*OPTICAL FIBRES*

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# Large-mode-area single-mode microstructured optical fibre for the mid-IR region

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***Abstract*. A single-mode microstructured optical fibre is fabricated from silver halogenide crystals. The fibre is intended for the mid-IR region and features a large mode area (13600 μm$^2$). It is shown experimentally and theoretically that the fibre is in fact single-mode at 10.6 μm and has an optical loss of 8 dB m$^{-1}$.**

***Keywords***: *single-mode optical fibre, microstructured optical fibre, crystalline optical fibre, IR spectroscopy, $CO_2$ laser, silver halogenide.*

## 1. Introduction

The investigation of microstructured silver halide optical fibers ($AgCl_xBr_{1-x}$) intended for the mid-IR region began several years ago. Silver halides are used for the production of flexible, non-toxic, and non-hygroscopic multimode optical fibres with a minimal optical loss of $\sim$0.1 dB m$^{-1}$ at 10.6 μm [1]. Multimode crystalline optical fibers find applications in IR spectroscopy and radiometry. They are also used for the transmission of laser energy [2]. However, to achieve single-mode propagation at 10.6 μm in a step-index fibre with the minimum technologically feasible core – cladding refractive index difference, the core diameter should be less than 40 μm [3], which makes it difficult to couple light into the fibre and reduces the laser damage threshold. At the same time, microstructured optical fibres can have a large mode area and simultaneously remain single-mode due to greater attenuation of the high-order modes.

Because crystalline fibres are produced by the extrusion technique, it is impossible to leave air holes in the fibre in the same way as it is done in the silica fibre technology. To form the necessary refractive index distribution in microstructured crystalline fibres, holes are drilled in the perform, and rods made from a material with a lower refractive index are inserted into the holes. Thereafter, a fibre is extruded from the resultant perform. The literature reports silver halide microstructured fibres with two or three rings of inserts arranged in the hexagonal or octagonal order. The loss in the fibres amounted to 5 – 15 dB m$^{-1}$ [4 – 7] and was caused by scattering from the insert interfaces and by scattering from pores in the fibre material, as well as by absorption by silver colloids.

In this paper, we report for the first time a single-mode microstructured crystalline optical fibre (MCOF) at 10.6 μm with a large mode area and a single ring of inserts (Fig. 1). Microstructured optical fibres with a single ring of inserts are referred to in the literature as 'leakage channel fibers' (LCF) [8, 9]. In such microstructured silica fibres, it is possible to obtain a rather large area of the fundamental mode (over 3000 μm$^2$ at $\lambda \sim 1.5$ μm [10]). However, to suppress the high-order modes, it is necessary to bend the fibre, because the loss of such modes increases with decreasing the bend radius faster than that of the fundamental mode.

Note that fabrication of an MCOF with a single ring of inserts is more convenient technologically: drilling of the holes takes less time, the risk of perform fracturing is lower, and it is easier to treat the surface of the holes after drilling.

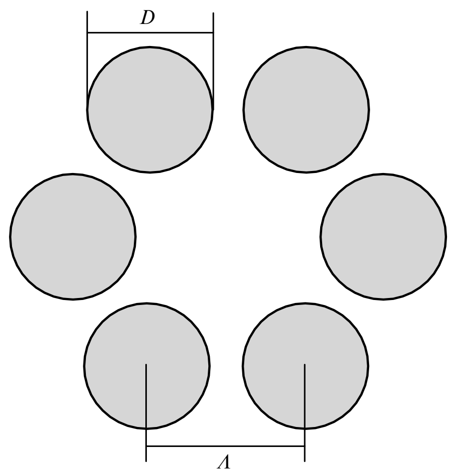


**Figure 1.** Schematic of the cross section of a leakage-channel MCOF ($D$ is the insert diameter, $\Lambda$ is the spacing between the centers of the neighbouring inserts).

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## 2. MCOF structure modeling

We modelled the MCOF structure with the help of the FemLab 3.1 program (Comsol). To estimate the MCOF loss due to leakage, an outer absorbing layer was added as described in [11]. Figure 2 gives the calculated leakage loss $\alpha$ for the first (fundamental) mode and the second mode for an MCOF with a single ring of inserts at a fixed ratio $D/\Lambda = 0.7$ and at various $\Delta c$ ($\Delta c$ is the difference of AgCl concentrations in the $AgCl_xBr_{1-x}$ compositions of the inserts and of the host matrix). The leakage loss was calculated from the propagation constant $n_{\rm eff}$ using the expression

$$\alpha = \frac{20 \times 10^{-6}}{\ln 10}\frac{2\pi}{\lambda}\,{\rm Im}\, n_{\rm eff},$$

where the wavelength $\lambda$ is taken in micrometers.

As is seen from Fig. 2, it is impossible to attain a significant (over 20 dB m$^{-1}$) suppression of the second mode with a low (below 0.1 dB m$^{-1}$) loss of the first mode. However, single-mode propagation in such fibres can be achieved by bending, because the bending loss of the first mode is smaller than that of the second mode.

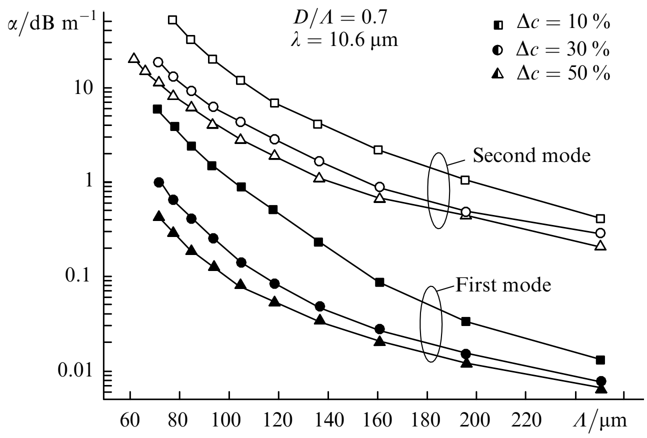


**Figure 2.** Dependences of the leakage loss of the first and the second modes on the distance between the centres of neighbouring inserts for different $\Delta c$.

The structure parameters of the experimental sample were chosen in such a way that the bending loss of the first mode at a bending radius $R = 15$ cm did not exceed 0.5 dB m$^{-1}$, while the bending loss of the second mode was maximum. The calculations for various $D/\Lambda$ and $\Delta c$ yielded an MCOF structure with $\Lambda = 127$ μm, $D/\Lambda = 0.65$ and $\Delta c = 25\,\%$. The effective MCOF core diameter amounted to 170 μm. The field intensity distribution in the core can be approximated with a Gaussian:

$$f(r) = \frac{1}{w\sqrt{\pi/2}}\exp\left(-2r^2/w^2\right),$$

where $w = 72$ μm. The calculated mode-field area is 13600 μm$^2$ (Fig. 3), and the calculated numerical aperture is 0.08.

The loss due to bending with radius $R$ for the first mode was calculated by the expression [12]

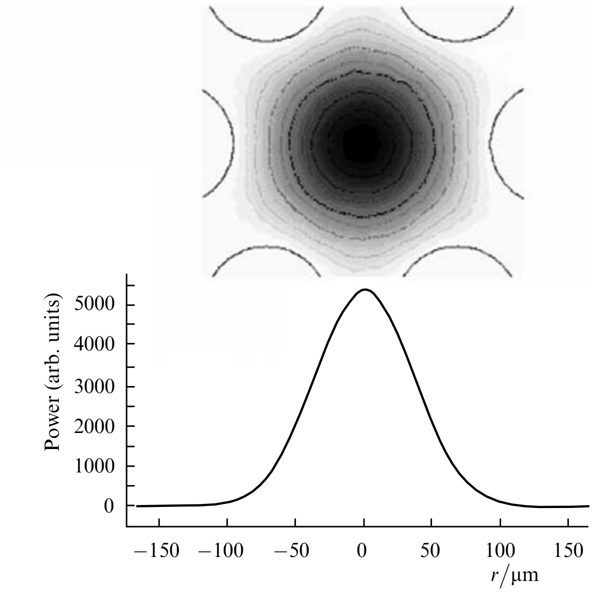


**Figure 3.** Power distribution of the first mode in the MCOF core.

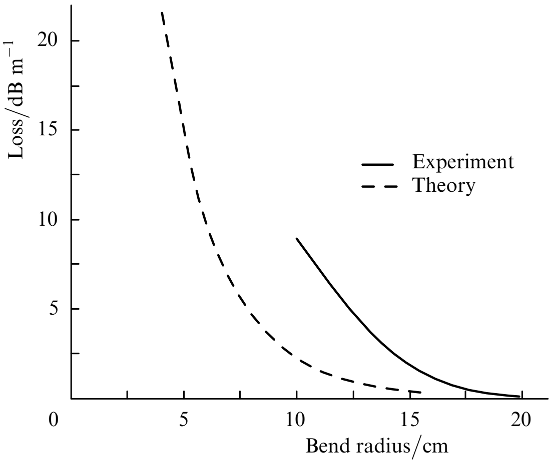


**Figure 4.** Dependences of the bending loss of the first mode on the bend radius.

$$\alpha(R) = \frac{8.686}{8\sqrt{6\pi}}\frac{1}{n_{\rm c}}\frac{\Lambda}{A_{\rm eff}}\frac{\lambda}{\Lambda}F\left[\frac{1}{6\pi^2}\frac{1}{(n_{\rm c})^2}\frac{R}{\Lambda}\left(\frac{\lambda}{\Lambda}\right)^2 V^3\right],$$

where $F(z) = z^{-0.5}\exp(-z)$; $A_{\rm eff}$ is the effective mode-field area; $n_{\rm c}$ is the core refractive index; $V$ is the fibre normalised frequency. The calculated loss due to bending for the experimental MCOF sample is shown in Fig. 4.

## 3. Measurements of MCOF parameters

The diameter of the MCOF preform made from $AgCl_{0.5}Br_{0.5}$ solid solution amounted to 12 mm. Six holes, 1 mm in diameter, were drilled in the preform in the hexagonal order, the distance between the centers of neighbouring holes being 1.53 mm. $AgCl_{0.75}Br_{0.25}$ rods of diameter 1 mm with a lower refractive index were inserted into the holes. An MCOF was obtained by extrusion through a 1-mm diameter die from an evacuated chamber.

A photograph of the 1-mm diameter MCOF endface is shown in Fig. 5. The averaged insert diameter is $\sim$170 μm,

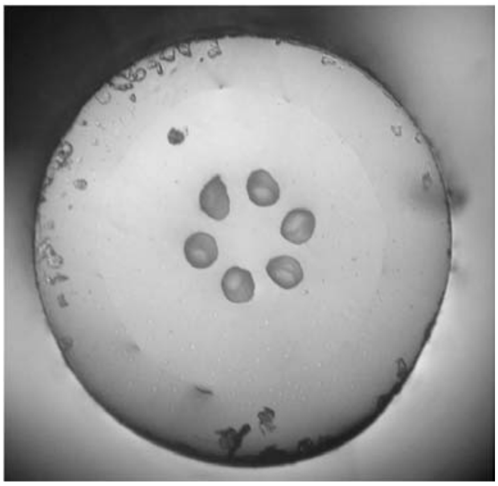

**Figure 5.** A photograph of the 1-mm diameter MCOF endface.

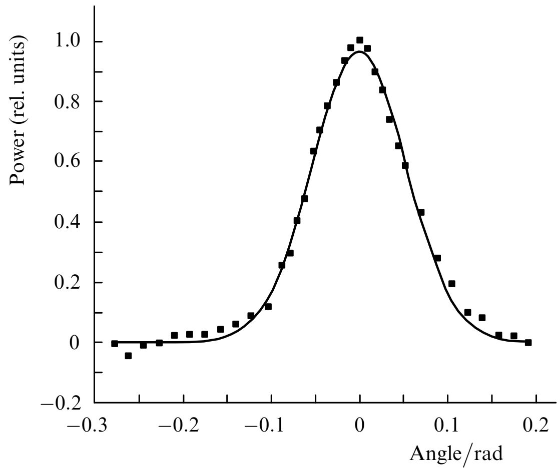


**Figure 7.** Measured far-field distribution (dots) and its approximation by a Gaussian.

the averaged distance between their centers is $\Lambda = 127$ μm. To avoid propagation of the cladding modes, the MCOF lateral surface was etched by sodium sulphate and covered with a light-absorbing ink.

To demonstrate that the fibre is virtually single-mode, we measured the near- and far-field light distributions at the fibre output. A $CO_2$ laser (GRP 'Plasma') with the following characteristics was used: $TEM_{00}$ beam, $\lambda = 10.6$ μm, power of up to 25 W, beam diameter of less than 6 mm, divergence of less than 8 mrad. The $CO_2$ laser radiation was focused into the MCOF core with a Ge lens with a focal length of 25 mm. The calculated focal spot size was 60 μm. The MCOF output power was measured with an Ophir Optics receiver (Model 3A) sensitive in the range 0.19 – 20 μm.

The far-field distribution was obtained by scanning the radiation from a photoreceiver along an arc around the MCOF axis in the plane containing the MCOF output endface (Fig. 6a), the distance between the MCOF output endface and the receiver being $L = 15$ cm. The scanning results are given in Fig. 7. The obtained distribution is described by a Gaussian, and the measured numerical aperture is 0.1. Taking into account the specific measurement scheme and the fact that the receiver diameter was 9.6 mm, the experimental aperture value can be considered to be in agreement with the calculated value of 0.08.

The near-field distribution (Fig. 8) was obtained by the 'knife' technique: the output power was measured in the process of closing step-by-step the output endface with a razor (Fig. 6b). The distribution obtained can be approximated by a Gaussian with $w = 71.4$ μm, which is also in agreement with the calculated value. During the experiment, the MCOF bend radius varied from 13 to 20 cm; however, this variation did not affect the parameters of the distributions.

Thus, we have demonstrated experimentally that the high-order modes do not manifest themselves in the far- and near-field distributions, and an MCOF with a single ring of inserts ensures single-mode propagation at 10.6 μm with a mode-field area of 13600 μm$^2$.

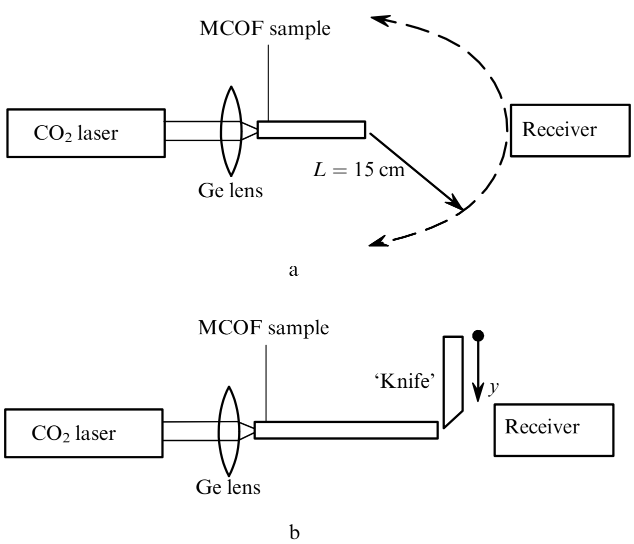


**Figure 6.** Scheme of the far- (a) and near-field (b) distribution measurement techniques.

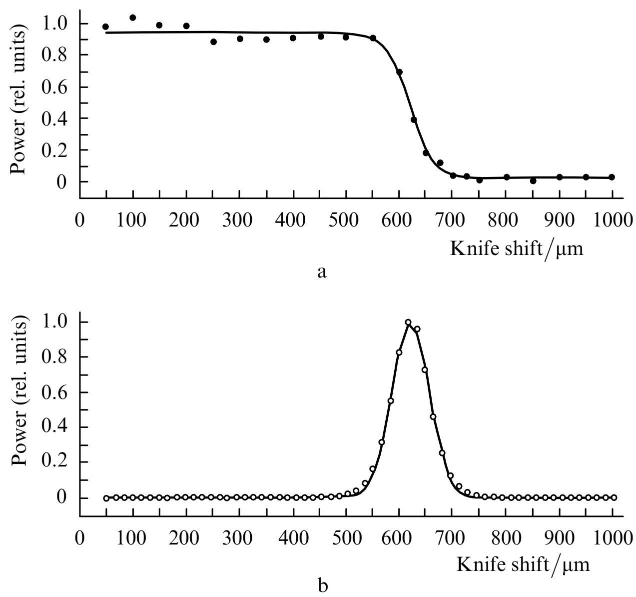


**Figure 8.** Measured near-field distribution (dark dots) and its approximation by a sigmoid curve (a); the sigmoid curve derivative (light dots) and its approximation by a Gaussian ($w = 71.4$ μm) (b).

The optical loss in a 1.5-m long MCOF piece measured by the cut-back technique amounted to $8.0 \pm 0.8$ dB $m^{-1}$. The dependence of first mode loss on the bend radius is shown in Fig. 4. The loss considerably exceeds the theoretical prediction, which is explained by scattering and absorption at the matrix – rod interfaces and by numerous microbendings. In the experiments the maximum input power was as great as $\sim 5$ W, which caused no damage to the material.

## 4. Conclusions

For the first time, a single-mode microstructured crystalline optical fibre for the mid-IR region with a single ring of inserts and a large mode area has been fabricated. It has been found experimentally that the fibre is in fact single-mode at the wavelength of 10.6 μm, which is in agreement with numerical calculations. Our further efforts will be aimed at improving the quality of the matrix – rod interfaces, which must result in a reduction of the loss due to scattering and absorption.

Single-mode microstructured crystalline optical fibers hold much promise for the delivery of powerful laser radiation, because their mode-field area is much larger than that of single-mode step-index crystalline optical fibers.

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