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Measurement of chromatic dispersion of microstructure optical fibers using interferometric method

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We present a modification of the interferometric method for the measurement of optical fiber chromatic dispersion using an easily aligned, almost all-fiber Michelson interferometer. Particular issues of the microstructure fiber characterization are discussed. Accuracy of the method is validated by comparing the chromatic dispersion measurement of the standard single-mode fiber with results obtained using the phase-shift method.

Keywords: chromatic dispersion, optical fiber measurements, microstructure optical fibers.

1. Introduction

Microstructure optical fibers (MOFs), the fibers that incorporate air holes running along their length, offer new optical properties as compared to conventional single-mode fibers (SMFs). These include new light-guiding mechanisms, different dispersion properties and new possibilities for design of non-linear fibers. Fundamentals of the MOFs and their design and fabrication are described, *e.g.*, in the monograph [1]. A particularly distinguished feature of MOFs is the extent of tailoring the fiber dispersion because the refractive index contrast between the MOF's core and cladding can be designed in much larger range than in conventional SMFs. In such a way, MOFs with high normal dispersion at the 1550 nm range can be designed for dispersion compensation applications. On the other hand, MOFs with anomalous dispersion can be designed in the wavelengths below 1270 nm (which is not possible in the case of conventional SMFs) that opens up applications to supercontinuum generation even in the visible spectrum. Therefore, the measurement of chromatic dispersion in a wide spectral range belongs to key tasks in MOF characterization. Phase-shift and pulse-delay techniques of chromatic dispersion measurement, commonly used in characterization of conventional SMFs, usually require long piece (hundreds of meters) of fibers for sufficiently accurate measurement. However,

the MOFs are often available only in short pieces or the prepared MOF may exhibit large longitudinal inhomogeneity and the measurement of the whole length would not provide correct results of its respective portions. Some MOFs have large attenuation and only a short length of the fiber can be used for the measurement. For these reasons, the interferometric method of chromatic dispersion measurement is often preferred because short pieces, usually tens of centimeters, of fibers can be accurately characterized with this method [2–6].

In this paper we describe a specific implementation of the interferometric method for the dispersion measurement. The merits of our implementation are easily built and aligned setup, low sensitivity of the measurement to external perturbation and the possibility to measure the dispersion in a wide spectral range (700–1600 nm). In our preliminary report [6] we have shown applicability of the method to chromatic dispersion measurement of highly erbium doped fibers and endlessly single mode MOF of core diameter compatible with the standard SMF (SSMF). Here we provide detailed analysis of possible errors in the technique, validation of the method on chromatic dispersion measurement of a standard SMF and we present application of the technique to characterization of a small-core microstructure fiber.

2. Principle of the method

The principle of interferometric methods lies in balancing the optical lengths of two arms of an interferometer, where the measured fiber is placed in the test arm and the reference arm contains the variable-optical-delay line (VODL). When the low-coherent light is launched into the interferometer, the interference fringes can be seen only when the optical path lengths (and hence the group delays) are almost equal. The recorded optical power variations *vs*. the VODL displacement constitute the interferogram that is used to evaluate the dispersion of the fiber under test. Many different implementations of the interferometric method for chromatic dispersion measurement were reported in literature [7–14]. Comprehensive overview of interferometric methods for chromatic dispersion determination can be found, *e.g.*, in [15].

The dispersion characteristics can be obtained by measuring the group delays τ_g from the interferogram's envelope for several discrete wavelengths λ_i [2, 9–11, 13]. The measured data $\tau_g(\lambda_i)$ are fitted by an analytical function, *e.g.*, by three- or five-term Sellmeier function or by parabola. The dispersion coefficient is then given by relation $D_\lambda(\lambda) = (1/L)\mathrm{d}\tau_g/\mathrm{d}\lambda$, where L is the length of the measured fiber sample. The dispersion characteristics can be calculated also by Fourier transform of one interferogram using the whole available spectrum of the source [12, 15]. In some measurement arrangements [3, 7, 8], the output spectrum is recorded for one or several lengths of the reference arm and the dispersion around the so-called equalization wavelength [16, 17] is derived from the measured spectral interferogram.

The interferometers are usually built using bulk optics components that give rise to the necessity of a time consuming alignment. A practical all-fiber Michelson interferometer for chromatic dispersion measurement was presented in [10, 11]

where the variable delay line was realized by stretching the fiber of the reference arm. The interferometric measurements are very sensitive to environmental changes so thermal and mechanical isolation or even active stabilization [3, 4, 7, 12] of the interferometers' arms are required.

In this article, we present a modification of the chromatic dispersion measurement method [11]. While retaining the ease of make up and alignment of the interferometer, in contrast to the other methods, our interferometer does not require special care to have stable conditions. Small temporal variation of the interferometers' arms can be even exploited to the interferogram measurement. Although the optical path lengths fluctuations have been already exploited for the group delay evaluation with subpicosecond (~0.3 ps) accuracy [13], in our implementation the accuracy is improved by more than one order to 10 fs.

3. Experimental setup

A schematic figure of the experimental setup is shown in Fig. 1. The beam splitter of the Michelson interferometer is formed by a wideband biconical tapered fiber coupler of 50:50 coupling ratio at a wavelength of 1300 and 1550 nm. The wideband, low-coherent light sources can be a halogen lamp, LEDs or amplified spontaneous emission from an optical amplifier.

The reference arm of the interferometer contains an air-path VODL. We used a microscope objective (Meopta 6.3×, NA = 0.18) to collimate the light emerging the fiber coupler. The mirror of the VODL is moveable by 2.5 cm with 0.2 μm resolution. The position of the mirror is measured by a calibrated optoelectronic probe with absolute accuracy of the mirror position determination of 0.3 μm in the whole travelling range. Although the air-path is up to 1.8 m long (its length is limited by the optical table we used) we routinely achieved the loss of the reference arm of only 2–3 dB. In order to keep the loss low and constant in the whole travel range of the mirror, we used a translation stage with a centrally placed actuator, so that the stage is free of a torsion moment. Another way to eliminate changes of the VODL losses due to mechanical instabilities was described in [18]. In this special configuration,

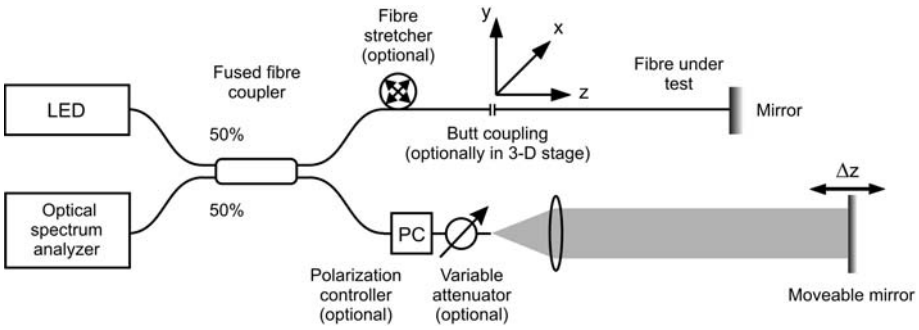

Fig. 1. Michelson interferometer setup for chromatic dispersion measurement.

the optical fiber in front of the microscope objective is placed in a mirror-finished ferrule and the beam is reflected back into the single-mode fiber after a second pass over the moveable mirror. The total air path is therefore four times the distance between the moveable mirror and the fiber end-face. Of course, a stretched fiber section can be used for the VODL like in [10, 11] and thus the interferometer can be made all-fiber and alignment-free. We tested this kind of VODL in our laboratory [19], but we prefer the air-delay line due to the ease of data processing. Moreover, the air-path VODL that we use does not require a complicated alignment. The length of the air-path VODL can be also easily adapted to various lengths of the fiber under test that is of particular importance for the specialty fiber characterization.

The fiber under test is usually connected to the fiber coupler using bare-fiber adapters and a mating sleeve. In case of the characterization of a fiber with a non-standard diameter or with a highly offset core, the fibers have to be aligned using 3-D translation stage. The reflection at the end-face of the measured fiber is usually obtained by a chemical deposition of silver at the cleaved end-face. Typical reflectivity of 75% was achieved. However, in the case of holey fibers measurement, the silvering is not applicable because the silvering solution soaks up to the holes by capillary elevation and instead of index-guiding effect of the air holes, a highly absorbing array of silver tubes is created. Therefore, the reflection at the holey-fiber end-face is obtained by laying the fiber end-face onto a mirror. The fiber is placed in a bare fiber adaptor and halved mating sleeve to provide a stable perpendicular position of the fiber axis with respect to the mirror. Again high reflectivity was achieved, but a disadvantage of this arrangement is a risk of damage of the mirror as well as of the fiber end-face. The MOF end-face can be cleaned in a similar way as a standard fiber connector with the exception that the cleaning wipe should be dry. Standard connectors are cleaned by paper or textile wipe soaked in a suitable solvent, *e.g.*, 91% isopropylalkohol. However, in case of the MOFs a risk of elevation of the solvent into the holes and a consequent increase of attenuation exists.

The mutual interference of the signal from the reference and test arms is detected by the optical spectrum analyzer (OSA). The OSA is operated in photodetector mode at the selected wavelength. Its spectral resolution $\Delta\lambda$ (that defines the coherence length $l_c = \lambda^2/\Delta\lambda$) was set to 10 nm. Since the best interference contrast is obtained when both interfering waves are of the same polarization and amplitude, an in-line polarization controller and variable attenuator based on changing fiber bend may be placed in one of the interferometer arms.

4. Measurement procedure and error analysis

The determination of the group delay is performed by balancing the optical path of the reference arm with VODL to the optical path of the test arm. For optical paths of the two arms holds:

$$n_{\mathrm{eff}}^{\mathrm{FUT}} L^{\mathrm{FUT}} + n_{\mathrm{eff}}^{\mathrm{SSMF}} L^{\mathrm{test}} = L^{\mathrm{air}} + n_{\mathrm{eff}}^{\mathrm{objective}} L^{\mathrm{objective}} + n_{\mathrm{eff}}^{\mathrm{SSMF}} L^{\mathrm{ref}}$$

where n_{eff} is the effective group index of the respective media, L^{ref} and L^{test} are the fiber lengths of the coupler branch in the reference and test arm, respectively. $L^{\text{objective}}$ is the length of the microscope objective and L^{FUT} and L^{air} are the length of the measured fiber and the air path, respectively. The optical paths are balanced when the contrast of the interference fringes is maximal. The fringe contrast is given by the visibility $V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum of the intensity with varying the phase difference of the interfering waves. In order to measure both values $I_{\max}$ and $I_{\min}$ for each mirror displacement Δz, phase variation of at least π is required. This can be done by controlled stretching of a piece of a fiber of one of the interferometers' arms by at least $\lambda/4$. We have observed that random phase fluctuations due to external perturbations like mechanical vibration or turbulent air flow are rather fast and of the order of several π. Therefore, we use this random fluctuation to detect $I_{\max}$ and $I_{\min}$. An example of the measured interferogram is in Fig. 2**a**. The measured interferogram $V(z)$ corresponds approximately to the function $\text{sinc}(z - z_i) = \sin(z - z_i)/(z - z_i)$, where z_i is the centre of the interferogram for i-th wavelength. This function is the Fourier transform of almost rectangular spectrum determined by OSA input slit aperture. The centre of interferogram's envelope is obtained by fitting the function $V(z)$ by a suitable analytic function, *e.g.*, the function sinc. Although the interferogram width is of the order of hundreds of microns, as can be seen in Fig. 2**a**, by using advanced data processing and non-linear curve fitting, one can easily determine the interferogram centre with the accuracy of about several microns, *i.e.*, only a small fraction of the actual interferogram width. The centre of interferogram's envelope determines the relative group delay $\Delta\tau_{g(i)}$, between the test and reference arm. In order to get the group delay difference introduced by the fiber under test itself, the group delays difference caused by the microscope objective and by the different lengths of the branches of the fiber coupler are added to the values of measured $\Delta\tau_{g(i)}$. We note that the difference

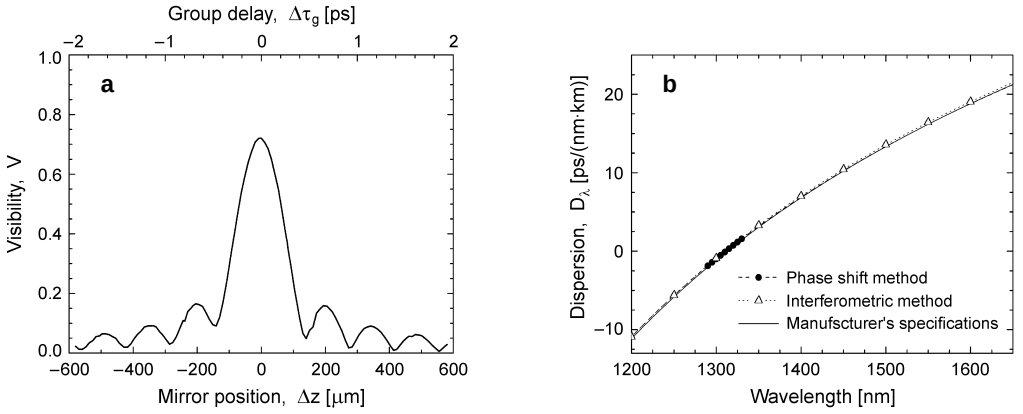

Fig. 2. Example of the measured interferogram's envelope (**a**). Chromatic dispersion of the standard single-mode fiber measured using three different methods; symbols on the curves stand for the wavelength where the group delay was measured (**b**).

of the branches of the fiber coupler was typically below 1 cm, much shorter than the length of the fiber under test. However, the fiber coupler arms should not be of exactly the same lengths to avoid parasitic interference from the cleaved fiber ends of the coupler.

The methods of chromatic dispersion determination in optical fibers that require longer measurement time usually suffer from a crucial drawback – they are critically sensitive to temperature drifts. The thermal expansion coefficient of silica fibers is small ($\alpha \approx 8\times10^{-7}$ per K), however, the refractive index of silica fibers may vary with temperature significantly, with thermo-optic coefficient $\delta n/\delta T \approx 1\times10^{-5}$ per K [20]. In order to assess the influence of the ambient temperature drifts, we measured repeatedly the interferogram at one wavelength during several hours, *i.e.* a period sufficiently longer than the time needed for the dispersion measurement. The fiber under test was a 1 m long piece of Corning SMF28e fiber. Simultaneously, the ambient temperature was recorded. The standard deviation of the measured ensemble of interferogram's centre positions was found to be 3 μm. It corresponds to the accuracy of 10 fs of the group delay determination. The ambient temperature during the measurement varied by 1.2 °C around 23 °C. When special precautions were made to maintain constant temperature (±0.1 °C) we obtained the interferogram's centre position with 0.5 μm standard deviation (*i.e.*, group delay accuracy of 1.7 fs). This accuracy is better than that expected due to temperature drift of the refractive index of one meter long optical fiber. It can be explained by elongation of the optical rail of the VODL made of cast-iron with thermal expansion coefficient of $\alpha \approx 9\times10^{-6}$ per K that partially compensates the temperature drift of the fiber under test.

5. Experimental results

In order to validate the accuracy of the presented method we measured chromatic dispersion of a standard single-mode fiber (ITU-T recommendation G.652) Corning SMF28e using two different methods. Firstly, we measured the dispersion of 1980 m long fiber on a spool with the phase-shift method. As a signal source, we used a hybrid-cavity fiber ring laser with a semiconductor optical amplifier. The laser was tunable in the range 1290–1330 nm. The output optical signal was modulated with 2 GHz rf-signal in a Mach–Zehnder $LiNbO_3$ amplitude modulator and launched into the fiber under test. The phase shift and corresponding group delay between the rf-modulation signal and the optical signal transmitted through the fiber was detected with the optical samplescope Agilent Infiniium 54855A. Secondly, the spectral dependence of the group delay was measured by the interferometric method in 1 m long fiber sample cut from the spool. In both methods, the measured dependence of the group delay *vs.* wavelength was fitted with a three-term Sellmeier polynomial $\tau(\lambda) = a_1 + a_2\lambda^2 + a_3\lambda^{-2}$, where a_i are the fitting coefficients. The dispersion is then given by $D(\lambda) = 0.25\, S_0(\lambda - \lambda_0^4/\lambda^3)$, where λ_0 and S_0 are the zero dispersion wavelength and dispersion slope at λ_0, respectively. The resulted values λ_0 and S_0 and their standard deviations are summarized in the Table and

T a b l e Comparison of the chromatic dispersion parameters of the standard single-mode fiber Corning SMF28e.

	Zero dispersion wavelength λ_0 [nm]	Dispersion slope at λ_0 S_0 [ps/(nm^2·km)]
Phase-shift method	1311.2 ± 1.2	0.0855 ± 0.0087
Interferometric method	1310.2 ± 1.0	0.0866 ± 0.0003
Specifications	$1302 \le \lambda_0 \le 1322$, typically 1313	≤ 0.089, typically 0.086

Fig. 2**b** together with the specification provided by the manufacturer. In the case of the interferometric method, we considered the standard deviations $\sigma_\tau = 10$ fs, $\sigma_L = 1$ mm and $\sigma_\lambda = 1$ nm, of the measured group delay, fiber length and optical wavelength, respectively. In the case of the phase-shift method, the respective standard deviations were $\sigma_\tau = 4$ ps, $\sigma_L = 10$ m and $\sigma_\lambda = 0.5$ nm. The results obtained with the phase-shift and interferometric methods are in excellent agreement. The relative difference between the dispersion coefficient D obtained by the two methods is less than 1.5% in the wavelength region around 1550 nm. The measured dispersion characteristics also correspond well to the specifications provided by the manufacturer. In order to show the importance of involving the corrections for the dispersion of the microscope objective used in the VODL, we calculated the chromatic dispersion also without the corrections. The zero dispersion wavelength of 1307.6 nm and the slope of 0.855 ps/(nm^2·km) were obtained. Therefore avoiding the corrections led to the error in determination of the zero dispersion wavelength of almost 3 nm.

Applicability of the method to the characterization of small-core MOF is demonstrated by the measurement of a MOF sample fabricated by the Crystal Fiber, Ltd., Lyngby, Denmark. This fiber is of small average core diameter of 3.5 μm to enhance the non-linear coefficient of the fiber. The period of hole structure in the cladding (the pitch) is 2.5±0.2 μm and the average pitch to hole size ratio is 0.4. A microscope photograph of the core region of the fiber end-face is in the Fig. 3**a**. A 3-D translation stage was used for the alignment of the MOF and the SSMF of

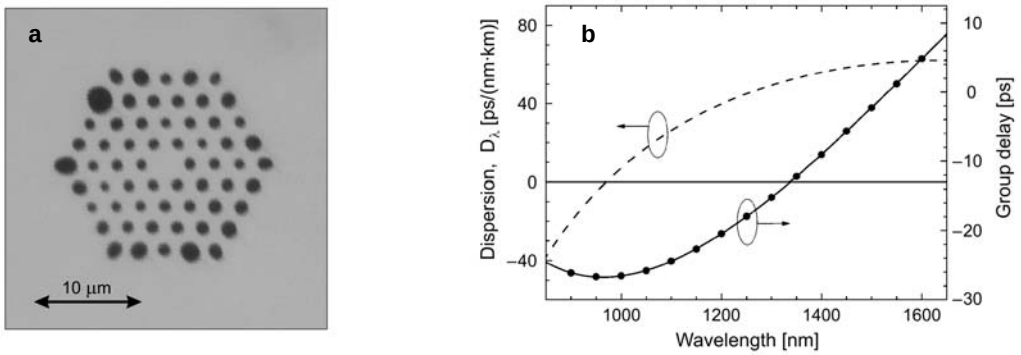

Fig. 3. Microscope photograph of the core region of the highly non-linear MOF sample (**a**). Group delay $\Delta\tau_g$ and chromatic dispersion D_λ of the measured MOF sample (**b**).

the fiber coupler in order to minimize the coupling loss. Measured group delay and dispersion is shown in Fig. 3**b**. The measured group delay points *vs*. wavelength were fitted with a five-term Sellmeier polynomial $\tau(\lambda) = a_1\lambda^4 + a_2\lambda^2 + a_3 + a_4\lambda^{-2} + a_5\lambda^{-4}$, where a_i are the fitting coefficients. Resulted zero dispersion wavelength and dispersion slope at λ_0 are $\lambda_0 = 963.8$ nm and $S_0 = 0.250$ ps/(nm^2·km), respectively. The halogen lamp was used for the chromatic dispersion measurement. It should be noted that with LED or ASE sources (that provide significantly higher spectral power density than the halogen lamp) one can measure fibers with even smaller mode field area than the tested MOF sample had.

6. Conclusions

A method of chromatic dispersion measurement of microstructure optical fibers using an easily built setup of the interferometric method was presented. In contrast to other interferometric methods, it does not require special care for maintaining the interferometer in perfectly stable conditions and in the same time, it offers high accuracy of the group delay determination. The accuracy of the group delay measurement is 10 fs (temperature variation in the laboratory environment was about 1 °C). Reliability of the method was validated by comparing the chromatic dispersion measurement of the standard single-mode fiber with the results obtained using the phase-shift technique. The applicability of the presented method to MOF characterization was demonstrated on measurement of a small-core MOF for non-linear applications. The presented method can be a practical tool for laboratories where exists the need of inexpensive and easily built setup for measurement of chromatic dispersion of short specialty optical fibers in a broad spectral range.

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