Fresnel Rhombs as Achromatic Phase Shifters for Infrared Nulling Interferometry

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I. Introduction

In the context of **exoplanet detection**, both ESA and NASA have proposed the concept of a space-based **Infrared Nulling Interferometer** in order to perform direct detections. However, such missions are technically very challenging and several aspects are still critical (formation flying, nulling interferometry,...). One of the most critical units of a nulling interferometer is the **phase shifter** because it has to provide a very accurate achromatic phase shift between the different arms of the interferometer over the whole operational spectral range. We propose a new family of achromatic phase shifters for infrared nulling interferometry. The principle is to implement optimized **Fresnel rhombs** according to the original scheme of Fig. 1, using the total internal reflection (TIR) phenomenon, modulated or not with **Zero-Order Gratings** (ZOG, see III. herebelow).

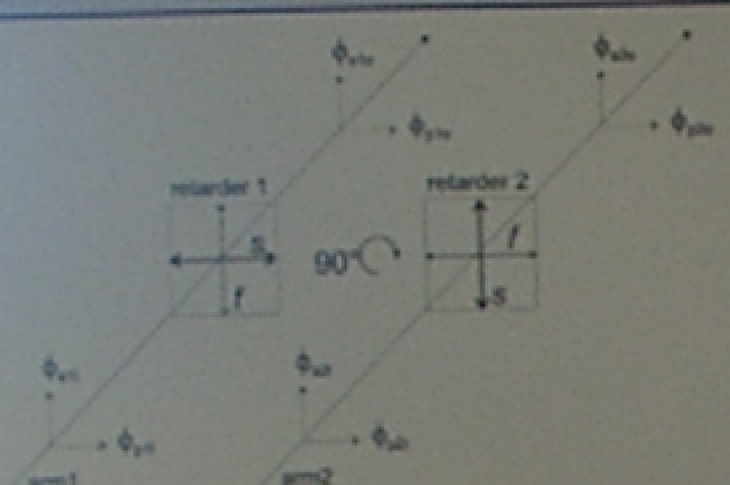

Fig. 1 Implementation of a vectorial phase shifter in a two-telescope nulling interferometer (Bracewell). The π retardance between the orthogonal polarization components *s* and *p* induced by the light differential optical delay between the slow (*s*) and fast axes (*f*) of the vectorial phase shifters 1 and 2 ($\Phi_{s1o} - \Phi_{p1o} = \Phi_{s2o} - \Phi_{p2o} = \pi$) can be spatially distributed between the interferometer arms. Indeed, a rotation of 90° of the retarder around the optical axis swaps the role of the polarizations so that at the output, the potentially interfering polarization states, i.e. the parallel ones, are in opposition, $\Phi_{s1o} - \Phi_{s2o} = \Phi_{p1o} - \Phi_{p2o} = +/- \pi$.

II. Principle

The Total Internal Reflection (TIR) phenomenon induces a **differential phase shift between the vectorial *s* and *p* polarization** components. This vectorial phase shift takes the following general form [2]

$$\Delta\phi_{s-p} = 2\arctan\left[\frac{\sqrt{\sin^2\theta - n_c^2}}{n_c^2\cos\theta}\right] - 2\arctan\left[\frac{\sqrt{\sin^2\theta - n_c^2}}{\cos\theta}\right]$$

where θ is the angle of incidence, larger or equal to θ_c, the critical angle defined as $\sin\theta_c = n_c = n_t/n_i$ and where n_i and n_t are refractive indices of the incident and emergent media, respectively.

Classical Fresnel rhombs are limited by the intrinsic index dispersion of the rhomb bulk material. Engraving a subwavelength grating on the TIR interface leads to a significant improvement. Indeed, the electromagnetic field evanescent interaction with the optimized micro-structure allows tuning the index ratios of the above equation. In order to compensate for incidence variations, we chose the double rhomb configuration (Fig. 2).

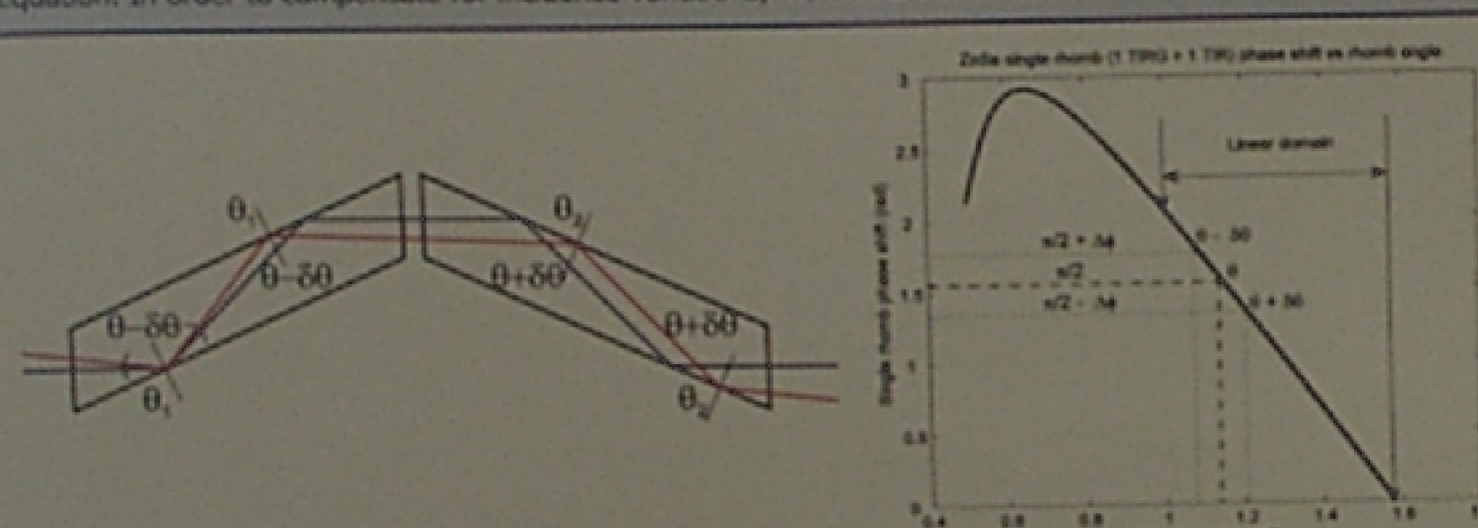

Fig. 2 Left: Principle of the Fresnel rhombs as achromatic phase shifters for infrared nulling interferometry. This scheme shows the double rhomb configuration (instead of the single one). θ_1 and θ_2 are respectively the angles of incidence upon TIR interfaces of the first and second rhomb. Right: The graph shows the relation between the rhomb angle and the induced phase shift. For the retardance values we wish, the dependency is linear, therefore, the use of a double rhomb can compensate incidence-angle variations δθ.

III. Subwavelength Gratings / ZOGs

When **the period of the grating is smaller than the wavelength** of the incident light, it does not diffract as a classical spectroscopic grating. All the incident energy is forced to propagate only in the zeroth order, leaving incident wavefronts free from any further aberrations. Subwavelength gratings are therefore often called Zero Order Gratings (ZOGs). This type of gratings behaves like homogeneous media with unique characteristics (e.g. artificial anisotropy). The key point is that by carefully **controlling the grating geometry** (via the grating parameters, see Fig. 3), we may adjust the optical refractive properties. To be more precise, the structure's form birefringence can be tuned in order to induce an achromatic phase shift between the polarization components TE and TM [3]. Theoretical results are displayed in Fig. 4 and Table 1.

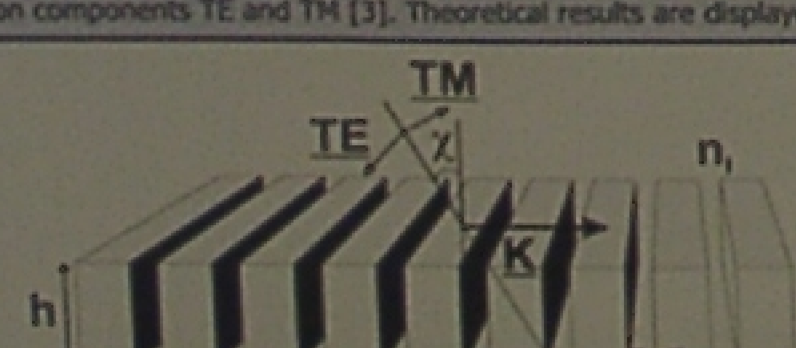

Fig. 3 ZOG schematic presenting the main parameters of the grating: the grating vector $|K| = 2\pi/\Lambda$, perpendicular to the grating lines, with Λ the period, the grating depth h and the so-called filling factor F, such that FΛ is the width of the grating ridges. TE and TM are the vectorial orthogonal polarization components of the X-incident light. n_I and n_{III} are the refractive indices of the incident and transmitting media, respectively. n_1 and n_2 are the refractive indices of the grating itself (in our case, $n_1 = n_I$ and $n_2 = n_{III}$).

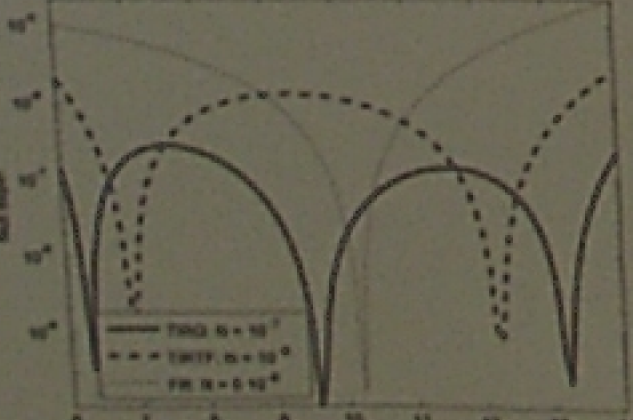

Fig. 4 *ZnSe* double rhomb Achromatic Phase Shifter (APS): comparison between Fresnel Rhomb (FR) with non treated TIR interfaces, TIR thin film (TIRTF) and TIR grating (TIRG). More than substantially improving the global (mean) null depth over the considered wavelength range, the TIRTF and the TIRG solutions significantly decrease the strong leakage at its edges, inevitable with the FR solution.

Material /band	Fresnel rhomb	TIRG APS
ZnSe / 6-11 µm	2×10^{-6}	1×10^{-8}
ZnSe / 6-14 µm	6×10^{-6}	1×10^{-7}
CdTe / 6-11 µm	2×10^{-7}	5×10^{-9}
CdTe / 11-18 µm	8×10^{-7}	1×10^{-8}
CdTe / 6 – 18 µm	2×10^{-6}	1×10^{-7}
KRS-5 / 6 – 11 µm	2×10^{-7}	NA
KRS-5 / 11 – 18 µm	1×10^{-6}	NA
KRS-5 / 6 – 18 µm	2×10^{-6}	NA

Tab. 1 Average null depths for the optimized Fresnel double rhomb and TIRG APS configurations for the selected infrared materials.

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IV. Conception and manufacturing

The first step in the fabrication of TIRG APS consists in imprinting a **photomask** of the grating in a photoresist coated on the chosen substrate material. The precision of this step is critical because it defines once and for all the lateral dimensions of the grating: its period Λ and the so called feature line, i.e., the period multiplied by the filling factor F. This pattern will then uniformly be transferred into the substrate by an appropriate **reactive plasma-beam etching** down to the desired depth. Concerning the *ZnSe* TIRG APS prototype designed for the 6-14 µm wavelength range, assuming a fixed 900-nm period, best solutions are searched using the Simplex-optimization method coupled to a rigorous diffraction algorithm with the free parameters left: the filling factor F, the grating thickness h and the incidence angle θ. Results of this optimization are displayed in Fig. 5.

Cutting and polishing trials of *ZnSe* rhombs with the appropriate specifications have already been conducted. The results of measurements in term of surface quality and roughness are comfortably within the specifications, and beyond our expectations with surfaces figures of λ/100 rms (λ = 632.8nm) and a roughness of 3 nm rms.

Concerning the TIR grating, the most appropriate method to manufacture the micro pattern into the rhomb material is based on **holographic lithography and dry etching process**. The first one is necessary for masking the parts of the substrates to be protected during the plasma etching process (Fig. 6 left). This technique is currently under development and the latest results are promising.

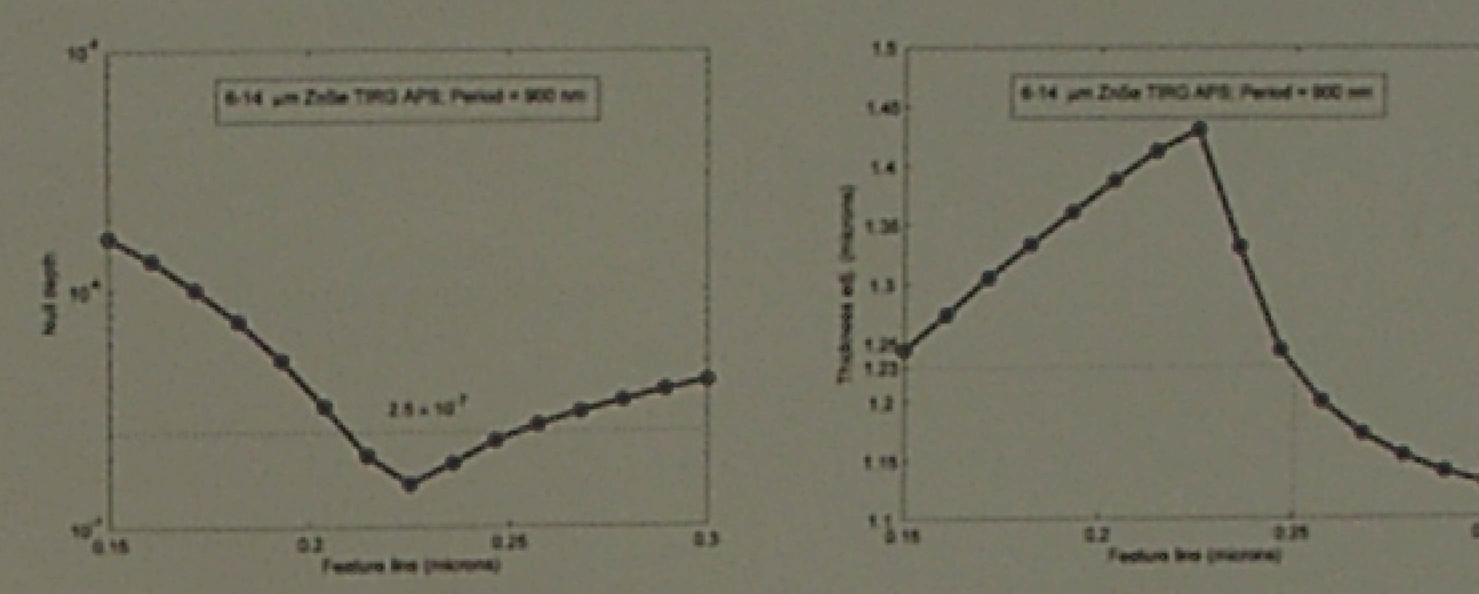

Fig. 5 6-14 µm *ZnSe* double rhomb APS with 900 nm period. Left: optimized null depth vs feature line. Right: thickness adjustment (optimized) vs feature line. These calculations were performed to assess the technical feasibility of the corresponding prototype. Conclusions are that we are well within acceptable tolerances, i.e. within a few percents for the geometrical parameters.

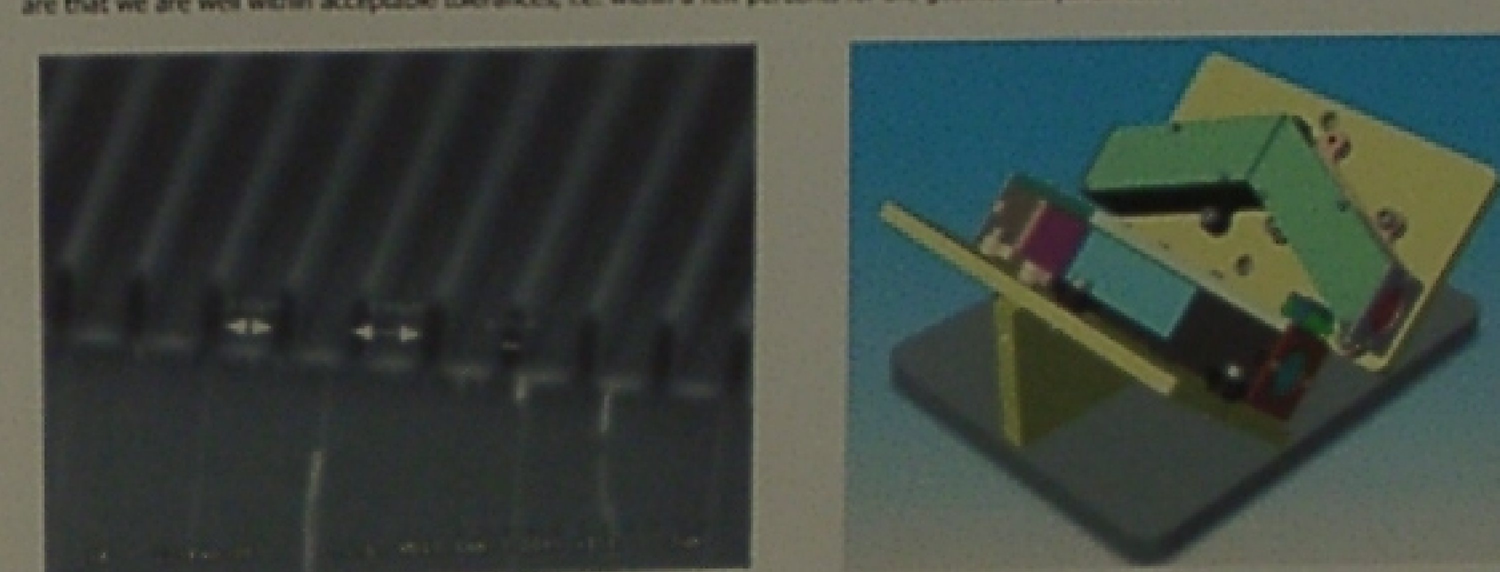

Fig. 6 Left: Micro-pattern on photoresist to be transfered by refractive plasma beam etching into the *ZnSe* substrate. The period and filling factors correspond to the design specifications, i.e., Λ = 0.9 µm for the period and ~ 250 nm for the feature line. Right: Illustration of the mounts of the rhombs and the practical implementation of the components in the interferometer at 45° from the test bench table, rotated by 90° from each other.

V. Measurement of a ZnSe Fresnel rhomb retardance

We conducted preliminary measurements of the performances of a *ZnSe* Fresnel rhomb at 632.8 nm with a simple polarimeter arrangement (Fig. 7). A governing equation relates the ratio of the intensities $I^{\pi/2}$ and I^0 of the two orthogonal polarization states to the orientation of the i/o polarizer, the retarder, and the retardance (Γ) [4]

$$\frac{I^0}{I^{\pi/2}} = \frac{\sin^2 2\alpha \sin^4\theta \sin^2(\Gamma/2)}{1 - 4(1-\sin^2\alpha\sin^2\theta)\sin^2\alpha\sin^2\theta\sin^2(\Gamma/2)}$$

where α is the inclination of the polarizer from the vertical position and θ the angle between the input polarization and the rhomb optical axis. **The results are in agreement with theoretical expectations.** We have measured a phase shift of 89.8°+/-1.5°, consistent with the theoretical 91.2°+/-0.5° retardance. This experiment also allowed us to **disentangle several parasitic effects** that could prevent the rhomb to reach its theoretical phase shifting potential. We have identified the primary source of perturbation as the **surface and bulk scattering** (~1%). Fortunately, we have demonstrated that it can be mitigated at least at the 10^{-5} level (accuracy of our optical setup) by inserting a spatial filter at the rhomb output.

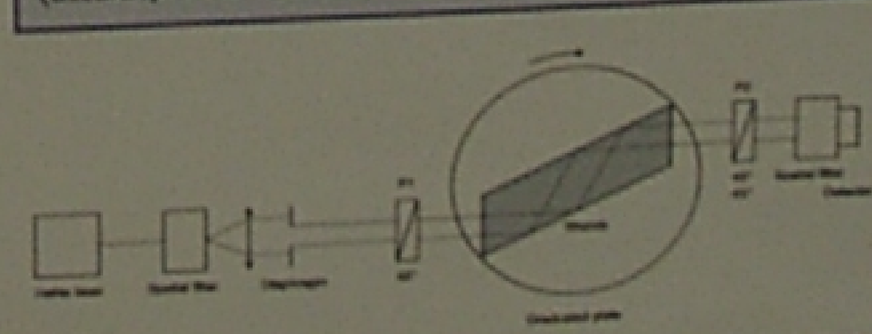

Fig. 7 Setup of the optical bench used to perform the *ZnSe* Fresnel rhomb retardance measurement. Linearly polarized light (through P1) is incident upon the *ZnSe* rhomb retarder, and the light emerges with an elliptical polarization. The intensities of the two orthogonal polarization states are measured with rotating the output polarizer (P2). A governing equation relates the ratio of these two intensities to the orientations of the input/output polarizer and the retardance.

Fig. 8 Picture of a *ZnSe* Fresnel rhomb

VI. Conclusions

We present here a new family of Achromatic Phase Shifters for thermal infrared radiations relying on the Total Internal Reflection phenomenon, modulated or not by integrated subwavelength gratings. Theoretical results show remarkable improvements over the classical Fresnel rhomb technique, which is always limited by the intrinsic dispersion of the bulk material used. We have also presented some design key points and encouraging preliminary measurements of the *ZnSe* prototype under manufacturing at the "Centre Spatial de Liège" (Belgium) under ESA contract. In the framework of R&D activities for the Darwin mission, this prototype will be tested on the Nulltimate test bench at the "Institut d'Astrophysique Spatiale" of Orsay (France) in the team of Alain Léger.

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