Electromagnetic and numerical modelling of active and nonlinear microcavities for semiconductor lasers and all-optical switches

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Semiconductor micron-size disk lasers with quantum wells (QWs) or dots, pumped via optical or current-injection schemes, exploit the “whispering-gallery” modes around the edge of thin circular disks or more complicated cavities. They are actively studied today as promising ultra-low-threshold light sources for dense photonic circuits. Vertical-cavity surface-emitting lasers (VCSELs) have been developed for a number of years as sources of visible and infrared light based on the confinement of optical field by distributed Bragg reflectors sandwiching a cavity layer with embedded QWs.

The team of IRE NASU has proposed a new approach to the analysis of such lasers that consists in introducing material gain in the optical cavity and studying a lasing eigenvalue problem (LEP) of new type, for an active open resonator. Although still a linear problem, the LEP can be viewed as a "warm model" of laser where the gain, i.e. the presence of light-emitting carriers, is taken into account through the “active” imaginary part of the cavity refractive index. The material gain, characterized in such averaged manner, can be uniform (whole cavity is active, e.g. if optically pumped with a wide beam) or concentrated in a part of cavity forming an active region (e.g., the same with a tightly focused pump beam). Mathematically, the LEP problems include the Maxwell equations, continuity conditions for the field tangential components at the boundaries, and radiation condition at infinity. New feature is that, instead of the search for the complex-valued natural frequencies (as for a passive open resonator), we seek the eigenvalues as the pairs of two real parameters - frequency and threshold value of material gain. These parameters are well-known and adequate quantities in self-excitation of electron devices and in optical lasing. Note that lasing thresholds have not been quantified with the previous theories as their study was substituted with the analysis of modal Q-factors, which do not characterize the lasing directly. IRE NASU team plans the following work program:

1. Investigate LEP for an arbitrary-shaped 2-D microcavity with the aid of the Fredholm second-kind integral equations with smooth or integrable kernels. Develop economic and accurate discretization procedures for the basic integral equations and reduce them to determinantal equations.
2. Study numerically the lasing spectra and thresholds of 2-D models of thin microcavity lasers with non-circular contours. Investigate possible tradeoffs between the lowering of threshold and better directionality in the models of non-circular microcavity lasers.
3. Investigate possibility of building the model of a microcavity laser with a partial active region.
4. Investigate LEP for a VCSEL-type planar microcavity between the Bragg reflectors with the aid of the transfer-matrix method and reduce them to transcendental equations. Develop economic and accurate procedure for computing the reflectivity of a stack of layers using the Mauguin polynomials.
5. Study numerically the lasing spectra and thresholds of 1-D models of VCSEL-type microcavity lasers with Bragg reflectors. Investigate the effect of the number of pairs of layers and their contrast on the lowering of modal thresholds.
6. Investigate possibility of building the model of a VCSEL-type laser with patterned reflectors and active region.

Nonlinear ring microresonators are promising elements for all-optical switching due to their strong resonant enhancement of optical power inside the cavity. Within last years, special interest has been paid to silicon on insulator structures due to their very high refractive index contrast and thus very strong optical field confinement and low bending loss. Hybrid structures (slotted Si waveguides filled with highly nonlinear materials) are being particularly attractive for low-power optical nonlinear switching.

Recently, novel algorithms for full-vector calculation of eigenmodes in bent waveguides and a rather general 2-D bi-directional mode expansion propagation algorithm based on harmonic expansion were developed by IPE (formerly IREE) team. Presently, an efficient and accurate iterative algorithm based on the solution of a nonlinear Schrödinger equation for modelling nonlinear effects based on $\chi^{(3)}$-type nonlinearity in ring microresonators is being developed. Within the joint project, the algorithm has to be improved and generalized in the following directions:

1. Modelling of linear and nonlinear characteristics of microresonators with complicated refractive-index cross-section composed of different materials. Proper procedure for the determination of the effective nonlinear parameter has to be developed.
2. Four-wave mixing and, if possible, Raman effects have to be included into consideration. While the inclusion of four-wave mixing effects seems to be basically technical problem, to properly include Raman effects, a proper form of the Raman response function has to be chosen, tested, and implemented.
2. For high pumping intensities, electron-hole pairs are excited by two-photon absorption in SOI waveguides. Optical properties of waveguides are then very strongly influenced by free-carrier effect (also known as “plasma dispersion effects”). These effects will be also properly included into the model of a nonlinear microresonator.