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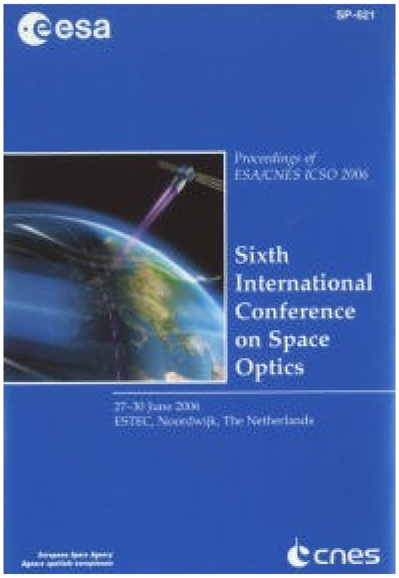

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SINGLE MODE CHALCOGENIDE GLASS FIBER AS WAVEFRONT FILTER FOR THE DARWIN PLANET FINDING MISSON

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ABSTRACT

The development of single mode chalcogenide glass fibers as wavefront filter for the DARWIN mission is reported. Melting procedures and different preform techniques for manufacturing core-cladding chalcogenide fibers are described. Bulk glass samples on the basis of Te-As-Se- and high Te-compositions have been characterized optically, by measurement of the absorption spectrum and the refractive index in the region 4 – 20 µm. Several chalcogenide core-cladding glass fiber configurations have been drawn and examined by microscopy. The mode propagation behaviour and numerical aperture of fiber samples have been determined by far field intensity distribution measurements, using a CO_2 laser at 10.6 µm. Single mode waveguide performance has been demonstrated for several fiber samples, coated with an absorbing Gallium layer for stripping of cladding modes.

1. INTRODUCTION

An important measuring technique under study for the DARWIN planet finding mission, is nulling interferometry [1]. The main goal of this mission is to identify terrestrial planets, orbiting around nearby stars and capable of having an atmosphere, so possibly supporting life. The principle of nulling interferometry is the destructive interference of the intense light emitted by a central star, thus enabling the detection of the weak infrared emission lines of the orbiting planet. This technique requires a perfect wavefront of the light beams to be combined in the interferometer. By using a single mode waveguide before detection, higher order modes are filtered and a virtually perfect plane wavefront is obtained

Since the main emission lines of the relevant atmospherical components like CO_2, O_3 and water vapour are all in the mid IR, from 4 – 20 µm, the envisaged single mode waveguides must be transparent in this spectral range.

In this paper, recent results on the development of suitable infrared transmitting, chalcogenide glass optical fibers are presented. Typical measuring results on fibers are presented and discussed in view of the envisaged application as wavefront filter in the mid IR.

2. OPTICAL PROPERTIES CHALCOGENIDE GLASSES

Several rods of varying Te-As-Se (TAS) glass compositions have been melted from the elements, using two purification stages. In a first step the 5N pure elements are heated in vacuum to remove the surface oxides, which are more volatile than the corresponding metal. In a second step, after fusion of the raw materials, the resulting glass is distilled to remove impurities like carbon which are less volatile than the TAS glass.

By applying these two subsequent purification steps of the raw materials, the oxygen contamination in the resulting TAS glass, causing extrinsic absorptions in the 4 – 20 µm DARWIN spectral window, can be reduced considerably.

For testing the effect of space conditions, especially the effect of high energy radiation on the optical properties, TAS chalcogenide glass samples are exposed to gamma radiation, simulating cosmic conditions. For this purpose the samples are placed in a hollow ball with a diameter of 130 mm. The ball is submerged in water and the sample is exposed to a radioactive Co60 source for 53 seconds. During this treatment the samples receive a total radiation dose of 0.1 kGy, simulating the estimated cosmic radiation dose for the DARWIN mission [1]. The optical absorption spectra, measured before and after this radiation treatment are shown in figure 1.

It can be observed in this figure that the extinction curves coincide within the estimated experimental error of 0.04 cm^{-1}. This implies that the radiation treatment has no measurable effect on the optical transmission of the TAS glasses in the transparent region.

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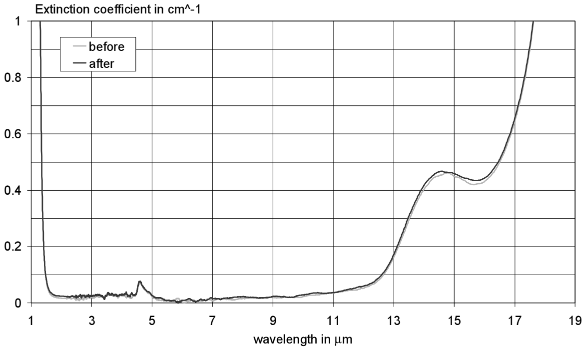

Fig.1: Absorption spectra of TAS glass samples before and after the radiation treatment.

Furthermore it can be observed in figure 1 that two absorption bands appear in the DARWIN spectral window: One band with a maximum around 14.3 µm and the other with a maximum beyond 20 µm, but with an absorption tail down to 16 µm. These bands are intrinsic, caused by As-Se vibrational modes in the glass matrix itself. Due to these two absorption bands, the usable transmission window of TAS glass optical fibers of the order of, typically, 10 cm length is limited to the wavelength region from 4 - 12 µm. Therefore recently, an exploratory study was started to develop new high-Te content glass fibers, without As and Se. It has been found that multicomponent (Te-Ge-Ga-I) chalcogenide glasses, with high Te content have an improved IR transmission in the spectral region beyond 12 µm, in comparison to TAS glasses. The maximum achievable transmission of high Te-glasses in the spectral region 12 – 20 µm is currently under study.

Figure 2 shows a preliminary measurement result of the spectral dependence of the refractive index of a Te-Ge-Ga-I glass composition, determined from optical reflection spectra [2].

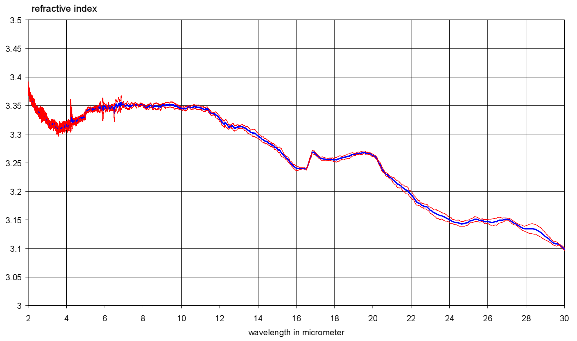

Fig. 2: Measured refractive index of high Te-glass (Te-Ge-Ga-I) versus wavelength

In figure 2 the blue curve represents the average of 6 independent reflection measurements. All the measurements fall within the interval indicated by the red curves. The dip in the measured refractive index below 4 µm is expected to be an artefact, possibly due to a very thin surface layer on the sample. The small spectral feature (jump) between 16 and 17 µm is due to an instrumental effect (change in grating of the IR spectrophotometer). As can be seen in this figure the refractive index of this particular glass composition varies typically between 3.25 and 3.35 in the DARWIN spectral range. It has been found that the refractive index can be controlled by slightly changing the glass composition, especially the Te/I ratio (a higher Te content results in a higher refractive index due to the high polarizability of Te).

3. DESIGN AND PREPARATION OF CORE-CLADDING CHALCOGENIDE GLASS FIBERS

3.1 Fiber design

For the broadband wavefront filtering application in DARWIN, the waveguide must satisfy strict requirements concerning operational wavelength range, diameter and profile of the fundamental optical mode, etc. Various waveguide technologies, including hollow fibers, planar waveguides, index guided photonic crystal fibers, photonic band gap fibers and the conventional step index single mode fiber were compared taking into account these requirements. On the basis of this comparison, the conventional single mode fiber was selected as most suitable technology for meeting all essential requirements for DARWIN.

For a conventional step index single mode fiber, the coupling efficiency will drop dramatically with longer wavelength. Hence, splitting the entire DARWIN wavelength range of 4 – 20 µm into several bands, involving different fiber designs, is the most favourable solution. As compromise, a dual bands system consisting of two different single mode fibers for each wavelength band is proposed: the short wavelength (SW) fiber and the long wavelength (LW) fiber.

Using the refractive index and dispersion data achieved for the bulk TAS glasses, waveguide modelling calculations resulted in the following parameters for the dual band configuration (see table 1).

Table 1: Dual wavelength band system

	Short wavelength	Long wavelength
Wavelength range (µm)	4 – 9	9 - 20
Cut off (µm)	3.7	8.5
Core radius (µm)	11	26
Cladding thickness (µm)	250	600
n_{core}	2.927	2.913
$n_{cladding}$	2.924	2.910

For the short wavelength (SW) fiber the relation between the Mode Field Diameter of the fundamental mode and the wavelength has been modeled, using a commercial fiber design software package. The calculation results are presented in figure 3.

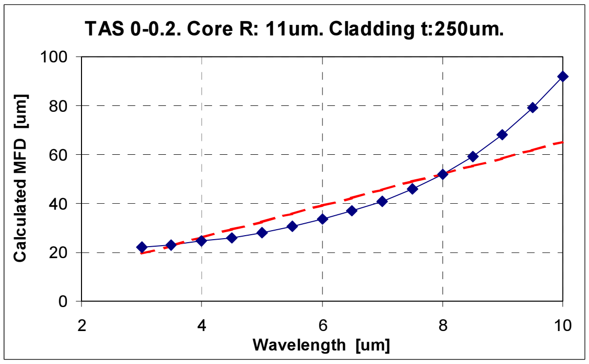

Fig. 3: Calculated Mode Field Diameter (MFD) for the Short Wavelength TAS fiber as a function of the wavelength (blue line with markers). The red dashed line presents the desired linear relation between the MFD and the wavelength for optimized coupling @ 8 µm.

It is important to note that the cut-off wavelength of the TAS SW fiber is calculated to be about 3.72 µm. Furthermore, the coupling efficiency over the operational wavelength is found to be higher than 80%. In the following the fiber manufacturing and characterization of an SW step index TAS fiber configuration are described.

3.2 Fiber manufacturing

Step index core-clad fibers were manufactured using different preform techniques, basically modifications of the well-known rod-in-tube prefom method.
For all techniques cladding tubes must be fabricated.
The cladding tubes have been made by the rotational casting method. The molten cladding glass contained in a quartz ampoule is subjected to fast horizontal rotation in a centrifugal machine with speeds between 3000 and 5000 rounds per minutes. Subsequently, the silica tube is annealed and cooled to room temperature. The dimensions are typically 4 mm internal diameter, 10 mm external diameter and 10 cm length. The internal diameter of the tube is defined by the weight of the glass introduced in the silica ampoule.
Core glass rods of 4 mm diameter are obtained by stretching a 10 mm rod in core glass composition with the help of a drawing tower. When using the common rod-tube method, a 4 mm core rod is inserted in a clad tube with an external diameter of 10 mm and an internal diameter of 4 mm. After stretching this core/clad1 preform into a new rod of 4 mm diameter, the rod-in-tube method can be repeated a few times in order to obtain a final core/clad1/clad2/clad3 preform with the required core/clad diameter ratio as in the final fiber. The fiber is drawn from the final preform. However, it has been found that, especially the critical interface for waveguiding, i.e. the interface between core and clad1, is far from perfect when the above common rod-in-tube method is applied. Therefore, alternative methods have been developed and tested. The modified methods are denominated as Internal Rotational Casting Method (IRCM), Fiber in Tube Vacuum (FTVM) and Rod in Tube Vacuum Method (RTVM). These different preform methods are described in separate papers [3,4].

TAS fibers with a core diameter of 22 µm and a cladding diameter of about 500 µm have been drawn from preforms, using a set-up, schematically shown in figure 4. The diameter is controlled by the rotational speed of the drum and the vertical speed of the preform in the furnace. Typically, fibers of 5 - 10 m length have been drawn without interruption or breakage.

Several fiber samples have been coated with an absorbing Gallium coating to eliminate the propagation of higher order optical modes in the cladding (cladding modes). For this, Gallium is melted in a holder at a temperature of 55 °C. Then the TAS fiber is pulled through the molten Gallium several times to obtain a homogeneous coating. The thickness of the coating varies typically between 15 and 45 µm. TAS fiber samples up to a length of 50 cm have been treated successfully using this method.

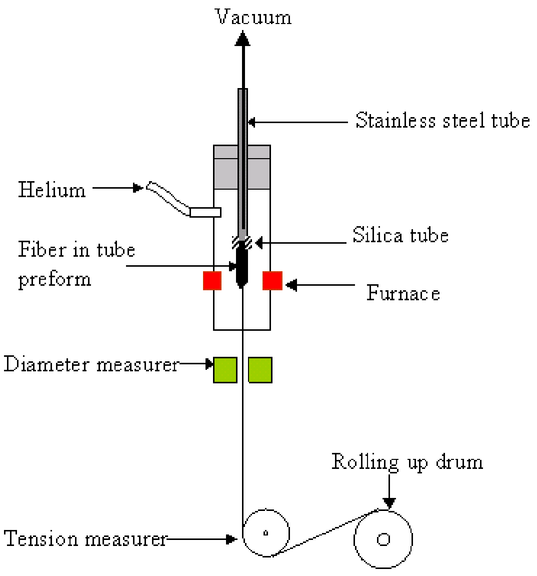

Fig. 4: Scheme of fiber drawing of preform by FTVM

4. OPTICAL CHARACTERIZATION OF CHALCOGENIDE GLASS FIBERS

4.1 Set-up for far field intensity measurements

To characterize the mode profile of transmitted light through the fiber samples, 2D far field intensity (FFI) distribution measurements have been carried out.

The set-up used for FFI measurements at 10.6 µm wavelength basically consists of a CO_2 laser and a 2D-array microbolometer IR CCD camera and is shown schematically in fig 5.

A pinhole of 18.3 µm diameter in front of the fiber sample ensures that the laser light is coupled mainly into the core of the fiber. The light transmitted by the fiber is analyzed by the IR camera.

With this set-up, measurements have been conducted on different, step index TAS fiber samples to evaluate the effect of different parameters on the performance of the fibers, including :

- Effect of absorbing Gallium coating for stripping the cladding modes
- Effect of fiber length on propagation of higher order modes
- Effect of fiber manufacturing method on far field intensity distribution

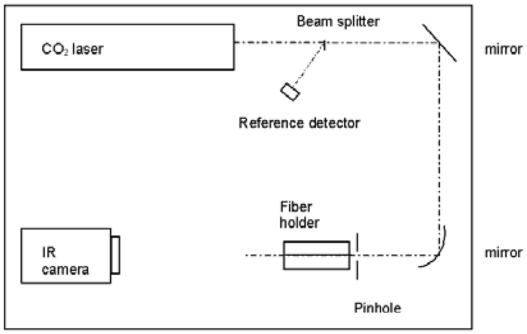

Fig. 5: Set-up for FFI distribution measurements with step index TAS fibers

4.2 Results of optical characterization

A typical far field intensity distribution of an uncoated step index TAS fiber is shown in figure 6. The large number of side lobes visible in this figure indicates the presence of many higher order modes in the transmitted signal.

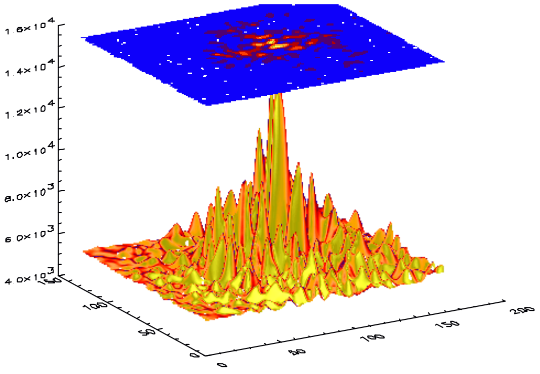

Fig. 6: Typical 2D far field intensity distribution of an uncoated step index TAS fiber, showing many side lobes

In order to suppress the propagation of cladding modes, a 23 cm long piece of a step index TAS fiber has been coated by an absorbing Ga coating. The measured far field intensity distribution of this 23 cm long Ga-coated TAS fiber is visualized in a 2D and 3D perspective in figure 7.

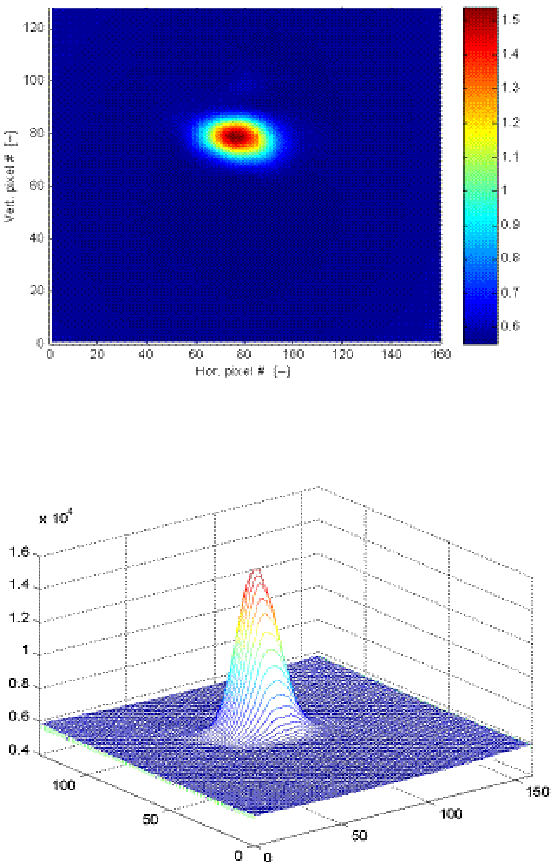

Fig. 7: Representation in 2D and 3D of far field intensity distribution of a 23 cm long TAS step index fiber sample, coated with an absorbing Ga-layer

Apparently, the transmitted signal has only one remaining peak with a Gaussian intensity distribution, indicating single mode operation of the fiber. However, as can be seen in figure 7, the output intensity is not circular symmetric, but elliptical. This is most probably caused by non-rotation-symmetric stresses, introduced during the fiber drawing process (IRCM).

It has been found that the Rod in Tube Vacuum Method (RTVM) provides improved control of the final fiber quality parameters, like a smooth interface between core and cladding and a good circularity of the core, as can be seen in figure 8 and 9. Figure 8 shows a cross section of a TAS fiber with a high refractive index contrast between core and cladding, prepared by RTVM. Figure 9 shows the far field intensity distribution of a 36 cm long TAS step index fiber, prepared by RTVM and coated with a Ga-layer. It can be seen in this figure that this fiber has a circular intensity distribution.

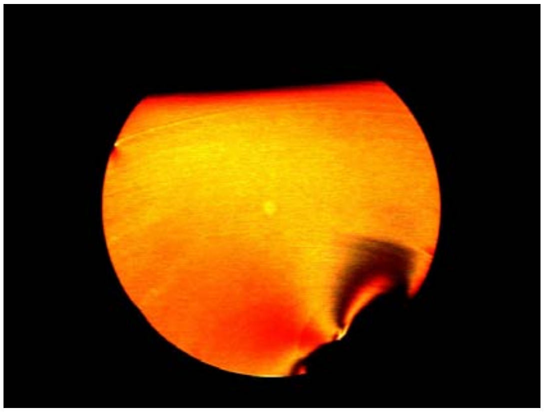

Fig. 8: Picture of a cross section of a high contrast step index TAS fiber prepared by RTVM

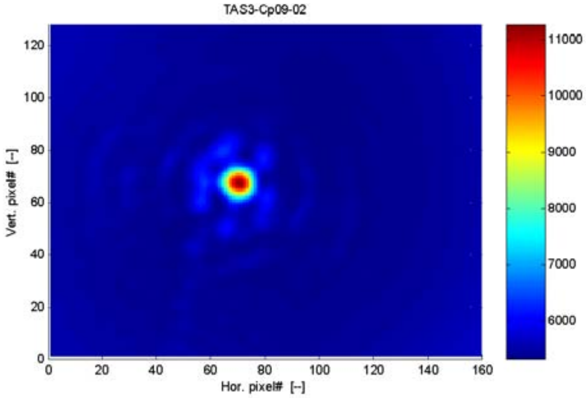

Fig. 9:FFI measurement @ 10.6 µm measured at a distance of about 10 mm from a 36 cm Ga-coated TAS fiber, prepared by RTVM

The attenuation of the single mode fiber samples has been measured by the cut-back method using the CO_2 laser at 10.6 µm. The attenuation at this wavelength is found to be about 0.1 dB/cm. Thus, it may be assumed that the minimum loss in the region 4 – 9 µm will be lower than 0.1 dB/cm.

5. CONCLUDING REMARKS

A two-wavelength band system based on two step-index single mode fiber configurations, one for the short wavelength range 4 – 9 µm and the other for the long wavelength range 9 – 20 µm , is designed for the DARWIN wavefront filter. Step index TAS chalcogenide fibers have been developed as candidate wavefront filter for the short wavelength band.

Far field intensity distribution measurements at 10.6 µm of Gallium-coated step index TAS fiber samples, prepared by different manufacturing methods, show a

Gaussian intensity distribution, indicating single mode operation.

Two intrinsic absorption bands in the TAS glass, due to As-Se vibrational bands, limit the usable transmission window of TAS fibers to the wavelength region from 4 – 12 µm. Therefore, current studies focus on extending the operational wavelength of chalcogenide glass fibers by changing the chemical composition to high Te-content glasses, without As and Se. Besides, improved methods for suppressing the propagation of cladding modes, e.g. by better absorbing coatings are being considered.

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