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Single-mode microstructured fibre for the mid-IR range

L.N. Butvina, O.V. Sereda, E.M. Dianov, N.V. Lichkova, V.N. Zagorodnev

***Abstract*.** **A single-mode microstructured fibre for the mid-IR region based on silver halide crystals is fabricated for the first time. It is shown theoretically and experimentally that the fibre is virtually single-mode at a wavelength of 10.27 μm and has optical losses equal to 2 dB m^{-1}. It is demonstrated that crystal microstructured fibres offer a number of advantages compared to common fibres made of silver halide crystals. A broad transparency window of these materials (2 – 20 μm) makes promising the use of these fibres in spectroscopy and in nonlinear fibre devices for the mid-IR region.**

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

1. Introduction

Microstructure fibres represent a new class of optical fibres with unique properties and the great potential for applications. For example, a microstructured fibre allows one to obtain the single-mode regime at a considerably greater area of the mode field than in a usual fibre, thereby reducing the efficiency of nonlinear processes [1]. By varying the geometrical parameters of the fibre, it is possible either to increase dispersion considerably or to flatten the dispersion curve [2]. The zero-dispersion wavelength can be varied in a broad range [3, 4]. The rapid recent development of the technology of microstructured crystalline fibres for the visible and near-IR regions stimulated the development of microstructured crystalline fibres for the mid-IR range [5].

In this paper, we report the fabrication and study of a microstructured fibre for $\lambda = 10.6$ μm made of silver halide crystals. The solid solutions of silver halides $AgCl_xBr_{1-x}$ (where $0 \leqslant x \leqslant 1$) are transparent in the region between 2.5 and 20 μm. As x increases, the refractive index of $AgCl_xBr_{1-x}$ decreases almost linearly from 2.16 to 1.98. These materials are used to fabricate flexible, nontoxic, and nonhygroscopic multimode fibres with minimal optical losses $\alpha \sim 0.1$ dB m^{-1} at a wavelength of 10.6 μm [6]. They are used in IR spectroscopy, radiometry, and for laser energy transmission [7]. However, attempts to fabricate a high-quality single-mode fibre from silver halides with low losses have not met with success so far [8].

The fabrication of a microstructured crystalline fibre is an important step in the development of IR fibres because such a fibre can operate in the nearly single-mode regime with a large mode-field area.

2. Structure simulation

We analysed the properties of a silver halide microstructured crystalline fibre by using the CUDOS MOF Utilities program developed at the Sidney University (Australia) [9]. The program uses the multiplicative calculation method, which is faster than other methods and allows the calculation of leaky losses of the mode related to the geometrical structure [10, 11]. We simulated the periodic structure consisting of cylindrical inserts of diameter $d = 41.6$ μm with the refractive index $n_1 = 2.075$ equal to the refractive index of $AgCl_{0.5}Br_{0.5}$. The inserts are arranged hexagonally in the matrix with the refractive index $n_2 = 2.132$ equal to the refractive index of $AgCl_{0.2}Br_{0.8}$; the distance between the insert centres was $\Lambda = 59.5$ μm. This structure maintained nine modes. The first mode had the efficient refractive index $n_{\text{eff}} = \beta/k_0$ (β is the propagation constant and k_0 is the wave number in vacuum) for which $\text{Re}\, n_{\text{eff}} = 2.1302$ и $\text{Im}\, n_{\text{eff}} = 7.48 \times 10^{-12}$, which corresponds to the leaky losses $\alpha = 1.9 \times 10^{-5}$ dB m^{-1}. The losses were calculated by the expression $\alpha = (20/\ln 10)2\pi/\lambda \text{Im} n_{\text{eff}} \times 10^6$, where the wavelength λ was measured in micrometers. The losses for high-order modes were considerably higher. For example, the second-order mode losses were approximately 125 dB m^{-1}. Such high losses should prevent the propagation of high-order modes even over short distances ($\sim$1 m) in the fibre.

3. Single-mode microstructured crystalline fibre

The preform for a microstructured crystalline fibre made of a solid $AgCl_{0.2}Br_{0.8}$ solution was 12 mm in diameter. It had holes drilled to form two concentric circles. The holes were arranged in the hexagonal order with a distance of 1.43 mm between their centres. The $AgCl_{0.5}Br_{0.5}$ rods of diameter 1 mm with the refractive index lower than that of the

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L.N. Butvina, O.V. Sereda, E.M. Dianov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: butvina@fo.gpi.ru, lesyaofmipt@mail.ru, dianov@fo.gpi.ru;
N.V. Lichkova, V.N. Zagorodnev Institute of Microelectronics Technology and High Purity Materials, Russian Academy of Sciences, 142432 Chernogolovka, Moscow region, Russia;
e-mail: Lichkova@ipmt-hpm.ac.ru, Zagorodnev@ipmt-hpm.ac.ru

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preform were inserted into holes. The microstructured fibre was fabricated from the preform by extrusion through a die of diameter 500 μm from an evacuated chamber.

Figure 1 shows a photograph of the microstructured fibre end. The average diameter of inserts was $d = 45$ μm and the average distance between their centres was $\Lambda = 62$ μm. The diameter of inserts in the fibre was somewhat larger that that in the preform ($d/\Lambda = 0.73$ versus $d/\Lambda = 0.7$). The fibre core diameter was ~79 μm. To avoid the propagation of cladding modes, the beginning and end of the fibre were covered with a polymer with a carbon filler, which strongly absorbs in the IR region. To prove that the fibre fabricated in this way is a single-mode one in fact, we performed two experiments.

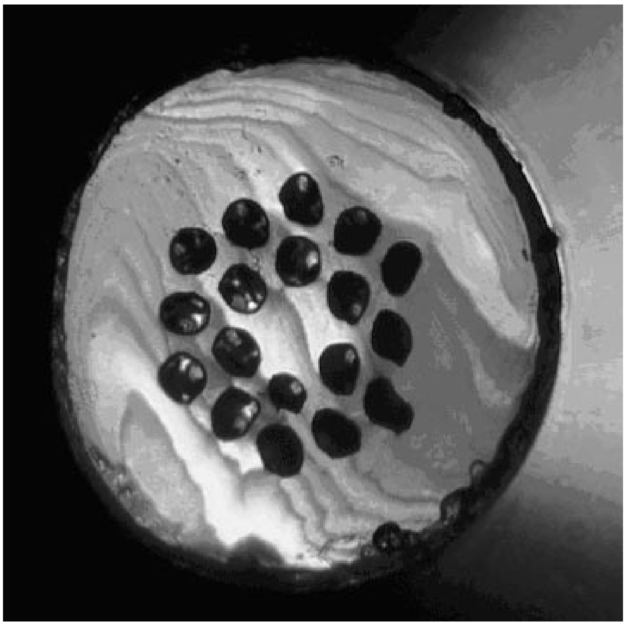

Figure 1. Photograph of the microstructured crystalline fibre end of diameter 500 μm.

In the first experiment, the CO_2 laser radiation was focused to the fibre core by a ZnSe lens with a focal distance of 30 mm. This radiation had the following parameters: the TEM_{00} mode, $\lambda = 10.2744$ μm (the 10R16 line), the output power ~5 W, the laser beam diameter less than 6 mm, the beam divergence less than 4.2 mrad, and the polarisation degree 90 %. The calculated diameter of the focal spot was 69.5 μm. The radiation power at the fibre output was measured with a mercury–cadmium–telluride (MCT) detector (Opto-Electronic Components, KR208-FSMA2-GI) sensitive in the region from 8 to 14 μm.

The far-field radiation distribution was obtained by scanning the radiation field by the detector at the distance $L_1 = 60$ cm from the fibre end. The near-field distribution was obtained by scanning the radiation field by a single-mode fibre coupled with the detector along the end of the microstructured fibre at the distance $L_2 \sim 50$ μm (Fig. 2). The diameter of the core of the single-mode step-index fibre was 40 μm. The cladding modes of this fibre were suppressed by the absorbing silver layer covering the fibre cladding. The results of scanning are presented in Figs 3 and 4.

In the second experiment, the laser radiation was coupled to the microstructured fibre through a multimode fibre with the core and cladding diameters of 900 and 1000 μm, respectively. We also measured the far- and near-field radiation distributions. These distributions, as in the first experiment, were described by a Gaussian and were independent of the radiation coupling conditions, i.e. of the distance between the multimode and single-mode fibres and the angle between them. Thus, we have demonstrated experimentally that the 10.27-μm radiation propagates in the microstructured crystalline fibre in the single-mode regime because no higher-order modes were observed in the far- and near-field radiation distributions.

Optical losses in the microstructured crystalline fibre measured by the 'cut-back' method for the fibre of length 2.5 m were 2.0 ± 0.8 dB m^{-1}. These losses considerably exceed

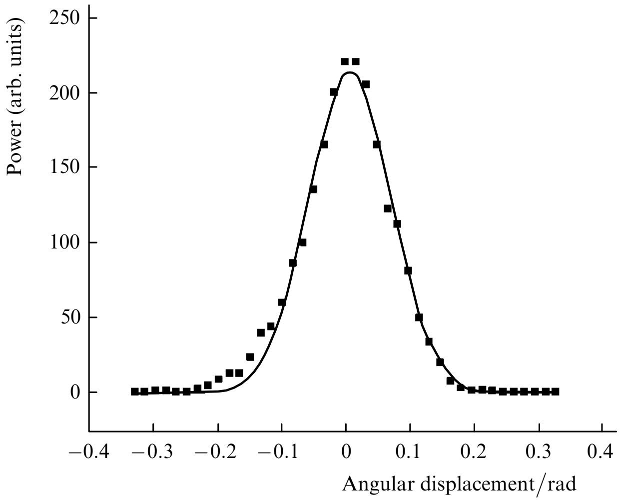

Figure 3. Experimental far-field radiation distribution (squares) approximated by a Gaussian (solid curve).

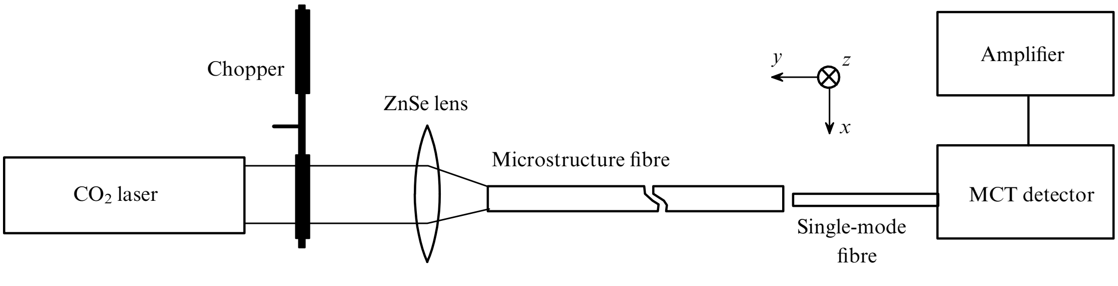

Figure 2. Scheme for measuring the near-field radiation distribution.

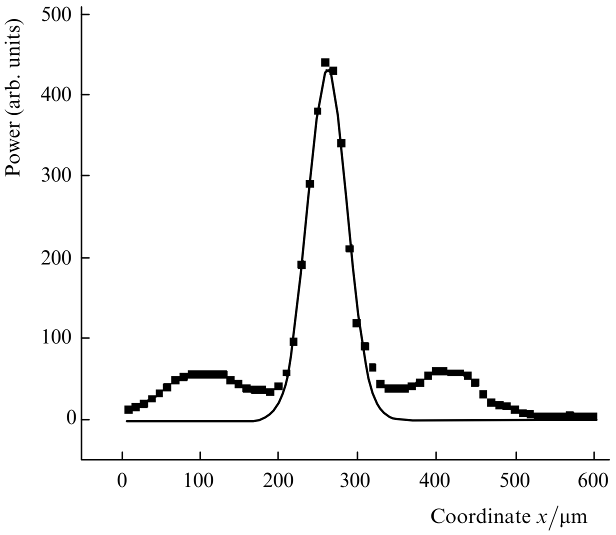

Figure 4. Experimental near-field radiation distribution (squares) approximated by a Gaussian (solid curve).

theoretical losses due to scattering and absorption at the matrix – insert interfaces. The maximum power at the fibre output was ~3 W. No damage of the fibre was observed in this case.

4. Conclusions

A microstructured fibre for the mid-IR region has been fabricated for the first time. It has been shown experimentally that this fibre is in fact single-mode for the 10.27-μm radiation, in accordance with numerical calculations. Further efforts will be directed to improve the matrix – insert interface in order to reduce scattering and absorption losses.

Microstructure crystalline fibres are quite promising for the transfer of high-power laser radiation because the mode-field area in them can considerably exceed that in usual single-mode crystalline fibres. Microstructure fibres for the mid-IR region with a small-diameter core and controlled dispersion value can be used in nonlinear-optical devices operating in the mid-IR spectral region.

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