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Experimental measurement and numerical analysis of group velocity dispersion in cladding modes of an endlessly single-mode photonic crystal fiber

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ABSTRACT

The optical properties of the guided modes in the core of photonic crystal fibers (PCFs) can be easily manipulated by changing the air-hole structure in the cladding. Special properties can be achieved in this case such as endless single-mode operation. Endlessly single-mode fibers, which enable single-mode guidance over a wide spectral range, are indispensable in the field of fiber technology. A two-dimensional photonic crystal with a silica central core and a micrometer-spaced hexagonal array of air holes is an established method to achieve endless single-mode properties. In addition to the guidance of light in the core, different cladding modes occur. The coupling between the core and the cladding modes can affect the endlessly single-mode guides. There are two possible ways to determine the dispersion: measurement and calculation.

We calculate the group velocity dispersion (GVD) of different cladding modes based on the measurement of the fiber structure parameters, the hole diameter and the pitch of a presumed homogeneous hexagonal array. Based on the scanning electron image, a calculation was made of the optical guiding properties of the microstructured cladding. We compare the calculation with a method to measure the wavelength-dependent time delay. We measure the time delay of defined cladding modes with a homemade supercontinuum light source in a white light interferometric setup. To measure the dispersion of cladding modes of optical fibers with high accuracy, a time-domain white-light interferometer based on a Mach-Zehnder interferometer is used. The experimental setup allows the determination of the wavelength-dependent differential group delay of light travelling through a thirty centimeter piece of test fiber in the wavelength range from VIS to NIR. The determination of the GVD using different methods enables the evaluation of the individual methods for characterizing the cladding modes of an endlessly single-mode fiber.

Keywords: endlessly single-mode fiber, cladding modes, photonic crystal fiber, group velocity dispersion

INTRODUCTION

In comparison to conventional step-index optical fibers PCF's offer the possibility to guiding light over broad wavelength rang exclusively in the fundamental fiber mode. In contrast to single mode optical step-index fibers, photonic crystal fibers (PCF) provide a few advantages. Beside single mode operation with a large mode area [1, 2], single mode operation over a very large wavelength range can be realized [3]. These unique features derive from the fact that optical properties of the guided modes in the core can be easily manipulated by changing the air-hole structure in the cladding [4]. In many publications the propagation properties of the fundamental mode in the centered core are the main interest [1-3]. Cladding modes are important if coupling between the core and the cladding modes occurs [5, 6] as in the case of conventional fibers [7]. The transition between cladding modes and the core mode can be modelled by finite element method FEM [8]. For some cladding modes a strong overlap with fundamental mode occurs which leads to very similar behavior as higher order modes (HOMs) in view mode fibers [8]. For most real world fiber launching conditions,

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the light propagates through the fiber in the PCF fundamental mode and in a few cladding modes. Furthermore for PCFs the dimension of the holes is very difficult to control during fabrication and variations of the microstructure influence the respective gladding modes. Knowledge of the exact dispersion characteristics of the guided modes will help to develop optimized endlessly single-mode PCFs. The determination of the dispersion of single mode fibers with different methods has been shown. One method, which is especially suited for short test fibers, is the spectral domain interferometric group delay measurement [9-11]. The temporal domain setup is another established method [12-14] and is close to the time of flight configuration. The time-frequency-domain method combines the benefits of both methods and allows the use of short test fibers [15-17]. The numerical modelling based on extracting the coordinates of cross-sections of PCFs and finite element method is also shown with different methods [18-20].

EXPERIMENTAL ARRANGEMENT AND METHODS

The optical setup consists of a Mach-Zehnder interferometer and uses a controllable delay line to investigate the time delay of the sample in order to find the equalization wavelength [14]. A micro positioning unit LNR25ZFS/M from THORLABS was used, which possess a linear resolution of 0.5 μm, and therefore allows for a time resolution on femtosecond time scales (Fig. 2). In this configuration the linear translation stage controls the reference length to equalize different propagation times. Both beams are recombined by the second non-polarizing beam splitter. The recombined beams are launched into the fibers of the Si-based (VIS) and InGaAs-based (NIR) spectrometers. If both branches are balanced by means of their dispersion profiles, an overall increased spectral intensity for the branches having identical lengths can be observed. The group delay τ was fitted with a three-term Sellmeier polynomial of the form:

$$\tau = \frac{a_1}{\lambda^2} + a_2 + a_3\lambda^2 \, . \tag{1}$$

A camera at the free output of the second polarization-independent beam splitter allows control of the coupling of light into the fiber core. With the aid of a bandpass filter, the examined spectral range can be controlled. It enables selective analysis of single fiber modes in the sample at defined wavelengths. By adjustment of the intensity of the reference signal with the help of the attenuator and control of the lunching conditions of the test fiber, single fiber modes can be measured and identified Fig. 1.

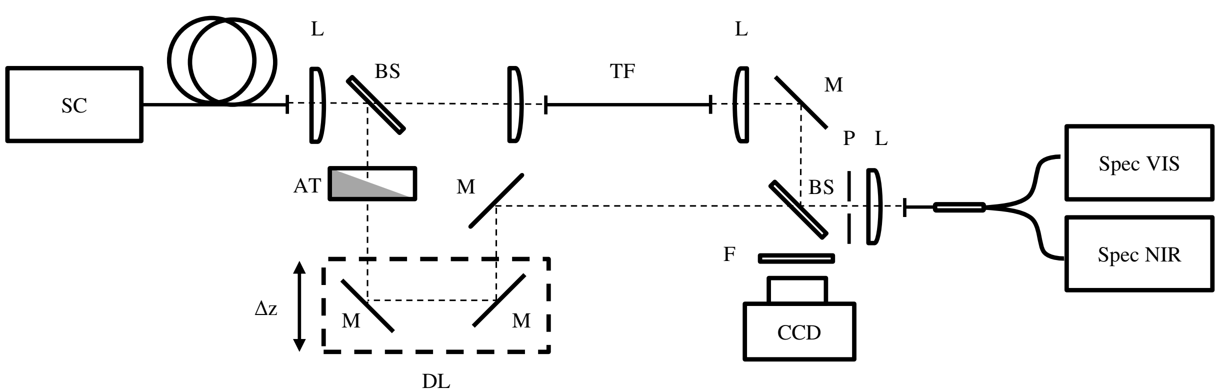

Figure 1. a) Interferometric setup used for the dispersion measurements. SC - supercontinuum light source, BS - non-polarizing beam splitter, DL - delay line, M - mirror, P - pinhole, TF - test fiber, L – lens, AT - attenuator, F - bandpass filter, CCD - camera and Spec - spectrometer. By varying the length of the reference branch relative to the test branch, one can obtain spectral modulations at the equalization wavelength for which the phase delay is negligible.

For the setup, a fiber-coupled supercontinuum light source developed and manufactured in cooperation with fiberware GmbH, is used. The optical properties are modeled based on a binary cross-sectional image taken from an SEM image and the finite element method.

EXPERIMENTAL RESULT

The cross section of the endlessly single-mode PCF (produced by fiberware GmbH) was recorded by a scanning electron microscope. To convert the greyscale image to a binary image, a defined threshold was set and the image was numerically filtered from noise, particles or scratches. Figure 2 a) shows a scanning electron microscope image of the fiber and b) the generated binary image of the sample used for the simulations [21].

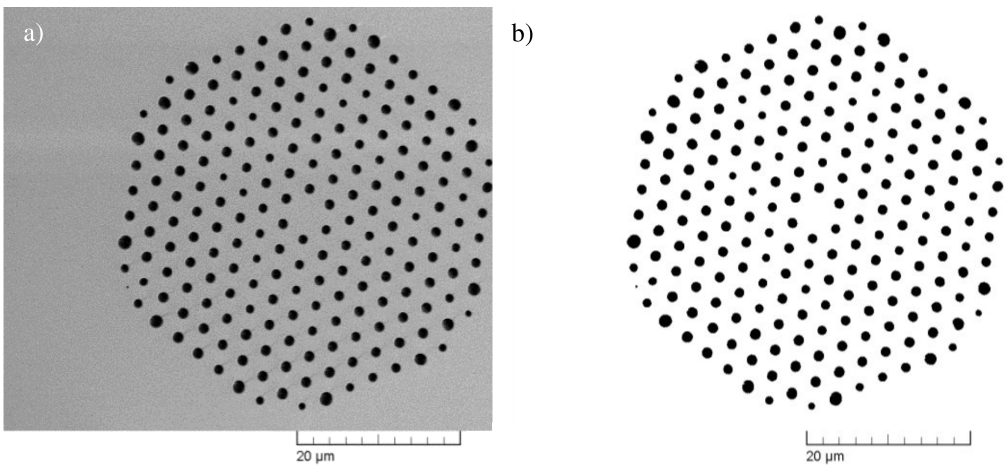

Figure 2. a) Scanning electron microscope cross-sectional image of the test fiber. b) Binary image of the sample.

The scaling the pixel size with high precision is very important to. Based on this knowledge it is possible to characterize the test fiber geometrically (Table 1).

Table 1. Geometric fiber parameters based on the fiber cross-sectional image.

	measurements
core diameter [µm]	5.1 ± 0.05
cladding diameter [µm]	48.7 ± 0.5
hole-to-hole distance [µm]	3.1 ± 0.05
hole diameter [µm]	1.2 ± 0.05
d/Λ	0.39

The hole diameter **d** to hole-to-hole distance **Λ** is less than 0.43 which leads to endlessly single-mode propagation [5]. Based on the binary image of the PCF cross-sections, a finite element method is employed for investigating the optical properties. Figure 3 a) shows modeled nearfield intensity profile of the FSM at 800 nm and b) shows the corresponding recorded nearfield intensity profile during the delay measurements.

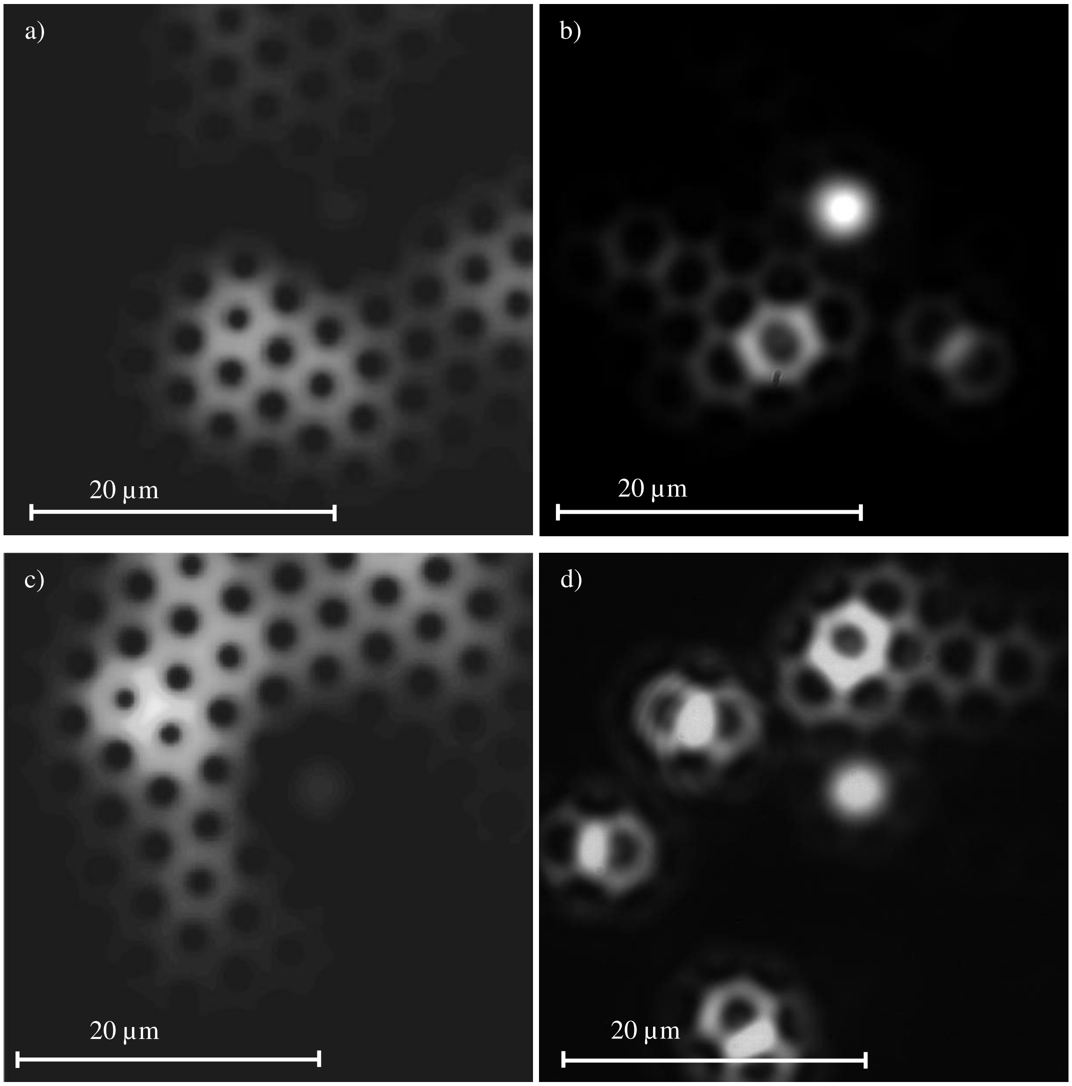

Figure 3. a) and c) Modelled intensity profile of the FSM at 800 nm and b) and d) recorded near-field image of the measured fiber at 800 nm.

The modeling further offers information about the group delay of the fundamental mode and the selected cladding modes. The results are compared with the group delay measurement Fig. 4. The modeled group delay of the fundamental mode fits the measured data well and small deviations in the range above one micron are based on an error of pixel size or wrong level of threshold for the binary image. The modeled nearfield intensity profile of the two chosen cladding modes matched the recorded nearfield intensity profile best, but the recorded images are probably a superposition of different cladding modes. This results in a larger deviation of group delay.

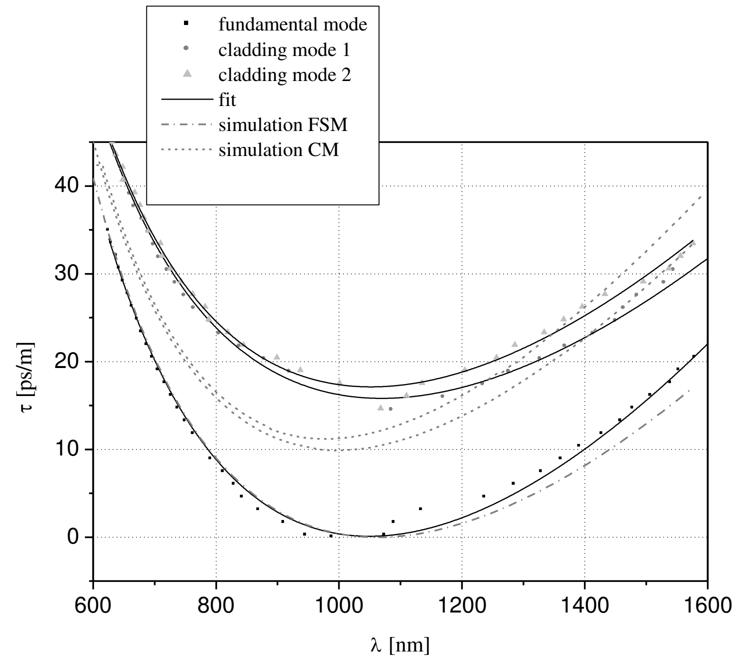

Figure 4. Measured group delay τ (λ) based on the time-frequency-domain method of the investigated fiber compared with the modelled optical properties of the fundamental mode and the two chosen cladding modes.

The investigated group delay τ(λ) in Fig. 4 was fitted using the Sellmeier polynomial. The calculated GVD is shown in Fig. 5. The measured zero-dispersion wavelength of 1049.09 ± 3 nm was near to the modeled zero-dispersion wavelength of 1060.4 nm.

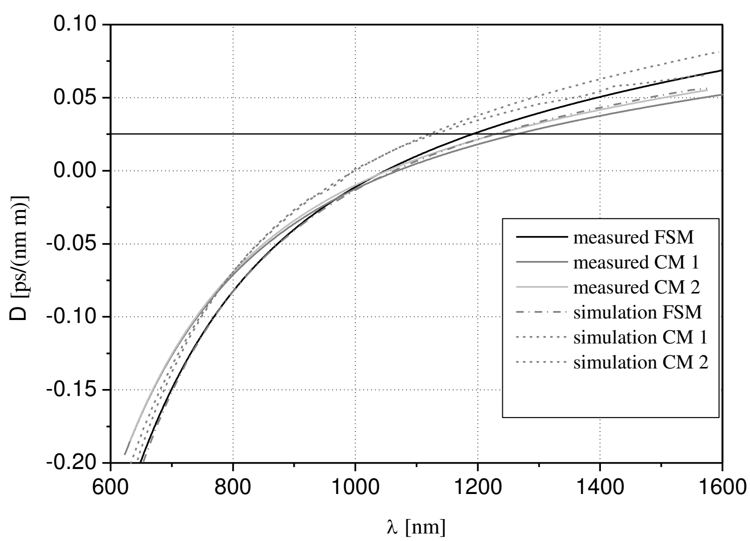

Figure 5. Measured group delay τ (λ) and group velocity dispersion based on the time-frequency-domain method of the investigated fiber compared with the modelled optical properties of the fundamental mode.

Table 2. Shows a comparison of the analyzed fundamental mode and the cladding modes.

Table 2. Parameters of the constituent fibers.

	measured FM	simulated FSM
Sellmeier polynomial R^2	0.992	0.999
a1[ps µm^2/m]	26.8 ± 0.01	31.1
a2 [ps/m]	-31.3 ± 1.5	-54.7
a3[ps / µm^2 m]	30 ± 0.05	20
zero-dispersion wavelength [nm]	1049.09 ± 3	1060.4

The error between simulation and measurement are explainable for the fundamental mode. The cladding modes show different results. Changes of the microstructure influence the optical properties significantly. The image processing on the scanning electron microscope cross-sectional image leads to unintentional size discrepancies that caused deviations from the real microstructure. These scaling problems will be calibrated in future measurements. The measured zero-dispersion wavelength of the cladding modes of 1069.5 ± 3 nm and 1052.7 ± 3 nm was far away of the modeled zero-dispersion wavelength of 996.1 nm and 998.9. It is hard to choose the right cladding modes and a superposition of different cladding modes affects the measurement results.

CONCLUSION

This report presented a comparison of different methods for determining the GVD of the fundamental mode and cladding modes of endlessly single mode PCF´s. Both methods allow one to characterize the possible guiding properties of micro structured fibers and offer a nearfield intensity profile for a defined wavelength. One method was based on a scanning electron microscope cross-sectional image of the test fiber and models the optical properties by a finite element method. This method needs no optical setup and for some applications (for example short fiber components) it's the only possibility to qualify the optical properties of the fibers. The methods show different advantages and disadvantages depending on the fiber geometry and the test fiber length. The results of measuring of the captured modes have been compared with modeling the optical properties of the test fiber based on a cross-sectional image. Time-frequency-domain dispersion measurements have been proven to be a good and gapless method for the determination of the dispersion, even if HOMs or cladding modes are guided. The measurement setup allowed for the investigation of different modes and a clear assignment of the dispersion curves.

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