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Hollow-core revolver fibre with a double-capillary reflective cladding

A.F. Kosolapov, G.K. Alagashev, A.N. Kolyadin, A.D. Pryamikov, A.S. Biryukov, I.A. Bufetov, E.M. Dianov

Abstract. **We report the fabrication of the first hollow-core revolver fibre with a core diameter as small as 25 μm and an optical loss no higher than 75 dB km^{-1} at a wavelength of 1850 nm. The decrease in core diameter, with no significant increase in optical loss, is due to the use of double nested capillaries in the reflective cladding design. A number of technical problems pertaining to the fabrication of such fibres are resolved.**

Keywords: *hollow-core fibre, revolver fibre, antiresonant fibre.*

Hollow-core glass fibres opened up new possibilities in the development of fibre optics [1]. The lowest optical loss so far (1.2 dB km^{-1}) is offered by so-called hollow-core photonic crystal fibres (HCPCFs), whose guidance properties are ensured by the photonic bandgap of a microstructured fibre cladding [2]. Another mechanism capable of ensuring guidance properties of a hollow core takes advantage of antiresonant reflection (similar to reflection from a Fabry–Perot interferometer; see e.g. a review by Poletti [3]). To confine light in hollow-core anti-resonant fibres (HC-ARFs), their core is surrounded by glass membranes identical in thickness, which is chosen such that interference of rays reflected from different membrane surfaces leads to a considerable increase in reflectivity for back-reflected light. As a result, the optical loss in the fibre decreases. The HC-ARFs differ from the HCPCFs in that a larger transmission bandwidth is possible, in combination with somewhat higher optical losses. The lowest optical loss in the HC-ARFs reported to date is 24 dB km^{-1} at a core diameter $D_c = 94$ μm [4] (the term 'core diameter' is here taken to mean the diameter of the circle that is inscribed in the central part of the cross section of the fibre and touches the elements of the reflective cladding). Note that the optical loss in the HC-ARFs is inversely proportional to the third, or higher, power of D_c [3], so lower losses are much easier to achieve at larger core diameters.

A special place among the HC-ARFs is held by hollow-core revolver fibres with a reflective cladding formed by a single ring of capillaries. Such a fibre design was first proposed in 2011 by Pryamikov et al. [5], who viewed it as a hollow-core fibre with a negative curvature of the core–cladding interface. Subsequently, this term was also applied to fibres with a hypocycloid-shaped core boundary [6] and with reflective cladding elements differing significantly in shape from circular capillaries [4]. The shape of such elements resembles a stylised image of an ice cream cone [3]. Gladyshev et al. [7] proposed a particular name for hollow-core fibres with a reflective cladding in the form of a single ring of circular (or elliptical) capillaries: hollow-core revolver fibres (HCRFs). Such fibres have a simple design, with a low fraction of light propagating in the fibre material (compared to that propagating through the hollow core) [8] and insignificant dispersion in their transmission windows [9]. The lowest optical loss obtained to date in the revolver fibres is at a level of 100 dB km^{-1} at $D_c = 109$ μm [10] and 50 dB km^{-1} at $D_c = 119$ μm [11]. In a recent study, Uebel et al. [12] obtained an optical loss of 180 dB km^{-1} at $D_c \approx 30$ μm by optimising the dimensions of HCRFs. In addition, efficient Raman generation has been demonstrated in an HCRF on the 1.06 → 1.9 μm vibrational transition of molecular hydrogen [7].

To further reduce the optical loss in HCRFs, more complex reflective cladding capillary designs were proposed in a number of studies (Refs [13, 14, 3, 15] in chronological order). Namely, double (Fig. 1b) and even triple (Fig. 1c) nested capillaries were proposed for use instead of standard capillaries (Fig. 1a). The use of nested capillaries should in principle lead to a reduction in optical leakage loss owing to the presence of additional tube elements, which reflect light and ensure constructive interference of reflected rays, thus increasing the fraction of light returning to the core.

Poletti [3] and Belardi [15] carried out a rather detailed numerical simulation of nested-capillary HCRFs. Since the capillary wall thickness determines the low optical loss bandwidth, it is desirable that all the walls be identical in thickness. At the same time, the width of the air gap between the capillary walls has a less critical effect on the reflection properties of the fibre cladding [15], but it is desirable that it be approximately $0.5D_c(1 + 2k)$, where $k = 0, 1, 2, ...$ [16].

Figure 1d shows a cross section of a fibre fabricated by Belardi [15], which has a design similar to that in Fig. 1b. According to Belardi [15], a positive effect of the nested capillaries in this design is limited by their small hole diameter and the distinction between the wall thicknesses of the large and small capillaries. Nevertheless, the optical loss in this fibre was about 200 dB km^{-1} at a number of wavelengths (in the range 500–1100 nm), $D_c = 51$ μm and a 1.27-μm wall thickness of the large capillaries.

A.F. Kosolapov, G.K. Alagashev, A.N. Kolyadin, A.D. Pryamikov, E.M. Dianov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; e-mail: kaf@fo.gpi.ru;
A.S. Biryukov, I.A. Bufetov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow region, Russia; e-mail: biriukov@fo.gpi.ru, iabuf@fo.gpi.ru

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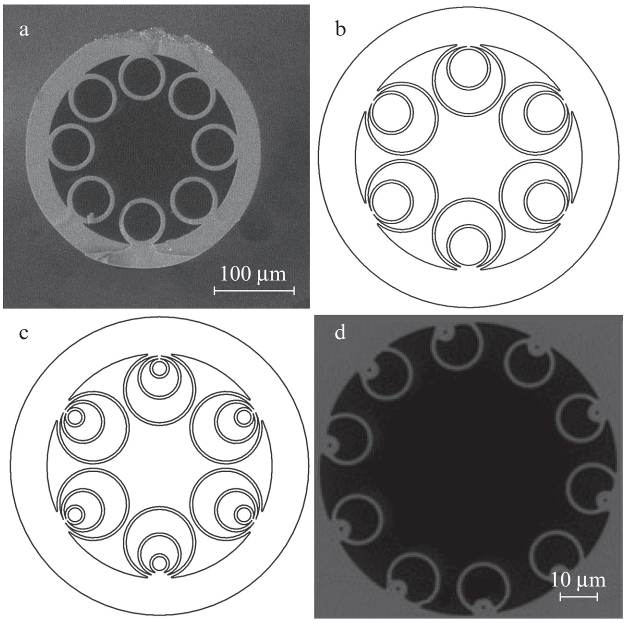

Figure 1. (a) Cross section of an HCRF with a loss of 50 dB km^{-1} and D_c = 119 μm [11], schematics of cross sections of HCRFs with (b) double and (c) triple nested capillaries [3, 13] and (d) cross section of an HCRF with a loss of 175 dB km^{-1} and D_c = 51 μm [15].

The purpose of this work was to examine the possibility of producing HCRFs with a core diameter substantially less than 50 μm in order to demonstrate various nonlinear effects in fibre at lower input powers (for example, to produce molecular gas Raman lasers operating at lower pump powers in comparison with H_2 lasers [7]). To this end, using computer simulation we optimised the design of HCRFs with double nested capillaries and a reduced core diameter, improved the fibre fabrication process and fabricated an HCRF with geometric parameters similar to those found by calculation. The computer simulation procedure used in this study was described in detail elsewhere [8]. We calculated parameters of fibres having different numbers (five to eight) of capillaries in their reflective cladding and assessed the stability of the optical parameters of the fibres to variations in their geometric dimensions, which are inevitable in the fibre fabrication process. As a result, we chose a fibre design with a reflective cladding consisting of five double nested capillaries, which is described below in greater detail.

A fibre preform was made from Heraeus Suprasil F300 high-quality silica tubes. The main preform fabrication steps are illustrated in Fig. 2. In the first step, five fibre cladding elements were produced. To this end, a specially prepared tube with an outer diameter D = 12.3 mm and inner diameter d = 8.4 mm was inserted into a tube with D = 25 mm and d = 21 mm and fused to it with an oxygen–hydrogen burner. The structure was drawn to an outer diameter of 6 mm (Fig. 2a) using a standard tower setup. To prevent tube collapse, an excess pressure of argon was maintained in the tubes during the drawing process.

It is worth noting some important technological aspects of this preform fabrication step. Since there is no central symmetry, the resultant tube is bent towards the inner capillary, so drawing was performed at the lowest possible tension in order to reduce the bend. Moreover, for the same reason the resultant double tube is slightly elliptical in shape (Fig. 2a). We believe that slight ellipticity of structure elements should not significantly degrade the optical properties of the fibre. Moreover, ellipticity prevents preform torsion during drawing, which makes it possible to obtain a double tube with minimum chirality.

As a result, we obtained five double tubes with an elliptical cross section and major ellipse axes of 6.12 and 6.28 mm (Fig. 2a). The tube bend (deviation from a straight line) did not exceed 1 mm per metre of the tube length.

In the second preform fabrication step (Fig. 2b), the double tubes were inserted into a 70-cm-long tube with D = 25 mm and d = 19 mm. On its ends, the double capillaries were secured with specially produced silica plates 1.27 mm in thickness (Fig. 2b). The ellipticity of the double tubes helped to properly orient them in the outer tube. Next, the assembly was exposed to the flame of an oxygen–hydrogen burner on a glass working lathe. The flame temperature, outer tube rotation rate and burner speed were adjusted so that the double tubes were fused to the outer tube without significantly deforming it. The process was monitored visually. In the third and fourth steps, the preform was drawn first to a diameter of 6 mm (Fig. 2c) and then into a 110-μm-diameter fibre (Fig. 2d). To prevent tube collapse, an excess pressure of argon was maintained in the structure.

The air core of the resultant fibre (Fig. 2d) is formed by five noncontacting double capillaries. The core diameter is D_c = 25 μm, the outer diameter of the fibre is 110 μm, and the inner diameters of the large and small capillaries are 29 and 15 μm. The average wall thickness of all the capillaries is 2.3 μm. The optical loss in the fibre was measured by the cutback technique using a 57-m length of the fibre, a monochromator with a diffraction grating ruled at 300 lines per millimetre, a Fianium supercontinuum source and an InGaAs

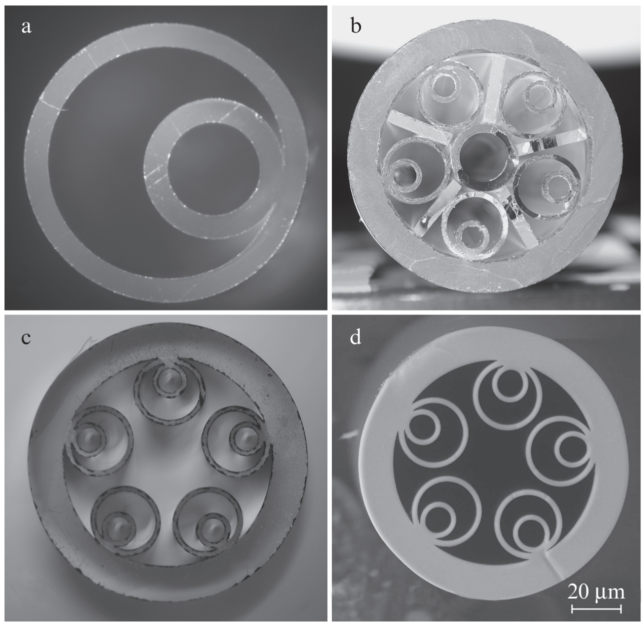

Figure 2. Cross-sectional photographs of optical elements in the main fibre fabrication steps for an HCRF with double nested capillaries: (a) double nested capillary preform 6.12–6.28 mm in diameter, produced in the first step; (b) preform assembly with silica elements between double capillaries, ∅25 mm; (c) fused and drawn preform (middle part), ∅6 mm; (d) cross-sectional scanning electron microscope image of the HCRF drawn from the preform, ∅110 μm.

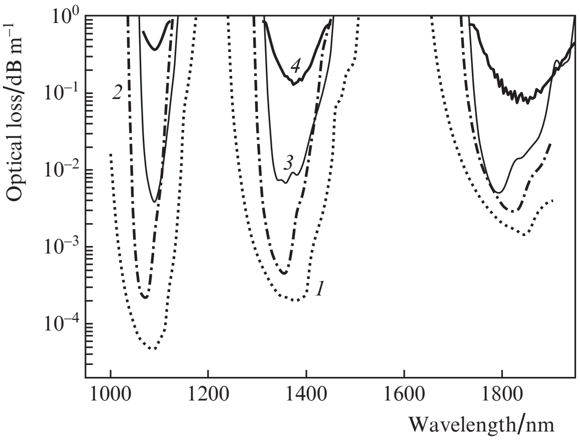

Figure 3. Optical loss spectra:
(*1*) calculated loss for an ideal fibre geometry (the capillaries have the form of equally spaced circumferences identical in wall thickness), (*2*) calculated loss in a fibre with constant deviations from an ideal geometry (circular capillaries, ~10% wall thickness difference and gaps between the cladding capillaries of 4.5 μm ± 20%), (*3*) calculated loss in a structure based on a photograph of a real fibre (elliptical capillaries, ~10% wall thickness difference and gaps between the capillaries of 4.5 μm ± 30%) and (*4*) experimentally measured loss.

detector. Figure 3 presents the measurement results together with numerical simulation results on the optical loss level in a fibre having the same design but with various deviations of its geometric parameters.

Curve (*1*) in Fig. 3 represents the calculated optical loss spectrum for an ideal fibre geometry, in which all the capillaries are identical in wall thickness and diameter and are equally spaced along a circumference around the fibre core. Such fibre should have very low losses: for example, the loss at a wavelength of 1.09 μm should be as low as 4.6×10^{-2} dB km^{-1}. With a 10% wall thickness difference and a ±20% spread in the gap between the capillaries, the achievable loss level is several times higher [curve (*2*)]. The actual fibre geometry (Fig. 2d) has even larger deviations from the ideal one. In particular, the cross sections of the capillaries are elliptical rather than circular in shape. The spread in capillary wall thickness is in this case also at a level of 10%, but the spread in the gap between the capillaries reaches ±30%. As a result of these deviations, the calculated optical loss is on average two orders of magnitude higher than that in the ideal geometry [curve (*3*)]. Finally, the experimentally measured optical loss in the fibre fabricated by us is one to two orders of magnitude above the loss calculated in the real model [curve (*4*)]. At the same time, the position of the transmission bands of the HCRF fabricated by us agrees well with model calculation results (the wavelengths of the minimum loss regions in Fig. 3 nearly coincide). The large quantitative discrepancy between the experimental data and numerical simulation results suggests that the model in question fails to properly take into account all factors that have a significant effect on the optical loss in the fibre. It may be that the deviations of the geometric shape of the real fibre from the ideal one are more complex than those adopted in our calculations. In particular, the model does not take into account variations in the geometric dimensions of the fibre along its length.

It is of interest to compare the optical loss spectra of the HCRF with a double nested capillary cladding (HCRF-2) and a fibre with a reflective cladding in the form of one ring of single capillaries (Fig. 1a), which was described previously [7] (HCRF-1). The capillary wall thicknesses in these fibres differ little (about 2.3 μm) and the spectral positions of their transmission bands nearly coincide. The minimum optical losses in HCRF-1 and HCRF-2 are also similar; about 100 dB km^{-1} at $\lambda \approx 2$ μm in HCRF-1 and 74 dB km^{-1} at $\lambda = 1.8$ μm in HCRF-2. At the same time, the core diameter in HCRF-2 (25 μm) is more than a factor of 2 smaller than that in HCRF-1 (57 μm). According to estimates of optical losses in antiresonant fibres [3], this decrease in core diameter should be accompanied by a factor of ~27 increase in optical loss relative to HCRF-1. Therefore, the use of double nested capillaries instead of singular capillaries allows one to considerably reduce the hollow core diameter with no dramatic rise in optical loss.

It is important to note that the double-capillary HCRF fabricated by us is quasi-single-mode. Since the diameter of its hollow core is small, high-order modes are strongly coupled to modes of the core–cladding interface [8]. The difference in loss between the fundamental mode for both polarisations and the first higher mode is about 1.5 orders of magnitude. This issue will be addressed in greater detail in our subsequent reports.

Thus, we have demonstrated the first revolver fibre with a reflective cladding formed by a single ring of double capillaries identical in wall thickness. This fibre design made it possible to reduce the hollow core diameter by more than a factor of 2, without increasing the optical loss in the fibre. Fibres having such a design, with a smaller hollow core diameter, should have lower losses due to splicing with standard fibres than do HCRFs with a reflective cladding in the form of one ring of single capillaries. Moreover, when filled with a gas, such fibres can be used in Raman lasers, accordingly at lower pump powers.

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