NANOSTRUCTURED INFRARED VORTEX PHASE MASKS FOR STELLAR CORONAGRAPHY

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Research shown here carried out at Space sciences, Technologies, and Astrophysics Research (STAR) Institute

Not an overview of ULiège photonics activities, also carried out at

- CSL (Centre Spatial de Liège): design, metrology, diffractive optics, solar cells, nano-structures, sensing, etching, etc
- CESAM (Complex and Entangled Systems from Atoms to Materials): quantum optics, nano-materials, etc
- probably others...
EXOPLANETS DOING THE DANCE
8 YEARS OF HIGH-CONTRAST IMAGING MONITORING

—HR8799 and its four giant planets—

2009-07-31  20 au  Jason Wang / Christian Marois
The star never turns off —> need specialized instruments to access HIGH CONTRAST (from 1,000 to 10,000,000,000) at SMALL ANGULAR SEPARATION (below 1 arcsec)
Stellar Coronagraphy

2013

- Small opaque mask
- Vortex phase mask

Diagram showing detector and light paths.
Vortex coronagraph

- Vortex phase mask
- Lyot stop
- Coronagraphic image plane

Perfect on-axis cancellation for a circular aperture
The Vortex Phase Mask

- Scalar vortex
  - helical piece of glass

- Vector vortex = spatially variant half wave plate
  - liquid crystal polymers
  - subwavelength gratings
  - photonic crystals
Genesis of the Annular Groove Phase Mask

- 4-quadrant PM → sub-wavelength grating → annular groove PM

Advantages:
- clear 360° discovery space
- achromaticity
Rigorous Coupled Wave Analysis

L band. Period = 1.42 µm, angle = 3.00°

Delacroix et al. (2013)
Manufacturing Diamond AGPM @ Uppsala

Diamond = ultra broadband transparency + many other convenient properties

1. diamond coated with Al and Si layers (sputtering)
   - thick Al layer
   - thin Si layer
   - thin Al layer
   - Al etching
   - Si etching

2. e-beam pattern transferred with solvent-assisted moulding
   - soft stamp replicated from e-beam
   - apply stamp
   - ethanol bath
   - baking

3. reactive ion etching
   - Al etching
   - Diamond etching

Vargas Catalan et al. (2016)
MWIR/LWIR TESTING ON VODCA BENCH
« Vortex Optical Demonstrator for Coronagraphic Applications »

Beam shaping

Laser Source

Shutter

Neutral Density & Filter

OAP1

OAP2

Single mode fiber

Parabolic Mirror

Camera

DM

AGPM mount

Lyot Stop

Coronagraphy

f = 609.6 mm

f = 609.6 mm

Jolivet et al. (2019)
A FEW YEARS TO GET IT RIGHT...

Anti-reflective grating on the back side

Peak rejection

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2.2 AGPM design and manufacturing

2.2.3 Anti-reflective gratings

The first AGPM manufactured had lower than predicted rejection ratio as the on-axis light reflected inside the AGPM was not canceled by the optical vortex. Fixing this issue is mandatory to reach performance close to the simulations and also to improve the throughput of the AGPM since coronagraphic instruments usually have to face the issue of low flux observations.

To avoid internal reflections, instead of a single layer film it is possible to use SG as an anti-reflective intermediate medium (Figure 2.7). The refractive index of a SG can be tuned by adjusting its filling factor and take the appropriate value to minimize the total reflectivity of the AGPM (Karlsson and Nikolajeff, 2003).

Delacroix (2013) described a ≈17% backside reflection of the bare diamond substrate in the L-band, reduced to ≈1.9% thanks to the ARG. The theoretical transmission in the L-band is averaged to ≈87% at L-band (limited by photon absorption in the diamond substrate, Forsberg and Karlsson (2013)).

Experimental results on the ARG are detailed in section 6.3.
**CURRENT STATE-OF-THE-ART**

Broadband filter (3.5 - 4.0 µm)

10+ SCIENCE-GRADE AGPMS NOW PRODUCED, RANGING FROM 2 TO 13 µm

Jolivet et al. (2019)
Next step: conquer the world

2015 + 2018 (L+M)  
NIRC2

2013 (L)  2015 (L+M)  
LMIRCam

2012 (L)  2012, 2018 (N)  
NACO

VISIR VISIR
The vortex works!

First light at Large Binocular Telescope (Arizona)

Debrè et al. (2014)
Detection of close companions

VLT/NACO: confirmation of a close brown dwarf companion around HD 206893

Keck/NIRC2: first image of the brown dwarf companion around HIP 79124
SEARCH FOR PROTO-PLANETS IN YOUNG DISKS

Reggiani et al. (2018)
Next destination: Extremely Large Telescope

ELT - 38m (2025)

VLT - 8m (2001)
BELGIUM CONTRIBUTING TO ELT/METIS

1:1 scale model

METIS PI
Period not constant, breaking ZOG condition $\rightarrow$ need to discretize the pattern
CHARGE-4 DESIGNS

Construction with straight lines

Construction with curved lines

Delacroix et al. (2014)
GRATING OPTIMIZATION: FDTD SIMULATIONS

MEEP simulations of charge-4 vortex (L. König, work in progress)
Trying various designs...
First Charge-4 components: done!

First manufactured charge-4 mask

Transitions between sectors shows up in 2D null depth map.
NEXT STEP: GOING FULL METASURFACE

Challenges: broadband, high throughput

Nanofin

Nanofin metalens

Devlin et al. (2017)

Nanopillar

Nanopillar metalens

Hsiao et al. (2017)

Chen, Zhu & Capasso (2020)

Shalaev et al. (2015)
On our way towards imaging other Earths

ELT/METIS end-to-end simulation
alpha Centauri A + two Earth twins
5h observation @ 10µm