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Preface to the anniversary issue

The great men do not die. They pass to eternity. Alexander Mikhailovich Prokhorov, who would be 90 on 11 July 2006, passed to eternity in January 2002.

The immortality of Alexander Mikhailovich Prokhorov is determined first of all by his works and his invaluable contribution to the world science, which has changed the appearance of the world and provided a new quality of our life.

But this is not the only reason for his immortality. And the people who were close to him well understand this. He was a very wise and kind man and was very good to people. This has made people kinder, and the particles of this kindness will be transmitted from one generation to another.

The matter of his life is living and developing. This issue of Quantum Electronics is one of the proofs of this. The authors of most papers published in this issue have an honour to call themselves pupils of Alexander Mikhailovich and work at the General Physics Institute founded by him and bearing now his name. I hope that Alexander Mikhailovich would not be ashamed for the pupils of his school.

I.A. Shcherbakov

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Development and study of Bragg fibres with a large mode field and low optical losses

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***Abstract*. A silica Bragg fibre with optical losses lower than 10 dB km^{-1} is fabricated for the first time. The Bragg fibre manufactured by the MCVD method is intended for operation at a wavelength of 1.06 μm and has the mode-spot diameter 18.5 μm (the mode-spot area is 270 μm^2). The fibre is considerably less sensitive to bending than step-index fibres and microstructure fibres with the same mode-spot size. The possibility of fabricating a Bragg fibre with the record mode-spot area (530 μm^2 at the operating wavelength of 855 nm) for all-silica fibres is demonstrated.**

Keywords: *fibre optics, Bragg fibres, large mode spot fibre.*

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1. Introduction

The development of fibre lasers emitting high output cw powers exceeding 100 W and average pulse powers above 10 W is one of the newest directions in fibre optics. The main problem in the elaboration of such lasers is the appearance of undesirable nonlinear processes such as stimulated Brillouin scattering or stimulated Raman scattering, as well as four-wave mixing, which drastically reduce the efficiency of the lasers and distort the shape of pulses amplified in high-power amplifying fibre stages. This problem is especially urgent in the development of pulsed fibre lasers with the peak powers achieving tens or even hundreds of kilowatts. The key to its solution is the use of fibres with a large fundamental-mode area (and, hence, with a reduced radiation power density in the fibre core).

Single-mode step-index fibres cannot provide a sufficiently large area of the mode field due to technological (difficulties in manufacturing and control of the parameters of fibres with the refractive-index difference between the fibre core and cladding less than 10^{-3}) and physical (large bending losses) restrictions. The core diameter of such fibres operating on the fundamental mode is restricted by the value of about 15λ (where λ is the wavelength at which the fibre operates; in the case of step-index fibres, this is the cut-off wavelength λ_c of the second mode). The diameter of the fundamental-mode field can be increased up to 30λ [1] by using few-mode fibres. The winding of such a fibre on a coil of a certain radius makes it possible, on the one hand, to filter higher modes and, on the other hand, to preserve low losses for the fundamental mode. However, the output beam quality deteriorates ($M^2 \simeq 1.4$) and, in addition, the necessity to use fibres bent with a certain radius substantially limits the scope of their applications. As a result, only fibres with the core diameters in the range from 11 to 20λ find practical applications.

Microstructure fibres, in particular, endlessly single-mode fibres attract increasing recent attention [2, 3]. It was demonstrated that microstructure fibres allow one to obtain a large diameter of the mode spot ($\sim 17\lambda$) along with low bending optical losses [4]. The fibre core can be increased up to 40λ in the few-mode regime [5]. As in the case of step-index fibres, one of the factors complicating the application of microstructure fibres is high bending losses. In addition, a complicated technology of their manufacturing is not favourable for their wide application.

The use of the popular method of modified chemical vapour deposition (MCVD) [6] is much more preferable for fabricating fibres with a large mode field. The fabrication of an essentially new waveguide structure – a Bragg fibre with a large mode field, was recently demonstrated in paper [7]. Unlike step-index and microstructure fibres, in which light propagates in the core due to total internal reflection, in Bragg fibres the light is localised in the fibre core due to resonance reflection of single-mode radiation from circular layers with a high refractive index surrounding the core. The authors of paper [7] fabricated a Bragg fibre with the core diameter of 34 μm (22λ) and the effective mode area of 517 μm^2 optimised for operating at a wavelength of 1.55 μm. This Bragg fibre had considerably lower bending losses than a step-index fibre with the mode field of the same size. At the same time, the radiation losses of this fibre were very high (about 0.6 dB m^{-1}), which made it unsuitable for most practical applications.

Later, the Bragg structure proposed in [7] was optimised to obtain for the first time a Bragg fibre with optical losses lower than 10 dB km^{-1} [8]. This paper is devoted to the study of Bragg fibres with large core diameters (above 20λ) and low radiation losses. We also demonstrate in the paper the possibility of increasing the core diameter of a Bragg fibre up to 46λ.

2. Optimisation of the index profile of a Bragg fibre with a large mode field

Figure 1 shows the typical structure of a Bragg fibre. The fibre core with the refractive index equal to that of silica glass or lower is surrounded by circular layers with high and low indices. In such a structure, a mode localised in the fibre core, which we will call the Bragg mode, can propagate. The propagation constant β of the Bragg mode is lower than the propagation constant of radiation in a pure silica glass from which the external cladding of the fibre is made (a part of the fibre cross section outside the circular structure). This gives rise to radiation losses for this mode. The leaking radiation power is 'reflected' in each circular layer with a high index, so that the energy flux in the radial direction decreases by a factor of

$$\frac{k^2 n_H^2 - \beta^2}{k^2 n_L^2 - \beta^2} = \frac{n_H^2 - n_{\text{eff}}^2}{n_L^2 - n_{\text{eff}}^2} \quad (1)$$

[9]. Here, n_H and n_L are the maximum and minimum refractive indices of circular layers; k is the wave number; and

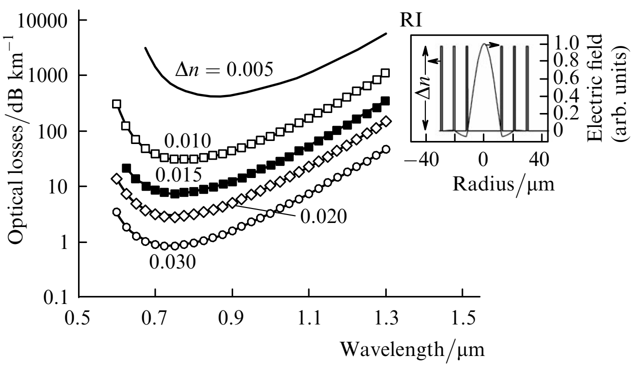

Figure 1. Theoretical spectral dependences of radiation losses in a Bragg fibre. The inset shows the constructed refractive index profile of this fibre.

$$n_{\text{eff}} = \frac{\beta}{k} \quad (2)$$

is the effective refractive index of the Bragg mode.

Thus, radiation losses of the Bragg mode can be decreased by increasing the number of layers with a high refractive index or by increasing the contrast of the structure (the difference $\Delta n = n_H - n_L$ between the maximum and minimum indices of the layers). To reduce the total size of the structure fabricated and avoid technological difficulties of the deposition of many layers, we decided to study here a Bragg fibre consisting of only three layers with a high refractive index. Figure 1 shows radiation losses for this Bragg fibre with the core diameter of 22.5 μm calculated for different values of n_H (and respectively Δn). One can see that, as Δn is increased from 0.005 (as in [7]) to 0.015, the radiation losses decrease almost by two orders of magnitude.

The thickness and position of the layers were selected so that the radiation losses at the operating wavelength of 800 nm were rather low, whereas the attenuation coefficients of higher modes were, on the contrary, high. Thus, the radiation losses for the LP_{11} mode, which has the lowest radiation losses among all the highest modes, exceeded 0.5 dB m^{-1} for $\Delta n = 0.015$. As a result, this Bragg fibre, not being a single-mode fibre in the generally accepted sense, will reveal single-mode properties when the fibre length exceeds a few metres.

One can see from Fig. 1 that the radiation losses for the fundamental Bragg mode can be reduced down to 1 dB km^{-1} only if $\Delta n > 0.030$. At the same time, a weak depression (reduction) of n_L of the layers with a low refractive index with respect to the refractive index n_{core} of the fibre core is much more efficient. In this case, expression (1) is no longer valid: the denominator $kn_L^2 - \beta^2$ becomes either zero or negative already for the depression $n_{\text{core}} - n_L = (2-3) \times 10^{-4}$, while exact calculations show that the radiation losses of the Bragg mode are reduced below 0.1 dB km^{-1} for $\Delta n = 0.015$.

3. Experimental results

3.1 Bragg fibre with a core diameter of 24λ

A BF503 Bragg fibre with the external diameter of 170 μm was drawn from a preform prepared by the MCVD method. The refractive index profile measured for this fibre is shown in Fig. 2. The depression of refractive indices of the layers with a low index with respect to that of the fibre core was 2×10^{-4}. To reduce bending losses outside the circular Bragg structure (at a distance of 37 – 42 μm from the fibre axis), an additional circular layer with a reduced refractive index was fabricated [7]. First of all, the single-mode property of the fabricated fibre was verified. The inset in Fig. 2 shows the near-field image of the Bragg mode obtained at the end of a 30-m fibre with an IR camera. Also, the near-field intensity distribution of the optical field in the Bragg fibre is presented, which is in good agreement with the calculated distribution. The diameter of the power density distribution for the fundamental mode of this fibre at the $1/e^2$ level was 18.5 μm at a wavelength of 1.064 μm. The effective mode area was 270 μm^2.

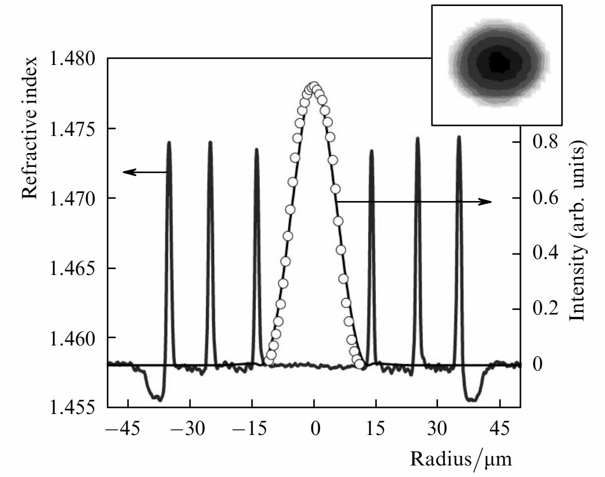

Figure 2. Refractive index profile of the BF503 fibre. The calculated (solid curves) and measured (circles) near-field intensity distributions of the Bragg mode. The inset shows the photograph of this distribution.

Optical losses in the BF503 fibre were measured by the cut-back method. In the proposed waveguide, not only the Bragg mode but also the modes localised in layers with a high refractive index can propagate. To eliminate the influence of these modes during measurements of optical losses, radiation should be coupled into the fibre and coupled out of it by using a usual single-mode fibre (Fig. 3). In our experiments, the Bragg and single-mode fibres were connected by fusion splicing, which provided a high reproducibility of the results of measurements (~ 0.1 dB) and allowed us to measure optical losses down to 10 dB km^{-1} on 20-m long Bragg fibres.

Figure 3 also shows the spectrum of optical losses in a 30-m long fibre wound on a coil of diameter 40 cm. The results of measurements show that optical losses at 1064 nm in this fibre do not exceed 10 dB km^{-1}.

Our further studies showed that these optical losses are caused to a great extent by bending losses. Optical losses measured in a straight fibre proved to be considerably lower. However, because of a small length of the straight fibre, we managed to perform measurements only in the part of the spectrum between 1400 and 1600 nm where radiation losses were rather high. At the same time, one can see that the spectral dependence of optical losses in a straight fibre is close to exponential. By extrapolating measured curve (*2*) in Fig. 3 to the short-wavelength region, we can estimate the

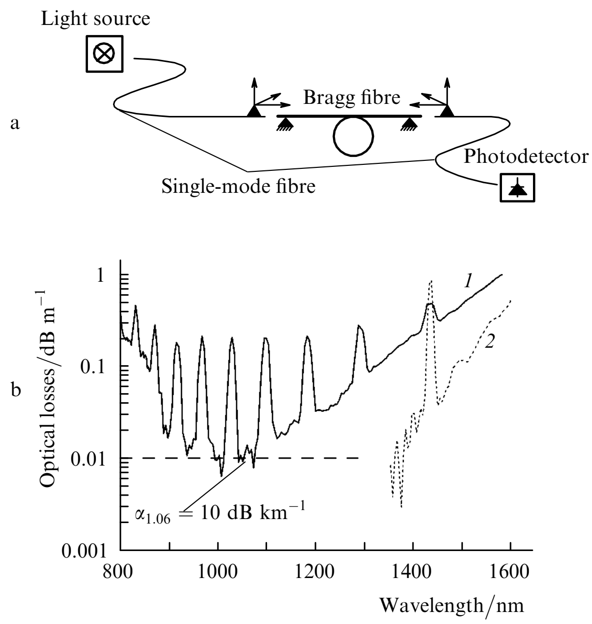

Figure 3. Scheme for measuring optical losses in a Bragg fibre (a) and the optical loss spectra for a 30-m long fibre with the radius of bending 20 cm (*1*) and a 3-m long straight fibre (*2*) (b).

radiation losses for the fundamental mode at a wavelength of 1064 nm as 0.05 – 0.5 dB km^{-1}, which corresponds to theoretical estimates (see section 2). Thus, the radiation losses of the fundamental mode in a straight BF503 fibre at a wavelength of 1064 nm are determined to a greater extent by the intrinsic optical losses at this wavelength (Rayleigh scattering losses are 0.6 dB km^{-1}) rather than by the radiation escape from the fibre.

Note that the spectra of optical losses both in the bent and straight fibres exhibited bands at 1027, 1099, 1183, 1291, and 1433 nm, which were not predicted theoretically. The observation of the output end face of the Bragg fibre with the IR camera showed that a mode localised in the high-index ring adjacent to the fibre core was present at these wavelengths (inset in Fig. 4). The theoretical analysis has shown that the propagation constants of the Bragg mode and one of the modes of the inner ring with a high refractive index at these wavelengths are equal. As a result, the energy transfer between the Bragg and circular modes occurs at these wavelengths, which reduces the Bragg mode power and gives rise to these bands in the optical loss spectrum.

3.2 Bending losses in various optical fibres with large mode fields

The constructive possibilities of the development of new single-mode fibres with a very large mode-spot diameter are restricted to a considerable extent by high bending losses. The typical feature of such fibres is that they should be virtually straight, which cannot be achieved in most applications. In this connection, the study and comparison of the sensitivity of optical fibres of different types to bendings is of great interest. We measured bending losses for a BF503 Bragg fibre and a single-mode Ge525sm fibre with approximately the same mode-spot diameter (19 μm) and the cut-off wavelength for the second mode equal to 1000 nm (Fig. 5). The electric field distribution and refractive index profile for a step-index fibre are shown

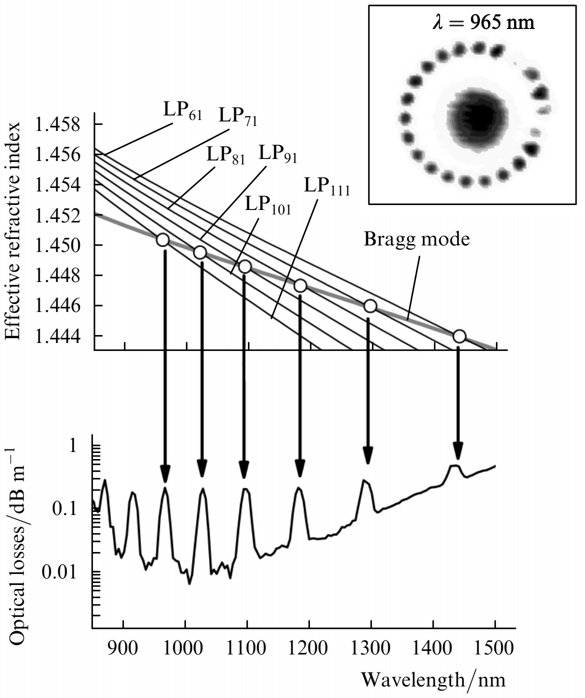

Figure 4. Wavelength dependence of the effective refractive index of the first-ring modes localised within a circular layer with a high refractive index and the smallest radius (at the top) and the optical loss spectrum (at the bottom). The insert shows the image of the fibre end upon excitation by one of the first-ring modes for the Bragg mode propagating at a wavelength of 965 nm.

in the inset in Fig. 5. Bending losses for fibres of both types were calculated by the method of finite elements. Similar calculations were performed for a microstructure fibre with the same mode-field diameter. One can see that the measured and calculated bending losses for the Bragg fibre and step-index fibre are in good agreement. This suggests that the calculations of bending losses in the microstructure fibre are also quite reliable. Our data show that the Bragg fibre is less sensitive to bendings among the three types of fibres

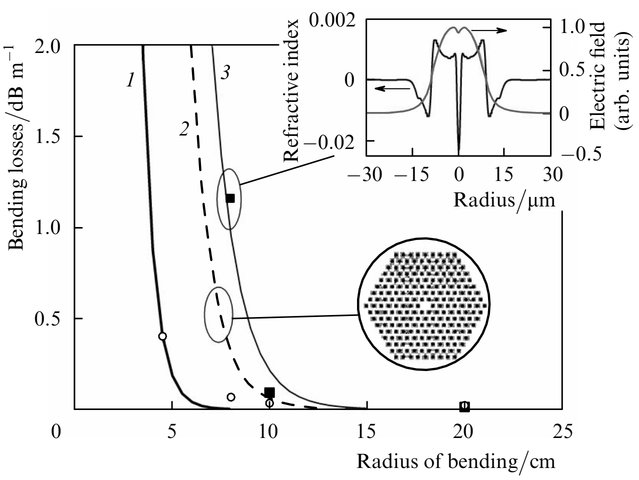

Figure 5. Bending losses in single-mode fibres of different types (curves are calculations, points are experiment): (*1*) Bragg fibre; (*2*) step-index fibre; (*3*) microstructure fibre with parameters $\Lambda = 15$ μm, $d/\Lambda = 0.44$, $N = 8$ (Λ is the distance between capillaries, d is the capillary size, N is the number of capillary rows). The inset shows the electric field distribution and the refractive index profile in a step-index fibre.

considered here. Bending losses in this fibre amount to 0.5 dB m^{-1} when the radius of bending is $R = 4.5$ cm, whereas these losses in the microstructure and step-index fibres are observed for $R = 7.5$ and 9 cm, respectively.

3.3 Splicing losses for Bragg and step-index fibres

Splicing losses appearing upon joining specially designed fibres with standard single-mode fibres, for which the elemental base of fibre optics (refractive-index gratings, couplers, etc.) is well developed, are no less important for many practical applications than bending losses.

Splicing losses were measured for the BF503 and Ge525sm fibres with the external diameter 125 μm, which were optimised for operating at a wavelength of 800 nm. The choice of these fibres was dictated by the possibilities of a standard apparatus used for fusion splicing. Splicing losses were measured at two stages. The signal spectrum was first measured after the propagation of light through the single-mode Ge525sm fibre with the mode-field diameter (12.8 μm, the cut-off wavelength $\lambda_c = 0.8$ μm) most close to the mode-field diameter (14.5 μm) of the BF503 Bragg fibre. At the second stage, the Ge525sm fibre was cut in the middle and a two-meter BF503 fibre was spliced to its ends. Splicing losses were measured by a change in the signal level with respect to the first measurement, taking into account that optical losses appeared at two splicing points. The optical loss spectrum presented in Fig. 6 shows that losses appearing upon splicing with the Ge525sm fibre did not exceed 0.7 dB (per splicing point). This value weakly changed when the mode-field diameter of the Ge525sm fibre was varied from 12 to 12.8 μm (by varying the external diameter), which suggests that the observed level of optical losses is determined by the difference in the distributions of mode fields in the Bragg and standard single-mode fibres.

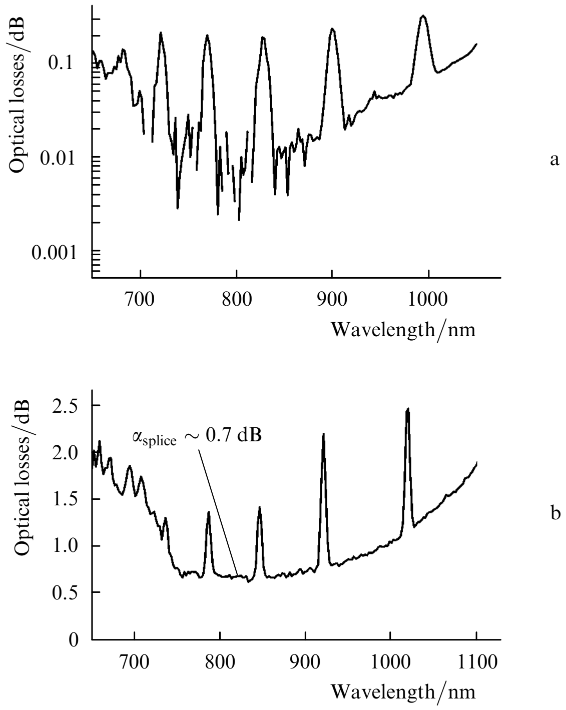

Figure 6. Optical loss spectra for a BF503 fibre with the external diameter of 125 μm (a) and at the splice with a single-mode step-index fibre (b).

Nevertheless, our data demonstrate that the mode of a Bragg fibre is well matched with the mode of a standard fibre, and a more careful selection of the mode-field diameter and refractive index profile will probably reduce splicing losses upon joining Bragg and standard fibres.

3.4 Bragg fibre with a core diameter of 46λ

The depression of the refractive index of circular layers with a low refractive index with respect to that of the fibre core provides in fact a combination of the principles of operation of the Bragg fibre and fibre based on total internal reflection. In this case, the Bragg mode proves to be almost the exact analogue of the LP_{04} mode, which could propagate in the fibre if instead of the depression of layers with a low index, the refractive index of the fibre core were increased by the same value Δn [or the refractive index of the whole fibre was increased by $(2-3)\times10^{-4}$]. In this case, radiation losses in a straight fibre are zero, and the sensitivity to bendings should be the same as in a fibre with the depression of layers with a low refractive index. In such a structure, demonstrated by the example of the BF503 fibre, both radiation and bending losses are very efficiently reduced. However, a further increase in the core diameter (at a fixed operating wavelength) in such fibres is problematic. Indeed, the difference $n_{\rm core}-n_{\rm L}$ of refractive indices in the fibre with the core diameter of the order of 40λ should not noticeably exceed 10^{-4}, otherwise higher modes with low losses will propagate in the fibre – first of all, the LP_{11} Bragg mode (the analogue of the LP_{14} mode in the 'raised' structure). The control of the refractive index with such a high accuracy during the fabrication of a preform is rather problematic, which makes impossible a further increase in the fibre core diameter.

At the same time, one of the most interesting properties of optical fibres, in which the propagation of light along the fibre axis is provided not by total internal reflection but by resonance reflection of light from external circular layers, is the reduction of radiation losses with increasing the core diameter [10, 11]. As a result, it can be expected that optical losses in a Bragg fibre with a depressed core and a large mode-field diameter will be not very high even in the case of a few layers ($\geqslant 3$) with a high refractive index. Indeed, as follows from theoretical calculations, radiation losses in a Bragg fibre presented in Fig. 7a (the number of layers is three, the depression of the refractive index of the core with respect to layers with a low refractive index is $n_{\rm L}-n_{\rm core}=0.0005$, and the core diameter is 46λ) can be lower than 50 dB km^{-1}.

Such a fibre was fabricated by the MCVD method. Figure 8 shows the refractive index profile and optical losses measured in this fibre. The external ring with a high refractive index was surrounded (as in the case of the BF503 fibre) by a depressed circular layer to reduce bending losses. Although the fibre structure was not optimal (the position of the last layer differs from the specified position, while the refractive index $n_{\rm core}$ of the fibre core is lower by 0.0005 than the specified index), optical losses in this fibre proved to be quite low (0.3 dB m^{-1} at a wavelength of 866 nm). The diameter of the mode power density distribution in the fibre was 26 μm (30λ), while the effective area of the mode spot was 530 μm^2 (see inset in Fig. 8).

Optical losses in a bent fibre of this design are rather high, which could be expected for a fibre with such a large mode-spot diameter. Note that upon bending, along with a

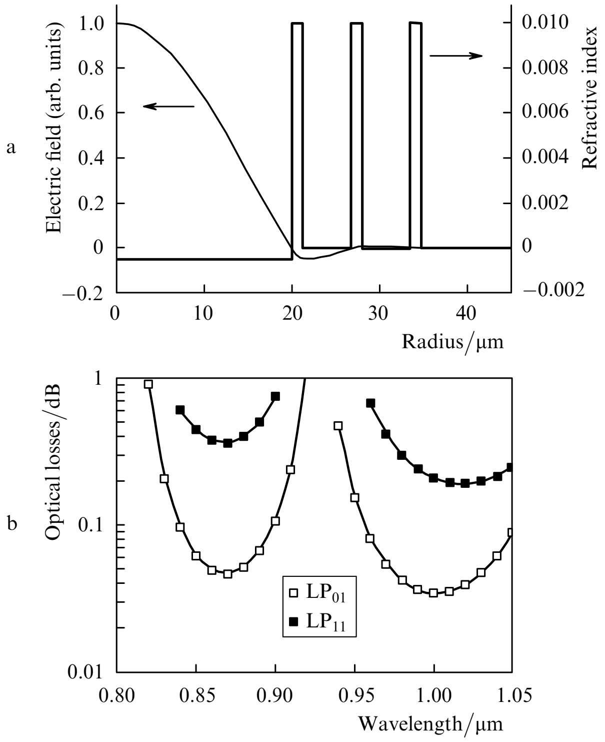

Figure 7. Refractive index profile of a Bragg fibre with a depressed core and the calculated electric field distribution for the fundamental mode (a), and the calculated radiation loss spectrum (b).

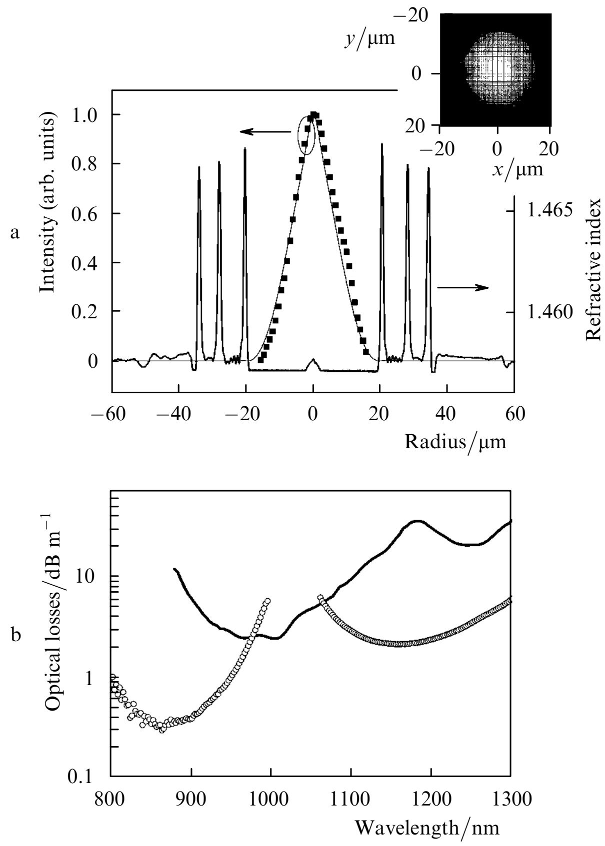

Figure 8. Refractive index profile of the BF541 fibre fabricated by the MCVD method and the calculated and measured near-field intensity distributions for the Bragg mode (a), as well as the measured optical loss spectra for a straight fibre (circles) and a fibre with the radius of bending 20 cm (solid curve) (b). The inset shows the near-field radiation pattern.

total increase in optical losses, the wavelength of minimal optical losses shifts, resulting in the increase in the sensitivity of the Bragg fibre to bendings at the wavelength of minimal optical losses.

4. Conclusions

Having optimised the design of a Bragg fibre, we obtained optical losses below 10 dB km^{-1} in the Bragg fibre with the radius of bending 20 cm. The Bragg fibre with the core diameter 24λ and only three layers with a high refractive index has a considerably lower sensitivity to bendings compared to step-index and microstructure fibres with the same size of the mode field. The possibility of manufacturing a single-mode optical fibre with the mode-field diameter of 30λ by the MCVD method has been demonstrated.

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