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New generation of optical fibres

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Abstract. **The growing need for information in contemporary society is the motivating force behind the development of fibre optics in general and optical fibre communications in particular. Intensive research effort has been concentrated on designing new types of optical fibres and extending their application field. This paper reviews results of research on new types of optical fibres: bismuth-doped active fibres, multicore fibres and hollow-core fibres, which can be used as key components of systems that ensure further increase in optical information transfer rate.**

Keywords: *optical fibre communications, bismuth-doped fibres and amplifiers, microstructured fibres, hollow-core fibres.*

1. Introduction

The history of the development of society is also to some extent the history of the development of means of communication. The higher the level of development of society, the greater is its need for information and, hence, for new, more advanced means of communication [1]. This relationship is best illustrated by the example of optical fibre communications. The advent of lasers in 1960 and low-loss optical glass fibres in 1970 led to the development of optical fibre communication systems. The first commercial optical communication systems were produced as early as 1980. The growing need in contemporary society for information has required ongoing progress in optical fibre communications, primarily through an increase in fibre data rate based on novel principles of information transfer and owing to the advent of novel components of communication systems. Optical fibre communications have become a strong impetus for the development of fibre optics, causing new types of optical fibre (OF), with novel capabilities, to emerge. Among the most important applications of OFs, note, first of all, fibre lasers and amplifiers, which are among the key elements of optical fibre communication systems, and fibre-optic sensors. These devices find wide application in various areas of modern technology and in medicine.

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In 2010, the situation in the field of optical fibre communications was characterised by the following main performance parameters:

1. Fibre transmission capacity in commercial communication systems reached 10 Tbit s^{-1}, and that in pilot systems was up to 100 Tbit s^{-1}.

2. In 2010, the world's communication systems used 1 billion kilometres of OFs (the number doubled by 2015).

3. The need for information in the developed countries increases by 30% to 40% every year, i.e. fibre transmission capacities at petabit levels will be needed in ten years.

Existing single-mode fibres are, however, incapable of transmitting information at such rates because of two basic limitations: optical nonlinearity of glass fibre and narrow information transfer bandwidth, which is determined by the gain bandwidth of the erbium-doped fibre amplifier [2, 3].

To date, the highest fibre capacity has been reached in wavelength-division multiplexing systems, in which fibre combines ~100 independent channels at different carrier wavelengths that lie within the gain band of an optical amplifier. The total information transfer rate is $B = nb$, where b is the channel data rate and n is the number of spectral channels. The information transfer rate can be raised by increasing both the number of channels and the channel data rate (to 400 Gbit s^{-1} and above). However, because of the above physical limitations, the total information transfer rate can only be increased in this way to a level of ~100 Tbit s^{-1}. Because of this, intensive research effort has recently been concentrated on new types of OF which would be able to eliminate the limitations on the increase in fibre transmission capacity.

This paper considers three types of OF which have been shown to be potentially capable of resolving the issue in question:

(1) bismuth-doped active fibres potentially attractive for making fibre lasers and optical amplifiers operating in the spectral ranges 1200–1500 and 1600–1800 nm, which contain no luminescence bands of efficient rare-earth analogues [4];

(2) multicore (single- and few-mode) fibres for fibre-optic space-division multiplexing systems [5]; and

(3) hollow-core microstructured fibres with low nonlinearity and potentially lower optical losses in comparison with silica-based fibres [6].

2. Bismuth-doped fibres

In modern high-speed optical fibre communication systems, information is transmitted within a narrow spectral range (1530–1610 nm), which is determined by the gain band of the erbium-doped fibre amplifier. Actually, use is made of a much narrower spectral range of the amplifier, 36 nm in width. However, as seen in Fig. 1 the spectral range of low optical losses in silica-based fibres is considerably broader. In particular, the spectral range where the optical loss is under 0.4 dB km^{-1}, which might be employed for information transfer, is 400 nm in width (1300–1700 nm).

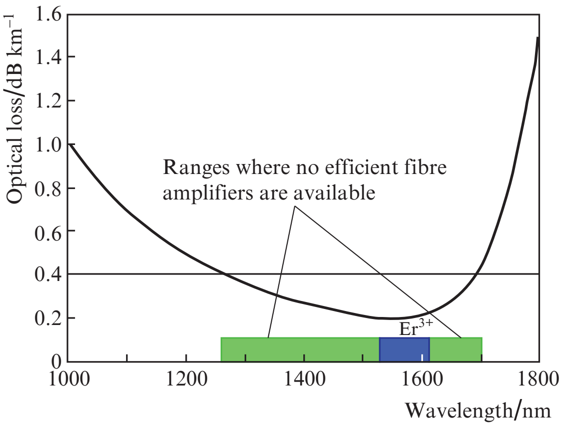

Figure 1. Optical loss spectrum of telecommunications fibre and spectral range of the erbium-doped fibre amplifier.

At present, however, efficient fibre amplifiers – necessary components of high-speed optical fibre communication systems – are still lacking in the spectral ranges 1300–1520 and 1610–1700 nm. The most efficient gain media in the near-IR spectral region are fibres doped with rare-earth elements. Unfortunately, their luminescence bands are unsuitable for making efficient fibre amplifiers in the above spectral ranges. In this connection, there is an urgent need for new active optical materials suitable for making efficient fibre lasers and optical amplifiers operating at the wavelengths in question. Attempts to produce such materials doped with transition metal ions have been unsuccessful.

In 2001, bismuth-doped aluminosilicate glass was found to luminesce in a wide spectral range (1000–1600 nm), with bandwidths from 200 to 300 nm [7]. This attracted great interest and gave impetus to a number of studies dealing with luminescence in bismuth-doped glasses of various compositions. The first bismuth-doped aluminosilicate glass fibres were fabricated simultaneously and independently in 2005 at the Fiber Optics Research Center (FORC), Russian Academy of Sciences (RAS), in cooperation with researchers from the G.G. Devyatykh Institute of Chemistry of High-Purity Substances, RAS [8], and at Sumitomo Electric Industries, Ltd. (Japan) [9].

The bismuth-doped fibres were produced by modified chemical vapour deposition (MCVD), a process widely used to fabricate standard OFs. The fibre core consisted of silica glass doped with bismuth and aluminium.

In the same year, researchers at FORC reported the first demonstration of lasing in bismuth-doped fibre [10]. In subsequent years, bismuth-doped aluminosilicate glass fibres were also made in France and England, and such fibres and related fibre lasers were studied for the first time in sufficient detail in a number of laboratories [11–18].

After the successful fabrication of the first bismuth-doped fibres and demonstration of lasing in them, our main purpose was to show that these fibres were indeed a laser medium promising for making fibre lasers and amplifiers operating in the spectral ranges 1200–1500 and 1600–1800 nm, where efficient rare-earth-based lasers and optical amplifiers were lacking. Bismuth is a p-block element, so its optical properties strongly depend on glass composition (in contrast to the rare-earth elements). In connection with this, to resolve the issue in question it was necessary to produce bismuth-doped fibres with a variety of core glass compositions. As a result, fibres were fabricated which had $Bi:SiO_2$, $Bi:GeO_2$, $Bi:GeO_2-SiO_2$, $Bi:P_2O_5-SiO_2$ and $Bi:P_2O_5-GeO_2-SiO_2$ cores containing no more than 0.02 at % bismuth. Their optical loss spectra (Fig. 2) contain several broad bands in the visible and near-IR spectral regions, which are convenient for pumping the corresponding bismuth-doped fibre lasers.

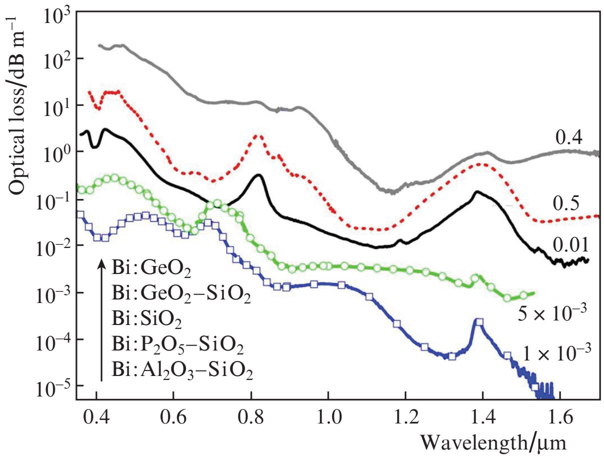

Figure 2. Optical loss spectra of various bismuth-doped fibres. The numbers at the curves indicate the degree of decrease in absorption in the spectrum (for convenience of comparison).

Results of a detailed study of the luminescence properties of those fibres, including measurements of their luminescence intensity as a function of both excitation and emission wavelengths in a wide spectral range (450–1700 nm), were reported in Ref. [19]. Here, we present only luminescence bands of four bismuth-doped fibres, from $Al_2O_3-SiO_2$, $P_2O_5-SiO_2$, SiO_2 and GeO_2-SiO_2, which have the greatest promise for the fabrication of fibre lasers (Fig. 3). Typical Al_2O_3 and P_2O_5 contents of the first and second types of fibre, respectively, are 2–5 mol %. The core of the third type of fibre occasionally contains a small amount (2–5 mol %) of GeO_2, which is added to improve the optical quality of the glass. The GeO_2 content of the fourth type of fibre is about 50 mol %. The luminescence lifetime in these fibres ranges from 500 to 900 μs. The strong overlap of the luminescence bands suggests that lasing might be possible throughout the spectral range 1000–1800 nm, but this is not quite so. Figure 4 shows the gain bands of these fibres, which provide more adequate information about possible lasing ranges.

The spectral ranges of possible efficient operation of fibre lasers based on the fibres under consideration are as follows: 1140–1215 nm ($Bi:Al_2O_3-SiO_2$), 1260–1360 nm ($Bi:P_2O_5-SiO_2$), 1390–1540 nm ($Bi:GeO_2-SiO_2$, $[GeO_2] <$ 5 mol %) and 1625–1775 nm ($Bi:GeO_2-SiO_2$, $[GeO_2] \approx$ 50 mol %). It follows from these data that bismuth-doped fibre lasers may have a large emission bandwidth: from 75 nm

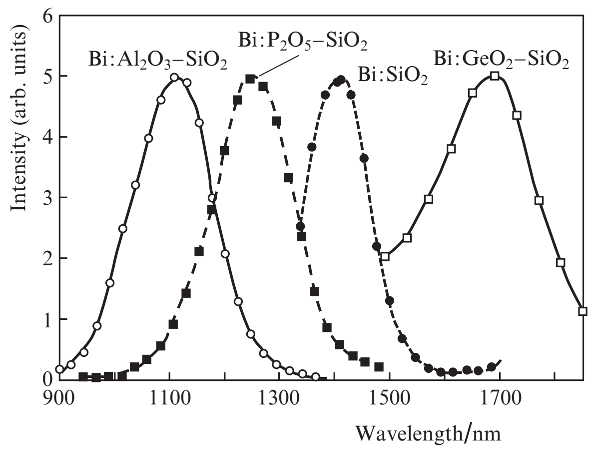

Figure 3. Luminescence spectra of various bismuth-doped fibres.

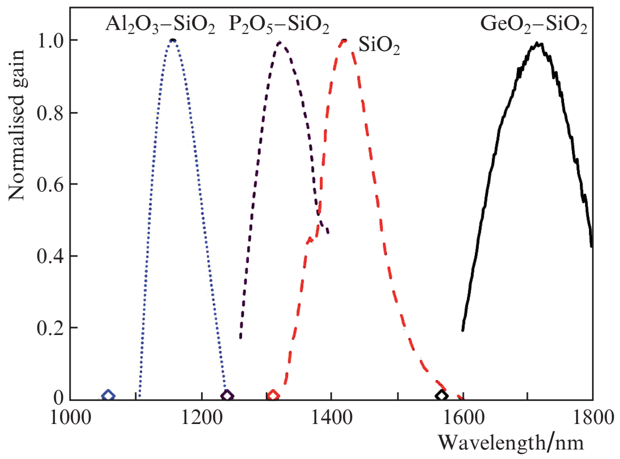

Figure 4. Gain spectra of various bismuth-doped fibres.

in the aluminosilicate laser to 150 nm in the germanosilicate lasers.

The fabrication of the four types of bismuth-doped fibre and investigation of their luminescence spectra made it possible to resolve the main issue: to develop corresponding fibre lasers and study their performance in a wide spectral range (1140 – 1775 nm).

Details of laser experiments and their results were described in original research articles [20 – 25] and reviews [26 – 28]. Here, we present only summary results of those studies (Fig. 5): laser wavelengths and maximum output powers of benchtop cw bismuth-doped fibre laser configurations demonstrated to date. The dots on the horizontal axis indicate the pump wavelengths (λ_p) and the associated laser wavelengths (the laser wavelengths corresponding to output powers less than 0.5 W are omitted). Also indicated are the maximum laser slope efficiencies.

Thus, the development of bismuth-doped silica fibres and the use of such fibres as gain media have made it possible to create a family of rather efficient fibre lasers operating in the spectral range 1140 – 1775 nm. It is important to note that this spectral region includes the ranges 1200 – 1500 and 1610 – 1775 nm, where efficient rare-earth-doped fibre lasers are lacking. The above results confirm that bismuth-doped glass fibres have great potential as new gain media for the near-IR spectral region.

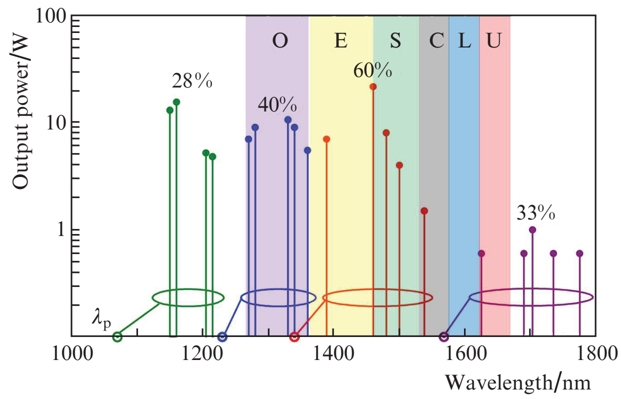

Figure 5. Output powers of various cw bismuth-doped fibre lasers operating in the spectral range 1140 – 1775 nm.

Unfortunately, there are a number of problems that have not yet been solved. Three of them are as follows:

the nature and structure of active bismuth centres are not yet fully clear,

efficient operation of bismuth-doped fibre lasers has only been demonstrated at very low bismuth concentrations (~0.01 at %), and

the efficiency of the bismuth-doped fibre lasers is still lower than that of the rare-earth-doped fibre lasers.

We believe that further fundamental studies will allow these problems to be solved.

3. Multicore optical fibres

The idea that an OF may have not one but several cores emerged more than 30 years ago, soon after the advent of single-mode fibres [29, 30]. The diameter of the guiding core in such fibres is less than 10 μm, which allows one to incorporate several cores even into a standard glass cladding of 125 μm diameter (Fig. 6). The core diameter in the then available multimode fibres was 50 μm or more, which ruled out such possibility.

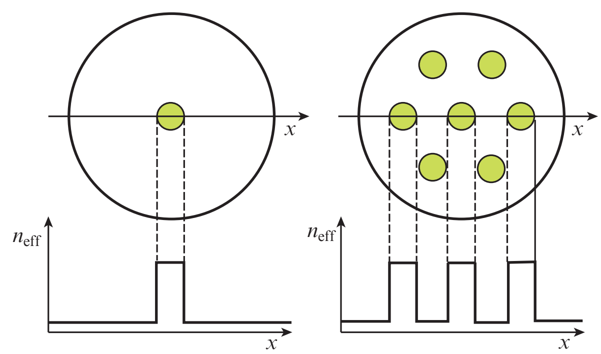

Figure 6. Cross sections and effective index profiles of a single-mode single-core (left) and a multicore (right) fibre.

The idea was not implemented for a long time, because major attention was focused on improving the properties of single-core fibres, extending the spectral range of channels, maximising wavelength-division multiplexing capacity and raising the channel data rate. It was recalled in relation to optical communications when reports emerged in 2009 – 2010 suggesting that a fibre capacity crunch was looming [31–33]. By analogy with wavelength-division multiplexing (WDM), the term 'space-division multiplexing' (SDM) emerged. High activity in these studies has been exhibited by the world's leading manufacturers of telecom fibres and OF communication systems (OFS, Corning, Alcatel-Lucent, NTT Group, NEC Corporation, Fujikura, Sumitomo and others) and associated research laboratories and centres. As a result, at least several hundred papers dealing with multicore optical fibres have been published in the scientific literature in the last five years. The reports are concerned with various designs of such fibres and the fabrication of pilot samples, as well as with various aspects of their application in optical fibre communication systems and experimental studies of their operation in prototype communication systems.

Descriptions of several tens of particular multicore fibre designs, differing to some extent from each other, can be found in the literature. They can be tentatively divided into three groups: multicore single-mode fibres with uncoupled cores, multicore few-mode fibres and multicore fibres with coupled cores. Consider their properties in greater detail.

Multicore single-mode fibres with uncoupled cores are the 'classic' fibres that were initially proposed for space-division multiplexing. Each core is assumed to be an analogue of a standard single-mode fibre, which allows all achievements in fibre transmission capacity to be used for it [34–36]. For this reason, the key requirement is to minimise the cross-talk between the cores (preferably, to under –25 dB [37]).

To meet this condition for fibre identical in core parameters to standard telecom fibre (mode field diameter of ~9 μm at a wavelength of 1550 nm; cutoff wavelength of ~1250 nm), the cores should be spaced at least 45 μm apart [38]. As a result, in the case of hexagonal close packing the fibre diameter should be about 200 or 280 μm for 7 and 19 cores, respectively (Fig. 7). At the same time, a substantial increase in fibre diameter is extremely undesirable from the viewpoint of mechanical reliability under service conditions: a thicker fibre experiences higher mechanical stress in response to the same slight random bends, which inevitably occur in optical fibre cables.

There are three approaches for reducing the core spacing while maintaining the low cross-talk level, which can be used in various combinations.

1. Reducing the mode field diameter by increasing the refractive index (RI) of the core and, accordingly, decreasing its diameter [39]. However, a marked decrease in mode field diameter may lead to difficulties in fusion-splicing such fibres and connecting them to coupling–decoupling devices, and an increase in RI leads to increased optical losses. So this approach is the least used.

2. Producing a difference in mode propagation constant (effective RI) between neighbouring cores due to a slight difference in RI and/or core diameter (Fig. 8). Such fibres are referred to as 'heterogeneous' [40], in contrast to homogeneous fibres with identical cores. A considerable fraction of the single-mode multicore fibres are heterogeneous. Advocates of homogeneous fibres criticise them for the extra difficulties in fusion splicing and buttjoining, because one has to additionally monitor the position of cores differing in parameters.

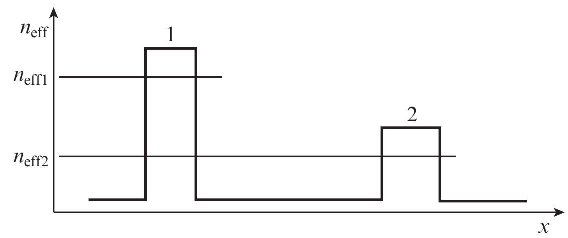

Figure 8. Effective index profiles of two neighbouring cores (1 and 2) in a heterogeneous multicore fibre.

3. Producing extra barriers between the cores in order to reduce the cross-talk from the layers with a reduced RI (fluorine-doped silica glass) in comparison with the silica glass of the cladding [41] or even from longitudinal air holes [42]. This approach adds technical difficulties to fibre fabrication, but there are no extra problems with the use of such fibres, so it is the most attractive.

An example of a widely used combination of the above approaches is a 12-core heterogeneous fibre having additional layers of low-index glass, with the cores arranged in a ring (Fig. 9) [43]. This fibre design minimises the number of nearest neighbours around each core. In this configuration, there

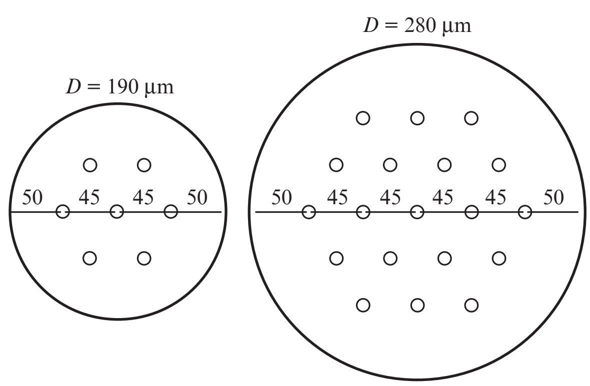

Figure 7. Cross sections of 7-core (left) and 19-core (right) OFs. The numbers specify the core spacing in microns.

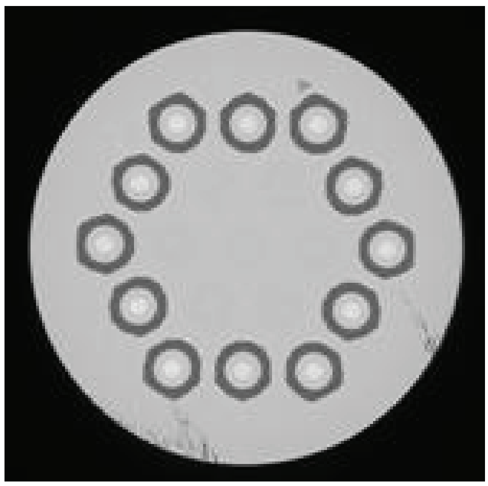

Figure 9. Cross-sectional image of a 12-core fibre [43]. The light spots are germania-doped silica glass cores, and the dark annular regions consist of fluorine-doped silica glass.

are only two neighbouring cores, so only two types of cores can be used. Such fibre ensured 1.01 Pbit s^{-1} transmission over 52 km.

The closest packing of cores can be exemplified by a heterogeneous fibre in which 30 cores of four types were accommodated in a 230-μm-diameter fibre (Fig. 10) [44].

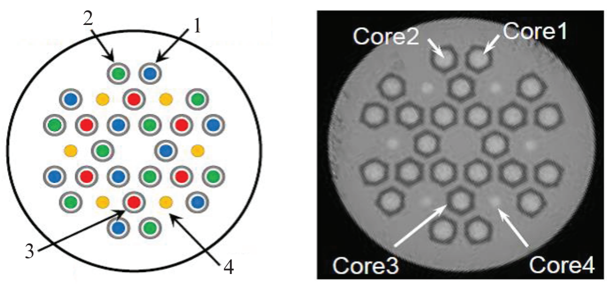

Figure 10. Schematic of the arrangement of different cores (1–4) and cross-sectional image of a 30-core fibre [44].

In practical application of single-mode multicore fibres with a high core packing density, one may encounter the problem of the effect of random bends along the fibre length on the cross-talk between the cores [45]. The point is that bends change the index profile of the fibre. In the case of a heterogeneous fibre and certain bend diameters, this may reduce the difference in propagation constant between neighbouring cores, thereby leading to a sharp increase in cross-talk between them (Fig. 11). In contrast, bends of a homogeneous fibre always give rise to a difference in propagation constant and, hence, lead to a decrease in cross-talk.

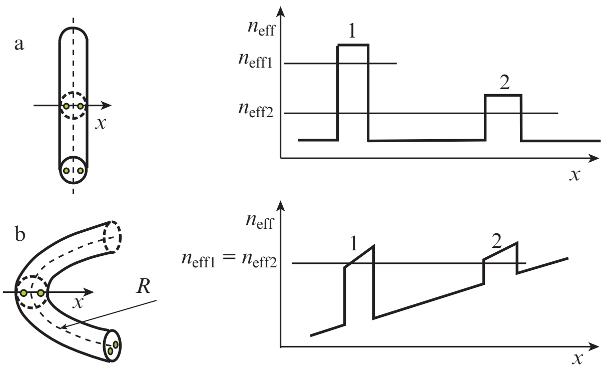

Figure 11. Equivalent effective index profiles of (a) a straight and (b) a bent dual-core heterogeneous fibre.

It seems likely that this undesirable effect in heterogeneous fibres can only be eliminated by using rectangular fibre cross sections and arranging the cores in a straight line along the wide face (Fig. 12) [46]. Such a fibre bends preferentially along an axis parallel to its large face (Fig. 12c), which does not change the relationship between the propagation constants of its cores.

Multicore few-mode fibres are the next step in the development of multicore fibres. A search for possibilities of increasing the data transmission rate first led to the idea of employing different modes of a multimode fibre for information

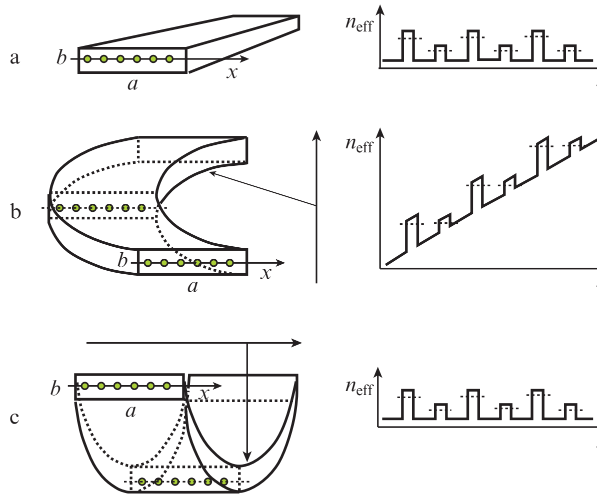

Figure 12. Effect of bending on the index profile of a multicore fibre with a rectangular ($a \times b$) cross section [46].

transfer [30]. In a certain sense, this is also a kind of space-division multiplexing.

Standard multimode fibres with a core diameter of 50 μm and above are not well suited to this purpose: at a large number of modes, their propagation constants differ too little, so signals rapidly experience cross-talk. For this reason, use is typically made of so-called few-mode fibres [47–49], which support only a few modes.

Even though differing in propagation constant, the signals carried by different modes experience marked cross-talk, but state-of-the-art techniques (multiple-input multiple-output, MIMO) proposed previously for coherent data transmission systems allow one to receive and successfully analyse such information [50]. In such a case, differential mode delay is a problem: signals carried by different modes of a step-index core differ in time delay over a 1-km path length by more than several nanoseconds, which makes successful signal processing impossible at distances over 10 km. The use of a graded index profile allows the delay to be reduced to a level of ~50 ps km^{-1}, which enables information transfer over hundreds of kilometres [51, 52].

Since the diameter of a few-mode core only slightly exceeds the core diameter in a single-mode fibre, they can be used in multicore fibres, even though at slightly greater core spacings [53–55]. In such fibres, the number of information channels is determined by the product of the number of cores with the number of modes.

Multicore fibres with coupled cores. In this case, the spacing between single-mode cores is reduced in order to increase core-to-core coupling. As a result, light propagates through all the cores as a supermode, with an intensity maximum located in one or a few cores [56–59]. The number of such modes depends on the structure of the fibre. On the whole, the picture is similar to that in the case of a few-mode single-core fibre. The fibre diameter can then be made smaller than the diameter of other types of multicore fibre. There are still not many reports concerned with this type of fibre.

Research on multicore fibres continues. The latest achievements are as follows: the data transmission rate reached to date is 2.05 Pbit s^{-1} with the use of a 9.8-km length of 19-core 6-mode fibre [60] and 2.15 Pbit s^{-1} with the use of a 31-km length of 22-core single-mode homogeneous fibre [61].

On the whole, it is worth noting that multicore fibres have demonstrated considerable potential and that their practical use is not far off. This is, however, prevented by the lack of reliable and cheap coupling–decoupling devices and efficient multicore fibre amplifiers.

Light coupling–decoupling devices. In the simplest case of single-mode multicore fibres, each core should be connected to a separate single-mode fibre for launching light from an appropriate source or for further processing of the signal transmitted through the core [62, 63]. In the case of few-mode multicore fibres, the problem is complicated by the fact that each core should be connected to a multimode fibre without disturbing the distribution of the signals over the modes, and then the different modes should be outcoupled from the cores of the individual few-mode fibres [64]. Simple, convenient and cheap solutions to this problem remain to be found.

Fibre amplifiers. For long-haul transmission, it is desirable to have the possibility of periodic signal amplification without outcoupling the signal from the fibre. The problem is that the amplifying fibre should be similar in design to passive multicore fibre and, at the same time, one should have the possibility of coupling pump light into each core or the possibility of efficient cladding pumping. In addition, one should ensure identical gains in each core and, in the case of a few-mode core, different gain coefficients for different modes – in order to compensate for the difference in optical loss between the modes. This issue is the subject of intense research, but appropriate solutions have not yet been found [65–67].

At present, there is an ongoing search for optimal space-division multiplexing fibre designs.

4. Hollow-core fibres

As pointed out above, the main factors limiting the growth of the data transmission rate in fibre-optic networks are the optical nonlinearity of glass fibre and the limited information transfer bandwidth. The advent of hollow-core fibres [68, 69] opened up the possibility of considerably reducing the influence of these limitations. First, the three orders of magnitude decrease in the density of the material through which by far the largest fraction of light propagates in a hollow-core fibre (usually filled with air at atmospheric pressure) ensures a roughly proportional decrease in fibre nonlinearity. Second, hollow-core fibres can potentially have optical losses under 0.2 dB km^{-1} in wavelength ranges determined by the nature and parameters of the fibres. In particular, estimates obtained by different researchers by numerically solving the problem of light propagation through optical fibre suggest that the optical loss in hollow-core silica fibres can be as low as α = 0.2 dB km^{-1} at a wavelength λ = 1620 nm, α = 0.13 dB km^{-1} at λ = 1900 nm [6], α < 0.1 dB km^{-1} in the range λ = 1600–2400 nm [70] and α = 0.03 dB km^{-1} at λ = 1000 nm [71]. This will allow one in the future to use hollow-core fibres (after the advent of well-developed technologies for the fabrication of such fibres) for information transfer in wavelength ranges where non-erbium optical amplifiers, employing rare-earth ions or bismuth-related and other active centres, are available. For example, optical fibre communication systems will be able to use thulium and holmium fibre amplifiers at wavelengths near 2 μm [72] and ytterbium fibre amplifiers near 1 μm.

At first glance, an insurmountable barrier to achieving low optical losses in hollow-core fibres is that these have no normal modes: the RI of their core is lower than that of their cladding, and light confinement in the core through total internal reflection is impossible. All modes in such fibres are leaky. It has turned out however that, in some hollow-core fibre designs, the optical loss can be reduced to an acceptable level through light reflection or scattering from fibre cladding elements.

In particular, even before the advent of low-loss silica-based fibres, Marcatili and Schmeltzer [73] examined the possibility of developing hollow-core fibres with a metallic or glass cladding in the form of a capillary tube (Figs 13a, 13b). Such fibres take advantage of the increase in the reflectivity of the interface between materials with different refractive indices when the angle of incidence approaches π/2, i.e. at small glancing angles of the beam. Spectrum (*1*) in Fig. 14 represents the optical loss in a planar analogue of such fibre from silica glass at a hollow core diameter D = 57 μm for one polarisation. Note that the data obtained for the simple planar model are in excellent agreement with an exact solution to the problem [73]. The fibre design was further improved by producing several thin metallic and dielectric layers on the inner surface of the guiding core in order to increase the reflectivity of the interface owing to interference effects [74]. Such fibres, however, have not found wide application, presumably because of the technical problems with their fabrication and the comparatively high optical loss in them (~0.2 dB m^{-1}).

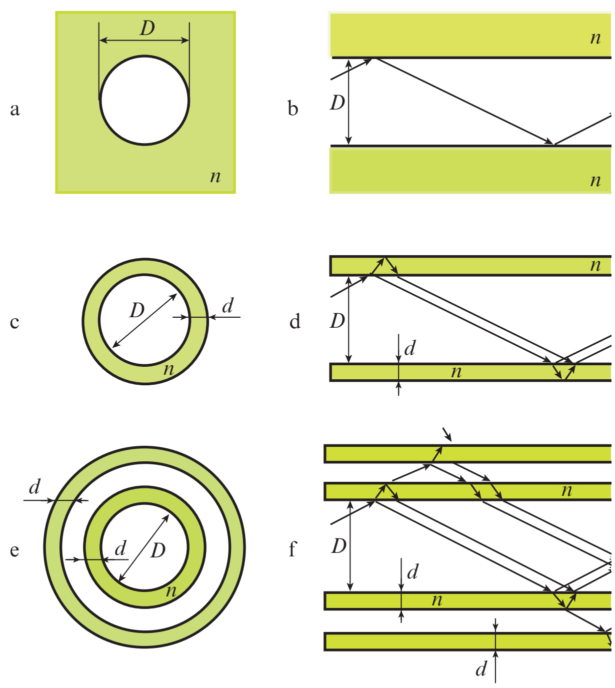

Figure 13. Three simple hollow-core fibre designs: (a, b) hollow glass capillary; (c, d) hollow glass capillary with a wall thickness (d) that ensures resonant reflection of light back into the core; (e, f) hollow-core fibre having two resonant-reflection walls.

It is known that a silica capillary with a wall thickness that ensures an increase in reflectivity for light propagating in the hollow core due to constructive interference of the waves reflected from the inner and outer surfaces of the capillary (Figs 13c, 13d) has substantially lower optical losses than does the configuration with one reflecting surface (Figs 13a, 13b) (see e.g. Zheltikov [75]). In particular, whereas the opti-

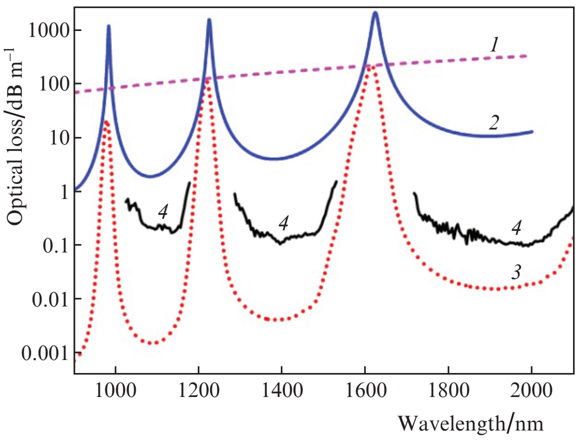

Figure 14. Optical loss spectra of (*1*) a planar single-wall light guide (Figs 13a, 13b) and (*2*) planar light guide with interference of the reflected rays on each wall surface (Figs 13c, 13d); (*3*) calculated optical loss spectrum of a revolver fibre with a 57-μm-diameter hollow core and 2.8-μm-thick capillary walls in its cladding; (*4*) experimentally measured loss in a fibre with the same parameters.

cal loss in the configuration represented in Figs 13a and 13b is proportional to λ^2/D^3 [73], that in the fibre schematised in Figs 13c and 13d is proportional to λ^3/D^4 [75]. The optical loss in a two-dimensional model for such fibre is represented by spectrum (*2*) in Fig. 14. It is seen that the reflection of light from the second surface of the capillary tube considerably reduces the level of losses (by about one and half orders of magnitude).

If the configuration represented in Figs 13c and 13d is modified by adding another concentric silica capillary tube such that its thickness and the gap between it and the inner tube satisfy the maximum reflectivity condition for light propagating through the fibre at a small glancing angle (Figs 13e, 13f), we find in a simple two-dimensional model [76] that the optical loss in such fibre is proportional to λ^5/D^6. Therefore, at λ/D = 1.1 μm/57 μm = 1/52 the optical loss in the fibre represented in Figs 13e and 13f should be lower than that in the fibre represented in Figs 13c and 13d by more than three orders of magnitude, down to ~1 dB km^{-1} (Fig. 14). It is worth noting that, in the literature, this reflection condition is typically referred to as an antiresonance condition [77, 78]. The reason for this is that, in the case of a Fabry–Perot interferometer, the resonance condition usually refers to light transmission rather than reflection. In Figs 13c–13f, the capillary walls essentially form Fabry–Perot cavities for light propagating through the fibre. One drawback to these fibre designs is that they are difficult to implement in practice: any contact of such a capillary resonator with, e.g., a supporting structure immediately impairs its resonance properties, leading to a sharp increase in optical loss.

It is probably for this reason that, in the past fifteen years, considerable research effort has been concentrated on hollow-core microstructured optical fibres (HC-MOFs), in which guidance properties are ensured by the large area of air–glass interfaces in the cladding. The mechanism of light confinement in the hollow core of the HC-MOFs depends on the nature of their microstructured cladding. Light confinement in the core of fibre with a complex reflective cladding design is ensured by constructive interference due to light scattering from one- and two-dimensional photonic crystal structures of the cladding. The wavelength ranges in which light cannot propagate through the cladding in radial directions are referred to as photonic bandgaps, by analogy with ordinary crystals. Transmission and high-loss regions are determined as well by resonance or antiresonance conditions for individual elements of the reflective fibre cladding. The HC-MOFs proposed to date have a variety of cross sections (Fig. 15).

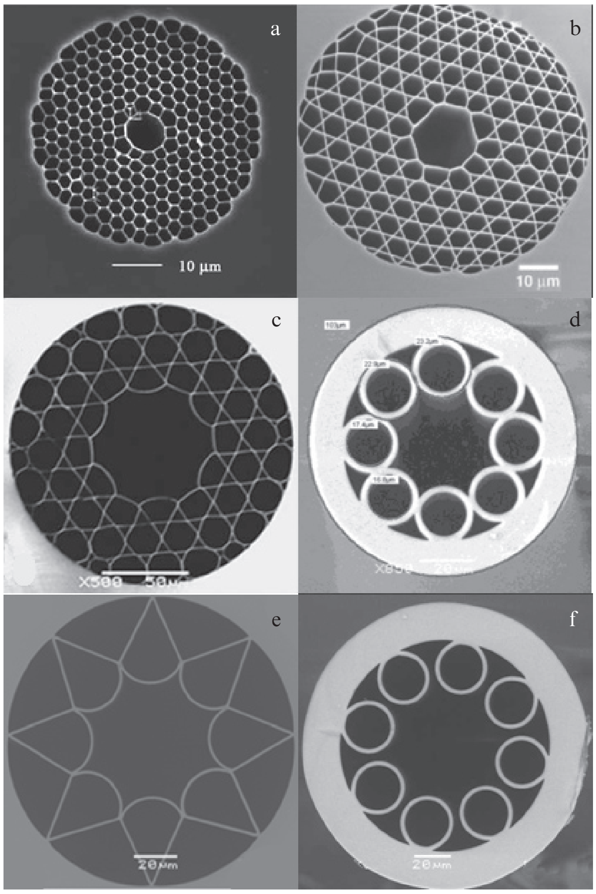

Figure 15. Cross-sectional images of various types of hollow-core optical fibres: (a) photonic crystal fibre with a hexagonal cladding structure [79]; (b) Kagome lattice photonic crystal fibre [81]; (c) Kagome lattice photonic crystal fibre with a hypocycloid-shaped core–cladding interface [83]; (d) hollow-core revolver fibre with contacting capillaries [84]; (e) hollow-core fibre with parachute-shaped cladding elements; (f) hollow-core revolver fibre with noncontacting capillaries [88].

The first fibre with a photonic crystal cladding had a hexagonal structure of the cladding (this type of fibre is represented in Fig. 15a [79]). The optical loss in such fibres was 13 dB km^{-1} in 2002 [80] and 1.2 dB km^{-1} in 2005 [6]. Later, the loss was reported to be near 2.8 dB km^{-1} [72]. Benabid et al. [81] reported fibres with another type of photonic crystal cladding, in the form of a Kagome lattice, which are characterised by a larger transmission bandwidth. In searching for a hollow-core fibre cladding configuration minimising the optical loss, Wang et al. [82, 83] proposed Kagome lattice photonic crystal fibres having a hypocycloid-shaped core–cladding interface bent towards the centre of the fibre (Fig. 15c). Such a bend was shown to reduce the optical loss in the fibre.

In 2011, researchers at FORC proposed microstructured fibres with a very simple design, whose cladding had the form of a single ring of capillaries [84] – so-called hollow-core revolver fibres (Fig. 15d) (see also Ref. [85]). In contrast to that in the fibre design in Fig. 13, the core–cladding interface in such fibres has a curvature of opposite sign, so they are referred to as fibres with a negative curvature of the core–cladding interface. Subsequently, Yu et al. [86] proposed fibres whose cladding consisted of elements resembling a stylised image of a parachute (Fig. 15e). But fibres of the type represented in Fig. 15d [84] differ significantly from other fibres with a negative curvature of the core–cladding interface: first, in that the elements of their cladding have cylindrical symmetry (more precisely, the elements have a nearly circular or elliptical cross section [87]) and, second, in that they can be arranged around the core without contacting each other, which allows fibre characteristics to be improved [88, 89] (Fig. 15f). Given the above, and the appearance of the fibres represented in Figs 15d and 15f, they were named 'hollow-core revolver fibres' (HCRFs) [85]. Clearly, the mechanism of light confinement in the core region in the HCRFs differs from that in photonic crystal cladding fibres. It seems likely that, as a rough approximation, the loss in such fibres can be described using a model fibre represented in Fig. 13d. The optical loss in an HCRF with a 57-μm-diameter core and 2.35-μm-thick capillary walls in its reflective cladding (the dimensions are borrowed from Ref. [85]) (Fig. 15f) is illustrated in Fig. 14. Curve (*3*) represents a calculated optical loss spectrum of such a fibre (with no allowance for possible process-related deviations of the fibre cross section from an ideal shape), and curve (*4*) represents an experimentally measured loss spectrum of a real fibre. It is seen that replacing the fibre design shown in Figs 13c and 13d, where the hollow core is bounded by a 2.35-μm-thick silica wall, by a ring of eight noncontacting capillaries with the same wall thickness, without changing the core diameter, reduces the calculated level of losses by about three orders of magnitude, down to ~1 dB km^{-1} (Fig. 14). Note that the fibres under consideration have identical positions of their bandgaps (where light has maximum propagation losses). The loss in the real fibre exceeds that calculated for an ideal fibre design: at the current level of technology, the former is ~100 dB km^{-1}. A considerable contribution to the increase in loss is probably made by slight variations in the cross sectional shape of the real fibre as compared to the ideal fibre design.

There is now experimental evidence that the development of hollow-core fibres has reached a level where they can be used in a variety of scientific and technological applications. Recent work has demonstrated the possibility of high transmission capacity (30 Tbit s^{-1}) in hollow-core fibres with a hexagonal photonic crystal cladding at wavelengths near 1.5 μm [90] and 100 Gbit s^{-1} over 1 km in the 2 μm range, where thulium-doped fibre amplifiers are capable of operating and there is presumably the possibility of reducing the optical loss in hollow-core photonic crystal fibres to 0.1 dB km^{-1} [91]. It should be especially emphasized that the hollow-core fibres can potentially have considerably lower optical losses in comparison with the existing telecom silica fibres, in a substantially broader wavelength range [6, 70, 71].

The unique properties of the hollow-core fibres open up wide possibilities of other applications. For example, ensuring long interaction lengths of light in gases and liquids (when these fill a hollow core), the hollow-core fibres allow one to create new fibre-optic sensors. In particular, the high transmission of hollow-core silica fibres in the mid-IR spectral region made it possible to produce methane and ethane sensors with 0.9 ppm sensitivity [92].

In fact, the hollow-core fibres open up a new field of the nonlinear optics of gases. To date, gas lasers employing such fibres have been demonstrated: acetylene (C_2H_2) lasers, operating in the 3 μm range [93, 94], and optically pumped iodine (I_2) vapour lasers [95]. Optical gain has been demonstrated in a discharge-pumped hollow-core fibre filled with a He–Xe gas mixture [96]. Hydrogen Raman lasers have been created which enable a highly efficient laser frequency shift by 4155 cm^{-1}, a value unreachable for solids [85, 97–99]. Note that efficient Raman lasers have been made using various types of hollow-core fibres: fibres with a Kagome lattice photonic crystal cladding [97, 98], fibres with parachute-shaped cladding elements [99] (Fig. 15f) and HCRFs [85].

The hollow-core fibres can emit broadband light due to a number of coupled nonlinear interactions when their core is filled with a gas possessing necessary nonlinear properties (noble gases or hydrogen). For example, pumping a hydrogen-filled hollow-core fibre with femtosecond pulses, Belli et al. [100] obtained a supercontinuum from the vacuum UV (124 nm) to the IR (1200 nm) spectral region.

Thus, the hollow-core fibres open up new, unique possibilities in both optical fibre communications and other areas of fibre optics.

5. Conclusions

Analysis of research results for a new generation of OFs in this paper leads us to the following conclusions:

The development of bismuth-doped silica-based fibres and the use of such fibres as gain media have made it possible to create a family of rather efficient fibre lasers operating in the spectral range 1140–1775 nm. In addition, the results obtained to date demonstrate the possibility of making efficient optical amplifiers in the ranges 1200–1500 and 1610–1775 nm, where efficient rare-earth-doped fibre lasers and optical amplifiers are lacking. Thus, the advent of bismuth-doped fibres as new gain media offers a real possibility of using the entire spectral range 1300–1700 nm for information transfer.

Multicore fibres are promising media for information transfer at petabit rates. Information transfer at rates of 1–2 Pbit s^{-1} over tens of kilometres has been demonstrated. There are, however, a number of technical problems, which should be resolved to ensure information transfer at such rates over large distances.

The development and extensive studies of various types of hollow-core fibres have opened up new possibilities of their application, including information transfer and the nonlinear optics of gases. However, there are still no hollow-core fibres with optical losses below those in silica-based fibres.

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