Additionally 10 undergraduates and 5 Masters students...
Apodizing Phase Plate (APP)

Adding this phase on your telescope pupil.....

....makes this PSF for all objects in your focal plane

- Chromatic
- Impossible to make complex patterns
- Only 180 degree search space
Pupil plane coronagraphs not degraded by telescope vibrations that AO cannot catch

VLT/NaCo 4 microns at real time speed
Pupil plane coronagraphs not degraded by telescope vibrations that AO cannot catch.

VLT/NaCo 4 microns at real time speed
Classical Phase

Drawings by Gilles Otten
Classical Phase

Drawings by Gilles Otten
Geometric Phase

Starlight as a sum of left handed and right handed circular polarisations...

Drawings by Gilles Otten
Geometric Phase

Starlight as a sum of left handed and right handed circular polarisations...

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Starlight as a sum of left handed and right handed circular polarisations...

Drawings by Gilles Otten
Geometric Phase

Starlight as a sum of left handed and right handed circular polarisations...
Geometric Phase

Opposite handed polarisation has opposite phase shift

Drawings by Gilles Otten
Enabling freeform phase patterns

Typically 1 micron accuracy over >50mm optics

Miskiewicz & Escutti (2014)
Vector APP coronagraph

Orientation of fast axis encodes the phase shift

- Inherently achromatic
- Liquid crystal allows complex pa
- Two PSFs
Geometric phase using self-aligning birefringent polymers

Fig. 8. The MTR fabrication procedure resulting in a monolithic broadband element, on a single substrate and alignment layer: (a) alignment layer processing; (b) LCP coating \((m = 1)\); (c) LCP photo-polymerization; and (d) repeat LCP coating and curing for \((m \geq 2)\).
5. Experimental validation

We now outline the essential MTR fabrication procedure, describe the specific experimental parameters we employed to generate several of the elements described above. We then characterize these samples and compare with both simulation and commercial alternatives. Our analysis reveals that MTRs are easily fabricated with standard tools and materials, and achieve excellent optical properties in all cases that correspond well to the simulations above.

5.1. Fabrication

In principle, MTR fabrication is as easy as coating at least three polymer layers, as shown in Fig. 8. First (a), the alignment layer is applied. Second (b), a layer of LCP is coated and allowed to align to the layer below. Third (c), the LCP layer is cured, usually by (UV) photo-polymerization, to form a cross-linked polymer network. Finally (d), one or more additional layers LCP are coated and cured, aligned by the top surface of the immediately prior LCP layer to orient its start angle, until the full MTR is completed. In practice, fabrication is quick (few minutes), very repeatable, and scalable to large areas - we routinely coat 2 to 6 inch diameter elements. We often laminate a glass endcap onto the exposed LCP final layer, for protection and anti-reflection effects.

For the results here, we used a photo-alignment material LIA-C001 (DIC Corp), on borofloat #176332 - $15.00 USD.

Fig. 7. Simulated output of the (achromatic) 2TR and (super-achromatic) 3TR HW designs, and their comparative Pancharatnam examples: (a) and (b) show the output for the lin-lin HW MTRs, with a linear (horizontal) input polarization; whereas (c) and (d) show the output from cir-cir HW MTRs, with a circular (right) input. Curves: 2TR (dashed), 3TR (bold), and corresponding Pancharatnam (dotted and dash dot, respectively).
Another important polarization element is the half-wave (HW) retarder, which transforms optical rotation. Similarly, HW retarders are sometimes used to transform circular to orthogonal linear polarization (c-c) or vice versa, depending on whether the retardation is an even or odd multiple of 

\[
\frac{\pi}{2}
\]

Achromatic and super-achromatic HW MTRs are used to achieve these transformations. The most preferable 2TR and 3TR designs were found for achromatic and super-achromatic HW-B behavior for all cases that correspond well to the simulations above. We often laminate a glass endcap onto the exposed LCP final layer, for protection and anti-reflection effects.

The fabrication procedure is quick and scalable to large areas - we routinely coat 2 to 6 inch diameter samples by spin coating both layers LCP are coated and cured, aligned by the top surface of the immediately prior LCP layer. In practice, fabrication is quick (few 20-30 minutes), very repeatable, and scalable to large areas - we routinely coat 2 to 6 inch diameter samples by spin coating both layers LCP are coated and cured, aligned by the top surface of the immediately prior LCP layer. In practice, fabrication is quick (few 20-30 minutes), very repeatable, and scalable to large areas.

In Fig. 8. First (a), the alignment layer is applied. Second (b), a layer of LCP is coated and cured, aligned by the top surface of the immediately prior LCP layer. In practice, fabrication is quick (few 20-30 minutes), very repeatable, and scalable to large areas - we routinely coat 2 to 6 inch diameter samples by spin coating both layers LCP are coated and cured, aligned by the top surface of the immediately prior LCP layer. In practice, fabrication is quick (few 20-30 minutes), very repeatable, and scalable to large areas.
Another important polarization element is the half-wave (HW) retarder, which transforms the polarization from linear to another (rotated) linear polarization or from linear to another (rotated) polarized state, such as vertical linear. The HW retarder can also accomplish optical rotation. Similarly, HW retarders are sometimes used to transform circular to orthogonal circular polarization or to transform orthogonal circular to another (rotated) circular polarization.

The QW MTR designs described above are always achromatic. However, the bandwidths are relatively narrow (450-650 nm for the 2TR QW-A design and 400-800 nm for the 3TR QW-A design, respectively), and therefore these designs are sometimes used to accomplish optical rotation in one wavelength range. For wider bandwidths at relatively smaller thicknesses, MTRs can be used in combination with other polarization elements to accomplish both transformations. The most preferable 2TR and 3TR designs were found for the 2TR HW-A and 3TR HW-B designs, respectively. In this HW case, the analogous normalized bandwidth definition is the bandwidths 450-650 nm and 400-800 nm, respectively, and are shown in Table 2. The QW MTRs and HW designs were compared in terms of their bandwidths when the Mauguin [13] condition is satisfied. However, MTRs can be used to achieve wider bandwidths when the Mauguin condition is satisfied. Hence, MTRs are easily fabricated with standard tools and materials, and achieve excellent optical properties in all cases that correspond well to the simulations above.

In summary, the 2TR HW-B and 3TR HW-B designs achieve achromatic and super-achromatic optical rotation. The bandwidths are much wider than those of the QW designs, and therefore these designs are sometimes used to accomplish optical rotation in one wavelength range without using other polarization elements.

Table 2. Summary of 2TR and 3TR HW designs.

<table>
<thead>
<tr>
<th>Design</th>
<th>QW Design</th>
<th>HW Design</th>
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</thead>
<tbody>
<tr>
<td>2TR HW-A</td>
<td>2TR QW-A</td>
<td>2TR HW-A</td>
</tr>
<tr>
<td>3TR HW-B</td>
<td>3TR QW-B</td>
<td>3TR HW-B</td>
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</tbody>
</table>

Figure 5. (a) Illustration of the three layer MTR (3TR). (b) The polarization evolution within the 3TR design.

Figure 6. (a) Simulation of the MTR HW-B design. (b) The polarization evolution within the MTR HW-B design.

Figure 7. Simulated output of the (achromatic) 2TR and (super-achromatic) 3TR HW designs, for circular input polarization.
In principle, MTR fabrication is as easy as coating at least three polymer layers, as shown.

The following results show that the normalized bandwidths of 2/3TR HW designs are similar to the analogous QW MTRs ("A" designs), sometimes used to accomplish both transformations. The most preferable 2TR and 3TR designs were found for optical rotation. Similarly, HW retarders are sometimes used to transform circular to orthogonal linear polarizations, and anti-reflection effects.

In summary, the 2TR HW-B and 3TR HW-B designs achieve achromatic and super-achromatic performance, respectively. In this HW case, the analogous normalized bandwidth definition is the wavelength range for which the normalized bandwidth is greater than 0.95. For the 2TR HW-A design, the normalized bandwidth is greater than 0.99 over the range of 470 to 700 nm, whereas the 3TR HW-A design is greater than 0.97 over the range of 412 to 700 nm.
Opens up a new parameter space for coronagraph designs
360 degree APPs
Prototype vAPP tested at optical wavelengths in Leiden

Otten+ (2014) SPIE 91511
Left-hand and right-hand circular polarizations have opposite phases
Broadband wavelength works

...but “leakage term” remains
Solved with:
Grating vector APP (gvAPP)

Otten, Snik et al. 2014 SPIE
MagAO on-sky (2015) at 3.9 microns

Unsaturated leakage term in every science image - it’s an astrometric and photometric reference!

Otten, Snik et al. (2017)
Grating aperture mask

Doelman+ (2017) SPIE
Lab measured PSF (monday!)

Courtesy Emiel Por
Subaru/SCExAO/CHARIS gvAPP
SCExAO Leakage term <5%

Leakage (%)

Wavelength (nm)
SCExAO gvAPP Transmission
First light at Subaru

Leakage Term
Single-mode Complex Amplitude Refinement coronagraph (SCAR)

Theory: Por and Haffert (2018) 1803.10691
Laboratory measurements: Haffert+ (2018) 1803.10693

Builds on idea of single-mode fiber as a rejection filter for starlight (Mawet+ 2017 ApJ) by shaping PSF with custom APP coronagraph
Single-mode Complex Amplitude Refinement coronagraph (SCAR)

Theory: Por and Haffert (2018) 1803.10691
Laboratory measurements: Haffert+ (2018) 1803.10693

Builds on idea of single-mode fiber as a rejection filter for starlight (Mawet+ 2017 ApJ) by shaping PSF with custom APP coronagraph

Putting SECOND order null across fibre face makes it BROADBAND
APP reimages star onto lenslet array with single mode fibres

![Diagram of APP reimagining star onto lenslet array with single mode fibres.](image-url)
Image of star on hex lenslets
APP squeezes two nulls across one lens.

\[ T = 98\% \]
APP squeezes two nulls across three lenses....

\[ T = 94\% \]
APP squeezes two nulls across six lenses...

\[ T = 63\% \]

Robust to 0.1 \( \lambda/D \) tip tilt error!
SCAR APP tested in the lab
...and multi-fibre SCAR on the way
Adding holograms to make focal plane wavefront sensors

Wilby+ 2007
Adding holograms to make focal plane wavefront sensors

Wilby+ 2007
gvAPP+WFS for balloon experiment
HiCiBaS in Aug 2018
vAPP for HiClBaS

modal WFS spots

leakage term (F&F phase retrieval)

phase diversity spots
Conclusions

- Complex broadband phase patterns are now possible
- Rich diversity of designs realisable
- Combining coronagraphs and wavefront sensing in one optic
- Pushing up the TRL

![Image](image1.png)