FOM - 14.0221

Annual report 2013

FOM programme nr. 138
'Stirring of light!'

Foundation for Fundamental Research on Matter
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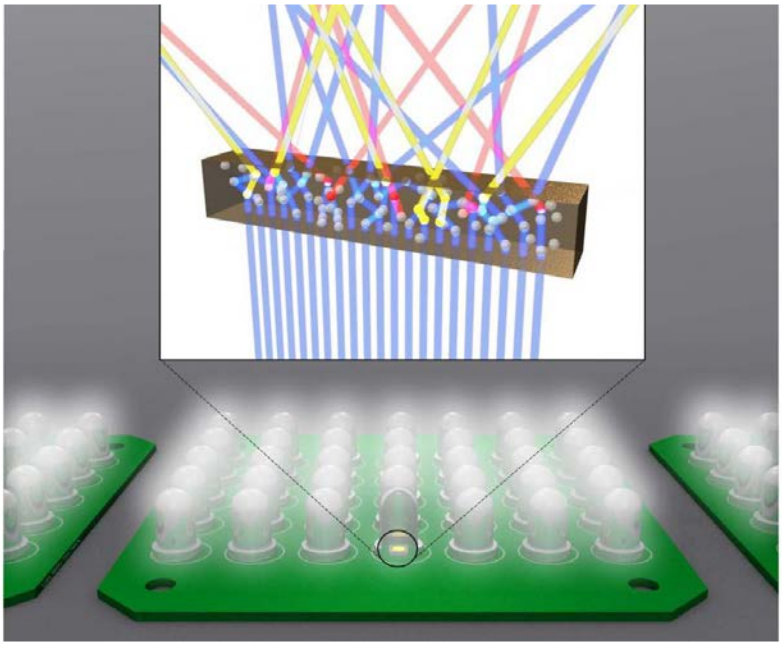

Artist's impression of the scattering of blue light from a semiconducting diode. In a scattering medium, the light is converted into a spectrum of colours to provide a source of diffuse white light.
Source: Complex Photonic Systems (COPS), University of Twente.

May 2014

Content

1. Scientific results 2013

The FOM programme Stirring of light! is gaining steam, now that all PhD students have on average completed their first year. This is reflected by the gratifying fact that many new results have appeared on wavefront shaping, optics, nanomaterials, and theory.

In the FOM programme Stirring of light!, we aim to control light propagation by means of wavefront shaping inside nifty nanophotonic media. Wavefront shaping is the spatial control of the phase of a coherent beam incident on a multiple scattering nanophotonic medium, in order to achieve optimal absorption or energy-conversion of light. To obtain the necessary high degree of control, we must suppress every source of noise. In the past year, the Twente team has realized that an important type of noise is caused by spatial intensity fluctuations within a laser beam.

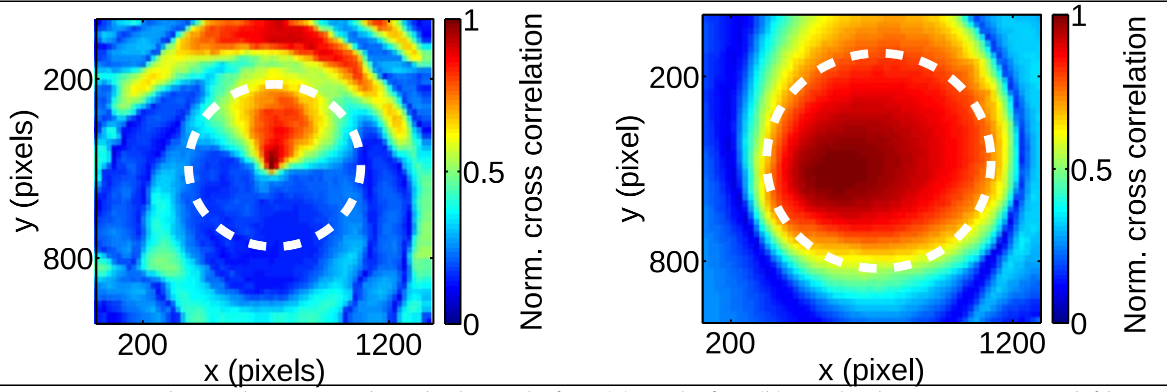

Figure 1: Spatial correlations within the beam before (a) and after (b) mode cleaning or spatial filtering. The white dashed circle denotes the beam diameter at $1/e^2$ of the peak intensity.

Figure 1(a) shows the spatial correlation within a laser beam, revealing that different parts of the laser beam fluctuate inhomogeneously. The inhomogeneous fluctuations in the beam affect wavefront shaping adversely. Therefore we implemented spatial filtering through a pinhole, resulting in the spatial correlation in Figure 1(b), where a high correlation is seen over a major part of the beam. With such a spatially homogeneous beam, we will pursue the predicted control of the energy density of light by means of wavefront shaping.

Ahead of planning, the Twente team has designed and built a *mobile* optical wavefront-shaping setup that can be readily moved to the location of one of the other teams. The mobility of the setup was repeatedly demonstrated by moving it to Amsterdam (several times) and Delft. The setup is so robust that even after transport in the back of a car, it is operational within one half hour. As a result, the fellow-teams have the opportunity to quickly start with wavefront shaping in combination with their own techniques.

The Leiden team is currently writing two experimental papers on scattering and transmission of light and surface plasmons on sub-wavelength holes in a metal film. This experiment, which extends the results presented in a recent Nature paper of our group, enables us to determine the relative weight of the electric and magnetic dipoles induces in this process. The experimental setup is shown in Figure 2.

Other research projects that are performed in Leiden involve: (i) cathodoluminescent imaging of nano-structured free-standing GaAs membranes and metal film (collaboration with Albert Polman at AMOLF), aimed to map the local density of optical states in these random structures, and (ii) modeling of scattering from sub-wavelength hole in dielectric films (collaboration with Kurt

Busch, Berlin), aimed to disentangle and minimize the relative role of free-space scattering compared to scattering in 2-D confined waveguide modes.

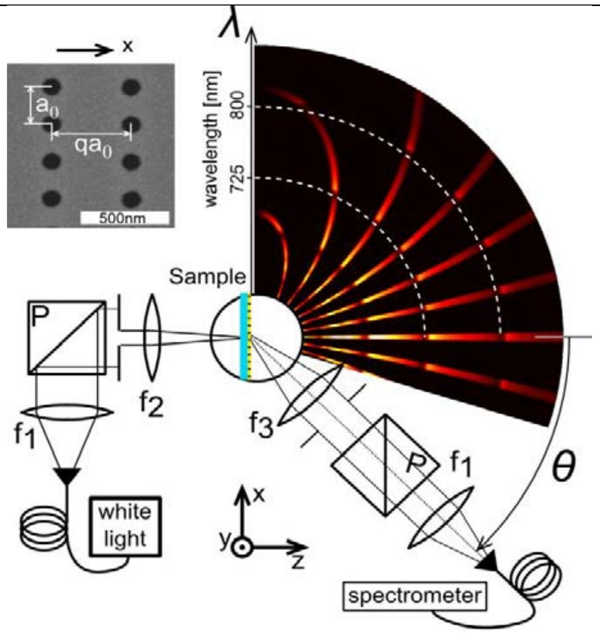

Figure 2:
Experimental setup to study scattering of light and surface plasmons on a gold film perforated with a rectangular array of sub-wavelength holes (SEM image in insert).
White light, incident from the left, is scattered into various diffraction orders, which are spectrally analyzed. The angle-resolved transmission spectra provide complete information on the relative weight and orientation of the radiating magnetic and electric dipoles.

All projects revolve around the central theme of 'scattering in quasi 2-dimensional structures'. We are currently designing a microscope with wave-front shaping capabilities for this study. This setup, with full spatial control of excitation and detection, should among others enable us to image the predicted hot and cold spots for excitation and emission in random structures. Designed randomness, aimed to optimize the mentioned spatial variations in LDOS, is the next goal.

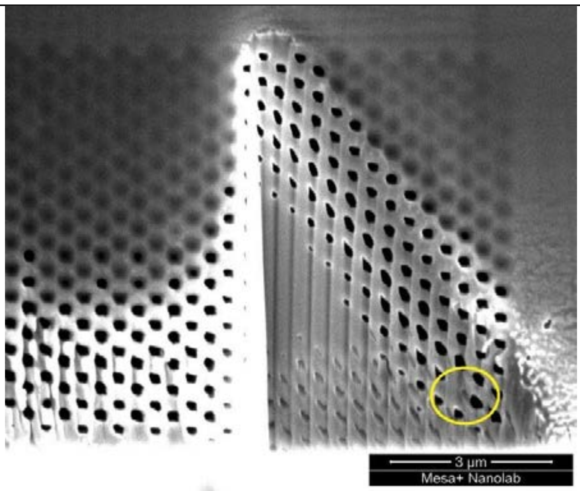

Figure 3: 3D photonic band gap crystal made from silicon. The crystal has a cubic diamond 'inverse woodpile' structure consisting of two perpendicular arrays of etched pores. The crystal contains two perpendicular pores designed to be smaller to create a cavity at the intersection (circle), following recent design by us. Part of this crystal has been milled with a focused ion beam to reveal the inside.

A second main aspect of the Stirring of light! programme is the development of advanced nanostructures wherein light is strongly confined, see for instance Figure 2. In 2013, the Twente team has made great progress in the fabrication of silicon photonic band gap crystals with controlled disorder. Such structures allow an ultimate control over light in three dimensions simultaneously, relevant to light emitting diodes and solar cells. Using the MESA+ cleanroom facilities a new fabrication scheme for 3D photonic band gap crystals was developed. The new scheme allows flexibility in the design including controlled defects that act as cavities to trap light deep inside the crystal, see Figure 3. We pursue a design recently proposed by Woldering *et al*. in our team, predicting tiny λ^3-sized nanocavities. In the near future, we will study the optical properties of the nanostructures in search of signatures of a nanocavity resonance. A novel exciting prospect that we foresee in this FOM programme is to exploit wavefront shaping to stir light onto a nanocavity within a 3D photonic band gap.

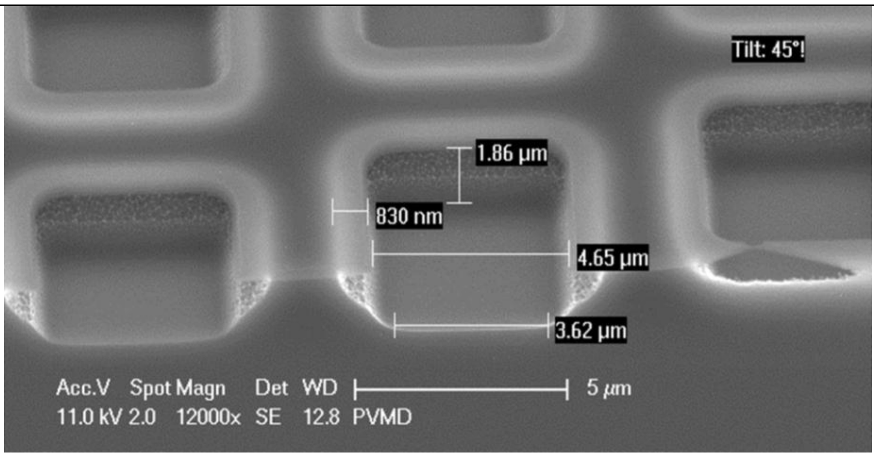

Figure 4: Micro-structure formed on crystalline silicon by reactive ion etching. The inclined surface is controlled by the etching process. As lately shown in thin-film silicon solar cells community, these µm-range indentations serve as optimal substrate on which to grow high-quality nc-Si:H while keeping high the absorption of light.

In a complementary effort, the Delft team has focused on texturing the 2D surface for the introduction of light-scattering interfaces and its implementation in thin-film silicon solar cells. Surface texturing was performed with different approaches, such as wet-etching of ZnO, glass texturing with sacrificial layer, anisotropic etching of crystalline silicon with photolithography (Figure 4).

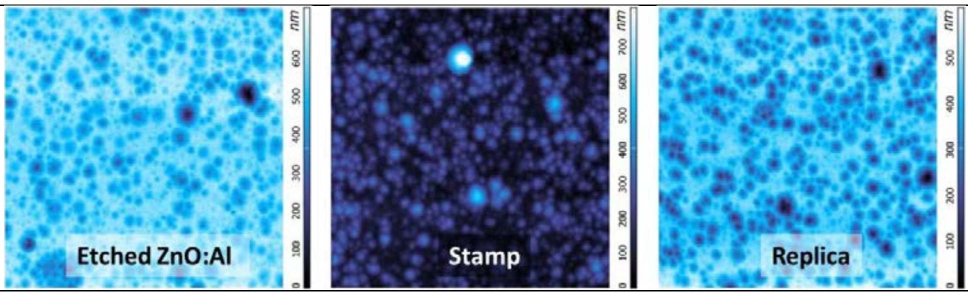

Figure 5: AFM scans of the master, stamp, and replica of wet-etched ZnO:Al. The images demonstrate a reliable replication from master to the final replica that the morphology is reproduced with a high resolution. The area of these scans is 20 × 20 µm².

Different kinds of surface texture were further transferred onto polymer or glass substrates by in-house developed nano-imprint technology (Figure 5). Single-junction and multi-junction thin-film silicon solar cells have been fabricated on top of these substrates in order to examine their effect on light absorption enhancement.

Several optical simulation methods were used to analyze and optimize solar cell configuration. These methods and models included 1D calculation for multi-layered structures based on Fresnel's equations (Figure 6), 2D ray-tracing method, 3D Finite Element Method, and scalar scattering theory. The development of multi-junction thin-film solar cells provides a platform for the upcoming studies within this project to demonstrate the effectiveness of manipulating light absorption.

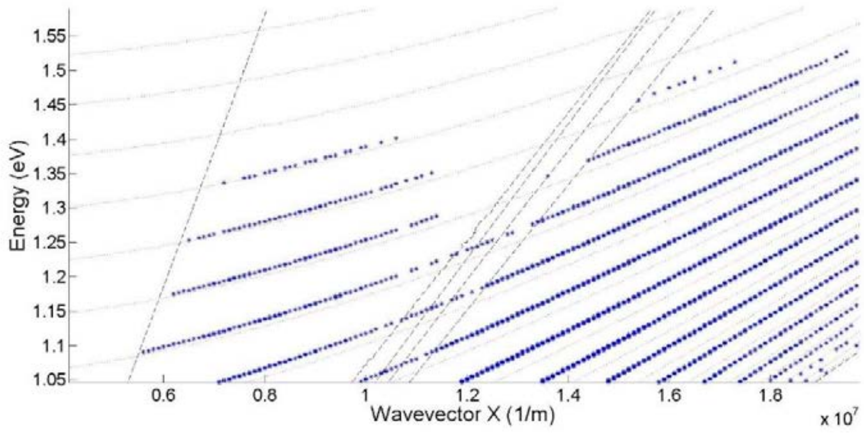

Figure 6: Dispersion diagram of a thin-film nanocrystalline (nc)-Si cell with flat interfaces. Blue stars show guided modes of S-polarization. The lines are calculated from ideal constructive interference in a nc-Si slab. Dashed lines show the light lines of constituent materials.

In our Stirring of light! programme, we also pursue self-assembled colloidal nanostructures to realize nanostructures complementary to bottom-up methods. In the past year, the Utrecht team has successfully fabricated colloidal crystals of silica rods in air. The structures were made by sedimentation of silica rods – with aspect ratios in the range of 6 to 12 – suspended in ethanol and subsequent drying. The obtained solids were not brittle and hardly formed cracks. In addition to their strongly scattering white appearance, Bragg diffraction of light was also visible from the surface, which was due to the layering of rods in the smectic phase (Figure 7A). These samples fulfil the goal of realizing samples with scattering anisotropy.

(A) **(B)**

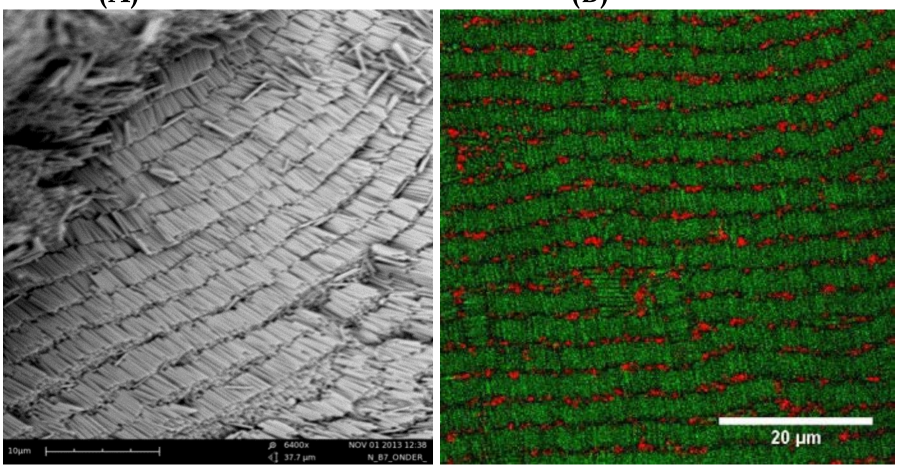

Figure 7: (A) Scanning electron micrograph of a solid of rod-shaped particles with length=2.2 µm, and diameter=0.2 µm. (B) Alternating layer phase of rods (green) and spheres (red) seen with confocal microscopy.

We have also studied the mixing of such systems with fluorescently labeled silica spheres that can be used as localized absorbers or emitters by the programme partners. It turns out that a thermodynamic phase separation occurs for many mixing ratios whereby the rods align parallel and form layers. These smectic layers can further order into a regular stacking interspersed with layers containing only spheres (Figure 7B). We are currently experimenting with electric fields in order to orient these ordered domains over larger length scales, which will greatly facilitate subsequent optical experiments.

Present-day understanding of complex nanophotonic systems is mainly based on theories describing infinite systems. Examples are random media and photonic crystals. Obviously, experiments are performed on materials of finite size. Many of the fascinating optical properties associated with these photonic systems - like a full photonic band gap, Anderson localization, and divergences in densities of states - have a strong size-dependence, the understanding of which will be crucial for the success of this field.

The AMOLF-Twente team has devised a new, original method that allows calculations of infinite systems to be extended to represent finite-size effects without actually reducing the size of the infinite system. The method is based on an extension of the wave-vector space of the Green's functions into the complex plane. FOM PhD student E. Yeganegi has successfully applied this theory to a one-dimensional model. Guided by Lagendijk, she has been busy developing the model for a three-dimensional finite photonic crystal. It seems that we finally have a theory that is able to explain exciting experimental data on the space-dependent LDOS in the photonic band gap. The 1-dimensional results have been published[1] and a manuscript describing 3-dimensional finite-size photonic crystals will be submitted in 2014. We expect that our model will be applicable to a wide range of complex photonic systems, as they are studied in this FOM programme, and even beyond.

Since the Eindhoven PhD student started working on this project on 1 December 2013, the there are no scientific results being achieved or published in 2013. Collective scatter-theory is further developed by collections of dust particles confined in the potential of a plasma. Since this system is rather flexible in terms of wavelength of light, particle size, inter-particle distance, etc., this exploration can be very effective.

2. Added value of the programme

Cohesion within this FOM programme is notably ensured by visits of each junior to each partner group for a whole day to get a good over-view of the expertise and infrastructure of all partners. In 2013, the first five PhD students (Delft, Leiden, Utrecht, Twente) have organized and performed one-day visits to each of the four involved sites, in the period between February and June 2013. During these visits, the PhD students have received overviews of research in the relevant team, as well as on the available facilities, both in optics and solar cell study, and in nanofabrication. As the Eindhoven team experienced delay, its team members will still visit the other facilities, and to present their infrastructure to the other teams.

In addition, the teams have developed various infrastructure and know-how that is of special usage to the partner teams in this FOM programme, partly following original planning, and partly as new developments. We are aware of the following features:

a - The Delft group has developed solar cell structures that are available to the other teams in this programme.
b - The microscope setup under development in Leiden will be used to analyze the performance of structured photovoltaic cells, in a collaboration with the Delft team.
c - The mobile wavefront shaping setup built in Twente will aid the programme-partners to quickly acquire new relevant know-how, notably in Eindhoven and Utrecht.
d - The insights on the spatial correlations obtained in Twente are relevant for programme-partners that will perform high-quality wavefront shaping, notably in Leiden and Eindhoven.
e - The nanostructures that have been realized in Utrecht are a suitable platform for light scattering experiments on samples with controlled optical inhomogeneity – so-called 'photonic cappuccino' – which is planned to be studied in collaboration with the Twente team.
f - The theoretical know-how on finite-sized nanophotonic systems is relevant to interpret various observations, notably the Leiden diffraction experiments.

[1] See Reference [11] in Section '4. Publications' below.

- g - The FOM programme Stirring of light! benefits from Eindhoven research since we explore - in a fundamental way - light scattering by both single particles and by complex structures of multiple scatterers.

3. Personnel

The first five PhD-positions had been filled early in 2013. The Eindhoven team has actively been searching for a high-level and suitable PhD-candidate. Although several candidates indicated their presence, we have found in Leroy Schepers the most suitable match with the foreseen work in the 'Stirring of light' programme. Leroy started his work in December 2013.

The hiring of the theory postdoc by the AMOLF team is experiencing unfortunate delay. A challenge is that the required skills are demanding, and a deep knowledge of and affinity with theory of complex photonic systems is required. Early on, colleagues have been (mass-) mailed about the vacancy, it was advertised on group website and during scientific presentations of AL. While several candidates were interviewed, none seemed convincing, hence new applicants are currently being considering. We have recently placed more ads in AcademicTransfer, Career.edu, Euraxess.eu, NRC carrière, and Twente.com, so we remain on the lookout.

Conforming to our programme-planning, we have been fortunate to attract world-leading scientist Prof. Hui Cao (Yale University) for a visit to the Netherlands in the summer of 2013. In collaboration with the group of Prof. Cao, the Twente has performed a simulation study that reveals intriguing effects of absorption of light in a waveguide, where light transport is seen to behave quasi-ballistically in presence of a strong absorption [3]. We are looking forward to more fruitful exchanges with Prof. Cao, as well as with the visitors of our FOM programme.

4. Publications

Since most PhD students are in their first year, most programme output is in the form of conference papers and presentations [4-5, 21-22, 31]. In a collaboration of the Twente and AMOLF teams with several Eindhoven colleagues, a first peer-reviewed paper has been published [1], with a second one due in spring 2014 [2]. A third paper is the result of the Twente and AMOLF collaboration on theory [11].

<u>11SOL01</u>

- [1] W.L. Vos, T.W. Tukker, A.P. Mosk, A. Lagendijk, and W.L. IJzerman, *Broadband multiple light scattering in white LED diffusers,* Appl. Opt. **52**, 2602-2609 (2013).
- [2] Y.F.V. Leung, A. Lagendijk, T.W. Tukker, A.P. Mosk, W.L. IJzerman and W. L. Vos, *Interplay between multiple scattering, emission, and absorption of light in the phosphor of a white light-emitting diode,* http://arxiv.org/abs/1311.6110 (2013) [Opt. Express, in press in 2014.]
- [3] S.F. Liew, S.M. Popoff, A.P. Mosk, W.L. Vos, and H. Cao, *Transmission channels for light in absorbing random media: from diffusive to ballistic-like transport* http://arxiv.org/abs/1401.5805.
- [4] D. Grishina, C.A.M. Hartveld, H. Wolferen, L.A. Woldering, A.P. Mosk, and W.L. Vos, *3D Silicon Photonic Bandgap Crystals With a Diamond-like structure* Summerschool '*Fabrication of Metamaterials*', Glasgow, UK, June 17-21, 2013 (poster).
- [5] O.S. Ojambati, D. Grishina, H. Yilmaz, A.P. Mosk, and W.L. Vos, *Enhanced absorption in a scattering medium* Summer school '*Controlling the propagation of waves in complex media*', Cargèse, France, May 27-29, 2013 (poster).

<u>11SOL02</u>

- [11] E. Yeganegi, A. Lagendijk, A.P. Mosk, and W.L. Vos, *Local density of optical states in the band gap of a finite one-dimensional photonic crystal*, arXiv.org/abs/1309.5730 (2013) [Appeared as: Phys. Rev. B **89**, 045123: 1-10 (Jan. 2014)].

11SOL03
- [21] F.T. Si, T. Papakonstantinou, O. Isabella, and M. Zeman, *Studies of Light Scattering Effect of Surface Morphology on Thin-Film Silicon Solar Cells Facilitated by Nano-Imprint Lithography Photo-voltaic Technical Conference* 2014 (Aix en Provence, France, May 2014), oral presentation.
- [22] F.T. Si, T. Papakonstantinou, A. Ingenito, G. Yang, H. Tan, O. Isabella, and M. Zeman, *Light scattering effect of nano-imprinted random textures on amorphous and nano-crystalline silicon solar cells* Submitted to *EU-PVSEC* 2014 (Amsterdam, Netherlands, Sept. 2014).

11SOL05
- [31] F. Mariani, K. Vendel, and M.P. van Exter, *Diffraction orders study of extraordinary optical transmission* NNV AMO 2013 conference, Lunteren October 2013, poster.

5. Valorisation and outreach

Twente (11SOL01)
The Twente team is maintaining active collaborations with ASML and IMEC concerning nanofabrication. With Philips Research and Philips Lighting, the team collaborates on light scattering, absorption, and re-emission in random structures typical of white LEDs.

Talks for broad audience:
[1] A.P. Mosk
'Ik zie, ik zie wat jij niet ziet' met lasers en computers
KNAW-Minisymposium: Revolutie in de optica: een TOMTOM voor fotonen, Royal Dutch Academy of Arts and Sciences (KNAW), Amsterdam, 21-3-2013

[2] W.L. Vos
Met een beslagen lens ziet men scherper
KNAW-Minisymposium: Revolutie in de optica: een TOMTOM voor fotonen, Royal Dutch Academy of Arts and Sciences (KNAW), Amsterdam, 21-3-2013

[3] W.L. Vos
Looking in and through opaque media (plenary)
NNV FYSICA 2013, TU Delft, 19-4-2013.

[4] W.L. Vos
Radio interview: *Wekker-wakker vraagcarrousel: Licht in plaats van röntgenstraling?*
Dutch National Radio 5, Omroep MAX, July 26, 2013,
www.wekkerwakker.nl/vraagcarrousel/artikel/nieuws/roentgenstraling

Popular news items about our paper [1] above:
[5] K. Tsakmakidis,
Research Highlight: *Scattered light for white LEDs*
Nature Mater. **12**, 472 (2013), www.nature.com/nmat/journal/v12/n6/pdf/nmat3677.pdf

Twente-AMOLF (11SOL02)
Talks for broad audience:
[11] A. Lagendijk

Organizer of the KNAW-Minisymposium: *Revolutie in de optica: een TOMTOM voor fotonen*
Royal Dutch Academy of Arts and Sciences (KNAW), Amsterdam, 21-3-2013

<u>Delft (11SOL03)</u>
None yet.

<u>Eindhoven (11SOL04)</u>
None yet.

<u>Leiden (11SOL05)</u>
Dr. Martin van Exter has become chairperson of the scientific advisory committee of the FOM-Philips IPP '*Nanophotonics for solid-state lighting*', headed by Prof.dr. J. Gomez Rivas. The optimum use of scattering and nano-scale structuring for solid-state lighting is the central theme in this IPP, as it is in our FOM programme.

Part of the Leiden outreach activities was the supervision of two talented high-school students in a pre-university project, which involved two weeks experimental work in our laboratory and provided them with the necessary data to write a 'profielwerkstuk'. This research, entitled 'Optische verstrooiing aan nanodeeltjes', involved spectral- and polarization-resolved scattering experiments on latex spheres and diluted milk and was supervised by FOM PhD Flavio Mariani.

<u>Utrecht (11SOL06)</u>
A number of colloidal nanostructure samples were shown to the general public as part of the 'Open Day' of the Physics Department at Utrecht University in 2014.

FOM - 12.0171/2
datum: 01-01-2014

APPROVED FOM PROGRAMME

Number	138.
Title (code)	Stirring of light! (SOL)
Executive organisational unit	BUW
Programme management	Prof.dr. W.L. Vos
Duration	2012-2017
Cost estimate	M€ 2.1

Concise programme description

a. Objectives

We aim to literally 'stir' light inside nanophotonic media. As a result, we can address the challenge: How can input light be absorbed as efficiently as possible in order to be converted to targeted forms of energy? These forms include electric power from a solar cell, or many colors in white-light illumination.

b. Background, relevance and implementation

In this FOM programme, we propose a radical departure from two traditional viewpoints in optics. First, scattering of light is traditionally considered to be a nuisance since it prevents us from looking straight through a window covered with dust. Recently, however, it has been realized that scattering of light is rather a great advantage. For example, our team has demonstrated that light can be focused much tighter with an intricate lens made of scattering material than with a usual transparent lens. Secondly, optical absorption is traditionally considered such a nuisance that any scientist in the field tries to avoid it. This aversion of absorption is understandable since nanophotonic media are designed to have photons scatter many times – as if they were pinballs - and thus absorption amounts to destroying of photons: 'game over!' Recently, however, it has been realized that optical absorption can be strongly manipulated – either enhanced or reduced – by controlling the incident light fields.

In order to radically depart from these two limiting traditions, we aim to literally 'stir' light inside nanophotonic media. As a result, we can address the challenge: How can input light be absorbed as efficiently as possible in order to be converted to targeted forms of energy? These forms include electric power from a solar cell, or many colors in white-light illumination.

We propose to fundamentally study and manipulate the optical phase space density for light – as it were 'stirring of light' through phase space – by combining in-sights gained from optical wavefront shaping with advanced structures made by colloidal self-assembly. As a result, we will be able to convert photons as efficiently as possible to other targeted forms of energy such as electric power, or transfer the energy of light to a different color. We wish to apply these concepts to realize a technology push for real devices such as solar cells, LEDs and broadband sources. Therefore we have assembled a team of fundamental and applied researchers from AMOLF, Delft, Eindhoven, Twente, Utrecht, including experimentalists and theorists, as well as researchers with a part-time industry affiliation.

Funding

salarispeil cao per 01-07-2012

bedragen in k€	≤ 2013	2014	2015	2016	2017	2018	≥ 2019	Totaal
FOM-basisexploitatie	642	496	534	385	72	-	-	2.129
FOM-basisinvesteringen	-	-	-	-	-	-	-	-
Doelsubsidies NWO	-	-	-	-	-	-	-	-
Doelsubsidies derden	-	-	-	-	-	-	-	-
Totaal	642	496	534	385	72	-	-	2.129

Source documents and progress control

a) Original programme proposal: FOM-11.1202
b) Ex ante evaluation: FOM-11.1401
c) Decision Executive Board: FOM-12.0170

Remarks

The final evaluation of this programme will consist of a self-evaluation initiated by the programme leader and is foreseen for 2017.

PT par. HOZB

Subgebied: 100% NANO

Historical overview of input en output

Input	personnel (in fte)				finances* (in k€)
	WP/V	WP/T	PhD	NWP	
2012	-	-	1.7	-	69
2013	-	-	5.0	-	227

Output	PhD theses	refereed publications	other publications & presentations	patents
2012	-	-	1	-
2013	-	1	29	-

* After closing the financial year.

PhD defences

2012
None.

2013
None.

Patents (new/changes)

2013
None.

Overview of projects and personnel

Workgroup FOM-D-58

Leader	Prof.dr. M. Zeman
Organisation	Delft University of Technology
Project leader	Dr. O. Isabella
Programme	Stirring of light!
Project (title + number)	Stirring of light in photovoltaic systems 11SOL03

FOM employees on this project

Name	Position	Start date	End date
F.T. Si	PhD	05 December 2012	04 December 2016

Workgroup FOM-L-31

Leader	Dr. M.P. van Exter
Organisation	Leiden University
Programme	Stirring of light!
Project (title + number)	Stirring of the local density of states of light 11SOL05

FOM employees on this project

Name	Position	Start date	End date
F. Mariani	PhD	01 June 2012	31 May 2016

Workgroup FOM-T-24

Leader	Prof.dr. W.L. Vos
Organisation	Twente University
Programme	Stirring of light!
Project (title + number)	Stirring of the energy density of light 11SOL01

FOM employees on this project

Name	Position	Start date	End date
D. Grishina	PhD	01 February 2013	31 January 2017
O.S. Ojambati	PhD	01 October 2012	30 September 2016

Workgroup FOM-U-09

Leader	Prof.dr. A. van Blaaderen
Organisation	Utrecht University
Programme	Stirring of light!
Project (title + number)	Stirring of light in colloidal systems 11SOL06

FOM employees on this project

Name	Position	Start date	End date
H.E. Bakker	PhD	01 April 2012	31 March 2016