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Detail Abstract: 3-D Photonic Crystal Fibers and Bose-Einstein Condensates in Optical Lattices

Identification of the problem and outlines about steps of research. (Chapter by chapter).

In the chapter 1 of this thesis, it is furthermore sketched how the frequency dependent propagation constant and the effective area of the fibers can be found.

In chapter 2, it will be sketched how Maxwell's equations together with a suitable set of approximations lead to a nonlinear Schrödinger equation as a governing equation for light propagation in PCFs. Subsequently several ways of treating the dispersion and the nonlinearity will be treated. Finally the numerical implementation will be addressed.

When a PCF is pumped with femtosecond pulses a supercontinuum is formed and the physical mechanisms at play in this process are investigated in this chapter 3. Simulations based on the model presented in the previous chapter serve to explain the scenario taking place when pulses propagate in the fibers. Subsequently the simulations are compared to experiments with good agreement.

Supercontinuum generation in a PCF with two zero dispersion wavelengths is investigated. The special dispersion of the fiber has a profound influence on the supercontinuum which is generated through self-phase modulation and phase matched four-wave mixing and not soliton fission as in the type of PCF investigated in chapter 4. The supercontinuum has high spectral density and is extremely independent of the input pulse over a wide range of input pulse parameters. Simulations show that the supercontinuum can be compressed to ultrashort pulses.

In this chapter 5, an introduction to the field of BEC physics will be given with emphasis on condensates in periodic potentials. A derivation of the Gross-Pitaevskii equation will be sketched, the equivalent equation in nonlinear atom optics to the nonlinear Schrödinger equation in nonlinear optics.

The aim of chapter 6 is to show that the dispersion properties imposed by an external periodic potential ensure both energy and quasi-momentum conservation such that correlated pairs of atoms can be generated by FWM from a Bose-Einstein condensate moving in an optical lattice potential. A condensate with initial quasi-momentum k_0 is transferred into a pair of correlated atomic components with quasi-momenta k_1 and k_2, if the system is seeded with a smaller number of atoms with the appropriate quasi-momentum k1. This process is revealed in the numerical solution to the Gross-Pitaevskii equation and the transfer in the process is almost complete (>95%).

Research results obtained and conclusion including the real impact of the research project.

A photonic crystal fibers.

A model based on a nonlinear Schrödinger equation was used to investigate the dynamics of the wave propagation in PCFs. The simulations of femtosecond pulses in a PCF with a single zero dispersion wavelengths revealed that soliton decay plays an important role in the supercontinuum generation. As the pump pulse evolves towards one or more stable solitons dispersive waves are emitted, centered at distinct wavelengths, determined by phase-matching. The dispersion of the PCFs has a profound influence on the supercontinuum. For a fiber with two closely lying zero dispersion wavelength the supercontinuum is generated through self-phase modulation and phase-matched FWM and not through the soliton decay process mentioned above. Self-phase modulation broadens the spectrum and hereby provides seed wavelengths for degenerate and non-degenerate four-wave mixing. A stable and intense supercontinuum is generated over a wide range of input pulse parameters. The supercontinuum exhibits a depleted region between the two zero dispersion wavelengths due to the FWM processes. For both types of fiber, the simulations were compared with experimental data for supercontinuum generation and showed good agreement. The model used in Chap. 4-5 to simulate the supercontinuum generation in PCFs can be used to predict the outcome of wave propagation in PCFs with any dispersion profile, fictive or real. Although the model is very powerful, there is still room for improvement. A full treatment of the second derivative with respect to z in the model would give a proper treatment of the backscattered light. Avoiding making the slowly varying envelope approximation would be an advantage especially when the pump pulses are short and the resulting spectra are very broad. The issue of causality and the fulfillment of the Kramers-Kronig relations could be thoroughly addressed for the dispersion. Of course a full 3D solution of the problem would be the most accurate, but it would be computationally heavy. The supercontinua examined in this thesis have already found applications particularly in nonlinear microscopy and frequency metrology. Indeed, the frequency metrology has been revolutionized by this new technology and the optical frequency standard of today is based on a frequency comb generated in a PCF [72]. A supercontinuum source has been produced by Koheras [69], based on FWM of nano-second pulses and further investigations of possibilities for FWM in the PCFs could be useful. The supercontinua are products of the ultra high nonlinearities combined with the tailorable dispersion in the fibers. Still, the PCFs have other unique and claddings, and being endlessly single mode. Furthermore, the fibers can act as good hosts for rare earth atoms and ions. Consequently, the prospects for applications of the fibers go far beyond the generation of supercontinua and its applications. It could be interesting to investigate the perspectives of a resonant two or three level system inside a PBG fiber. Physically an atomic gas is placed in the air core of a photonic band gap fiber and strong nonlinear behaviour is expected as a result of the high intensity of the light. Alternatively, the two or three level system could be present as dopant rare earth atoms in the silica core of an index guiding PCF, but in this case the atomic lines will be seriously broadened. The effects of third harmonic generation, lasing without inversion, electromagnetically induced transparency and quantum computing could be addressed. To model the system the electric field of the light propagating in the fiber and the polarization of the atomic gas need to be solved in a self consistent manner. The system is very rich both from a quantum optical and atom optical point of view, since the PBG fibers can act as a combined waveguides for light and atoms. Due to the dipole forces of light guided in a hollow core fiber, not only atoms but also molecules and particles can be trapped. The PBG fibers are very promising for sensing purposes, not only can reactant molecules be kept and transported in the fibers. Additionally, the PBGs can be made to exactly fit the frequencies of light emitted in certain processes by specific organisms. In medicine they could be used to transport a drug to a specific difficultly accessible place in the body, and if the drug was photo-sensitive, the fiber could be used to guide the light initiating the drug as well. Already evanescent wave sensing has been demonstrated with a PCF in aqueous solution [31]. In the perspective of producing all optical networks the fibers could be used to create central components such as switches and frequency converters based on phase-matched processes. The PCFs are excellent for building new lasers. In fact lasing has already been demonstrated in rare earth doped double clad fibers, where the outer core is pumped and the lasing is taking place in the inner core [19–23]. The micro structured fibers truly have opened a wide range of opportunities since the structure can be tailor-made for specific purposes. Additionally, the field has benefited from the symbiosis between theoretical suggestions and the actual production of new fibers. Photonic crystals with other geometries than the fibers could be engineered to fulfill certain phase-matching conditions. For instance 2D planar wave guides and full 3D crystals could be designed to provide phase-matching for four wave mixing.

Bose-Einstein condensates in optical lattice.

Phase-matched FWM in the system of a BEC in an optical lattice was investigated in the thesis. The dispersion properties imposed by the external periodic potential provides energy and quasi-momentum conservation. Hence, an efficient FWM process can take place, where pairs of atoms are created. When seeded, up to 95% of the atoms originally in the condensate with wave vector k_0 can be transferred into the correlated pair of states with k_1 and k_2, as revealed by numerical solution of the Gross-Pitaevskii equation. The system performs Rabi-oscillations between the k_0 and the k_1, k_2 states, due to the coupling to a very narrow continuum of states. The oscillatory behavior is confirmed by a number state analysis with few modes. A natural extension of the work presented would be a stability analysis to thoroughly investigate the role of transverse excitations and the energetic and dynamic instabilities found at the edge of the Brillouin zone. Of course an experimental demonstration of the proposed phase-matched FWM process could be very interesting as well. The introduction of superlattices could provide new possibilities for phase matching conditions. Possibilities for phase-matched processes in particular the FWM could be investigated for condensates in 2D and 3D lattice potentials. Condensates on chips possess many advantages with respect to creating a small and mobile setup. The chip trap potentials can be tuned to phase-match various processes for instance the FWM process reported in the previous chapter. In this way efficient beam-splitters for atom interferometers able to measure gravitational variations could be created. The neutral atoms in the optical lattice sites as well as the atoms on chips could act as qubits and the systems could potentially be excellent for quantum computation purposes. For instance the Mott insulator phase has been suggested [110] for a quantum register. Perhaps the most important property of BECs in optical lattices is the great flexibility the system offers as a model system for condensed matter physics and fundamental quantum statistics. Due to the tunability of the strength of the periodic potentials and the dimensionality, phase-transitions such as the Mott-insulator and Tonks gas have been investigated. The introduction of fermions and boson-fermion mixtures, not to speak of molecules, certainly opens the doors for investigations of complex quantum statistical systems.

Many ideas can be directly transferred between the two fields. The engineering of the dispersion relation for a BEC due to the optical lattice is equivalent to the dispersive engineering for a PCF due to the micro-structuring. New and interesting ideas can arise by merging the two fields. For instance it could be possible the move entire BECs inside PBG fibers. For both fields the engineering of the periodic structures can be carried out in 1, 2, and 3 dimensions and there are certainly many possibilities yet to be discovered and investigated in both of the fields.