Nulling interferometry for exoplanet detection using polarization properties

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ABSTRACT

We present a new type of nulling interferometer that makes use of polarization properties to have on-axis destructive interference. The proposed design, which only involves commercial components and no achromatic device, is also suitable for internal modulation. This type of interferometer should enable a high rejection ratio in a theoretically unlimited spectral band. We implemented that concept on a two-beam white-light interferometer and we present here the first experimental results.

Keywords: Interferometry, Polarization, Astronomical optics, Nulling

1. INTRODUCTION

The first exoplanet has been discovered in 1995 by Mayor and Queloz.[1] Since that moment, more than one hundred and fifty planets have been detected. Most of them were found by indirect methods,[2,3] which means that only some effects that the planet has on its star have been detected.

The challenge for direct detection of Earth-like exoplanets is the huge brightness contrast between the star and the planet and their small angular separation. Nevertheless, this should be possible with a technique called nulling interferometry,[4] which 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 destructive interference occurs for the star light and 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 10^6 in the mid-infrared region.

Another major difficulty is that this high rejection ratio should be achieved in a wide spectral band (typically from 5-18 μm), in order to obtain spectral information from the planet. To cancel the light from the on-axis star in such a wide band, most nulling interferometers use an achromatic phase shifter. Such a device creates a phase shift quasi-independent on the wavelength and, therefore, allows a high rejection ratio in a broad band. But, technically, it is quite challenging to build these phase shifters.

In this paper, we present a totally new type of nulling interferometer that makes use of polarization properties of light in order to have on-axis destructive interference.[5] We also present a first attempt of implementation of the concept in an experimental set-up. The general theory behind this concept has already been reported in an earlier paper[6] with an analysis of sensitivity to imperfections. Note that a similar analogy has been proposed in visible coronography.[7] This paper is organized as follows. In Section 2, we derive the general condition to have on-axis destructive interference for an N-telescope array and apply that condition in the case of a two- and a three-telescope configurations. In Section 3, we use that generalized condition to propose a design of a new type of nulling interferometer. In Section 4, we look at the transmission maps that can be obtained with the proposed design. In Section 5, we present the first attempt of implementation of that concept in an experimental set-up. Our conclusions are then summarized in Section 7.

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2. GENERALIZED NULLING CONDITION

In this section, we derive the general nulling condition to have on-axis destructive interference with an array of N telescopes, including polarization of light.

Let us consider an array of N telescopes and let us assume that we can apply independent phases and amplitudes ϕ_j and A_j to each beam before recombination. To cancel the light from the star, we need on-axis destructive interference. We can show[8] that the condition to have such a destructive interference (nulling condition) is given by

$$\sum_{j=1}^{N} A_j \exp(i\phi_j) = 0. \tag{1}$$

A more general condition can be derived assuming independent states of polarization for each beam. Using Jones formalism[9] to describe polarization, the generalized condition is given by

$$\sum_{j=1}^{N} \vec{A_j} \exp(i\phi_j) = \sum_{j=1}^{N} \begin{pmatrix} A_{x,j} \\ A_{y,j} \end{pmatrix} \exp(i\phi_j) = 0, \tag{2}$$

where $A_{x,j}$ and $A_{y,j}$ are complex numbers. This condition can be applied to N ($N > 1$) telescopes. But, in practice, the cases $N = 2$ and $N = 3$ are quite realistic in the near future. For this reason, we present these two cases in detail.

2.1. Example 1: Two-beam nulling interferometer

In the case of a two-beam nulling interferometer, the generalized nulling condition in Eq. (2) simply amounts to

$$\vec{A_1} \exp(i\phi_1) = -\vec{A_2} \exp(i\phi_2). \tag{3}$$

In most current nulling interferometers, this condition is satisfied by applying a π-phase shift between the two beams ($\phi_2 = \phi_1 + \pi$). The condition in Eq. (3) could also be fulfilled without any phase shift but considering a polarization rotation of π ($\vec{A_1} = -\vec{A_2}$). This is a fundamentally different approach, as it will appear more clearly in the following example.

2.2. Example 2: Three-beam nulling interferometer

In this case, we have the following nulling condition.

$$\vec{A_1} \exp(i\phi_1) + \vec{A_2} \exp(i\phi_2) + \vec{A_3} \exp(i\phi_3) = 0. \tag{4}$$

If we assume that all the beams have the same phase, we have

$$\vec{A_1} + \vec{A_2} + \vec{A_3} = 0. \tag{5}$$

This condition can be fulfilled by rotating the polarization of the beams. For example, if we impose a horizontal linear state of polarization on the first beam, we could satisfy the condition in Eq. (5) using

$$\vec{A_1} = A_0 \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \vec{A_2} = A_0 \begin{pmatrix} \cos\left(\frac{2\pi}{3}\right) \\ -\sin\left(\frac{2\pi}{3}\right) \end{pmatrix} \text{ and } \vec{A_3} = A_0 \begin{pmatrix} \cos\left(\frac{4\pi}{3}\right) \\ -\sin\left(\frac{4\pi}{3}\right) \end{pmatrix}, \tag{6}$$

which are only obtained by rotation of polarization. This shows that we can satisfy the nulling condition without any phase shifter by only rotating the polarization and consequently cancel the light coming from an on-axis star.

If a planet is orbiting around that star, then the planetary light coming from the different telescopes will have different optical path lengths. Therefore, it is interesting to look at the detected intensity as a function of the optical path differences between the three beams. Let us first consider the monochromatic case with a

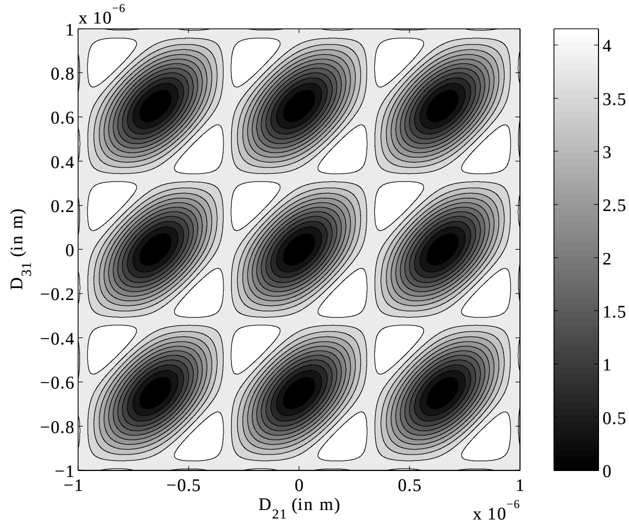


Figure 1. Normalized detected intensity (simulation) as a function of the optical path differences (OPD) between the three beams.

wavelength λ. The detected amplitude as a function of the optical path differences is given, within a phase factor, by

$$\vec{A}_{tot} = \vec{A_1} + \vec{A_2} \exp\left(i2\pi D_{21}/\lambda\right) + \vec{A_3} \exp\left(i2\pi D_{31}/\lambda\right). \tag{7}$$

where D_{21} and D_{31} are, respectively, the optical path differences between beams 2 and 1 and between beams 3 and 1. The detected intensity is then given by the square modulus of the amplitude in Eq. (7).

In the case of the example of Eqs. (6), we find the detected intensity depicted in Fig. 1. The rejection ratio, defined as the ratio between the maximal and minimal intensities of the interference pattern, is theoretically infinite.

Our example shows that we can make three differently-polarized (but coherent) beams interfere with a theoretically perfect contrast. This is also true for N beams provided that $N > 2$. The second consequence is that, since the intensity depends on the optical path differences, it should be possible to have constructive interference for the light coming from the planet. The important fact is that the destructive interference takes place at the zero-OPD position. In that case, there is no wavelength-dependent phase difference between the beams.

3. APPLICATIONS IN WIDE-BAND NULLING INTERFEROMETRY

In this section, we use the generalized condition to design a new type of nulling interferometer that allows a high rejection ratio in a wide spectral band.

Reaching the amplitudes in Eqs. (6) for every wavelength in the spectral band would require the use of achromatic polarization rotators. This is possible by combining different waveplates to create achromatic half-wave plates[10] or by using zero-order gratings.[11] But the approach that we choose is different, as explained below.

Suppose a system of N beams, initially horizontally linearly polarized. Each polarization is then changed using a simple waveplate whose principal axis makes an angle α with the horizontal (see Fig. 2). If T_r and T_α are the complex transmission coefficients of the waveplate in its principal directions ($T_r = |T_r|$ and $T_\alpha = |T_\alpha| \exp\left(i\phi_{o-e}\right)$, where ϕ_{o-e} is the phase difference between the ordinary and extraordinary axes), we can show[6] that the polarization state after the waveplate is given by

$$\vec{A} = A \begin{pmatrix} T_r \cos^2\alpha + T_\alpha \sin^2\alpha & \frac{1}{2}\sin 2\alpha \left(T_r - T_\alpha\right) \\ \frac{1}{2}\sin 2\alpha \left(T_r - T_\alpha\right) & T_r \sin^2\alpha + T_\alpha \cos^2\alpha \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = A \begin{pmatrix} T_r \cos^2\alpha + T_\alpha \sin^2\alpha \\ \frac{1}{2}\sin 2\alpha \left(T_r - T_\alpha\right) \end{pmatrix}. \tag{8}$$

Since we want on-axis destructive interference without any phase difference between the beams and assuming that all the waveplates are exactly identical but with different orientations, we must satisfy

$$\sum_{j=1}^{N} A_j \begin{pmatrix} T_r \cos^2\alpha_j + T_\alpha \sin^2\alpha_j \\ \frac{1}{2}\sin 2\alpha_j\,(T_r - T_\alpha) \end{pmatrix} = \begin{pmatrix} T_r \sum_{j=1}^{N} A_j \cos^2\alpha_j + T_\alpha \sum_{j=1}^{N} A_j \sin^2\alpha_j \\ \frac{1}{2}\,(T_r - T_\alpha)\sum_{j=1}^{N} A_j \sin 2\alpha_j \end{pmatrix} = 0 \tag{9}$$

By using conventional waveplates in a wide spectral band, T_r and T_α are wavelength-dependent in such a way that the first component of the vector in Eq. (9) cannot be equal to zero for every wavelength. The second component, on the other hand, can be canceled achromatically by a proper choice of the amplitudes A_j and angles α_j. If we add, for each beam, a perfect vertical linear polarizer after the wave plate (see Fig. 2), the amplitude of the j^{th} beam is then given by

$$\vec{A_j} = \begin{pmatrix} 0 \\ \frac{1}{2}A_j\,(T_r - T_\alpha)\sin 2\alpha_j \end{pmatrix}, \tag{10}$$

and the nulling condition simply amounts to

$$\sum_{j=1}^{N} A_j \sin 2\alpha_j = 0. \tag{11}$$

This condition is not wavelength-dependent. Therefore the null is achromatic if we assume identical wavepelates. Given certain amplitudes A_j, the on-axis destructive interference is obtained by properly choosing the angles α_j. Note that there is an infinitely large number of angular settings for which the nulling condition in Eq. (11) can be fulfilled.

In the proposed type of nulling interferometers, each beam encounters a horizontal linear polarizer, a waveplate and a vertical linear polarizer (see Fig. 2). Thus, it should be possible to reach a high rejection ratio in a wide spectral band with simple commercially-available components.

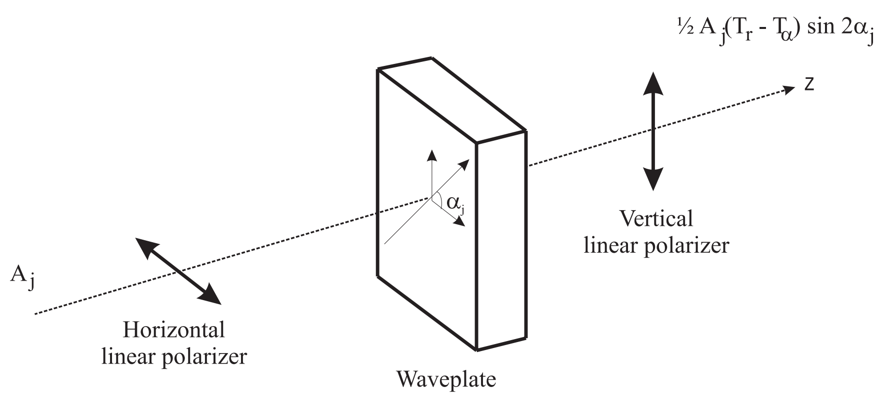


Figure 2. Design of a new type of nulling interferometer. Each beam encounters a horizontal linear polarizer, a waveplate and a vertical linear polarizer.

Note that we would have obtained similar results if the beams were initially vertically linearly polarized. We then could use a polarizing beam splitter instead of the first linear polarizer and apply the same principle to both outputs of the beam splitter so that no light would be lost.

4. TRANSMISSION MAP AND MODULATION

In this section, we look at direct consequences of the proposed design in the case of a three-beam nulling interferometer.

4.1. Transmission map

Let us consider N coplanar telescopes looking in the same direction z (see Fig. 3). The position of the j^{th} telescope is given in polar coordinates by (L_j, δ_j). For a point source located at an angular separation from the optical axis θ and at an azimuth angle φ, the detected complex amplitude $\vec{f_\varphi}(\theta)$ is given by

$$\begin{aligned}\vec{f_\varphi}(\theta) &= \sum_{j=1}^{N} \vec{A_j} \exp\left(ikL_j\theta\cos\left(\delta_j-\varphi\right)\right)\\ &= \sum_{j=1}^{N} \begin{pmatrix} 0 \\ \frac{1}{2}A_j\left(T_r-T_\alpha\right)\sin 2\alpha_j \end{pmatrix} \exp\left(ikL_j\theta\cos\left(\delta_j-\varphi\right)\right).\end{aligned} \tag{12}$$

Note that this expression is not general in the sense that the star which we point at lies on the z-axis. If this was not the case, there would be additional delays that are not taken into account here. If we define the transmission map $T_\varphi(\theta)$ as the normalized detected intensity, we have

$$T_\varphi(\theta) = \frac{\left|\vec{f_\varphi}(\theta)\right|^2}{\max\left[\left|\vec{f_\varphi}(\theta)\right|^2\right]}. \tag{13}$$

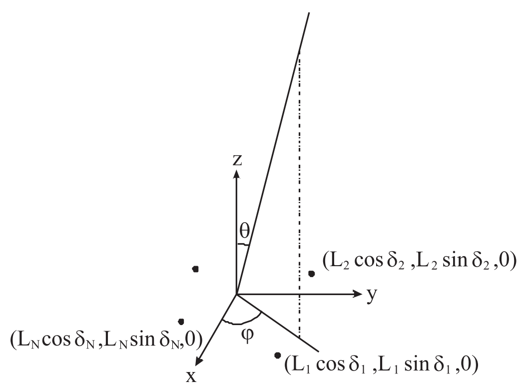
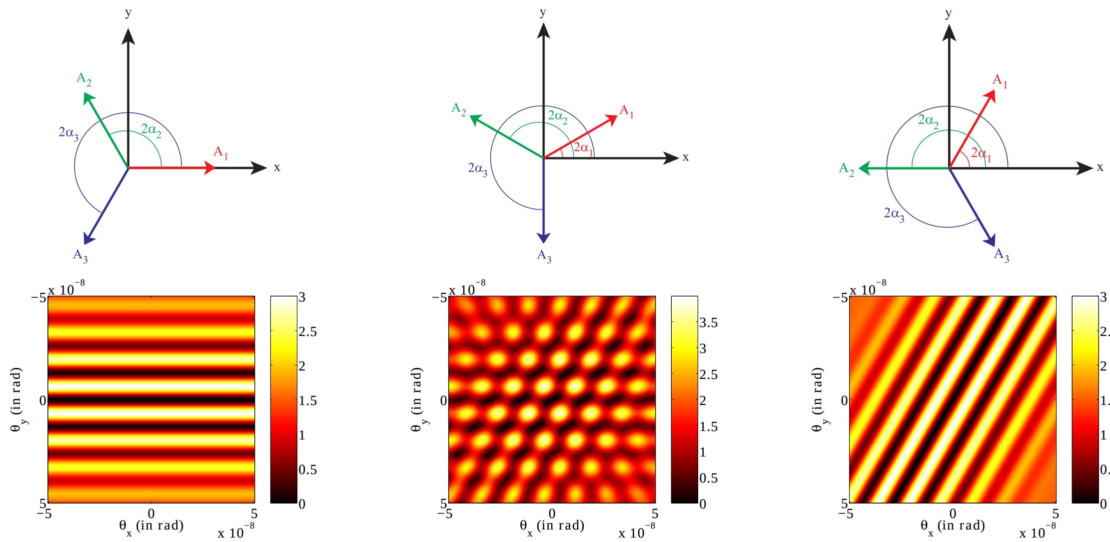


Figure 3. Array of telescopes (dots) situated in the plane $z = 0$ and looking in the z direction. The angles θ and φ define the direction of the incoming light. The position of the j^{th} telescope is given in polar coordinates by (L_j, δ_j).

4.2. Modulation

Another difficulty that could prevent us from directly detecting an Earthlike exoplanet is the possible emission from exo-zodiacal dust near the orbital plane of the planet, as in our own solar system. We, a priori, do not know anything about the exo-zodiacal cloud, but we can assume that it is centro-symmetric. Because of this central symmetry, this problem could be handled by using modulation techniques. A possible solution is to use external modulation, which consists in rotating the whole telescope array around its center, but this gives rise to very slow modulation and it will considerably decrease the number of targets that we can observe during a space mission. A more convenient solution is internal modulation. With this technique, we do not change the positions of the telescopes. Via optical means, we create different transmission maps that we combine in order to create modulation maps.

We can see, by the substitution of Eq. (12) in Eq. (13), that the transmission map depends on the angles α_j. But, as we have seen in Section 3, there is an infinity of possibilities for the choice of the angles α_j (as long as the nulling condition in Eq. (11) is fulfilled). Therefore, by changing the angles α_j, we can have a continuous set of transmission maps, which allows fast internal modulation.



(a) (b) (c)

Figure 4. Simulated three-telescope transmission maps corresponding to different waveplate orientations. All these maps have been calculated with the following parameters: $A_1 = A_2 = A_3$, $L_1 = L_2 = L_3 = 25m$ and $\delta_1 = 0, \delta_2 = 2\pi/3, \delta_3 = 4\pi/3$, and for a spectral band going from 500 to 650nm. (a) $2\alpha_1 = 0, 2\alpha_2 = 2\pi/3, 2\alpha_3 = 4\pi/3$, (b) $2\alpha_1 = \pi/6, 2\alpha_2 = \pi/6 + 2\pi/3, 2\alpha_3 = \pi/6 + 4\pi/3$, (c) $2\alpha_1 = 2\pi/6, 2\alpha_2 = 2\pi/6 + 2\pi/3, 2\alpha_3 = 2\pi/6 + 4\pi/3$.

Fig. 4 shows an example of a set of three transmission maps in the three-telescope case that have been obtained by only rotating the waveplates. In these transmission maps, the maximal intensity has been normalized to a value given by $\left(\sum_{j=1}^{N} |A_j/A_1 \sin 2\alpha_j|\right)^2$. Note that this is just an example out of a continuous range of transmission maps. Nevertheless, it can be shown that any of these transmission maps can be represented by a linear combination of three others. Therefore, three different transmission maps are sufficient to get the entire continuous set.

5. PRELIMINARY RESULTS

In this section, we present the first attempt to implement the proposed design in an experimental set-up.

5.1. Experimental set-up

The experimental set-up is depicted in Fig. 5. It 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 (the interferometer is originally a three-beam interferometer[12,13] but only two beams are used here). 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 sent to a single-mode optical fiber for 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.

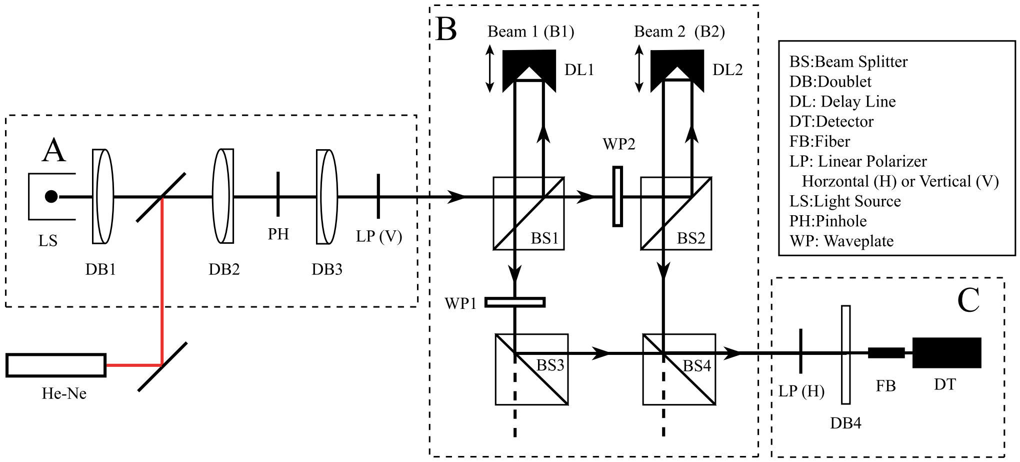


Figure 5. The experimental set-up can be divided in three blocks: the star-simulator (A), the interferometer (B) and the detection stage (C).

5.2. Measurements

Before placing the waveplates in the set-up, we first checked that the polarizers were crossed. We then maximize the output signal of one of the beams (the one with the lowest intensity) by adding the waveplate and orienting it optimally. Afterwards, we positioned the other waveplate oriented as such to match the intensities between the beams (indeed, in this type of nulling interferometer, the waveplates can also be used as a amplitude-matching device[6]).

In order to check the alignment, we first performed measurements with monochromatic light (He-Ne laser). Results are depicted in Fig. 6. We can see that a rejection ratio of 10^4 has been reached, which is limited by vibrations in our set-up.[13]

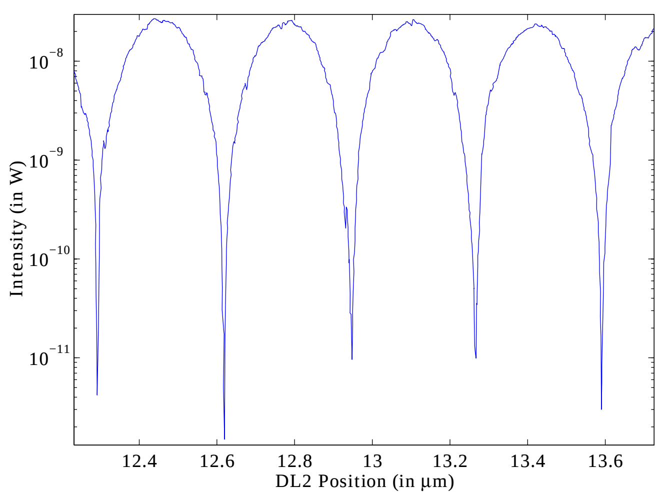
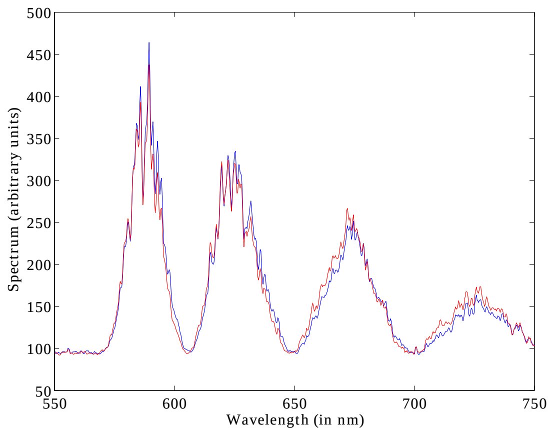
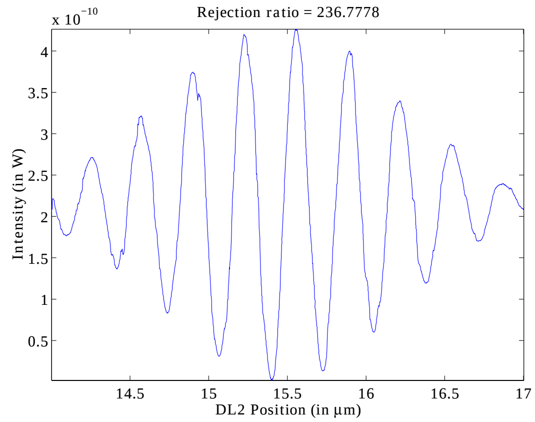


Figure 6. Experimental results with He-Ne laser and multiple-order half waveplates.

The spectrum of the white light covers the wavelength range from 550 to 750 nm but since we use multiple-order waveplates the spectrum is not fully transmitted, as shown explicitly in Fig. 7(a). As we can see, the waveplates are half-waveplates at 632 nm (maximum of transmission). The measured interference pattern is depicted in Fig. 7(b). We reached a rejection ratio of 230 in a wide spectral band (which is not bad considering



(a)



(b)

Figure 7. Experimental results with white light and multiple-order half waveplates. (a) Spectra of the two beams due to the multiple-order waveplates and (b) white-light interference pattern.

the large spectral mismatchings between the beams in the set-up[13]). But we can see in Fig. 7(b) that the interference pattern is not symmetric with respect to the minimum. This is most probably due to dispersion. Indeed, different path lengths in glass will give rise to such asymmetry. In this case, asymmetric patterns lead to lower rejection ratios and therefore, this effect has to be compensated.

6. OUTLOOK

For future experiments, we will replace the multi-order waveplates by very identical achromatic waveplates. We also absolutely need to compensate for the dispersion effect due to different path lengths in glass in order to achieve a high rejection ratio. Note that this rejection ratio will be probably limited by spectral mismatchings present in the set-up, which should be solved by replacing the beam-splitters.

7. CONCLUSIONS

We presented a new type of nulling interferometers that makes use of polarization properties of light to have on-axis destructive interference.

We have derived an expression for the general N-beam condition to have on-axis destructive interference, including amplitude, phase and polarization. We have applied it in the case of a two- and a three-beam nulling interferometer. We have shown that mutually fully coherent beams with different states of polarization can interfere with a theoretically perfect contrast, as long as $N > 2$.

We have seen in the monochromatic case that an infinitely large rejection ratio was possible without any phase shifter, using only polarization rotation. In a wide spectral band, a high rejection ratio is still possible without any achromatic phase shifter with, for example, an achromatic polarization rotator. The approach we chose only involves commercial elements: linear polarizers and waveplates. Our new type of nulling interferometers should allow a high rejection ratio in a wide spectral band without any achromatic device.

We have shown that the proposed design allows to obtain a continuous set of transmission maps by only rotating the waveplates, which is very suitable for fast internal modulation.

We implemented this idea and we have presented the first results. In the monochromatic case, we reached a rejection ratio of 10^4, which is limited by vibrations in the set-up. In a wide spectral band (from 550 to 750 nm), we reached a rejection ratio of 230 with conventional multi-order waveplates. We have seen that this low rejection ratio is probably caused by different path lengths in glass, which could be easily compensated for.

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