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DARWIN NULLING INTERFEROMETER BREADBOARD III – SYMMETRY REQUIREMENTS AND MODAL FILTERING

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ABSTRACT

In a nulling interferometer, the requirements on uniformity of phase, amplitude, and state of polarisation among the interferometer arms are stringent and hardly to be met in practice. The application of modal filters makes deep nulling possible as such filters may reduce the mismatch of interfering fields. We review the principle of modal filtering and discuss the achievable filter bandwidth and the effect of coupling phase. We give an overview over waveguides suitable for modal filtering, including also lossy multi-mode waveguides.

Key words: modal filter, spatial filter, nulling, interferometry, single-mode waveguide.

1. NULLING INTERFEROMETRY

Nulling interferometry with multiple telescopes is a promising concept for detecting and analysing Earth-like exoplanets orbiting Sun-like stars at interstellar distances. It provides both high on-axis light suppression due to a strong dependence of the transmission on the light's angle of incidence and a high angular resolution due to a large baseline.

In the simplest arrangement, the sum of star and planet waves is received by two identical telescopes (Bracewell 1978). One of the resulting signals is subject to a phase change of $\Delta\varphi = \pi$ and both signals are superimposed to obtain interference. The star light is strongly reduced by the on-axis null of the interferometers receive characteristic, while the planet's light experiences constructive interference by proper adjustment of the baseline ($d = \lambda/(2\Theta)$).

An actual interferometer for DARWIN will consist of more than two telescopes forming a two-dimensional array. This allows to obtain higher star light suppression ratios due to a broader on-axis null. Asymmetric configurations further allow for modulating the receive characteristic by sequentially forming interferometers from a sub-set of the available telescopes.

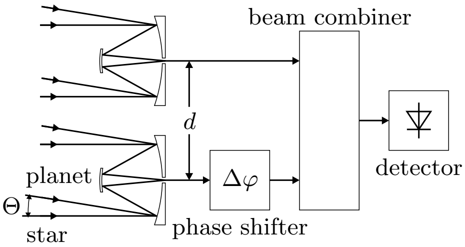

Figure 1. Principle of a nulling interferometer.

The nulling capability is degraded by any asymmetry caused by a sub-optimal optical setup or by any wavefront errors caused by instrumental or environmental disturbances. Thus the requirements on uniformity of phase, amplitude, and state of polarisation among the interferometer arms are stringent and hardly to be met in practice (Mennesson et al. 2002). However, especially the application of modal filters makes deep nulling possible as such filters may eliminate local disturbances within the amplitude profile and the phasefront.

2. SPATIAL VERSUS MODAL FILTERING

Both spatial and modal filters allow for reducing the mismatch of interfering fields. However, they depend on different physical principles (Wallner et al. 2003):

Spatial filtering is the blocking of certain spatial frequency components of the input field. The shape of the output field therefore depends on the shape of the input field.

Pinholes may act as spatial filters. The input field is confined by a circular aperture and focussed by a lens onto a pinhole located in the lens' back focal plane. Because the focal field is the spatial frequency representation of the input field, the pinhole blocks all spatial frequency components exceeding its cutoff frequency and thus acts as a spatial low-pass filter. The output field only contains the low-order spatial frequencies of the input field.

Modal filtering is the projection of the input field on a field with predefined amplitude and phase distribution. The shape of the output field therefore does not depend on the shape of the input field.

Single-mode waveguides may act a modal filters. The incident field is focussed onto the input face of the single-mode waveguide. All modes but the fundamental mode are radiated off, thus leading to a spatial steady state after a certain distance. The output field is characterised by a plane phasefront and an amplitude profile which is solely determined by the waveguide's physical properties.

3. MODAL FILTERING

Efficient modal filtering requires a spatially steady and predefined field distribution at the output of the filter. This can be achieved with single-mode waveguides or with multi-mode waveguides with highly differing mode attenuation. In the latter case the waveguide length required to damp the unwanted modes is much longer than in case of single-mode waveguides which require a short length of a few centimetres in order to radiate off the unguided modes (Wallner et al. 2002). In all cases, any inhomogeneities of the materials or of the interface between the materials could cause mode coupling.

In an ideal modal filter, the output field E_{out} is proportional to the filter's eigenmode mode F, i.e.

$$E_{\text{out}} = \zeta \cdot F \ . \qquad (1)$$

The filter action is simply given by a single parameter, the (complex) field coupling efficiency ζ between the filter's input field E_{in} and the filter's eigenmode F,

$$\zeta = \iint_{\mathcal{A}} E_{\text{in}} F^* \, d\mathcal{A} \ . \qquad (2)$$

Here $\mathcal{A}$ indicates the overlap area of E_{in} and F, usually the waveguide's input face. Note that $\eta = |\zeta|^2$ is the well-known power coupling efficiency.

Although modal filters may not influence global defects such as optical path delay errors, intensity errors, differential change in polarisation, or differential birefringence, they may eliminate local defects as pointing errors, phase fluctuations, or amplitude fluctuations. Input field perturbations cause a reduced output power, quantified by $|\zeta|^2$, and a slight phase shift, quantified by $\angle\zeta$.

Because the coupling efficiency ζ is defined as the overlap integral between the input field E_{in} and the waveguide's eigenmode F (see Eq. 2), maximum coupling efficiency can be achieved if E_{in} is matched to F to the best possible degree. For the case of plane wave to single-mode fibre coupling by an apertured lens, 78.6% of the input power can be coupled to the fundamental mode if the lens is designed to yield an Airy radius of $r_s = 1.87\rho$. Here ρ denotes the fibre's core radius. This value of 78.6% can only be obtained at single-mode cutoff, i.e. for $V = 2.405$. The normalised frequency V is defined by $V = 2\pi\rho(n_{\text{co}}^2 - n_{\text{cl}}^2)^{1/2}/\lambda$, where n_{co} and n_{cl} are the refractive indices of core and cladding, and λ is the wavelength. Any Fresnel losses have been neglected for this calculation. If the fibre's fundamental mode is approximated by a Gaussian distribution with a modefield radius of $w_0 = 1.07\rho$, the calculation yields a slightly higher maximum value of 81.45%. Note that this approximation is good only near single-mode cutoff.

3.1. Significance of coupling phase

Because interferometry relies on exact phase relations between the fields to be combined, the coupling phase $\angle\zeta$ plays an essential role in modal filtering. Already small changes in the phase of Eq. (2) have a severe impact on the null depth N which is proportional to the squared modulus of the phase difference between the interfering fields. The main sources of coupling phase differences are phasefront perturbations, tilt of the input waves, or defocus of the coupling system.

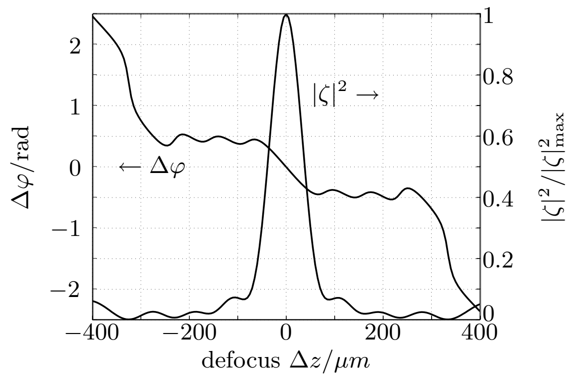

Figure 2. Power coupling efficiency $|\zeta|^2/|\zeta|^2_{max}$ and coupling phase error $\Delta\varphi$ as a function of defocus Δz for $\lambda = 1.55\mu m$.

Figure 2 shows the influence of defocus Δz of the coupling system on both the amount of coupled power and the coupling phase. Shown is the power coupling efficiency $|\zeta|^2$ and the coupling phase error $\Delta\varphi$, defined by the phase of the coupling efficiency in case of defocus relative to the coupling phase without defocus. The effect of optical path change, $\exp(j2\pi/\lambda \cdot \Delta z)$, has been subtracted. For this calculation a wavelength of $\lambda = 1.55\mu m$ and typical values for the waveguide and the coupling optics have been used. Optimum coupling conditions are assumed for $\Delta\varphi = 0$. A phase error as high as $\pi/3$ shows up for a defocus leading to a 50% reduction of $|\zeta|^2$. The coupling phase also depends on the wavelength.

3.2. Broadband operation

ESA's DARWIN instrument is intended to operate in a wide spectral band from 4 to 20 microns. Modal filtering within such a wide bandwidth requires a steady-state field distribution at the filter's output over the entire wavelength range. For single-mode waveguides this can be achieved if the waveguide is designed to be single-mode for the smallest wavelength in question. Best performance can only be obtained for the design frequency V_0 corresponding to the design wavelength λ_0. For fixed coupling optics and waveguide parameters, the coupling efficiency then changes significantly with changing frequency. Figure 3 shows the frequency dependence of the power coupling efficiency $|\zeta|^2$ for the case of plane wave to single-mode fibre coupling. For a coupling system optimised for maximum coupling at single-mode cutoff, i.e. at $V_{\rm opt} = 2.405$, $E_{\rm in}$ as well as F show similar wavelength dependence within the first octave below cutoff. As a consequence, the coupling efficiency stays above 80% of its maximum value. For decreasing V, the coupling efficiency decreases as the matching between F and $E_{\rm in}$ worsens. This is indicated by the chain dotted lines in Fig. 3 which show the dispersion of the Airy radius (r_s/ρ) and the fibre's modefield radius (w_0/ρ). The latter is defined as that $1/e^2$-power radius of a Gaussian distribution which yields a maximum overlap integral with F. For lens/fibre systems optimised for a smaller normalised frequency, less maximum power can be coupled to the fibre. This behaviour is shown for $V = 1.2$ and $V = 1$. If the coupling system is optimised for each frequency, i.e. for $V_0 = V$, the coupling efficiency stays above 80% of its maximum value for the entire wavelength range. However, this would require adaptive coupling optics.

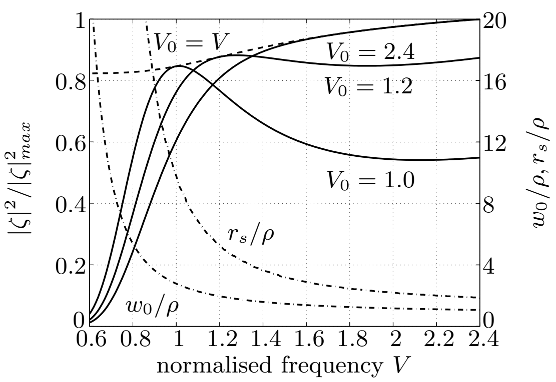

Figure 3. Power coupling efficiency dispersion for different optimised lens/fibre configurations specified by V_{opt}. The dash-dotted lines give the dispersion of the Airy radius r_s/ρ and the fibre's modefield radius w_0/ρ for $V_{opt} = 2.4$.

Broadband operation with comparable modal filtering performance requires a (relative) uniform coupling efficiency for all wavelengths. This is only possible when using adaptive coupling optics (see Fig. 3), or when splitting the wavelength range into multiple bands. In the latter case, one can use multiple waveguides, each appropriately designed for the special band, or one can use a single waveguide with multiple, appropriately designed coupling optics.

Figure 4 shows a possible choice of filter bands for a bandwidth of two octaves. The criterion for the selection of the design frequency V_0 is minimum variance of $|\zeta|^2$ within the selected band (the variance is indicated by the dashed lines). The first band, band I, can be rather large as the coupling efficiency shows only little dispersion in the first octave below single-mode cutoff. Minimum variance is obtained for a design frequency of $V_0 = 1.2$. The second octave is split into two bands because of the strong wavelength dependence of the coupling efficiency far from cutoff. Band II from $V = 0.8$ to 1.2 has minimum variance for $V_0 = 0.95$. Minimum variance for band III from $V = 0.6$ to 0.8 is obtained for $V_0 = 0.7$.

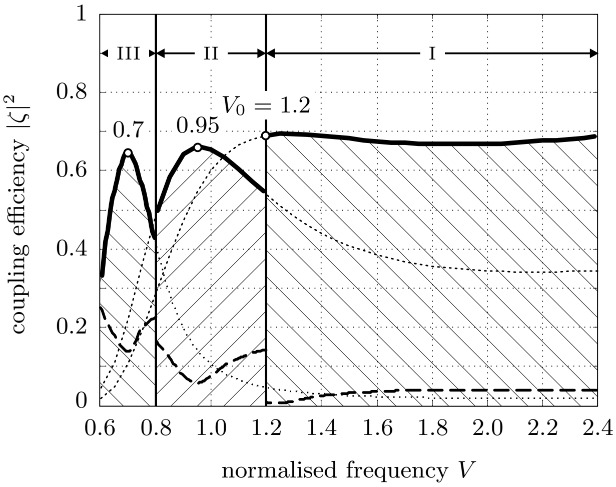

Figure 4. Different filter bands for broadband modal filtering over two octaves. The criterion for the choice of the design frequency V_0 is minimum variance of the power coupling efficiency $|\zeta|^2$ within the respective band.

4. REALISATION OF MODAL FILTERS

Efficient modal filtering requires a spatially steady and predefined field distribution at the output of the filter which can be achieved with single-mode waveguides or multi-mode waveguides with highly differing mode attenuated.

4.1. Single-mode waveguides

Single-mode waveguides only support the fundamental mode. After a certain distance, all modes but the fundamental mode are radiated off and a spatial steady state is achieved. If no inhomogeneities are present, this steady state is retained up to the filter output. Only the final part of the modal filter has to be ideal in order to provide good filter action.

The choice of core and cladding materials and of waveguide geometry determine the filter's insertion loss and filter bandwidth. The following waveguides are suitable for modal filtering:

- Step-index fibres with arbitrary refractive index differences between core and cladding or fibres with a smoothed-out profile have an infinitely large single-mode bandwidth and moderate insertion loss.
- Double-step-index fibres have an infinitely large single-mode bandwidth if the refractive index values of the steps decrease with increasing radius. For W-fibrs, where the index of the centre region is smaller than that of the outer region, the single-mode bandwidth is finite as the fundamental mode has a finite cutoff frequency. In all cases the insertion loss is medium.
- Integrated optics waveguides with a symmetric core/cladding structure have an infinitely large single-mode bandwidth. Those with an asymmetric structure have a finite bandwidth. Integrated optics waveguides show medium insertion loss.
- Index-guiding or bandgap-guiding photonic crystal fibres (PCFs) consist of a single material but with a (periodic) structure of holes running along the fibre axis. Index guiding PCFs behave as step-index fibres with a wavelength-dependent cladding index. By proper choice of hole diameter and hole spacing it is possible to obtain single-mode operation for all wavelengths and thus an infinitely large single-mode bandwidth. Bandgap-guiding PCFs rely on bandgap effects and thus have a very narrow single-mode bandwidth.

4.2. Multi-mode waveguides

Multi-mode waveguides can be used as modal filters if higher-order modes are more heavily attenuated than the fundamental mode. This can be achieved with a lossy cladding material. It is possible to achieve arbitrary higher-order mode suppression, but the required waveguide lengths of several metres cause a high insertion loss of the filter.

The choice of cladding materials, the waveguide geometry, and the waveguide length determine the filter capability and the filter's insertion loss and filter bandwidth. The following two types of hollow fibres may serve as modal filters:

- Dielectric hollow fibres consist of a hollow core and a dielectric cladding material with a refractive index lower than unity. A suitable cladding material could be Saphire with a refractive index of $n = 0.67-j0.04$ at $\lambda = 10.6\mu m$ and a real part of n smaller than unity in the range from 10 to $16.7\mu m$. Because dielectric hollow fibres work as conventional step-index fibres, they can be made single-mode for a certain wavelength range by proper core dimensions. However, practical core diameters of hollow fibres are in the range of several hundreds of microns which allows for a lots of fibre modes. In this case, a certain fibre length of several metres is required to achieve appropriate attenuation of the higher-order modes. The filter bandwidth is limited by the range where the cladding index is lower than unity.
- Dielectric and metallic coated hollow fibres are made of a hollow core and a glassy cladding with a metallic and a dielectric film deposit on the inner wall. Wave guiding is obtained by internal reflection at the metallic layer where the dielectric film minimises the loss caused by the metal. The dielectric film can only be optimised for one mode and one wavelength. Because of this, the fibre can be designed that the higher-order modes experience higher attenuation than the fundamental mode. Because the attenuation is strongly dependent on the wavelength, the filter bandwidth is limited. Practical fibres have a core diameter of several hundreds of microns and the cladding is made of silica glass with a silver and a silver-iodide film.

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REFERENCES

Ronald N. Bracewell, Detecting nonsolar planets by spinning infrared interferometer, 1978, Nature 274, 780-782

Reinhold Flatscher, Zoran Sodnik, Klaus Ergenzinger, Ulrich Johann, Rob Vink, Darwin Nulling Interferomter Breadboard I – System Engineering and Measurements, these proceedings

Bertrand Mennesson, Marc Ollivier, Cyril Ruilier, Use of Single-Mode Waveguides to Correct the Optical Defects of a Nulling Interferometer, 2002, Journal of the Optical Society of America 19, 596-602

Oswald Wallner, Walter R. Leeb, Peter J. Winzer, Minimum Length of a Single-Mode Fiber Spatial Filter, 2002, Journal of the Optical Society of America 19, 2445-2448

Oswald Wallner, Walter R. Leeb, Reinhold Flatscher, Design of Spatial and Modal Filters for Nulling Interferometers, 2003, Proc. SPIE 4838, 668-678