MA 24: Terahertz Spintronics I

Time: Wednesday 9:30–13:15 Location: EB 202

MA 24.1 Wed 9:30 EB 202

Exact diagonalization study of THz two-dimensional spectroscopy in quantum magnets — •Yoshito Watanabe[1], Simon Trebst[1], and Ciarán Hickey[2] — [1]Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany — [2]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

Two-dimensional coherent spectroscopy (2DCS) is a method used to study the nonlinear responses of systems. Recent advancements in THz generation techniques suggest the potential for 2DCS in investigating quantum magnets. This approach is theoretically proposed to discern fractionalized excitations in quantum magnets, a capability distinct from traditional linear-response methods.

Current 2DCS research often focuses on solvable models like the one-dimensional transverse field Ising model (1d-TFIM). However, there is a growing need for numerical methods that simulate 2DCS more broadly to interpret experimental data accurately.

This study addresses these methods, specifically using exact diagonalization (ED) to examine one-dimensional models. We outline ways to bridge the gap between numerical simulation results from smaller systems and experimental results typically gathered in the thermodynamic limit.

Having established the numerical techniques, we analyze how integrability-breaking terms affect the 2DCS spectra of the 1d-TFIM, which has experimental relevance to the quasi-1d spin-chain compound CoNb2O6.

MA 24.2 Wed 9:45 EB 202

Accessing ultrafast spin-transport dynamics in copper using broadband terahertz spectroscopy — •Reza Rouzegar[1,3], Jiri Jechumtal[2], Oliver Gueckstock[1,3], Wolfgang Hoppe[5], Quentin Remy[1], Tom Seifert[1], Georg Woltersdorf[5], Piet Brouwer[1], Markus Münzenberg[4], Tobias Kampfrath[1], and Lukas Nadvornik[2] — [1]Freie Universität Berlin — [2]Charles University, Prague — [3]Fritz-Haber-Institute, Berlin — [4]Universität Greifswald — [5]Martin-Luther-Universität Halle

We study femtosecond spin currents through Cu in CoFeB(2 nm)|Cu(d)| Pt(2 nm) stacks by terahertz emission spectroscopy. In our approach, spin currents are transmitted through a Cu(d) interlayer with thickness d and converted into a measurable charge current in Pt. The spin current $j_s^d(t)$ vs time t behind the Cu layer exhibits an increasing delay and stronger dispersion when d increases [1]. Using an analytical dynamic-diffusion model, we can describe the spin current propagation for a spin velocity of 1.1 nm/fs, which agrees well with the Fermi velocity of Cu, and an electron scattering time of $\tau = 4 \pm 2$ fs. In the framework of our model, we can separate ballistic and diffusive components of the spin current [1]. We conclude that, for thicknesses of $d \geq 2$ nm, the spin current is dominated by diffusive transport.

[1] J. Jechumtal, R. Rouzegar, et.al., arXiv:2310.12082 (2023).

MA 24.3 Wed 10:00 EB 202

Observing terahertz orbital-angular-momentum currents with giant relaxation length in tungsten — •Tom Sebastian Seifert — Department of Physics, Freie Universität Berlin, Arnimallee 14, 14195 Berlin

Terahertz emission spectroscopy (TES) is a powerful tool to reveal photocurrent dynamics with femtosecond time resolution [1]. An exciting application for TES arises in the emerging field of orbitronics that exploits the electron orbital momentum L for possible data-processing applications [2]. However, direct experimental observation of L currents, their extended propagation lengths and their conversion into charge currents has remained challenging. Here, we optically trigger ultrafast angular-momentum transport in Ni|W|SiO2 thin-film stacks [3]. The resulting terahertz charge-current bursts exhibit a marked delay and width that grow linearly with the W thickness. We consistently ascribe these observations to a ballistic-like L current from Ni through W with a giant decay length (80 nm) and low velocity (0.1 nm/fs). At the W/SiO2 interface, the L flow is efficiently converted into a charge current by the inverse orbital Rashba-Edelstein effect, consistent with ab initio calculations. Our findings establish orbitronic materials with long-distance L transport as possible candidates for future efficient and ultrabroadband orbitronic terahertz emitters, and an approach to discriminate Hall-like and Rashba-Edelstein-like conversion processes.

[1] Leitenstorfer, A., et al., J. Phys. D 56(2023).
[2] Go, D., et al., EPL 135 (2021).
[3] Seifert, T.S., et al., Nat. Nanotechnol. 18, (2023).

MA 24.4 Wed 10:15 EB 202

THz excitations in Fe2Mo3O8 and how they track a highly unusual magnetization reversal — •Joachim Deisenhofer[1], Somnath Ghara[1], Vladimir Tsurkan[1], Lilian Prodan[1], Maxim Mostovoy[2], Evgenii Barts[2], Kirill Vasin[1,3], Mikhail V. Eremin[3], Istvan Kezsmarki[1], Felix Schilberth[1], Dmytro Kamenskyi[1], and Alexey R. Nurmukhametov[3] — [1]Experimental Physics V, Center for Electronic Correlations and Magnetism, Institute for Physics, University of Augsburg, D-86135 Augsburg, Germany — [2]Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands. — [3]Kazan, Russia.

We investigated the THz excitations in the polar honeycomb antiferromagnet Fe2Mo3O8 in external magnetic fields and their optical toroidal effect, together with the temperature dependencee of the electronic transitions in the mid- and near-infrared frequency range. Using an advanced single-ion approach for the Fe ions, we are able to describe the optical excitation spectrum from the THz to the near-infrared regime and model the toroidal optical effect successfully. Moreover, we show that the lowest-lying optical mode tracks an unusual magnetization reversal in lightly Zn-doped Fe2Mo3O8: The magnetization reversal of the field-induced ferrimagnetic state at the coercive field occurs via the antiferromagnetic state, i.e. a magnetization compensation on the atomic level instead of the usual compensation by macroscopic domains.

MA 24.5 Wed 10:30 EB 202

On-chip sub-THz electrical pulse train generation by sequentially emitting Spintronic Terahertz Emitters — •Bikash Das Mohapatra[1] and Georg Schmidt[1,2] — [1]Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, Von-Danckelmann-Platz 3, 06120 Halle, Germany — [2]Interdisziplinäres Zentrum für Materialwissenschaften, Martin-Luther-Universität Halle-Wittenberg, Heinrich-Damerow-Strasse 4, 06120 Halle, Germany

This study explores the concept of using a sequence of ultrashort electrical pulses[1] generated by spintronic THz emitters (STE) integrated into a waveguide. The fundamental frequency of the resulting burst is determined by the position of the respective emitters and the pulse propagation velocity in the waveguide. The result is an electrical pulse train, currently at sub-THz frequencies but theoretically the frequency range can be extended into the THz regime. The electrical response was measured using a 50 GHz sampling oscilloscope. These pulse trains are subject to tuning based on the STE size, path length between the STEs, and the position of the laser spot. Notably, the central frequency of the power spectrum is determined by the inter-STE distance. Furthermore, various temporal and spatial manipulation techniques enable the digital encoding of these pulse trains. This work is quite promising for the development of components with potential Ultrafast Spintronics device applications.

[1] W. Hoppe et al. "On-Chip Generation of Ultrafast Current Pulses by Nanolayered Spintronic Terahertz Emitters", ACS Applied Nano Materials 2021 4(7), 7454-7460, DOI: 10.1021/acsanm.1c01449

MA 24.6 Wed 10:45 EB 202

Terahertz spin transport and spin charge conversion dynamics in topological-insulator|ferromagnet heterostructures — •Genaro Bierhance[1,2], Chihun In[2], Enzo Rongione[3,4], Reza Rouzegar[2], Oliver Gueckstock[2], Emanuele Longo[5,6], Tom Sebastian Seifert[2], Roberto Mantovan[5], Henri Jaffrès[3], Athanasios Dimoulas[7], and Tobias Kampfrath[1,2] — [1]FHI Berlin, Germany — [2]FU Berlin, Germany — [3]CNRS, Paris, France — [4]ICN2, Barcelona, Spain — [5]CNR-IMM, Italy — [6]ICMAB, Barcelona, Spain — [7]NCSRD, Athens, Greece

Topological insulators are promising materials for terahertz (THz) spintronic devices due to their topologically protected surface states with spin-momentum locking, which unveil channels for spin-charge interconversion (SCI). Here, we study ultrafast spin transport and SCI in F|TI stacks consisting of a ferromagnetic metal layer (F) and a topological-insulator film (TI). An incident femtosecond laser pulse induces a spin voltage and, thus, spin transport from F to TI. Subsequent SCI launches a transverse charge current that emits a broadband THz electromagnetic pulse. A detailed analysis of the obtained THz emission signal dynamics in the TI Bi_2Te_3 reveals two relaxation components with distinct time scales: a quasi-instantaneous and a significantly longer response. Remarkably, the extracted time constant (300 fs) of the latter is independent of the chosen F material (Fe or Co). We ascribe these observations to a slower response of either spin transport or SCI in Bi_2Te_3, indicating the importance of intermediate states in these structures.

MA 24.7 Wed 11:00 EB 202

Tunable ultrabroadband hybrid terahertz emitter combining a spintronic terahertz source and a GaSe crystal — •Afnan Alostaz[1,2], Oliver Gueckstock[1], Jungwei Tong[1], Jana Kredl[3], Chihun In[1], Markus Münzenberg[3], and Tom S. Seifert[1] — [1]Department of Physics, Freie Universität Berlin, Germany — [2]Peter Grünberg Institut-6, Forschungszentrum Jülich GmbH, Jülich, Germany — [3]Institut für Physik, Universität Greifswald, Greifswald, Germany

Linear terahertz time-domain spectroscopy (THz-TDS) is a sensitive probe for material characterization including thickness measurements of thin layers. To widen the impact of THz-TDS systems, the THz bandwidth should be maximized, ideally exceeding 15 THz

Here, we introduce a hybrid THz-emitter concept based on a spintronic THz emitter (STE) [1] that is deposited onto a thin freestanding GaSe nonlinear crystal. By tuning the parameters of this hybrid emitter and by superimposing the generated THz pulses from the STE and GaSe, we generate an ultrabroadband THz spectrum covering the full range from 1 to 40 THz without any gaps at high spectral amplitudes, resulting in ultrashort THz-pulse durations of only 32 fs.

Finally, we demonstrate a tunability of the carrier-envelope phase by the external magnetic field from unipolar or bipolar THz pulses with ultrashort duration that are well suited as ultrabroadband THz probe pulses.

[1] Seifert, T., Jaiswal, S., Martens, U. et al. Nature Photon. 10 (2016).

15 min. break

MA 24.8 Wed 11:30 EB 202

Rotating spintronic THz emitter for high-power and field-driven applications at MHz repetition rates — •Alkisti Vaitsi[1], Vivien Sleziona[1], Luis E. Parra Lopéz[1], Yannic Behovits[2], Fabian Schulz[3], Natalia Martín Sabanés[4], Tobias Kampfrath[2], Martin Wolf[1], Tom S. Seifert[2], and Melanie Müller[1] — [1]Fritz Haber Institute, Berlin, Germany — [2]Freie Universität Berlin, Berlin, Germany — [3]CIC nanoGUNE, San Sebastian, Spain — [4]IMDEA Nanoscience, Ciudad Universitaria de Cantoblanco, Madrid, Spain

We demonstrate high-power operation of a broadband spintronic terahertz emitter (STE) excited with up to 18 W pump power at MHz repetition rates for THz-field-driven applications. By rotating the STE at angular speed on the order of 100 Hz, we achieve optimal power conversion efficiency at fluences of $\sim 1\ mJ/cm^2$ at average power densities of $\sim 350\ W/cm^2$, well above the laser damage threshold of thin metallic films. The rotating STE design is scalable and eliminates material degradation due to thermal heating. Optimizing further the THz propagation from the rotating STE, we achieve peak THz fields of up to 10 and 6 kV/cm incident on the junction of a THz scanning tunneling microscope at 1 and 2 MHz repetition rate, resulting in $\sim 5\ V$ and 8 V THz bias voltages inside the STM. We discuss performance limiting saturation mechanisms and present an optimal setup design for application of the STE in THz-STM and other field-driven applications.

MA 24.9 Wed 11:45 EB 202

Broadband spintronic terahertz source with peak electric fields exceeding 1.5 MV/cm — •Reza Rouzegar[1,2], Alexander Chekhov[1,2], Yannic Behovits[1,2], Bruno Serrano[1], Maria Syskaki[3], Charles Lambert[4], Dieter Engel[5], Markus Münzenberg[6], Gerhard Jakob[3], Mathis Kläui[3], Tom S. Seifert[1], and Tobias Kampfrath[1,2] — [1]Freie Universität Berlin — [2]Fritz-Haber-Institute of MPG — [3]Johannes Gutenberg University Mainz — [4]ETH Zürich — [5]Max-Born-Institute in Berlin — [6]Universität Greifswald

Spintronic terahertz emitters (STEs) allow one to generate ultrashort terahertz electromagnetic pulses by excitation with a femtosecond laser pulse. Here, we significantly improve the performance of an STE by a factor of up to 6 in field amplitude by optimizing the management of light and heat flow. Our new Si-based STE (Si-STE) design features almost 100% pump absorptance, enhanced terahertz outcoupling and maximized heat-transport into the substrate. Using high energy pump pulses (energy 5 mJ, duration 80 fs, wavelength 800 nm), we generate THz pulses with peak electric fields of 1.5 MV/cm, a fluence of the order of 1 mJ/cm^2, with a gapless spectrum covering the range 1-11 THz. We compared our new Si-STE design to $LiNbO_3$, which is the gold standard of table-top high-power terahertz sources. We find comparable peak fields and fluences. The optimized STE (Si-STE) still has all attractive features of the standard STE, e.g., straightforward rotation of the terahertz polarization plane by an external magnetic field, ease-of-use and independence of the pump wavelength.

MA 24.10 Wed 12:00 EB 202

Broadband spintronic sampling of true terahertz electric fields — •Alexander Chekhov[1], Yannic Behovits[1], Julius Heitz[1], Maria-Andromachi Syskaki[2], Bruno Rosinus Serrano[1], Amon Ruge[1], Jana Kredl[3], Markus Münzenberg[3], Gerhard Jakob[2], Mathias Kläui[2], Tom Seifert[1], and Tobias Kampfrath[1] — [1]Department of Physics, Freie Universität Berlin, 14195 Berlin, Germany — [2]Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany — [3]Institut für Physik, Universität Greifswald, 17489 Greifswald, Germany

The increasing bandwidth of intense terahertz (THz) sources demands the development of new methods for the sampling of broadband THz electromagnetic pulses. Here, we demonstrate a spintronic approach to THz-electric-field detection based on measuring the THz spin accumulation that is induced at a ferromagnet/heavy-metal (FM/HM) interface by a THz electric field. To put this scheme to the test, we apply ultrabroadband THz pulses from a spintronic THz emitter to FM|HM stacks and probe the transient optical birefringence. We find that the measured signal has the same shape as the driving THz field without any distortions over the full range of 0.1-12 THz. By studying various FM|HM stacks, we reveal the mechanism behind the observed signals and maximize the detector efficiency. Our work not only provides new opportunities in THz photonics but also new insights into THz spin dynamics at interfaces.

MA 24.11 Wed 12:15 EB 202

Ultrabroadband terahertz time-domain spectroscopy of giant magnetoresistance — •Zdenek Kaspar[1,2], Oliver Gueckstock[1], Bikash Das Mohapatra[3], Tom S. Seifert[1], Georg Schmidt[3], and Tobias Kampfrath[1] — [1]Freie Universität Berlin, Germany — [2]Institute of Physics of the Czech Academy of Sciences, Czech Repiblic — [3]Martin-Luther-Universität Halle-Wittenberg, Germany

We perform broadband terahertz (THz) time-domain spectroscopy on giant magnetoresistance (GMR) stacks F1|Cu(3.2 nm)|F2 where F1, F2 are ferromagnetic metal thin-films with parallel (↑↑) or antiparallel (↑↓) in-plane magnetization. By utilizing ultrashort THz electric-field pulses, we measure the GMR contrast at 1-25 THz in a current-in-plane (CIP) geometry.

Our data reveal a notable decrease of the GMR contrast from 2% to 1.5% from 1 THz to 25 THz. Remarkably, we observe an almost frequency-independent time delay of 15 fs of the GMR response relative to the driving THz field. We attribute this delay to the time required for an electron to propagate through the Cu layer between F1 and F2 and to undergo spin-dependent scattering at the F1|Cu and Cu|F2 interfaces. This notion is supported by experiments, in which we increase/decrease the Cu thickness and observe an increase/decrease of the time delay.

MA 24.12 Wed 12:30 EB 202

Theoretical analysis of the terahertz radiation spin-based sensors design — •Ievgeniia Korniienko[1], Pablo Nieves[1,2], Oksana Chubykalo-Fesenko[3], and Dominik Legut[1] — [1]IT4Innovations, VSB-TU Ostrava, Ostrava, Czech Republic — [2]University of Oviedo, Oviedo, Spain — [3]Instituto de Ciencia de Materiales de Madrid, ICMM-CSIC, Madrid, Spain

In recent years, there has been an increased interest in terahertz (THz) radiation, which is caused on the one hand by the success in creating

THz emitters [1], and on the other hand by the potential applications of radiation in this range [2]. Although there is a wide variety of THz detectors they all show sensitivity to the electrical component of THz electromagnetic radiation [3]. THz magnetic field directly couples to the spins by the Zeeman interaction making it possible to detect THz radiation by magnetic dynamics observation. In our work, we theoretically analyze the possibilities to create spin-based detectors that would be sensitive to the magnetic component of THz radiation [4]. We explore the potential capabilities of such sensors, their application limits, and also provide an analysis of potential candidates among ferromagnetic materials. The obtained theoretical dependencies can be useful to reduce the impact of measurement inaccuracies and noises on the THz signal.

[1] T. Seifert, et al.: Nature Photonics 10, 483 (2016). [2] A. Y. Pawar, et al.: Drug Invention Today 5, 157 (2013). [3] S. S. Dhillon, et al.: Journal of Physics D: Applied Physics 50, 043001 (2017). [4] I. Korniienko, et al.: Phys. Rev. Applied (under review).

MA 24.13 Wed 12:45 EB 202

Terahertz detection of magneto-photocurrent in topological insulator Bi_2Se_3 — •Chihun In[1,2], Genaro Bierhance[1,2], Deepti Jain[3], Tom Seifert[1,2], Oliver Gueckstock[1,2], Roberto Mantovan[4], Seongshik Oh[3], and Tobias Kampfrath[1,2] — [1]Department of Physics, Freie Universität Berlin, 14195 Berlin, Germany — [2]Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, 14195 Berlin, Germany — [3]Department of Physics and Astronomy, Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA — [4]CNR-IMM Unit of Agrate Brianza, Via Olivetti 2, Agrate Brianza, MB 20864, Italy

Femtosecond laser excitation can drive ultrafast photocurrents in topological insulators (TIs) such as Bi_2Se_3. Here, we report THz emission from Bi_2Se_3 thin films by applying a magnetic field of $|\boldsymbol{B}| = 0.3$ T parallel to the film plane. First, we find a pronounced THz emission signal odd in $\boldsymbol{B}$ that changes its sign with $\boldsymbol{B}$. Second, we observe a strong reduction of the THz amplitude as bismuth is substituted by indium. The reduced spin-orbit coupling strength of $(Bi_{1-x}In_x)_2Se_3$ removes the Dirac surface state at a critical concentration of $x = 0.07$. Therefore, the suppressed THz signal of $(Bi_{1-x}In_x)_2Se_3$ for $x > 0.07$ suggests that the Dirac surface state and spin-momentum locking are critical to the emergence of the observed THz magneto-photocurrent. The time dependence of the photocurrent will be extracted, and possible interpretations will be discussed.

MA 24.14 Wed 13:00 EB 202

Magnon terahertz spin transport in metallic Gd|Pt thin-films — •Oliver Gueckstock[1,2], Tim Amrhein[1], Tom S. Seifert[1], Martin Weinelt[1], Tobias Kampfrath[1,2], and Nele Thielemann-Kühn[1] — [1]FU Berlin, Berlin, Germany — [2]FHI Berlin, Berlin, Germany

Transport of spin angular momentum is a fundamental operation required for future spin-electronic devices. To be competitive with other information carriers, it is required to push spin transport to ultrafast time scales [1]. Here, we use femtosecond laser pulses to trigger ultrafast spin transport in prototypical F|N bilayers from a ferromagnetic layer F into a nonmagnetic metal layer N [2]. Following absorption of the pump, a spin current in F is launched and converted into a transverse charge current in N, where it gives rise to the emission of a THz electromagnetic pulse [2]. Two driving forces can occur: (i) a temperature gradient (Seebeck-like effect) [3] and (ii) a spin-voltage gradient [4]. In metallic F, (ii) dominates and relies on conduction electrons, while (i) is found for insulating F [3,4]. Remarkably, in the fully metallic ferromagnet Gd, we find Seebeck-type dynamics and, thus, spin transport due to magnons. This finding highlights the great importance of magnon-mediated spin transport, in particular in metallic systems. References: [1] Vedmedenko et al., J. Phys. D: Appl. Phys. 53, 453001 (2020), [2] T. Seifert et al., Nat. Phot. 10, 483 (2016), [3] T. Seifert et al., Nat. Comm. 9, 2899 (2018), [4] R. Rouzegar et al., Phys. Rev. B 105, 184408 (2022).