REVIEW OF CONCEPTS AND CONSTRAINTS FOR ACHROMATIC PHASE SHIFTERS

Yves Rabbia [(1)], Jean Gay [(2)], Jean-Pierre Rivet [(2)], Jean-Louis Schneider [(2)]

[(1)] Observatoire de la Côte d'Azur, Av Copernic, 06130 Grasse, France
rabbia@obs-azur.fr

[(2)] Observatoire de la Côte d'Azur, BP 4229, 06304, Nice, France
gay@obs-azur.fr, rivet@obs-azur.fr, Jean-Louis.Schneider@obs-azur.fr

INTRODUCTION

The search for earth-like exoplanets requires nulling interferometry in the thermal infrared domain. Nulling is needed because the star overshines the planet and the starlight must be eliminated. Thermal infrared is selected so as to record the light radiated by the planet itself , not the one from the star, reflected by the planet, but also because the flux ratio between star and planet is fainter than in the visible. Search for "life" (as known on Earth) requires large bandwidth observation so as to allow spectroscopy [1]. Achromatic Phase Shifters (APS) are crucial components since they govern destructive interference of the lightwaves collected from the star. The effective phase shifts to perform between collected lightwaves depends on the instrumental configuration but the achromaticity of the phase shift is needed in any case so as to achieve the nulling over the largest possible spectral bandwidth, what is required for detection of the planet (signal to noise ratio) and for its spectroscopic study as well.
Since several concepts have been devised for Achromatic Phase Shifting, it is important to consider them before selecting the appropriate device in the framework of a nulling interferometry project. Some of them are an extension of concepts already used in optical instrumentation, some others have been specifically devised for large bandwidth nulling missions. Others incidentally revealed applicable to the topic.
In this paper we report on various types of APS's, found in the literature. We recall the general constraints to satisfy, the underlying principle, and the critical points pertaining to their use over large bandwidths in the infrared thermal domain for nulling interferometry.
The topic is considered in the framework of a space mission since the constraints to meet are covering the ones encountered in ground-based nulling projects, at the exception of the thermal background.
Basically two families of concepts are found in the literature : the ones using materials through which light is made to travel, the others using mostly mirrors and properties of reflection.
In section 1 we recall the context of use and the required performance and the related meaning of achromaticity.
In section 2 we describe the main concepts, in section 3, the state of the art is given and critical points are delineated in section 4.

1. PHASE SHIFTING IN THE CONTEXT

1.1. The Context

In this paper we consider the case of a N-aperture space-based interferometer. Actually the problem remains to perform a given phase shift between a two-aperture interferometer. The targeted phase shifts depends on N and on how the collected beams are combined to interfere. Expectable values of the targeted shift are π and $\pi/2$ and any arbitrary fraction of π. A small departure from those values could be targeted for reasons external to the APS itself.
Typically (Earth-Sun) the ratio (flux from star)/(flux from planet) in thermal infrared is about 10^6, so the destructive interference must reject the light from the parent star at this level. Stating R = (collected flux)/(non-rejected light) to quantitfy the rejection, the context then requires R to be larger than 10^6.
As already mentioned, this performance must be achieved over the whole spectral domain of work. On DARWIN this domain extends from 6 μm to 18 μm and could even be extended longward (H2O band).
For some reasons (fiber optics and else) this domain could be splitted and covered piecewise. This would release the constraints on achromaticity but correlatively would increase the complexity and weight of the recombining device.

So that, splitting the spectral domain must be considered at the latest stage of the chain and achromaticity over the whole bandwidth must be kept in mind as a prime goal.
Beside the need for the highest rejection of the parent star, stands the need for the highest transmission of the photons from the planet. A transmission not less than 0.95 is currently aimed at. This latter implies that both polarisations have to be transmitted, in other words, that the nulling process is able to work in a dual-polarisation mode.
Be it for space-based or for ground-based instrumentation, the mission context requires to take into account the coupling of APS's with the interferometric infrastructure. Though the APS's are considered for themselves and as working with stabilised beams (pupilla position and beam direction) this point is to be looked at in terms of "how a given concept would be sensitive to departures from ideal beams ?".

1.2. Phase Shifting Requirements

Achieving a given rejection R at a given wavelength implies that several conditions must be satisfied by the interfering lightwaves. These conditions regard the accuracy of the performed shift, the equality of intensities, the accuracy of the alignment of polarisations, the stability of optical paths on each beam.

1.2.1. General Constraints regarding Rejection

The monochromatic intensity after recombination (residual intensity from nulling) is given by the general and quite familiar expression, as used in [2]:

$$I_{null} = I_1 + I_2 + 2.\sqrt{I_1.I_2}.\cos(\pi + \phi) \tag{1}$$

where I_1 and I_2 are intensities on respective beams, suffering from defects mentionned above and where ϕ is an extra phase resulting from unaccurate shift and optical path misbalance. Stating $I_2 / I_1 = \beta$ and $I_1 = I_0$ (the collected intensity on each beam), we write :

$$I_{null} = I_0 .(1+\beta).[1 - \frac{2.\sqrt{\beta}}{1+\beta}.(1 - \frac{\phi^2}{2})] \tag{2}$$

and finally $R = 2.I_0 / I_{null}$

From (2) and considering separately the defects, we find that to maintain R ≥ R_{target} we must restrict the phase defect ϕ (with $\beta = 1$) such as $\phi \leq \sqrt{\frac{2}{R_{target}}}$ radian, and the amplitude mismatch (with $\phi = 0$) such as $\beta \geq 1 - \frac{2}{\sqrt{R_{target}}}$

Looking at R_{target} = 10^6 we extract some numerical estimates of constraints for each separate defect.
Phase shift departure must not exceed 10^(-3) radian, optical paths must be stable at the nanometer level, ratio of intensities must not depart from unity by more than 2.10^(-3) and polarisation misalignment by θ (one lightwave to the other) must be such that $\theta \leq 10^{-2}$ rad.
Since defects are not likely to occur alone, those constraints have to be made more severe, as a rule of thumb they have to be scaled by the number of defects, or conversely the target rejection has to be scaled up accordingly.

1.2.2. Impact of Achromaticity

The constraints derived here above ignore the wavelength. Achromaticity is obtained when rejection remains larger or equal to the target rejection whatever the wavelength is (in the relevant spectral domain). A safe way to reach achromaticity is to reset the constraints given above with a majoration of the chromatic quantities ϕ and β, in other words we state $\phi = Sup_{\Delta\lambda}(\phi(\lambda))$ and $\beta = Sup_{\Delta\lambda}(\beta(\lambda))$, where $\Delta\lambda$ is the working wavelength interval.
Fig. 1 illustrates the case for a departure ε with respect to the target phase shift and shows how severe can be this choice, up to make mandatory the splitting of the spectral interval. Another approach, more tolerant, could be to use the average of ε(λ) over Δλ.
Thus, the impact of achromaticity concerns either the setting of constraints for a given targeted rejection or the evaluation of the rejection effectively achievable taking into account the bandwidth.

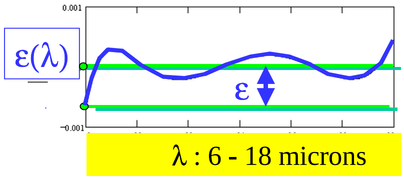

Fig. 1. An exemple of variation of the phase shift error ε(λ) versus the wavelength. The maximum error ε depends on the selected spectral interval,and can be lowered by splitting the total interval in parts, each having its own error profile and maximum error..

Another impact regards the assessment of performance of various APS's concepts and their comparison. In order to quantify the achromaticity capability, a criteria could be the product (rejection).(concerned bandwidth / total bandwidth) that could be noted "achromatic rejection criterium".

1.2.3. Other Constraints

As already mentioned constraints are set by the interface with the interferometer configuration in which unavoidable unstabilities related to pointing and to pupilla position have to be considered. Another constraint regards the wavefront quality, in other words aberrations that must be minimized, be it at the price of photons.
Also constraints are set by the mission environment in flight (temperature, outgassing, ...) and before flight (thermal cycles, vibrations). So that Robustness and compactness have to be considered. Actually those aspects should not be the concern of the APS designers but it must be kept in mind that the less sensitive to those unstabilites, the better the APS's concept.

2. EXAMPLES OF APS CONCEPTS

2.1. Tentative Classification for APS's

In the framework of nulling interferometry, the various phase shifter concepts found in the literature can distributed in families and splitting the list can be made from different points of view.
A first sorting regards absolute and differential concepts. The former shifts the phase of a wavelight on a unique beam, while the other needs to deal with two beams and performs the phase shift at recombination. Such a distinction is not really relevant here since components must be inserted on each beam at least to accurately balance the opticals paths.
Another distinction regards the origin of the phase shift. Essentially we find concepts in which light travels through optical materials and concepts where light only sees mirrors. In the former case the phase shift process implies that optical properties of material governs the shift, whilst in the other only properties of reflexion on mirrors are involved.
Eventhough mirror-only concepts might use some travel of light through materials, their optical properties are not governing the phase shift process.
An additional distinction has to be made regarding the operating phase shift and regards the choice, discrete or continuous, of the shift value. The continuous choice allows selecting any fraction of π. In this respect it does not appears as being that important since π and π/2 seems to be the prime targets, but it might reveal important especially if small offset from this values reveals necessary to achieve.
Finally APS's differs regarding the origin of achromaticity : intrinsic achromaticity or compensated chromaticity. In the former case the phase shift is "by nature" independant of wavelength whilst in the other achromaticity results from competing effects suitably dealt with.

2.2. Concepts based on Optical Properties of Materials

In this group we find classical concepts, already used in optical engineering and which performance must be made suitable for nulling at high achromatic rejection.

2.2.1. Fresnel's Rhombs

Fresnel's rhomb are rather standard components used to achieve a relative phase shift ϕ (generally π/2) between s and p polarisations of the incident field. They rely on properties of total reflexion, described by Fresnel's formulae [3] what involves the relative refractive index $n = n_{vacuum} / n_{material}$, (implying n < 1) and the incidence θ_i of the beam.

The relative phase shift $\phi = \phi_p - \phi_s$ is given by the formulae [3] :

$$\phi = 2.\tan^{-1}\left(\frac{\cos\theta_i.\sqrt{\sin^2\theta_i - n^2}}{\sin^2\theta_i}\right) \tag{3}$$

This formulae applies as soon as the incidence is larger than the limit incidence set by $\sin\theta_{\lim} = 1/n$. The phase shift is achromatic except that a wavelength dependancy remains in "n" but works at second order. Besides, its variation versus incidence has a maximum $\phi_{\max}$ for $\theta_{\max}$.
From proper choice of incidence and refractive index of the material a continuous set of phase shifts, but gradient $\partial\phi / \partial\theta_i$ increases when θ_i is not located near $\theta_{\max}$, and tolerance on pointing reduces accordingly.
As suggested by Title & Rosenberg, 1981 [4] a phase shift by π is achievable by coupling two regular Fresnel's rhombs each giving a π/2 relative phase shift for a linear polarisation at azimuth 45° (see Fig.2).
In a nulling scheme with two beams, this couple is set on one arm but some material must be inserted on the other arm so as to balance the optical paths. However, only one direction of polarisation would be then usable. A specific arrangement (J. Gay, unpublished) is able to achieve at recombination, a π phase shift working with any polarisation (hence in dual-polarisation mode). Fig.2 schematically summarizes the comments given here above.

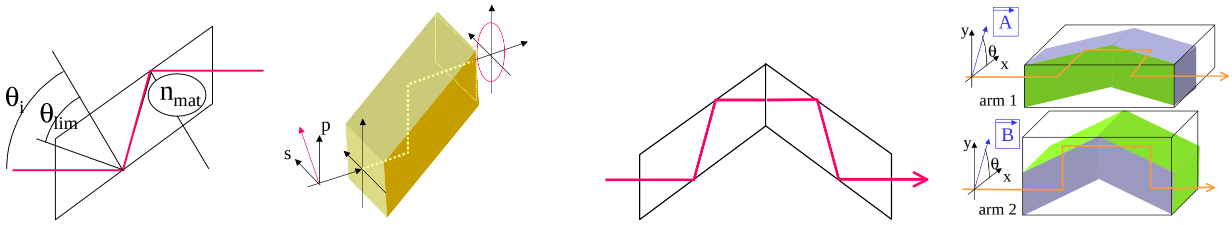

Fig. 2. Extreme left and center left : generic and frequent use of Fresnel's rhomb. Center right : cascading two regular Fresnel's rhombs. Extreme right : the specific "orthogonal" disposition for nulling in dual polarisation mode.

2.2.2.Composite or Twisted Rhombs

Especially devised for nulling and to achieve achromatic phase shifts other than π or π/2 (J. Gay, unpublished) this concept is based on total reflexion. It uses, on each intrerferometric arm, a couple of isoscele prisms having unequal refractive indexes and being assembled in such way that the lightwave meets successively two planes of incidence each perpendicular to the other . Such a "composite rhomb" or "twisted rhomb" makes this approach somewhat departing from the Fresnel rhomb phase shifters.
When traveling through the prism the lightwave experiences a chromatic phase shift resulting from propagation in a dispersive material to which is added an achromatic phase shift induced by total reflexion. This latter depends on the polarisation of the incident wave.
This concept is differential and the final shift obtained at recombination is governed by the geometry of the rhombs (to control both incidence and pathlengths) and by proper choice of the refractive indexes of the two materials.
Fig.3 describes schematically the device. As reported in [2] the final phase shift ϕ is given by

$$\phi = \phi 1 - \phi 2 = \tfrac{2.\pi}{\lambda}.[(n_1 - n_2).(d_1 - d_2)] + (\phi_{p1} + \phi_{s2} - \phi_{s1} - \phi_{p2}) \tag{5}$$

where d_1 and d_2 are optical paths in respective prisms, ϕ_{p1} and similar, pertains to achromatic phase shifts for a given polarisation and a given material.

As soon as we have the same geometry for the two "rhombs" ($d_1=d_2$), the chromatic terms mutually cancel. The remaining terms are achromatic and their values are governed by the angles of incidence and by the refractive indexes (n_1 and n_2) according to Fresnel's formulae for total reflexion [3].
By proper selection of materials and incidences a given value of phase shift can in principle be achieved.
Only single polarisation mode is usable with this concept.

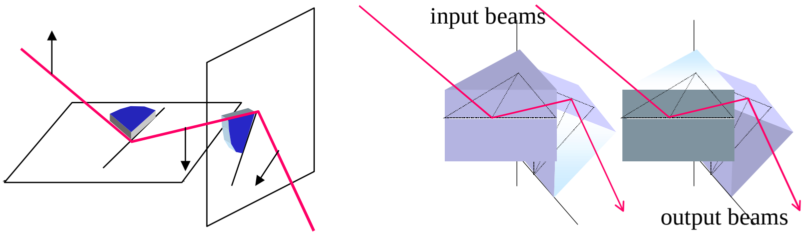

Figure 3. Schematic description of the principle. Left : the two successive incidence planes in a rhomb are made orthogonal (permutation of p and s polarisation). Right : dealing with two beams and permutation of materials from one rhomb to the other.

2.2.4. Birefringent Plates

Birefringent plates are commonly used to dephase a linearly polarised quasi-monochromatic lighwave (quaterwaves plates, halfwaves plates). In order to work with non-monochromatic light various devices have been devised and used as "achromatic phase shifters",[4], [5],[6],[7],[8],[9],[10],[11].
The basic principle, recalled in [2], is to use a cascade of retardation plates, so as to perform a sequence of polarisation changes, each providing a chromatic phase shift. The net result, from competing opposite effects, is a constructed quasi-achromatic phase shift. The formalism of Jones' matrixes provides the algebra of the process [7],[10]. The Poincaré sphère [4], [5],[6] is a convenient graphical way to tackle the principle : each polarisation state is represented by a point on the sphere and any polarisation change (including an achromatic change of the "geometric phase") is represented by an arc over the sphere, the length of which is proportional to the phase change. In cas of a cyclic change the phase shift is given by the solid angle subtending the circuit. Unequal lengths from chromatic changes are dealt with in such a way that, after a sequence of changes, the endpoint is not wavelength dependant (or nearly independant). Fig. 4 describes the way Poincaré sphère is used and Fig.5 shows an arrangement of plates and the corresponding paths on the Poincaré sphère.
Such arrangements, under the generic name "geometric phase approach" can be built from a set of usual retardation plates given suitable orientations of neutral axis or from a set of especially designed birefringent plates of various materials, with definite thicknesses and orientations of neutral axis [7],[10].
This concept is absolute and allows achieving any value of phase shift with the capability of fine tuning. Its use on a two-beam interferometer is possible [8],[9],[11]. Let us note that the birefringent approach does not allow working in the dual-polarisation mode. A scheme might be devised to release this limitation but is apparently not published.

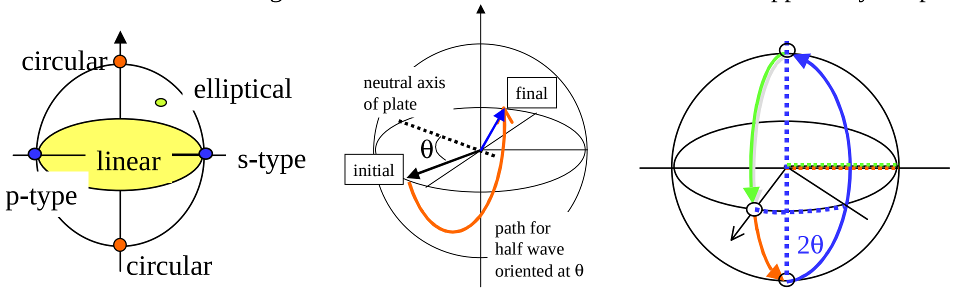

Fig.4. Schematic description of the use of the Poincaré sphére. Left : location of various polarisation states. Center : relation between neutral axis and geometric phase shift. Right : exemple of a close-path yielding a given phase shift ($2.\theta$)with quarterwave and halfwave plates suitably oriented

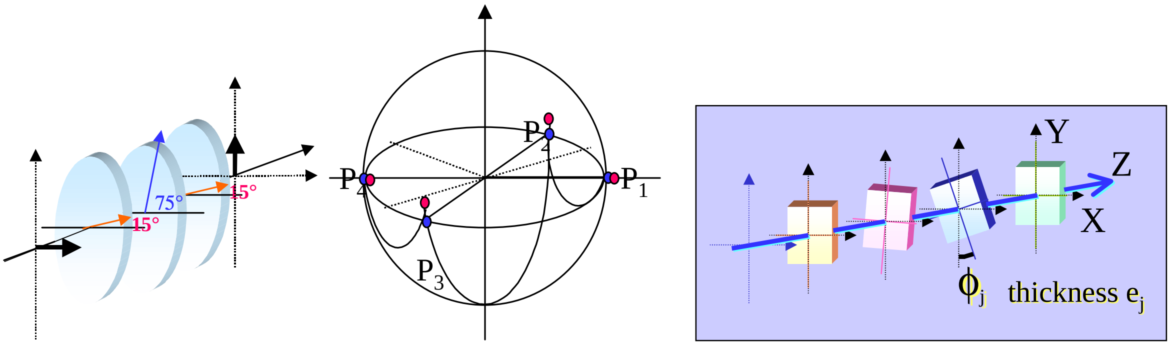

Fig.5 Examples of use of birefringent plates. Left : use of standard (λ/4 and λ/2) retardation plates [4]. Center : behaviour of chromatic phase changes ending at a unique point for all wavelengths. Right : use of a sequence of dedicated plates (material and thicknesses) and orientations [7],[10].

To increase the bandwidth over which achromatism applies (or to make the shift more accurate) the number of plates can be increased (more parameters to adjust the shift as achromatic) but this is done at the expense of energy losses.

2.2.5. Dispersive Plates

This concept [12], [13], [14], uses a cascaded plates with different and competing dispersions $\partial n / \partial \lambda$ and through which light is travelling. It is a convincing example of compensated chromatism : the goal is to achieve a global optical path proportional to wavelength so as to compensate for the 1/wavelength dependancy of the phase shift induced by travel through material. As reported in [12] the expression of OPD for a set of K plates indexed by k is given by :

$$\mathrm{OPD}(\lambda) = d_0 + \sum_1^K (n_k(\lambda) - 1).d_k \tag{6}$$

where d_0 is the OPD when no plate is inserted, d_k and n_k respectively are the thickness and the refractive index of the element number k. Being given a target value ϕ for the phase shift, the residual shift $\varepsilon(\lambda)$ is expressed by :

$$\varepsilon(\lambda) = \frac{2\pi}{\lambda}.\mathrm{OPD}(\lambda) - \phi = \frac{2\pi}{\lambda}.[d_0 + \sum_1^K (n_k(\lambda) - 1).d_k] - \phi \tag{7}$$

For a given arm, after selecting the spectral range (λ_1, λ_2), the target value ϕ, the number of plates K, and the materials (giving the n_k), it is possible to find the deeper residual dwell, by the least square method applied on the d_k's. Actually the parameter to minimize is expressed by :

$$\Gamma = \left[< \varepsilon^2 > \right]^{1/2} \quad \text{where} \quad < \varepsilon^2 > = \frac{1}{\lambda_2 - \lambda_1} . \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda)^2 . d\lambda \tag{8}$$

and the process works by getting the condition : $\partial\Gamma / \partial d_k = 0$ to be satisfied for every k.

Fig.6 gives a candid description of the cascade. Actually in order to avoid problems of spurious light and to eliminates sensitivity to beam unstabilies, a better design is employed and relies on prismatic components.

A complete and updated description of the approach used by Bokhove and co-workers [12] is given in the paper by H. Bokhove in these proceedings, to which the reader is invited to refer.

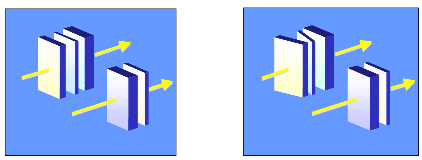

Fig. 6 : A candid description of the set-up using dispersive plates [12]. Left : sequence of plates on each arm. Right : fine tuning from thickness adjustment by tilting plates.

2.3. Concepts using Properties of Reflection

By contrast with most of the concepts mentioned in the preceeding section, the mirror-only approaches have been devised for nulling experiments. They are based on intrinsically achromatic properties of the reflection of light. The usual achromatic behaviour found when using mirrors has been the leading idea for their conception.

One approach, (field reversal) is developped by Serabyn and co-workers [15], [16], [17], [18] the other (focus crossing) is developped by Gay and co-workers from the core process used in the Achromatic Interfero Coronagraph [19], [20], [21].Details are given in the dedficated paper "the mirror approach" in these proceedings by the present authors.

2.3.1 Electric Field Vector Reversal

The principle is based on the properties of light at reflection, showing unidentical behaviours for the s and p components of the electric field of the incident light (s for perpendicular to incidence plane) : the s component undergoes a dephasing by π at reflection and not the p component, as described by Fresnel's formula [3] :
No need to recall the formulae, since the point is that for the s component a minus sign is present, or equivalently an achromatic phase shift by π.
A sequence of reflections on a couple of periscope-like set-ups is the basis to perform an achromatic π-phase shift between two lightwaves. As illustrated in Fig. 7, this concept is differential and the targeted phase shift operates only at recombination.

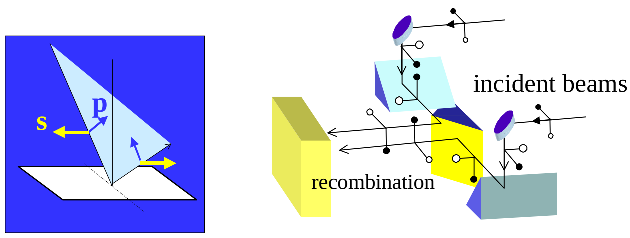

Fig. 7.Behaviour of polarisations in the field reversal concept. Left : the basic process.
Right : arrangement of reflections leading to opposite polarisations of each type, before recombination [18]

Actually this concept is not simply a phase shifter but also includes the recombination scheme, which provides two nulled outputs. The functional description of this approach can be graphically summarized as shown in Fig.8 (constructive output are not showed). In Fig. 8 also appears the recombination set-up designed to be fully symmetric and so to avoid degradation of nulling efficiency caused by beamsplitters [18]. On each beam, lightwave experiences the same set of interactions with the non-symmetric beamsplitters BS1 and BS2, placed in reverse positions.
This concept, by nature, seems to be limited to a π phase shift. However, recent work by Tavrov et co-workers [23] has shown that a $\pi/2$ achromatic phase shift is achievable by an "out-of-plane" configuration

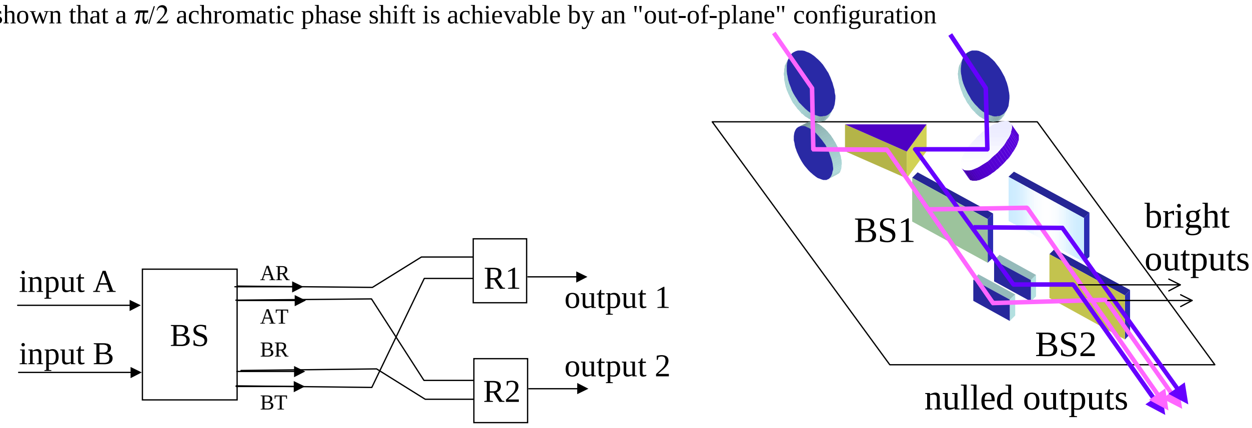

Fig. 8. Recombination scheme. Left : the functional process.Each incoming beam meets a beamsplitter (BS) which delivers a reflected part and a transmitted part. The set-up is made to simultaneously mix reflected, transmitted, A and B contributions as shown. Right : A global schematic view of the set-up.

2.3.2. Focus Crossing

This concept uses an intrinsically-achromatic approach, with a mirrors-only set-up. It is intended to provide a fixed phase shift which can be either π or π/2 depending on the selected design. Though it can work as an individual phase shifter on a single beam, the dephasing process is inserted in a recombining scheme yielding two nulled outputs.
The principle is based on an achromatic property of light : a lightwave crossing a focus experiences a phase shift by π whatever the wavelength. Inserting an additional focus along one arm of the interferometer results in a final phase difference of π between the interfering lightwaves, as soon as the optical path difference is made zero.

This phase shift property is reputed to work in a two steps process, each providing a π/2 phase shift and both located at focus. It is possible to spatially separate the two steps so as to end up with a π/2 phase shift when the second step is rejected at infinity. This latter phase shift mode can be performed by using cylindrical optics. The basic set-up is schematically described in Fig. 9.
Pupilla are dealt with so as to control suitable positioning at recombination. Thanks to symmetry properties of the set-up, the system remains an afocal device with unit magnification. A double beamsplitter-pass recombination scheme allows avoiding problems with beamsplitters (see Fig. 9). Such a recombiner basically reproduces the architecture of the Achromatic Interfero Coronograph [19], [20], [21].
Depending on the recombination scheme, the need for a phase shift by π/2 appears. For example, and taking into account a π/2 phase shift inserted between transmitted and reflected waves at a beamsplitter, a design using division of wavefront (collimator and mask) and a beamsplitter to recombine the beams would not require an APS shifting the phase by π, but by π/2 instead.
The focus crossing approach can be designed to provide either of these values. Fig. 10 illustrates that point.
Note that the need for a π/2 phase shift is not cancelled by the recombination scheme since two outputs have to be mixed. More details on this concepts are given in the paper "The mirror approach" in these proceedings by the present authors.

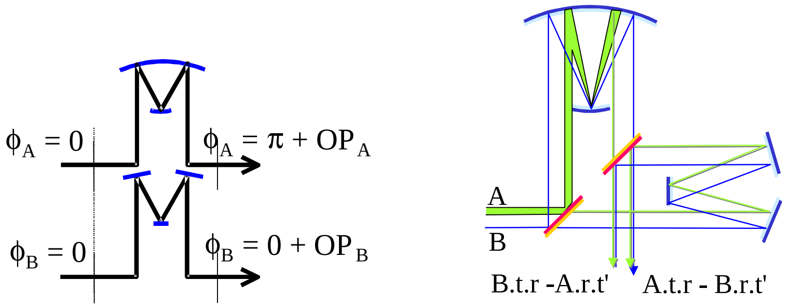

Fig.9. Left : Schematic of the basic set-up for APS based on focus-crossing. An extra-focus is inserted in one arm of the interferometric combiner, by means of a cat's eye made of curved mirrors, thus yeilding an achromatic phase shift of π . In the other arm, an optical train made of flat mirrors affords the optical path balance. Right : The recombination set-up, with double pass through reversed beamsplitters (coating first seen or substrate first seen)

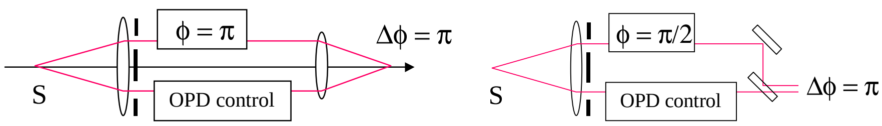

Fig. 10. Two recombination schemes using beams from spatially separated amplitudes.
Left : APS with π phase shift needed. Right : APS with π/2 phase shift is needed.

2.4. Miscellaneous : Use of Holographic Gratings and Emerging Technologies

2.4.1. Holographic Gratings

This type of APS, developped by George & Stone,1988 [23], provides a chosen arbitrary phase shift. Eventhough light travels through material (transmission gratings), the origin of the phase shift is a diffraction process.

The light travelling through a sequence of 3 holographics gratings suitably configured (see Fig. 11), experiences a phase shift which consists of a chromatic part (optical path) and an achromatic part which is induced by a controled translation x_0 of the central grating, perpendicular to the propagation axis. When used in differential mode (one triplet on each interferometric arm) the chromatic terms in each interfering arms mutually cancel. The optical path is built from proper selection of diffraction orders along which propagation is driven. The sequence of diffraction effects is described in Fig.11

As derived in [23] , the phase shift at output can be written $\Phi(\lambda)=\phi_{achrom}(x_0)+\phi(\lambda)$ where the last term is governed by optical path. When optical paths for A and B are made equal, the final phase shift is $\Phi(\lambda)=\phi_{achrom}(x_{0A})-\phi_{achrom}(x_{0B})$

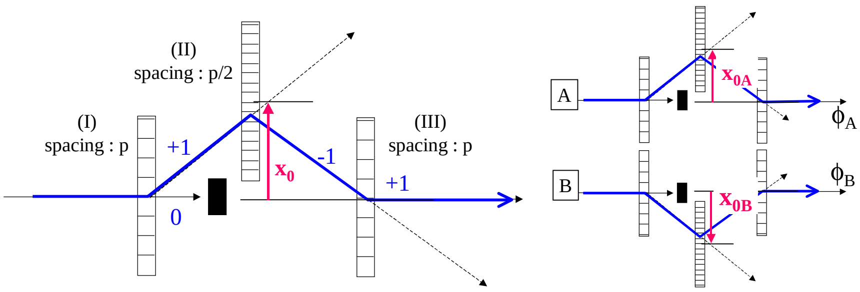

Fig. x. Left : the basic configuration for making a phase shift depending on x_0. Right : Using the basic configuration in differential mode to obtain an achromatic phase difference between lightwaves from beams A and B. Note the different spatial period for the central gratings.

This concept is not adapted to work in dual-polarisation mode since polarisations are not treated the same (at least for transmission) what tends to lower the nulling efficiency. Besides, results reveal unadequate in our context [23].

2.4.2. Emerging Technologies

Besides rather conventional concepts, some new approaches are emerging relying on specific techniques used in other fields : birefringence of form (also named sub-λ gratings or Zero-Order-Gratings) [24], integrated optics [25], multilayer coating [26]. Those approaches, more or less mature and more or less fitting the phase shift requirements, could prove to be alternative ways beside the various APS concepts mentioned in the preceeding sections.

3. STATE OF THE ART

Dispersive plates, birefringent plates, holographic gratings, field reversal, focus crossing have been used as real devices. Relevant rejection measurements are available except for the last one. As far as we know, best results have been obtained with dispersive plates et with field reversal. Birefringence yielded 17000 in the visible but at the price of poor transmission [11]. Demonstrated rejection with dispersive plates : 10^4 over 0.4-0.7microns [12], uptdated performance is given in H. Bokhove's talk (these proceedings). Demonstrated rejection with field reversal : greater than 10^4, visible, 18% bandwidth [17], 17000 , thermal infrared laser diode, 9000 thermal infrared (Serabyn, private communication). Numerical simulations yielded 7.10^4 over 0.4 – 1 micron [delft] and 10^5 over 7 – 17 microns [14]

4. CRITICAL POINTS

For all presented concepts of APS's optical aberrations must be eliminated or reduced since rejection is sensitive to phase defects within the pupilla at the recombination step. The use of spatial filtering, including monomode optic fibers can achieve such a correction but at the price of loosing photons or of reduced achromaticity. Also, availability of fibers usable in the thermal infrared domain yet remains nowadays a serious issue.

For APS using properties of materials several issues have to be considered : photon losses at surfaces (Fresnel's losses), multiple reflections (losses and rejection degradation), severe optical quality (difficulty depending on the used material). The main concern remains availability of suitable materials for the infrared thermal domain (spectral transmission, easy machining, homogeneity, available volume) and the precise knowledge of their optical properties (at least longward of 12 microns).

For APS using reflection on mirrors take advantage of their natural achromatism. Identified critical points essentially are : severe optical quality, pathlengths adjustment and stability (difficulty induced by bulky architecture), spurious polarisation effects (reflection on metals) and fixed (not tunable) discrete phase shifts values.

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