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Polarisation characteristics of light from multimode optical fibres

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***Abstract*. The polarisation beats accompanying decay of LP-mode groups in multimode optical fibres with a step refractive index profile are considered. The theoretical dependences of the degree of linear polarisation on the optical fibre length and light exit angle are determined based on the waveguide properties of these groups. The results obtained are compared with the existing theoretical concepts. It is shown that the light emerging from a multimode optical fibre near its axis can retain linear polarisation in fibres up to several meters long. Some experimental results are reported, which confirm the basic theoretical conclusions.**

Keywords: *optical fibre, polarisation.*

1. Introduction

An important characteristic of optical fibres is the degree of polarisation of light at the fibre output. The theoretical description of the change in the light polarisation in fibres has been well developed for single-mode and few-mode fibres. The physical phenomena accompanying light propagation and its main properties, as well as the design features of polarisation-maintaining fibres were generalised, in particular, in [1, 2]. The data in the literature on the polarisation characteristics of multimode fibres are contradictory. Some researchers claim that multimode fibres fail to maintain polarisation. This conclusion is confirmed by numerous experimental data. However, other experimental studies demonstrate a possibility of maintaining linear polarisation in multimode fibres. For example, according to [3], the integral degree of linear polarisation p is maintained in an optical fibre of length $L = 0.7$ m, with a step refractive index profile and a core radius $r_0 = 100$ μm. Special fibre systems based on multimode fibres for transmitting polarised light are also known [4]. However, the possibility of using multimode fibres for polarised light transmission is hindered by the absence of theory correctly describing their polarisation characteristics.

The ray depolarisation theory [3, 5] describes the main process occurring when light is introduced into a multimode fibre with a step refractive index profile. This is the decrease in the degree of linear polarisation of light emerging from fibre with an increase in the fibre length or in the light exit angle with respect to the fibre axis. The main drawback of the ray theory is the contradiction between the known experimental data, according to which the integral degree of linear polarisation of light emerging from a long fibre can be considered negligible (at $L \to \infty$ the degree of polarisation $p \to 0$), and the theoretical dependence, according to which p should tend to $1/2$ at $L \to \infty$; i.e., the integral degree of linear polarisation should be 50 %. This contradiction remains unclear.

Numerical methods are difficult to apply for calculating the polarisation characteristics (see, for example, [6, 7]); moreover, they cannot reveal in full measure the main properties of the effect studied. The choice of physical model for numerical calculations is also an urgent problem, which affects the accuracy and validity of the calculation results.

Both the ray theory and the above-mentioned numerical methods are used to calculate the polarisation characteristics in the near-field diffraction zone. Rays propagating at different angles to the fibre axis are separated in space in the far-field diffraction zone. These rays do not interfere; therefore, the ray approach is inapplicable in the far-field diffraction zone. As will be shown below, the polarisation characteristics of light emerging from a multimode fibre with a step refractive index profile depend on the mode composition and, therefore, on the exit angle of light. Thus, the spatial polarisation characteristics of light from fibre in the far-field zone are of great interest.

The theory considered below is based on the waveguide properties [8] of linearly polarised (LP) mode groups of a cylindrical dielectric fibre. This approach made it possible to refine the existing ray theory, explain the known experimental data, and reveal new polarisation effects.

2. Polarisation beats in LP-mode groups

Fibre hybrid modes (and) are known to form LP-mode groups [9]. The groups LP_{0j} (j is a radial index) are formed by the modes HE_{1j}, which are linearly polarised. Similarly to the group LP_{01} in single-mode fibres, the polarisation beats of the mode groups LP_{0j} are caused by fibre defects. The mode groups LP_{lj} (l is the azimuthal index) are formed by TM_{0j}, TE_{0j}, and HE_{2j} modes at $l = 1$ and the $HE_{l+1,j}$ and $EH_{l-1,j}$ modes (which have different propagation constants [9]) at $l > 1$. In this context, at $l \neq 0$ the polarisation beats are determined by the waveguide mode properties and may occur even in fibres with ideal cylindrical symmetry.

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The main difficulty in calculating the parameters of polarisation beats for LP groups is to find the difference in the propagation constants of the waveguide modes forming a given group [8]. Within the approximation of weakly directed modes, Unger [9] proposed the following expression for the difference in the eigenvalues of the waveguide modes forming a mode group LP_{lj}:

$$\Delta u^{\mathrm{LP}} = -\frac{(n_1^2 + n_2^2)u_{l\pm l,j}}{2n_1^2 V}, \tag{1}$$

where n_1 and n_2 are the refractive indices of the fibre core and shell, respectively; u is an eigenvalue; $V = 2\pi r_0 \mathrm{NA}/\lambda$ is the normalised fibre frequency; r_0 is the core radius; NA is the numerical aperture; and λ is the light wavelength. However, the calculation of Δu using numerical solution of the characteristic equation showed that at $V \to \infty$ the asymptote for Δu is not $1/V$, as follows from (1), but $1/V^2$ [8]. Accordingly, for multimode fibres, formula (1) underestimates Δu by $2-3$ orders of magnitude. Thus, we used another approximation [8, 10, 11]:

$$\Delta u^{\mathrm{LP}} \approx \frac{\xi_{l,j}^2 \mathrm{NA}^2}{2\pi \zeta_{l,j}^2 n_1}, \tag{2}$$

where $\xi_{l,j}$ is the jth root of the derivative of the lth order Bessel function; $\zeta_{l,j}^2 = V^2 - \xi_{l,j}^2$. Then the difference in the propagation constants [8, 11] can be written as

$$\Delta\beta_{i,j}^{\mathrm{LP}} \approx \frac{\xi_{l,j}^3 \mathrm{NA}^2 \lambda}{4\pi^2 n_1^2 r_0^2 \zeta_{l,j}^2}. \tag{3}$$

The accuracy of formulas (2) and (3) was checked numerically in a wide range of normalised frequencies, numerical apertures, and refractive indices, using different azimuthal and radial indices of the modes. The calculation showed [11] that formulas (2) and (3) can be used to estimate the fibre polarisation parameters at $r_0 > 10$ μm, excluding the near-cutoff waveguide modes.

Separate modes of emerging light are known to be localised in a narrow angular range [12, 13] and obey the relation $u/V \approx \theta/\theta_{\mathrm{cr}}$, where θ is the exit angle and y_{cr} is the aperture angle. Hence, (3) can be written as [10]

$$\Delta\beta \approx \frac{\mathrm{NA}^3 \theta_{\mathrm{n}}^3}{2\pi n_1^2 r_0}, \tag{4}$$

where $\theta_{\mathrm{n}} = \theta/\theta_{\mathrm{cr}}$ is the normalised exit angle. Formula (4) is also valid when a flat electromagnetic wave is introduced into a fibre at an angle θ to its axis [10]. The phase incursion for the waveguide modes forming an LP-mode group with an exit angle θ at the fibre length L is $\Delta\beta L$, where $\Delta\beta$ is determined by expression (4). The polarisation beat wavelength L_{b} is determined from the condition

$$\Delta\beta L_{\mathrm{b}} = 2\pi. \tag{5}$$

We find from relation (3) that

$$L_{\mathrm{b}} = \frac{8\pi^3 n_1^2 r_0^2 \zeta_{i,j}^2}{\xi_{i,j}^3 \mathrm{NA}^2 \lambda} \tag{6}$$

and, using (4), obtain the relationship between L_{b} and the normalised light exit angle θ_{n}:

$$L_{\mathrm{b}} = \frac{4\pi^2 n_1^2 r_0}{\mathrm{NA}^3 \theta_{\mathrm{n}}^3}. \tag{7}$$

With the mode groups LP_{0j} and LP_{1j} excluded from consideration, we find that for the low-order mode group LP_{21} the polarisation beat wavelength at $V = 1000$ (NA $=$ 0.25, $\lambda = 1$ μm) exceeds 4×10^6 m, whereas at $V = 100$ and 20 it is about 500 and 0.9 m, respectively. For the higher order LP groups, according to formula (7), L_{b} is much smaller, than for the LP_{21} group. Near the cutoff ($u_{ij} \approx V$) at $V = 1000$ L_{b} decreases to several tens or even few meters (depending on the group indices) and to few centimeters at $V = 20$.

When determining the polarisation beat parameters for the LP_{ij} groups at $i \neq 0$, one must take into account that, in contrast to the fundamental mode, the directions of the electric and magnetic fields of the waveguide modes forming these groups depend on the azimuthal angle φ. Let us present the field projections for the modes forming the LP_{ij} group ($\boldsymbol{E}_1$, $\boldsymbol{E}_2$) in the near-field diffraction zone at $r =$ const as follows [9]:

$$E_{x_1} \propto A_{E_1}\cos(l\varphi), \quad E_{x_2} \propto -A_{E_2}\cos(l\varphi), \tag{8}$$

$$E_{y_1} \propto A_{E_1}\sin(l\varphi), \quad E_{y_2} \propto A_{E_2}\sin(l\varphi). \tag{9}$$

At $A_{E_1} = -A_{E_2} \equiv A$ and $A_{E_1} = A_{E_2}$ expressions (8) and (9) describe the fields of the LP group with $E_x \neq 0$, $E_y = 0$ and $E_x = 0$, $E_y \neq 0$, respectively. If there is a phase difference ψ ($A_{E_2} = A\exp(-\mathrm{i}\psi)$) between the modes, the total field can be written as

$$\mathrm{Re}E_x \propto A\cos(l\varphi)(1 + \cos\psi), \quad \mathrm{Im}E_x \propto A\cos(l\varphi)\sin\psi, \tag{10}$$

$$\mathrm{Re}E_y \propto A\sin(l\varphi)(1 - \cos\psi), \quad \mathrm{Im}E_y \propto -A\sin(l\varphi)\sin\psi. \tag{11}$$

Let us introduce a parameter p_{r}, which characterises the integral degree of linear polarisation in the layer $r + \Delta r$ in the form [14]

$$p_{\mathrm{r}} = \frac{\int_0^{2\pi}(E_x E_x^* - E_y E_y^*)\mathrm{d}\varphi}{\int_0^{\pi}(E_x E_x^* + E_y E_y^*)\mathrm{d}\varphi}. \tag{12}$$

After carrying out some transformations, we find from (10) and (11) that

$$E_x E_x^* = A^2\cos^2(l\varphi)[(1 + \cos\psi)^2 + \sin^2\psi], \tag{13}$$

$$E_y E_y^* = A^2\sin^2(l\varphi)[(1 - \cos\psi)^2 + \sin^2\psi]. \tag{14}$$

Then, integrating (12) (with allowance for the equality $\int_0^{2\pi}\cos^2(l\varphi)\mathrm{d}\varphi = \pi$), we obtain

$$p_{\mathrm{r}} = \cos\psi. \tag{15}$$

The fundamental difference of the polarisation beats in the LP_{lj} groups with $l > 0$ from the polarisation beats in the fundamental mode group is that, first, the beats under consideration are due to the waveguide properties of the cylindrical dielectric fibre modes in the absence of birefringence, and, second, at $\psi = \pi + 2\pi m$ and $\psi = 2\pi m$ (m is an integer), independent of the electric field direction at the fibre input, the total field is directed orthogonally to the input field. At $\psi = \pi/2 + \pi m$ we have $p_{\mathrm{r}} = 0$. With allowance for the fact that p_r is independent of r, the condition $p_r = 0$ means that the integral degree of linear polarisation of the mode group is also zero. The change in the sign of p_r with a change in ψ is due to the change in the polarisation direction to orthogonal. In the classical determination the integral degree of linear polarisation [14] p is calculated over the entire cross section of the emerging light beam and is related to p_r (12) as follows: $p = |p_r|$. Accordingly, the derivative of the function $p(\psi)$ has a discontinuity at the point $p = 0$. The integral degree of linear polarisation p for an individual LP group and a set of LP groups should be interpreted, similarly to the depolarisation of light [7], as a transition from a state with a uniform linear polarisation to a state with a spatially nonuniform polarisation.

Equating the phase difference incursion $\Delta\beta L$ to $\pi/2$, we use formula (4) to derive the expression for the normalised exit angle θ_{dn} at which $p_r = 0$:

$$\theta_{dn} = \left(\frac{\pi^2 n_1^2 r_0}{L}\right)^{1/3} \frac{1}{\mathrm{NA}}. \quad (16)$$

Therefore,

$$\theta_d = \theta_{dn}\theta_{cr}. \quad (17)$$

Obviously, θ_{dn} should be less than unity. If expression (16) yields $\theta_{dn} > 1$, this means that at specified fibre parameters the phase difference ψ does not reach $\pi/2$ even at $\theta = \theta_{cr}$. When considering the angular dependences, it is expedient to introduce a function $p_a(\theta)$, which, like p_r ($p = |p_a(\theta)|$), characterises the degree of linear polarisation in the angular range from θ to $\theta + \Delta\theta$ at $\Delta\theta \to 0$. If induced birefringence and intermode energy exchange are absent, within the approximation used, at $\theta \to 0$ and any value of L, we have $p_a \to 1$. This is an error of the model used; it is caused by the replacement of discrete $\Delta\beta_{ij}$ values with the continuous function $\Delta\beta(\theta)$. However, it will be shown below that this discrepancy does not affect much the accuracy of calculating the polarisation characteristics if the increase in the angular divergence of light propagating along fibre is taken into account. On the assumption that the angular distribution of the emerging light intensity $I(\theta)$ is constant within the aperture angle, the change in the degree of linear polarisation in the range $0 \leqslant \theta_n \leqslant \theta_{dn}$ can be described by a function in the form $\cos(\alpha\theta_n^3)$, where $\alpha = \mathrm{NA}^3 L/(2\pi n_1^2 r_0)$ is the proportionality factor.

3. Polarisation properties of the set of LP-mode groups

Generally, there are many waveguide modes propagating in a multimode fibre; therefore, in any angular range $\Delta\theta$, even at $\Delta\theta \to 0$, different waveguide modes with similar propagation constants will interfere. The correlation between the modes, which is caused by the fibre core defects and leads to energy exchange between the modes in the angular range $\theta \pm \Delta\theta_s$, significantly affects the resulting dependences of the degree of linear polarisation on θ and other parameters. The polarisation characteristics for real situations can be exactly calculated using only numerical methods, and this calculation is fairly difficult for practical applications. There are alternative approaches to approximate calculation of p and p_a, which allow one to take into account the above-mentioned effects. With due regard to the difference in the spatial distributions of the waveguide mode fields, one can sum the intensities in two polarisation directions for the modes with exit angles in a specified range, comparable with the estimations of $\Delta\theta_s$ (model 1). The opposite approach is to sum the field strengths, neglecting the spatial mode distribution; i.e., this is an analogy of ray approach [3, 5], with allowance for the wave properties (model 2). A comparison of the estimates with the experimental data showed that both approaches correctly describe the character of change in $p_a(\theta)$ in the range $0 \leqslant \theta_n < \theta_{dn}$ and, therefore, the dependence of p on the entrance angle. However, in the first case, at $L \to \infty$, $p_a \to 0$ and $p \to 0$, in accordance with the known experimental data, whereas in the second case $p_a \to 1/2$ and $p \to 1/2$; here, oscillations of $p_oa(L)$ and $p(L)$ are described more exactly.

On the assumption that the light arriving at the fibre input has a directional pattern half-width σ (the light angular divergence σ is due to the energy exchange between modes), the p value for model 1 can be calculated from the formula

$$p = \frac{|p_r - p_i|}{p_r + p_i}, \quad (18)$$

where

$$p_r = \int_0^1 \cos^2\left(\frac{L\mathrm{NA}^3\gamma_n^3}{2\pi r_0 n_1^2}\right)\exp\left(-\frac{\gamma_n^2}{\sigma_n^2}\right)\gamma_n d\gamma_n; \quad (19)$$

$$p_i = \int_0^1 \sin^2\left(\frac{L\mathrm{NA}^3\gamma_n^3}{2\pi r_0 n_1^2}\right)\exp\left(-\frac{\gamma_n^2}{\sigma_n^2}\right)\gamma_n d\gamma_n; \quad (20)$$

$\gamma_n = \gamma/\gamma_{cr} = \gamma/\theta_{cr}$ is the normalised entrance angle of light with respect to the fibre axis; and $\sigma_n = \sigma/\theta_{cr}$ is the normalised directional pattern half-width. For model 2,

$$p = \frac{|p_r^2 - p_i^2|}{p_r^2 + p_i^2}, \quad (21)$$

where

$$p_r = \int_0^1 \cos\left(\frac{L\mathrm{NA}^3\gamma_n^3}{2\pi r_0 n_1^2}\right)\exp\left(-\frac{\gamma_n^2}{\sigma_n^2}\right)\gamma_n d\gamma_n; \quad (22)$$

$$p_i = \int_0^1 \sin\left(\frac{L\mathrm{NA}^3\gamma_n^3}{2\pi r_0 n_1^2}\right)\exp\left(-\frac{\gamma_n^2}{\sigma_n^2}\right)\gamma_n d\gamma_n. \quad (23)$$

The obtained dependences $p(L)$ (see Fig. 1) illustrate the above-mentioned properties. The increase in σ_n corresponds to expansion of the range of excited modes, which reduces the fibre length at which the degree of linear polarisation of emerging light (Fig. 1) can be high.

The angular dependences of the degree of linear polarisation $p_a(\theta_n)$ at $\theta_n < \theta_{dn}$ are correctly described within both aforementioned models. However, the change in $p_a(\theta_n)$ in the entire range of exit angles $0 < \theta_n < 1$ (decrease in p_a with an increase in θ_n from zero to θ_{dn} and damping oscillations at $\theta_n > \theta_{dn}$) are correctly characterised only within model 1. An example of calculated dependences is shown in Fig. 2. Neither model 1 nor model 2 allows one to calculate exactly the angle θ_{dn}; therefore, it is expedient to calculate the dependence $p_a(\theta_n)$ using some approximation.

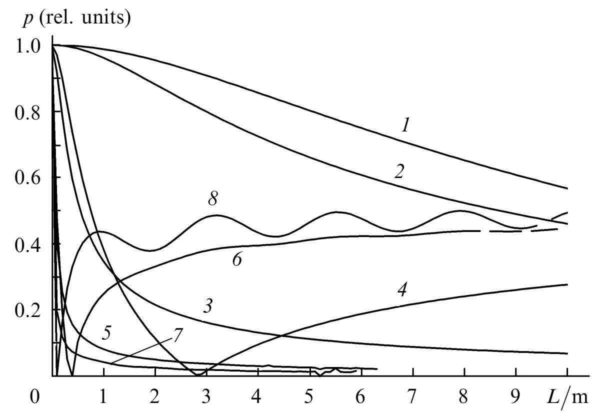

Figure 1. Calculated dependences of the integral degree of linear polarisation of emerging light on the fibre length L at $\lambda = 0.6328$ μm for a fibre with $r_0 = 100$ μm, NA = 0.25, and $n_1 = 1.45$, obtained within (*1, 3, 5, 7*) model 1 and (*2, 4, 6, 8*) model 2 at $\sigma_n = 0.1$ (*1, 2*) 0.1, (*3, 4*) 0.25, (*5, 6*) 0.5, and (*7, 8*) 0.75.

Furthermore, it will be experimentally shown that a possible simple approximation of the dependence $p_a(\theta_n)$ for real multimode fibres is the function

$$p_a(\theta_n) = p_0 \cos\left(\frac{L\mathrm{NA}^3\theta_n^3}{2\pi r_0 n_1^2}\right)\exp\left(-\frac{\theta_n^2}{s_n^2}\right), \tag{24}$$

where p_0 and s_n are approximation coefficients ($p_0 \leqslant 1$). Applied calculations can be performed on the assumption that $s_n \approx \theta_{dn}$. For high-quality fibres s_n can be larger than θ_{dn}, while $p_0 \approx 1$. For low-quality fibres $s_n < \theta_{dn}$ and $p_0 \ll 1$. The larger the effect of induced birefringence and intermode energy exchange in fibre, the smaller p_0. Thus, the approximation coefficient p_0 can be used for objective estimation of the fibre quality when the above-mentioned effects are taken into account.

The LP_{0j} and LP_{1j} mode groups, for which expression (4) is invalid, only slightly affect the polarisation characteristics because of their comparatively small number. In the case of uniform mode excitation the quantity $1/V$ can be used to roughly estimate the contributions of both LP_{0j} and LP_{1j} [8]. Therefore, in multimode fibres a decrease or increase in the integral degree of linear polarisation, which is related to the number of LP_{0j} and LP_{1j} groups, does not exceed few percent and can be neglected.

Note that the integral degree of linear polarisation p cannot be calculated by integrating $p_a(\theta_n)$ (24) over the exit angle θ_n, disregarding the intensity distribution $I(\theta)$.

At $\theta_n > \theta_{dn}$, for real multimode fibres, $|p_a| \ll 1$; therefore, one can assume that at $\theta > \theta_d$ the emerging light lacks linear polarisation, and the angle θ_d can be referred to as the cutoff angle for linear polarisation of emerging light.

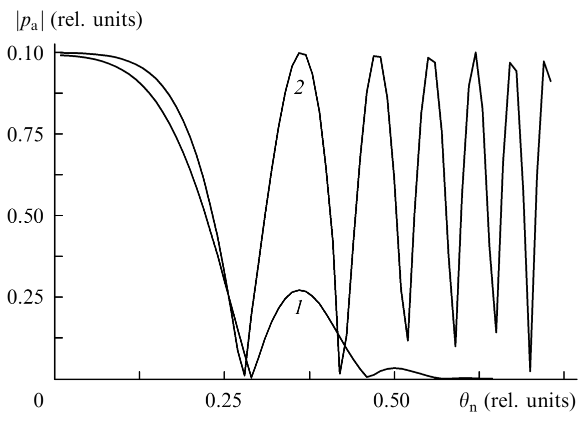

Figure 2. Theoretical dependences of the degree of linear polarisation on the exit angle of light for a fibre with $L = 0.5$ m, $r_0 = 100$ μm, NA = 0.43, and $n_1 = 1.45$, obtained within model 1 [integrated intensities, (*1*)] and model 2 [integrated field strengths, (*2*)].

4. Experimental study

The experiments were performed on fibres of different length, with a step refractive index profile. A He–Ne laser beam ($\lambda = 0.6328$ μm) was introduced into a fibre through several layers of AK5192 light-scattering lacquer, which was deposited on the input face to provide a uniform excitation of waveguide modes [15]. The light from the fibre, after passage through an analyser, was recorded in the far-field diffraction zone by a matrix TV camera on a dull screen. Typical angular intensity distributions $I(\theta)$ are shown in Fig. 3. To reduce the effect of speckle structure of emerging light on the measurement accuracy, the dependence of the degree of linear polarisation on θ was calculated using the $I(\theta)$ distributions averaged over the azimuthal angle. The obtained dependences $p_a(\theta)$ for two fibres [fibre 1 with $r_0 = 100$ μm, $L = 0.5$ m; fibre 2 (taken from

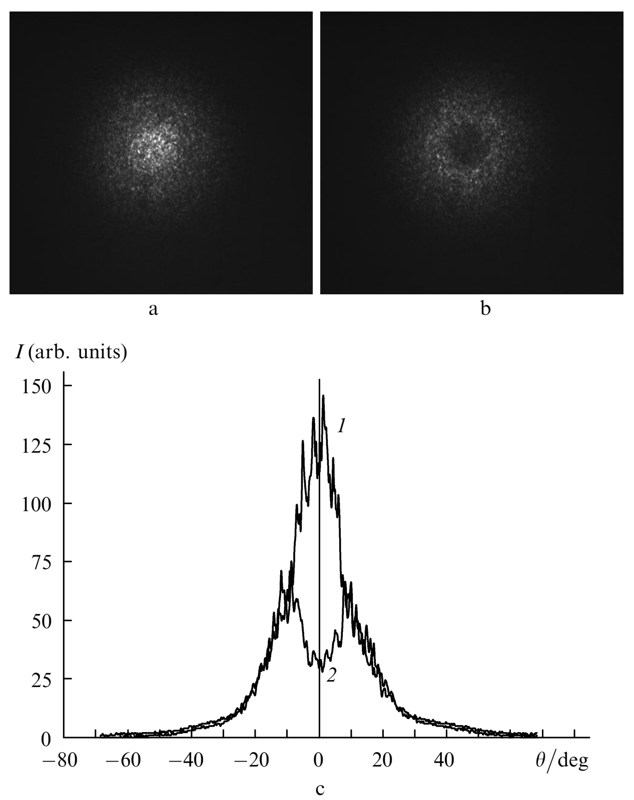

Figure 3. Spatial distributions of emerging light for two orthogonal angles of rotation of the analyser: (a) the analyser is in the position corresponding to the polarisation of emerging light near the axis and (b) the analyser is orthogonally oriented. (c) Experimental angular dependences of emerging light intensities for two orthogonal analyser orientations (*1, 2*) at $\lambda = 0.6328$ μm, $L = 0.5$ m, $r_0 = 100$ μm, NA = 0.43, and $n_1 = 1.45$.

a bundle of single fibres) with $r_0 = 10$ μm, $L = 0.25$ m] are shown in Figs 4 and 5, respectively. The dependence of p_a on θ is in agreement with the theoretical curve. For fibre 1 the experimental and calculated values of θ_d are, respectively, $\sim 9.5°$ and $9.3°$ [the calculation was performed with $n_1 = 1.45$ and $\theta_{cr} \approx 25°$ (at a level of 1/e), NA = 0.43]. For fibre 2 the calculated and experimental values were, respectively, 5.5° and 5.4° (at $\theta_{cr} \approx 33°$). Similar results, confirming the theory, were obtained for other fibres. Some difference between the calculated and experimental data is most likely to be caused by the error in determining the exit angle and numerical aperture for fibres. A significant discrepancy between the experimental and theoretical θ_d values was observed for fibres with high internal strains (in particular, for a polymer fibre with a rigid protective cover); they manifested themselves in a peculiar intensity distribution in the far-field diffraction zone [13, 16].

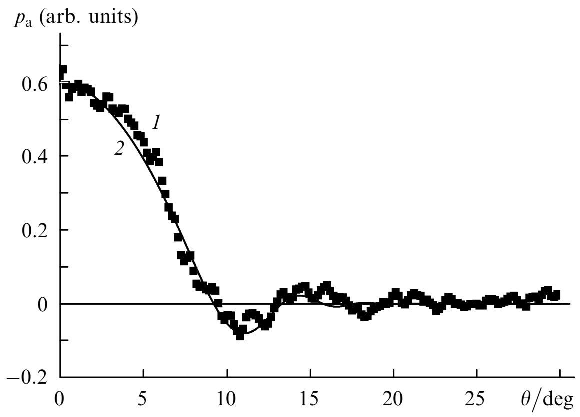

Figure 4. Dependence of the degree of linear polarisation of light on the exit angle for fibre 1 with $L = 0.5$ m, $r_0 = 100$ μm, NA = 0.43, and $n_1 = 1.45$: (*1*) experimental data and (*2*) approximation according to formula (24) with the parameters $p_0 = 0.6$ and $s = 8°$.

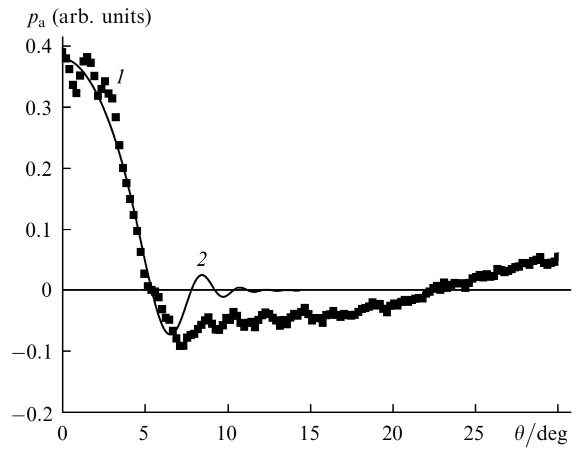

Figure 5. Dependence of the degree of linear polarisation of light on the exit angle for fibre 2 with $L = 0.25$ m, $r_0 = 10$ μm, NA = 0.56, and $n_1 = 1.45$: (*1*) experimental data and (*2*) approximation according to formula (24) with the parameters $p_0 = 0.38$ and $s = 5.2°$.

The angular positions of the local minima of the function $p_a(\theta)$ at $\theta > \Theta_d$ (i.e., higher order maxima) depended on the measurement conditions and fibre bending parameters and generally could not be multiply reproduced.

The integral degree of linear polarisation p of the light emerging from fibre 1 was 0.15, and p_a near the fibre axis ($\theta \ll \theta_d$) was 0.5 – 0.7. When modes were excited in an fibre with a nonscattering (polished) input face by a laser beam directed along the fibre axis (the input angle $\gamma = 0$), the distribution $I(\theta)$ was narrower than that shown in Fig. 1; however, the θ_d value remained nearly the same. The p value was 0.94 and p_a (near the axis) was 0.98. Hence, the low integral degree of linear polarisation of emerging light in the case of uniform mode excitation is caused by the wide angular spectrum of the light propagating through the fibre. A comparison of the p_a values near the fibre axis for the cases considered above suggests that uniform mode excitation is accompanied by energy transfer from the higher order (depolarised) modes into lower order modes (with $\theta \ll \theta_d$). A similar effect was observed for an optical fibre bundle.

It was experimentally found that a bending with a radius above 0.1 m barely affected the polarisation characteristics of the light emerging from the fibres under study. As a result, the above-described dependences could be multiply reproduced.

5. Conclusions

It was theoretically established and experimentally confirmed that the waveguide modes of an optical fibre with a step refractive index profile, with an exit angle below θ_d (linear polarisation cutoff), can maintain linear polarisation. The calculated and experimental θ_d values are in good agreement.

The fundamental difference of multimode fibres from the polarisation-maintaining fibres is that a rotation of the plane of polarisation at the multimode-fibre input causes a rotation of the plane of polarisation at the fibre output, whereas in single-mode fibres the maintained plane of polarisation is related to the geometric parameters of the fibre core. Since the core cross section in multimode fibres exceeds that in single-mode fibres by several orders of magnitude, and multimode fibres are characterised by a much higher efficiency of introducing light from extended sources, it is expedient to use them to supply polarised light to measuring tools (for example, in spectroscopy) and design optical fibre sensors. In view of the aforesaid, multimode fibres can be used as optical vortex generators [17] with specified parameters of the emerging light field to manipulate microparticles [18] and perform diagnostics of screw internal stresses and dislocations in solids, optical crystals, nanostructures, and biological objects.

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