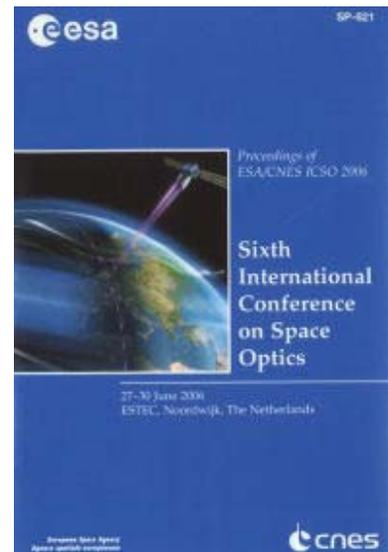


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Improving the fiber coupling efficiency for DARWIN by loss-less shaping of the receive beams

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IMPROVING THE FIBER COUPLING EFFICIENCY FOR DARWIN BY LOSS-LESS SHAPING OF THE RECEIVE BEAMS

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ABSTRACT

For the DARWIN mission the extremely low planet signal levels require an optical instrument design with utmost efficiency to guarantee the required science performance. By shaping the transverse amplitude and phase distributions of the receive beams, the single-mode fibre coupling efficiency can be increased to almost 100%, thus allowing for a gain of more than 20% compared to conventional designs. We show that the use of "tailored freeform surfaces" for purpose of beam shaping dramatically reduces the coupling degradations, which otherwise result from mode mismatch between the Airy pattern of the image and the fibre mode, and therefore allows for achieving a performance close to the physical limitations. We present an application of tailored surfaces for building a beam shaping optics that shall enhance fibre coupling performance as core part of a space based interferometer in the future DARWIN mission and present performance predictions by wave-optical simulations. We assess the feasibility of manufacturing the corresponding tailored surfaces and describe the proof of concept demonstrator we use for experimental performance verification.

1. INTRODUCTION

The DARWIN mission [1] will search for "earth-like" planets in the vicinity of a central star. This means finding a weak scattering small object near to a very bright light source. In order to cope with the contrast between the star and planet a nulling interferometer is set up that shall cancel out the starlight by destructive interference of the three (or more) receive beams. For improving the performance of interferometer the superimposed beams are coupled into an optical single mode fibre which acts as a modal filter. The detected signal at the end of the fibre therefore is (relatively) free of disturbances which may have been introduced by the optical path in front of the fibre.

Two major challenges result from the DARWIN scenario:

- a nulling ratio of better than $1.5 \cdot 10^{-5}$ [2]
- broadband operation over the wavelength range from $4\mu\text{m}$ to $20\mu\text{m}$

2. FIBRE COUPLING ASPECTS

The efficiency of coupling light into a single-mode fibre depends strongly on the matching between the incident diffraction pattern and the principal mode of the fibre. A conventionally imaged point source forms an Airy pattern in the image. That differs from the propagation function of the fibre, the fibre mode, and the coupling efficiency CE (η) will not be better than 78%.

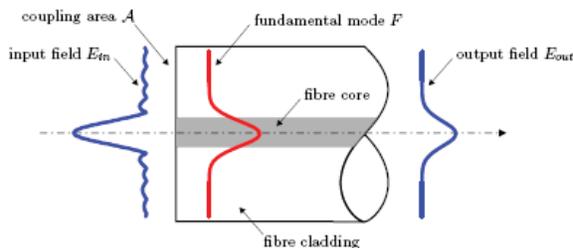


Fig 1. The coupling scenario

That ultimate 78% are reached only at the cut-off frequency of the fibre, which corresponds to the shortest wavelength λ_c for single mode operation. The coupling efficiency drops, with increasing slope, at higher wavelengths.

The drop as such can not be avoided. But to some degree the slope of the curve CE versus λ may be tuned such that at least over one octave λ_c - $2\lambda_c$ one obtains a flat and almost constant curve. That is illustrated in Fig. 2. That figure plots CE versus the fibre frequency, which is proportional to the inverse λ :

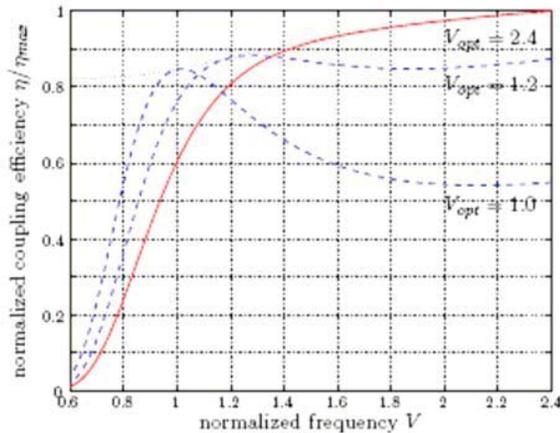


Fig. 2. Drop of the CE versus decreasing frequency V i.e. increasing wavelength λ , for 3 focal lengths.

The x-Axis in Fig. 2 shows the normalized frequency V, which is proportional to the inverse λ :

$$V = \frac{2\pi}{\lambda} r_k \sqrt{n_{co}^2 - n_{cl}^2} \quad (1)$$

where r_k is the core radius and n_{co} , n_{cl} are the refractive indices of core and cladding. All of them are system constants¹, and V varies only with $1/\lambda$ for a given fibre.

A frequency of 2.405 is the cut-off-frequency, the limit of single mode operation. For ultimate CE, η_{max} , the focal length of the imager would be tuned such that the diffraction Airy has the best match to the fibre mode at a λ corresponding to $V=2.4$. That is done in almost all practical applications. The red curve $V_{opt}=2.4$ shows the spectral behaviour. If the focal length is instead tuned such that the best match results at $2\lambda_c$, (dotted blue curve $V_{opt}=1.2$), the CE is sub-optimal at shorter wavelengths. Within λ_c and $2\lambda_c$, η varies only little between 0.84 and 0.89.

3. FIBRE COUPLING WITH IMPROVED EFFICIENCY

As mentioned above, there is a potential gain of 20% in CE if the mode mismatch can be resolved. This means that the uniform intensity of the incoming beam has to be transformed into an intensity distribution that matches in its diffraction pattern the back-propagated fibre mode. This "beam shaping" must not affect the

¹ We may ignore dispersion $n=f(\lambda)$ here, as this affects both n_{co} and n_{cl} , and the difference varies much slower.

other properties of light, i.e. wavefront error and polarisation.

3.1 Optical design aspects

The optical design has to provide two main functions, beam shaping and fibre coupling. In order to be prepared for operation in the DARWIN wavelength range all optical surfaces shall be reflective. For to having suitable fibres available now which can be implemented in a proof of concept demonstrator, the spectral range for the breadboard is defined from 633 nm to 1550 nm.

The intensity redistribution is performed by means of tailored free form surfaces. The approach was developed by the company OEC in Munich [3]. One surface will also alter the optical path difference. Thus a second free form surface is needed to correct for the wave front error of the first surface.

The two beam shaping surfaces (Beam Shaping Optics, BSO) receive and provide a collimated beam. A third parabolic mirror delivers the beam to a focus on the fibre tip (Fibre Coupling Optics, FCO) (Fig. 3).

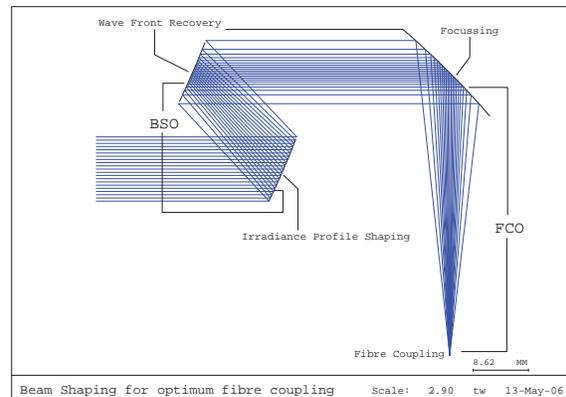


Fig. 3. Optical Design of Beam Shaping (BSO) and Fibre Coupling Optics (FCO).

Remarkable in Fig. 3, the first mirror receives a beam with equal ray density, which changes than into a density profile with concentration in the middle.

The theoretical fibre coupling efficiency results to 90%, thus 12% more than the CE of a flat beam profile. The remaining 10% CE loss result because of that design does not use the outer part of the fibre mode. In order to do that, the beam spread after the first mirror needs to be increased by 3 times, the secondary mirror and the parabola in diameter too. The second design iteration has also tilted the mirrors out of plane to make it more compact. That system is shown in Fig 4. That design reaches a maximum theoretical coupling efficiency of 95%.

A third design evolution may eliminate the third mirror and combine the wave front recovery and the imaging function together in one single mirror.

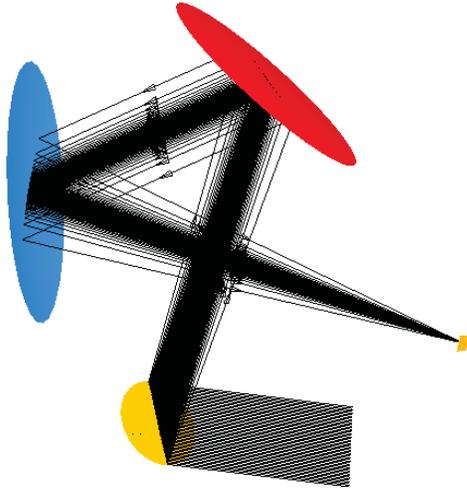


Fig 4: The system with enlarged secondary and tertiary mirrors.

After trading-off several design options, requirements and design drivers a three mirror design in a three-dimensional configuration was selected, see Fig. 5.

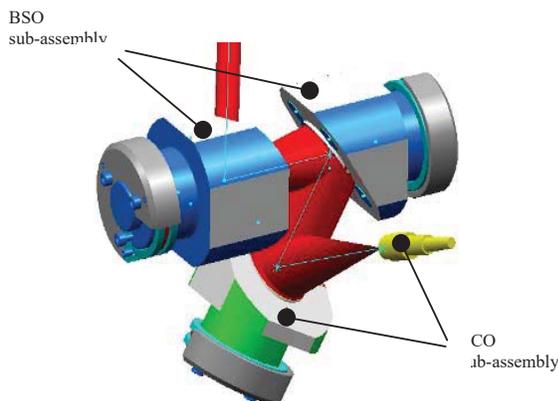


Fig. 5. Opto-mechanical set-up of the beam shaping and fibre coupling optics

The fibre is an OFS Clearlite 630-11 with a cut-off wavelength of 580 nm. The nominal wavelength of operation would be 633 nm. The focal length is tuned such that maximum CE is reached at 1064 nm. The focal length (68 mm) is adjusted such that the best coupling efficiency is reached at 1064 nm ($V_{opt}=1.27$, see Fig. 2). Experimental operation is foreseen at laser lines of 633, 1064 and 1300 nm plus also incoherent “white” light

3.2 Simulation

3.2.1 Implementation

The tailored surfaces are implemented to optical design software CodeV or ASAP for performance analysis. Additionally the ESA proprietary software "beam warrior" shall be used to simulate the full interferometer performance of DARWIN.

The plot in Fig. 3 was created with commercial CodeV software. It is able to process the free form surfaces, represented as NURBS with open knots, via a dedicated user programmed surface model written in C. The rays can be traced as in any conventional optical system. For purpose of coupling efficiency analysis, the last step from the last parabolic mirror to the image needs the diffractive beam propagator.

Fig. 4 was produced with ASAP software. No specific programming work was needed here as this software can process parametric surfaces. The NURBS only needed a conversion to Rational Bicubic Splines. The accuracy (rms wave front error $\sim \lambda/500$) is acceptable. As Design 2 became available just recently, we present at this place the simulation from Design 1, Fig. 3.

3.2.2 Sensitivity and tolerances

The simulations have investigated first the sensitivity of the optical set-up to misalignments and surface shape errors. These tolerances result more stringent compared conventional optics. Concerning the practical purpose of Darwin, the operation wavelengths are longer by a factor of at least 7, and the tolerances scale up accordingly.

Tolerance	Limit
Tilts	< 6 μ rad
Shifts	< 0.3 μ m
Surface figure (WFE_{RMS})	< 3.2 nm

Table 1: Alignment and stability tolerances

The simulation results show that beam shaping improves the fibre coupling efficiency significantly to the cost of the alignment and manufacturing tolerances. For the proof-of-concept demonstrator the requirements are challenging but feasible if recently available on the edge manufacturing technologies are applied.

3.2.3 Spectral performance

Another aspect consisted in how this concept would change the spectral behaviour from Fig. 2. Normally, both the Airy radius and the fibre mode field diameter increase with the wavelength. The beam shaping is made geometrically and does not scale with the wavelength. The mode matching was designed for 1064 nm.

In fact, Fig. 2 could be roughly reproduced with CodeV. The graphs from Fig. 2 correspond to the dotted lines in Fig. 6, i.e. without the beam shaping. The effect of the beam shaping is shown with the solid lines, which are all above the dotted lines. For sake of easy comparison, the normalization in Fig. 6 is made the same way as in Fig. 2, i.e. to the maximum achievable CE when optimized at $V=2.4$ (shortest single mode operating wavelength). For the beam shaping optics, this means both the focal length and the beam shaping are optimized for this specific wavelength. In the simulation, only the wavelength changes, the fibre stays constant with $V=2.4$ at 580 nm.

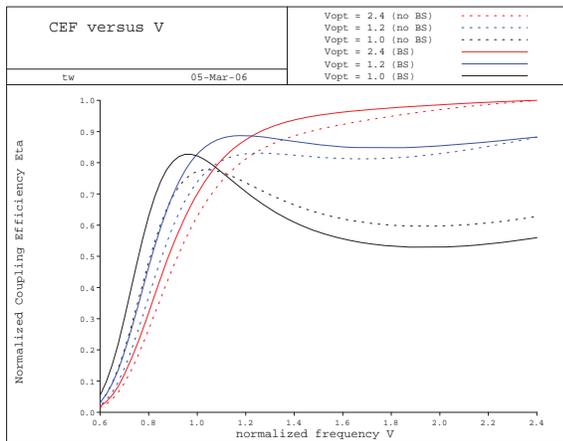


Fig. 6: Spectral behaviour of *normalized* coupling efficiency. $V=2.4$ is 580 nm, $V=1.2$ is 1160 nm.

The absolute effect of the beam shaping is provided in Fig. 7, which refers to *absolute* coupling efficiencies.

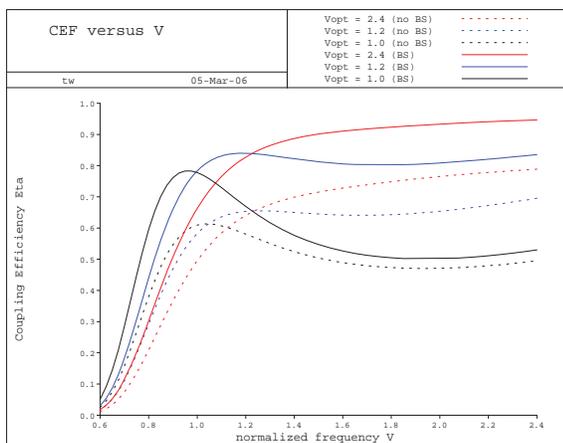


Fig. 7: Spectral behaviour of *absolute* coupling efficiency.

The blue curve for $V_{opt}=1.2$ is almost flat between $V=1.2$ and $V=1.4$. As can be seen from Fig. 6, the degradation of $V_{opt}=1.2$ paid at $V=2.4$ is identical to the non-shaped system, i.e. the blue solid and dotted

curves come together at the right side. At all longer wavelengths towards the left the solid curve is always above the dotted. Thus there is even a relative improvement compared to the non-shaped system. The absolute improvement is obvious from Fig 7.

3.2.4 Effect of central obscuration

Reflective telescopes have a central obscuration in the beam caused by the secondary mirror, unless the telescope would be made in an off-axis configuration. The degradation effect consists not only in the loss in power at the obscuration. Moreover, the central part of the fibre mode – the best part – is not used.

The beam shaping could be designed such that it also closes that gap in the middle. But even if not specifically designed for that feature, there is already an improvement with the present Design 1 (Fig. 3) which is shown in Fig. 8. Again, the dotted curves refer to no beam shaping and the solid curves to the beam shaping. The blue curves refer to systems with no obscuration and the red curves contain a central obscuration of 1/6 of the outer diameter.

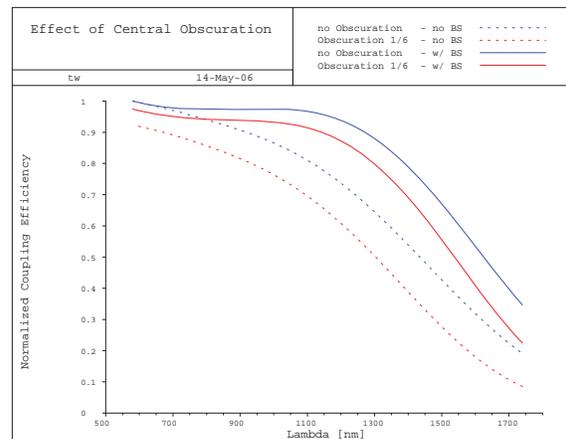


Fig. 8: Effect of central obscuration on the *normalized* coupling efficiency

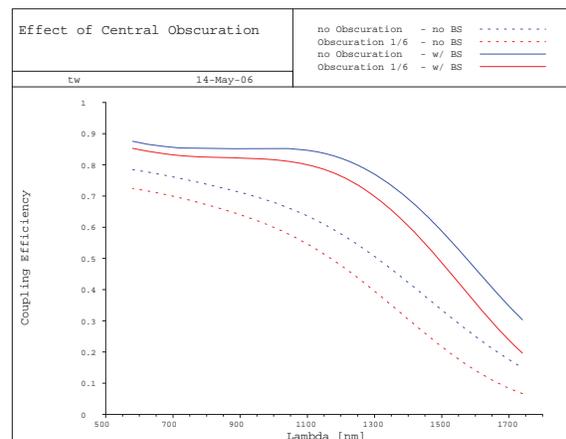


Fig. 9: Effect of central obscuration on the *absolute* coupling efficiency

As can be seen from Fig. 8, the difference between obscured and not obscured system is lower with beam shaping in particular at the short wavelength. Note that the focal length was optimized in this case at $V=2.4$, the short wavelength. The normalization is made to the maximum CE for the not obscured system at $V=2.4$. Whoever is confused with the normalization, he may refer to Fig. 9 which contains the absolute coupling efficiencies.

3.3 Evaluation

At the time that this paper is written the detailed design of a Proof-Of-Concept Demonstrator (POCD) has been released. The POCD shall allow the evaluation of the beam shaping concept from a real world experiment. The test programme will assess the impacts of various parameters onto the performance, i.e. onto fibre coupling efficiency and nulling in the first degree. The introduced variations will be wavelength, optical aberrations, field angle, and polarisation. The measurements of the set-up with beam shaping optics will be compared to those of the set-up with two folding mirrors which replace the beam shaping surfaces.

The POCD consists of three sections (Fig. 10):

- I. Input beam support equipment:
 - Generation of two collimated beams of top-hat intensity
 - Setting and maintaining of the optical path length difference between the beams
 - Introducing / Correction of wavefront errors
- II. The POCD core:
 - Beam shaping
 - Fibre coupling
- III. Detection of the optical output power at the fibre end

The input beam support equipment is provided by TNO (Delft, The Netherlands) as an adapted and extended version of the Achromatic Phase Shifter (APS) breadboard [5],[6].

The POCD core's mechanical design is shown in fig. 11. The beam shaping optics subassembly can easily be exchanged by a folding mirror set-up, the non-beam shaping optics, which defines the nominal conditions without beam shaping. The mechanical design of the mirrors is the same for any mirror except for the optical surface. Several alignment supporting elements are implemented.

4. ACKNOWLEDGEMENTS

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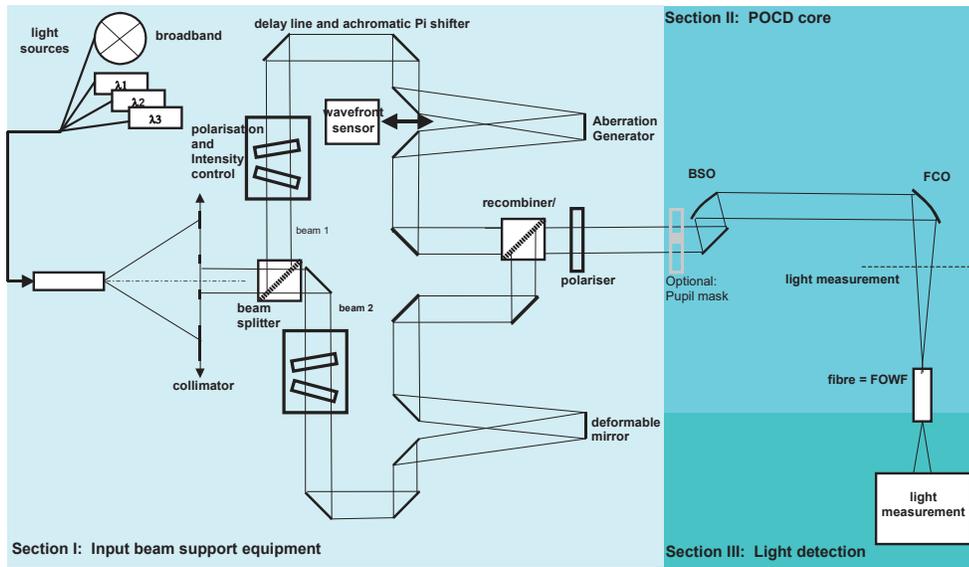


Fig. 10. Proof-Of-Concept Demonstrator scheme

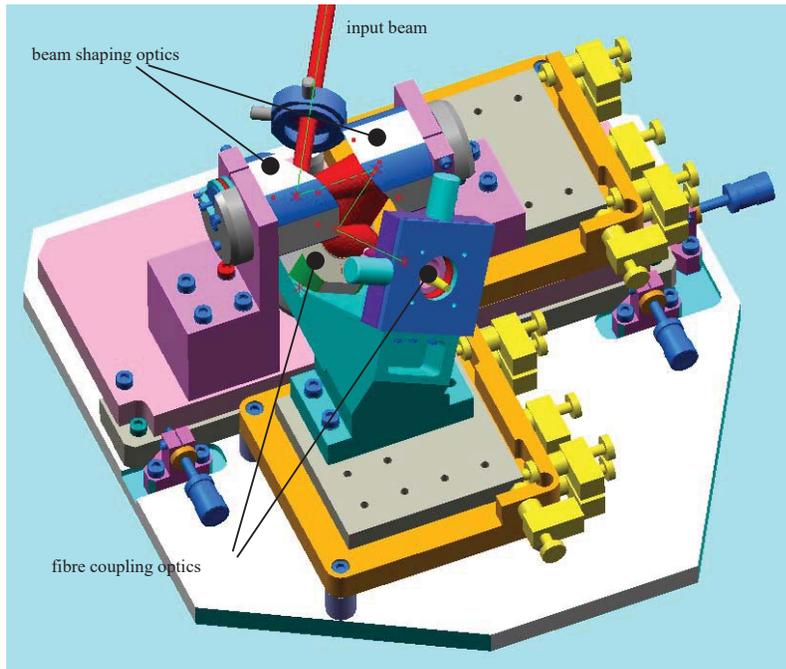


Fig. 11. Mechanical design of the Proof-Of-Concept Demonstrator core