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Composite three-layer potassium and silver halide fibre for the mid-IR range

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Abstract. **We report for the first time the possibility of co-extrusion of silver and potassium halide crystals to produce double-clad polycrystalline IR fibres. This combination allows the disadvantages inherent in each of the crystals separately to be overcome. The resulting fibres have stable long-term transmission and can be used to transmit CO_2 laser radiation. The loss in the fibre at a wavelength of 10.6 μm constitutes 0.75 dB m^{-1}.**

Keywords: *mid-IR range, silver halide, potassium halide, IR fibre.*

1. Introduction

Currently, there is a practical need for mid-IR optical fibres to transmit laser radiation, particularly at a wavelength of 10.6 μm of the widely used CO_2 laser. Its radiation is used in high-power industrial installations, as well as in a number of other applications (in particular, in surgery), where the transmitted average power is not as high (10–30 W). To date, these problems are solved mainly with the help of hollow metal or hollow Bragg optical fibres [1, 2]. Despite the fact that some fibres of this type have a loss at a level of ~0.2 dB m^{-1} [2], this level is still high for many applications, the loss in hollow fibres being strongly dependent on the bending radius, which also makes them difficult to use.

Among the fibres transmitting in the wavelengths region from 8 to 10 μm, extrusion fibres made of solid solutions of silver halides (up to 50 dB km^{-1} per 10.6 μm [3]) currently exhibit the lowest loss. Unfortunately, their widespread implementation is hampered by disadvantages such as photosensitivity and low damage threshold by cw laser radiation, which leads to rapid melting of the rear end face of fibre. This is especially true in using silver halides as a fibre core because of their tendency to disproportionation during the heating, which leads to the formation of absorbing silver clusters.

We have examined all the crystals used in IR optics as a transmission medium for CO_2 laser radiation, and found that some of them possess a set of properties necessary for the manufacture of composite microstructured IR fibres by extrusion. These are the presence of a cubic lattice, the possibility of plastic deformation with an acceptable rate and at an acceptable temperature (up to 300 °C), the presence of five independent sliding systems at the deformation temperature (the von Mises criterion for homogeneous plastic deformation). These properties are inherent in several, transparent mid-IR crystals, namely sodium and potassium halides (KCl, KBr, NaCl), as well as their solid solutions and a number of other metal halides. These crystals are relatively accessible and well-studied, which greatly simplifies the work with them. Essential disadvantages of such crystals (Table 1) are their hygroscopicity and brittleness.

Works on the manufacture of optical IR fibres from alkali halide crystals have shown that such optical fibres can be obtained by extrusion with optical losses less than 1 dB m^{-1} and can transmit CO_2 laser radiation of significant power [4]. However, their use is difficult and limited due to the rapid degradation of such fibres in a normal humid atmosphere.

This paper shows how this disadvantage can be overcome by introducing a second cladding made of another material impermeable to water molecules into the extrusion preform. To this end, we propose to use a second cladding of a nonhygroscopic polycrystalline solid solution of AgClBr, which in our case performs simultaneously three functions: reduces the coefficient of friction during extrusion, protects fibre from water vapour and improves mechanical properties of the resulting composite extrusion fibre. One of the fundamental advantages of potassium halides over silver halides is the absence of intraband states in the valence band [5], which, in

Table 1. Optical and thermophysical properties of alkali-halide crystals of KCl, CsI and silver halides [1].

Crystal	Minimum absorption at λ = 10.6 μm/dB km^{-1} (single crystal)	Refractive index at λ = 10.6 μm	Thermal conductivity/ 10^2 cal °C^{-1} cm^{-1} s^{-1}	Thermal expansion coefficient/ 10^{-6} °C^{-1}	Melting point/°C	Solubility/g (100 g of water)$^{-1}$	Disadvantages
AgCl	60	1.98	2.6×10^{-3}	30	457	2×10^{-4}	Photosensitive
0.5AgCl–0.5AgBr	26	2.12	1.5×10^{-3}	33	418	7×10^{-5}	Photosensitive
KCl	30	1.45	16×10^{-3}	36	776	34.7	Brittle, hygroscopic
CsI	40	1.74	2.7×10^{-3}	48	621	44	Hygroscopic

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contrast to silver halides, leads to the absence of intraband absorption in potassium halides in the mid-IR range.

Of all alkali halide crystals, we selected potassium halides, the coefficient of thermal expansion of which is close to that of silver halides. The value of fundamental minimum optical loss determined by multiphonon absorption at $\lambda = 10.6$ μm is 4.4×10^{-6} dB m^{-1} for KBr and 0.035 dB m^{-1} for KCl [6]. In work [4], a loss value of 1 dB m^{-1} was achieved for unprotected fibres with a KBr core and a KCl optical cladding, but no effective way was found to prevent their degradation.

2. Composite fibre fabrication and results

Prior to extrusion of composite fibres, a preform was assembled (Fig.1), consisting of a core and two claddings. The second cladding of AgClBr solid solution performed a protective function. The core material was the $KCl_{0.1}KBr_{0.9}$ solid solution (refractive index $n = 1.518$ at $\lambda = 10.6$ μm) grown by the Bridgman–Stockbarger method at the Institute of Microelectronics Technology and High-Purity Materials, Russian Academy of Sciences. The material of the first optical cladding was a KCl crystal. Such crystals are publicly available. The core of the KClKBr single crystal was placed into the KCl cladding, and then they together were placed into a special AgClBr cylinder manufactured by extrusion. The AgClBr protective layer protects the fibre from negative effects of moisture, reduces the coefficient of friction in the die and improves the mechanical properties of the fibre, i.e. reduces the brittleness and radius of elastic bending to 100 fibre diameters, or 0.5% relative to the elongation caused by bending.

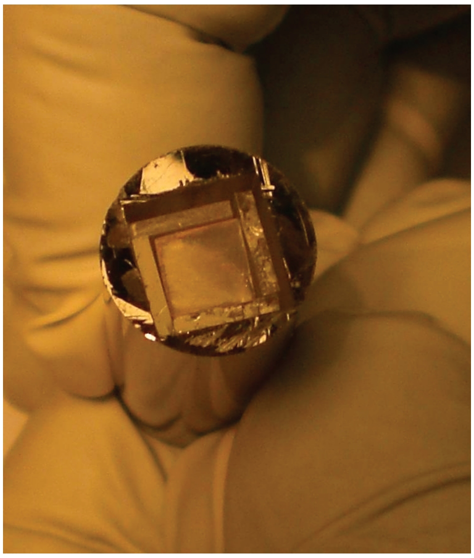

Figure 1. Composite preform for extrusion.

The preform diameter was 12 mm, and the diameters of the drawn KBrCl/KCl/AgClBr fibre composition were 465/870/1000 μm. A photograph of the fibre end face is shown in Fig. 2. The resulting three-layer preform was reversely extruded. The extrusion temperature was 210 °C, the pressure reached 3 tons, and the extrusion rate was about 1 mm min^{-1}. As a result, a 4-m-long fibre with an outer cladding diameter of 1 mm was drawn. The multimode IR fibre aperture constituted NA = 0.44. The interface roughness between the core and cladding (Fig. 2) is due to the crystalline nature of the original substances. The end faces of the optical fibres were made with a special knife having a 10-micron slice thickness; the end-face quality was controlled with a MBS-10 microscope. The transmission spectrum of the resulting fibre after extrusion was measured at room temperature by a Vector-22 spectrometer (Bruker) with a DTGS detector (Fig. 3). Spectrum measurements performed a week later did not reveal statistically significant transmittance changes.

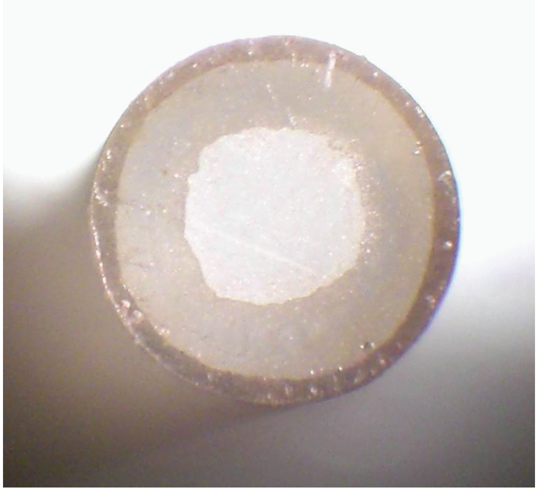

Figure 2. Photograph of the composite polycrystalline IR fibre end face.

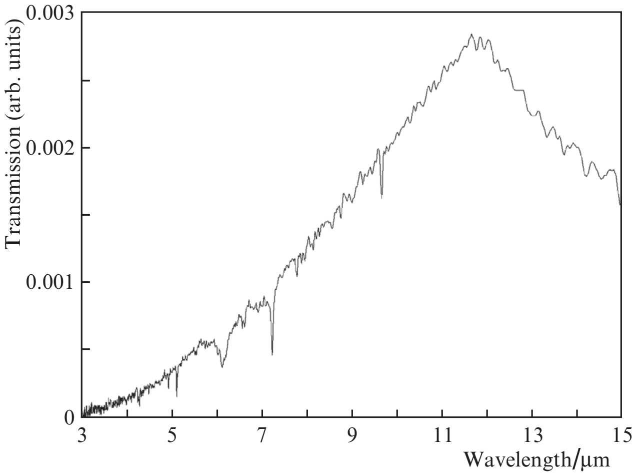

Figure 3. Transmission spectrum of a 1.5-m-long fibre.

To experimentally determine the magnitude of losses and laser power transmittance in the obtained fibres in the region of 10.6 μm, a CO_2 laser-based setup was assembled, the radiation of which was focused onto the fibre using a lens of antireflective Ge ($f = 30$ mm). The laser power was measured with a ROFIN-SINAR calibrated thermocouple detector. The fibre with a length of $L = 1.3$ m steadily transmitted cw radiation to the maximum possible laser output power of 30 W. The output power constituted 0.41 W with an input power of 0.56 W. Thus, given Fresnel reflections at the end faces, the value of optical loss in a 1.3-m-long fibre at $\lambda = 10.6$ μm amounted to 0.75 dB m^{-1} with an error up to 5%. The output power was linearly dependent on the input power up to the values of 30 W. Optical loss value A (dB m^{-1}) in the fibre was calculated based on the Lambert–Beer law $P_{\text{out}} = P_{\text{in}}(1 - R)^2\exp(-AL)$ (P_{out} and P_{in} are the output and input powers, R is the reflection coefficient, and L is the fibre length in meters) according to the formula:

$$A = 10L^{-1}\lg[(P_{\text{in}}/P_{\text{out}})16n^2(1+n)^{-4}]. \qquad (1)$$

In this calculation, we neglected the loss due to the roughness of the end faces of the multimode optical fibres; therefore, the real losses are even lower.

3. Conclusions

The possibility of co-extrusion of silver and potassium halide crystals to manufacture a double-clad polycrystalline fibre for the mid-IR range is shown for the first time. Using this method, a composite double-clad IR fibre has been manufatured for the first time, consisting of a polycrystalline core of $KCl_{0.1}KBr_{0.9}$ composition, a KCl optical cladding, and an AgClBr protective waterproof cladding. This combination of crystals allows one to overcome the disadvantages peculiar to each of them separately. The resulting fibre has a stable long-term transmission and can be used to transmit CO_2 laser radiation. The loss value in the fibre at a wavelength of 10.6 μm constituted 0.75 dB m^{-1}.

The fibre transmission spectrum shows that the main source of losses is scattering. We believe that this is scattering on the fibre inhomogeneities, namely, on the rough boundary between the core and cladding, and also on the intergranular micropores. Further work will be aimed at improving the structure of composite extrusion fibres and reducing their optical losses.

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