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Microinterferometric measurements of the refractive index in cylindric two-layer lightguides

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Interferometric measurement methods of the refractive profile $n(r)$ of the two-layer lightguide fibres made of multicomponent glass by using the two-crucible method are described. The results of the refractive index measurments along the fibre diameter are reported. The accuracy of the methods presented is compared.

1. Introduction

Wide and versatile application of the gradient lightguides in the integrated optics circuits, among others, encourages the elaboration of the methods of analysis and measurements of the gradient lightguide parameters, and, in particular, the distribution of the light refractive index along the fibre diameter. This distribution is usually called the refraction profile $n(r)$ of the fibre, where r is the distance from the core centre in the fibre cross-section.

The refraction profiles $n(r)$ of the optical fibres can be determined by using different methods, of which the interference [1, 2], transmission [3, 4] and reflection methods [5, 6] proved to be very useful in practice.

The application of the interference method to determine the refractive index profile $n(r)$ enables the more diversified examinations and measurements than those performed with the help of the other two methods [1].

The basic assumptions of the above method is the cylindric symmetry of the refractive index distribution in the fibre core. This distribution is well described by the function

$$n(r) = n(0)\left[1-\Delta\left(\frac{r}{a}\right)^{a}\right], \tag{1}$$

where, $\Delta = \dfrac{n(0)-n(a)}{n(0)}$,

$n(0)$, $n(a)$ — the refractive indices in the midpoint and at the edge of the fibre, respectively.

However, this assumption is not always fulfilled by the production technologies employed in practice. Preservation of the fibre and core diameters in all directions of the fibre cross-section remains still a very difficult and open problem.

The error due to nonconstant external diameter of the coating, which is introduced by the used technology may be eliminated, at least partially, in many ways. In this paper this is realized by equalizing the refractive index of the fibre coating with that of the immersion fluid.

The measurement of the refraction profile $n(r)$ by the interference method was made with the help of the Biolar PI interference-polarization microscope. This microscope belongs to the microinterferometers of shearing type in which two identical object waves, shifted transversally with respect to each other, interfere mutually. The produced interference image has the form of rectilinear interference fringes deformed in opposite directions and is situated at the place where the ordinary and extraordinary images of the object examined are formed.

The refraction profile $n(r)$ is here determined from the course of interference fringes by measuring point-by-point their deviation within the region of the examined fibre. It should be noticed that the images of the objects examined must be mutually sheared in, at least, 50%. Therefore, the thickness of the examined fibres is restricted and for the objective of magnification $10\times$ may not be greater than 64 μm.

2. The measurement of the averaged refraction profile $\bar{n}(r)$

The examined optical fibres obtained by the two-crucible method are characterized by continuous change of the refractive index at the core-coating border. The assumption of the refractive index steadiness within the fibre coating allows to employ the method of the refraction profile determination $n(r)$ for the lightguides of the step-index type described in paper [1] in order to determine the refractive index distribution in the fibres examined, i.e. to measure the so-called averaged refraction profile $n(r)$.

Following the method reported in [1] the fibre was placed in an immersion fluid of known refractive index n_m, being close to the refractive index of the coating n_p, and the differences in the optical paths were determined from the shape of the interference fringes using the formula

$$\delta_{(p,r)} = \frac{p-p_0}{h}\lambda, \tag{2}$$

where $\delta_{(p,r)}$ – optical path difference between an arbitrary ray passing through the coating (core) and the light running aside,

p_0 – position of the fringe of examined interference order outside the fibre region,

p – position of the fringe deviated in the fibre,

h – interfringe distance,

λ – wavelength of the light employed.

Next, by using the formulae

$$n_p = n_m + \frac{\delta_p}{2\sqrt{s_p(d_p - s_p)}}, \tag{3}$$

$$n_r = \frac{\delta_r - 2\sqrt{s_p(d_p - s_p)}\,(\bar{n}_p - n_m)}{2\sqrt{s_r(d_r - s_r)}} + n_p, \tag{4}$$

where s_p, s_r — distances from the edge of the coating and core, respectively,
d_p, d_r — thicknesses of the fibre and core, respectively,
n_p, n_r — refractive indices of the coating and core, respectively,
first the refractive index distribution in the coating (3) was determined, then from the values of n_p the average value of $\bar{n}_p$ = const was estimated, finally by using (4) the refractive index distribution in the lightguide core was found.

The parameters p, p_0, h appearing in the formula (2) and the parameters s_p, d_p, s_r, d_r from the formulae (3) and (4), may be measured directly with the help of a micrometer ocular or, as it has been done in this work, by making a photo of the fibre image and analysing the negative with the help of a universal measuring microscope Universal-Meßmikroskop (UM).

It is possible to obtain a negative of sufficiently sharp interference fringes (fig. 1) when the respective photomicrographies are properly made and processed.

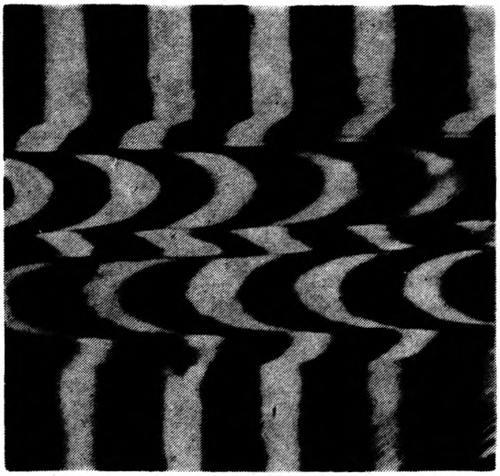

Fig. 1. Sheared image of the lightguide fibre in the field of interference fringes, $n_m < n_p$. Photographic magnification 607 ×

The error of δ_p and δ_r measurement depends closely on the way of fixing the position of maximal blacking of the examined interference fringes. In the method applied this position was determined visually and the measurement error was about 0.02 λ.

The advantage offered by this method is that there exists a possibility of repetitive measurement of these parameters under the same (unchanged) experimental conditions recorded on the film. The emploiment of a photometer coupled with a microscope allows to determine δ with the accuracy greater at least by one order of magnitude [7].

The refractive index of the immersion fluid n_m has been determined with the help of the Abbe refractometer assuring the accuracy $\pm 2\cdot 10^{-4}$ for the temperature 298 K read out with the accuracy ± 0.01 K.

The method of average refraction profile determination suffers from great error amounting to about ± 20 % (as it follows from the tables 1 and 2). Hence,

Table 1. Error of the refractive index measurement for the coating n_p

Source of error	Error of estimation	Measurement error for n_p
Measurement of δ_p		
$p-p_0$	$\pm 0.2\%$	
h	$\pm 0.1\%$	$\pm 0.5\%$
λ	$\pm 0.2\%$	
Measurement of position		
s_p	$\pm 0.1\%$	
d_p	$\pm 0.1\%$	$\pm 0.2\%$
Readout error	$\pm 0.5\%$	$\pm 0.5\%$
Measurement of n_m		
Accuracy of instrument	$\pm 2\cdot 10^{-4}$	$\pm 4\%$
$-\dfrac{\Delta n_m}{\Delta t}$ ($t = 278$ K)	$\pm 3.5\cdot 10^{-4}$	$\pm 3\%$
Readout error $t = 298$ K	$\pm 0.04\%$	$\pm 0.04\%$
Change in the external diameter of the fibre ($\Delta d_p = 1$ μm)		$\pm 2.9\%$
Total measurement error n_p		$\pm 7.1\%$

Table 2. Error of the refractive index n_r in core

Source of error	Error of estimation	Measurement error for n_r
Measurement of δ_r	$\pm 0.5\%$	$\pm 0.5\%$
Measurement of position		
s_r	$\pm 0.1\%$	
d_r	$\pm 0.1\%$	$\pm 0.2\%$
Readout error	$\pm 0.5\%$	$\pm 0.5\%$
Measurement of n_m		$\pm 6.4\%$
Measurement of n_p		$\pm 7.1\%$
Change in the fibre core diameter ($\Delta d_r = 1$μm)		$\pm 9.2\%$
Total measurement error n_r		$\pm 13.3\%$

the obtained refraction profile (fig. 2, curve 1) is of low accuracy and may not be used in deeper considerations concerning the phenomena occurring in the fibre at the core-coating border. The rapid changes of the refractive index in the core, which may be seen in the graph, are to a considerable degree caused by the deviation of the external coating surface from the cylindric form. However, for the technologists specializing in production of optical fibres the prifile obtained in this way offers information sufficient to determine the practical usefulness and applicability of the lightguides produced. The low cost of the method described and a relatively easy construction of the measuring setup provide additional advantages from the practical viewpoint.

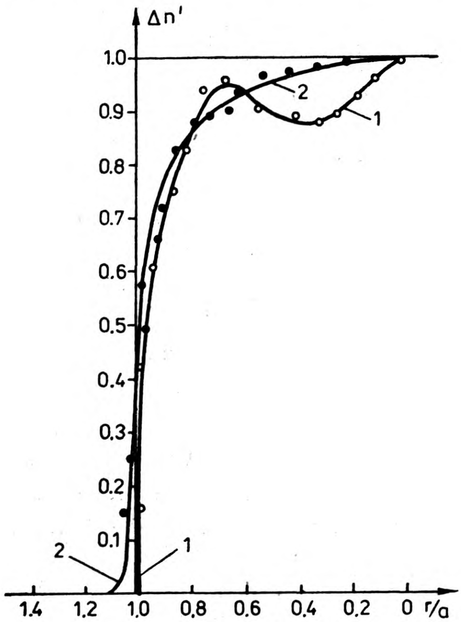

Fig. 2. Refraction profile of the lightguide fibre:

1 – averaged, 2 – obtained with the method o : refractive index equalizing, $\Delta n'$, r/a – normed values of the refractive index and fibre diameter, respectively

3. Measurement of the refraction profile $n(r)$

The dependence $n(r)$ (fig. 2, curve 2) may be more accurately determined after the measurement perturbations generated by the lightguide coating are removed. This has been done by equalizing the refractive index of the coating with that of the immersion fluid, so that $n_p - n_m = 0$ (fig. 3). The equality

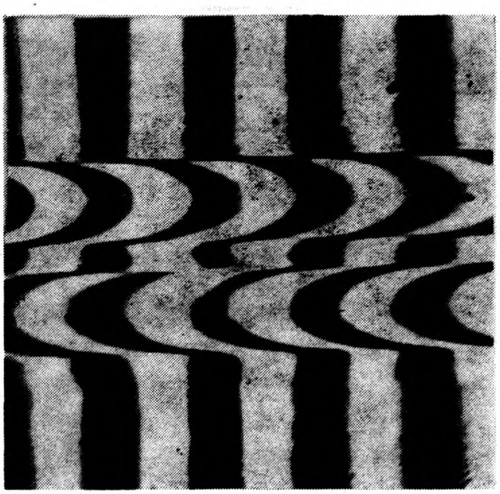

Fig. 3. Total shear of the lightguide fibre located in the immersion fluid of refractive index $n_m = n_p$. Photographic magnification 607 ×

of both the refractive indices achieved by a suitable choice of the immersion fluid was assessed visually with the help of a Biolar PI interference-polarization microscope. Next, the values of y_A, δ_A, δ_0 and a, determined by analysis of the obtained negative, were substituted to the equations [1]:

$$\delta_A = 2\sqrt{a^2-y_A^2}\,[n(0)-n(a)] - \frac{n(0)-n(a)}{a^\alpha} \int_0^{2\sqrt{a^2-y_A^2}} (x^2+y_A^2)^{\alpha/2}\,dx, \tag{5}$$

$$\delta_0 = 2a[n(0)-n(a)]\frac{\alpha}{\alpha+1},$$

where δ_A — optical path difference at the distance y_A from the core centre,
δ_0 — optical path difference at the core centre,
y_A — distance from the core centre,
a — core radius,
Δn — $n(0)-n(a)$ — difference of the refractive index in the centre at the edge of the core,
α — exponent of the function $n(r)$ [8].

The equations (5) and (6) have been solved numerically with respect to Δn and α by using the Odra 1305 computer. The block diagram of the setup for the measurement of the refraction profile in the lightguide is presented in fig. 4.

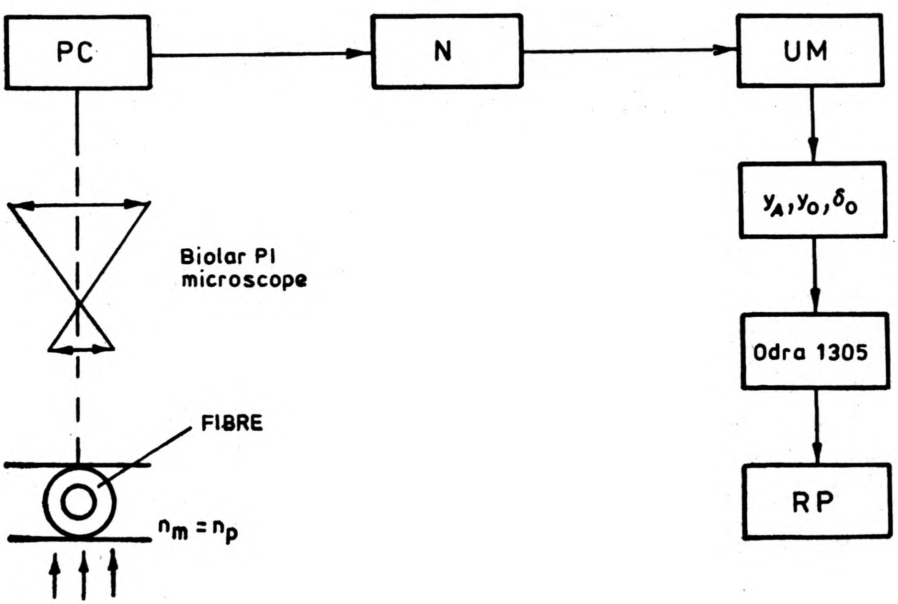

Fig. 4. Block diagram of the setup to measure the dependence $n(r)$.
PC — photographic camera, *N* — negative, *RP* — refraction profile

The measurement error of the parameter $\Delta n = n(0) - n(a)$ determined with the method described was about 15% (table 3), being comparable with the error with which the same magnitude was estimated by Stone [5].

Table 3. Measurement errors Δn and a

Source of error	Error of estimation	Measurement error for Δn
Measurement of $n_m = n_p$		
Accuracy of instrument	$\pm 2\cdot 10^{-4}$	$\pm 4\%$
$-\dfrac{\Delta n_m}{\Delta t}$ $(t = 278$ K)	$\pm 3.5\cdot 10^{-3}$	$\pm 3\%$
Readout error ($t = 298$ K)	$\pm 0.04\%$	$\pm 0.04\%$
Measurement of δ_0, δ_A		
δ_0	$\pm 0.5\%$	$\pm 0.5\%$
δ_A	$\pm 0.5\%$	$\pm 0.5\%$
Measurement of position		
y_A	$\pm 0.1\%$	$\pm 0.1\%$
a	$\pm 0.1\%$	$\pm 0.1\%$
Readout error	$\pm 0.5\%$	$\pm 0.5\%$
Measurement of exponent		
α	$\pm 20\%$	$\pm 5\%$
Change in the fibre core diameter ($\Delta d_r = 1 \mu m$)		$\pm 12.3\%$
Total error		$\pm 15\%$

It should be emphasized that after the equations (5) and (6) have been programmed properly the method described is less time-consuming and tedious than the averaging method presented in Section 2 of this paper.

4. Conclusions

In the microinterferometric measurements of the refraction profile of the lightguide fibres the accuracy of the optical path difference determination is, as it was mentioned earlier, the fundamental problem. The difficulty in the measurement of δ lies in the fact that this magnitude should be determined at the midpoint of the examined interference fringes as exactly as possible.

The interference fringes obtained in the filed of view of the Biolar PI microscope are wide, thus the probability of the unique determination of this parameter is considerably reduced.

An application of the suitably constructed interference microscope of Fabry-Pérot type [9] would allow to determine the optical path difference with at least twice higher accuracy.

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Микроинтерферометрические измерения распределения коэффициента преломления в цилиндрических двухслойных световодах

Описаны интерферометрические методы измерения рефракционного профиля $n(r)$ двухслойных световодных волокон, изготовленных из многокомпонентных стёкол двухтигельным методом. Приведены результаты измерения распределения коэффициента преломления вдоль диаметра волокна. Сопоставлена точность предложенных методов.