PERSEE: description of a new concept for nulling interferometry recombination and OPD measurement

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ABSTRACT

Nulling interferometry requires, among other things, a symmetric recombination module and an optical path difference control system. The symmetric recombination stage has been particularly studied over the last ten years and several concepts are now well known. One of them is the "Modified Mach Zehnder" (MMZ) interferometer, proposed by Serabyn and Colavita (2001) [1]. In this paper, we describe a new version of the MMZ beam combiner which provides a deep null signal in the science channel and, at the same time, phase-sensitive signals in the so-called co-phasing channel. From the latter, accurate optical path difference measurements can be derived. This beam combiner works in the 0.8 to 3.3 µm spectral range (0.8 to 1.5 µm for the co-phasing channel and 1.65 to 3.3 µm for the science channel). Both optical functions can be implemented in the same device thanks to an original optical design involving dedicated phase shifts. In this paper, we describe its principle and detail the optical and mechanical design.

Keywords: PERSEE, Modified Mach-Zehnder interferometer, OPD, nulling interferometry, beam combiner, free flying

1. INTRODUCTION

Nulling interferometry is one of the direct detection methods assessed to find and characterize extrasolar planets and particularly telluric ones. Within this framework, several space based projects, such as Darwin [2;3], TPF-I [4;5], PEGASE [6;7] or FKSI [8], are based on free flying techniques with very stringent constraints on positioning and stability to reach the deep and stable rejection of central-star light required for exoplanets detection. Satisfying all these requirements is a great challenge and a key issue of these missions. Therefore, we decided, in the context of the PEGASE mission, to study this question experimentally. PERSEE (Pegase Experiment for Research and Stabilization of Extreme Extinction) [9] laboratory test bench has been under development since 2006 by a consortium composed of Centre National d'Etudes Spatiales (CNES), Institut d'Astrophysique Spatiale (IAS), Observatoire de Paris-Meudon (LESIA), Observatoire de la Côte d'Azur (OCA), Office National d'Etudes et de recherches Aéronautiques (ONERA), and Thales Alenia Space (TAS) who shared its experience on MAII [10]. It is funded by CNES R&D. The aim of PERSEE is to couple a nulling interferometer with a free flying Guidance Navigation and Control (GNC) simulator introducing realistic perturbations and correcting them with active internal loops controlling the optical path difference and the pointing. One of the key sub-systems of PERSEE is the recombination module which must allow, deep nulling and an optical path difference (OPD) control at the same time. ONERA is in charge of the accurate OPD-measurements subsystem (Fringe sensor (FS) channel) and develops a first simplified test beam combiner. IAS develops the deep nulling subsystem (scientific channel). The final beam combiner for PERSEE is developed jointly by IAS (master-builder), CNES and ONERA. In this paper, we present its working concept and the optical and mechanical design.

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2. BEAM COMBINER PRINCIPLE

The recombination stage of PERSEE has two functions. The first is to provide a nulled output to perform nulling interferometry in the IR “scientific” band (1.65 to 3.3 µm). The second is to generate four “ABCD” outputs [11] in the fringe sensor band (0.8 to 1.5 µm). The two-beam interference pattern is generally sampled in four quadratic points (π/2 phase-shifted). These quadratic points have special positions: two extrema and two inflexion points (Figure 1):

- D (Dark): the minimum corresponding to the dark fringe. It’s the working point of the nulling channel.
- B (Bright): the maximum corresponding to the second complementary output of the nulling channel.
- A (Ascending): inflexion point on the ascending front. It’s at this point that the intensity’s sensibility due to the phase-shift between the beams is maximum.
- C (desCending): inflexion point on the descending front, the sensibility of the intensity due to the phase-shift is also maximum here.

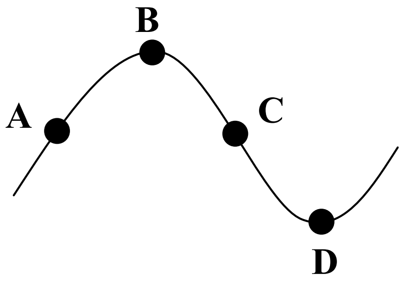

Figure 1: ABCD points of the interference pattern

The fringes have to be stabilized at the level of 1.0 nm rms. Both the scientific and FS bands share the same optical components. The integration of these two functions in the same module is one of PERSEE’s key points because it reduces the differential stability requirements between the co-phasing metrology and the nulling interferometer.

3. OPTICAL DESIGN OF THE BEAM COMBINER

To perform deep nulling interferometry we need a **symmetric** recombination module [1]. Several concepts have been studied over the last ten years such as the Michelson or Mach Zehnder interferometer. On the basis of the experience acquired on the IAS’s test bench SYNAPSE [12], we decided to develop an interferometer based on a modified Mach Zehnder (MMZ) geometry.

3.1 The Modified Mach-Zehnder geometry

The geometry of the Mach-Zehnder-like beam combiner was proposed by Serabyn and Collavita in 2001 [1]. It is an achromatic beam combiner, based on the Mach-Zehnder interferometer, in which there is an additional mirror to become a **double** beam combiner (Figure 2). This system allows an optimally symmetric beam combination in terms of phase, amplitude and polarization. Among the interferometric beam combiners, the MMZ is one of the simplest because it has a few mirrors. Thus it is more compact and has fewer reflections. This concept was tested during the study of the laboratory performance of the Keck Nuller [13]. It also was implemented and verified on the SYNAPSE test bench [12]. It produced a 10^{-4} nulling level in the K band. On PERSEE, we propose an improvement of this design to reach PERSEE’s requirements.

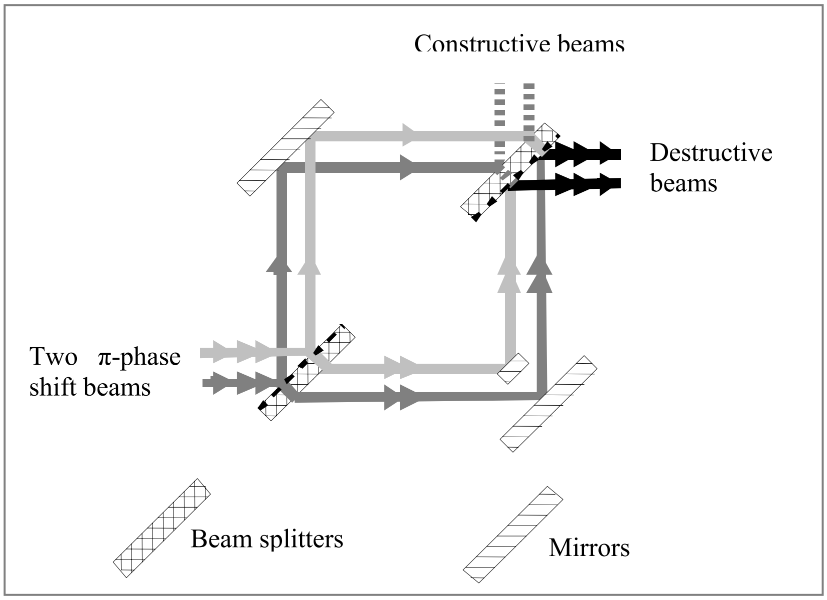

Figure 2: Modified Mach Zehnder interferometer geometry

3.2 PERSEE's beam combiner requirements

During the definition phase of PERSEE in 2006, a list of requirements was established for the recombination module. We will describe them here.

The module will work in the spectral range from 0.8 to 3.3 µm. The scientific channel covers the range from 1.65 to 3.3 µm (cut in 5 spectral bands) and the FS channel covers the range from 0.8 to 1.5 µm (cut in 2 spectral bands). In the infrared spectral band, the combiner is designed to reach an average null of 10^{-4} with a stability of 10^{-5} over a few hours. Moreover, it generates four outputs A, B, C, and D in the FS band. To produce the FS π/2 phase-shift, we introduce an optical path difference of $\lambda/4 \pm 50$ nm at $\lambda = 1$ µm between the BD and AC outputs. The stability of the AC optical path has to be better than 0.5 nm rms versus BD. The input beams have a diameter of 10 mm and the distance between them is 40 mm at the entry of the beam combiner. The module is as compact as possible, the dimensions not exceeding 400 x 300 x 100 mm^3.

From these specifications, we developed the dedicated optical design.

3.3 PERSEE's beam combiner optical design

The system is made of 4 beam splitters and 2 mirrors (Figure 3). We have chosen to modify the "Serabyn-Colavita" configuration somewhat [1] to obtain a more compact geometry. We have transformed the two "Serabyn-Colavita" mirrors into one and separated the entry beam splitter into two shifted beam splitters to maintain the symmetry of the concept.

The incident angle in Serabyn-Colavita's classical configuration is 45° [1]. This allows for a simple geometry, more compact and easier to align. However, in order to reduce differential-polarization effects between the two arms of the system, we impose a narrower reflection angle. Thanks to Frédéric Lermaquis' (Institut Fresnel, Marseille, France) studies, we conclude that 30° is the best angle for a good balance between s and p polarization transmission and reflection factors.

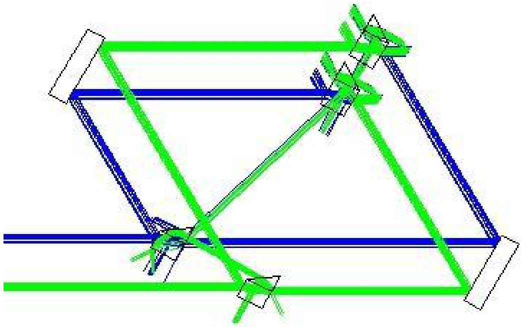

Figure 3: PERSEE’s beam combiner optical design

3.4 Beam splitters geometry

To avoid collinear stray light generated by parallel plates (Figure 4), we use special plate geometry. This concept has been proposed and successfully verified on the SYNAPSE test bed [12]. The idea is to combine a trapezoidal design (Figure 4) with an adequate plate thickness (>10 mm) in order to eliminate the major part of stray light parallel to the main beam.

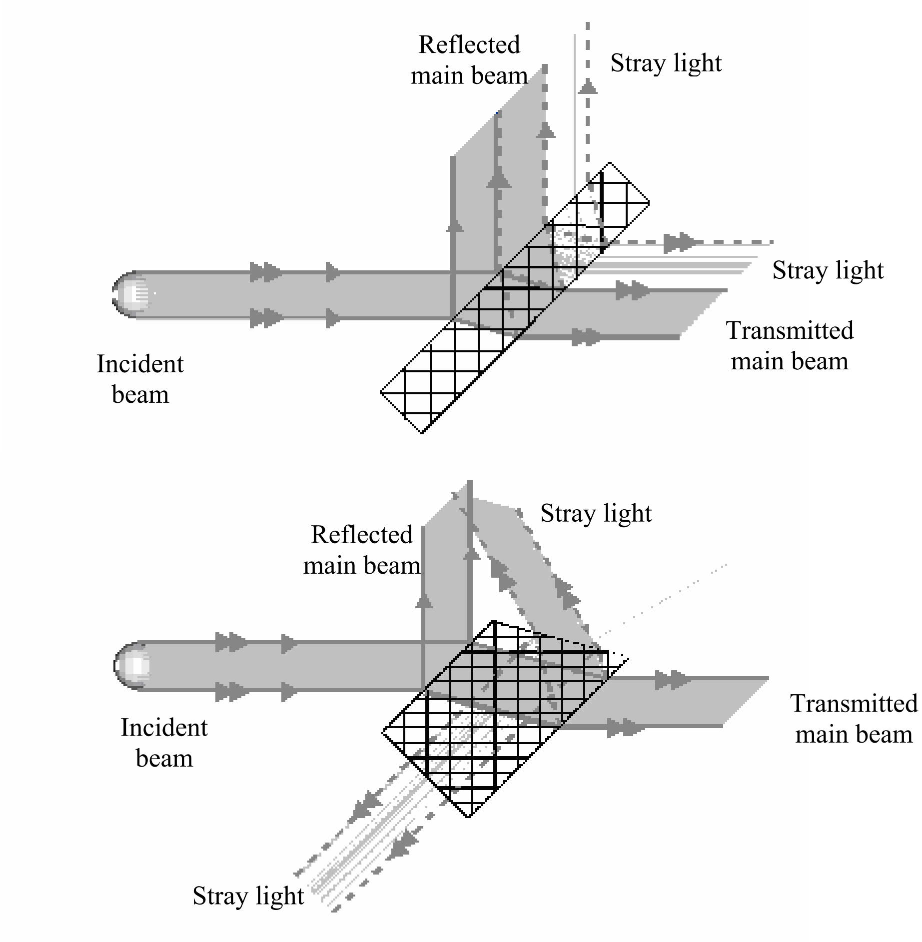

Figure 4: Parallel-plate geometry (top) and Trapezoidal geometry (bottom)

Thanks to this particular geometry and a appropriate positioning of the incident beam on the entry face of the plate, the main part of the internal stray light is rejected toward the plate's edges or in a direction other than the useful beam.

3.5 Substrates and coatings

Concerning the plate substrate, as the spectral domain ranges from visible to infrared (0.8 to 3.3 µm), two materials seem to be particularly appropriate: CaF_2 ($n \approx 1.4$ at $\lambda = 2$ µm) and ZnSe ($n \approx 2.4$ at $\lambda = 2$ µm). We have chosen CaF_2 because it has the advantage of having a low index of refraction. This allows avoiding anti-reflective coatings on the reverse surface of the plates. For the mirror substrate, we have chosen Zerodur because of its extremely low thermal expansion coefficient.

Concerning the plate coatings, we need to deal with the whole spectral range applying a minimum number of layers (inferior to 10). The *rt* product has to be greater than 0.17 between 1.65 µm and 3.3 µm and greater than 0.12 between 0.8 to 1.5 µm in order to reach the intended performance. A study has been carried out by Frédéric Lermarquis to find the best trade-off between the materials and the number of layers. The ideal pair is ZnS ($n \approx 2.2$ at $\lambda = 2$ µm) and YF_3 ($n \approx 1.4$ at $\lambda = 2$ µm), but to cover the whole spectral domain, a complex stack formula and a high number of layers is needed. It would be very difficult to realize. The study has shown that we could considerably simplify the coating by using silicon as high-index layers (but this leads to absorption losses under 1.2 µm).Therefore, we have opted for a three-layer Si-YF_3 coating (Figure 5) with a few 0.1 nm rms uniformity of the layer thickness.

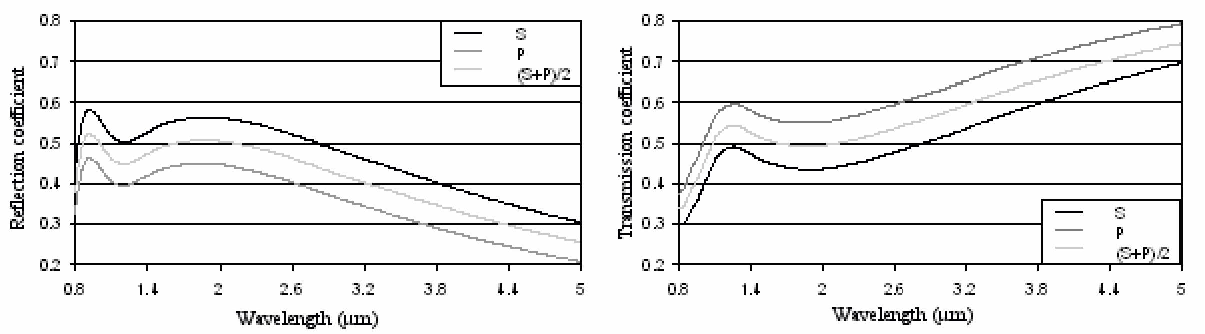

Figure 5: Reflection (left) and transmission (right) coefficients for a three-layer Si-YF_3 coating with an incidence of 30°.

For the mirrors, we use non-protected gold with a reflection coefficient better than 0.97 in the whole spectral range.

4. MECHANICAL DESIGN

4.1 Requirements

To determine the different specifications (optical, positioning, mechanical and thermal) we compute two models of the optical design. One model is made using Zemax software and the other is an IDL routine. The IDL model is less developed than the Zemax one. Its goal is to check and compare the results of the other model. The two models allow to introduce alignment and positioning errors, and differential thickness between two beam splitters. Zemax model allows, furthermore, to introduce defaults in the layer thickness of the coatings and thermal effects (dilation due to temperature increase). All these simulations have allowed us to determine the specifications and the maximum positioning tolerances that the beam combiner could accept in order to achieve the predicted performances. Thanks to an appropriate design, we could minimize the differential OPD between IR and SF channels and make the system intrinsically very stable.

4.2 Concepts

The mechanical and thermal stability is crucial for our beam combiner, thus, a study of several mechanical concepts is currently under way. A first solution is to develop a design where the optical components are assembled by molecular adherence. This approach, however, has the advantage and the drawback of making further adjustments impossible after the adhesion. A second solution is a custom mechanical design with dedicated plates, allowing adjustment without loosing the alignment. We want a maximum of 50 alignment sequences during the lifetime of PERSEE.

5. CONCLUSION

PERSEE's beam combiner optical design is now well-defined. It is based on a modified Mach-Zehnder interferometer. The system is designed to combine a nulling beam combiner and a fringe sensor. We have determined all the optical and mechanical specifications. Work on the mechanical design is currently in progress. The manufacturing of the optical components will begin in June 2008 and the whole system should be ready for test in January 2009. ONERA's prototype for FS channel [14] validation will give its first results this Summer.

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REFERENCES

[1] Serabyn, E. and Colavita, M. M., "Fully Symmetric Nulling Beam Combiners", *Applied Optics* **40**, 1668-1671 (Apr. 2001).

[2] Léger, A., et al., "Darwin: Mission concept for the ESA Horizon 2000+ program", ESA, 1993.

[3] Léger, A., et al., "Darwin, a proposal for Cosmic Vision 2015-2025 ESA Plan", ESA, 2007.

[4] Lawson, P. R. and Dooley, J. A., "Technology plan for the Terrestrial Planet Finder Interferometer", JPL 05-5, NASA, 2005.

[5] Angel, J. P. R. and Woolf, N. J., "An Imaging Nulling Interferometer to Study Extrasolar Planets", *ApJ.*, **475**..373A (1997).

[6] Ollivier, M., et al., "PEGASE: an infrared interferometer to study stellar environments and low mass companions around nearby stars", proposal for Cosmic Vision 2015-2025 ESA Plan, ESA, 2007.

[7] Le Duigou, J. M., et al., "PEGASE: a space-based nulling interferometer", *Proc. SPIE* **6265**, pp. 62651M (2006).

[8] Danchi, W. C. and Lopez, B., "The Fourier Kelvin Stellar Interferometer (FKSI) – A practical infrared space interferometer on the path to the discovery and characterization of Earth-like planets around nearby stars", *Comptes Rendus Physique* **8**, 396–407 (Apr. 2007).

[9] Cassaing, F. et al., "PERSEE: a nulling demonstrator with real-time correction of external disturbances", *To be presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **7013**, paper 7013-70 (June 2008).

[10] Weber, V., Barillot, M., et al., "Nulling interferometer based on an integrated optics combiner", *Proc. SPIE* **5491**, pp. 842-850 (2004).

[11] Shao, M., Colavita, M. M., et al., "The Mark III Stellar Interferometer", *Astronomy and Astrophysics* **193**, 357-371 (1988).

[12] Brachet F., Etude et développement d'un déphaseur achromatique pour l'interférométrie en frange noire, PhD thesis, University of Paris-Sud (XI), 2007.

[13] Mennesson, B., et al., "Laboratory performance of the Keck Interferometer nulling beam combiner", in Towards Other Earths: DARWIN/TPF and the Search for Extrasolar Terrestrial Planets, ed. M. Fridlund & T. Henning (ESA SP-539; Noordwijk: ESA), 525-528.

[14] Houairi, K., "PERSEE, the dynamic nulling demonstrator: recent progress on the cophasing system", *To be presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **7013,** paper 7013-67 (June 2008).