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# THEO MURPHY INTERNATIONAL SCIENTIFIC MEETING ON

# Metallic metamaterials and plasmonics

**Wednesday 2 and Thursday 3 June 2010**

Organised by Professor Bill Barnes, Dr Alastair Hibbins and Professor Roy Sambles FRS (University of Exeter); Professor Nader Engheta (University of Pennsylvania)

- **Programme and abstracts**
- **Speaker biographies**
- **Poster titles and poster abstracts**

# Metallic metamaterials and plasmonics

**2 – 3 June 2010, organised by Professor Bill Barnes, Dr Alastair Hibbins, Professor Roy Sambles FRS and Professor Nader Engheta**

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# Metallic metamaterials and plasmonics

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**Wednesday 2 and Thursday 3 June 2010**

## Synopsis

Our ability to control and harness light is undergoing a revolution, one that exploits the special properties of metals and our ability to structure them on a sub-wavelength scale. These plasmonic and metallic metamaterials provide challenges for physicists and engineers that demand a multi-disciplinary approach. This meeting brings together scientists from different sub-disciplines to exchange knowledge and forge new ideas.

## Wednesday 2 June 2010

**09.20 Welcome by Ian Cooper**, Director, Finance & Operations, Royal Society
**Welcome by Professor Bill Barnes**, Organiser

**Session 1 – Electromagnetic metallic metamaterials**
**Chair Professor Bill Barnes, University of Exeter, UK**

**09.30 Photonic metamaterials: recent progress**
Professor Martin Wegener, Karlsruhe Institute of Technology, Germany

We review our recent experimental progress regarding three-dimensional metamaterials operating at optical frequencies. This includes (i) three-dimensional gold-helix metamaterials made by direct laser writing (DLW) and gold electroplating that can be applied as compact broadband circular polarizers – in analogy to the good old wire-grid polarizers for linear polarization of light. Here, light propagates along the helix axis (J.K. Gansel et al., Science 25, 1513 (2009)). More recently, (ii) we have also fabricated structures allowing for studying the case that the magnetic field of the light is parallel to the gold-helix axis (unpublished). Furthermore, (iii) we have realized and characterized three-dimensional carpet cloak structures by DLW (T. Ergin et al., Science, in press (2010); online March 18, 2010). Possibly, (v) we also discuss using very highly doped semiconductors as alternatives for usual metals such as gold (unpublished).

**10.00 Discussion**

**10.15 Free-space excitation of propagating surface plasmon polaritons**
Professor Lukas Novotny, University of Rochester, USA

Understanding species diversity patterns represents one of the most fundamental problems in ecology. Most research in this area has focused on spatial gradients of species richness and diversity, with a smaller area of emphasis dedicated to understanding the temporal dynamics of diversity. However, few attempts have been made to understand the linkages between spatial and temporal patterns related to diversity. Here we argue that patterns of spatial and temporal diversity and the processes that drive them are inherently linked and that our understanding of diversity will be substantially improved by considering them simultaneously. We review work that has explicitly or implicitly addressed these linkages and suggest future directions for understanding the underlying connections between these two traditionally isolated fields of research.

**10.45 Discussion**

**11.00 Coffee**

**11.30 Light in plasmonic structures - an investigation beyond the diffraction limit**
Professor Kobus Kuipers, FOM Institute for Atomic and Molecular Physics, The Netherlands

One of the key features of interest of plasmonic nanostructures is their ability to confine and enhance light fields on a scale that is (much) smaller than the wavelength in the surrounding medium. The strong interplay between the geometry and the light results in highly structured light fields on the nanoscale.

In this presentation I will show recent progress in the visualization of such light fields beyond the diffraction limit. Surface plasmons launched from periodic arrays of holes exhibit the Talbot effect. By exploiting a recent advance in the measurement of vector fields with near-field microscopy, we were able to determine the symmetry of MIM modes in plasmonic slot waveguides and of plasmonic nanowire modes. Transition radiation –better known as cathodoluminescence– in which an focused beam of electrons produces the emission of light, is another valuable tool to investigate plasmonic structures. We exploit its unique properties to study subwavelength holes.

**12.00 Discussion**

**12.30 Lunch**

**Session 2 – Poster session and discussion**
**Chair Professor Ortwin Hess, University of Surrey, UK**

**13.45 Spasers, nanolasers, and ultrafrast nanoplasmonics**
Professor Mark Stockman, Georgia State University, USA

Nanoplasmonics deals with collective electron dynamics on surfaces of metal nanostructures, which arises as a result of excitations called surface plasmons. The surface plasmons localize optical energy in nanoscopic regions creating highly enhanced, ultrafast local optical fields. We will briefly review numerous existing applications of nanoplasmonics in science, technology, and biomedicine. From the latest developments and original work in nanoplasmonics, we will concentrate on SPASER (Surface Plasmon Amplification by Stimulated Emission of Radiation) as a generator of optical fields on the nanoscale and ultrafast nanoamplifier. Another subject related to ultrafast plasmonics to be considered is surface-plasmon-induced drag-effect rectification (SPIDER). This ultrafast effect generates subpicosecond pulses of nanolocalized THz fields.

**14.15 Discussion**

**14.30 Transformation optics at optical frequencies**
Professor Sir John Pendry FRS, Imperial College London, UK

Transformation optics tells us how a distortion of space, and the objects it contains, maps into changes of the effective electric and magnetic responses of the distorted materials. This can be exploited to generate new devices from familiar ones. For example it is well known that a slab of negatively refracting material has lens like properties and can focus light. However the images are always of exactly the same size as the objects. This restriction can be lifted by applying transformation optics to create a negatively refracting magnifying lens that also has the property of sub wavelength. In the exact formulation both electrical and magnetic properties are equally affected by the transformation, but in the near field approximation at optical frequencies we can neglect the magnetic component. This leads to some novel devices that will be described in this talk.

**15.00 Discussion**

**15.15 Tea**

**15.45 Poster session**

**17.00 Close**

**Thursday 3 June 2010**

**Session 3 – Plasmonics**
**Chair Professor Mark Stockman, Georgia State University, USA**

**09.30 Electrochemical tuning of SP resonances of single gold nanocrystals**
Professor Paul Mulvaney, University of Melbourne, Australia

The spatial confinement of conduction electrons in sub-wavelength structures such as metal nanocrystals leads to surface plasmon resonances.

We demonstrate here that the surface plasmon resonance of a single gold nanocrystal can be both passively and actively modulated directly by altering the electron density of the metal. The changes in the plasmon resonance of single particles are detected *in situ* using dark field microscopy to study the scattered light (Rayleigh Spectra) from single gold nanocrystals. Using this technique we are able to observe chemical reactions of single gold nanocrystals, including a catalytic cycle.

Electrochemical charging of the nanoparticles allows the reversible, active modulation of the surface plasmon resonance. The scattering spectra of single gold rods have been measured as a function of the applied potential in an electrochemical cell using dark field microscopy. It is demonstrated that the surface plasmon resonance can be reversible and rapidly tuned by tens of nanometres.

**10.00 Discussion**

**10.15 Quantum plasmonics**
Professor Mikhail Lukin, Harvard University, USA

We will discuss our recent work involving the interface of quantum optics and nanoscale plasmonics. Specifically, we will discuss the experiments demonstrating strong coupling between individual optical emitters and single plasmons guided in metallic nanowires. We will also describe our recent efforts towards development of nanoscale plasmonic resonators and novel techniques for on-chip generation and detection of individual plasmons. Possible applications of these techniques will be described.

**10.45 Discussion**

**11.00 Coffee**

**11.30 Molecular plasmonics – light meets molecules at the nanoscale**
Dr Wolfgang Fritzsche, Institute of Photonic Technology, Germany

Certain metal nanoparticles exhibit the effect of localized surface plasmon resonance when interacting with light, based on collective oscillations of their conduction electrons. The interaction of this effect with molecules is of great interest for a variety of research disciplines both in optics and in life sciences. The paper attempts to describe and structure this emerging field of molecular plasmonics situated between the molecular world and plasmonic effects in metal nanostructures, and demonstrates the potential of these developments for a variety of applications.

**12.00 Discussion**

**12.30 Lunch**

## Session 4 – Active plasmonics and metamaterials
**Chair Professor Lukas Novotny, University of Rochester, USA**

**14.00 Plasmonics: development of new materials**
Professor Harry Atwater, California Institute of Technology, USA

Since 2000, quantitative full field electromagnetic modeling and powerful nanostructure fabrication tools have catalyzed the development of plasmonics as a truly nanoscale photonics discipline. We now have a good understanding of plasmonic modes and localized waveguide modes, and recently first examples of active plasmonic materials and devices that enable gain, carrier excitation and complex index modulation have been demonstrated. What will the next ten years bring? First, there are compelling applications in solar energy. Recent progress in plasmonic photovoltaics illustrates that plasmonic design can yield important and practical photovoltaic device improvements. More fundamentally, there is also now the opportunity to achieve new material performance by exerting active control over metallic carrier densities and local field intensities. Plasmonic materials with losses lower than those exhibited by silver may be achievable by lowering the carrier density in materials such as conducting oxides. Controlling the carrier density in a regime intermediate between ordinary metals and dielectrics enables control of the complex dielectric function of a metal. Finally, active tuning of local fields in nanoscale gaps of coupled resonators on highly compliant polymer substrates enables wide tunability of metamaterial resonances, and leads to a new approach to surface-enhanced infrared absorption spectroscopy, which is metamaterial resonances are tuned through absorption lines to enable molecular sensing.

**14.30 Discussion**

**14.45 Metamaterials, Cloaking and Plasmonic Lasers**
Professor Xiang Zhang, University of California at Berkeley, USA

Metamaterials are artificially designed subwavelength composites that possess extraordinary properties not existing in naturally occurring materials. In particular, they can alter the propagation of electromagnetic waves resulting in negative refraction, subwavelength focusing and even in cloaking of macroscopic objects. Such unusual properties can be obtained by a careful design of dielectric or metal-dielectric composites on a deep sub-wavelength scale. The metamaterials may have profound impact in wide range of applications such as nano-scale imaging, nanolithography, and integrated nano photonics. I will discuss a few recent experiments demonstrating intriguing phenomena associated with Metamaterials. These include subdiffraction limit imaging and focusing, low-loss and broad-band negative-refraction of visible light, negative-index metamaterials and the first cloak operating at optical frequencies; an all-dielectric “carpet cloak” with broad-band and low-loss performance. I will also present our recent demonstration of a deep sub-wavelength plasmonic laser.

**15.15 Discussion**

**15.30 Tea**

**16.00 Leveraging field enhancement in metamaterials and plasmonics**
Professor David R. Smith, Duke University, USA

*Abstract not available.*

**16.30 Discussion**

**16.45 Panel discussion: overview and future directions**

**17.00 Close**

## Organiser, speaker and chair biographies

**Professor Harry Atwater, California Institute of Technology, USA (Speaker)**
Harry Atwater is currently Howard Hughes Professor and Professor of Applied Physics and Materials Science at the California Institute of Technology. Atwater received his SB (1981), SM (1983), and PhD (1987) in Electrical Engineering from the Massachusetts Institute of Technology.

His research interests center around plasmonics, metamaterials, and also photovoltaics and photoelectrochemical solar fuel production. He is an early pioneer in surface plasmon photonics; he gave the name to the field of plasmonics in 2001. He has authored or co-authored over 200 publications, and his group's developments in the plasmonics field have been featured in *Scientific American* and in research papers in *Science, Nature Photonics* and *Advanced Materials.*

He currently serves as Director of Caltech's Resnick Institute for the Science of Energy, is also Director of the DOE Energy Frontier Research Center on Light-Matter Interactions in Solar Energy Conversion, and is also Director of the Caltech Center for Sustainable Energy Research.

Atwater is founder and chief technical advisor for Alta Devices, a Silicon Valley-based solar energy company, and Aonex Corporation, a compound semiconductor materials company. He is also a editorial board member for Surface Review and Letters.

Atwater has been honored by awards including the Joop Los Fellowship from the Dutch Society for Fundamental Research on Matter, 2005; AT&T Foundation Award, 1990; NSF Presidential Young Investigator Award, 1989; IBM Faculty Development Award, 1989-1990; Member, Bohmische Physical Society, 1990; IBM Postdoctoral Fellowship, 1987.

Professor Atwater has consulted extensively for industry and government, and has actively served the materials community in various capacities, including Material Research Society Meeting Chair (1997), Materials Research Society President (2000), AVS Electronic Materials and Processing Division Chair (1999), and Board of Trustees of the Gordon Research Conferences. In 2008, he served as Chair for the Gordon Research Conference on Plasmonics.

**Professor Bill Barnes, University of Exeter, UK (Organiser and Chair)**
Professor Barnes has been fascinated by science since an early age. An interest in astronomy led to the choice of a Physics degree, and he hasn't looked back since. Current research involves the interaction between light and matter - particularly through the use of the metals - a field known as plasmonics. Professor Barnes received BSc and PhD Physics from Exeter in 1983 and 1986 respectively. From 1986 - 1992 he was a research fellow in the Optoelectronics Research Centre at Southampton University. In 1992 he was appointed to a staff position at Exeter. Professor Barnes is fortunate enough to be a Royal Society Wolfson Research Merit Award Holder.

**Dr Wolfgang Fritzsche, Institute of Photonic Technology, Germany (Speaker)**
After completing his PhD thesis in physical chemistry in 1994 at the Georg-August-University Göttingen

(Germany) with the work carried out at the Max-Planck-Institute for Biophsical Chemistry Göttingen, he spent two years as a postdoc at the Iowa State University. He returned 1996 to Jena (Germany) to work there at the Institute for Photonic Technology (IPHT). Here he established a group Molecular Nanotechnology, and since 2001 he is head of the Nanobiophotonics department. His research interest focuses on Molecular Plasmonics based on combinations of metal nanoparticles, DNA as well as microstructured chips for potential applications in nanooptics and bioanalytics.

**Dr Alastair Hibbins, University of Exeter (Organiser)**
Alastair Paul Hibbins was born in Somerset, United Kingdom in 1975. After graduating with a BSc in Physics from the University of Exeter, United Kingdom in 1996, he undertook research into grating coupling of surface plasmon polaritons at visible and microwave frequencies during his PhD. Since then, he has studied the electromagnetic response of photonic, plasmonic and metamaterial structures as a member of the Electromagnetic Materials research group at Exeter. In 2004 he was awarded a prestigious EPSRC Advanced Fellowship, and in April 2007 was appointed as a Lecturer in Physics / Electromagnetics / Photonics / Plasmonics. His 40 publications in peer-reviewed journals (including one in Science and seven in Physical Review Letters) have attracted more than 600 citations, and include studies of ultra-thin absorbers, enhanced transmission phenomena, plasmonic metamaterials and coupled resonator systems. He now leads a group PhD students and researchers working on metamaterial-themed projects, funded on EPSRC projects and by industries including BAE Systems, QinetiQ and Dstl.

**Professor Kobus Kuipers, FOM Institute for Atomic and Molecular Physics, The Netherlands (Speaker)**
Kobus Kuipers obtained his Masters with distinction at the University of Amsterdam in 1990. In 1994 he obtained his PhD for work on high-temperature scanning tunnelling microscopy of surface diffusion phenomena at AMOLF. He won the Oppenheimer Fellowship 1994 of the University of Cambridge (UK) to investigate the dynamics of mass-selected nanoclusters. In 1997 he became an assistant professor at the University of Twente. In 2000 he was appointed as a program director of the MESA+ Research Institute (Twente). In 2001 he received a personal chair at the University of Amsterdam. In 2003 he moved to the FOM Institute AMOLF and also became a part-time professor at the University of Twente. In 2003 he won the prestigious NWO-VICI subsidy to investigate nonlinear optics at the nanoscale. He became head of the Center for Nanophotonics at AMOLF in 2006.

Kobus has published more than 110 papers in refereed international journals of which 2 in Science, 3 in a journal of the Nature-family and 18 in Physical Review Letters. In 2004 he became an elected member of De Jonge Akademie, a section of the Royal Dutch Academy of Sciences. In 2009 he was elected a Fellow of the Optical Society of America.

**Professor Mikhail Lukin, Harvard University, USA (Speaker)**
Mikhail Lukin received the PhD degree from Texas A&M University in 1998. He was a post-doctoral fellow at the Institute for Theoretical Atomic and Molecular Physics at Harvard University from 1998-2001. He joined the faculty of Harvard Physics Department as an Assistant Professor in 2001 and has been a Professor of Physics at Harvard since 2004. He is a fellow of the Optical Society of America. His research interests include quantum optics, quantum control of atomic and nanoscale solid-state systems, quantum dynamics of many-body systems and quantum information science. He has co-authored over 150 technical papers and has received a number of awards, including Alfred P. Sloan Fellowship, David and Lucile Packard Fellowship for Science and Engineering, NSF Career Award, Adolph Lomb Medal of the Optical Society of America, AAAS Newcomb Cleveland Prize and I.I.Rabi prize of American Physical Society.

**Professor Paul Mulvaney, University of Melbourne, Australia (Speaker)**
Paul Mulvaney is an ARC Federation Fellow and Professor of Chemistry in the School of Chemistry and Bio21 Institute at the University of Melbourne.

He received his PhD degree at the University of Melbourne in 1989, working on surface electron transfer reactions with Professor Franz Grieser. He has worked as a research associate at the ANU Applied Maths Department (1988-89) and the Argonne National Laboratory in Chicago in 1986-87, 88. He was appointed as a research scientist at the Hahn-Meitner-Institute for Nuclear Research in Berlin from 1989-1992 with Professor Arnim Henglein, where he studied pulse radiolysis and the nucleation of nanocrystals. In 1993 he returned to the University of Melbourne as an ARC QEII Research Fellow, and he accepted a Faculty position in 1997. In 1999, he spent time in Palo Alto with Quantum Dot Corporation. He was a Humboldt Research Fellow in 2000 at the Max-Planck Insitute for Colloids and Surfaces in Golm with Professor Markus Antonietti, and again in 2005 at the CAESAR Nanotechnology Institute in Bonn with Professor Michael Giersig. He is currently Chair of the Australian Colloid and Surface Chemistry Division of the Royal Australian Chemical Institute.

His current interests include the optical properties of single quantum dots, surface plasmon spectroscopy and nanocrystal based electronics. To date he has published some 180 scientific papers averaging around 50 citations per publication. His h-index is 53.

Professor Mulvaney currently serves on the editorial boards of Advanced Functional Materials, Journal of Materials Chemistry, Langmuir, Small and PCCP. He was made a Fellow of the Australian Academy of Sciences in 2009.

**Professor Lukas Novotny, University of Rochester, USA (Speaker and Chair)**
Professor Novotny earned his Dipl. El-Ing (M.S. in Electrical Engineering) in 1992 and his Dr. sc. techn. (Doctor of Technical Sciences) in 1996, both from the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. His doctoral research was in close collaboration with the IBM Research Laboratory in Switzerland and dealt with theoretical questions in near-field optics. After three years as a postdoctoral fellow at the Pacific Northwest National Laboratory in Washington, working on new schemes of near-field optical microscopy and single molecule spectroscopy, Professor Novotny joined the faculty of the Institute of Optics in 1999 as an Assistant Professor. He was promoted to Associate Professor in 2003 and full Professor in 2007. He holds joint appointments in Physics and Biomedical Engineering. Professor Novotny is the author of "Principles of Nano-Optics", published by Cambridge University Press.

**Professor Ortwin Hess, University of Surrey, UK (Chair)**
Ortwin Hess studied physics at the University of Erlangen and the Technical University of Berlin. He obtained the Dipl Phys (MSc) and Dr rer-nat (PhD) degrees at the Technical University of Berlin in 1990 and 1993, respectively. From 1990 to 1992 he has been Research Associate in Edinburgh and spent a Post-Doc at the University of Marburg (1993 - 1994). From 1995 to 2003 Ortwin has been Head of the Theoretical Quantum Electronics Group at the DLR in Stuttgart, Germany. He has a Habilitation in Theoretical Physics at the University of Stuttgart (1997) and became Adjunct Professor in 1998. Since 2001 he is Docent of Photonics at Tampere University of Technology in Finland. Ortwin has been Visiting Professor at Stanford University (1997 - 1998) and the University of Munich (2000 - 2001). Since March 2003 Ortwin holds the Chair of Theoretical Condensed Matter and Optical Physics in the Department of Physics and the Advanced Technology Institute. He is Head of the Theory and Advanced Computation Group.

**Professor Sir John Pendry FRS, Imperial College London, UK (Speaker)**
John Pendry is a condensed matter theorist. He has worked at the Blackett Laboratory, Imperial College London, since 1981. He began his career in the Cavendish Laboratory, Cambridge, followed by six years at the Daresbury Laboratory where he headed the theoretical group. He has worked extensively on electronic and structural properties of surfaces developing the theory of low energy diffraction and of electronic surface states. Another interest is transport in disordered systems where he produced a complete theory of the statistics of transport in one dimensional systems.

In 1992 he turned his attention to photonic materials and developed some of the first computer codes capable of handling these novel materials. This interest led to his present research which concerns the remarkable electromagnetic properties of 'metamaterials' whose properties owe more to their micro-structure than to the constituent materials. These made accessible completely novel materials with properties not found in nature. Successively metamaterials with negative electrical permittivity, then with negative magnetic permeability were designed and constructed. These designs were subsequently the basis for the first material with a negative refractive index, a property predicted 40 years ago by a Russian scientist, but unrealised because of the absence of suitable materials. This project culminated in the proposal for a 'perfect lens' whose resolution is unlimited by wavelength.

More recently, in collaboration with a team of scientists at Duke University, he has developed the concept of 'transformation optics' which prescribes how electromagnetic lines of force can be manipulated at will. This enabled a proposed recipe for a cloak that can hide an arbitrary object from electromagnetic fields.

**Professor Roy Sambles FRS, University of Exeter, UK (Organiser)**
Professor Roy Sambles has been Professor of Experimental Physics at The University of Exeter since 1991. His present research concerns primarily the electromagnetic properties of structured metals and the viscodynamics of liquid crystals. He was awarded the George Gray medal of the British Liquid Crystal Society in 1998, and the Young Medal and Prize by the Institute of Physics in 2003, and elected a Fellow of the Royal Society in 2002. He is a Fellow of the Institute of Physics. In addition to his research activities he is presently a Council member of the EPSRC, a member of: the Scientific Advisory Committee for IoP publishing; the editorial board of 'Thin Solid Films'; the Defence Scientific Advisory Council; and the Counter Terrorism Science and Technology Centre Oversight Board.

**Professor David R. Smith, Duke University, USA (Speaker)**
Dr David R. Smith is currently the William Bevan Professor of Electrical and Computer Engineering Department at Duke University and serves as Director for the Center for Metamaterial and Integrated Plasmonics. He holds a secondary faculty appointment in the Physics Department at Duke University and a Visiting Professor of Physics at Imperial College, London. Dr Smith received his PhD in 1994 in Physics from the University of California, San Diego (UCSD). Dr Smith's research interests include the theory, simulation and characterization of unique electromagnetic structures, including photonic crystals, metamaterials and plasmonic nanostructures. Smith and his colleagues demonstrated the first left-handed (or negative index) metamaterial at microwave frequencies in 2000, and also demonstrated a metamaterial "invisibility cloak" in 2006. In 2005, Dr Smith was part of a five member team that received the Descartes Research Prize, awarded by the European Union, for their contributions to metamaterials and other novel electromagnetic materials. In 2006, Dr Smith was selected as one of the "Scientific American 50." In 2009, Dr Smith was named a *Citation Laureate* by Thomson-Reuters ISI Web of Knowledge, for having among the most number of highly cited papers in the field of Physics over the past decade.

**Professor Mark Stockman, Georgia State University, USA (Speaker and Chair)**
Mark I Stockman received his PhD and DSc degrees from institutes of the Russian Academy of Sciences. Currently he is Professor of Physics at Georgia State University, Atlanta, GA, USA. He also served as a Distinguished Professor at Ecole Normale Supérieure de Cachan (France) and Ecole Supérieure de Physique and de Chimie Industrielle (Paris, France), and also as a Guest Professor at University of Stuttgart (Germany), Max Plank Institute for Quantum Optics (Garching, Germany), and Ludwig Maximilian University (Munich, Germany). A major direction of his research is theoretical nanoplasmonics, especially theory of ultrafast and nonlinear nanoscale optical phenomena. He is a co-inventor of SPASER (nanoplasmonic laser). He is an author of 160 major research papers and presented many invited and keynote talks at major international conferences. He taught short courses on nanoplasmonics and related topics at major international meetings and scientific institutions in US, Canada, Europe, Asia, and Australia.

**Professor Martin Wegener, Karlsruhe Institute of Technology, Germany (Speaker)**
We review our recent experimental progress regarding three-dimensional metamaterials operating at optical frequencies. This includes (i) three-dimensional gold-helix metamaterials made by direct laser writing (DLW) and gold electroplating that can be applied as compact broadband circular polarizers – in analogy to the good old wire-grid polarizers for linear polarization of light. Here, light propagates along the helix axis (J.K. Gansel et al., Science 25, 1513 (2009)). More recently, (ii) we have also fabricated structures allowing for studying the case that the magnetic field of the light is parallel to the gold-helix axis (unpublished). Furthermore, (iii) we have realized and characterized three-dimensional carpet cloak structures by DLW (T. Ergin et al., Science, in press (2010); online March 18, 2010). Possibly, (v) we also discuss using very highly doped semiconductors as alternatives for usual metals such as gold (unpublished).

**Professor Xiang Zhang, University of California at Berkeley, USA (Speaker)**
Xiang Zhang is the inaugural Ernest S. Kuh Endowed Chaired Professor at UC Berkeley and the Director of NSF Nano-scale Science and Engineering Center (NSEC). He is also a Faculty Scientist at Lawrence Berkeley National Laboratory (LBNL).

Professor Zhang is an elected member of National Academy of Engineering (NAE) and Fellow of four societies: APS (The American Physical Society), OSA (The Optical Society of America), AAAS (The American Association for the Advancement of Science), and SPIE (The International Society of Optical Engineering). Professor Zhang received PhD from UC Berkeley (1996). He was an assistant professor at Pennsylvania State University (1996-1999), and associate professor and full professor at UCLA (1999-2004) prior joined Berkeley faculty in 2004.

Professor Zhang's current research focused on nano-scale science and technology, materials physics, photonics and bio-technologies. He has published more than 180 technical papers including publications in *Science* and *Nature*. He has given over 150 Keynote, Plenary and Invited talks at international conferences and institutions. He served as a Co-Chair of NSF Nanoscale Science and Engineering Annual Grantee Conferences in 2004 and 2005, Chair of Technical Program of IEEE 2nd International Conference on Micro and Nano Engineered and Molecular Systems in 2007, and is a Chair of Academic Advisory Board for The Research Center for Applied Science (RCAS), Academia Sinica, Taiwan, ROC.

In 2008, Professor Zhang's research has been selected by *Time Magazine* as one of "*Top Ten Scientific Discoveries of the Year*" and "*50 Best Inventions of the Year"*, *Discover Magazine*'s "*Top 100 Science Stories*" in 2007, and *R&D Magazine*'s *top 25 the Most Innovative Products of 2006*.

Professor Zhang is a recipient of NSF *CAREER Award* (1997); SME *Dell K. Allen Outstanding Young Manufacturing Engineer Award* (1998) and *ONR Young Investigator Award* (1999). He was awarded *Chancellor's Professorship* by UC Berkeley (2004-2009), "*Distinguished Lecturer*" by University of Texas at Austin in 2004 and SEMETECH in 2005, respectively, and "*Rohsenow Lecturer"*at MIT in 2009.

## Poster numbers and titles

| | | |
|---|---|---|
| **1** | Christos Argyropoulos | Accurate and efficient FDTD modeling of plasmonic structures |
| **2** | Dr Audrey Berrier | Molecularly induced activation of the strong coupling regime between porphyrins and surface plasmon polaritons |
| **3** | Matthew Biginton | Microwave transmission through an overlapping, pair of frequency selective surfaces |
| **4** | Elizabeth Brock | Experimental investigation of laterally confined surface waves |
| **5** | Celia Butler | Broadband transmission through a single layer of metamaterial clad in dielectric |
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# Poster abstracts

## 1. Accurate and efficient FDTD modeling of plasmonic structures

Christos Argyropoulos, Atiqur Rahman, and Yang Hao (Queen Mary, University of London, UK)

Recently, plenty of potential applications have been proposed based on plasmon propagation, such as nano-antennas, novel near-field optical microscopy devices, nano-lens with subwavelength resolution and plasmonic solar cells. However, the accurate modeling and characterization of these interesting devices remains challenging and currently available commercial simulation packages suffer from inherent limitations in dealing with novel materials and sub-wavelength structures.

In this work, we propose new Finite-Difference Time-Domain (FDTD) algorithms to model the plasmonic devices with increased accuracy and robustness. The proposed method applied to model metamaterials with dispersive, spatially-dependent and anisotropic material properties [1, 2]. Conformal and spatial averaging FDTD techniques have been proposed to accurately quantify the plasmon propagation [3, 4]. Finally, a parallel FDTD algorithm [5] has been demonstrated to model computationally intensive problems, such as 3-D nano-lenses and plasmonic solar cells, which require very fine spatial resolutions.

[1] Y. Zhao, C. Argyropoulos, and Y. Hao, Opt. Express, vol. 16, No. 9, 6717-6730, 2008.
[2] C. Argyropoulos, Y. Zhao, and Y. Hao, IEEE Trans. on Ant. and Propag. 57, pp. 1432-1441, 2009.
[3] Y. Zhao, and Y. Hao, IEEE Trans. on Ant. and Propag. 55, pp. 3070-3077, 2007.
[4] Y. Zhao, and Y. Hao, FDTD Modeling of Nanoplasmonic Solar Cells, APS 2009, Charleston, USA.
[5] Y. Zhao, and Y. Hao, Journal of Comp. Phys., vol. 228, No. 9, 7300-7312, 2009.

## 2. Molecularly induced activation of the strong coupling regime between porphyrins and surface plasmon polaritons

Audrey Berrier (Center of Nanophotonics FOM Institute AMOLF, The Netherlands), Peter Offermans (Holst Centre, The Netherlands) Ruud Cools and Christophe Arnold (Center of Nanophotonics FOM Institute AMOLF, The Netherlands); Siewert Brongersma and Mercedes Crego Calama (Holst Centre, The Netherlands); Jaime Gómez Rivas (Center of Nanophotonics FOM Institute AMOLF, The Netherlands)

We demonstrate the active control of the coupling strength between porphyrin dyes and surface plasmon polaritons (SPPs) propagating at the interface of a metallic thin film by variation of the number of molecules of nitrogen dioxide. When exposed to nitrogen dioxide the porphyrin molecules react with the gas molecules and optically active electronic state around 1.77 eV is activated. This state couples strongly with the SPP leading to an anti-crossing behavior in the dispersion relation. At zero energy detuning between the electronic state and SPP mode the reflectance increases with the effective oscillator strength of the optical transition. The magnitude and the width of the anti-crossing are tunable as a function of the NO2 concentration of the gas penetrating the active layer. Therefore, the coupled system can be molecularly tuned from the weak coupling to the strong coupling regime.

### 3. Microwave transmission through an overlapping, pair of frequency selective surfaces

Matthew Biginton, Roy Sambles and Alastair Hibbins (University of Exeter, UK); Ian Youngs (Defence Science & Technology Laboratory, UK)

There is much current interest in the transmissivity response of novel metamaterial structures. In this present study, the microwave response of a square array of circular apertures in a metallic sheet above which are concentrically placed metallic discs is explored both experimentally and numerically. The two layers are separated by a distance which is much less than the wavelength, and the discs have radii somewhat larger than the apertures. The volume bound by the overlap region between the discs and apertures supports a family of resonances that mediate strong resonant transmission.

### 4. Experimental investigation of laterally confined surface waves

Elizabeth Brock and Alastair Hibbins (University of Exeter, UK)

A recent theoretical study has proposed that a chain of closely spaced metallic cuboids (“dominos”) in contact with a metallic surface can support electromagnetic surface modes (“domino plasmons”) [1]. The authors of that paper conclude that, when the sides of the chain are left open, the mode propagation is insensitive to the chain’s width, even if made subwavelength. In the present study, we provide experimental verification of this phenomenon in the microwave regime. We use a dipole antenna to provide near-field excitation of the surface mode, and record the magnitude and phase of the signal as a function of frequency at the opposite end of the chain. In this way, we are able to determine the mode’s dispersion. We compare our experimental results to the predictions of a finite element method model.

[1] D. Martin-Cano et al, Optics Express 18, 755 (2010)

### 5. Broadband transmission through a single layer of metamaterial clad in dielectric

Celia Butler, Alastair Hibbins and Roy Sambles (University of Exeter, UK); Peter Hobson (QinetiQ, UK)

A single layer of metallic subwavelength mesh clad in dielectric is illuminated by collimated microwave radiation normally incident to the surface. The transmission spectrum obtained shows a pass band of near complete transmission across the frequency range 7 – 15 GHz. Numerical modelling reveals that standing waves in the dielectric layer couple via evanescent fields supported in the square subwavelength holes of the metallic mesh. Increasing the refractive index of the dielectric while keeping the optical path length constant improves the reflectivity from the front and back faces of the sample. In this way, the width of the supported modes are decreased, thereby allowing for an investigation into the origin of this phenomenon.

### 6. Nanophotonic split-ring antenna for surface enhanced Raman spectroscopy

Alasdair Clark, Andrew Glidle, David Cumming and Jonathan Cooper (University of Glasgow, UK)

We explore the use of nano metallic split-ring antenna as powerful, multifunctional biosensors with dichroic optical properties. Fabrication via electron-beam lithography allows for the strict control over structural geometry that is necessary to accurately tune the ring’s multiple, polarisation dependant plasmon resonances to particular wavelengths. In doing so, we demonstrate that we can tune their optical response such that they exhibit two independently addressable high frequency plasmon resonance modes, each tuned to the absorption wavelength of a differently coloured Raman reporter molecule and its corresponding laser excitation wavelength. This allows the single geometry ring structures to act as tailored SERRS sensors for low concentration DNA analyses at two distinct wavelengths.

We go on to investigate the optical properties of novel multi-split ring antennas with gap sizes of ~5nm, dimensions significantly smaller than has previously been achieved in such structures. Achieving gaps of this size allows us to confine the plasmon to a few square nanometres, generating the enhancements required for extreme Raman sensitivity.

### 7. Surface plasmons on rectangular bi-gratings

Thomas Constant, Alastair Hibbins and Roy Sambles (University of Exeter, UK)

In this work, the reflectivity of a rectangular metallic bi-grating illuminated with plane polarised light is explored. The grating is essentially comprised of two monogratings of different pitches, ‘crossed’ at 90 degrees and fabricated of gold or silver. With suitable choice of pitch such a grating may couple visible incident radiation directly, via grating scattering, to surface plasmon polaritons. One of the gratings is designed with very short pitch, such that it cannot be used to match the momentum of the incident visible photons to the surface plasmon polariton. However its depth and pitch may be used to effectively ‘tune’ the boundary conditions at the metal surface, thereby modifying the surface plasmon polariton dispersion and hence the coupling to the surface plasmon polariton by the other grating. In effect we are able to ‘design’, by use of the short pitch grating, the surface plasmon response of the metal.

### 8. Scalable metallo-dielectric metamaterials

Nicholas Gibbons, Mathias Kolle, Ulrich Steiner and Jeremy J. Baumberg (University of Cambridge, UK)

We utilise a novel approach for the scalable manufacturing of planar metamaterials fabricated through floating and rolling-up of flexible metallo-dielectric bilayers. Such structures have many unusual and exciting optical properties and can be assembled in a range of configurations and with lateral patterning. Primarily we demonstrate Bragg-arranged regimes which possess strong reflection and transmission resonances in their spectra. These configurations also exhibit enhanced non-linear response due to the arrangement of the gold layers and we show a strongly intensity dependant refractive index through time resolved pump-probe measurements. Additionally we investigate dimensional down-scaling of film thicknesses towards fabrication of anisotropic and superlensing multilayers. Simulations based on impedance matching techniques demonstrate high k modes to which we can couple by utilising corrugated and diffractive thin film roll-up configurations.

### 9. Surface plasmon lifetime studies and biosensing application of 2D metallic nanohole arrays

D. Y. Lei (Imperial College London, UK), J. Li (The Chinese University of Hong Kong), A. Fernandez-Dominguez (Imperial College London, UK), H. C. Ong (The Chinese University of Hong Kong) and S. A. Maier (Imperial College London, UK)

We have studied surface plasmon polariton (SPP) lifetimes in two-dimensional arrays of blind holes pierced on gold surfaces. They are determined from the linewidths of the resonant dips appearing in the specular reflection spectra for such structures. We find a strong dependence of plasmon lifetimes on the resonant wavelength and the hole geometry. Through both experiments and numerical simulations, we analyze the validity of the Rayleigh approximation and also explore the range of wavelengths and geometric parameters where it fails. We show that the behaviour of surface plasmon polariton lifetimes can be understood as resulting from the interplay between the intrinsic metal absorption and the scattering of surface waves by single isolated holes. Our study has allowed us to choose an optimized geometry with the longest lifetime (the narrowest spectral linewidth) and test it as a plasmonic biosensor. Numerically, we have investigated its refractive index sensitivity and overall figure of merit (FOM). We have found that the FOM is high up to 156.2

at optical frequencies due to extremely narrow SPP resonances. We point out that our nanohole arrays will find great potential applications in biosensing.

### 10. Bending electromagnetic waves at a sharp corner

Wenjia Liu (Imperial College London, UK), Jingjing Zhang (Technical University of Denmark) and Yu Luo (Imperial College London, UK)

Metamaterials, artificially structured subwavelength building blocks, offer great opportunities to manipulate electromagnetic fields. The integration of this kind of materials with transformation optics has lead to the realization of invisibility cloak which steers light around an object to make it invisible. This approach has now become a powerful tool to create materials with electromagnetic functionalities absent in nature and has been applied in the design of many novel electromagnetic devices. Inspired by this idea, we discuss the possibility of using metamaterials to bend electromagnetic waves at a sharp corner. Two different approaches are proposed reach this goal. One is based on spatially gradient transformation media, which guides the incoming waves around the corner, creating the illusion of a flat empty space. The other makes use of homogeneous negative-refractive-index materials with an appropriately designed geometry, where light rays are refracted and redirected into the bended waveguide without reflection. Numerical simulation is performed to verify the validity of the proposed devices.

### 11. Electromagnetic modes supported by structures with singularities

Yu Luo and John Pendry (Imperial College London, UK)

Plasmonic systems containing singularities, such as metallic wedges and rough surfaces, are of particular interest since they enable the manipulation of light and electronic signals at subwavelength scale. Although computers are widely used to investigate these structures, they have limited value in studying singularities. In this work, we deploy the theory of transformation optics to create analytical relationships between a canonical 2-dimensional metallo-dielectric system and a general class of singular structures. We find that the transformed structures can efficiently harvest light over a broadband spectrum, concentrating and delivering energy to a nano-scale region around the singularity. The divergent aspects of the structure as well as the influence of the source location and incident wave polarization on the surface plasmon excitations have also been discussed in detail. Our analysis may inspire potential applications in single molecular detection, efficient light harvesting, and surface enhanced Raman scattering.

### 12. Excitation of microwave modes supported by deep hole arrays

Helen Rance, Alastair Hibbins and Roy Sambles (University of Exeter, UK)

The microwave modes supported by a meta-surface comprised of a square array of finite-depth, subwavelength holes in a metallic substrate are experimentally studied. The evanescent nature of the fields in the substrate below the cut-off frequency of the holes provides the necessary effective boundary conditions for a surface mode to be supported [1]. In the present study, we consider the azimuthal dependence of the surface mode and its interaction with the family of depth-quantised waveguide modes.
Since the surface mode exists beyond the light line for a planar interface it can only be excited via enhancement of the incident momentum. An additional coupling grating, having twice the pitch of the array, is used to provide the necessary momentum matching condition. The manner in which the position and character of this coupling grating perturbs the dispersion of the modes supported is explored.

[1] Hibbins *et al*. Science 308, 670 (2005)

### 13. Experimental realization of subradiant and superradiant resonances in ring/disk plasmonic nanocavities as building blocks for new optical metamaterials

Yannick Sonnefraud (Imperial College London, UK), Niels Verellen (IMEC, Belgium; INPAC-Institute for Nanoscale Physics and Chemistry, Belgium; ESAT-TELEMIC, Belgium), Heidar Sobhani (Rice University, USA), G.A.E. Vandenbosch (ESAT-TELEMIC, Belgium), Victor V. Moshchalkov (INPAC-Institute for Nanoscale Physics and Chemistry, Belgium), Pol van Dorpe (IMEC, Belgium), Peter Nordlander (Rice University, USA) and Stefan A. Maier (Imperial College London, UK)

Plasmonics holds great promises in the control of light-matter interactions, as well as light manipulation, on the nanoscale. Metallic nanostructures with a designed plasmonic response are indeed the main avenue towards optical metamaterials. So far, good control on the spectral position of the resonance has been achieved, by modifying the shape and size of the metallic nanostructure employed in the metamaterials' unit cell. However, little work has been done on achieving linewidth control, although the radiative properties are a critical parameter to consider for applications ranging from slow-light to biosensing. We will show how one can tailor the plasmon resonance of structures consisting of nanodisks and nanorings in close proximity. While adjusting its geometrical parameters, one can not only change the position of the plasmon resonance, but its widths as well, creating super- and subradiant modes, as well as Fano-type lineshapes.

All the effects above-mentioned are highly sensitive to small changes in the dimensions of the particles. To accurately correlate theory and experiment, one needs to use techniques sensitive at the single particle level. We will present experimental measurements of plasmon resonances of the structures discussed above, demonstrating the creation of sub- and super radiant modes in these ring-disk cavities.

### 14. Aspect ratio dependence of microwave response for hole arrays

Melita Taylor, Alastair Hibbins and Roy Sambles (University of Exeter, UK)

The EM transmission response of square arrays of square holes in two-dimensional perfectly conducting sheets has been previously studied using an analytical modal matching technique [e.g., *Hendry et al, 2008*]. The present study further develops this modelling by breaking the four-fold symmetry in terms of both the array and hole geometry exploring the consequential changes in the observed response due to the rectangular symmetry of holes or grating or both. It demonstrates that the position of the transmission resonance is dictated by both the cavity mode within the holes, and also the 'overlap integrals' of the diffractive fields with these cavity modes. The changes in the overlap integrals resulting from the broken symmetry alters the strength of individual Fourier coefficients, thereby causing the observed variation in the EM response.

### 15. Shaping the optical response of nanoantennas

Giorgio Volpe, Sudhir Cherukulappurath, Roser Juanola, Gabriel Molina-Terriza and Romain Quidant (ICFO – Institute of Photonic Sciences, Spain)

Plasmonic nanostructures such as antennas, [1-4] metal-insulator-metal stacks [5] or tapered wires [6] have been designed to confine light in truly sub-wavelength (sub-$\lambda$) volumes opening new opportunities to enhance the interaction of light with small quantities of matter down to the molecular level. Beyond confining light at fixed locations, imposed by the structure geometry, there is a need for dynamical spatial control of such *hot-spots*, for instance to achieve selective optical addressing of different nearby nano-objects. Several strategies borrowed from the field of coherent control have recently been suggested to reach this goal. A first approach relies on temporally shaping the phase and amplitude of an ultrashort laser pulse illuminating the nanostructures. [7] By combining pulse shaping with a learning algorithm, Aeschlimann et al.

have recently demonstrated experimentally the feasibility of generating user-specified optical near field response of a star-like silver object. [8] Experimental control of the local optical response of a metal surface was also achieved by adjusting the temporal phase between two unshaped ultrashort pulses. [9] Alternatively, the idea of time reversal has been lately proposed by Li and Stockman. [10] In this approach, a femtosecond optical nano-source is locally coupled to the surface plasmon oscillations of a complex plasmonic system leading to the subsequent radiation of electric field in the far zone. Time-reversing the later and sending it back to the system as an excitation wave thus provides the right illumination conditions for concentrating light at the initial local source location.

Here we propose a novel approach based on continuous light flows which aims at achieving a deterministic control of plasmonic fields by using the spatial polarization inhomogeneities of high order beams such as Hermite-Gaussian (HG) and Laguerre-Gaussian (LG) beams. We show both experimentally and numerically that spatial phase shaping of the illumination field provides an additional degree of freedom to drive nano-optical antennas and consequently control their near field response. Furthermore, the potential of this approach to deterministically confine light at specific locations of a more complex metallic nanostructure is also demonstrated.

Muhlschlegel, P., *et al.,* Science *308*, (2005) 1607.
Schuck, P. J., *et al.*, Phys. Rev. Lett. 94, (2005) 017402.
Aizpurua, J., *et al*., Phys. Rev. B 71, (2005) 235420.
Novotny, L., Phys. Rev. Lett. 98, (2007) 266802.
Miyazaki, H. T., Kurokawa, Y., Phys. Rev. Lett. 96, (2006) 097401.
Stockman, M., Phys. Rev. Lett. 93, (2004) 137404.
Stockman, M., Faleev, S. V., Bergman, D. J., Phys. Rev. Lett. 88, (2002) 067402.
Aeschlimann, M., *et al.*, Nature 446, (2007) 301.
Kubo, A., *et al.*, Nano Lett. 5, (2005) 1123.
Li, X., Stockman, M., Phys. Rev. B. 77, (2008) 195109.

## 16. Tunneling of electromagnetic waves through sub-wavelength channels

Jingjing Zhang (Technical University of Denmark), Yu Luo (Imperial College London, UK) and Niels Asger Mortensen (Technical University of Denmark)

We suggest a possible way of tunneling electromagnetic waves through channels with sub-wavelength cross sections, which is based on the coordinate transformation methodology. Compared with the ENZ material approach which works for limited electromagnetic mode, the channel designed with transformation methodology can potentially squeeze and support all the incoming waves regardless of the polarizations and the transmission modes. Not only the magnitude but also the phase information of EM waves will be restored at the output interface of the channel. Numerical simulations are performed to demonstrate this idea.