGs for gain spectrum flattening of Er-doped fiber amplifiers was demonstrated in ref.[87]. The gain spectrum variation of less than 1 dB at a gain of more than 30 dB was obtained in a wide spectral range 1526 – 1560 nm. This result turned out to be comparable with the values attainable with the best flattening techniques. By using several LPGs, gain spectrum flatness of ~0.2 dB was achieved [88]. The main advantages of this method is simplicity of the grating fabrication, a wide spectral range and a high gain value of the flattened spectrum, low insertion loss at the pump wavelength, and the absence of back-reflected light.

LPGs are also efficient at smoothing amplified spontaneous luminescence spectra of Nd^{3+} (ref.[89]) and Er^{3+} (ref.[90]) ions. The power of such fiber broadband sources with flattened emission spectrum can achieve tens and hundreds of milliwatts.

CONCLUSION

At present, fiber gratings have become an important component of various fiber-optic systems. The ever-growing optical communication market, development of ultra-high-bit-rate communication systems, world-wide distribution of Internet, and intense interest in smart systems of control and diagnostics of different physical objects all require wide use of photoinduced fiber gratings. Investigation of the photorefractive effect in optical fibers, optimization of the existing grating writing techniques as well as development of new techniques are one of the most important problems of modern fiber optics.

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