

Polarization Aberrations in the Modified Mach-Zehnder Interferometer

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ABSTRACT

Context. Over the past two decades, ground- and space-based instruments revealed a vast diversity of planet types, establishing the search for habitable worlds as a central objective of modern astronomy. Nulling interferometry enables the characterization of Earth-like exoplanets in the mid-infrared, however instrumental errors such as polarization aberrations can degrade the performance, limiting the achievable null depth.

Aims. We aim to quantify the impact of polarization aberrations in the Exoplanet Explorer nulling interferometer beam combiner across the 2–20 μm spectral band to determine whether diattenuation and retardance impose a limit on reaching the target null depth of 10^{-6} .

Methods. We perform a preliminary polarization analysis of a MMZ beam combiner using transmission and reflection data from a commercial beamsplitter. We evaluate the path-dependent s- and p-polarization throughput, and the system diattenuation.

Results. The preliminary results show a chromatic and a polarization dependent behavior of the MMZ. While the balanced outputs show an overall lower diattenuation.

Conclusions. We will model the beamsplitter's multilayer dielectric coating, enabling us to simulate the transmission (T, T') and reflection (R, R') coefficients of the beam splitter based on the surface of incidence. Furthermore, we will simulate the complete Exoplanet Explorer nulling interferometer. The results should provide requirements on polarization aberrations at the subsystem level to reach the desired null depth of 10^{-6} .

Keywords: Nulling interferometry, polarization aberrations, telescope, exoplanets.

1. INTRODUCTION

Over the past two decades, ground- and space-based instruments such as HARPS¹ and Kepler² revealed a vast diversity of planet types, establishing the search for habitable worlds as a central objective of modern astronomy. Major space agencies designated it as a top priority for the next generation of large space observatories. To characterize exoplanetary atmospheres, coronagraphy is considered at UV to NIR wavelengths for HWO³ and TIANLIN.⁴ Conversely, nulling interferometry is more suited at mid-IR wavelengths, where the thermal emission of temperate terrestrial planets is at its peak. This relaxes the required star-to-planet contrast ratio to $\sim 10^6$ relative to $\sim 10^9$ in reflected light, and the large baseline of nulling interferometers provides the required angular separation of ~ 100 mas to characterize Earth-like exoplanets in the mid-infrared. Moreover, many molecular biosignatures such as H₂O, CO₂, O₃, N₂O, NH₃, and CH₄ are present in the mid-IR band.

Built upon the concept proposed by Bracewell in 1978,⁵ space-based nulling interferometry missions were proposed by NASA and ESA in the early 2000s, respectively with TPF-I and Darwin. However, the missions studies were discontinued in the late 2000s. Recently, nulling interferometry regained momentum with several ground- and space-based projects such as GLINT,⁶ Asgard-NOTT,⁷ LIFE,⁸ MEAYIN,⁹ and the Exoplanet Explorer nulling interferometer.¹⁰ The Exoplanet Explorer nulling interferometer is an ESA-funded project investigating

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the feasibility of a single-spacecraft nulling interferometer, operating in the mid-infrared between 3–20 μm , and aiming to detect and characterize temperate rocky exoplanets around nearby stars. The scope of the project encompasses system architecture development, optical chain design, mechanical architecture and performance assessment. The optical design development spans the individual telescope assemblies, the beam combination and control, the spectral dispersion, and the detection. This includes detailed trade-offs between telescope configurations, pupil transfer systems, achromatic phase shifters (APS), the control and monitoring system, the beam combiners, the fiber injection and the spectral analysis through spectrograph.^{10–13} Furthermore, critical aspects such as polarization management, wavefront quality control, and radiometric performance are addressed. Polarization management is especially important in high contrast instrument, as it has been shown to be a contrast limiter in nulling interferometry by several studies.^{14–16}

1.1 Goal of the Study

The objective of this work is to quantify whether polarization aberrations impose a fundamental limit on reaching a target null depth of $N = 10^{-6}$ within the beam combiner of a nulling interferometer. Specifically, we aim to design polarization optimized beam combiner configurations that are either polarization-agnostic or optimized for full-Stokes polarimetry. In the preliminary case study, we simulate the polarization aberrations arising in the Modified Mach-Zehnder (MMZ) used in the Exoplanet Explorer project.¹¹ In later phases, we will simulate the entire optical chain of the Exoplanet Explorer and compare our simulations against our testbench in order to demonstrate compensation strategies that mitigate polarization aberrations in a nulling interferometer. The remainder of this paper is organized as follows: Sec. 2 provides a theoretical overview of polarization aberrations. Sec. 3 reviews the working principle of the MMZ and the Exoplanet Explorer’s beam combiner optical design. Sec. 4 details the simulation methodology, the simulation results, and present our testbed dedicated to the measurements of polarization aberrations in nulling interferometry. Finally, we summarize our results and discuss future works in Sec. 5.

2. POLARIZATION ABERRATIONS

Polarization aberrations correspond to the spatial variations of the polarization states, both in amplitude (known as diattenuation) and phase (known as retardance). They arise from the response of polarization to the coating, the optical design geometry, and the imperfections of the surfaces and the optical alignment. In most optical systems, polarization aberrations have a marginal influence on the instrumental performance when compared to wavefront aberrations and other sources of error, thus these aberrations are often disregarded. However, in high contrasts instruments like nulling interferometers and coronagraphs, polarization aberrations must be taken into account to achieve the scientific objectives.

2.1 Polarization Ray Tracing, Jones Pupil, Diattenuation and Retardance

Polarization ray trace combines standard ray tracing with the vector properties of polarization to understand the impact of the optical system on the polarization across the beam cross-section and to balance the polarization aberrations introduced by the different optical surfaces. The polarization aberrations in an optical system depend on the pupil coordinates (σ_x, σ_y) and the field coordinates (τ_x, τ_y) . The field corresponding to a Sun-Earth-like system is almost zero, thus we assume that the polarization aberrations are only a function of the pupil coordinates. We use the Jones formalism, which provides the amplitude and the absolute phase of the individual rays, however each ray is fully polarized. Usually, the ideal optical system preserves the input polarization, ensuring that a beam with a uniform polarization entering the optical system exits with the same uniform polarization state. Using the Jones formalism, the resulting polarization function is described by the identity Jones matrix, and any deviation from the identity matrix is referred to as polarization aberrations. Thus we have the following relation between the incoming and exiting electric field,

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix}_{out} = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}_{in}, \quad (1)$$

where $E_1 = A_1 e^{i\phi_1}$ and $E_2 = A_2 e^{i\phi_2}$ are the vector components of the electric field. In the formalism, each Jones matrix is associated to one ray, therefore by taking all the Jones matrices for all the pupil coordinates, we can create a 2x2 map, representing the Jones matrices evolution with the pupil coordinates i.e., the Jones pupil.

In order to compute the diattenuation and retardance from the Jones pupils, we use the polar decomposition method. This method and the formalism of polarization aberrations has been developed by McGuire and Chipman *Polarized Light and Optical Systems*.^{17–20} Here, we shortly describe how to obtain the diattenuation and the retardance from the Jones matrix. Using the polar decomposition theorem, we can write the Jones matrix J as the product of a unitary and a Hermitian matrix.

$$J = UH = H'U, \quad (2)$$

where the Hermitian matrix H corresponds to the diattenuation of the Jones matrix J , and the unitary matrix U corresponds to the retardance of the Jones matrix J . We compute U and H as follow,

$$JJ^\dagger = H^2 \quad \text{and} \quad U = JH^{-1}. \quad (3)$$

Then, we can get the normalized eigenvectors $\hat{v}_\pm$ and eigenvalues $\lambda_\pm$ of H and U , and calculate the diattenuation, the retardance, as well as their orientation and ellipticity. For the diattenuation matrix H , the eigenvalue λ_+ is the maximum diattenuation transmittance and the eigenvalue λ_- is the minimum diattenuation transmittance. The normalized eigenvectors represent the maximum and minimum diattenuation transmission direction of the system. In other words, they correspond to the polarization states that are the most and least transmitted by the system. The diattenuation intensity is given by

$$D = \frac{\lambda_+^2 - \lambda_-^2}{\lambda_+^2 + \lambda_-^2}. \quad (4)$$

The eigenvalues of the retardance matrix U represent the phase accumulated on the fast and slow axes, and the eigenvectors represent the fast and slow axes of the system. The eigenvalues of the retardance matrix U have a magnitude equal to 1, meaning that the eigenvalues can be written as

$$\lambda_\pm = e^{-i\phi_\pm}. \quad (5)$$

The retardance is given by the magnitude of the difference between the angle of the two eigenvalues

$$\delta = |\phi_+ - \phi_-|. \quad (6)$$

3. MODIFIED MACH-ZEHNDER

The MMZ beam combiner is a fully symmetric achromatic beam combination scheme for two input beams. It is one of the most common designs used in bulk optics nulling interferometry and has been implemented in several testbeds, including SYNAPSE,²¹ Keck²² and NICE.²³ For two in-phase input beams, the MMZ produces constructive interference on the balanced output (cf. Serbayn and Colavita (2001)²⁴ and Fig. 4 (a) for more details). To obtain a destructive interference on the balanced output, the nulling interferometry case, one can introduce a π phase shift on one of the beams via an achromatic phase shifter (APS).

Fig. 1 illustrates the transmission (T, T') and reflection (R, R') coefficients of a beam splitter based on the surface of incidence. For a dielectric coated beamsplitter, a relative phase shift occurs upon reflection from a low to high refractive index medium, Fig. 1 (b), compared to a reflection from a high-to-low refractive index medium, Fig. 1 (a). The reflection and transmission coefficients of beamsplitters can differ significantly, especially in their s- and p-polarization response. Because reaching a perfect destructive interference requires the beams to have equal intensities and polarization, carefully engineering the coating and the beam combiner design is critical. This is further complicated by the chromaticity beamsplitters often exhibit.

Fig. 4 (a) depicts the phase behavior at the balanced and unbalanced outputs of an MMZ preceeded by an APS. To balance the intensities at the dark outputs, the two beamsplitters in the MMZ are rotated by 180° with respect to each other. This ensures the beam paths producing the dark outputs both undergo one transmission and one reflection on the beamsplitters, only requiring T and T' to be matched as seen in Tab. 1 and Fig.4 (a). We define the four optical paths inside the MMZ as follow:

- Path 1: $T'_{BS} R_{\text{mirror}} T'_{BS}$.



Figure 1. Plate beamsplitters with a dielectric coating. (a) The phase is shifted by $+\pi$ upon reflection when the beam transitions from a medium with a lower refractive index to a medium with a higher refractive index. (b) The phase does not change upon reflection when the beam transitions from a medium with a higher refractive index to a medium with a lower refractive index.

- Path 2: $T'_{BS} R_{\text{mirror}} R'_{BS}$.
- Path 3: $R'_{BS} R_{\text{mirror}} T_{BS}$.
- Path 4: $R'_{BS} R_{\text{mirror}} R_{BS}$.

Taking into account the beamsplitter phase shifts defined in Fig. 1, the two beams at the balanced outputs (dotted arrows in Fig. 4 (a)) accumulate a net π phase difference resulting in destructive interference. Conversely, the two beams at the unbalanced outputs (dashed arrows), do not have any net phase difference, resulting into constructive interference.

Table 1. Amplitude transmission/reflection coefficients and phase difference for each output of the MMZ seen in Fig. 4 (a). We dropped the amplitude contribution of the gold mirrors for clarity because they are equivalent for all paths.

Outputs	A	B	C	D
	balanced	balanced	unbalanced	unbalanced
Amplitude	$R'T + T'R'$	$T'R' + R'T$	$T'T' + R'R$	$R'R + T'T'$
Phase Difference $\Delta\phi$	π	π	0	0

3.1 Exoplanet Explorer Beam Combiner

The Exoplanet Explorer nulling interferometer¹⁰ is an ESA-funded project investigating the feasibility of a single-spacecraft nulling interferometer, operating in the mid-infrared between 3–20 μm . The complete optical design is detailed by Mazzoli et al.¹¹ The Exoplanet Explorer nulling interferometer features a double Bracewell beam combination scheme (cf. Fig. 2). The light from the four telescopes are first combined in pairs by two MMZ (cf. Fig. 3 & 4 (a)). Each beam combiner has 4 outputs, 2 bright (constructive) outputs and 2 dark (nulled) outputs. Then the nulled outputs are further recombined in the cross combiner to obtain the science beams (cf. Fig. 4 (b)).

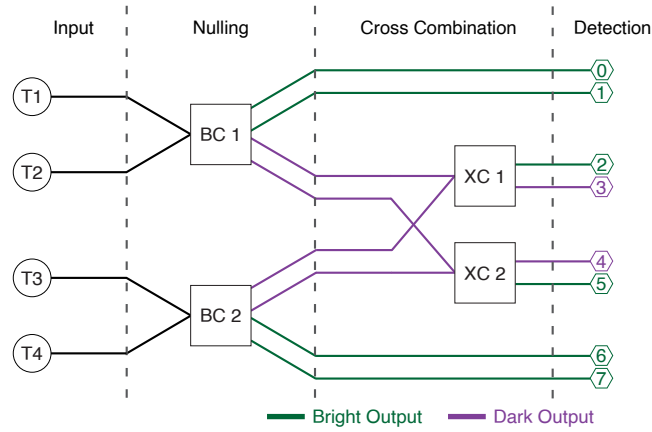


Figure 2. Double Bracewell beam combination scheme of the Exoplanet Explorer nulling interferometer. The input of the 4 telescopes are first combined in pairs by the nulling stage using 2 beam combiners. Each beam combiner has 4 outputs, 2 bright (constructive) outputs and 2 dark (nulled) outputs. Then the nulled outputs are further recombined in the cross combiner and we obtained the science beams.

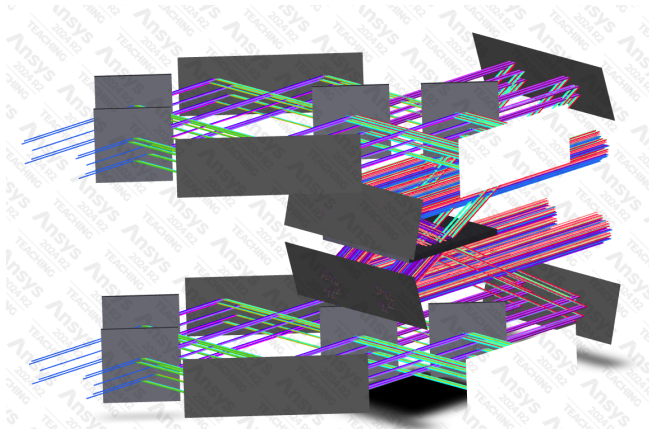


Figure 3. 3D view of the Exoplanet Explorer nulling interferometer beam combiner design. The beam combination scheme is described by Fig. 2. It features 2 MMZ performing the nulling and a cross combination stage further recombines the nulled outputs.

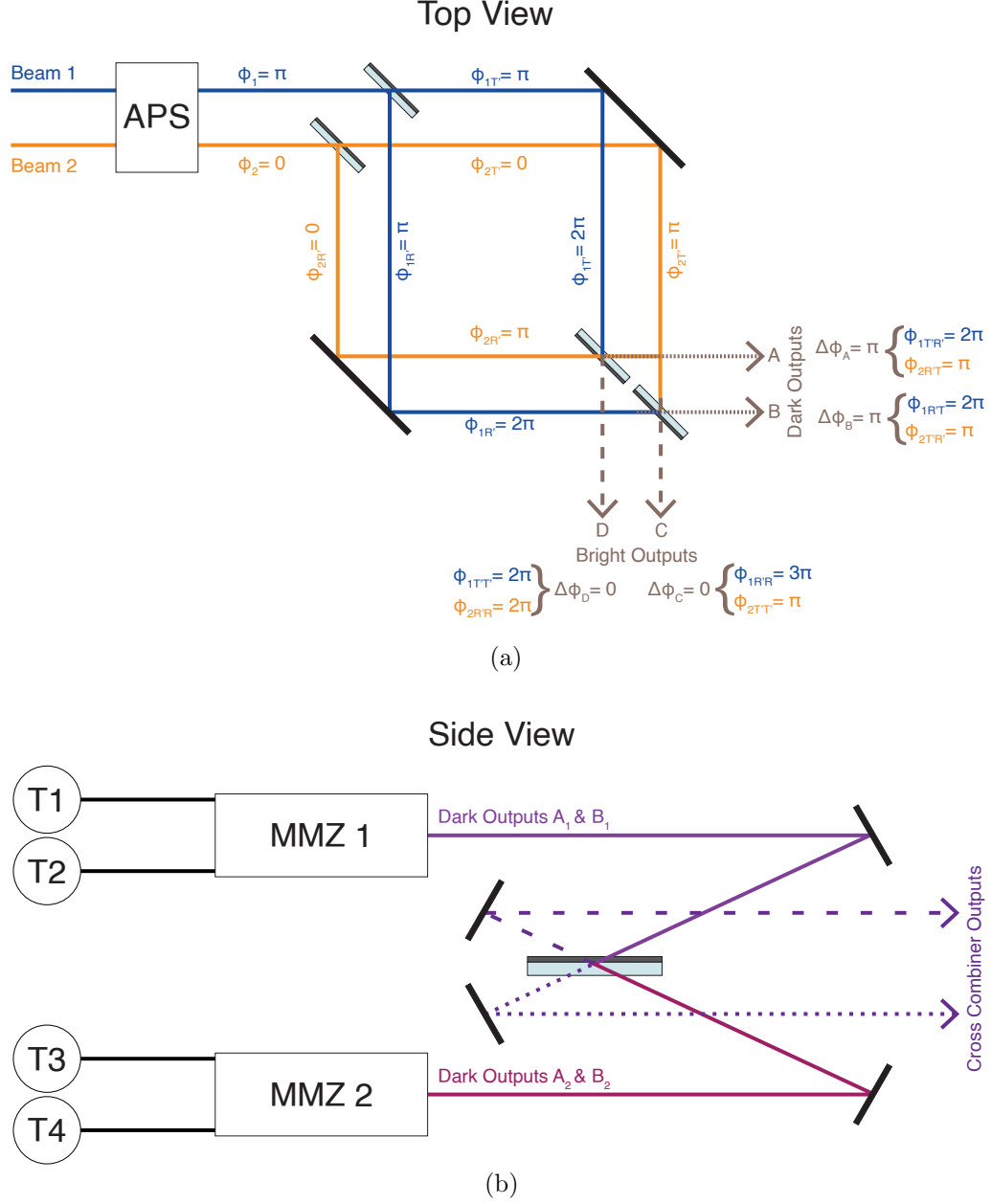


Figure 4. (a) Top view and (b) side view schematic of the Exoplanet Explorer nulling interferometer beam combiner. The 3D view can be seen in Fig.3. (a) Schematic of the Modified Mach-Zehnder (MMZ) interferometer. The APS adds a phase difference of π to one of the beams such that the balanced outputs, represented by the dotted arrows, are nulled. The dashed arrows represent the unbalanced outputs where constructive interference occurs.

4. RESULTS AND DISCUSSION

We present preliminary results analyzing the impact of polarization on the MMZ beam combiner used in the Exoplanet Explorer nulling interferometer. We focus on the diattenuation introduced by the beamsplitters and mirrors inside the MMZ, specifically how the polarization aberrations differ between the multiple beam paths within the interferometer. These preliminary results rely on the Thorlabs BSW711 beamsplitter measured reflectance and transmittance. In future iterations, we will model a multilayer dielectric beamsplitter coatings, allowing us to quantify the reflectance, transmittance and phase for multiple angle of incidence as well as the

asymmetries (R , R' and T , T'). Conversely, we use measured refractive index data provided by the Liège Space Center (CSL) for the gold coated mirrors.

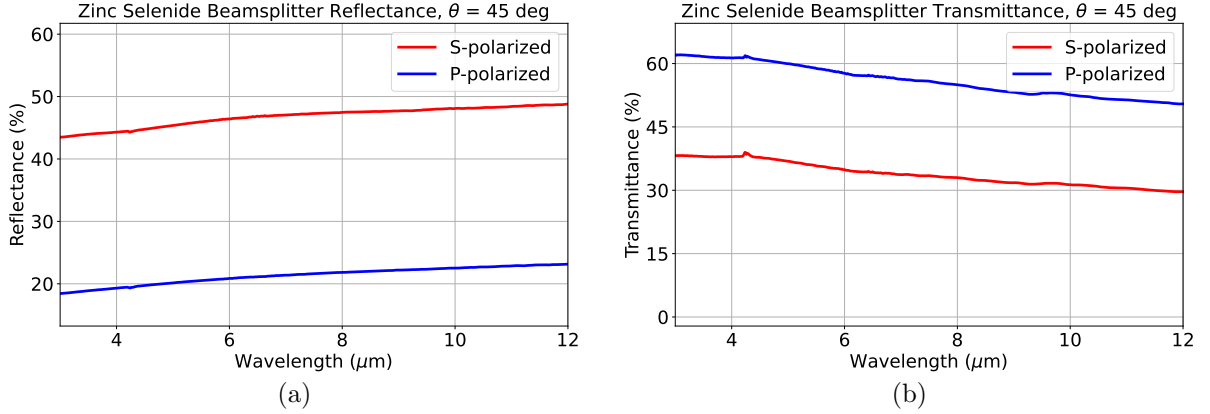


Figure 5. Reflectance (a) and transmittance (b) for Thorlabs BSW711 beamsplitter used to simulate the MMZ beam-splitters.

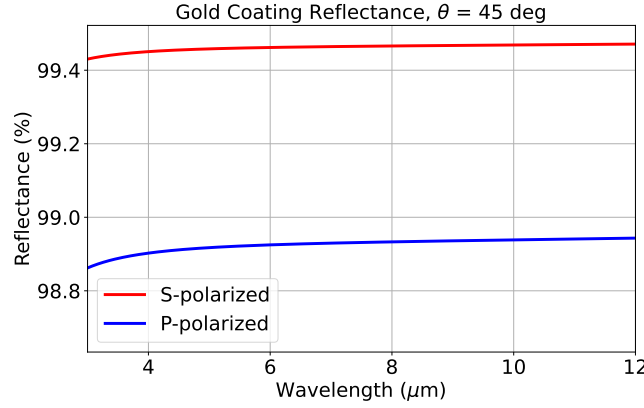


Figure 6. Reflectance of CSL's gold coating used to simulate the MMZ mirrors.

Because we rely on the measured beamsplitter reflectance and transmittance data, we can understand that the incident surface orientation of the beamsplitter shown in Fig. 1 does not affect our simulation results. Thus, path 2 and path 3 are identical as seen in Fig. 7. In Fig. 7 (a), we show that the throughput varies significantly across the different paths and between the s- and p- polarizations. The throughput also exhibits a wavelength dependence. This highlights the need to optimize the beamsplitter coatings for 50:50 splitting of both s- and p- polarization and phase matching over a large spectral band. The diattenuation of the different beam paths is presented in Fig. 7 (b). Path 2 and path 3 show an overall lower diattenuation than the other paths, because the balanced beam paths minimize the throughput offset between s- and p- polarization. Optimizing the coating response to s- and p- polarization will be key to improve the system diattenuation.

In future works, we will design the beamsplitter's multilayer dielectric coating and use the Transfer Matrix Method (tmm) to simulate the interaction of light with the thin-film. This will enable us to distinguish between R and R' , as well as T and T' , and to evaluate the coating-induced phase shifts and quantify their contribution to the null depth degradation. Our objective is to simulate the impact of polarization aberrations on the null depth for several beam combination schemes, across the 2-20 μm band. Furthermore, we plan to incorporate the polarization aberrations originating from the Exoplanet Explorer nulling interferometer telescope design,¹³ from the relay optics lines, and the achromatic phase shifter.

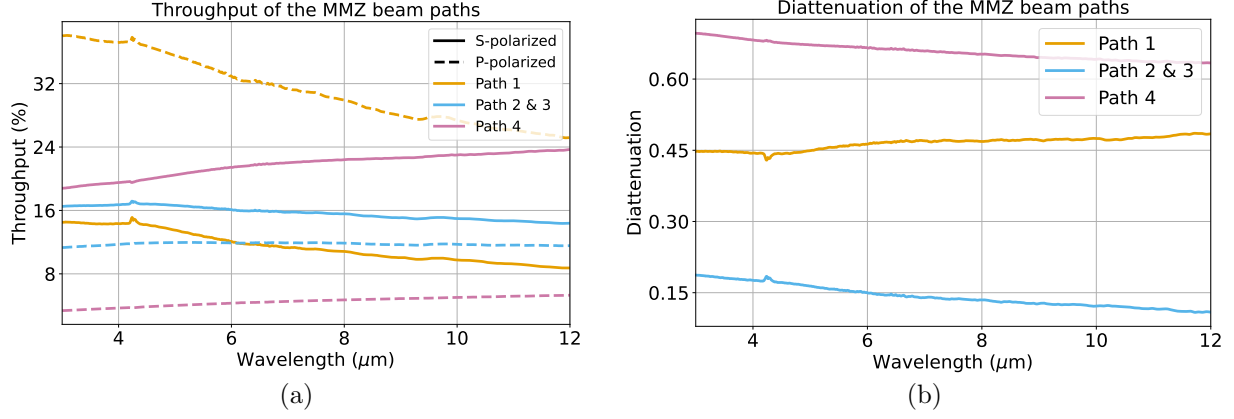


Figure 7. (a) Throughput and (b) diattenuation of the different beam paths in the MMZ.

4.1 Testbench

We are currently developing a testbench capable of characterizing polarization aberrations in a nulling interferometer, shown in Fig. 8. The setup is designed to allow full-Stokes generation and measurement across the beam cross-section. The testbench will provide an experimental understanding of the evolution of polarization aberrations through the delay line, achromatic phase shifter and beam combiner, as well as their impact on the null depth.

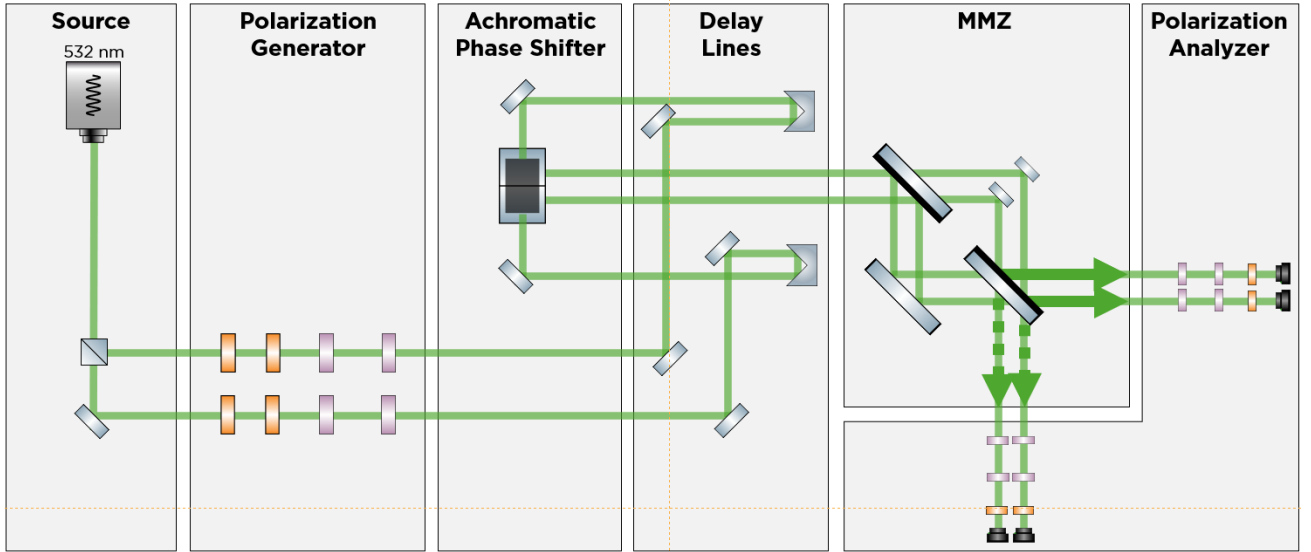


Figure 8. Optical layout of the polarization aberrations characterization testbench.

5. CONCLUSIONS AND FUTURE WORK

We presented a preliminary analysis of the polarization aberrations inside the beam combiner using reflection and transmission data from Thorlabs BSW711 beamsplitter, confirming the wavelength and polarization dependence of the MMZ. We will perform further analyses where we use our own beamsplitter multilayer dielectric coating design and employ the Transfer Matrix Method (tmm) to simulate the transmission (T , T'), reflection (R , R') and phase coefficients of the beam splitter based on the surface of incidence. Furthermore, we will simulate the entire Exoplanet Explorer nulling interferometer optical chain to evaluate the impact of the telescopes orientation, the pupils rotations, the beam paths and the different subsystems. The results should provide requirements

on polarization aberrations at the subsystem level to reach the desired null depth of 10^{-6} . Finally, to verify experimentally our simulations, we are building a testbench to study the behavior of polarization in the beam combiner and in the phase shifter.

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