Investigation and Control of Ultrashort Pulse Propagation in Photonic Crystal Fibers and Fiber Lasers in the Near Infrared Wavelength Region

Júlia Fekete

Ph.D. Theses

Supervisor:
Róbert Szipőcs, Ph.D.
Research Institute for Solid State Physics and Optics
of the Hungarian Academy of Sciences

Eötvös Loránd University, Faculty of Science
Physics Doctorate School
Head of the Doctorate School: Prof. Zalán Horváth
Statistical Physics, Biophysics and Physics of Quantum Systems Doctorate Program
Program leader: Prof. Jenő Kürti

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Background

During my Ph.D. work, I was dealing with ultrashort pulse propagation in optical fibers. Propagation of ultrashort pulses is highly affected by dispersion and nonlinearities. The nonlinear effects in optical fibers might be of orders of magnitude higher than in bulk optical components in case of a focused beam because of the long interaction length of light with matter. This fact gave rise to novel investigation methods in nonlinear optics. At the same time, under controlled circumstances optical fibers can transmit light with low loss over long distances with negligible distortion of the signal. For these reasons optical fibers are extremely widely used and found applications in many fields of research and engineering.

The nonlinear and the dispersion parameters that determine ultrashort pulse propagation in optical fibers can be modified by the design of the fiber structure. They are especially variable in the so-called photonic crystal fibers which consist of glasses with different dopants and hollows filled with air or other gases.

Due to the normal material dispersion in the visible and near infrared wavelength regions, the different spectral components of the pulses gain different delays (the pulses become “positively chirped”) during propagation in standard silica fibers and other optical elements. This leads to temporal broadening of the pulse. For various applications, where shorter pulses are needed, the material dispersion has to be overcome, (the pulses need to be “dechirped”) which can be achieved for example by the use of photonic crystal fibers. In the dispersion compensation process it is important to consider the peak intensity of the compressed pulse. The nonlinear effects induced by the high intensity of the pulse may lead to spectral distortion and even breaking up of the pulse. Effective compensation of the dispersion while avoiding nonlinear distortions are possible by the application of hollow-core photonic crystal fibers. In these fibers nonlinearity is reduced because most of the energy is confined in the air core, which has a negligible nonlinear coefficient.

For some applications such as the investigation of ultrashort processes it is necessary to compress the pulses. The minimum temporal pulse duration is determined by the spectrum due to the Fourier transform relationship. To obtain shorter pulse durations than the Fourier transform limited width, spectral broadening by a nonlinear optical process has to be realized. This can be accomplished by fiber nonlinearities.

Ultrashort pulses are originally generated by complicated setups including dye lasers exploiting colliding pulse mode-locking or solid-state lasers. Due to the advances in optical fiber technology, considerable attention is drawn by light sources that consist of fiber optical components, possibly in an all-fiber setup. The advantages of passively mode-locked fiber lasers compared to solid-state lasers include compactness, environmental stability, lower cost and low maintenance. Ultrashort pulses that are generated by all-fiber oscillators around 1 µm are compressible to as short as some 100 fs, according to previous works.

Motivation and methods

Hollow-core photonic crystal fibers guide light by the photonic bandgap effect of the cladding structure. This is in contrast to standard silica fibers, which guide light by the total internal reflection in the core. For total internal reflection the core needs to have a higher refractive index than the cladding, thus air-guidance is impossible with such fibers. In theory, the loss of air-core fibers within the bandgap is lower than the loss of solid-core fibers, because of the scattering of light in media. In practice, however, hollow-core fibers have higher transmission loss and the bandgap includes additional loss peaks. In realistic, so-called hollow-core Bragg photonic bandgap fibers silica struts are inserted to hold the space between concentric silica layers. The loss mechanisms arise due to the presence of the struts. We can distinguish surface modes, which cause loss due to symmetry concerns, and the leaking modes, which are caused by the increased electric field in the air layers due to an incorrect design of the structure. According to an analogy with one-dimensional Bragg structures our purpose was to investigate the loss mechanism caused by the leaking modes and to eliminate them in the fiber design procedure.

The self-phase modulation is the most common nonlinear process in optical fibers. It corresponds to a nonlinear temporal phase-shift on the pulse which is proportional to the temporal intensity function of the pulse. By the Fourier transformation of the temporal function it leads to broadening and modulation of the spectrum. In case of ultrashort pulses this phase-shift might reach a high value at relatively low pulse energies. By taking the linear (dispersive) and nonlinear phase-shifts into account in the simulations, optimization of the propagation parameters might lead to spectral broadening and pulse compression. My aim was the experimental demonstration of compression of a pulse below it's Fourier transform limit.

Our further goal was to develop an all-fiber, passively mode-locked ytterbium laser that generates ultrashort pulses that are compressible to a few 100 fs. Beside the experimental realization our aim was to determine the principles of the mode-locking mechanism by the characterization of the output pulses.

Results

Thesis 1 We have proposed a method for the proper design of photonic bandgap dielectric structures used at grazing incidence [T1]. The theory is based on the one-dimensional multilayer design, that I applied to one- and two-dimensional structures. I have compared plane photonic bandgap dielectric mirrors of different design principles and suggested dielectric mirrors to be used in grazing incidence as laser mirrors. Based on the one-dimensional results, we extended the model to two-dimensional photonic bandgap dielectric structures and applied it to all-silica hollow-core Bragg photonic bandgap fibers. I investigated the principles of the elimination of leaking modes in realistic hollow-core Bragg photonic bandgap fibers. I found leaking mode free structures and we compared the results to simulations done by the full-vectorial finite element method, taking the appropriate fiber structure into account. Results show that the one-dimensional model is capable of giving estimates for the design of leaking mode free hollow-core Bragg photonic bandgap fibers and thus represents an effective complementary tool to simulations done by complicated and time-consuming full-wave solvers.

Thesis 2 Pulse compression below the Fourier transform limit can be realized by nonlinear spectral broadening. For sub-nanojoule pulse energies, this can be achieved in a photonic crystal fiber with reduced core size. According to simulations of pulse propagation and optimization of the pre-chirp and subsequent dispersion-compensation coefficients, I have experimentally demonstrated two-fold pulse compression on nearly transform limited 24 fs pulses from a Ti:sapphire laser around 800 nm [T2].

Thesis 3 We have developed a passively mode-locked, all-fiber, all-normal dispersion ytterbium ring oscillator, working at 1.03 µm. The laser produces picosecond pulses, that can be dechirped by an external grating pair to $\sim$ 200 fs pulse durations [T3]. We have investigated the laser characteristics as an aim to better understand the theory of mode-locking in fiber oscillators, operating in the normal dispersion regime. We found, that the pulse-shaping in the oscillator is based on nonlinear polarization evolution in the fiber sections together with spectral and temporal filtering by a polarizing element.

PhD related publications

Refereed journals

[T1] J. Fekete, Z. Várallyay, R. Szipőcs, "Design of high bandwidth one- and two-dimensional photonic bandgap dielectric structures at grazing incidence of light," Applied Optics **47**, 5330-5336 (2008).

[T2] Z. Várallyay, J. Fekete, Á. Bányász, R. Szipőcs, "Optimizing input and output chirps up to the third-order for sub-nanojoule, ultra-short pulse compression in small core area PCF," Applied Physics B **86**, 567-572 (2007).

[T3] J. Fekete, A. Cserteg, R. Szipőcs, "All-fiber, all-normal dispersion ytterbium ring oscillator," Laser Physics Letters **6**, 49-53 (2009).

Other PhD related publications

[T1.1] J. Fekete, Z. Várallyay, R. Szipőcs, "Design of leaking mode free hollow-core photonic bandgap fibers," in *Optical Fiber Communication Conference*, OSA Technical Digest Series (Optical Society of America, 2008), paper JWA4.

[T2.1] Z. Várallyay, J. Fekete, Á. Bányász, R. Szipőcs, "Sub-nanojoule pulse compression in small core area photonic crystal fibers below the zero dispersion wavelength," Trends in Optics and Photonics **98**, 571-576 (2005).

[T2.2] Z. Várallyay, J. Fekete, Á. Bányász, S. Lakó, R. Szipőcs, "Sub-nanojoule pulse compression down to 6 fs in photonic crystal fibers," *CLEO Europe*, Munich, Germany, June, 2005.

[T2.3] R. Szipőcs, J. Fekete, Á. Bányász, Z. Várallyay, "Pulse Compression with Highly Nonlinear Photonic Crystal Fibers by Optimization of Input and Output Chirp Parameters up to the Third-Order," in *Optical Amplifiers and Their Applications*, Technical Digest (CD) (Optical Society of America, 2005), paper ME6.

[T2.4] Z. Várallyay, J. Fekete, Á. Bányász, S. Lakó, R. Szipőcs, "Sub-nanojoule pulse compression down to 6 fs in photonic crystal fibers," *CLEO/QELS Conference*, Baltimore, Maryland, USA, May 22-27, 2005, paper JThE21.

[T2.5] Z. Várallyay, J. Fekete, Á. Bányász, S. Lakó, R. Szipőcs, "Sub-nanojoule pulse compression down to 6 fs in photonic crystal fibers," *Advanced Solid State Photonics Conference*, Vienna, Austria, February 6-9, 2005, paper WD2.

[T3.1] Fekete J., Cserteg A., Szipőcs R., "Módusszinkronizált, normál diszperziójú szálintegrált itterbium ring oszcillátor," *Kvantumelektronika konferencia*, Budapest, 2008.