Second-order polarization-mode dispersion in photonic crystal fibers

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While the polarization decorrelation length is the scale on which the ensemble average \( S_i(x) \) reaches its asymptotic value of 0, the diffusion length \( d_d \) is defined as the distance it takes for the value of \( S(x) \) to reach its asymptotic value of 1/3. This asymptotic value is 1/3 since the Stokes vectors are asymptotically uniformly distributed on the Poincaré sphere. We define the diffusion length to be the maximum of the values \( d_1, d_2, \) and \( d_3 \). In Fig. 2, we show the results for different values of \( \alpha \).

These results show that as the ratio \( \alpha / \tau \) converges to the isotropic value 1, the local diffusion length becomes proportional to the fiber decorrelation length \( d_0 \). However, the diffusion length has the same convolution dependence on \( d_0 / \tau \) for all values of \( \alpha / \tau \), except for the isotropic case \( \alpha / \tau = 1 \), which is a singular limit. Thus, a small ellipticity has no significant effect on the system behavior as compared to the case of only linear birefringence. However, the variation in the diffusion lengths for small \( \tau \) and \( \alpha \) becomes larger indicates that the interaction between nonlinearity and PMD is changed as the ellipticity is increased.

In conclusion, we have described the dependence of the intrinsic polarization decorrelation rate and the diffusion length on the amount of ellipticity present in an optical fiber. These results demonstrate in particular that the expression for the DGD in terms of the fiber decorrelation length does not depend on the strength of ellipticity. However, the diffusion length is in general anisotropic on the Poincaré sphere, which affects nonlinear interactions. A small ellipticity does not significantly affect results that are predicted by a model that assumes that fibers are linearly birefringent.

References

Second-Order Polarization-Mode Dispersion in Photonic Crystal Fibers


We report the first experimental measurements of second-order Polarization-Mode Dispersion (PMD) in two successive 900-meter pulls of a silica Photonic Crystal Fiber.

Introduction

Photonic Crystal Fibers (PCFs) form a new class of optical fibers, which have attracted significant attention during the last few years [1,2,3]. PCFs are silica fibers with a large number of air-holes located in the cladding region. The size and location of these air-holes provide a large degree of design flexibility, which has been used to tailor the optical properties and design large-mode area fibers for long-haul transmission. Recently, PCFs with very low loss have been reported [4], which further strengthened the possibility of using PCFs for long-haul transmission. A second-order parameter for long-haul transmission is Polarization-Mode Dispersion (PMD). PMD causes different polarizations to propagate with different velocities, which causes pulse broadening in a communication system [7]. PMD can be classified into first- and second-order PMD, where first-order PMD describes the Differential Group Delay (DGD) between the two orthogonal Principal States of Polarization (PSPs) [8]. This section describes the worst case, i.e., the wavelength dependence of the PMD and the DGD, which is given in the following sections.

The first experimental measurements of first-order PMD in PCFs were reported in [9], where the DGD was measured on three 100-meter silica PCFs with different core sizes. In this paper, we present the first experimental measurements of second-order PMD in two 900-meter successive pulls of PCFs, pulled under different conditions.

Experiment

The two studied PCFs had a triangular air-holes structure with a normalized air-hole size of \( \Lambda = 0.43 \). The background material was fluorine-doped silica, which lowered the refractive index contrast between the core and cladding material. The core radius was \( 1.15 \times 10^4 \) with respect to pure silica. Two 900-meter fibers, referred to as PCF1 and PCF2, were drawn from the same preform but under different pulling conditions. These fibers were coiled on two 160mm diameter spools and spliced at both ends with a 1-meter pigtail with FC/PC connectors. The interferometric measurement of the two fibers at the beginning of each was performed, and it shows an increased air-hole size of PCF2, compared to PCF1. The air-hole size of PCF1 and PCF2 was 1.46mm and 1.32mm, respectively. The eccentricity of the cores was quantified using the formula: \( \varepsilon = r_{min}/r_{max} \), where \( r_{min} \) and \( r_{max} \) is the minimum and maximum distances between two diagonal air-holes surrounding the core. The eccentricity of the cores of PCF1 and PCF2 were 0.014 and 0.017, respectively, indicating a slightly more eccentric core in PCF2 than in PCF1.

The first experimental measurements of second-order Polarization-Mode Dispersion (PMD) in PCFs were reported in [9]. The DGD and the PMD was calculated using the Jones Matrix Eigenanalysis [14], and the two second-order parameters, the DGD and the rotation rate of the PSPs (\( \Omega \)), was calculated from the wavelength derivative of the DGD and the PSP vector, respectively.

Results and Discussion

The measured first- and second-order PMD parameters for PCF1 and PCF2 are shown in Figs. 2 and 3, respectively. Figure 2 shows the DGD, which indicates that the interaction between nonlinearity and PMD is changed as the ellipticity is increased.

Figure 3. DGD, PCD and 2k measured on PCF2.

Figure 4 and 5 shows the measured Probability Distribution Function (PDF) of the DGD of PCF1 and PCF2, respectively. The dashed line indicates the Maxwell distribution for the theoretical DGD in the strong mode-coupling regime. The PMD of PCF1 and PCF2 was measured to 2.9ps and 7.1ps, respectively. These values were measured using an 800nm broadband LED centered around 1550nm. These values are comparable to standard single-mode fiber values reported in the mid-1990's [15]. It should also be mentioned that the measured PMD on 300-meter was measured to 0.9ps and 2.2ps, respectively, and thereby indicating strong wavelength dependence of the PMD. The PDF of the DGD clearly indicates that PCF2 is closer to the strong mode-coupling regime than PCF1, even though PCF2 has 3 times more PMD. This indicates that the birefringence is increased and the mode-coupling length is decreased in PCF2 compared to PCF1.

Figure 4. Probability Distribution Function of the DGD measured on PCF1.
Figure 5. Probability Distribution Function of the DGD measured on PCF2.

Conclusion
We have successfully measured first- and second-order PMD on two successive pulls of a triangular structured PCF. The two PCFs were pulled under different conditions, which affected both the birefringence and the mode-coupling length. The experiment showed that the PMD of these fibers behaved in the same way as in standard fibers and could be treated using conventional methods. The reported PMD was comparable to the PMD reported in the mid-1990s for standard fibers.

References
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Figure 1. Conventional fixed gain amplifier design vs. emerging variable gain amplifier design and next generation amplifier function, which exhibits variable gain, configurable midstage access and fast transient control.

3. Next generation EDF design considerations
In contrast to the next generation EDF amplifier requirements, conventional EDF amplifiers have limited dynamic operating range and hence poor gain and power range. Therefore, system engineers have had to place variable optical attenuators (VOA's) in front and after the amplifier, as shown on the left hand side in Fig.1, to buffer the increased variability. This causes severe OSNR and optical power penalties as well as significantly lower wall-plug efficiencies, increased size and added cost. Also, system vendors had to merge the VOA and the amplifier controls together on a higher level, further increasing complexity and cost and reduces overall performance.

Recently emerging controlled amplifier designs, as shown in Fig.1, as well, partially circumvent this problem by providing a much wider dynamic gain and power range. Fig.2 shows the Noise Figure benefit of such a variable gain amplifier [8] as a function of optical gain compared to a conventional fixed gain amplifier. However, these designs still require to place two amplifiers back-to-back to compensate for high loss components. Additionally, the performance optimization that balances the two amplifiers and the midstage loss must be implemented at a higher system level, which intrinsically limits the overall performance.

Furthermore, for the transient controller to operate most effectively, its performance parameters must match the requirements dictated by the latest generation of high-speed optical switches, which are able to initiate adds and drops with rise- and fall times of as little as 1 µs and power changes of at least 15 dB. Moreover, power spikes due to techno-