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An investigation of polarization cross-coupling in air-core photonic bandgap fibers

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ABSTRACT

Polarization cross-coupling is one of the most important problems in air-core photonic bandgap fibers (PBF). In this research, polarization cross-coupling is investigated for PBFs of different lengths. The analyzing and simulation results show that the orientation of the birefringent axes induced by residual core ellipticity fluctuates with an average period of $\sim$2.5 cm and random angles uniformly distributed over approximately $[-7.5°, 7.5°]$. The birefringent orientation in PBF varies much more frequently and strongly than that in any conventional fiber because of the difference in drawing process, and this is the most important factor causing the strong polarization cross-coupling in PBFs.

1. Introduction

In conventional fiber, perturbations along the fiber can cause mode-to-mode coupling. These perturbations stem from asymmetries in the fiber stress and geometry, such as variation of elliptical cross sections, microbends, or microtwists. They can originate in the preform, in the drawing process, or in applying process [1,2]. Often such a fiber is visualized or modeled as a sequence of random birefringent sections in which the birefringent orientation varies arbitrarily while the birefringence strength is kept fixed, according to one of the two physical models given by [3]. For example, in communication fibers, the beat length L_B is $\sim$10 m, and the orientation of the birefringence is randomly varying on a length scale that is on the order of 100 m [3].

Photonic bandgap fibers (PBF), in which light is confined in an air core by means of photonic bandgap, have attracted significant interest in recent years, owing to the fact that they have lower nonlinear coefficients, Rayleigh scattering and much better adaptability to temperature, radiation, as compared to silica fibers [4,5]. These beneficial features make PBFs a perfect choice for communication and some fiber-optical sensors, such as a fiber-optical gyroscope. In PBFs, residual core ellipticity arising during the drawing process is the primary factor of large birefringence, and many papers have ever studied it [6–9]. What is more, strong polarization cross-coupling exists in PBF and it is several orders of magnitude larger than that in conventional fiber according to our test results, and this is actually one of the most important problems in the current PBF [10]. As similar as the conventional fiber, the polarization cross coupling is mainly caused by the variation of the orientation of the birefringence, and can be modeled and explained with the above-mentioned model. Obviously, the orientation of the birefringence in PBFs varies in a different way from that in conventional fiber because of different internal structure and drawing process. However, few papers have ever deeply and quantitatively investigated the variation of orientation of the birefringence in PBFs and the induced strong polarization cross-coupling.

In this paper, we employ the model mentioned above to explain and simulate the polarization cross-coupling in PBFs, and get the optimized parameters through comparing the theoretical and simulation results to the test results which were obtained by an optical coherence domain polarimeter (OCDP) in [10]. Based on these analyzing results, we, to our best knowledge, first and quantitatively determine the period and magnitude of the variation of orientation of the birefringence in PBF, which perfectly explain such strong polarization cross-coupling in PBF. In addition, the variation of the orientation of the birefringence can reflect the axial uniformity along the PBFs, so it simultaneously provides a method to evaluate the drawing quality of PBFs.

2. Test results of polarization cross-coupling in PBFs

In an ideal 7-cell PBF with a perfectly symmetric and unperturbed structure, the air-guided fundamental modes are

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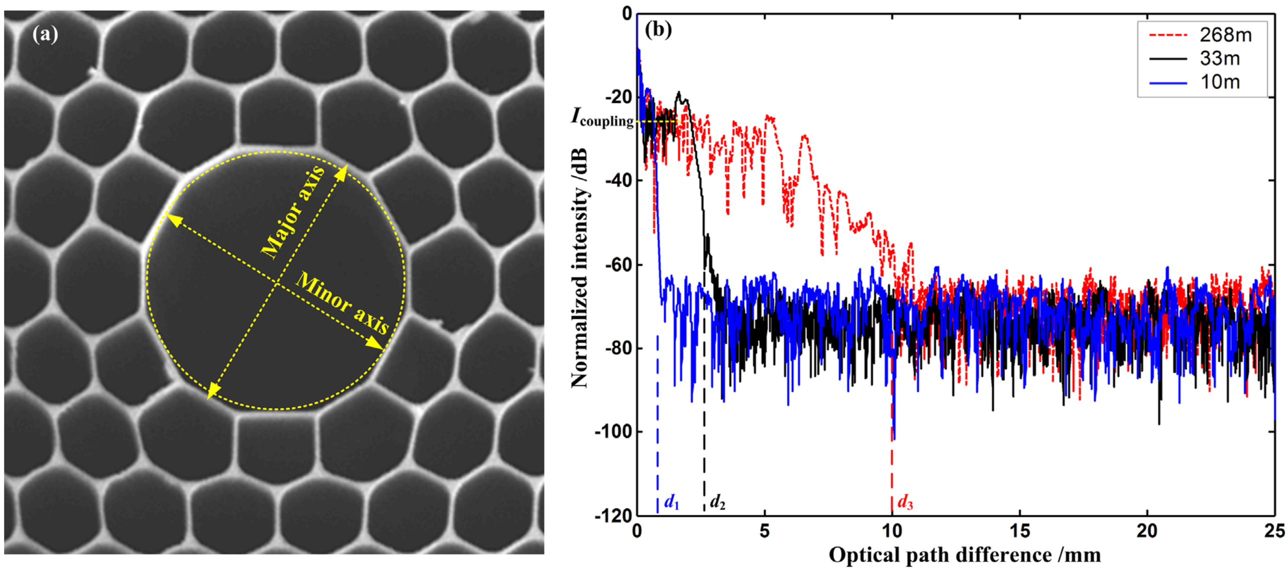

Fig. 1. (a) SEM picture of a PBF and (b) test results for polarization cross-coupling in PBFs [10].

degenerate, and thus there is no polarization dependence. However, residual core ellipticity is inevitable in a real PBF owing to unintentional deformation of the innermost ring of air holes surrounding the core during the drawing process, as illustrated in Fig. 1(a) [8,9]. Distortions of these structures can cause large and noticeable effects on the fiber's polarization properties, and the test results for polarization cross-coupling in several PBFs of different lengths using OCDP have been obtained in [10], as shown in Fig. 1(b). In Fig. 1(b), the curves (also called coherence function) can be described by two parameters: the polarization cross-coupling intensity ($I_{coupling}$) which is defined as the value of the flat part in the coherence function and which shows the degree of polarization coupling in the PBF; and the maximum optical path difference (OPD, d) which is defined as the maximum OPD between primary waves and secondary waves, denoted as d_1, d_2, and d_3 for PBFs of 10 m, 33 m, and 268 m, respectively.

Although the magnitude of the birefringence induced by the core ellipticity is as high as 10^{-5} and the corresponding beat length L_B is on the order of centimeter, $I_{coupling}$ is around -30 dB, which is several orders of magnitude larger than that of any conventional fiber. The strong polarization cross-coupling contributes to a large degree to the factors of limiting its practical application in some areas.

3. Simulation results of polarization cross-coupling in PBFs

3.1. Modeling

The coherence function that directly reveals polarization cross-coupling has been tested using OCDP for PBFs of different lengths and shown in Fig. 1(b). An OCDP is composed of a polarization interferometer and an optical path compensation module, as illustrated on the left and right in Fig. 2, respectively [11,12]. In polarization interferometer, a primary wave from a light source enters the PBF along one birefringent axis after being polarized, and while propagating through the PBF, it produces a large number of secondary waves. Those primary and secondary waves couple to a common axis and interfere with each other after passing through a 45° analyzer.

The optical spectrum at the output of the polarization interferometer can be calculated by

$$E_{out}(\lambda_j) = P_{45^\circ} \prod_{i=1}^{N} \begin{bmatrix} e^{-j\frac{2\pi\Delta n}{\lambda_j}L_i} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \cdot P_{0^\circ} E_{source}(\lambda_j). \quad (1)$$

where N is the number of elements in the PBF; Δn is the index difference; λ_j is the jth discretized wavelength of the source; $E_{source}(\lambda_j)$ and $E_{out}(\lambda_j)$ are the amplitudes of the light wave at wavelength

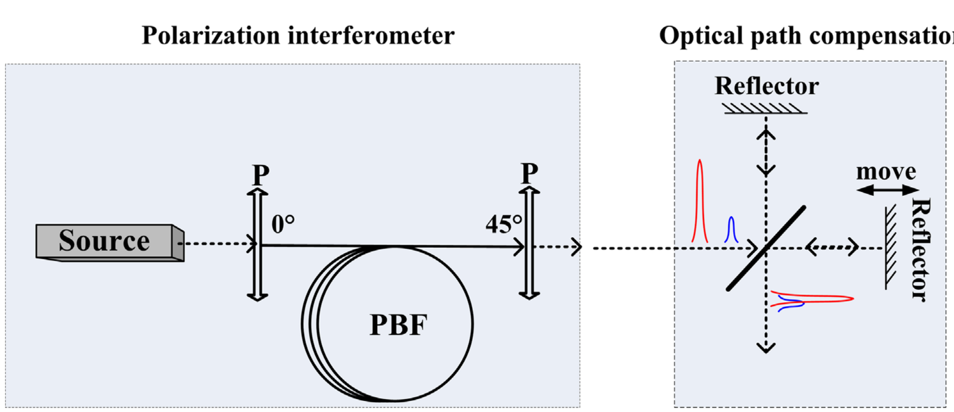

Fig. 2. Working principles of an OCDP.