**Dieses Dokument ist eine Zweitveröffentlichung (Verlagsversion) /
This is a self-archiving document (published version):**

Tobias Baselt, Tobias Popp, Bryan Nelsen, Andrés Fabián Lasagni, Peter Hartmann

**Comparative investigation of methods to determine the group
velocity dispersion of an endlessly single-mode photonic crystal fiber**

Erstveröffentlichung in / First published in:

SPIE Optics + Optoelectronics. Prague, 2017. Bellingham: SPIE, Vol. 10232 {Zugriff am: 22.05.2019}.

DOI: <https://doi.org/10.1117/12.2265688>

Diese Version ist verfügbar / This version is available on:

<https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-351372>

„Dieser Beitrag ist mit Zustimmung des Rechteinhabers aufgrund einer (DFGgeförderten) Allianz- bzw. Nationallizenz frei zugänglich.“

This publication is openly accessible with the permission of the copyright owner. The permission is granted within a nationwide license, supported by the German Research Foundation (abbr. in German DFG).

www.nationallizenzen.de/

PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Comparative investigation of methods to determine the group velocity dispersion of an endlessly single-mode photonic crystal fiber

Tobias Baselt, Tobias Popp, Bryan Nelsen, Andrés Fabián Lasagni, Peter Hartmann

Tobias Baselt, Tobias Popp, Bryan Nelsen, Andrés Fabián Lasagni, Peter Hartmann, "Comparative investigation of methods to determine the group velocity dispersion of an endlessly single-mode photonic crystal fiber," Proc. SPIE 10232, Micro-structured and Specialty Optical Fibres V, 102320K (16 May 2017); doi: 10.1117/12.2265688

SPIE.

Event: SPIE Optics + Optoelectronics, 2017, Prague, Czech Republic

Comparative investigation of methods to determine the group velocity dispersion of an endlessly single-mode photonic crystal fiber

Tobias Baselt^{*abc}, Tobias Popp^b, Bryan Nelsen^{ab}, Andrés Fabián Lasagni^{ac}, Peter Hartmann^{ab}

^aFraunhofer-Institut für Werkstoff- und Strahltechnik IWS, 01277 Dresden, Germany

^bUniversity of Applied Sciences Zwickau, Institute of Leupold-Institute for Applied Natural Sciences / Optical Technologies, D-08056 Zwickau

^cTechnische Universität Dresden, Institute of Manufacturing Technology, George-Bähr-Straße 3c, 01069 Dresden, Germany

ABSTRACT

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 guidance. There are two possible ways to determine the dispersion: measurement and calculation. We calculate the group velocity dispersion GVD based on the measurement of the fiber structure parameters, the hole diameter and the pitch of a presumed homogeneous hexagonal array and compare the calculation with two methods to measure the wavelength-dependent time delay. We measure the time delay on a three hundred meter test fiber with a homemade supercontinuum light source, a set of bandpass filters and a fast detector and compare the results with a white light interferometric setup. To measure the dispersion of optical fibers with high accuracy, a time-frequency-domain setup 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 endlessly single-mode fiber.

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

1. INTRODUCTION

In conventional step-index optical fibers, the guiding properties are strongly dependent on the guided wavelength. The propagation exclusively in the fundamental fiber mode is only possible in a limited spectral range. One way to describe the characteristics of optical fibers is to define a fiber parameter V . Fibers with a fiber parameter of less than 2.4 exclusively allow the propagation of radiation in the fundamental mode [1]. The fiber parameter V depends on the radius of the fiber core a , the wavelength λ of the guided electromagnetic radiation and the refractive index ratio between the core n_1 and cladding n_2 . The fiber parameter V is defined as:

$$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda} NA \quad (1)$$

Based on the Eq. 1, there is a wavelength below where high order modes (HOM) can propagate and only a small spectral range allows propagation exclusively in the fundamental space-filling mode (FSM). Step-index single mode fibers offer only minimal possibilities and handle the V parameter by adapting the fiber geometry. Therefore, the possibilities to adjust the chromatic dispersion are limited [2]. In contrast to single mode optical fibers, photonic crystal fibers (PCF) provide a few advantages. Beside single mode operation with an extremely large core size [3, 4], single mode operation over a very large wavelength range can be realized [5]. Analogous to that model of the V parameter, the comparable parameter V_{eff} for PCFs can be defined [6] as

$$V_{eff} = \frac{2\pi\Lambda}{\lambda} \sqrt{n_1^2 - n_{eff}^2} = \frac{2\pi\Lambda}{\lambda} NA \quad . \quad (2)$$

The effective refractive index of the cladding, n_{eff} , and the effective core radius, a_{eff} , are highly dependent on the wavelength of the propagating radiation and the periodic modulation of the refractive index on the scale of the optical wavelength [7].

$$n_{eff} = \frac{\beta_{FSM}}{k} \quad (3)$$

PCFs show large waveguide dispersion but it is very hard to fabricate the fibers with similar quality as step-index fibers. The dimension of the holes is very difficult to control during fabrication which influences the dispersion characteristics. Knowledge of the exact dispersion characteristics 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 suited especially for short test fibers, is the spectral domain interferometric group delay measurement [8- 10]. The temporal domain setup is another established method [11-13] 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 [14-16]. The numerical modelling based on extracting the coordinates of cross-sections of PCFs and finite element method is shown in different groups [17-19]. To determine the dispersion of the endlessly single-mode PCF the last three methods are evaluated.

2. EXPERIMENTAL ARRANGEMENT AND METHODS

Two optical setups for different test fiber lengths have been developed. The first 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 spatial resolution of 0.5 μm , and therefore allows for a time resolution on femtosecond time scales (Fig. 1, a)). 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:

$$\tau = \frac{a_1}{\lambda^2} + a_2 + a_3\lambda^2 \quad (4)$$

A camera at the free output of the second polarization-independent beam splitter allows control of the coupling of light into the fiber core. It enables selective analysis of single fiber modes in the sample and, by adjustment of the intensity of the reference signal with the help of the attenuator, single fiber modes can be measured and identified. The second setup required a much longer test fiber length and measured the time of flight for a defined wavelength (Fig. 1, b)). In order to detect the temporal delay, two identical detectors (PD10CF from THORLABS) and a 1 GHz bandwidth oscilloscope (HDO6104 TELEDYNE LECROY) were used.

Figure 1. a) Interferometric setup used for the dispersion measurements. SC - supercontinuum light source, BS - non-polarizing beam splitter, DL - delay line, M - mirror, TF - test fiber, 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. b) Time of flight measurement setup to determine the group delay of the test fiber for different wavelength. F – bandpass filter, D1 - reference detector, L lens and D2 - delay detector.

For both setups 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 and the finite element method.

3. EXPERIMENTAL RESULT

The cross section of the endlessly single-mode PCF (produced by fiberware GmbH) was collected by a scanning electron microscope. To create a clean, binary image, a defined threshold has to be set and the image has to be cleaned from noise, particles or scratches. Figure 2 a) shows a scanning electron microscope image of the fiber and b) the binary image of the sample used for the simulations.

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

In the next step it is important scaling the pixel with high precision. Based on this knowledge it is possible to characterize the test fiber geometrically and to calculate the fiber parameter V (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
V-parameter	2.3
d/Λ	0.39

The fiber parameter of 2.3 is less than 2.405 and the relation between 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 intensity profile of the FSM at 800 nm and b) shows the recorded profile during the delay measurements.

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

The modeling further offers information about the group delay and group velocity dispersion of the modelled fiber mode. The results are compared with the group delay measurement with the time of flight configuration in Fig. 4. The 280 m length of the test fiber is short for this method which leads to a larger error.

Figure 4. Measured group delay $\tau(\lambda)$ and group velocity dispersion based on the time of flight method of the investigated fiber compared with the modelled optical properties of the fundamental mode.

The investigated group delay $\tau(\lambda)$ in Fig. 4 was fitted using the Sellmeier polynomial ($R^2 = 0.975$). The Sellmeier coefficients Form. 4 are $a_1 = 29.79 \cdot 10^7 \pm 1.2 \cdot 10^6$, $a_2 = -54.4 \pm 2.5$ and $a_3 = 3 \cdot 10^{-5} \pm 9 \cdot 10^{-7}$. Also, the calculated GVD is shown. The measured zero-dispersion wavelength of 1047.8 ± 5 nm was near to the modeled zero-dispersion wavelength of 1060.4 nm. To qualify these results with a reference procedure a 46.1 cm piece of the sample was measured with the time-frequency-domain method, Fig. 5.

Figure 5. Measured group delay $\tau(\lambda)$ 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.

The investigated group delay $\tau(\lambda)$ in Fig. 5 was fitted using the Sellmeier polynomial ($R^2 = 0.992$). The Sellmeier coefficients are $a1 = 26.79 \cdot 10^7 \pm 1.2 \cdot 10^3$, $a2 = -31.3 \pm 1.5$ and $a3 = 3 \cdot 10^{-5} \pm 5 \cdot 10^{-7}$. The measured zero-dispersion wavelength of 1049.09 ± 3 nm was closer to the modeled zero-dispersion then the results measured with the time of flight method. Table 2. shows a comparison of the applied methods.

Table 2. Parameters of the constituent fibers.

	time of flight	time-frequency-domain	Simulation
Sellmeier polynomial R^2	0.975	0.992	
$a1$ [ps $\mu\text{m}^2/\text{m}$]	29.8 ± 0.12	26.8 ± 0.01	31.1
$a2$ [ps/m]	-54.4 ± 2.5	-31.3 ± 1.5	-54.7
$a3$ [ps / μm^2 m]	30 ± 0.09	30 ± 0.05	20
zero-dispersion wavelength [nm]	1047.8 ± 5	1049.09 ± 3	1060.4

The error between both measurements is not big enough to be justified by the short sample length for the time of flight measurement setup. It is hart to produce a uniform PCF with a length of 500 m and changes of the microstructure influence the optical properties significant. The image processing on the scanning electron microscope cross-sectional image leads to unintentional changes that caused deviations from the real microstructure.

CONCLUSION

This report presented a comparison of different methods for determining the GVD of optical fibers. Two of the presented methods were used to measure the group delay and calculate the GVD. 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 both measurement setups 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 HOM or cladding modes are guided. The measurement setup allowed the investigation of different modes and a clear assignment of the dispersion curves.

ACKNOWLEDGMENTS

The authors want to thank the Federal Ministry of Education and Research for financial support under grant number FKZ 03FH004PX3 as well as the members of the optical technologies working group at the West Saxon University of Applied Sciences Zwickau, the company fiberware GmbH and Prof. Lasagni at the Institute of Manufacturing Technology (Technische Universität Dresden) for fruitful discussions.

REFERENCES

- [1] Tünnermann, A., Zellmer, H., Schöne, W., Giesen, A. and Contag, K.: „New Concepts for Diode-Pumped Solid-State Lasers” Topics in Applied Physics. Jena: Springer (2000) Davis, A. R., Bush, C., Harvey, J. C. and Foley, M. F., "Fresnel lenses in rear projection displays," SID Int. Symp. Digest Tech. Papers 32(1), 934-937 (2001).
- [2] Kunimasa Saitoh, Masanori Koshiba: “Numerical Modeling of Photonic Crystal Fibers”. JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 23, NO. 11, (2005).
- [3] J.C. Knight, T.A. Birks, R.F. Cregan, P.St.J. Russell, and J.P. de Sandro, “Large mode area Photonic crystal fiber,” Electron. Lett., Vol.34, pp.1347-1348, June (1998).

- [4] Baselt, T., Taudt, Ch. and Hartmann, P. "Group-velocity dispersion analysis of large mode-area doped fibers implemented in a laser cavity during operation" Proceedings of the SPIE, Volume, number 9344-96 (2015).
- [5] T. A. Birks, J. C. Knight, and P. St. J. Russell, "Endlessly single-mode photonic crystal fiber," *Opt. Lett.*, vol. 22, no. 13, pp. 961–963, (1997).
- [6] Yang, S., Zhang, Y., Peng, X., Lu, Y., Xie, s." Theoretical study and experimental fabrication of high negative dispersion photonic crystal fiber with large area mode field" Vol. 14, No. 7, *OPTICS EXPRESS* (2006)
- [7] Knight, J. C., Birks, T. A., Russell P. St. J. and Atkin, D. M., "All-silica single-mode optical fiber with photonic crystal cladding" *Optics Letters*, Vol. 21, Issue 19, pp. 1547-1549 (1996)
- [8] Karda's, T. M. and Radzewicz, C., "Broadband near-infrared fibers dispersion measurement using white-light spectral interferometry," *Optics Communications* 282, 4361 – 4365 (2009).
- [9] Shang, H.-T., "Chromatic dispersion measurement by white-light interferometry on metre-length single-mode optical fibres," *Electronics Letters* 17, 603 – 605 (1981).
- [10] Zhao, Y. C. and Fleming, S., "Direct measurement of second-order dispersion using multi-section interference fringes in spectral domain," *Measurement Science and Technology* 16, 1628 – 1630 (2005).
- [11] Tateda, M., Shibata, N. and Seikai, S. "Interferometric method for chromatic dispersion measurement in a single-mode optical fiber," *Journal of Quantum Electronics QE-17*, 404 – 407 (1981).
- [12] Thevenaz, L., Pellaux, J.-P. and von der Weid, J.-P., "All-fiber interferometer for chromatic dispersion measurements," *Journal of Lightwave Technology* 6, 1 – 7 (1988).
- [13] Spittel, R., M'orl, K., Reichel, V. and Bartelt, H., "Dispersion characterization of microstructured optical fibers," *Proc. DGaO* (2008).
- [14] Baselt, T., Taudt, Ch. and Hartmann, P., "Time-frequency-domain dispersion measurement in rare earth doped large effective mode area multicore fibers," *Proc. SPIE* 8961, 89612Z 7 (2014).
- [15] Baselt, T., Taudt, Ch., Lasagni, A. F., Hartmann, P., "Experimental measurement of group velocity dispersion during operation in cladding-pumped large-mode-area Yb-doped fibers," *SPIE.OPTICAL METROLOGY* 9525,142 (2015).
- [16] Böswetter, P., Baselt, T., Ebert, F., Basan, F. and Hartmann, P., "Evaluation of a time-frequency domain interferometer for simultaneous group-velocity dispersion measurements in multimode photonic crystal fibers," *Applied Optics* 50, E32 – E37 (2011).
- [17] Wang, L.W., Lou, S. Q., Chen, W. G., Li, H. L., "A novel method for rapidly modeling optical properties of actual photonic crystal fibers," *Chinese Phys. B* 19 (2010).
- [18] Shen, Y., Lou, S., Lian, Z., Zhao, T., Wang, X., "Evaluation of optical properties for real photonic crystal fiber based on total variation in wavelet domain," *Optical Fiber Technology*, Volume 31, 1–12 (2016).
- [19] Fokoua, E.N., Sandoghchi, S.R., Chen, Y., "Accurate modelling of fabricated hollow-core photonic bandgap fibers," *Opt. Express*, 23 (18) (2015).