Abstract

This doctoral thesis is devoted to investigation of exciton-polariton X waves in a semiconductor microcavity. Results of this research have been presented in three papers: “Exciton-polariton localized wave packets in a microcavity”, published in the Physical Review B, “Numerical modeling of excitonpolariton Bose-Einstein condensate in microcavity”, published in Computer Physics Communications as well as “Superluminal X-waves in a polariton quantum fluid”, an experimental article published in the Laser Science & Applications. They constitute a thematically-related series of publications. Together with this guide they form a complete PhD thesis. X waves are highly localized wave packets capable of traveling over long distances with high speed and without diffraction i.e. without losing their focusing. They are named after their characteristic shape of a letter “X” which is present both in the configuration (real) and momentum (frequency) space. Unlike some other types of localized wave packets, X waves exist in linear as well as in nonlinear media. Up to date, they have been demonstrated in e.g. acoustic and electromagnetic waves (“light bullets”) as well as matter waves in an ultracold gas. They have already found interesting applications. For example, they are used in ultrasound imaging to improve resolution of medical examinations and in telecommunications as a basis of low-power directional radio transmitters. Exciton-polaritons are quasiparticles formed from photons strongly coupled to excitons (electronhole pairs). They are created in a semiconductor microcavity pumped by a laser. These systems have already been used to demonstrate Bose-Einstein condensation and superfluidity in high temperatures. Microcavities offer a high control over the quasiparticles and their full state is easily readable with an ultrafast holographic technique. The research hypothesis of this thesis states that exciton-polaritons can form X waves. This hypothesis has been confirmed with numerical simulations followed by experiments. Investigations were split into three stages. In the first step, a set of time-dependent Gross-Pitaevskii equations describing the system was solved to obtain a quasi-stationary solution. An analysis of the dispersion relation of the lower polaritons revealed an inflection point which was used to inverse the sign of an effective photon mass along one of the microcavity axes – a necessary condition for the existence of X waves. The second stage involved development of numerical software modeling the dynamics of the superfluid for realistic parameters. The C++ programs used the Runge-Kutta method of the 4th order which was modified and optimized for solving Gross-Pitaevskii equations with supercomputers. Simulations showed that the quasi-stationary solution leads to formation of X waves and that they can be formed from a Gaussian pulse in the presence of a nonlinearity. This is an important result which simplifies their generation in an experiment. The third step comprised experiments which demonstrated exciton-polariton X waves and allowed to investigate their properties, e.g. quantized phase vortexes and superluminal velocity. The experimental results reveal a good agreement with numerical computations. Therefore, the research hypothesis has been proved. Exciton-polariton X waves studied in this dissertation can be used in development of e.g. signal carriers suitable for the future polaritonic devices. This research will also pave the way for investigation of localized waves in similar media. The developed numerical software can be widely used in examination of exciton-polariton dynamics. It has already focused attention of the scientific community conducting studies of e.g. exciton-polariton gyroscopes (Prof. Yuan Ren, Duke University, Durham, USA and Beihang University, Beijing, China) and exciton-polariton superfluid lattices (Dr. Mitchell Anderson, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland).