MODELLING OF MICRO AND NANO-SCALE RESONATORS AND LENSES FOR DENSE PHOTONIC CIRCUITS

As micro-scale optoelectronics evolves towards the nano-scale, more complex integrated photonic circuits are urgently needed, capable of small-volume light guiding and processing. Semiconductor microlasers play a key role as miniature sources of light with ultra-low power consumption and high degree of integrability, e.g., lasing in disk resonator with 1-10 micron diameter has been reported at room temperatures, both with photo-pump and carrier injection. Improved laser designs are needed with control of threshold and modal stability via proper design of the cavity and pump characteristics. Moreover, it is usually necessary to provide highly directional radiation of laser, a feature that can be achieved using micro-lenses. Micro-lenses with diameters in the micron to several hundred microns range are used to boost the efficiency of semiconductor optical devices such as detectors and emitters. When combined to emitters, they can compress the light output pattern. In detector applications, they enhance sensitivity. Although advanced techniques have successfully been developed for their fabrication, the electromagnetic features of many of these lenses are still far from clear.

The computer-aided analysis and modelling of resonators and lenses is a way to reduce the cost and time of design. However, the modelling of the optical fields in micro-resonators and micro-lenses is presently based on quite rough analysis tools namely either analytical Geometrical Optics (GO) solutions, finite-difference time-domain (FDTD) numerical codes, or small-contrast and paraxial approximations like the beam-propagation method (BPM). All of these approaches have limited accuracy if the distance to the optical resonators and lenses and their dimensions are comparable to the wavelength. For example, the staircasing of scatterer boundaries and back-reflections from the computational windows are well-known sources of errors in FDTD that often make it nearly impossible to unambiguously interpret the results of electromagnetic simulations. If designers could work with more accurate and economic optical simulation tools, then they would be able to develop photonic circuits with a higher degree of integration.

The project thus aims to research the analysis and design of micro-size optical resonators and lenses for light processing. This will be achieved by the mathematical and numerical study of the corresponding wave scattering problems as the boundary-value problems for the set of Maxwell’s equations with exact or generalized boundary, edge, and radiation conditions. The underlining concept is the use of boundary integral equations (BIEs), which do not require small-contrast or high frequency approximations and lead to convergent, stable, and efficient numerical algorithms. The directivity of radiation, efficiency of focusing, wavelength dependences, and the field patterns in the near and far zones will result from this analysis, and the ways to improve these characteristics will be elaborated and analyzed. Most of the research will be done with 2-D models; however some effort will be applied to develop 3-D IE-based solutions for rotationally symmetric components. The use of IE formulations implies reducing each original boundary-value problem to an equivalent IE whose class of solution is determined by the corresponding edge and radiation conditions. In each case the IE will be obtained from the corresponding conditions at the boundary of the light scattering object. Both for semiconductor resonators and dielectric lenses this is a set of electromagnetic transmission conditions. Models of transparent scatterers are well developed in the microwave field; however they have not been widely used before in optical simulations. Full-wave IEs are always of singular type. Therefore they should be either converted to the Fredholm second-kind IE by using the Method of Analytical Regularization (MAR) and then discretized, or directly solved numerically with the Method of Discrete Singularities (MDS). Both methods have been developed in Kharkov since the 1970’s. Each of them has its specific merits and the both have guaranteed convergence and controlled accuracy – unlike FDTD, BMP and GO. On solving the IEs, one obtains the surface or polarization currents, near and far optical-field patterns, and can easily compute optical field characteristics such as directivity, side-lobe level, and focusing efficiency.