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Metamaterials for optics and photonics applications in space

Summary Report

EUROPEAN SPACE AGENCY
CONTRACT REPORT

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Abstract

Metamaterials are a novel technique that allows for tailoring unfamiliar optical characteristics in artificial materials that do not occur in nature. Some of the applications that were recently highlighted in literature were optical cloaking, or far-field optical hyperlens imaging of sub-diffraction limited objects. Primary goals of the activity were to survey available techniques that may be beneficial for space exploration and remote sensing, to design a metamaterial for optical/infrarad applications in space, to develop a conceptual design of a demonstration instrument for a follow-on activity.

The entire field of metamaterials is still a relatively young area of research with a wide field of different effects and devices that are still investigated mostly on numerical level and proof-of-principle experiments. Potential instrument applications for remote sensing have been identified (color-filters, polarization scramblers, absorber-layers) and a detailed performance analysis for polarization scrambling structures has been conducted. We worked out an instrument concept for such a scrambling device and implemented a ray- tracing software to evaluate the performance of metamaterials in such a conceptual instrument. An outline for a follow-on activity has been provided with the aim of finding a design and the manufacturing technology for a sufficiently performing polarization scrambler.

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Applicable documents

[AD1] Statement of Work "Metamaterials for optical and photonic applications in space", TEC-MMO/2009/25, Issue 1, June 18, 2009.

Reference Documents

[RD1] L. Fu, P. Schau, K. Frenner, H. Giessen, W. Osten, H. Schweizer cosine Research B.V., University Stuttgart, "META – Overview and assessment of potential space applications based on metamaterials", technical note, CR-META-TN01, Issue 2 revision 1, January 11, 2011.

[RD2] S. Hannemann, L. Fu, P. Schau, A. Tittl, K Frenner, H. Schweizer "META – Preliminary Design Report", technical note, CR-META-TN02, Issue 1, August 5, 2011.

[RD3] S. Hannemann, L. Fu, P. Schau, M. Schäferling, A. Tittl, K Frenner, H. Schweizer, "META – Detailed Design Report", technical note, CR-META-TN03, Issue 1, January 19, 2011.

[RD5] S. Hannemann, "META – Final evaluation and roadmap for optical metamaterials", technical note, CR-META-TN04, Issue 1, January 22, 2011.

Abbreviations

4th-PI — 4. Physikalisches Institut
CUSS — Common Ulm Stuttgart Server
ESA — European Space Agency
FSS — frequency selective surface
ISS — International Space Station
ITO — Institut für Technische Optik
LRSPP — long-range surface plasmon polariton
MTM — metamaterial
OD — optical density
PMTM — Plasmonic metamaterial
SPP — surface plasmon polariton
SRSPP — short-range surface plasmon polariton
WSD — weak spatial dispersion

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1 Introduction

This document summarizes the work performed by cosine, 4th Physikalisches Institut Universität Stuttgart (4th-PI) and the Institute for Technical Optics (ITO) Stuttgart on the project "Metamaterials for optics and photonics applications in space" which was conducted for ESA under contract No. 4200022943/10/NL/AF. Metamaterials are a novel technique that allows for tailoring unfamiliar optical characteristics in artificial materials that do not occur in nature. Some of the applications that were highlighted in literature were optical cloaking [*Nature Photonics* **1**, 224–227 (2007)], or far-field optical hyperlens imaging of sub-diffraction limited objects [*Science* 23 March 2007, p. 1666]. In order to survey available techniques that may be beneficial for space exploration and remote sensing, ESA set up this project.

1.1 Project goals

The primary goals of the endeavour were the following:

- to explore the potential optical applications for metamaterials, concening potential space applications
- to design a metamaterial for optical/infrarad applications in space
- to develop a conceptual design of a demonstration instrument for a follow-on activity.

1.2 Team

The team working on the activity consisted of three parties:

- cosine Research B.V. (prime) (Netherlands)
- 4. Physikalisches Institut, Universität Stuttgart (Germany)
- Institut für Technische Optik (ITO), Universität Stuttgart (Germany)

The team was put together to bundle different expertises in order to deliver high quality output to ESA. While cosine has a long record of successful collaboration with ESA in the field of optics and X-ray instrumentation development projects, the two partners from Stuttgart University are leading experts in the field of metamaterials.

1.3 Work packages

In order to achieve the goals to best customer satisfaction we split the work according to the statement of work (AD1) and with respect to the needs of the consortium.

The work was divided into four main work packages:

The work was conducted according to the following logic. In a first stage (WP1000) the consortium performed literature studies and reviews to obtain a thorough overview on the available techniques and possibilities for potential space applications. The detailed work on that is presented in the technical note [RD1]. After that the consortium together with ESA decided which of the available metamaterial techniques would be viable for a preliminary design study. Of the presented options a list of three metamaterials were selected. For these three selected metamaterial-based techniques preliminary studies were performed. The consortium investigated manufacturability, performed preliminary performance evaluations, potential applications

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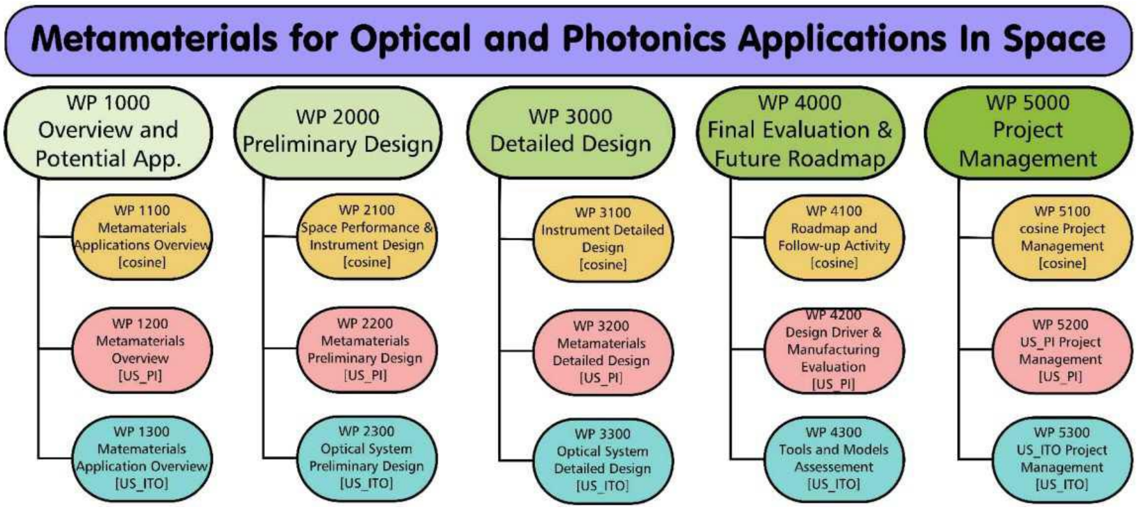

Figure 1: META work package breakdown structure.

in space instrumentation and presented the work in another technical note [RD2]. At that stage the team and ESA selected one of the three metamaterials for detailed design. Within the detailed design phase of the project, the consortium performed detailed performance analysis. The final selected metamaterial device was a polarization scrambler. A conceptual instrument design was derived, the design parameters for the metamaterial were investigated in detail, and at the end a thorough performance analysis of the instrument concept was conducted and presented in the "Detailed Design Report"[RD3]. After that a final evaluation of the conceptual instrument design was provided and a roadmap for optical metamaterials was worked out and presented in [RD4].

1.4 Deliverables

In the following table all deliverables according the statement of work [AD1] are listed.

Item	Name
TN1	"Overview and assessment of potential space applications based on metamaterials"
TN2	"Preliminary design of three on metamaterials based instruments/devices"
TN3	"Detailed design of a metamaterial based instrument/device"
TN4	"Final evaluation and roadmap for optical metamaterials"
FR	Final Report
SR	Summary Report
A	Abstract
PM	Performance Models

1.5 Overview

The work performed in the project will be presented as follows: First the summary of reviewed metamaterials will be given and how we arrived to the pre-selection of the first three metamaterials. After that the work on modelling and preliminary design studies will be briefly presented. After that the final metamaterial will be introduced and the work on the detailed design be presented. Finally the instrument concept and performance analysis will be summarized and the

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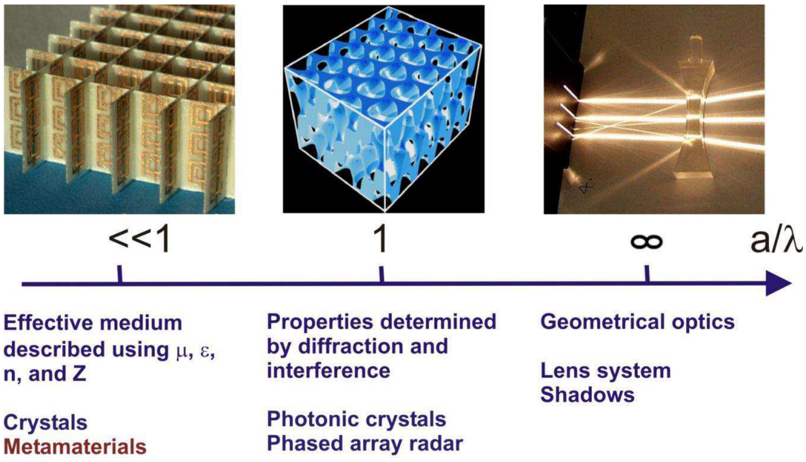

Figure 2: Metamaterials consist of structures smaller than the wavelength and can therefore be discribed as medium with assigned effective constants such as ε, μ, n, and Z.

final roadmap for a follow-on instrument development project will be outlined.

2 Metamaterials—General survey

2.1 Metamaterials—Definition

Metamaterials have been defined as being “artificial optical media with sub-λ structures”. In general metamaterials exhibit responses that are not available in natural materials. All metamaterials that were investigated in this project owe their “unnatural” behaviour largely to plasmonic effects.

Plasmonics is a field of optics occurring at the interfaces to metals where light induces collective electron excitations, called plasmons. These allow for extreme light concentration to subwavelength volume (high refractive index of metals). Plasmonic effects are used in the design of metamaterials were photon-plasmon interactions mediate between the nanoscale metallic structures and the propagating radiation. In fact, this opens an entire new field of research were it is possible to engineer materials with previously unknown optical characteristics. It has been shown before in the range of radar- and microwaves. Here we investigated possible extensions into the visible domain.

2.2 Types of metamaterials

Among others the following classes of metamaterials have been reviewed in the first project phase.

- Negative refractive index materials
- Cloaking devices
- Artificial chirality devices
- Hyperlenses
- Perfect Absorbers
- Plasmonic sensors
- Optical nano-antennas

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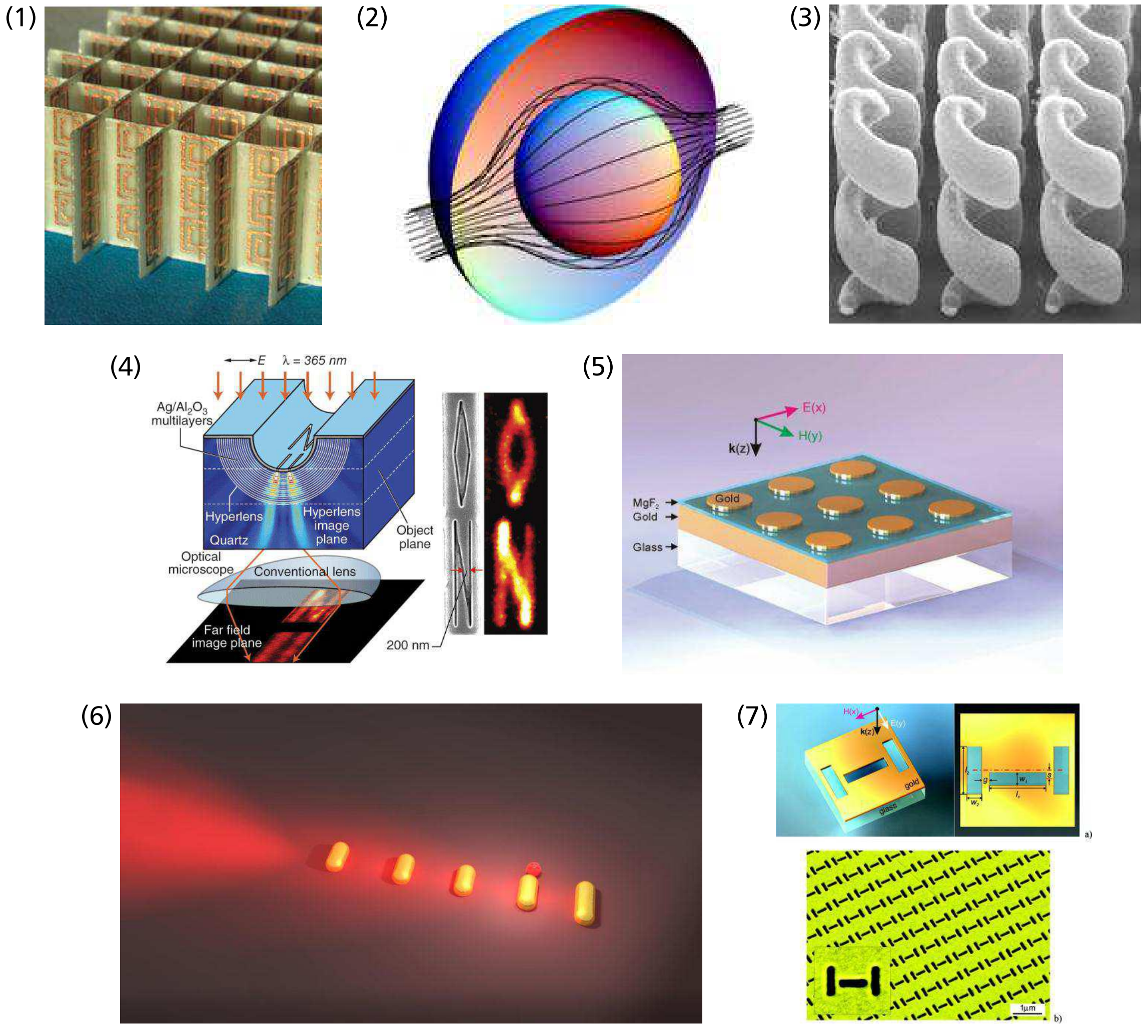

Figure 3: Representations of different metamaterials and applications. (1) negative index materials, here for microwaves. (2) cloaking devices. (3) Artificial chiral devices. (4) Hyperlens. (5) Perfect absorber. (6) Optical nano-antennas. (7) Plasmonic sensors.

The detailed review of these metamaterials was provided to ESA in technical note [RD1]. In that report we have elaborated in detail about the manufacturability of the different devices, the manufacturing techniques, functionalities, potential use of metamaterials for ultra-dense integration, possibilities of nanoprocessing of light using them and more.

The report [RD1] is split in two main chapters about "Metamaterials" and "Application of Metamaterials". In the chapter Metamaterials are first classified in 2D- and 3D-metamaterials, of which the general features are explained. For the 2D metamaterials we report spectral characteristics in detail. Sometimes these are alternatively referred to as frequency selective surfaces. Already a small number of 2D-layers produce pronounced optical effects such as:

- beam polarization and beam filtering
- polarization rotation simmilar to waveplates
- large spectral changes in reflectivity or transmittivity due to tiny changes of the electromagnetic environment around the MTM-structure (an important effect for sensing and low power switching).

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2.3 Nanofabrication techniques for metamaterials

A key requirement of plasmonic metamaterials in the visible range is the control of geometry down to a 10 nm scale. At longer wavelengths—due to the linear scaling properties of metamaterials—larger dimensions can be used for proof-of-concept structures to demonstrate the principle functionality. In [RD1] we reviewed different nano- fabrication techniques to obtain optical plasmonic metamaterials (PMTM). The most flexible, and indispensable technique to obtain proof-of-concept structures is electron beam lithography (EBL) followed by focused ion beam (FIB) milling, interference lithography (IL), and nano-imprint lithography (NIL). In terms of mass production capability, the list is starting with NIL, IL and shadow lithography based on polystyrene spheres. However, it is fair to say, that multicolumn E-beam lithography also has high throughputs comparable with optical lithography. All of these techniques are suitable for fabrication of 2D arrays and among them NIL seems most favorable for mass production. We also discuss how 2D techniques can be used to realize 3D-structures by suitable stacking techniques. Very elegant techniques to obtain 3D structures with high complexity are direct laser writing and/or e-beam writing in conjunction with electron-less plating techniques. Which techniques will win in the future depends strongly on the goal, *e.g.* large scale or small scale production. Meander-like structures used in high density Blu-ray discs are already in the mass production status. We recommend the NIL-technique for large scale production and the direct writing techniques (laser and/or e-beam) for very complex 3D-structures. Also colloidal techniques in conjunction with self-assembly appear attractive.

2.4 Applications for metamaterials

In chapter 3 of [RD1] Applications of metamaterials are classified into three main fields:

- Metrology
- Optical data processing devices
- Coatings

We described the fundamental properties of plasmonic structures for beam shaping to overcome the Abbe limit, which exists in standard imaging systems. We also review the status of near field super lenses and discuss their restrictions for practical applications. It is shown that far field applications can be achieved using PMTM-structures with magnification properties. In this field, highlights are certainly MTM-structures with hyperbolic dispersion and metamaterials on the basis of non-periodic meander stacks (meander layers with zoomed periods sometimes called supergrating meander structures). The field of optical data processing devices is most promising for ultra-dense integrated circuits and is seen as a new rising research field with strong impact. Some encouraging results concerning compact plasmonic circuits are already published, which can be viewed as a highlight and might lead to all-plasmonic nano-processing of light. Also, spectacular properties of plasmonic structures are demonstrated for filtering and polarization beam splitters, which can consist of only a few meander layer structures. The use of slow light media can drastically improve the precision of interferometer devices and optical image processing devices. The perfect absorber layer can also be viewed as a highlight. It is useful in optical instruments as well as in optical data processing circuits to suppress unwanted cross-talk by scattered light. The realization of this function by plasmonic metamaterials requires only the combination of two layers. Altogether, frequency selective surfaces (FSS) based metamaterials can be viewed as very promising for a very wide range of applications from metrology to

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coatings.

3 Metamaterials based instrument concepts

3.1 Motive for the selection process

Based on the metamaterial designs found during the literature survey and evaluated in during the first and second stage of the project [RD1,RD2], the consortium with ESA selected three metamaterial concepts for closer investigation. ESA was mostly interested in applications related to remote sensing. As a result near-field related concepts such as a hyperlens were not selected. Instead we focussed on color filters, perfect absorbers, and polarization scramblers.

These three selected applications were suggested by the consortium to be made available by two principally different metamaterial structures. The meander structures presented in [RD2] can be used to produce color filtering and as polarization active structures such as scramblers. For the absorber functionality a different structure (*cf.* Figure 2) was investigated.

During the preliminary design study we conducted performance evaluations and presented them to ESA [RD2]. In that report we investigated perfect absorber structures to produce new concepts for baffle coatings and internal coatings aimed at reducing straylight. It turned out that the perfect absorber structures had either a limited spectral range at which they absorb or a limited range of angles of incidence. Therefore, and for the reason that project resources are limited, such perfect absorber structures were dismissed for detailed analysis. It still may be possible to improve the concept in the future. Ideas for that were presented in [RD2].

As a result the meander structures were selected for detailed design. They offer a wide range of potential applications (color filters, polarizers, polarization scramblers, retarder plates). At this point the choice between color filters and polarization scramblers were more based on technical interest for innovation. While the state of the art for both kinds of applications is already on a high level performance-wise, polarization scramblers are still massive devices (Cornu, Lyot, Wedge depolarizers) and it would be beneficial to space applications to reduce their weight. Here metamaterial designs could step in. As described in [RD2, RD3] a design based on meander structures could look much like a multilayer color filter: A relatively thin glass substrate onto which the filter/scrambler is deposited. Additionally, the concept could prove to accept a large numerical aperture. These two drivers, increased numerical aperture (and/or field-of-view) and reduced mass, were the reasons for selecting polarization scramblers as the study direction for the detailed design of this project.

3.2 Instrument concept for polarization scrambler

The instrument concept for a polarization scrambler studies during this project was based on a simple idea: For some spectrometry applications related to Earth observation it is crucial to have an instrument that exhibits radiometric levels at the detector that do not depend on the input polarization but solely on the radiometric level at the entrance aperture.

Since experimental testing could not be performed—the meander structures were numerically simulated in order to find suitable parameters for future production—we implemented an instrument concept by raytracing a generic optical setup such as shown in Figure 4. The instrument concept consists of an entrance aperture, a flat metamaterial layer that acts as the polarization scrambler, an ideal (infinitely thin) lens and a detector plane that is placed in the focal plane of the lens. In Figure 4 three incident collimated beams are depicted to show an extended field-of-view. The concept represents a typical setting for a remote sensing instrument, which is focussed at infinity. The detector plane could be a 2D detector array such as an APS or a CCD, but also a slit as it is used in many spectrometers.

During the preliminary and detailed design phase we implemented a raytracing application that allows for performance analysis of any metamaterial based layer placed at the entrance aperture of the conceptual instrument.

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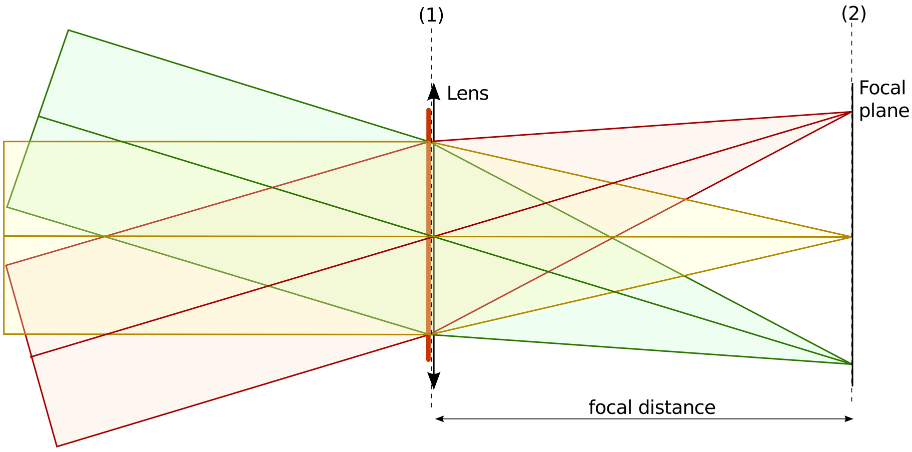

Figure 4: Instrument concept for a metamaterial based polarization scrambler: A metamaterial is deposited at the entrance aperture. A lens (here an ideal thin lens) focusses the input light onto a detector plane.

3.3 Performance analysis

The performance analysis of the conceptual instrument is done using a raytracer. Initially we intended to use a commercial application to implement the instrument concept. However, it turned out that the complex polarization active behaviour of the metamaterial structures could not be simulated with any of our available software packages. ZEMAX, for instance, does support Jones-Matrix calculations, and also ASAP provides such functionality in principle. However, our metamaterial structures need Jones matrices that change as a function of the angle of incidence and of the wavelength of the incident light. Both could not be done. Therefore we programmed our own raytracer.

The functionality of the raytracer is reported in more detail in [RD3]. Here we leave it at saying, that general Müller-matrix files for several metamaterial structures were provided by the Stuttgart groups. The raytracer loads these Müller-matrices and performs the complete raytracing based on the implemented instrument design and allows for calculation of the following:

- Total transmission efficiency
- Total residual degree of polarization on the detector plane
- Intensity distributions on any plane along the optical axis (for instance the source and detectors planes)
- Residual polarization profiles on any plane along the optical axis (for instance the source and the detector planes)

3.3.1 Results

The performance analysis for the instrument concept was conducted using three different metamaterial structures. Each of which the corresponding Müller-matrix datasets were provided by 4th-PI and ITO. A detailed discussion of their methods to calculate the Müller matrices is provided in [RD2,RD3]. As input light we used purely polarized light (linear 0°, 45°, −45°, 90°, left/right-circular, and completely non-polarized light. Each of these cases were send through the raytracer and the resulting intensity distributions and residual polarization distributions were plotted and the data analysed. In Figure 5 the intensity profiles on the focal plane are depicted, in Figure 6 the residual polarizations on the focal plane are plotted.

In the Figures the results are presented for three different metamaterials, labelled as 'double meander' and 'meander' and the 'double mesh' structure. The performance of each of the

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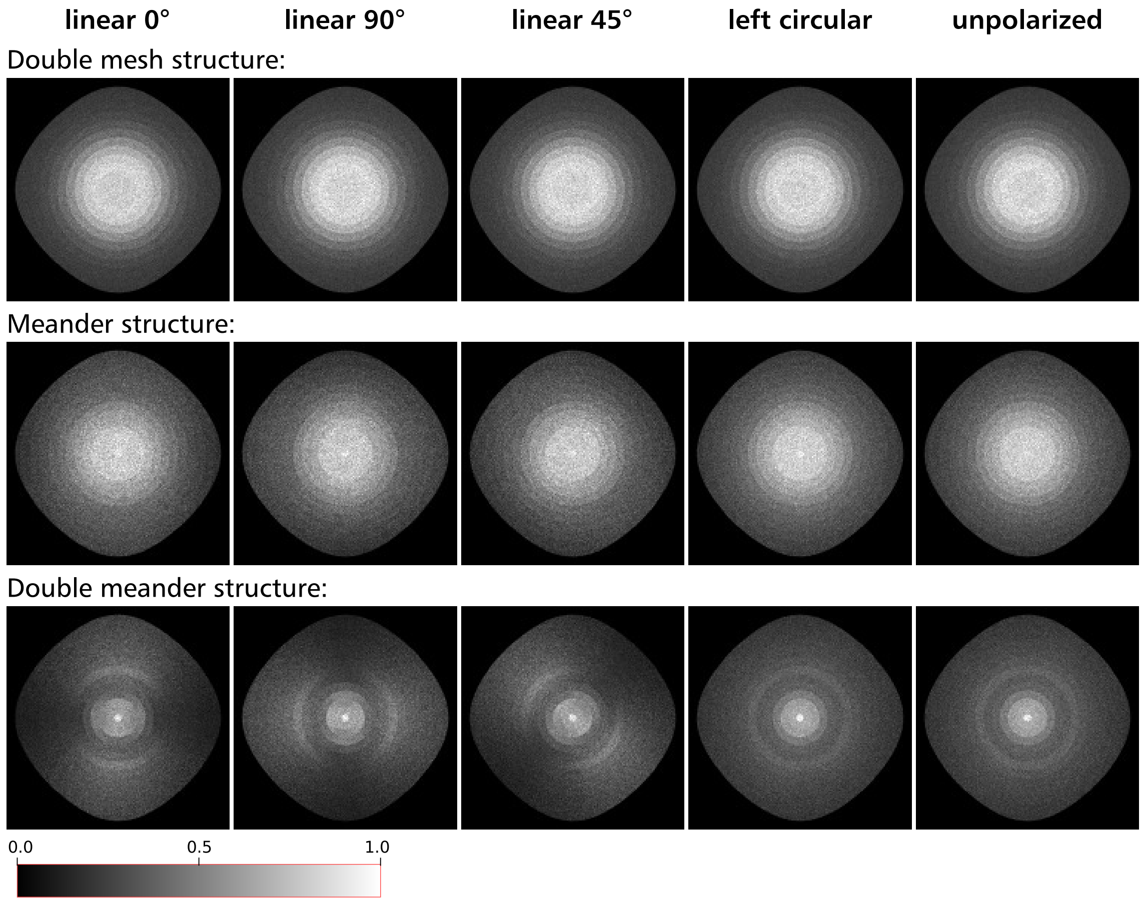

Figure 5: Intensity profiles on the focal plane rendered for different input polarizations and metamaterial structures. $N_A = 0.5$, $f = 100$ mm. The right-circular polarization was left out because it delivers the same profiles as the left-circular polarization. The intensity profiles are individually normalized and their color scale is depicted at the bottom of the figure.

metamaterials can be judged based on the fact that the input polarizations were pure and the intensity distribution on the source is homogeneous (*cf.* [RD3]). In an ideal world the polarization scrambler should present a near homogeneous intensity distribution on the focal plane. Since any real input polarization state can be understood as a linear combination of several pure polarization states and purely non-polarizad light, the residual polarization should vanish for any of the possible pure input polarization states. The detailed discussion about the result can be found in [RD3]. Here we summarize them in the following bullet points:

- Of the tested metamaterials the 'double mesh' and the 'meander' structure exhibit intensity profiles independent of the input polarization (Figure 5), radially symmetric, however not entirely homogeneous. This is acceptable because the inhomogeneity can be understood as vignetting and hence corrected out by postprocessing.

- The intensity profiles of the 'double meander' vary with polarization. This is an issue a polarization scrambler must not exhibit. Further research is required, and since the issue does not occur in the other two metamaterials, we expect that there should be a solution to this.

- The residual polarization profiles in Figure 6 indicate significant residual polarization left on the detector plane. The 'double mesh' starts to depolarize at increased angles of incidence (> 10°). The 'meander' structure depolarizes the circular polarization but exhibits substantial (40% – 50%) residual polarization. The residual polarization on the 'double meander' structure is both significant (≈ 20%) and non-homogeneous, circular polarization

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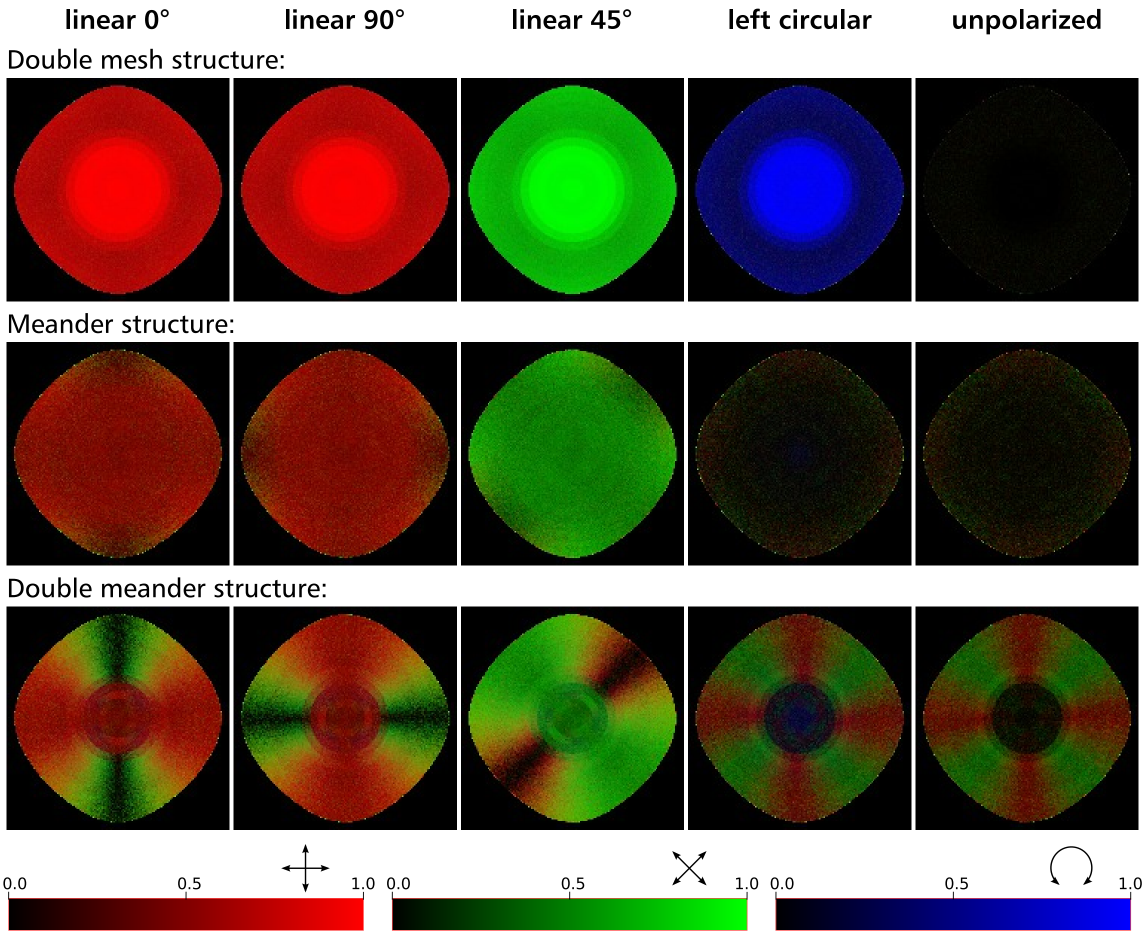

Figure 6: Residual polarization $\left|S_{1,2,3}/S_0\right|$ profiles on the focal plane rendered for different input polarizations and metamaterial structures. $N_A = 0.5$, $f = 100\,\mathrm{mm}$. The input polarizations 'right-circular' and 'linear -45°' were left out for the sake of better a overview. A color scale is provided at the bottom of the figure. The three basic colors red, green, and blue represent the absolute value of the residual polarizations in the three stokes components S_1 (linear 0°/90°: red), S_2 (linear 45°/–45°: green), S_3 (right/left circular: blue).

renders depolarized within a limited field-of-view ($< 10°$), and non-polarized light even gets partially polarized at angles of incidence $> 10°$.

3.3.2 Discussion and conclusions

From the results presented in Figures 5, 6 we conclude, that the investigated polarization scrambling devices show substantial polarization active behaviour that lead to partial depolarization. Evidently, a polarization scrambler intended to depolarize the incident light completely should perform substantially better. However, taking into consideration that the research area of optical metamaterials is relatively new, it is not surprising, that a perfect recipe for a polarization scrambler has not been found yet. Further research is required and we consider it promising. The benefits for instrument applications in space would be a considerable mass reduction and potentially a larger acceptance field-of-view or numerical aperture.

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3.4 Roadmap for follow-on study

A roadmap for a follow-on study is outlined in [RD4]. He we summarize the study logic of the suggested follow-on activity: Since our polarization scrambling device as presented in Section 3.3 requires improvement, a first step towards an instrument device is to search for more recipes of metamaterial structures. In parallel to such activity it is recommended to start some test manufacturing rounds. At the current state of knowledge we are able to simulate different kinds of metamaterials, for example any metamaterial that is build on a similar structure as the three 'double mesh', 'meander' and 'double meander structures', however it is also important to figure out how close a realistic manufactured device performs in actuality compared to the numerical results we achieved in this study. During the project we performed some experimental testing in order to check, whether the type of corrugated metallic structures perform in any way as we predicted—which was confirmed in [RD2]. However, there are structural differences between the numerical model and the experimental device that restricted the confirmation to qualitative level and to a proof of principle. In a future effort for presenting a working recipe for an important functionality as a polarization scrambler experimental confirmation on a quantitative level is required. It needs therefore to be investigated how precisely and accurately a metamaterial recipe can be reproduced and what exact performance that recipe exhibits both numerically and experimentally.

The follow-on study could focus on device level. As described in this document and in [RD3], the polarization scrambler can be thought of as a glass substrate with a metallic metamaterial layer deposited on one of the faces—much as with familiar multilayer color filters. The experimental test could be performed in a basic optical setup that resembles the setup of our ray-racer: the metamaterial filter, an optical lens for focussing (for instance a good quality camera lens and a detector area. Additionally, a polarized light source will be required and a polarization analyser on the detector side.

Once the step towards a functional device is made, instrument designs could be outlined on conceptual level. Such concept should include restrictions imposed by the performance range of the metamaterial device.

A more detailed bullet point task list, work-package breakdown structure and a cost estimate is provided in [RD4].

3.4.1 Suggestions for follow-on study

A few key suggestions for the follow-on study based on the experiences within this project are listed here:

- The spectral ranges of the polarization scrambling devices were rather limited in this project ($\approx$ 10% of central wavelength). We suggest strongly to aim for larger spectral ranges during the follow-on activity.
- The residual polarization needs to be lowered. We expect that a polarization scrambler should depolarize to a 1%-level of residual polarization or lower. However, that may depend on the application ESA is interested in and should be clarified in WP1000 of the follow-on activity.
- The transmittance of the polarization scrambler should be improved if possible. The follow-on activity should investigate also into that direction in WP1000 and WP2100.

3.5 Roadmap—Conclusion

We have outlined a roadmap for an follow-on activity that targets on the design, manufacturing and verification of a metamaterial based polarization scrambler. Based on the findings of this project we can state that metamaterials represent a promising technology for polarization

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active elements such as polarization scramblers. The benefits for space exploration and space-born remote sensing applications would be a substantial reduction of overall instrument mass by replacing bulky prism-based depolarizers with a coating on a near-planar substrate and a potential extension of the acceptance field-of-view/numerical aperture.

The current state-of-knowledge about polarization scramblers based on metamaterials requires further improvement both in finding the right metamaterial structure and verification of a manufacturing technology. Both are covered by the presented roadmap.

4 Project conclusion

We have investigated potential optics and photonics applications of metamaterials for space exploration, especially remote sensing. We conducted an extensive literature survey [RD1] and evaluated the current state of the art. The entire field of metamaterials is still a relatively young area of research with a wide field of different effects and devices that are still investigated mostly on numerical level and proof-of-principle experiments. Potential instrument applications for remote sensing have been identified (color-filters, polarization scramblers, absorber-layers) and a detailed performance analysis for polarization scrambling structures has been conducted. We worked out an instrument concept for such a scrambling device and implemented a ray-tracing software to evaluate the performance of metamaterials in such a conceptual instrument. The metamaterial structures we have tested so far depolarize the input light to a limited extent ($\approx$ 50% or lower residual polarization) which is not yet sufficient. However, we have shown, that the investigated metamaterials offer the potential of future development of such devices with sufficient performance. An outline for a follow-on activity has been provided with the aim of finding a design and the manufacturing technology for a sufficiently performing polarization scrambler.