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Progress in Photosensitivity – Fundamentals and Overview

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Abstract

A comprehensive survey of photosensitivity in glasses comprising permanent refractive index changes induced by laser exposure is reviewed. Progress, demands and remaining issues are discussed from various points of views such as pattern and properties of laser-written phase structures, assessment of glasses and dopants, characterisation and mechanisms of photosensitivity, benefits and potential applications, types and requirements of write lasers.

1. Introduction

A widely used definition of photosensitivity (PS) is the formation of a permanent refractive index change Δn by laser exposure. This phenomenon is of great practical importance to write directly micro- and nanostructures such as gratings and waveguides into glasses, which has an enormous impact on the fabrication, tailoring and design of optical and photonic devices. Main benefits of PS are manufacturing of phase (Δn) structures by fast and easy laser writing as well as creation of novel Δn structures, which cannot be provided by other methods.

PS is a multifaceted phenomenon. Depending on the certain interests of scientists, engineers and users, it is regarded from various point of views such as pattern and properties of laser-written Δn structures, assessment of glasses and dopants, characterisation and mechanisms of PS, benefits and potential applications, types and requirements of write lasers.

The aim of this paper is to review briefly the results obtained in the field of PS of glasses, which are covered by the definition given above. Since Δn creation is closely connected with other laser-induced phenomena such as defect formation, induced absorption and densification, results on these subjects are of interest, too, especially for understanding the mechanisms of PS which in turn is of practical importance for tailoring PS for definite applications. Beyond summarizing the progress in PS obtained so far, the paper is intended to highlight the issues and requirements relating to choice of glasses and lasers, elucidation of PS mechanisms and methods for PS characterization.

The growing attraction of PS is demonstrated by the vast number of references. This survey cannot go into details, but attempts to provide a comprehensive overview regarding the different points of views listed above. Section 2 reports the main features and fabrication techniques of different Δn structures. Section 3 summarizes glasses, dopants and lasers used to generate PS. Further, the relationships between glass absorption and write laser wavelength are examined. Section 4 describes the properties and potential applications of PS-based devices. Section 5 reviews the theories and models on PS mechanisms. Methods for determination of laser-induced refractive index changes and PS mechanisms are presented in Section 6. Last, the paper summarizes the progress in PS obtained so far and ventures an outlook over envisaged future trends.

2. Features and fabrication techniques of Δn structures

There are two main types of phase structures that differ in their refractive index patterns: gratings and waveguides. The feature of gratings is periodical Δn modulation as shown schematically for a fibre Bragg grating (FBG) in Figure 1a. Waveguides consist of constant Δn in one or two dimensions as depicted in Figure 1b for a channel waveguide. Recently, the combination of both structures has gained increasing attraction. First, writing a waveguide and then imprinting a grating in this waveguide. Other types of Δn structures are obtained by uniform exposure of a sample, which is less important for practical applications but very essential for characterisation of PS as shown below.

According to the patterns and dimensions of the Δn structures and of the starting devices in which they are imprinted, gratings and waveguides can be divided into different categories as shown in Table 1 [1-66]. Bragg gratings are characterized by Δn periods in the micro- and submicrometer range. Fibre Bragg gratings are one-dimensional (1D) gratings, which have been extensively studied in the last decade and are now commercial available. Recently, the formation of 1D Bragg gratings in channel waveguides of planar devices has gained attraction for fabrication of compact devices suitable for integrated optics. Planar or thin gratings (2D) are restricted to two dimensions either by the use of a thin photosensitive film or by strong absorption of the bulk glass at the write laser wavelength. Volume gratings (3D) have been imprinted in fibre preform slices (ca. 100-300 μm) for examination of PS mechanisms and in thicker glass samples (ca. 1-7 mm) for potential application in holographic information storage. In contrast to Bragg gratings, long period gratings have Δn periods of several hundred micrometers. They have been produced in optical fibres.

Similar to planar gratings, the dimension of 1D waveguides is restricted by thin photosensitive film or strong glass absorption. fs-laser-exposure in the near infrared enables fabrication of 1D waveguides inside of bulk samples. In glasses with a high transparency at the write laser wavelength, self-written 1D waveguides and direct-written 2D waveguides are obtained in bulk samples.

FBGs were first produced internally by launching laser light at 488 nm into a Ge-doped silica fibre. Backreflection from the fibre end resulted in a standing wave pattern inside the fibre core, which formed the grating. This method has nowadays no practical importance as it is restricted to the use of visible laser light and has low efficiency. Breakthroughs in FBG inscription were achieved by external side writing methods such as interferometric, phase-mask and point-by-point techniques [1,2,6,67]. Planar and volume gratings are exclusively fabricated by external methods [22-24,26,28,35,41,44].

Similar to gratings, waveguides can be written by self-induced or direct method. Self-writing is a recently developed technique of increasing interest [52-54,64,65]. Direct writing by sample translation is more frequently used because it does not make special demands on sample transparency and thus on write laser wavelength [48-51,55-63,66].

3. Glasses, dopants and writing lasers

PS has been studied for a large variety of glasses and dopants. Excluding fs-laser-exposure at about 800 nm, the glasses used for grating inscription and uniform laser exposure can be summarized into different groups according to their compositions and PS behaviour.

Bragg gratings and the extent of achievable Δn values have been thoroughly studied for silica-based glasses in form of optical fibres and preforms [1-14,68-73], thin films [18,20-22] and bulk samples [29,30]. Comprehensive information and detailed reference lists about PS of silica-based glasses using VUV and UV lasers (157-350 nm) are provided in excellent review articles [1-6]. PS was first discovered in Ge-doped silica. The common element in these glasses is the so-called germanium-oxygen-deficient-centre (GODC) at 240 nm. To enhance PS of Ge-doped silica, the impact of different codopants has been examined. For example, tin and boron dopants increase, but phosphorous decreases PS [1-4,11,12,20,21,30,68-70].

Further, Ge-free Al- and P-doped silica fibres and thin films have been of interest. In these glasses, rare earth ions (especially Ce^{3+}) or Sn ions are successful dopants to create PS by laser exposure at 240-300 nm [2-4,7-10,13,71,72]. In addition, high PS has been obtained in Sn-doped silica fibres [14]. A very efficient method to increase Δn by an order of magnitude to 10^{-3} is the treatment of silica-based fibres and thin films with hydrogen, mostly at low temperature and high pressure [1-5,9,10,18,29,30,69].

Fibre Bragg gratings were produced in Ce^{3+}-doped heavy metal fluoride (HMF) glasses using lasers at about 250 nm [15-17]. The impact of different rare earth ions on volume gratings in bulk HMF glasses [31] and on planar gratings in HMF glass thin films [24] was studied for laser exposure at 244 and 248 nm. Thin gratings in bulk undoped HMF glasses were obtained by laser irradiation at 193 nm [27].

Volume gratings using visible laser lines (455-488 nm) were imprinted in various oxide glasses doped with more than 1mol% Eu_2O_3. The refractive index change is generally lower than in photosensitive silica-based devices [32-41].

Volume gratings using laser exposure at 325 nm were obtained in multicomponent silicate glass containing silver, cerium and fluoride ions as active dopants [42-44].

There are a few studies on thin gratings in heavy metal oxide glasses (lead-silicate) [28] and thin films (lead-germanate) [23]. Using UV laser exposure (244-325 nm), high Δn values were created at the laser-exposed surface [28].

Recently, the PS of sodium-containing silicate glasses is of growing interest. In these glasses, first waveguides are produced by ion exchange and subsequently gratings or uniform refractive index changes are imprinted by UV laser exposure [19,25,26,74,75].

The effect of direct waveguide writing using lasers at 244 nm or 248 nm was studied for germanium-doped silica [48-50], fluorophosphate [51,66], sodium-germanium-borosilicate [55], lead-silicate [56] and sulphide [57] glasses. Blue or infrared laser light were used for self-induced waveguide writing in As-sulphide [52] and Ge-doped silica [53,54] thin films as well as in Ce^{3+} doped Ga-La-sulphide [64] and Nd^{3+}-doped borosilicate [65] bulk glass samples.

Using fs-laser-exposure in the near infrared, waveguides were directly imprinted in a variety of glasses with different compositions [58-63].

The lasers used mainly for studying PS and imprinting of Δn structures are listed in Table 2. In the UV range around 250 nm, cw and pulsed laser sources are available which differ in their properties. The pulsed KrF excimer laser at 248 nm provides plenty of power density, but the cw frequency-doubled argon ion laser at 244 nm exhibits a much higher energy and beam pointing stability and spatial coherence [1,67]. Thus depending on the certain applications, cw or pulsed lasers are favoured.

Magnitude and mechanism of PS depend on the relationships between glass absorption and write laser wavelength. One can distinguish three extreme cases as shown in Figure 2. I) The laser wavelength is in the range or even lower than the absorption edge of the glass. As a result of the strong laser beam absorption, one-photon-processes are prevailing and the laser-induced effects are restricted to a thin layer at the exposed sample surface. Examples are Ge-doped silica glass illuminated at 157 nm [2], HMF glass irradiated at 193 nm [27], lead-silicate [28,56] and sulphide [57] glasses under UV exposure. II) The write laser selectively excites localised defect or dopant states within the band gap. Examples are Ge-doped silica [1,2,20,21,30,70], Eu^{2+} and Ce^{3+} doped glasses [7-9,15-17,24,31,66,71,72] under UV exposure at 240-290 nm as well as Eu^{3+} doped glasses irradiated at 466 nm [34-41]. III) The laser wavelength does not coincide with linear glass absorption. However, nonlinear processes can create refractive index changes. In the case of fs-laser-exposure at about 800 nm, phase structures were produced in numerous glasses of different compositions owing to the large intensity at the focal point of the laser [58-63,76]. As a result of the highly nonlinear dependence of Δn formation on the beam intensity, the phase structures are restricted to the focal point [60,63,76]. This allows fabrication of localised structures inside of glass samples. Another example of PS formation driven by nonlinear processes is laser exposure of Ge-doped silica glass at 488 nm [1,2,6,53].

4. Properties and applications of different PS-based devices

Uniform FBGs are characterized by constant period of the grating planes, constant Δn modulation amplitude and phase fronts perpendicular to the fibre axis. A narrow band of the incident light within the fibre is reflected successive by scattering from the index variations. The strongest interaction or mode-coupling occurs at the Bragg wavelength given by $\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$, where λ_B is the free space centre wavelength of the back-reflected input light, n_{eff} is the effective refractive index of the fibre core at the free space centre wavelength and Λ is the grating period. The induced refractive index profile of a uniform sinusoidal FBG can be expressed as $\Delta n(z) = \Delta n_{mean} + \Delta n_{mod} \cdot \cos(2\pi z / \Lambda)$, where Δn_{mean} is the mean (average) refractive index change, Δn_{mod} is the induced refractive index modulation and z is the distance along the fibre longitudinal axis [1,2,6].

The reflectivity, R, of a uniform FBG at the centre wavelength increases with Δn_{mod} and grating length, L, $R = \tanh^2(\pi \cdot M_p \cdot \Delta n_{mod} \cdot L / \lambda)$, where M_p is the fraction of the single-mode power contained in the fibre core. When a grating is formed with a saturated exposure, then the effective length will be reduced as the transmitted signal is depleted by reflection. As a result, the spectrum will be broaden appreciably and depart from symmetric sinc or Gaussian shape spectrum whose width is inversely proportional to the grating length [1,2,6].

FBGs are attractive for a large number of various applications in telecommunication and laser systems based on selective separation of closely spaced wavelengths such narrow band add/drop filters, bandpass filters and laser cavity mirrors. Variation in grating period, Δn modulation amplitude pattern and phase front direction result in different types of FBGs with various properties used for dispersion compensation, gain flattening and mode conversion. Further, multiple and phase shift gratings are of practical importance [1,2,6,77]. Since both refractive index and grating spacing depend on temperature and strain, the Bragg wavelength is affected by these parameters. This phenomenon is utilized in FBG sensors [1,2,6], but it is detrimental in dense multiplexing (DWDM) systems with closely spaced signal channels [78].

Recently, the imprinting of 1D gratings in planar devices has received attraction for integrated optics [19,79]. Due to the short device length, only a short grating length is possible and thus a higher Δn is required in order to obtain high reflectivity as in long FBGs.

Planar and volume gratings are characterized by their diffraction efficiency which is defined as the ratio between diffracted and incident probe beam intensity. Usually, low-power HeNe laser at 633 nm is used as probe laser. The maximum diffraction is obtained at the Bragg angle, which depends on probe wavelength, λ_p, and grating period, Λ, $\sin\theta_B = \lambda_p / (2 \cdot \Lambda)$. In the planar wave approximation of Kogelnik's theory [80], the diffraction efficiency of a transmission grating is given by $\eta = \sin^2(\pi \cdot \Delta n \cdot L / (\lambda_p \cdot \cos\theta_B)$. Similar to FBGs, the diffractivity depends on Δn modulation amplitude and grating length. In the simplest case, the grating length is proposed to be equal to the sample or film thickness. However, if the sample absorbs strongly the write laser beam, improvements of the simple model are necessary. One approach is introduction of an effective grating (or sample) thickness at 1/e distance, $d_{\text{eff}}=1/\alpha_w$, determined from the absorption coefficient at the write laser wavelength, α_w, [31]. Another approach is modelling of the Δn profile with grating length, i.e. sample depth, z, by an exponential decay function, $\Delta n(z)=\Delta n_0 \exp(-\alpha_w z)$, where Δn_0 is the refractive index change at the exposed sample surface [25,28,30]. Hamad and Wickstedt [81] developed an accurate model taking into account the impact of write laser absorption and ratio of the sample thickness to that of the overlap length of the intersecting write beams on efficiency and spatial profile of diffraction.

The most important application of volume gratings is holographic information storage, where the object is placed in one of the write beams. For writing, both object and reference beams are turned on with high power. For reading, only the reference beam is used at low power. Compared with crystals such as $LiNbO_3$, glasses are of advantage concerning long-term storage, room temperature operation and multiple readings without degradation. At high write power, even real-time processing is possible [33,42,82]. Other potential applications are based on the high spectral and angular selectivity of thick Bragg gratings such as narrow band filters, mode selectors, spatial filters and optical switchers, which are used in telecommunications and laser systems [42,82].

Waveguide writing is very attractive for fabrication of channel waveguides in compact optical devices. Compared with photolithography and reactive ion etching, it is an easy and fast process [49,50,55]. The absence of sharp bends minimizes radiation losses. In case of self-writing, buried waveguides can be produced in one-step and complex structures can be tailored by the write beam shape [64,65]. Waveguides are characterized by several methods: recording of waveguide images and mode profiles, detection of surface changes by optical and atomic force microscopy or profilometer runs, measurement of propagation losses [49,50,55-59,63,66]. Compared with FBGs, the determination of Δn of waveguiding structures in planar devices is difficult. In case of complex non-circular mode profiles, modelling is required to deduce accurate Δn values from numerical aperture measurements. Furthermore, attenuation loss affects mode profile, numerical aperture and thus refractive index change. In case of self-writing experiment, Δn is determined from simulation of the beam output narrowing during the writing process [64,65].

The knowledge of the growth and decay dynamics of PS is of importance for tailoring and characterisation of PS. On the one side, the growth of Δn and related parameters such as reflectivity of FBGs and diffractivity of volume gratings depends on exposure time and dosage. On the other side, they are affected by power density and fluence per pulse. The slope of the latter type of growth curves provides information about the contributions of linear and nonlinear processes [1-5,9,31,35,41,70]. For combination of waveguide and grating inscription, growth curves are necessary to know the suitable power density values for first waveguide writing and subsequently grating inscription in the laser-written waveguides. Decay dynamics of PS dependent on time and temperature are of practical implications to assess long-term and thermal stability of gratings. Generally, isochronal annealing experiments are used for modelling the decay by power law or aging curve approach [2].

5. Mechanisms of PS

The understanding of microscopic mechanisms of PS in glass is required for fully exploiting the potential of PS. Depending on glass composition and laser exposure conditions, several models are proposed to explain the experimental results. However, the complete understanding of the microscopic origins often remains an issue.

One main mechanism is described by the so-called colour centre model. It is based on defect centre related changes in the UV absorption that give rise to refractive index changes from the visible up to the infrared by the Kramers-Kronig (KK) relationship, $\Delta n(\lambda') = \frac{1}{2\pi^2} \cdot \int_{\lambda_1}^{\lambda_2} \frac{\Delta\alpha(\lambda)}{1-\lambda^2/\lambda'^2} d\lambda$, where $\Delta\alpha$ is the laser-induced absorption coefficient. λ_1 and λ_2 are the boundaries of the spectral range within which the absorption changes are taken into account. λ' is the wavelength at which the refractive index change is calculated [2,4,73]. A feature of this model is the selective excitation of defects and dopants. The subsequent processes can be divided in two types: photooxidation and sensitization. In case of photooxidation, the excited defects or dopants act as electron donors, e.g. GODC [1,2,20,21,30,68,70], Eu^{2+} [66] and Ce^{3+} [7,31,72] at about 250 nm irradiation. The electrons released from the donors are caught by traps in the glass matrix, leading to the formation of electron defect centres that demonstrate strong UV absorption as a results of higher polarizability, e.g. Ge E' or PO_3 defect centres. In case of sensitization, the excited electrons are not fully removed from the sensitizer ions, e.g. Tb^{3+} and Ce^{3+} ions under 250 nm irradiation. The energy released by relaxation to the ground state is transferred to the glass matrix resulting in the formation of intrinsic hole and electron defect centres [10,66]. Precise determination of the contribution of the colour centre model to Δn values obtained from grating reflectivity is complex since the KK relationship is strictly local [73]. It requires measurement of induced absorption spectra at different exposure times and power densities for modelling the periodic refractive index change along the fibre axis from induced absorption. Fourier analysis would give the mean refractive index change, Δn_{mean}, and the amplitude of the refractive index modulation, Δn_{mod}, corresponding to the induced absorption spectra. In case of saturation at high power densities, the sinusoidal pattern of the total refractive index change is more and more distorted. As a result, Δn_{mean} is greater than Δn_{mod}. Under this condition, the Δn value calculated directly by KK equation from induced absorption spectra obtained by uniform exposure at one power density cannot be related to Δn_{mean} or Δn_{mod} measured from Bragg wavelength shift and grating reflectivity, respectively. In addition, the precise use of the KK relationship requires absorption measurements covering the whole range of absorption changes. However, if a large part takes place in the VUV region, measuring facilities are often lacking. Further, a shift of the absorption edge cannot be taken quantitatively into account. In case of strong attenuation of the laser beam inside the sample, models are required to extract an effective absorption change from the absorption profile with depth.

Another widespread contribution to PS especially in silica-based glasses is described by the so-called densification model [1-5,83]. Densification that means volume change is accommodated by photoelastic effect that means change in polarizability. According to the Lorentz-Lorenz-relationship, both effects result in refractive index increase. In silica-based glasses, densification originates from the collapse of high-order ring structures to low-membered ones. Depending on dopants, hydrogen treatment and write laser, densification or colour centre model contribute more or less to the observed refractive index change in silica glasses. For example, densification plays a main role in Al-doped silica, whereas the colour centre model accounts for a large part of the PS in hydrogen loaded Ge-doped silica [3-5].

In general, structural rearrangements under laser exposure may result in a refractive index change. In contrast to silica-based glasses, As_2S_3 and Zr-Ba-fluoride glasses having more dense structure demonstrate photoexpansion due to widening of interlayer distances, which gives rise to negative Δn [27,84].

The stability of PS depends on its formation mechanism. In case of structural changes, local melting or damage processes, thermally very stable refractive index changes can be obtained [1,2,4,5,47]. On the contrary, PS based on colour centre mechanism starts to be erased at about 100°C and can be fully annealed at 900°C due to low defect centre stability [1,2,20,21,68,70].

In Eu^{3+} doped glasses under exposure with visible laser lines, hot phonon-induced local structural modifications are responsible for PS. Nonradiative multiphonon relaxation after excitation of Eu^{3+} ions at or near 466 nm results in high local effective temperature which in turn allows ionic motion in the environment around Eu^{3+} ions. It is thought that two different configurations with different refractive index give rise to photosensitivity [35,38-41].

PS of so-called photo-thermo-refractive (PTR) glass is based on precipitation of microcrystals in the bulk glass exposed to near UV laser radiation at 325 nm. PTR glasses are multicomponent silicate glasses doped with cerium, silver and fluorine. First UV exposure releases electrons from the cerium ions that are trapped by silver ions. Thermal treatment at 450-550°C leads to formation of metallic silver particles, which serve finally as nucleation centres for sodium fluoride microcrystal growth at 500-550°C. After this stage, refractive index decreases in exposed areas due to the lower refractive index of the crystalline phase compared with the glass matrix [42,44].

6. Methods for characterisation of PS

The most important parameter to characterize PS is of course the laser-induced refractive index change. The Δn modulation amplitude of gratings is determined from the reflectivity of FBGs [1,2,9,73] or diffraction efficiency of planar and volume gratings [9,15,24,25,28,30,31,44,81]. For FBGs, the mean refractive index change is measured from the shift of the Bragg wavelength [9,73] or from refractive index profiles [48,69]. Up to now, there is no standard method for determination of accurate refractive index changes of waveguiding structures written in planar devices as explained above. Employing exposure of a certain part of a sample (fibre, preform slices or glass plates), refractive index change at the exposed area can be measured by prism coupler method [26,75,85], dual-beam reflectance technique [86] or several interferometric methods such as Mach-Zehnder [74,87], in-fibre [71], dual-core fibre [72] and liquid-cell [88] interferometers.

Measurements of laser-induced absorption and electron spin resonance spectra provide information about defect centres and thus the contribution of the colour centre model [1,2,10,12,14,18,20,21,30,66,68,70,72,73,85]. Examination of surface changes is essential for assessment of laser-induced densification, expansion or damage of exposed glass samples [3-5,9,24,27,28,55,56].

7. Summary and outlook

PS in the sense of laser writing is an important tool in the design and fabrication of photonic devices. It is a fast and easy process and novel phase structures are possible. FBGs in silica-based glasses are well developed and already commercial available. They are of great importance in optical communications and laser systems. Further, they receive growing attraction for sensor applications. Gratings and waveguides in planar devices are of mounting interest because they enable the fabrication of compact devices for integrated optics. For this purpose, high refractive index changes of about 10^{-2} magnitude are required. Thus, much work is now undertaken to increase PS. The progress of PS of planar devices is closely connected with the progress in fabrication of thin photosensitive films. Bulk glasses have potential applications for high-density information storage by means of volume holograms. The future will show if they can compete with other materials studied for holographic storage.

The progress in PS is strongly connected with further improvement of lasers and fabrication techniques. The choice of glasses and dopants depends on the choice of the write lasers and the glass compatibility with a variety of other demands with regard to reliability and costs of PS-based devices.

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Table 1: Patterns and dimensions (D) of Δn structures and starting devices in which they are laser-written. Sample thickness is designated by d.

Δn structure			starting device		Refs.
type	dimension	description	dimension	description	
Bragg grating Λ ~ 0.5-5 μm	1D	fiber Bragg grating	1D	single-mode fiber	[1-17]
		channel waveguide Bragg grating		channel waveguide in planar device	[18,19]
	2D	planar or thin grating *limited to film dimension*	2D	thin film on substrate	[20-26]
		planar or thin grating *limited to exposed surface*		bulk glass with strong absorption at write laser wavelength	[27,28]
	3D	volume grating	3D	fiber preforms: d = 0.1-0.3 mm	[3-5,15,17]
				bulk samples: d = 1-7 mm	[29-44]
Long period grating Λ > 100 μm	1D	long period fiber grating	1D	single-mode fiber	[45-47]
Waveguides	1D	channel waveguide *limited to film dimension*	2D	thin film on substrate	[48-54]
		channel waveguide *limited to exposed surface*	3D	bulk glass with strong absorption at write laser wavelength	[55-57]
		channel waveguide *limited to focal point*		fs-laser-exposure	[58-63]
		channel waveguide *limited by self-writing*		bulk glass transparent at write laser wavelength	[64,65]
	>1D	multi-mode	3D	bulk glass transparent at write laser wavelength	[55,66]

Table 2: Lasers used for creation of photosensitivity.

spectral range	laser wavelength	laser type	regime
VUV	157nm	F_2	pulsed ~tens ns
UV	193nm	ArF excimer	pulsed ~tens ns
	244nm	Argon ion frequency doubled	cw
	248nm	KrF excimer	pulsed ~tens ns
	266nm	Nd:YAG frequency quadrupled	pulsed ~ tens ns
	325nm	HeCd	cw
VIS	455-488nm	Argon ion	cw
NIR	~800nm	Ti:sapphire	pulsed ~100fs

Figure 1: Schematic illustration of fiber Bragg grating (a) and channel waveguide (b).

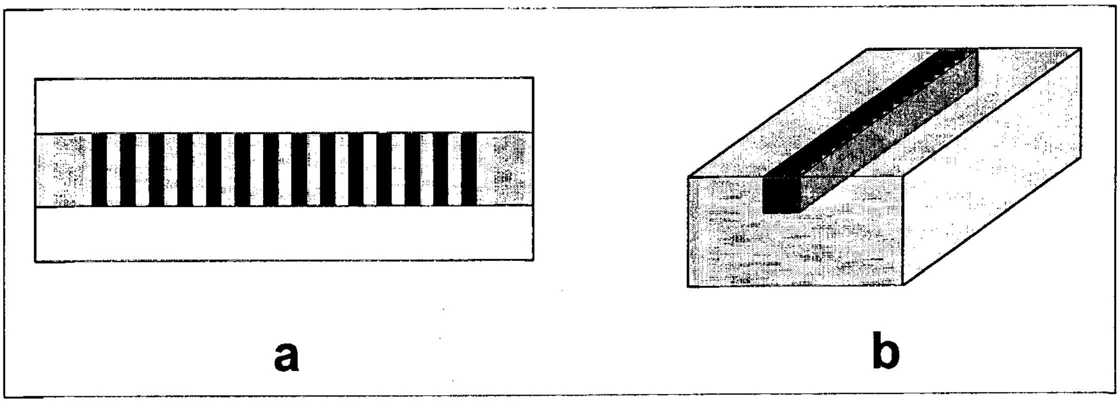

Figure 2: Schematic illustration of the relationship between glass absorption spectrum and write laser wavelength λ_w.