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Single-mode crystalline optical fibres for a wavelength of 10.6 μm

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Abstract. **Single-mode crystalline optical fibres for transmitting the 10.6-μm CO_2 laser radiation with optical losses 4 – 5 dB m^{-1} are fabricated for the first time.**

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

1. Introduction

Systematic efforts in the development of crystalline fibres for the mid-IR region (3 – 22 μm) were initiated in 1978, when polycrystalline fibres were first fabricated from the solid solution of KRS-5 thallium halides by the method of extrusion of a single-crystal preform through a die. Polycrystalline fibres were fabricated from solid homogeneous solutions of silver chloride, bromide, and iodide with a cubic lattice. These materials were chosen because they have low optical losses in the range from 3 to 20 μm, are nontoxic, unlike thallium halides, and admit considerable strain hardening during extrusion [1]. Polycrystalline fibres exhibit a peculiar elastic and plastic behaviour, which is different from that of glass fibres. The surface of these fibres does not require a protective cladding in principle due to the plastic nature of their destruction even at liquid nitrogen temperature. Such fibres were fabricated for a long time without a cladding [2], because cladded fibres had considerable losses due to light scattering at the core – cladding interface.

To fabricate cladded polycrystalline fibres, original technologies were developed. Due to optimisation of the extrusion parameters and the technology of crystal growing, the light scattering by vacancy micropores produced upon extrusion was reduced by more that an order of magnitude and the roughness at the core – cladding interface was decreased. Earlier, we developed multimode cladded fibres with a smooth interface and optical losses of no less than 1 dB m^{-1} in the greater part of the transmission region (3 – 20 μm) and with minimal losses equal to 0.15 dB m^{-1} [3]. The structural perfection of the core-cladding interface achieved in [3] allowed us to fabricate for the first time single-mode crystalline fibres for a wavelength of 10.6 μm with losses less than 5 dB m^{-1}. The minimal losses in single-mode crystalline fibres studied in previous papers [4, 5] amounted to 30 dB m^{-1} at 10.6 μm.

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2. Results

Polycrystalline fibres are extruded from the $AgCl_xBr_{1-x}$ crystals (where $0 \leqslant x \leqslant 1$ is the mole fraction of AgCl in the solid solution). The refractive $n(x)$ of the $AgCl_xBr_{1-x}$ solid solutions decreases almost linearly from $n(0) = 2.17$ to $n(1) = 1.98$ at a wavelength of 10.6 μm. We fabricated single-mode crystalline fibres from single crystal solid solutions of silver halides, by using $AgCl_{0.5}Br_{0.5}$ for the fibre core and $AgCl_{0.55}Br_{0.45}$ for the fibre cladding. The difference Δx in their compositions was 0.05, which corresponds to the difference $\Delta n = n_{co} - n_{cl} \approx 0.01$ in the refractive indices of the fibre core and cladding. The theoretical numerical aperture of the fabricated fibre was NA = 0.2.

To obtain the single-mode regime in a fibre with a circular core, the wave parameter $V = ka(n_{co}^2 - n_{cl}^2)^{1/2}$ should be smaller than $V_0 = 2.405$, where $k = 2\pi/\lambda$, and a is the core radius. Thus, the core diameter d should be smaller than $d(\lambda, \mathrm{NA}) = \lambda V_0/\pi\mathrm{NA}$. For $\lambda = 10.6$ μm and NA = 0.2, the maximum core diameter at which the single-mode regime is realised, should be equal to 40.5 μm.

The core diameter of the single-mode crystalline fibre with NA = 0.2 was 35 μm and the cladding diameter was 500 μm (Fig. 1). The length of the fabricated single-mode fibre was $\sim$ 5.5 m. To verify that radiation propagates in the fibre core, we focused the CO_2 laser radiation on the fibre end by means of a special germanium objective with the focal distance $f = 15$ mm. The side surface of the fibre was covered with a metal silver layer. Thus, the cladding modes were absorbed in the metal layer. Measurements were performed by using a 10.2744-μm single-mode CO_2 laser [the TEM_{00} mode, $\lambda = 10.2744$ μm (the 10R16 line), the output power $\sim$5 W, the radiation divergence less than 4.2 mrad, and the polarisation degree 90 %], a 100-MHz Tektronix TDS 2014 oscilloscope (the digitising time 1 ns), and a mechanical chopper (with the 1 : 30 on-off time ratio).

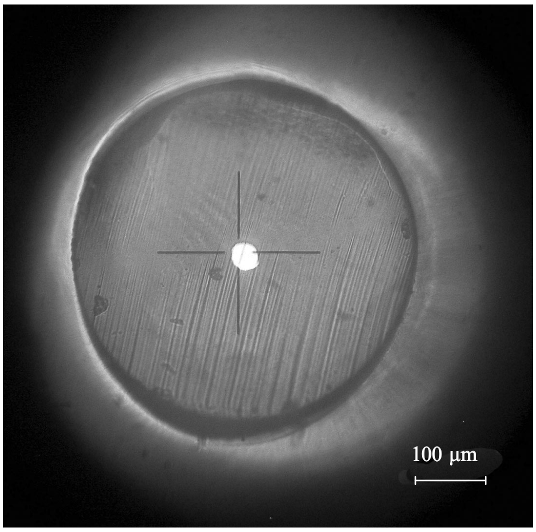

Figure 1. Photograph of a single-mode crystalline fibre end.

Optical losses in the single-mode fibre measured by the cut-back method were 4–5 dB m^{-1}.

The maximum radiation power incident on the fibre end in experiments was ~ 3 W. No damage of the fibre was observed.

The far-field radiation distribution was measured with a mercury–cadmium–tellurium (MCT) detector with a fibre input [6]. Figure 2 shows the far-field radiation distribution for a single-mode crystalline fibre, which was obtained by displacing transversely the end of the receiving fibre with respect to the single-mode fibre when the distance between the ends of the fibres was $L = 7$ cm. The far-field radiation distribution is well described by the Gaussian $P = \{A/[w(\pi/2)^{1/2}]\}\exp\{-2[(\varphi - \varphi_c)/w]^2\}$, where P is the radiation power; φ is the displacement angle of the receiving fibre; $\varphi_c = -0.0062 \pm 0.00073$; $w = 0.12887 \pm 0.00145$; and $A = 0.39552 \pm 0.00386$. The correlation coefficient is $R^2 = 0.99612$. The numerical aperture measured at the 5 % level is 0.16.

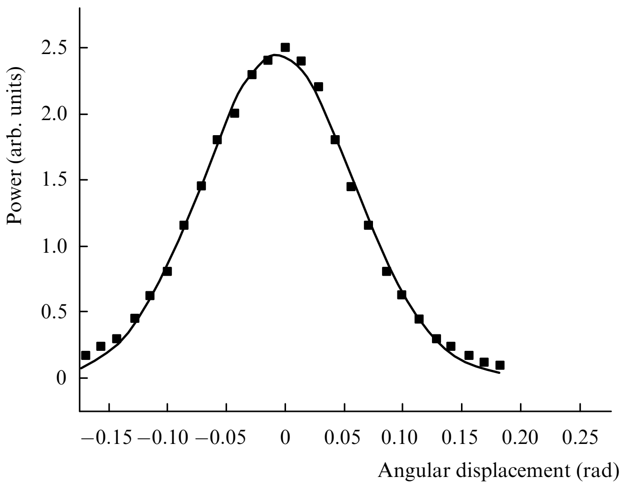

Figure 2. Far-field radiation distribution for a single-mode crystalline fibre and its Gaussian approximation. The numerical aperture NA measured at the 5 % level is 0.16.

3. Conclusions

We have fabricated a single-mode crystalline fibre for a wavelengths $\lambda > 10$ μm and measured the output radiation profile. Single-mode crystalline fibres can be applied for the transfer of radiation from CO_2, CO, quantum-cascade [7], and other IR lasers, the filtration of modes [8], and in IR laser spectroscopy and systems of optical IR sensors. Multifibre cables of single-mode fibres can be used to obtain thermal images [9]. The possibility of the development of mid-IR fibre lasers has been also demonstrated.

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