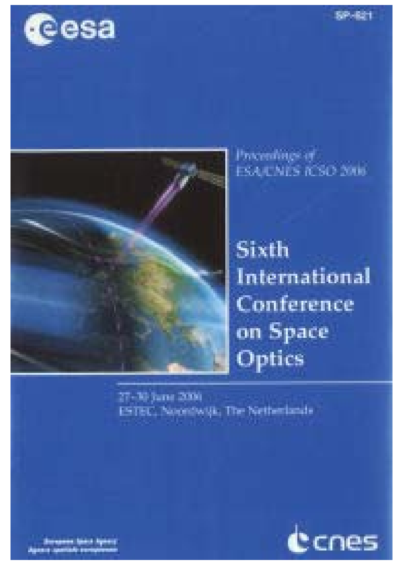
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 105672G · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308140

MANUFACTURING OF CHALCOGENIDE AND SILVER-HALIDE SINGLE-MODE FIBRES FOR MODAL WAVEFRONT FILTERING FOR DARWIN

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ABSTRACT

Modal wavefront filtering is mandatory in nulling interferometers dedicated to detect extrasolar planets. Several activities have been initiated by ESA for developing single-mode waveguides for the mid-infrared.

We present the development of fibres to be used for modal filtering within the European DARWIN mission and its scientific precursor GENIE: Chalcogenide fibres fit the wavelength range up to about 11 microns, while silver halide fibres can cover the full DARWIN wavelength range from 6.5 to 20 microns. A wide range of different manufacturing methods have been applied for producing step-index fibres. We also present the first results of manufacturing photonic crystal silver halide fibres.

We tested the modal wavefront filtering capability of the fibres in a Mach-Zehnder interferometer fed by a CO_2-laser. In addition we recorded the transverse output beam profile for each fibre. The results of both measurements are strong indicators for single-mode operation.

We identified the critical issues experienced in the course of this manufacturing activity. The efficient removing of cladding modes and the required length of the fibres, commonly strongly underestimated, turned out as the keys for successful demonstration of single-mode behaviour. We found dedicated and compatible materials acting as mode stripper for both fibre materials used.

We highlight the required steps for further improvement of the manufactured fibres and for a reasonable continuation of the fibre development activities for DARWIN.

1. BACKGROUND

The European DARWIN mission [1] wants to detect and analyze terrestrial exoplanets orbiting Sun-like stars. Nulling interferometry [2] allows for visual detection and interferometric imaging of such planets. Stringent requirements are imposed onto the instrument because the capability to separate both signals must be excellent due to the close proximity of star and planet. DARWIN's operating band is in the mid-infrared and even here the contrast ratio of star and planet is huge. The bandwidth of the instrument ranges from 6.5 µm to 20 µm as absorption lines of the main biomarkers shall be identified at 7-8 µm (methane), 9.6 µm (ozone), 15 µm and 18 µm (carbon dioxide), and 6-8 respectively 17-20 µm (water). A nulling interferometer provides both high on-axis light suppression and high angular resolution. The tremendous requirements given by the DARWIN mission call for advanced observation techniques like a rotating telescope array and phase chopping and a sophisticated instrument design together with the development of novel subsystems and optical components with so far unrivalled quality.

The European Space Agency (ESA) has initiated system studies, technology development programs to provide key elements, and breadboard activities to demonstrate stable nulling at laboratory conditions. The Ground-Based European Nulling Interferometry Experiment GENIE [3] is intended as next step towards DARWIN. It can be seen as a scientific precursor for DARWIN. GENIE shall be implemented as a permanent instrument on VLTI [4] at Paranal/Chile and will perform a systematic survey of candidate targets for DARWIN in order to screen out in advance all stars surrounded by too bright exo-zodiacal dust clouds.

To achieve deep nulling of the star signal the individual interferometer arms have to be equalised with respect to intensity, phase, and state of polarisation. Modal wavefront filtering of the output signals with single-mode fibres is required for removing the wavefront errors of the affordable and feasible high-quality optics.

2. SINGLE-MODE FIBRES FOR DARWIN

ESA initiated within its DARWIN technology development program several single-mode fibre activities and Astrium has been awarded with one contract [5]. Because up to date no single mode fibres were available for the mid infrared, the technology activity aimed at

Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

- research and trade-off of possible fibre designs
- assessment of suitable materials
- development of manufacturing techniques
- production of fibre samples
- experimental verification of the samples

The specific requirements on the fibre are listed in Tab. 1 with emphasis on the suppression of higher order fibre modes.

EADS Astrium Germany led the activity, all fibre samples have been produced by ART Photonics, Germany, and selected samples have been tested by Vienna University of Technology in a realistic interferometer set-up.

Parameter	Requirement
Wavelength range	4 to 20 µm
Suppression ratio of higher-order modes	10^6
Total insertion loss goal	< 1.5 dB
Operational temperature	40 K
Radiation susceptibility	no damage or darkening up to 10^4 Rads (100 Gy)
Manufacturing process reproducibility	should enable 5% or better parameter realisation

Tab. 1: Technical requirements on fibre samples.

In contrast to spatial filtering with a pinhole which is restricted to blocking of spatial frequency components, modal filtering is the projection of an external field onto a field with predefined transverse amplitude and phase distribution within the waveguide [6].

We investigated different realisations of the modal wavefront filter including step-index fibres, integrated optical waveguides, index guided photonic crystal fibres, and hollow fibres. Two single mode candidates have been selected for further exploration offering the broadest bandwidth and the lowest insertion loss:

- single or double step index fibre
- index-guiding photonic crystal fibre

We calculated from theory the minimum length required to damp all higher order fibre modes within the single mode fibre. The result is given in Fig. 1. Several millimetres of fibre are required only to establish the single mode. We assumed as a worst case that the non-fundamental power of all leaky modes is contained in mode LM_{11}, the leaky mode characterised by the lowest damping. This mode is assumed to be damped by 8 orders of magnitude in our example to fit the DARWIN requirements for sure. The cladding has been assumed to be infinitely extended and no reflection at the cladding air interface occurs. The short fibres required by theory encouraged us at the beginning to see the fibre attenuation as a non critical topic.

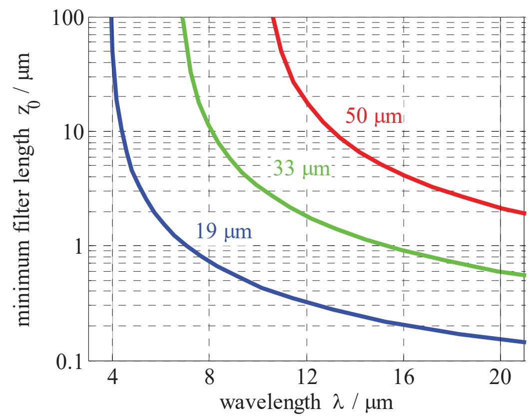
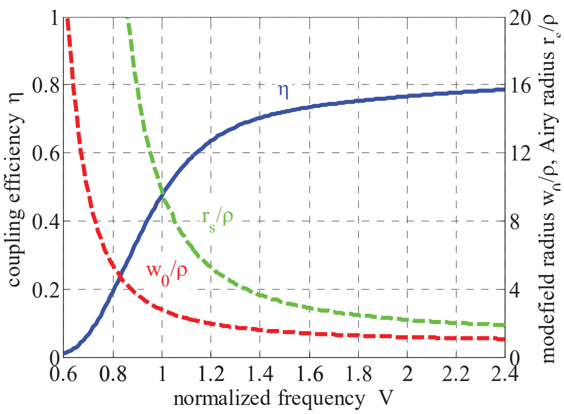


Fig. 1: Required single-mode fibre length to safely remove all cladding modes. The calculation assumes a silver halide step-index fibre of numerical aperture NA=0.15. Three different core diameters are shown.

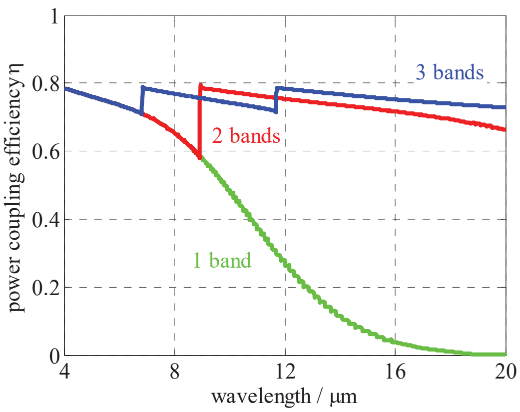
The ideal wavefront filter is broadband and would cover the entire DARWIN band. The coupling efficiency when light is coupled into a single-mode fibre is degrading rapidly if the fibre is used over more than 2 octaves as can be seen in Fig. 2. Mode-field diameter and diameter of the Airy field at the fibre entrance are strongly diverging and are the reason for the rapid coupling loss. Hence, we recommend to split the DARWIN band into two sub-bands keeping the coupling losses reasonably low. The different wavefront filters are inserted after the interferometer core and will not increase the complexity of the instrument. The fibre can be optimised for each subband and different materials can be implemented, e.g. chalcogenide glass for the lower DARWIN band and silver halides for the upper band.

3. MID-IR MATERIALS AND FABRICATION TECHNOLOGIES

Surveying the materials transparent in the mid infrared, only a few candidates can be used for manufacturing single-mode waveguides. Chalcogenide glasses can be drawn to achieve the small core diameter required for single mode behaviour. Arsenic sulphide glasses are useable up to 6.5 micron whereas GAST fibres (germanium, arsenic, sulphur, and tellurium) are transparent between 4 and 11 micron.



theoretical coupling efficiency



coupling loss by splitting to sub-bands

Fig. 2: Dispersion of coupling efficiency. The sub-bands are chosen to obtain equal relative bandwidth. The latest DARWIN requirements (6.5-20 μm) are well covered by the upper two bands of the 3-subband approach.

Chalcogenide fibres are manufactured by drawing preforms or by crucible drawing. If preforms are required they are fabricated by rod-in-tube techniques or by casting methods where melted core material is cast into a cladding tube. Our fibre samples have been produced applying the double crucible method.

Longer wavelengths can be handled by using polycrystalline materials like silver halides. The soft material cannot be drawn but must be extruded to thin fibres under high pressure and elevated temperature. To obtain the thin core diameters, preforms are usually extruded several times until a final extrusion produces the thin single mode fibre. The preforms are fabricated by mechanical combining of core rods and cladding tubes, by dropping core material into cladding tubes with the aid of capillary forces, or by special preform growth methods [7] combining core and cladding directly from the melt avoiding any contamination within the forming process.

Polycrystalline fibres have been manufactured from all three methods. The most difficult one was the preform growth technique requiring the precise control of many growth parameters. Hence, we continued successfully with the mechanical preform combining but also with the capillary technique sucking core material into a thin borehole.

Multimode silver halide fibres are routinely used in the mid infrared and show losses as low as 0.2 dB/m at 10.6 micron. Our approach was to start with the well established multi-mode technique and to adapt and to improve it in order to reduce the numerical aperture and/or the core diameter to obtain single mode devices.

4. PHOTONIC CRYSTAL FIBRES

Photonic crystal fibres (PCF) are based on structures with a periodic refractive index variation in the plane perpendicular to the fibre axis and an invariant index structure along it. Index guiding PCFs show a high index core and operate by total internal reflection. Air holes at wavelength scale are embedded in some dielectric material. PCFs can be single mode for all wavelengths if the relative air hole diameter is sufficiently small.

Photonic crystal fibres are produced from glasses by drawing. Index guiding PCFs made of polycrystalline material must be extruded because of the soft material. All regions with lower refractive index must be filled up with material of lower index as the final extrusion would squeeze off all air holes. Two materials are needed therefore and the manifold internal boundary zones are one critical issue. The fabrication of silver halide PCFs is much more difficult than the drawing of glassy materials.

PCFs realised as bandgap guiding or air-guiding devices were not considered in the realisation phase as both suffer under bandwidth limitations and broadband devices cannot be expected for a DARWIN application. Common to both variants is a central hole in the fibre. Hence, the guided modes extend less or more into the dielectric materials and are damped there.

5. SINGLE-MODE FIBRE SAMPLES

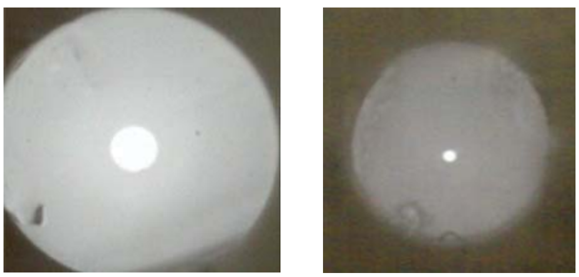
For step-index fibres, the second order mode, LP_{11}, has a normalised cut-off frequency of

$$V_C = \frac{2\pi\rho}{\lambda_C}\sqrt{n_{Core}^2 - n_{Clad}^2} = \frac{2\pi\rho}{\lambda_C} NA = 2.405 \qquad (1)$$

below which it cannot exist. A fibre has to be designed for the lowest wavelength of operation, λ_c. Single mode behaviour can be achieved by reducing the numerical aperture, NA, and/or reducing the core radius, ρ. The refractive indices of core and cladding are given by n_{core} and n_{clad}.

5.1 Chalcogenide Fibre Samples

We realised in total more than nine different fibre samples made of chalcogenide glass arsenic sulphide (AsS) and GAST (germanium, arsenic, selenium, and tellurium). All fibres were drawn by the double crucible technique and the fibre diameter was adjusted by varying the drawing speed/force. Photographs of both fibre types are shown in Fig. 3.



AsS multi-mode fibre
20/125 µm

GAST SM fibre
17/450 µm

Fig. 3: Realised chalcogenide glass fibres.

5.2 Silver-halide Fibre Samples

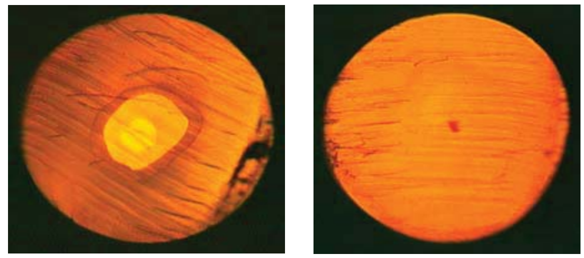
Applying Eq. 1 single mode can be obtained by reducing the numerical aperture or by reducing the core diameter. Using a low NA allows to increase the core diameter and vice versa. For silver halide fibres the margin for playing with NA and core diameter is much lower. We experienced a limitation of the NA given by approximately 3% composition difference of core and cladding material. Below that value core and cladding are not separated anymore. Best fibres have been produced for high NA or larger core diameters. Fibres with extended cores are easier to produce and deliver better (more circular) core shapes.

Best core quality is achieved if the core is composed of 75% AgBr and 25% AgCl (eutectic point). We realised more than 35 fibre samples different in composition difference, core diameter, and number of extrusions from three different preform manufacturing methods. Seven fibres achieved the right geometry and NA and two of them (see Fig. 4) showed single-mode behaviour after being coated with a special immersion layer.

The best results have been achieved with high composition differences of 15-20%. The required small core diameters are obtained by multiple extrusions, normally two with the preform and one final to get the fibre.

capillary suction
2 preform extrusions
1 final extrusion

mechanically combined
preform, also 2 preform
+ 1 final extrusions



15% composition difference
1/15 mm → 20/500 µm
V=2 at λ=10.6 µm

20% difference
0.5/15 mm → 15/500 µm
V=1.7 at λ=10.6 µm

Fig. 4: Realised silver halide fibres, both single mode.

6. PHOTONIC CRYSTAL FIBRE SAMPLES

Photonic crystal fibres have been manufactured for the first time in the soft silver halide material. Four different techniques have been applied aiming all at a regular concentric distribution of zones with high and low refractive index. We focussed on the index guided PCF starting with a high index in the fibre centre.

We first investigated a fan-like structure where rills are sawed into a cylinder made of core material. The rills are filled up with bare AgCl fibres spiraled around the core. The following extrusion process of the preform turns the radiator-like structure to the axial direction. The idea and the results obtained after extrusion are shown in Fig. 5 on the left side.

In the next try we drilled holes into a disk made of core material and filled them up with AgCl bare fibres as shown in Fig. 5 on the right side.

Another idea was to alternately wrap foils made of AgCl respectively AgBr around a central AgBr core as shown in Fig. 6 on the left side. This approach produced a reasonably well structured preform structure and good circular shape after the extrusion process.

The fourth method experimentally tried was to closely attach AgCl and AgBr fibres along a circular AgBr core and to surround the entire package by an AgBr cladding tube. This approach is shown in Fig. 6 at the right side.

All produced fibre samples did not achieve the required high quality in terms of core shape, fibre dimension, and distribution of zones with different refractive behaviour. A lot of experimental work and additional effort have been identified to improve the techniques in a next step for obtaining the right geometric structures.

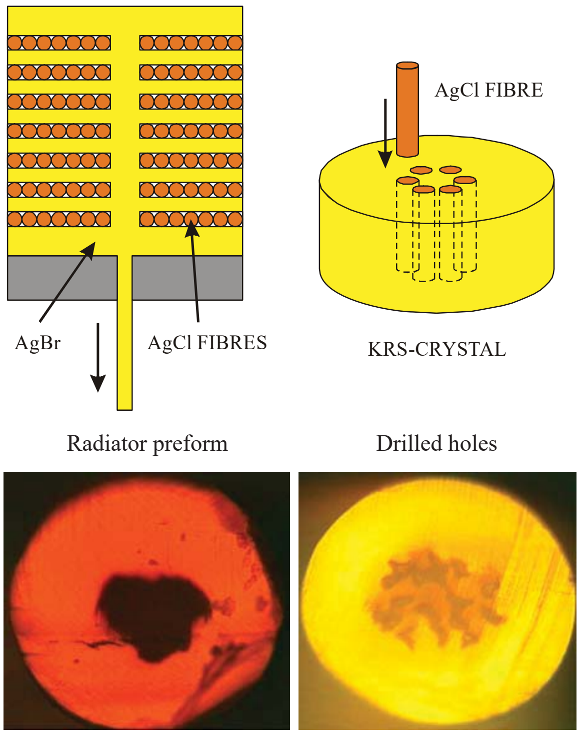


Fig. 5: First set of realised photonic crystal fibres.

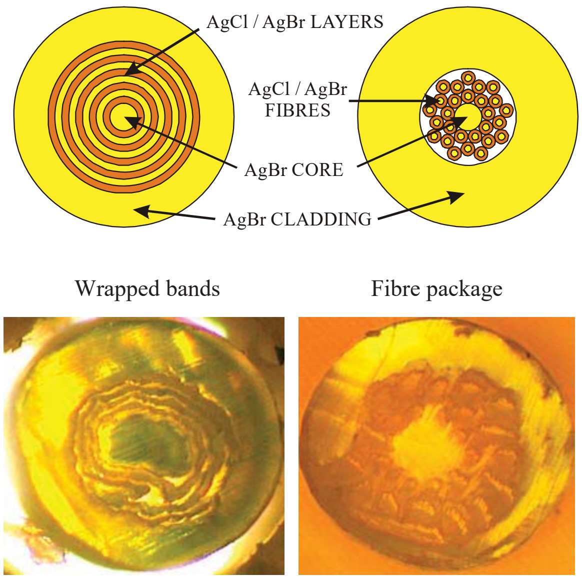


Fig. 6: Second set of realised photonic crystal fibres.

7. PERFORMANCE TESTS

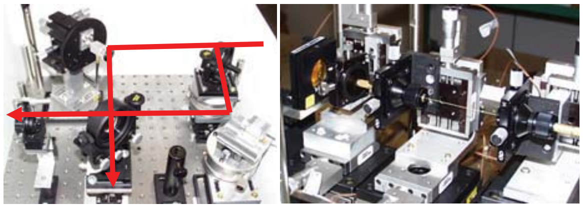
The single-mode fibre is a distributed element and the unique spatial fibre mode needs some fibre length for being established. Any perturbation within the fibre will cause small deviation from the pure single mode. The crystalline structure of polycrystalline material can have a serious impact on the shape and the homogeneity of the core. Hence, observing the spatial intensity distribution at the fibre output is not sufficient to characterise the mode suppression capability of a single mode fibre. However, measuring a Gaussian-like intensity profile at the fibre output independent on the launching conditions into the fibre is a first indicator for single-mode operation but for quantitative evaluation a test interferometer setup is certainly required.

We realised a highly symmetric Mach-Zehnder interferometer and measured the power contrast ratio of constructive to destructive output with and without modal filter. The improvement in output power contrast can be directly designated to the fibre's filter action. A photograph of the Mach Zehnder test setup is shown in Fig. 7 on the left whereas the detection section and the fibre sample under test (greenish color) are shown on the right. Constructive and destructive interference are achieved by modulating the optical path difference by moving the upper left mirror of Fig. 7 by a piezo-ceramic transducer. The rejection ratio of an interferometer setup in the laboratory without fibre is as low as some hundreds whereas with single-mode fibres we measured values of typically several ten thousands, limited only by the quality of the interferometer. Our setup was fed by a CO_2-laser and all components including the detector were optimised for the 10.6 micron wavelength.

We recorded the far-field output beam intensity with a single pixel detector and with a two-dimensional mid infrared camera. We measured the interferometric suppression in our test interferometer at 10.6 micron, and we checked the spectral transmission to get an indication on the useable operating wavelength range.

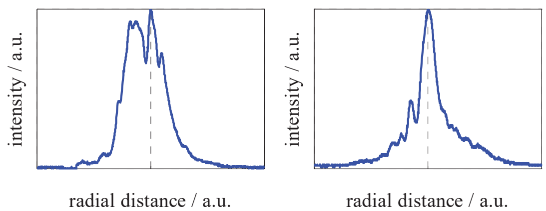
The intensity profiles measured at the fibre output are shown in Fig. 8 for the silver halide sample and in Fig. 9 for the chalcogenide GAST fibre. Both fibre types had to be covered by an efficient mode stripping layer to avoid any reflection of light at the cladding/air boundary. Without immersion layer a clear multi-mode propagation of the light can be identified whereas the application of the stripping layer produces a good approach to the unique fibre mode expected for single mode operation. The measured filter action was between 100-200 for the AgClBr fibre and 200-400 for the GAST fibre. The limitation came from the stability of the interferometer itself.

The extruded silver halide fibre samples had a length of 40 cm whereas the drawn chalcogenide fibres were 18 cm in length. The fibres must be considerably longer than predicted by theory to develop the single mode and this is attributed to the non-perfect core quality and shape on one hand but also to the limited cladding diameter yielding to spurious reflections at the air interface of the step-index fibre.



interferometer core   fibre sample under test

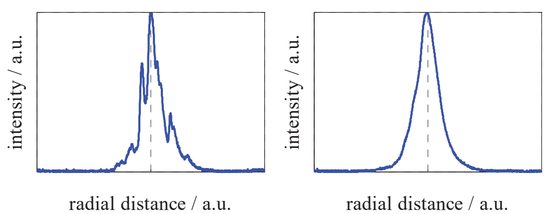
Fig. 7: Mach Zehnder test interferometer operating at 10.6 µm used to estimate the suppression of higher order modes.



no immersion coating
multi mode

100-250 nm coating
single mode

Fig. 8: Measured beam profiles of extruded silver halide sample. An added mode stripping layer enabled single mode operation for the first time in this material.



no immersion coating
multi mode

mode stripper applied
single mode

Fig. 9: Measured beam profiles of drawn chalcogenide glass fibre (GAST). An added mode stripping layer is again mandatory to obtain single mode operation.

8. CONCLUSIONS

We presented the results and the status of developing single-mode fibres to be used within the European DARWIN mission and its terrestrial technology precursor GENIE. Single-mode fibres have been successfully produced from extruded poly-crystalline silver halide and from drawn chalcogenide glass. The achievements are summarised in Tab. 2. Silver halide fibres can be used within the entire DARWIN band from 6.5-20 micron whereas the chalcogenide GAST fibre is suited up to about 11 micron. The manufacturing of the soft silver halide fibres turned out to be much more critical than the well established drawing process applied to glassy fibres.

Absorbing coatings are the key for single mode operation as the leaky modes are not perfectly absorbed in the short fibre samples used so far. We found immersion layers chemically and optically compatible with both fibres.

Parameter	**Silver halide step index fibre**	**Chalcogenide glass fibre**
Wavelength	5.5 to 20 µm tested at 10.6 µm	3 to 11 µm tested at 10.6 µm
Numerical aperture	0.34	0.15
Core/cladding	20/500 µm	17/450 µm
Normalised frequency at 10.6 µm	2	0.8
Operational temperature	4 K test passed	no cryogenic testing done
Radiation susceptibility	irradiated with 20 kRads at 0.7 Gy/minute shielding required	not yet tested
Suppression ratio of higher-order modes	demonstrated in interferometer	demonstrated in interferometer
	limited to 100-200 by set-up	

Tab. 2: Achievements of single-mode fibre development activity on both fibre technologies.

9. FINDINGS FROM SILVER-HALIDE TECHNOLOGY DEVELOPMENT

We identified a series of critical items during the manufacturing activity of the silver halide fibre.

A non-perfect core quality gives explanation for the high damping observed. We noted a considerable graining supposed to serve as scattering centres. The size of the grains must be further reduced by proper choice and optimising all extrusion parameters. We can vary the number of extrusions, the temperature, the pressure, and the extrusion speed. A detailed spectral analysis is required to identify potential scattering sources. A more sensitive FTIR spectroscopy is certainly necessary based on cooled detector equipment. All contaminations brought in during the preform fabrication and the multiple extrusion process must be further reduced to eliminate all potential scattering sources.

The extrusion process itself induces cracks at the core/cladding boundary. This can be controlled by optimising the process parameters and subsequent annealing and is expected to be very time consuming. The numerical aperture must be optimised to get out the best core/cladding boundary. The minimum composition difference is 3% and sets the upper limit on the possible core diameter. Higher composition differences and larger core diameters are both easier to manufacture and yield a better core respectively boundary quality.

The shape of the fibre core over length is corrugated by pressure oscillations which have to be minimised by better controlling of the extrusion process.

An additional mode stripping layer has been found to be mandatory and is the only way to achieve single mode operation. The estimated "short" length of the waveguide is not sufficient as the assumptions there were to use an infinitely extended cladding material and to have absolutely no reflection at the boundaries. The experienced need for a reasonable fibre length makes the fibre attenuation an important issue being underestimated at the beginning of the activity. The silver halide dissolves many materials useful as absorbing coating. So, it remains difficult to find compatible materials and to apply them properly on the soft fibre.

Broad-band anti-reflection soft coatings or coatings of the same hardness must be applied on the facets to reduce the Fresnel losses of 12.5% per facet for silver halide fibres respectively 23.3% per facet for chalcogenide fibres.

10. RECOMMENDATIONS ON CONTINUATION OF TECHNOLOGY DEVELOPMENT

As a next step the manufactured fibres should be characterised in full detail and the entire operating wavelength range shall be assessed. The AsS and the GAST fibre are both nice candidates for the GENIE instrument [3] possibly implemented at the VLTI in Paranal/ Chile. Our test interferometer was fed by a CO_2-laser. For full characterisation of the fibres we need a broadband interferometer or a set of interferometers optimised for different sub-bands and equipped with different laser sources. Reasonably strong lasers are available at 3.39 µm (HeNe), around 5 µm (CO), and 10.6 µm (CO_2). Lead-salt lasers are too weak but quantum cascade lasers can be tailored to any wavelength, for example to the several design wavelengths of a dispersive phase shifter of higher order and vital for the DARWIN mission.

In the execution of the manufacturing and testing activity we experienced that a fast feedback is very helpful to change process parameters in a time efficient way. The measurement tools need improvement.

The test of mode stripping measures may be started with the chalcogenide fibre samples first as the core/cladding quality is already high there and these fibres offer already a nice circular core shape. The drawing technology of glasses is much more advanced than the extrusion needed for the soft polycrystalline materials.

The photonic crystal fibre is currently seen as supporting measure for conventional step-index fibres. Based on the good results achieved with step-index fibres we feel that photonic crystal structures are not yet needed. The practical realisation of those structures is extremely difficult as can be seen from our first samples made by various technology approaches.

11. ACKNOWLEDGMENTS

The work described was performed under ESA/ESTEC contract AO/1-4023/01/NL/CK, Single-mode fibres for DARWIN, awarded to EADS Astrium GmbH (Germany) teaming with ART-Photonics GmbH (Germany), and Vienna University of Technology (Austria). The authors are grateful to Joao Pedro N. Pereira do Carmo, Tatyana Sakharova, and Walter R. Leeb for their contribution and assistance. The authors thank M. Churbanov and V. Shiryajev for their support on chalcogenide fibres.

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