

Optimization of chromatic dispersion of microstructure optical fibers using interferometric method For RZ and NRZ Modulation formats

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Abstract— 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. We are taking experimental consideration and simulating the results on OPTIWAVE simulator. We are also analysing the result and error

Index Terms— Chromatic Dispersion, interferometer, microstructure fiber, RZ and NRZ modulation formats, SMF, VODL

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 super continuum 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 implemen-

tation 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 PRINCIPALE 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 $D\lambda(\lambda) = (1/L)d\tau_g/d\lambda$, 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 sub pico second (~ 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 bi conical tapered fiber coupler of 50:50 coupling ratio at a wavelength of 1300 and 1550 nm.

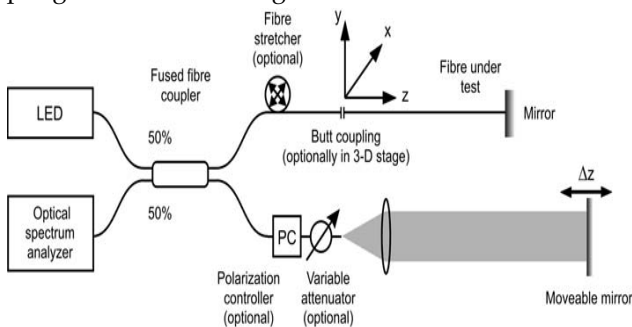


Fig 1 Michelson interferometer setup for chromatic dispersion measurement.

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 \times ,

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 μ m resolution. The position of the mirror is measured by a calibrated optoelectronic probe with absolute accuracy of the mirror position determination of 0.3 μ m 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, 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% isopropyl alcohol. 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 photo detector 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, 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 ($\alpha \approx 8 \times 10^{-7}$ per K), however, the refractive index of silica fibers may vary with temperature significantly, with thermo-optic coefficient $\delta n/\delta T \approx 1 \times 10^{-5}$ 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 $^\circ\text{C}$ around 23 $^\circ\text{C}$. When special precautions were made to maintain constant temperature (± 0.1 $^\circ\text{C}$) 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 $\alpha \approx 9 \times 10^{-6}$ per K that partially compensates the temperature drift of the fiber under test.

5 SIMULATION FOR DISPERSION MEASUREMENT AND RESULT ANALYSIS

In this Section we show an example of a maximization procedure. We will optimize the launch power and DCF length to maximize the Q factor at the receiver. Upgrading an existing noise-limited fiber plant requires an increase in launched power, which in turn brings the fiber nonlinearities. It has been shown that nonlinear return to zero (RZ) coding offers significant advantages for high bit rate transmission systems [21][22]. Because the fiber dispersion and Kerr nonlinearities balance each other in this case, the launched power is not limited by self phase modulation (SPM). But this configuration requires careful selection of launch power and dispersion compensating fiber (DCF) length. Figure 2 shows the project layout. SMF fiber parameters are as follows: Attenuation is 0.171 dB/km, dispersion is 17.7 ps/nm/km, effective

area is 80 micron square, $n_2 = 2.7 \times 10^{-20}$ m²/W, length is 100 km. DCF fiber parameters are as follows: Attenuation is 0.6 dB/km, dispersion is -80 ps/nm/km, effective area is 30 micron square, $n_2 = 3 \times 10^{-20}$ m²/W, length is 100 km [23]. Bit rate is 10 Gbps, 7th order PRBS bit sequence and Gaussian beam profile is used. The receiver sensitivity is -17 dBm. The receiver sensitivity is -17 dBm. An attenuator is used to find the power penalty. Attenuation of the attenuator is initially set to 0 when the optimization is performed. Later, another optimization is carried out to find the power penalty by comparing back-to-back performance transmission and link performance. This is done by varying the attenuation of the attenuator to get the same Q factor as we got from back-to-back transmission. The received power (P_{received}) is then compared with the receiver sensitivity to find the power penalty. Power penalty is given as P_{penalty} (dB) = -17 dBm - P_{received} (dBm). Parameters for the optimization tool are as follows: Initial laser power and DCF length are set to 20 dBm and 20 km respectively. Lower and upper bounds of power are defined as 15 dBm and 25 dBm, 0 and 30 km for DCF length. The termination tolerance of the parameter is 1, that of the result is 0.1. The Maximum Q Factor is obtained after 15 calculations, when the laser power is about 19 dBm and DCF length is about 10 km. At the optimum point, the Maximum Q Factor is ~20. Received average power is -8.25 dBm.

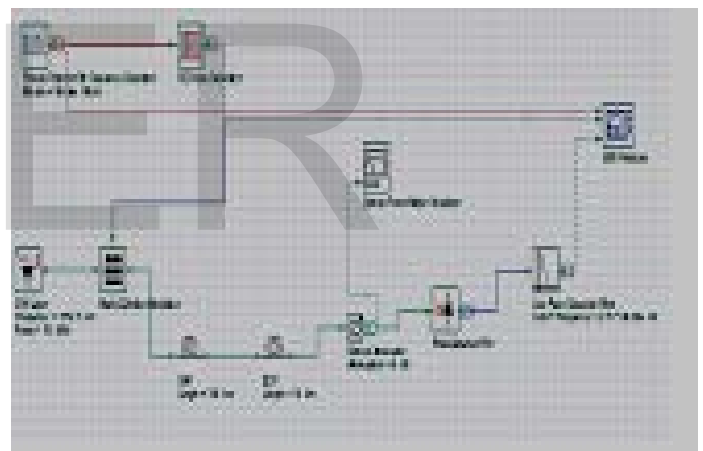


Fig 2- Project layout for simulation

Maximum Q Factor for back-to-back propagation was about 68. This shows that the optimum dispersion compensation corresponds to about 45 km of compensated SMF (~963 ps/nm residual dispersion) with ~20 dBm launch (~16 dBm average) power. We also found that the power penalty at 10⁻⁹ BER is 0 dB for optimum values (Required received power to get 10⁻⁹ BER is around -17 dBm, which is same as the receiver sensitivity). Figure 2 shows the eye diagram after 100 km of propagation with optimum parameters. In [23], it has been shown that similar results can be obtained from a NRZ modulation format for a single span system, by leaving the correct amount of residual dispersion in the system. In this case, the optimum residual dispersion is lower than that of RZ case. We have performed similar optimizations for NRZ modulations. The receiver sensitivity is -15.6 dBm. Maxi-

imum Q is obtained after 4 calculations when laser power is ~19 dBm (~16 dBm average power), and DCF length is ~18 km. At the optimum point, Maximum Q Factor is ~10 and received average power is -12.3 dBm. We have found that the power penalty at 10⁻⁹ BER is ~1 dB for the optimum values when NRZ is used. Optimum dispersion compensation corresponds to about 80 km of compensated SMF (~355 ps/nm residual dispersion).

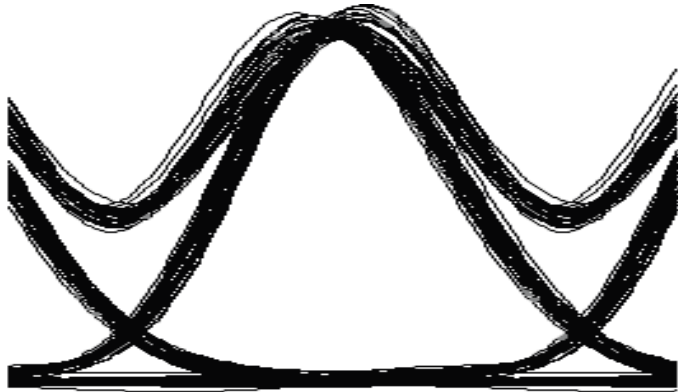
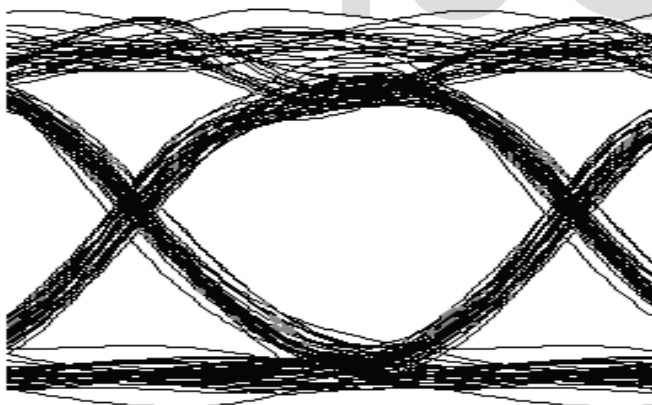


Fig 3- Eye Diagram in optimum mode RZ modulation Format

Figure 4 shows the eye diagram after 100 km of propagation with optimum parameters when NRZ modulation format is used. The obtained results agree well with the experimental findings of [23] and [24]. Furthermore, comparing the Q factors at optimum points shows that, in fact RZ modulation can tolerate more distortion and reach longer transmission distance

Fig 4-Eye diagram NRZ modulation in optimum parameters



parameters

6 CONCLUSION

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 envi-

ronment 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 measurement of chromatic dispersion of short specialty optical fibers in a broad spectral range. We have simulated the dispersion for RZ and NRZ modulation formats and observe that RZ modulation can tolerate more distortion and reach longer transmission distance.

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