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Optimized Alvarez phase plates for hyperspectral imaging

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A confocal approach for hyperspectral imaging is presented. Alvarez-Lohmann lenses are utilized to tune the systems focal length and hence the wavelength band filtered from the spectrum. The design of aberration corrected phase plates is examined as well as their manufacturing by precision milling. In a first characterization bands of 100 nm were filtered out of a continuous spectrum.

1 Introduction

Hyperspectral imaging is the enhancement of two dimensional spatial image data by highly resolved spectral information. A further characterization of the specimen under test is achieved by resolving wavebands which are normally invisible to the human eye or three colour photo sensors. The data recorded this way may reveal information not only about the form and position of a probe but e.g. also about the materials it consists of or the type and state of biological tissue. Applications which a significantly benefit from hyperspectral imaging are e.g. food safety and quality control, gas detection, biochemical research and remote sensing.

2 Hyperspectral imaging systems

The detection of three dimensional data with a two dimensional detector, like a CCD, requires multiplexing either in time or space [1, 2]. Most commercially available systems for hyperspectral imaging use a dispersive element like a grating or prism to spectrally differentiate the signal. The spatial resolution is achieved by scanning the object space, see Fig.1. Such a system records the full spectrum of a picture line at a time while the spatial information is multiplexed in time.

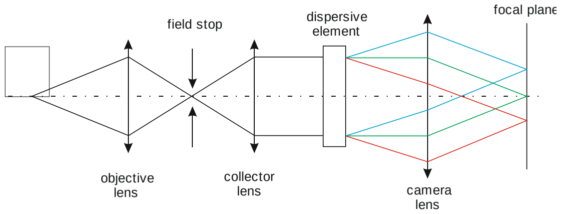

Fig. 1 *Principle of a laterally separating hyperspectral imaging system composing the whole picture e.g. by a scanning object or field stop*

3 Confocal approach

A different approach is the wavelength separation by a confocal setup. In confocal chromatic sensors the axial chromatic aberration of the imaging optical system is used to produce multiple foci (one for every wavelength) which are spread along the optical axis. A pinhole placed in a specific focal plane blocks off most light except the wavelength which is ideally focused at the pinhole position. This principle is generally used for precise distance measurement in microscopes or industrial applications [2]. The downside is that these systems are only able to perform single point imaging. The full object is imaged by scanning the pinhole over the field of view. In hyperspectral imaging this would require two scanning processes, a lateral for the spatial data and an axial for the spectral information. In our approach we expand the confocal principle to full field imaging (Fig.2). Hence only an axial scanning is necessary to record the 3D data. This scanning process shall be performed by tunable optical elements.

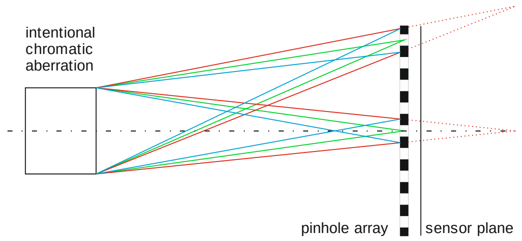

Fig. 2 *Principle of a axially separating hyperspectral imaging system, composition of spectrum by axial scanning*

4 Alvarez-Lohmann lenses and their adjustment for a hyperspectral setup

A well-known concept for tunable optical systems are Alvarez-Lohmann lenses. Two cubic phase plates are combined in a way that no change in the phase function occurs. A lateral shift of the plates in opposite directions introduces a spherical phase function with a curvature proportional to the displacement. Mathematically these phase plates can be described as polynomials [3, 4], which allows for adjustment of the elements to specific tasks. In a confocal hyperspectral setup this concept has to be adapted to the specific needs. The system requires a defined focal length for the zero shift position and its focal length shall be positive over the whole tuning range. To combine the pictures taken at different wavelengths the spot positions must stay constant and independent from the displacement of the plates. A focus variation in the magnitude of the chromatic aberration (<2 mm) and a relatively high numerical aperture to achieve a good spectral discrimination are important design parameters. In addition further coefficients of the polynomial description of the phase function can be implemented for aberration correction.

For the design of a starting system the classical Alvarez surface was used and enhanced by terms for focus, coma, spherical aberration, astigmatism and field curvature. Optimization was performed with the help of a cost function which included, besides spot size and form as well as axial chromatic aberration, the conditions mentioned above. To reduce higher order aberration coefficients up to 7th order were considered.

5 Design Results

The system was designed for a maximal displacement of the phase plates of ±1 mm. Within this tuning range the spectral band can be chosen continuously from a spectrum between 450 nm and 750 nm. Table 1 summarizes the characteristics of the system.

Lens Data	
spectrum	450 nm – 750 nm
object distance	
f' (λ=600 nm)	59.45 mm - 61.29 mm
numerical aperture (NA)	0.052 – 0.054
maximum field angle	3°
optical diameter	7 mm
average rms spot radius	4.43 µm
Axial chromatic aberration	1854 µm

Tab. 1 *Design results of hyper chromatic Alvarez-Lohmann Lens system*

The spectral behaviour of the system is shown is Fig.3. Spectral bands below 100 nm are achieved for smaller wavelengths while in the longer wavelength range up to 200 nm bandwidths occur due to larger obtainable spot diameters for these wavelengths.

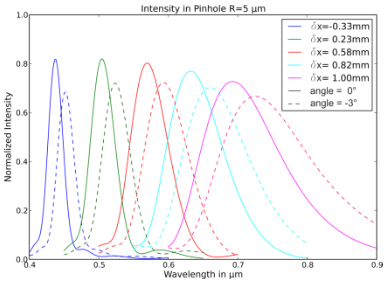

Fig. 3 *Simulation of the filtering characteristics*

6 Fabrication and experimental results

For the fabrication an ultra-precision micro milling centre was used. Through the application of a 4 step process, including dual rough milling, diamond tool finishing and manual polishing, a surface roughness of Ra ~ 10 nm was realized. In a first experimental setup (see Fig.4) the chromatic behaviour was analysed for the on axis spot. Light of a xenon source was spatially filtered and collimated. The phase plates were aligned to focus the beam onto a pinhole aperture of 20 µm. A fibre coupled spectrometer was used to measure the spectrum behind the pinhole. A bandwidth of less than 100 nm FWHM could be filtered at any position in the initial spectrum of the source by shifting the plates.

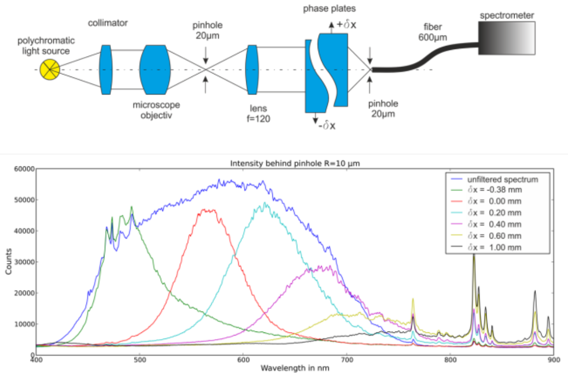

Fig. 4 *Experimental setup and measured spectra for different shift positions of the phase plates*

7 Conclusion

Confocal chromatic sensors are feasible for hyperspectral imaging. Varifocal optical elements like Alvarez-Lohmann lenses enable a sensitive and continuous tuning of the filtered spectrum.

8 Acknowledgements

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