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Polarization-mode dispersion of large mode-area photonic crystal fibers

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Abstract

We report on an experimental study of the polarization properties of large mode-area photonic crystal fibers (PCFs). We find that such fibers may exhibit very low birefringence and polarization-mode dispersion (PMD) indicating a highly symmetrical hole structure over a long length. Moreover, the influence of temperature on the polarization-mode dispersion is investigated. The results show that it is possible to fabricate photonic crystal fibers with polarization-mode dispersion, which is nearly insensitive to changes in temperature.

Keywords: Photonic crystal fiber; Polarization-mode dispersion; Birefringence; Beat length; Differential group delay

1. Introduction

Photonic crystal fibers (PCFs) are a new class of optical fibers having a cross-section with a periodic air–silica microstructure [1]. The structure provides a wavelength-dependent effective index for the cladding and can allow single-mode guidance throughout the visible and near infrared [2]. The optical properties of PCFs are primarily governed by the number and size of the air holes, along with their geometrical distribution around the core of the fiber. These fibers are particularly suitable, e.g., for applications that require high power delivery, since they can allow single-mode operation with large mode area [3]. The large core area reduces the impairments arising from various nonlinear effects, which limit the performance of high-power systems. Large mode-area PCFs find applications for instance in high-power single-mode signal transmission [4], and in amplifiers and lasers [5].

An important factor to be considered in high bit rate systems that operate at high-power levels is polarization-mode dispersion (PMD). Due to PMD, the different polarization modes propagate with different velocities which leads to pulse

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broadening and limitation on the operation at high bit rates, at 40 Gbit/s and above.

In this paper, we experimentally investigate the polarization properties of novel large mode-area PCFs utilizing different conventional measurement techniques. Moreover, the influence of temperature on the PMD is studied to gain a better understanding of the behavior and sensitivity of the PMD in PCFs.

2. Fiber samples

The investigated fiber samples are three large mode-area PCFs having a hexagonal hole structure in the cladding area. The core sizes (the mean distance between opposite hole edges of the core) of the samples are 10.8, 14.8 and 19.4 μm and the fibers are labeled PCF10, PCF15 and PCF20, respectively. The optical microscope images of the samples are shown in Fig. 1. The ratio of the hole diameter, d, to the pitch of the structure, Λ, is $\sim$0.45–0.50 for all the fibers. The length of each fiber is approximately 100 m and they are spliced at each end to a meter long standard single-mode fiber (SMF-28) with a FC/PC connector. Finally, the samples were wound on spools having a diameter of 160 mm.

3. Measurement results

The PMD of the fiber samples was measured using conventional measurement techniques [6]. The samples were kept on the same spools during all the measurements to provide similar measurement conditions. The measurements were performed at multiple locations with three different techniques in order to increase the reliability of the results. At Helsinki University of Technology (HUT) the Jones matrix eigen analysis (JME) and fixed analyzer (FA) methods were used by employing a commercially available PMD analyzer (Tektronix, former Profile, PAT9000B) and a tunable laser source (1510–1650 nm). The measurement techniques applied in the Group of Applied Physics, Geneva (GAP) were the JME and the interferometric (IF) method. The light source for the JME technique was a tunable laser with a tuning range of 1455–1612 nm and for the IF method a polarized LED having a spectrum of 1517–1565 nm (FWHM). At Crystal Fibre A/S (CF), the PMD was investigated by utilizing the FA method with a tunable laser in the range of 1510–1640 nm. A summary of the measured PMD values is given in Table 1.

Since the measured PMD values are small, the employed measurement range will not allow for a sufficient averaging to determine the PMD precisely. The PMD variation, $\Delta\tau_{\Delta\omega}$, for the frequency range, $\Delta\omega$, used in the measurements can be calculated from the equation [7]

$$\Delta\tau_{\Delta\omega} = \mathrm{PMD}(1 \pm 0.9/\sqrt{\mathrm{PMD} \cdot \Delta\omega}), \qquad (1)$$

where PMD is the mean PMD value of the fiber. The inherent measurement limitation stems from the fact that the differential group delay (DGD), PMD is defined as mean DGD, is a statistical

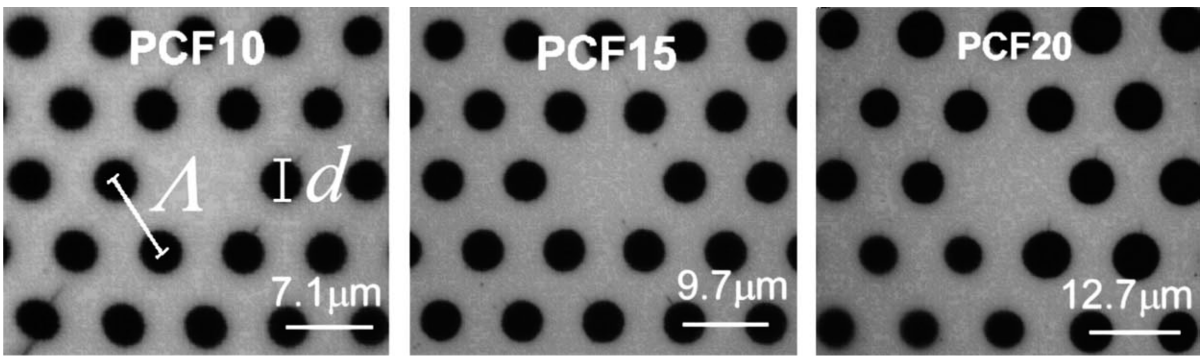

Fig. 1. Optical microscope images of the fiber samples PCF10, PCF15 and PCF20.

Table 1
Measured PMD in fs ($k = 0.824$ for FA)

	PCF10	PCF15	PCF20
JME (HUT)	451	~5	153
FA (HUT)	421	0	146
JME (GAP)	308	~7	241
IF (GAP)	275	<50	240
FA (CF)	321	0	181

quantity due to random polarization mode coupling and changing local birefringence. Therefore, DGD is wavelength sensitive and DGD at one wavelength fluctuates over time due to varying environmental conditions. Since the accuracy of today's conventional techniques is close to the theoretical limit [7], an expansion of the measurement set would be required to further increase the measurement accuracy. Fig. 2 shows a comparison between the PMD values measured at HUT (JME), GAP (JME) and CF (FA). The inherent limitation of the measurement methods shown by solid lines and given by Eq. (1) was calculated using an average wavelength range of $\Delta\lambda \sim 140$ nm ($\Delta\omega \sim 106 \times 10^{12}$ s^{-1}). The measured values are in good agreement with this intrinsic uncertainty limit, which is present in all PMD measurements.

The PMD values measured at HUT using the FA and JME methods are in good conformity (see Table 1), as the measurements were performed within a short time period. The stability of the measurements at HUT is presented in Fig. 3(a), which shows the wavelength dependence of the differential group delay measured with the JME method for PCF10. The PMD values corresponding to the measurements are shown in Fig. 3(b). The measurements were performed during a period of 19 days and the temperature variation within the same time period was less than 2 °C. It can be observed that there are only small changes in the traces and in the obtained PMD values while the external conditions are kept unchanged. The PMD values measured using the IF and JME methods at GAP are also in good agreement in the wavelength range covered by the LED. The results of CF are closer to the values obtained at GAP in the case of PCF10 and HUT in the case of PCF20. Furthermore, the difference between the measurement results indicates that the fibers have a fairly strong polarization-mode cou-

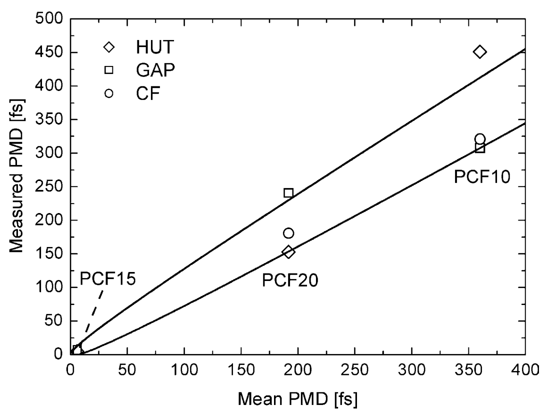

Fig. 2. Measured PMD and the expected standard deviation of the measurement (solid lines, $\lambda \sim 140$ nm).

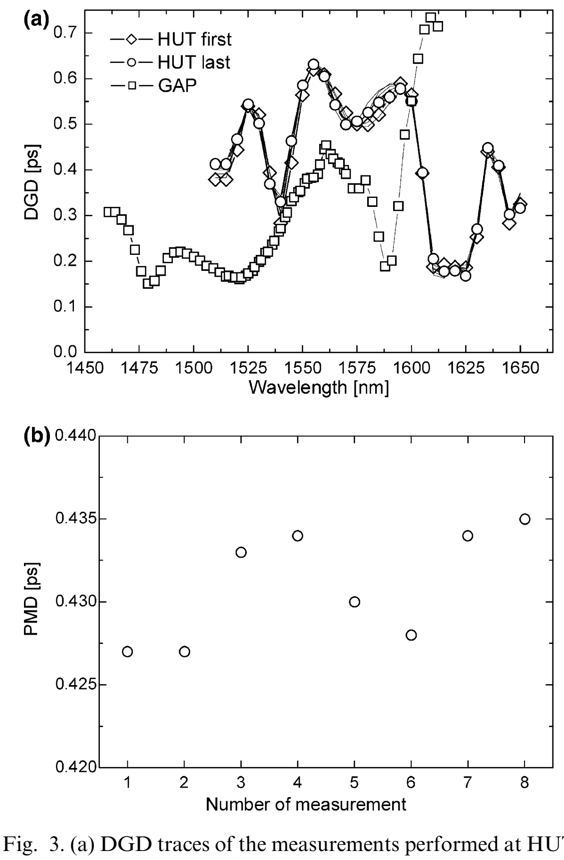

Fig. 3. (a) DGD traces of the measurements performed at HUT over a period of 19 days (a DGD trace measured at GAP is also displayed) and (b) the corresponding PMD values.

pling. To investigate this a step further, the DGD traces measured at HUT and GAP (see Fig. 3(a)) are studied more closely. The time interval between the measurement at GAP and the first measurement at HUT was one week and the temperature difference was ~2 °C. Both traces show strong variations of DGD with wavelength, which is an evident sign of the presence of a fairly strong polarization-mode coupling. Therefore, these fibers can be expected to belong to the strong polarization-mode coupling regime and a mode-coupling factor, k, of 0.824 was used in connection with the FA method (k-factor equals 1 for weak mode coupling).

To determine the local birefringence (inversely proportional to beat length) of the fiber samples, their beat lengths were measured at GAP using a coherent reflectometric method [8]. The results of the measurements are given in Table 2. The beat lengths varied only little with distance, which is a sign of a good homogeneity of the hole structure. Due to symmetry constraints, the birefringence of an ideal hexagonal PCF structure is zero [9]. In practice, the structure is always to some degree asymmetric leading to local birefringence, which again gives rise to DGD between the polarization modes. The local birefringence is likely to increase for a decreasing size of the structure [10]. This can be seen for PCF10 and PCF20, whose beat lengths differ by a factor of ~2. The beat length of PCF15 is, however, much longer and results in a PMD value close to the measurement limit indicating an excellent symmetry in the hole structure over a long length. The PMD coefficient for this fiber is ~0.02 ps/km$^{1/2}$, which is comparable to the PMD coefficients of the state-of-the-art standard fibers. To our knowledge, this is the first observation of such a low PMD value showing high quality of the fiber and could lead to a major breakthrough in the production of long PCF structures [4].

To gain a better understanding of the behavior and sensitivity of the PMD in PCFs, we have also studied the influence of temperature on the phenomenon. The total birefringence in any fiber is a combination of a geometrical birefringence and stress-induced birefringence. The stress-induced birefringence is caused by an asymmetrical stress field and can be sensitive to temperature. For instance, rapid cooling of the glass during the fabrication can induce asymmetrical thermal stress in fibers. This effect may also occur in PCFs although they are made from one material having a uniform composition. In contrast to standard single-mode fibers, PCFs fabricated from pure silica do not suffer from a temperature sensitive internal birefringence resulting from the differential thermal expansion of the core and the cladding due to their different chemical compositions. Since pure silica has a very low thermal expansion coefficient ($\sim 5.5 \times 10^{-7}$ K^{-1}), the thermal expansion of the glass structure has an insignificant influence on birefringence. Furthermore, the difference between the rates of change of the refractive index of core and cladding (increases at a slower rate) with temperature is only relevant when the temperature change is high [11]. However, since a coating has a much higher thermal expansion coefficient ($\sim 5.0 \times 10^{-5}$ K^{-1}) than silica, the stress [12,13] caused by the thermal contraction mismatch of silica and coating material can induce birefringence and change the mode coupling if the structure of the PCF is initially asymmetric.

The influence of temperature on the PMD was experimentally investigated using a computer-controlled thermal chamber utilizing the FA and JME methods at HUT. Due to a PMD value close to the measurement limit, this test was not performed for PCF15. The fiber spools were placed inside the chamber and the PCFs were connected to the analyzer by employing short single-mode fibers with a FC/APC connector at the analyzer end. The measurements were performed in steps of five degrees in the temperature range from 25 to 80 °C, which was the operating range of the thermal chamber. Fig. 4 displays the temperature dependence of the PMD and the inherent measurement uncertainty for PCF10. A comparison between the values measured with the FA and JME techniques shows that the results agree to within the inherent measurement limit predicted by Eq. (1). It can be

Table 2
Beat lengths measured at GAP

	PCF10	PCF15	PCF20
L_b (m)	0.73	21.0	1.6

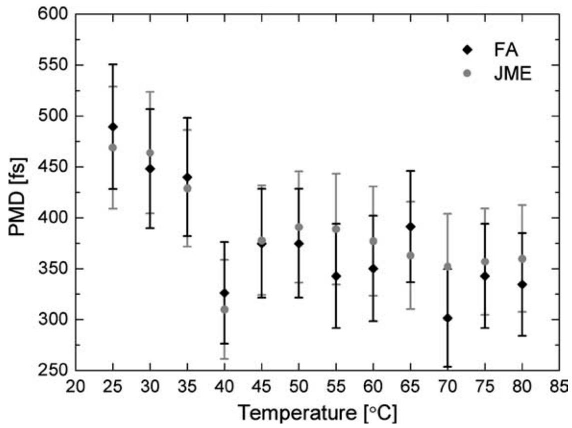

Fig. 4. Temperature dependence of the PMD for PCF10 ($k = 0.824$ for FA).

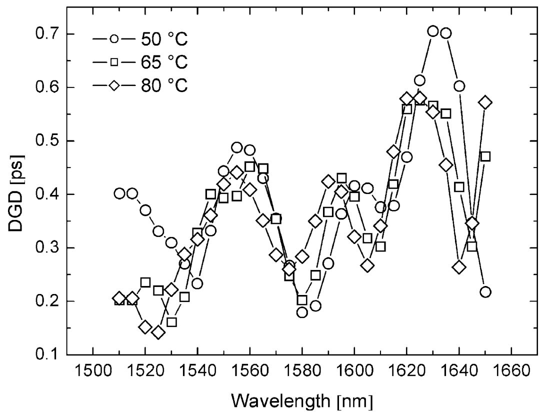

Fig. 6. Differential group delay for PCF10 at the temperature of 50 °C (circles), 65 °C (boxes) and 80 °C (diamonds).

observed that the PMD decreases with temperature until the temperature is $T \sim 40$ °C and then stays almost constant as temperature is further increased. The temperature dependence of the PMD for PCF20 is given in Fig. 5. Again, the results of the FA and JME methods are within the PMD measurement limitation. A same kind of trend can be observed for PCF20. Now, the PMD decreases with temperature until the temperature is $T \sim 50$ °C. In the case of both fibers, the shapes of the DGD traces were found to be quite similar at high temperatures, with the exception of a small wavelength shift (see Fig. 6 for PCF10). This indicates that there are no significant external forces acting on the fibers at high temperatures. The difference between the PMD values obtained during the temperature test and the initial measurements at HUT for PCF20 is most likely a consequence of changed winding conditions (low winding tension) caused by the shipping of the spools and a result of the intrinsically strong mode coupling.

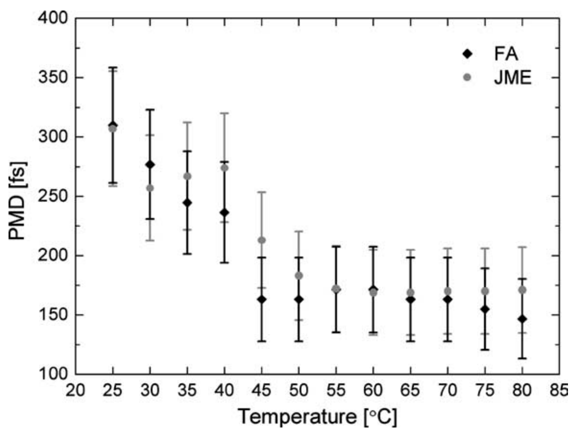

Fig. 5. Temperature dependence of the PMD for PCF20 ($k = 0.824$ for FA).

The coating of the PCFs is a single-layer acrylate coating, in contrast to conventional dual-layer coatings with a soft buffer layer between the glass cladding and acrylate. Hence, the glass of the fiber is in direct contact with the coating material and therefore poorly shielded from any externally applied pressure and from stresses in the coating. In this particular case, the primary mechanical stress contribution is expected to come from the coating since the winding tension of the fibers was low and the fibers were placed inside the chamber and thus stayed isolated from the external environment during the measurements. The amount of thermal stress induced by the single-layer coating depends, e.g., on Young's modulus and the effective thermal expansion coefficient of the coating material and on the temperature change from the application temperature of the coating material [12,13]. The coating of the sample fibers is applied at a temperature of $T \sim 35$ °C and subsequently UV-cured which further increases the temperature. Due to the high thermal expansion coefficient and high Young's modulus of the acrylate together with the initially asymmetric hole structure and irregularities in the placement of the acrylate, the coating induces thermal stress in the fiber at low temperatures. The coating induced asymmetric stress in turn gives rise to birefringence and therefore increases the PMD. Heating the fiber eliminates part of the external contributions to the total PMD and indicates that the PMD is nearly insensitive to changes in temperature at high temperatures.

To compare the observed behavior in PCFs with conventional dual-coated fibers having a comparable PMD value in fs, we have measured the temperature dependence of the PMD for a 16 km long single-mode fiber. The temperature test could not be conducted with dual-coated PCFs, since the current manufacturing process allows only fabrication of PCFs with a single-layer coating. The coating of this particular single-mode fiber is composed of a two-layer UV-cured acrylate, which provides good protection against external forces. The measurements were performed utilizing the FA ($k = 0.824$) and JME methods in the wavelength range of 1510–1650 nm at HUT. Fig. 7 shows how the PMD varies with temperature. The measurement results of the FA and JME methods are within the PMD measurement limitation given by Eq. (1) and therefore in good conformity. In contrast to PCFs, no clear relationship between the temperature and PMD can be observed. The most plausible explanation for this is that the highly symmetrical structure of the single-mode fiber together with the protective buffer layer makes the fiber more resistant against coating induced nonuniform thermal stresses at low temperatures. This indicates that PCFs with a low and to a large extent temperature insensitive PMD value can be expected when applying conventional dual-layer coatings to highly symmetrical fiber structures (PCF15).

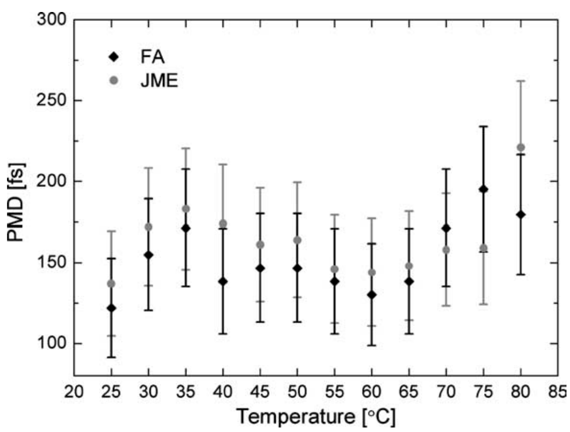

Fig. 7. Temperature dependence of the PMD of a 16 km long single-mode fiber ($k = 0.824$ for FA).

4. Discussion

We have experimentally analyzed the polarization properties of large mode-area PCFs utilizing conventional measurement techniques at the wavelength range important for optical communications. One of the samples exhibits a greatly reduced local birefringence and a very low PMD value indicating an excellent symmetry in the cladding hole structure over a long length. To our knowledge, this is the first observation of such a low PMD value, which is a sign of a high quality of the fiber. This could lead to a major breakthrough in the production of long PCF structures.

Moreover, we have studied the influence of temperature on the PMD. It was found that the PMD decreases as the temperature increases up to a certain value beyond which the PMD stays almost constant. This is explained by the coating induced thermal stress on the fiber at low temperatures. The results indicate that it is possible to fabricate PCFs having to a large extent temperature insensitive PMD by employing conventional dual-layer coatings. The application of such coatings allows for further improvement of the room temperature PMD values of single-coated PCFs.

Furthermore, measuring the temperature dependence of the PMD could prove to be a convenient means to analyze the PMD of the single-coated PCFs arising from intrinsic structural and extrinsic factors, since it has an advantage of being able to change or even eliminate some of the contributions to the total PMD.

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