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Effect of deformation of stress-applying parts on birefringence and mechanical stresses in Panda fibres

B. Stádník

Institute of Radio Engineering and Electronics, Czechoslovak Academy of Sciences, Lumumbova 1, 182 51 Prague 8, Czechoslovakia.

S. Pták

National Research Institute for Machine Design, 190 11 Prague 9, Czechoslovakia.

J. Doupovec

Institute of Physics of CEPR, Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Czechoslovakia.

The effect of deformation of stress-applying parts on birefringence and mechanical stresses of polarization-maintaining Panda fibres is given. This investigation was carried out theoretically by means of a finite element method.

1. Introduction

Monomode optical fibres that can maintain state of polarization of an optical beam over a long distance are convenient for use in coherent optical communication systems and fibre-optic sensors. Optical birefringence can be introduced into an optical fibre by means of various mechanisms, e.g., mechanical stress-applying parts, core or jacket ellipticity, bends, twists, side pressure, etc. However, the polarization-maintaining fibres with various shapes and configurations of stress-applying parts are of special interest [1]. These fibres exhibit very high value of birefringence which is homogeneous over the entire fibre cross-section [2] and, as a consequence of this, a good polarization-holding ability is achieved. Among these types, the Panda fibre, having circular shape of stress-applying parts, was designed and fabricated with very low loss and crosstalk, due to its relatively simple technology [3], [4].

Material birefringence and mechanical stresses in optical fibres with stress -applying parts have been analyzed by an analytical method [2], finite element method [5], and experimental photoelastic method [6]. We have studied the effect of translation and mechanical deformation of stress-applying parts on changes of birefringence and mechanical stresses inside a fibe core theoretically by means of the finite element method which we have found to be very effective. Provided that the variations of stress-applying parts are sufficiently small, a linear topological model can be used.

2. Deformation of stress-applying parts

The Panda fibre under investigation is given in Fig. 1, where it is indicated as (1). This basic structure has two identical stress-applying parts of a circular shape, which are displaced in such a manner that high polarization-maintaining ability, low crosstalk and low absorption loss of this fibre is obtained [3]. The other models, indicated as (2)–(8) in Fig. 1, are the deformed structures. The diameter of the basic fibre structure (1) is taken to be $2b = 100\%$, the diameter of a fibre core $2a = 6.3\%$, the diameter of stress-applying parts $t = 18\%$, and the distance between the core centre and the stress-applying parts $r = 12\%$. Thus, the ratio $r/a = 3.8$, which is in accordance with a recommended value $r/a = 4$ [3]. The diameter of the basic stress-applying parts is taken in such a manner that these parts including those deformed be confined in a region $r_0 < 38\%$. This is required in order not to diminish the fibre birefringence [7].

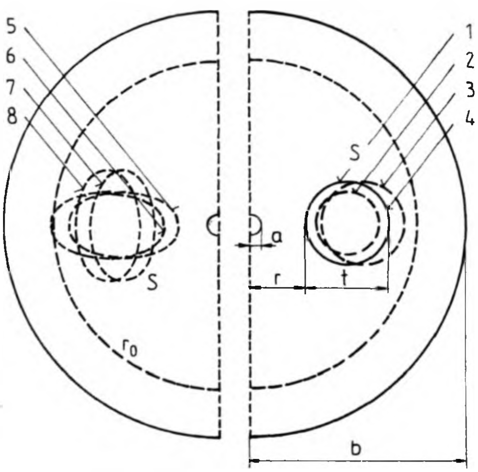

Fig. 1. Circular and elliptical deformation of stress-applying parts of a Panda fibre. S — stress-applying parts. 1 — basic structure, 2 — diminished diameter of stress-applying parts, 3 — horizontal translation, 4 — basic structure without a fibre core $\alpha_{cr} = \alpha_{cl}$, 5 — horizontal elliptical deformation, 6 — translated horizontal deformation, 7 — vertical deformation, 8 — translated vertical deformation

Circular deformation of stress-applying parts of a fibre is shown also in Fig. 1. The diameter of the diminished stress-applying parts (2) is taken $t_1 = 14\%$. It is about 20% less than t. The translation of circular stress-applying parts (3) in a horizontal direction in relation to the basic stress-applying parts (1) is also taken about 20%.

Stress-applying parts deformed elliptically and translated in relation to the basic parts (1) are also shown in Fig. 1. Two kinds of this deformation are considered. The cases (5) and (6) represent stress-applying parts deformed horizontally, while the cases (7) and (8) show stress-applying parts deformed vertically. The translation of the parts (6) in a horizontal direction in relation to the parts (5) as well as that of the parts (8) in relation to the parts (7) is assumed also to be about 20%. The ellipticity of the parts (5)–(8) is taken in such a manner that the magnitude of their cross-section areas equals to that of the basic parts (1). The case (4) represents the fibre structure having basic stress-applying parts (1) and no core.

The material of the fibre is assumed to have the following parameters: elastic modulus of the core, cladding and stress-applying parts $E_{cr} = E_{cl} = E_{sp} = 7830$ (kG/mm^2), corresponding to Poisson's ratio $\nu_{cr} = \nu_{cl} = \nu_{sp} = 0.186$, temperature expansion coefficients $\alpha_{cr} = 9.4 \times 10^{-7}$ (1/°C), $\alpha_{cl} = 5.4 \times 10^{-7}$ (1/°C), $\alpha_{sp} = 10.5 \times 10^{-7}$ (1/°C), and temperature change $\Delta T = -650$°C [5].

We believe that all the fibre structures having parameters indicated above represent majority of types of polarization-maintaining Panda fibres used in practice [2]–[5].

3. Finite element method

The following set of equations was solved:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix} = \frac{E(\nu-1)}{(\nu+1)(2\nu-1)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \text{sym.} & 1 & 0 \\ & & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} & -\varepsilon_{xx}^{(0)} \\ \varepsilon_{yy} & -\varepsilon_{yy}^{(0)} \\ 2\varepsilon_{xy} & -2\varepsilon_{xy}^{(0)} \end{bmatrix}$$

where

$$\begin{bmatrix} \varepsilon_{xx}^{(0)} \\ \varepsilon_{yy}^{(0)} \\ 2\varepsilon_{xy}^{(0)} \end{bmatrix} = [(1+\nu)\alpha \Delta T - \nu k_1] \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix},$$

with the assumptions:

$$\sigma_{zz} = k_1 \neq 0, \qquad \sigma_{xz} = \sigma_{yz} = 0,$$

$$\varepsilon_{zz} = k_2 \neq 0, \qquad \varepsilon_{xz} = \varepsilon_{yz} = 0.$$

Here, σ and ε are components of stress and strain tensors, respectively; k_1, k_2 are constants. The magnitude of ε_{zz} was determined in such a manner that

$$\int_F \sigma_{zz} dF = 0$$

where F is an entire cross-section area of a fibre. This condition is consistent with a self-equilibrating stress state of polarization-maintaining Panda fibres in which the birefringence is produced by temperature deformation of stress-applying parts.

The discretization of one-quarter of the fibre area was produced by means of isoparametric quadratic elements. The computation model contained 647 nodal points. The computation error (expressed by an energy norm) was determined to be less than 0.01% within the entire fibre core region.

4. Birefringence and mechanical stresses

Material birefringence is directly proportional to the difference of principal stresses, $B = C\ (\sigma_1 - \sigma_2)$, where C is the stress-optic coefficient.

The birefringence of the polarization-maintaining fibre structures (1)–(8) shown in Fig. 1 is given in Fig. 2. The straight lines show the dependence of this birefringence

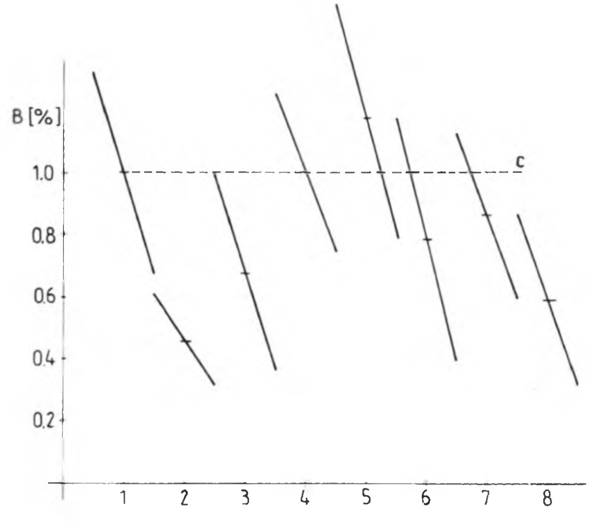

Fig. 2. Birefringence of Panda fibre structures shown in Fig. 1

on the horizontal translation. The full scale on a horizontal axis holds for this translation of 20%. Left sides of the points (1)–(8) lying on the horizontal axis hold for translations of stress-applying parts in a direction towards the fibre core, and vice versa. The next example illustrates this more clearly. The following fibre structures have the same value of birefringence (see Fig. 2, line c) basic structure (1), structure (3) translated to the core about 20% structure (4), structure (5) translated from the core about 10%, and structures (6) and (7) translated to the core approximately about 10%.

The principal mechanical stresses, σ_1 and σ_2, in the centre of a fibre core are given in Fig. 3. Here, σ_z is the axial pressure, and γ is the rotation angle of directions of principal stresses. As it is seen except the structure (4), all the mechanical stresses in the fibre core centre are positive.

The deviations of the birefringence, ΔB, are given in Figs. **4a**, **b**. These dependences are shown on horizontal and vertical axes of symmetry, and on circumference points of the core in relation to the core centre.

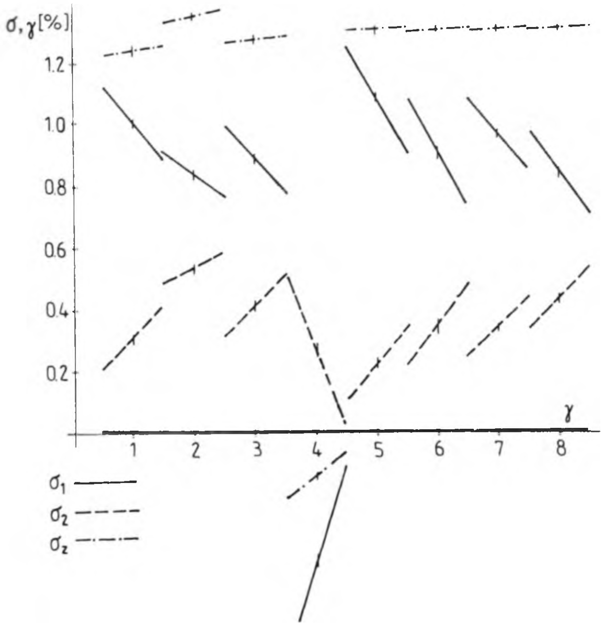

Fig. 3. Mechanical stresses in a fibre core: σ_1, σ_2 — principal stresses in horizontal and vertical directions, respectively; σ_z — axial stress, γ — rotation angle

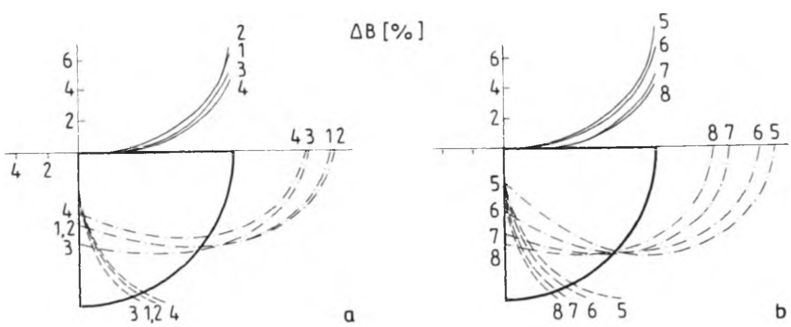

Fig. 4. Deviations of birefringence in a fibre core: **a** — horizontal axis, **b** — vertical axis

The deviations of principal stresses, $\Delta\sigma_1$ and $\Delta\sigma_2$, are given in Figs. 5**a**–**d**. The deviations of the rotation angles of these stresses, $\Delta\gamma$, are shown in Figs. 6**a**, **b**.

5. Conclusion

The birefringence of a Panda fibre is strongly influenced by core dopants, changes of diameter and translation of stress-applying parts. The change of the birefringence due to translation of stress-applying parts is very high and it depends on their

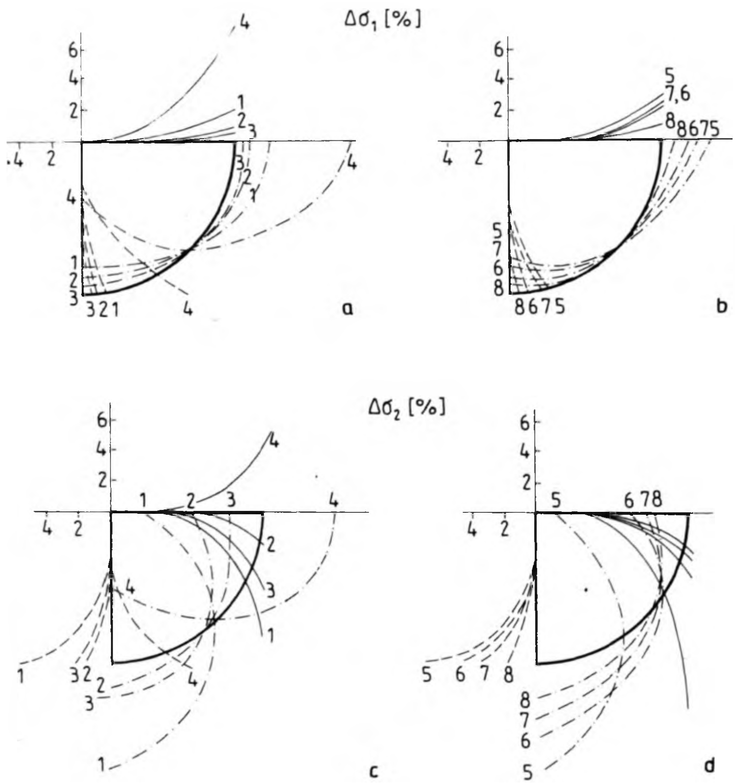

Fig. 5. Deviations of mechanical stresses: **a, b** — principal stresses σ_1; **c, d** — principal stress σ_2

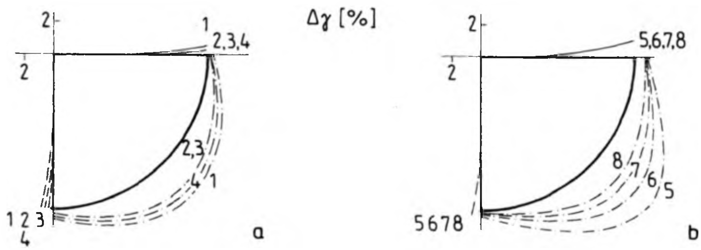

Fig. 6. Deviations of rotation angle of principal stresses: **a** — principal stress σ_1; **b** — principal stress σ_2

diameter. The greater this diameter, the greater is the change of birefringence. If the stress-applying parts are translated to the core, the birefringence increases, and vice versa. The highest deviations of birefringence take place in the circumference points of a fibre core on horizontal and vertical axes of symmetry. Their magnitudes are of several percents and they are of opposite signs. Thus, the centre of a Panda fibre core is the point of minimum birefringence in a horizontal direction, and it is the point of maximum birefringence in a vertical direction.

The magnitude of the principal mechanical stress σ_2 in a vertical direction is lower approximately about 30% than σ_1 in a horizontal direction. All these principal stresses are tensions except the principal stress σ_2 (and also σ_z) of the Panda fibre structure without a core, which is a compression. Small deviations of rotation angle of principal stresses take place in the circumference points of a fibre core. Maximum deviations lie in the directions which are declined 45° from the axis of symmetry of a fibre structure.

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Эффект деформаций частей, вызывающих напряжения на двуперломлении и механические напряжения в фибрах Панда

Исследован эффект деформаций частей, вызывающих напряжения на двупреломлении и в фибрах Панда, сохраняющих поляризацию. Упомянутые выше теоретические исследования выполнены методом конечных элементов.