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Optical properties of microstructure tellurite glass fibres

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Abstract. **The dispersion characteristics and waveguide optical losses are calculated by the multipole method for microstructure optical fibres with a continuous core, which can be made of a tellurite glass holding much promise for fibre optics. The effect of geometrical parameters on the optical properties is studied and conditions for the single-mode propagation of radiation in such fibres are determined.**

Keywords: *microstructure (holey) fibres, dispersion, optical losses, fibre modes.*

1. Introduction

It is known that the localisation of light within the core of conventional optical fibres occurs due to total internal reflection. The optical properties of fibres depend considerably on the radial profile of the refractive index and its weak in principle variation (contrast) between the fibre core and cladding.

In [1], silica fibres were proposed with the refractive-index contrast Δn exceeding considerably (in principle, more than by an order of magnitude) Δn in conventional fibres. This is achieved due to the presence of continuous longitudinal holes in the cladding arranged in the cross section in some or another order. These promising fibres are called holey or microstructure fibres.

A great contrast between the refractive indices of the fibre core and cladding determines the unique optical properties of holey fibres. In particular, by varying the cladding geometry (hole size, their number and relative arrangement), one can control the dispersion properties of the fibre: shift its zero dispersion to both sides with respect to the wavelength of the zero material dispersion, change the slope of the dispersion curve, obtain multiple crossings of the dispersion curve with the wavelength axis. The single-mode propagation regime in holey fibres can be provided in a broad spectral range both for a comparatively large and small effective cross section of the mode field. In this case, a high symmetry of arrangement of holes in the cladding and their identical size are not necessary at all.

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Thus, the basic mechanism of formation of directed radiation in microstructure optical fibres, as in conventional fibres, is the total internal reflection effect. The properties of holey fibres were studied in many theoretical and experimental papers and discussed in a number of monographs (see, for example, [2]).

The theoretical analysis of optical properties of microstructure fibres, as of many other problems of electrodynamics, is based on the solution of the Helmholtz wave equation for longitudinal components of the field. There exist several semi-analytic methods for its solution, which use the expansion of the general solution in different bases of orthogonal functions. In particular, the bases of trigonometric functions are used in the method of expansion in plane waves, the bases of orthogonal polynomials, for example, the Hermite – Gaussian polynomials, etc. However, to obtain good convergence of the solution, many harmonics should be taken into account in its expansion, which deteriorates the calculation efficiency (its rate and accuracy). The number of harmonics in the expansion can be substantially reduced (thereby increasing the calculation efficiency) taking into account the fact that, as a rule, the elements of a structure under study have a circular symmetry. In this case, the method of expansion of the field components in the basis of cylindrical functions, the so-called multipole method [3, 4], seems the most natural.

The aim of this paper is analysis of the optical properties of holey tellurite glass fibres. The dispersion characteristics, waveguide optical losses and conditions for the single-mode regime of light propagation in such fibres are studied depending on the geometrical parameters of the structure: a total number of holes in the fibre cladding, their size, and the distance between them. The analysis is performed by the above-mentioned multipole method.

The TeO_2 glass used in holey fibres studied in the paper is quite promising for fibre optics. First, its refractive index is greater approximately by a factor of one and a half than that of a silica glass (see, for example, [5]) and, therefore, the cladding – core contrast Δn is greater, which simplifies the control of chromatic dispersion. Second, tellurite glasses also have higher nonlinear properties (the third-order susceptibility of some of them can be ~ 40 times higher than that for silica glasses [6]), which makes holy fibres promising for the use in various nonlinear radiation frequency converters. Note also that the melting temperature of tellurite glasses is much lower [5] than that of silica glasses, which can be important for the manufacturing technology of fibres.

Although at present the material optical losses in tellurite glasses (~ 1 dB m^{-1} [5]) still greatly exceed their assumed low fundamental losses, a study of the optical properties of tellurite fibres is of current interest in connection with the expected progress in technologies.

2. Fibre geometry and the solution method

The cross section of a typical microstructure fibre considered here is shown in Fig. 1. The fibre is a circular glass rod with the refractive index n and radius R_0, which has N through cylindrical holes of diameter d (the same for all the holes in our case). The arrangement of holes in the cross section of typical microstructure fibres corresponds to the hexagonal symmetry with the distance Λ between the centres of the adjacent holes. The central region in this symmetric structure, where a hole is absent, and its nearest surrounding play the role of the fibre core. In practice, the glass rod has an external cladding ($r \geqslant R_0$) made of a different material with the refractive index $n_{\rm j}$.

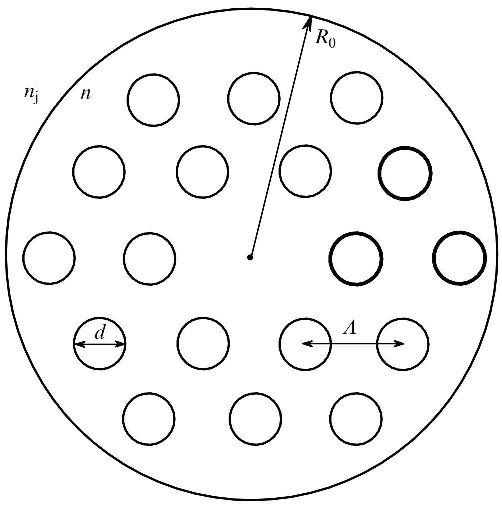

Figure 1. Cross section of a microstructure fibre (in this example, with two rows of holes around the fibre core).

Our theoretical analysis is based, as usual, on Maxwell's equations represented in the form of wave equations. We assume that light propagates in a medium with the magnetic susceptibility equal to unity everywhere and the dielectric constant ε independent of time and homogeneous in each of the components of the fibre (glass, air, and cladding). The time dependences of the electric $\boldsymbol{E}_0$ and magnetic $\boldsymbol{H}_0$ components of a monochromatic wave with the frequency ω have the form $\boldsymbol{E}_0 = \boldsymbol{E}{\rm e}^{-{\rm i}\omega t}$ and $\boldsymbol{H}_0 = \boldsymbol{H}{\rm e}^{-{\rm i}\omega t}$. Then, the vectors $\boldsymbol{E}$ and $\boldsymbol{H}$ in each of the materials of the fibre satisfy the Helmholtz equations

$$\left(\Delta + \frac{\omega^2 \varepsilon}{c^2}\right)\begin{Bmatrix} \boldsymbol{E} \\ \boldsymbol{H} \end{Bmatrix} = 0, \tag{1}$$

where c is the speed of light in vacuum.

Let us now take into account the translational invariance of the field along its propagation direction z, which will determine the dependence of the field components on the longitudinal coordinate in the form $\exp({\rm i}\beta z)$, where β is the phase propagation constant (the longitudinal component of the wave vector). By representing now each of the vectors $\boldsymbol{E}$ and $\boldsymbol{H}$ as a sum of the transverse and longitudinal components

$$\boldsymbol{E} = (\boldsymbol{e}_t + e_z \boldsymbol{z})\exp({\rm i}\beta z), \quad \boldsymbol{H} = (\boldsymbol{h}_t + h_z \boldsymbol{z})\exp({\rm i}\beta z)$$

(where $\boldsymbol{z}$ is the unit vector along the z axis), we find that any of the longitudinal components of the field (e_z or h_z) satisfies the equation

$$(\Delta_\perp + k_{\rm m}^2)V = 0. \tag{2}$$

Here, $k_{\rm m} = (k_0^2 n_{\rm m}^2 - \beta^2)^{1/2}$ is the transverse component of the wave vector in the fibre material with the refractive index $n_{\rm m}$ ($n_{\rm m} = n, 1.0$ and $n_{\rm j}$ for glass, air, and cladding, respectively); $k_0 = 2\pi/\lambda$ is the wave number of a free space; λ is the radiation wavelength in vacuum; and $\Delta_\perp = \Delta - \partial^2/\partial z^2$ is the transverse Laplacian. The relation between the transverse and longitudinal components of the field is determined by Maxwell's equations.

Equations (2) were solved, as mentioned above, by the multipole method. This method is self-consistently described in most detail in [7], where it was used to analyse the optical properties of microstructure silica fibres. The method is based on the representation of fundamental solutions (2) for each of the elements of the fibre structure with a circular cross section (all the holes and boundary of the fibre with radius R_0) in the local cylindrical coordinate system connected with the given element. Then, by using the Graf summation theorem for cylindrical functions, these solutions are written in one coordinate system. The field in the fibre is represented as a sum of the fields scattered from all sources, which are the holes and the outer boundary of the fibre. In turn, the field from each source is, generally speaking, a sum (linear combination) of an infinite number of cylindrical harmonics. By subjecting the field expansions found in this way to boundary conditions at all interfaces in the structure, we obtain a system of linear homogeneous algebraic equations in the expansion coefficients. It is known that the nontrivial solution of this system exists only when the system determinant is zero. The solution of the latter equation gives the dispersion equation relating the propagation constant β (or the effective refractive index $n_{\rm eff} = \beta/k_0$) with the radiation wavelength for the known geometry of the system.

It follows from the above discussion that the multipole method can be used to calculate only the structures consisting of cylindrical elements with a circular cross section. However, because no restrictions are imposed in this case on the relative arrangement of these elements in the cross section, holey fibres with arbitrarily arranged circular holes with different diameters can be analysed in general. In this more general case, the field at an arbitrary point of the cross section is represented by a sum of partial contributions from each of the different elements of the structure, while the symmetrical arrangement of holes allows one to consider the problem only within some sector of the fibre cross section. The required distribution can be found by subjecting the field components to the boundary conditions at the interfaces between sectors (see details in [7]). Depending on the symmetry class, the calculation rate can be increased by several times compared to the general case.

Of all the tellurite glasses we considered a particular glass of the $0.8{\rm TeO}_2 - 0.2{\rm WO}_3$ chemical composition (the numerical coefficients denote molar fractions). The material dispersion of this glass determined by the Sellmeyer dependence

$$n^2(\lambda) = A + \frac{B}{1 - C/\lambda^2} + \frac{D}{1 - E/\lambda^2} \quad (3)$$

is known [8]. Here, $A = 2.4909866$; $B = 1.9515037$; $C = 5.6740339 \times 10^{-2}$; $D = 3.0212592$; $E = 225$; and the wavelength is measured in micrometers.

The roots of the dispersion equation are calculated in the complex plane. In this case, because no data on the spectral dependence of optical losses in tellurite glasses are available in the literature, the material losses were neglected, and the values of $\mathrm{Im}n_{\mathrm{eff}}$ obtained in the solution were completely determined by waveguide losses. In the future, when the reliable experimental data of material losses will be obtained, these losses can be readily taken into account by introducing the imaginary part into dependence (3).

The group velocity υ_{gr}

$$\frac{\upsilon_{\mathrm{gr}}}{c} = \left(\mathrm{Re}n_{\mathrm{eff}} - \lambda\frac{\mathrm{dRe}\,n_{\mathrm{eff}}}{\mathrm{d}\lambda}\right)^{-1}, \quad (4)$$

and the dispersion parameter D

$$D = -\frac{\lambda}{c}\frac{\mathrm{d}^2\mathrm{Re}\,n_{\mathrm{eff}}}{\mathrm{d}\lambda^2}; \quad (5)$$

were found from the calculated real part $\mathrm{Re}n_{\mathrm{eff}}$, while the waveguide losses (in dB km^{-1}) were calculated from the expression [9]

$$\alpha = 20k_0 \lg \mathrm{e}\,\mathrm{Im}\,n_{\mathrm{eff}}, \quad (6)$$

where k_0 is measured in km^{-1}.

3. Results and discussion

It is obvious that the main optical properties of holey fibres made of tellurite glass and of holey silica fibres should be qualitatively similar. However, from the practical point of view it is important to have an idea of their quantitative difference. This difference is illustrated by the calculated optical characteristics of tellurite holey fibres presented in Figs 2–7.

One of the most important features of holey fibres is a strong dependence of their dispersion properties on the structure geometry. Of no less interest is also their ability to maintain the single-mode propagation of radiation in a much broader spectral range than in conventional fibres. In this case, the cross-section area of the field mode can be varied in a very broad range.

Figure 2 presents the spectral dependences of the effective mode refractive index $\mathrm{Re}n_{\mathrm{eff}}$, the group velocity, and the dispersion parameter for the fundamental mode of fibres with different geometries. One can see, in particular, that the greater is the air content in the cladding, the greater is the difference of the dispersion properties of the fibre from those of the bulk glass, this difference increasing with the wavelength of light. The latter is clear, because the longer is the wavelength, the less sensitive is radiation to structural inhomogeneities, the fibre geometry being fixed. In this case, the field is more and more homogeneously distributed in the cladding whose refractive index tends to some averaged value determined by the relative content of air. Correspondingly, the refractive-index contrast of the fibre core and cladding monotonically increases with increasing λ. An vice versa, the shorter is the wavelength (λ is smaller than the characteristic size of structural inhomogeneities), the stronger is the field localisation in glass regions of the fibre (mainly due to total internal reflection) and the weaker is its penetration into air holes. The effective refractive index gradually approaches the refractive index of the glass, resulting in a decrease in the contrast Δn. However, this does not lead in the limit to the loss of waveguide properties of the structure because, as the values of Δn and λ decrease

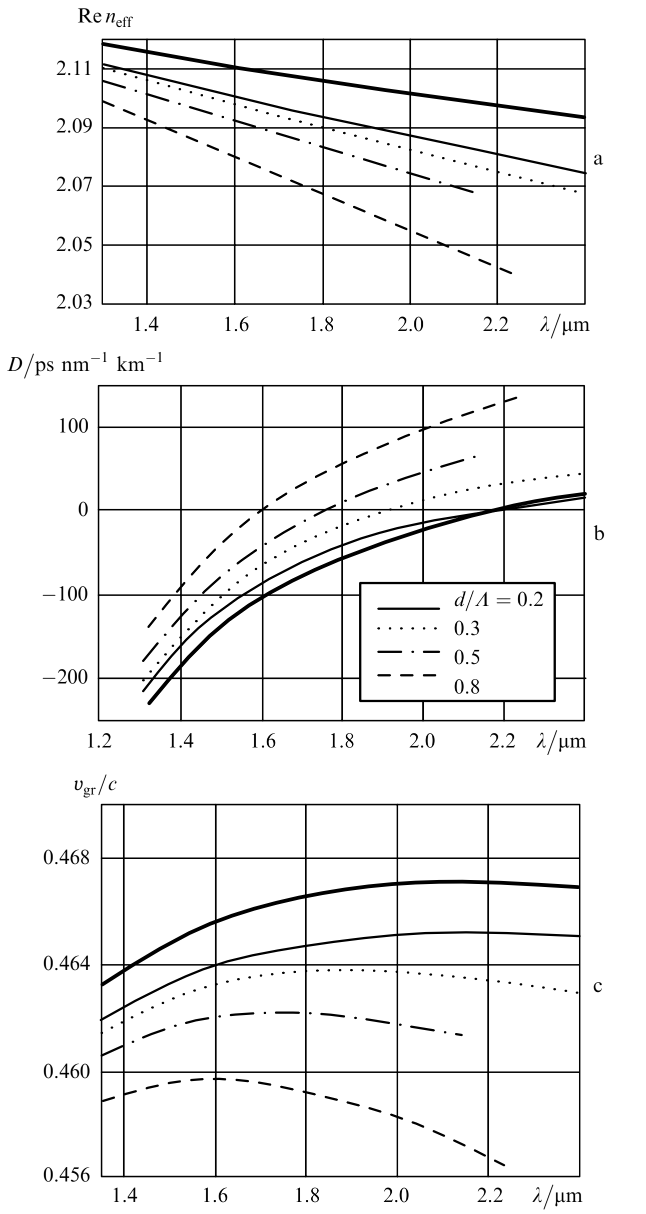

Figure 2. Spectral dependences of the effective refractive index $\mathrm{Re}n_{\mathrm{eff}}$ (a), the dispersion parameter D (b), ad the ratio υ_{gr}/c of the group velocity to the speed of light in vacuum (c) on the air content in the fibre cladding (the d/Λ ratio) for a holey fibre with three rows of holes around the fibre core for $\Lambda = 2.3$ μm. The calculations are presented for the fundamental mode of the fibre. The solid thick curves show the dependences corresponding to the purely material dispersion (3) for a bulky glass.

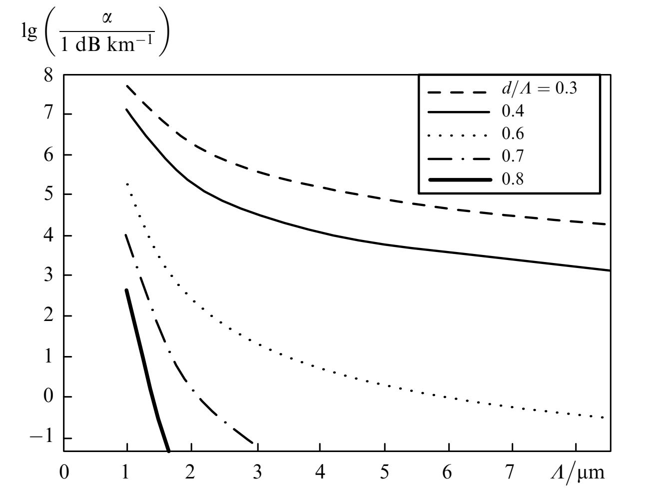

Figure 3. Dependences of the waveguide losses on the distance Λ between the centres of the adjacent holes for different ratios d/Λ in holey fibres with two rows of holes. The calculations were performed for the radiation wavelength $\lambda = 1.55$ μm.

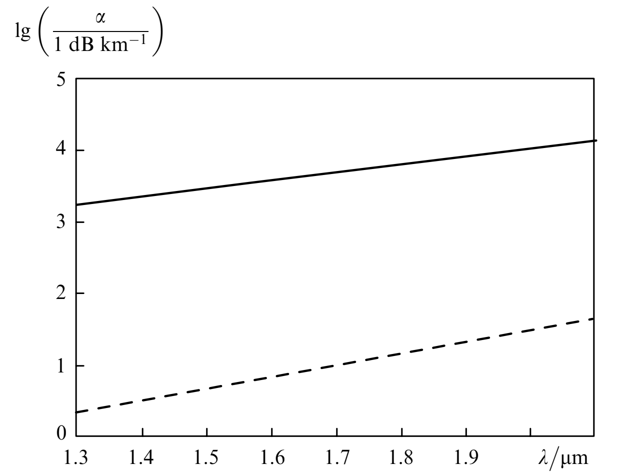

Figure 4. Waveguide losses for the fundamental mode of a holey tellurite glass fibre with two (upper straight line) and three (lower straight line) rows of holes as functions of the radiation wavelength. The curves are obtained for $\Lambda = 2.5$ μm and $d/\Lambda = 0.5$.

simultaneously, the dimensionless characteristic parameter V of the fibre tends to a constant value.

One can see from Fig. 2b that the zero value of the material chromatic dispersion in a tellurite glass corresponds to a considerably longer wavelength (~ 2.2 μm) than for a silica glass. In fibres, the waveguide dispersion is added to the material dispersion, and the zero value of D, as in the case of holey silica fibres, shifts to the blue. The number of rows (layers) of holes around the fibre core (two or more) almost does not affect the dispersion characteristics of fibres; however, it affects considerably the waveguide losses. The value of these losses is demonstrated in Figs 3 and 4. In particular, one can see from Fig. 3 that the waveguide losses rapidly decrease with increasing the air content in the cladding (with increasing the d/Λ ratio), large distances between the holes being preferable at fixed d. Figure 4 shows losses in fibres with two and three rows of holes. The qualitative result of this comparison is obvious in advance

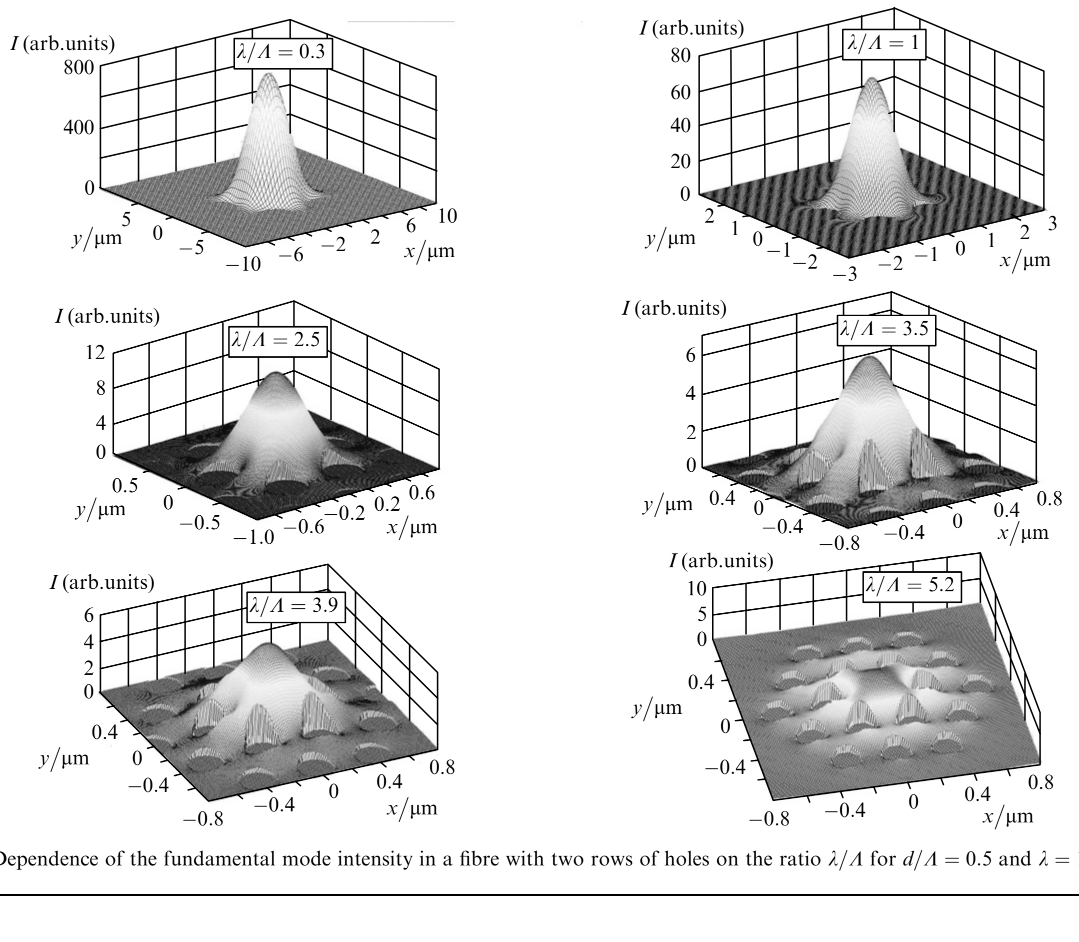

Figure 5. Dependence of the fundamental mode intensity in a fibre with two rows of holes on the ratio λ/Λ for $d/\Lambda = 0.5$ and $\lambda = 1.55$ μm.

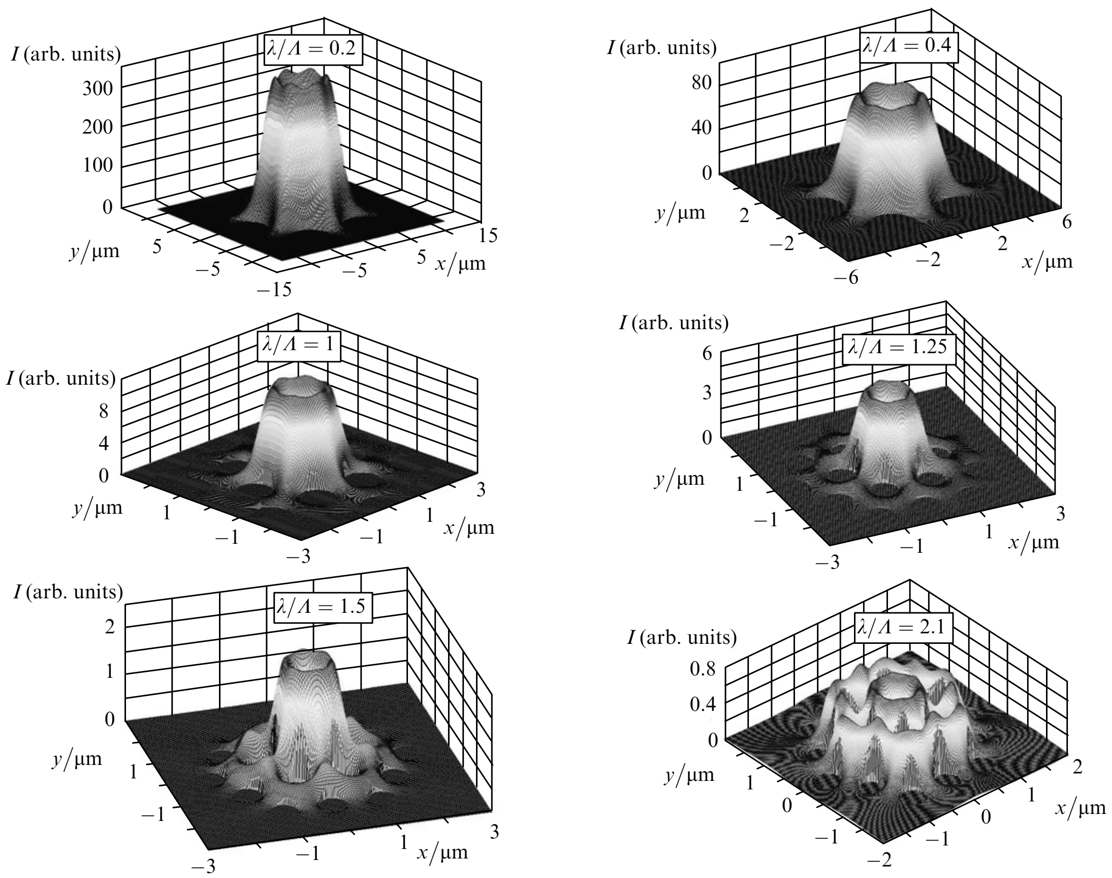

Figure 6. Same as in Fig. 5, but for the next (after the fundamental) mode.

and is determined by the air content in the cladding. Our calculations show that the waveguide losses in a fibre with three rows of holes are so small that the total losses, even in the case of expected low material losses, will be determined by the latter. Therefore, it seems unlikely that tellurite holey fibres with three rows of holes will be required.

To find the region of variation of geometrical parameters of tellurite glass holey fibres in which the single-mode propagation of radiation can be realised, we plotted the dependences of losses for the fundamental and first higher modes of the fibre on the distance Λ between the centres of adjacent holes for different ratios d/Λ. The results of some calculations are presented in Figs 5–7.

Figure 5 shows the change in the intensity of the fundamental mode of the fibre (the real part of the longitudinal component of the Poynting vector) with decreasing the parameter Λ. One can see that, beginning from some values $\Lambda < \lambda$, the process of delocalisation and disappearance of the mode gradually develops. For the most descriptive presentation of this process, the most optimal scales for the mode intensity and the transverse dimensions of the mode field were used in each picture.

Figure 6 shows a similar behaviour for the first of the higher modes of the fibre. By comparing Figs 5 and 6, we see that the higher modes are delocalised noticeably faster than the fundamental mode (the range of variation in the parameter Λ required for delocalisation is noticeably narrower). The effective refractive index n_{eff} for higher modes decreases faster with increasing λ than that for the fundamental mode, these modes are no longer guided in the fibre and the fibre becomes single-mode.

Figure 7 presents the results of a search for the parameters of a holey tellurite fibre determining the possibility of its operation in the single-mode and multimode regimes. One can see that, as in the case of holey silica fibres, the region of the single-mode regime is rather broad.

The data obtained in the paper can be used for the design of microstructure tellurite fibres with the required dimension of the mode field and needed dispersion properties.

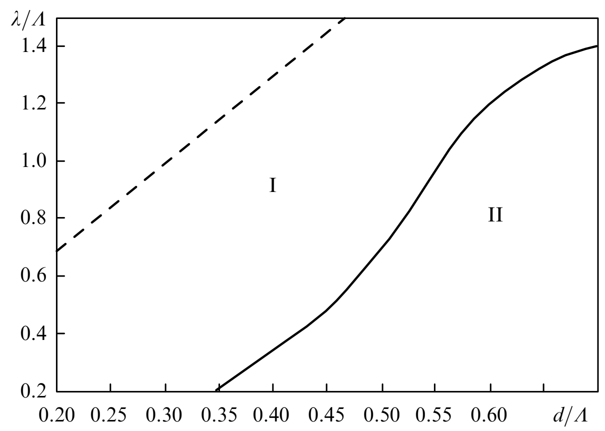

Figure 7. Regions of the single-mode (I) and multimode (II) regimes of radiation propagation in a holey fibre with two rows of holes. The dashed straight line is the upper boundary of the single-mode regime region (delocalisation of the fundamental mode).

In conclusion, note once more that the waveguide optical losses in a tellurite fibre, for example, with three rows of holes are rather low. Therefore, the total losses (including material losses) will be determined by the latter losses, which at present amount to ~ 1 dB m^{-1} due to the inadequate manufacturing technology of tellurite glasses. The theoretically predicted fundamental material losses should be noticeably lower than those for silica glasses.

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