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Waveguide characteristics of single-mode microstructural fibres with a complicated refractive index distribution profile

A.V. Belov, E.M. Dianov

***Abstract*. The method of equivalent step profile of the refractive index is used to calculate the main waveguide characteristics of single-mode microstructural fibres (MFs). A new structure is proposed for such fibres with a W-shaped profile of the refractive index distribution. The dispersion characteristics of such fibres were calculated by solving the scalar wave equation. It is shown that the chromatic dispersion zero may shift to the short-wavelength region ($\lambda_0 \approx 0.8$ μm) in such structures while the single-mode propagation regime is preserved. A number of MF structures with a complicated distribution of the refractive index profile are proposed and the possibility of assembling such structures in circular quartz tubes is discussed.**

Keywords: *optical fibres, microstructural fibres, fibre dispersion.*

Photonic crystals have been developed extensively in recent years as a new research trend in optics. Photonic crystals are formed on the basis of various optical structures with a periodic spatial variation of the permittivity, resulting in the formation of the so-called forbidden photonic bands [1]. Local defects of various types in such structures change the symmetry of photonic crystals and cause the localisation of photons in the vicinity of the defect. In the case of extended defects, this facilitates the formation of waveguide structures of the optical fibre type.

Another type of waveguide structures are the so-called microstructural fibres (MFs), which are usually made of a single material, fused silica. The transmission of light in such structures is ensured by a periodic structure formed by silica and air. The most popular are structures consisting of identical quartz capillaries forming a hexagonal close-packed structure in which the central capillary is replaced by a quartz rod.

Initially, such structures were treated as photonic crystals. However, it was shown later that the waveguide parameters of such structures can be obtained in the model of total internal reflection of light, and hence these structures were called microstructural fibres. Indeed, because the MF cladding consists of quartz capillaries, its effective refractive index is smaller than the refractive index of the core, and hence we can treat MFs as conventional optical fibres.

However, the waveguide parameters of the MF differ considerably from the characteristics of standard optical fibres. This is due to the fact that, first, the difference in the refractive indices of the core and the cladding in the MF is about two orders of magnitude larger than in conventional fibres. Second, the effective refractive index of the MF cladding depends much more strongly on the radiation wavelength than in standard fibres, which accounts for a number of unique waveguide characteristics of MFs.

In view of these two distinctions, the wavelength of zero chromatic dispersion in the MF may shift towards the wavelength region below 1.3 μm (zeroth wavelength of chromatic material dispersion in fused silica), which is impossible in standard optical fibres. In addition, single-mode propagation may be observed in the MF cladding virtually in the entire spectral range when the size of capillary holes is relatively small.

A variety of theoretical methods were proposed for calculating the waveguide characteristics of MFs [2 – 6]. We used the equivalent step profile model, first proposed by Birks et al. [2], to calculate the MF parameters. Fig. 1

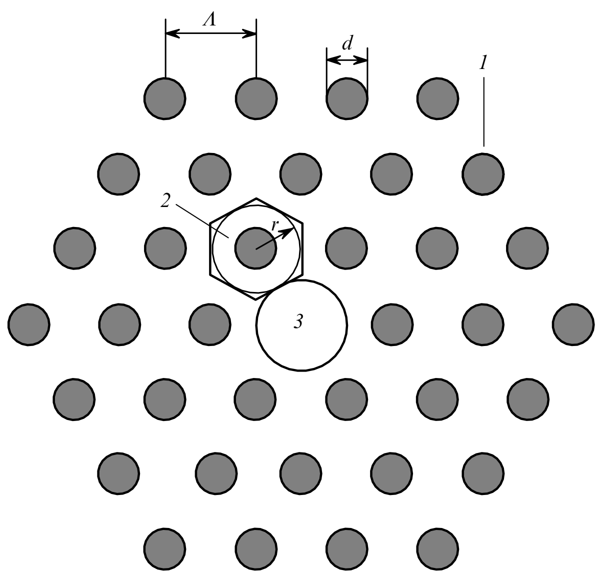

Figure 1. Cross section of an MF with a hexagonal packing of quartz capillaries: (*1*) holes with $d/\Lambda = 0.45$; (*2*) unit cell with a hexagonal packing; (*3*) core.

A.V. Belov, E.M. Dianov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow

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shows the cross section of hexagonal packing of quartz capillaries, in which the central capillary is replaced by a quartz rod. To calculate the effective refractive index $n_{\mathrm{eff\,cl}}$ of the cladding, the hexagonal unit cell shown in Fig. 1 was replaced by a circle of radius $\Lambda/2$, where Λ is the distance between the centres of the quartz capillaries. Then, the scalar wave equation was solved for the circular unit cell under the assumption that the field $E(r)$ satisfies the boundary condition $\mathrm{d}E(r)/\mathrm{d}r|_{r=0} = 0$. The solution was found by the iterative technique proposed in Ref. [7].

Fig. 2 shows the theoretical distribution of $n_{\mathrm{eff\,cl}}$ for an MF with $d/\Lambda = 0.6$, where d is the capillary diameter. The effective refractive index of the cladding obviously varies within the following limits: for $\lambda \to 0$, we have $n_{\mathrm{eff\,cl}} \to n_{\mathrm{q}}$, where $n_{\mathrm{q}} = 1.45$ is the refractive index of silica; for $\lambda \to \infty$, we have $n_{\mathrm{eff\,cl}} = 1 + (1 - d^2/\Lambda^2)\Delta n$, where Δn is the difference in the refractive indices of silica and air. In our case, $n_{\mathrm{eff\,cl}} \to 1.288$ for $d/\Lambda = 0.6$. Then, by solving the scalar wave equation for the effective core of the MF taking into account the theoretical value of $n_{\mathrm{eff\,cl}}$ and assuming that the core radius is equal to $\Lambda/2$, we determined the effective refractive indices for the fundamental (LP_{01}) and the first higher (LP_{11}) modes.

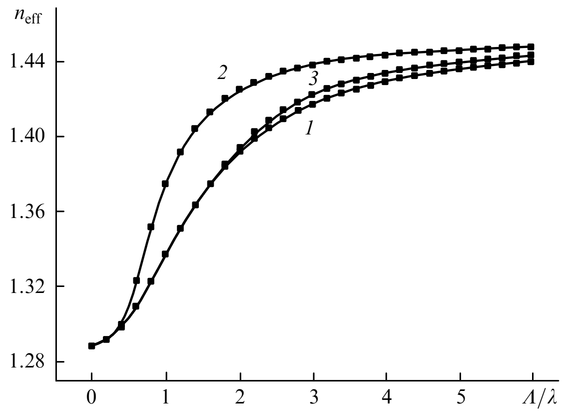

Figure 2. Dependences of the effective refractive indices for the cladding (*1*), fundamental (*2*) and the first higher mode (*3*) of an MF.

Similarly to standard single-mode fibres, the characteristic parameter V_{eff} for holey fibres can be determined from the expression

$$V_{\mathrm{eff}} = \frac{2\pi}{\lambda}\frac{\Lambda}{2}\left(n_{\mathrm{q}}^2 - n_{\mathrm{eff\,cl}}^2\right)^{1/2},$$

where λ is the wavelength. For the scalar approximation used by us, the parameter $V_{\mathrm{eff\,cr}}$ corresponding to the cutoff wavelength of the first higher mode is ~ 2.4. Note that more precise methods of calculating the waveguide characteristics of holey fibres give $V_{\mathrm{eff\,cr}} \approx 2.11$ [6].

Fig. 3 shows the values of V_{eff} calculated for two MF structures with diameters $d/\Lambda = 0.45$ and 0.6 of the capillary holes. One can see that for $d/\Lambda = 0.45$, the parameter $V_{\mathrm{eff}} < 2.4$ for virtually any wavelengths, i.e., MFs remain single-mode structures in the entire spectral range if $d/\Lambda \leqslant 0.45$. This is one of the main distinctions between the waveguide characteristics of MFs and standard single-mode fibres in which the difference Δn in the refractive indices of the core and the cladding is independent of the wavelength, and hence the parameter $V \to \infty$ for $\lambda \to 0$. For the MF, the value of Δn decreases considerably with decreasing λ (see Fig. 2) and therefore the parameter $V \to \mathrm{const}$ for $\lambda \to 0$.

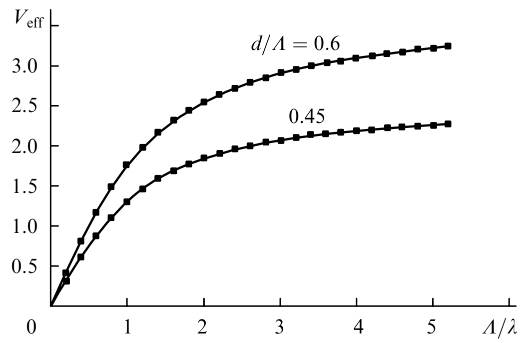

Figure 3. Dependences of V_{eff} for two values of the parameter d/Λ.

The spectral dependence of chromatic dispersion was determined by using the theoretical dependence of the effective refractive index n_{eff} of the core according to the formula

$$D = -\frac{\lambda}{c}\frac{\mathrm{d}^2 n_{\mathrm{eff}}}{\mathrm{d}\lambda^2}.$$

The material chromatic dispersion of pure silica of the MF core was obtained from the three-term Sellmeyer equation [8]. Fig. 4 shows the dispersion curves calculated for different values of d/Λ and for $\Lambda = 2.3$ μm. One can see that the zeroth wavelength of chromatic dispersion is displaced to shorter wavelengths ($\lambda < 1$ μm) for relatively large diameters of the holes ($d/\Lambda > 0.45$). In addition, one can see that holey optical fibres with a flattened dispersion curve in a wide spectral range 1.1 – 1.5 μm can be fabricated for certain values of d/Λ (~ 0.35).

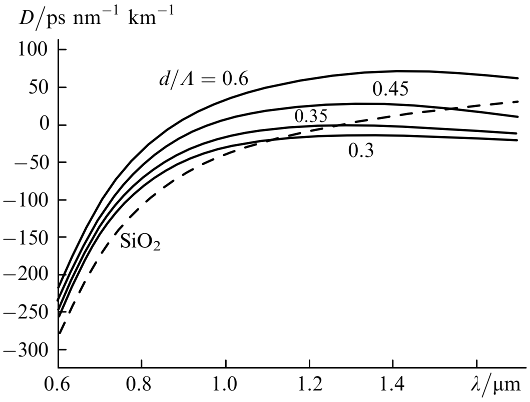

Figure 4. Theoretical wavelength dependences of the chromatic dispersion in an MF for various values of the parameter d/Λ and $\Lambda = 2.3$ μm. The dashed curve shows the dependence $D(\lambda)$ for fused silica.

The behaviour of the dispersion curve depends significantly on a number of other parameters and, first of all, on the distance Λ between the centres of holes and on the core diameter d_{core}. Fig. 5 shows the wavelength dependences of $D(\lambda)$ for $d/\Lambda = 0.45$ and for $\Lambda = 2.3$ μm for different values

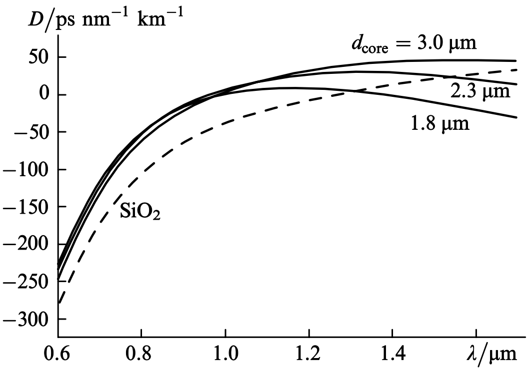

Figure 5. Theoretical wavelength dependences of the chromatic dispersion in an MF ($d/\Lambda = 0.45$ and $\Lambda = 2.3$ μm) for different values of the core diameter d_{core}. The dashed curve shows the dependence $D(\lambda)$ for fused silica.

of d_{core}. One can see that fibres with a flattened dispersion curve can also be fabricated at small values of the core diameter ($d_{core} \approx 1.8$ μm).

The size of the mode spot is another important waveguide characteristic of the MF. By calculating the mode-spot size, we can estimate the splicing losses for MFs, bending and microbending losses, and several other parameters. Note that the spectral dependence of the mode spot is as important as the estimate of its size. We determined the diameter of the mode spot in the MF associated with the bending losses from the expression [9]:

$$\omega_b = \left[\frac{\int E^2(e) r^3 \mathrm{d}r}{\int E^2(r) \mathrm{d}r} \right]^{1/2}.$$

Fig. 6 shows the spectral dependence of the mode-spot diameter calculated from this expression for an MF with parameters $d/\Lambda = 0.6$ and $\Lambda = 2.3$ μm. One can see that the spot diameter is small (3–4 μm) and varies by a factor not larger than 1.5 when the wavelength changes from 1.0 to 2.3 μm. Therefore, such an MF has quite low theoretical bending losses over a wide spectral range.

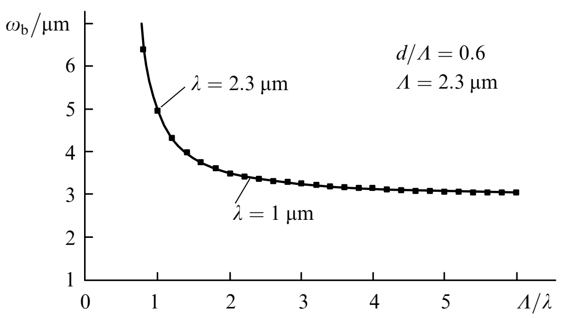

Figure 6. Dependence of the mode-spot diameter on Λ/λ for $d/\Lambda = 0.6$, $\Lambda = 2.3$ μm.

It was mentioned above that the wavelength may shift to the short-wavelength region ($\lambda_0 < 0.9$ μm) for relatively large capillary diameters ($d/\Lambda = 0.6$). In this case, however, an MF is no longer a single-mode fibre. For this reason, we propose here to use fibres with a complicated distribution of the refractive index profile (W-profile) to provide a single-mode propagation and a blue shift of the zeroth wavelength of chromatic dispersion. In this case, the inner diameter of the capillaries located in close proximity of the MF core is larger than that of the remaining holes in the cladding, resulting in the formation of a layer near the core whose effective refractive index is lower than that in the cladding (Fig. 7).

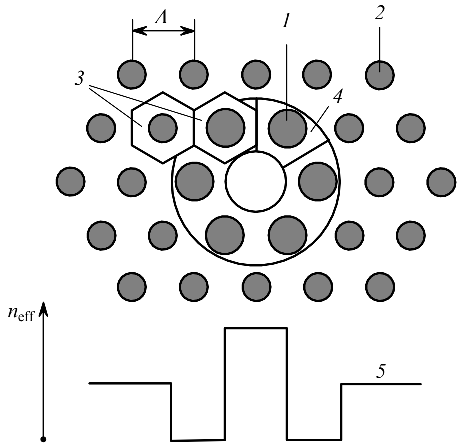

Figure 7. Cross section of an MF with a hexagonal packing of quartz capillaries and the W-profile: (*1*) holes with $d/\Lambda = 0.6$; (*2*) holes with $d/\Lambda = 0.45$; (*3*) unit cell with a hexagonal packing; (*4*) equivalent unit cell in the depressed cladding; (*5*) effective refractive index distribution.

The effective thickness of the depressed cladding was determined from the condition that the effective area of the hole in the equivalent unit cell (a sector in the depressed cladding) is equal to the ratio of the hole area to the area of a hexagonal unit cell. Under this condition and for the chosen parameters of the optical fibre ($d/\Lambda = 0.6$ in the depressed cladding), the effective cladding radius r_{cl} is 1.3Λ.

Fig. 8 shows the chromatic dispersion curve calculated for a given W-profile. One can see that the dispersion curve in the short-wavelength region ($\lambda < 1.0$ μm) coincides with the dependence $D(\lambda)$ for an MF whose cladding is completely filled by holes with $d/\Lambda = 0.6$. On the other hand, it is known that, because of the large leakage losses for the first higher mode, the presence of depressed cladding leads

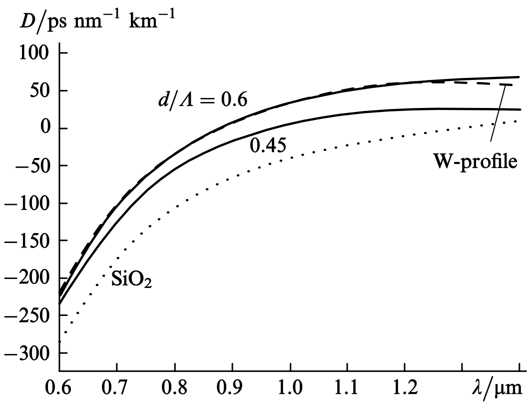

Figure 8. Dependences of the chromatic dispersion calculated for an MF with a step profile for $d/\Lambda = 0.45$ and 0.6, and for an MF with the W-profile of the refractive index distribution. The dashed curve shows the dependence $D(\lambda)$ for fused silica.

to a considerable blue shift of the cutoff frequency [10]. For a small thickness of the depressed cladding ($r_{cl}/r_{core} < 2$), the effective cutoff wavelength for the MF is determined by the difference in the refractive indices of the core and the outer cladding.

Note that such structures can be formed directly in circular quartz support tubes using capillaries of various inner and outer diameters. Fig. 9 shows the cross section of such an assembly and the distribution of the effective refractive index. Note that the MF assembly in a circular quartz tube considerably simplifies the technological process of gradual formation of blanks and drawing of single-mode optical fibres from the blanks. Fig. 10 shows another possible cross section of such a structure; the presence of 12 capillaries in a layer leads to a more uniform field distribution in the azimuthal direction. Note that the use of capillaries with various inner and outer diameters in the outer cladding permits the formation of MFs with a more complicated refractive index profile in the cladding than the simple W-profiles. This is especially important from the point of view of choosing the refractive index profile of a microstructure optical fibre having a flattened chromatic dispersion curve in a wide spectral range (0.8 – 1.7 μm).

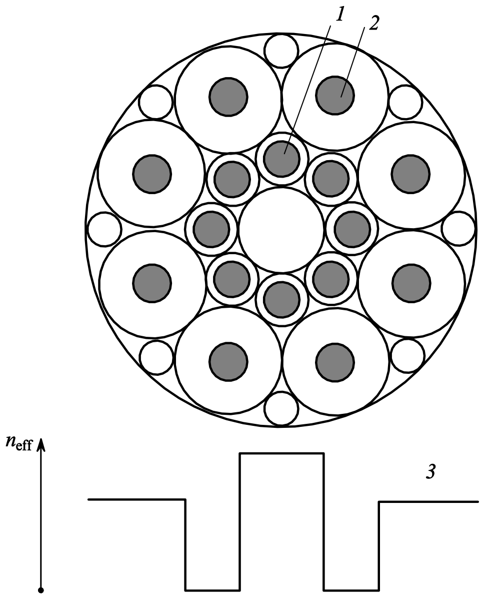

Figure 9. Cross section of an MF with a layer-by-layer packing of capillaries with various inner and outer diameters: (*1*) holes with $d/\Lambda = 0.6$; (*2*) holes with $d/\Lambda = 0.45$; (*3*) effective refractive index distribution in the fibre with the W-profile.

Note in conclusion that the method described in this work for determining the waveguide characteristics of MFs by solving the scalar wave equation is an approximate one. It was shown in Ref. [3] that the error of this method is not large in the short-wavelength region and for relatively small holes ($d/\Lambda < 0.35$). The dispersion curves calculated in this work for holes of large diameters ($d/\Lambda \approx 0.6$) are in good agreement with the results of more exact calculations [3, 5] and the experimental results [11] obtained in the short-wavelength region ($\lambda < 1.0$ μm). Our results differ from those obtained by more exact methods mainly for wavelengths above 1.2 μm.

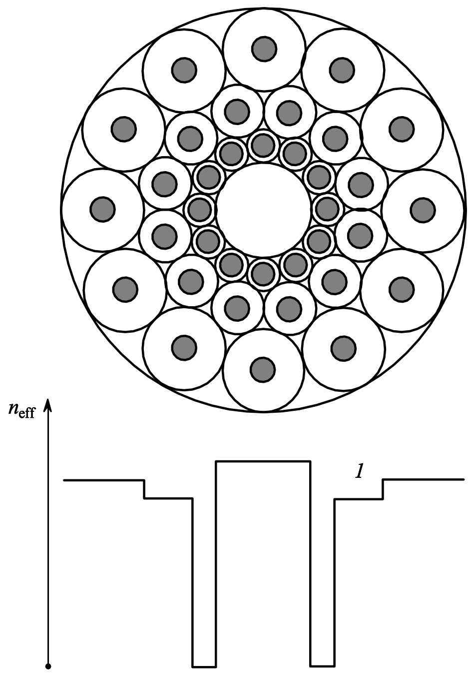

Figure 10. Cross section of an MF with a complicated distribution of refractive index profile: (*1*) effective refractive index distribution.

Thus, we have used the method of equivalent step profile to determine the main waveguide characteristics of holey single-mode optical fibres. Structures of holey fibres with the W-profile of the refractive index distribution are proposed. It is shown that zero of chromatic dispersion in such structures may be displaced to the short-wavelength region ($\lambda_0 \approx 0.8$ μm) while the single-mode propagation regime is preserved. A number of MF structures with a complicated distribution of the refractive index profile and the possibility of formation of assemblies of such structures in circular quartz tubes are also proposed.

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