Chromatic coupling efficiency of a single-mode optical fiber for nulling interferometry

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Single-mode waveguides are very important in nulling interferometry, because they provide natural wavefront filters, essential for a quasi-perfect destructive interference. Another key condition is that each component of a nulling interferometer has to be achromatic. The use of single-mode waveguides can affect this achromaticity condition because the coupling of light into a waveguide is wavelength-dependent. In this paper, we will analyze the effect of different parameters, such as geometry, misalignments and aberrations on the wavelength-dependent coupling efficiency of a single-mode optical fiber and the consequences in nulling interferometry.

Introduction

The first exoplanet has been discovered in 1995 by Mayor and Queloz [1]. Since that moment, more than one hundred and sixty planets have been detected. All of these planets were found by indirect methods, which means that we only detected certain effects that the planet has on its star and not direct radiation from the planet.

Nulling interferometry [2] seems a promising way to directly detect light coming from an Earth-like exoplanet. It consists in looking at a star-planet system with an array of telescopes, and then combining the light from these telescopes in such a way that, simultaneously, destructive interference occurs for the star light and (partially) constructive interference for the planet light. The ratio between the intensities corresponding to constructive and destructive interference is called the rejection ratio. To be able to detect an Earth-like planet, this ratio should be of the order of at least \(10^6\).

In order to obtain some spectral information from the planet, this high rejection ratio should be achieved in a wide spectral band. This leads to very stringent requirements in terms of amplitude and phase of the fields to be combined. Indeed, in order to have a perfect destructive interference, two beams must have achromatically the same amplitude and there must be an achromatic \(\pi\)-phase shift between the two beams. Therefore, achromaticity is the key condition to reach a very high rejection ratio.

Another important stage in a nulling interferometer is wavefront filtering. This filtering can be achieved by focusing the beams onto a single-mode optical fiber [3]. Indeed, whatever the incident field, the field after the fiber is given by the fundamental mode of the fiber, multiplied by a factor. This factor (which can be complex) is called the coupling efficiency. Since the coupling is wavelength-dependent, it can affect the achromaticity condition by chromatically changing the amplitude and the phase of the beams and, therefore, it can limit the rejection ratio.

In this paper, we will analyze the effect of different parameters, such as geometry, misalignments and aberrations on the coupling efficiency of a single-mode optical fiber and the consequences of its wavelength-dependence on the rejection ratio.
Definitions

If $E_i(x,y,\lambda)$ denotes the complex incident field in the aperture plane (i.e. before the focusing optics), the coupling efficiency can be expressed as [4, 5]

$$\xi(\lambda) = \frac{E_i(x,y,\lambda)\tilde{F}_0(x,y,\lambda)\,dxdy}{|\tilde{F}_0(x,y,\lambda)|^2\,dxdy},$$

(1)

where $\tilde{F}_0(x,y,\lambda)$ is the fundamental mode of the fiber, back-propagated in the aperture plane, $x$ and $y$ are the spatial coordinates in that plane and $\lambda$ is the wavelength.

We can also define the power coupling efficiency $\eta$ as

$$\eta(\lambda) = \frac{|E_i(x,y,\lambda)\tilde{F}_0(x,y,\lambda)\,dxdy|^2}{|E_i(x,y,\lambda)|^2\,dxdy \cdot |\tilde{F}_0(x,y,\lambda)|^2\,dxdy}.$$  

(2)

The power coupling efficiency represents the percentage of the incident power that enters the fiber (Fresnel losses are neglected).

Beam combination

In order to have interference, beams need to be combined. There are two different types of combination: uniaxial and multiaxial (see Fig. 1). In both cases, wavefront filtering is done after combination.

For both types of combination, given certain optical fiber and focusing optics, there is one optimal geometry of the beams for which the power coupling efficiency is maximal. For the following simulations, we will consider imperfections and misalignments with respect to these optimal geometries.

Numerical simulations

For all simulations, we will consider a step-index single-mode optical fiber, with a numerical aperture $NA = 0.125$ and a core radius $a = 1.2\,\mu m$. We choose the focal length of the focusing optics to be $f = 3.5\,cm$ and the wavelength range from 500 to 650 nm. Note that these parameters have been chosen to match the components that we use in our nulling interferometer set-up. Furthermore, the fundamental mode is assumed to be gaussian.

Effect of the beam diameter

First, we consider small variations of the beam diameter around the optimal value ($D_{opt} = 7.5\,mm$ in the uniaxial case and $D_{opt} = 4.7\,mm$ in the multiaxial case). Since the coupling efficiency will be real, we will only consider the power coupling efficiency.
In Fig. 2, we can see that changes in the beam diameter chromatically affect the coupling efficiency, leading to spectral mismatching. We can also see that coupling efficiency is less sensitive to changes in the beam diameter in the multiaxial case. If we bring to interference two beams with different diameter (assuming that we can achromatically compensate for amplitude-mismatching due to different size of the beams), the worst-case rejection ratio will be higher than $10^6$ if the diameters are matched within 2.5% in the uniaxial case and within 20% in the multiaxial case.

**Effect of a beam offset**

We now consider small offsets with respect to the optimal position of the beam ($x_0 = 0$, centered on the axis of the fiber in the uniaxial case and $x_0 = 2.35$ mm in the multiaxial case).

In Fig. 3, we can see that a multiaxial set-up is much more sensitive to offsets. Indeed, if we consider the interference between a perfectly positioned beam and an offset beam (assuming again achromatic amplitude-matching), the offset should be smaller than 14% of the beam diameter in the uniaxial case and 2% of the beam diameter in the multiaxial case, in order to have a rejection ratio of $10^6$. 

![Diagram](image-url)
Effect of aberrations

The optical fiber is used as a wavefront filter. Therefore, the coupling efficiency is affected by aberrations. Aberrations will not only affect the amplitude, but also the phase of the beams. To see the effect of aberrations, we look at the coupling of a randomly-chosen wavefront with a RMS deviation of 60 nm ($\lambda/10$). We then make two aberrated beams interfere and look at the rejection ratio after amplitude and piston corrections. Both uniaxial and multiaxial cases lead to similar results. After 500 simulations, the average rejection ratio is of the order of $10^4$, which is very low. The wavefront deviation should be less than $\lambda/20$ to have a $10^6$ rejection ratio. Note that this requirement is instrumentally less stringent in the mid-infrared region, where nulling interferometry should be finally performed.

Outlook and conclusions

Integrated optics is of great importance for space applications. Indeed, this technology allows the implementation of a very stable optical system on a single chip, reducing considerably the volume, the weight of a set-up and therefore the cost of a space mission. In nulling interferometry, we have seen that the chromaticity introduced by such waveguides can be a problem to reach a high rejection ratio. From the simulations, we conclude that uniaxial combination is less sensitive to beam offset than in the multiaxial case. On the other hand, small variations in the diameter of the beams will lead to disfavorable consequences in the case of uniaxial combination. We have also seen that aberrations can drastically limit the rejection ratio in the visible domain since wavefront quality of the order of $\lambda/20$ RMS or less is required. Technologically, this requirement should be easier to achieve in the infrared region.

A possible solution to chromatic mismatchings induced by wavelength-dependent coupling would be the use of single-mode photonic crystal fibers that seem to be endlessly single-mode and to have a fundamental mode quasi-independent on the wavelength. But this still has to be studied and tested in an experimental set-up. Nulling interferometry should finally be performed in a wide spectral band going from 5 to 20 $\mu$m. Infrared waveguides that are single-mode for such a wide band are still under development and study. But it seems reasonable to think that, in such a broad band, chromaticity induced by these waveguides can seriously affect the rejection ratio.

References


