Quantum Electronics **35** (9) 835 – 838 (2005)

OPTICAL FIBRES

PACS numbers: 42.81.Cn
DOI: 10.1070/QE2005v035n09ABEH010353

Measurement of dispersion in optical fibres with a microstructure cladding

A.E. Levchenko, A.S. Kurkov, S.L. Semenov

***Abstract*. Based on the interferometric technique, a setup is built for measuring the spectral dependence of chromatic dispersion in fibres with a microstructure cladding. The setup provides measurements in a broad spectral range from 670 to 1550 nm taking birefringence in the fibre into account. The results of measurements of dispersion in a standard fibre with this setup and a commercial device are in good agreement.**

Keywords: *optical fibres, microstructure fibres, chromatic dispersion.*

1. Introduction

Optical fibres with a microstructure cladding belong to a relatively new type of optical fibres. Their specific feature is the formation of the refractive-index profile due to the presence of air gaps in a reflecting cladding. This allows a considerable increase in the difference of the refractive indices of the fibre core and cladding, resulting in a drastic change in the nonlinear and dispersion characteristics of microstructure fibres compared to standard fibres. Microstructure fibres can be used as dispersion compensators, devices for soliton compression, amplifiers and optical-signal converters based on nonlinear effects. The basic properties of these fibres and their applications are considered, in particular, in paper [1] and monograph [2].

The zero-chromatic dispersion wavelength of microstructure fibres can be varied in a broad spectral range from 0.7 to 1.6 μm depending on the fibre structure. Therefore, the spectral dependence of chromatic dispersion is one of the basic characteristics of these fibres. The aim of our paper is to develop the technique for measuring the dispersion characteristics of microstructure fibres. The following requirements were taken into account: the necessity of measurements in a broad spectral range, the possibility of measurements at a high level of optical losses (up to hundreds of dB km^{-1}), the study of fibres with the core diameter in the range from 1 to 10 μm, and the consideration of the polarisation properties of samples.

2. Choice of the measurement technique

Almost all the techniques for determining chromatic dispersion are based on the measurement of the spectral dependence of the group delay. The chromatic dispersion coefficient D of a fibre is determined from the difference of group-velocity delays $\tau(\lambda)$ of light signals at different wavelengths in a fibre of the known length L by using the expression

$$D = \frac{1}{L}\frac{\mathrm{d}\tau(\lambda)}{\mathrm{d}\lambda}, \tag{1}$$

where λ is the wavelength of light.

The variety of techniques for measuring chromatic dispersion is determined by the number of techniques for measuring time delays. At present, the most popular are the three techniques for measuring group delays [3]: phase shift, pulse delay, and interferometric.

The phase shift technique compares the phases of a signal transmitted through a fibre and of the reference signal. The obtained phase shifts $\varphi(\lambda)$ are related to group delays by the expression

$$\tau(\lambda) = \frac{\varphi}{2\pi f}, \tag{2}$$

where f is the signal modulation frequency.

The phase delay is measured at several wavelengths. The results of measurements are processed by fitting the experimental values with the appropriate function $\tau(\lambda)$.

The development of the phase shift technique is the differential phase shift technique [4] in which the relative phase shifts and relative delays τ_1 and τ_2 are measured for two signals at closely spaced wavelengths λ_1 and λ_2. Dispersion at the wavelength $\lambda_{1/2}$ equal to the half-sum of the wavelengths λ_1 and λ_2 is determined by the linear approximation

$$D(\lambda_{1/2}) = \frac{1}{L}\frac{\tau_1 - \tau_2}{\lambda_1 - \lambda_2}. \tag{3}$$

Because the typical modulation frequency of the optical-signal amplitude is tens of megahertz, the minimal length of a fibre under study should be approximately 1 km to provide the sufficient measurement accuracy.

The pulse delay technique for determining chromatic dispersion is based on the direct measurement of the time of flight of pulses at different wavelengths propagating

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A.E. Levchenko, A.S. Kurkov, S.L. Semenov Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: kurkov@fo.gpi.ru

Received 9 June 2005
Kvantovaya Elektronika **35** (9) 835 – 838 (2005)
Translated by M.N. Sapozhnikov

in a fibre of the specified length [5, 6]. This technique can be used to measure the time delay of optical pulses propagating forward and backward in a fibre of a specified length, i.e., after reflection from the remote end of the fibre. As in the phase shift technique, the required length of a fibre under study is ~ 1 km, which is determined by the accuracy of measurement of the relative time delay of two pulses.

The interferometric technique is based on measuring the wavelength dependence of the group delay in a fibre placed in the interferometer arm. This technique has several modifications [7–14]. A substantial difference of the interferometric technique from the pulse delay and phase shift techniques is that measurements are usually performed with fibres of a submetre length (for example, the fibre length in [13] was 25.86 mm), which excludes the influence of structural inhomogeneities over the fibre length and provides more reliable information on the relation of the structural parameters of the fibre with chromatic dispersion. In addition, optical losses in the fibre affect to a considerably lesser degree the possibility of measurements and their accuracy.

A disadvantage of the techniques considered above is the impossibility of correct measurements of birefringent fibres because these techniques give the chromatic dispersion coefficient averaged over two polarisations. However, to describe correctly nonlinear processes such as four-wave mixing in fibres, it is necessary to known accurately the dispersion-curve profile. Therefore, a setup is needed for measuring polarisation dispersion. Unfortunately, no commercial devices are available for measuring for one polarisation. Having analysed the available techniques for group-delay measurements, we chose the interferometric technique for the experimental realisation.

3. Experimental setup

The scheme of the setup borrowed from papers [11, 12] is shown in Fig. 1. We assembled a two-beam interferometer. A single-mode fibre (SMF) of length ~ 50 cm under study was placed in one of the arms of the interferometer. As a point light source, the exciting SMF piece was used (as a rule, the same fibre as the fibre under study) in which, in turn, light from a radiation source was coupled. A specific feature of the class of microstructure fibres is a small diameter of their core (a few hundreds of nanometres and above), which leads to high coupling losses. For this reason, we used an ytterbium-doped fibre superluminescent source [15] and several different super-luminescent diodes (Superlum Diodes Ltd, Moscow) covering piecewise continuously the wavelength range 670–1550 nm. The delay line length (the air arm of the interferometer) was varied by changing the position of prism (*9*) with a micrometric screw. In addition, the prism position was modulated with a precision electromechanical modulator with the modulation amplitude up to 2 mm and the oscillation frequency up to 20 Hz.

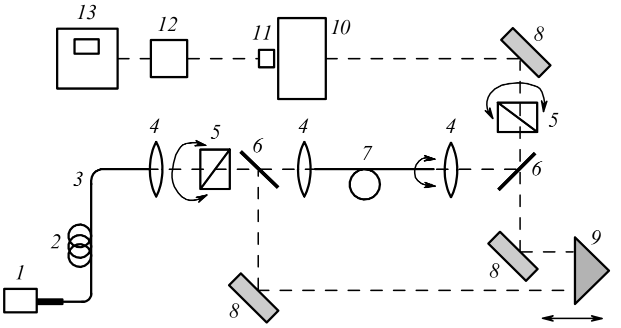

Figure 1. Scheme of the setup: (*1*) superluminescent source; (*2*) polarisation controller; (*3*) single-mode fibre; (*4*) objective; (*5*) polariser; (*6*) beamsplitter; (*7*) fibre sample; (*8*) highly reflecting mirror; (*9*) right-angle prism with an electromechanical suspension; (*10*) monochromator; (*11*) photodetector; (*12*) amplifier; (*13*) oscilloscope.

Unlike previous papers, the use of an electromechanical modulator with such a large modulation amplitude provided the real-time recording of the entire interference pattern, which, in turn, because of a large set of distributions, gave the opportunity to increase the accuracy of determining the interference maximum and considerably reduced the influence of external perturbations such as possible turbulent flows in the air arm and optical table vibrations.

The interference signal produced in the case of equal optical paths in the air and fibre under study was detected with a germanium photodetector placed behind a monochromator. Figure 2 shows the typical interference pattern. We paid special attention to maintain the single-mode excitation regime of the fibre and preserve the polarisation of light propagating in the fibre. For this purpose, two polarisers (Glan prisms) were used, one of which was placed in front of the interferometer and another behind the interferometer. Each polariser was mounted in a holder providing its rotation around the optical axis. The second polariser was used only for adjustment and was removed during measurements.

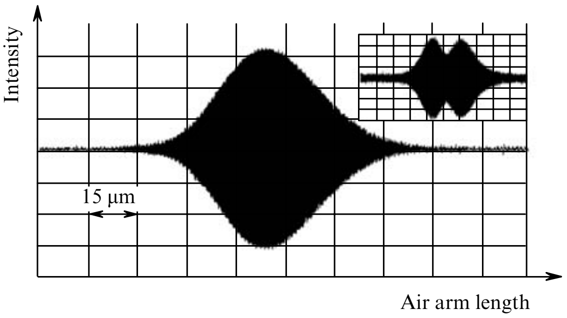

Figure 2. Typical correlation signal in the zero-dispersion region. The inset shows the interference signal observed in a strongly birefringent fibre in the case of incorrect adjustment of radiation polarisation.

Microstructure fibres have, as a rule, noticeable birefringence. For example, birefringence B in paper [16] was 1.5×10^{-4}. To increase the visibility of the interference pattern, it is necessary to provide the coincidence of polarisation of radiation in the interferometer with the birefringence axes of the fibre under study. In this case, polarisation at the fibre output should be parallel to the polarisation of radiation in the air arm of the interferometer. The polariser at the interferometer input was adjusted to provide the maximum degree of polarisation at the fibre output. The latter was determined by rotating the output polariser when the air arm of the interferometer was blocked. The holder of the output end of the fibre allowed the rotation of the fibre end around its axis, thereby aligning the polarisation of radiation at the fibre output parallel to the polarisation of radiation in the air arm of the interferometer. The polarisation controller in the exciting SMF piece was used to achieve the maximum transmission of a signal through the first polariser.

The use of an electromechanical suspension to modulate the prism position simplified the control of the interference-pattern quality during the interferometer adjustment. For example, the inset in Fig. 2 shows the interference signal that appears because the polarisation of input radiation does not coincide with the polarisation axis of the fibre and the polarisation of radiation does not coincide with polarisation in the air arm. Note that by mounting the second polariser, we can remove either the first or second maximum of the signal. However, the regime of measurements with two polarisers leads to the spectral selection of wavelengths, which impairs the accuracy of measuring the position of the interference-pattern maximum, thereby increasing the interpolation error.

4. Results

We measured in the experiments the spectral dependence of the relative position of the interference-signal maximum with an accuracy of ± 2 μm. Figure 3 shows this dependence obtained for the H04.09.14.10 sample. The inset in Fig. 4 shows the photograph of the fibre end. The fibre core diameter was 2.9 μm, the filling coefficient $k = d/\Lambda$ for the first layer of holes was 0.75 and for the second layer – 0.79 (d is the hole diameter, Λ is the distance between the centres of holes). The radiation losses in the fundamental mode at a wavelength of 1500 nm were lower than 10 dB km^{-1}. The group delay was approximated, as a rule, by a six-membered polynomial of the form

$$\tau(\lambda) = \frac{\Delta l(\lambda)}{c} = A + B\lambda^2 + C\lambda^{-2} + D\lambda^4 + F\lambda^{-4} + G\lambda^6 \quad (4)$$

[where $\Delta l(\lambda)$ is the wavelength dependence of the length of the interferometer air arm]; the corresponding curve is presented in Fig. 3.

The chromatic dispersion coefficient was calculated by the expression

$$D = \frac{1}{Lc}\frac{\mathrm{d}\Delta l(\lambda)}{\mathrm{d}\lambda}. \quad (5)$$

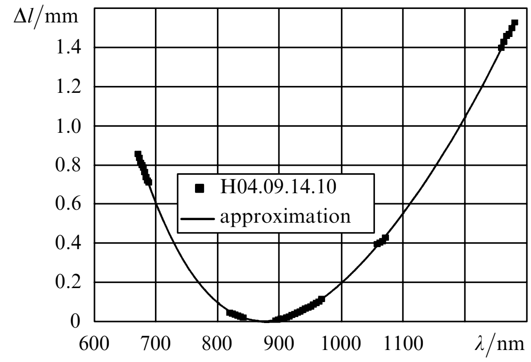

Figure 3. Spectral dependence of the position of the correlation-function maximum for the H04.09.14.10 sample.

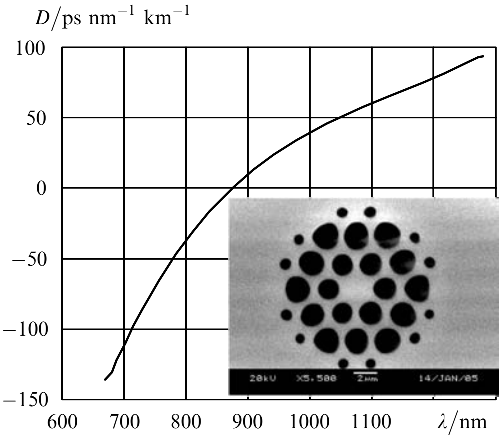

Figure 4. Spectral dependence of chromatic dispersion for the H04.09.14.10 sample. Th inset shows the photograph of the fibre end.

Figure 4 shows the plot of the group-velocity dispersion for the microstructure fibre studied in the paper. The zero-chromatic dispersion wavelength for this fibre was 874 nm.

A disadvantage of this measuring scheme is that the interferometer is not initially balanced. The unbalance appears due to the presence of two microobjectives in one of the arms of the interferometer and of a right-angle glass prism in another arm. Therefore, the prism size was selected to provide the optical path approximately equal to that in microobjective lenses. The error of measuring the group delay caused by the residual unbalance of the interferometer arms was estimated as $< 0.5\,\%$.

To verify the correctness of measuring chromatic dispersion with our setup, we studied a standard telecommunication SMF 28 Corning fibre. Figure 5 presents the plots of group-velocity dispersion obtained for this fibre. The points correspond to measurements performed for a 25-km fibre using a commercial CD 400 PerkinElmer setup. The dashed line shows the dependence $D(\lambda)$ presented by PerkinElmer, and the solid line is the $D(\lambda)$ curve obtained using our setup. The scatter of the values of D in the 1530-nm region was smaller than 4 %. The error of measuring the zero-dispersion wavelength for the SMF 28 fibre by our technique was 2 nm; this error can be either the measure-

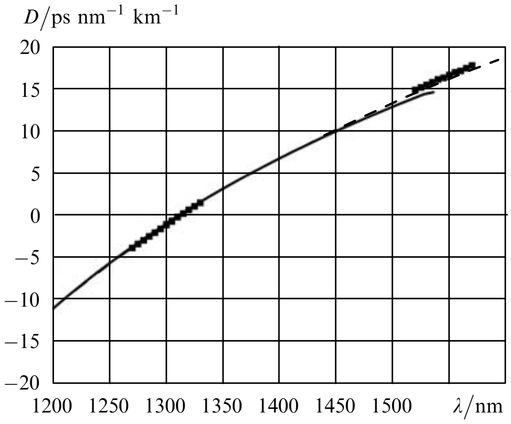

Figure 5. Dependences of the group-velocity dispersion for the SMF 28 fibre. The points correspond to the measurements performed using a CD 400 setup; the dashed curve is the theoretical dependence; the solid curve is the results obtained using our setup.

ment error or can appear due to the local variation in the fibre shape. These results demonstrate the acceptable accuracy of measuring the spectral dependence of chromatic dispersion.

5. Conclusions

We have built the setup for measuring by the interferometric technique the polarisation spectral dependence of chromatic dispersion in a short fibre with a microstructure cladding. The setup allows one to perform measurements in a broad spectral range from 670 to 1550 nm. The modulation of the length of the air arm of the interferometer simplifies the interferometer adjustment and measurement of the relative delay. The setup takes into account the birefringence of a fibre under study. Good agreement was obtained between the measurements of a standard fibre performed using our setup and a commercial device.

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