



Universiteit  
Leiden  
The Netherlands

## **It's just a phase: high-contrast imaging with patterned liquid-crystal phase plates to facilitate characterization of exoplanets**

Doelman, D.S.

### **Citation**

Doelman, D. S. (2021, June 22). *It's just a phase: high-contrast imaging with patterned liquid-crystal phase plates to facilitate characterization of exoplanets*. Retrieved from <https://hdl.handle.net/1887/3191978>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/3191978>

**Note:** To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <https://hdl.handle.net/1887/3191978> holds various files of this Leiden University dissertation.

**Author:** Doelman, D.S.

**Title:** It's just a phase: high-contrast imaging with patterned liquid-crystal phase plates to facilitate characterization of exoplanets

**Issue Date:** 2021-06-22

# It's just a phase

High-contrast imaging with patterned liquid-crystal phase  
plates to facilitate characterization of exoplanets

David Sebastiaan Doelman



# It's just a phase

High-contrast imaging with patterned liquid-crystal phase  
plates to facilitate characterization of exoplanets

## Proefschrift

ter verkrijging van  
de graad van doctor aan de Universiteit Leiden,  
op gezag van rector magnificus prof.dr.ir. H. Bijl,  
volgens besluit van het college voor promoties  
te verdedigen op dinsdag 22 juni 2021  
klokke 15.00 uur

door

David Sebastiaan Doelman

geboren te  
Amsterdam, Nederland  
in 1993

Promotor: Prof. dr. C. Keller  
Co-promotor: Dr.ir. F. Snik

|                    |                           |                               |
|--------------------|---------------------------|-------------------------------|
| Promotiecommissie: | Prof. dr. Huub Röttgering | Universiteit Leiden           |
|                    | Prof. dr. Ignas Snellen   | Universiteit Leiden           |
|                    | Dr.ir. S. Pereira         | Technische Universiteit Delft |
|                    | Prof. dr. P. Tuthill      | University of Sydney          |
|                    | Dr. E. Huby               | Observatoire de Paris         |

*Dedicated to my grandfather,  
Corstiaan Arie Drogendijk*

**Front cover:**

Artist impression of the detection of a gas giant using the vector-Apodizing Phase Plate coronagraph at installed in the Subaru/SCEXAO instrument. The phase pattern is encoded in the orientation of white lines.

Image of the gas giant by Danielle Futselaar and Franck Marchis.

Cover design by the author.

ISBN: 978-94-6419-239-1

An electronic copy of this thesis can be found at <https://openaccess.leidenuniv.nl>

© David S.Doelman, 2021



# Contents

|          |                                                                                    |            |
|----------|------------------------------------------------------------------------------------|------------|
| <b>1</b> | <b>Introduction</b>                                                                | <b>1</b>   |
| 1.1      | The era of exoplanet characterization . . . . .                                    | 3          |
| 1.1.1    | Methods of exoplanet characterization . . . . .                                    | 3          |
| 1.1.2    | Direct imaging of HR 8799 . . . . .                                                | 4          |
| 1.2      | Direct imaging systems . . . . .                                                   | 7          |
| 1.2.1    | The challenge of direct imaging . . . . .                                          | 7          |
| 1.2.2    | A modular view of high-contrast imaging . . . . .                                  | 8          |
| 1.3      | Ground-based and space-based high-contrast imaging . . . . .                       | 20         |
| 1.3.1    | The compatibility of ground and space . . . . .                                    | 20         |
| 1.3.2    | The current state and limitations . . . . .                                        | 22         |
| 1.4      | Broadband enabling technologies . . . . .                                          | 24         |
| 1.4.1    | Properties of the geometric phase . . . . .                                        | 25         |
| 1.4.2    | Geometric phase in the Jones formalism . . . . .                                   | 28         |
| 1.4.3    | A different look on geometric phase: a personal note . . . .                       | 31         |
| 1.4.4    | Technical implementation of a GPH . . . . .                                        | 35         |
| 1.5      | This thesis . . . . .                                                              | 39         |
| 1.6      | Future Outlook . . . . .                                                           | 43         |
| 1.6.1    | A ground-based perspective . . . . .                                               | 43         |
| 1.6.2    | A space-based perspective . . . . .                                                | 48         |
| 1.6.3    | New applications of liquid-crystal technology for exoplanet<br>detection . . . . . | 50         |
| <b>2</b> | <b>The world of vAPP</b>                                                           | <b>61</b>  |
| 2.1      | Introduction . . . . .                                                             | 62         |
| 2.2      | Design of a gvAPP . . . . .                                                        | 65         |
| 2.2.1    | Dark zone considerations . . . . .                                                 | 66         |
| 2.2.2    | Optimization of the APP design . . . . .                                           | 69         |
| 2.2.3    | Adding functionality with holograms . . . . .                                      | 70         |
| 2.2.4    | Additional design choices . . . . .                                                | 76         |
| 2.3      | Observing and data reduction . . . . .                                             | 81         |
| 2.3.1    | Influence of the D-shaped dark zone . . . . .                                      | 81         |
| 2.3.2    | Influence of wavelength smearing . . . . .                                         | 84         |
| 2.3.3    | Data reduction . . . . .                                                           | 84         |
| 2.4      | The world of vAPP . . . . .                                                        | 86         |
| 2.4.1    | The vAPP: a global view . . . . .                                                  | 86         |
| 2.4.2    | The vAPP: individual properties . . . . .                                          | 91         |
| 2.5      | Current status and future developments . . . . .                                   | 101        |
| 2.6      | Conclusion . . . . .                                                               | 103        |
| <b>3</b> | <b>L-band spectroscopy of HR 8799 c,d,e with a vAPP-ALES com-<br/>bination</b>     | <b>109</b> |
| 3.1      | Introduction . . . . .                                                             | 110        |
| 3.2      | Characterization of the dgvAPP360. . . . .                                         | 113        |
| 3.3      | Observations and data reduction . . . . .                                          | 116        |

|          |                                                                                               |            |
|----------|-----------------------------------------------------------------------------------------------|------------|
| 3.3.1    | Spectral cube extraction . . . . .                                                            | 117        |
| 3.3.2    | Data reduction . . . . .                                                                      | 119        |
| 3.3.3    | Spectral extraction . . . . .                                                                 | 122        |
| 3.4      | Results . . . . .                                                                             | 124        |
| 3.5      | Discussion . . . . .                                                                          | 125        |
| 3.5.1    | Data reduction and the increased flux of HR 8799 d . . . .                                    | 125        |
| 3.5.2    | Implications of the common flat and featureless spectra . .                                   | 128        |
| 3.6      | Conclusions . . . . .                                                                         | 129        |
| <b>4</b> | <b>Minimization of polarization leakage</b>                                                   | <b>133</b> |
| 4.1      | Introduction . . . . .                                                                        | 134        |
| 4.1.1    | Diffractive phase plate coronagraphs . . . . .                                                | 134        |
| 4.1.2    | The Vector Vortex Coronagraph . . . . .                                                       | 135        |
| 4.1.3    | The vector Apodizing Phase Plate coronagraph . . . . .                                        | 136        |
| 4.1.4    | Leakage mitigation strategies . . . . .                                                       | 136        |
| 4.2      | Double-grating diffraction theory . . . . .                                                   | 138        |
| 4.2.1    | The geometric phase hologram . . . . .                                                        | 138        |
| 4.2.2    | The double-grating element . . . . .                                                          | 140        |
| 4.2.3    | Simulated broadband performance of double-grating elements                                    | 141        |
| 4.2.4    | The effect of non-zero grating separation . . . . .                                           | 143        |
| 4.2.5    | Multi-grating coronagraph architectures . . . . .                                             | 144        |
| 4.3      | Experimental results of double-grating implementations . . . . .                              | 146        |
| 4.3.1    | Lab setup and double-grating manufacturing . . . . .                                          | 146        |
| 4.3.2    | Characterization of the double-grating polarization leakage                                   | 148        |
| 4.3.3    | Separation of the double-grating PSF . . . . .                                                | 149        |
| 4.4      | Experimental results for a double-grating Vector Vortex Coronagraph                           | 151        |
| 4.5      | The double-grating vector-Apodizing Phase Plate for the Large<br>Binocular Telescope. . . . . | 154        |
| 4.6      | Multi-grating coronagraphs and system-level perspectives . . . . .                            | 156        |
| 4.6.1    | Multiple grating combinations . . . . .                                                       | 156        |
| 4.6.2    | Applications of multiple-grating focal-plane coronagraphs .                                   | 158        |
| 4.7      | Conclusions . . . . .                                                                         | 159        |
| <b>5</b> | <b>Lab demonstration of Holographic Aperture Masking</b>                                      | <b>163</b> |
| 5.1      | Introduction . . . . .                                                                        | 164        |
| 5.2      | Theory . . . . .                                                                              | 164        |
| 5.2.1    | Multiplexed holographic blazed gratings . . . . .                                             | 166        |
| 5.2.2    | Liquid-crystal technology . . . . .                                                           | 167        |
| 5.2.3    | Polarimetry with HAM (HAMPol) . . . . .                                                       | 169        |
| 5.3      | Design . . . . .                                                                              | 169        |
| 5.3.1    | Bandwidth . . . . .                                                                           | 169        |
| 5.3.2    | One dimensional combinations . . . . .                                                        | 170        |
| 5.3.3    | Multiplexed gratings . . . . .                                                                | 171        |
| 5.4      | Lab results . . . . .                                                                         | 174        |
| 5.4.1    | Manufactured design . . . . .                                                                 | 174        |

|          |                                                                           |            |
|----------|---------------------------------------------------------------------------|------------|
| 5.4.2    | Manufacturing and lab testing . . . . .                                   | 175        |
| 5.5      | Conclusion . . . . .                                                      | 177        |
| 5.6      | Acknowledgements . . . . .                                                | 177        |
| <b>6</b> | <b>Holographic aperture masking with the Keck OSIRIS Imager</b>           | <b>179</b> |
| 6.1      | Introduction . . . . .                                                    | 180        |
| 6.2      | HAM design . . . . .                                                      | 183        |
| 6.2.1    | Geometric phase holograms . . . . .                                       | 184        |
| 6.2.2    | General considerations for a HAM design . . . . .                         | 186        |
| 6.3      | The influence of polarization leakage . . . . .                           | 193        |
| 6.4      | Design of a prototype mask for Keck OSIRIS . . . . .                      | 199        |
| 6.5      | Data reduction pipeline . . . . .                                         | 200        |
| 6.5.1    | Pipeline overview . . . . .                                               | 200        |
| 6.5.2    | Spectroscopic closure phase extraction . . . . .                          | 202        |
| 6.6      | Manufacturing of prototypes HAM v1 and<br>HAM v1.5 . . . . .              | 204        |
| 6.7      | Lab tests . . . . .                                                       | 206        |
| 6.7.1    | The Point-spread function . . . . .                                       | 208        |
| 6.7.2    | Closure phases . . . . .                                                  | 209        |
| 6.8      | On-Sky Verification . . . . .                                             | 212        |
| 6.8.1    | Binary HD 90823 . . . . .                                                 | 212        |
| 6.8.2    | Observations . . . . .                                                    | 213        |
| 6.8.3    | Data Reduction . . . . .                                                  | 215        |
| 6.8.4    | Spectroscopic parameter retrieval . . . . .                               | 218        |
| 6.9      | Conclusions and Outlook . . . . .                                         | 223        |
| 6.10     | Appendix: Spectral resolution of the holographic interferograms . . . . . | 224        |
| <b>7</b> | <b>The vector-Zernike wavefront sensor</b>                                | <b>229</b> |
| 7.1      | Introduction . . . . .                                                    | 230        |
| 7.2      | Theory . . . . .                                                          | 232        |
| 7.3      | Simulation . . . . .                                                      | 233        |
| 7.4      | Lab results . . . . .                                                     | 236        |
| 7.5      | Chromaticity of the vZWFS . . . . .                                       | 237        |
| 7.6      | Conclusion . . . . .                                                      | 239        |
| <b>8</b> | <b>Multi-color holography</b>                                             | <b>241</b> |
| 8.1      | Introduction . . . . .                                                    | 242        |
| 8.2      | Concept of multi-color liquid-crystal holography . . . . .                | 244        |
| 8.3      | Lab experiment and result . . . . .                                       | 246        |
| 8.3.1    | Design of the multi-color geometric phase holograms . . . . .             | 246        |
| 8.3.2    | Manufacturing process . . . . .                                           | 247        |
| 8.3.3    | Lab setup . . . . .                                                       | 248        |
| 8.3.4    | Experimental results . . . . .                                            | 248        |
| 8.4      | Wide-gamut and true-color holography . . . . .                            | 250        |
| 8.4.1    | Color selection . . . . .                                                 | 250        |

|          |                                        |            |
|----------|----------------------------------------|------------|
| 8.4.2    | True-color holography . . . . .        | 251        |
| 8.4.3    | True-color vAPP coronagraphs . . . . . | 253        |
| 8.5      | Conclusion . . . . .                   | 256        |
| <b>9</b> | <b>Nederlandstalige samenvatting</b>   | <b>259</b> |
|          | <b>List of Publications</b>            | <b>267</b> |
|          | <b>Curriculum Vitae</b>                | <b>271</b> |
|          | <b>Acknowledgements</b>                | <b>272</b> |