

Refractive index dispersion of doped silica for fiber optics

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Received 10 July 2002; received in revised form 19 September 2002; accepted 14 October 2002

Abstract

The spectral dependencies of refractive index have been measured in Ge-, P-, N-, Cl-, B-, F-, and Al-doped silica glasses as well as in undoped silica glasses using bulk prism samples cut from optical fiber preforms. The latter have been fabricated by MCVD-, PCVD-, and SPCVD-processes. Based on the experimental results, material dispersion in the glasses has been analyzed, which is one of the most important parameters for fiber optics. An assumption has been made regarding the origin of the significant discrepancy of the zero-dispersion wavelength of nominally identical glass compositions in different publications. The effect of chlorine admixture on the dispersion curves has been investigated. Nitrogen-doped silica is shown to be a promising material for broadband graded-index multimode fibers.

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PACS: 78.20.Ci; 42.81.Ht

Keywords: Refractive index dispersion; Chromatic dispersion; Material dispersion; Inter-modal dispersion; Multimode fiber; Nitrogen-doped silica fiber

1. Introduction

One of the basic parameters, characterizing a given glass as an optical material is the refractive index dispersion. This parameter is of a particular importance in complex optical systems, in which aberration due to dispersion is to be fully mini-

mized (e.g., in optical telescopes), or where the precise value of dispersion is to be known in a wide spectral range (e.g., in prism spectrum analyzers).

Refractive index dispersion is of major importance in fiber optic telecommunications. In particular, the information capacity of a single-mode fiber depends primarily on its chromatic dispersion. The latter consists of waveguide and material dispersion. The waveguide dispersion can be adjusted by choosing an appropriate refractive index profile of the fiber, whereas, the material disper-

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sion is an invariable characteristic of a specific material (e.g., see [1]). Therefore, reliable and accurate data on the material dispersion is indispensable in designing high-bit-rate optical communication systems.

$$M^{1/4} \frac{k d^2 n}{c dk^2} : \quad \text{§1P}$$

Multimode fibers are usually used in fiber-optic local area networks. In this case, inter-modal dispersion is the main factor limiting the information capacity (e.g., see [2]). A graded-index profile of the fiber core is used to minimize this dispersion. However, the optimal profile shape also depends on refractive index dispersion of the core and cladding materials and is defined by formula (2) [1,3]

$$\frac{n_1}{n_2} k^{1/4} n_1 \frac{dk}{dk} 1 + 2D \frac{r}{a} \frac{a_{opt}}{a} r^{1/2} \quad r < a \quad \text{§2P}$$

$$\frac{n_1}{n_2} k^{1/4} n_2 \quad r \geq a \quad \text{§2P}$$

where n_1 is the maximum value of core refractive index, n_2 the refractive index of cladding, $D^{1/4} n_1^2 + n_2^2 = 2n_1^2$, r the distance from the fiber center, and a is the core radius;

$$a_{opt}^{1/4} 2 p y + D \frac{\partial^4 p y}{\partial^5 p 2y} ; \quad \text{§3P}$$

where

$$y^{1/4} \cdot \frac{2n_1}{N_1} \frac{k}{D} \frac{dD}{dk} ; \quad \text{§4P}$$

and N_1 is the material group index:

$$N_1^{1/4} n_1 + k \frac{dn_1}{dk} ; \quad \text{§5P}$$

The last term in (3) is small and can be neglected.

As follows from (2)–(5), optimal profile parameter a_{opt} depends on the dispersion characteristics of core and cladding materials and varies with wavelength. Hence, it remains to be an acute task to find an optimal core material for which the a_{opt} parameter would not significantly depend on wavelength in a wide spectral region. Finding a single optimal profile for a wide spectral region would make it possible to use one and the same fiber at different wavelengths without a reduction of the bit-rate due to inter-modal dispersion. It would permit application of a practically unlimited

number of spectral channels and, hence, a dramatic increase of the information capacity of optical communication links. Thus, accurate determination of the material dispersion of the fiber glass is a topical problem.

Germanium is currently the most important dopant when forming the core of the silica fiber [4]. Apart from germanium some other dopants are used, e.g., phosphorus, fluorine, boron, and aluminum [3,5,6]. A comparatively new dopant is nitrogen [7]. In many ways nitrogen-doped-silica-core fibers are quite competitive with germanosilicate fibers. The former are superior to germanosilicate fibers in a number of parameters, such as radiation resistance and thermal resistance of in-fiber Bragg gratings [8–10]. Among the advantages of nitrogen-doped silica-core fibers is their potential low cost, because nitrogen is far cheaper than germanium and its resources cannot be exhausted.

Dispersion properties of doped glasses for fiber optics have been studied during the last 30 years; however, the results of different authors vary greatly (e.g., see [2,11]). This research work is aimed at clarifying the disputable points related to dispersion of glasses for fiber optics by means of increasing the accuracy and spectral range of the dispersion measurements. In addition to traditional dopants to silica, we investigate nitrogen and chlorine, the latter being an intrinsic technological admixture present in all optical fibers. We also compare data on undoped silica, synthesized by the modified chemical vapor deposition (MCVD) [12], plasma-activated chemical vapor deposition (PCVD) [13], surface plasma chemical vapor deposition (SPCVD) [14] technologies.

2. Experiment

The $n dk/d\lambda$ dependence was measured by the classic method of white light decomposition on a prism cut from the material under study. The optical scheme of the experimental set-up is shown in Fig. 1. A parallel white light beam from a halogen lamp was collimated by elliptic and parabolic mirrors and then fell on the prism. The decom-

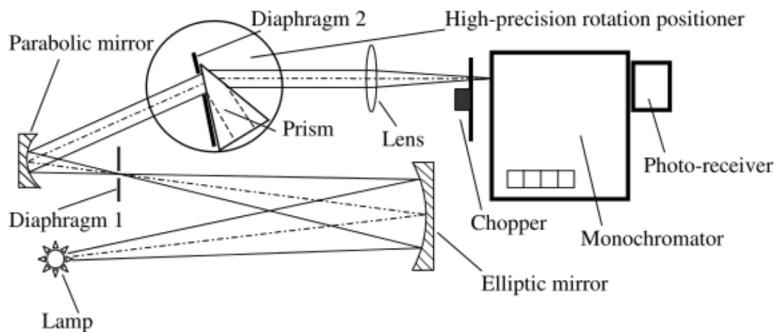


Fig. 1. Optical diagram of the experimental set-up.

posed light passed through a monochromator and was registered by a photoreceiver installed behind the exit slit of the monochromator. The prism was placed on a rotational micropositioner and the light wavelength incident on the monochromator entrance slit varying in rotating the prism (Fig. 2). The measuring procedure consisted in finding the prism rotation angle ensuring the maximal signal at the wavelength set by the monochromator. Knowing this angle, one can calculate the refractive index of the material at a given wavelength (see formula (6))

$$r_1 \approx \arcsin(\sin i_1) \approx n - 1;$$

$$i_2 \approx jr_1 + a_j \approx \arcsin(\sin i_2) \approx r_2;$$

$$h \approx i_1 + i_2 \approx r_1 + r_2 \approx i_1 + a_j r_2;$$

δ6p

All the angles in (6) are shown in Fig. 2.

The measurements were carried out in the wavelengths range 0.3-2.61 m with a step of 10-50 nm. As photoreceivers we used a photomultiplier for wavelengths 0.3-0.8 1 m and a cooled InSb photodiode for wavelengths 0.8-2.6 1 m. The

photoreceiver signal was processed by a lock-in. The lock-in, the rotational micropositioner, and the monochromator were controlled by a computer. Thus, the measuring procedure was fully automated.

The experimental set-up allowed measuring $n(k)$ to an accuracy better than 10^{-4} . For further data processing, in particular for defining material dispersion and a_{opt} from relations (1) and (3), the experimental points were approximated by three-term Selmeier formula (7) [4,15].

$$n^2 \approx 1 + \frac{a_i k^2}{k^2 + b_i^2}; \quad \text{δ7p}$$

where k is the wavelength, n the refractive index as a function of k , a_i the oscillator strength, and b_i is the oscillator resonance frequency.

Calculation of the derivatives based on approximation (7) depends on the spectral interval within which the measurements have been performed. For example, let us consider what would happen if we would not take into account some experimental points for sample 1 available for the spectral range 0.4-2.0 1 m. Removing the experimental points in the ranges between 0.3-0.4 and 2.05-2.6 1 m and thus narrowing the spectral interval lead us to the following values for Selmeier coefficients: $a_1 \approx 0.9415$; $b_1 \approx 0.07478$; $a_2 \approx 0.16251$; $b_2 \approx 0.14261$; $a_3 \approx 0.51434$; $b_3 \approx 7.64773$. These values significantly differ from those listed in the table. Obviously the derivatives of the $n(k)$ function will differ too. That is why it is very important to widen the spectral range in order to improve the accuracy of the derivatives of the $n(k)$ dependence.

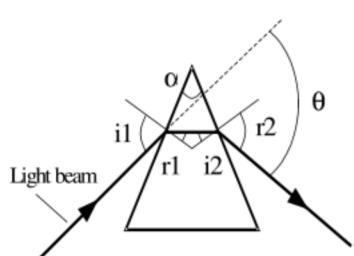


Fig. 2. Light dispersion in a prism.

Table 1
Experimental samples characterization

Number of sample	Preparing technology	Doping elements and its concentration	Dn	Sellmeier coefficients a_i	Sellmeier coefficients b_i
1	MCVD	Cl (\blacklozenge 0.06 wt%)	–	0.50716 0.59707 0.69879	0.04014 0.11359 8.81674
2	SPCVD	Cl (\blacklozenge 0.05 wt%)	–	0.70209 0.40292 1.60979	0.05714 0.1239 12.95448
3	PCVD	Cl (0.3 wt%)	–	0.88671 0.21675 0.69401	0.07954 0.1244 8.83315
4	SPCVD	Cl (3.4 wt%)	0.0029	0.53502 0.577 0.65548	0.04792 0.11548 8.63483
5	PCVD	F (0.9 wt%) Cl (0.13 wt%)) 0.0068	0.87219 0.21238 0.94959	0.07417 0.1298 10.22611
6	SPCVD	B (out of range of the spectrometer) Cl (\blacklozenge 0.06 wt%)) 0.0014	0.54956 0.55151 1.52791	0.03566 0.11823 12.54703
7	SPCVD	Al (4.9 wt%) Cl (\blacklozenge 0.06 wt%)	0.009	0.91249 0.21688 0.77945	0.08088 0.12558 9.39992
8	PCVD	GeO ₂ (4.5 mol%) Cl (0.16 wt%)	0.0062	0.49211 0.62925 0.59202	0.04807 0.11275 8.29299
9	PCVD	GeO ₂ (11.6 mol%) Cl (0.16 wt%)	0.0166	0.49795 0.65295 0.83515	0.04407 0.11754 9.86362
10	MCVD	P (12.5 wt%) Cl (\blacklozenge 0.03 wt%)	0.0135	0.51512 0.62804 1.0743	0.02636 0.11614 10.6931
11	SPCVD	N (1.6 wt%) Cl (0.9 wt%)	0.0151	0.49798 0.64994 1.39632	0.05043 0.11155 12.14576

Glass specimens studied are listed in Table 1. The prisms with a vertex angle of 30° were made of fiber preforms. The measurements were conducted in the working zone composed of the doped core of the preform (Fig. 3). The working zone was set aside by a diaphragm on the lateral prism surface. The core radius varied from sample to sample in

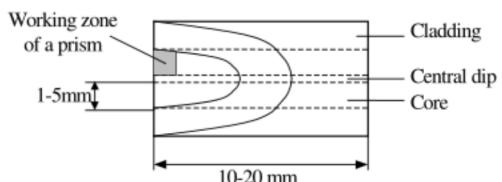


Fig. 3. Lateral view of a prism used in the experiments.

the range of 1–5 mm, inhomogeneity of the samples being less than 10^{-4} .

3. Results and discussion

The result of the $n\partial k/\partial \lambda$ measurement in undoped silica fabricated by the MCVD method is presented in Fig. 4. The solid line shows the approximation of the experimental points with the help of formula (7).

As is seen from Fig. 4, three-term Sellmeier relation (7) well approximates the experimental data in the spectral region under consideration. Unlike [16], where $n\partial k/\partial \lambda$ calculations were made from indirect measurements, no abnormality in the dispersion curve behavior, at least within the experimental error of less than 10^{-4} , was observed. Therefore, by contrast to [16] our data confirms applicability of formula (7) for approximation of $n\partial k/\partial \lambda$ curves in the region of high transparency.

The wavelength range in the vicinity of zero dispersion $k_0 \approx M \lambda_0^{1/4} / 0.1$, where temporal broadening of a signal propagating through a fiber is nearly minimal, is of much interest for fiber optics [11]. As was discussed above, dispersion in a single-mode fiber is primarily determined by the dispersion properties of the core material. Let us consider the results of the material dispersion measurements in various glasses for fiber optics. Fig. 5 shows $M \lambda_0^{1/4}$

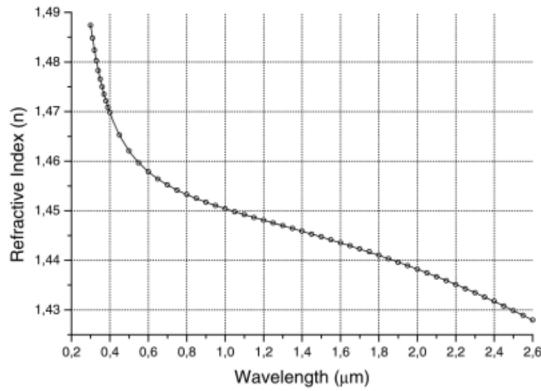


Fig. 4. Refractive index dispersion of undoped MCVD silica glass.

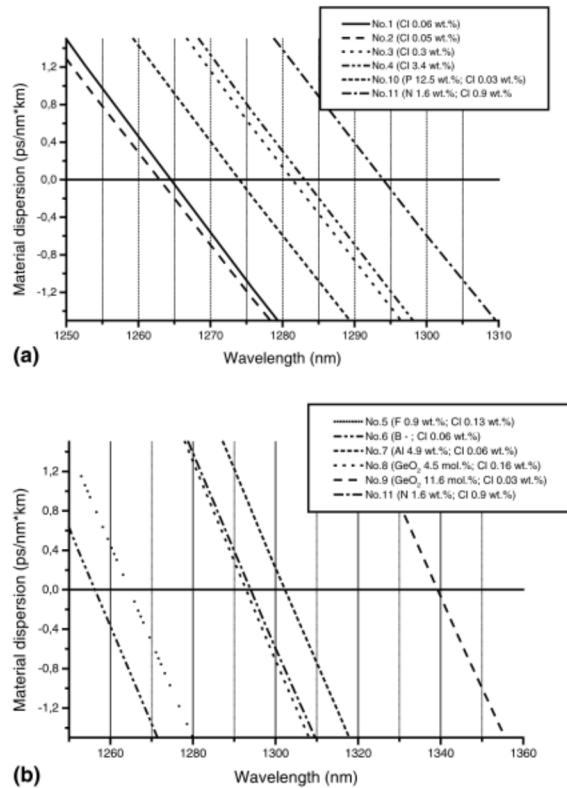


Fig. 5. Material dispersion of the glass samples.

plots for various silicas calculated from the experimental data by formula (1).

First, let us compare undoped silicas (Fig. 5(a)) fabricated by different technologies. As follows from Fig. 5(a), the values of k_0 for the MCVD and SPCVD glasses practically coincide; however, for the PCVD silica, k_0 is shifted to longer wavelengths. This can be due to different chlorine content in the glasses. According to the chemical analysis, the former two glasses contained 0.05–0.06 wt% of chlorine, while the latter contained 0.3 wt%. To check the assumption of the role of chlorine, we made a glass containing 3.4 wt% of chlorine using the SPCVD technology. It was found that the presence of chlorine in the glass did shift the zero dispersion wavelength to longer wavelengths (Fig. 5(a)). However, this shift turned out to be disproportionately great for the PCVD undoped silica. Note that literature values of the zero dispersion wavelength of undoped silica also

vary in the range 1.26–1.285 l m [6,11,17]. In all likelihood, it is peculiarities of the technological process (including deposition of silica on the inner surface of a substrate tube and its collapsing (e.g., see [12]) that influence the position of the zero dispersion wavelength. For example, technology-dependent point defects, such as oxygen-deficient centers or fabrication-induced stresses, can significantly influence the behavior of the dispersion curve. Although stress in fibers and fiber preforms may be rather different, we will not discuss here the influence of this important effect on fiber dispersion.

Now let us consider the behavior of zero dispersion wavelength in doped glasses for fiber optics (Table 1, Fig. 5). The k_0 value of the fluorine-doped glass practically coincides with that of undoped silica synthesized by the MCVD technology. Our result agrees with the data [6]; however, as well as in the case of undoped silica, the results obtained in different papers significantly vary [6,17].

Boron and fluorine incorporation in the glass decreases refractive index. But unlike fluorine, boron strongly shifts k_0 to shorter wavelengths. This property, as is known from [2], can be used to compensate the dispersion alteration due to germanium doping.

Aluminum is usually applied in erbium-doped active fiber. Al considerably influences the dispersion properties of silica, shifting k_0 to longer wavelengths. These data are in agreement with the results of previous research [3].

Germanium-doped silica is currently the most important material for fiber optics. We examined two specimens of germanosilicate glass obtained by the PCVD technology with different Ge content (Fig. 5(b)). In Fig. 6, the k_0 dependence on the amount of germanium dioxide in the glass is depicted. For comparison, the results of other papers [2,11,17,18] are given in the same plot. The solid line is a linear approximation of our results and those taken from the literature. As follows from Fig. 6, the results on germanosilicate glass considerably vary. This variation can be attributed to the peculiarities of the specific fabrication technologies, which might result in different concentration of chlorine and point defects, such as

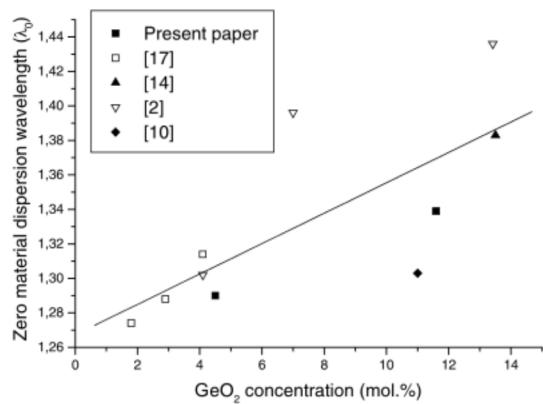


Fig. 6. Comparative data on zero material dispersion wavelength of Ge-doped glasses. The solid line is a linear fit of our results and those taken from the literature.

germanium oxygen-deficient centers (GODCs). The above factors are usually not taken into account in interpreting the refractive index dispersion in silica glasses. In particular, it is known that the GODCs concentration in glasses with the same germanium content can vary by four orders of magnitude [19] depending on the specific technology. It is likely that the concentration of point defects is the major cause of the k_0 discrepancy in different papers, because variations in the chlorine concentration cannot result in such a considerable k_0 shift (see Fig. 5(a)). The influence of specific point defects on the glass dispersion properties calls for further study.

Phosphorus-doped silica is also widely used in fiber optics and optoelectronics. Phosphorus incorporation in silica increases its refractive index practically without alteration of dispersion. It follows from [17] that k_0 in phosphorus-doped silica is insignificantly shifted to shorter wavelengths. According to our results, k_0 shifts to longer wavelengths, as compared to undoped MCVD silica, and to shorter wavelengths as compared to undoped silica fabricated by PCVD (Fig. 5(a)). Generally, it can be concluded that material dispersion of phosphorus-doped silica is similar to that of undoped silica. Hence, a unique property of phosphorus-doped silica, as follows from formula (2), is that it can be used for fabrication of wide-band multimode fibers with minimal inter-modal dispersion in a broad spectral

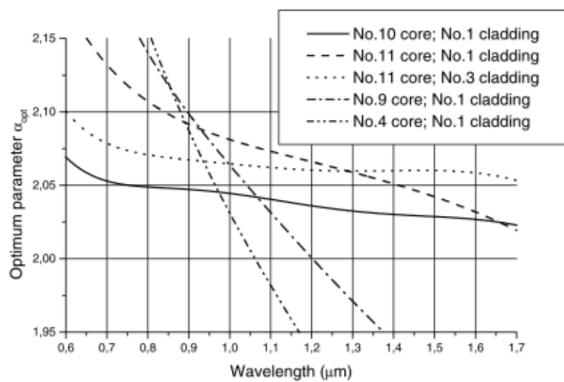


Fig. 7. Optimal a -profile parameter as a function of wavelength for multimode graded-index fibers of different glass compositions.

range. Fig. 7 shows the dependence of the optimal refractive index profile parameter a_{opt} , calculated by formula (2), on wavelength for variously doped glasses for fiber optics. A glass composition can be considered as optimal, if a_{opt} is practically unchanged in a wide spectral range. It is seen (Fig. 7) that the calculated index profile parameter a_{opt} varies only slightly in the case of phosphorus-doped silica, from 2.02 to 2.05, in the spectral range 0.7–1.71 m. This fact makes it possible to fully cover the currently existing spectral telecom windows using a unified refractive index shape of multimode graded-index fibers regardless of the specific spectral window.

Nitrogen-doped silica is of particular interest (Fig. 5(a) and (b)). Even a small addition of nitrogen strongly increases the refractive index of silica (Table 1). Therewith, nitrogen doping does not significantly alter the material dispersion of silica (Fig. 5(b)). It should be noted that chlorine admixture also influences the dispersion of nitrogen-doped silica (Table 1). Thus, if we take into account the chlorine contribution, the dispersion alteration caused immediately by nitrogen incorporation will turn out to be minimal. In other words, as a result of nitrogen doping the refractive index of silica increases evenly in a wide spectral region. This fact opens up possibilities for using nitrogen-doped silica as the core material of wide-band graded-index fibers. As follows from formula (2), the fiber cladding material considerably influences the a_{opt} value.

Until recently, multimode graded-index fibers with an undoped silica cladding and phosphorus-doped silica core were known to be the only candidates for applications in wide spectral ranges. As is seen from Fig. 7, a_{opt} for nitrogen-doped-silica-core undoped-silica-cladding fibers does not strongly depend on wavelength either. For comparison, similar dependencies are also depicted for such dopants as germanium and chlorine. When finding optimal technology, it is necessary to keep in mind a considerable influence of chlorine contained in both core and cladding of the fiber, as well as an influence of possible point defects, on a_{opt} . To illustrate such possible effects, Fig. 7 shows a_{opt} dependences for identical nitrogen-doped-silica-core fibers with an undoped silica cladding fabricated by different methods. Thus, by optimizing the chlorine concentration in the core of graded-index nitrogen-doped silica fibers with regard to the dispersion properties of the undoped cladding, one can minimize the inter-modal dispersion in the fibers simultaneously in the whole range from 0.7 to 1.71 m.

4. Conclusion

The refractive index as a function of wavelength was directly measured to a high accuracy in a wide spectral range for standard and new silicas for fiber optics. The results of the measurements were used to analyze the material dispersion of these glasses. The influence of the technological chlorine impurity on the dispersion curves was revealed. The dispersion parameters of new materials for fiber optics, e.g., nitrogen-doped silica, were determined. In particular, it was found that nitrogen-doped silica is a well-suited material for wide-band graded-index fibers. It was shown that the dispersion properties of such fibers can be easily optimized for any type of silica used in the cladding.

Acknowledgements

The authors are grateful to Dr. M.M. Bubnov for MCVD specimens supply and to Dr. V.M. Mashinsky for a fruitful discussion of the results achieved.

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