

Towards photonic crystal based polarimetric instruments for earth observation

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ABSTRACT

Optical metamaterials and nanostructures are promising technologies for space applications. Through the engineering of the optical response on the wavelength scale of the incident light, they allow for new functionalities combined with a small form factor. This opens opportunities for remote sensing, where new applications could be unlocked or the ratio of performance to the physical system volume could be significantly improved. We propose a system featuring photonic crystals for polarimetric applications in the visible range and report on the experimental realization and optical characterization of photonic crystals. The imperfections of the manufactured structures are incorporated in our simulation process and compared to the measured photonic crystal response.

Keywords: Spectropolarimetry, imaging, photonic crystals, metaoptics

1. INTRODUCTION

Spectropolarimeters are important instruments for earth observation.^{1,2} The polarimetric properties of scattered light play a crucial role in climate monitoring.³ A main goal of spectropolarimeters is to measure the spectrally dependent degree and angle of the linear polarization (DoLP and AoLP) of the observed light. In remote sensing applications, this information is combined with the atmosphere model to extract the concentrations of different aerosols. Aerosols are small particles such as dust particles over the Sahara or sulfates from burning fossil fuels. Aerosols are among the largest sources of uncertainty in estimates of the earth radiation budget including uncertainties on aerosol-cloud interactions. For greenhouse gas emission measurements, they influence the light path which can lead to errors in the measured gas concentrations. For the correct prediction of aerosol concentrations, multi-angular measurements of DoLP and AoLP are required.

Many conventional spectropolarimeters include dispersive elements followed by polarization modulation optics. This can be realized in modern instruments as a combination of band-pass filters and polarizers⁴ or different spectral or temporal modulation techniques.^{1,5} Currently, compact and rigid solutions of computational spectropolarimeters are developed with the rise of nanomaterials.⁶ They shift the complexity of the system to the post processing of the data instead of direct measurement techniques. The information is retrieved from the measured data with the use of a reconstruction algorithm and prior knowledge about the system and the parameters to retrieve. Novel structures such as metasurface arrays⁷ and liquid crystals⁸ combined with a computational back-end were demonstrated as feasible solutions for polarimetric applications. As an alternative, photonic crystals (PhCs) are a type of nanostructures whose refractive index is periodically modulated on the subwavelength scale. The periodicity determines the appearance of interesting optical features, such as photonic band gaps or Fano resonances.⁹ In comparison to metasurface filters,⁷ this can lead to a more diverse transmission spectrum. The optical response of PhCs depends on the angle of incidence, the wavelength, and the polarization of the incident light, rendering them a promising platform for both spectrometers and spectropolarimeters. A combination of photonic crystals with a computational back-end was already demonstrated as a feasible alternative to conventional instruments in the field of greenhouse gas observations.¹⁰ We propose a photonic-crystal-based computational spectropolarimeter for reconstructing DoLP and AoLP in the visible spectral range.

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2. CONCEPT DESCRIPTION

The core concept is to place an array of asymmetric photonic crystal filter on a detector and retrieve the spectrally dependent DoLP and AoLP of the incident light. The polarimetric information is collected from 5 viewing angles to ensure sufficient angular information for the aerosol retrieval. A schematic representation of one viewing angle is shown in Fig. 1(a). This geometry is implemented at all viewing angles with the same set of nanostructures. Photonic crystal filters are arranged in stripes on the detector perpendicular to the along-track (ALT) direction. The spectral dependence of transmission of the PhCs makes them efficient spectral filters. A set of uncorrelated filters provides a basis for the spectral reconstruction without using additional diffracting elements in the system. Polarimetric sensitivity is achieved with asymmetric unit cells, which creates a transmission difference in p- and s- polarized light (Fig. 1(b)). This makes the photonic crystals both spectral and polarization filters. The transmission spectra of the PhC have sharp diverse features, in contrast to standard bandpass filters. They can be tailored by varying the parameters of the unit cell in the range from 200 nm to 1000 nm. The size of the structures allows the manufacturing with electron beam (e-beam) lithography. Since the filters are directly placed in front of the detector, stray light is reduced and the spectral integration over the whole visible range significantly increases the signal-to-noise (SNR) of the system. From the integrated signal on the detector and the known transmission functions of the filters, the spectrally dependent DoLP and AoLP are retrieved.

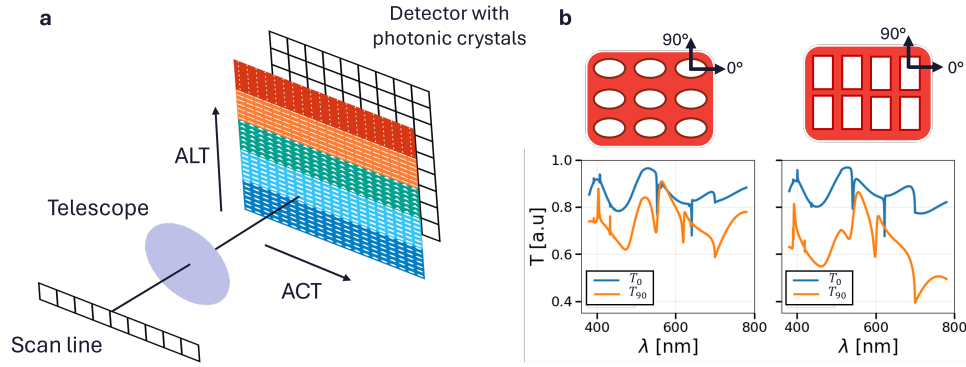


Figure 1. Schematic representation of one viewing angle of the spectropolarimeter with photonic crystals (left). Examples of the asymmetric photonic crystals and their simulated transmission spectra (right).

For every viewing angle the interaction between the incident light and a system of photonic crystals can be described in a matrix form. The detected intensities for every type of photonic crystal I present themselves as a superposition of the incident Stokes vector S_{in} and a measurement matrix D , which contains the spectral information about every photonic crystal.

$$I_{\text{out}} = DS_{\text{in}} \quad (1)$$

The contribution of the circular light from the atmosphere is negligible, such that a three element Stokes vector (at a fixed wavelength) is sufficient for characterisation. Thus, for m wavelength to Stokes vector has $3m$ elements. The number of photonic crystals can be different from the number of wavelengths considered. In that case pseudo-inverse techniques are applied for the reconstruction of S_{in} . We combine the matrix inversion with the total variation regularization to ensure the reconstruction of the Stokes vector. The DoLP and AoLP can be derived for each wavelength λ_m from the reconstructed components of S as:

$$\text{DoLP}_{\lambda_m} = \frac{\sqrt{(S_{\lambda_m}^1)^2 + (S_{\lambda_m}^2)^2}}{S_{\lambda_m}^0} \quad (2)$$

$$\text{AoLP}_{\lambda_m} = \frac{1}{2} \arctan \frac{S_{\lambda_m}^2}{S_{\lambda_m}^1}$$

3. PHOTONIC CRYSTAL NANOFABRICATION

The 2D asymmetric photonic crystals were nanofabricated in an SiN layer. This material was selected due to its transparency over the visible range. The photonic crystals were manufactured by electron beam (e-beam) writing and Reactive Ion Etching (RIE). An overview of the manufacturing process is presented in Fig. 2. Every step of the manufacturing was investigated in the development process, since the optical response of the photonic crystals is directly related to the accuracy of manufacturing.

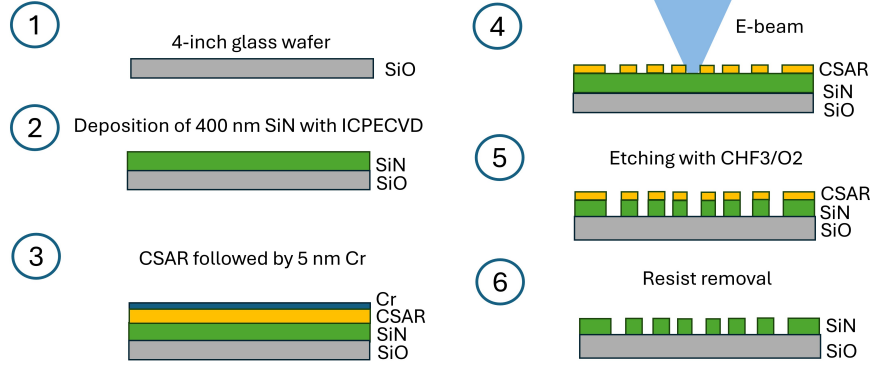


Figure 2. Schematic representation of the nanofabrication flow: 1) Glass wafer, 2) deposition of SiN layer with the ICPECVD, 3) application of resist and Cr layer, 4) e-beam exposure, 5) dry etching of SiN, 6) resist removal.

Amorphous silicon nitride with a thickness of 400 ± 20 nm is deposited on $500 \mu\text{m}$ thick glass wafer with Inductively Coupled Plasma Chemical Vapour Deposition (ICP-PECVD). A combination of SiH₄ and N₂ under 10 mTorr is used. The optical properties of the resulted deposited material depend on the temperature of the deposition and proportion between flow of two gases. The overview of the tested recipes is presented in Tab. 1.

	Recipe 1	Recipe 2	Recipe 3
Temperature	150	150	300
N2 [sccm]	26	50	50
SiH4 [sccm]	25	5	5

Table 1. Comparison of ICP-PECVD parameters

	Recipe 1	Recipe 2	Recipe 3
Gas	CHF3/Ar	CHF3/O2	SF6/CHF3
Flow	25 sccm/25 sccm	50 sccm/2.5 sccm	50 sccm/100 sccm
Operating pressure	0.8 Pa (8 ubar)	1 Pa (10 ubar)	6 Pa (60 ubar)
RF power	50 W	50 W	80 W
Etch rate SiN nm/min	15-20	29	25

Table 2. Comparison of RIE parameters

The optical properties were verified with ellipsometry measurements. They show that the first recipe has a high absorption in the wavelength range from 350nm to 500nm, while recipes 2 and 3 are transparent in the full range of interest. The recipe 2 was selected as a baseline for the SiN manufacturing. To transfer the pattern on the SiN layer, a 400 nm layer of positive e-beam resist CSAR was applied and baked at 160 C for 5 min. To reduce charging effects during the e-beam writing process, the resist is covered with 5 nm of Cr. The e-beam parameters were optimized to allow for large area ($>1 \text{ cm}^2$) writing, leading to a trade-off between writing speed and pattern accuracy. After exposure, the Cr layer is stripped and afterwards the resist is developed for 60 seconds with pentyl acetate and rinsed in IPA to reduce drying spots. The etching of the Silicon Nitride was performed in a RIE system with a standard parallel plate configuration. During the process development phase three different etching

recipes were tested (Tab. 2). The lowest taper angle and the most uniform etching was achieved with the Recipe 2. However, scanning electron microscope (SEM) images demonstrated some nanofabrication imperfections (Fig. 3). The most common issues that could be observed after the nanofabrication are presence of the tapering angle, rounding of the edges, overetching or etching not until the end point. To study the contribution of these errors we have implemented these parameters into the simulation procedure to close the gap between the simulated and experimental data.

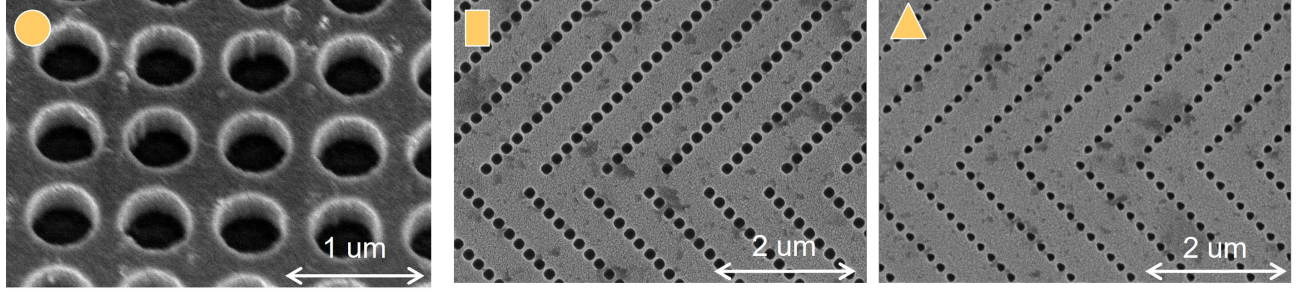


Figure 3. SEM image of the manufactured samples with the etching recipe 2.

4. LUMERICAL SIMULATIONS

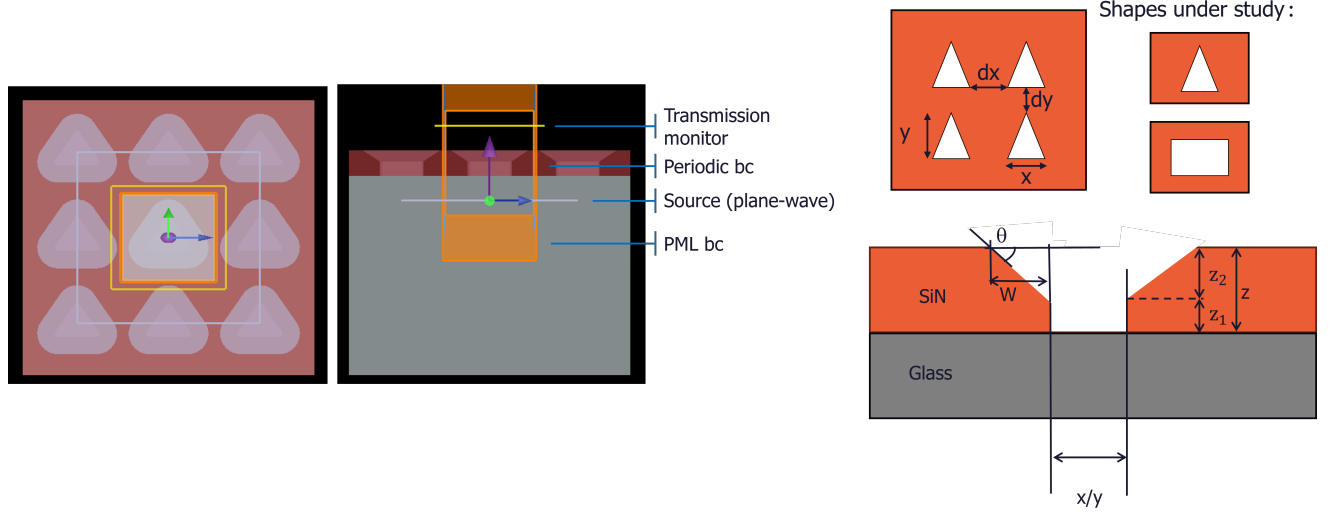


Figure 4. Lumerical simulation setup.

To implement nanofabrication imperfections in the simulation of optical response procedure, we set up a finite-difference time-domain (FDTD) simulation. It features a glass wafer, covered with SiN layer of 400 nm. The thickness of SiN layer z could be varied based of the direct measurement of the SiN layer after the deposition. The tapering angle θ , overetching width W and radius of rounding of the edges could be manually set in accordance with the data from SEM inspection. The schematic configuration of the simulated structures is shown in Figure 4.

5. COMPARISON WITH EXPERIMENTAL DATA

For the optical characterization of the photonic crystals, an experimental setup based on a monochromator (Omni- λ 3003i, Zolix) illuminated with a Laser-Driven Light Source (LDLS) XWS-30 from Hamamatsu was used (Fig. 5,(a, b)). The white light source was fiber-coupled to the monochromator entrance port. It contains

a grating with 1200 g/mm and a peak diffraction efficiency at 500 nm. The spectral resolution during the measurements was $\Delta\lambda \approx 1.56$ nm. The output fiber with a core of 550 μm is achromatically collimated using a reflective collimator Thorlabs RC04FC. Then, the first achromatic lens with $F = 7.5$ cm focuses the beam on a spot, located in the focal plane of the second lens with $F = 30$ cm. A wire-grid polarizer was used to select the incident polarization. The beam-size was larger than the detector itself to reduce edge effects such as intensity drop-offs. The photonic crystal was placed manually directly on the cover glass of a CMOS detector (FLIR BFS-U3-17S7M-C) with an active area of 14.4 mm $\times$ 9.9 mm). The distance between the cover glass and the sensitive area of the detector is several millimeters. The overall transmission T_{PhC} is measured by computing the ratio between the measured integrated intensity of the desired area I_{PhC} with and without the PhC chip present I_{ref} :

$$T_{\text{PhC}} = \frac{I_{\text{PhC}} - I_{\text{dark}}}{I_{\text{ref}} - I_{\text{dark}}}, \quad (3)$$

Where I_{dark} corresponds to the dark images taken for every exposure time under study. The use of the same area for the normalization makes it possible to correct for beam non-uniformity.

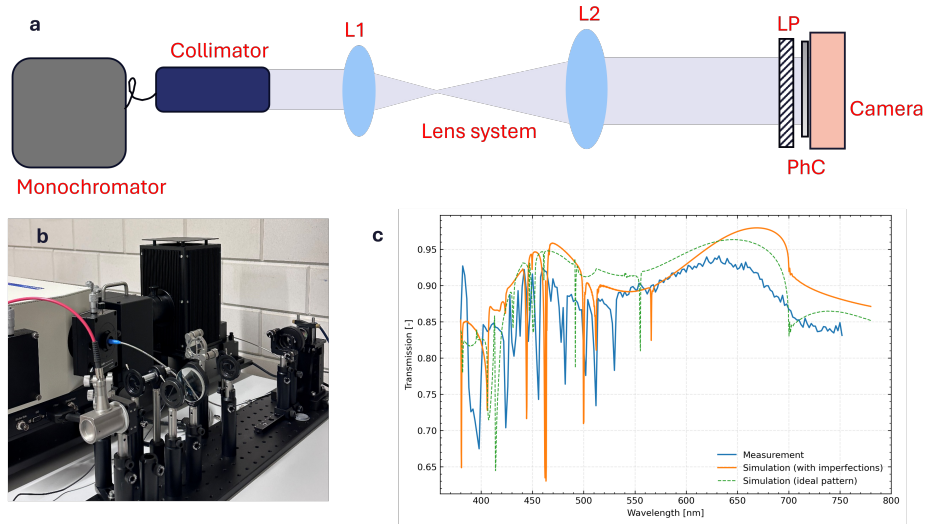


Figure 5. (a) Measurement setup for the transmission study of photonic crystals, (b) photo of the measurement setup, (c) comparison between the simulation and optical response of the nanofabricated PhC.

An example measurement of a manufactured photonic crystal is shown in (Fig. 5 (c)). The transmission measurement demonstrates discrepancies between the measured and simulated transmission spectra of the ideal structure. To mitigate the difference, we have included the experimentally obtained refractive index from the ellipsometric measurement into the FDTD simulation. Additionally, the analysis of the etch depth demonstrated that the nanofabricated example PhC sample was not fully etched, with an etch depth of 280 nm followed by a remaining layer 120 nm of SiN. The SEM images demonstrated a straight etch, so the contribution of the tapering angle in the simulation was considered negligible. The contribution of the rounding edges to the optical response of the structures was thoroughly studied. We have found that it depends on the hole shape type. The optical response of the triangular shapes is more sensitive to the rounding of the corners, while rectangular shapes appear more robust. We consider the contribution of the rounding angles negligible when the rounding size r is significantly smaller than a typical structure size (1% deviation of transmission over the spectral range). The rounded edges with $r = 60$ nm and etch depth of 280 nm were taken into account in the improved FDTD model. The results demonstrate a more accurate prediction of the transmission response of the structures compared to the ideal case. The developed simulation tools will be used in the guidance of further improvements of the manufacturing process.

6. CONCLUSION

We have discussed an instrument concept for polarimetric remote sensing with asymmetric photonic crystals. The nanofabrication of the photonic crystals is a crucial step towards this novel instrument type. We have demonstrated the implementation of realistic nanofabrication errors in the simulation process. This approach improves the correspondence between simulated and measured data, which will support the filter selection from a library of designed filters. We intend to use the measured photonic crystals optical response for the reconstruction of the spectral dependent DoLP and AoLP. Further improvements of the nanofabrication will be combined with a full experimental demonstration of the reconstructive spectropolarimeter.

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