1. PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan)

Project title:
Functional hybrid nanostructures composed of metallic nanoparticles and photon avalanching nanocrystals doped with lanthanide ions.

1.1. Project goals

The key idea of this project is to develop and optimize plasmon nanostructure-photon avalanche nanocrystal assemblies and optimize them towards significant reduction of the excitation light power required to observe photon avalanche emission. In particular, we want to address the following tasks:
- demonstrate that interaction with plasmon excitations can influence the optical properties of avalanching nanomaterials;
- verify the impact of the spectral and geometrical factors on such interactions;
- understand the role of fundamental effects in the performance of hybrid nanostructures.

1.2. Outline

Photon avalanche emission is a process observed in rare earths doped inorganic nanocrystals. It is characterized by non-linear relation between excitation power and resulting luminescence intensity. Due to high susceptibility of the optical properties of avalanching nanomaterials on the excitation power they can be applied for optical imaging and sensing with the lateral resolution much below the diffraction limit, offering unprecedented possibilities for biomedical research. However, high excitation power required to induce this effect is the main limiting factor for this approach. Remedy can be found in coupling such materials with noble metal nanostructures featuring plasmon excitation – collective resonant photoinduced oscillations of plasma resulting in strong local field enhancement. To allow that, we plan to develop biochemical functionalization to assemble hybrid avalanche-plasmon nanostructures with controlled internal separation, what is of crucial importance for optimization of the field enhancement.

1.3. Work plan

Goals of this proposal will be realized in three ways:
- Different methods of chemical surface modification will be examined, including streptavidin-biotin and biological body-antibody pairs, as well as DNA-based methods, resulting in specific binding and assembling of hybrid nanostructures with defined arrangement
- Optical and electron microscopy methods will be employed to control the assembling process and to verify the optical properties of single hybrid nanostructures
- Numerical model will be developed for proper understanding the role of fundamental optical interactions occurring in studied hybrid nanosystems

1.4. Literature *(max. 7 listed, as a suggestion for a PhD candidate preliminary study)*

M. Szalkowski, A. Kotulska, M. Dudek, Z. Korczak, M. Majak, Ł. Marciniak, M. Misiak, K. Prorok, A. Skripka, P. J. Schuck, E. M. Chan, A. Bednarkiewicz
"Advances in the photon avalanche luminescence of inorganic lanthanide-doped nanomaterials" Chemical Society Reviews, 54 (2025), 983-1026.
DOI: 10.1039/D4CS00177J

A. Bednarkiewicz, M. Szalkowski, M. Majak, Z. Korczak, M. Misiak, S. Maćkowski
"All-optical data processing with photon-avalanching nanocrystalline photonic synapse" Advanced Materials, 35 (2023), 2304390.
DOI: 10.1002/adma.202304390

Ch. Lee, E. Z. Xu, Y.i Liu, A. Teitelboim, K. Yao, A. Fernandez-Bravo, A. M. Kotulska, S. H. Nam, Y. D. Suh, A. Bednarkiewicz, B. E. Cohen, E. M. Chan & P. J. Schuck
"Giant nonlinear optical responses from photon-avalanching nanoparticles"
Nature, 589 (2021) , 230–235.
DOI: 10.1038/s41586-020-03092-9

M. Dudek, M. Szalkowski, M. Misiak, M. Ćwierzona, A. Skripka, Z. Korczak, D. Piątkowski, P. Woźniak, R. Lisiecki, P. Goldner, S. Maćkowski, E. M. Chan, P. J. Schuck, A. Bednarkiewicz "Size-dependent photon avalanching in Tm3+ doped LiYF4 nano, micro, and bulk crystals" Advanced Optical Materials, 10 (2022), 2201052.
DOI: 10.1002/adom.202201052

D. Jankowski, K. Wiwatowski, M. Żebrowski, A. Pilch-Wróbel, A. Bednarkiewicz, S. Maćkowski, D. Piątkowski
"Luminescent Nanocrystal Probes for Monitoring Temperature and Thermal Energy Dissipation of Electrical Microcircuit" Nanomaterials, 14, 24 (2024), 1985.
DOI: 10.3390/nano14241985

K. Wiwatowski, K. Sulowska, R. Houssaini, A. Pilch-Wróbel, A. Bednarkiewicz, A. Hartschuh, S. Maćkowski, D. Piątkowski
"Single up-conversion nanocrystal as a local temperature probe of electrically heated silver nanowire" Nanoscale, 15 (2023), 10614-10622.
DOI: 10.1039/d3nr01461d

1.5. Required initial knowledge and skills of the PhD candidate

Candidate should be familiar with construction and operating of optical setups, in particular microscopic devices (widefield or confocal). Experience in spectroscopic studies of nanomaterials, including methods of sample preparation, chemical surface modification and optical measurements (absorption, emission, transmission) will be beneficial. Candidate should be familiar with the basic interactions present in nanostructures, including plasmon interactions and energy transfer mechanisms, and experienced with numerical modelling thereof.

1.6. Expected development of the PhD candidate’s knowledge and skills

During the project realization PhD candidate will be engaged into interdisciplinary studies, including microscopy, spectroscopy, surface chemistry, nanotechnology and material science. It will include samples designing and optimization, optical measurements, as well as theoretical modelling, all of this providing comprehensive insight into the modern research methodology on the attractive scientific topic. It is expected that PhD candidate will develop his/her knowledge about the processes taking place in the hybrid nanosystems, in particular plasmon interactions, details of lanthanide’s photophysics and assembling of complex functional nanosystems. PhD candidate will also have an opportunity to construct and operate on home-built unique microscopic setups, as well as to advance his/her understanding of observed effects on the ground of theoretical insight into their nature. After project completing PhD candidate will be expected to become an expert in optical studies of nanosystems, able to manage interdisciplinary research.