ACHROMATIC PHASE SHIFTERS : THE "MIRROR" APPROACHES

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INTRODUCTION

This paper is intended to complement the preceeding one "Review of Concepts and Constraints for Achromatic Phase Shifters" (to which, now and on, we assign the label "paper I" and reference [1]) and is dedicated to the phase shifters concepts using mostly or exclusively mirrors. Here achromaticity is intrinsically obtained. The phase shift process results from the properties of reflection. The case of total reflection (Fresnel's rhomb and twisted rhombs) is eventually not considered here, since the process involves a travel of light within a material. Thus, the present topic is restricted to two concepts : the "electric field vector reversal" and the "focus crossing". This restriction traces the fact that the various problems associated with the use of materials for the infrared are then eliminated.
In section 1 we recall briefly the main features of each concept, in section 2 and 3 we consider each concept respectively. State-of-the-art is briefly recalled in section 4 and a discussion is outlined in section 5.

1. QUICK-LOOK AT FUNCTIONAL FEATURES

In this section the terminology refers to Paper I [1].
Achievable Phase Shift Value : both concepts are "discrete" achromatic phase shifters, and deliver a phase shift by π. Focus crossing can deliver also a $\pi/2$ shift.
Achromaticity : as mentioned above the achromaticity is intrinsic (as opposed to a "compensated chromaticity") and originates in properties of reflection indepedant of wavelength.
The "Field Reversal" is basically "differential" (final phase shift experienced at the recombination step). The "Focus Crossing" is employed as differential though being abslolute (phase shift obtained on a single beam). Both concepts deliver a couple of nulled outputs (and correlatively two bright outputs).
For both also, architecture of current set-up is rather bulky (as compared to other naturally compact devices) and are subject to some optical path unstabilites, able to affect the nulling performance. However, technical solutions are existing to make them compact and stable with respect to optical paths.
Dual-polarisation mode : both concepts are able to perform achromatic phase shifts applicable to both polarisations and simultaneously , what maintains a high energy throughput.
In order to avoid ill-controled and chromatic additional phase shifts caused by dielectric coatings, reflection on metal might be better. However, this implies to use a complex optical index, which does not explicitely appear in the Fresnel's formula for reflection, but is included in a complex (and fictitious) refraction angle. A consequence is the possible appearance of some ellipticity in the reflected light-waves.

2. ELECTRIC FIELD VECTOR REVERSAL

This concept has been studied and developed by Serabyn and co-workers [2],[3],[4],[5] and has involved two different set-ups used successively. Both set-ups are fed by light-waves travelling along two separate beams and then mixed so that two channels appear at output, each conveying a combination of the incident light-waves (see Fig.1). Therefore the field reversal concept rather is a complete nulling beam combiner than simply a phase shifter. In the first set-up [2],[4], incident beams are co-phased and the π phase shift is performed within a modified Michelson interferometer by proper arrangement of s-type and p-type reflections. In the second one [5] the π phase shift between the two incident light-waves is performed prior to enter the combining set-up, which then can be any conventional (constructive) two-beam interferometer.

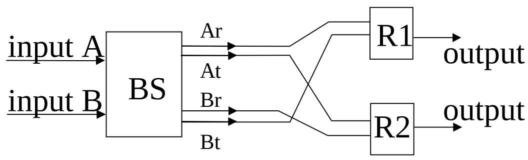

Fig. 1. Functional representation of the field reversal concepts. Notation "Ar" (and similar) does not mean "product A by r", and simply traces the two separate contributions (reflected and transmitted) of A and B after splitting at entry. R1 and R2 denotes the two recombination channels.

2.1. Basics

The phase shift process relies on the reversal of the "s-type polarisation" component of the incident field occuring at reflection, what is equivalent to a π achromatic phase shift, and is traced simply by the presence of a minus sign in the Fresnel's reflection coefficients :

$$\rho_s = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \quad \text{and} \quad \rho_p = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \tag{1}$$

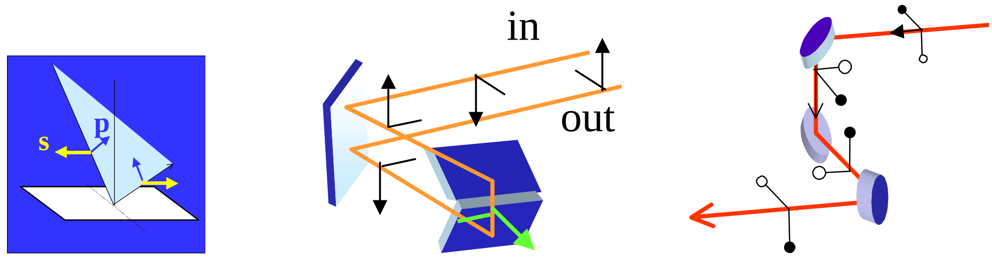

Fig. 3. Dealing with field reversal. Left : the basic process. Center : arrangement used in the first set-up. Right : arrangement used in the second set-up (this latter does not make a π shift on an individual beam)

2.2. Two Optical Set-ups

2.2.1. The roof-mirrors set-up

This set-up is described on Fig. 3. Two separate incident beams are impinging at location A and B on a beamsplitter at entry.

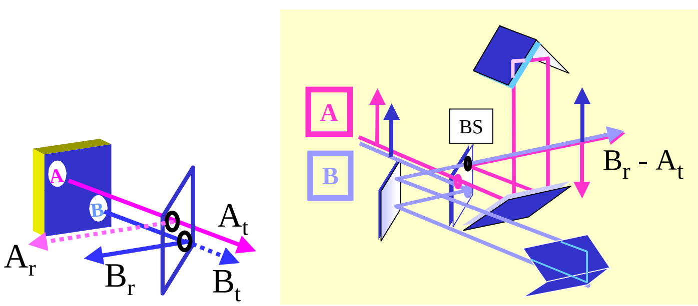

Fig. 3. Schematic representation of the set-up using beamsplitter at entry and othogonalized roof-mirrors to perform a relative π phase shift between mixed fields. Left : geometry of inputs. Right : global set-up. Only the paths related to one output is shown for graphic clarity.

The paths followed make the reflected A meeting the transmitted (and phase shifted) B on the beamsplitter (for recombination). Similarly, as shown on the drawing, transmitted (and phase shifted) A is recombined with reflected B, at a separate output.
This rather complicated and delicate configuration is likely to cause optical pathlengths unstabilities and has eventually been replaced by a new and fully symmetric configuration.

2.2.2. The Fully Symmetric Nulling Beam Combiner

This design [5] has been conceived from the idea that the vector reversal and the recombination stage could be separated. A simple way to achieve a relative phase shift by π between two incident light-waves is to use a pair of right-angle periscopes where the reflection effects on s and p polarisations are permuted, as shown in Fig. 4.
Then, once the relative π phase shift is performed, the recombination can be made by means of a conventional (constructive) interferometer (Michelson, Sagnac, Mach-Zenhder). A modified Mach-Zehnder configuration has been preferred (less mirrors and full symmetry) and is described in Fig.4., where appear two reversed identical beamsplitters. This latter feature allows using non-symmetric beamsplitters (generally unavoidable) without degrading the nulling efficiency. The degradation would result from an uncomplete nulling caused by unequal reflection factors and transmission factors whether coating is met first (respective coefficients r and t) or substrate is met first (respective coefficients r' and t') by the light-wave.
Let us note ψ_1 and ψ_2 the fields at entry, with amplitude A and -A (because of the relative π phase shift) . One output results from the following sequence : reflection on BS1, reflection on mirror, transmission by BS2 for ψ_1 and similar sequence for ψ_2 : transmission by BS1, reflection, reflection on BS2. The total resulting field at this output is $\psi_1 + \psi_2$ and we have for the p-type polarisation (minus sign traces the π phase shift):

$$\psi_{1p} = -\psi_{2p} = \rho_p A_p . r_p .(t'_p - t_p)$$

A similar derivation for the s component leads to : $\psi_{1s} = -\psi_{2s} = \rho_s A_s . r_s .(t_s - t'_s)$
On the other output the same product of coefficients is also found.
Even in the presence of internal absorption, the reciprocal coefficients t' and t are identical [5], what gives two nulled outputs for both s and p components. So that this set-up allows working with broadband and dual-polarisation light.
In case of reflection on metal, some spurious ellipticity might appear and distort this derivation. Actually, since s and p polarisation do not interfere, the problem is ruled out as soon as homologous polarisation directions are well matched from one recombination channel to the other.
In order to suitably drive the beams so as to have ψ_1 and ψ_2 properly mixed, an extra internal optical path must be added. The balance of optical paths can be performed by an external optical path as shown in Fig.5.

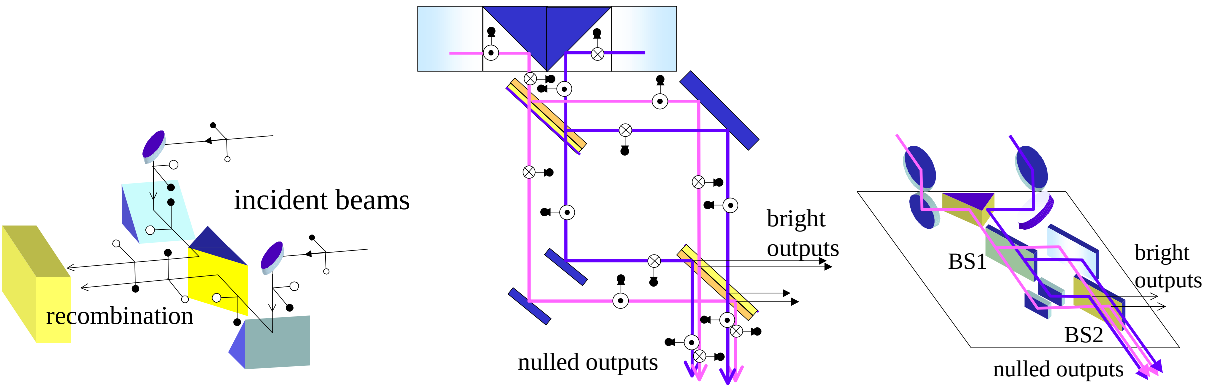

Fig. 4. Schematic representation of the "fully symmetric" set-up. Left : the process yielding a relative π phase shift. Center : gestion of vector fields along each recombination channel. For bright outputs, the orientation of the vectors seems to yield a nulling but, due to unequal r and r' coefficients, this is not the case. Right : Global view of the set-up.

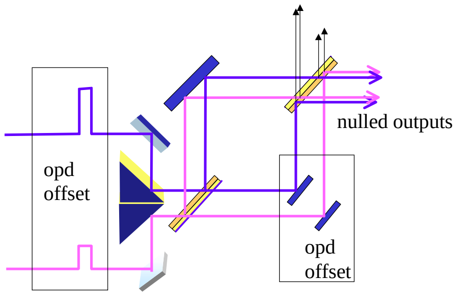

Fig. 5. Extra optical path needed within the Mach-Zenhder recombination scheme and external compensation by offsetting the delay line

3. FOCUS CROSSING

This concept is illustrated by the Achromatic Interfero Coronagraph [6], [7], [8], [9], and 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 nulling outputs.

3.1. Brief Reminder on Principle

The principle (see Paper I, these proceedings) is based on an achromatic property of light : a lightwave crossing a focus experiences a phase shift by π whatever the wavelength [10]. Inserting an additional focus along one arm of the interferometer, results in a final phase difference of π between the interfering lightwaves at output of the APS, 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. 6.
Matching pupilla at recombination is required [11]. Thanks to symmetry properties of the set-up, the system remains an afocal device with unit magnification and position of pupilla are controlled at the optical design stage.

3.1.1. The Phase Shift Process

The phase shift occuring at the crossing of a focus is described by several authors either theoretically or heuristically [10], [12], and including Fourier Optics algebra (Rabbia and Gay, not yet submitted). Beside those descriptions (including the π/2 phase shift), the effect is experimentally demonstrated by the Meslin fringes [10], by using intra focal and extra focal observations of fringes in a Michelson-like set-up [9], and by the observations made with the Achromatic Interfero Coronograph [8] which relies on the focus crossing effect to remove the light on a on-axis point-like source as shown in Fig. 6.

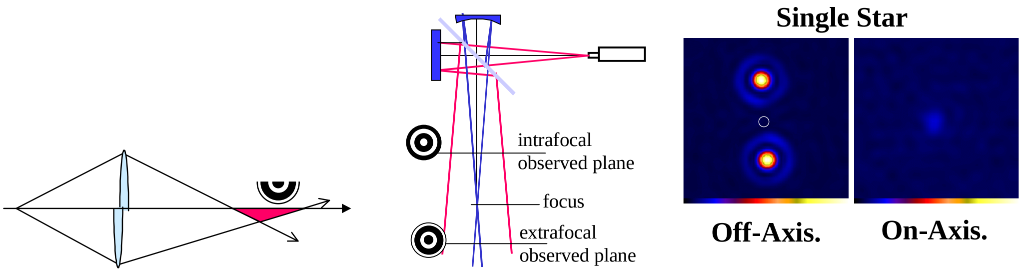

Fig.6. Experimental illustrations of the focus-crossing π phase shift effect. Left : set-up to observe Meslin fringes. Center : dedicated set-up to verify the focus-crossing effect by intra-focal and extra-focal observations in a Michelson-like interferometer with wavefronts of unequal curvatures. Right : a couple of images recorded on the sky with the AIC : a single star, is set first off-axis (yielding a couple of twin images) and then on-axis (yielding removal of the starlight).

The case of $\pi/2$ phase shift is heuristically described as a limiting case of the astigmatism aberration, which gives two separate foci, each yielding a $\pi/2$ phase shift at crossing, what results in a π phase shift away from the two foci. Sending the second foci at infinity (what is achieved by using a cylindrical lens) allows only a $\pi/2$ phase shift to occur at the focus crossing. This is illustrated in Fig.7

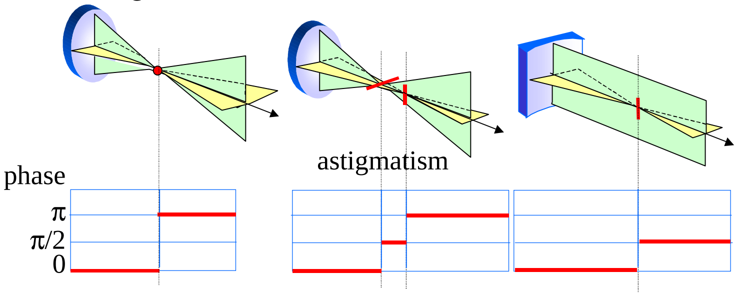

Fig.7. An heuristic interpretation of the $\pi/2$ phase shift origin, as an uncomplete π phase shift (built from two successive steps each bringing $\pi/2$). Left : single focus, π shift in one shot. Center : Astigmatic lens, two foci, two successive $\pi/2$ steps. Right : cylindrical lens (extreme astigmatism) only one step, only $\pi/2$ shift.

Alternate designs

Since the basis of the process is to have a parallel beam on one arm and a focused beam on the other arm, the generic configuration can be modified as shown in Fig.8. In case of a beam compressor is needed such alternate designs might reveal very interesting. Care must be taken in the design, to control pupilla position matching.

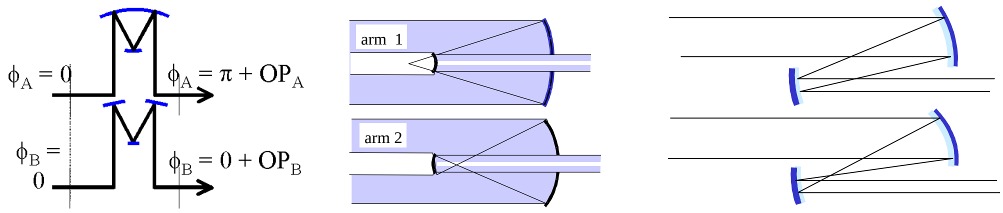

Fig. 8. Alternate designs for the focus-crossing concept. Left : generic design. Center and Right : alternate designs using unequal optical powers on each arm. Pupilla position is controled by changing mirror separation, at the price of an extra-optical path, which is compensated for, by external delay line.

3.1.2. *Specific and Miscellaneous Features*

- Symmetrisation of Images.

As shown on Fig.8, the π phase shift is achieved by a cat's eye system, which also perform rotation of the pupilla. This property is considered as a trouble since, when employed in a coronograph, two symmetrical images of a given off-axis object are appearing (see Fig. 6). Actually, in our context, viewing this aspect as a trouble does not make sense since each collecting aperture (be it for DARWIN or for GENIE) is not resolving the observed couple, and each beam works in a zero-field-of-view mode, and there is no point with symmetrisation.

- Reflection on Metals

Using metallic reflection is needed in order to reach high energy throughput. Using dielectric coating, to enhance the reflection efficiency, might induce additional and uncontrolled phase effects even with identically treated components.
Because the optical indexes to handle with metals are complex numbers, so are reflection coefficients and no longer the phase change is governed by simply the minus sign. Therefore some ellipticity occurs and a linearly polarized lightwave becomes slightly elliptical after reflection (this effect is also occuring in the field reversal approach). This situation might react on the nulling efficiency via polarisation unmatching and amplitude unmatching [1], because effective indexes might differ from one mirror to another one. The effective value (complex) of optical indexes are reputed to be depending on the way the metallic deposit is made. Thus, full symmetry between arms is somewhat perturbated and the nulling efficiency is lowered. However, the value of the optical index is reputed to stabilizes as soon as the thickness of the reflecting metal is larger than a few times the penetration length (itself roughly being of few wavelengths) [10].

Moreover, as described in next subsection, simulations made for the incidence dispersion effect (based on the design of the existing achromatic interfero coronagraph) show that, using reflection on gold, the suspected degradation on nulling, even with three cumulated reflections, is clearly negligible (few 10^{-8}) with respect to the targeted extinction (10^{-6}).

- Differential dispersion of incidences .

Rays impinging on the triple flat optical train have the same angle of incidence, whilst rays impinging on the cat's eye have an incidence variable with the point of impact (see Fig. 9.). Since incidence appears in the expression of the reflection coefficients, unequal behaviour between the beams is to be expected, hence an uncomplete nulling and degradation of performance. Actually, as mentioned above, the effect appears (from numerical simulations) as being rather unsubstantial

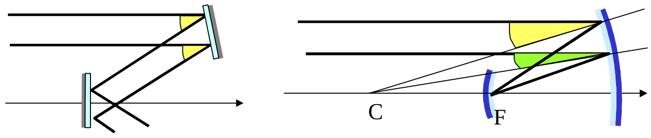

Fig. 9. Illustration of the differential dispersion of incidence in the "focus-crossing" concept.
Incidence is uniform for all rays in the triple-flat optical train, whilst it is variable with the point of impact in the cat's eye optical train.

3.1.3. Recombination Scheme

Once phase shift is achieved on one beam, recombination provides the nulled intensity. One way to do it is to use a collimator with two entries and to work in the Young's fringes mode (dark central fringe). Another way is to work in the flat-tint mode, by superimposing the beams (uniformly dark area) as shown in Fig. 10. This latter mode does not satisfy the "symmetry" conditions, required to reach the relevant level of nulling [3]. With the "focus-crossing" approach, recombination is performed in a way similar to the one used in the "fully symmetric field reversal" approach, but there is no extra optical path difference to compensate for. As described in Fig. 10, beams A and B, meet a first beamsplitter, then they are driven along the respective optical trains and eventually are mixed by an identical beamsplitter but reversed, so as to balance the coefficients applying at reflection and at transmission.
Once having the two nulled outputs, we have to gather them. Again two recombination modes are available, but now the symmetry constraint is not applying and the "flat-tint" mode is reliable, since recombination is already achieved and so any extra-chromatism is not a trouble. In that case an APS concept which would provide a $\pi/2$ phase shift, is useful.

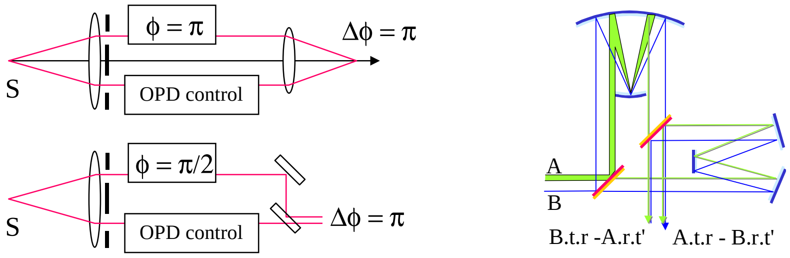

Fig. 10. Recombination modes for nulling. The collimator on the left features two collected beams from a star.
Left, upper : the Young's fringes recombination mode, π phase shift needed, symmetry satisfied.
Left, bottom : the flat-tint recombination mode, here , because of a $\pi/2$ relative shift at the beamsplitter, a $\pi/2$ shift is needed instead. Symmetry is broken by the (chromatic) recombination plate.
Right : fully symmetrical recombination, using resversed identical beamsplitters. Two nulled outputs, which in turn, must be gathered.

A comment, specific to "focus-crossing" and regarding energy transmission for the planet, is worth giving here.
Using focus-crossing is untruly reputed to reduce the throughput by a factor of 2. This probably results from the sometimes made confusion, that is to identify the focus-crossing APS and the Achromatic Interfero Coronagraph [6], [7], [8], [9]. When collected amplitudes are A and B, reflection and transmission factors at beamsplitter are r,t (layer met first) and r' and t' (substrate met first), and whith a Mach-Zehnder type recombinator (see Figure 10),we have two outputs each providing the amplitudes (with self-explaining notations) :

$$\psi_1 = A.r.t.\exp(i.(\phi_{APS} + \phi_A) + B.r.t'.\exp(i.\phi_B)$$

and a similar expression for ψ_2 , in the other channel of the Mach-Zehnder. The phases ϕ_A and ϕ_B contain optical path differences. Generally t and t' are considered equal (see section 2.2.2.) The resulting intensity for one channel is : $I = R.T.(A^2 + B^2 + 2.A.B.\cos(\phi_{APS} + \phi_A - \phi_B))$ where R and T are usual factors for energy : $R = |r|^2$ and $T = |t|^2$. Assuming A=B (what means that optical transmissions are equal on each arm) we have for the star $\phi_{APS} = \pi$ and $\phi_A - \phi_B = 0$, resulting, as expected, in a nulled intensity. For a planet located on a maximum of the transmission map we have $\phi_{APS} = \pi$ and $\phi_A - \phi_B = \pi$, the intensity from the planet (amplitude "a") is given by $I_{planet} = R.T.r_{opt}.(a^2 + a^2 + 2.a^2) = R.T.r_{opt}.4.a^2$. Thus, with two outputs we have a total energy $2.(4.R.T.r_{opt}.a^2)$ where a^2 is the energy from the planet collected on each telescope.All the collected energy from the planet is recovered but the factor $4.R.T.r_{opt}$, and not a at deficit by a factor of two (with R = T= 0.5, the factor reduces to r_{opt}).

4. STATE-OF-THE-ART

4.1. Field Reversal

For the first set-up encouraging results have been obtained with progressively increasing quality, as for example rejections 10^6 with HeNe laser, a few 10^4 with a 18% bandwidth, rejection of 1.7 10^4 in infrared (10 µm) with laser diode and 300:1 with a 10% bandwidth [2], [4]. Yet, results were better when isolating one polarisation at output, what tends to show that some ellipticity must be taken care of. To-date, no results respective to the second set-up have been found in the literature, but rejection of 9000:1 in mid infrared have been obtained with a laser diode (Serabyn, 2002, private comm.)

4.2. Focus Crossing

The focus crossing phase shift property has been used in the Achromatic Interfero Coronagraph [7],[8] which has been succesfully tested on the sky. However the targeted rejection performance when observing through atmospheric turbulence is not comparable to the required rejection in the present context. Nevertheless, practical experience with set-ups using focus crossing has been acquired.
Recently, a laboratory set-up, simply aiming at a preliminary demonstration with respect to π and π/2 phase shifting, and using commonplace components has been implemented at O.C.A. It is schematically described in Fig. 11.
Demonstration of π phase shift is made in terms of interference fringes with dark center, a phase shift of 180° ± 1° has been obtained and a rejection of nearly 10^4 has been reached . Demonstration of the π/2 phase shift has been made and is described in the following
The π/2 case, involving cylindrical optics proved to be very sensitive to the optical adjustments and to the quality of components (shaping) which, in a prelimlinary set-up, were both of unsufficient quality. Thus, by the time of the GENIE workshop, the principle of the π/2 shift was not completely validated,as shown during the talk).

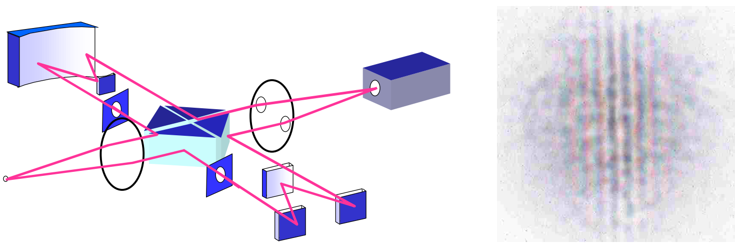

Fig. 11. Left : Schematic of the preliminary set-up (path difference balance included). Collimators (input and output to camera) are actually made with mirrors (to avoid external chromatism), but here, for drawing convernience, lens are featured. Right : an example of recorded fringe pattern (negative image).

It is conceivable that looking at the fringe patterns is not a convincing way to validate the processes (especially for the π/2 case) even with displayed colors. Recorded images have been processed so as to make clearly readable the phase shift in the respective situations : no shift, π shift and π/2 shift. The analysis method relies on Fourier Transform and numerical filtering, and take advantage of the unavoidable spatial offset experienced by the fringe pattern, with respect to a reference on the camera target. The data processing is summarized in Fig.12.

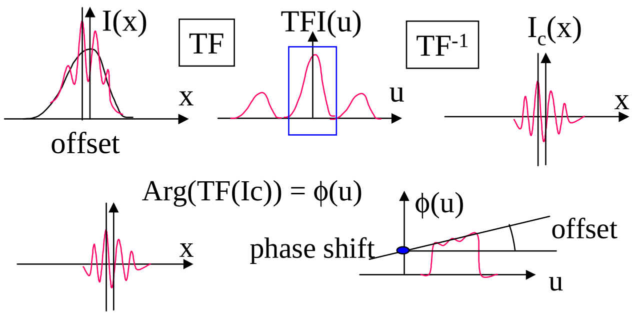

Fig. 12. Outlines of the phase shift extraction process. Up : cleaning the fringe pattern (notice spatial offset). Down : determination of the phase shift, in spite of spatial offset which only reacts on the slope of the fitted-line. Accurary of the phase shift is essentially a matter of signal to noise ratio.

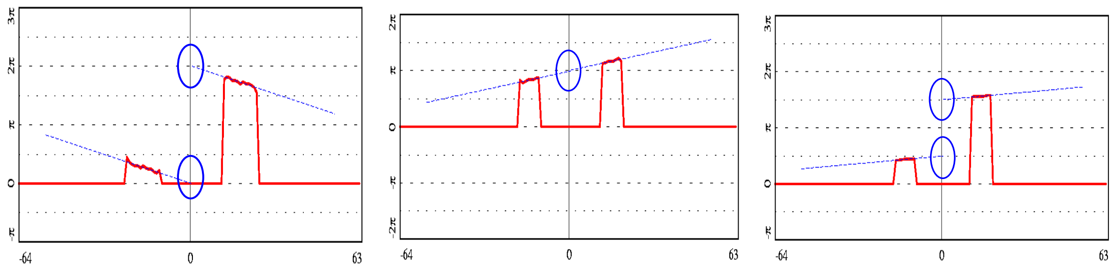

Figure 13. Examples of fits providing the phase shift value from recorded fringes. Left: zero phase shift obtained with triple-flat on each arm. Center : π phase shift obtained with triple-flat and "spherical" cat's eye. Right : $\pi/2$ phas shift obtained with triple-flat and cylindrical cat's eye.

## 5.	DISCUSSION

In this section we essentially give a brief view on advantages and drawbacks of each approach.

### 5.1.	Field Reversal

Advantages
The first attractive feature of this approach (as for the "focus-crossing") is the use of mostly mirrors. This feature, nearly eliminates problem regarding availability of materials for the thermal Infrared and is expected to provide the most complete achromaticity over any bandwidth of work. Also, the symmetric crossing of beamsplitter largely relaxes the constraints of having a beamsplitter ratio R/T uniform over the spectral bandwidth. Besides, the highest energy throughput is expected, since energy loss from Fresnel reflections at vacuum/material interface do not occur with mirrors. Moreover, reflection efficiency can be made very high by a suitable choice of metal.
Thus, intrinsic achromaticity and high energy throughput are the key-words.

Drawbacks
However the full benefit of high reflectivity only happens when both polarisations can be used simultaneously. This is in principle achievable but available measurements tend to put some doubt on this capability, and could be linked to some ellipticity created by reflection on metal. Full symmetry should compensate for such effect but demonstration is still to be made.
Another drawback is the sensitivity to optical path unstabilities, what is a consequence of the architecture using separate components. However, this point is likely to be largely minimized by using a compact architecture in which molecular contact assembling is relied on (see Fig. 14.).

A possible drawbacks is the reputed unique achromatic phase shift value "π", achievable with the "field reversal" concept. Recent work [13] by Tavrov and co-workers (which we did not know by the time of the GENIE workshop) could open the possibility of making reasonably achromatic $\pi/2$ phase shift.

5.2. Focus-Crossing

Advantages

Large spectral bandwidth. From the use of mirrors and from the achromatic nature of the dephasing process the acceptable bandwidth is limited only by the metal used at reflection and by the transmission of the recombiner (for example because of beamsplitter in the set-up shown in Fig. 10.). Using Gold allows excellent spectral response for the 6-20 μm specified spectral range.

High rejection is expected since the identified defects induce residual energy at the level significantly below the specified 10^{-6} extinction. In addition they essentially come from adjustment defects or design parameters and not from fundamental limits, except maybe for the $\pi/2$ case which has to be better understood on theoretical ground.

High energy throughput is obtained firstly from the ability to use both polarisations simultaneously (natural light) and secondly from the limited number of mirrors in the set up. This however concerns the APS itself and not the recombination step (an issue common to all APS's) and which induces some losses. Moreover, an alternate design for focus crossing, based on beam compressors, if allowed, reduces further the number of reflections.

The recombining set-up, using a double pass through a beamsplitter relaxes the need for a uniform R/T ratio versus wavelength, what largely opens the ,otherwise limited,choice of materials for thermal infrared.

Taking care of pupilla position (matching pupil plane) help maintaining the afocal-unit-magnification capability. Note that such pupil plane matching has to be done with any APS.

Drawbacks

Focusing on an optical surface (secondary of cat's eye) is not a good situation and will require a specific high care of surface quality and highly clean conditions of operation.

In addition, the control in position of the secondary mirror meets a stringent upper tolerance (few microns).

Control of the balance of optical path within the APS itself is delicate though it can be compensated for by the external delay line. The architecture involving spatially spread elements (like in "field reversal") increases the difficulty of optical path control, but a compacted structure using molecular contact assembling and implemented under interferometric control is a solution.

Adjustment of the set-up, in terms of precise orientation of sensible axis and plans is also needed to eliminates residual ellipticity along the optical train. Actually the drawback exists at a differential level, since identical elliptiticity on each arm allows to maintain high interference efficiency in the nulling process.

Our conclusion on the "mirrors approaches" is that they both are good candidates for the APS's to consider in the perspective of DARWIN and GENIE.

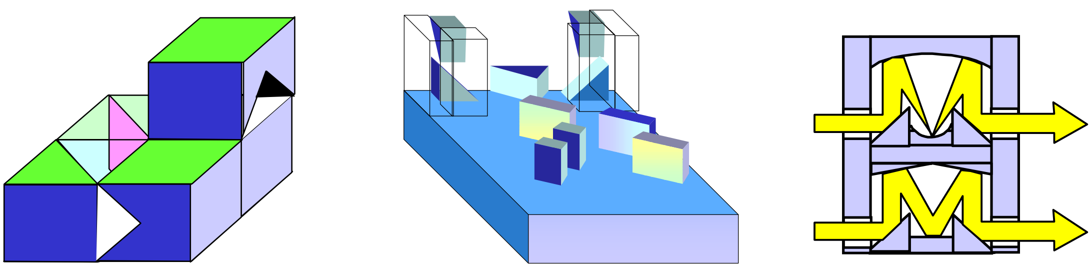

Fig. 14. Possible configurations yielding compact architecture and accurate control of the zero-optical-path-differences, for the three set-ups mentioned in this paper. Left : compact set-up for the "roof-top mirrors" design. Center : compact set-up for the "fully symmetric recombiner" design, also applicable to the "focus-crossing" approach. Right : compact set-up for the "focus-crossing" design.

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