Summary of the Ph.D. thesis

Dispersion characterization of microstructured optical fibers using spectral interferometry

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1. Introduction

Nowadays there are numerous applications of optical fibers, not only in telecommunication, but also in medical and scientific research for mobile transport of laser pulses, not to mention their role in sensorics. The demand for further development is constantly growing, and the attempt to extend the current limits of performance drew interest toward new alternatives. By drifting away from classical fiber optics the invention of photonic crystal (PCF) and Bragg-type fibers in the nineties have presented new opportunities in photonics. The most enticing feature of these microstructured fibers is that they can fulfill the requirements of many applications since their optical properties, such as dispersion, birefringence, nonlinearity and guiding characteristics can be tailored by the proper design of their geometrical structure. It is possible to design almost dispersion-free fibers, for instance. The feasibility of guidance in air, more precisely, in a hollow core is especially advantageous as it could facilitate high-power pulse delivery with remarkably low losses and reduced nonlinearity. Due to their inherent attributes hollow-core (HC) PCFs can be employed in fiber optic gyroscopes, for gas spectroscopy, for high-power pulse delivery and compression, in endoscopy, in low latency optical communication systems, or as different type of sensors. Although the fiber drawing methods have become sophisticated and precise in the past decades, it cannot be guaranteed that the manufactured fiber structure will have the exact same geometry as designed even if it has a relative simple geometry. As a consequence, the optical properties of the actual fiber might be different than that of the modelled. In order to take into account the effects of the manufacturing process during the design phase and to increase the efficiency of the production of the fiber with the desired properties, therefore reduce the costs, a high-precision measurement method is needed.

Spectrally resolved interferometry (SRI) is an accurate linear method that is widely used technique for spectral phase characterization of various optical element and fibers as well. SRI has numerous advantages. It is relatively cheap compared to nonlinear techniques, does not require long fiber samples and most importantly, it is applicable in higher order dispersion retrieval, which is a common feature of microstructured fibers.

In the course of my thesis I will explore the applicability of different spectral interferometric evaluation methods in the dispersion retrieval of a Bragg-type and a hollow-core photonic crystal fiber.

2. Aims

1. In the production of microstructured optical fibers or during adjustment of optical systems where the second order (group delay, *GDD*) dispersion is to be reduced, the effects of higher order dispersion might become significant. Unlike in the case of common glass plates or conventional fibers in such circumstances the spectral phase contains third or higher order coefficients, therefore in theory more stationary phase points (SPPs) can be formed in the spectrally resolved interferograms. If so, studying the SPPs might provide information on the dominance and sign of given higher order dispersion and therefore present a real-time monitoring possibility. In the work I will thoroughly examine the relationship between the number, movement and shape of the SPPs appearing on the spectral interferograms and the higher order dispersion coefficients. I will demonstrate the effect of the dominance of various dispersion coefficients on the spectral interferograms by the means of simulations written in MathCad.

Testing the efficiency and the reliability of the SPP method as a higher order dispersion monitoring process experimentally would also be useful. To do so, I will build a spectrally resolved Mach-Zehnder and a Michelson interferometer and retrieve the dispersion of a solid-core Bragg-fiber and a prism pair using the SPP method.

2. The dispersion of the optical fibers can be measured with other spectral interferometric techniques besides the SPP method. The theoretical and experimental works presenting these methods, however, did not provide their comparison. In order to choose the most adequate

method for characterizing short (<1m) optical fibers a detailed study is lacking. Additionally, it would be of great advantage to test the sensitivity of the evaluation methods to the presence of higher order dispersion. It would be also important to find out how the presence of leaking modes, which might appear within the transmission spectrum of these fibers, affects the accuracy of the measurements. Accordingly, my aim is to compare and study the stationary phase point, the minima-maxima (MM), the cosine function fit (CFF) and the conventional (FT) as well as the windowed Fourier-transform (WFT) methods regarding their accuracy in higher order dispersion retrieval of microstructured fibers. The previously tested Bragg-fiber will serve as a sample, which has sharp resonances in its transmission spectrum.

3. Since the application of hollow core photonic fibers has numerous advantages I decided to study their dispersion properties as well. The HC-800 type fibers have soon acquired respectable attention and different research groups started studying them. Most of these studies dealt with the HC-800-01 fibers, however, currently only the HC-800-02 type is available for purchase. Some properties of the HC-800-02 PCF have already been studied, however, only in a smaller wavelength range compared to its operating range. Consequently, I aim to experimentally investigate the dispersion and polarization characteristics of the HC-800-02 fiber in its full operating wavelength range (760 to 870 nm) using spectral interferometry combined with the FT evaluation method. I will retrieve the dispersion along both polarization directions of the fiber. Fibers are often coiled or bent during use which might intorduce mechanical tension to the system. Since the birefringent and dispersion properties might be affected by this, in addition to the tests with straight fibers measurements I performed with bent and coiled samples as well. The scaling of dispersion with fiber length, i.e. the uniformity of the fiber was also verified by testing samples of various lengths ranging from 10 to 97 cm.

4. As the polarization mode dispersion (PMD) can be a limiting factor in numerous applications, its experimental retrieval is of great significance. By exciting both polarization modes of the HC-800-02 PCF simultaneously I will determine the PMD with the FT method using an indirect and a direct approach, and then compare their precision.

5. Since the windowed Fourier evaluation method retrieves the group delay (*GD*) of the sample directly, from which the sign and the dominance of higher order dispersion can also be predicted, the applicability of the method in the case of different fibers is worth testing. My aim was to explore the benefits of an improved, high resolution windowed Fourier-ridges (WFR) algorithm in comparison to the conventional FT method. The HC-800-02 PCF will serve as a sample.

3. Methods

Using simulations prepared in MathCad 14 software I examined the relationship between the number, movement and shape of the SPPs and the higher order dispersion. To fit the wavelength range in the forthcoming measurements I used the range of 700-900 nm in the simulations. I investigated the effects of third, fourth and fifth order dispersion. The results of the simulations were compared with measurements performed on a 30-cm-long Bragg-type microstructured fiber and a prism pair having adjustable dispersion consisting of fused silica prisms having apex angles of 67°. To do so, I built a Mach-Zehnder and a Michelson interferometer. The broadband Ti:S source (Femtolasers, Rainbow, pulse length: 6 fs, central wavelength: 800 nm, FWHM = 150 nm) was used in the case of the fiber, while I used a 100-W halogen lamp to illuminate the setup containing the prism pair. A high resolution spectrometer (Ocean Optics HR4000, 700-900 nm, spectral resolution: 0.2 nm) was used in the case of the fiber, and one with a lower resolution (Avantes 3648, 200-1100 nm, spectral resolution: 1 nm). The SPP method was used to evaluate the recorded interferograms.

Later, I used a 37-cm-long Bragg-fiber to compare the SPP, MM, CFF, FT and WFT methods. The measurements were performed in the wavelength range between 740 and 840 nm. I built a Mach-Zehnder interferometer, which was illuminated with a homemade Ti:S oscillator (pulse length: 20 fs, central wavelength: 800 nm, FWHM = 60 nm). The high resolution spectrometer was used to study the interference pattern.

To retrieve the polarization-dependent dispersion of the HC-800-02 photonic crystal fiber I used a Mach-Zehnder interferometer illuminated by the Rainbow Ti:S. Again, I used the high resolution spectrometer as a detector. The measurements were done in the 760-870 nm wavelength range and the recorded interferograms were evaluated by the FT and the MM methods. I placed the fiber probes into the sample arm of the interferometer in different positions. Additionally, I tested samples of different lengths.

To examine the benefits of the WFR method I also used the HC-800-02 fiber in my measurements relying on the same experimental setup as before. I performed the measurements between 760 and 840 nm by exciting the polarization modes of the fiber separately and simultaneously as well.

4. Results

T1. I investigated the effect of dispersion of various orders on the interference pattern by the means of simulations prepared in MathCad. I demonstrated that by analyzing the number, movement and shape of the stationary phase points it is possible to predict which dispersion order is dominant in the spectral phase. Dominant third order produced two, combined group delay and fourth order dispersion three, joined third and fifth order dispersion resulted in the appearance of four stationary phase points. I concluded that the positions of the stationary phase points can be determined with high precision, apart from the case of pure fourth order dispersion, when the stationary phase point becomes too broad at low time delays, which usually affects the precision of the measurement. The relationship between the stationary phase points and the higher order dispersion was studied experimentally with measurements performed on a 30-cm-long Bragg-type microstructured fiber and a prism pair having adjustable dispersion consisting of fused silica prisms having apex angles of 67°. The results obtained with the Bragg-fiber were in agreement with the simulations. The results of monitoring in the case of the prism pair were in contradiction with those of the simulations. This can be interpreted as a consequence of the relatively short spectral range analyzed during the measurements, and the fact that the complete movement of the stationary phase points was not monitored. I concluded that the retrieval of the coefficients with measurements is crucial to decide which dispersion term is dominant [1,7,8,13,15].

T2. I compared five spectral interferometric evaluation methods in higher order dispersion retrieval in the wavelength range between 740 and 840 nm using a 37-cm-long Bragg-fiber sample. I concluded that the stationary phase point and the minima-maxima methods were insensitive to the presence of higher orders, while the cosine function fit method proved to be very precise in these cases. The precision of the windowed Fourier-transform evaluation method was well below the expectations. I concluded that the conventional Fourier-transform evaluation method provided the dispersion coefficients of the tested Bragg-fiber with the highest accuracy up to the fifth order. I demonstrated that only the two Fourier-transform techniques were capable to detect the phase jumps caused by the absorption valleys appearing in the spectrum of the fiber [2,5,6,9−11].

T3. I experimentally retrieved the polarization-dependent chromatic dispersion of short (< 1m) HC-800-02 photonic crystal fiber samples of up to the sixth order in the wavelength range between 760 and 870 nm using Fourier-transform spectral interferometry. I demonstrated that the dispersion curves obtained for the two polarization axes of the fiber were different. The curves in the lower wavelength regime retrieved by excitation of the fast and the slow polarization modes differed from the one calculated using the data provided by the manufacturer about 70% and 198%, respectively. It was shown that the measured *GDD* was negative and much lower in absolute value along both polarization axes than that of conventional fused silica single-mode fibers of similar length. I showed that all other higher order dispersion coefficients were positive and that the third order dispersion (*TOD*) is the dominant term in the spectral phase of the fiber. I concluded that the dispersion was mostly independent on the placement and fiber length in both polarization directions [3,12,14].

T4. I experimentally retrieved the polarization mode dispersion of short (<1m) HC-800-02 photonic crystal fiber samples with an indirect and a direct approach in the wavelength range between 760 and 870 nm employing spectral interferometry. The polarization mode dispersion was obtained using the Fourier-transform method in the case of the indirect method and also for the longer samples measured by the direct method. The differential group delay of shorter fibers was determined using minima-maxima method. The comparison of the results of my measurements and previously published data revealed that it is not possible to manufacture completely identical fibers, therefore the experimental retrieval optical properties is of great importance. It was also shown that the precision of the direct method was greater only when longer samples were measured, since that approach did not depend on the precise excitation of a given polarization mode or on the accuracy of the translator stage in the reference arm. In the case of shorter fibers the accuracy of the direct and indirect methods was comparable [3,12,14].

T5. I experimentally retrieved the polarization-dependent chromatic dispersion of short (<1m) HC-800-02 fibers by exciting the orthogonal polarization modes simultaneously and separately in the wavelength range between 760 and 870 nm using spectral interferometry. The recorded interferograms were evaluated using an improved version of the windowed

Fourier-ridges algorithm. The retrieved dispersion and differential group dispersion curves obtained from a single interferogram with simultaneous excitation of the modes were in complete agreement with the ones I got with the windowed or the conventional Fourier-method for interferograms recorded with separate excitation. I demonstrated that the sign and the dominance of higher order dispersion can also be predicted visually from the shape of the *GD* curve obtained with the windowed Fourier-ridges algorithm without any further signal processing [4].

5. Publications related to the thesis

- **Peer-reviewed journals**

[1] **T. Grósz**, A. P. Kovács, K. Mecseki, L. Gulyás, and R. Szipőcs, „Monitoring the dominance of higher-order chromatic dispersion with spectral interferometry using the stationary phase point method," Opt. Commun. **338**, 292−299 (2015).

[2] **T. Grósz**, A. P. Kovács, M. Kiss, and R. Szipőcs, „Measurement of higher order chromatic dispersion in a photonic bandgap fiber: comparative study of spectral interferometric methods," Appl. Opt. **53**(9), 1929−1937 (2014).

[3] **T. Grósz**, A. P. Kovács and K. Varjú, „Chromatic Dispersion Measurement along Both Polarization Directions of a Birefringent Hollow-core Photonic Crystal Fiber Using Spectral Interferometry," Appl. Opt. **56**(19), 5369−5376 (2017).

[4] **T. Grósz**, M. Horváth, and A. P. Kovács, „Complete dispersion characterization of optical fibers from a single interferogram using the windowed Fourier ridges algorithm," Opt. Express, megjelenés alatt (2017).

- **Conference proceedings**

[5] A. P. Kovács, **T. Grósz**, and M. Kiss, „Measurement of higher order dispersion in a photonic fiber using spectral interferometry," AIP Conf. Proc. **1462**, 112−115 (2012).
[6] **T. Grósz**, M. Kiss, and A. P. Kovács, „Characterisation of optical pulses travelling through a photonic crystal fibre using Fourier-transform spectral interferometry," Proc. SPIE **8775**, Micro-structured and Specialty Optical Fibres II, 87750E-1 (2013).
[7] **T. Grósz**, and A. P. Kovács, „Higher order dispersion measurement using the stationary phase point method," Proc. SPIE **9128**, Micro-structured and Specialty Optical Fibres III, 91280R-1 (2014).
[8] **T. Grósz**, L. Gulyás, and A. P. Kovács, „Advanced laboratory exercise: Studying the dispersion properties of a prism pair," Proc. SPIE **9793**, Thirteenth International Topical Meeting on Education and Training in Optics and Photonics (ETOP), 97931N-1 (2015).

- **Conference presentations and posters**

[9] A. P. Kovács, **T. Grósz**, and M. Kiss, „Measurement of Higher Order Dispersion in a Photonic Bandgap Fiber Using Spectral Interferometry," LEI 2011 - Light at Extreme Intensities, Szeged, Hungary (November 14-18, 2011), poster P12
[10] **T. Grósz**, M. Kiss, and A. P. Kovács, „Dispersion Measurement of Photonic Crystal Fibers up to Fifth Order Using Spectral Interferometry," 5th EPS-QEOD Europhoton Conference on Solid-State, Fibre, and Waveguide Coherent Light Sources, Stockholm, Sweden (August 26-31, 2012), poster TuP33
[11] **T. Grósz**, M. Kiss, and A. P. Kovács, „Characterisation of Optical Pulses travelling through a Photonic Crystal Fibre Using Fourier-transform Spectral Interferometry," SPIE Optics and Optoelectronics, Prague, Czech Republic (April 15-18, 2013).

[12] **T. Grósz**, R. Szipöcs, and A. P. Kovács, „Measurement of Polarization-dependent Chromatic Dispersion in a Birefringent Hollow-core Photonic Crystal Fiber Using Spectral Interferometry," 3rd Workshop on Specialty Fibers and their Applications, Sigtuna, Sweden (August 28-30, 2013), poster F2.10
[13] **T. Grósz**, and A. P. Kovács, „Higher Order Dispersion Measurement Using the Stationary Phase Point Method," SPIE Photonics Europe, Brussels, Belgium (April 14-17, 2014) poster 9128-27
[14] **T. Grósz**, K. Csonti, R. Szipőcs, and A. P. Kovács, „Measurement of the Polarization Mode Dispersion in a HC-800 Photonic Crystal Fiber," 6th EPS-QEOD Europhoton Conference on Solid-State, Fibre, and Waveguide Coherent Light Sources, Neuchâtel, Switzerland (August 24-29, 2014) poster TuP-T1-P-16
[15] **T. Grósz**, L. Gulyás, and A. P. Kovács, „Advanced laboratory exercise: Studying the dispersion properties of a prism pair," ETOP 2015, Education and Training in Optics and Photonics, Bordeaux, France (June 29-July 2, 2015) paper 962