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OPTICAL FIBRES

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Photonic bandgap single-mode optical fibre with ytterbium-doped silica glass core

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***Abstract*.** **A photonic bandgap fibre with an ytterbium-doped silica glass core is fabricated and investigated. The possibility of implementing single-mode operation of such fibres in a wide spectral range at a large (above 20 μm) mode field diameter makes them promising for fibre lasers and amplifiers. To ensure a high quality of the beam emerging from the fibre, particular attention is paid to increasing the optical homogeneity of the ytterbium-doped core glass.**

Keywords: *photonic bandgap fibres, fibres with a large mode field area, ytterbium-doped fibres.*

1. Introduction

One of the main advantages of fibre lasers and amplifiers based on silica fibres is their low sensitivity to thermooptical distortions and, as a result, high beam quality, even at high powers. However, in contrast to bulk laser elements, radiation in fibre lasers and amplifiers, first, is concentrated in the fibre core (whose diameter does not exceed few micrometers) and, second, propagates along the active fibre, which is many meters long. The high radiation intensity and long propagation path lead to significant nonlinear optical effects, which cause undesirable distortion of the spectrum of the fibre laser or amplifier pulse. One of the ways for reducing nonlinear optical effects is to decrease the radiation intensity by increasing the core diameter. Another necessary condition for a high beam quality is that the fibre operation remains single-mode with an increase in core diameter.

Currently, the most widespread single-mode optical fibres with a large core diameter (above 20 μm) are hollow microstructured ones. The use of this design is based on the fact that a fibre with certain parameters can remain single-mode in a very wide spectral range [1].

Single-mode propagation of light in a wide spectral range is also observed in photonic bandgap fibres with a silica core [2]. The cross section of such a fibre is shown in Fig. 1.

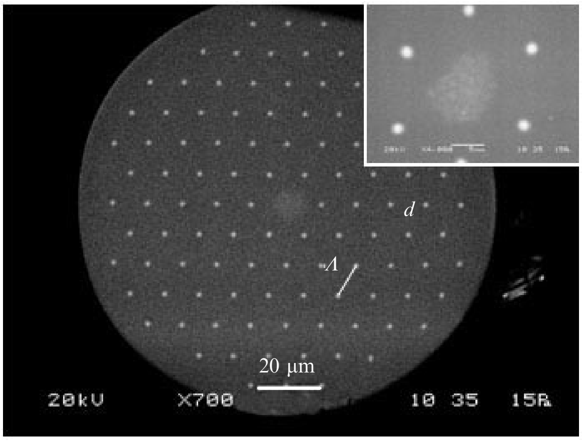

Figure 1. Electron microscope image of a fibre face: the hexagonally ordered bright spots are the elements of photonic-crystal cladding doped with germanium oxide (d is the cladding element diameter, Λ is the distance between the centres of neighbouring elements). The inset shows an enlarged image of the fibre core region doped with Yb.

Its cladding is a 2D photonic crystal and consists of silica cylinders doped with germanium oxide, which are hexagonally arranged in pure silica. The refractive index of glass doped with germanium oxide exceeds that of pure silica; the relative difference in the refractive indices is from 1 % to 2 %. Light is localised in the optical fibre core, which is formed by the absence of one (as in Fig. 1) or several cladding elements, in the regions corresponding to the photonic bandgap.

The first photonic bandgap fibre with a silica core was demonstrated in [3]. The ratio of the cladding element diameter d to the distance between the centres of neighbouring elements Λ was 0.34 or more in this study and some subsequent studies on this subject. We showed [2] that fibres of this type also localise light and have relatively low optical losses at a small ($\leqslant 0.12$) d/Λ ratio; at the same time, they may have a mode field of large diameter (above 20 μm) and be single-mode in a wide spectral range. This fact gives an impetus to study the possibility of applying such optical fibres as laser and amplifier elements. The absence of holes in the cross section is an attractive feature, which makes simpler their fabrication and handling in comparison with hollow microstructured fibres [1].

In this paper, we report the results of developing and studying photonic bandgap fibres with an ytterbium-doped

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core. When forming an active fibre for a laser or amplifier, the change in the refractive index and the optical inhomogeneity of the core glass that are caused by doping should not affect the fibre waveguide properties. Therefore, special attention was paid to the formation of a uniform core glass using the assembly and extension technique. We investigated the mode composition, optical losses, and generation characteristics of the fibre obtained.

2. Theoretical simulation of waveguide properties

As was noted above, the cladding of the fibre under study is a two-dimensional photonic crystal and its core is a defect of this crystal. Therefore, it is convenient to describe the properties of optical fibres with a photonic band gap using band diagrams [4]. Figure 2 shows the energy band diagram for a fibre with a ratio of the cladding element diameter to the distance between neighbouring elements equal to $d/\Lambda = 0.12$ and a difference of 0.028 in the refractive indices in the cladding. The core existence is due to the absence of one of the rods. The energy band diagram is plotted in the $(\beta - kn_0)\Lambda$, λ/Λ coordinates, where β is the mode propagation constant, $k = 2\pi/\lambda$, and n_0 is the silica refractive index. The band diagrams were calculated by the plane-wave method [5] using the MIT Photonic-Bands (MPB) software package [6].

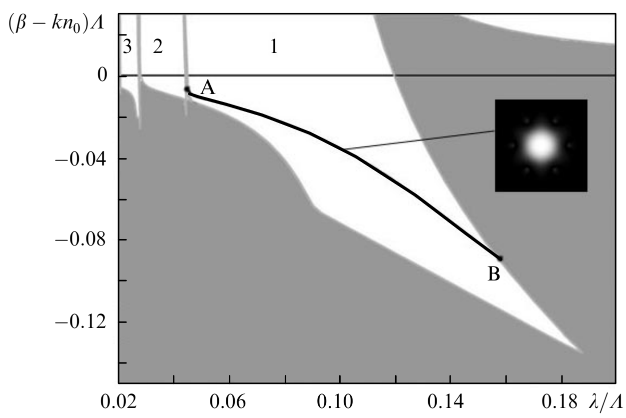

Figure 2. Energy band diagram of a fibre with a ratio $d/\Lambda = 0.12$ and a difference in the refractive indices in the cladding of 0.028 (β is the mode propagation constant, $k = 2\pi/\lambda$, n_0 is the silica refractive index).The regions where cladding modes exist are shown gray, the band gaps are shown white, and the dispersion curve of the core mode is in bold. A and B are the cutoff points of the fundamental core mode. The inset shows the core mode intensity distribution.

The regions where modes of the fibre cladding (photonic crystal) exist are shown grey in Fig. 2. The structure of these bands is determined by only the periodic cladding structure and is independent of the existence and form of the fibre core. The first three band gaps are shown white. Due to the presence of band gaps, separated by domains of existence of cladding modes, the fibre transmission spectrum consists of high-transmission bands (which correspond to photonic crystal band gaps), separated by gaps where the fibre core mode is not localised. In this study we investigated only the longest wavelength (fundamental) band gap (denoted by 1 in Fig. 2).

The dispersion curve of the core (defect) mode lies within the band gap. Calculations show that an optical fibre with specified parameters is characterised by only one dispersion curve of the core mode in the band gap; therefore, the fibre is single-mode within the entire fundamental band gap. The intensity distribution for the fibre core mode (Fig. 2, inset) has one central and six lateral parts.

The dispersion curve of the core mode crosses the bandgap edges at the points A and B, where the core mode is cut off. According to the energy band diagram, there are both long-wavelength (at the point B) and short-wavelength (at the point A) cutoffs of the fundamental core mode; therefore, the spectral range of mode existence in the fibre under study is approximately 0.6 – 1.8 μm (at $\lambda = 11.4$ μm).

3. Fibre fabrication and study

Fibre fabrication involves two stages: preparation of a preform and its subsequent drawing to the fibre. The fibre perform was fabricated from a bunch of rods [7]. The rods, which formed elements of the preform cladding, were obtained by drawingof an MCVD perform having a core doped with germanium oxide. The rod diameter was about 1 mm.

A rod of the same diameter from ytterbium-doped silica was used as a core. In this case, as for hollow microstructured fibres, the averaged refractive index of the doped core material should be equal to the refractive index of undoped silica. To obtain a high-quality beam from a fibre laser or amplifier, one must have the refractive index of the core material uniformly distributed over the cross section (the size of the region of change in the refractive index of the fibre core should not exceed 1 μm). However, the refractive index distribution over the core diameter in an MCVD fibre generally contains large annular inhomogeneities ($\Delta n \approx \pm 0.001$, ring thickness of several micrometers), which are caused by variations in the dopant concentration, arising upon layer-by-layer deposition of doped glass. Therefore, a rod for the fibre preform core was fabricated using the technique that makes it possible to increase the core glass optical homogeneity in comparison with the cores of MCVD performs.

The rod was prepared as follows: the undoped cladding was completely removed (by etching in hydrofluoric acid) from several MCVD performs having an ytterbium-doped core. Then the thus obtained rod-like cores were extended into thinner (1 mm in diameter) rods. Thirty segments of these rods was used to form an assembly, which was then placed in a silica tube and heated to melt into a monolithic rod; the latter was drawn into a rod-like preform of necessary diameter (about 1 mm). As a result, the characteristic size of the optical inhomogeneities caused by concentration fluctuations in the rod obtained was much smaller (by a factor of more than 5) than the size of inhomogeneities in the initial preforms.

The rods for the cladding elements and fibre core were used to form an assembly, which was then placed in a silica tube and heated to melt into a monolithic preform rod. Specifically this preform was drawn into the fibre under study. In this fibre the ratio of the diameter of photonic-crystal cladding elements (rods doped with germanium oxide) to the distance between the centres of neighbouring rods was $d/\Lambda = 0.12$, the distance between the centres of neighbouring rods was $\Lambda = 11.4$ μm, and the difference in the refractive indices in the cladding was $\Delta n = 0.028$. The fibre diameter was 135 μm, and the diameter of the ytterbium-doped part was 10 μm. To form a light-guiding cladding around the core for the diode-pump radiation, a polymer coating with a refractive index below that of silica was deposited on the fibre. The numerical aperture of the optical fibre formed by total internal reflection at the glass/polymer interface was 0.4.

The core modes were studied by coupling light with different wavelengths into the fibre; the intensity distribution at the fibre output face was recorded by a CCD camera. Under different excitation conditions in the range of 850 – 1200 nm the observed intensity distribution at the fibre output face was approximated well by a Gaussian distribution (higher order modes were not observed). The mode field diameter was 18 μm.

Within the first band gap we measured the spectrum of optical losses. The latter were determined by the cutback method, where the powers of light transmitted through two fibre segments of different length are compared (under the same input conditions).

Since the cladding elements can guide light due to the total internal reflection, a special attention was paid to exciting only the core mode when measuring optical losses. To this end, a standard single-mode fibre with a mode field diameter of 6 μm was spliced to the input and output of the fibre segment under study. Measurements were performed on 2- and 45-m segments; the length of the short comparison segment of the fibre studied was 0.5 m in both cases.

The optical-loss measurements on a 2-m segment made it possible to estimate the edges of the fundamental band gap in the fibre under consideration. As can be seen in Fig. 3a, the transmission band is in the range from 850 to 1400 nm. The optical losses increase at the transmission band edges. The sharp increase in optical losses near 1 μm is due to the absorption of ytterbium ions. The above-mentioned interval is in the theoretically found spectral range of core mode existence (600 – 1800 μm). The measured range is narrower than the calculated one because the fibre core mode undergoes large optical losses near the band gap edges.

The loss measurements on a 45-m segment made it possible to determine the minimum optical losses; they were found to be 80 dB km^{-1}, a value corresponding to the range of 1100 – 1200 nm. To exclude a sharp increase in losses due to microbends, the fibre was packed into a coil of free turns 33 cm in diameter, without winding on a reel. In [2] the minimum optical losses in a similar fibre with a pure silica core were determined to be 20 dB km^{-1}.

To measure the maximum absorption of ytterbium ions, white light was introduced from the end face into the pump cladding of optical fibre, and the fraction of light absorbed by the fibre core was measured. The absorption was found to be 1.2 and 0.3 dB km^{-1} at wavelengths of 980 and 915 nm, respectively.

Lasing in the fibre under study was obtained in the scheme shown in Fig. 4a. A linear array of 910-nm multimode laser diodes was used as a pump source. The fibre face F1 and mirror M2 formed a laser cavity. Aspherical lenses L1 and L2 were used to introduce pump radiation into the fibre. To protect the pump source from the fibre laser radiation and to extract this radiation, a dielectric mirror M1 with a high reflectance (HR) at the lasing wavelength (1.03 – 1.06 μm) and a high transmittance (HT) at the pump wavelength were placed between the lenses. The feedback at the fibre output was performed via a dielectric mirror M2, which was located either closely to the fibre face F2 or so as to reflect the light transmitted through the lens L3.

The length of the fibres studied varied from 20 to 45 m, the slope efficiency in different schemes reached 50 % – 55 %, and the average lasing threshold was 1 W (Fig. 4b). The scheme with a lens had a lower efficiency as compared to the scheme with the mirror M2 adjacent to the fibre face.

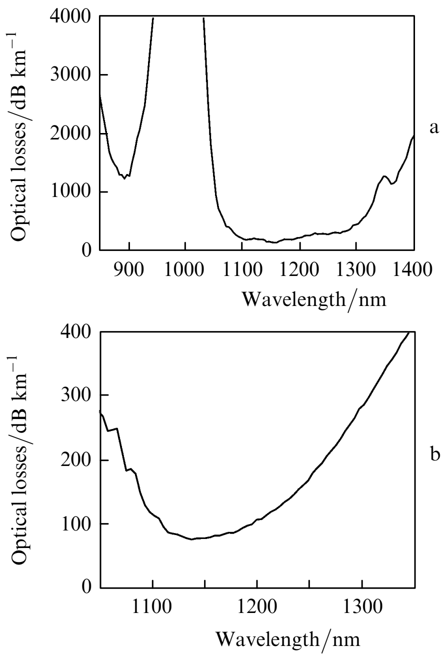

Figure 3. Optical-loss spectra measured on fibre segments with lengths of (a) 2 and (b) 45 m.

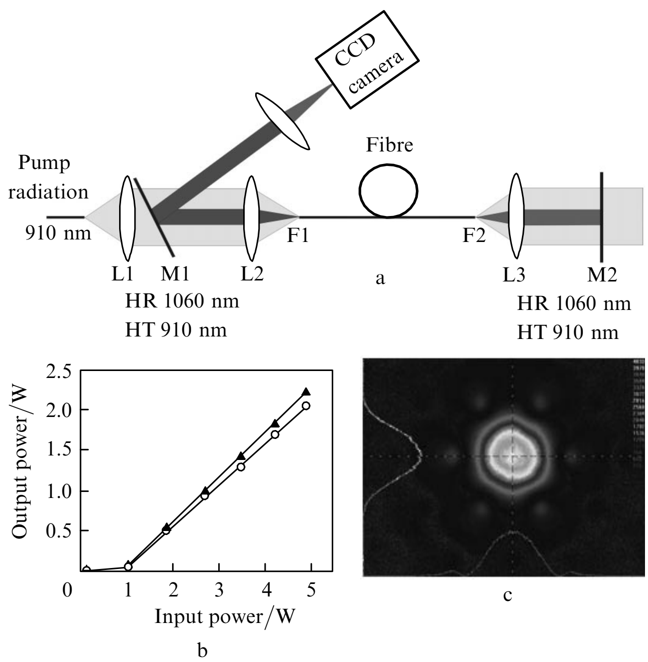

Figure 4. (a) Schematic of the setup for studying the fibre lasing characteristics, (b) the dependence of the output power on the introduced pump power, and (c) the intensity distribution at the fibre output face.

Obviously, this is related to the additional optical losses in the lens. The low (for fibre ytterbium lasers) slope efficiency is caused by the relatively low concentration in the core, which leads to an increase in the fibre working length and the related passive optical losses in the cavity.

The distribution of the relative intensity of the output radiation at the fibre face, recorded by a CCD camera, is rather complicated; it consists of a central part and six lateral parts, a configuration corresponding to the fundamental fibre mode (Fig. 4c). The intensity distribution in the central part is close to Gaussian and contains 90 % light power. The other 10 % are for the lateral parts. The power distribution between the central and lateral parts, as well as the number and shape of the lateral parts, depend on the fibre design.

4. Conclusions

A photonic bandgap single-mode optical fibre with an ytterbium-doped silica core was fabricated and investigated. Its mode field diameter is relatively large: 18 μm. However, this fibre design makes it possible to increase the mode field diameter with conservation of a high beam quality. Due to the absence of air holes in the fibre cross section, such a fibre is easier to fabricate and use in comparison with hollow microstructured ones.

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References

1. Knight J.C., Birks T.A., Russell P.St.J., Atkin D.M. *Opt. Lett.*, **21**, 1547 (1996).
2. Egorova O.N., Semjonov S.L., Kosolapov A.F., Denisov A.N., Pryamikov A.D., Gaponov D.A., Biriukov A.S., Dianov E.M., Salganskii M.Y., Khopin V.F., Yashkov M.V., Gurianov A.N., Kuksenkov D.V. *Opt. Express*, **16**, 11735 (2008).
3. Argyros A., Birks T.A., Leon-Saval S.G., Cordeiro C.M.B., Luan F., Russell P.St.J. *Opt. Express*, **13**, 309 (2005).
4. Joannopoulos J.D. *Photonic Crystals. Molding the flow of light* (Princeton: Princeton Univ. Press, 2008).
5. Johnson S.G., Joannopoulos J.D. *Opt. Express*, **8**, 173 (2001).
6. http://ab-initio.mit.edu/mpb.
7. Bjarklev A., Broeng J. *Photonic Crystal Fibers* (Boston: Kluwer Acad. Publ., 2003).