Measurement of the group dispersion of the fundamental mode of holey fiber by white-light spectral interferometry

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Abstract: We present a new method for measuring the group dispersion of the fundamental mode of a holey fiber over a wide wavelength range by white-light interferometry employing a low-resolution spectrometer. The method utilizes an unbalanced Mach-Zehnder interferometer with a fiber under test placed in one arm and the other arm with adjustable path length. A series of spectral signals are recorded to measure the equalization wavelength as a function of the path length, or equivalently the group dispersion. We reveal that some of the spectral signals are due to the fundamental mode supported by the fiber and some are due to light guided by the outer cladding of the fiber. Knowing the group dispersion of the cladding made of pure silica, we measure the wavelength dependence of the group effective index of the fundamental mode of the holey fiber. Furthermore, using a full-vector finite element method, we model the group dispersion and demonstrate good agreement between experiment and theory.

OCIS codes: (060.2270) Fiber characterization; (060.2300) Fiber measurements; (120.3180) Interferometry; (999.999) Photonic crystal fiber;

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1. Introduction

The group dispersion, that is, the wavelength dependence of the group index, belongs to one of the fundamental dispersion characteristics of optical fibers. The chromatic dispersion, which can be obtained by simply differentiating the measured relative group index, is a significant characteristic that affects the bandwidth of a high speed optical transmission system through pulse broadening and nonlinear optical distortion. Chromatic dispersion of long length optical fibers is determined by two widely used methods [1]: the time-of-flight method which measures relative temporal delays for pulses at different wavelengths, and the modulation phase shift technique which measures the phase delay of a modulated signal as a function of wavelength.

White-light interferometry based on the use of a broadband source in combination with a standard Michelson or a Mach-Zehnder interferometer [2] is considered as one of the best tools for dispersion characterization of short length optical fibers. White-light interferometry usually utilizes a temporal method or a spectral method. The temporal method involves measurement of the group delay introduced by an optical fiber which is placed in one of the interferometer arms and evaluating the temporal shift of the peak of the cross-correlation interferogram. As the central wavelength is varied, the relative group delay of different frequency components is observed directly [3]. Alternatively, the spectral distribution of the phase delay over the full bandwidth of the white-light source is obtained in a single measurement by a Fourier transform of the cross-correlation interferogram [4]. The dispersion characteristics of the fiber sample under study can be obtained by simply differentiating the measured phase delay.

The spectral method is based on the observation of channeled spectrum [5, 6, 7, 8] and involves measurement of the period of the spectral fringes in the vicinity of a stationary-phase point in the recorded spectral interferogram [5, 6]. The main limitation of this method is related to the fact that the spectral interference fringes far from the stationary-phase point [7] are difficult to resolve. Fortunately, the measurement of the chromatic dispersion of a fiber sample is still possible in the vicinity of the stationary-phase point if one shifts it in successive steps

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to different wavelengths [8]. The feasibility of the interferometric techniques has been demonstrated in measuring the dispersion in microstructured and holey fibers [9, 10, 11]. To the best of our knowledge, non of these methods directly measure the dispersion of group effective index.

In this paper, a new technique, based on white-light interferometry and employing a low-resolution spectrometer, is used for measuring the group effective index dispersion of the fundamental mode of a holey fiber over a wide wavelength range. The technique utilizes an unbalanced Mach-Zehnder interferometer with a fiber under test placed in one arm while the other arm has adjustable path length to record a series of spectral signals and to measure the equalization wavelength as a function of the path length. We revealed that there is an apparent path length discrimination between the spectral signals associated with the fundamental mode supported by the fiber and light guided by the outer cladding of the fiber. Using the fact that the group dispersion of the cladding, which is made of pure silica, is known, we were able to identify the spectral signal related to the fundamental mode and to measure the dispersion of the group effective index. Furthermore, using a full-vector finite element method, we modelled the dispersion of the group effective index and demonstrated good agreement between experiment and theory.

2. Experimental method

Let us consider an unbalanced Mach-Zehnder interferometer as shown in Fig. 1 with a fiber under test of length z supporting the guided mode of the phase effective index $n_{eff}(\lambda)$. The fiber is placed in the first (test) arm of the interferometer that comprises optical components (lens 1 and lens 2) to which the effective thickness d and refractive index $n_c(\lambda)$ correspond. The other (reference) arm of the interferometer has the adjustable path length L in the air so that the group OPD $\Delta^{g}_{MZ}(\lambda)$ between the beams in the interferometer is given by:

$$\Delta^{g}_{MZ}(\lambda) = L - l - N_{eff}(\lambda)z - N_c(\lambda)d, \tag{1}$$

where l is the path length in the air in the test arm, and $N_{eff}(\lambda)$ and $N_c(\lambda)$ are the group (refractive) indices satisfying the relation:

$$N(\lambda) = n(\lambda) - \lambda \frac{\mathrm{d}n(\lambda)}{\mathrm{d}\lambda}. \tag{2}$$

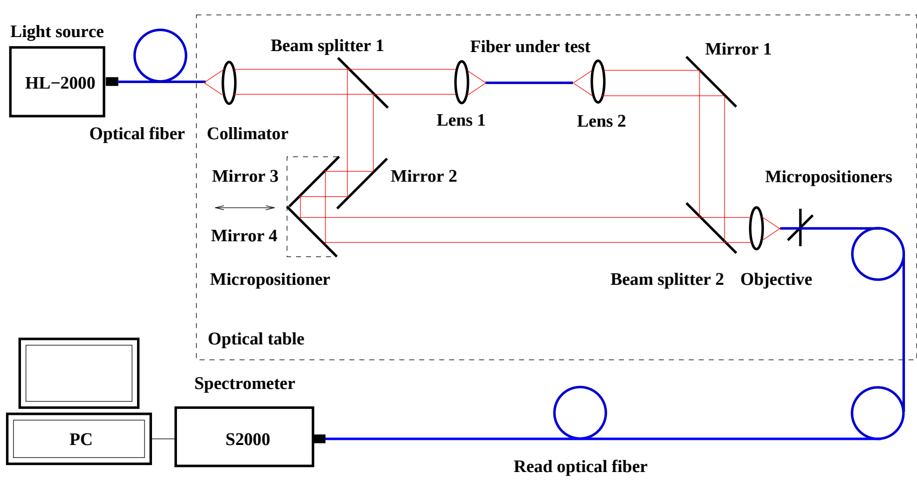

Fig. 1. Experimental setup with an unbalanced Mach-Zehnder interferometer to measure the group dispersion of the mode supported by a fiber under test.

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Let us consider now that the spectral interference fringes recorded in the setup have the largest period in the vicinity of a stationary-phase point for which the group optical path difference is zero at one specific wavelength λ_0, referred to as the equalization wavelength [12]. The condition $\Delta^{g}_{MZ}(\lambda_0) = 0$ gives for the overall path length $L = L_o = L_o(\lambda_0)$ for which the equalization wavelength λ_0 is resolved in the recorded spectrum the relation:

$$L_o(\lambda_0) = N_{eff}(\lambda_0)z + N_c(\lambda_0)d + l. \tag{3}$$

The light is also guided in the gallery of the cladding modes arising in the microstructured and solid parts of the cladding. As shown in [13], attenuation of the modes propagating in the microstructured region is very high and reaches 1-5 $dB\,cm^{-1}$, depending on wavelength range. Therefore, most of the energy is transmitted through the modes propagating in the solid part of the cladding. These modes are very well confined in the glass (except the ones close to the cut-off), which justifies the assumption that their group effective index is equal to the group index of the glass $N_g(\lambda)$. It is worth mentioning that correctness of this simplifying assumption was recently confirmed experimentally in [14] by direct interferometric measurements of the group index of light transmitted through the solid part of the cladding in the holey fiber. Furthermore, such an assumption was also used in earlier works [15] devoted to dispersion measurements in conventional fibers. In consequence, the spectral interference fringes associated to the cladding modes, which arise in the vicinity of the equalization wavelength λ_0 but for the different path lengths $L = L_g = L_g(\lambda_0)$, may be represented by the following equation:

$$L_g(\lambda_0) = N_g(\lambda_0)z + N_c(\lambda_0)d + l, \tag{4}$$

where $N_g(\lambda_0)$ is the group index of the glass at the equalization wavelength λ_0. Using Eqs. (3) and (4), we obtain the simple relation:

$$N_{eff}(\lambda_0) = N_g(\lambda_0) + [L_o(\lambda_0) - L_g(\lambda_0)]/z, \tag{5}$$

which means that the group effective index $N_{eff}(\lambda_0)$ of the mode supported by the fiber can be measured directly as a function of the equalization wavelength λ_0 if the fiber length z and the dispersion of the group index $N_g(\lambda)$ of the glass (pure silica) are known. The main limitation of the method is in the measured wavelength dependences of the path lengths $L_o(\lambda_0)$ and $L_g(\lambda_0)$ that must be known for the same equalization wavelengths λ_0.

Another possibility for measuring the group effective index $N_{eff}(\lambda_0)$ as a function of the equalization wavelength λ_0 is based on the knowledge of only a single value of the path length $L_g(\lambda_{0r})$ at one specific equalization wavelength, λ_{0r}, the reference one. In this case, we need to know the group dispersion of the optical components, which is measured in the unbalanced Mach-Zehnder interferometer with the fiber removed. If the corresponding path length is denoted as $L_c = L_c(\lambda_0)$, we can measure the path length difference $\Delta L_c(\lambda_0) = L_c(\lambda_0) - L_c(\lambda_{0r})$ given by

$$\Delta L_c(\lambda_0) = \Delta N_c(\lambda_0)d, \tag{6}$$

where $\Delta N_c(\lambda_0) = N_c(\lambda_0) - N_c(\lambda_{0r})$ is the differential group index of the optical components. Equation (4) can be rewritten as

$$L_g(\lambda_0) = L_g(\lambda_{0r}) + \Delta N_g(\lambda_0)z + \Delta N_c(\lambda_0)d, \tag{7}$$

where $\Delta N_g(\lambda_0) = N_g(\lambda_0) - N_g(\lambda_{0r})$ is the differential group index of the glass. On substituting Eq. (7) into Eq. (5) and using Eq. (6), we obtain the final relation for the group effective index $N_{eff}(\lambda_0)$:

$$N_{eff}(\lambda_0) = N_g(\lambda_{0r}) + [L_o(\lambda_0) - L_g(\lambda_{0r}) - \Delta L_c(\lambda_0)]/z, \tag{8}$$

which is easy to use if the group index $N_g(\lambda_{0r})$ of the fiber glass is known at the reference equalization wavelength λ_{0r}.

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3. Experimental setup

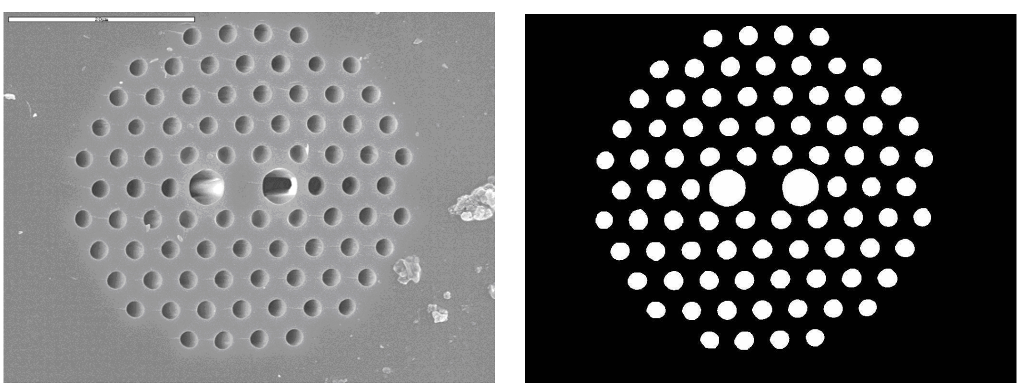
The setup for measuring the dispersion of the group effective index of the mode supported by the fiber using spectral-domain white-light interferometry is shown in Fig. 1. It consists of a white-light source: a quartz-tungsten-halogen lamp (HL-2000HP, Ocean Optics, Inc.) with launching optics, a single-mode optical fiber (FS-SN-3224, 3M), a collimating lens, a bulk-optic Mach-Zehnder interferometer with plate beam splitters (BSW07, Thorlabs), a micropositioner connected to mirrors 3 and 4 of the interferometer, a microscope objective, micropositioners, a fiber-optic spectrometer (S2000, Ocean Optics, Inc.), an A/D converter and a personal computer. In the test arm of the interferometer is inserted a combination of a fiber sample and optical components (shown schematically in Fig. 1 as lens 1 and lens 2) represented by a microscope objective (10×/0.30, Meopta), and an achromatic lens (74-ACR, Ocean Optics, Inc.). The fiber sample is pure silica holey fiber (PM-1550-01, Thorlabs) [17] of length $z = (50650 \pm 10)\ \mu$m.

4. Numerical modelling

Prior to the measurements, we model the dispersion of the modes supported by the investigated holey fiber. Its cross-section obtained by the scanning electron microscope (SEM) is shown in Fig. 2(a). A full-vector mode solver based on hybrid edge/nodal finite-element method (FEM) [16] was used to calculate the propagation constants of guided modes. In this approach, the following eigenequation is solved

$$\begin{bmatrix} -\nabla_\perp \times \nabla_\perp \times + k_0^2 \varepsilon(\vec{r}) & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \vec{E}_\perp \\ E_z \end{bmatrix} = \beta^2 \begin{bmatrix} 1 & \nabla_\perp \\ \nabla_\perp & \Delta + k_0^2 \varepsilon(\vec{r}) \end{bmatrix} \begin{bmatrix} \vec{E}_\perp \\ E_z \end{bmatrix}, \quad (9)$$

where $(\vec{E}_\perp, E_z)$ is the electric field vector (eigenvector) and β is the propagation constant of the mode (eigenvalue). To find the eigenpairs of the above equation, we used the Arnoldi method as an eigensolver and an unsymmetrical multifrontal method as a solver of linear system of equations. The calculations were carried out for the real geometry of the fiber [17]. The binary image of the fiber cross section shown in Fig. 2(b) was used as a mask to generate the mesh for FEM, which reflected the real shape and location of each hole. To assure high accuracy of numerical results, we applied a mesh composed of about 170 000 triangular elements and took into account the dispersion of the refractive index of the pure silica glass.



(a) (b)

Fig. 2. (a) SEM photograph of the investigated holey fiber and (b) binary mask used for mesh generation.

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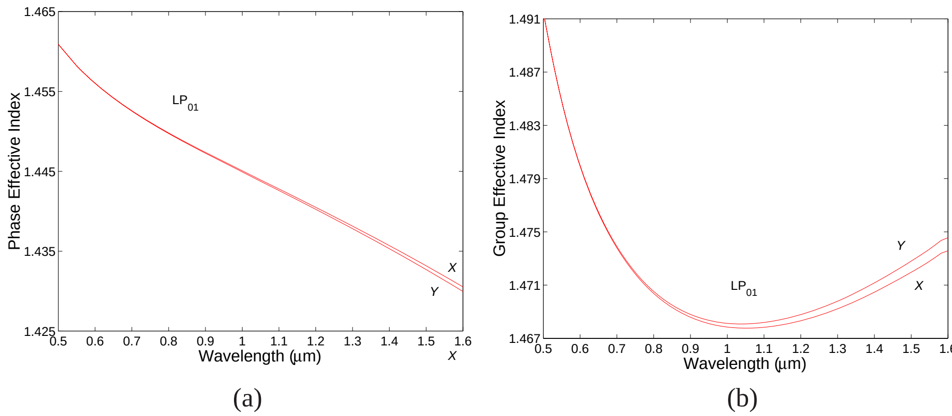

Fig. 3. Calculated phase (a) and group (b) effective indices of the LP_{01} mode of respective polarizations as a function of wavelength.

Figure 3(a) shows the wavelength dependence of the phase effective index $n_{eff}(\lambda) = \beta(\lambda)/(2\pi/\lambda)$ for the fundamental (LP_{01}) mode supported by the fiber. Figure 3(b) then shows the wavelength dependence of the group effective index $N_{eff}(\lambda)$ calculated by means of Eq. (2) for the LP_{01} mode. It should be noted that there is a minimum in the group effective index. In Figs. 3(a) and 3(b) are shown the effective indices for two orthogonal polarizations and the apparent discrimination between them is demonstrated.

5. Experimental results and discussion

First, the measurement was performed on a combination of the fiber sample and optical components in the setup shown in Fig. 1. Prior to the measurement we utilized the main advantage of the setup, which is in fiber connection of a light source (that can be exchanged) with the interferometer. We used a laser diode instead of the halogen lamp to check the right excitation of the modes supported the fiber, and the precise placement and alignment of the optical components in the test arm by observing the interference fringes. The optical field corresponding to the fundamental mode was revealed at the output of the test arm together with some patterns indicating that the light was also guided by the outer cladding of the fiber [14].

During the dispersion measurement we adjusted such a path length in the reference arm of the interferometer that allows to resolve spectral interference fringes. Figure 4(a) shows an example of the recorded normalized spectral signal (denoted as F+OCs) obtained by subtracting the reference signal (without the interference) from the interferogram. It clearly shows that the spectral interference fringes can be identified only in the vicinity of the equalization wavelength $\lambda_0 = 664.54$ nm. To reveal the dependence of the equalization wavelength λ_0 on the adjusted path length $L_o = L_o(\lambda_0)$, we displaced manually the stage with mirrors 3 and 4 by using the micropositioner with a constant step of 10 μm and recorded the corresponding spectral signals. Using this method, we revealed that the equalization wavelength λ_0 can be resolved in two different spectral ranges from 515 to 807 nm and from 769 to 882 nm. Figure 4(b) shows an example of the normalized spectral signal (denoted as G+OCs) recorded in the second spectral range with the spectral interference fringes arising in the vicinity of the equalization wavelength $\lambda_0 = 816.42$ nm. The spectral signal was preprocessed to remove the noise and the equalization wavelength was determined precisely by an autoconvolution method [18]. It is clearly seen that the spectral signal from Fig. 4(b) has substantially lower visibility in comparison with that

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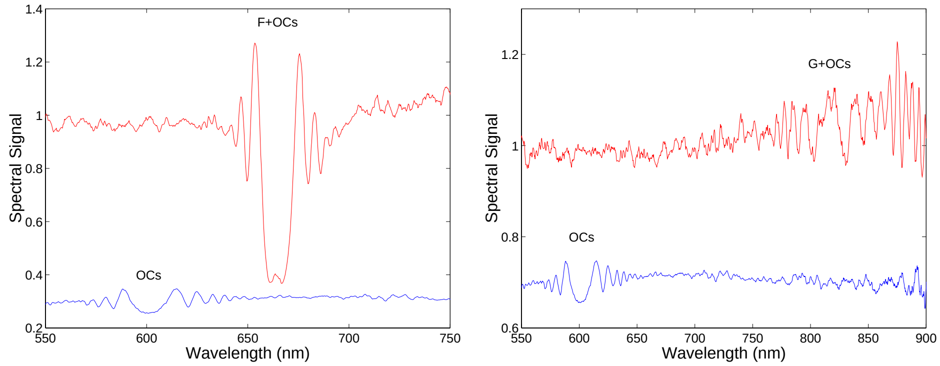

(a) (b)

Fig. 4. Examples of the recorded spectral signals: (a) optical components (OCs), fiber plus optical components (F+OCs); (b) optical components (OCs), glass plus optical components (G+OCs).

from Fig. 4(a). This is due to the fact that the light is guided by the outer cladding so that in this spectral signal the group dispersion of the fiber glass is encoded [14]. Moreover, the measured path lengths $L_o(\lambda_0)$ and $L_g(\lambda_0)$ are with the same equalization wavelengths λ_0 in too narrow spectral range from 769 to 807 nm to use Eq. (5). Better is to utilize Eq. (8) when only a single value of the path length $L_g(\lambda_{0r})$ at the reference equalization wavelength λ_{0r} needs to be known.

In the second step, the measurement was performed for the optical components for which the equalization wavelength cannot be resolved with the unbalanced Mach-Zehnder interferometer alone. A method of tandem interferometry [19] was used, which utilizes a Michelson interferometer placed in between the source and the unbalanced Mach-Zehnder interferometer and an appropriate OPD in the Michelson interferometer was introduced to resolve the spectral interference fringes at the output of the Mach-Zehnder interferometer. We checked the precise placement and alignment of the microscope objective and the achromatic lens in the test arm by observing the interference fringes when a laser diode was used instead of the halogen lamp. Figures 4(a) and 4(b) show an example of the recorded spectral signal (denoted as OCs) with the spectral interference fringes arising only in the vicinity of the equalization wavelength $\lambda_0 = 601.35$ nm.

From the two measurements described above, the wavelength dependences of the adjusted path length were obtained. In the first case we revealed that the overall path length difference $L_o(\lambda_0) - L_g(\lambda_{0r})$ varies from 1840 to -120 μm, when the reference equalization wavelength $\lambda_{0r} = 816.42$ nm was chosen. The measured values are shown in Fig. 5(a) by the crosses and there is an apparent discrimination between the values that can be attributed to the fundamental mode guided by the fiber (denoted as F+OCs) and to the light guided by the solid part of the cladding (denoted as G+OCs). Similarly, the spectral signals recorded for the second case revealed that the equalization wavelength λ_0 can be resolved in the spectral range from 509 to 869 nm and that the path length difference $\Delta L_c(\lambda_0)$ varies from 470 to -90 μm. The measured values are shown in Fig. 5(a) by the crosses together with the polynomial fit.

Knowledge of the measured dependences and the fiber length z enabled us to calculate the group effective index $N_{eff}(\lambda_0)$ of the fundamental mode as a function of the equalization wavelength λ_0. The function, which was obtained by means of Eq. (8) and the known group index $N_g(\lambda_{0r})$ of the pure silica glass [12], is represented in Fig. 5(b) by the crosses and it is shown together with the calculated functions also shown in Fig. 3(b). This figure confirms very good

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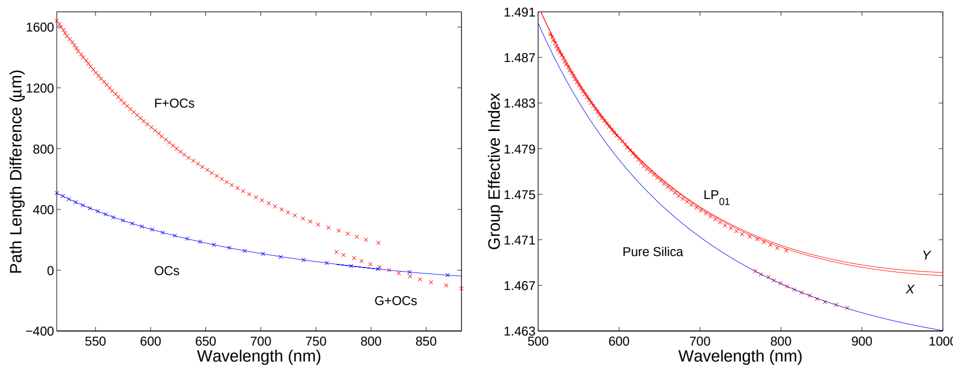

(a) (b)

Fig. 5. Path length difference (a) and group effective index (b) measured as a function of wavelength: optical components (OCs), fiber plus optical components (F+OCs), glass plus optical components (G+OCs); LP_{01} mode, pure silica (solid lines are theoretical functions).

agreement between theory and experiment, and also shows that the group effective index of the fundamental mode is substantially higher than the group index of the pure silica glass. Furthermore, no apparent discrimination between the group effective indices for the orthogonal polarizations was revealed in the measured spectral range. This is owing to short length of optical fiber used in the experiment.

We can estimate a precision of the group effective index measurement. If the reference equalization wavelength is determined with an error of $\delta(\lambda_{0r})$, the path length difference $\Delta L = L_o(\lambda_0) - L_g(\lambda_{0r}) - \Delta L_c(\lambda_0)$ is adjusted with a precision of $\delta(\Delta L)$ and the length z of the fiber is known with a precision of $\delta(z)$, the group effective index N_{eff} is obtained with a precision given by the following formula:

$$\delta(N_{eff}) = \sqrt{\left[\frac{\mathrm{d}N_g(\lambda_{0r})}{\mathrm{d}\lambda_{0r}}\delta(\lambda_{0r})\right]^2 + \left[\frac{\delta(\Delta L)}{z}\right]^2 + \left[\Delta L\frac{\delta(z)}{z^2}\right]^2}. \tag{10}$$

In our case, the error $\delta(\lambda_{0r})$ is 0.32 nm (the wavelength difference corresponding to adjacent pixels of the spectrometer linear CCD-array detector), the precision $\delta(\Delta L)$ is 1 μm and the precision $\delta(z)$ is 10 μm so that the precision $\delta(N_{eff})$ in determining the group effective index is 2×10^{-5}. Higher measurement precision can be achieved, for example, using a longer fiber. However, the maximum length of the investigated fiber is limited by resolving power of the spectrometer.

6. Conclusions

We proposed a new technique for measuring the dispersion of group effective index in the fundamental mode of a holey fiber over a wide wavelength range. The technique, which is based on white-light interferometry employing a low-resolution spectrometer, utilizes an unbalanced Mach-Zehnder interferometer with a fiber under test placed in one arm and the other arm with adjustable path length. A series of the spectral interferograms were recorded to measure the equalization wavelength as a function of the path length, or equivalently the dispersion of the effective index. We revealed that there is an apparent path length discrimination between the spectral signals associated with the fundamental mode supported by the fiber and light guided by the outer cladding of the fiber. Using the fact that the group dispersion of the pure-silica

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cladding is known, we measured the wavelength dependence of the group effective index of the fundamental mode of the holey fiber. Furthermore, we modelled the group dispersion using a full-vector finite element method and demonstrated good agreement between experiment and theory. The use of the method, whose main advantage is in easy inspection of the optical field at the output of the test arm, can be extended for measuring the group dispersion of the spatial and/or polarization modes supported by a fiber under study.

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