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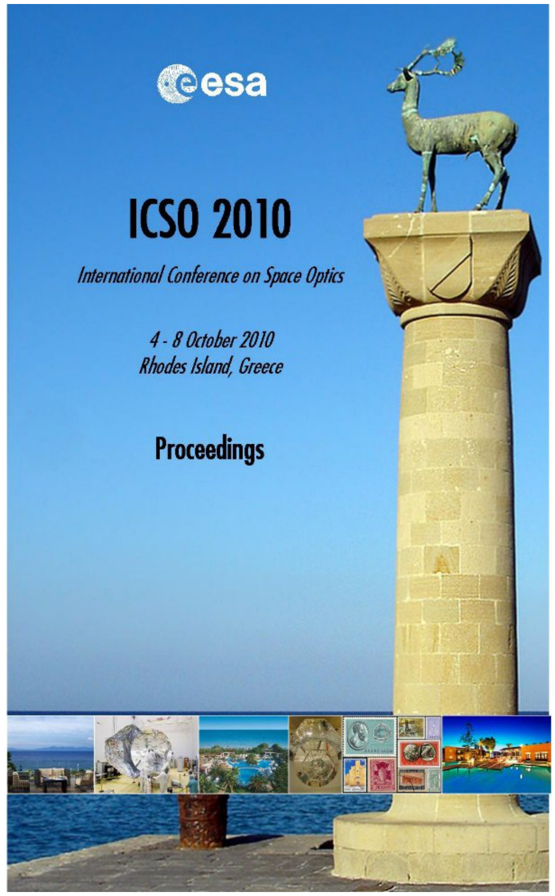

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MANUFACTURING AND TESTING OF WAVEFRONT FILTERS FOR DARWIN

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ABSTRACT

Wavefront filtering is mandatory in the realisation of nulling interferometers with high star light suppression capability required to detect extrasolar planets, such as the one foreseen for the ESA Darwin mission.

This paper presents the design, manufacturing, and test results of single mode fibres to be used as wavefront filters in mid-infrared range. Fibres made from chalcogenide glass and silver halide crystals were produced. The first class can serve as wavefront filters up to a wavelength of 11 microns, while silver halide fibres can be used over the full Darwin wavelength range from 6.5 to 18 micron. The chalcogenide glass fibres were drawn by double crucible method whereas polycrystalline fibres from silver halides were fabricated by multiple extrusion from a crystalline preform.

Multi-layer AR-coatings for fibre ends were developed and environmentally tested for both types of fibres. Special fibre facet polishing procedures were established, in particular for the soft silver halide fibre ends. Cable design and assembly process were also developed, including termination by SMA-connectors with ceramic ferrules and fibre protection by loose PEEK-tubings to prevent excessive bending and chemical attacks for fibres.

The wavefront filtering capability of the fibres was demonstrated on a high quality Mach-Zehnder interferometer. Two different groups of laser sources were used to measure the wavefront filtering of the fibres by using a CO-laser for testing in the lower sub-band and a CO_2-laser to check the upper sub-band.

Measurements of the fibres far field intensity distribution and transmission were performed for numerous cable samples. Single mode behaviour was observed in more than 25 silver halide fibre cables before AR-coating of their ends, while after that 17 cables were compliant with all technical requirements. Residual cladding modes existing in short single mode fibres were effectively removed by applying of a proper absorbing jacket to the fibre's lateral surface and by adding an oversized output aperture in front of fibre ends.

Several fibres were exposed to gamma radiation of total dose of 25, 50, and even 500 krad. No deterioration was found on AR-coated fibre ends and on fibre material. Five fibres were irradiated by proton radiation of 10MeV energy and 10^{10} p/cm^2 equivalent fluence. Several fibres were cooled down to 10 K by plunging them in a dipstick into liquid Helium. Silver halide fibres survived that test when cables were properly assembled. The brittle chalcogenide glass fibres were much more sensitive to thermal gradients and the related cables did not survive the thermal shock.

Critical issues have been revealed in multiple drawings of chalcogenide glass fibres where core and cladding composition were not stable at some fabrication stages - resulting in a poor single mode guiding. Much better results have been achieved with polycrystalline fibres from silver halides made with a small core and low NA and enabling single mode guiding in the mid infrared.

I. 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 like methane, ozone, carbon dioxide, and water. A nulling interferometer provides high on-axis light suppression and high angular resolution. Advanced observation techniques like a rotating telescope array and phase chopping and a sophisticated instrument design are essential.

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. Deep nulling requires the individual interferometer arms to be equalised with respect to intensity, phase, and state of polarisation. Modal wave-front filtering of the output signals with single-mode fibres is required for removing the wavefront errors of affordable and feasible high-quality optics.

II. 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. We focused on polycrystalline silver halide that offers good transmission over the full Darwin band. The soft material must be extruded. The band between 6.5 and 11 µm can be covered by drawn glass fibres made of GeAsSeTe (GAST). We proposed two subbands to keep the coupling losses low.

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

Parameter	Requirement
Wavelength range	6.5 to 20 µm
Number of subbands	≤ 3
Total transmission	> 57%
Suppression ratio of higher-order modes	$> 10^4$
Maximum dimension	40 cm
Operational temperature	40 K
Rotation of polarisation	< 1 degree
Radiation susceptibility	no damage or degradation after 50 krad
Parameter reproducibility	2% or better

Table 1: Technical requirements on fibre samples.

The goal of this activity was to bring the technology from TRL4 up to TRL5-6. The fibre samples were put in protective tubings, the facets are polished and equipped with multilayer AR-coatings. The fibre ends are mounted in standard SMA connectors for comfortable experiencing.

The samples were exposed to the Darwin operating temperatures of <40 K and dedicated gluing techniques were developed to survive the cooling gradients.

Fibre cables and AR-coatings were irradiated by gamma and proton radiation of 50 krad and $1.05 \cdot 10^{10}$ p/cm^2 and 10 MeV energy.

All manufactured samples have been performance tested before and after the environmental test by

- visual inspection of facets under microscope
- transmission of fibre
- mode suppression

EADS Astrium Germany led the activity and did the performance tests in a representative interferometer. All fibre samples have been produced by Fibre Photonics, UK.

III. MANUFACTURING OF HALIDE FIBRES

Silver halides are soft and must be extruded. The number of extrusions must be minimised but also the amount of deformation per extrusion must be limited to achieve small grain size, god optical contact, and circular core shapes.

Careful mechanical combining of the preforms were the success for core circularity.

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

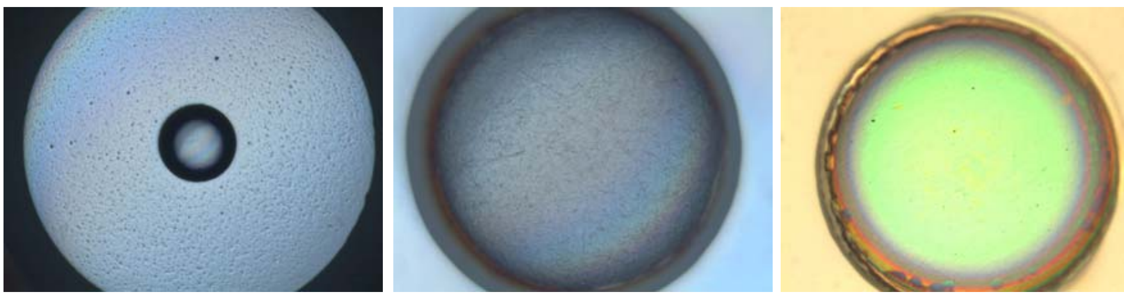
$$V_C = \frac{2\pi\rho}{\lambda_C}\sqrt{n_{Core}^2 - n_{Clad}^2} = \frac{2\pi\rho}{\lambda_C} NA = 2.405 \quad (1)$$

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 are given by n_{core} and n_{clad}.

We found that it is easier to manufacture fibres with large core diameter and low index difference as the other way around. Composition differences as low as 2% between core and cladding allow the use of silver halide even for the lower subband of 6.5 to 11 µm.

Short fibres with a length of around 30 cm are recommended to keep the intrinsic damping low. Mode cleaning cannot be perfectly done if there are spurious small defects along the fibre. We attached an oversized pinhole at the fibre's output to achieve perfect mode suppression even for short and not optimum fibres.

All fibres are equipped with a pure silver layer attached on the cladding to efficiently absorb cladding modes.



polished ceramic ferrule | details of polished fibre end | multi-layer AR-coating applied

Fig. 1: Fibre end of realized SM-87-7 fibre after polishing and AR-coating.

IV. MANUFACTURING OF GLASS FIBRES

GAST glass is transparent in the lower subband and were drawn from the double crucible method.

However, the glass is still brittle and must be inline coated by a plastic polymer to avoid breaking during coiling. Later this stabilising layer must be stripped again and must be replaced by a more effective cladding mode absorption layer.

The resulting fibre was sensitive to cooling gradients and did not survive the 40 K test. A protecting polymer layer on the absorbing layer is highly recommended but could not be realised for budgetary reasons.

Even worse was the fact that we were not able to find the right set of drawing process parameters to avoid mixing of core and cladding material. We varied pressure of outer crucible, pressure of inner crucible, temperature of crucibles, diameter of inner crucible, and drawing speed. Several different core and cladding glass compositions were tried.

The core diameter can be not easily determined in glass. Hence, the forming of a core was experimentally searched for and that was extremely time-consuming.

Finally, we switched to silver halide also in the lower subband. A core diameter of 45-55 µm and 2% composition difference should allow to obtain single mode operation together with low insertion loss. A related CCN to the main contract has been released by ESA.

V. PERFORMANCE TESTS

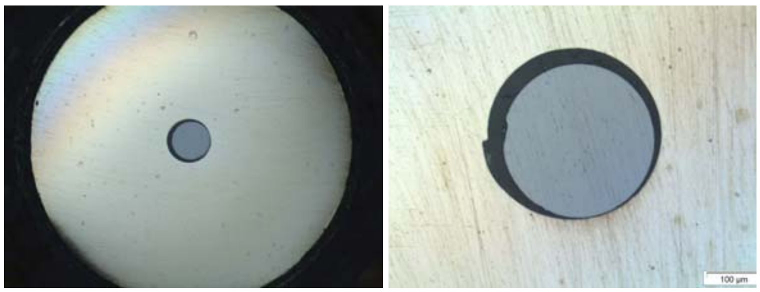
The single-mode fibre needs some fibre length for establishing the unique spatial mode. Any perturbation within the fibre will cause small deviation from the pure single mode. The crystalline structure of polycrystalline material can have a serious impact on the shape and the homogeneity of the core. 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 representative for Darwin 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.

The rejection ratio of our interferometer setup without fibre is as low as hundred whereas with single-mode fibres we measured values of 14,900 maximum, limited only by the stability of the interferometer. Our setup was fed by a CO- or a CO_2-laser and all components including the detector were optimised for both wavelengths.

A. Chalcogenide Fibre Samples

We realised in total more than 35 different fibre samples made of chalcogenide GAST glass (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. The length of the fibre samples is typically around 25-30 cm. Photographs of the non AR-coated fibre ends are shown in Fig. 2.



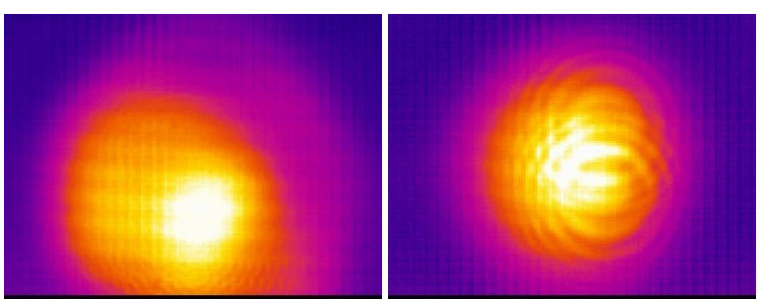
SMA-connector with GAST fibre inserted — GAST fibre with 270 µm diameter in more detail

Fig. 2: Facet of realized GAST fibre with 270 µm cladding diameter.

B. Silver-halide Fibre Samples

Applying Eq. 1 single mode transmission can be obtained by reducing the numerical aperture or by reducing the core diameter. Using a low NA allows the increase of 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 2-3% composition difference of core and cladding material. Below that value core and cladding are not separated anymore.

Best core quality is always achieved if the core is composed of 75% AgBr and 25% AgCl (eutectic point). We realised more than 46 fibre samples with large core (see Fig. 3) and 31 samples with reduced core (see Fig. 4). The samples are different in composition and core diameter. All fibres were made by multiple extrusions from a mechanically combined preform.



no aperture at output — 100 µm aperture added

Fig. 3: Output intensity of realized SM-87-7 fibre with 47/500 core/cladding and 2% composition difference.

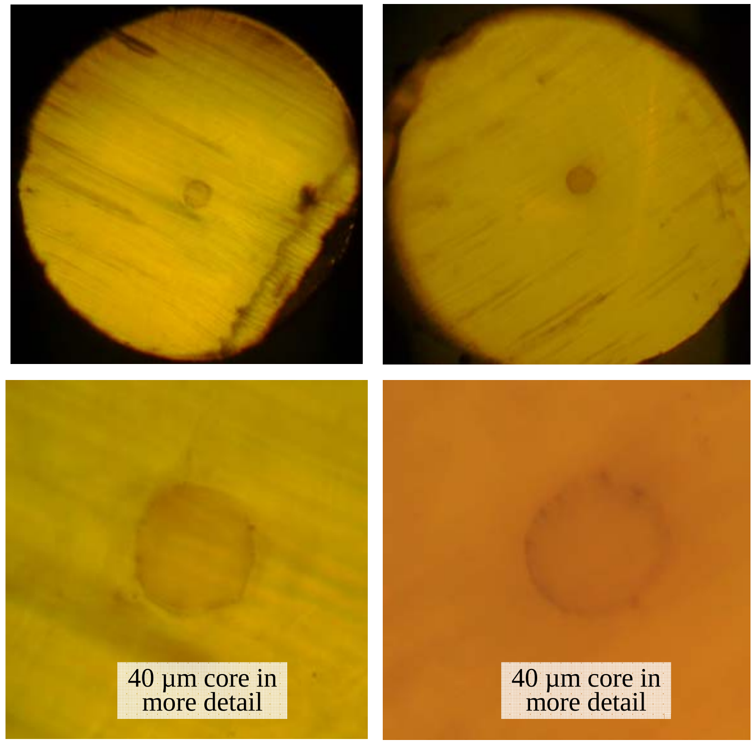


Fig. 4: Cross-section of realised SM-96 PIR fibre with 40/490 µm core/cladding and 2.5% composition difference.

25 fibres manufactured for the upper sub-band were prepared for multilayer AR-coating and 18 of them were accepted after that coating. Finally, 17 fibre samples passed the performance tests and were fully compliant to the requirements. The fibre length is again between 25 and 30 cm. All fibres have a special immersion layer on the cladding to reduce the cladding modes. Residual unwanted modes at the fibre output are efficiently suppressed by adding an oversized aperture.

VI. CONCLUSIONS

We presented the results of manufacturing single-mode fibres to be used within the European Darwin mission and related applications. Single-mode fibres have been successfully produced from extruded poly-crystalline silver halide but still not from drawn chalcogenide glass. The achievements are summarised in Tab. 2.

Parameter	**Silver halide step index fibre**		**Chalcogenide glass fibre**
Wavelength	5.5 to 11 µm, tested at 5.6 and 10.6 µm	10 to 20 µm tested at 10.6 µm	5.5 to 11 µm tested at 5.6 and 10.6 µm
Core/ cladding	25/300 45/500 µm	47/500 µm	16-25/235 µm 35/283 µm
Operational temperature	no cryogenic test done	40 K 10 K passed	failed during cryogenic test
Susceptibility to gamma radiation	not tested	50 krad total dose passed	50 krad total dose exposed to multimode fibre
Susceptibility to proton radiation	not tested	exposed to 10 MeV protons of 10^{10} p/cm^2 but still not evaluated	proton irradiation not performed
Higher-order mode suppression	under test now	>14,900 at 10.6 µm	no single mode seen

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

Silver halide fibres can be used within the entire Darwin band from 6.5-20 micron whereas the chalcogenide GAST fibre is in principle suited up to 11 micron if the problem of non-laminar flow during drawing is solved. The manufacturing of the soft silver halide fibres is well matured and the material can be used also for the lower subband. Silver halid material is better matched to cryogenic temperatures in contrast to the brittle glass.

Multi-layer AR-coatings have been manufactured for both subbands and both materials, the soft silver halide and the hard GAST glass.

A special gluing technique applied to the SMA connectors and the jacketed fibres allowed to survive the cryogenic test.

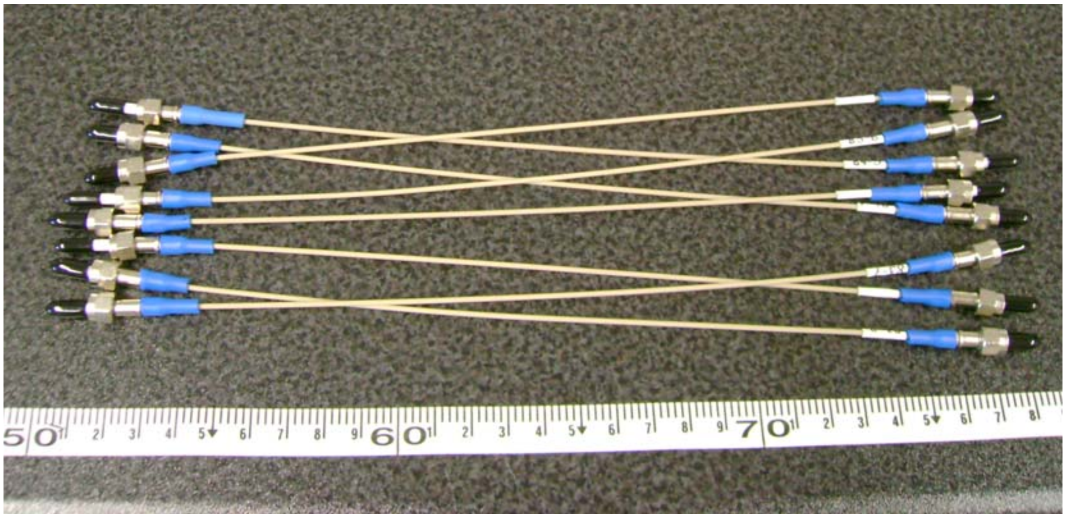


Fig. 5: Photograph of assembled PIR cable.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

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