Annular Groove Phase Mask coronagraph in diamond for mid-IR wavelengths

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Christian Delacroix is most thankful to the FRIA – FNRS for their financial support.
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1. Subwavelength gratings for extrasolar planetary system imaging and characterization

Phase-mask coronagraphs are known to provide high contrast imaging capabilities while preserving a small inner working angle. Scientifically speaking, it allows observing the close environments of stars, enabling the search for exoplanets or circumstellar disks. On the technical side, it can be used with smaller telescopes or at longer wavelengths. We use subwavelength gratings as artificial birefringent elements and we take advantage of their properties to synthesize achromatic phase-mask coronagraphs. The grating equation that gives the diffraction angles θ_m for the different transmitted orders m, can be written as :

$$-n_i \sin\theta_0 + n_t \sin\theta_m = \frac{m\lambda}{\Lambda}$$

θ_0 being the incidence angle, λ the observed wavelength, Λ the grating period, and n_i and n_t being the refractive indices of the incident and transmitting (substrate) media, respectively. The period must absolutely be smaller than λ/n_t so that only the zeroth order is allowed to propagate outside the grating (Fig. 1). For this reason, these structures are called ZOGs (Zeroth Order Gratings).

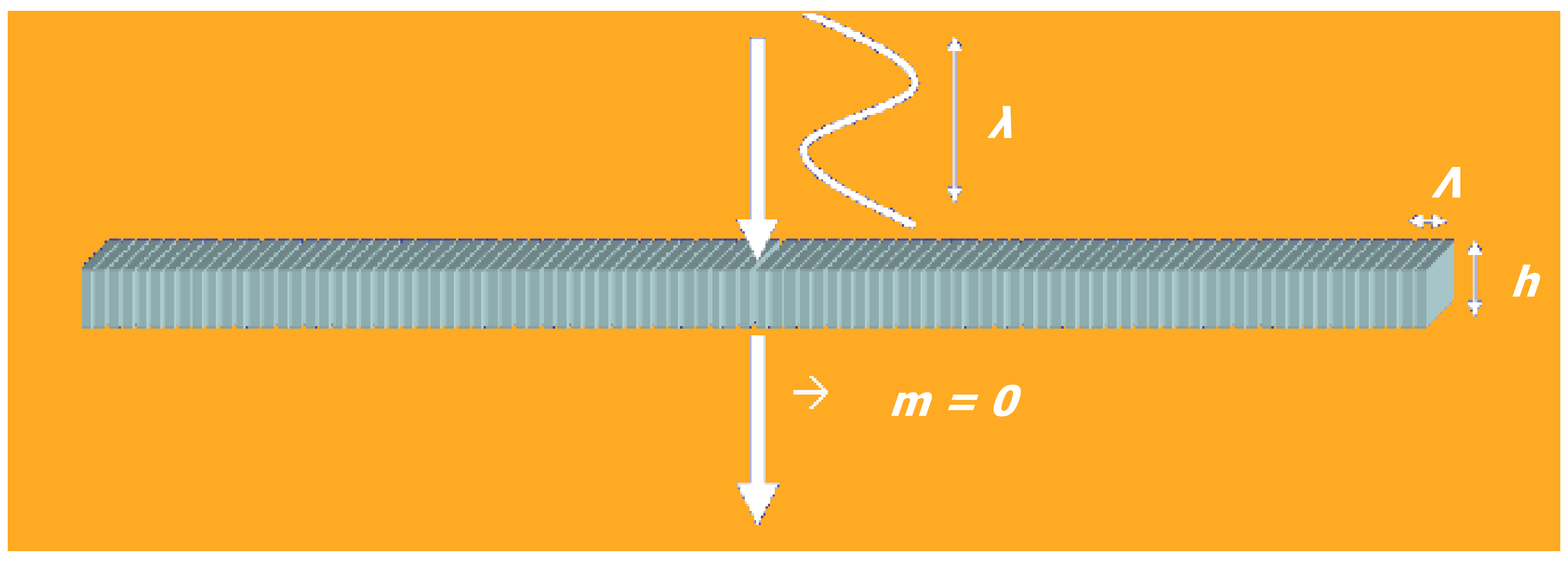

Fig. 1 Subwavelength gratings are gratings which spatial period is smaller than the wavelength of the incident light, divided by the refractive index of the grating substrate. Only the zeroth order is transmitted.

2. Annular Groove Phase Mask coronagraph

The Annular Groove Phase Mask (AGPM, Mawet et al. 2005) is the natural evolution of the well-proven Four Quadrant Phase Mask (FQPM, Rouan et al. 2007). Its biggest advantage on the FQPM is that it avoids the transition zones between the quadrants, which lead to a loss of information. In fact, the AGPM coronagraph synthesizes an optical vortex which consists of a micro-optical circular subwavelength grating with a continuous phase distribution (Fig. 2). The discontinuity in the very center of the coronagraph leads to a total starlight rejection in the theoretically ideal case. with a particular period, thickness and filling factor, we can produce an achromatic mask for a large spectral band, in the visible or IR.

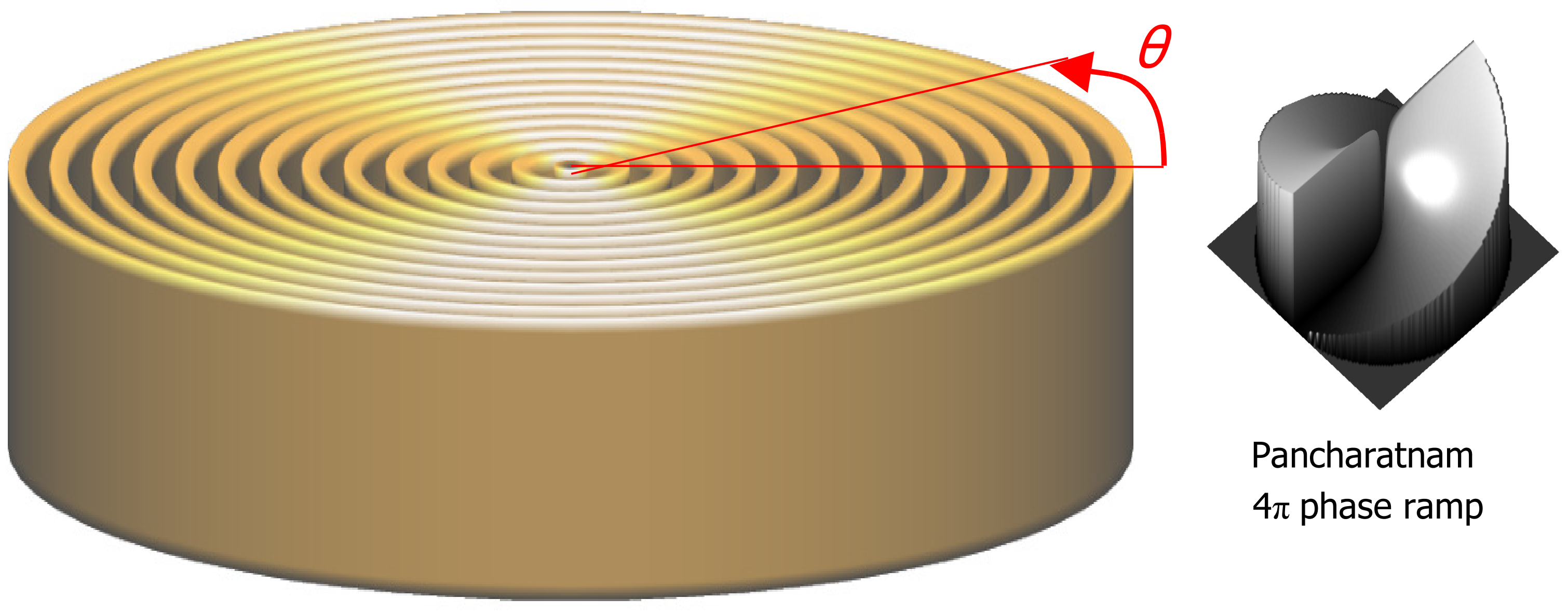

Fig. 2 The AGPM synthesizes an achromatic optical vortex of topological charge l_p=2, generating the 4π Pancharatnam phase ramp ($e^{\pm i2\theta}$, θ=[0,2π]) .

3. Diamond AGPM : numerical results with the Rigorous Coupled Wave Analysis

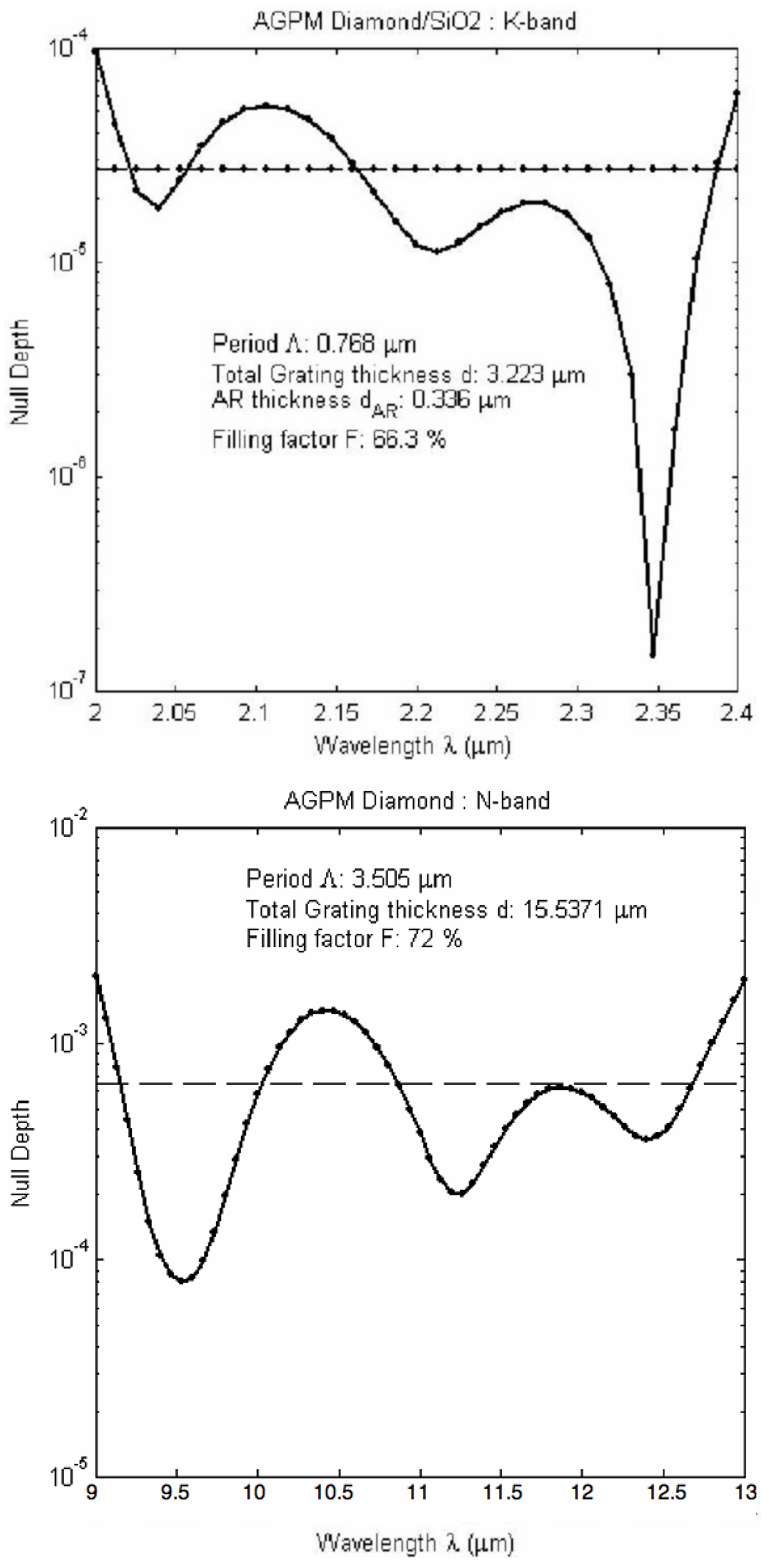

Fig. 3 Top, the mean null depth over the hole K-band is $\mu \approx 3 \times 10^{-5}$, provided to make an AR-coating in Silica. Bottom, the AR-coating is not necessary at 10 µm since it doesn't really improve the performances. The mean null depth over the hole N-band is $\mu \approx 6.5 \times 10^{-4}$, which is enough from a scientific point of vue.

The scalar theories of diffraction are not efficient in the subwavelength domain. In order to simulate the grating response and to calculate its form birefringence $\Delta n_{form} = \Delta n_{TE\text{-}TM}$ we must take the vectorial nature of light into account. Therefore, we have performed realistic numerical simulations using the Rigorous Coupled Wave Analysis (RCWA, Moharam & Gaylord, 1981). The RCWA resolves the Maxwell equations and gives the entire diffractive characteristics of the simulated structure. In Figure 3, we present the RCWA results for a subwavelength grating engraved in a diamond substrate. The null depth takes into account the phase errors with respect to π, $\varepsilon(\lambda) = \Delta\Phi_{TE\text{-}TM}(\lambda) - \pi$, and amplitude mismatches $q(\lambda) = \eta_{TE}(\lambda) / \eta_{TM}(\lambda)$:

$$N(\lambda) = \frac{\left[1-\sqrt{q(\lambda)}\right]^2 + \epsilon(\lambda)^2 \sqrt{q(\lambda)}}{\left[1+\sqrt{q(\lambda)}\right]^2}$$

Diamond has several advantages:

· a high refractive index, which is crucial since it is severely linked to the grating aspect ratio ;

· a high transmission over a wide IR spectral band, which is likely to suit many instruments like SPHERE on the VLTI, or EPICS and METIS on the future E-ELT.

We chose to focus on both the K-band which is compatible with many instruments, and the N-band for which the diamond is one of the unique solutions.

4. Manufacturing : first prototypes

The prototype manufaturing of the diamond AGPM involves a concerted action with both the Centre Spatial de Liège (Belgium) and the Uppsala University's Angström Laboratory (Sweden). The fabrication of N-band coronagraphs has begun (Fig. 4), using e-beam lithography, nano-imprint lithoragphy (NIL) and reactive ion etching (RIE). The first prototypes are currently undergoing a grating profile metrology, which is also challenging. We combine surface metrology on molded replica with diffraction analysis: experimental performance measured on a visible and near-infrared optical polarimetric bench and cross correlation with theoretical simulations using RCWA.

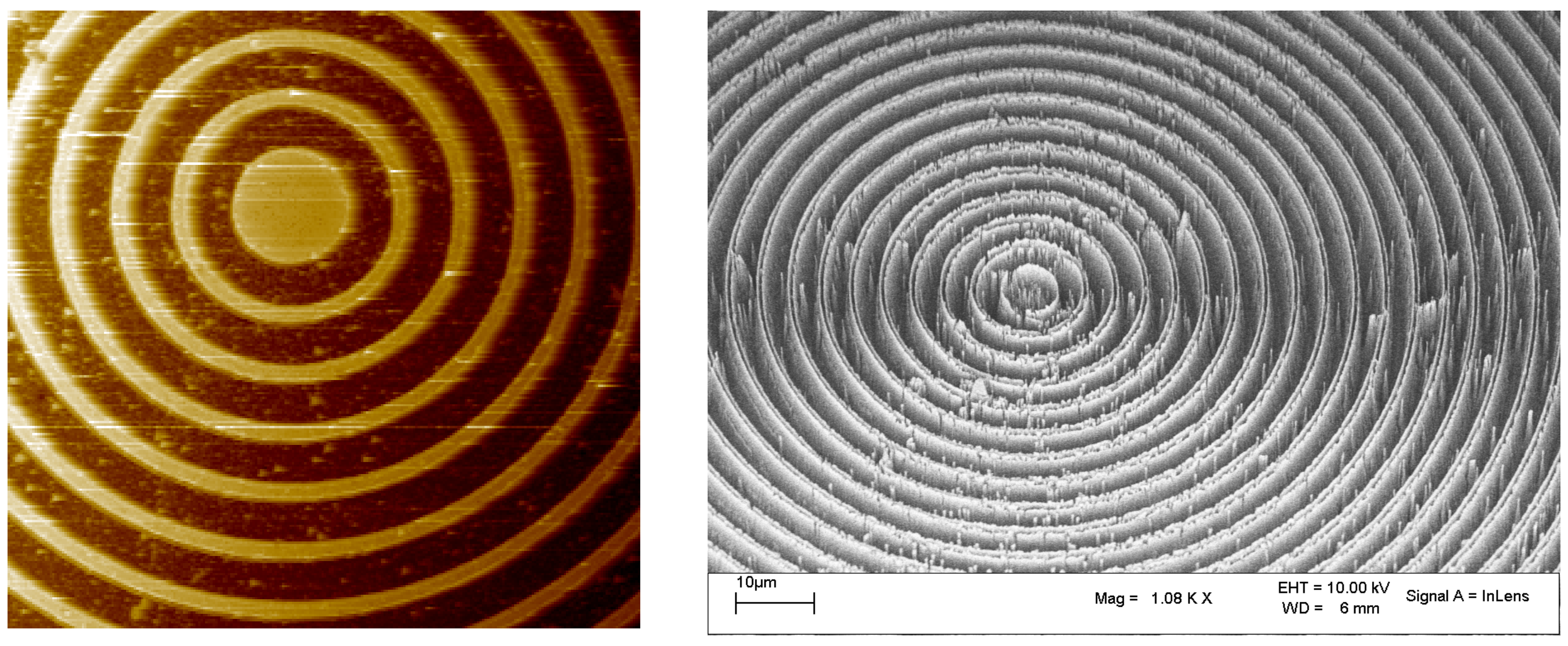

Fig. 4 Left, AFM (atomic force microscope) picture of the aluminium mask on top of the diamond substrate, obtained by nano-imprinting the ebeam master using a special NIL resist. Right, SEM (scanning electron microscope) picture of the etched diamond after RIE process.