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A large core microstructured fluoride glass optical fibre for mid-infrared single-mode transmission

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ABSTRACT

A microstructured optical fibre based on an alumino-zirco-chloro-fluoride glass has been fabricated in which the light-guiding structure comprises a single ring of air-holes, machined directly into the preform rod using an ultrasonic drill around a large effective solid core. The objective was single-moded transmission of longer mid-infrared wavelengths at high laser power without causing radiation damage to the fibre material. It has been demonstrated that this fibre preserves high laser beam quality and can transmit wavelengths between 2.1 and 4.7 μm, single-moded in an effective core of diameter 79 μm. Optical fibre transmission losses from 1.4 to 10.3 dB m^{-1} have been measured over this wavelength range. No damage was observed in the fibre at peak pulse power, setting a lower limit of >1 GW cm^{-2} for the laser damage threshold. Brightness was preserved at wavelengths longer than 4 μm.

1. Introduction

There are many applications in laser machining, surgery and defence which require flexible light-guides to transport high-power mid-infrared continuous wave or pulsed laser radiation efficiently while preserving laser brightness.

The aim of the present work is to fabricate an optical fibre which can transmit high power laser light in the 2–5 μm wavelength band over distances of several metres without causing damage to the fibre or degrading the beam quality of the launched light. The waveguide is required to be flexible and robust and capable of functioning in hostile environments with little shielding to protect against vibration, dust and temperature fluctuations.

1.1. Fibre material

Mechanically robust fibre materials were sought which have low transmission loss and are resistant to laser damage in the desired spectral range. Silica glass, the most common optical fibre material is certainly robust, having high tensile strength and resistance to thermal shock. However, silica has a spectral window only from 0.3 to 2 μm and is virtually opaque to wavelengths longer than 2 μm. It also suffers laser-induced damage at quite low power [1,2] and is therefore unsuitable for the present application.

Poly-crystalline silver halide fibres have transmission losses of 1–2 dB in the wavelength range 3–20 μm but have limited fibre length (<20 cm) and mechanical strength, being drawn from single

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crystals [3,4]. Glasses which can be drawn into optical fibre include chalcogenide glasses and heavy-metal fluoride glasses. The properties of both chalcogenide and heavy-metal fluoride fibres have been summarised by Harrington [5] and Haynes et al. [6].

Chalcogenide glass fibres may be transparent up to 10 μm. Churbanov et al. have reported a As–S fibre [7] which is transparent over the wavelength range 2–6 μm except for an impurity absorption due to H–S between 3.9 and 4.4 μm. A solid, step-index chalcogenide glass fibre developed at the US Naval Research Laboratories [8] has transmission loss <0.6 dB m^{-1} at wavelengths up to ~9 μm and power carrying capacity of 1 GW cm^{-2} for pulsed and 1 MW cm^{-2} for continuous wave. Core diameter in the NRL fibre ranges from 8 to 600 μm.

Heavy-metal fluoride glasses were discovered in 1975 [9] and many compositions which are transparent between 0.3 and ~7 μm are now commercially available. Fluoride glass fibres are less robust than silica but can nevertheless be made in multi-kilometre lengths, sufficiently strong to be spooled and handled. Some are attacked by water but the effect is minimised in suitable compositions. Fluoride glasses are generally resistant to radiation damage [10–12], though rare earth doping may lower the damage threshold [13].

Yamashita [10] has reported an alumino-zirco-chloro-fluoride glass composition ($25.1AlF_3$:$12.8ZrF_4$:$11.1YF_3$:45(CaF_2 + MgF_2 + SrF_2 + BaF_2):5.7NaCl mol%) developed by the Hoya Corporation, Japan for delivery of a Er:YAG laser beam used for dental surgery. This fibre is claimed to have a laser damage threshold of >8 kW cm^{-2} for continuous wave at 2.94 μm and losses less than 1 dB m^{-1} up to 4 μm in a core diameter of 450 μm. The fibre preforms were fabricated by extrusion with a large solid core surrounded by a thin solid cladding of lower refractive index. The susceptibility of these fibres to high peak-power laser damage has not yet been fully reported.

Both fluoride and chalcogenide glasses were considered for the present application. Fluoride glasses have a number of advantages over the chalcogenides, including lower refractive index, relatively high thermal conductivity, low change of refractive index with temperature and greater mechanical strength. Refractive indices of fluoride glasses lie between ~1.4 and 1.8, while those of chalcogenide glasses are ~2.4–3.5, so reflection losses at air-glass interfaces would be 4–6 times greater in chalcogenide than in fluoride fibres. The main disadvantage of fluoride glasses is their lower infrared limit, around 6–7 μm, compared with chalcogenides, which may be transparent up to ~10 μm. Chalcogenides tend to be more stable glasses but are more difficult to fabricate. Fluoride glasses of the type developed by Hoya were chosen for the present project.

1.2. Fibre design

Optical fibres can be made of any optically transparent material which has sufficient tensile strength and viscosity (η) of $\sim 40 \times 10^6$ Pa s ($\log_{10}\eta = 7.6$) at an easily accessible temperature. Fibres can be either solid or 'microstructured'. In microstructured fibres an array of holes around an effective core serves to confine the light. The material of a microstructured fibre is usually of uniform refractive index while the holes, which extend throughout the length of the fibre, are usually air-filled.

The number of optical modes which can be carried in a solid fibre depends on wavelength, refractive index, numerical aperture and core diameter. A single mode is usually desirable, which mean the core diameter must be small. In silica fibre a single-mode core diameter is typically ~8–10 μm for wavelengths 1.31–1.55 μm and in fluoride fibres ~1 μm for wavelengths around 2.5 μm. Microstructured fibres can be single-moded over a wide range of wavelengths, even when the core is quite large, regardless of fibre material [14]. A large core is desirable so that power can be distributed over a large cross-section area and higher laser power can be carried. It was decided to fabricate a microstructured fluoride glass fibre with a large solid core.

Microstructured fibre can have a solid or air-filled core. In the former, light travels through the solid material used to make the fibre. In the latter it travels in air. Transmission loss is less in air than in glass, so the ideal fibre would be an air-cored microstructured fibre of glass with low optical loss. However, air-cored fibre, sometimes called photonic band-gap (PBG) fibre, requires very precise geometry and PBG fibres are notoriously difficult to make in any material. It was therefore decided to start with the simpler option and attempt to fabricate a solid core microstructured fibre in fluoride glass. If this was successful an air-cored fibre might be attempted later, based on knowledge acquired in the fabrication of the solid core fibre. A solid core microstructured fibre in silica glass has been reported by Wong et al. [14] for transmission of a wavelength of 1.064 μm in an effective core diameter of ~21 μm and a microstructured chalcogenide fibre with an effective core diameter of 10 μm, made by capillary-stacking, has been reported by Monro et al. [15]. No reports of a microstructured fluoride glass fibre have been found in the literature.

2. Experimental procedures

2.1. Glass properties, characterisation and preparation

Hoya were asked to make special high quality fluoroaluminate glass rods for the project. They fabricated these in batches of three rods at a time. Assuming the fabrication method used was the same as that described by Yamashita [10], glass constituents were first melted together and then cooled to the consistency of thick paste, which was extruded through a horizontal stainless steel die. After extrusion the rods were surface skimmed to remove contamination and annealed to remove residual stresses. Hoya measured a range of optical, thermal, physical, chemical and mechanical properties of the rods and then dispatched them in sealed packs filled with inert gas. The properties measured included refractive index, glass transition temperature, coefficient of thermal expansion, specific gravity, hygroscopicity and Young's Modulus. After the glass rods were received from Hoya the compositions of the glasses were analysed using energy dispersive X-ray spectroscopy (EDS).

2.2. Fibre design

Microstructured fibre preforms are commonly made either by drilling an array of holes in a solid cylinder of glass or other transparent material or by stacking capillary tubes of the chosen material to form the required hole configuration. Fluoride glass capillary tubes are not readily available and could not be fabricated by Hoya, so an ultrasonic drilling method was chosen.

The hole array used was dictated partly by theory and partly by the size of available glass rods and drill sizes and the limitations of the ultrasonic drilling process. The rods delivered by Hoya were 8 mm in diameter and 100 mm long and it was possible to drill holes 1 mm in diameter to a depth of 100 mm with reasonable precision. Smaller holes could not be drilled over the 100 mm length because of the flexibility and fragility of the very small drill bits. There was simply not much room in such a small cross-section for a large array of holes, a large effective core and a wide perimeter outside the holes. Holes could not be placed too close to the outer wall of the rod, because they would distort and possibly close up during fibre-drawing.