*Optica Applicata, Vol. XVI, No. 1, 1986*

# On the refractive dispersion index of optical fibres

Mirosława Bożyk

Department of Physics, Technical University of Białystok, ul. Wiejska 45a, 15-351 Białystok, Poland.

The behaviour of spectral dispersion in two-layer optical fibres of the step-index type (thin-layer 2wBc and high aperture 2wLS) and in a gradient four-layer fibre 4wHB was studied. The refractive indices of the various layers of the fibres were determined by the transverse interference method using an interferometer of the "shearing" type. The effect of different dispersions of the immersion medium and the fibre material on the measurement of the difference in the optical paths in the fringe interference field was also investigated. The results of investigations of the dispersion in the fibres were compared with the dispersion curves of the initial glass used in production of these fibres. For fibre 2wLS a change in the parameter $\Delta n$ as a function of wavelength $\lambda$ was found and an approximately 11% increase of the mean dispersion value of its core in comparison with the mean dispersion of the initial material was noted. In the other fibres an agreement of the values of the respective mean dispersion with an accuracy of $\pm 5\%$ was found.

## 1. Introduction

The distortion of light impulses transmitted by glass optical fibres is mainly caused by the property of the material (material dispersion) and the construction of the optical waveguide (mode dispersion). The increasing time of a light impulse per unit fibre length due to material dispersion is determined by the equation [1]

$$\Delta\delta = -\frac{\lambda}{c}\frac{d^2n}{\delta\lambda^2}\Delta\lambda \tag{1}$$

where $\frac{\lambda}{c}\frac{d^2n}{d\lambda^2} = \frac{d\delta}{d\lambda}$ is the core material dispersion.

As far as the design and production of optical fibres as well as their latter application are concerned, it is of great importance to find spectral fields such that the material dispersion be minimum and the information transmitted at the maximum speed. The determination of the dependence $\Delta n(\lambda)$ in the optical fibre indicates that such a fibre does not function properly as a centre of light propagation, which can be used whenever it is necessary to maintain a constant value $\Delta n$ in a given spectral range.

## 2. The effect of difference in dispersions of immersion fluids and the fibre on the measurement of the difference between optical paths

For the correct measurement of differences in optical paths in two- (or more) layer optical fibres, it is essential that the interference orders be correctly assigned to the deflected fringe in the fibres. Direct identification of the interference orders is possible if the following conditions are fulfilled [2]:

$$n_m(\lambda)-n_{r_i(p)}(\lambda) = \text{const}, \tag{2}$$

$$n_{r_i}(\lambda)-n_p(\lambda) = \text{const} \tag{3}$$

or

$$R_{r_i(p)} = \text{const} \tag{4}$$

and

$$\Delta = \frac{n_{r_i}-n_p}{n_{r_i}} \ll 1 \tag{5}$$

where: $n_m$, $n_p$, and $n_{r_i}$ — refractive indices of the immersion fluid cladding and core, respectively, $i = 0, 1, 2, 3, \ldots$ — number of internal layers of multilayer fibre cores, and $n_{r(i=0)}$ denotes the refractive index of the central layer near the axis (and $R_{r_i(p)}$ — deflection of the interference fringe in the core) cladding, $R_{r(i=0)}$ being the deflection on the fibre axis.

In transverse interference methods in which the fibres should be immersed in a fluid the refractive index of which is chosen so that $n_m = n_p$, the mean dispersions of the fluid and those of the various fibre layers are usually not equal.

In white light, this difference results in coloration of the zero fringes of the interference order in the fibre pattern and in achromatization of the fringe of a higher order. Coloration of the zero fringe within the cladding and core (in the area of their total splitting) is the same (Fig. 1) when the condition (3) holds, otherwise it changes which (Fig. 2b) indicates that the parameter $\Delta n = n_r - n_p$ of the fibre depends on the wavelength $\lambda$.

Chromatization of the zero fringe of the interference order does not make difficult the identification of interference orders if the difference in refractive indices between the cladding and the core or any of the internal layers of the fiber is small. The deflection of the fringes in the core is then not greater than $1\lambda$, which guarantees an easily confirmed coupling of the deflected fringes with the non-deflected ones. For high-aperture fibres, where $\Delta n \geq 0.1$, it is advisable to use sufficiently strong objectives to ensure clearly evident coupling of the fringe (Fig. 2a, b) and (Fig. 3a, b), bearing in mind that in the area within

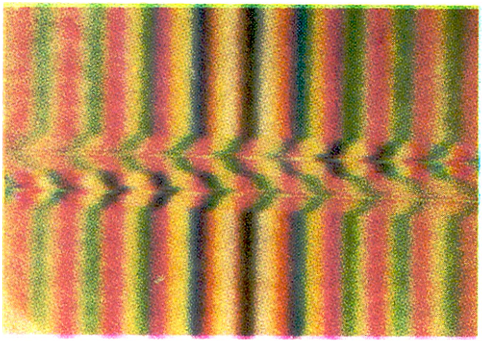
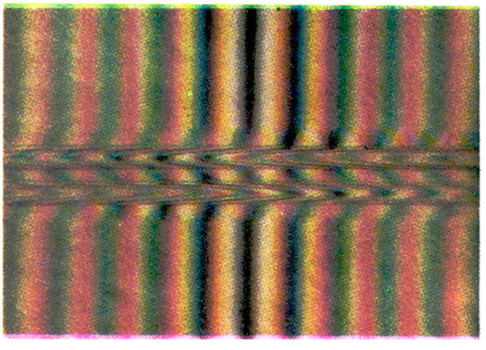


Fig. 1. Complete splitting of the pattern of a two-layer optical fibre, 2wBc, in the striated interference field: $n_m = n_p = 1.5373$. Photograph magnification $130\times$, $t = 19.7°$ C



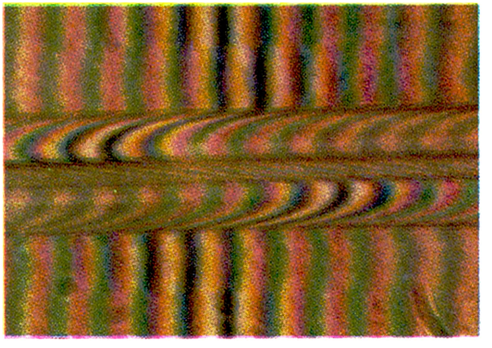
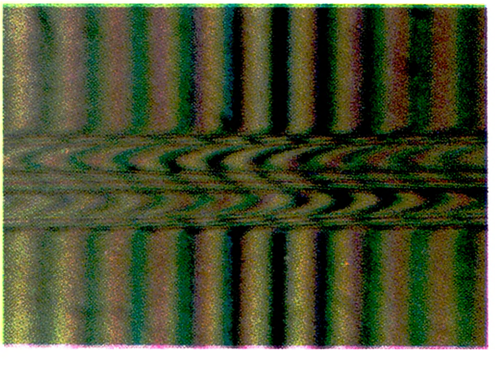


Fig. 2. Splitting of the pattern of a high-aperture optical fibre, 2wLS, in the fringe interference field: **a** – objective magnification $10\times$, photograph magnification $130\times$, **b** – objective magnification $40\times$ ($n_m = n_p = 1.5682$, $t = 17.5°$ C)



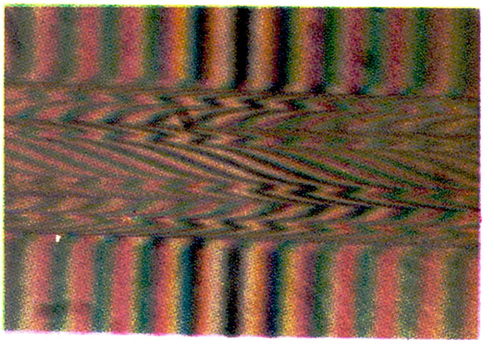


Fig. 3. Splitting of the pattern of a four-layer optical fibre, 4wHB [3], in the fringe interference field: **a** – objective magnification $10\times$, photograph magnification $130\times$, **b** – objective magnification $20\times$, photograph magnification $260\times$ ($n_m = n_p = 1.5083$, $t = 17.5°$ C)

the edge and the fibre axis the differences in the optical paths can be measured only when $d_r = 2\times 500/\beta_{max}$, where: $d_r$ — core diameter, $\beta_{max}$ — maximum objective magnification. When the interference fringe deflection exceeds 3 interfringe distances, the objectives of a high magnification are not useful and some other methods of identifying the interference orders in the fibre pattern should be found.

## 3. Measurement of optical fibre spectral dispersion

In spectral dispersion of two-layer optical fibres of the "step-index" type (fibres 2wBc and 2wLS) was determined by applying the transverse interference method, described in a previous paper [4], assuming a step distribution of the refractive index on the cladding — core border. In four-layer gradient fibres, 4wHB, however, this dispersion was determined by the zone approximation interference method [5]. In both the methods, we used an interferometer of the "shearing" type, i.e., a Biolar PI interference-polarization microscope. The measurements were made in a fringe interference field, the fibres being arranged perpendicularly to the direction of the fringes from the background of the visual field [6]. The refractive indices in various layers of the fibres were determined for the selected wavelengths in a spectral range of 450–650 nm. The required wavelengths were obtained using interference filters produced by VEB Carl Zeiss, Jena, and PZO, Warsaw. A highly monochromatic light source — He-Ne laser — was also used.

The refractive index of the cladding $n_p = n_m$ was determined by a generating the refractive coefficient gradient of the immersion medium in which the fibre under study was immersed [7]. This method makes it possible to measure the deflection of the fringe in the core (in the internal layers of the fibre if multilayered) without the troublesome and time-consuming procedure of changing the immersion fluid for each wavelength $\lambda$ used in the experiment.

### 3.1. Analysis of the results of the measurements

The behaviour of the spectral dispersions in the optical fibres observed in the photomicrographs (Figs. 1, 2 and 3) confirms the reciprocal positions of the immersion fluid and fibre dispersion curves presented in Figs. 4, 5 and 6.

The course of the immersion fluid dispersion curves in parallel to that of the core dispersion occurred only in fibre 2wLS (Fig. 5 — curves 2, 3, 4, 5, and 6), as indicated by the achromatism of the zero fringe of the interference order in the core of this fibre (Fig. 2). In other fibres and in the 2wLS fibre cladding, marked differences in the mean dispersion values of the immersion fluids and various fibre layers (see the Table) cause a complete chromatization of the zero fringe of the interference order. The coloration of this fibre being the

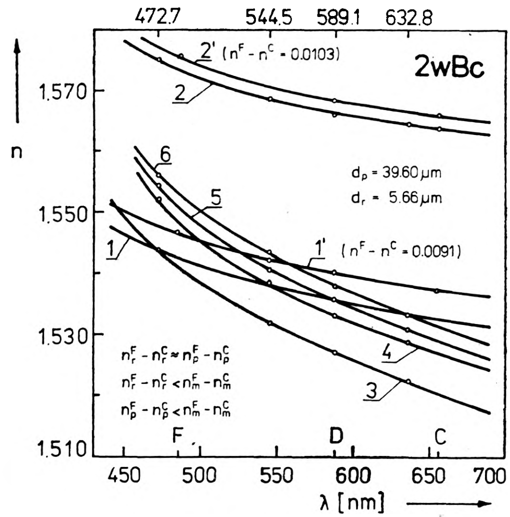



Fig. 4. Dispersion curves of fibre, 2wBc (1 — cladding, 2 — core), immersion fluids (curves 3, 4, 5 and 6) and the initial glass used for the cladding and core (curves 1′ and 2′)

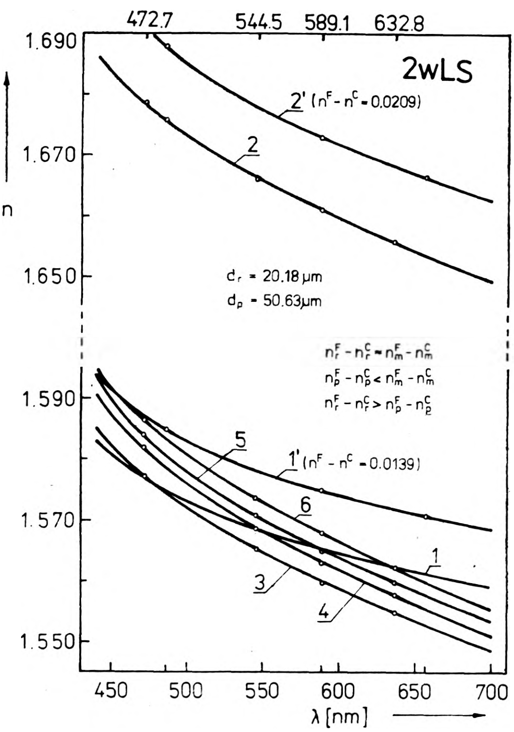



Fig. 5. Dispersion curves of fibre, 2wLS (1 — cladding, 2 — core), immersion fluids (curves 3, 4, 5 and 6) and initial glass used for the cladding and core (curves 1′ and 2′)

Mean values of cladding and core dispersion (compared with the mean values of the dispersion of the initial glasses), immersion fluids and the values of the fringe deflection $R_r$ determined for wavelengths in a spectral range of 450–650 nm

| Fibre | λ [nm] | $R_r$ [μm] | $n_p^F - n_p^C$ / $n^F - n^C$ | $n_r^F - n_r^C$ / $n^F - n^C$ | $n_{m_3}^F - n_{m_3}^C$ | $n_{m_4}^F - n_{m_4}^C$ | $n_{m_5}^F - n_{m_5}^C$ | $n_{m_6}^F - n_{m_6}^C$ |
|---|---|---|---|---|---|---|---|---|
| 2wBc | 472.7 | 62.3 | 0.0096 | 0.0102 | | | | |
| | 544.5 | 69.1 | | | | | | |
| | 589.1 | 59.3 | | | 0.0210 | 0.0215 | 0.0215 | 0.0217 |
| | 632.8 | 58.5 | 0.0091 | 0.0103 | | | | |
| 2wLS | 472.7 | 647.7 | 0.0140 | 0.0235 | | | | |
| | 544.5 | 647.7 | | | | | | |
| | 589.1 | 647.8 | 0.0139 | 0.0209 | 0.0235 | 0.0240 | 0.0242 | 0.0243 |
| | 632.8 | 647.6 | | | | | | |

| Fibre | λ [nm] | $R_{r(i=0)}$ [μm] | $R_{r(i=1)}$ [μm] | $R_{r(i=2)}$ [μm] | $n_p^F - n_p^C$ / $n^F - n^C$ | $n_{r_0}^F - n_{r_0}^C$ / $n^F - n^C$ | $n_{r_1}^F - n_{r_1}^C$ / $n^F - n^C$ | $n_{r_2}^F - n_{r_2}^C$ / $n^F - n^C$ | $n_{m_4}^F - n_{m_4}^C$ | $n_{m_5}^F - n_{m_5}^C$ | $n_{m_6}^F - n_{m_6}^C$ | $n_{m_7}^F - n_{m_7}^C$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4wHB | 472.7 | 719.2 | 335.0 | 352.1 | 0.0095 | 0.0102 | 0.0095 | 0.0105 | | | | |
| | 544.5 | 716.3 | 329.2 | 348.2 | | | | | | | | |
| | 589.1 | 716.3 | 327.0 | 347.8 | | | | | 0.0200 | 0.0197 | 0.0198 | 0.0220 |
| | 632.8 | 713.1 | 325.0 | 345.0 | 0.0094 | 0.0103 | 0.0091 | 0.0103 | | | | |

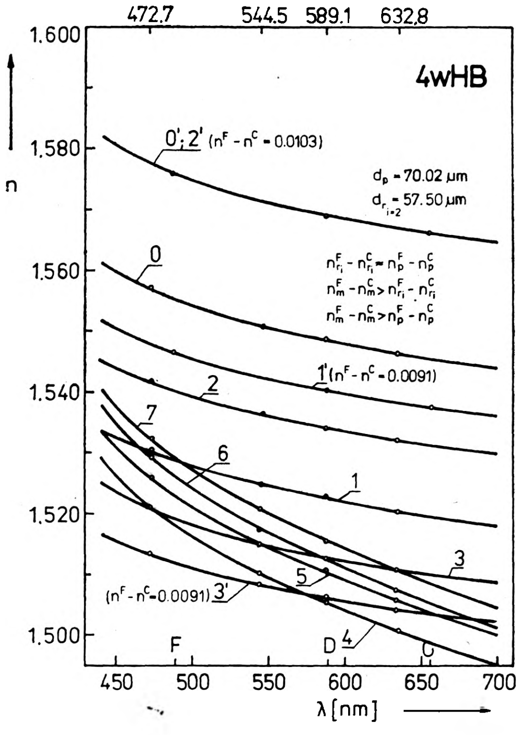



Fig. 6. Dispersion curves of fibre 4wHB (internal layers — 0, 1, and 2, cladding — 3), immersion fluids (curves 4, 5, 6 and 7) and the initial glass used for the three internal layers and cladding (curves 0, 1′, 2′ and 3′)

same within the whole area (Fig. 1 and Fig. 3) if the mean dispersions of its layers are equal (Tab. **A**, **C**) which indicates at the same time a reciprocal parallelity of the respective dispersion curves (Fig. 4 — curves 1 and 2, Fig. 6 — curves 0, 1, 2, and 3). If this condition is not fulfilled (Fig. 5 — curves 1 and 2), then the coloration of the fringe of the same order in the cladding and the core (Fig. 2) is different.

Studies of the fibre spectral dispersion are of importance not only in identifying interference orders but also in evaluating the propagation properties of the fibres. The results obtained in the present studies show that the mean dispersion of the refractive coefficients of the core (internal layers) and the 2wBc and 4wHB fibre claddings differed only slightly from the mean dispersions of the initial glasses used for the production of the fibres (the curves 1, 1′, 2, 2′ in Fig. 4, as well as the curves 0, 0′, 1, 1′, 2, 2′ 3, 3′ in Fig. 6 are parallel to each other).

The values of these dispersions (Tab.) were consistent with the accuracy of ±5 %. In the fibres, 2wBc and 4wHB, no changes were observed in the parameter $\Delta n$ as a function of wavelength $\lambda$. The only exception was observed in fibre 2wLS, in which the parameter $\Delta n$ decreased substantially with the increasing wavelength, and for the extreme values of $\lambda$ in the applied spectral range, i.e., for $\lambda = 632.8$ nm and $\lambda = 472.7$ nm, the values of $\Delta n$ were 0.0885 and 0.1005, respectively. A similar relation, though not so striking as in the fibre, was noted in the initial glass used for the cladding and the core (Fig. 5 — curves 1 and 2). The mean dispersion of the 2wLS fibre core amounting to 0.0026 increased with respect to the mean dispersion values of the initial glass ($n^F - n^C = 0.0209$) used for the core.

## 4. Discussion of errors

The accuracy of the dispersion investigations carried out by the interference method depends mainly on the accuracy of the measurement of the difference in the optical paths and on the variant of the transverse interference method adopted for determining the distribution of the refractive index in the fibre. In these investigations, the accuracy of optical path difference determined by the visual method was $\pm 0.01$ μm. On the other hand, the accuracy of the transverse interference method variant adopted was $\pm 10\%$ $\Delta n$ for "step-index" type fibres (fibres 2wBc and 2wLS) and $\pm 7\%$ $\Delta n$ for the "gradient-index" type (fibre 4wHB) [8]. The refractive index of the cladding $n_p = n_m$ was determined by means of refractometric plates with the accuracy of $\pm 0.0005$, taking account of the effect of temperature on the refractive coefficient of immersion fluid [7].

The parameters of the fibre geometry essential in calculations were determined by the microscopic method using phase contrast [9, 10] with the accuracy of $\pm 0.06$ μm. The wavelengths obtained by means of interference filters were determined by the interference method [11] with the accuracy of $\pm 0.005$ μm.

## 5. Conclusions

As these studies have shown, the magnitude of interference deflection in the core of two-layer (in the internal layers if the fibre is multilayer) depends on the value of the parameter $\Delta n = n_r - n_p$ and the type of immersion medium used. For the measurements of optical fibre dispersion by the transverse interference method the best conditions are those in which $n_m = n_p$, since then it is possible to determine the cladding refractive index and at the same time to measure the deflection of the fringe in the internal (core) layers of the fibre. This can be done directly only when the equation

$$n_m^F - n_m^C = n_p^F - n_p^C = n_r^F - n_r^C$$

guaranteeing the achromatism of the zero fringe of the interference order in white light is satisfied.

An appropriate identification of the interference orders is of a particular importance when the measurements are made in a monochromatic light in which the differences in the colour of the fringes are not visible and the resulting pattern may lead (usually where the $\Delta n$ values are high) to an erroneous assignment of interference orders to the deflected fringes.

The studies of the spectral dispersion in optical fibres (and even a visual analysis of the interference pattern of the fibre observed in white light) make it possible to classify the fibres according to their propagation properties. The difference in the colour of fringes of the same order in the area of a complete fibre splitting indicates that the parameter $\Delta n$ depends on the wavelength $\lambda$ (where the coloration of striae of the same order is the same in the cladding and in the core $\Delta n(\lambda) = \text{const}$).

In view of the fact that the spectral dispersion in the optical fibres may behave in different ways, the dispersion relations of the materials used in the production of the fibres and of the optical fibres themselves should be known. This means that the requirements concerning compulsory refractometric investigations of the initial materials and fibres as well as of the techniques of such investigations should be more strict.

*Acknowledgements* — The author wishes to express her gratitude to Prof. Maksymilian Pluta of the Central Optics Laboratory, Warsaw, for his valuable comments and advice on these studies.

## References

[1] Cozens J. R., Electron. Lett. **12** (1976), 413–417.
[2] Dorau K., Pluta M., Przegląd Włókienniczy (in Polish) **2** (1981), 70–75.
[3] Dorosz J., Romaniuk R., [in] *III Krajowe Sympozjum: Światłowody i ich zastosowanie*, Jabłonna 1982 (in Polish), Vol. 1, 1982, 29–41.
[4] Pluta M., [in] *II Krajowe Sympozjum: Światłowody i ich zastosowanie*, Jabłonna 1979 (in Polish), Vol. 2, 1979, 148–177.
[5] Bożyk M., Optica Applicata **12** (1982), 119–121.
[6] Pluta M., *Mikroskopia optyczna* (in Polish), PWN, Warszawa 1982, Chapt. 14.
[7] Bożyk M., Elektronika (in Polish) **6** (1983), 10–16.
[8] Bożyk M., Doctor's Thesis (in Polish), Institute of Physics, Warsaw Technical University, Warszawa 1983.
[9] Dorau K., Pluta M., Przegląd Włókienniczy (in Polish) **3** (1983), 112–120.
[10] Bożyk M., Optica Applicata **14** (1984), 31–37.
[11] Pluta M., Optica Applicata **12** (1982), 19–35.

*Received July 10, 1985*

## О дисперсии показателя преломления в оптических волокнах

Обследовано сохранение спектральной дисперсии в двухслойных оптических волокнах типа „step-index" (тонкопленочном 2wBe и высокоапертурном 2wLS) и градиентном четырехпленочном волокне 4wHB. Показатели преломления отдельных пленок волокон определены методом попереч-

ной интерференции с применением интерферометра типа „shearing". Обследовано тоже влияние разных дисперсий иммерсионной среды и материала волокон на измерение оптической разности хода в интерференционном полосчатом поле. Полученные результаты дисперсионных измерений в оптических волокнах, сопоставлены с дисперсионными кривыми стекол, использованных в технологии для изготовления этих волокон. Для волокна 2wLS представлено измерение параметра $\Delta n$ как функцию долготы волны $\lambda$, а тоже рост (ок. 11%) числового значения средней дисперсии его сердцевины в сопоставлении со средней дисперсией выходного материала. Остальные волокна представляли согласие числовых значений соответствующих средних дисперсий с точностью $\pm 5\%$.