**Research statement – Prof. Yonatan Sivan**

My group performs theoretical research in nano-photonics, studying a range of fundamental wave physics problems, ultrafast and non-equilibrium phenomena in solid-state systems, fundamental studies of the electronic, thermal and optical response of metal nanostructures, as well as various generic applications, including microscopy, optical communications, and photochemistry. We study many material platforms including plasmonic and semiconductor nanostructures, low electron density Drude materials such as metal oxides and nitrides, metamaterials and photonic crystals. The research relies on a synergy of analytical, asymptotic and numerical techniques, but usually involves collaboration with a top experimental group.

Here is a short description of some of the research projects we are currently studying:

1. **Steady-state electron non-equilibrium in metals –** we developed a first-of-its-kind model that combines detailed semi-quantum equations describing the electron non-equilibrium distribution in the metal with macroscopic equations that ensure particle and energy conservation of the system (photon-electron-phonon-environment). This model allowed us to determine the relative importance of thermal and non-thermal effects in these systems; we corrected a long list of famous papers studying this problem with only a qualitative theory. This is a first step towards re-interpretation of metal-assisted photocatalysis experiments (project 2), light emission from metals (project 3) and extension of the model to semiconductors (project 4). Recent work uses this model to study charge transport in molecular junctions, photo/thermionic emission from (optically-illuminated) metal nanostructures etc.. With Dubi group, BGU Chemistry.
2. **Plasmon-assisted photocatalysis** – in this project, we show that the popular claims that the non-equilibrium electrons generated in illuminated metal nanoparticles are the source for the observed faster chemical reactions is in many cases, even if not all, is completely wrong. Instead, we show that a simple thermal mechanism is theoretically, far more likely. This is done by, first, performing the first theoretical study ever that accounted for thermal and non-thermal effects in the study of the electron distribution in illuminated metals; this study showed that non-thermal effects are extremely smaller than thermal effects. Then, we identified a series of experimental and conceptual errors in some of the most famous papers on the topic, and showed that a simple 19th century thermal model can reproduce the measured data perfectly with essentially no fitting parameters. The project involves sophisticated modelling of thermal effects in realistic systems, including heat conduction and fluid rotation. Theoretical work done with Dubi and Baraban groups, BGU Chemistry. Experimental work done in collaboration with Rosen group (TAU), Rodriguez group (Tomsk) and Ctistis group (Gottingen).
3. **Electron non-equilibrium in noble metals and low electron density Drude materials –** As an extension of project 1, we adapted our model to ultrafast illumination of high and low electron density Drude materials and included also the role of interband transitions. This led to the development of the first ever comprehensive (electronic, photonic and thermal) theory for the ultrafast dynamics of the electron distribution in these systems. We revealed a range of new findings, such as the importance of momentum conservation in electron-phonon interactions, the possibility of the chemical potential to become negative, and explained correctly the physical nature of the nonlinear optical response and the damage threshold in these systems.
4. **Theory of light emission from metals –** As an extension of projects 1 and 3, we developed the first ever comprehensive (electronic, photonic and thermal) theory for light emission from metals following both CW and pulsed illumination. As a by-product, we showed how to fix current approaches for thermometry based on metal luminescence. Theoretical work done with Dubi group, BGU Chemistry. Experimental work done in collaboration with Lupton group (Regensburg) and Orrit group (Leiden).
5. **Ultrafast diffusion of heat in metals**. As a natural continuation of project3 1 and 3, we studied the ultrafast diffusion of heat in thin films of metals, with the aim of realizing an ultrafast thermos-optic switch. We performed the first theoretical study of this problem, considering the self-erasure of optically-induced heat gratings [Sivan & Spector, submitted]. We also liaised with the group of N. van Hulst (ICFO, Spain) who demonstrated these effects experimentally [Science Advances 2019] and with the group of K.-J. Tielrooij (ICN2, Spain) who demonstrated the surprising effect of negative diffusion in this system.
6. **Electron non-equilibrium in semiconductors –** As an extension of project 1, we developed the first ever comprehensive (electronic, photonic and thermal) theory for the steady-state electron distribution in semiconductors. We revealed a range of new physical effects, such as the difference between electron and hole temperatures, nonlinearity of temperature rise and identified the underlying time scale for each effect. With Dubi group, BGU Chemistry.
7. **Highly efficient computational electromagnetism** – we develop a semi-analytic method (spectral mode decomposition) that allows to calculate the field distribution and, in particular, the Green function for complex nanostructures. Our method resolves a wide range of numerical problems associated with existing methods, and enables a simple way, faster by several orders of magnitude, to model complicated physical effects such as thermal emission, van der Waals forces, Purcell modification of fluorescence properties, dipole-dipole energy transfer and quantum friction. We also apply the method to the design of metamaterials with complex unit-cells. With Gilles Rosolen (Mons, Belgium), Muljarov group (Cardiff, UK) and Genevet group (Cote-de Azur France and NTU, Singapore).
8. **Thermal metamaterials –** we study the possibility to engineer the thermal emission from nanostructures subject to high temperatures to enable the optimization of solar radiation harvesting, development of narrow infrared sources, study emission from non-isothermal structures, as well as several military applications. This project involves highly sophisticated computations (enabled by the method described in project 7), and a test of fundamental physical Laws like the Kirchhoff’s Law; with the group of Prof. Z. Jacob, Purdue University.
9. **Study of spatio-temporal Fano resonances in optical waveguide systems –** theFano resonance is a fundamental wave phenomenon resulting from interference of two channels. This phenomenon has been extremely well studied, but only for monochromatic waves. We perform one of the first studies of this phenomenon for pulsed beams, and observe a plethora of novel effects.
10. **Stimulated Brillouin microscopy at high resolution –** we model, for the first time, the stimulated Brillouin signal for strongly focused beams, with the goal of understanding and eventually optimizing the resolution and brightness of the signal, enabling an efficient way to map the elastic properties of biological systems. Applications range from fundamental studies of the wave physics to the detection of sick cells (cancer, malaria etc.); with the group of Dr. A. Bilenca, BGU.

**Past work**

1. **The use of metallic nanoparticles in super-resolution microscopy** – we showed that specially-designed metallic nano-particles can improve the resolution and signal brightness in STimulated-Emission-Depletion (STED) microscopy and to reduce the intensities it requires. So far, we experimentally demonstrated an 8-fold reduction of the required intensity using particles as small as 15nm on average, or similarly, a resolution 2-3 better than the diffraction limit. We currently work on improving these results, and initiating efforts to apply the technique to real-life biological problems. Our approach opens the way to a cost reduction of the STED microscopes, and in turn, to greater availability of these microscopes, thus, enabling many further discoveries of nano-scale processes occurring in biological systems. With the group of S. Hell (Nobel Prize Laureate 2014, Germany), and with groups of S. Maier and P. French (UK).
2. **The thermal nonlinear response of metal nanostructures** – this work was aimed at understanding the temperature rise in the metal nanoparticles. This revealed a complicated and unusually strong sensitivity of the optical properties of the metal to intense illumination and scattering from them. We showed that this scattering can be explained as a thermal effect. This strong response also enables the use of these particles as labels for super-resolution imaging in non-biological systems. Collaboration with the experimental group of S.W. Chu, NTU, Taiwan.
3. **Transformation Optics for nonlinear media** – we apply Transformation Optics, famous for enabling invisibility cloaking, to media with a nonlinear optical response. This allowed us so far to calculate frequency conversion from complex metal nanostructures analytically for the first time, and gave us fundamental insights of the underlying physics. ISF funded research; jointly with A. Fernandez Dominguez (Universidad Autonoma de Madrid).
4. **Ultrafast optics using transient Bragg mirrors** – we showed how to employ transient Bragg mirrors for extreme manipulations of ultrashort pulses such as time-reversal, low power femto-second spectroscopy, and especially short pulse generation at arbitrary wavelength and duration. We also showed grating erasures on femtosecond time scales due to heat diffusion in metals or charge carrier diffusion in semiconductors, so that the optical functionality is turned off even if the system does not return to equilibrium. The latter approach may lead to the design of ultrafast (i.e., femto-second) thermal modulators, a task which is usually dimmed impossible and to the breaking of the speed barrier on switching based on free-carrier excitation. We also investigated various aspects of the spatio-temporal dynamics of coupled pulses. With the group of Prof. A. Isha’aya, BGU.
5. **Pulse** **propagation in time-varying media; pulse propagation in slow and stopped light regimes –** in conjunction with project 14, we developed an efficient, exact and simple formulation describing the propagation of pulses in media whose optical properties change in time. We also extended the formulation for pulse propagation in slow and stopped light regimes, enabling simulations which are far simpler than the full wave simulations performed so far for this regime. We proposed a new scheme for true stopping of light.
6. **Designs of magnetic and negative refractive index metamaterials.** This work is based on a modal analysis of metal wire clusters. As part of that, we performed the first ever multipole expansion for wire media under general oblique incidence conditions, and provided a simple polarization-based explanation to the seemingly contradictory assigning of magneto-electric coupling to these structures. These findings appear in [P.Y. Chen, Y. Ben-Yakar and Y. Sivan, Phys. Rev. B, 2016].
7. **Simulating** **artificial black-holes in table-top** **optical experiments –** we are involved in modelling the experimental attempts to measure Hawking radiation in optical analogues of black-holes, based on ideas from fluid mechanics, like acceleration of fluid motion through a narrow channel (Laval Nozzle); with Prof. Bar-Ad, Tel Aviv University.
8. **Loss compensation in plasmonic metamaterials with gain media (post-doctorate)**
9. **TeraWatt pulse focusing in the atmosphere (PhD)**
10. **Optical solitons in complex nonlinear microstructures (PhD)**