5.2 Vector Apodizing phase plate coronagraph for MagAO-X

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1. Requirements

1. The vector Apodizing Phase Plate (vAPP) shall operate close to the Halpha-wavelength, between 650 nm and 675 nm.
2. The pupil diameter shall be undersized from 9mm of the incoming beam by a factor of 0.956, to 8.6 mm.
3. The vAPP shall define the pupil for downstream optics. This can be implemented using a high-frequency polarization grating outside of the pupil, scattering the light outside the pupil outside of the FOV.
4. The coronagraph shall be on a 1 inch diameter $\lambda/20$ substrate with AR coating and a wedge.
5. The dark zone shall have an inner working angle of 2.1 λ/D.
6. The dark zone shall have an outer working angle of 10 λ/D.
7. The dark zone shall have a design contrast of 10^{-5}.
8. The dark zoned shall have a D-shape, displaced from the PSF core by the inner working angle with an outer radius of the outer working angle.
9. The design Strehl ratio of the coronagraphic PSF shall be higher than 50%.
10. The transmission of the vAPP device shall be higher than 70% in the specified wavelength range.
11. The vAPP shall produce coronagraphic PSFs within the inner 3"x3" FOV of the 6"x6" FOV on the detector.

2. Goals

1. The first additional goal w.r.t. the baseline requirements above integrates focal plane wavefront sensing to measure at least 9 Zernike modes from Zernike mode 4 up, with a maximum of 36 modes. This can be implemented with the holographic modal wavefront sensor, which is implemented by adding a phase pattern on top of the vAPP pattern.
2. A second upgrade of the vAPP is to develop a version of the vAPP with requirements listed above, and additionally consists of a first step to make the vAPP broadband. This is achieved by producing an "achromatic" retarder by stacking three liquid-crystal layers. This device can then be operated in narrow band filters between 550 nm and 1100 nm.
3. A different implementation of low-order wavefront sensing with of the vAPP can be achieved by producing a "wavelength-selective" device, where the transmission into the coronagraphic PSFs is close to 100% around H-alpha and transmission into the regular leakage-term PSF is close to 100% at surrounding wavelength. By physically separating the leakage term into a different optical path this light can be used for low-order wavefront sensing.
4. An ultimate broadband vAPP device would consist of a regular polarizing beam-splitter (i.e. not a grating), in combination with an achromatic quarter-wave retarder. The leakage terms then overlap with the coronagraphic PSFs and need to be minimized by design of both the half-wave retarder structures of the liquid crystals and the properties of the quarter-wave plate.

3. The vector apodizing phase plate coronagraph

The vector apodizing phase plate (vAPP) is a pupil-plane coronagraph that modifies the phase of the incoming wavefront. This modification allows for redistribution of the light in the point spread function (PSF) to create an area where the star light is suppressed, i.e. a dark zone. In this dark zone, the decrease in stellar light allows for the detection of faint companions. By splitting both circular polarizations we obtain two coronagraphic PSFs with dark zones on either side of the PSF.

3.1 Benefits of the vAPP

- Insensitive to tip-tilt errors
- Insensitive to partially resolved star
- Small inner working angle
- Single optic
- Easy alignment
- High contrast (for ground-based purposes)
- Close to full coverage around star
- Inherently achromatic
- Extreme phase patterns possible
- Opportunities for implementing (focal-plane) wavefront sensing
- Natural combination with polarimetry

3.2 Technical details of the vAPP

The vAPP coronagraph (Snik et al. 2012, Otten et al 2014, 2017) can be described by a half-wave retarder where the fast axis orientation is a function of the pupil-plane coordinates. For left-handed circular polarization input, the output will be right-handed circular polarization, with a phase pattern depending on the orientation pattern of the fast-axis. Similar, right-handed circular polarization switches to left-handed circular polarization, now with opposite phase. The applied phase is ±twice the angle of the fast-axis orientation and is pure geometric phase, inherently independent of wavelength.
While geometric phase is achromatic, the retardance is a function of wavelength. A leakage terms appears when the retardance is not perfectly half-wave. There is no phase induced to the leakage term, other than aberrations caused by imperfections in the optic itself. For the unpolarized light of the star, the vAPP generates three PSFs, two PSFs with a dark zone on opposite sides and a leakage PSF.
The orientation of the fast-axis can be controlled with high precision using a liquid-crystal alignment layer in combination with a direct-write technique (Miskiewizc, Escuti 2014). The vAPP can be written with pixel-sizes down to 5 micron. The wavelength-dependent retardance is controlled with multiple twisted self-aligning liquid-crystal layers on top of the alignment layer. The layered retarder structures are called multi-twist retarders (MTRs) (Komanduri 2013).

4. Vector Apodizing Phase Plate for MagAO-X

4.1 Baseline phase pattern

The vAPP for MagAO-X was created using a global linear optimization algorithm from Emiel Por (Por et al. in prep) to calculate the phase pattern that creates a dark zone at the specified location with a maximized Strehl ratio. For MagAO-X, the inner working angle is 2 λ/D, the outer working angle is 10 λ/D, the dark zone has a contrast better than 10^{-5} and the Strehl ratio of this design is 60%. The design is shown in Fig. 1.

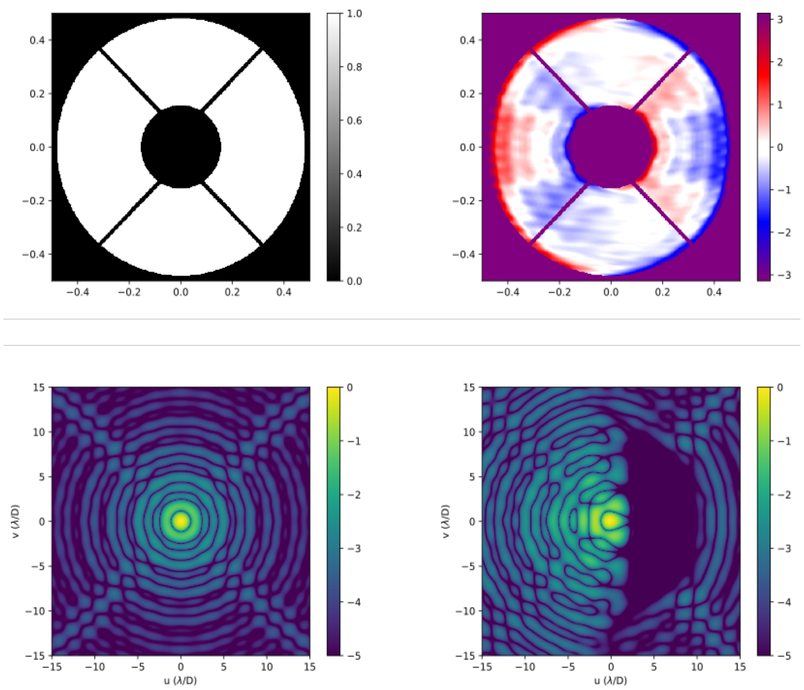

Figure 1: Top left: *Aperture of MagAO-X.* ***Top right:*** *Phase pattern of the vAPP.* ***Bottom left:*** *PSF of the aperture with constant phase.* ***Bottom right:*** *PSF of the vAPP with a D-shaped dark zone from 2-10 λ/D and contrast better than 10^{-5}.*

As mentioned in the section 3.2, the vAPP coronagraph will create three PSFs: two coronagraphic PSFs with dark zones on opposite sides and a leakage term PSF. To separate these on the detector, a "polarization grating" is added on top of the phase pattern, which imposes a linear phase ramp which changes sign for the two polarization states, i.e. the two coronagraphic PSFs. This polarization grating will thus split the left- and right-circular polarization PSFs, shifting them on the detector. The amount of splitting depends linearly on wavelength because it is imposed by a grating, but this is not an issue given the narrow spectral bandwidth of this setup. The leakage term goes through unaffected and ends up at the center of the detector. The combined PSF (right) for unpolarized light going through the grating vAPP (left) is shown in Fig. 2 as it would be on the MagAO-X detector for H-alpha wavelength. The phase pattern was reoptimized using Gerchberg-Saxton to remove crosstalk between the two coronagraphic PSFs and the leakage-term PSF.
To further simplify the vAPP and also integrate the amplitude mask in the actual phase pattern, we will write a very high frequency grating in the white area of Fig. 2. This effectively diffracts all the unwanted light outside of the pupil (as defined by this optic) outside of the beam/FOV. The exact angle and direction of this diffractive light, and how it is kept away from the focal plane is TBD.

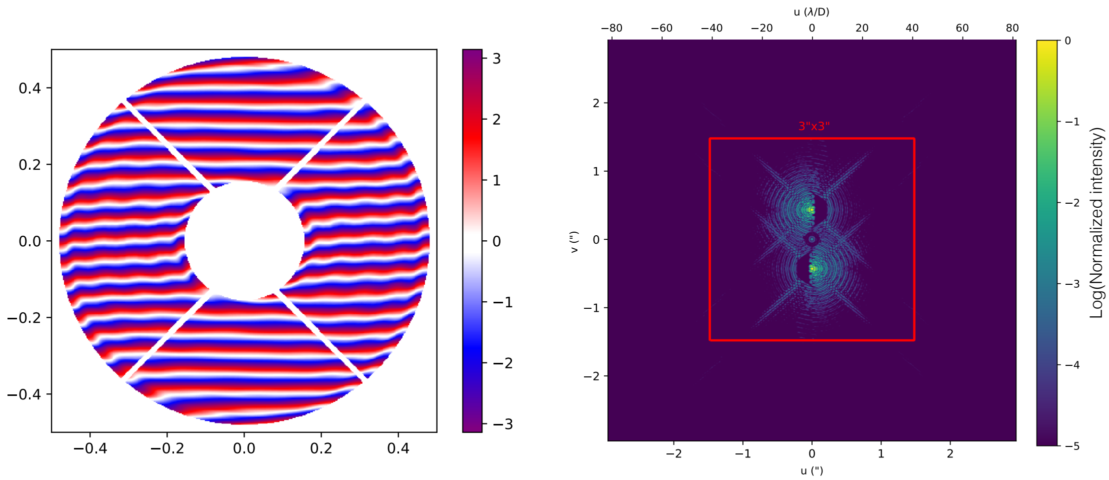

Figure 2: Left: *The phase of the grating vAPP with a grating added in the vertical directon.* ***Right****: The combined PSF of the vAPP for λ=656 nm. The top and bottom PSFs are separated on the detector by the polarization grating. The center PSF is the leakage PSF with 1% leakage at λ=656 nm.*

4.2 Additional features

With the baseline design for the phase described in section 4.1, additional features can be added for increased functionality. These features come at little cost and include alterations to the phase pattern and different optimizations for the liquid crystal structure. In total, four options can be provided and these will be explained in further detail in the different sections below. The options are:

1) The vAPP with broadband 3-layer liquid-crystal design with the baseline phase pattern.
2) The vAPP with broadband 3-layer liquid-crystal design with a holographic modal wavefront sensor on top of the baseline phase pattern.
3) The vAPP with a wavelength selective 3-layer liquid-crystal design with the baseline phase pattern.
4) The vAPP with a wavelength selective 3-layer liquid-crystal design with a holographic modal wavefront sensor on top of the baseline phase pattern.

Both the broadband (1-2) and wavelength selective (3-4) liquid-crystal designs have their advantages and disadvantages and are mutually exclusive. The option to add the holographic modal wavefront sensor is independent of the choice of liquid-crystal designs.

The first vAPP device will have the extra features of option 2, with the broadband 3-layer liquid-crystal design and a holographic modal wavefront sensor on top of the baseline phase pattern.

4.2.1 Goal #1: Focal plane wavefront sensing with holograms

A great advantage of the liquid crystal technology is that it allows the flexibility to add almost any phase pattern. Here, we exploit this freedom to add holograms with Zernike modes to sense wavefront aberrations up to the detector. The holographic modal wavefront sensor (Wilby et al. 2017), creates two copies per mode of the central PSF on opposite sides of the PSF, aberrated by ±mode that we want to sense. When this wavefront error mode is present in the optical system, one spot will be less aberrated, while the other spot is even more aberrated. Comparing the relative amplitude of the two spots gives the sign and the amount of aberration in the system.

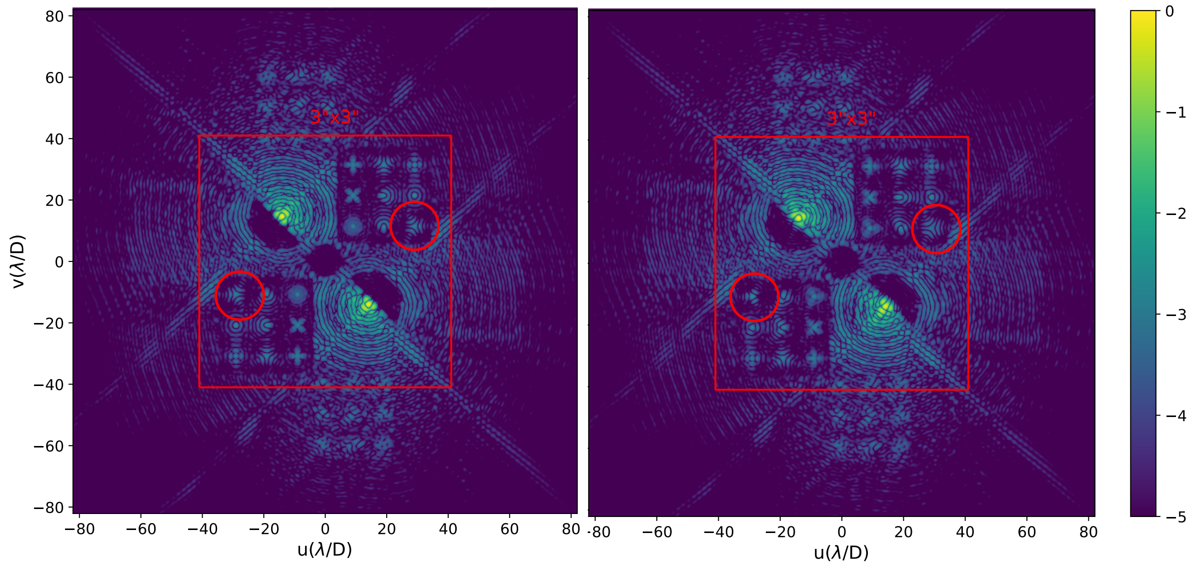

***Figure 4**: PSF of the focal plane holographic modal wavefront sensor (with 0% leakage assumed). The polarization grating orientation is rotated to create more space for the holograms. **Left**: The PSF without aberration. **Right**: The PSF with trefoil (Z_9). The hologram in the left circle has higher intensity than the hologram on the right. The applied aberration can be constructed from this information.*

For MagAO-X, a preliminary design contains 9 spots that fit in the 3"x3" FOV for increased readout speed. The ideal PSF is shown on the left in Fig. 4; the PSFs are aberrated with trefoil (Z_9) on the right.
For every mode four copies are generated, two for every polarization. The amount of light in the modes has to be sufficient to be detected for (slow) closed-loop control of the non-common path aberrations, which is estimated to be 1% per mode. Therefore, there is a trade-off between adding more modes and the amount of light in the coronagraphic PSFs. There is room for more modes on the detector outside of the 3"x3" FOV, however, the trade-off study still has to be done.

4.2.2 Goal #2: Broadband liquid-crystal design

The twist and thickness of the liquid crystal stack is optimized to reduce the leakage as much as possible around H-alpha. For observations around H-alpha i.e. from 650 nm to 675 nm, one layer (1TR) of liquid crystals allows for a leakage below 2%. To increase the bandwidth, a stack with three layers (3TR) is necessary. For this MTR, the leakage is below 1% from 550 nm to 1.1 µm, as shown in Fig. 3.
To fulfill goal #1, a vAPP device can be produced with a 3TR liquid crystal structure. The cost of 1TR vs 3TR are the added layers of only a few microns thick. This does almost nothing to the transmission of the device in the selected wavelength range. The cost increases slightly.

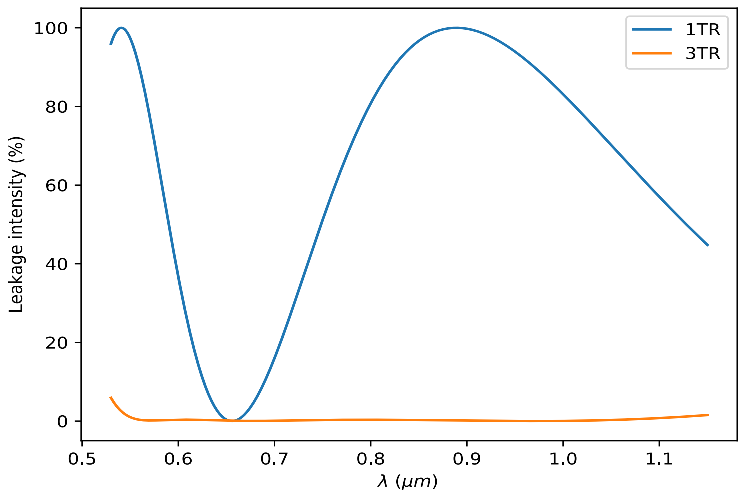

Figure 3: *Leakage intensity vs. wavelength for one layer of liquid crystals (1TR) and three layers of liquid crystals (3TR) with different twist and thickness. For the 1TR, the leakage is sub 2% between 650nm and 675 nm. The 3TR design has a leakage below 1% from 550 nm to 1.1 μm.*

4.2.3 Goal #3: Low-order wavefront sensing with a wavelength-selective vAPP

The half-wave retardance profile of the liquid crystal layers can be optimized to any profile by changing the twist and thickness of the layers. This freedom allows for a different way of low-order wavefront sensing. The retardance is optimized to increase the leakage term intensity (transmittance) to close to 100% outside of the scientific wavelength range, as shown in Fig. 5. On the left, we show the leakage intensity (transmittance) as function of wavelength. The leakage-term intensity is a few % around H-alpha and mostly above 80% outside of this band. The PSF in the middle panel corresponds to location 1 in the left panel of Fig. 5, with close to 100% leakage-term intensity at 580 nm. Location 2 in Fig. 5 corresponds to the PSF in the right panel, with close to 100% intensity in the coronagraphic PSFs at the H-alpha wavelength.

The leakage term can be separated in the focal plane, e.g. with a slightly rotated glass plate with a small mirror at the location of the leakage term. The reflected light of the leakage-term can be used in a low-order wavefront sensor.

The leakage term of the wavelength-selective vAPP is inherently broadband. To make good use of all the light in this leakage term, a broadband wavefront sensor is necessary. One option would be a vector-zernike WFS (Doelman et al. in prep 1), that uses a liquid crystal Zernike focal plane mask. For opposite polarization states, the Zernike mask applies a $\pm\pi/2$ geometric phase to part of the core of the PSF in a subsequent focal plane. By splitting the opposite polarization states with a quarter-wave plate and a Wollaston prism, two pupil images are created that can be used not only for achromatic phase aberration measurements, but also for achromatic amplitude aberration measurements.

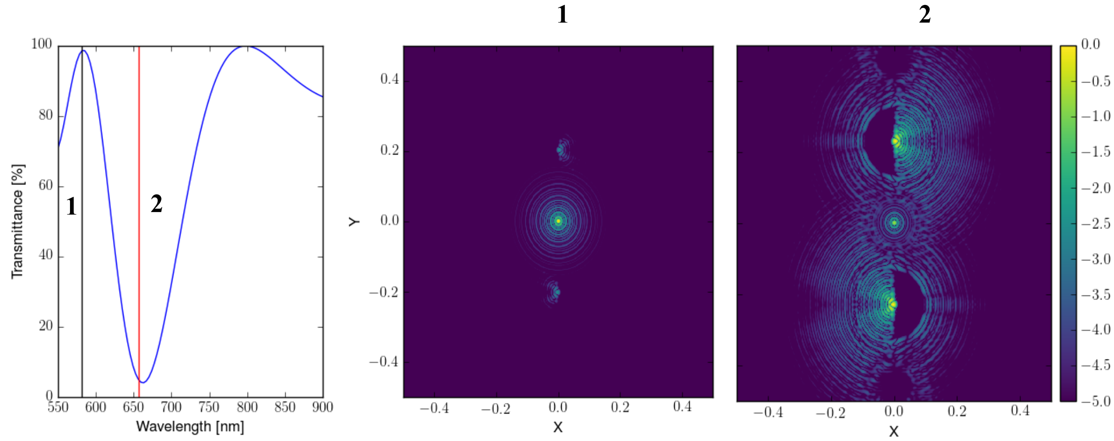

Figure 5: Left*: Leakage-term intensity (transmittance) as function of wavelength. The leakage term intensity is lowest around H-alpha and mostly above 80% outside of the scientific band.* ***Center:*** *The PSF corresponding to 580 nm (black line left panel), with a leakage term of close to 100%, and almost no light in the coronagraphic PSFs.* ***Right:*** *The PSF corresponding to the H-alpha wavelength (656 nm, red line left panel). Most of the light is in the coronagraphic PSF and almost none in the leakage PSF.*

5. Goal #4: A truly broadband vAPP coronagraph

To combine the high-contrast imaging (HCI), as enabled by the vAPP at MagAO-X, with high-resolution spectroscopy (HRS) with e.g. RHEA (Feger et al. 2014) or an integrated HCI+HRS approach as is currently being developed in Leiden (Por et al. in prep; Haffert et al. in prep), the vAPP needs to deliver achromatic splitting in addition to achromatized retardance performance. Achromatic splitting of linear polarization is easily implemented by replacing the dichroic splitter in front of the two science cameras with a polarizing beam-splitter cube (either based on a dielectric coating or a wiregrid structure). An additional quarter-wave plate (QWP) is then required to convert the two opposite circular polarization states of the two coronagraphic PSFs to the linear polarization states that the beam-splitter splits. This QWP can be positioned directly after the vAPP optic, as the two relevant linear polarization states are eigenvectors of the optical system in between the vAPP pupil and the beam-splitter (they correspond to the S and P directions on all mirrors). The vAPP itself then consists of the phase pattern as depicted in Fig. 1, with a broadband 3TR liquid-crystal structure design as presented in Fig. 3.

The main challenge of this implementation is to sufficiently suppress the leakage terms that emerge due to offsets from half-wave retardance of the vAPP and from quarter-wave retardance of the QWP. As there is no longer a grating to inherently separate the coronagraphic PSFs from the leakage PSF, the retardance profile of the vAPP needs to be <1% over the entire bandwidth to suppress the first Airy ring of the regular leakage-term PSF in the dark holes to <3E-4. Even then this term would still dominate the intensity error budget inside the dark hole. And because for a combination with a fiber-feed to a hi-res spectrograph it is unlikely that a "rotation-subtraction" technique (see Otten et al. 2017) can be applied to enhance the contrast during data-reduction, this leakage term needs to be suppressed in a different way. Fortunately, we have already introduced the "double-grating-vAPP" (Doelman et al. in prep 2), which combines a grating-vAPP with a regular polarization grating, which effectively delivers the desired phase pattern without any splitting. However, it diffracts out the leakage terms of both liquid-crystals patterns, effectively suppressing the leakage terms by a factor of ~100 to 1E-4, leading to a print-through of the first Airy ring of only ~3E-6.

Such a diffraction trick cannot be implemented for the QWP, and thus we will need to procure a "achromatic" or even a "superachromatic" QWP. An achromatic QWP consists of a quartz and a MgF2 plate with their fast axes crossed, such that their retardance dispersions largely cancel out. Over a 40% bandwidth, the retardance is typically constrained within 0.24–0.26 waves[1]. The offset from quarter-wave retardance causes a mixing of the two coronagraphic PSFs, that scales with $\sin^2(\Delta\delta)$, so the 0.01 wave retardance offsets cause a typical leakage of 0.4%. But the first "Airy ring" on the bright side of the coronagraphic PSF has a relative intensity of 0.26, leading to an untolerable intensity in both dark holes of ~1E-3. So, it will be necessary to use a so-called "superachromatic" QWP, that consists of a stack of 3 quartz+MgF2 combinations at different angles. Such plates can have a maximum retardance offset of 0.001[2], and thus suppress the leakage to <1E-4. However, the fast axis orientation of this type of QWP necessarily varies with wavelength, leading to additional leakage terms. In addition, the large number of crystal plates can cause significant amounts of WFE and "polarization aberrations" (Breckinridge et al. 2015). A better option may in the end be found by optimizing a thin (unpatterned!) liquid-crystal stack. The design trade-off and tolerance analysis on this is all still TBD.

Another alternative solution would be based on the production of a fully rotationally symmetric PSF that does not need to be split, and is optimized to deliver high contrast when feeding a multi-fiber system (Por et al. in prep; Haffert et al. in prep). A double-grating implementation then suppresses all pertinent leakage terms.

[1] http://www.b-halle.de/EN/Catalog/Retarders/Achromatic_Quartz_and_MgF2_Retarders.php
[2] http://www.b-halle.de/EN/Catalog/Retarders/Superachromatic_Quartz_and_MgF2_Retarders.php