FOM - 14.0209

Annual report 2013

FOM programme nr. 124
'Nanoscale quantum optics'

Foundation for Fundamental Research on Matter
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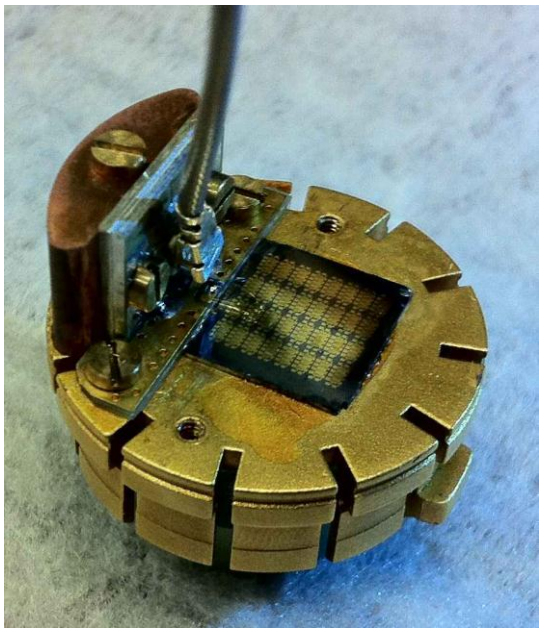

Image of the chip containing detectors such as those used in the experiments. The chip is located on a copper fixture.

May 2014

Content

1. Scientific results 2013

The FOM programme 'Nanoscale quantum optics' (NQO) is now in its third year, and significant progress has been made in all parts of the programme, as described below.

The study of *spontaneous emission at the nanoscale* (Challenge 1) is progressing along two lines: semiconductor quantum dots (QDs) and nitrogen-vacancy (NV) centers in diamond. On the QD side, work at TU/e has resulted in bright emission lines for QDs grown at only 10 nm from an etched surface - an important milestone for their controlled coupling to plasmonic antennas, which is now under investigation. After the ground-breaking demonstration of spin entanglement in NV centers last year (published in Nature), work at TUD has continued towards realizing teleportation between remote single quantum emitters.

Work on *stimulated emission at the nanoscale* (Challenge 2) has resulted in the first observation of surface plasmon lasing in metal hole arrays by the Leiden group, and published in Phys. Rev. Lett. Moreover, the measured angular dependence of the emission spectra enabled the mapping of the dispersion of the surface plasmons (= plasmonic band structure) and quantifying the (backward and sideward) scattering rate of surface plasmons incident on a sub-wavelength hole. At AMOLF, room-temperature lasing in complementary structures, i.e. periodic arrays of plasmon particles was observed, mediated by in-plane distributed feedback, combined with a strong signature of plasmonic resonances. Lasing was also observed in plasmon lattices that are quasiperiodic, aperiodic, or have correlated disorder, leading to a quest to unravel (Anderson) localized modes in plasmon nanoparticle array lasers.

The investigations on *Detection of quantum light at the nanoscale* (Challenge 3) are continuing to bring a wealth of results, taking advantage of the combination of the detector tomography methods developed at Leiden and the superconducting nanowire detectors fabricated at TU/e. By a very accurate measurement of the detector's multiphoton response, a 'universal' scaling law has been discovered, which describes the detector's click probability as a function of current and photon energy. The comparison of this scaling law and of its temperature dependence to the existing theoretical models has allowed evidencing the role of quasi-particle diffusion and vortices in the detector's operation (paper in press in Phys. Rev. Lett.). Moreover, the systematic study of detectors with different lengths has revealed an unexpected dependence of the critical current and efficiency on length, which represents a strong evidence of continuously distributed inhomogeneities at the sub-100 nm scale. Together, these results represent perhaps the most significant progress in the understanding of the physics of photodetection in superconducting nanowires in the last few years.

Finally, the activity on *Optical nonlinearities at the nanoscale* (Challenge 4) has greatly progressed. After the first demonstration of bunching of two single plasmons on-chip (published in Nature Nanotechnology), work at TUD has continued towards the integration of plasmon sources and detectors. At AMOLF clear evidence of second- and third-harmonic generation from plasmonic structures has been obtained. Investigations are currently underway to determine two things. First, is the harmonic radiation generated in a guided mode along the wire and subsequently scattered to the far field, or is it unguided and merely generated locally by a nonlinear interaction of the guided fundamental mode with local geometrical imperfections? Second, what is the role of the geometry of the plasmonic nanowire on the efficiency of the conversion process?

2. Added value of the programme

The NQO programme is strongly contributing to reinforcing the coherence and collaboration between the research programmes of the participating groups in the area of quantum optics. Some examples:

- The groups in Leiden and TU/e have a joint and very successful activity on the characterisation of nanoscale detectors. The collaboration nicely takes advantage of the complementarity of the nanotechnology/nanophotonics expertise in Eindhoven and the quantum optics competence in Leiden. In another NQO-related theme (plasmonic lasers), nanofabrication is realised by a student from Leiden in the TU/e cleanroom, again showing the relevance of this collaboration. Further joint activities in a distinct, but related field (semiconductor quantum optics) are being initiated.
- Several contacts have taken place between TU/e and AMOLF on possible joint programmes in nanophotonics, and a collaboration has been started in the field of optomechanics (Verhagen's and Fiore's groups). A student exchange within the NQO programme (from Fiore's group to Koenderink's group) is planned in 2014.
- Dr. M.P. van Exter (Leiden) spent a sabbatical period in AMOLF in 2012.
- A national workshop in the field of Micro- and Nano-scale Quantum Optics (involving also groups outside NQO) has been organised in Eindhoven in 2013.
- A Lorentz center workshop on 'Nanoscale Quantum Optics' has been organised (De Dood, Wubs, Fiore) and will take place in June 2014.
- Several contacts and collaborations with external groups are taking place, including with Danish Technical University, the Ames lab (Iowa, USA) and the LENS/Univ. Florence.

3. Personnel

All the NQO positions have been filled and the corresponding PhD projects are in good course. Guest visits took place in 2012 (two in AMOLF and one in Delft), and one more is scheduled next year (AMOLF).

4. Publications

<u>10NQO01</u>

- *Z. Zhou, G. Frucci, F. Mattioli, A. Gaggero, R. Leoni, S. Jahanmirinejad, T.B. Hoang, and A. Fiore,* Ultrasensitive N-Photon Interferometric Autocorrelator, Phys. Rev. Lett. 110, 133605 (2013).

<u>10NQO02</u>

- *H. Bernien, B. Hensen, W. Pfaff, G. Koolstra, M.S. Blok, L. Robledo, T.H. Taminiau, M. Markham, D.J. Twitchen, L. Childress, R. Hanson,* Heralded entanglement between solid-state qubits separated by three meters, Nature 497, 86 (2013).
- *R.W. Heeres, L.P. Kouwenhoven, V. Zwiller,* Quantum interference of surface plasmons, Nature Nanotechnology 8, 719 (2013).

<u>10NQO03-1</u>

- *J.J. Renema, G. Frucci, Z. Zhou, F. Mattioli, A. Gaggero, R. Leoni, M.J.A. de Dood, A. Fiore, M.P. van Exter*, Universal response curve for nanowire superconducting single-photon detectors, Phys. Rev. B 87, 174526 (2013).
- *F. van Beijnum, P.J. van Veldhoven, E.J. Geluk, M.J.A. de Dood, G.W. 't Hooft, M.P. van Exter,* Surface plasmon lasing observed in metal hole arrays, Physical Review Letters, 110, 206802 (2013).

<u>10NQO03-2</u>

- *Q. Wang and M.J.A. de Dood,* An absorption-based superconducting nano-detector as a near-field optical probe, Optics Express 21, 3682 (2013).

5. Valorisation and outreach

Even though the research carried out in this programme is of fundamental nature, short-term valorisation opportunities are possible in the field of superconducting detectors, where TUD's spin-off Single Quantum is active. Discussions between TU/e, TUD and Single Quantum about possible joint projects are taking place.

The following outreach activities, related to the broad field of optics, have been realised by NQO members in 2013:

- A.F. Koenderink, interview in NewScientist [Nederlandstalige editie], 6, 70-71, December 2013 '*Je Moet Kinderen Zelf Onderzoek Laten Doen*' in de rubriek Opinie: De Jonge Akademie.
- F. Koenderink, lezing '*Licht en nanotechnologie*', eindexamenklassen VMBO-TL natuurkunde en scheikunde, EemsDelta College, Delfzijl, 12 December 2013.
- F. Koenderink with Stichting Atelier van Licht: '*Atelier van Licht*' exposition at Stedelijk Museum for children (3-8 yrs old) with their parents, from 22 December 2012 to 6 January 2013. Approximately 4900 visitors.

APPROVED FOM PROGRAMME

Number	124.
Title (code)	Nanoscale quantum optics (NQO)
Executive organisational unit	BUW
Programme management	Prof.dr. A. Fiore
Duration	2011-2015
Cost estimate	M€ 3.0

Concise programme description

a. Objectives

This programme aims at investigating quantum optical processes on the deep subwavelength scale, that is in structures where the optical field shows strong spatial variations on <100 nm scale, well below the diffraction limit. We will study spontaneous and stimulated light emission, optical detection and optical nonlinearities at the nanoscale and at the single-quantum level.

b. Background, relevance and implementation

The investigation of atom-photon interaction is an important topic in modern physics and represents the basis for virtually all optical technologies. In particular, quantum optics has been an ideal playground for testing the foundations of quantum mechanics as well as novel ideas for quantum information processing using photons. So far, quantum optical experiments have been performed with fields, which are either freely-propagating or confined in optical cavities of the scale of one or few wavelengths, as limited by diffraction. This programme aims at investigating for the first time quantum optical processes on the deep subwavelength scale. At this length scale, the basic assumptions and approximations used to describe radiative processes in the solid-state break down as the field length scales become comparable to excitonic wavefunctions in semiconductor nanostructures. Our fundamental understanding of cavity quantum electrodynamics (QED) is challenged by the polaritonic nature of plasmonic excitations and their ultrashort lifetimes. The dynamic and statistical properties of nanoscale lasers are expected to deviate widely from conventional laser theory due to the ultrafast recombination timescales and extreme field inhomogeneities. Even the basic concept of photon absorption in the near-field has never been addressed experimentally at the single-quantum level. Besides opening novel and intriguing research directions, the peculiar properties of subwavelength fields can be exploited to optimize light-matter coupling or explore new functionalities, for future application in classical and quantum photonics.

This programme will focus on four key challenges, which arise in the investigation of quantum optical effects at the nanoscale:
1. Developing a physical description of spontaneous emission and cavity QED at the nanoscale.
2. Understanding stimulated emission and nanolasers on a deep subwavelength scale.
3. Investigating the subwavelength structure of quantum states of light in the near-field.
4. Studying optical non-linearities at the nanoscale and at the single-quantum level.

Funding

salarispeil cao per 01-07-2012

bedragen in k€	≤ 2013	2014	2015	2016	2017	2018	≥ 2019	Totaal
FOM-basisexploitatie	1.683	546	282	-	-	-	-	2.511
FOM-basisinvesteringen	520	-	-	-	-	-	-	520
Doelsubsidies NWO	-	-	-	-	-	-	-	-
Doelsubsidies derden	-	-	-	-	-	-	-	-
Totaal	2.203	546	282	-	-	-	-	3.031

Source documents and progress control

a) Original programme proposal: FOM-10.1233
b) Ex ante evaluation: FOM-10.1406
c) Decision Executive Board: FOM-10.1714

Remarks

The final evaluation of this programme will consist of a self-evaluation initiated by the programme leader and is foreseen for 2016.

PT par. HOZB

Subgebied: 100% NANO

Historical overview of input en output

Input	personnel (in fte)				finances* (in k€)
	WP/V	WP/T	PhD	NWP	
2011	-	-	2.5	-	344
2012	-	0.9	7.0	-	561
2013	-	1.0	8.0	-	650

Output	PhD theses	refereed publications	other publications & presentations	patents
2011	-	-	3	-
2012	-	1	21	-
2013	-	7	34	-

* After closing the financial year.

PhD defences

2011
None.

2012
None.

2013
None.

Patents (new/changes)

2013
None.

Overview of projects and personnel

Workgroup FOM-D-41

Leader	Prof.dr.ir. L.P. Kouwenhoven
Organisation	Delft University of Technology
Project leader	Dr. V. Zwiller
	Prof.dr.ir. R. Hanson
Programme	Nanoscale quantum optics
Project (title + number)	Cooperative and nonlinear optical processes at the nanoscale 10NQO02

FOM employees on this project

Name	Position	Start date	End date
B.J. Hensen	PhD	01 March 2012	29 February 2016
I. Esmaeil Zadeh	PhD	01 August 2011	31 July 2015

Workgroup FOM-E-06

Leader	Prof.dr. A. Fiore
Organisation	Eindhoven University of Technology
Programme	Nanoscale quantum optics
Project (title + number)	Spontaneous emission and light detection at the nanoscale 10NQO01

FOM employees on this project

Name	Position	Start date	End date
M. Cotrufo	PhD	15 October 2012	14 October 2016
Y. Cho	postdoc	07 February 2012	06 February 2015
R. Gaudio	PhD	01 November 2011	31 October 2015

Workgroup FOM-L-02

Leader	Prof.dr. E.R. Eliel
Organisation	Leiden University
Project leaders	Dr. M.J.A. de Dood
Programme	Nanoscale quantum optics
Project (title + number)	Quantum optical fields at the nanoscale 10NQO03-2

FOM employees on this project

Name	Position	Start date	End date
Q. Wang	PhD	01 August 2011	31 July 2015

Workgroup FOM-L-31

Leader	Dr. M.P. van Exter
Organisation	Leiden University
Programme	Nanoscale quantum optics
Project (title + number)	Quantum optical fields at the nanoscale 10NQO03-1

FOM employees on this project

Name	Position	Start date	End date
J.J. Renema	PhD	01 February 2011	31 January 2015

Group Kuipers

Leader	Prof.dr. L. Kuipers
Organisation	FOM Institute AMOLF
Programme	Nanoscale quantum optics
Project (title + number)	Singular and nonlinear quantum optics at the nanoscale 10NQO07

FOM employees on this project

Name	Position	Start date	End date
A.K. de Hoogh	PhD	01 September 2011	31 August 2015

Group A.F. Koenderink

Leader	Prof.dr. A.F. Koenderink
Organisation	FOM Institute AMOLF
Programme	Nanoscale quantum optics
Project (title + number)	Spontaneous and stimulated emission in subwavelength plasmon resonators 10NQO04

FOM employees on this project

Name	Position	Start date	End date
A.H. Schokker	PhD	01 October 2011	30 September 2015