

Nulling interferometry beam combiners with optimal integrated phase sensing

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ABSTRACT

The Voyage 2050 report has identified the infrared characterization of rocky temperate exoplanets one of the highest priorities for ESA in the coming decades. Due to the need of high angular resolution in the mid infrared, nulling interferometry appears as the only way to reach this ambitious goals. The contrast level mandates the use of high-contrast imaging techniques to avoid the effects of astrophysical and fundamental noise associated with the star light. This push to longer wavelength requires pushing the boundaries of diffraction limit of monolithic telescopes by employing interferometry. Here, we discuss the choice of the nulling combiners which serve as coronagraphs for interferometers. We start by offering a brief explanation of the measuring principle, highlighting the fact that the measurement relies directly on the knowledge and control of the incoming wavefront, much as it does for coronagraphs. This prompts the implementation of high performance closed loop phase control on a separate beam path provided by a dichroic beamsplitter upstream of the nuller, in combination with an alternate technique to evaluate from measurements made at the science beam combiner an offset brought about by this non-common path. Since it must be performed outside of the the nulling configuration, this additional operation has a cost both in operational overhead, and in the specification of linearity for the beam control actuators. The low luminosity of rocky planets pushes the design constraints to maximize usable scientific throughput. After introducing a metric to quantify usable nulling throughput, we show how that maximal throughput is generally contradictory to combiner architectures providing real-time phase-sensing outputs. We then analyze how integrated optics triconplers have previously produced a form of compromise to that effect, and we propose a new bulk optics solution more suitable for the broadband mid-infrared bandwidth of possible LIFE space mission. This new variation of the modified Mach-Zehnder topology proposed by Serabyn¹ produces a pair of phase sensing outputs with near zero non-common path. It is optimal in that regard as it does so solely by recycling light that is already shed by its self-balancing property. As a result, we evaluate the sensitivity of such a device to input piston errors as a function of the elementary beamsplitter properties and show what can already be achieved by commercial off-the-shelf beamsplitters.

Keywords: nulling interferometry, high-contrast, exoplanet imaging, beam-combiner, fringe tracking, wavefront sensing

1. INTRODUCTION

The confirmed detection of thousands of exoplanets to date has given us a partial view of the large abundance and diversity of planetary systems around nearby stars. In most cases our knowledge remains limited to some orbital parameters in the case of radial velocity or transit methods. Obtaining information on their actual surface properties, temperature, and atmospheric composition has only been possible in a limited number of cases where

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the conditions were most favorable and remain limited by the combination of small angular separation and high contrast between host star and planet.

As stated in the Voyage 2050² senior committee report, investigating the conditions at the surface of small and temperate planets is becoming a priority. The large gathering power and good stability of the James Webb space telescope (JWST) has allowed transmission spectroscopy of planets around low mass stars, where the contrast is low enough, and the planned Ariel³ mission should extend this effort to a large number of hot giant planets. Yet this method is limited on multiple aspects. i) Only small fraction of planets offer a transit viewed from the Earth, which limits the sample of nearby systems. ii) The signal of interest is tiny fraction of the recorded stellar flux, which leads to a limitation by photon noise and stellar activity noise which become prohibitive for earth-like exoplanets.

In the contrast regime implied by temperate rocky exoplanets (10^{-7} - 10^{-10}), it is necessary to optically separate (i.e. resolve) the planet light from the star light before sending it to the spectrograph, by specialized devices such as coronagraphs or nulling interferometers. This approach are currently represented by ambitious space mission projects like Habitable Worlds Observatory (HWO) and the Large Interferometer for Exoplanets (LIFE). HWO is centered on a coronagraphic instrument and a large diameter telescope targeting visible light spectrum reflected by the planets. LIFE aims at obtaining thermal emission light from temperate planets in the mid infrared, which pushes the mission to an interferometer with baselines of tens of meters.

For both instrument concepts, the capability to overcome the large contrast between the star and the planets relies on the capability to channel on-axis light away from the science channel by a control of the phase of the wavefront gathered by its aperture(s). For the visible light, a contrast of 10^{-10} requires a wavefront control to about ~ 10 pm is required; for mid-infrared, a contrast of 10^{-7} requires a wavefront control of about ~ 1 nm. But the underlying physics and operating principles are shared.

To obtain this sort of precision and stability, active close-loops methods are used. While they are called adaptive optics in the case of continuous pupils and fringe tracking in the case of more sparse collectors, they share most of their properties and limitations. One of the key fundamental elements dictating the architecture of these high-contrast missions is a property that has seldom been expressed in the literature : the idea that rejecting starlight to collect planet light makes the instrument incapable to sense the wavefront errors that lead to parasitic leakage terms due to a sign degeneracy. This fundamental limitation and its workarounds have been pivotal in high-contrast instrument architecture.

An additional constraint is that rocky planets are small and even the most nearby ones only provide a handful of photons per second and per spectral channel and meter squared of collecting power. As a result, the throughput of the science channel remains a powerful design driver for the architecture.

With this work, we explore some of the compromise entailed at the heart of high-contrast instruments between wavefront phase sensing and throughput. We do this with considerations around the modified Mach-Zehnder nulling beam combiners which boast deep and achromatic nulling but for which the pair of bright outputs cannot be used for phase sensing. After proposing a design of such a combiner for integrated optics, we propose further modifications to allow fringe sensing without compromising on the throughput. We then proposes a numerical application with commercial off the shelf beamsplitters adapted for space-based mid-infrared nulling.

2. MODIFIED MACH-ZEHNDER NULLER

2.1 BASE PRINCIPLE

In nulling interferometry, the problem of diffracted parasitic starlight shifts from a continuous disc wavefront and can be reduced to the interference of two beams. The obtention of a dark hole is replaced by the obtention of a null with fewer degrees of freedom, as enforced by a single mode spatial filter, such as a waveguide.

Obtaining a deep interferometric null from a pair of collected beams be combined with a relative phase shift of π and that the science outputs receive precisely balanced contributions from both input beams. The modified Mach-Zehnder (MMZ) arrangement proposed by Serabyn and Colavita¹ showed in Fig.1 has been a leading solution put forward for several ground-based and space missions like the Keck nuller,⁴ DARWIN⁵ and TPF⁶ to guaranty balanced contributions over broad bands.

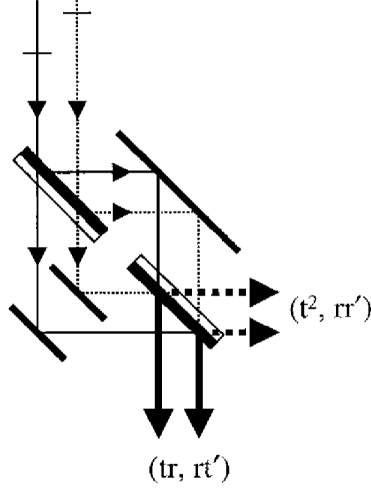


Figure 1. Optical schematic of the MMZ (credit Serabyn and Colavita, 2001¹) showing the different so-called symmetrical architectures compatible with equal mixing of the beams to the science channel.

Contrary to a normal Mach-Zehnder interferometer which works on a single input beam, the MMZ recombines two beams and the balancing of the contributions is obtained by having both beams pass twice in the beamsplitters, once in each direction. This way, both contributing beams are affected by a transmission and a reflection, giving them the same throughput as long as the beamsplitters have identical beamsplitting properties. As such, any imbalance inherent to the splitting affects throughput instead of null depth performance, as seen in section 2.2.

Given that such designs are meant to operate with a single mode spatial filter, this device may also be modeled as integrated optics. We propose such an equivalent design in integrated optics following the schematics of Fig. 2. The building block beam-combiners can be any of the classical technical solutions and can be modelled for an arbitrary wavelength by the matrix M_c :

$$M_c = \begin{bmatrix} \sqrt{\sigma} & -\sqrt{\tau}e^{-j(\Delta-\frac{\pi}{2})} \\ \sqrt{\tau}e^{-j(\Delta-\frac{\pi}{2})} & \sqrt{\sigma}e^{-2j(\Delta-\frac{\pi}{2})} \end{bmatrix}, \quad (1)$$

where σ and τ are the reflection and transmission coefficients for a beamsplitter, or the cross and bar coefficients for a photonic coupler, and Δ is the associated phase term.

The layout is used to compute the matrix of the global combiner:

$$M_{raw} = \begin{bmatrix} \sigma e^{-2.0j(\Delta-\frac{\pi}{2})} & -\sqrt{\sigma}\sqrt{\tau}e^{-3.0j(\Delta-\frac{\pi}{2})} & \sqrt{\sigma}\sqrt{\tau}e^{-3.0j(\Delta-\frac{\pi}{2})} & \tau e^{-2.0j(\Delta-\frac{\pi}{2})} \\ -\sqrt{\sigma}\sqrt{\tau}e^{-j(\Delta-\frac{\pi}{2})} & \tau e^{-2j(\Delta-\frac{\pi}{2})} & \sigma e^{-2.0j(\Delta-\frac{\pi}{2})} & \sqrt{\sigma}\sqrt{\tau}e^{-1.0j(\Delta-\frac{\pi}{2})} \\ \sqrt{\sigma}\sqrt{\tau}e^{-1.0j(\Delta-\frac{\pi}{2})} & \sigma e^{-2.0j(\Delta-\frac{\pi}{2})} & \tau e^{-2j(\Delta-\frac{\pi}{2})} & -\sqrt{\sigma}\sqrt{\tau}e^{-j(\Delta-\frac{\pi}{2})} \\ \tau e^{-2.0j(\Delta-\frac{\pi}{2})} & \sqrt{\sigma}\sqrt{\tau}e^{-3.0j(\Delta-\frac{\pi}{2})} & -\sqrt{\sigma}\sqrt{\tau}e^{-3.0j(\Delta-\frac{\pi}{2})} & \sigma e^{-2.0j(\Delta-\frac{\pi}{2})} \end{bmatrix} \quad (2)$$

This model can be used either to simulate an integrated optics device, or to simulate a bulk optics device using a single mode spatial filter.

2.2 NUMERICAL APPLICATION

Using this model, we can input the values of the individual component. Here, we propose a numerical application with commercial off-the-shelf beamsplitters offered by Thorlabs.⁷ These broadband beamsplitters, which properties are illustrated in Fig. 3 would be appropriate for a broadband space interferometer in the mid infrared from ~ 3 to $\sim 18\mu m$, but is limited by the transmission of the substrate above $15\mu m$.

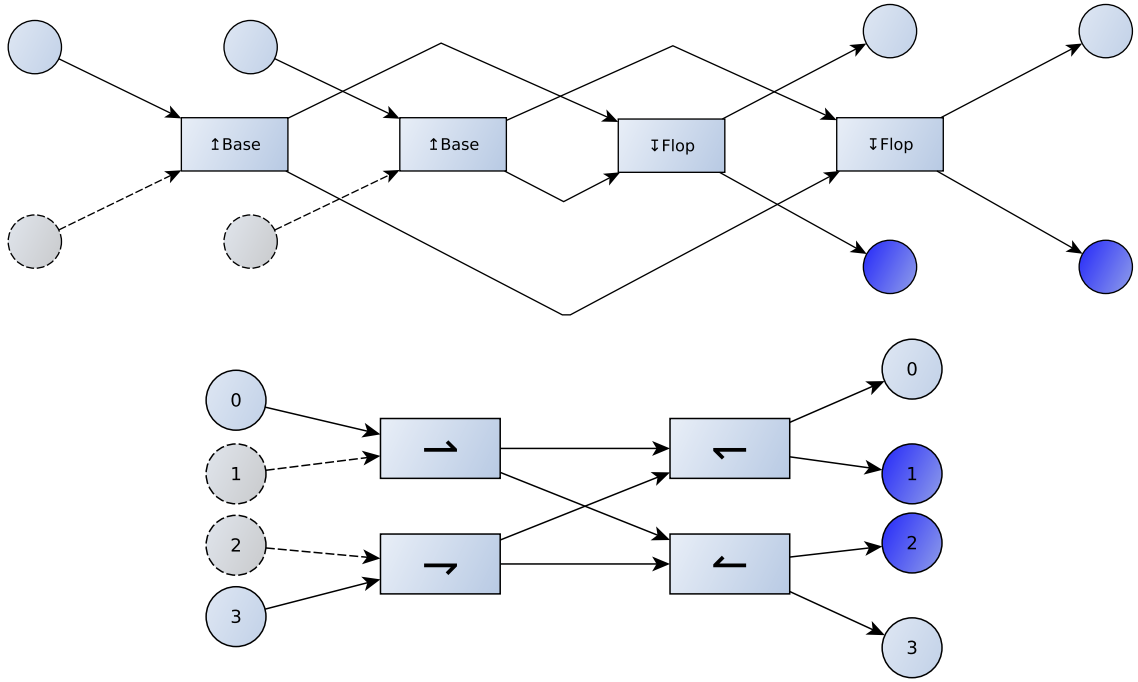


Figure 2. Top: Example layout of a integrated optics MMZ, best matching the bulk-optics configuration. The direction of the half-arrows indicate the orientation of the couplers. Bottom: a modified arrangement of the IO MMZ, minimizing the number of crossover between waveguides. This configuration highlights the overall symmetry. Outputs in dark blue are selected to be the balanced dark outputs.

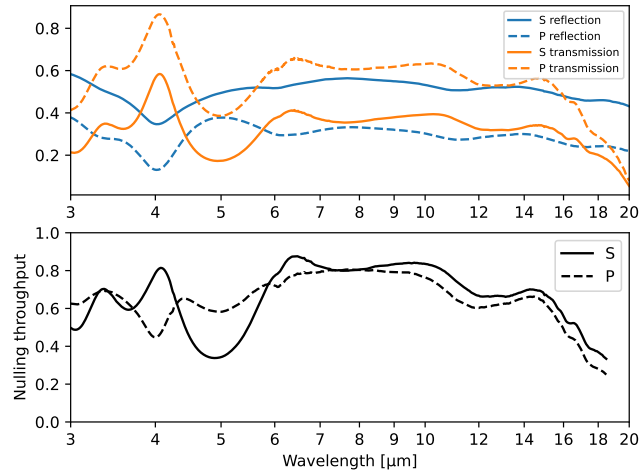


Figure 3. Top: the coupling coefficients of the initial elementary combiner. Bottom, the throughput on the science channel (i.e. dark channels) is related to the initial balancing of the coupling coefficients.

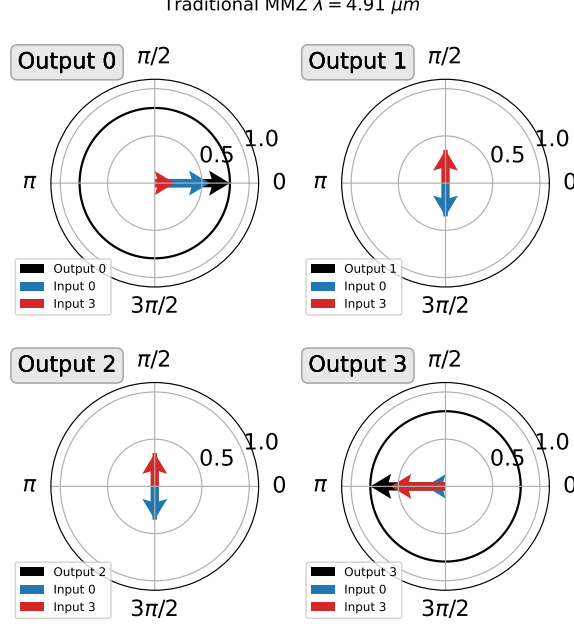


Figure 4. The initial IO MMZ at wavelength of $4.9\mu\text{m}$. By construction, obtaining nulls on outputs 1 and 2 leads to cophased sum at the outputs 0 and 3.

A numerical application of this beamsplitter model to equation 2.1, we can see that the chromatic imperfections to the initial balancing lead to drops in throughput instead null depth degradation. Although the transmission of the substrate itself make this plot harder to read, the effect remains visible in comparison between the two polarizations.

2.3 LEVERAGING THE BRIGHT OUTPUTS

To understand the behavior of a combiner, one can plot the complex amplitude transfer matrix, showing the complex phasors corresponding to the different contributions to the different outputs. The plot in fig. 4 shows that both dark outputs have perfectly balanced contributions onto the dark outputs. It also shows that the bright outputs contain imbalanced contributions of the inputs from which we would want to extract phase information to help close an optical path control loop. However we can see that those contributions are perfectly cophased when the contributions to the dark outputs are nulled. As a result, the first derivative of the output intensity I relative to phase φ around the null is zero:

$$\left(\frac{\partial I}{\partial \varphi}\right)_{\text{null}} = 0. \quad (3)$$

In other words, the phase information is degenerate on these two bright outputs.

However, since the contributions are imbalanced in opposite ways (input 3 is dominant in output 0 while input 0 is dominant in output 3), combining the two outputs together in an extra stage as shown in fig. 5 will break this degeneracy, while leaving the dark outputs untouched.

Indeed, in figure 6 the bright outputs which are now 0 and 1 are made up of a better balanced contribution of the same input, this time with a non-zero relative phase. Computing the first derivative of the differential output in this new configuration highlights the dependency of this metric of sensitivity to the piston p with the transmission and reflection terms.

$$\left(\frac{\partial I}{\partial p}\right)_{\text{null}} \propto \frac{\sqrt{\sigma\tau}(\tau^2 - \sigma^2)}{\lambda}. \quad (4)$$

This can be further illustrated by plotting the difference of output intensity ΔI for the combiner at different wavelengths of the model around the null, as shown on the right pane of figure 6. At piston 0, where the ideal

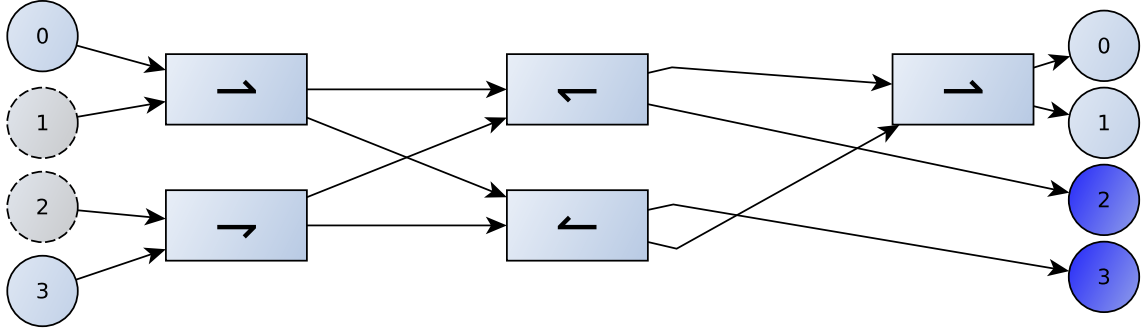


Figure 5. Layout of the proposed sensing architecture for a IO MMZ. Producing interference of the bright outputs offers is here more complicated than in the initial layout illustrated by Figure 2, as it requires crossing of the dark outputs, but mitigation strategies can be implemented.

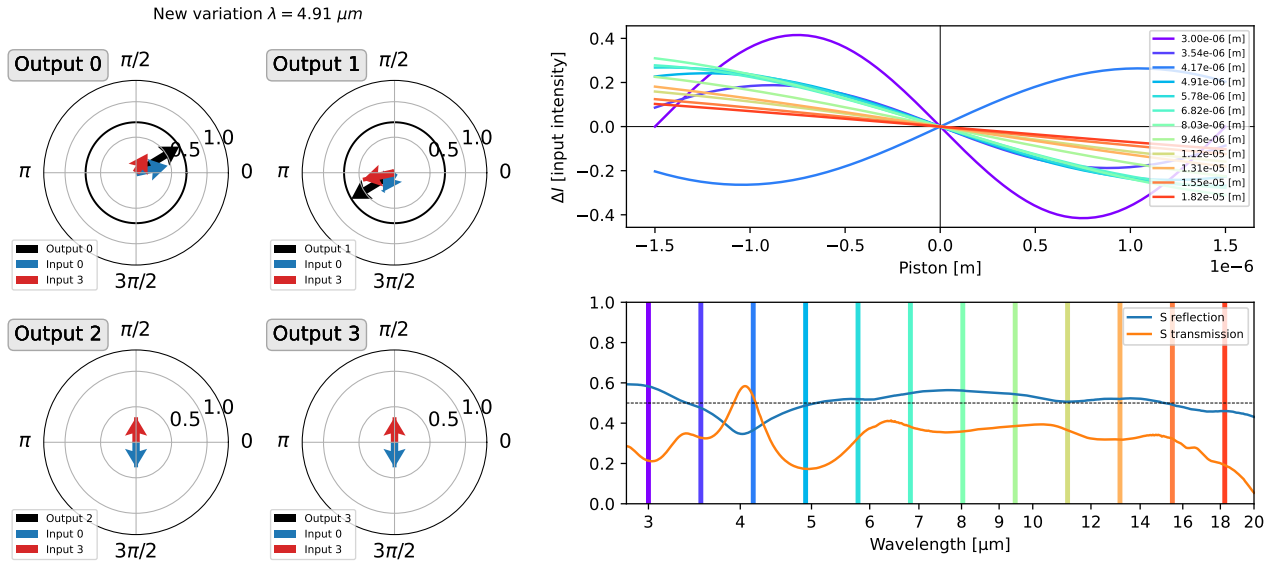


Figure 6. Left: The modified IO MMZ at $4.9\mu m$. With the modification the sum of contribution phasors of unequal modulus leads to coherent sums of different phases at outputs 0 and 1, lifting the degeneracy and allowing input phase sensing on these outputs. Right: the intensity difference $\Delta I = I_1 - I_0$ between the sensing outputs while the input optical path is scanned by $\pm 1\mu m$ around the null. For many wavelengths, the slope is small, but it becomes larger the farther away the individual couplers are from being balanced.

null is reached, the different wavelengths behave differently, and the wavenlengths that were most imbalanced in the elementary combiners have the highest first derivative to piston and are therefore the most sensitive to use for fringe tracking. This is especially visible at $\sim 4\mu\text{m}$ where the transmission becomes higher than the reflection, leading to an inverted derivative of the differential outputs.

This altered beam combiner architecture preserves the benefits of balanced dark outputs, but offers a non-degenerate sensitivity to optical path errors. Yet this sensitivity is obtained by leveraging imbalanced light that is shed from the science outputs. In cases where the beamsplitters are perfectly balanced, the bright outputs would be perfectly balanced, and their recombination would not lift the phase degeneracy.

3. CONCLUSIONS

The design of efficient and well-balance beam combiners is crucial for nulling interferometric observations of exoplanets and is paired with the need to fine tune and stabilize of the relative phase of the input beams is an additional challenge. Here we have proposed a new variation of the Modified Mach-Zehnder nuller which can be built either in integrated optics or in bulk optics.

Modelling this design reveals that the phase information on the bright outputs is normally degenerate, but that the degeneracy can be lifted by combining them together again. This offers new architecture possibilities both for integrated optics and for bulk optics combiners to leverage near common-path fringe sensing during science integration.

Numerical applications using commercial off-the-shelf beamsplitters, shows a direct dependency of the phase sensitivity with the initial imbalance of the splitter. This illustrates how the phase sensitivity comes at the cost of some potential off-axis throughput from the science outputs. This applies to a variety of combiners, including coronagraphs, which all make this compromise.

In the case of the MMZ nuller presented here, this cost is already paid in order to balance the contributions to the dark outputs, and is recycled for sensing. This combining scheme has been put forward for the Exoplanet Explorer mission concept⁸ and would be applicable to the LIFE space mission,⁹ as well as ground based beam-combiners such as Asgard/NOTT¹⁰ or the LBTI nuller.¹¹

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