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Application of equidensities for transverse interferometry of optical fibres

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The method of narrowing wide interference fringes by means of a tone-separating equidensimetric conversion of the interference image of an optical fibre is presented. Obtained equidensities were used to calculate the refractive index profile of a fibre by the transverse interference method. The measurement error caused by the fringe shift read-out error was estimated as 0.0012, which equals to 3% of Δn (the difference between the cladding index and the index of a measured core).

1. Introduction

The method of a transverse interferometry used in measurements of the refractive index profile of optical fibres demads a very high accuracy of the direct measurement of optical path differences.

The commonly used two-beam interference produces wide interference fringes which results in a poorer accuracy of fringe shift measurements.

These wide interference fringes were narrowed by a tone-separating (equidensimetric) conversion of fiber interferograms taken by means of a "shearing" type double refracting interferometer such as BIOLAR PI microscope [1]. A special photo-chemical method used made it possible to obtain an interferogram without optical distortions. Then an equidensimetric conversion of this interferogram was made resulting in very narrow equidensities corresponding exactly to the direction and size of the shift of interference fringes.

An analysis of the equidensimetrically conversed microinterferogram performed by means of a digitizer linked to a microcomputer enabled a univocal determination of the zero-order fringe shift and a precise measurement of the optical paths difference.

The proposed method can be used to determine variations in the refractive index profile of both a single-core and multi-core fibres. This paper presents measurements of a six-core optical fibre produced in the Optical Fiber Division of the Glass Works "Białystok" by a three-crucible method [2] developed by J. Dorosz.

2. Differential pattern of an optical fibre in a fringe interference field

A BIOLAR PI interference-polarization microscope enables the examination of optical fibres in a fringe interference field or in a uniform field by the transverse interference (TI) method with a split interference image or by the differential transverse interference (DTI) method [3], [4]. The types of interference mentioned above are obtained by the choice of appropriate mutually oriented birefrigent prisms of the Wollaston type (the tube and objective) introduced into the optical system of a BIOLAR PI microscope [1], [3]. The splitting of the interference images obtained from the tube birefrigent prism is constant and the value of the splitting is changed by rotating the objective prism round the optical axis of the objective.

Effective interference in the image plane is obtained when the condenser diaphragm slit is set up perpendicularly to the resultant splitting direction of light waves, arising from the mutual orientation of the prisms [3].

The type of interference method is chosen depending on the type of fibre to be examined. Due to the complicated geometrical structure of the six-core fibre (Fig. 1) and its large diameter ($d = 357$ μm) the observations were performed in a fringe interference field using the differential transverse interference (DTI) method.

Having the fibre placed in an immersion liquid and oriented perpendicularly to the straight of the background in the image plane of the microscope a differential image of the fibre is observed (Fig. 2) in the form of shifted fringes characteristic of the DTI method.

The rotation of the fibre round its main axis by an angle resulting from the geometry of the fibre (Fig. 1) made it possible to observe individual regions of the

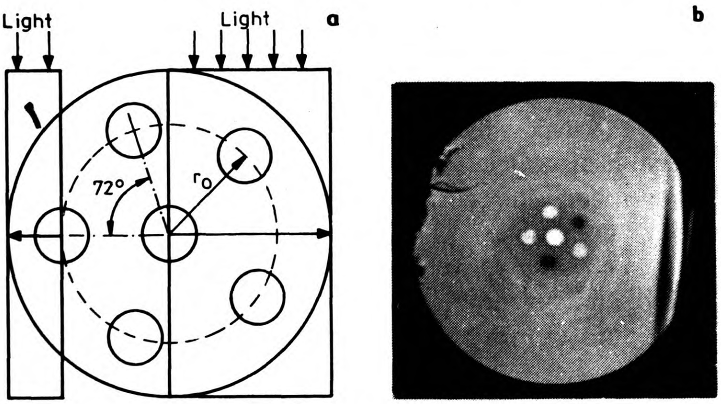

Fig. 1. Six-core optical fibre produced by the three-crucible method [2]. (**a**) Schema of the cross-section of an ideal symmetric six-core fibre with a marked region and direction of data acquisition concerning the fringe shift within the central core and the outer one. (**b**) Photograph of the end face of a randomly chosen segment of the six-core fibre

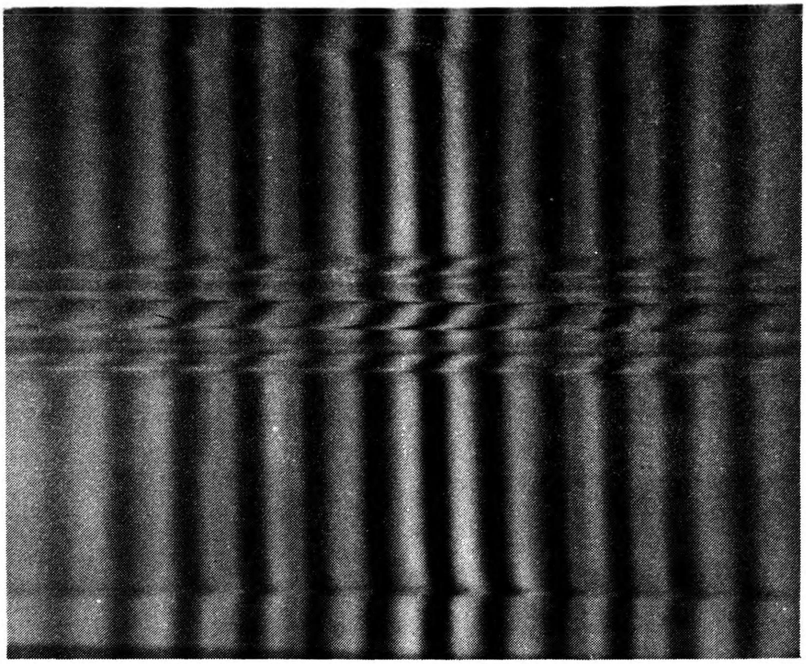

Fig. 2. Microphotograph of the six-core fibre placed in the differential interference field: $n_1 = 1.525$, $t = 20°C$, $\lambda = 550$ nm; birefrigent prisms: the tube and the objective in substractive orientation: enlargement of the photo 551 × (1, 2, 3 – numbers of measured cores)

fibre which meet the measurement requirements of the DTI method, and to measure fringe differential shifts in selected cores.

3. Tone-separating (equidensic) conversion of an optical fibre microinterferogram

For the interpretation of a fibre fringe pattern to be correct, it is essential to perform a precise and explicit determination of the centre of the shifted fringe. A photo-chemical tone-separating method was used for modifying the contrast of the fibre fringe pattern to change its form from condtinuous to discrete (Fig. 3). The method allows us to depict geometrical points of an equal optical density as equidensic narrow lines.

The tone-separating conversion of an interference image of a six-core fibre was performed by means of the KODAK combined masks method [5]. The equidensic conversion realized by means of the method described above is a sum of succesive exposures of well-chosen negatives and positives of the fibre fringe pattern. Starting from an exposure of the most dense negative 1n (Fig. 4) through the next exposure of the first positive 1p and the second negative 2n assembled together, to the last exposure of the most dense positive 2p one obtains a tone-separating (equidensimet-

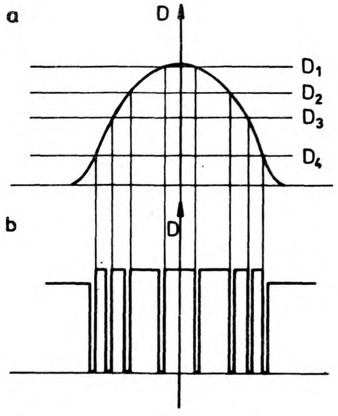

Fig. 3. General principle of the tone-separating treatment of an interference fringe. (**a**) Continuous representation of the optical density of an interference fringe obtained by a linear projection of the microscopic image contrast. (**b**) Equidensimetric representation of the optical density of a fringe. D_1, D_2 – optical densities of arbitrarily chosen points on a fringe shown in the form of line connecting geometrical points of the same optical density; l – equidensity width ($l \to 0$)

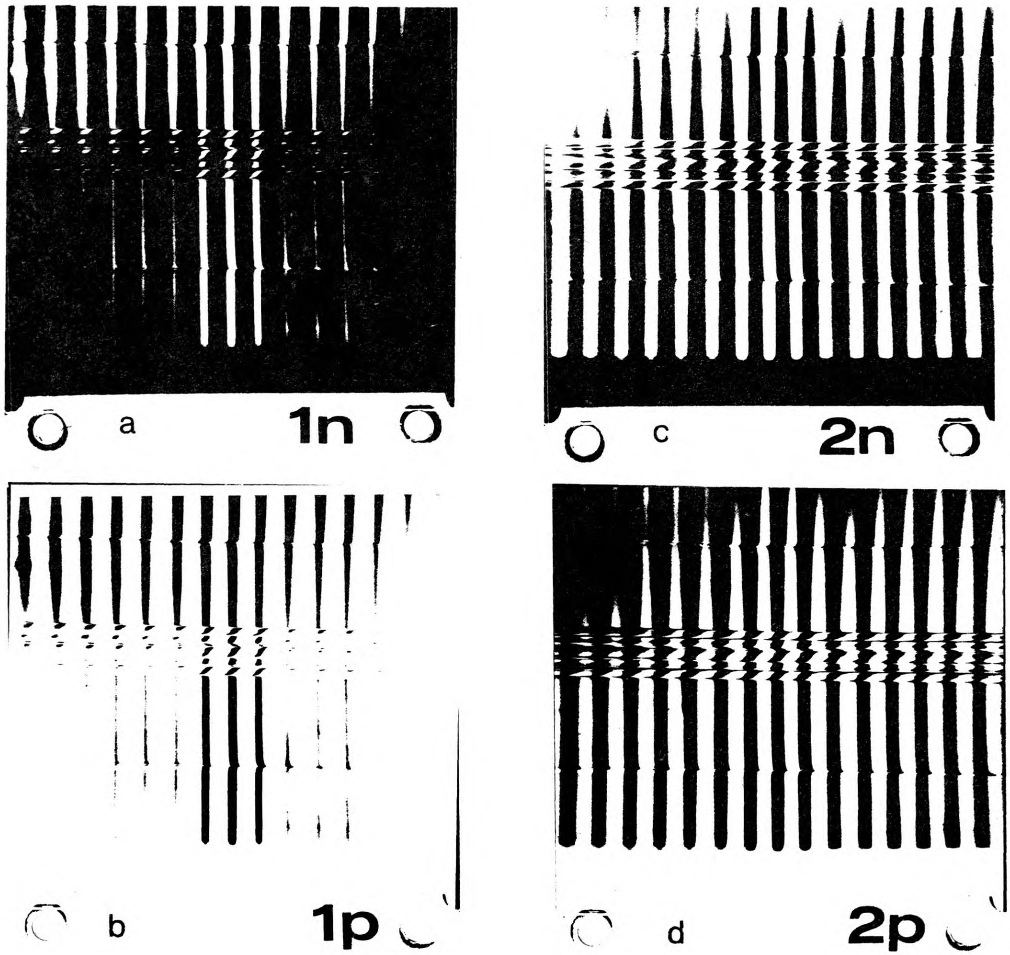

Fig. 4. Component negatives (**a**, **c**) and positives (**b**, **d**) of the six-core fibre interference pattern used during the tone-separating conversion by the KODAK combined masks method. The graphic copies deprived of half-tones were made on a "Lith" high-contrast graphic plate

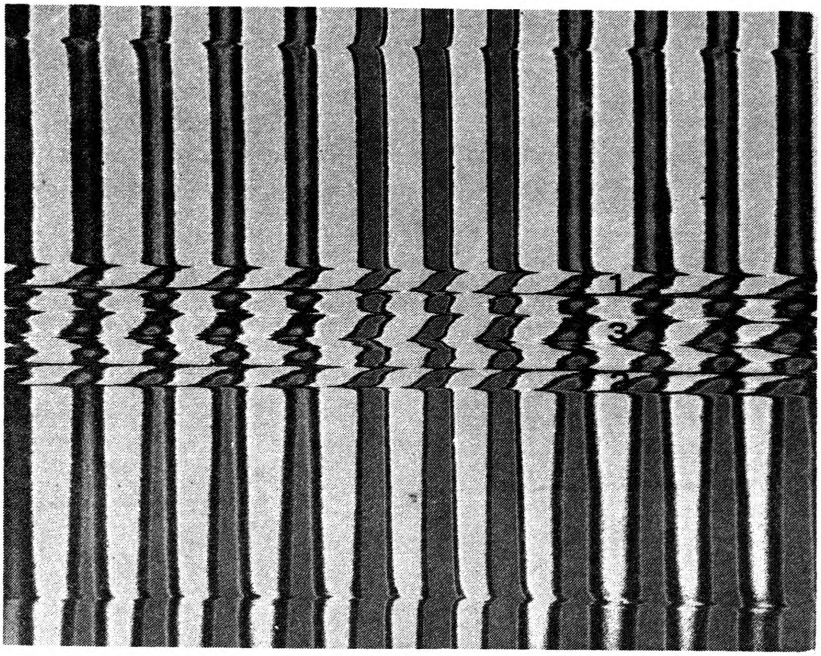

Fig. 5. Tone-separating conversion with two equidensities of the interference pattern of the six-core shown in Fig. 2. Measured cores are designated with numbers 1, 2, 3

ric) conversion with two equidensities (Fig. 5). The direction and size of the shift of equidensities correspond exactly to the direction and size of the fringe shift in the fibre, but the measurement of the shift taken from the tone-separating conversion is much more precise because the equidensities are very narrow ($l \to 0$).

4. Method of reconstruction of the refractive index profile of a multicore fibre

The examined fibre has six cores inserted in the cladding of a fixed refrective index n_c. The centers of five outer cores are distributed on a circumference at equal distances r_0 from the main axis of the fibre and the sixth one is placed in its central part (Fig. 1**a**). It is assumed that the fibre and each individual core show a cylindrical symmetry and that their symmetry axes are parallel to the main axis of the fibre.

The fibre is embedded in an immersion oil of the refractive index n_l close to that of the cladding and it is observed in the direction perpendicular to its main axis using the interference-polarization BIOLAR PI microscope by the differential transverse interference (DTI) method. From the interference pattern obtained a shift of a fringe vs the pattern transverse coordinate $\Delta R_i(\tilde{y})$, $(i = 1, \ldots, 3)$ was read for each of the investigated cores.

If the split s of the interference pattern is sufficiently small, the differential shift of the fringe $dR_i(\tilde{y})$ can be related to the shift of the fringe $R_i(\tilde{y})$ obtained by the total shearing method [6]

$$\frac{dR_i(\tilde{y})}{d\tilde{y}} \approx \frac{dR_i(\tilde{y})}{s}. \tag{1}$$

It was shown [7] that there is a strict relation between the derivative $dR_i(\tilde{y})/d\tilde{y}$ and the deflection function Ψ_i of rays deviated from their initial direction by the investigated cylindrical object

$$\Psi_i = -\arcsin\left(\frac{\lambda}{D}\frac{dR_i(\tilde{y})}{d\tilde{y}}\right) \tag{2}$$

where D – interfringe spacing related to a phase shift of 2π.

On the basis of the above metioned Equations (1) and (2), the deflection function ψ_i of each probing beam can be calculated. Simultaneously $\tilde{y}$ coordinates read in the image plane are recalculated into their initial coordinates y [8]

$$y = \tilde{y}\cos(\Psi_i). \tag{3}$$

The calculated deflection function $\Psi_i(y)$ is sufficient to complete the reconstruction of the measured refractive index distribution [7]

$$n_i = \exp\left(\frac{1}{\pi}\int_u^1 \frac{\Psi_i(y)dy}{\sqrt{y^2-u^2}}\right), \quad 0 \leqslant u \leqslant 1, \tag{4}$$

and

$$r = \frac{u}{n_i}$$

where r – radiatal position.

Furthermore, due to a slight mismatch of the cladding and immersion indices the refractive index of the cladding was additionally reconsrtucted from the fringe shift in the cladding by applying the following expression [7]

$$n_c = -\frac{yn_I}{\sin\left[\dfrac{\Psi(y)}{2} - \arcsin(y)\right]} \tag{5}$$

To symplify the calculations the refractive index in Eq. (4) was normalized in respect to the refractive index of the surrounding medium (the cladding, when reconstructing the refractive index profile of the core, and the immersion, when reconstructing the refractive index of the cladding).

The last stage of reconstruction of the index profile is the renormalization of obtained results.

5. Results

The fringe shift was read out from an enlarged photo of the tone-separating (Fig. 5) conversion of the obtained differential interference pattern of a six-core fibre (Fig. 2). The semi-automatic method presented in [6] was used.

The measurement error caused by the uncertainty of the fringe shift data read out was estimated as 0.0012, which is equal to 3.1% of Δn for cores 1 and 2, and 2.8% of Δn for core number 3. The error resulting from the approximative nature of Eq. (1) depends on a proportion of the core radius to the image split s (referred, of course, to the object plane).

From the analysis described in [9] the error was estimated as 3.5% of Δn for cores 1 and 2, and 2.5% for core 3.

Figures 6–8 show: read fringe shifts, calculated deflection functions, and reconstructed refractive index profiles of the fibre cores. The refractive index of the cladding reconstructed by the method described in the previous section was 1.5267.

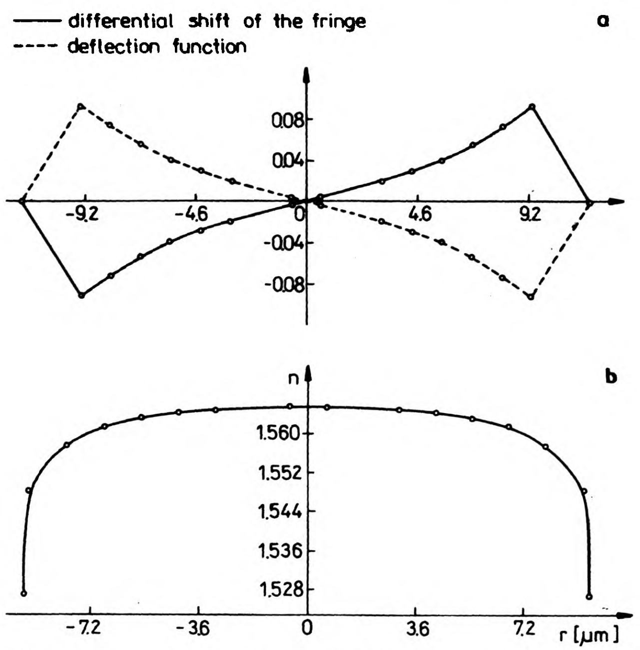

Fig. 6. Differential shift of the fringe $(\lambda/D)dB_1(\tilde{y})/d\tilde{y}$ in function of the pattern transverse coordinate $\tilde{y}$ and the deflection function $\Psi_1(y)$ [rad] in function of the initial cordinate y(**a**). Refractive index profile $n(r)$ for core number 1 reconstructed from the deflection function presented in Fig. 6**a** (**b**)

6. Conclusions

Conversion of the fibre interference pattern performed by means of the photo-chemical tone-separating method enables geometrical points of an equal optical density lying on a wide interference fringe to be shown in the form of equidensities.

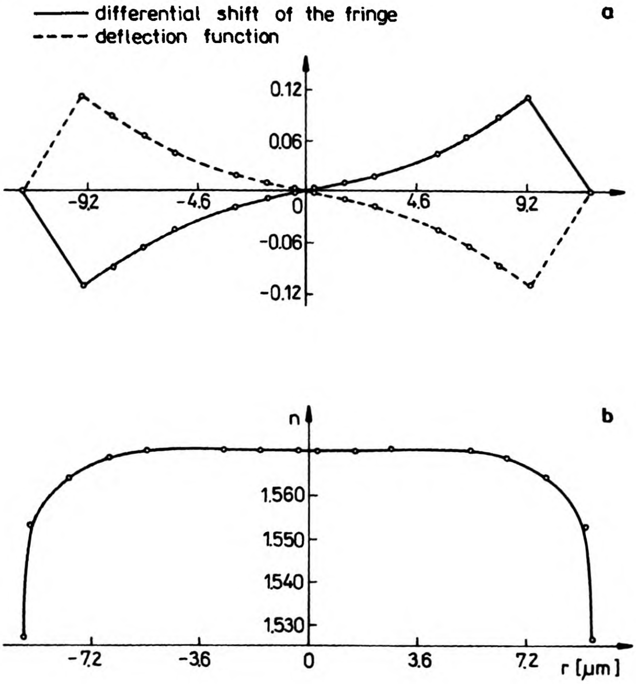

Fig. 7. Differential shift of the fringe $(\lambda/D)dR_2(\tilde{y})/d\tilde{y}$ in function of the pattern transverse coordinate $\tilde{y}$ and the deflection function $\Psi_2(y)$ [rad] in function of the initial cordinate y (**a**). Refractive index profile $n(r)$ for core number 2 reconstructed from the deflection function presented in Fig. **7a** (**b**)

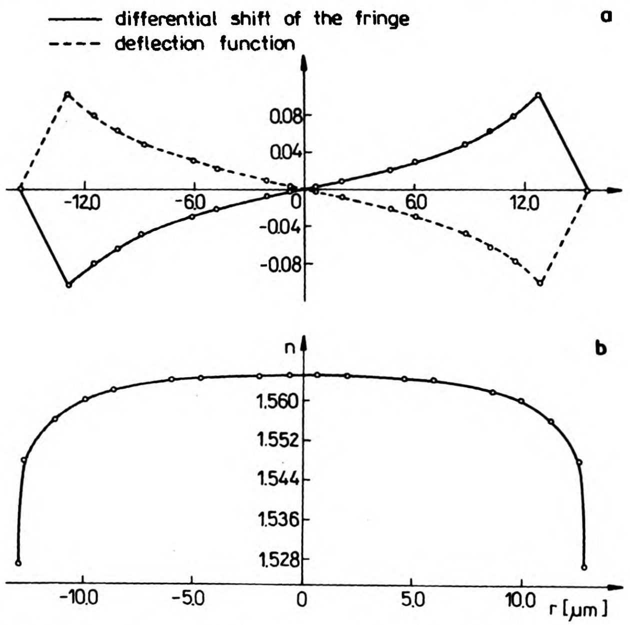

Fig. 8. Differential shift of the fringe $(\lambda/D)dR_3(\tilde{y})/d\tilde{y}$ in function of the pattern transverse coordinate $\tilde{y}$ and the deflection function $\Psi_3(y)$ [rad] in function of the initial cordinate y (**a**). Refractive index profile $n(r)$ for core number 3 reconstructed from the deflection function presented in Fig. 8**a** (**b**)

The method gives the advantage of a very good sharpness and insignificant width ($l \to 0$) of equidensities in the whole examinated region of the fibre. The sharpness of higher order equidensities is the same as that for the zero-order fringe. The possibility of obtaining the mean value of the fringe shift for several equidensities of different interference orders additionally improves the measurement accuracy.

From the analysis of the fringe shift read-error it follows that the proposed method allows us to obtain the final results with accuracy comparable to that obtained by authors of [9].

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Применение эквиденситометрии в поперечной интерферометрии оптических волокон

Представлен способ суживания широких полос двухлучевой интерференции, который заключается в проведении эквиденситометрического преобразования интерференционного образа оптического волокна. Полученное преобразование использовано при вычислении рефракционного профиля оптического волокна методом поперечной интерференции. Погрешность измерения, вызванная ошибкой изгиба интерференционной полосы, составляет около 0,0012 λ, что означает 3% Δn между оболочкой и измеренной сердцевиной волокна.

Проверил Станислав Ганцаж