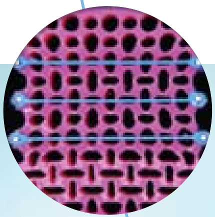
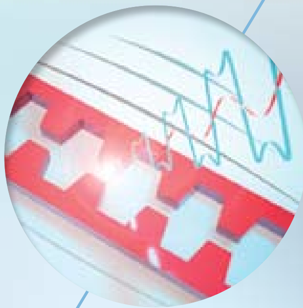
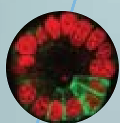




AMOLF **Strategic Plan** 2017-2022



AMOLF

AMOLF physics of functional complex matter

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AMOLF is part of the Netherlands Organisation for Scientific Research NWO

Preface

I am honored to present to you the AMOLF Strategic Plan for the period 2017-2022. In this plan we present our new mission statement and our research plans within four themes at the forefront of international research in the field of functional complex matter. We outline our ambitions in establishing new national and international collaborations, and in strengthening our national role in the coordination of large research programs. Together, these plans and ambitions define the national and international role of AMOLF as a research institute for the coming years.

Writing a strategic plan is a process which involves many interactions and discussions, and this plan is no exception. This plan is the result of intense effort of our scientific and support staff. We also strongly profited from the excellent advice of external advisors, including the members of our advisory board and the executive boards of FOM and NWO. It was extremely rewarding to see how this new plan developed over the last year. I hereby would like to thank everyone wholeheartedly for their contributions!

Huib Bakker
Director

July 31, 2017

Contents

Executive summary

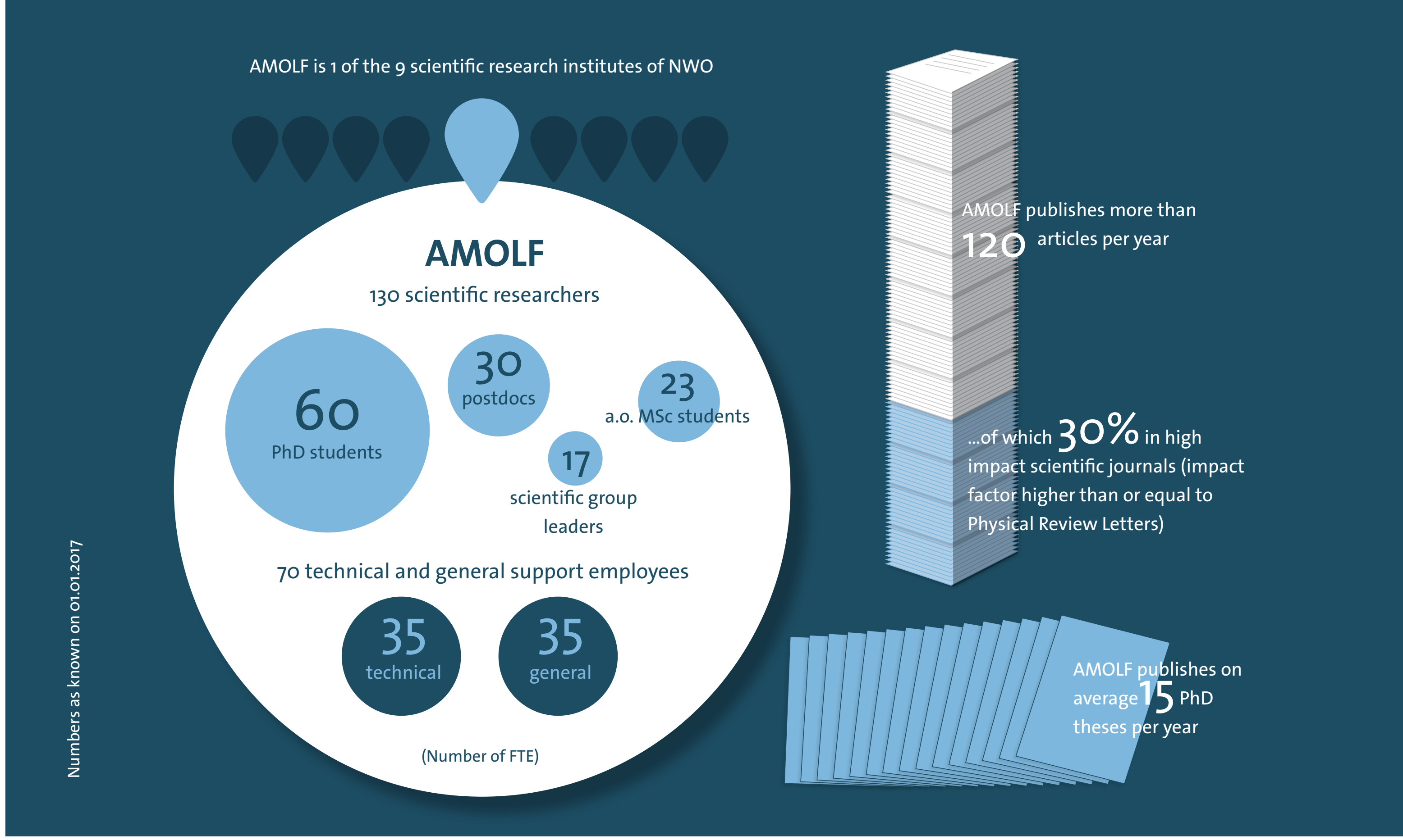
AMOLF performs leading research on the fundamental physics and design principles of natural and man-made functional complex matter. The institute uses the knowledge obtained to create novel functional materials, and to contribute to the solution of societal challenges in renewable energy, green ICT, sustainable materials, and healthcare. Examples include nano-structured materials that perfectly absorb light in solar cells, mechanical metamaterials with programmable properties, and living systems with adaptive functions. The institute is one of the nine scientific research institutes of the Netherlands Organisation for Scientific Research (NWO), employs about 130 researchers (17 research group leaders, 60 PhD students, and 30 postdocs) and 70 employees for technical and general support. AMOLF publishes on average 15 PhD theses and over 120 papers per year of which about 30% appear in high-impact scientific journals (impact factor ≥ Physical Review Letters).

AMOLF initiates and develops research themes that are new to the Netherlands, often combining expertise from different research fields, like in the recently started Designer Matter theme. To enable a fast and successful start of new research themes, AMOLF strives to be an outstanding and attractive place for tenure-track group leaders, and offers an optimal environment for research and training. The institute also places a strong emphasis on the development of advanced scientific instrumentation, as this is key to performing cutting edge physics research. AMOLF therefore serves as an incubator for Dutch science in starting new research themes, in attracting and training of scientific talent, and in developing scientific instrumentation.

AMOLF coordinates many national research programs that are realized in close collaboration with universities and other research institutes. AMOLF is also highly efficient in initiating and performing public-private partnership projects. A recent example is the development of the Advanced Research Center for Nanolithography (ARCNL), in collaboration with ASML. As both an incubator and a coordinator, AMOLF is a key instrument for enabling NWO to achieve its strategic objectives.

For 2017-2022, AMOLF's research program will comprise four intertwined research themes: Nanophotonics, Nanophotovoltaics, Designer Matter and Living Matter. These themes are connected by the central aim of understanding how function emerges in complex matter and leveraging this understanding to create completely new forms of adaptive and responsive (smart) materials. The interaction between research groups studying natural and man-made systems leads to strong cross-fertilization effects. Our research ambitions are supported by the following strategic actions:
- Expand our new research theme Designer Matter;
- Invest significantly in the innovation of scientific instrumentation, in particular in the equipment of the AMOLF NanoLab cleanroom;
- Introduce a data management policy to make our research data accessible to the outside world.

AMOLF aims to increase the proportion of female scientific group leaders to 25% in 2022 with the following actions:
- Actively scout female talent for tenure-track positions and participate in NWO's WISE (Woman In Science Excel) program;
- Improve the mentoring of women in PhD and postdoc positions to increase the percentage of women pursuing an academic career;
- Provide senior female role models, e.g. by inviting a representative number of female speakers for our scientific colloquia.



AMOLF also aims to strengthen its coordinating role in national and international research programs with the following actions:
- Enhance the collaboration with other institutes and university groups by developing new collaborative research programs, by establishing external part-time appointments of AMOLF group leaders at universities, and by offering guest positions for external researchers at AMOLF;
- Continue to take a leading role in the organization of the Dutch National Research Agenda thematic route on material research (Materials - Made in Holland), and participate in several other thematic routes of the Dutch National Research Agenda;
- Start public-private partnerships with small/medium enterprises (SMEs), aimed at the development of novel functional material systems or new instrumentation, and collaborate with research groups located at TNO institutes;
- Establish formal strategic partnerships with selected European institutes with a similar research focus, e.g. the Max Planck institutes in Mainz and Dresden, Institut Curie in Paris, EMBL in Heidelberg, and ICFO in Barcelona. Such partnerships will take the form of collaborative research projects, training and exchange of students, joint summer schools, joint postdoctoral fellowships, and mutual visits of scientific staff members.

To realize its ambitions, AMOLF requests an increase of 740 k€ to its annual mission budget. This budget increase is required to keep the scientific infrastructure state-of-the-art and to fulfill AMOLF's regional function within the Amsterdam Science Park as a central facility for nanofabrication and characterization (300 k€). Additional budget is needed to pay for the costs of the new data management policy (100 k€), to enable the accelerated increase of the proportion of female scientific group leaders to 25% in 2022 (130 k€), and to cover the costs of guest positions and collaborative projects with university groups (210 k€).


1. Mission
1.1. The initiation and development of new research directions
1.2. The recruitment and high-level training of scientific talent
1.3. Interdisciplinary and collaborative research program
1.4. The initiation and coordination of national research programs
1.5. The development of advanced scientific instrumentation
1.6. Strong connections with industry

1. Mission

AMOLF carries out leading research on the fundamental physics and design principles of natural and man-made functional complex matter. We use the knowledge we obtain to create novel functional materials that can provide solutions to societal challenges in renewable energy, green ICT, sustainable materials, and healthcare. We pursue these goals by being a flexible and dynamic scientific research institute that works with small teams of highly qualified scientists on focused research themes, and in which new research directions are regularly initiated.

AMOLF's mission statement is:

To initiate and perform leading fundamental research on the physics of complex forms of matter, and to create new functional materials, in partnership with academia and industry.

Our current research program comprises four themes: Nanophotonics, Nanophotovoltaics, Designer Matter, and Living Matter. These themes are connected by the central aim of understanding how functions emerge in complex matter. Examples include light-matter interactions in nanostructured metamaterials for solar cells, shape-morphing mechanical metamaterials, and life-like and living adaptive materials. The development of advanced scientific instrumentation, new multiscale fabrication techniques, novel theoretical concepts, and innovative computational techniques are vital assets for our research.

AMOLF plays a distinct role in national and international academic research characterized by:
- The initiation and development of new research directions;
- The recruitment and high-level training of scientific talent;
- A unique interdisciplinary and dynamic research program;
- The initiation and coordination of national research programs;
- The development of advanced scientific instrumentation;
- Strong connections with industry.

These characteristics make the institute a key instrument for enabling the Netherlands Organisation for Scientific Research (NWO) to achieve its strategic objectives.

1.1. The initiation and development of new research directions

AMOLF regularly initiates and pioneers novel research themes that are new to the Netherlands. We started Systems Biophysics (2000) and the Center for Nanophotonics (2005). Both research themes quickly became very successful and continue to evolve in new directions. At the onset of the previous strategic period, in 2012, we started a FOM focus group on Light Management in Photovoltaics, which has meanwhile taken off in full force with the appointment of three new international tenure-track group leaders within this theme (2012, 2014, 2016). Most recently, we initiated the research theme Designer Matter with three new research groups (2014, 2015, 2016). The ability of AMOLF to start new research themes is facilitated by a dynamic turnover of its scientific staff. AMOLF is a very

attractive place to start a tenure-track career and AMOLF's staff members are highly attractive candidates for senior academic positions in the Netherlands and abroad. This creates a constant flux, with on average one staff member joining and one leaving each year from a total scientific staff of 16 to 18 group leaders.

AMOLF serves as an incubator for Dutch science, both in terms of launching new research themes that usually develop into larger national research programs in which university partners and industry participate, and in terms of the training of talented group leaders who eventually move to a university or another (international) research institute. AMOLF's dynamic program also enables us to respond efficiently to new scientific and societal developments. AMOLF, for instance, played a leading role in founding the Advanced Research Center for Nanolithography (ARCNL), an exciting new form of public-private collaboration where academic and industrial partners join forces for long-term (>10 years) research.

1.2. The recruitment and high-level training of scientific talent

Tenure-track group leaders are an important asset of AMOLF, since they bring in new ideas and launch new research themes. AMOLF therefore strives to be an internationally outstanding and attractive place for starting principal investigators. We realize this goal with a unique combination of characteristics. First, right from day one of their appointment, tenure-track group leaders operate as independent scientists so that they can develop their international research profile and visibility in a short time span of circa four years. Second, we provide significant start-up funding and high-level technical and administrative support to facilitate a rapid start. This is particularly important for starting new research areas that require the in-house development of novel advanced scientific instrumentation. Third, while a tenure-tracker enjoys complete scientific independence, intense mentoring from the tenured scientific staff, internal reviewing mechanisms, and professional courses in leadership are in place. Finally, the research culture of AMOLF is strongly focused on scientific collaboration. The success of our model is illustrated by our recent hires of tenure-track group leaders from Harvard (2x), EPFL, Cambridge and Stanford. Other indicators are the success of AMOLF group leaders in obtaining national and international personal grants (NWO Innovational Research Incentives Scheme, ERC grants), and in appointments as full professor at a Dutch university soon after tenure.

AMOLF is highly committed to training junior scientists, from undergraduate students to PhD students and postdocs. To attract international top talents, AMOLF invests in an optimal environment for research and training. This environment is created by the relatively small size of the research groups that allows daily supervision by the group leaders, a collaborative atmosphere with joint seminar and poster sessions, and an extensive program of high-level courses for personal and scientific development. Over the last ten years, five PhD students from AMOLF were awarded the FOM Physics Thesis Award, the annual award for the best PhD thesis in physics in the Netherlands. AMOLF PhD students were also awarded three FOM Valorisation Chapter Prizes, out of the seven awarded since the inception of this prize. A large proportion (66%) of AMOLF's PhD students and postdocs come from outside the Netherlands (mainly Europe and USA). The quality of our master's internship program is illustrated by AMOLF master's students winning master's thesis prizes, including the National Shell graduation prize in 2011, 2014 and 2016.

1.3. Interdisciplinary and collaborative research program

AMOLF's research program is highly interdisciplinary, bridging physics, chemistry, biology, and engineering. Over the last decades, an increasing number of international research institutes have broken disciplinary boundaries by connecting themes. Leading examples that are comparable to AMOLF in terms of their research portfolio combine light and life (ICFO, Nano-GUNE, LENS, Fresnel Institute, IST Austria, MPI Erlangen and MPI Mainz), light and structured materials (Centers in Southampton, Exeter and ANU) or life and designer materials (Wyss Institute at Harvard). The research program of AMOLF focusses on the understanding of how functions emerge in complex matter. A particular strength of AMOLF is the combination of expertise in optical physics and biophysics with expertise in materials science and chemistry, which creates a unique platform from which new research directions readily emerge.

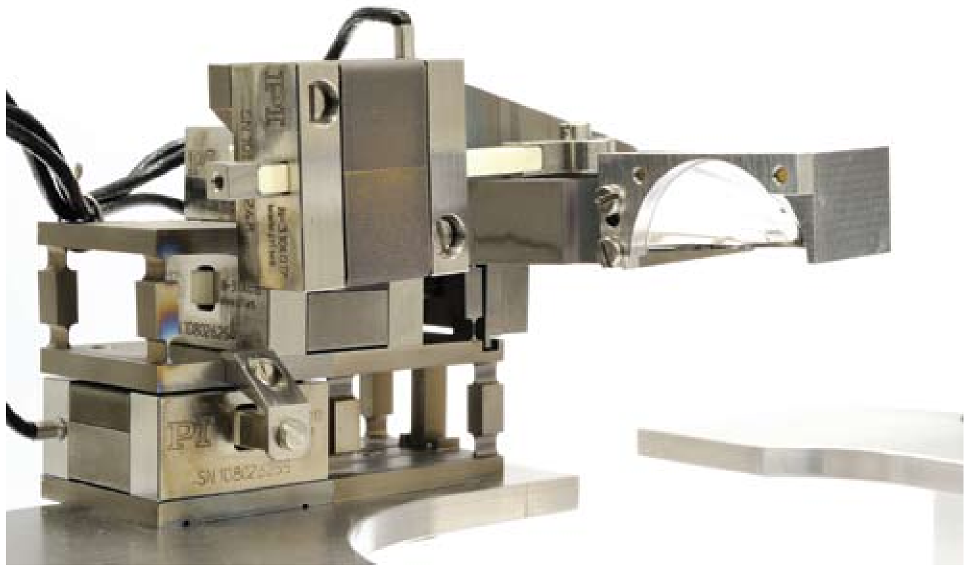
AMOLF has a non-hierarchical organization model in which the research program is carried out by small research teams that closely interact and collaborate across group and department boundaries. Such a highly collaborative operation is found in very few places worldwide.

1.4. The initiation and coordination of national research programs

AMOLF has strong connections with the Dutch universities. Besides joint participation in collaborative research programs, most of AMOLF's tenured scientific group leaders are affiliated as a professor (adjunct/by special appointment) with one of the universities. Moreover, as a national NWO research institute, we play a coordinating role in many national research activities. Examples of large programs oriented towards fundamental research are the FOM programs 'Light management in new photovoltaic materials' (A. Polman; 2011-2019), 'Proton mobility in confinement' (H.J. Bakker; 2010-2016), 'Spatial design of biochemical regulation networks' (A.M. Dogterom; 2009-2015), 'Plasmonics' (L. Kuipers; 2008-2014), 'The signal is the noise: seeking physical fluctuations in organism-scale behavior' (T.S. Shimizu; 2015-2020), and 'Spatio-temporal patterns of membrane protein activity' (P.R. ten Wolde; 2014-2018). Examples of programs in collaboration with industry are the FOM Industrial Partnership Programs (IPPs) 'Nanophotonics for solid-state lighting' with Philips (2014-2018) and 'Hybrid soft materials' with Unilever (2015-2019). We also played a national coordinating role in NanoNextNL (2010-2016), a large collaborative research initiative (125 M€) of 130 partners in academia and industry. We are currently contributing to the definition and implementation of the Dutch National Research Agenda in the areas of energy, nanophotonics, materials, and life sciences. With the increasing interdisciplinarity of our research program, we are extending our collaborations to partners with expertise in chemistry, biology and engineering. Here we have a highly complementary approach, with AMOLF providing advanced measurements and a quantitative physics approach.

1.5. The development of advanced scientific instrumentation

AMOLF has a strong tradition in designing and developing novel scientific instrumentation, which has been key to the institute's successful past performance. A recent example is the angle-resolved cathodoluminescence imaging system developed by the group of A. Polman. This system combines the spatial resolution of an electron microscope with the spectral resolution of an optical spectrometer, thus forming a unique instrument to probe the optical properties of nanostructures at the nanoscale. This system is now being marketed by DELMIC.



Piezoelectrically actuated mirror mount for cathodoluminescence (CL) developed at AMOLF. This technology is now a commercial CL product offered by DELMIC BV.

Central experimental techniques at AMOLF are at present electron and light microscopy, ultrafast spectroscopy, and optical characterization techniques of photonic matter (also see Chapter 7). In view of the crucial role of instrumentation development in our research, AMOLF strongly values high-level technical support in mechanical engineering, precision manufacturing, electronics engineering, and software engineering. In addition, AMOLF values its state-of-the art laboratories for materials manufacturing. We have a dedicated cleanroom for nanofabrication (AMOLF NanoLab Amsterdam, one of the five nodes of NanoLabNL, the Dutch national facility for nanotechnology research), an additive manufacturing lab for metamaterials and soft robotics, chemistry labs for synthesis of (in)organic photovoltaic materials, and biomolecular labs for research on living matter. All of the labs are shared by multiple research groups and support is provided by small teams of technical specialists.

1.6. Strong connections with industry

Our ambition is to use the fundamental insights obtained in our research to create novel functional materials that are useful in renewable energy, sustainable materials, green ICT, food, and healthcare. To fulfill this mission, we have a strong tradition of collaboration with industrial partners in the Netherlands and abroad. At present, approximately 30% of our research is performed with industrial partners, through contracts, large Industrial Partnership Programs (IPPs), smaller-scale public-private partnership projects, and until 2016 within the national NanoNextNL program.

AMOLF is an attractive collaborator for industrial partners because of the high quality and societal relevance of our research program, and because of our track record of quickly and effectively starting up collaborative projects.

During the last strategic period, we had a successful IPP with Philips Research (2005-2014) on 'Improved solid-state light sources' (led by J. Gómez Rivas). Within this IPP, one of AMOLF's Nanophotonics research groups was located on the Philips High Tech Campus to stimulate knowledge transfer between AMOLF and Philips. This program was followed by the IPP program 'Nanophotonics for solid-state lighting' (A.F. Koenderink). Recently, another large IPP program 'Hybrid soft materials' (G.H. Koenderink) was started with Unilever. AMOLF groups also increasingly participate in smaller public-private partnership projects with companies including FEI, ASML, and Bruker.

In 2014, we established an entirely new private-public institute, the first of its kind in the Netherlands: the Advanced Research Center for Nanolithography (ARCNL). The ARCNL (annual budget 10.0 M€ for 10 years; 100 FTE) is located next to AMOLF and was developed in collaboration with ASML. The AMOLF-led proposal, in partnership with the University of Amsterdam and VU Amsterdam, was selected by ASML in a bid procedure with four competitors. ARCNL was first initiated as a new department of AMOLF and became independent in September 2015. We have an ongoing collaborative research program with ARCNL, that includes a shared research group, led by a tenure-track group leader, and three additional PhD projects that are carried in collaboration between AMOLF and ARCNL research groups. AMOLF also provides the technical and administrative support for ARCNL.

Opening of ARCNL's laboratory building, November 2014, by State Secretary S. Dekker and M.A. van den Brink, President and CTO of ASML.

2. Ambition and strategy

2. Ambition and strategy

2.1. Vision and ambitions

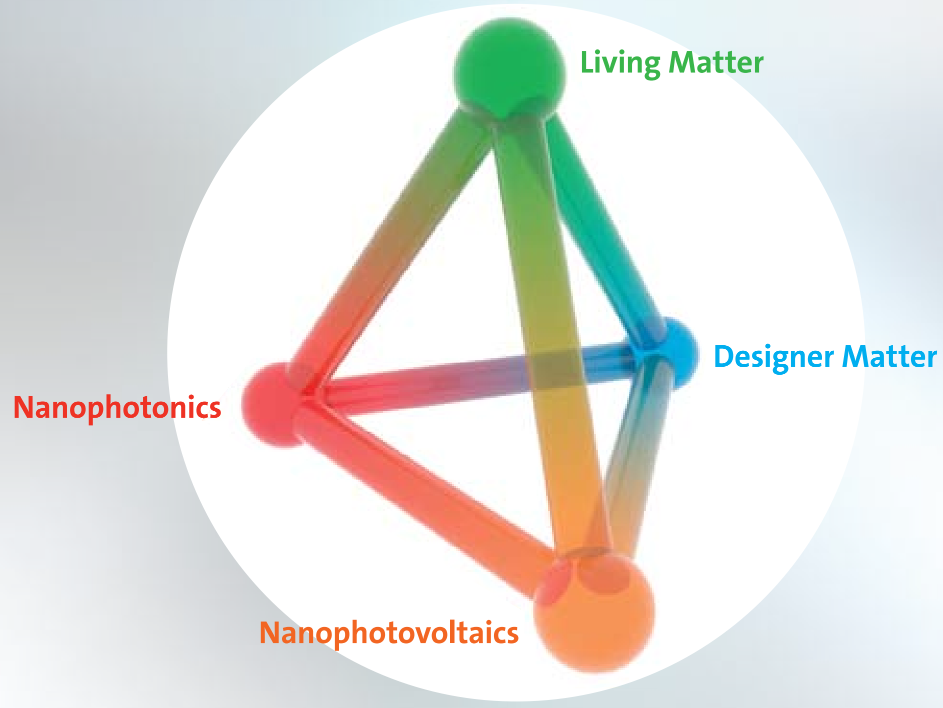
Over the last years, tremendous progress in our understanding of complex forms of matter, both living and non-living, has been made. An intriguing characteristic of complex matter systems is that they possess properties and functionalities that surpass those of the simpler constituent parts, a phenomenon known as emergence. A clear example is the living cell, which shows a range of advanced functionalities that result from complex interactions of the constituent molecules. Recent years have also showed a rapid advance of techniques to fabricate and control ever more complex materials. A striking example is the recent development of highly structured forms of matter, so-called metamaterials, showing unprecedented material properties. For the coming years we foresee exciting opportunities in the understanding of natural and man-made complex matter, which will provide rich inspiration for new material systems with tailored and responsive chemical, biological, mechanical, and optical functions.

Our present research program forms an excellent starting point to play an international leading role in the research of functional complex matter. We already play a key role in the development of optical metamaterials that can perfectly absorb light in solar cells, shape the wave fronts of light sources or exhibit negative refraction, as well as mechanical metamaterials with an unusual, programmable response to external forcing. AMOLF also has a strong position in the physics of living matter, having studied how the functions of cellular systems emerge from the interactions of their constituent parts. Collectively, these characteristics provide a very exciting springboard for creating novel forms of matter and materials.

In the coming strategic period, we will push the physical understanding and quantitative characterization of the emergent properties of complex matter, and leverage this understanding for the design and creation of novel functional materials. We anticipate that the close interactions between AMOLF's research groups studying living and man-made systems will lead to strong cross-fertilization effects. For instance, a basic understanding of the working mechanisms of (multi)cellular systems can inspire the design of active gels, soft robotics, and even hybrid machine-living systems. Conversely, designing new materials such as metamaterials and soft robots and studying their physical properties may provide unexpected insights into the physical mechanisms and operating principles of living matter.

With our research results we aim to contribute to pressing societal issues such as sustainable energy, advanced manufacturing, green ICT, the sustainable production of food, and regenerative medicine. Our research directly links to many of the grand societal challenges within the EU Framework for Research and Innovation (Horizon 2020), especially in relation to 'Health', 'Food Security', and 'Secure, Clean and Efficient Energy'.

In the coming years, we wish to intensify our coordinating role in national and international research programs. Research on complex matter and functional materials offers many opportunities to develop new national, collaborative research programs with university groups, other NWO institutes and the research institutes of the Royal Netherlands Academy of Arts and Sciences (KNAW). We thereby hope to play a pivotal role in connecting the NWO institutes and the Dutch universities, and also in strengthening the interactions between the disciplines of physics, chemistry, biology, and engineering, so that we can contribute to the success of the new NWO domains of Science and Applied Engineering Sciences. We will also pursue new collaborations with industrial partners in the research areas of the Dutch Top Sectors High-Tech Systems & Materials, Chemistry, Energy, and Life Science & Health, and we will continue



our central role in the implementation of the research vision proposed in the Dutch National Research Agenda. At the international level, we aim to build new strategic, formal partnerships with a few selected institutes within Europe (e.g. Max Plank institutes, ICFO) that have a shared interest in the physics of complex matter and advanced materials.

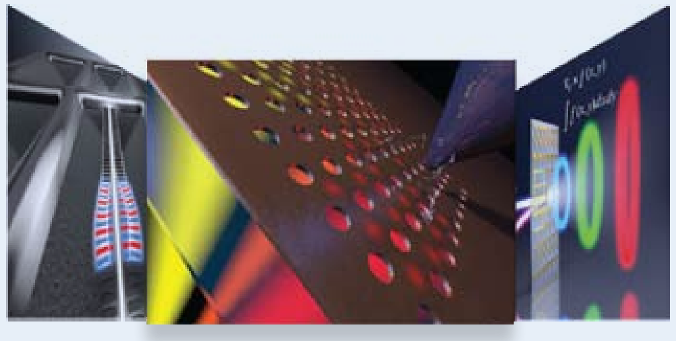
In the coming strategic period, we also have the ambition to increase the proportion of female scientific group leaders to at least 25% in 2022 through several targeted actions. We have a good gender balance among our PhD students and postdocs, of which about 30% are women. However, within our scientific staff, the gender balance is not yet optimal (on January 1, 2017 only 2 out of the 17 scientific group leaders are women (12%), implying that scientific talent is lost along the career trajectory.

2.2. Research program

Our future research program will be implemented in four strongly intertwined research themes: Nanophotonics, Nanophotovoltaics, Living Matter, and the new research theme Designer Matter, which we will expand in the coming strategic period. The four research themes jointly address many conceptually exciting and fundamental questions, such as:

- How do architecture and interactions induce complex and responsive behavior of relatively simple constituents?
- What are the fundamental physical limits on shaping degrees of freedom like light and motion, and can we design materials that function at these limits?
- Can we program the functions of living systems and thus provide new insights in biology and new solutions in healthcare?
- How do we imbue man-made materials with life-like 'hardware' to control motion and 'software' to control sensing and response?

In the following section, we outline we outline our main research plans within each of the four research themes. More detailed descriptions can be found in the subsequent chapters.



Adapted from Science - Koenderink, Alù and Polman (2015)

• Nanophotonics

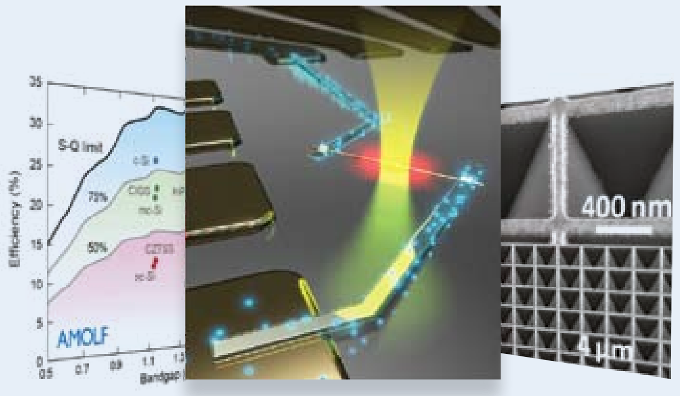
We aim to develop a new field that we coin 'Hybrid Nanophotonics'. The word hybrid refers to the combined control of light and phonons, electrons, spins, and excitons by nanoscale shaping of materials. Hybrid also means the combination of nanophotonic strategies to manage light from molecule to optical circuit to macroscopic optics. An important aspect of the research program will be the exploration of light-matter interactions near their fundamental classical and quantum mechanical limits. At the interface of Nanophotonics and Designer Matter, we will create nonlinear optomechanical metamaterials, enabling the optical actuation of mechanical motion, and, conversely, the mechanical actuation of optical function. The research insights obtained within Nanophotonics will be used in the design of novel photonic materials, with applications in material science, photovoltaics, and engineering, and in the development of advanced microscopy and spectroscopy techniques to study man-made and living matter.

Groups
- A.F. Koenderink
- A. Polman
- E. Verhagen
- E.C. Garnett
- E. Alarcón Lladó
- S.R.K. Rodriguez (starting november 2017)

Collaborating groups
- B. Ehrler
- M.L. van Hecke
- H.J. Bakker

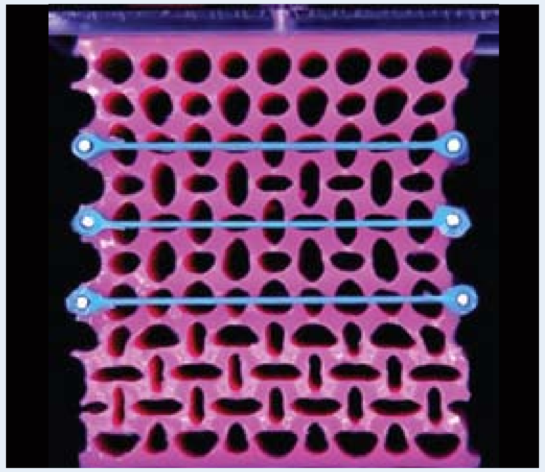
• Nanophotovoltaics

We aim to develop new concepts in photovoltaic conversion that can lead to practical solar cells with unprecedented efficiencies. We will develop optical metasurfaces, interfaces, and subwavelength 3D geometries to enhance the absorption and concentration of light, with the aim of beating the thermodynamic Shockley-Queisser limit for photovoltaic energy conversion in conventional designs. We will design smart functional structures with tailored geometries that act as efficient light antennae to enhance photovoltaic efficiencies. This topic will strongly benefit from the combined expertise of Nanophotovoltaics and Designer Matter. We will also develop novel hybrid and multi-junction solar cells, including hybrid organic/inorganic geometries in which the organic material serves as a singlet-fission agent, with the aim of achieving conversion quantum efficiencies beyond 100%.



Groups
- A. Polman
- E.C. Garnett
- B. Ehrler
- E. Alarcón Lladó

Collaborating groups
- A.F. Koenderink
- W.L. Noorduin
- H.J. Bakker



• Designer Matter

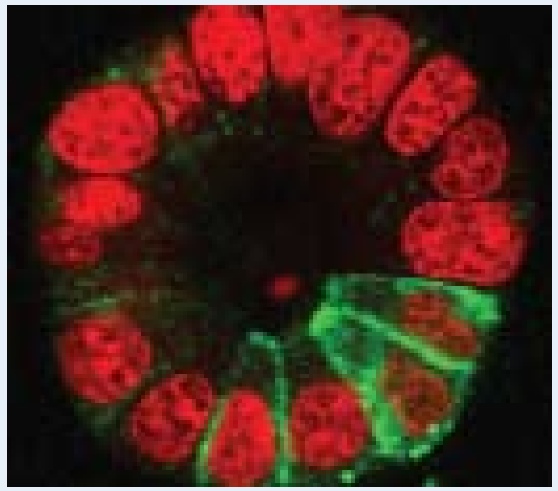
Designer Matter encompasses the design, understanding, and fabrication of materials with functionalities that emerge from the constituents and architecture in a nontrivial manner. Our ultimate goal is to rationally design materials with any functionality imaginable, i.e. solving the 'inverse' problem. Future goals are to design programmable materials whose mechanical or optical properties can be changed on demand, to deepen our understanding of how complex functionalities arise in materials consisting of simple building blocks, and to develop novel theoretical and algorithmic approaches to materials design. We will focus on soft mechanical metamaterials, mineralizing structures, hierarchical self-organized materials like metal-organic frameworks (MOFs), and soft robotic matter with embedded active and sensing elements. An ambitious and exciting new topic will be the design of hybrid machine-living systems in collaboration with the Living Matter theme.

Groups
- M.L. van Hecke
- W.L. Noorduin
- J.T.B. Overvelde
- H.J. Bakker

Collaborating groups
- G.H. Koenderink
- E. Verhagen
- A.F. Koenderink

• Living Matter

Living systems can be viewed as a remarkably rich example of self-organized matter that can autonomously grow, replicate, and reprogram its own properties. Our main goal is to understand how the unique functions of cellular and multicellular systems emerge from the organization and interactions of the constituent parts. In the coming strategic period we will focus on two main research lines. First, we aim to reconstruct cellular functions from isolated molecular components to generate autonomous synthetic cells. Meeting this challenge will fundamentally deepen our understanding of what life is, open new avenues of engineering life at the cellular scale, and provide new concepts to design novel smart materials. Second, we aim to elucidate the physical principles by which cells autonomously self-organize into multicellular tissues and organs using data-rich live-cell imaging. By going to the tissue scale and working with mammalian model systems, we can directly connect our research to applications in regenerative medicine and organ-on-chip models for human disease.



Groups
- G.H. Koenderink
- S.J. Tans
- P.R. ten Wolde
- B.M. Mulder
- T.S. Shimizu
- J.S. van Zon

Collaborating groups
- M.L. van Hecke
- J.T.B. Overvelde
- H.J. Bakker

Ambition and strategy

2.3. Specific strategic actions

The realization of our scientific and strategic ambitions will be advanced by several additional strategic actions that are outlined in the following section.

2.3.1. Innovation of scientific instrumentation

We plan several actions to keep our infrastructure state-of-the art:
- We will modernize our cleanroom (AMOLF NanoLab Amsterdam) with several deposition tools to respond to the increasing demands in material diversity, high-throughput, and improved nano-patterning accuracy. This is essential to our plans for hybrid nanophotonics and the integration of nanophotonics from molecules to optical circuits. The Designer Matter and Living Matter themes will also benefit from this investment. The investments are also of regional and national importance, as the AMOLF NanoLab is extensively used for research and education by external partners from academia and industry. Moreover, a state-of-the-art cleanroom can attract novel academic and industrial partners to the Amsterdam Science Park.
- We will develop a picosecond time-resolved cathodoluminescence microscope to spectroscopically probe materials and nanophotonic devices at the nanoscale.
- We will invest in a new fast computer cluster that will be shared by the Designer Matter and Living Matter themes for synthetic cell scale simulations and design algorithms for programmable materials. An in-house computer cluster enables us to rapidly and efficiently develop new algorithms and avoid turn-around delays.
- We will invest in novel microscopy techniques for quantitative time-lapse imaging of developing multicellular organisms and mammalian organoids.

2.3.2. Introducing an advanced data management policy

AMOLF is committed to a high standard of research integrity and actively supports the NWO ambition to make high-quality data available on Open Access terms. The present research integrity standards are already high, due to a strong formal and informal network of supervision in collaborative small teams. The responsibility for organizing data management (within a secured storage environment) lies primarily with the research groups, which accommodates the fact that AMOLF is characterized by a large pluriformity of projects and state-of-the-art, often homebuilt setups.

We are currently implementing a new, ambitious, data management policy for the coming five-year period that gives researchers new instruments for data stewardship responsibilities, and moves towards making publication-quality data Open Access. This policy will include:
- Per group data management plans to formalize stewardship practices;
- Improved and partially digitized lab notebooks;
- Standardization of data formats and inclusion of FAIR practices for metadata and version control in our research flow and in-house acquisition software;
- Training of researchers in a mandatory course to work with these tools;
- A transparent, formalized system to store the entire research record associated with each paper that we publish in a sealed ‘data replication package’.

These steps form the basis for ultimately implementing Open Access to data replication packages underlying papers as well as other high-quality datasets. This ambition will require significant investment in a secure storage and internet portal environment, and efforts to balance Open Access against the interest of IP in, for instance, public-private partnership projects. After developing best practices for data management and storage, we will share these insights with academic research groups and other research institutes.

2.3.3. Improving the gender balance among our scientific staff

AMOLF promotes an inclusive culture and a family-friendly working environment. Institute-wide regulations are in place for maternity and parental leave, for working part-time, and for working flexible hours or from home. Employees also have the opportunity to buy additional leave days. For tenure-track group leaders, the timing of the tenure decision, normally after four years, can be postponed to compensate for maternity and parental leave. AMOLF has a good gender balance among the PhD students and postdocs, of which 30% are women, a fraction that roughly corresponds to the fraction of female students taking up physical or technical studies at Dutch universities (40% for physical studies and 23% for technical studies in 2015). Unfortunately, a high percentage of these women leave academia at each stage of the academic career, which means that talent is being lost. In our own scientific staff, only 2 out of 17 of the group leaders are women as of January 1, 2017 (12%). Our ambition is to increase the proportion of female scientific group leaders to 25% in 2022. To realize this ambition, around 50% of the new group leaders that we will hire in the coming years will be women. In view of the average turn-over of group leaders at AMOLF, we expect that we will hire circa 5 new group leaders until 2022, of which 2-3 will be women.

Ambition and strategy

The realization of this ambition is further supported by the following actions:

- We will stimulate young female scientists to pursue a career in science after obtaining their PhD or finishing their postdoc term at AMOLF. We will therefore set up mentoring programs for female scientists.
- We will provide senior female role models, e.g. by inviting a representative number of female speakers for our scientific colloquia and by taking care that ~50% of speakers are women in the summer schools we will organize following the establishment of strategic partnerships with other European institutes.
- We intend to increase the proportion of female scientific group leaders to 25% in 2022. To this purpose, we will actively scout talented female researchers for tenure-track and other senior scientific positions that will become available in the coming years. Female candidates will be invited beforehand to give seminars at the institute, and will be actively encouraged to apply on an individual basis. Moreover, we will participate in the NWO Women In Science Excel (WISE) program initiated in 2016. This program provides talented female scientists an opportunity to develop or expand their own research group at one of the NWO research institutes. We hope to attract one or two talented female tenure-track group leaders through the WISE program. When hiring group leaders, we are sometimes hampered in attracting the preferred candidate due to the two-body problem, which occurs when both partners pursue a career in academia. Although we provide the best assistance we can, AMOLF does not have the capacity to solve this problem alone and joint efforts from NWO-I, possibly together with the KNAW and Dutch universities, are needed.

Personnel category	Female (%)	Target figures (%)
Management Team	40% (2 out of 5)	40%
Group leaders	12% (2 out of 17)	25%
Postdocs	30% (10 out of 33)	33%
PhD students	30% (19 out of 63)	33%

(January 1, 2017)

2.3.4. Enhancing national collaborations with university groups and other institutes

AMOLF has close links with university groups and other institutes, in the form of the exchange of junior and senior scientists, teaching in academic curricula, and collaborative research programs. In the coming strategic period we will further strengthen our connections to Dutch academia and extend these towards other disciplines (especially chemistry, biology, and engineering).

Strengthening the collaboration in research with university groups

We aim to intensify our collaborations with Dutch university groups by applying for joint funding within the context of the new domains of NWO, the Top Sectors, and the Dutch National Research Agenda:

- The Nanophotonics research theme is naturally aligned for partnerships with Delft University of Technology (quantum information), Eindhoven University of Technology (Photonic Integration Institute) and Utrecht University (wavefront shaping).
- Within the Nanophotovoltaics theme, AMOLF leads the national PV collaboration with Delft University of Technology, Eindhoven University of Technology, Utrecht University, University of Groningen, Radboud University, University of Amsterdam, VU Amsterdam, ECN and TNO aiming to coordinate research at a national scale. As a first step, we will apply for funds for a national SOLARLab investment from the NWO call for the National Roadmap Large-Scale Research Infrastructure (June 2017). In Amsterdam, we initiated a research initiative together with the University of Amsterdam, VU Amsterdam, and ECN, which focuses on the harvesting of solar energy (‘Solardam’).
- The Living Matter theme is a key partner in a large 10-year research program on synthetic cells (BaSyc Zwaartekracht consortium, 2017-2027) that is led by the Delft University of Technology and also includes the VU Amsterdam, Wageningen University & Research, Radboud University, and the University of Groningen. Together with VU Amsterdam, Utrecht University and Erasmus MC, we have spearheaded a novel research direction to uncover the role of randomness in animal behavior (FOM program, 2015-2020). Given our increasing focus on multicellular systems and the connection to health, we are also developing new connections with developmental biology groups at Utrecht University and VU Amsterdam.
- Within the Designer Matter theme we aim to complement our physics-based approach with engineering and chemistry. We are developing new connections with engineering approaches at Delft University of Technology in the areas of micromechanics, design, and metal-organic frameworks, and with chemistry groups at the ICMS at Eindhoven University of Technology and Radboud University. In addition, we have started to intensify our ties with soft matter efforts at Utrecht University, Leiden University and the University of Amsterdam, through the joint appointment of M.L. van Hecke and the guest position of M. Dijkstra.

Strengthening research collaborations with other institutes

We will intensify our contacts with the other NWO institutes, the KNAW institutes, and the new NWO Advanced Research Centers ARCNL and ARC-CBBC:

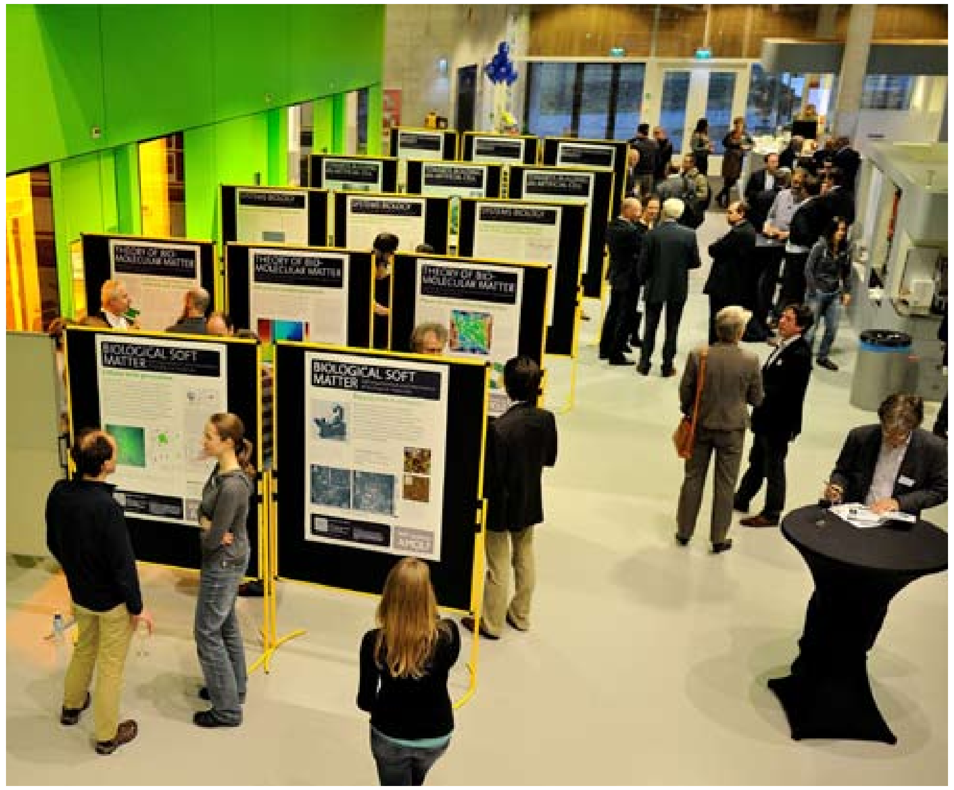
- Within the Nanophotovoltaics research theme, AMOLF closely collaborates with ECN and TNO (see above). With NWO institute DIFFER we have a joint research program on solar fuels. We aim to extend this collaboration with a joint program on the splitting of water using smart proton-conducting membranes.
- Within the Living Matter theme, we aim to expand our contacts with the Hubrecht Institute of the KNAW. We have recently established a new collaboration to study the physics of organ development and disease, using organoid systems. This pairing optimally combines our expertise in advanced quantitative microscopy and mathematical modeling with the biology know-how and single-cell RNA sequencing techniques of the Hubrecht Institute. In the coming period we aim to intensity this strategic collaboration by applying for joint funding.
- The Designer Matter theme will explore collaboration opportunities with the newly established national research center for chemical building blocks, the ARC-CBBC.
- With regard to the development of advanced instrumentation we will strengthen our links with the NWO institutes Nikhef, SRON and ARCNL. We are already collaborating with Nikhef on the detection of electrons and ions using Medipix detectors. We will continue this collaboration in the framework of electron microscopy. Finally, we will explore opportunities for collaboration on sensitive (infrared) light detection, also involving SRON.
- We will stimulate the scientific collaboration of AMOLF and ARCNL within an ongoing

joint research program that includes a joint research group and three additional PhD projects that are carried out in close collaboration between AMOLF and ARCNL research groups.

Establishing closer personal ties via dual appointments and guest positions for researchers
We envision two additional actions to forge closer ties between AMOLF and research groups at Dutch universities and other institutes:

- We will increase the number of joint appointments of AMOLF scientists at Dutch universities. Currently most tenured group leaders of AMOLF are appointed at various Dutch universities (VU Amsterdam, University of Amsterdam, Utrecht University, Leiden University, Wageningen University & Research, Delft University of Technology, and Eindhoven University of Technology). Most of these appointments are in the form of 0% contracts, with the exception of M.L. van Hecke (50%) and B.M. Mulder (20%), whose dual appointments lead to fruitful collaborations with the Physics Department of Leiden University and the Laboratory of Cell Biology at Wageningen University & Research.
- We will offer part-time guest positions at AMOLF to university group leaders. We recently started this program with two guest positions, filled by W.C. Sinke (Professor of Sustainable Energy, University of Amsterdam and ECN), and by M. Dijkstra (Professor of Soft Condensed Matter, Debye Institute, Utrecht University). In the coming years, we aim to increase the number of part-time positions, coupled to junior positions co-supervised by AMOLF and guest staff members.

Poster session during the Industrial Affiliates Day at AMOLF.



2.3.5. Continue to take a leading role in the Dutch National Research Agenda

The Dutch National Research Agenda was initiated in 2016 and defines key cross-sectoral research themes for the coming years. We believe the Agenda offers an exciting opportunity to launch new collaborative research initiatives with universities, research institutes (in particular TNO, M2i, and ECN), and universities of applied sciences. Several research themes defined in the Agenda are connected to functional complex matter and smart material systems. We will continue to take a coordinating and connecting role in the development and organization of the Agenda thematic route on material research (route 'Materials - Made in Holland'). We will also continue our participation in the thematic routes in the areas of life sciences and energy: routes 'Origins of life' with our biophysical research, 'Building blocks of matter and fundaments of space and time' with our research on nanophotonics and emergence in complex matter, and the route 'Energy Transition' with our research on nanophotovoltaics.

2.3.6. Broadening the scope of collaboration with industrial partners

Our ambition is that the fundamental insights that we gain in our research support the Dutch high-tech industry and are translated to solutions for societal challenges in renewable energy and improved healthcare. To achieve this goal, we realize approximately 30% of our research in close partnership with industry. In our experience, this 70:30 ratio between fundamental research and research in public-private partnerships forms an optimum balance between curiosity-driven research and valorization. The main actions in the coming strategic period are the following:

- We aim to develop new types of public-private partnerships with smaller companies to diversify our portfolio of public-private collaborations. For instance, NWO Topsector funds as well as new financial instruments of the NWO domains Science and Applied and Engineering Sciences enable small-scale projects with SMEs, who pay 10-25% of the costs. We also aim to start collaborations with TNO institutes such as the Optics group of TNO Delft, which will help us to contribute to space research, metrology, and the semiconductor industry.
- We will continue to encourage our junior and senior researchers to explore the possibility of combining their research results with potential industrial applications. To stimulate an application outlook, we financially reward the submission of patentable invention disclosures, and we organize an Industrial Affiliates day every two years. From 2016 to 2021, AMOLF will participate together with the University of Amsterdam, VU Amsterdam, Amsterdam University of Applied Sciences, and Nikhef in the IXAnext 'Talent for Innovation' program, which was set up to facilitate and initiate innovative public-private collaborative research in the Amsterdam region, with a focused program for physics research. This initiative was subsidized by the City of Amsterdam with 7.2 M€.

2.3.7. Enhancing international collaborations and partnerships

We have an extensive portfolio of international research collaborations that were initiated on the basis of specific scientific expertise and collaboration. In addition, we participate in a small number of strategic partnerships that connect us to international consortia of groups, e.g., through MURIs (Caltech, Stanford, Austin), the Biophysics Circle with annual meetings (with EMBL, MPI PCS Dresden), the European Scientific Coordination Network on 'Evolution, Regulation and Signaling' (with groups in France, Denmark, Sweden, Germany), and FET Open (program with leading optomechanics groups in Europe).

In the coming period, we aim to build new strategic, formal partnerships with a few selected institutes within Europe with whom we share an interest in studying the physics of complex matter and advanced materials (see also Section 1.3). We will explore this option with the Max Plank institutes in Mainz and Dresden, EMBL in Heidelberg, Institut Curie in Paris, and ICFO in Barcelona. These partnerships will take the form of collaborative research projects, training and exchange of PhD students for 3-6 month periods, annual joint summer schools, and joint programs for postdocs that can take the form of a competition for prestigious fellowships, e.g. AMOLF - Max Planck fellowships, in which the laureates work for one year at AMOLF and one year at the partner institute. We envision that partnering with other European institutes will create a network for joint strategic leverage in the European science policy and funding landscape. Realization of this ambition would be strongly promoted by professional support from the new NWO organization.

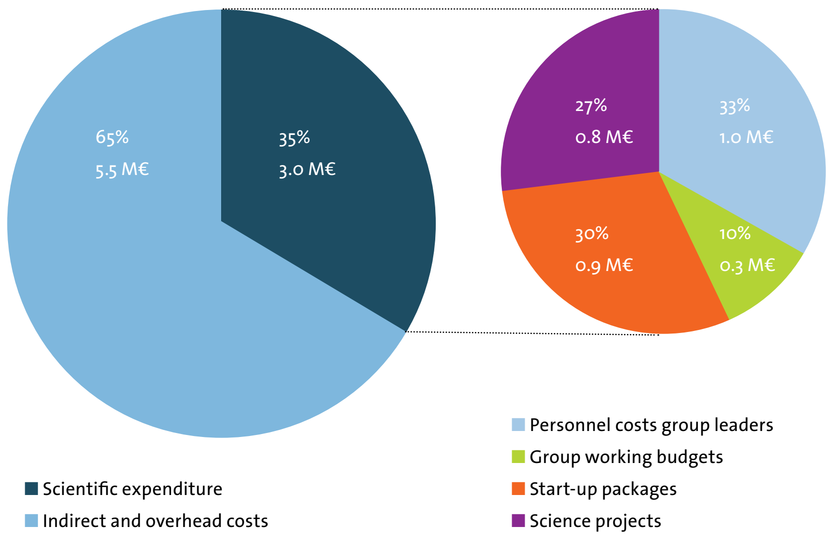
2.4. Financial paragraph

Current financial situation

From 2017 onwards, AMOLF will receive annual funding from NWO totaling 9.3 M€, which comprises an annual ‘mission budget’ of 8.5 M€ as well as funding for AMOLF's strategic programs (760 k€ in 2017). The mission budget pays for most of the indirect and overhead costs, i.e. the technical and administrative support, the acquisition and maintenance of the technical and scientific infrastructure, and the exploitation and maintenance of the building. In 2017, about one third of the mission budget (3.0 M€) is used to cover direct research costs, including the salaries of scientific group leaders, group working budgets (20 k€ per group per year), and the start-up packages of new tenure-track group leaders, illustrated by the Figure to the right. The scientific expenditure of the mission budget covers only a small part of the direct costs of our research activities: nearly all research projects and approximately 90% of the junior scientists (PhD students and postdocs) are paid from grants obtained in competition, amounting to an annual total of 7.2 M€.

The high turnover of research groups at AMOLF, and the resulting frequent granting of start-up packages to new group leaders, puts considerable pressure on our mission budget. However, this turnover provides AMOLF with the flexibility to start new research directions. We believe it is important to supply new group leaders with an excellent start-up package to make a good start. A typical start-up package includes 200-300 k€ for investments in equipment and two junior scientist positions (PhD salaries, and material and cleanroom budgets, amounting to a total of ~600 k€). The total costs of a tenure-track position for five years (salary of around 450 k€, investments, junior positions, and material budgets) thus amounts to roughly 1.3 M€. These costs constitute a significant portion of the scientific expenditure of the mission budget (see Figure, amounting to 900 k€ in 2017).

Total expenditure in mission budget **Research expenditure in mission budget**



AMOLF total prognosed expenditure in the mission budget in 2017 (left) and the specification of the prognosed scientific expenditure of 3.0 M€ in 2017 (right).

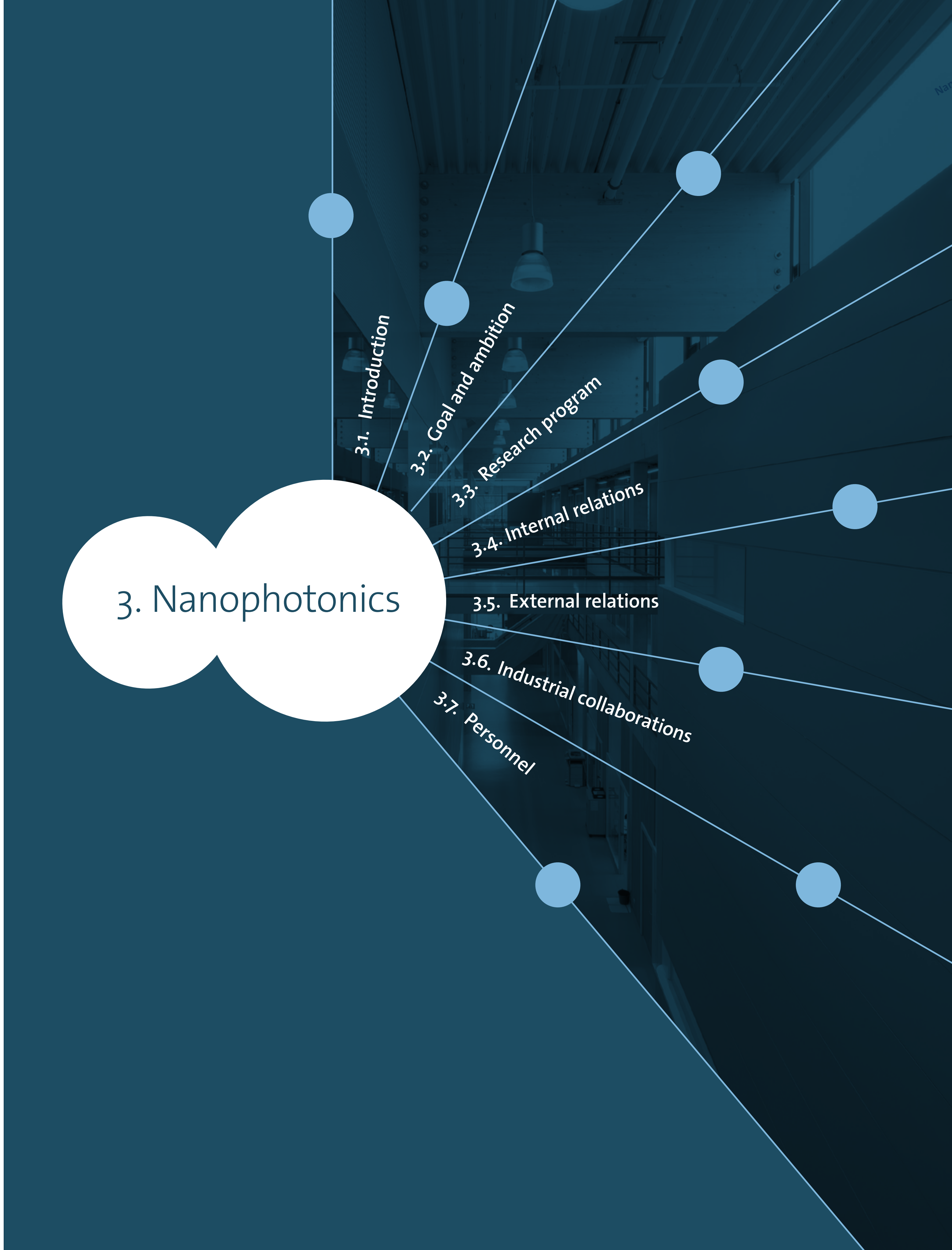
Request to support strategic actions

Our ambitions for the coming strategic period require several strategic actions whose costs exceed the present AMOLF mission budget. We therefore ask NWO to raise the mission budget of AMOLF by 740 k€ per year. Specifically, our strategic actions give rise to the following needs:

- We have the ambition to increase the percentage of female scientific staff to 25% in 2022. To realize this ambition, circa 50% of the new group leaders that we will hire in the coming years will be women. In view of the average turn-over of group leaders at AMOLF, we expect that we will hire around 5 new group leaders until 2022, of which 2-3 will be women. We expect these new group leaders to partly come through the NWO WISE program, but we anticipate that we will also receive applications from excellent female candidates who do not directly match with an open position for a tenure-track group leader. We believe it is important to have the flexibility to hire excellent female tenure-track group leaders before a vacancy opens, but this implies additional costs. We request an increase of our mission budget to cover these additional costs (of a group leader salary and group working budget), which we estimate to be 130 k€ per year.
- AMOLF will implement an Open Access and Open Data policy with effect from 2017. A key aspect of this policy is that all research data should be made accessible to the outside world. The implementation of this policy involves an institutional effort in terms of personnel and data storage capacity, the costs of which are not covered by the present mission budget. We estimate that the additional costs of the new data management policy will amount to 100 k€ per year. Best practices for data management developed at AMOLF will be shared with other academic groups and research institutes in the Netherlands.
- To develop strategic alliances with universities and other research institutes, we will organize workshops and summer schools, develop exchange programs for students and postdocs, and provide guest positions at AMOLF with a research project that includes a junior

scientist position. We aim to realize two permanent guest positions, both at 20% fte and complemented by one junior position (PhD student or postdoc), and an exchange program for PhD students with our international partner institutes. We also wish to establish joint postdoc positions with other European institutes such as the Max Planck society in the form of prestigious fellowships. These initiatives will amount to a total additional investment from our mission budget of 210 k€ per year.

- AMOLF invests 300 k€ mission budget per year in the maintenance and renewal of the institute's basic support infrastructure (ICT, mechanical workshop, electronics engineering, etc.). Scientific infrastructure is mainly funded by external funding, obtained in competition, and within the investment budgets of tenure-track start-up packages. However, external infrastructure funds do not generally cover the maintenance and renewal of existing scientific equipment. This specifically affects the AMOLF NanoLab, the Amsterdam node in the Dutch national facility for nanotechnology NanoLabNL. It is essential to keep our high-maintenance equipment for nanofabrication state-of-the art, for the benefit of the AMOLF research groups and to fulfill our regional role in providing advanced nanofabrication and characterization support for ARCNL, the University of Amsterdam and VU University Amsterdam, for example. Until 2016, AMOLF annually received an additional 280 k€ of investment funds from NWO to cover these aforementioned costs. However from 2017 onwards, these funds are no longer available. We therefore request an increase to the mission budget of 300 k€ per year to provide sufficient financial means for the maintenance and the depreciation of the scientific infrastructure, especially of the NanoLab.



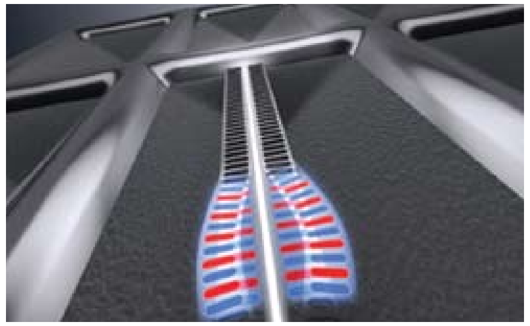
3. Nanophotonics

3.1. Introduction

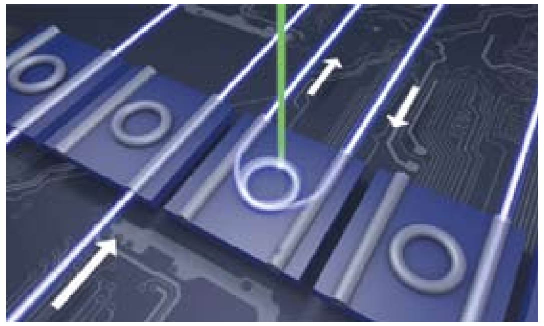
Nanophotonics is the science of controlling light generation, manipulation, transport, and detection on ultrasmall length scales. This control is obtained by sculpting materials with nanoscale precision into structures that confine, refract, reflect, diffract, emit, absorb, and amplify light. AMOLF's Center for Nanophotonics plays a key role in this field as one of the largest concentrations of nanophotonics research at the national and international level. Over the past decade, we have developed dielectric resonators that store light for very long periods of time, plasmonic systems for ultimate confinement, and metamaterials and metasurfaces to control the flow of light beyond the limits of conventional optical materials. This toolbox offers many opportunities to process the energy and information content of light, encoded in polarization, frequency, wavefront amplitude, and phase. This will not only allow us to control light itself, but also achieve strong and selective interaction of light with other degrees of freedom like phonons, electrons, spins, and excitons.

Beyond the universal human fascination with light, its control is crucial for dealing with several modern societal challenges. Nanophotonics plays a key role in quantum information and green ICT, promising to remove dramatic bottlenecks in speed and power consumption of information technology. Solid-state lighting has already replaced conventional lamps, and will lead to completely new forms of intelligent lighting. Furthermore, managing light is crucial for converting sunlight into electricity and fuel. Finally, light is a physicist's most precise metrology and spectroscopy tool for measuring length, time, motion, and the energetic structure of matter. Nanophotonics addresses these applications over a hierarchy of length scales, starting at molecular matter and ranging up to integrated macroscopic devices.

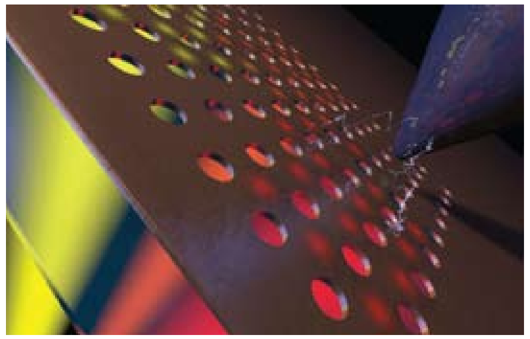
Our vision for nanophotonics: future nanophotonics is 'hybrid', integrating dielectric resonators, plasmonics and metamaterials, simultaneously controlling light, motion, electronic transitions, spins, charge and current (Figure adapted from Science, 2015).



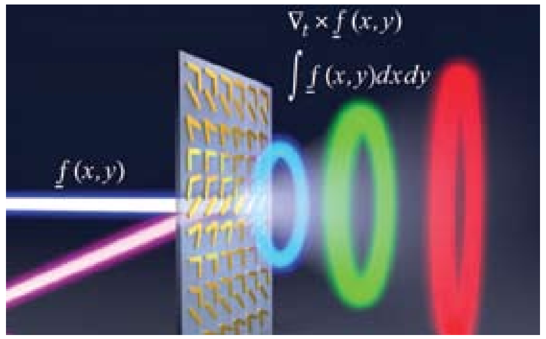
Optomechanical resonator.



Vision of non-reciprocal optical integrated circuit enabling logic functions for densely integrated optical computing, enabled by opto-mechanics.



Plasmonic-dielectric resonator design, coupled to an emitter.



Optical metasurface perform complex operations on arbitrary incident wavefronts. Gain and nonlinearity ensure function well beyond the current state of the art.

3.2. Goal and ambition

Based on the exquisite control that we have achieved over all vector components of light in space and time, we aim for a new frontier that we have coined 'hybrid nanophotonics'. Hybrid means that we will simultaneously control light and the degrees of freedom with which light interacts, thus achieving combined and unprecedented levels of control of light and phonons, electrons, spins, and excitons. At the same time, we will combine the strengths of various platforms we have developed to control light at the nanoscale, like plasmonics, dielectric resonators, and metamaterials, to realize hybrid nanophotonic architectures that manage light on length scales from molecule to circuit to the macroscopic world. Hybrid nanophotonics will thereby open new vistas on applications in solid-state lighting, photovoltaics, and the optical internet.

Typical optical functions like reshaping optical signals, absorbing light efficiently over broad bandwidths, or shaping fluorescent and thermal emission, are subject to performance limits set by linearity, reciprocity, and passivity of materials, causality and sometimes even by thermodynamics. The development of new smart materials with unprecedented nanophotonic functions therefore requires the exploration of these fundamental performance limits, i.e. discovering how to operate near these limits, and eventually developing strategies to bypass these limits.

3.3. Research program

The research theme is divided into 4 interrelated subthemes that are strongly connected to the other research themes of AMOLF. Within each subtheme, multiple groups closely collaborate, including groups from the Nanophotovoltaics program. The close links between the groups working in the theme and industrial partners ensure efficient knowledge transfer and rapid application of the insights.

• Subtheme 1: Hybrid nanophotonic matter for emitters, excitons, and spins

• A.F. Koenderink
• E. Verhagen
• E.C. Garnett
• A. Polman
• E. Alarcón Lladó

A major goal in many disciplines is the efficient addressing of matter with light, at the level of single photons, emitters, excitons and spins. Nanophotonics has developed distinct strategies for this purpose, usually regarded in isolation: dielectric cavities store photons for a very long time period (ultrahigh Q) in micron-sized volumes, juxtaposed to plasmonics that uses metals to confine light to volumes down to $(\lambda/100)^3$, for just a few optical cycles. We will pursue 'hybrid nanophotonics': the integration of distinct strategies with unique benefits. For instance, plasmonic antennas cleverly placed in dielectric resonators can give plasmonic confinement with the Q of dielectric resonances. This approach bridges length scales from molecule to photonic integrated circuits, and promises an independent control of the strength of the light-matter interaction and the bandwidth over which the interaction occurs. We will also start a new research line (starting fall 2017) exploring cavity-exciton systems to control gain and nonlinearities for functionalities in light-matter manipulation well beyond the state of the art. Application areas range from 'arbitrary quality factor' cavity QED, to THz bandwidth structures for ultrafast optical signal processing, to sensing, and to field-enhanced Raman and ultrafast infrared molecular spectroscopies. Hybrid nanophotonics also plays a crucial role in the simultaneous management of light and charge in structures with plasmonic and dielectric resonances in solid-state lighting and in nanophotovoltaic structures.

Subtheme 2: Coupling light and motion in optomechanical metamaterials

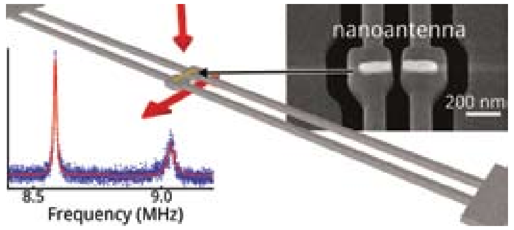
E. Verhagen • A.F. Koenderink • M.L. van Hecke •

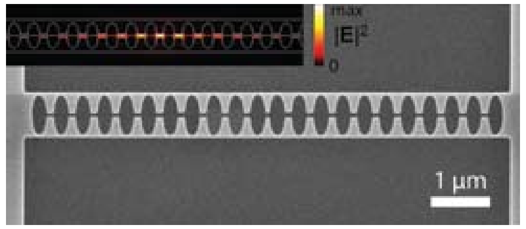
The radiation pressure of light in nanoscale resonators can be so strong that it drives mechanical vibrations of MHz-GHz acoustic resonators. We will develop optomechanical resonators with unprecedented photon-phonon coupling strengths. This provides a route to control the quantum state of macroscopic mechanical resonators, and enables ultraprecise mass and displacement sensors. Further, two-way coupling of light and sound will provide very strong nonlinearity and even non-reciprocity, and thereby disruptive nonlinear devices, isolators, and circulators for sound and light that can be integrated as on-chip elements. Beyond single units, we target opto-mechanical metamaterials: extended arrays of coupled opto-mechanical unit cells. These metamaterials promise fundamental breakthroughs, like topological insulator physics for sound and light. We will also generalize opto-mechanics to use the vector nature and phase-structure of confined fields. This will generate light-helicity specific forces on chiral matter, and couple orbital angular momentum of light to torque.

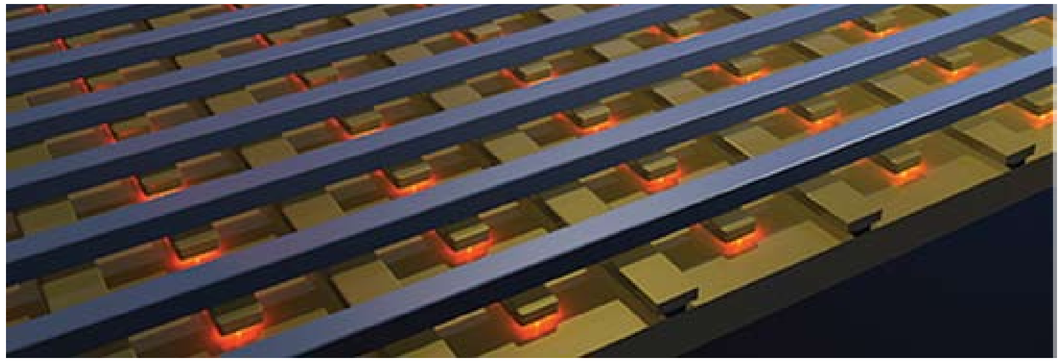
Subtheme 3: Fundamental limits on shaping light, and its energy, noise and information content

E. Verhagen • E.C. Garnett • A.F. Koenderink • A. Polman •

Optical functions like broadband near-100% absorption, spatiotemporal reshaping of optical signals by circuit elements or metasurfaces, shaping thermal emission, or tailoring chiroptical interactions are constrained by material linearity, passivity, and reciprocity, and at a fundamental level by causality and thermodynamics. The metasurface field brought to optics the notion of inverse-problem based design: for any function a prescribed nanophotonic geometry that performs it can be found. Often this prescription falls outside of fundamental constraints, identifies fundamental bounds for optimal performance, and points out how to access hitherto unimaginable functions by nonlinearity, gain, or non-reciprocity. We will explore what this viewpoint means for optimal designs of scatterers, metasurfaces and resonators for nanophotovoltaics, wavefront re-shaping for lighting, microscopy and optical signal processing, radiative cooling and thermal emission, and far-field and near-field chiral responses. By including gain and strong nonlinearities, we will bypass fundamental limitations to obtain 100% efficient wavefront control, and non-reciprocity for one-way optical devices. The new research line that we start in fall 2017 will use cavity-polariton physics to harness the propagation of energy, noise and information in networks of strongly interacting photons.







Top left: optomechanical resonator based on a plasmonic antenna on Si_3N_4 beams.

Top right: optomechanical resonator with exceptionally high optomechanical coupling constant.

Bottom: artist impression of an optomechanical metamaterial with a 2D array of resonators.

Subtheme 4: Advanced instrumentation and materials

• A. Polman • A.F. Koenderink • B. Ehrler • E.C. Garnett • E. Alarcón Lladó • H.J. Bakker

AMOLF has a strong track record in developing near-field microscopy, nanomanipulation, ultrafast spectroscopy, cathodoluminescence (i.e., nanoscopy using electron beam excitation) and momentum-space imaging, which accesses radiation patterns of single nano-objects. In the coming years we aim to develop picosecond cathodoluminescence microscopy. Through optical triggering of ultrashort electron pulses, we will realize ultrafast (optical) pump (electron) probe cathodoluminescence microscopy, gain local insight in carrier dynamics in novel materials, and probe single quantum emitter physics in resonant photonic structures with nanometer resolution. Further, we will develop interferometric momentum spectroscopy. Fully mapping polarization and phase in Fourier space applied to extended nanophotonic structures will reveal the physics of topological photonic protection, and for single nanostructures will give full multipole-decomposition insight into metasurfaces and chiral scatterers, and into spin and orbital angular momentum control of light.

New research line

Starting in the fall of 2017, the Nanophotonics theme will expand with a new tenure-track group leader, S.R.K. Rodriguez, who will develop cavity-exciton polaritons as a hybrid nanophotonic platform to realize complex networks in which photons strongly interact. Microcavity array exciton-polariton systems form an ideal testbed to study noisy, nonlinear and dissipative processes, as they provide exquisite control over the strength of nonlinearity, coupling constants and loss, and allow for the measurement of transport phenomena over a time axis spanning 15 orders of magnitude. This research line will combine mechanically tunable cavity arrays with nonlinearities in organic materials, perovskites and 2D semiconductors, thereby bridging optomechanics, materials developments in the Nanophotovoltaics theme. Conceptually, this topic is closely related to the study of signal transport, collective emergent phenomena and nonreciprocal transport in complex, noisy networks in the Living Matter theme (P.R. ten Wolde and J.S. van Zon), and Designer Matter theme (J.T.B. Overvelde and M.L. van Hecke).

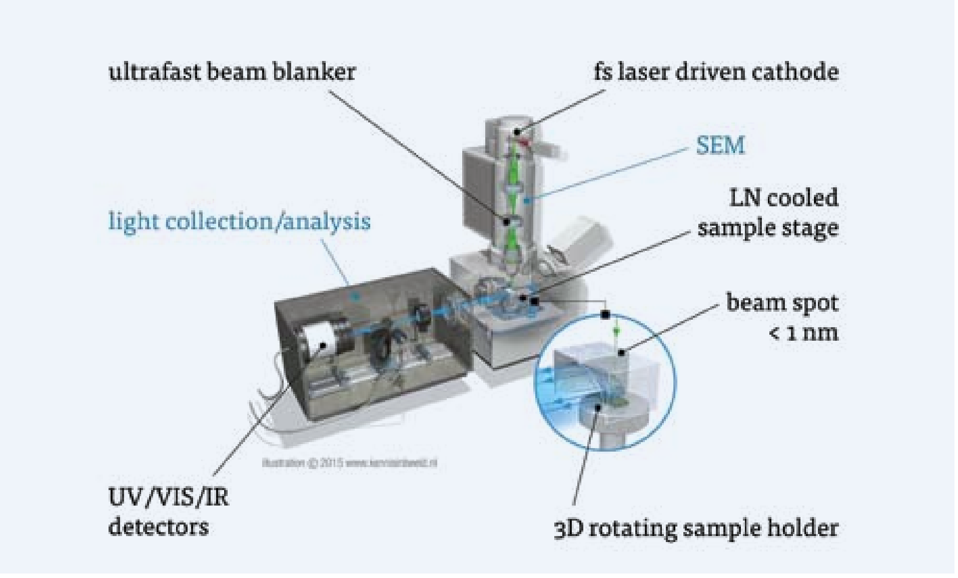
3.4. Internal relations

The research theme Nanophotonics is strongly connected to Nanophotovoltaics and with it forms the Center for Nanophotonics. There exist a strong synergy with this theme, in research questions, instrumentation, and in training. Examples are the joint interest in the fundamental boundaries on scattering and absorption, the photophysics of single quantum dots and molecular emitters and their interaction with nanophotonic structures, and the development of scatterometry and superresolution imaging of the photonic parameters of nanostructures. The bond is strengthened at the junior scientist level by joint weekly poster sessions and seminars that serve both as training and as a seed for new collaborations. The Designer Matter theme provides many exciting intersections with optics and nanofabrication. These include the design of 3D optical structures, the optical actuation of motion, the mechanical actuation of optical function, and the development of strongly nonlinear optomechanical metamaterials with two-way coupling between light and mechanics. With the Living Matter theme, a main connecting topic is the development of novel imaging techniques for super-resolution and 3D imaging of photonic figures of merit, ultrafast and fluorescence spectroscopies, and the development of nano/microfabrication by for instance, dip-pen lithography.

3.5. External relations

National

Nanophotonics is a key research direction for many scientific, societal, and technological challenges. The research program fits well with the targets of the FOM 'Focusnotities' on nanoscience and the recent NWO report 'Dutch Materials', and directly contributes to important applied and fundamental challenges defined in the Dutch National Research Agenda. Indeed, nanophotonics is strongly represented in several Agenda routes.



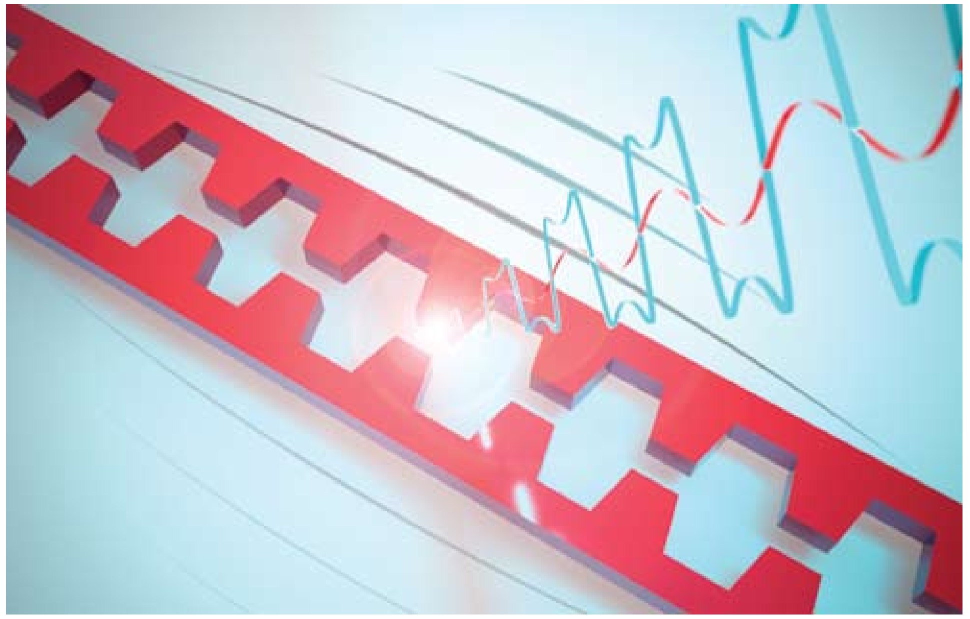
Advanced Instrumentation.

Diagram of the picosecond cathodoluminescence microscope currently being developed at AMOLF. A commercial SEM is operated with a modified, fs laser driven cathode to provide electron pulses. Light emitted by the sample is collected by a parabolic mirror. The set up will allow real space, Fourier space, spectral and temporally resolved cathodo-luminescence imaging.

The Center for Nanophotonics plays a leading role in initiating national research activities that engage Dutch universities and high-tech industries, as evident from NanoNextNL (overall leadership, Beyond Moore theme), FOM program leadership and participation (Plasmonics (2008-2014), Nanophotovoltaics (2009-2015), and Nanoscale Quantum Optics (2011-2015)), and IPP programs. The research theme Nanophotonics has strong collaborative ties with Eindhoven University of Technology (integrated photonics, III-V quantum optics), Leiden University (plasmonics and quantum optics), the University of Amsterdam (quantum information, silicon photonics, photovoltaics), Delft University of Technology (nanomechanics, spintronics), and Utrecht University (active photonics). Partnerships further take shape through appointments, and teaching in master curricula in Nanophotonics (A.F. Koenderink and E. Verhagen) and Photovoltaics (A. Polman, B. Ehrler, E.C. Garnett, and T. Gregorkiewicz) of the University of Amsterdam and VU Amsterdam. The ambition is to continue defining the frontier of photonics in the Netherlands, also in the new structure of NWO. Furthermore, we hope to establish a partnership with the new Photonic Integration Institute, and with TNO, so that the Netherlands is strongly positioned to cover the entire spectrum from fundamental research to integration in photonic applications.

International

The Center for Nanophotonics is among a select set of European centers of excellence like ICFO (Barcelona), the Max Planck Institute in Erlangen, the Optoelectronics Research Centre in Southampton, and LENS (Florence). Other universities and institutes with excellent researchers in photonics include Caltech, Stanford, Columbia, ETH, EPFL, CuDOS (Sydney, Canberra), DTU (Copenhagen) and Imperial College (London). The Nanophotonics theme at AMOLF has over 30 international collaborating partners spread over the top institutions mentioned above. In the past five years, the Nanophotonics researchers have been highly successful in attracting ERC funding (six ERC grants). Photonics is well aligned with the grand challenges of Horizon 2020, and the Nanophotonics theme is well positioned to build strong alliances, as illustrated by its contacts (formalized in several agreements and consortia memberships) with other large EU centers in photonics. We will continue to invite sabbatical guests each year to build new interdisciplinary collaborations in directions intersecting nano-optics, materials science, and (electrical) engineering/applied sciences.



Artist impression: Tiny vibrations of nanoscale strings are converted to light signals. Whereas this usually produces a 'clean' modulation (shown in red), the extremely strong interaction between motion and light produces light signals that are distorted like the sound of an overdriven rock guitar (shown in blue) (Nature Communications, 2017).

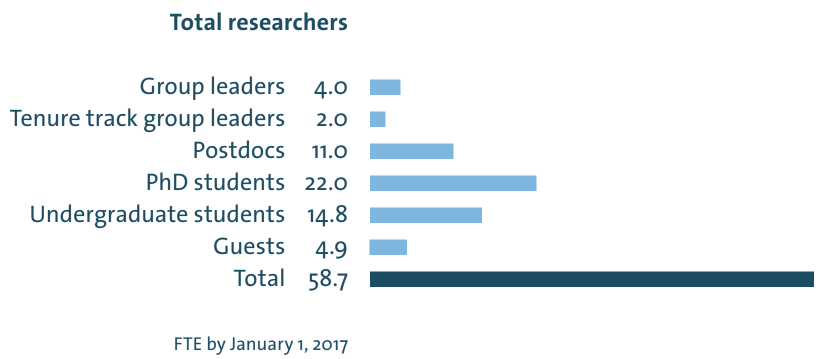
3.6. Industrial collaborations

The Nanophotonics research theme explores fundamental research with applications in green ICT (energy-efficient information technology), solid-state lighting, photovoltaics, optical sensing and metrology, and advanced instrumentation. These are directions that have a prominent position in several Top Sector High-Tech Systems & Materials roadmaps. The Nanophotonics researchers have a longstanding tradition of collaborating with companies like Philips, FEI, Lumileds, NXP, and ASML through FOM IPPs, Technology Foundation STW projects, and NanoNextNL consortia.

Since 2005, AMOLF has collaborated intensely with Philips, with the current IPP partnership (2014-2019) focusing on nanophotonic solid-state lighting. Following its split from Royal Philips, we are now exploring new research directions with Philips Lighting. AMOLF and ARCNL have jointly started several new collaborative projects with ASML, focusing on subwavelength resolution wafer inspection and photochemistry. The Nanophotonics research theme further involves collaboration with FEI and the startup DELMIC, cofounded by AMOLF, in instrument development for material characterization and cathodoluminescence. With regard to green ICT, the nanophotonics research feeds into the Dutch integrated optics community represented in COBRA and Photon Delta (Eindhoven University of Technology), and Lionix & XiO Photonics (Twente). AMOLF is strongly connected with these partners through NanoNextNL and PhotonicsNL (IOP and EU programs for academia and SMEs). Furthermore, we hope to establish a partnership with optical systems experts at TNO and the Dutch metrology institute VSL. We hope that the larger diversity in funding instruments available within the new NWO organization will allow us to establish collaborations with SMEs.

3.7. Personnel

The Nanophotonics research theme is strongly intertwined with the Nanophotovoltaics theme and together they form the Center for Nanophotonics. As research groups participate in both research themes, only aggregate numbers can be given for personnel. In 2017 the Center for Nanophotonics will have about 59 FTEs: 4 scientific group leaders (A. Polman, A.F. Koenderink, E. Verhagen, and E.C. Garnett), 2 scientific tenure-track group leaders (B. Ehrler and E. Alarcón Lladó), 11 postdocs, 22 PhD students, 15 undergraduate students, and 5 guests. In fall 2017, S.R.K. Rodriguez will start as tenure-track group leader.



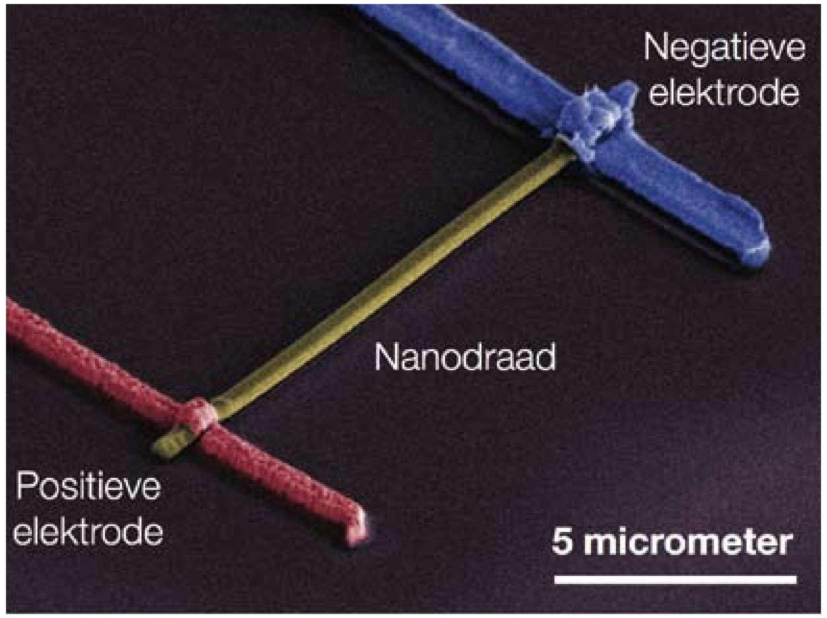
4. Nanophotovoltaics

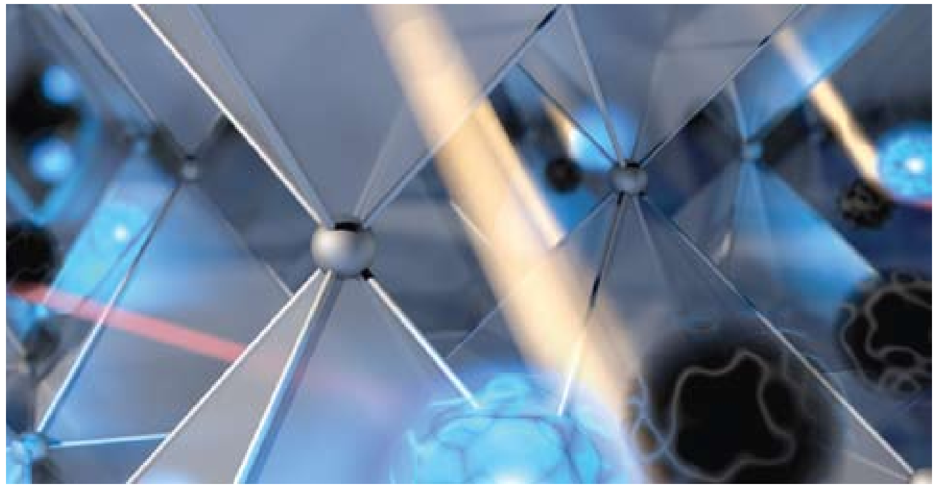
4.1. Introduction

Photovoltaics, the direct conversion of sunlight to electricity, is a promising technology that enables the generation of electrical power at a very large scale. It has the potential to make a significant contribution to a clean, affordable, and sustainable energy supply for our society. However, to make photovoltaic energy sources fully competitive with fossil fuel technologies, the costs of these sources must be further reduced and, related to that, the efficiency of photovoltaic energy conversion must be further increased. These goals cannot be achieved by a simple extension and/or optimization of existing photovoltaic conversion concepts and technologies. Therefore the key challenge in photovoltaics energy research is to discover new, original, and effective energy conversion concepts that increase the conversion efficiency and reduce materials and fabrication costs.

In the past decades, photovoltaics research worldwide has very much focused on the science and engineering of new photovoltaic materials and geometries. In contrast, the understanding and optimization of the flow and capture of light in photovoltaic systems has been quite an overlooked research area. Since the establishment of the Center for Nanophotonics at AMOLF in 2005, a large body of knowledge and expertise has been built up at AMOLF on the behavior of light at the nanoscale. Taking advantage of the nanophotonics expertise, AMOLF started a new program 'Light Management in New Photovoltaic Materials' (FOM Focus Group LMPV) in 2012. The new program investigates advanced nanoscale light and carrier management with the aim of improving photovoltaic energy conversion. The program brings together expertise in fundamental nanophotonics, materials synthesis, device physics, spectroscopy, nanofabrication, and nanocharacterization. Since its formal start in 2012 the LMPV program has grown to about 30 researchers, and a critical mass has been reached to make an impact in the rapidly evolving research field of 'light management in photovoltaics'.

Limits and losses in nanophotonic solar cells quantified using integrating sphere microscopy (Nature Nanotechnology, 2016)





Photon recycling enables ultra-high efficiency perovskite solar cells (Science, 2016).

4.2. Goal and ambition

The worldwide photovoltaics industry has a turnover approaching 100 B€ per year, and is mostly based on Si solar panels with an efficiency of 15-20%. Any new photovoltaic design concept that can enhance absolute efficiency by 1% and that can be applied on a large scale, has a potential value of several billions of euros. Therefore, more than in any other research field, major progress in photovoltaics research is measured in (very) small steps.

The goal of the Nanophotovoltaics theme is to develop a fundamental understanding of the interaction of light with photovoltaic nanomaterials, and to apply this knowledge to eventually realize photovoltaic conversion concepts that surpass existing technology. To reach this goal we will take advantage of fundamental light-scattering processes using nanoscale plasmonic and dielectric scattering geometries, and we will grow new hybrid organic/inorganic geometries and semiconductor nanomaterials with enhanced conversion efficiencies. Our research program targets three efficiency goals:

- towards 30%: light coupling, trapping and carrier collection geometries to reach or stretch the ultimate limits of Si technology;
- 30-40%: hybrid solar cell geometries based on organic/inorganic materials, and thin-film/wafer-Si tandem cells;
- beyond 40%: novel III-V nanowire geometries and other hybrid architectures.

Achieving these goals requires the synthesis and development of entirely new materials and solar cell architectures. It also requires fundamental research on hybridizing strategies that combines concepts from dielectrics and metamaterials with the management of light on length scales from the molecular scale to that of a solar panel. The Nanophotovoltaics program's primary goal is to achieve a fundamental understanding of basic physical phenomena that are relevant for future application in photovoltaics. In many cases, demonstrator devices are made as well, either at AMOLF or together with partners.

4.3. Research program

The Nanophotovoltaics theme focuses on several strongly interconnected research lines that cover the entire chain: material design/fabrication/assembly, to optimizing light capture and charge harvesting, to application in demonstrator devices.

Subtheme 1: Challenging the Shockley-Queisser limit

E.C. Garnett • A. Polman • E. Alarcón Lladó • B. Ehrler • A.F. Koenderink

Efficient coupling and trapping of light in semiconductor geometries over a broad spectral range is crucial for the efficient photovoltaic energy conversion. Optical metasurfaces, interfaces, and subwavelength 3D geometries can serve to enhance the absorption and concentration of light in solar cells. In metasurface geometries the redistribution of scattered light is controlled by engineering the (spatially-varying) phase of scattered light. In 3D nanowires or dielectric Mie cavities resonant absorption of light can lead to concentration of light, bringing materials closer to the radiative recombination limit with corresponding increases in output voltage. Key questions are: which metasurface design can lead to efficient light trapping, and how can inverse design be used to create an effective spectrum-splitting meta-interface for tandem solar cells? And can nanoscale asymmetric light absorption/emission geometries be used to beat the thermodynamic Shockley-Queisser limit for photovoltaic energy conversion in conventional planar cells (isotropic radiative emission, 1-sun illumination), or enable efficiencies closer to the Shockley-Queisser limit than what planar solar cells usually provide? Realizing this in practice would be a major breakthrough for the field of photovoltaics. The results of these insights will be applied to improve the efficiency of several materials: Si, GaAs, InP, CIGS (copper-indium-gallium-selenide), CdTe, and perovskites.

Subtheme 2: Towards nanomaterials with bulk crystalline properties

E.C. Garnett • B. Ehrler • A. Polman • E. Alarcón Lladó • W.L. Noorduin •

We will further develop our solution-chemistry based methods to fabricate ultrathin monocrystalline halide perovskites, and correlate spatially-resolved optical, electrical, structural, chemical, and crystallographic properties to understand the mechanisms behind the exceptional conversion efficiency but poor stability of these materials. We will investigate spatial gradients in chemical composition and the formation of heterojunctions, and optimize doping density and distribution. Optimizing surface roughness, surface passivation, annealing treatments, and control over crystal structure and orientation using solution or vapor phase grown materials will be investigated. By combining solution chemistry and soft-nanoimprint technology we will develop a new method for making nanopatterned monocrystalline thin-films based on nanocube assembly and welding. This approach constitutes a new strategy for making patterned metal, semiconductor, and insulator layers with a material quality similar to that of bulk single crystals. We will apply these new geometries as light management layers in multi-junction solar cells, as nanopatterned active solar cell absorbers, and as transparent electrodes on a multitude of solar cell materials, including high-efficiency Si solar cells.

Subtheme 3: Hybrid and multi-junction solar cells with efficiencies exceeding 30%

B. Ehrler • E.C. Garnett • A. Polman • E. Alarcón Lladó • H.J. Bakker • A.F. Koenderink •

We will investigate the process of singlet fission in organic materials, where the energy from a high-energy photon is shared between two lower-energy triplet excitons. In a hybrid organic/inorganic geometry the organic materials are coated onto an inorganic semiconductor with the aim of harvesting carriers with a conversion quantum efficiency >100%. Our work will focus on obtaining a fundamental understanding of the singlet/triplet formation process, and how it depends on the molecular environment and on the character of the excited states involved. We will study interfaces between organic and inorganic semiconductors with a particular focus on transport of triplet excitons and transfer across interfaces. These novel insights will be applied to hybrid solar cells composed of a singlet fission layer on Si, perovskite, and CIGS-based cells. In parallel to the hybrid organic/inorganic approach, we will develop perovskite/Si and III-V nanowire/Si tandem solar cells with the aim of attaining a photovoltaic efficiency above 30%. We will also develop a nanopatterned interdigitated back contact (IBC) geometry in combination with resonant light-scattering geometries to achieve efficient spectral splitting between the two semiconductors.

Subtheme 4: 3D additive manufacturing of solar cells with ultrahigh efficiency potential

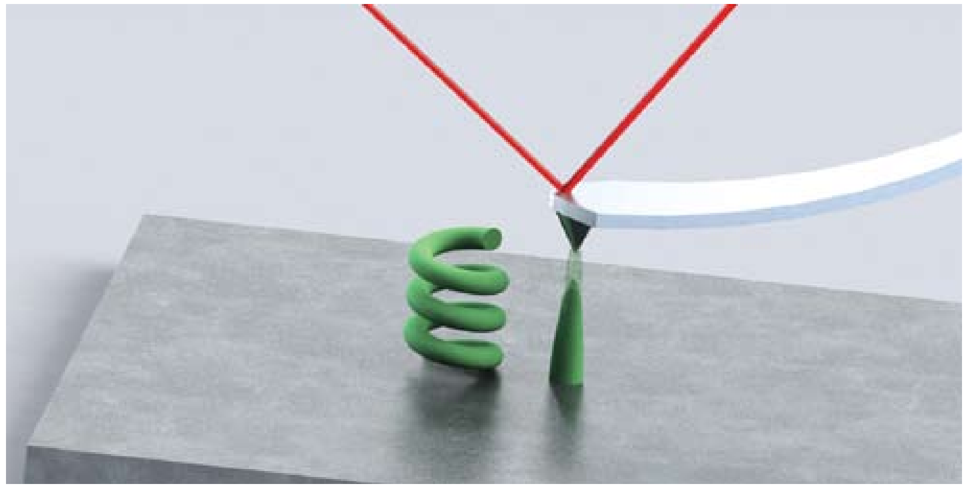
• E. Alarcón Lladó • E.C. Garnett • A. Polman • B. Ehrler

Semiconductor nanowires provide extended degrees of freedom that can be exploited to fabricate new and unconventional solar cell designs from both optical and electrical points of view, at low cost. Using a novel scanning-probe based electrochemical process, we will expand the boundaries of 3D additive nano-manufacturing for the bottom-up fabrication of functional nanostructures based on metals, dielectrics, and semiconductors. This solution-based approach may resolve the cost issue associated with III-V semiconductors such as GaAs, while maintaining the high PV efficiency intrinsic to these materials. We will investigate how light interacts with the nanostructures as a function of shape and array distribution, and how to exploit these properties for solar energy conversion and light emission. The nanowire geometries can be made into flexible arrays, enabling applications in small consumer electronics or the construction of integrated photovoltaics. The electrochemical processes uniquely enable fabrication of nanowire solar cell geometries with 3D-controlled material composition opening up a broad range of 3D multi-junction architectures. The 3D architecture further provides unique opportunities for light concentration and spectral splitting using optical resonances.

Subtheme 5: Novel device concepts and integration

• A. Polman • E.C. Garnett • B. Ehrler • E. Alarcón Lladó

In parallel to the new nanostructured materials and device architectures described above, we will investigate alternative approaches to harvest energy from the sun. We will investigate how metal/semiconductor nanowire core/shell geometries can be exploited as integrated light and carrier collection networks, and complementarily, how these geometries could serve as efficient generators of solar fuel from photocatalytic reactions.



Nano-electrochemical growth of 3D photovoltaic architectures.

Furthermore, a parallel multi-junction device geometry based on planar integrated optical waveguiding and spectrum splitting will be developed targeting an efficiency above 40%. We will also explore how novel 2D materials such as MoS_2 and WSe_2 can be exploited as ultrathin light-harvesting materials, and we will integrate these in 3D architectures that combine strong light absorption and efficient carrier collection.

4.4. Internal relations

The Nanophotovoltaics theme is organized together with the Nanophotonics theme in the Center for Nanophotonics of AMOLF, with several principal investigators participating in both themes. Every week Nanophotonics colloquia and poster sessions are held with both themes participating. This strong entanglement includes the push for advanced instrumentation and materials, and the study of conceptual topics such as fundamental limits on light absorption, scattering, and emission. Collaborations with the Living Matter theme include soft-imprint nanopatterning, fluorescence lifetime imaging, and super-resolution microscopy. The Designer Matter theme provides many exciting intersections with photovoltaics like the use of ultrafast spectroscopy to study carrier dynamics in semiconductor materials, and the design of complex 3D nano-, micro-, and macroscale architectures for solar cells and solar panels.

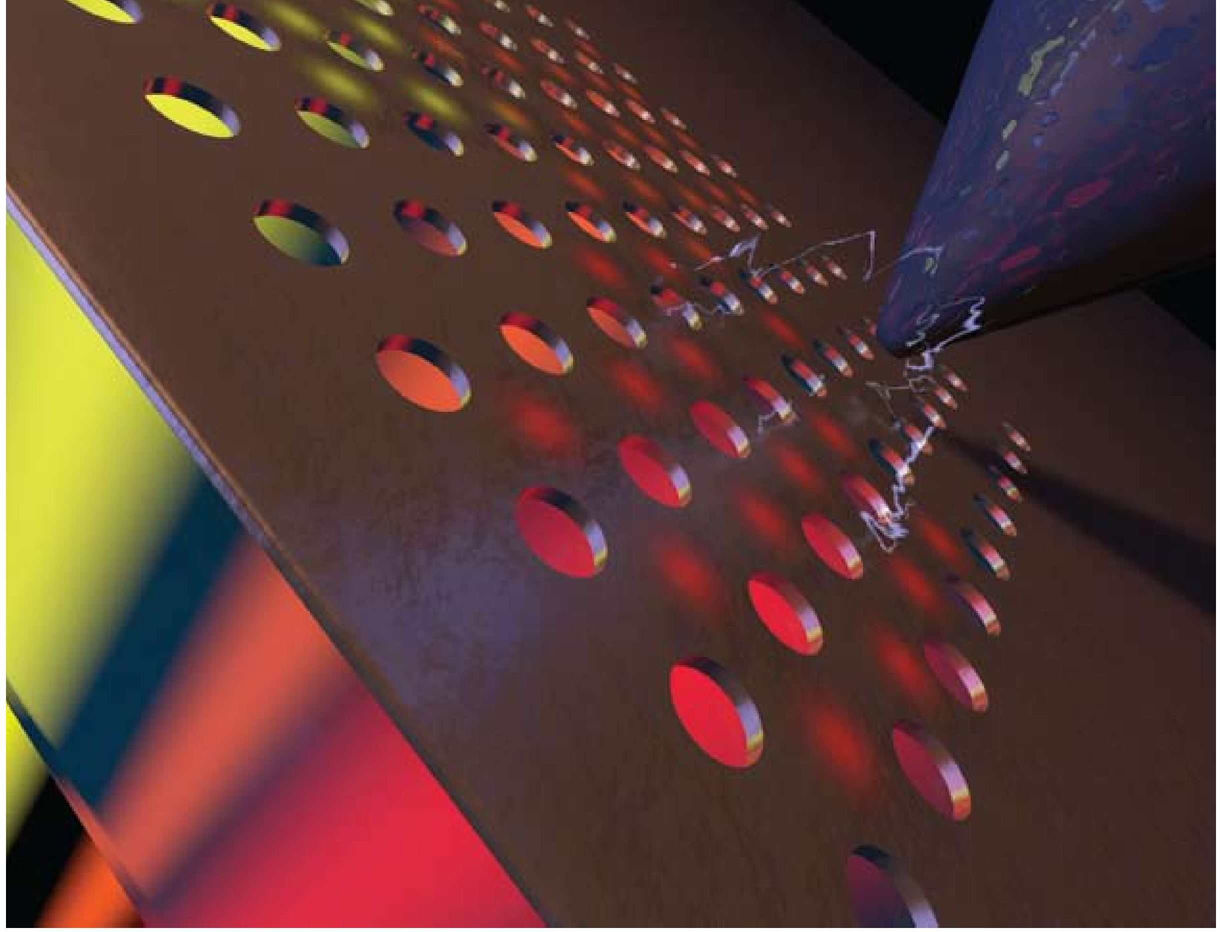
4.5. External relations

National

Photovoltaics research is a key element in the NWO future vision report 'Dutch Materials' and the route 'Materials - made in Holland' of the Dutch National Research Agenda, both initiatives chaired by A. Polman. Photovoltaics research is also an important component in the Dutch National Research Agenda route 'Energy Transition'. Energy research forms an important part of the strategic plans of NWO and of the Top Sectors Energy and High-Tech Systems & Materials.

AMOLF's photovoltaics research program is organized as an NWO focus group and collaborates with nearly all Dutch research groups active in photovoltaics (University of Amsterdam, VU University, Eindhoven University of Technology, Delft University of Technology, Utrecht University, Radboud University, DIFFER, and ECN). AMOLF has taken the initiative to create a coordinated national research program in photovoltaics, in which all Dutch universities, ECN, and TNO participate. In Amsterdam, AMOLF, University of Amsterdam, and VU University Amsterdam together form the Solardam consortium, in which over 100 researchers in solar energy collaborate. AMOLF regularly organizes workshops and international symposia on nanophotovoltaics to stimulate collaboration with partners in and outside of the Netherlands. The nanophotovoltaics group leaders teach in the master programs Advanced Materials and Energy Physics (AMEP) and Science for energy and sustainability of the University of Amsterdam and the VU University Amsterdam. We also set up a solar test field at AMOLF for research projects of bachelor's and master's students.

A major recent development is the intention of ECN to move its Solar division (60 FTEs) from Petten to Amsterdam Science Park. It is AMOLF's ambition to make optimal use of



Plasmo-electric effect creates photovoltage in resonant plasmonic nanohole arrays (Science, 2014).

the unique combination of fundamental research at AMOLF and technology development at ECN within the Amsterdam Science Park. AMOLF and ECN together form a concentrated large-scale research effort in PV with over 100 researchers and technical staff, covering all aspects from materials synthesis and characterization to application in prototype devices and technology development for industrial users.

International

The realization of new sources of renewable energy is at the heart of the International Climate Agreement, signed by 195 countries in 2015. It is also part of Mission Innovation, a worldwide initiative in which (so far) 20 countries including the Netherlands have agreed to double their research and development budgets in renewable energy. Photovoltaics is well aligned with the grand societal challenges of Horizon 2020. AMOLF's nanophotovoltaics program has research collaborations with many international partners, including California Institute of Technology, Stanford University, University of Pennsylvania, Northwestern University, University of New South Wales, University of Cambridge, University of Oxford, Kyushu University, University of Bath, Helmholtz Center Berlin, Ecole Polytechnique Federale de Lausanne, and the Fraunhofer Institute Freiburg.

4.6. Industrial collaborations

AMOLF's Nanophotovoltaics theme is part of the TKI Urban Energy research and innovation program, in which parties such as AMOLF, Delft University of Technology, ECN, Tempress, Levitech, Roth & Ray, DSM, and Eurotron share their expertise. We collaborate with Philips

Lighting within an IPP on solid-state lighting. We have a research contract with FEI and DELMIC on advanced electron microscopy, and we perform scanning-probe electrochemistry in collaboration with Bruker. In addition, several projects are carried out together with ECN. To facilitate the transfer of novel photovoltaic concepts to industrial users, a knowledge transfer agreement has been signed with ECN. This agreement includes the transfer of patents and licensing fees.

4.7. Personnel

The Nanophotovoltaics research theme is strongly intertwined with the Nanophotonics theme and together these form the Center for Nanophotonics. As research groups participate in both research themes, only aggregate numbers can be given for personnel. In 2017 the Center for Nanophotonics will have about 59 FTEs: 4 scientific group leaders (A. Polman, A.F. Koenderink, E.C. Garnett, and E. Verhagen), 2 scientific tenure-track group leaders (B. Ehrler and E. Alarcón Lladó), 11 postdocs, 22 PhD students, 15 undergraduate students, and 5 guests. In fall 2017, S.R.K. Rodriguez will start as tenure-track group leader.

Total researchers

Group leaders	4.0
Tenure track group leaders	2.0
Postdocs	11.0
PhD students	22.0
Undergraduate students	14.8
Guests	4.9
Total	58.7

FTE by January 1, 2017

5. Designer Matter

5.1. Introduction

We are at the dawn of a revolution in our ability to design, understand, and ultimately make dramatically new forms of matter, ranging from materials with a combination of properties not found in nature, to matter that reprograms its function in response to environmental stimuli. This new field is referred to as Designer Matter, and brings together physicists, chemists, material scientists, computer scientists and engineers. Designer Matter encompasses a wide variety of systems and scales, and will be key in creating novel designed materials that address major societal challenges in sustainable energy (adaptive photovoltaics and efficient devices), high-tech systems (smart, programmable and robotic matter), and health-care (intelligent prosthetics and medicine).

In 2014, AMOLF initiated the Designer Matter program that focuses on designing, understanding and fabricating complex functional matter. The materials and material-systems that we study feature a prominent role of architecture at the mesoscopic scale, with functionalities emerging from the constituents and architecture in a nontrivial manner. Our research addresses intellectually deep questions concerning the emergence of shape, behavior, and properties, which are key to obtaining a deeper understanding of both synthetic as well as naturally occurring functional material systems. This research program is fluidly connected to most of the other research within AMOLF, and is positioned at the forefront of national and international trends.

Rational design of a 3D mechanical metamaterial that can morph into arbitrary shapes (Nature, 2016).

5.2. Goal and ambition

Our ultimate goal is to rationally design and make materials with any functionality imaginable, i.e. solving the 'inverse' problem. Exciting goals ahead are the creation of materials that autonomously move, sense, and adapt to their environment, the control over self-assembling architectures using simple environmental cues, and the design of programmable materials whose properties can be modulated on demand.

The Designer Matter effort strives to be at the forefront of this scientific field by initiating new activities that are complimentary to pre-existing lines of research, and keeping an interdisciplinary and explorative profile that is substantially different from research that is already pursued elsewhere (especially in the Netherlands). Our research program requires a mix of backgrounds, leading to a diversity of scientific expertise that is rarely found under a single roof in the Netherlands. Internationally, such a mix has already been proven to be successful. Started in 2014, Designer Matter has attracted four members, working on the fabrication of materials through self-organization (W.L. Noorduin), the molecular properties of hierarchal self-organized materials like hydrogels and metal-organic frameworks (H.J. Bakker), mechanical metamaterials (M.L. van Hecke), and soft robotic matter (J.T.B. Overvelde).

5.3. Research program

Our research program encompasses passive and active materials, and we seek to understand emergent properties and to shape these through rational design. We identify three distinct research subthemes that are described below.

• Subtheme 1: Architected Matter

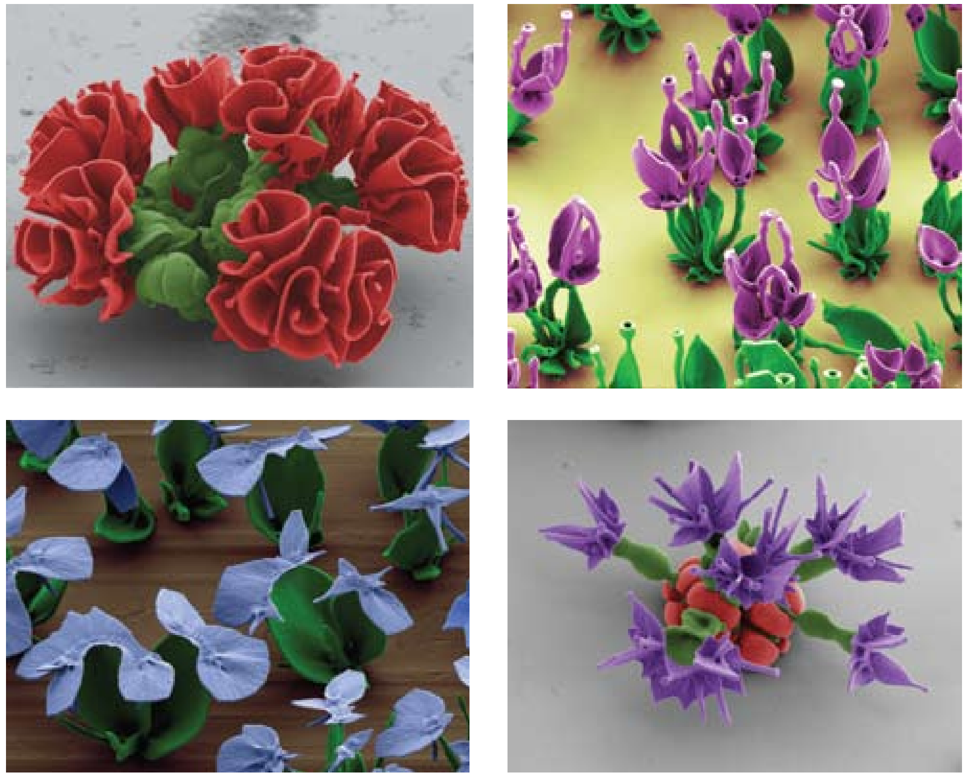
- W.L. Noorduin
- J.T.B. Overvelde
- M.L. van Hecke
- H.J. Bakker

Material properties are ultimately determined by microstructure, and we study the emergence of properties over a range of length scales. At the macroscale, we will develop soft and flexible mechanical metamaterials, where we leverage mechanical instabilities, frustration, chemical cues, and structural complexities to obtain shape-shifting materials, metamaterials with unusual mechanical response, reprogrammable materials, and memory effects. At the microscale, we will explore the emergence of new materials due to guided self-assembly, and aim to design mechanisms that can sort, arrange, and assemble building blocks from the molecular level up to the microscale, to create functional materials such as pharmaceutical compounds that require chirality and optical architectures. At the molecular scale, we will explore new functionalities arising from the architecture of hierarchal, self-organized hydrogels and metal-organic frameworks (MOFs). For these systems we will study how the architecture and non-covalent intermolecular (hydrogen bonds) of relatively simple molecular units conspire to create macroscopic, responsive visco-elastic, and transport properties.

• Subtheme 2: Design

- M.L. van Hecke
- J.T.B. Overvelde
- W.L. Noorduin
- H.J. Bakker

The development of novel theoretical and algorithmic approaches to the design of complex matter will be crucial for the level of complexity that we wish to realize. In fact, internationally we perceive an increasingly closer interaction between experiment, simulation,



SEM pictures (false colored) of micrometer-scale hierarchal complex structures grown by controlling crystallization and diffusion (Science, 2013, 2017).

and theory in this field. Such activity will greatly benefit from the existing expertise in the theoretical groups of the Living Matter theme. The ultimate test of our understanding of the emergence of nontrivial properties is to be able to solve the inverse problem: how can we assemble building blocks in such a way that desired functionalities emerge? We will explore this question using genetic and evolutionary search algorithms to design mechanical metamaterials, which we subsequently will create and test. We also aim to develop new rational design strategies using combinatorics of building blocks to obtain desired functionality. Furthermore, we will develop and model new routes to control nucleation, polymorphism, shape, and hierarchical organization of mineralizing structures, and to design self-organizing functional molecules and materials.

• Subtheme 3: Animated Matter

J.T.B. Overvelde •
W.L. Noorduin •
M.L. van Hecke •

We aim to infuse architected matter with activity, establishing a new class of materials with life-like functionalities that we refer to as animated matter. The collective behavior that emerges due to feedback between activity and geometry is virtually unexplored, but we expect animated materials to autonomously oscillate, polarize, snap, twist, or form non-equilibrium patterns, depending on the nature of the driving, coupling, and architecture. At the macroscale, we will introduce soft robotic matter: soft-architected materials with embedded active and sensing elements, inspired by the recent developments in soft robots. At the microscale, we will study the emergence of spatio-temporal oscillations that arise in soft thermosensitive environments, such as hydrogels due to feedback between confinement, heat generation, and crystallization. Finally, we will explore how active instabilities can be employed to obtain shape-changing and motile behavior in man-made materials.

New directions

We have identified several promising directions that will strengthen and complement these research thrusts as well as the broader AMOLF research programs. First, structured smart hydrogels are prime examples of architected matter that can be used to actuate materials, with the ultimate goal of realizing life-like or even hybrid machine-living systems. Second, hybrid materials, which unite mechanical and chemical phenomena, solids, and fluids, or optical and mechanical elements, provide new routes to create and design functional materials. Third, an overarching theme that is emerging is to use activity and complexity to create reprogrammable materials, which not only change function in response to external stimuli, but also have inherent information-processing capacities. Finally, pushing the level of complexity in our designer materials requires the development of new fabrication strategies as well as novel theoretical and algorithmic approaches for their design. Our research will continue to connect macro- and micro-scale, as well as experimental and theoretical activities. Moreover, these potential themes provide ample opportunities for connecting themes within AMOLF, in particular Designer Matter and Living Matter, as well as forging new external links, in particular with groups working in supramolecular chemistry, while maintaining a distinct complementary profile due to the strong physics focus at AMOLF.

5.4. Internal relations

Many activities within AMOLF have a natural link with Designer Matter. The Nanophotovoltaics theme connects through questions of self-assembly, 3D structuring, the design of smart photovoltaic materials and devices, and strong opportunities for joint research exist at this interface. There are direct links with the Nanophotonics theme, including the design of (optical) metamaterials, and hybrid mechano-optic metamaterials, the study of fundamental questions on the breaking of reciprocity symmetry, and the bottom up self-assembly of optically active matter. The biological design principles studied within the Living Matter theme can be translated to new forms of matter: shape-changing and force-generating matter, matter that actuates and senses, and matter whose spatiotemporal organization mimics that of cells or tissues. In addition, our ultrafast spectroscopy facilities can be used to probe the molecular origin of the viscoelastic properties and mechanics of bio(mimetic) materials. Finally, the processing of information, which is a crucial aspect of Designer Matter, is a theme that connects both to the Nanophotonic and the Living Matter efforts.

5.5. External relations

National

Since the Designer Matter effort is in its build-up phase, our list of external relations is expected to grow substantially. In the Netherlands, our aim is to play a pivotal role. Presently, we are closely connected to the Physics Department at Leiden University through M.L. van Hecke's dual appointment, and are forging closer ties with a variety of Dutch departments with designer matter-related work: Delft micromechanics and Delft design, ICMS in Eindhoven, and the groups of Gascon (MOFs, Delft University of Technology) and Kouwer (supramolecular hydrogels, Radboud University). We also aim to use long-term guest appointments to this purpose, with M. Dijkstra (Debye Institute, Utrecht University) having started in spring 2016. Our research fits well within future perspectives described in the

FOM ‘Focusnotities’ on condensed matter physics and phenomenological physics, in Dijkgraaf's Vision Paper 2025, in the Dutch materials initiative as described in the 2016 NWO report ‘Dutch Materials - Challenges for Materials Science in the Netherlands’, as well as the Top Sectors and the Dutch National Research Agenda.

International

Internationally, we have strong ties with Harvard University’s John A. Paulson School of Engineering and Applied Sciences where two of our group leaders hold affiliations. J.T.B. Overvelde holds an associate appointment and works closely with groups focusing on soft robotics, as well as the design of nonlinear metamaterials with interesting phononic and acoustic properties. W.L. Noorduin has a visiting scholar position in the group of J. Aizenberg to jointly work on self-assembly strategies.

5.6. Industrial collaborations

We are setting up collaborations with industrial partners both locally (Océ, Suprapolix, Heerema, and Syncom BV) as well as internationally (Puma and Janssen Pharmaceutica). For example, at the start of fall 2016, the group of W.L. Noorduin has started a collaboration with the chemical company Syncom BV in Groningen on the use of steady-state principles towards functional molecules (two year postdoc position funded by the Top Sector scheme). In the coming years, we see ample opportunities to connect to societal and industrial needs and programs.

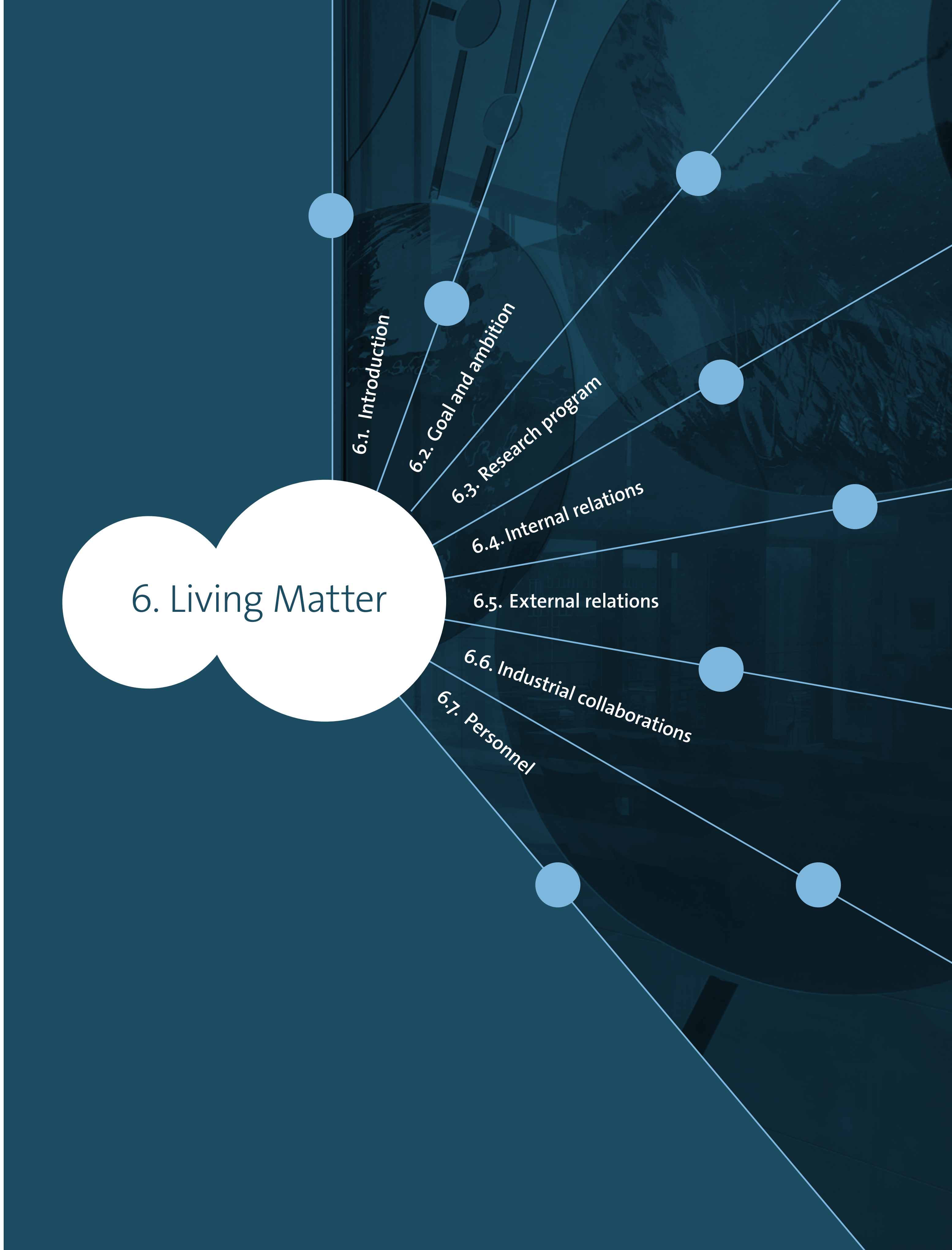
5.7. Personnel

The research program Designer Matter will have about 29 FTEs in 2017: 2 scientific group leaders (M.L. van Hecke and H.J. Bakker), 2 scientific tenure-track group leaders (W.L. Noorduin and J.T.B. Overvelde), 12 PhD students, 4 postdocs, 7 undergraduate students, and 3 guests. Three of these groups are still in the buildup phase. It is our ambition that this research theme is expanded with an additional tenure-track research group.

Total researchers

Group leaders	1.5
Tenure track group leaders	2.0
Postdocs	4.2
PhD students	11.4
Undergraduate students	7.0
Guests	3.0
Total	29.1

FTE by January 1, 2017



6. Living Matter

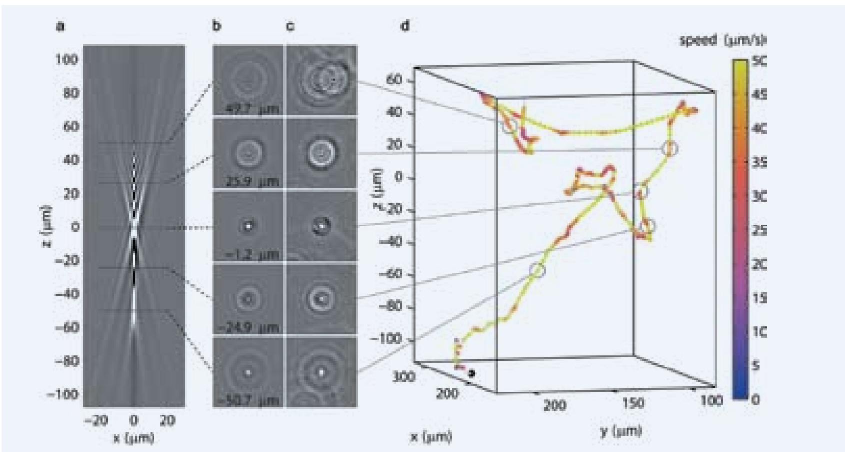
6.1. Introduction

Living systems are the ultimate example of complex and functional matter. Cells have the remarkable ability to autonomously grow, replicate, sense and respond, and self-organize into multicellular systems. From a physicist's perspective, cellular systems are a unique class of active soft matter: they exhibit continual internal driving by molecular processes that harness chemical energy to generate forces. Moreover, they have the striking ability to (re)program their own properties using biomolecular networks that perform computations. For instance, cells use multiple signaling cues to decide when to replicate and where to move.

At the molecular scale, the identities and structures of most components of the cell are known thanks to revolutionary advances in genomics, proteomics, structural biology, and single-molecule biophysics. However, how these nonliving components collectively give rise to the emergent properties that govern life at the level of a cell is still a wide-open question. The physical principles by which cells autonomously self-organize into multicellular tissues and organs are even less well understood. Our research lies at the heart of these two questions: we study how the biological functions of living systems at the cellular and multicellular scale emerge from the organization and interactions of the constituent parts. The Living Matter program targets an exciting interface between physics, biology, and materials science. We use quantitative experimental techniques and theories from physics to address questions relevant to biology and biomedicine. Conversely, living matter provides us with rich inspiration for biologically inspired engineering of new functional materials with applications in regenerative medicine, foods, smart materials, and soft robotics.

6.2. Goal and ambition

Our central aim is to elucidate how functions of cellular and multicellular systems emerge from their constituent parts in order to achieve a systems-level understanding of living matter. Starting from our extensive experience in 'bottom-up' reconstruction of cellular functions from purified molecular components, our ambition in the next years is to push the boundaries of synthetic biology to generate autonomous synthetic cells from a minimal set of components. Meeting this challenge will fundamentally deepen our understanding of what life is, open new avenues of engineering life at the cellular scale, and provide new concepts to design functional materials. Recently we have also started to develop complementary 'top-down' approaches, where we dissect the basis of cell functions using data-rich live-cell imaging, microfluidics, and theoretical modeling. We will expand this approach towards multicellular systems, using *C. elegans* nematodes and mammalian mini-organs as model systems. By going to the tissue scale and working with mammalian model systems, we will be able to directly connect our research to biomedical applications in regenerative medicine and the development of in vitro organ-on-chip models for human disease.



The groups of T.S. Shimizu and S.J. Tans developed a new method to track the movement of bacteria swimming in three dimensions (3D). This technique now makes it possible to reveal the individuality of bacterial swimming behavior with applications in medical research (Nature Communications, 2016).

6.3. Research program

Our research directions are organized around three key functions of living matter, as detailed below. Within each subtheme, multiple experimental groups (T.S. Shimizu, S.J. Tans, G.H. Koenderink, and J.S. van Zon) and theoretical groups (P.R. ten Wolde, B.M. Mulder, and J.S. van Zon) collaborate. The central tool in our experiments is quantitative microscopy coupled with automated image analysis and local force measurements. These imaging experiments are greatly augmented by microfluidics technology, which allows us to perform long-term imaging of living systems in precisely controlled microenvironments. The theoretical modeling uses non-equilibrium statistical physics, thermodynamics, and information theory, and also involves the development of new particle-based simulation methods.

• Subtheme 1: Cellular mechanics & self-organization

• G.H. Koenderink
• T.S. Shimizu
• S.J. Tans
• B.M. Mulder
• P.R. ten Wolde

We study the physical principles that underlie the functional mechanical properties and spatio-temporal organization of cells. This requires state-of-the-art insights into emergent behavior in multiscale, complex, stochastic systems. Our approach is to combine quantitative experiments on well-defined model systems reconstituted from purified cellular constituents with theoretical modeling and particle-based simulations. We focus on the spatial organization of the cytoskeleton and its role in cell mechanics and active force generation of chromosomes and their role in regulation of gene expression, and of chaperone systems and their role in protein folding. Our ultimate aim is to harness our expertise in cellular self-organization together with our work on cellular decision-making (cf. subtheme 2) to generate synthetic cells that exhibit life-like behavior. The aim here is to understand the minimal components and the governing physical principles required to create synthetic cells capable of life-like, self-replication or migration.

• Subtheme 2: Cellular decision making and information processing

• P.R. ten Wolde
• T.S. Shimizu
• S.J. Tans

Cells program themselves using biochemical networks that perform computational tasks. We study the design principles of these networks, focusing on the role of stochasticity that arises because cellular computations are performed by small populations of molecules. This leads to questions at the forefront of modern non-equilibrium statistical physics. Our experiments are focused on cell growth and motility in bacteria, the simplest unicellular organisms, and in the nematode *C. elegans*, a simple model organism (~103 cells) with a nervous system composed of only 300 cells. Both systems are ideally suited for a physics-based approach since they are genetically well-characterized and amenable to live-cell imaging across the full range of biological scales, from single molecules to the entire organism. We couple experiments to theory and simulations that address the reliability and thermodynamics of cellular information transmission. We focus on the fundamental limits on the accuracy of sensing and prediction, and the implications of this for the optimal design of signaling systems in bio-inspired functional matter.

Subtheme 3: Cellular self-organization into multicellular systems

J.S. van Zon •
S.J. Tans •
G.H. Koenderink •
B.M. Mulder •
P.R. ten Wolde •

Tissues and organs have complex functional structures that arise from the self-organization of living building blocks. Our aim is to understand the physical principles by which local interactions, mechanical forces, and information processing conspire to allow cells to autonomously form functional organs and tissues. As model systems we use the nematode *C. elegans* and mammalian 'organoids', small mini-organs that were recently shown to be able to develop in vitro from mouse or human stem cells. We will perform quantitative measurements of cell fate decisions in *C. elegans* and intestinal organoids to elucidate how cells are able to coordinate their development in time and space to generate viable organisms in a manner that is robust to stochastic fluctuations. Since cell differentiation involves rare, stochastic switching events, we will couple these experiments with Forward Flux sampling simulations. To reveal how embryos and organs acquire their functional shapes, we will combine imaging with selective laser ablation of cells and multiscale simulations of tissue growth.

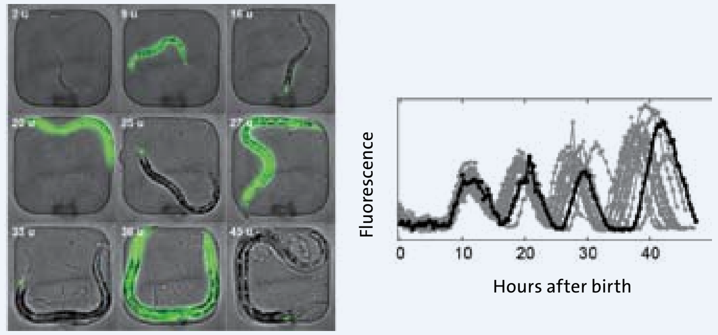
6.4. Internal relations

We plan to forge close connections between the activities in the Living Matter program and the new Designer Matter program, with the aim of translating biological design principles into novel concepts for functional materials. Inspired by our expertise in biomolecular self-organization and cell mechanics (subtheme 1), we aim to design shape-changing and animated matter using hierarchical structuring and active force-generating elements. Moreover, we will design new structured materials borrowing reaction-diffusion and other self-organization principles from living cells. We will use AMOLF's unique ultrafast spectroscopy facilities to measure the molecular basis of the stimuli-responsive mechanical response of biological and bio-inspired hydrogels. Using our expertise in information processing in cells (subtheme 2), we will explore strategies to create soft-robots that detect and respond to external cues (J.T.B. Overvelde). Finally, we will use our expertise in multicellular self-organization (subtheme 3) to devise strategies to create hybrid living/non-living matter. With the Nanophotonics and Nanophotovoltaics groups we share a strong interest in nanoscale lithography and single molecule imaging and spectroscopy. We will continue to jointly develop superresolution and single molecule microscopy (following on successful collaborations of T.S. Shimizu with E.C. Garnett, and G.H. Koenderink with A.F. Koenderink in the areas of nanowire photovoltaics and model biomembranes), as well as optical and dip-pen lithographic techniques.

6.5. External relations

National

Our research program fits well within national perspectives such as the cross-sectoral NWO Molecular Building Blocks of Life program, and the route 'Origins of Life' of the Dutch National Research Agenda. Furthermore, our research contributes a bio-inspired materials perspective to challenges defined in the recent NWO vision document 'Dutch Materials' and the Dutch National Research Agenda route on Materials. We are firmly embedded in the Dutch biophysics



The Van Zon group developed a new method for long-term fluorescence time-lapse imaging with single-cell resolution of the development of many *C. elegans* larvae confined in microfabricated chambers. They thus revealed for the first time how the molecular clock that controls the timing of *C. elegans* development varies between worms (Nature Communications, 2016).

community, which includes physics and biology groups at all the major universities and various NWO and KNAW institutes (Hubrecht, CWI, NKI). AMOLF is a key partner in the newly established NWO Zwaartekracht consortium BaSyc, which aims at developing a fully synthetic cell capable of like-like reproduction. This is an ambitious 10-year research program led by the Delft University of Technology with partners from AMOLF, VU Amsterdam, Wageningen University & Research, University of Groningen, and Radboud University. AMOLF is represented in the 'Physics of living systems' Advisory Board of NWO and in the Program Committee of the annual Dutch Biophysics meeting. Together with the VU Amsterdam, we co-organize bimonthly biophysics meetings targeted at junior scientists across the Netherlands. We play a leading role in initiating national research activities that engage Dutch universities and industries, as evident from leadership and participation in FOM and IPP programs (Spatio-temporal patterns of membrane protein activity, The signal is the noise: seeking physical origins of fluctuation in organism-scale behavior, Physics of DNA processes in a fully packed environment, Controlling the mechanics of soft materials, Hybrid Soft Materials IPP). Close ties with Dutch universities are ensured by adjunct professorships and teaching in master curricula at Delft University of Technology (S.J. Tans), VU Amsterdam (P.R. ten Wolde, T.S. Shimizu, and G.H. Koenderink), and Wageningen University & Research (B.M. Mulder, 0.2 FTE). The ambition is to continue to play a leading role in Dutch biophysics research and to take advantage of the closer interactions of physics, biology, and chemistry in the new Science domain of NWO. The connection to the new NWO Science domain is strongly supported by the recent appointment of G.H. Koenderink as chair of the 'disciplinekamer natuurkunde' of this domain. Additionally, we expect that opportunities will arise to contribute to biomedical sciences within the new Medical Sciences domain of NWO (now ZonMw).

International

Internationally, we participate in the 'Circle' network with other European centers of excellence in physics of life (EMBL (Heidelberg), Institut Curie (Paris), and Max Planck Institute PKS (Dresden)), with whom we organize annual meetings for PhD students and postdocs that rotate between the partner institutes (last organized at AMOLF in 2015). We further participate in a European Scientific Coordination Network on 'Evolution, Regulation and Signaling' that brings together leading biophysicists from France, Denmark, Sweden, Germany, and the Netherlands. A major fraction of our output is realized in collaboration with international partners in Europe (e.g. Institut Curie (Paris), Fresnel Institute (Marseille), Forzungszentrum Jülich, MPI Mainz, MPI Dortmund, TU Dresden, Heidelberg University, University of Münster, University of Oxford, and Imperial College London) and outside of Europe (e.g. MIT, Stanford, Yale University, University of Washington, University of Michigan, University of Denver, University of Utah, UCLA, Boston University, Columbia University, and the Riken Quantitative Biology Center in Osaka). We have been highly successful in attracting ERC funding (two ERC Starting grants and one ERC Synergy grant) and our research is closely aligned with the grand societal challenges of Horizon 2020.

6.6. Industrial collaborations

Our research strongly connects with societal challenges in the areas of food, health, and biomaterials. We thus collaborate with industrial partners from diverse sectors:

Food

We lead the IPP 'Hybrid soft materials' (2015-2020) funded by Unilever, FOM, NWO-ALW, and TKI AgroFood. In this program, we collaborate with Unilever, University of Amsterdam, and Wageningen University & Research to study how physical principles can be used to control the rheological properties of food products.

Health and biomaterials

We have collaborative projects with several small Dutch biotech companies. Together with Fibriant (Leiden), we are exploring the biomechanical and cell-instructive functions of recombinant fibrinogens. Together with Hoekmine (Utrecht), we are developing 'disease-on-a-chip' experimental platforms for studying bacterial infections of intestinal organoids. Together with LUMICKS (Amsterdam), we are developing single-molecule force spectroscopy over extended temperature ranges. In the coming years, our ambition is to initiate additional collaborative projects with new industrial partners, leveraging our experience in biomaterials, on-chip cell culture, automated time-lapse imaging, and mathematical modeling. This will be done in cooperation with the new Institute for human Organ and Disease Model Technologies (hDMT).

Computational techniques

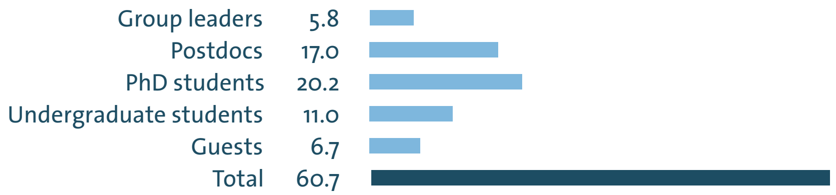
We participate in the Computational Sciences for Energy Research initiative, a large public-private partnership established in 2012 by Shell, NWO, and FOM. Here we are extending Green's Function Reaction Dynamics to simulate reaction-diffusion processes in complex environments on a micro- and mesoscopic level.

In the coming years we foresee a growing emphasis on collaborations with SMEs in life sciences, pharma, and biomaterials that take advantage of the larger diversity of financial instruments in the new NWO and the Top Sectors.

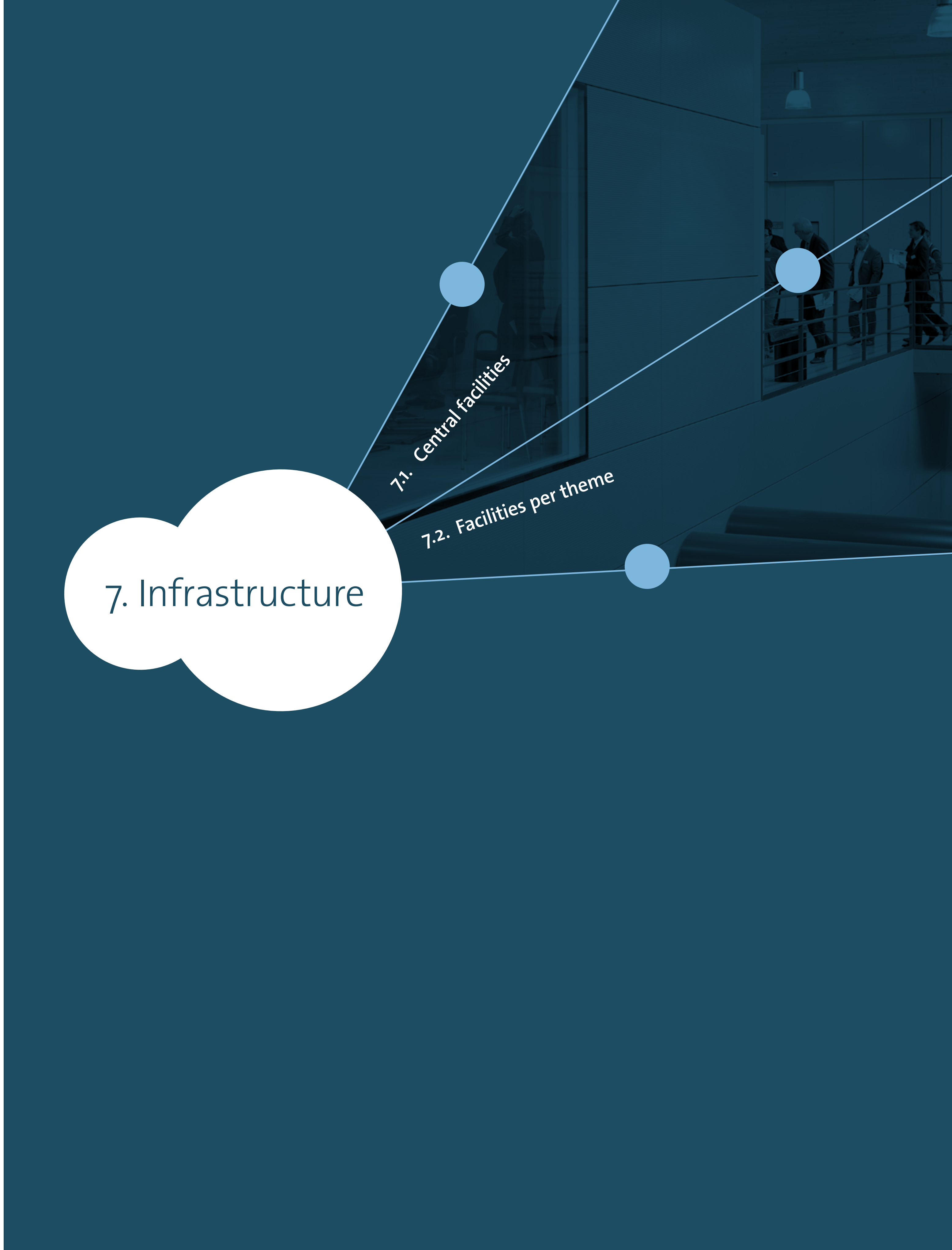
6.7. Personnel

In 2017, the Systems Biophysics department has approximately 60 FTE: 6 tenured scientific group leaders (G.H. Koenderink, B.M. Mulder, T.S. Shimizu, S.J. Tans, P.R. ten Wolde, and J.S. van Zon), 17 postdocs, 20 PhD students, 11 undergraduate students, and 6 guests.

Total researchers



FTE by January 1, 2017



7. Infrastructure

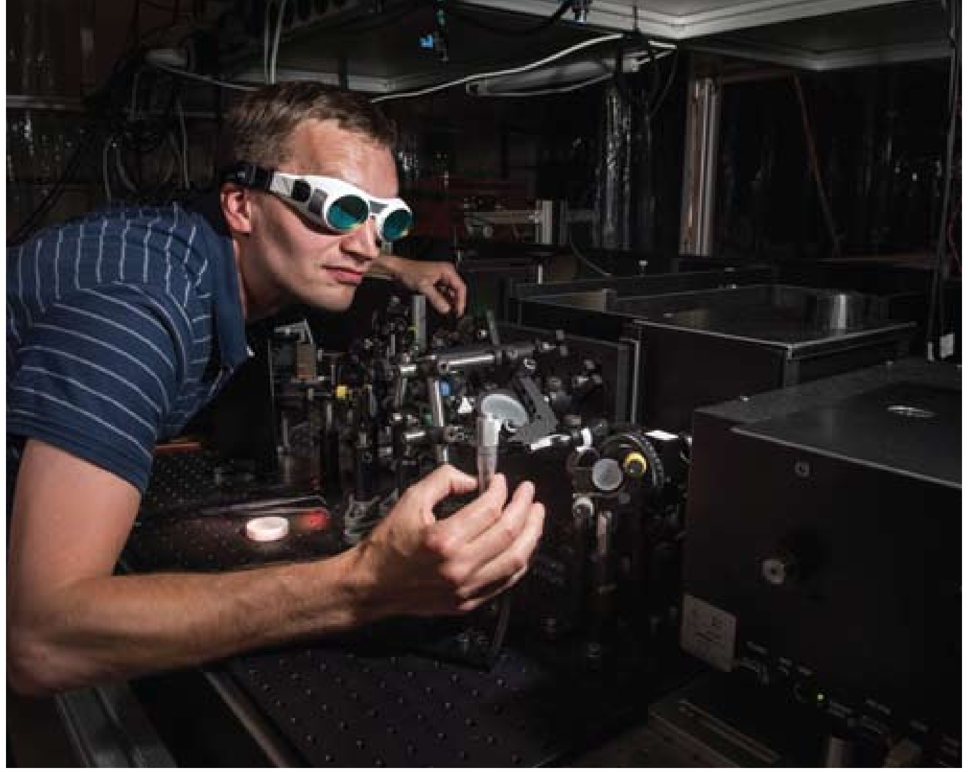
AMOLF offers state-of-the-art research infrastructure that is organized to maximize sharing and synergy between research groups within and across the four research themes. Sample preparation is done in shared labs including the AMOLF NanoLab Amsterdam cleanroom, which also serves as a regional facility. Experimental facilities for advanced microscopy, ultrafast spectroscopy, and mechanical analysis are partly also pooled as shared facilities, and partly run as group labs. A large fraction of the experimental setups at AMOLF are made from custom parts, control electronics, and software designed and created in-house.

7.1. Central facilities

7.1.1. AMOLF NanoLab Amsterdam

The AMOLF NanoLab Amsterdam is a lean-and-mean cleanroom facility for nanofabrication and materials characterization. The facilities include focused ion beam milling, UV optical lithography, a 50 keV electron beam lithography system, reactive ion etching of silicon-based photonic structures, material deposition, and a Nanoscribe for direct writing of 3D structures in polymer. In addition, the NanoLab offers a soft-conformal imprint lithography tool (SCIL) that was recently developed with Philips Research, and is now available under license from Süss Microtec. The tool is ideal for nanophotovoltaics since it is capable of large-area replication of nanoscale patterns. Moreover the tool has been further developed in partnership with Philips. The characterization tools of the NanoLab include SEM with EDX and STEM mode, AFM, profilometry, and ellipsometry. We are currently developing a novel solid-state detector for the STEM instrument together with Amsterdam Scientific Instruments for use in electron back-scatter diffraction (EBSD) of beam-sensitive materials (e.g. halide perovskites).

AMOLF NanoLab Amsterdam.



Ultrafast spectroscopy lab.

The operation of the AMOLF NanoLab is supported by five research technicians who train the users, maintain the equipment, and develop new protocols. The NanoLab is used by nearly all AMOLF groups and is also heavily used by groups from across the Amsterdam Science Park (ARCNL, Nikhef, University of Amsterdam, and VU Amsterdam) and from elsewhere in the Netherlands (Universities of Utrecht, Leiden, Nijmegen, and Wageningen, as well as institute SRON). From 2017 onwards, the AMOLF NanoLab Amsterdam is one of the five nodes of NanoLabNL, the Dutch national facility for nanotechnology research, that provides an open-access infrastructure for R&D. The AMOLF NanoLab also plays a key part in AMOLF's role in teaching University of Amsterdam and VU Amsterdam master's students, and is central to industrial collaborations with partners like FEI, ASML, Philips, TNO, and SMEs like DELMIC and Optics11. It is primarily equipped for the patterning and material requirements of nanophotonic and photovoltaic systems, but it is also well suited for nanopatterning of (opto)fluidic devices.

7.1.2. Molecular and cell biology laboratories

We have a large ML1-safety level laboratory with facilities for molecular biology and recombinant protein production. We also have ML1- and ML2-safety level laboratories for cell and tissue culture. Finally, we have a dedicated facility for *C. elegans* nematode growth and maintenance, which includes incubators, stereomicroscopes, and a genetic manipulation pipeline to create fluorescence-based reporters of gene expression and targeted deletions. These laboratories are supported by four life sciences research technicians with complementary expertise in molecular cloning, protein biochemistry, and mammalian and organoid cell culture.

7.1.3. Ultrafast spectroscopy laboratory

For the characterization of both biomolecular and nanophotonic systems, we have an ultrafast spectroscopy lab with several femtosecond pump-probe setups based on amplified Ti:Sapphire systems. Techniques include one- and two-color vibrational pump-probe spectroscopy, 2D vibrational spectroscopy, and phase-sensitive sum-frequency generation, over widely tunable frequency bands centered in the mid-IR. In addition, ultrafast pulse interferometry and pump-probe measurements across the visible and near-IR are available to interrogate nanophotonic and photovoltaic structures. A very recent technology development is picosecond cathodoluminescence microscopy, where femtosecond laser technology is incorporated in a cathodoluminescence imaging setup. This allows us to perform ultrafast time-resolved luminescence nanoscopy and pump-probe spectroscopy on the new material systems we study in photovoltaics, and it can also be used for quantum nanophotonic structures and 2D semiconductor optoelectronic materials (TMDCs).

7.1.4. Multi-scale mechanical characterization

A pervading theme in both the Living Matter and Designer Matter themes is mechanical characterization of complex matter and functional materials. We have an array of techniques addressing length scales from nanometric to macroscopic. At the nanoscale, we have several optical tweezer systems integrated with fluorescence microscopy. At the micron-scale, we have a commercial dual-optical tweezer system integrated with a microfluidic flow device, and a micropipette aspiration system suitable for measurements on whole cells. At the macroscopic scale, we have shear rheometers, a custom-built rheoscope, and a wide range of mechanical characterization testing devices (uniaxial, torsional, 3D scanning, high-speed imaging).

7.1.5. Computation

An important activity in AMOLF is the development of novel computational methods to model living systems (Living Matter theme) and to design materials by algorithmic design (Designer Matter theme). We consider in-house development and testing essential to avoid turnaround delays. We therefore are upgrading our computer cluster to a 10 + 1 nodes/36 cores per node/256 Gb RAM per node system. This cluster is tailored for particle-based algorithms to model self-organization and reaction-diffusion systems in living systems and for large-scale continuum mechanics simulations.

7.2. Facilities per theme

7.2.1. Nanophotonics

The groups of the Nanophotonics theme share an extensive array of optical characterization tools tailored for nanophotonic and optoelectronic systems. These include scanning near-field microscopy, time-resolved microphotoluminescence and spectroscopy at single emitter level, pressure-dependent spectroscopy, and supercontinuum white light scatterometry to probe devices from the UV to the infrared. A dedicated lab is also equipped for input-output measurements, scatterometry, interferometry and control of ultra-high Q devices (Q~10^9). Important tools that have been developed in-house are quantitative quantum efficiency measurement tools (EQE, IQE, PL), Fourier microscopy to measure single-object radiation patterns, and angle-resolved cathodoluminescence imaging. Most recently, we added a cryogenic quantum-limited optical measurement setup to study nano-optomechanical systems.

7.2.2. Nanophotovoltaics

The Nanophotovoltaics theme has built up extensive chemical laboratories for the wet-chemical and vapor-phase synthesis of semiconductor and metallic nanowires, quantum dots, and inorganic films. We can thus fabricate complete organic/inorganic nanophotovoltaic devices such as hybrid perovskite devices and quantum dot solar cells. Recently we have also started to develop local electrochemistry of nanowire structures and III-V chemistries in a Bruker AFM instrument. Furthermore, we share an extensive array of advanced optical characterization tools with the nanophotonics theme, including scanning photocurrent spectroscopy, absorption spectroscopy, time-resolved pressure-dependent photoluminescence, angle-resolved cathodoluminescence imaging, and quantum efficiency measurement tools. For the translation to device performance we also set up an electric probe station integrated with a solar simulator and a test field for solar panels that enables long-term testing of photovoltaics under realistic outdoor conditions.

7.2.3. Designer Matter

We have a range of 3D printing facilities available to create mechanical metamaterials and soft robotic materials. These range from modified FDM printers to a Nanoscribe system, which allows structuring in the sub-micron range. We combine these techniques with a variety of digital manufacturing techniques, such as vinyl/paper cutting, water jetting and laser cutting, which allow high accuracy and throughput rates. For molecular-scale materials, we recently established a chemical synthesis and characterization lab tailored for crystallization reactions.

7.2.4. Living Matter

The Living Matter theme has a well-developed infrastructure for studying living matter from the scale of single molecules to that of multicellular systems. The central tool in our experiments is quantitative microscopy coupled with automated image analysis. We strongly benefit from the cleanroom facilities of the AMOLF NanoLab, which allows us to produce microfluidic devices for long-term, on-chip cell culture. We share a diverse array of microscopy techniques selected for their complementarity. These include confocal scanning microscopes, single-molecule microscopy, fluorescence lifetime microscopy, and super-resolution techniques (PALM/STORM and structured illumination microscopy). For long-term, live imaging of cellular dynamics in organoids and single live *C. elegans* animals, we developed time-lapse imaging microscopy coupled with custom image analysis software. We are currently extending this approach to light-sheet imaging of organoids, with the aim of imaging multiple organoids in parallel, with sufficient spatial and temporal resolution to track all cells over multiple days.

8. Support

8.1. Support divisions

AMOLF provides high-quality technical and administrative support to facilitate its scientific research. The support facilities comprise four technical engineering divisions, the AMOLF NanoLab Amsterdam, and specialized research technicians (44 FTEs) and seven administrative divisions (37 FTEs). The technical and administrative divisions also support ARCNL. Sharing support divisions offers scale advantages for both institutes in terms of costs, expertise, and capacity. Consequently, the total number of employees working in the support divisions will increase gradually from 74 FTEs in 2014, at the start of ARCNL, to 94 FTEs in the coming years, including 20 FTEs support for ARCNL. At the end of 2016 ARCNL had 55 FTEs scientific personnel and AMOLF had 137 FTEs scientific personnel (including all undergraduate students).

8.2. Technical engineering

AMOLF supplies excellent technical support. The in-house facilities at AMOLF for the design and manufacturing of measurement equipment, electronics, and software engineering are essential for setting up new, innovative research directions, which is central to the AMOLF's mission. AMOLF has four technical engineering groups: Software Engineering, Electronics Engineering, Mechanical Engineering, and Precision Manufacturing. These groups support both AMOLF and ARCNL. The dynamic nature of AMOLF in starting new research directions requires that the technical support divisions are well-equipped, are able to accommodate new methods and techniques, and receive adequate training to pick up new developments.

Besides the technical engineering divisions, AMOLF employs 11.5 FTE research technicians. Research technicians are members of the scientific research groups and provide direct scientific support for the research setups. These technicians do not work for one single research group but flexibly divide the work within the team according to demand and expertise.

Some technicians are specialized in a specific scientific field, e.g. laser technology or microscopy. The group technicians generally also serve as intermediaries between the scientists and the technical support divisions to coordinate complex projects. In the AMOLF NanoLab, 4.9 FTEs of specialized technicians are employed.

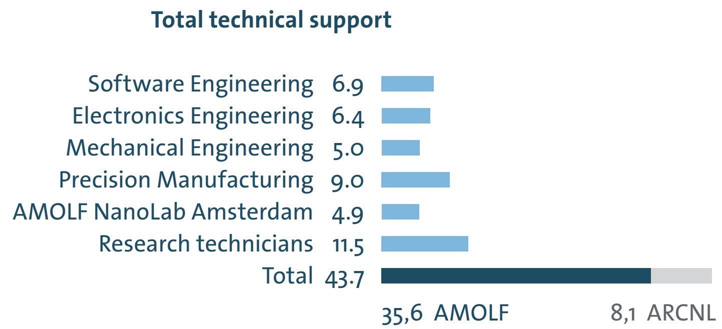
8.3. Administrative support

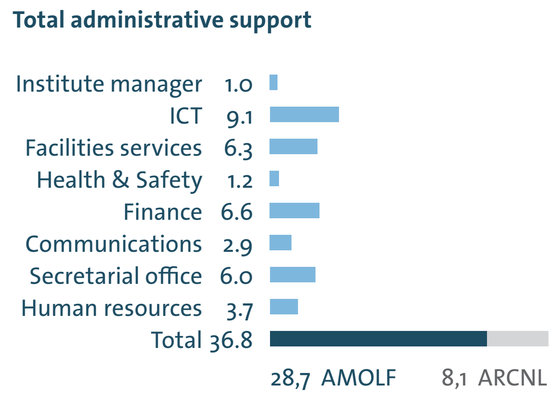
High quality administrative support is vital for creating a productive research environment. Administrative support is provided by ICT, Facilities services, Health & Safety, Finance, Communications, Secretarial office and Human resources. All administrative support divisions, except the secretarial office, support both AMOLF and ARCNL.

In 2016, several processes within the administrative divisions were digitized and administrative software systems were updated or replaced. This includes a renewal of the financial administration software, a new AMOLF website, an automated recruitment and selection system and a new digital environment for lab safety. In the coming years, the goal is to optimize these systems and make them part of the regular workflow, resulting in a professional software support environment.

Another important future development will be the implementation of a data management protocol. At the national level, NWO has set up a framework of guidelines for responsible data management to ensure that publicly funded research is freely and sustainably available. We anticipate that the implementation of an advanced data management policy will strongly affect the AMOLF support divisions. For example, within the ICT division, investments in data storage and retrieval are essential, data validation and certification protocols need to be developed, and experimental data acquisition software needs to be adapted together with the Software Engineering department.

As of January 1 2017, AMOLF is part of the new NWO-I Foundation. NWO-I supports the NWO institutes by serving as back office for several administrative services and expertise. Also NWO-I provides support for long-term strategic planning and serves as a liaison with external stakeholders. The scope of the back office services that will be provided by NWO-I is currently being finalized. The outcome of this process will to some extent impact the (front office) administrative services at AMOLF.





FTE by January 1, 2017

Appendix: Organization chart

AMOLF physics of functional complex matter

DIRECTOR Huib Bakker

SCIENCE

Nanophotonics / Nanophotovoltaics

Femius Koenderink

- Resonant Nanophotonics – Femius Koenderink
- Photonic Forces – Ewold Verhagen
- Photonic Materials – Albert Polman
- Nanoscale Solar Cells – Erik Garnett
- Hybrid Solar Cells – Bruno Ehrler
- 3D Photovoltaics – Esther Alarcón Lladó

Designer Matter

Martin van Hecke

- Mechanical Metamaterials – Martin van Hecke
- Self-Organizing Matter – Wim Noorduin
- Soft Robotic Matter – Bas Overvelde
- Ultrafast Spectroscopy – Huib Bakker

Living Matter

Gijsje Koenderink

- Biological Soft Matter – Gijsje Koenderink
- Theory of Biomolecular Matter – Bela Mulder
- Biochemical Networks – Pieter Rein ten Wolde
- Biophysics – Sander Tans
- Systems Biology – Tom Shimizu
- Quantitative Developmental Biology – Jeroen van Zon

SUPPORT

MANAGER Paula van Tijn

Technical Engineering

- Software Engineering – Marco Konijnenburg
- Electronics Engineering – Duncan Verheijde
- Mechanical Engineering – Iliya Cerjak
- Precision Manufacturing – Jan van der Linden
- NanoLab Amsterdam – Hans Zeijlemaker

General Support

- Facilities
- Administration

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AMOLF physics of functional complex matter