Towards deterministic highly efficient single photon sources based on circular Bragg grating cavities

Anna Musiał\textsuperscript{1,2}, Benjamin Wohlfeil\textsuperscript{3}, Sven Burger\textsuperscript{3}, Arsenty Kaganskiy\textsuperscript{1}, Ronny Schmidt\textsuperscript{1}, Esra Yarar Tauscher\textsuperscript{1}, Tobias Heuser\textsuperscript{1}, Sven Rodt\textsuperscript{1} and Stephan Reitzenstein\textsuperscript{1}

\textsuperscript{1}Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany
\textsuperscript{2}Laboratory for Optical Spectroscopy of Nanostructure, Department of Experimental Physics, Wrocław University of Technology, Wrocław, Poland
\textsuperscript{3}Zuse Institute Berlin, Berlin, Germany

Growing interest in the field of quantum information processing and secure data transmission requires realization of very efficient non-classical light sources. The implementation of quantum protocols makes the deterministic fabrication technologies very desirable \cite{1}. A main limitation of up-to-date solutions is the extraction efficiency of emission from quantum dots (QDs) embedded in semiconductor material. Recently, circular Bragg grating cavities (CBGC) have been proposed for this purpose \cite{2}. Extraction efficiencies up to 80\% have been theoretically predicted for these structures (with optics of 0.7 numerical aperture) and first structures with a single QD as an active medium have been realized \cite{2}.

The present work focuses on the modelling of CBGC using finite element method within commercial solver – \textit{JCMWave}. This is a first step towards realization of efficient single photon sources with a deterministically integrated QD. It is planned to combine high extraction efficiencies inherent to new cavity design with a deterministic in-situ cathodoluminescence lithography \cite{1} enabling to design the final device with respect to its spectral features and output characteristics. For this purpose, detailed knowledge of the influence of cavity geometry on the electro-magnetic field distribution, fundamental mode energy, quality factor of the cavity (Q-factor), Purcell enhancement factor, optimal position of the QD within the cavity and finally the extraction efficiency of the source, is required. In the first step, an empty cavity was considered and its geometry was optimized with respect to the Q-factor of the cavity. Due to the complex, but circular symmetrical cavity geometry, 2D calculations were performed to allow for comprehensive parameter studies with reasonable computational effort. In this analysis cavity parameters such as: central defect radius - $r_c$, the thickness of the membrane – $t$, the depth - $d$, width - $w$ and number – $N$ of the Bragg grating trenches, as well as grating period - $\Lambda$ and filling factor - $D=w/\Lambda$, were varied. The results proved significant decrease of in-plane losses for filling factors below 0.4 and the possibility of further improvement using aperiodic chirped structures. In the next step, the active structure was simulated and the influence of the location of QD in the cavity was studied. The QD was at first modelled as a point source and afterwards more realistically treated as a dipole-like emitter. To determine the extraction efficiency, a propagation of light and a far field emission pattern was calculated in the framework of Fourier analysis. This enables to include the characteristics of the optical setup and detection system (numerical aperture, efficiency). It was shown that in view of the extraction efficiency the Q-factor of the cavity has to be kept on the moderate level to optimize the overall device performance in terms of maximum photon extraction efficiency. These results are very important as the active medium of the device would consist of self-assembled QDs and the resonator has to be designed and matched to the chosen high quality QD and its optical properties and fabricated precisely relatively to the QD position.