BIREFRINGENT ACHROMATIC PHASE SHIFTERS FOR NULLING INTERFEROMETRY AND PHASE CORONAGRAPHY

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ABSTRACT

Achromatic Phase Shifters are mandatory components in the field of nulling interferometry and phase coronagraphy. Indeed, in order to detect faint objects (e.g. exo-planets) around a central bright star, one must attenuate the latter by all means. To do this, the most efficient way is to "create" a destructive interference on the blinding light. This technique is called nulling and is common to the two fields mentioned above; the first with several telescopes, the second with only a single aperture. How does it work? The incoming light from the central object is divided into several beams on which one applies a differential π phase shift by means of these so-called phase shifters. Then, when the beams are properly recombined together, they simply subtract from each other. "Achromatic" means that we can apply this process over a large spectral bandwidth. This quality will not only be required for the detection and characterization of exo-planets but also for several other astrophysical objects involving huge contrasts like dust shells around young bright stars, AGN,... The proposed birefringent phase shifters and the original implementation schemes we suggest should provide flexible and powerful solutions for these purposes.

Key words: Nulling Interferometry; Phase coronagraphy; Achromatic Phase Shifters; Sub-Wavelength Gratings.

1. INTRODUCTION

The idea of using vectorial phase shifters (vectorial in the sense that the phase shift takes place between vectorial components s (or TE) and p (or TM) of the incident light) in nulling systems like phase coronagraphs and interferometers is quite new. Such phase shifters already exist and are well-known in the opticians' community. However, the stringent characteristics required by the astrophysicists in order to achieve large dynamics (up to 10^{10} for an exo-earth in the visible and 10^7 in the thermal IR) are much more severe and require state-of-the-art performances.

The principle is to design the best achromatic vectorial phase shift (usually π, but other values are possible) within error budget recommendations and then to implement it in the selected nulling system.

The rejection ratio R of a nulling system is defined and accordingly related to the phase shift variance as follows

$$R = \frac{I_{without\,phase\,shift}}{I_{with\,phase\,shift}} = \frac{4}{\sigma^2} \tag{1}$$

It implies that the lower the variance, the better the phase shift quality and consequently the better the rejection ratio.

2. ACHROMATIC WAVEPLATES

Waveplates are optical elements which introduce a phase shift between the vectorial components s and p of the incident light. Most of them use the property of birefringence. Birefringence is a natural property of anisotropic crystals but can also be artificially created using 1D sub-wavelength gratings.

2.1. Naturally birefringent achromatic waveplates

Achromatic waveplates (half-wave, quarter-wave,...) are commonly produced by combining two plates of different birefringent materials with properly chosen thicknesses. Since the dispersion of the birefringence is different for the two materials, it is possible to specify the retardation values within a wavelength range. Hence, the retardation of the resulting waveplate can be made little sensitive to wavelength change (Hariharan 1996).

If we consider a combination of two such birefringent plates of thicknesses d_a and d_b and with parallel optical axes, the usual design condition for achromatism

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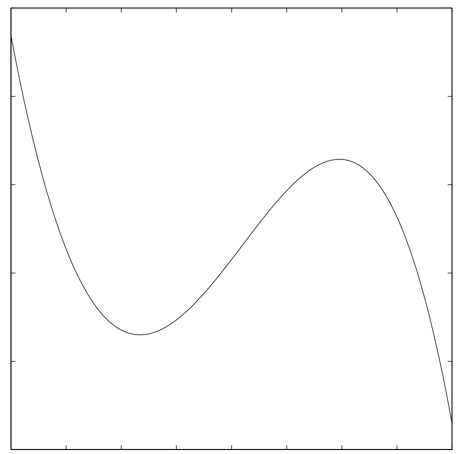

Figure 1. CdS/CdSe achromatic half-wave plate simulation for the 9-13 microns wavelength range.

is that the retardation of the system should be equal to half a wave (for a half-wave retarder) at two selected wavelengths λ_1 and λ_2, so that we have

$$d_a \Delta n_a(\lambda_1) + d_b \Delta n_b(\lambda_1) = \frac{\lambda_1}{2} \quad (2)$$

$$d_a \Delta n_a(\lambda_2) + d_b \Delta n_b(\lambda_2) = \frac{\lambda_2}{2} \quad (3)$$

where $\Delta n_a(\lambda_1)$, $\Delta n_b(\lambda_1)$, $\Delta n_a(\lambda_2)$ et $\Delta n_b(\lambda_2)$ are, respectively, the values of the birefringence of the two materials at these two wavelengths.

A solution for Equations 2 and 3 can be obtained only by combining a material with a positive birefringence with one having a negative birefringence. Conversely, if the two plates are set with their optical axes at 90 degrees, a solution is possible only with materials whose birefringences have the same sign.

The interest in using naturally birefringent phase shifters and a reason why they are commercially available comes from the fact that, usually, the birefringence is two orders of magnitudes smaller than the indices. So an error on the thicknesses contributes to the phase shift two orders of magnitude less. On the other hand, we need very accurate measurements of the birefringence for the materials used, over the range of wavelengths to be covered.

A first Achromatic Four Quadrant Phase Mask Coronograph prototype (Rouan et al. 2000) made of commercially available achromatic waveplates is being assembled and will soon be tested in the visible in our team (see below for implementation topics). We expect good performances with this component.

In the mid-IR domain, the lack of birefringent materials is the major problem. Moreover, the few ones

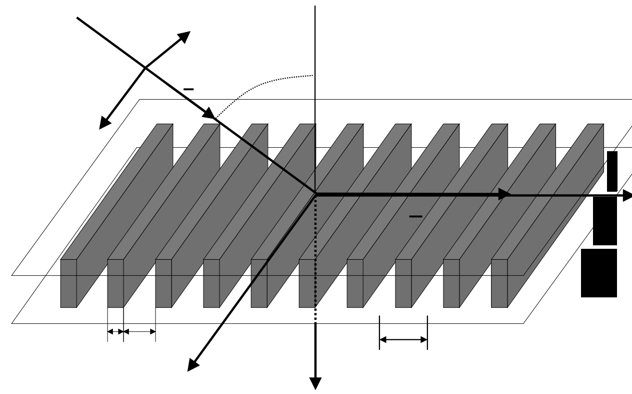

Figure 2. Surface relief grating. Geometry of the diffraction problem. Parameter definition. Vectorial decomposition of incident natural light.

that can be found have large indices, involving more loss due to spurious Fresnel reflections. However, it seems that the couple CdS/CdSe is a good candidate to undergo achromatization optimizations for the infrared domain with promising results (see Figure 1).

The phase shift quality for optimal thicknesses of this couple gives an equivalent rejection ratio of $R = 200000$ for a theoretical spectral resolution of 2.75.

If a third material was incorporated, the equivalent rejection ratio could reach 10^6. As said before, there are not many candidates, but solutions with $AgGaSe_2$, for instance, are possible.

2.2. Artificially birefringent achromatic waveplates : ZOGs

ZOGs (Zeroth Order Gratings) consist in subwavelength gratings, i.e. the period of the structure is smaller than the wavelength of the incident light. They do NOT diffract light in the sense that only the zeroth transmitted and reflected orders are allowed to propagate outside the grating regions, leaving incident wave fronts free from any further aberrations.

Whether a diffraction order propagates or not is determined by the well-known grating equation from which we can thus find a "ZOG condition" on the grating period to wavelength ratio

$$\frac{\Lambda}{\lambda} \leq \frac{1}{n_i \sin\theta - n_t \sin\theta_m} \quad (4)$$

with θ representing the incidence angle, θ_m the diffraction angle of the mth order, n_i and n_t, the refractive indices of incident and transmitting media respectively.

ZOGs present very specific properties : 1D ZOGs are seen as homogeneous and anisotropic media by

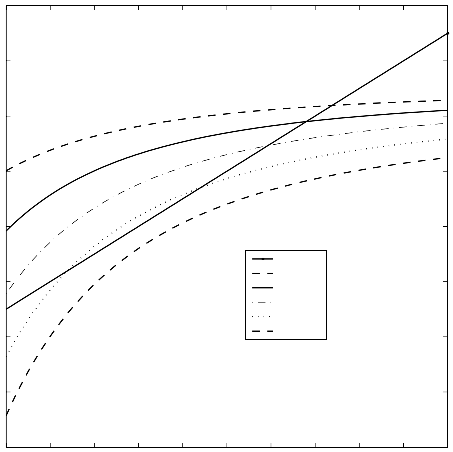

Figure 3. Search of tangency between linear ideal birefringence and effective ones.

the incident fields (they present two effective indices as the field vibrates parallel or perpendicular to the grooves; n_{eff}^{TE} (or n_{eff}^{s}) and n_{eff}^{TM} or (n_{eff}^{p}), respectively). It is the so-called "form birefringence". The dispersion of this artificial birefringence can be partially controlled by adjusting the grating parameters such as the period Λ, the depth d, the fill factor $F = \frac{b}{\Lambda}$ (ratio of the width of grating grooves to the period) and the incidence angle θ (see Figure 2).

2.2.1. Dispersion of form birefringence

Interaction between the periodically modulated permittivity and the vectorial electromagnetic field inside a grating leads to interesting effects on the phases and amplitudes of the external propagating fields.

In the quasi-static limit, i.e. when the ratio $\frac{\Lambda}{\lambda} << 1$, simple homogeneization treatment involving average considerations leads to the two following effective indices corresponding to TE (Transverse Electric) and TM (Transverse Magnetic) states of polarisation (Born & Wolf 1999)

$$n_{eff,0}^{TE} = (F\epsilon_a + (1-F)\epsilon_b)^{\frac{1}{2}} \tag{5}$$

$$n_{eff,0}^{TM} = (\frac{\epsilon_a \epsilon_b}{F\epsilon_b + (1-F)\epsilon_a})^{\frac{1}{2}} \tag{6}$$

where $(\epsilon_a)^{\frac{1}{2}} = n_a$ and $(\epsilon_b)^{\frac{1}{2}} = n_b$ are the structure's real indices, and where F is the fill factor. This immediate approach is called the Zeroth Order Effective Medium Theory (EMT0).

But when the ratio $\frac{\Lambda}{\lambda}$ is no longer negligible, the latter closed-form expressions for the effective refractive indices are no longer correct. In such a case, second order EMT (EMT2), which is deduced from the electromagnetic propagation in stratified media theory, allows to derive these expressions for the effective indices (Rytov 1956)

$$\begin{aligned} n_{eff,2}^{TE} &= \{n_{eff,0}^{TE} + \frac{1}{3}(\frac{\Lambda}{\lambda})^2 \pi^2 F^2 (1 \\ &\quad -F)^2 (n_a^2 - n_a^2)^2\}^{(\frac{1}{2})} \end{aligned} \tag{7}$$

$$\begin{aligned} n_{eff,2}^{TM} &= \{n_{eff,0}^{TM} + \frac{1}{3}(\frac{\Lambda}{\lambda})^2 \pi^2 F^2 (1-F)^2 (\frac{1}{n_a^2} \\ &\quad -\frac{1}{n_a^2})^2 (n_{eff,0}^{TM})^6 (n_{eff,0}^{TE})^2\}^{(\frac{1}{2})} \end{aligned} \tag{8}$$

In addition to the dependence on the ratio $\frac{\Lambda}{\lambda}$, thus on the **wavelength**, we can also notice the dependence of the effective indices on other parameters available in a design procedure: the grating period Λ, the fill factor F, the grating depth d and the grating real indices n_a and n_b.

The wavelength dependence of the effective indices is consequently also found in the form birefringence Δn_{form} which is defined as follows: $\Delta n_{form} = n_{eff}^{TE} - n_{eff}^{TM}$ or, equivalently, $\Delta n_{form} = n_{eff}^{s} - n_{eff}^{p}$. This phenomenon is called the *dispersion of form birefringence*. We must emphasize the term "form". Indeed, this property is essentially given by the geometry, no longer by the intrinsic characteristics of the materials.

This control we have on the optical properties of this particular type of grating (we may speak of "refractive index engineering") allows us to design achromatic waveplates.

2.2.2. Design in transmission

The propagation in a birefringent medium along the optical axes leads to the following phase shift between the ordinary (s or TE) and extraordinary (p or TM) wave components

$$\Delta\phi = \frac{2\pi}{\lambda}\,\Delta n\, l \tag{9}$$

where Δn is the birefringence and l, the propagation path length.

One searches the ideal birefringence which could compensate for the hyperbolic dependence of the phase shift expression (9) so as to obtain an achromatic phase shift. The latter, in the case of a π phase shift should be

$$\Delta n_{form} = \frac{\lambda}{2h} \tag{10}$$

with the so-called form birefringence Δn_{form}. By carefully selecting the grating parameters (incidence should also be considered), it is possible to make the form birefringence tangent to the ideal birefringence (see Figure 3 in which the fill factor is the free parameter), thus partially compensating for the $\frac{1}{\lambda}$ dependence of the phase shift expression within an appreciable wavelength range (Kikuta et al. 1997).

Numerical simulations are based upon the Rigorous Coupled Wave Analysis (Moharam & Gaylord 1982). Indeed, in the sub-lambda domain, scalar diffraction theories fail dramatically; the vectorial nature of light must be taken into account. Furthermore, homogeneization theories like EMT2, even if qualitatively useful, are not accurate enough because they don't take evanescent waves into account.

RCWA optimizations led then, for instance, to a phase shift quality corresponding to an equivalent rejection ratio of $R = 600000$ (see Figure 4).

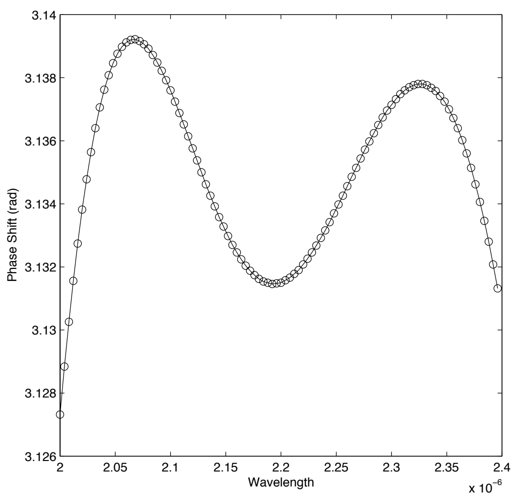

Figure 4. ZOG achromatic half-wave retarder simulation for the K band (2-2.4 microns). Equivalent rejection ratio of $R = 600000$. Transmission mounting.

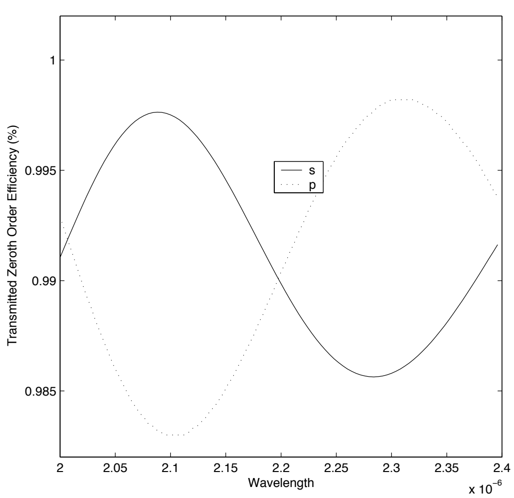

Figure 5. Transmission efficiencies for Si/SU-8/CdTe ZOG.

This simulation was done for the K band. The material used was silicon (transparent in this wavelength range) for the substrate. The modulated region of the grating is composed of silicon from the substrate and a photoresine used for planarization (Deguzman et al. 2001). The incident medium is CdTe to minimize parasitic Fresnel reflections at the outer interface. One can see the result of such a configuration as far as transmission efficiencies are concerned in Figure 5.

The difficulty in the transmission design is to manage simultaneously the differential efficiency between s (or TE) and p (or TM) components of incident polarization and the phase quality. However, several strategies are possible and have led in our example to interesting results (see Figure 4 and Figure 5).

2.2.3. Design in reflection

To overcome the differential transmittance problem, one could use the total internal reflection phenomenon. Indeed, the total reflection leads automatically to 100 % efficiency for both polarizations and the control of the effective indices allows to compensate for the natural dispersion of the material used.

The phase shift between the s and p components in this case would be (Born & Wolf 1999):

$$\begin{aligned} \Delta\phi(\lambda) &= 2\arctan\{-\frac{\sqrt{\sin^2\theta - n^s_{eff}}}{\cos\theta}\} \\ &- 2\arctan\{-\frac{\sqrt{\sin^2\theta - n^p_{eff}}}{(n^p_{eff})^2\cos\theta}\} \quad (11) \end{aligned}$$

Numerical simulations made according to RCWA lead, for instance, to an equivalent rejection ratio $R = 1250000$ for the 6-8.75 microns band (see Figure 6).

This example is for a CdTe substrate imprinted with a sub-lambda grating. The latter is back illuminated with proper incidence to reach the total internal reflection regime

2.3. Manufacturing

As written before, natural birefringences are usually two orders of magnitude lower than indices. This relaxes manufacturing constraints at the level of thickness control which is consequently also reduced by two orders of magnitude.

For artificially birefringent components, systematic variations of grating parameters led to the following conclusion : the achromaticity of the design can be easier controlled than the exact and essential π phase shift. However, the flexibility of the design procedure allows to compensate for the lack of precision of a

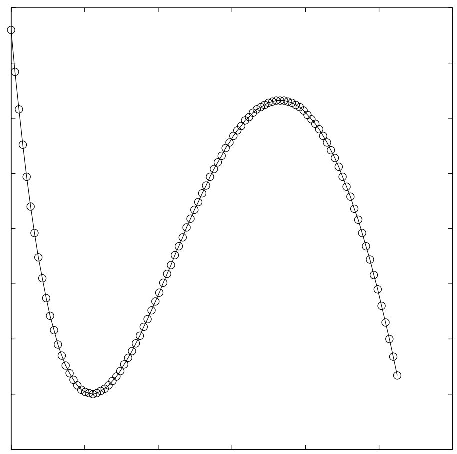

Figure 6. ZOG achromatic half-wave plate simulation for the 6-8.65 microns wavelength range (spectral resolution of 2.75). Reflection mounting.

single parameter by variation of other ones, including a posteriori possibilities with the incidence angles.

It follows that the specifications on the grating parameter precisions are within the most advanced nanotechnology techniques available in microelectronics industry, such as Electron-Beam lithography and Reactive Ion Etching. Their tight control is nevertheless critical and requires systems equipped with in situ monitoring possibilities (Lalanne et al. 1999).

2.4. Implementation

The implementation on interferometers (Bracewell, see Figure 8) and coronagraphs (Four Quadrant Phase Mask Coronagraph, see Figure 7) of such components is under study in our team. It is theoretically quite immediate and elegant.

Considering two identical birefringent structures rotated by 90 degrees from one another, we retrieve for each state of polarization the "designed" achromatic phase shift. So it works with natural light. As we have the same component (under the hypothesis of perfect replication) just rotated in each arm of the interferometer or quadrant of the coronagraph, the only resultant phase shift is the designed vectorial one.

Nevertheless, the alignment between the quadrants or arms must be finely controlled and is directly related to the nulling ratio expected.

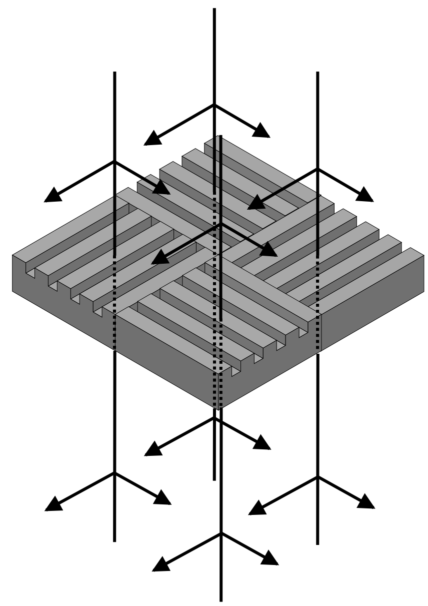

Figure 7. Four Quadrant Phase Mask Coronagraph implementation.

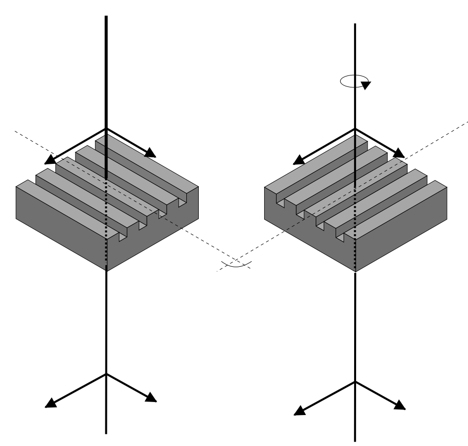

Figure 8. Interferometer implementation.

3. CONCLUSION

The birefringence approach to achromatic phase shifters is quite new in the community of astrophysicists and is intended to provide flexible solutions. Our aim in this paper was to give a panel of possibilities and performances of such components.

As far as ZOGs are concerned, we point out the flexibility of the entire approach. This flexibility is based on the number of free parameters available in the design procedure. Moreover, given the speed at which microelectronic technologies are currently developing, more accurate control of additional parameters will become possible every year, opening the door to rapid substantial performance improvements.

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