Design of a polarization nulling interferometer for exoplanet detection

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ABSTRACT

We present the design of a new testbed experiment to demonstrate nulling interferometry using polarization properties. This three-beam set-up is perfectly symmetric with respect to the number of reflections and transmissions and should therefore allow a high rejection ratio in a wide spectral band.

Keywords: Interferometry, Nulling interferometry, Polarization, Astronomical optics, Exoplanet detection

1. INTRODUCTION

Despite all efforts spent on search for exo-planets, direct detection of an Earth-like planet remains very challenging, mainly because of the huge brightness contrast between star and planet and because of their small angular separation. A promising way to overcome these difficulties and therefore directly detect light coming from an Earth-like planet is nulling interferometry.[1] This technique consists in combining light from several telescopes in such a way that destructive interference occurs for the star light and (partially) constructive interference for the planet light.

In addition to canceling the light from the star and thus making possible direct detection of Earth-like planets, nulling interferometry should also offer the possibility to obtain spectral information from the planet if destructive interference can be achieved simultaneously for all wavelengths in a wide spectral band (typically from 5-18 μm[2]). To realize that, very stringent requirements must be fulfilled in terms of amplitude, phase and polarization of the beams to be combined. In most current nulling interferometers, an achromatic phase shifter is used to obtain destructive interference for all wavelengths in the spectral band. Unfortunately, the manufacturing of these phase shifters can be technically challenging and their achromatic behavior does not always fulfill the requirements.

Recently, we proposed a different approach based on polarization properties of light.[3] Indeed, we show that interferometry with a theoretically-perfect contrast is possible by combining beams with different states of polarization and we presented a new type of nulling interferometer that should allow high rejection ratio with commercially-available components.

In this paper, we present the current status of the implementation of this conceptual idea in an experimental set-up. In Section 2, we will review briefly the principles of polarization nulling interferometry. In Section 3, we will show and discuss the previously-obtained results. Finally, in Section 4, we will show the new design of a polarization-based nulling interferometer.

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2. POLARIZATION NULLING INTERFEROMETRY

In this section, we will briefly describe the theoretical concept of polarization nulling interferometry.

Let us consider an array of N telescopes and let us assume that we can apply independent phases ϕ_j, independent amplitudes and independent states of polarization to each beam before recombination. Using Jones formalism[4] to describe polarization, we can show[3,5] that the condition to have on-axis destructive interference (nulling condition) is given by

$$\sum_{j=1}^{N} \vec{A}_j \exp(i\phi_j) = \sum_{j=1}^{N} \begin{pmatrix} A_{x,j} \\ A_{y,j} \end{pmatrix} \exp(i\phi_j) = 0, \tag{1}$$

where $A_{x,j}$ and $A_{y,j}$ are complex numbers representing the state of polarization (and the amplitude) of the j^{th} beam. The idea of polarization nulling interferometry is to fulfill this condition without using phase-shifters and using OPD adjustments to keep the phases ϕ_j identical. In this case, the nulling condition in Eq. (1) amounts to

$$\sum_{j=1}^{N} \begin{pmatrix} A_{x,j} \\ A_{y,j} \end{pmatrix} = 0, \tag{2}$$

As explained in Spronck,[3] this condition can be fulfilled merely by rotation of the polarization direction of the beams before combination. In order to get destructive interference simultaneously for all wavelengths in the spectral band, we would need achromatic polarization rotators such as achromatic waveplates[6] or zero-order gratings.[7]

Another possibility[3,5] to fulfill the nulling condition in Eq. (2) is to use, for each beam, a combination of crossed linear polarizers with a waveplate in between. The angle that the principal axis of the waveplate makes with the horizontal is α_j as shown in Fig. 1. If T_r and T_α are the complex transmission coefficients of the waveplate in its principal directions ($T_r = |T_r|$ and $T_\alpha = |T_\alpha| \exp(i\phi_{o-e})$, where ϕ_{o-e} is the phase difference between the ordinary and extraordinary axes), we can show that the polarization state after the waveplate is given by

$$\vec{A}_j = A_j \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} T_r \cos^2 \alpha_j + T_\alpha \sin^2 \alpha_j & \frac{1}{2}(T_r - T_\alpha) \sin 2\alpha_j \\ \frac{1}{2}(T_r - T_\alpha) \sin 2\alpha_j & T_r \sin^2 \alpha_j + T_\alpha \cos^2 \alpha_j \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = A_j \begin{pmatrix} 0 \\ \frac{1}{2}(T_r - T_\alpha) \sin 2\alpha_j \end{pmatrix}. \tag{3}$$

Considering identical waveplates for all beams (but with different orientations), the nulling condition in Eq. (2) simply amounts to

$$\sum_{j=1}^{N} A_j \sin 2\alpha_j = 0. \tag{4}$$

Given the amplitudes A_j, on-axis destructive interference for all wavelengths simultaneously can be achieved by a proper choice for the orientation of the waveplates α_j.

The main advantages of this method are:

- **Achromaticity.** With perfectly identical waveplates, the null is inherently achromatic. Only the transmission of the interferometer is wavelength-dependent.
- **Simplicity.** The proposed design only involves commercially-available optical components and does not require manufacturing of technologically-challenging devices such as an achromatic phase-shifter.
- **Amplitude matching.** The rotation of the waveplates with respect to the crossed polarizers allows accurate amplitude matching and therefore removes the need for an extra amplitude-matching device.
- **Internal modulation** The proposed design also inherently includes an internal modulation device. Indeed, the rotation of the waveplates also allows very fast internal modulation, which is very important to discern a possible planet from other signals that can reach the detector.

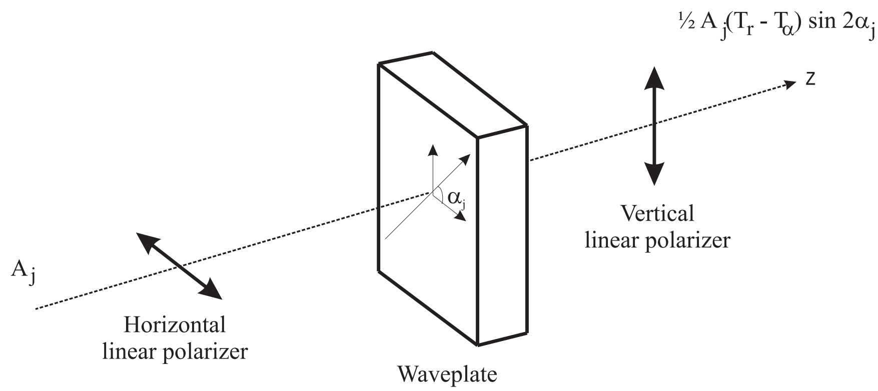

Figure 1. Schematic layout of the studied nulling interferometer. Each beam passes through a horizontal linear polarizer, a waveplate and a vertical linear polarizer.

Note that instead of waveplates, other devices such as image rotators (which only involve mirrors) could be used in a similar way. This could be of importance in the infrared region (between 5 and 18 μm) where it might be technically difficult to realize waveplates (achromatic or not) for the whole spectral band.

3. EXPERIMENT

3.1 Experimental set-up

The experimental set-up is depicted in Fig. 2. It is originally a three-beam interferometer[8,9] but only two beams were used for these preliminary measurements. The set-up can be divided in three blocks: the star simulator (A), the interferometer (B) and the detection stage (C).

In the star simulator, light from a Xe arc lamp (LS) is focused onto a 5 μm-pinhole (PH) via achromatic doublets (DB). Light is then collimated and vertically-polarized with a Glan-Laser linear polarizer (LP (V)). For alignment purpose, we also use a He-Ne laser that we focus onto the same pinhole using a folding mirror.

In the interferometer, two beams are created and then recombined with the help of four beam splitters. Each beam encounters, before recombination, a retro-reflector acting as a delay line and a multiple-order waveplate (half-waveplate at 632 nm). The optical path differences between the beams can be varied by changing the position of the delay lines (DL) with piezo-actuators.

After recombination, the beams encounter a horizontal Glan-Laser linear polarizer (LP (H)) and are directed to a single-mode optical fiber for wavefront filtering. The fiber is then connected to a powermeter (DT) to detect the outcoming intensity. The interference pattern is then given by the measured intensity as a function of the position of the delay lines. We define the rejection ratio as the ratio between the maximum and the minimum of the interference pattern.

3.2 Measurements

After checking that the polarizers were crossed and that the waveplates were optimally positioned, we performed monochromatic measurements (He-Ne laser) in order to check the alignment. The results are depicted in Fig. 3 (a). We can see that a rejection ratio of 10^4 has been reached, which is probably the limit allowed on our set-up due to vibrations.[9]

Since we used multiple-order waveplates (half-waveplates at 632 nm), the spectrum of the white light (from 550 to 750 nm) is not fully transmitted. The measured interference pattern is depicted in Fig. 3(b). The measured rejection ratio was 230 in a wide spectral band. Given the fact that important spectral and polarization mismatches drastically limit the performances of this set-up,[9] these results were expected. Apart from that, we can see in Fig. 3(b) that the interference pattern is not symmetric with respect to the minimum of the pattern. This is most probably due to differential dispersion, since different path lengths in glass will give rise to such asymmetry. In this case, dispersion decreases the performances of the interferometer and therefore, this effect has to be compensated.

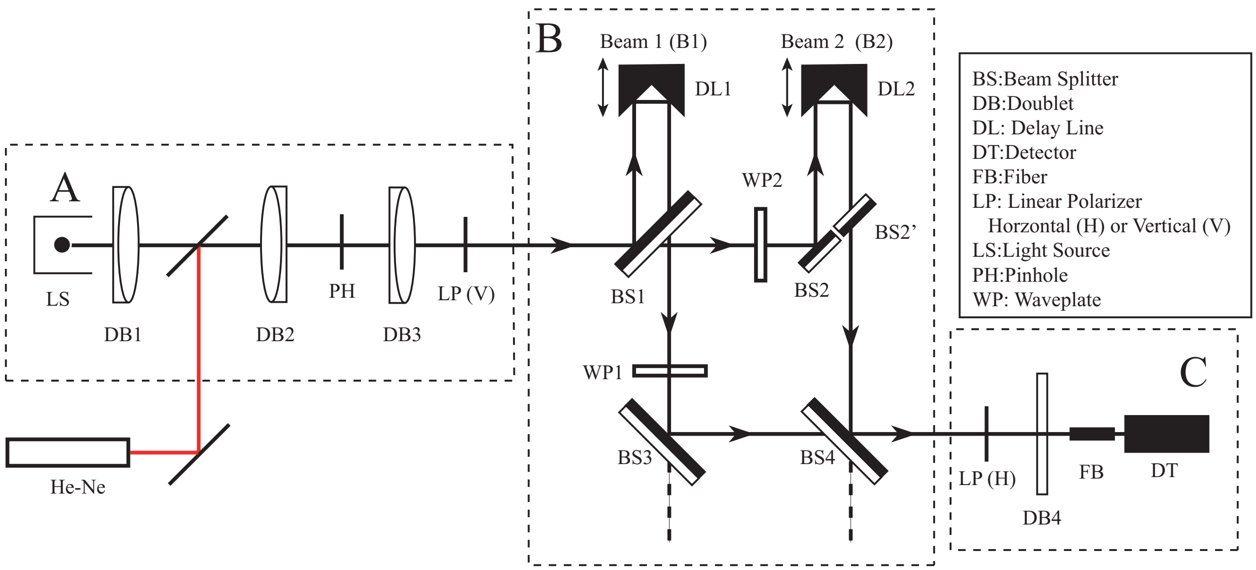

Figure 2. The experimental set-up can be divided in three blocks: the star-simulator (A), the interferometer (B) and the detection stage (C).

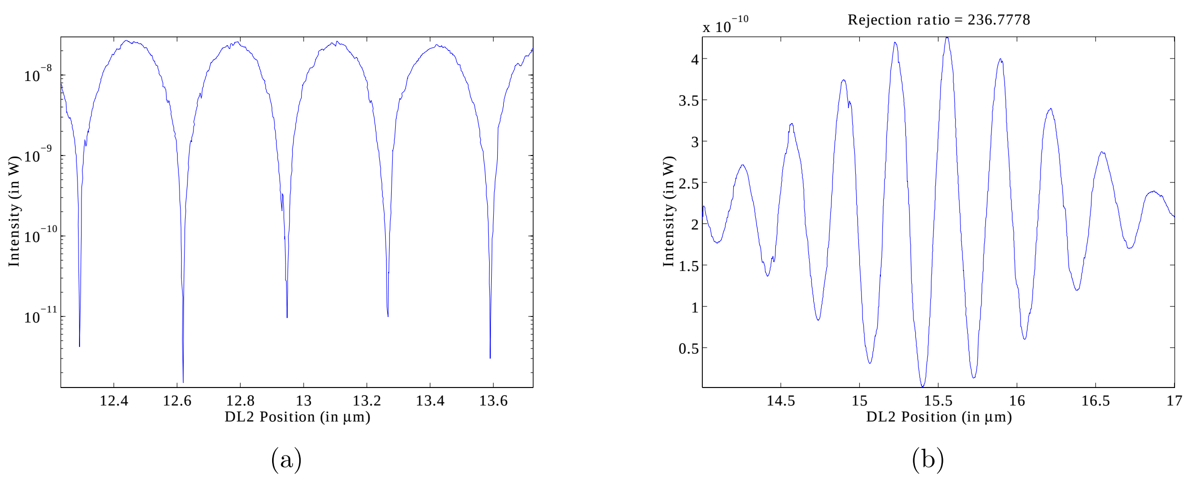

Figure 3. Interference patterns measured on our polarization nulling interferometer using multiple-order waveplates with (a) He-Ne laser (logarithmic scale) and (b) white light (linear scale).

4. DESIGN OF A NEW EXPERIMENTAL SET-UP

As mentioned in Section 3.2, important spectral mismatches of the order of 20% over the spectral band have been pointed out.[9] These spectral mismatches are mainly due to imperfections in the coatings of the beam-splitters. We also have observed important polarization mismatches. Both amplitude and polarization mismatches resulted in drastical limitations on the rejection ratio.

Another major problem in the set-up presented in Section 3.1 is the lack of symmetry: the number of front- and back-transmissions and of front- and back-reflections of the beams are not the same, making the set-up not optically symmetric. Indeed, consider the beam-splitters represented in Fig. 2 and assume that all beam-splitters are identical. The complex transmission coefficients of the beam-splitters are given by t_p, t_s, t'_p and t'_s and the complex reflection coefficients are given by r_p, r_s, r'_p and r'_s, where the subscript s or p refers to s- or p-polarization, while the $'$ denotes a backside transmission or reflection. We can show that, in order to have perfect destructive interference, these coefficients must fulfill the conditions

$$\begin{aligned} t'_s = t_s \text{ and } t'_p = t_p, \\ t_p r_s = r_p t_s. \end{aligned} \tag{5}$$

These conditions must be fulfilled for all wavelengths in the spectral band. It is reasonable to think that the first condition in Eq. (5) is easily fulfilled: frontside and backside transmission coefficients are identical (which is not true for reflection coefficients). However, the second of these conditions is not trivial to satisfy for all wavelengths. Note that this set-up is perfectly symmetric when used as a phase-based nulling interferometer as originally designed. The lack of symmetry only arises when the set-up is used as a polarization nulling interferometer.

Therefore, because of these important mismatches and the lack of optical symmetry, we propose a new design for a three-beam polarization nulling interferometer.

4.1 Proposed design

A schematic drawing of the proposed set-up is depicted in Fig. 4. This a two-level three-beam polarization-based nulling interferometer. The light source is on the lower level, while the detection takes place on the upper level.

The light source (LS) is a visible Xe arc source with a spectral band going from 550 to 750 nm. Light from this source is focused onto a single-mode optical fiber (OF). For alignment, a He-Ne laser will be focused onto the same optical fiber. A collimating optics (CO) system is used to collimate the light coming from the fiber. The light is then linearly polarized using a Glan-Laser polarizer (LP).

With the help of three beam-splitters (BS), three identical beams are created. Each beam then encounters a waveplate (WP). These waveplates must be as identical as possible but having different orientations (see Section 2). Each beam then goes through a parallel glass plate (DP) that can be tilted to compensate for eventual dispersion. The beams are then reflected backwards by cat's eye-type delay lines (DL). These delay lines are mounted on a micrometer screw for coarse OPD corrections and are fine-tuned using a piezo-activated mirror. The beams come back one level higher in such a way that they do not pass through the dispersion plates and the waveplates a second time. A two-level instead of a double-path set-up is needed since the waveplates can only operate in single path.

The beams are recombined with the same beam-splitters as the ones used for beam-splitting. Indeed, beam separation and combination are totally symmetric in this proposed set-up. The combined beams are then sent to a single-mode optical fiber for wavefront filtering and detection.

Some of the flat mirrors will be piezo-actuated to correct for residual tip/tilt between the beams. Note that the polarizers will be used before beam separation and after beam combination to make sure that no differential polarization orientation limits the rejection ratio.

The main advantages and features of this experimental set-up are:

- **General.** It is a three-beam visible polarization nulling interferometer. The waveplates can be replaced by a image-rotator or a similar polarization device. The set-up can also be converted into a traditional nulling interferometer by replacing the waveplates with some kind of achromatic phase-shifter.

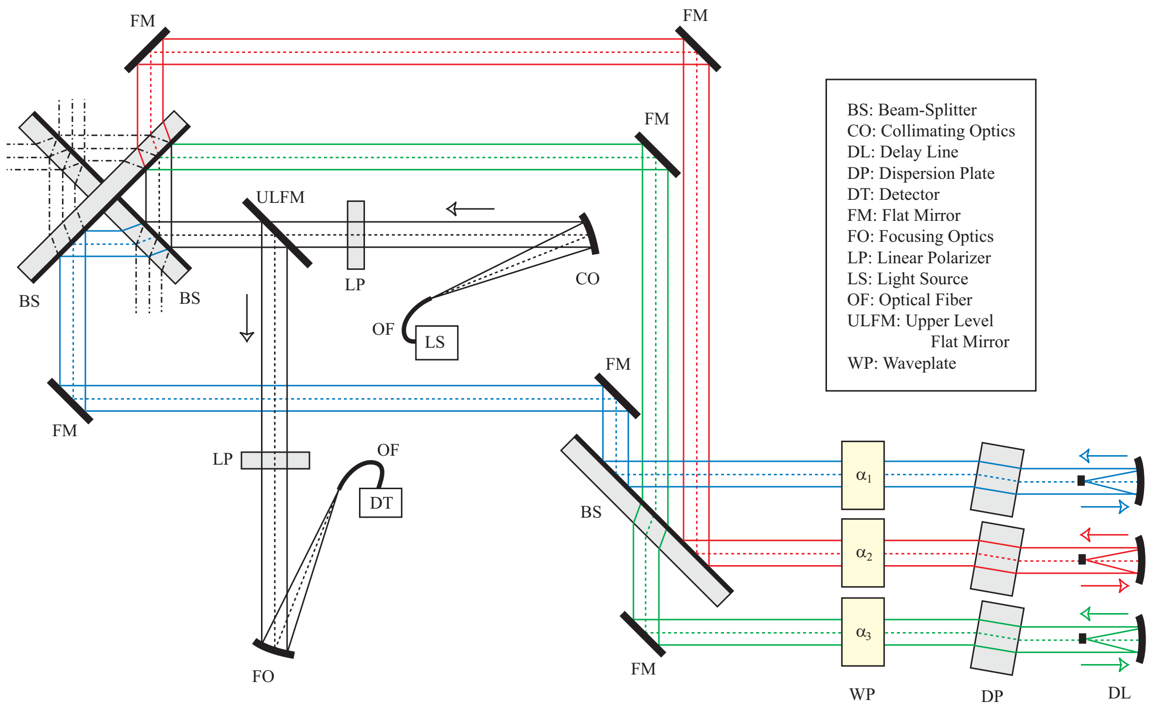

Figure 4. Design of a new experimental two-level set-up.

- **Symmetry.** It is entirely symmetric: all beams have the same number of frontside, backside-transmissions and reflections. As a consequence, if the beam-splitters are identical, all beams are perfectly identical, which was not true in the set-up described in Section 3. In addition, the beam generator and the beam combiner are independently symmetric. Therefore, if the beam generator were to be replaced by three telescopes, the set-up would not lose its symmetry.
- **Fringe tracking.** Three outputs of the beam-combiner (dash-dotted lines in Fig. 4) can be used for complete three-beam end-to-end fringe tracking.
- **Amplitude matching.** As mentioned in Section 2, accurate amplitude matching can be achieved by rotation of the waveplates.
- **Dispersion compensation.** In this set-up, we also added glass plates to compensate for possible dispersion.

4.2 Tolerances of the optical components

In this section, we review some of the well-known requirements that are common to most of nulling interferometers but we will mainly focus on tolerances specific to the proposed design depicted in Fig. 4.

Here are some of the requirements needed to reach 10^5-rejection ratio in a broad spectral band:

- **Beam-splitter transmission/reflection coefficients.** The absolute value of the transmission/reflection coefficients of the beam-splitters is not important in this design as long as the beam-splitters are identical. For convenience, 50/50 beams-splitters have been chosen. The transmission/reflection coefficients of the beam-splitters must be identical within 0.1%. The coatings of the beam-splitters should also be homogeneous within 0.1%.
- **Beam-splitter parallelism.** The absolute wedge angle of the beam-splitters must be less than 1 mrad and the wedge angles must be identical for all beam-splitters within 10-20 μrad.

- **Tip/tilt.** The tip/tilt between two beams should be corrected within 5 μrad, which will be achieved my piezo-actuated tip/tilt mirrors.
- **Wavefront quality.** A wavefront quality of $\lambda/20$ RMS over the beams is needed to have a 10^5 rejection ratio. This number should be multiplied by two and by the square root of the number of optical surfaces for the equivalent requirement in terms of surface.
- **Dispersion compensation.** The path difference in glass should be corrected within 40 nm, which means that the rotation of a 20-mm dispersion plate should be accurate within typically 100 μrad.
- **Extinction ratio of the polarizers.** The extinction ratio of the linear polarizers should be at least 10^5, as it is the case for the Glan-Laser polarizers that we will use.
- **Birefringence of the waveplates.** The absolute birefringence of the waveplates is not very important as long as they are identical. However, the differential birefringence between two different waveplates must be smaller than $\lambda/1000$. Note that in order to meet this requirement, stress-free mounting should be used for all optical components.
- **Polarizers and waveplates rotation.** The polarizers and waveplates must be rotated with an accuracy of 1 mrad.

Except for the wavefront quality requirement which could not be guaranteed, the set-up has been designed and the optical components have been selected to meet these requirements.

5. CONCLUSIONS

We have presented experimental results to demonstrate polarization nulling interferometry obtained on our table-top experiment. We have identified serious limitations in our set-up: amplitude and polarization mismatches, lack of symmetry between the beams and dispersion problems. Given these limitations, a new set-up has been designed.

The proposed design is a three-beam visible polarization-based nulling interferometer. It is entirely symmetric with respect to the number of frontside, backside-transmissions and reflections. It allows complete three-beam end-to-end fringe-tracking, accurate amplitude-matching and dispersion compensation. Internal modulation is also possible.

Finally, we defined and analyzed the requirements that the optical components should satisfy in order to achieve a 10^5 rejection ratio in a wide spectral band.

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