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CHARACTERIZATION OF STEP INDEX OPTICAL FIBERS USING TWO-BEAM INTERFEROMETRIC METHOD

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The Pluta polarizing interference microscope is used to measure the refractive index profile and material dispersion of step index optical fibers. The refractive index profile of the fiber has been determined experimentally at different wavelengths using two-beam interference technique. Measuring these values at different wavelengths gives useful information about the structural behavior of highly oriented fibers. Also, the theoretical consideration for determining the refractive index is given. Some optical parameters which characterize the optical fiber such as the numerical aperture NA, normalized frequency ν, the acceptance angle θ_{a} and the number of modes M_N propagating in the fiber with wavelength have been calculated. Also, the constants of the Cauchy's dispersion formula were determined.

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1. *Introduction*

The refractive index profile of the optical fiber core plays an important role in characterizing the optical properties of the fiber. It allows determination of the fiber numerical aperture, the number of propagation modes within the fiber core and the dispersion of the fiber's material. So, the detailed knowledge of the refractive index profile allows the prediction of the impulse response of the fiber and consequently the information carrying capacity of the fiber can be estimated [1]. The ideal measuring method should satisfy the following conditions: non destructive, applicable to any profile, high measurement accuracy, high resolution and easy measurement and data processing.

Different methods were used to determine the fiber's refractive index profile such as: near field method, X-ray microanalysis, scanning electron microscope and interferometric methods [2].

Many authors have applied interferometric techniques to determine the optical properties of fibers [3,4]. Pluta used his double refracting interference microscope with variable amount and direction of wavefront shear to study the refractive indices and birefringence of synthetic polymer fibers [5]. The idea of the Pluta polarizing interfrence micoscope is based on the two-beam interference technique. The microscope gives a uniform field or fringe interference field with a continusly variable amount and direction of lateral image duplication [5].

Žurek and Zakrzewski [6] determined the refractive indices and birefringence of cotton fibers using the Pluta microscope. Hamza et al. [7] used Pluta polarizing interference microscope to study the refractive index profiles of cylindrical fibers having core-cladding structure.

Hamza et al. [8] determined the core cladding refractive index difference and the index gradient profile parameter of the graded inex (GR-IN) optical fibre. Multiple-beam Fizeau fringes and Pluta polarizing microscope are used for this study. A new method, based on a derived mathematical expression is used to estimate the fringe shift inside GR-IN of the fibre core. The estimated and experimental values of the fringe shift, along the core radius, are used to obtain the refactive index profile of the optical fibre.

Kovacević et al. [9] studied the modelling of the loss and mode coupling due to an irregular core-cladding interface in step index plastic optical fibers. They model such loss and mode coupling by ray tracing. The results show mode coupling and relative loss per unit fiber length caused by the core cladding interface irreguarities. The loss is high close to the input fiber end where mode coupling is intense.

Material dispersion $\mathrm{d}n/\mathrm{d}\lambda$ plays an important role in fiber optics performance, where n is the refractive index and λ is the wavelength of the light [10,11]. This quantity is described by the well-known Cauchy's formula.

The aim of the present work is to use Pluta polarizing interference microscope to measure the refractive index profile of optical fibers. Experimental results of refractive index profile for a step index multi-mode fiber at different wavelengths have been obtained and consequently, the material dispersion of the fiber was determined. The relationship between some optical properties which measured and dispersion properties are also illustrated throughout the spectral dispersion curve and some dispersion parameters for this fibre.

2. *Theoretical considerations*

2.1. *Determination of refractive-index profiles of fibers*

A Pluta two-beam interference microscope with a modified method is used to determine the refractive indices of a core-cladding structure fiber [7]. This method is applied to fibers with regular and irregular cross-sections. In this study, the irregularity in the fiber cross-section is dealt with by considering the area enclosed under the fringe shift produced in the microinterferogram. This area represents the optical path difference integrated across the fiber [12].

When a beam of plane-polarized monochromatic light is incident on a homogeneous fiber, the incident wave front will be distorted [10]. Consider a fiber having a core-cladding structure with circular cross-section of radius R and cylindrical core surrounded by a cylindrical cladding of thickness e. Let n_{L}, n_{cl} and n_{C} be the refractive indices of the immersion liquid, the cladding and the core, respectively. Using the Pluta interference microscope with light of the wavelength λ, the interference fringes suffer shifts $Z(x)$ as they cross the fiber at distance x from its centre.

The relation between the interference fringe shift $Z(x)$, n_{L}, n_{cl} and n_{C} is given by [7]

$$\begin{aligned} \frac{Z(x)\lambda}{h} &= 2n_{\mathrm{cl}}\left\{\left[R^2-\left(\frac{n_{\mathrm{L}}d}{n_{\mathrm{cl}}}\right)^2\right]^{1/2}-\left[(R-e)^2-\left(\frac{n_{\mathrm{L}}d}{n_{\mathrm{cl}}}\right)^2\right]^{1/2}\right\} \qquad (1)\\ &\quad +2n_{\mathrm{C}}\left[(R-e)^2-\left(\frac{n_{\mathrm{L}}d}{n_{\mathrm{C}}}\right)^2\right]^{1/2}-n_{\mathrm{L}}\left[(R^2-d)^{1/2}+(R^2-x^2)^{1/2}\right], \end{aligned}$$

for $R > d \geq 0$, where d is the distance between the incident beam and the fiber centre. For a homogeneous fiber with a constant refractive index ($n_{\mathrm{cl}} = n_{\mathrm{C}}$), $e = 0$, Eq. (1) takes the form

$$\frac{Z(x)\lambda}{h} = 2n_{\mathrm{cl}}\left[R^2-\left(\frac{n_{\mathrm{L}}d}{n_{\mathrm{C}}}\right)^2\right]^{1/2}-n_{\mathrm{L}}\Big[(R^2-d^2)^{1/2}+(R^2-x^2)^{1/2}\Big], \qquad (2)$$

for $R > d \geq 0$. Using Eqs. (1) and (2), one can determine the refractive index profile of the optical fiber from the data taken from the interferograms.

2.2. Material dispersion

In Ref. [12], mathematical formulae have been derived for the shape of two-beam interference fringes crossing a cylindrical multi-layer fiber, immersed in a liquid of refractive index n_{L} and having m layers. The refractive indices of the layers are $n_1, n_2, \ldots n_m$, where n_1 is the refractive index of the outer layer and n_m is that of the inner layers (core).

The following equation represents a relation between the fringe shift $Z(x)$ and the refractive index at a point x along the fibre radius [7]

$$\left(\frac{\lambda}{2h}\right)Z = \sum_{Q=1}^{M}\big(n_Q - n_{Q-1}\big)\big(r_Q^2 - x^2\big)^{1/2}, \qquad Q = 1, 2, \ldots, m\,, \qquad (3)$$

where λ is the wavelength of the used monochromatic light, h is the interfering spacing and r_Q are the radii of layers, which are given by [12]

$$r_Q = \left(y^2 - x^2\right)^{1/2}. \tag{4}$$

To calculate the fiber cladding and core refractive indices n_{cl} and n_{c}, the fiber is immersed in a liquid of refractive index n_{L}. When $x = r_{\mathrm{C}}$ and $x = 0$, respectively, Eq. (3) takes the following form [12]

$$\left(\frac{\lambda}{2h}\right) Z_{\mathrm{cl}} = \left(n_{\mathrm{cl}} - n_{\mathrm{L}}\right) r_{\mathrm{clc}}, \tag{5}$$

$$\left(\frac{\lambda}{2h}\right) Z_0 = \left(n_{\mathrm{cl}} - n_{\mathrm{L}}\right) r_{\mathrm{cl}} + \left(n_{\mathrm{C}} - n_{\mathrm{cl}}\right) r_{\mathrm{C}}\,, \tag{6}$$

where $r_{\mathrm{clc}} = (r_{\mathrm{cl}}^2 - r_{\mathrm{C}}^2)^{1/2}$ and r_{cl}, r_{C} are the radii of cladding and core, respectively. Z_{cl} is the fringe shift in the cladding region, Z_0 is the fringe shift in core region [7]. The variation of the refractive index of the fiber material with the wavelength can be written using the known Cauchy's dispersion formula for the fiber [13]

$$n(\lambda) = a + \frac{b}{\lambda^2}\,, \tag{7}$$

where $n(\lambda)$ is the refractive index at a given wavelength λ, and a and b are the Cauchy's constants which depend on the fiber material and characterize its dispersion activity. The dispersive power of the fiber material is given by the following equation [13]

$$\frac{\mathrm{d}n}{\mathrm{d}\lambda} = -\frac{2b}{\lambda^3}. \tag{8}$$

Equations (7) and (8) can be used for light vibrating parallel and perpendicular to the fiber axis.

3. *Results and discussion*

A multimode step index optical fiber [Ge-B doped SiO_2], having a core radius ($r_{\mathrm{c}} = 10.8$ μm) and total diameter 24 μm, is used to show the effect of refraction of the incident beam by the fiber when differences between the fiber cladding and core refractive indices are detectable. The fiber is placed on a microscope slide with fixed ends and is immersed in a matching liquid. The objective prism of the Pluta polarizing interference microscope is rotated to obtain maximum duplication of the two images of the fiber. Then the slit diaphragm is rotated to make a suitable angle with the fiber axis to obtain the sharpest fringes. Microinterferograms have been registered by a CCD camera fixed to the microscope to show the effect of variation of refractive index of the fiber with wavelength [13]. These microinterferograms, which consist of dark and bright fringes of equal width, are shown in Figs. 1a to 1d, which were obtained using wavelengths of 546 nm, 550 nm, 577 nm and 590 nm, respectively. Special computer software [7] is used to determine the refractive index profile of the optical fiber using the data taken from the interferogram.

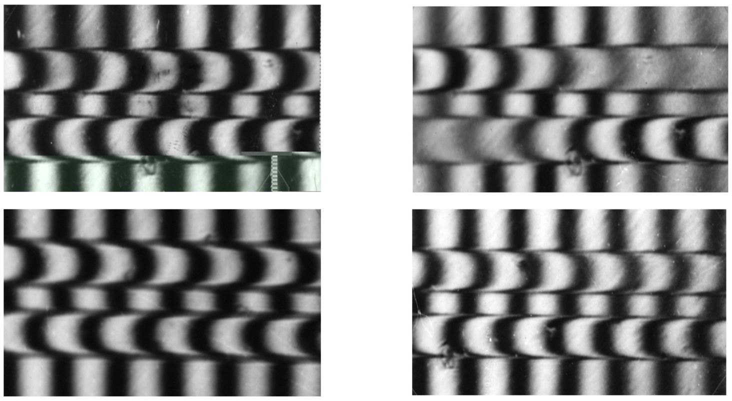

Fig. 1. Interferograms of step index optical fiber at wavelengths: $\lambda = 546$ nm *and* $\lambda = 550$ nm *(upper left and right), and* $\lambda = 577$ nm *and* $\lambda = 590$ nm *(lower left and right).*

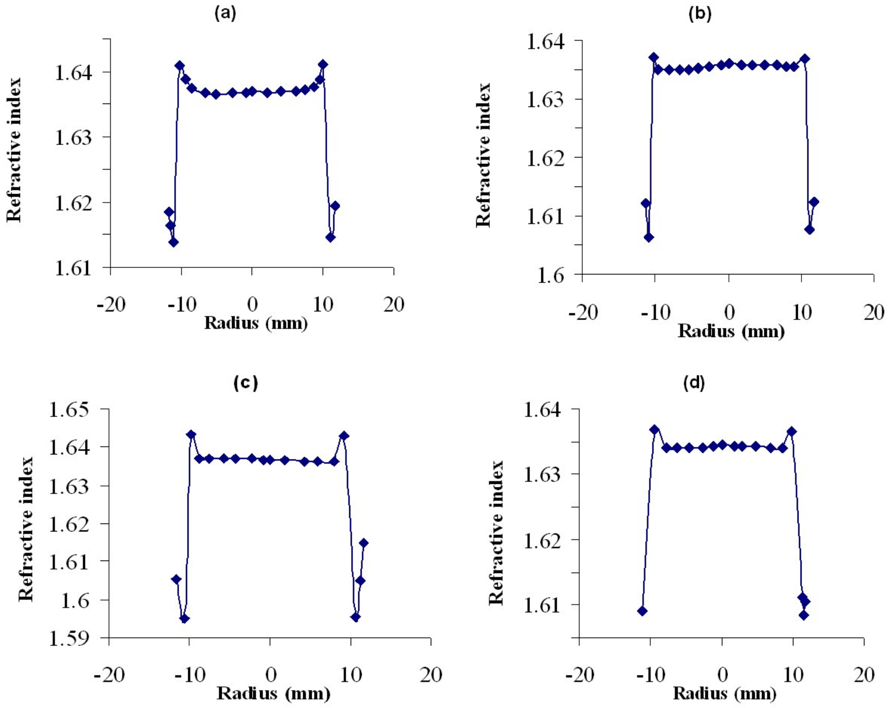

Fig. 2. The refractive index profiles for the wavelengths, a) $\lambda = 546$ nm, b) $\lambda = 550$ nm, c) $\lambda = 577$ nm *and* d) $\lambda = 590$ nm.

The calculated refractive index profiles are shown in Figs. 2a−2d with an accuracy of about 0.001 μ. These figures show the refractive index profiles at different wavelengths.

One can notice from Fig. 2 that the refractive index of the core is nearly constant for the same wavelength. Using Eqs. (5), (6) and figures in the microinterferograms, $n_{\rm cl}$ and $n_{\rm c}$ may be calculated, hence, the dispersive power of the fibers is obtained. The variation of refractive index n at the fiber centre ($r = 0$) with wavelengths are given in Table 1. Figure 3 shows the spectral dispersion curve of step index optical fiber core. Plot of the relation between the refractive index and the reciprocal of the square of the wavelength of the incident light is shown in Fig. 4. This figure show that the dispersion is well described by the Cauchy dispersion formula.

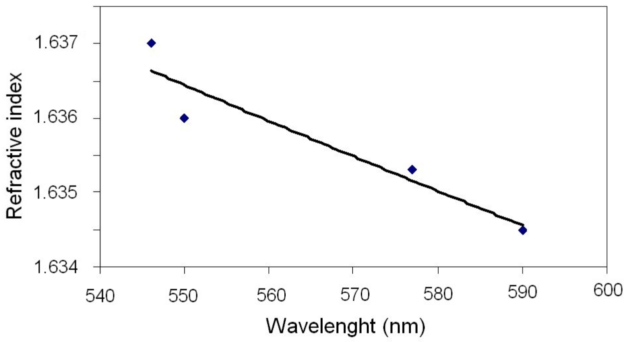

Fig. 3. The spectral dispersion curve of step index optical fiber core.

TABLE 1. Variation of refractive index n at the fiber center with wavelength λ.

Wavelength [nm]	$n(\lambda)$
546	1.6377 ± 0.001
550	1.6362 ± 0.001
577	1.6353 ± 0.001
590	1.6345 ± 0.001

From the slope and intersect, the constants a and b of the Cauchy's formula are obtained. Figure 4 expresses the fact that the refractive index decreased as the wavelength increased. Thus, the fiber materials have normal dispersion behaviour in this region of the spectrum.

The Cauchy's constants were calculated and found to be $a = 1.618$ and $b = 5935$ nm^2, whenever the dispersive power is equal to 3.65×10^{-5} nm^{-1}.

The cladding−core refractive index difference governs some optical fibre parameters such as the numerical aperture, the acceptance angle, the normalized frequency and the number of modes. These parameters are determined using the experimental data and shown in Table 2.

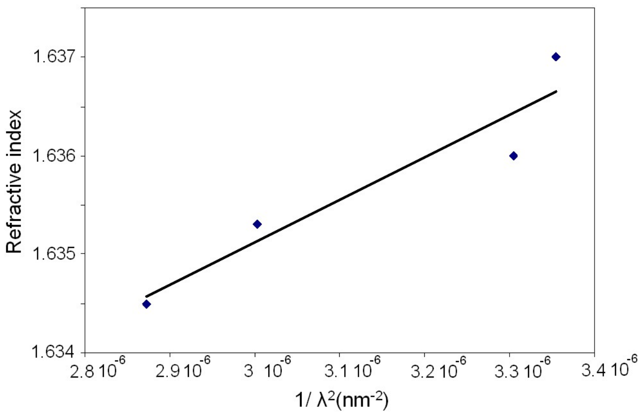

Fig. 4. Variation of refractive index n with $1/\lambda^2$.

TABLE 2. Variation of numerical aperture NA, normalized frequency ν and the number of modes M_N with wavelength.

λ [μm]	NA	ν	M_N	θ_a [deg]
0.546	0.2804	35.089	308	16.28
0.550	0.3023	37.2785	347	17.58
0.577	0.3373	39.6484	393	19.70
0.590	0.3390	38.97	380	19.80

4. Conclusion

Two-beam interference Pluta microscope is used to study the optical properties of step index optical fiber sample in the case where difference between the fibre cladding and core refractive indices is detectable. The refractive index profiles were measured experimentally using this technique. This technique is based on Pluta polarizing interference microscope with a CCD video camera to determine the refractive index profile of the core-cladding fiber. The dispersion curve of the fiber material is obtained using plane polarized monochromatic light vibrating parallel and perpendicular to the fiber axis and hence the dispersion of the fiber material has been investigated. It is concluded that the refractive index of the core is nearly constant for the same wavelength.

Cauchy's dispersion constants and dispersive power of the fiber material, which well describe the interaction of the light ray with the fiber material on the molecular level, have been determined.

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PROUČAVANJE OPTIČKIH VLAKANA SA SKOKOVITIM INDEKSIMA LOMA INTERFEROMETRIJSKOM METODOM S DVA SNOPA

Primijenili smo Plutinov polarizacijski interferometrijski mikroskop u mjerenjima profila indeksa loma i disperzije materijala optičkih vlakana sa skokovitim indeksima loma. Mjerili smo profil indeksa vlakna za više valnih duljina primjenom interferentne metode s dva snopa. Ta mjerenja na više valnih duljina dala su važne podatke o strukturnim svojstvima jako usmjerenih vlakana. Opisuju se također osnove teorije za određivanje indeksa loma u vlaknima. Izračunali smo niz optičkih parametara koji su značajke optičkih vlakana: brojnog otvora, normalizirane frekvencije, ν, kuta prihvaćanja, θ_a, i broja modova, M_N, kojima se na nekoj frekvenciji šire valovi. Također smo odredili konstante Cauchyjeve disperzijske formule.