Ultra-long working distance spectroscopy of single nanostructures with aspherical solid immersion micro-lenses

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Standard experimental setup for spectroscopic studies of single semiconductor nanostructures requires an microscope objective in front the studied sample. In order to avoid photon losses the numerical aperture (NA) of used microscope objective should be as high as possible. On the other hand longer distance from the sample to the light collecting optics (working distance, WD) is often desirable. It is particularly important in systems with restricted access to the sample, e.g., in case of split-coil superconducting magnets. Commercially available microscope objectives with magnification 100x has NA=0.6 for WD=8 mm, which is not sufficient for all applications.

In this work we present aspherical micro-lenses which redirects emitted photons from semiconductor nanostructure into light cone of NA=0.025 - the outcoming light can be collected by 1 inch-diameter lens at the distance of 590 mm from the sample. Resulting working distance is more than 70 times longer than the one offered by conventional microscope objectives.

Micro-lenses were fabricated by two-photon polymerization direct laser writing (TPP-DLW). This technique allows for three dimensional printing of micro objects made of transparent non-conductive resin that withstands cryogenic temperatures [1]. The resin after polymerization has refractive index n=1.52 which is intermediate value between higher refractive index of semiconductor and much lower refractive index of air. As a result, one also obtain an increase in photon extraction efficiency due to reduction of internal reflection of light in semiconductor.

We demonstrate usability of the proposed solid immersion lenses with single self-assembled CdTe/ZnTe quantum dots ($\lambda \approx 600$ nm) containing single manganese and cobalt ions. The lenses were also tested at shorter wavelength with single CdSe/ZnSe quantum dots ($\lambda \approx 500$ nm). Finally, we show that our solution works for monolayers of transition metal dicalcogenites (TMDs), in particular $MoSe_2$ and WSe_2 ($\lambda \approx 750$ nm), thus confirming the feasibility of broadband operation of fabricated lenses.

Presented micro-lenses could be especially useful for single nanostructure spectroscopy in very high magnetic fields - due to the absence of metal elements as well as in microwave cavities or optical dilution refrigerator systems.

[1] A. Bogucki, Ł. Zinkiewicz, W. Pacuski, P. Wasylczyk i P. Kossacki. *Opt. Express* **26,** 11513–11518 (2018)