Optica Applicata, Vol. XIV, No. 1, 1984

Application of phase-contrast to the optical fibre refractive profile measurement*

Mirosława Bożyk

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

The influence of immersion medium on an optical fibre phase-contrast image was analysed. The microdensitometric method for the measurements of geometric fibre parameters from its phase-contrast image received by means of negative phase-contrast instrument KFA is shown. The refractive profile of gradient fibre was determined by the phase contrast method (Ph-C method) and it was compared with the refractive profile determined by the traverse interferometry method (TI).

1. Introduction

The principle of phase-contrast in the optical microscopy consists in a direct transformation of phase changes of a light wave in phase object into visible by eye light intensity changes in microscopic image of this object. Thus, the phase-contrast gives possibilities of observation of phase objects such as optical glass fibres which are invisible in an ordinary optical microscope.

Of a number of different phase-contrast instruments co-working with optical microscopes the negative phase-contrast instrument KFA developed by Maksymilian Pluta and produced by the Polish Optical Works in Warsaw deserves a special notice. This instrument is one of the most sensitive phase-contrast devices, and at the same time is characterized by a very good range of irreversible contrast for objects, the refractive index of which is greater than that of the surrounding medium.

2. The influence of immersion medium on phase-contrast image of the optical fibre

The negative phase-contrast device KFA is useful particularly for the observation of phase objects with a refracting index not smaller than that of the immersion medium. In the case of single-layer fibres of *step-index* type it means that the light intensity I_o of the fibre image is bigger than the intensity I_t of

* This paper has been presented at the European Optical Conference (EOC'83), May 30–June, 4, 1983, in Rydzyna, Poland.

the visual field background ($I_o > I_t$). At the white light the visual field background of the microscope can take different shades of sepia colour causing thereby an intensification of the fibre image contrast.

In the situation when the fibre is bi-layered, the immersion medium is selected so that its refractive index n_m be equal to the cladding refractive index ($n_m = n_p$). Then the cladding takes the colour of the visual field background ($I_p = I_t$) and the fibre core remains bright, $I_r > I_p = I_t$ because $n_r > n_p = n_m$. Such a procedure allows us to obtain proper observation and measurement conditions (under which the influence of halo and shading is smaller) in negative phase contrast.

A high sensitivity of the negative phase-contrast instrument KFA gives the possibility of the exact estimation of equalization state of refractive indices of immersion fluid and of cladding material, provided that the mean dispersions of immersion fluid and fibre material are equal to each other ($n_m^F - n_m^C = n_p^F - n_p^C = n_r^F - n_r^C$).

In another case the phase-contrast image of the cladding takes a colour different from sepia (Fig. 1). It is a so-called dispersion staining [1], where its intensity depends on the objective magnification and the size of phase ring. The phase-contrast images of the fibre of *step-index* type have a constant light intensity both in the cladding (I_p = const) and in the core (I_r = const). But the phase-contrast images of the gradient fibres show the change of light intensity along the core diameter. The change of the light intensity in the fibre core $2wL$, shown in Fig. 2, is connected with the distribution of refractive index. The intensity I_r in the given micro-area of the core fibre $2wL$ depends on both the refraction index of the ambient environment of the micro-area and on the refractive index of the immersion medium in which the fibre is placed.

3. The measurement of the fibre geometric parameters

Optical isotopic fibres due to their shape behave as cylindrical lenses. In this connection the image diameter of the core or the cladding of this fibre, observed in microscopic image plane, depends to a certain degree on the refractive index of the immersion medium surrounding it. We can eliminate the lenticular effect of the fibre placing it into an immersion fluid with the refractive index of $n_m = n_p$. At such a procedure the diameter of the core image is as close as possible to the real one, where $\Delta = (n_r - n_p)/n_r \leqslant 1$, or when the fibre has a floating of the refractive index at the limit core-cladding.

The measurement of geometric parameters can be made directly from the phase-contrast fibre image by means of a micrometric ocular. The accuracy of the core diameter measurement with objective magnifications of $10\times, 20\times, 40\times$ included by the negative phase-contrast instrument KFA, then amounts to $\Delta d = \pm 0.250$ μm, ± 0.124 μm and ± 0.066 μm, respectively.

Twice better measurement accuracy of the core diameter (at the same value of magnification) can be obtained by means of a microdensitometric method.

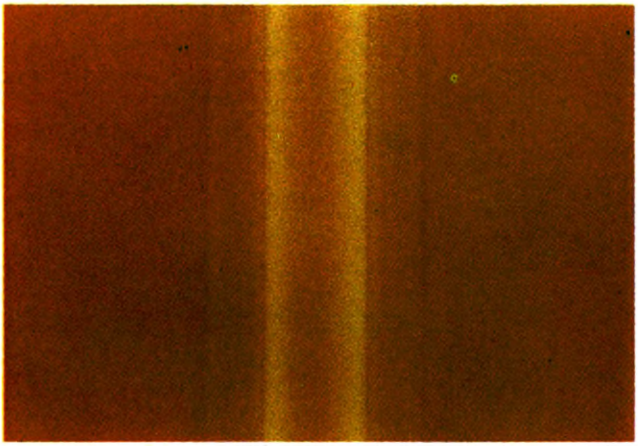

Fig. 1. The phase-contrast image of a bi-layered optical fibre obtained by a negative phase-contrast instrument, KFA; $m_n = n_p = 1.5325$, $t = 19$ °C, $n_m^F - n_m^C = 0.0209 > n_p^F - n_p^C = 0.0091$. A photograph made at the white light, visible fibre cladding; colour different from sepia

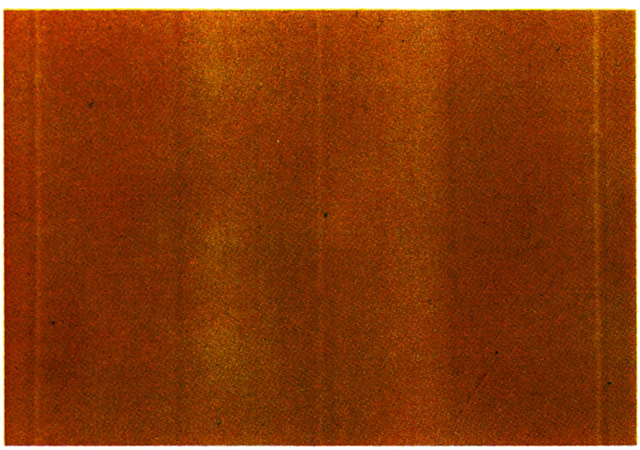

Fig. 2. The phase-contrast image of a bi-layered optical fibre $2wL$, obtained by a negative phase-contrast instrument, KFA; $n_m = n_p = 1.4589$, $t = 19$ °C, $I_t = I_p < I_r$, $n_m^F - n_m^C = 0.0161 \approx n_p^F - n_p^C = 0.0167 \approx n_r^F - n_r^C = 0.0162$. A photograph made at the white light, rapid change of the refractive index at the axial area of the fibre, visible exactly (characteristic of CVD technology)

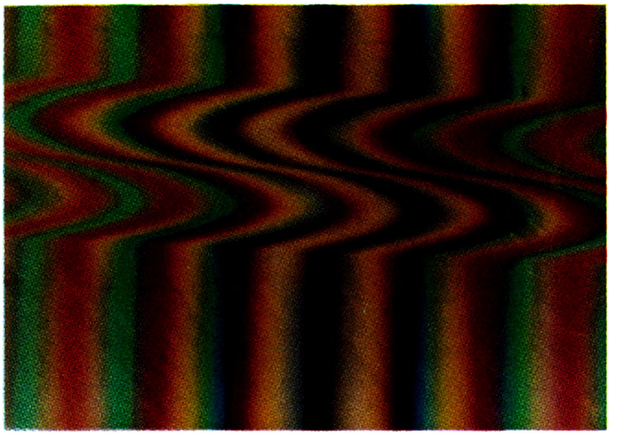

Fig. 6. Double core images of the fibre $2wL$ in an interference fringe field: $n_m = n_p = 1.4589$, $t = 19$ °C. A photograph made at the white light

In this method the fibre geometric parameters are determined from the densitometric curve resulting from scanning of the negative of the fibre phase-contrast image by means of a microdensitometer. It is required that scanned negatives have a very good quality of the phase-contrast image as a whole. Figure 3 shows the densitometric curve obtained from scanning of image negative of the fibre $2wL$ (a photograph of this fibre can be seen in Fig. 2). The boundary core-cladding is established in the fibre $2wL$ in the middle* of the densitometric curve between the maximum and minimum of light intensity recorded at this area (Fig. 3).

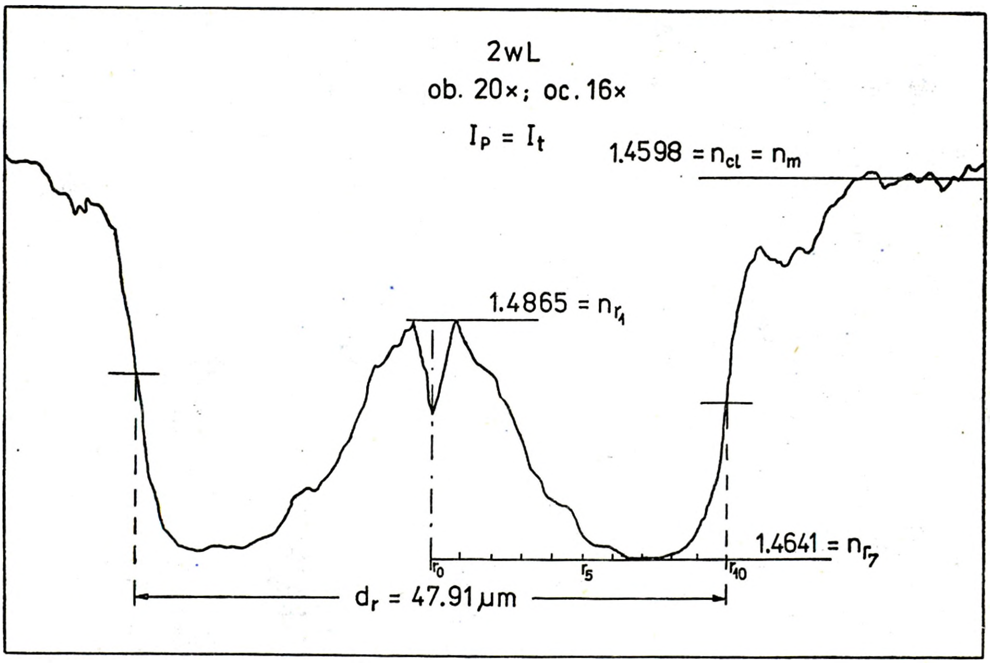

Fig. 3. Densitometric curve resulting from scanning of a negative phase-contrast image of the fibre core $2wL$. A photograph (the positive) of the fibre $2wL$ is shown in Fig. 2

It must be stressed that, as it follows from the literature [3], the measurement error of the core diameter (Δd) should be as small as possible, since it influences the exactitude of established parameter $\Delta n = n_r - n_p$ in the way similar to that of the measurement error of the optical path difference ($\Delta\delta$).

* According to [2] the real edge placement of an amplitude microobject corresponds to the coefficient 0.25. In this paper the value of the coefficient was 0.5, because of the character of examined objects (not flat but cylindrical phase objects), and because of employing a non-coherent light.

4. Establishing of fibre refractive profile from its phase-contrast image

From the phase-contrast image of the fibre we can not only determine its geometrical size but also (when the fidelity of the phase-contrast imaging is particularly good, i.e., when the halo and shading are as small as possible) estimate the refractive index distribution in the fibre and establish its refractive profile.

The dependence of the light intensity (I) in the phase-contrast image of the fibre on the change of the optical path difference (δ) is non-linear in the broad range of changes (δ). The linearity of this dependence is preserved well enough only for small values of δ, especially when transverse dimensions of the examined object are not large.

The conditions are well satisfied by a bi-layered quartz fibre $2wL$ obtained by CVD method, for which the parameter $\Delta n < 0.03$.

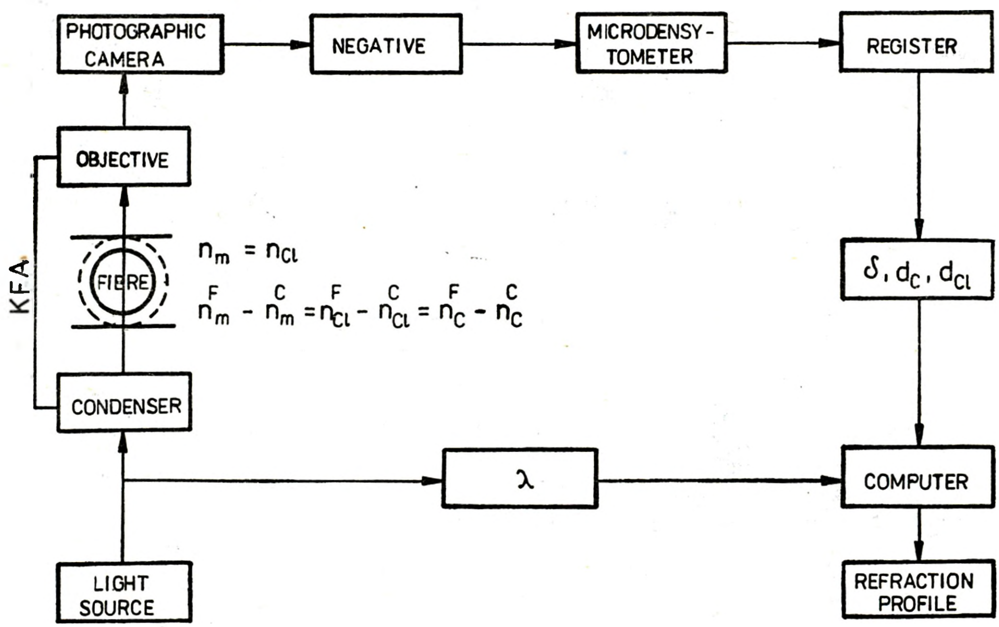

Fig. 4. The block-diagram of the method for establishing refractive profiles of optical fibres, employing the phase contrast (Ph-C) method

In order to establish refractive profile of the fibre $2wL$ by phase-contrast method (Ph-C method, Fig. 4) this fibre is placed into an immersion fluid with refractive index and mean dispersion value chosen in such a way that the following equations be fulfilled: $n_m = n_p$ and $n_m^F - n_m^C = n_p^F - n_p^C = n_r^F - n_r^C$. Afterwards the light intensity value (I) is read from the received densitometric curve, which results from scanning of fibre negative. In this paper the values I are given for 10 (regularly distant one from another) points of the fibre radius (Fig. 3.) The optical path difference at these points was calculated from the formula

$$\delta = \frac{\varphi\lambda}{2\pi} \tag{1}$$

where φ – the phase difference caused by the fibre read out from a dependence $I(\varphi)$, λ – light wavelength (the white light was used, assuming $\lambda = 550$ nm).

The refractive index in each of 10 measurement points of the core radius (with the assumption that the fibre is axially symmetrical) was calculated from the formula [4, 5]

$$n_i = \frac{\sum_{k=1}^{i} A_{ik}\delta_k}{2a} + n_m \tag{2}$$

where δ_k – the optical path differences calculated from the formula (1), A_{ik} – coefficients concerning only geometric dependences at partitioning of the fibre core into 10 equal angular zones, a – core radius.

In Equation (2) the refractive index n_m of the surrounding (immersion liquid + fibre cladding + some zones of fibre core) depends, for a given zone of fibre core, on the point in which the refractive index n_i should be determined. As it results from the densitometric curve from Fig. 3, the direction of light intensity changes is equal in the phase-contrast image of the fibre $2wL$. In the area between fibre axis and core edge three micro-areas with permanent direction of light intensity changes can be found. The respective sizes of the first, second and third areas are: r_0 to r_1, r_1 to r_7 and r_7 to r_{10}. In this connection we take for refractive indices: n_{r_0} (the first area), from n_{r_1} to n_{r_6} (the second area) and from n_{r_7} to $n_{r_{10}}$ (the third area) taking respectively: $n_m = n_{r_1}$, $n_m = n_{r_7}$ and $n_m = n_p$. The refractive profile of the fibre $2wL$ established with the phase-contrast (Ph-C) method is shown in Fig. 5.

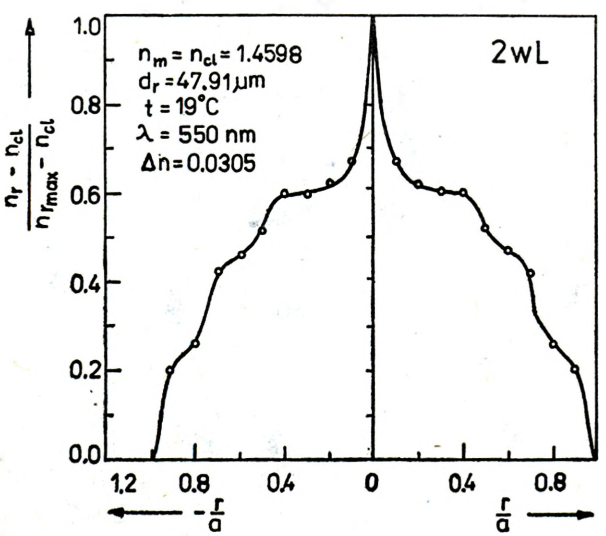

Fig. 5. The refractive profile of the fibre $2wL$ established by the phase-contrast (Ph-C) method

Under the same experiment conditions the refractive profile of the fibre $2wL$ was established by the transverse interference method (TI method). Setting a microscope Biolar PI onto fringe interference we obtained in the visual field of this microscope an interference image of the fibre $2wL$ (Fig. 6). The optical path differences in the transverse interference method were calculated from the formula

$$\delta = \frac{R\lambda}{h} \tag{3}$$

where $R = |p - p_0|$ (p – position of the zeroth fringe of interference in the fibre, p_0 – position of the same fringe beyond the fibre area, h – interfringe distance).

The values of optical path differences calculated from the formula (3) were inserted into Eq. (2), in this method the value of refractive index n_m is constant and amounts to $n_m = n_p$. The refractive profile of the fibre $2wL$ established by the transverse interference method is shown in Fig. 7. From the comparison

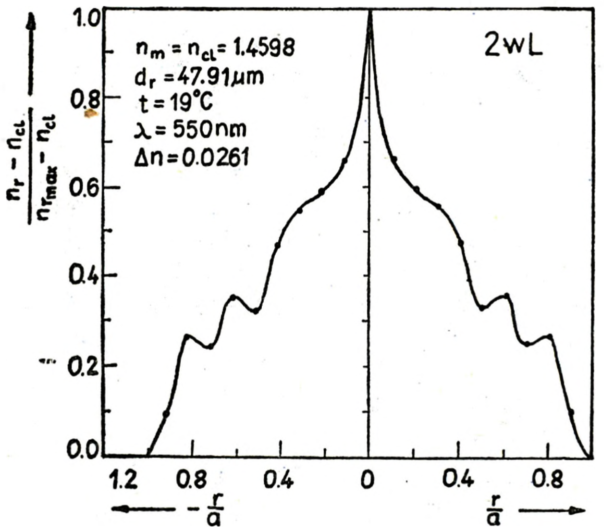

Fig. 7. The refractive profile of the fibre $2wL$ established by the transverse interference (TI) method

of both profiles we see that the values of characteristic parameter Δn of the fibre $2wL$ are constant. In the phase-contrast method (Ph-C method) $\Delta n = 0.0261$ but in the transverse interference method (TI method) $\Delta n = 0.0305$.

5. Conclusions

The method for refractive profile determination of gradient optical fibres from their phase-contrast images gives us a certain possibility to establish the refractive index distribution in these fibres. This method requires a further study and in particular photographic recording (Fig. 4) which is time-consuming and which produces considerable mistakes that should be omitted. This method, however, may be used even today for a fast estimation of a fibre structure both from geometric and refractive index distribution aspects. If the measurement of geometric parameters by the microdensitometric method employing a phase-contrast gives very exact results (e.g., $\Delta d = \pm 0.06$ μm, magnification of objective $20\times$ and of ocular $16\times$), then the refractive profile of the fibre obtained with the phase-contrast (Ph-C) method has for the present more qualitative than strictly quantitative character.

In spite of the above mentioned shortcomings of the Ph-C method it is worthy to emphasize that it is non-destroying and more sensitive than other interference methods. The negative phase-contrast instrument KFA co-working with a microscope Biolar PI enables the observation and measurements of very small (of some Angströms) changes in optical path differences.

Acknowledgements – The author is much obliged to Prof. Maksymilian Pluta for his valuable remarks and advices which influenced essentially the content and form of this paper.

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Received August 3, 1983