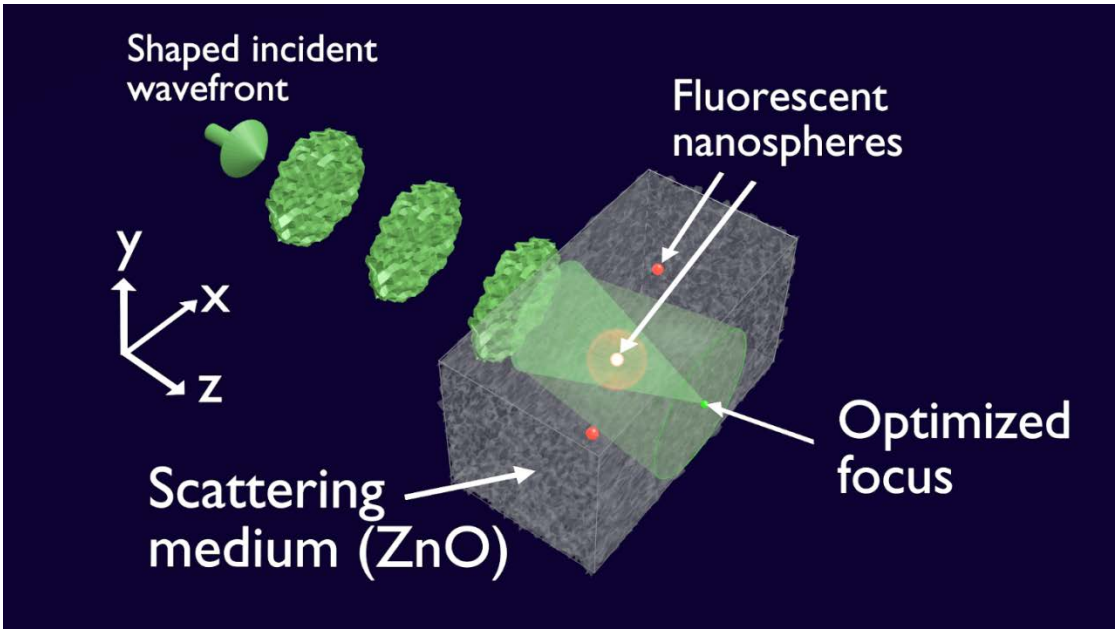
Nederlandse Organisatie voor Wetenschappelijk Onderzoek

Annual report 2016

FOM programme nr. 138
'Stirring of light!'



Method to probe the 3D (x; y; z) spatially-resolved local energy density that is enhanced by wavefront shaping. Incident green light is wavefront shaped to an optimized focus at the back surface of a scattering medium (ensemble of ZnO nanospheres) to excite open transmission channels. The scattering medium is sparsely doped with fluorescent nanospheres that probe the local energy density of the green incident light at different positions (x; y; z) by emitting orange light in proportion to the local energy density of the green excitation light.

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Content

1. Scientific results 2016

One of the central goals of FOM 'Stirring of light!' project is to use the powerful technique of **optical wavefront shaping** - invented in the Netherlands - to control light propagation and absorption in scattering media. Wavefront shaping involves controlling the phasefront of a coherent light beam that is incident on a complex nanophotonic medium in order to focus the beam behind such an opaque sample, and exciting prospects that are the subject of this FOM-programme. A second main aspect of the 'Stirring of Light!' programme is the **development of advanced nanostructures** and metamaterials wherein light is strongly confined.

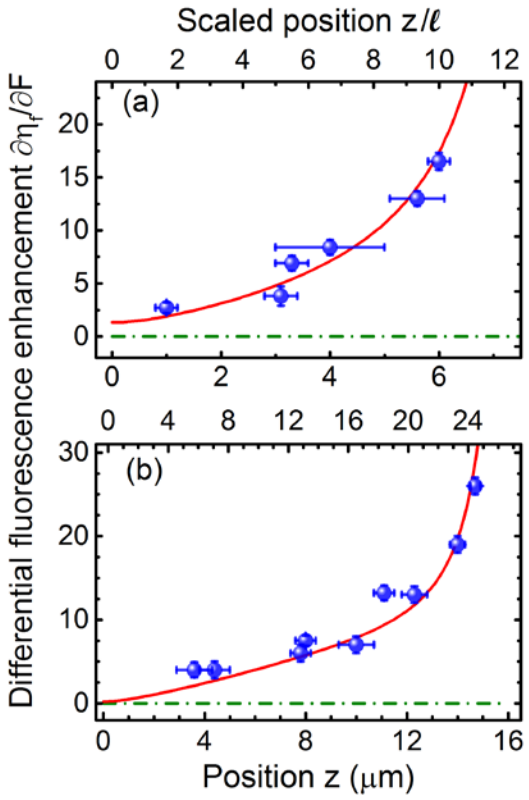

Figure 1: Measured differential fluorescence enhancement ($\partial\eta_f/\partial F$) versus position z and scaled position z/ℓ (ℓ is the mean free path) for two samples with thickness (a) L = 8 μm and (b) L = 16 μm. The fluorescent nano-spheres are centered on the optical axis at (x0,y0) = (0,0). Blue circles are measured data with error bars. The red curve is the energy density enhancement predicted by our 3D model without adjustable parameters. The green dash-dotted curve indicates zero energy density enhancement [06].

It is well-known from random matrix theory that the transport of waves such as light through complex media is described by so-called channels that are eigenmodes of the transmission matrix. Remarkably, open transmission channels with near-unity transmission are predicted to perfectly transmit a properly designed incident field even if the medium is optically thick. It has recently been demonstrated that light is sent into open transmission channels by a spatial shaping of the incident wavefronts. This development has led to tightly focused transmitted light (referred to as 'optimized light'), enhanced optical transport through a scattering medium, and imaging through, and even inside a scattering medium. In contrast, only very few studies have addressed the energy density of optimized light [01-03] that plays a central role in applications of light-matter interactions such as solid-state lighting and solar cells, as studied in our FOM-programme 'Stirring of light!' It is a critical and open question how the energy density is controlled upon the excitation of open channels, and what the resulting 3D energy density is. In particular, the 3D energy density profile of shaped light has never been studied to date.

Therefore, the Twente team has performed a study of the 3D local spatially-resolved energy density in a 3D scattering medium, with optimized incident light. Using a spatial light modulator (SLM), we shape incident green light to a focus at the back surface of a disordered ensemble of ZnO nanoparticles, a procedure that is known to couple light into open channels. The resulting energy density is probed locally by fluorescent nanospheres. The density of the nanospheres is so low that only one of them is present in the illuminated volume. Wavefront shaping increases the local energy density by an enhancement factor $\eta_f(x,y,z)$. Thus, the fluorescence emission of a nanosphere that is proportional to the local energy density at its location, is enhanced by the same factor. We performed measurements on several nanospheres inside a sample and for each individual sphere we measure two key parameters, namely the nanosphere location (x,y,z) and the differential fluorescence enhancement ($\partial\eta_f/\partial$F). The fidelity *F* quantifies the overlap between the experimentally-generated wavefront and the perfect wavefront that optimally couples light to the target. Figure 1 shows our main new results: the measured differential fluorescence enhancement versus depth z for different sample thicknesses. The differential fluorescence enhancement increases with z from front to back, and up to 16 and 26 with thickness. The data deviates significantly from the uncontrolled limit ($\partial\eta_f/\partial$F = 0), which reveals that wavefront shaping of light changes the local energy distribution. We propose a 3D model without free parameters that describes all our data – including scans versus transverse coordinates - very well. These results offer new insights on the 3D redistribution of the energy density in 3D complex media that is

crucial to applications: For white LEDs, wavefront shaping could serve to control the color temperature by optimizing for 'warm' or 'cold' white light. Our results are also applicable to wavefront shaping of classical waves such as acoustic and pressure waves, and to quantum waves such as electrons in nanostructures.

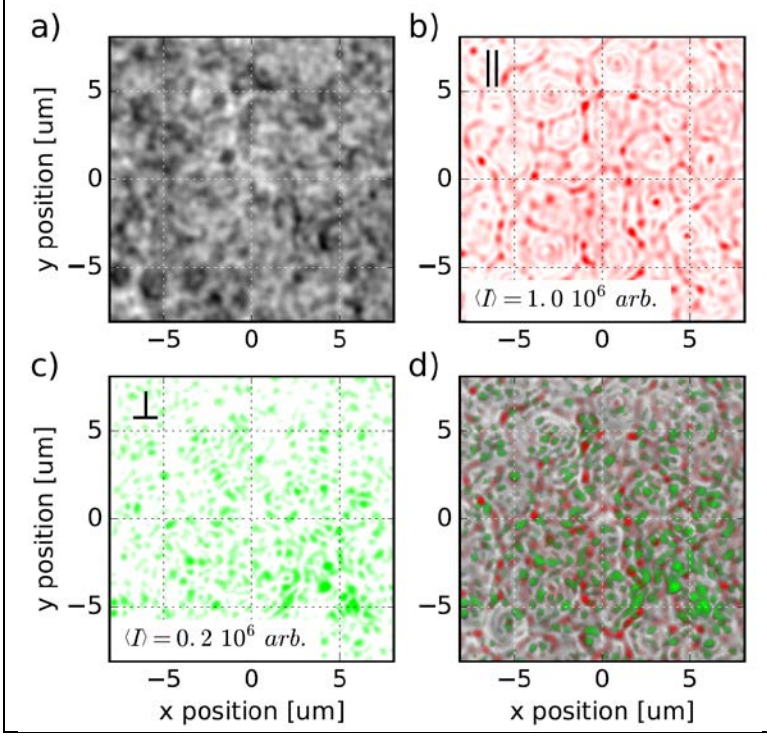

Figure. 2 A rough silicon solar cell has a very different appearance if illuminated with (a) filtered broad band incoherent light or when illuminated with (b-c) laser light. When we look at the reflection under coherent illumination, we analyze the (b) parallel and (c) orthogonal components: the results show that different areas reflect the two polarizations. (d) shows the combined image. From the comparison we try to quantify how much of the reflected light has propagated inside the cell before being detected.

Progress towards the use of 'stirred light' has been made by our consortium in the study of wavefront shaping of light incident on a photovoltaic cell. To this end, the **TUD** team has prepared tailor-made samples of rough, thin-film Si solar cells. These samples are being studied with the **UL** group's optical instruments, in collaboration with the **UT** team.

One of the research directions for the understanding of the photovoltaic cells was characterizing the transport of light in a strongly absorbing medium. A rough Si solar cell is very different from the more common random scattering samples, which typically exhibit strong scattering and very weak or no absorption, and where optical propagation can often be described as a diffusion process. This approximation is no longer valid when absorption becomes dominant, like in Silicon.

This makes it even more important to have methods to characterize light transport in the two dimensional structure of a thin Si cell. When light shines on rough Si solar cells, this is scattered at the surface and enters the Si layer at high angle, with the effect of a longer propagation length in the active layer and more efficient absorption. Nevertheless, part of the light which penetrates in the Si manages to escape again via the rough interface.

We study how this propagation happens, looking at both the emission at the surface and the far-field of the reflected light in two orthogonal linear polarizations and using both intensity shaping and phase-modulations techniques to understand the details of the process. The goal is to demonstrate and quantify the amount of absorption enhancement feasible with wavefront shaping techniques.

The **Leiden** team has developed a new method to measure transport and absorption properties of random scattering media. In this method we used a spatial light modulator to control the phase of the light field incident on a random scattering medium. We divide the illumination beam into two halves, obtaining ideally two distinct input fields which propagate within the sample volume. These fields are also reflected back and interfere at the sample interface. While imaging the reflected speckle pattern at the sample surface, with the spatial light modulator we introduce a variable phase shift between the two halves of the beam; the effect is that the intensity of the speckle pattern oscillates locally, as function of the phase shift, between values which

depend on the amplitudes of the reflected fields resulting from each of the illumination halves. We measure these variations for each pixel within the illuminated field of view.

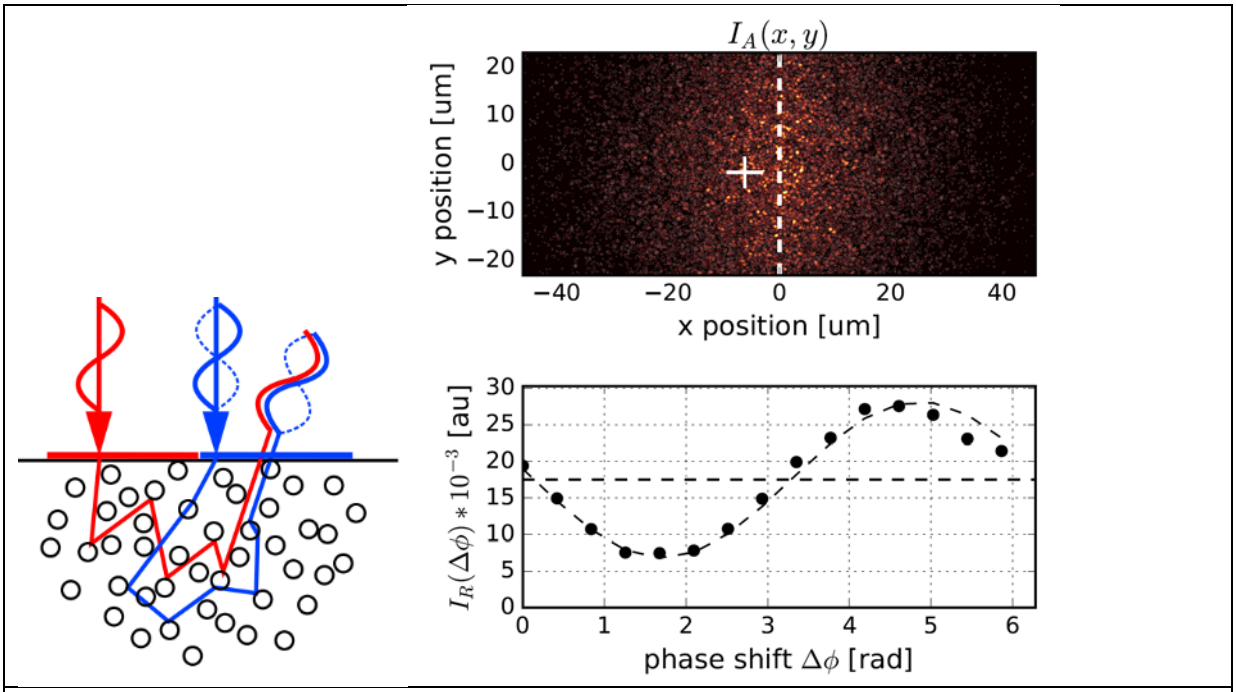

Figure. 3 Introducing a phase shift between two halves (left panel) of the illumination spot (x>0 and x<0) changes the relative phase of two reflected field components that interfere at the interface. This produces an oscillation in the speckle intensity at each point of the sample. The effect of the phase-shift at a single pixel (bottom right) is that the final intensity has a sinusoidal depending on the relative phase between the two field components. The central value and the amplitude of the oscillation give information on the transport properties of the sample. The false-color plot (top right) shows a map of the measured oscillation amplitude as a function of the position (x,y) over the sample surface, when a phase delay is introduced between the two halves of the illuminating Gaussian beam. The oscillation amplitude decays with distance from the phase-step at x=0, with a profile that depends on the properties of the medium.

In Fig. 3 we show the result of our measurements: the intensity of a single pixel oscillates sinusoidally (bottom right panel) when a phase shift is introduced between the illumination on the right and left side of the sample (left). We extract the amplitude of the oscillation for every pixel and plot this in a false-color plot (upper panel). It is clear how the speckle oscillation decreases with increasing distance from the phase step, as the amplitudes of the two interfering fields depend on the position on the sample and on the scattering properties of the medium: the stronger the scattering power, the quicker is the attenuation of the injected light and the shorter is the distance at which light emerges from the sample after propagation. We model the average effect of scattering on field attenuation using diffusion theory, as all the assumptions of this approximation are verified in our system, and developed a model to describe the average intensity oscillation of speckles as function of scattering and absorption mean free path of the sample.
By fitting this model to the experimental data we were able to retrieve scattering and absorption parameters of three different complex media. This new method is non-invasive and can be easily implemented in standard optical microscopes to measure scattering properties in biological sample, as alternative to point-like illumination diffusion technique. Being based on interference instead of intensity, this new method benefits from the 'amplification' effect for weak field similar to homodyne detection schemes, allowing to measure weaker fields that have propagated deeper in the material. The Twente team has exchanged sample with the Leiden team and performed coherent backscatter measurements to help calibrate the new method.

Extending their previous work on quadruple-junction (4J) thin-film silicon solar cells, the **TUD** team is among the first worldwide to demonstrate 4J cells using four absorber materials with different semiconductor bandgaps (Figure 4 Left). This structure improves the spectral utilization of the sunlight, thus reduces the undesired losses caused by the thermalization process. As a new component in the 4J cell, high-performance thin-film hydrogenated amorphous silicon germanium solar cells have been developed to effectively utilize the light in the red-infrared spectrum. The supporting doped layers are optimized taking into account the integration in the 4J cells [22]. For the broadband enhancement of light absorption, the advanced modulated surface textured front electrode made of highly transparent conductive oxide is incorporated in the 4J cells. Having optimized the electrical interconnection between the component subcells, the reported result confirm the potential of the proposed 4J structure [21].

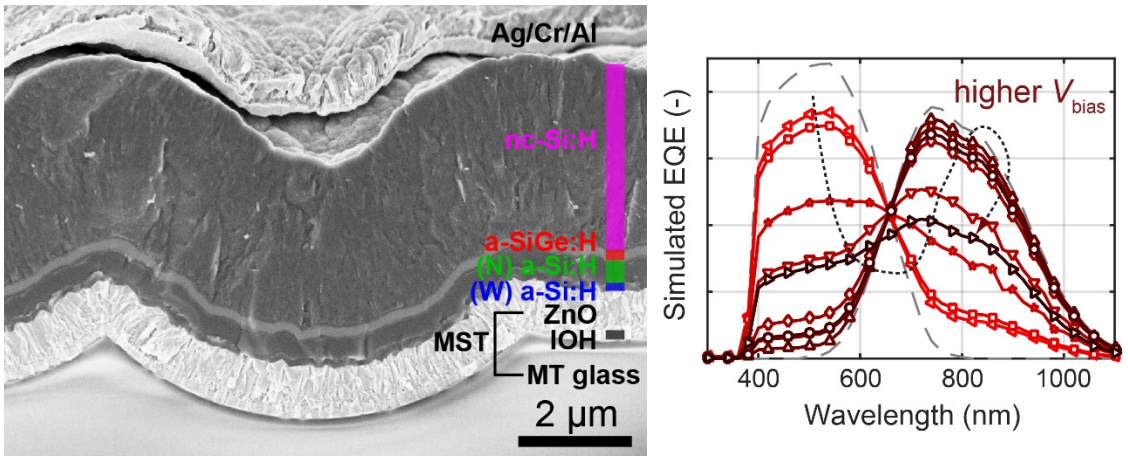

Figure 4 ***Left:*** *Cross-sectional scanning electron microsope image of a quadruple-junction thin-film silicon solar cell deposited on a modulated surface textured (MST) front electrode using no less than four different absorber materials [21].* ***Right:*** *Illustration of how the spectral response measurement of a tandem device is affected by measurement conditions, here the bias voltage V_{bias}, leading to undesired artefacts [23].*

In addition, the **TUD** team has explored the internal opto-electrical interactions of multi-junction solar cells subject to external stimulations in the process of spectral response measurements. Inappropriate measurement procedure or data interpretation may result in an erroneous understanding of the outcome, thus undermine the validity of the scientific findings and hinder the development of high-performance multi-junction solar cells. Assisted by modeling, the team has demonstrated how the solar cell properties and the measurement conditions can be related to measurement artifacts. It is shown that either a defective solar cell or an improper configuration of illumination and voltage during the measurement can drastically transform the measured spectral profile from the ideal one, meaning a faulty output (Figure 4 Right). These changes have been clearly visualized and quantified with comprehensive explanations. Based on such analyses, photovoltaic researchers can diagnose the irregularities in practical measurements. Besides, guidelines are provided for preventing artifacts and for unambiguous data interpretation. It is anticipated that this work leads to more reliable characterizations and reports on multi-junction solar cells [23].

A second main aspect of the '*Stirring of Light!*' programme is the **development of advanced nanostructures** and metamaterials wherein light is strongly confined. To investigate the performance of any three-dimensional (3D) photonic nanostructure, it is vital to view their internal structure. For one or two-dimensional (2D) nanostructures, the dimensionality is sufficiently low to assess the detailed structure with planar imaging techniques such as scanning electron microscopy (SEM), or atomic force or scanning tunneling microscopy. To look inside 3D nanostructures, one supplements SEM with micromachining or ion beam milling to slice away part of the structure. Unfortunately, this approach is destructive and irreversible, and not *in situ*. While transmission electron microscopy is capable of high-resolution 3D imaging, the required sample thickness $L < 1$

μm strongly hampers its suitability for 3D photonic nanostructures. For an *in situ* and non-destructive structural characterization of 3D nanostructured materials, X-ray techniques are ideal in view of their high penetration and high resolution. Hence, the **UT** team has performed synchrotron X-ray tomography on diamond-like photonic band gap crystals made from silicon. To achieve nanometer spatial resolution, projection microscopy or zoom tomography is employed. Its main features are that the X-ray beam is focused, and that the sample is placed at a small distance downstream from the focus to collect magnified Fresnel diffraction patterns on the detector. The 3D nanostructures under study have the inverse woodpile structure that is defined by two perpendicular 2D arrays of pores that run in the Z and X-directions. Both 2D arrays have a centered rectangular structure with lattice parameters *(a,c)* that correspond to diamond (hkl = 110) faces. For cubic diamond-like crystal structures, the lattice parameters fulfill the condition $a/c = \sqrt{2}$.

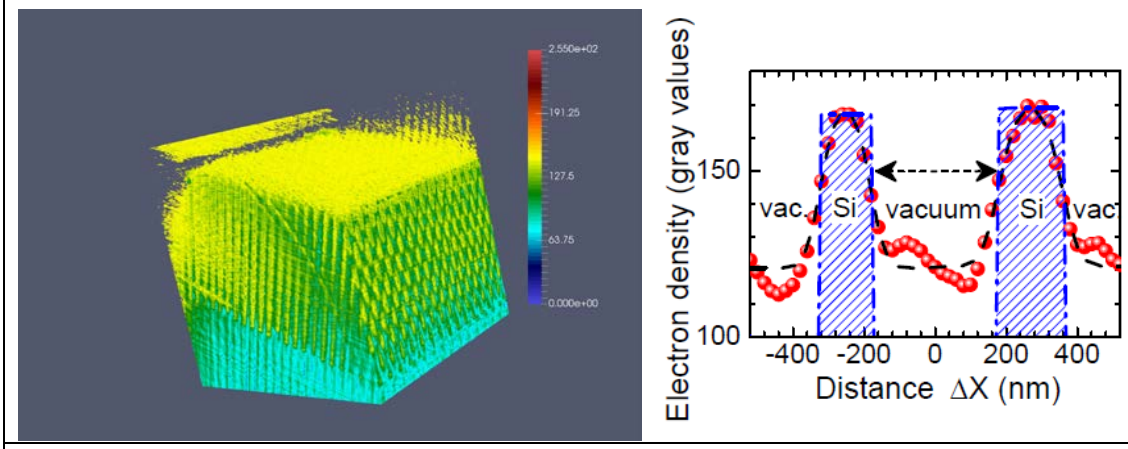

Figure 5. ***Left****: Bird's-eye view of the sample volume of a 3D photonic crystal reconstructed from X-ray tomography. The color scale is the material density ρ(X;Y;Z) interpolated between air and silicon, the latter set to 255.* ***Right****: Density profile in the X-direction through pores in silicon (red circles). The black dashed curves is the convolution of a square density function (blue hatched bars) and a Gaussian resolution function [04].*

Figure 5 shows the reconstructed volume of one crystal. A closer inspection indeed reveals two sets of pores running in the Z and the X-directions, matching the design. Figure 5 also shows a cross-section in the X-direction through three pores in the reconstructed volume. To interpret the density, we propose a simple model of a binary normalized density function for silicon and vacuum convoluted with a Gaussian resolution function. The adjustable model parameters are the width of a Si-wall, the Gaussian resolution, the amplitude, and a background. The data are well modeled with two Si-walls with widths w1 = 140 nm and w2 = 176 nm. Given the 20 nm voxel size and the spatial resolution, this agrees with the design w = 156 nm. The resolution widths (32 nm and 37 nm) agree well with the measured X-ray beam size. Modelling of the structure offers a straightforward future path to input tomographic structural data into ab initio numerical codes (FEM, FDTD) to compute nanophotonic properties. This opens the prospect to do *model-free* calculations of metamaterial to predict experiments and device functionality [04].

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 UU team** has successfully implemented a device to follow the assembly of colloids by doctor blade coating (DBC) in real space and real time. We used a modified parallel shear plate mounted on top of an inverted confocal laser scanning microscope, of which the top plate was replaced by a cassette that contained a blade oriented perpendicular to the substrate. We analyzed the observed flow profiles during DBC using a DPIV algorithm.
The flow profile observed during DBC, with the parameters used here, closely resembled Landau-Levich flow, which is also often observed during dip-coating for a completely wetting liquid. Crystalline domains were observed to form inside the steady meniscus before they were pulled out to form a film. At the region of film entrainment, the large crystalline domains were broken up in smaller crystalline domains reducing the order in the resulting film. This was probably due to back flow of solvent into the steady meniscus at the boundary of

the steady meniscus and the film entrainment region. We were able to obtain a free standing colloidal particle film of 300 µm × 300 µm by using UV light to polymerize the solvent ETPTA after DBC. In future, the size of the free standing colloidal film could be enlarged by moving the substrate during polymerization and by using a confocal objective with a lower numerical aperture to enlarge the spot size.

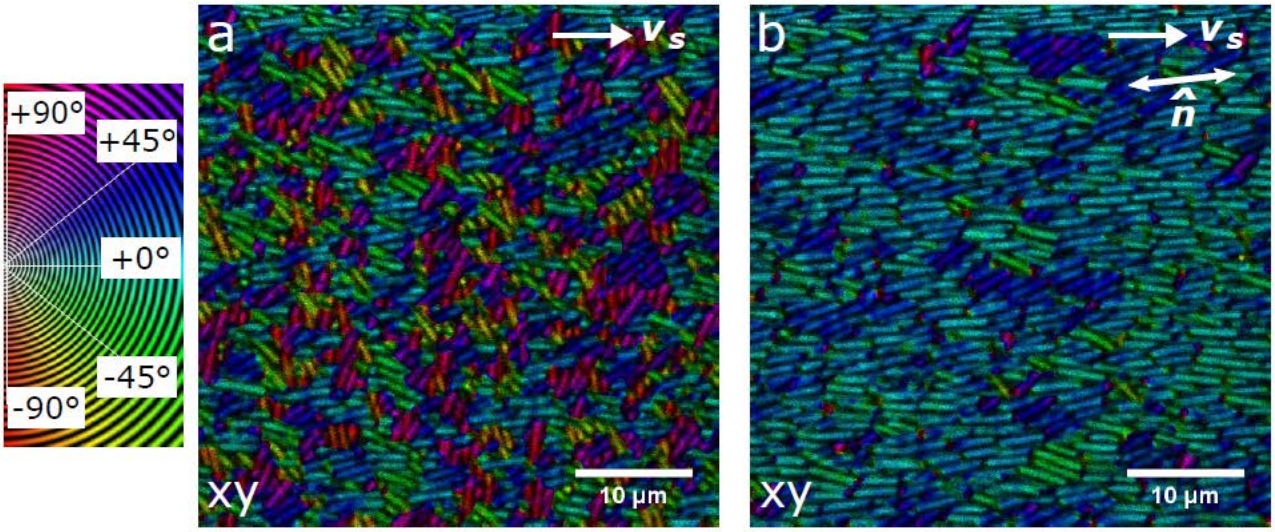

Figure. 6. Confocal snapshots of the doctor blade coating of a 30 vol% silica rod suspension at a speed of v_s = 2.5 µm/s. The image was taken 300 µm downstream from the blade. (a) Confocal xy-image taken 4 minutes after the start of the coating, showing no orientational order. (b) Confocal xy-image taken 7 minutes after the start of the coating, showing shear alignment. The color in the images indicates the average pixel orientation. The arrows denoted v_s indicate the movement of the substrate relative to the blade. The double arrow in (b) denotes the nematic director.

DBC of silica rods resulted in shear alignment of the rods inside the steady meniscus (Figure 6). However, silica rods were not flow aligned inside the resulting particle film. We expect that back flow of dispersion at the boundary of the steady meniscus and film entrainment region, distorted the alignment of silica rods that ended up in the particle film. We argue that better aligned particle films could be obtained in two ways: either by faster blading to obtain thicker films or by local polymerization of the aligned silica rods inside the steady meniscus during the process of DBC.

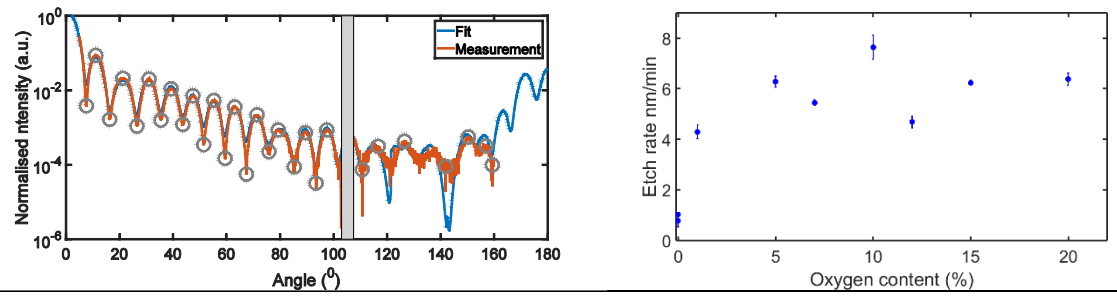

Figure. 7 ***Left:*** *Normalised scattered light intensity from a plasma-confined particle as function of scattering angle. By fitting the data, the particle's refractive index and time-dependent radius are found.* ***Right:*** *The etch rate of a confined particle as function of the gas fraction of oxygen. Small amounts of oxygen already increase the etch rate significantly.*

The **TUE team** has investigated multiple light scattering by utilizing a dusty plasma as dynamic and controllable scatter sample. Charged micrometer sized particles can be confined and controlled in a plasma. Therefore these particles form a cloud which acts as scatter sample, which is adjustable by tuning plasma parameters. In order to explore the effects of higher order scattering (light which scatters on average more than once within the

sample), the density of scatterers in the sample should be high. Before, the dusty plasma community never aimed for high density clouds and the TUE team has been the first to actively tune the plasma in order to achieve dense particle clouds. It is found that by pushing the particle densities to high numbers, the dust cloud is becoming instable as ion drag forces in the cloud become dominant over electrostatic forces. This leads to collective movement of particles through the plasma volume and even to the creation of a void (a large volume in the plasma with no particles present). Due to these surprising phenomena the scatter sample can only be kept stable for densities lower than 10^{11} /m^3. As a result signal from first order scattering is 4 orders of magnitudes stronger than the signal from multiple scattering and differentiating between different orders has appeared not possible.

The research of the TUE team has continued with the interaction between light and a single particle confined in a plasma. Previously, the researchers found a way to extremely sensitively monitor the properties the confined particle by means of Mie scattering. Refractive index of a particle can be determined while the size of the particle is measured in a time resolved in situ fashion. Due to the precision of this technique, small changes in the particle (composed from polymers) radius are found which is explained by plasma etching. To understand these etching processes, oxygen, a species known to be capable of etching, is added to the pristine argon discharge. As is shown in figure 7, only small amounts of oxygen are sufficient to significantly enhance etching of the particle, while increasing the gas fraction of oxygen has little effect.

To get a complete understanding of the influence of oxygen on the plasma, resonance measurements are performed. By modulating the plasma power, forces on a single microparticle are altered periodically and the particle will oscillate in the plasma sheath. Knowledge about the forces acting on the particle and the particle charge is acquired by finding the resonance frequency. Currently, a model which provides the electric fields and species densities in the plasma is under development. By combining the measurements with this model, the electric forces and particle charge in an oxygen plasma will be quantified.

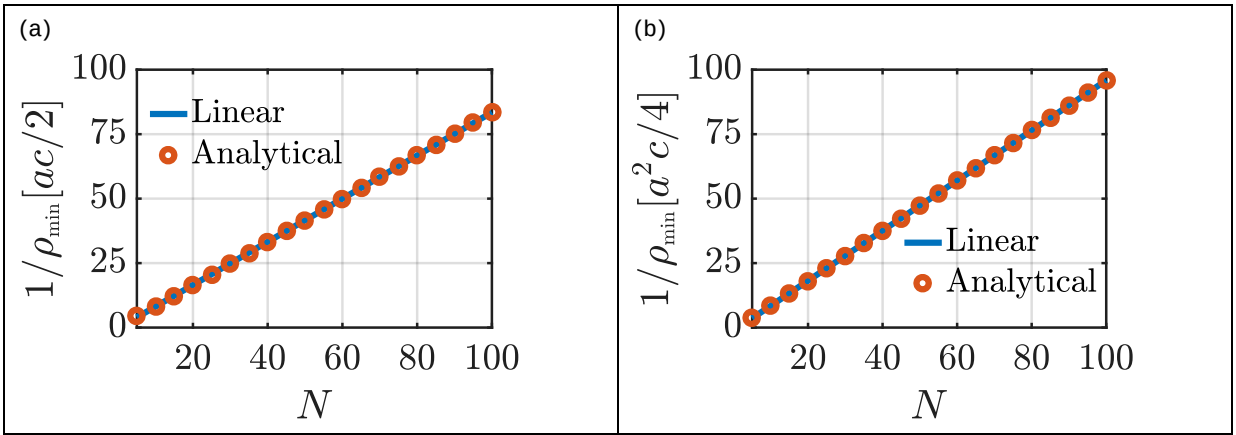

Figure 8. *Minimum DOS inside the photonic bandgap as a function of the number of unit cells N in each dimension of a 2D (a) and a 3D (b) photonic crystal. The 2D crystal (a) is made of a square array of cylinders of permittivity $\varepsilon = 12.9$ and radius $R = 0.2a$ with a the lattice constant. The bandgap is only found for the s-polarization. The 3D crystal in (b) is a cubic inverse woodpile with a tetragonal unit cell with lattice constants a and c with a ratio $a/c = \sqrt{2}$. The cylindrical air holes have a radius R=0.24a in the silicon host that has a permittivity $\varepsilon = 12.1$. Surprisingly in both examples, the DOS decreases linearly with the number of unit cells in each direction, as demonstrated by the perfect overlap with linear fit (solid blue).*

Theoretical interpretation of experimental observations on control of light propagation and emission is also an integral part of our 'Stirring of Light!' programme. On this aspect, the **AMOLF-Twente** team have developed an original approach for calculating the density of states (DOS) in photonic bandgap crystals with finite support. By considering the Bloch mode spectrum of an infinite crystal, they demonstrate how the DOS in a finite support realization of these structures approaches the infinite crystal-size limit that is found in research literature. In their approach, the quasi-normal modes found in finite support crystals are described by Lorentzians with a non-zero linewidth which makes it possible to describe the non-vanishing DOS inside the photonic bandgap. However, the linewidth of quasi-normal modes has an inverse relationship with the crystal

size (along with other physical and geometrical parameters) due to which the spilling of DOS in the bandgap decreases with increasing crystal size L (in each spatial direction) and eventually becomes zero in the theoretical limit of infinite crystal (L→∞). What is remarkable about their calculations is the discovery that the DOS inside the bandgap decreases linearly with crystal size regardless of the dimensionality of the crystal. Figure 8(a) shows the minimum DOS in the bandgap of a 2D square lattice crystal made of cylinders with area a^2N^2 where N is the number of unit cells. The same is shown in Fig. 8(b) for an inverse woodpile crystal of volume a^2cN^3. In each case, we find that the minimum DOS decreases linearly with increasing number of unit cells N in each spatial dimension.

2. Added value of the programme

Cohesion within this FOM-programme was from the start ensured by mutual visits of all early-career scientists (PD, oio) to each partner group for a whole day to get an overview of the expertise and infrastructure of all partners. This programme item has been completed.

Figure 9. Group picture of the 'Plasmonics And Light Scattering (PALS) ' workshop, held at the University of Exeter (UK), June 21-24, 2016. Invited speakers included Tomas Cizmar (University of Dundee), Simon Horsley (University of Exeter), Wilbert IJzerman (Philips Lighting, Eindhoven), Femius Koenderink (FOM Institute AMOLF, Amsterdam), Allard Mosk (University of Utrecht), Otto Muskens (University of Southampton), Kevin Vynck (University of Bordeaux), Jérome Wenger (Fresnel Institute, Marseille), and Martijn Wubs (Technical University of Denmark). See also www.pals2016.com

From 21-24 June 2016, the project partners have held a workshop jointly with several leading international teams in nanophotonics at the University of Exeter (UK), called 'Plasmonics And Light Scattering (PALS) Workshop', that was co-organized with Prof. Bill Barnes, Dr. Jacopo Bertolotti, Alba Paniagua Diaz, Dr. Alex Teulle (Exeter), Dr. Riccardo Sapienza (King's College London, UK), and Prof. Rémi Carminati (ESPCI ParisTech, France). In addition to didactic talks on advanced topics by leading international scholars (see Figure 9) there were several lively poster sessions where the 'Stirring of light!' participants presented their results to each other as well as to all fellow workshop participants to receive feedback and gauge our advanced position in the international field.

On 22 September 2016, at the PhD defense of O.S. Ojambati (Twente), prof. Zeman (Delft) was member of the thesis jury, to notably discuss the implications of the results to photovoltaics.
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:

a) The TUD team has developed solar cell structures, both amorphous and nanocrystal-line, for the other teams in this programme. The UL team studies these structured silicon samples for enhanced absorp¬tion under illumination with spatially structured light, in collaboration with the UT.
b) The UL team built a SLM-based confocal microscope setup for position-resolved lifetime meas¬urements. This setup is available for study of the LDOS by the other teams.
c) The UT team has successfully developed with TUE (and ASML) novel nanofabrication techniques for Si nano-photonics.
d) The mobile wavefront shaping setup built at the UT is at full disposition to all programme partners, especially those without major optics infrastructure (TUE and UU) to obtain know-how on wavefront shaping.
e) Insights on the spatial correlations obtained at the UT are helpful for programme-partners in Leiden that aim to perform high-quality wavefront shaping.
f) Nanostructures made in Utrecht are suitable for light scattering studies with controlled optical inhomogeneity – so-called 'photonic cappuccino' – that is studied with the UT.
g) Theoretical modeling of light scattering from ab-initio by the Twente-AMOLF team is underway to shed light on spatial correlations of the transmitted light, as observed in experiments done at UL, in close collaboration with TUD and UT.
h) The programme benefits from TUE research as they explore in a fundamental way light scattering by both single particles and by complex structures of multiple scatterers.
i) Organize a joint workshop on 'Plasmonics, and light scattering (PALS)' in June 2016 in Exeter.

3. Personnel

Appointed personnel

All positions have been filled.
After his successful graduation (with special honors), Dr. O.S. Ojambati has stayed for 6 months as a postdoc in Twente to finish papers (3 submitted and counting), finish the development of a theory that will lead to several papers, and orient on a next career step; as a result, he has accepted the offer to become postdoctoral fellow at Cambridge University in the leading group of Prof. Jeremy Baumberg as of 1 April 2017.
After a successful first year as postdoc in Twente (see Fig. 1), Dr. P. Hong has accepted a position as staff member (with supporting grant) in the School of Science, Nanjing University of Science and Technology, in China, as of January 15, 2017. We are happy that Dr. R. Uppu has accepted to fill the vacancy as of March 1, 2017; currently, Dr. Uppu is busy setting up the planned wavefront shaping setup that is compatible with silicon nanostructures notably for photonic crystals and silicon photovoltaics (as per pro¬gram planning.)

Distinguished guest scientists

Conforming to our programme-planning, we have been fortunate to attract world-leading scientist prof. Hui Cao (Yale University) for multiple visits to the Netherlands. Following her visit in 2013, she visited in the spring of 2015, as invited speaker at a Lorentz Center Workshop 'Transformations in Optics'. In collaboration with the group of prof. Cao, the UT team has published a Phys. Rev. B of absorption of light in a disordered waveguide, where light transport is seen to behave quasi-ballistically in presence of a strong absorption [Phys. Rev. B (2014)]. Since Jan. 2016, the UT PhD graduate Dr. Hasan Yilmaz (former FOM oio) has joined Cao's group as a postdoc.
With well-known theorist Dr. Martijn Wubs (DTU Denmark), we have derived theory to elucidate the role of the local density of states on Förster resonant energy transfer, a prime interaction between different light emitters in nanometre vicinity. A paper has been published (New J. Phys. (2016)).
With the leading teams of prof. Bill Barnes (University of Exeter), dr. Jacopo Bertolotti, prof. Riccardo Sapienza (King's College), and prof. Remi Carminati (Paris Tech), we have organized a joint workshop on 'Plasmonics, and light scattering (PALS)' in June 2016 in Exeter (see above).

4. Publications

11SOL01 and 11SOL07 (Twente)

a. Scientific (refereed) publications

- [01] O.S. Ojambati, H. Yılmaz, A. Lagendijk, A.P. Mosk, and W.L. Vos
  Coupling of energy into the fundamental diffusion mode of a complex nanophotonic medium
  New J. Phys. **18**, 043032: 1-13 (2016)
- [02] O.S. Ojambati, A.P. Mosk, I.M. Vellekoop, A. Lagendijk, and W.L. Vos
  Mapping the energy density of shaped waves in scattering media onto a complete set of diffusion modes
  Opt. Express **24**, 18525-18540 (2016)
- [03] O.S. Ojambati, J.T. Hosmer-Quint, K.J. Gorter, A.P. Mosk, and W.L. Vos
  Controlling the intensity of light in large areas at the interfaces of a scattering medium
  Phys. Rev. A **94**, 043834: 1-9 (2016)
- [04] W.L. Vos, D.A. Grishina, P. Cloetens, C.A.M. Harteveld, and P.W.H. Pinkse
  Looking inside three-dimensional (3D) silicon photonic band gap crystals
  arXiv.org/abs/1610.02051 (submitted, 2016)
- [05] O.S. Ojambati, E. Yeganegi, A. Lagendijk, A.P. Mosk, and W.L. Vos
  Non-Rayleigh distribution of reflected intensity from photonic crystals with disorder
  arXiv.org/abs/1611.10355 (submitted, 2016)
- [06] P. Hong, O.S. Ojambati, A. Lagendijk, A.P. Mosk, and W.L. Vos,
  3D spatially-resolved optical energy density enhanced by wavefront shaping,
  arXiv.org/abs/1703.08230 (submitted, 2017)

b. Presentations at (inter)national scientific conferences

- D.A. Grishina, T. Tajiri, J. Hofste, O.S. Ojambati, J. Perez-Vizcaino, S. Iwamoto, and W.L. Vos, *Cavity in a silicon inverse woodpile 3D photonic band gap crystal*, Conference on Photonic and Electromagnetic Crystal Structures (PECS-XII); York, UK (17-22 July 2016).
- O.S. Ojambati, H. Yilmaz, A. Lagendijk, A.P. Mosk, and W.L. Vos, *Launching optical energy into the fundamental diffusion mode of a complex nanophotonic medium* (*invited*), META'16, the 7th International Conference on Metamaterials, Photonic Crystals and Plasmonics; Malaga, Spain (25-28 July 2016).

11SOL02-1 (Twente-Amolf)

a. Scientific (refereed) publications

- [11] D. Devashish, S.B. Hasan, J.J.W. van der Vegt, W.L. Vos
  Reflectivity calculated for a 3D silicon photonic band gap crystal with finite support
  Phys. Rev. B. (Accepted for publication in 2017)
- [12] D. Sikdar, S.B. Hasan, M. Urbakh, J.B. Edel, A.A. Kornyshev
  Unravelling the optical responses of nanoplasmonic mirror-on-mirror metamaterials
  Phys. Chem. Chem. Phys. **18**, 20486 (2016).
- [13] S. Wolf, J. Rensberg, A. Johannes, R. Thomae, F. Smit, R. Neveling, M. Moodley, T. Bierschenk, M. Rodriguez, B. Afra, S.B. Hasan, C. Rockstuhl, M. Ridgway, K. Bharuth-Ram, and C. Ronning,
  Shape manipulation of ion irradiated Ag nanoparticles embedded in lithium niobate,
  Nanotechnology **27**, 145202 (2016)

b. Presentations at (inter)national scientific conferences

- S.B. Hasan, E. Yeganegi, A.P. Mosk, W.L. Vos, and A. Lagendijk
  Scaling of the density of states in 3D photonic bandgap crystals with finite support,
  The 12th International Symposium on Photonic and Electromagnetic Crystals Structures (PECS-XII) 2016, York, UK.
- S.B. Hasan, E. Yeganegi, A.P. Mosk, W.L. Vos, and A. Lagendijk
  Scaling of the density of states in 3D photonic bandgap crystals with finite support,
  Plasmonics And Light Scattering Workshop (PALS) 2016, Exeter, UK.

11SOL03 (Delft)

a. Scientific (refereed) publications

- [21] F.T. Si, O. Isabella, H. Tan, and M. Zeman
  Quadruple-junction thin-film silicon solar cells using four different absorber materials
  Solar RRL, 1700036 (2017)
- [22] F.T. Si, O. Isabella, and M. Zeman
  Thin-film amorphous silicon germanium solar cells with p- and n-type hydrogenated silicon oxide layers
  Solar Energy Materials and Solar Cells **163**, 9 – 14 (2017)
- [23] F.T. Si, O. Isabella, and M. Zeman
  Artifact Interpretation of Spectral Response Measurements on Two-Terminal Multijunction Solar Cells
  Advanced Energy Materials **7**, 1601930 (2016)

b. Presentations at (inter)national scientific conferences

- F.T. Si, O. Isabella, and M. Zeman, *Strategies towards high-efficiency quadruple-junction thin-film silicon-based solar cells*, 26th International Photovoltaic Science and Engineering Conference (PVSEC-26); Singapore (24 – 28 October 2016).

11SOL04 (Eindhoven)

a. Scientific (refereed) publications

- [31] Antipov, S. N., Schepers, L. P. T., Vasiliev, M. M., & Petrov, O. F.
  Dynamic behavior of polydisperse dust system in cryogenic gas discharge complex plasmas.
  Contributions to Plasma Physics **56**, 296-301 (2016).

b. Presentations at (inter)national scientific conferences

- L.P.T. Schepers, J. Beckers, W.L. IJzerman. *In-Situ Monitoring of Plasma – Particle Interactions by Mie Scattering on a Single Particle.* 28th NNV-Symposium on Plasma Physics and Radiation Technology, Lunteren, the Netherlands (March 15- 16, 2016).

11SOL05 (Leiden)

a. Scientific (refereed) publications

- [UL] Scientific publications on the work from 2016 are expected in 2017

b. Presentations at (inter)national scientific conferences

- F. Mariani, and M. P. van Exter
  Scattering media characterization with phase only wavefront modulation,
  Plasmonics And Light Scattering Workshop (PALS) 2016, Exeter, UK (June 2016).

11SOL06 (Utrecht)

a. Scientific (refereed) publications

- [51] H. E. Bakker, S. Dussi, B. L. Droste, T. H. Besseling, C. L. Kennedy, E. I. Wiegant, B. Liu, A. Imhof, M. Dijkstra, and A. van Blaaderen
  Phase diagram of binary colloidal rod-sphere mixtures from a 3D real-space analysis of sedimentation–diffusion equilibria
  Soft Matter **12**, 9238 - 9245 (2016)
- [52] H. E. Bakker, T. H. Besseling, J. E. G. J. Wijnhoven, P. H. Helfferich, A. van Blaaderen, and A. Imhof
  Microelectrophoresis of Silica Rods Using Confocal Microscopy
  Langmuir **33,** 881−890 (2017)

b. Presentations at (inter)national scientific conferences

- None.

11SOL07

a. Scientific (refereed) publications

- See 11SOL01

b. Presentations at (inter)national scientific conferences

- See 11SOL01

5. PhD defences

O.S. Ojambati
Stirring of the propagation and the absorption of light in complex nanophotonic systems
University of Twente, 22 September 2016, advisors: W.L. Vos, A.P. Mosk, and A. Lagendijk

H.E. Bakker
Directed Assembly of Colloidal Rods. Spheres and their Mixtures
Utrecht University, 13 February 2017, advisors: A. van Blaaderen and A. Imhof

F. Mariani
Scattering and losses in 2D optics (working title)
University of Leiden, scheduled in June 2017, advisor: E. R. Eliel

D.A. Grishina
Fabrication and characterization of 3D photonic nanostructures (working title)
University of Twente, scheduled on 13 July 2017, advisor: W.L. Vos

F.T. Si
Quadruple-junction thin-film silicon solar cells (working title)
Delft University of Technology, scheduled in September 2017, advisors: M. Zeman and O. Isabella

6. Valorisation, outreach and patents

Twente (11SOL01, 11SOL02, 11SOL07)

a) Education: Supervised 3 B.Sc. student projects (K.J. Gorter, D. Gram, and B. Slettenhaar) on wavefront shaping and on nanofabrication.
b) Outreach to small and medium enterprises (SME): 'Quantum credit card' demo by T. Tentrup and W.L. Vos at the business exhibit of the MicroNano Conference, Amsterdam (December 2016).
c) Outreach to small and medium enterprises (SME): talk by W.L. Vos at 'NanoTech&Photonics4SME' (Leusden, 12 April 2016).
d) Industry collaborations: The UT team maintains active collaborations with ASML, TUE, and TNO on Si 3D nanofabrication. The team collaborates with Philips Lighting on light scattering, absorption, and re-emission in random structures typical of white LEDs.

Delft (11SOL03)
Outreach to enterprises: Poster 'Thin-film silicon solar cells: State-of-the-art and outlook' by F.T.Si at Sunday Conference, Veldhoven (23 November 2016).

Eindhoven (11SOL04)
Presentation and poster at the ILIAD 2016 & Holst Symposium, Eindhoven (November 17th, 2016). W.L. IJzerman and L.P.T. Schepers.

Leiden (11SOL05)
M.P. van Exter, talk on 'Fascination for Light' for group of 10-15 refugees (LUMC, Leiden, March 2016)

Utrecht (11SOL06)

a) Supervised a M.Sc. student (A. Grau Carbonell) on assembly and phase behavior of rods.

b) Samples of assembled colloidal rods were shown to the general public as part of the 'Open Days' of the Physics Department at Utrecht University on 5 March, and 18 and 19 November 2016.

7. Vacancies

None.

FOM - 12.0171/5
datum: 01-01-2017

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 01-01-2016

bedragen in k€	≤ 2016	2017	2018	2019	2020	≥ 2021	Totaal
FOM-basisexploitatie	2.057	72	-	-	-	-	2.129
FOM-basisinvesteringen	-	-	-	-	-	-	-
Doelsubsidies NWO	-	-	-	-	-	-	-
Doelsubsidies derden	-	-	-	-	-	-	-
Totaal	2.057	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.

HO par. HOZB

Subgebied: 100% NANO

Overview of projects and personnel

Workgroup FOM-D-58

Leader	Prof.dr. M. Zeman
Organisation	Delft University of Technology
Project leader	Dr. O. Isabella
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	5 December 2012	4 June 2017

Workgroup FOM-E-22

Leader	Prof.dr.ir. G.M.W. Kroesen
Organisation	Eindhoven University of Technology
Project leader	Prof.dr.ir. W.L. IJzerman
Project (title + number)	Stirring of light in broadband light sources (11SOL04)

FOM employees on this project

Name	Position	Start date	End date
L.P.T. Schepers	PhD	1 December 2013	30 November 2017

Workgroup FOM-L-31

Leader	Dr. M.P. van Exter
Organisation	Leiden University
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	1 June 2012	30 November 2016

Workgroup FOM-T-24

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

FOM employees on this project

Name	Position	Start date	End date
O.S. Ojambati	PhD	1 October 2012	1 October 2016
D. Grishina	PhD	1 February 2013	31 July 2017

Leader	Prof.dr. W.L. Vos
Organisation	Twente University
Project (title + number)	Theory of stirring of light (11SOL02-1)

FOM employees on this project

Name	Position	Start date	End date
S.B. Hasan	WP/T	1 August 2015	31 July 2017
O.S. Ojambati	PhD	1 October 2016	31 March 2017

Leader	Prof.dr. W.L. Vos
Organisation	Twente University
Project (title + number)	Stirring of light in silicon nanostructures (11SOL07)

FOM employees on this project

Name	Position	Start date	End date
P. Hong	WP/T		15 January 2017

Workgroup FOM-U-09

Leader	Prof.dr. A. van Blaaderen
Organisation	Utrecht University
Project leader	Dr. A. Imhof
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	1 April 2012	31 August 2016