Spectral-domain measurement of phase modal birefringence in polarization-maintaining fiber

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Abstract: We report on a new and simple method for measuring the wavelength dependence of phase modal birefringence in a polarization-maintaining fiber. The method is based on application of a lateral pointlike force on the fiber that causes strong coupling between polarization modes and utilizes their interference resolved as the channeled spectrum. The change of the phase retrieved from two recorded channeled spectra that are associated with the known displacement of coupling point is used to determine the phase modal birefringence as a function of wavelength. A windowed Fourier transform is applied to reconstruct precisely the phase change and the phase ambiguity is removed provided that we know the phase change of the spectral fringes at one specific wavelength. The measured wavelength dependence of phase modal birefringence is compared with that resulting from the group modal birefringence measurement.

OCIS codes: (060.2270) Fiber characterization; (060.2300) Fiber measurements; (120.3180) Interferometry; (260.1440) Birefringence;

References and links

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#88299 - $15.00 USD Received 5 Oct 2007; revised 30 Oct 2007; accepted 16 Nov 2007; published 5 Dec 2007

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1. Introduction

Polarization-maintaining fibers (PMFs) have attracted considerable interest for a number of applications, including e.g. polarization-sensitive optical devices and fiber-optic sensors of various physical quantities employing interferometric techniques. For these applications, it is important to know the dispersion, i.e. the wavelength dependence, of the phase and group modal birefringence in the PMFs. Several methods have been developed to measure the dispersion of birefringence in PMFs over a wide spectral range. A wavelength scanning technique can be applied to either short [1] or long fibers [2]. A standard technique of time-domain tandem interferometry [3] uses processing of either a single interferogram [4, 5] or a series of interferograms at different wavelengths [6, 7, 8] recorded in a tandem interferometer. The latter technique is a modification of a lateral force method proposed and demonstrated for precisely measuring the phase modal birefringence in PMFs [9].

Recently, a new measurement technique employing a low-resolution spectrometer at the output of a tandem configuration of a Michelson interferometer and an elliptical-core PMF [10, 11] has been used to measure the dispersion of group modal birefringence over a wide spectral range [11]. In comparison with the standard time-domain tandem interferometry, the technique of spectral-domain tandem interferometry uses a series of the recorded spectral interferograms to resolve the so-called equalization wavelengths [10, 11] at which the overall group optical path difference (OPD) is zero. Measuring the equalization wavelengths as a function of the OPD adjusted in a Michelson interferometer, the wavelength dependence of the group modal birefringence in the PMF is obtained [11].

In this paper, a new and simple method to measure the wavelength dependence of phase modal birefringence in an elliptical-core PMF is presented using spectral-domain white-light interferometry. The method is based on application of a lateral pointlike force on the fiber that causes strong coupling between polarization modes and utilizes their interference resolved as the spectral fringes (channeled spectrum). The phase modal birefringence as a function of wavelength is determined from the change of the phase retrieved from two recorded channeled spectra that are associated with the known displacement of coupling point. A windowed Fourier transform is applied to reconstruct precisely the phase change and the phase ambiguity is removed provided that we know the phase change of the spectral fringes at one specific wavelength. The wavelength dependence of phase modal birefringence measured over a broad spectral range is compared with that resulting from the group modal birefringence measurement and good compatibility of the results is confirmed.

2. Experimental method

Consider a PMF of length z supporting two polarization modes over a broad spectral range. We can introduce the wavelength-dependent differential propagation constant $\Delta\beta(\lambda) = \beta_x(\lambda) - \beta_y(\lambda)$, where $\beta_x(\lambda)$ and $\beta_y(\lambda)$ are propagation constants for the respective polarization modes. We define the beat length $L_B(\lambda)$ as

$$L_B(\lambda) = 2\pi/\Delta\beta(\lambda), \tag{1}$$

#88299 - $15.00 USD Received 5 Oct 2007; revised 30 Oct 2007; accepted 16 Nov 2007; published 5 Dec 2007

the phase modal birefringence $B(\lambda)$ as

$$B(\lambda) = \lambda / L_B(\lambda), \tag{2}$$

and the group modal birefringence $G(\lambda)$ as

$$G(\lambda) = B(\lambda) - \lambda \frac{\mathrm{d}B(\lambda)}{\mathrm{d}\lambda} = -\lambda^2 \frac{\mathrm{d}[B(\lambda)/\lambda]}{\mathrm{d}\lambda}. \tag{3}$$

Figure 1 illustrates a simple experimental setup we propose for measuring the wavelength dependence of phase modal birefringence $B(\lambda)$ in a PMF. Light from a white-light source passes through a polarizer and is focused by a microscope objective into the PMF under test. The transmission azimuth of the polarizer is adjusted parallel to the symmetry axis of the PMF so that only one polarization mode is excited in the tested fiber. A pointlike force is applied to the tested fiber causing polarization coupling so that a fraction of light is coupled into the polarization mode that is not excited at the input of the tested fiber. The two polarization modes are propagating through the fiber of length L, which is given by the distance of the coupling point from the fiber end. The two polarization modes are mixed with an analyzer and their interference is resolved by a spectrometer as channeled spectrum. The transmission azimuth of the analyzer is adjusted at 45° with respect to the polarization axes of the PMF. The spectrum recoded by the spectrometer of a Gaussian response function can be represented in the form [10, 11]

$$I(\lambda) = I_0(\lambda)\{1 + V(\lambda)\exp\{-(\pi^2/2)[G(\lambda)L\Delta\lambda_{\mathrm{R}}/\lambda^2]^2\}\cos[(2\pi/\lambda)B(\lambda)L]\}, \tag{4}$$

where $I_0(\lambda)$ is the reference (unmodulated) spectrum, $V(\lambda)$ is a visibility term, and λ_{R} is the width of the spectrometer response function.

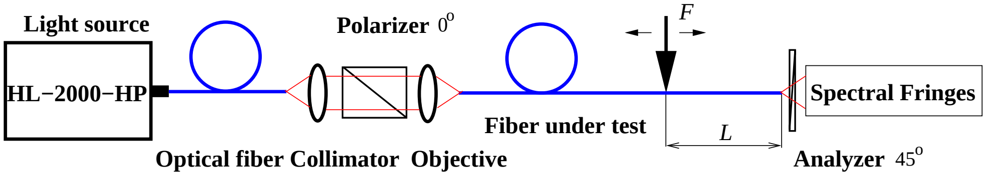


Fig. 1. Experimental setup for measuring the wavelength dependence of phase modal birefringence in fiber under test.

In response to the displacement $\Delta L = L_2 - L_1$ of the coupling point along the tested fiber, a phase shift of channeled spectrum (spectral interference fringes) is observed, from which the beat length can be determined according to the relation

$$L_B(\lambda) = 2\pi\Delta L / \Delta\phi(\lambda), \tag{5}$$

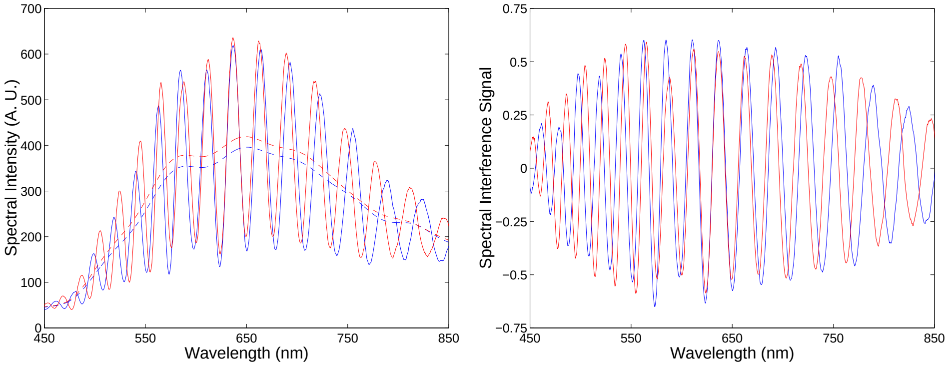
where $\Delta\phi(\lambda) = \phi_2(\lambda) - \phi_1(\lambda)$ is the wavelength-dependent phase change corresponding to two phase functions $\phi_2(\lambda)$ and $\phi_2(\lambda)$ reconstructed from two successive channeled spectra. The ambiguity of $2m\pi$, where m is an integer, in the phase retrieval from the two recorded channeled spectra can be removed by a simple procedure. In the first step we choose in the recorded spectrum interference maximum (minimum) which is resolved at one specific wavelength λ'. Next, the phase shift of the channeled spectrum with the displacement of the coupling point is inspected and in the second step we adjust such a displacement ΔL for which another maximum (minimum) is resolved in the recorded spectrum at the same wavelength λ' and the phase change $\Delta\phi(\lambda') = 2\pi$. Similarly, successive phase changes $\Delta\phi(\lambda') = 4\pi$, 6π, ..., can be adjusted at the wavelength λ'. The fiber beat length $L_B(\lambda)$ determined from Eq. (5) enables us to calculate the phase modal birefringence $B(\lambda)$ from Eq. (2).

3. Experimental configuration

The setup used for measuring the wavelength dependence of the phase modal birefringence in a PMF by spectral-domain white-light interferometry is shown in Fig. 1. It consists of a white-light source: a quartz-tungsten-halogen lamp (HL-2000-HP, Ocean Optics, Inc.) with launching optics, an optical fiber, a collimating lens, Glan Taylor calcite polarizer (Thorlabs), a microscope objective (10×/0.30), a PM fiber under test, a tip connected with a micropotioner, an analyzer (Polaroid), micropositioners, a fiber-optic spectrometer (S2000, Ocean Optics, Inc.), an A/D converter and a personal computer. The PMF under test is an elliptical-core fiber with the cutoff wavelength of 620 nm. A loop of the fiber was used to strip off the higher-order modes and to smooth the reference spectrum as much as possible. The spectrometer has a spectral operation range from 350 to 1000 nm and its spectral resolution is limited by the effective width of the light beam from the read optical fiber. We used the read optical fiber with a 50 μm core diameter which results in a Gaussian response function with the width $\Delta\lambda_{\mathrm{R}} = 2.7$ nm.

4. Experimental results and discussion

After optimizing excitation conditions to assure that only one polarization mode is excited in the tested PMF, a pointlike force was applied. Similarly, after optimizing detection conditions to assure the highest visibility of spectral interference fringes, the channeled spectrum was recorded for the first distance L_1 of the coupling point from the fiber end. Figure 2(a) shows the corresponding recorded spectrum by the blue curve. Next, the displacement $\Delta L = L_2 - L_1 =$ 7450 μm of the coupling point along the tested PMF was adjusted provided that the phase change $\Delta\phi(\lambda')$ at chosen wavelength $\lambda' = 637.08$ nm is approximately 2π. Figure 2(a) shows the corresponding recorded spectrum by the red curve and illustrates the wavelength-dependent phase change, which is larger then 2π for the wavelengths shorter then λ' (see the shift to the right) and smaller then 2π for the wavelengths longer then λ' (see the shift to the left).



(a) (b)

Fig. 2. (a) Two recorded channeled spectra with the corresponding unmodulated spectra. (b) Two spectral interference signals constructed from the spectra shown in Fig 2(a).

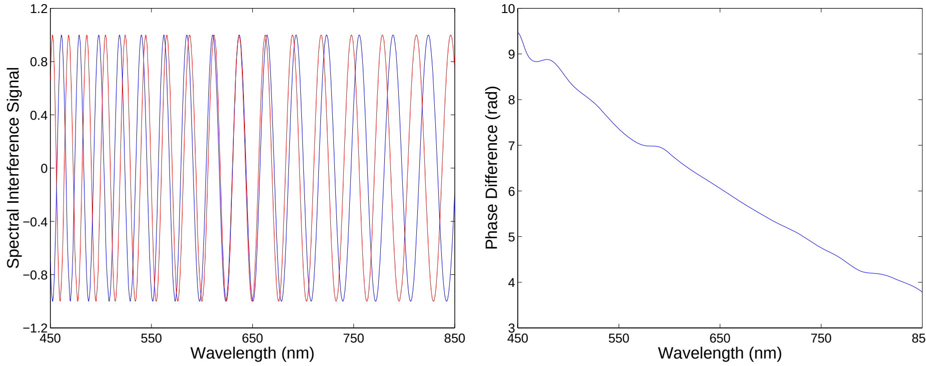
To reconstruct precisely the spectral phase functions $\phi_1(\lambda)$ and $\phi_2(\lambda)$ from the two recorded channeled spectra, a new procedure of the phase retrieval in the wavelength domain was applied [12]. It is based on the processing of the spectral interference signal $S(\lambda)$ defined as

$$S(\lambda) = I(\lambda)/I_0(\lambda) - 1. \tag{6}$$

In the first step, the unmodulated spectrum $I_0(\lambda)$ needs to be reconstructed from the recorded channeled spectrum. It is obtained as the inverse Fourier transform of the zero-order com-

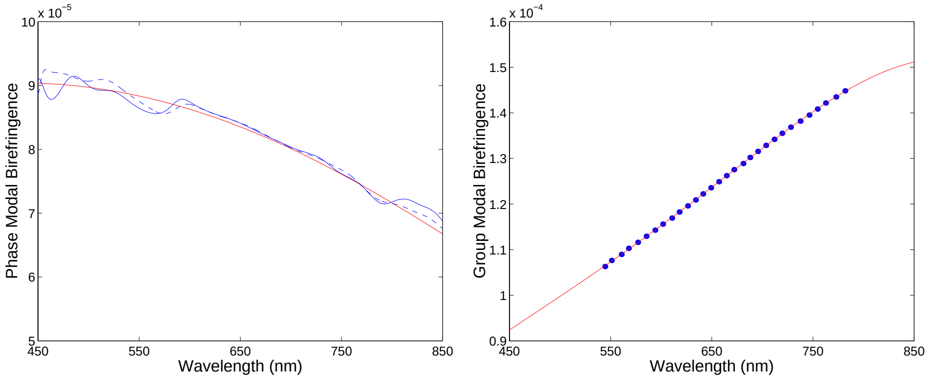
#88299 - $15.00 USD Received 5 Oct 2007; revised 30 Oct 2007; accepted 16 Nov 2007; published 5 Dec 2007

ponent of the Fourier spectrum of the recorded channeled signal [13]. Figure 2(a) shows the unmodulated spectra corresponding to the two recorded channeled spectra by the dashed lines. Figure 2(b) then shows the corresponding spectral interference signals that clearly illustrate the wavelength-dependent phase change. In the second step, the spectral phase functions $\phi_1(\lambda)$ and $\phi_2(\lambda)$ were retrieved from the spectral signal $S_1(\lambda)$ and $S_2(\lambda)$ using a procedure based on a windowed Fourier transform applied in the wavelength domain [12]. From the retrieved spectral phase functions, the signals $\cos[\phi_1(\lambda)]$ and $\cos[\phi_2(\lambda)]$ were constructed as shown in Fig. 3(a). Figure 3(a) once again clearly demonstrates the wavelength-dependent phase change with $\Delta\phi(\lambda') \approx 2\pi$ at $\lambda' = 637.08$ nm. This fact is also confirmed in Fig. 3(b) which shows the retrieved phase difference $\Delta\phi(\lambda)$ that decreases with increasing wavelength.



(a) (b)

Fig. 3. (a) Two spectral interference signals constructed from the retrieved phase functions $\phi_1(\lambda)$ and $\phi_2(\lambda)$ and the corresponding phase difference (b) as a function of wavelength.



(a) (b)

Fig. 4. Phase (a) and group (b) modal birefringences measured as a function of wavelength (red curves correspond to a polynomial fit).

Figure 4(a) finally shows by the blue curve the wavelength dependence of the phase modal birefringence $B(\lambda)$ determined from Eqs. (2) and (5). These equations can be used to estimate the precision $\delta B = B\sqrt{[\delta(\Delta\phi)]^2/\Delta\phi^2 + [\delta(\Delta L)]^2/\Delta L^2}$ of the phase modal birefringence measurement, which is affected by the precision $\delta(\Delta\phi)$ with which the phase difference is known and by the precision $\delta(\Delta L)$ of adjusting the displacement. In our case we estimate $\delta(\Delta\phi) = 2\pi/100$ and $\delta(\Delta L) = 1$ μm, so that $B(\lambda') = 8.55 \times 10^{-5}$ at $\lambda' = 637.08$ nm is known with precision $\delta B(\lambda') = 8.55 \times 10^{-7}$. We can also estimate the minimum B_{min} and maximum B_{max} birefringences that can be measured by the technique. The minimum birefringence is given by $B_{min}(\lambda) = \lambda\Delta\phi/(2\pi\Delta L_{max})$, where ΔL_{max} is the maximum displacement adjustable in the setup. For $\Delta L_{max} = 2.5$ cm (travel of the micropositioner) and $\Delta\phi = 2\pi$ we obtain $B_{min}(\lambda) = 2.6\times 10^{-5}$ at $\lambda = 650$ nm. The maximum birefringence is limited by the resolution of the channeled spectra [see the overall visibility in Eq. (4)] and is given on the assumption $B(\lambda) = G(\lambda)$ by $B_{max}(\lambda) = [\lambda^2/(\pi\Delta\lambda_{\mathrm{R}}L)]\sqrt{\ln 2/V_{\mathrm{R}min}}$, where $V_{\mathrm{R}min}$ is the minimum visibility. For $L = 1$ cm and $V_{\mathrm{R}min} = 0.5$, we obtain $B_{max}(\lambda) = 5.9\times 10^{-3}$ at $\lambda = 650$ nm.

The measured phase modal birefringence $B(\lambda)$ in the elliptical-core PMF can be compared with that resulting from the group modal birefringence $G(\lambda)$ measured by a method of spectral-domain tandem interferometry [11]. Figure 4(b) shows by markers the group modal birefringence $G(\lambda_0)$ determined for respective wavelengths λ_0. The red line in the same figure represents the group modal birefringence $G(\lambda)$ obtained from the values $-G(\lambda_0)/\lambda_0^2$ fitted to a fourth-order polynomial. The polynomial order is sufficiently high because the fit is characterized by a correlation factor as high as 0.99998. The corresponding absolute phase modal birefringence $B(\lambda)$, with $B(\lambda)/\lambda$ represented by a fifth-order polynomial, is shown in Fig. 4(a) by the red curve. It was obtained by combining the relative phase modal birefringence $B(\lambda)$ with the measured one [blue curve in Fig. 4(a)] to reach minimal deviation between them. The difference between the determined values is approximately within $\pm 2.6\times 10^{-6}$. In order to reduce the deviation, the larger displacement ΔL of the coupling point along the tested PMF has to be adjusted. In our case we adjusted $\Delta L = 14900\ \mu$m with $\Delta\phi(\lambda') \approx 4\pi$ at $\lambda' = 637.08$ nm. The corresponding phase modal birefringence $B(\lambda)$ is shown by the dashed curve and the above difference is approximately within $\pm 2\times 10^{-6}$. The difference can be attributed to the distortions of the channeled spectra and thus the retrieved phase difference [see Fig. 3(b)] due to the wavelength-dependent polarization coupling and/or the presence of the residual higher-order modes supported by the fiber.

5. Conclusions

We used a new and simple spectral-domain method to measure the wavelength dependence of the phase modal birefringence in an elliptical-core PMF over a wide spectral range (450 to 850 nm). The method is based on a lateral pointlike force applied on the fiber that causes strong coupling between polarization modes and resolving the channeled spectrum arising due to interference of the modes. The change of the phase retrieved from two recorded channeled spectra that are associated with the known displacement of coupling point was used for determining the phase modal birefringence as a function of wavelength. The phase change was reconstructed precisely by a windowed Fourier transform and the phase ambiguity was removed provided that the phase change of the spectral fringes at one specific wavelength is known. The measured wavelength dependence of phase modal birefringence was compared with that resulting from the group modal birefringence measurement. Good compatibility of the results was confirmed.

We demonstrated the applicability of the spectral-domain white-light interferometric technique that can be extended for dispersion characterizing of other fibers guiding two polarization modes over a wide spectral range (Panda and bow-tie fibers, PCFs). Moreover, if the proposed technique is combined with the data from group modal birefringence dispersion measurement, then the obtaining of phase modal birefringence dispersion can be substantially simplified because the measurement can be performed at one specific wavelength (e. g., λ') only.

Acknowledgements

The research was partially supported by the Grant Agency of the Czech Republic (project No. 102/06/0284), by the grant MSM6198910016, and by the COST Action P11.