2023 SUMMER SCHOOL

Hosted at University College Cork, Ireland

EXTREME NONLINEAR OPTICS IN SOLIDS

August 13 to August 18

Early Bird Registration Deadline is March 10, 2023

Dedicated to the memory of Stephan W Koch

SCHOOL ORGANIZERS

John McInerney, University College Cork, Ireland

Jerome V. Moloney, University of Arizona, USA

THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Department of Physics
Roinn na Fisice

Thomas Brabec, University of Ottawa

Lecture 1—Strong Field Physics in Atomic and Molecular Gases

- Quantum equation of motion
- Numerical solutions: Density function, configuration interaction, multi-configuration Hartree Fock
- Analytical approach - strong field approximations
- Ionization: Keldysh and WKB approach; multiphoton versus tunnel ionization
- High harmonic generation (HHG) and attosecond (asec) science: simple man model
- Asec techniques: streaking measurement of asec pulses, molecular tomography, attosecond transient absorption spectroscopy
- Quantum optical aspects of high harmonic generation

Lecture 2—Strong Field Physics in Solids

- Quantum equation of motion - one electron-hole model
- Ionization of solids: Keldysh and generalized Keldysh models; towards PHz electronics
- HHG in solids: inter- and intraband currents, length versus velocity gauge; Bloch gauge phase and gauge dependence (details left for Andrew), simple man models, Wannier versus Bloch basis, resonant versus non-resonant contributions.
- HHG experiments: inter versus intraband current, all optical measurement of bandgap and dipole, HHG tomography of impurity / exciton orbitals
- Strong field physics in solids – the role of noise

Lecture 3—Strong Field Physics in Nano-Devices

- Microscopic particle in cell (MicPIC) code – a classical ab-initio light matter interaction approach
- Dynamics of nano-plasmas
- HHG in nanostructures: various mechanisms
- Ionization of nanotips
- Focused HHG from metamaterials

Steven Cundiff, University of Michigan

Lecture 1— Introduction to TMDs

- Layered materials
- Optical properties of Transition Metal Dichalcogeides
- TMD heterostructures

Lecture 2—Experimental Implementation of Ultrafast Spectroscopy in Semiconductors

- Basics of Ultrafast Optics
- Transient Absorption Spectroscopy
- Four-wave-mixing Spectroscopy
- Multidimensional Coherent Spectroscopy

Lecture 3—Ultrafast Spectroscopy and Dynamics of Carriers in TMDs

- Carrier Dynamics in TMD Monolayers
- Optical broadening in TMD monolayers
- Ultrafast processes in TMD heterostructures
- Ultrafast Spectroscopic Imaging of TMD monolayers and heterostructures

Rupert Huber, University of Regensburg

Lecture 1—Extremely Non-Perturbative Terahertz Nonlinearities

- Generation and subcycle detection of phase-locked terahertz fields
- From weak to atomically strong terahertz fields
- High-harmonic generation in semiconductors
- Clocking dynamical Bloch oscillations

Lecture 2—Strong-Field Acceleration of Electrons in Quantum Materials

- High-harmonic generation in topological insulators
- Subcycle band structure videography and band structure engineering
- Lightwave valleytronics
- Attosecond chronoscopy of correlations

Lecture 3—Lightwave Electronic Imaging

- Scanning near-field optical microscopy
- Lightwave-driven scanning tunnelling microscopy
- Single-molecule orbital movies
- Femtosecond atomic forces and multi-messenger lightwave nanoscopy

Frank Jahnke, University of Bremen

Lecture 1—Nonequilibrium Carrier Dynamics in Semiconductors

- Interplay of intense light-matter interaction with carrier-carrier and carrier-phonon scattering: Semiconductor Bloch equations with dephasing and relaxation contributions
- Nonequilibrium carrier effects in semiconductor lasers
- Optical properties of TMDCs under intense excitation and nonequilibrium carrier dynamics

Lecture 2—Microscopic Theory of Semiconductor Lasers

- Semiconductor quantum wells and quantum dots as optical gain media
- Semiclassical laser theory with input from semiconductor Bloch equations
- Laser threshold and modulational response of semiconductor lasers
- Quantum theory of light applied to semiconductor nanolasers and thresholdless lasers

Lecture 3—Atomically Thin Two-Dimensional Semiconductors Based on TMDCs

- Introduction to TMDCs, electronic state calculations, excitons and trions in TMDCs
- Valleytronics, excitons in hetero-bilayers and twisted bilayers
- Interplay of excitons and free carriers, excitonic Mott transition and phase diagram
- Quantum-dot like states and single-photon emission in TMDCs

Mackillo Kira, University of Michigan

Lecture 1—Theory of Extreme Lightwave and Many-Body Interactions

- Crash course to many-body quantum mechanics
- Quantum Dynamic Cluster Expansion (QDCE)
- Crash course to semiconductor quantum optics
- QDCE theory of excitons, lightwave electronics, and quantum-optics

Lecture 2—Lightwave Electronics with Excitons

- From linear to extreme terahertz (THz) excitations of excitons
- Principles of quasiparticle colliders
- Crystal-momentum combs
- Super-resolution mapping of band-structure and geometric effects

Lecture 3—Quantum Information in Lightwave Electronics

- Wigner representation of lightwave excitations and quantum light
- Controlling valleytronic qubits
- Attoclocking of many-body correlations
- Prospects of quantum spectroscopy

Miroslav Kolesik, University of Arizona

Lecture 1—Extreme NLO in Solid-State Media Driven by MIR Optical Pulses

1.1. Poly-crystalline materials: Harmonic and supercontinuum generation in mid-infrared
- Examples of experimental results
- Physical mechanisms, including strong-field interactions and phase-matching in disordered materials
- Numerical modeling challenges

1.2. Computer-aided modeling for mono- and poly-crystalline materials
- Nonlinear pulse propagation
- Material description, comparison with extreme NLO in gaseous media
- Examples of simulation results
- Open (computational) problems and interesting applications

Lecture 2—High-Harmonic Generation in Off-Resonantly Driven Solid-State Media, Part I

2.1. HHG simulation with Semiconductor Bloch Equations
- Formulation of the model system, length and velocity gauge, transition-dipole moments and Berry connections
- Numerical considerations and challenges, structure gauge

2.2. Full Brillouin zone, SBE-based HHG simulator
- Gauge-independent SBE solver algorithm
- Enforcing material symmetry
- Integrating and mapping the HHG sources over full Brillouin zone

Lecture 3—High-Harmonic Generation in Off-Resonantly Driven Solid-State Media, Part II

3.1. Continuation: Full Brillouin zone, SBE-based HHG simulator
- HHG-spectra and crystal symmetry
- Quantitative assessment of material models
- Sample-orientation and polarization effects, comparison to experiments
- Dephasing, sampling and convergence issues

3.2. From a "point model" to simulations of experiments
- Propagation effects
- Spatial-filtering effects

Torsten Meier, University of Paderborn

Lecture 1—Semiconductor Bloch Equations I
- Optical Bloch equations for two bands
- Inter- and intraband excitations, e.g., Bloch oscillations & high-harmonic generation
- Hartree-Fock semiconductor Bloch equations for two bands

Lecture 2—Semiconductor Bloch equations II
- Excitons, band gap & field renormalization
- Brief overview: many-body correlations
- Injection/shift/rectification currents

Lecture 3—Coherent Phototransport Effects in Semiconductors
- Semiconductor Bloch equations with inter- and intraband excitations
- Two-color charge & spin photocurrents
- Transient Wannier-Stark localization, HHG, Berry curvature & anomalous currents

Poster Session—We encourage students to highlight their own research.

Jorg Hader, University of Arizona

Lecture 1— Influence of Coulomb correlations on linear and nonlinear properties of monolayer TMDCs

- Microscopic many-body description
- Influence of incoherent carriers on linear response
- Influence of excitonic correlations on HHG
- Influence of carrier relaxation
- Influence of polarization dephasing

Andrew Parks, University of Arizona

Lecture 1— Gauge Invariant Formulation of the Semiconductor Bloch Equations

- Review gauge symmetry of periodic solids
- Obtaining gauge invariant equations for light-material interactions
- Discuss technical and conceptual advantages of gauge invariant formalism
- Example application: modeling high harmonic generation in solids

2023 School on Extreme Nonlinear Optics in Solids

The sudden untimely passing of Professor Stephan W Koch on September 12 2022 in Marburg, Germany has left a huge void in our community. Stephan's impact on semiconductor optics and microscopic many-body physics in general has been immense and immeasurable. He will be greatly missed.

Besides being an outstanding researcher, Stephan was also an excellent teacher who played a prominent role in prior summer schools hosted by University College Cork (UCC), Ireland. The last such school planned for 2020 had to be cancelled due to COVID.

The U.S Air Force Office for Scientific Research and their EOARD (London) counterpart have been generous in offering funding support to enable this school to move forward. We have assembled a high quality group of school lecturers who were close colleagues of Stephan over the years.

LECTURERS

Thomas Brabec, University of Ottawa, Canada

Steven Cundiff, University of Michigan, USA

Rupert Huber, University of Regensburg, Germany

Frank Jahnke, University of Bremen, German

Mackillo Kira, University of Michigan, USA

Miroslav Kolesik, University of Arizona, USA

Torsten Meier, University of Paderborn, Germany

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