Polarization mode dispersion reduction in spun silica holey fibres

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Abstract: *We report the fabrication of a spun holey optical fibre. Our experiments show that the complex air/glass transverse structure can be retained when the preform is spun during the fibre drawing process. Measurements of differential group delay (DGD) confirm that significant reductions in polarization mode dispersion (PMD) can be readily achieved using this approach.*

1. Introduction

Optical fibers that have a transverse refractive index profile which exhibits perfect rotational symmetry of order greater than 2 (including hexagonally stacked holey fibers) support at least one pair of degenerate orthogonally polarized modes [1]. However, in practice, all real fibers exhibit a degree of asymmetry, which can arise either as a result of geometrical imperfections occurring during the waveguide fabrication process, or through the freezing-in of some non-symmetric stress distribution within the fiber. The net effect is that the degeneracy of the orthogonal polarization modes is broken, and each polarization mode propagates with different phase and group velocities. This effect, known as polarization mode dispersion (PMD), causes pulse broadening and signal distortion and it represents a serious limiting factor for high bit rate optical communication systems. In several papers it has been shown that PMD can be effectively reduced by spinning the fibre during drawing [2,3]. Spinning techniques work extremely well for conventional transmission fibers and PMD values well below 100fs/km$^{1/2}$ are now routinely achieved for these fibers. To date few studies have been made of the polarization properties of holey fibers. It is known that designs with small scale cores, high air-fill fractions and significant structural asymmetries result in very large intrinsic birefringence [4], with <0.5 mm beat lengths possible. Some PMD characterization in large mode area (LMA) holey fibers has been reported [5,6], however despite this, little attention has been paid to date as to how low a PMD value might reliably be achieved in holey fibers. In a recent paper we reported the first results showing that spinning of holey fibers was possible and that a reduction in the PMD of holey fibers was achievable using this approach [7]. In the present paper we provide further results in this direction and report measurements confirming PMD reduction in spun holey fibers. We compare spun and non-spun fiber samples with more closely matched structural characteristics than that reported in our previous work. These experiments eliminate any possible concerns that the PMD reduction previously reported might have been caused by structural variation between our initial spun and non-spun fibers. Our results show that it should thus be possible to routinely produce holey fibers, for a broad range of possible structural designs and scale sizes, with PMD characteristics similar to those of conventional spun fibers.

2. Fabrication

In order to test the possibility of PMD reduction in holey fibers we attached a rotating chuck onto the preform feed mechanism of our fiber draw tower. In the experiments reported herein the rotation rate of preform was restricted to 600 rpm and the preform was designed to provide LMA holey fibers with a nominal specification in terms of Λ and d/Λ of 7.5 μm and 0.5 respectively. Two fibers were sequentially drawn from the same perform during a single drawing run at rotation speeds of 0, 600 rpm. In both cases the temperature of the draw furnace was 2005 ºC, the preform feed speed was set at 1.6 mm/minute and the fiber draw speed set at 16 m/minute.

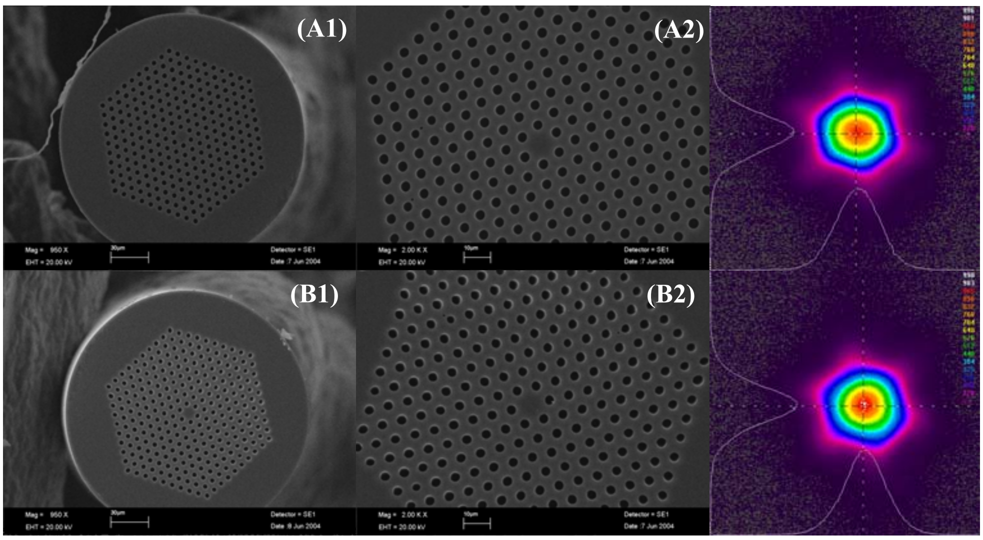

Fig. 1. Scanning electron micrograph images and far-field patterns at 1.06 μm of fiber sample A (up) and B (bottom).

Given these draw parameters the spin period of the spun fiber is 2.67 cm**.** The fiber samples were wound onto spools with a diameter of ~32 cm in an identical fashion, without overlap of the fiber, for storage and measurement purposes. Table 1 summarizes the key parameters for the two fiber samples - length of fiber *L*, the hole-to-hole spacing Λ, the normalized hole diameter *d/*Λ, the eccentricity of the core region and the spin period**.** The corresponding cross-sectional scanning electron micrograph (SEM) images of the fiber samples are shown in Figure 1. As can be seen from the SEMs, very good fiber structure is retained both for the case of spun and non-spun fiber.

Table 1. Parameters of the LMA HFs

Fiber sample	**Rotation rate (rpm)**	**L[m]**	**Λ [μm]**	**d/Λ**	**eccentricity (*e*)**	**Spin period [cm]**
A	0	125	7.6	0.49	0.011	—
B	600	125	7.5	0.47	0.015	2.67

3. Fiber Characterization

Fibers A and B both exhibit relatively high values of d/Λ and since recent theoretical work indicates that d/Λ <0.45 is required to obtain rigorously endlessly single-mode guidance these HFs might be expected to be slightly multimode in the wavelength range 1-1.6μm. Fortunately, the mode characterization showed that each of the fibers is effectively single-mode in practice, as can be seen from Fig. 1, in which the far-field pattern of fiber A at 1.06 μm is displayed. We attribute the effective single-mode guidance to the fact that any higher order modes are very leaky, and so any radiation launched into these possible modes is readily lost.

We first assessed the intrinsic birefringence of the non-spun fiber A using a crossed polarizer technique with a polarized broadband source with a 80nm bandwidth at a wavelength of 1.06μm. Fig. 2 (left) shows the recorded spectra for a fixed orientation of the input polarizer referred to as Φ_1 with and without output polarizer (analyzer). Before calculating the oscillation period from the fringe pattern, the data was smoothed using a moving average and normalized with respect to the incident spectrum. The corresponding averaged and normalized spectra are displayed in Fig. 2 (right).

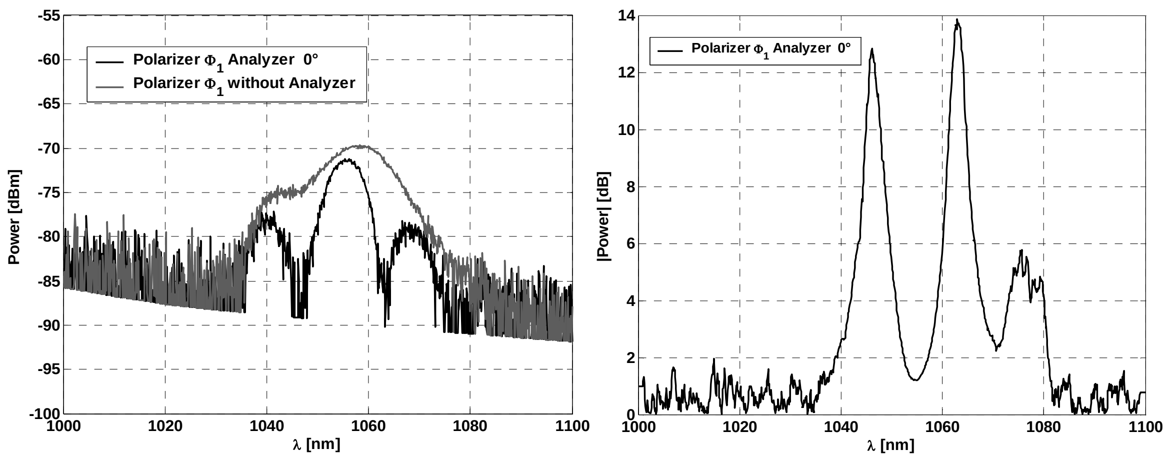

Fig. 2. Fringe patterns of fiber A for different angular orientations of the output polarizer and a fixed orientation of the input polarizer (left). Normalized and averaged spectra (right).

From the spectra we were then able to estimate the intrinsic linear (phase) birefringence $\Delta\beta$ and hence the effective fiber beat-length (defined as $2\pi/\Delta\beta$). Note that in estimating the beat length we have effectively ignored the birefringence dispersion term ($d(\Delta\beta)/d\lambda$)). The resulting beat length estimate is of the order of ~2 m, which is around two orders of magnitude longer than the spin period of the spun sample. We could not assess the intrinsic linear birefringence of the spun fiber B due possibly to the reduction of the birefringence due to the spinning. In order to quantify the ensuing PMD reduction we then measured the DGD of both fibers as a function of wavelength using the Jones Matrix Eigenanalysis (JME) method which is the preferred technique for measuring the PMD of relatively short lengths of low PMD fibers. Note that fiber A and spun fiber B have identical lengths, very similar geometrical parameters and are spooled precisely the same way. Thus we can make definite comparative statements concerning the relative magnitude of the PMD of these two fibers without needing to make any assumptions regarding fiber length normalization effects. In Fig. 3 we plot a set of results of the differential group delay as a function of wavelength for the two samples. Since the fibers have exactly the same length, similar structure and the conditions of measurement were identical for both samples we can immediately assert that a greater than ten-fold reduction in the mean DGD is obtained. We thus conclude that spinning is the primary cause of the observed DGD reduction.

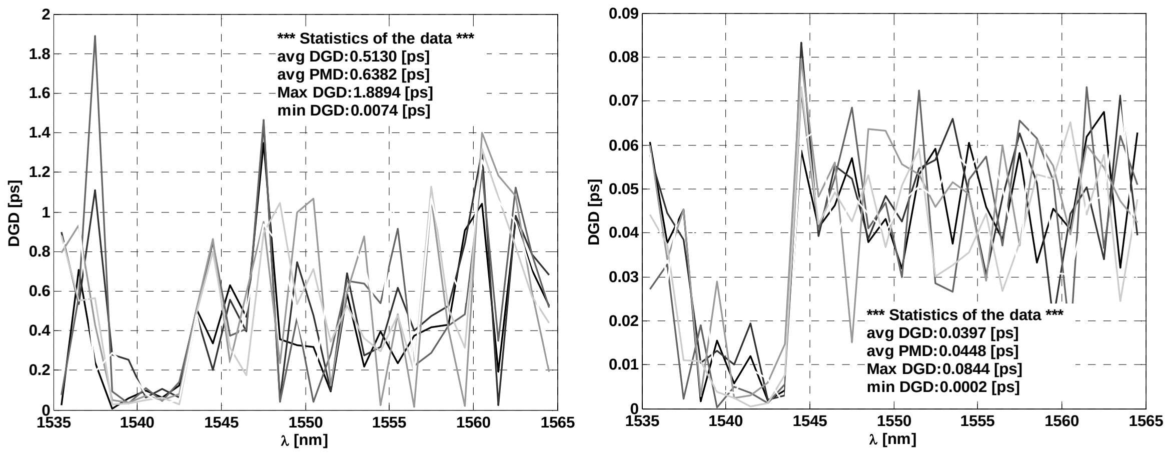

Fig 3. DGD of the samples A (left), B (right) and C (left bottom) as a function of wavelength.

From the data is possible to assess the mean PMD values. The PMD Δτ is defined as the rms value of the DGD and the accuracy limitation to the PMD measurement is then expressed by [8]:

$$\Delta\tau_{meas} = \overline{\Delta\tau}\left(1 \pm \frac{\alpha}{\sqrt{\overline{\Delta\tau}\,\Delta\omega}}\right), \qquad (1)$$

where Δω is the frequency range considered in the measurement, $\overline{\Delta\tau}$ is the theoretical mean PMD, while $\Delta\tau_{meas}$ is the measured value of the PMD and $\alpha \approx 0.9$. In Table 2 the mean DGD and PMD values normalized with respect to the square root of the lengths of the fibers are summarized. This normalization assume that the fiber is in the statistical regime such that the coupling length is short relative to the fiber length. In the last column we report also the PMD measurement uncertainty calculated via Eq. 1 using the measured mean PMD values as an estimate of the underlying theoretical mean. Although the uncertainty increases for small values of measured PMD, the fiber B is clearly seen to exhibit more than an order of magnitude decrease in PMD as compared to fiber A. The numerical estimate of the PMD value for fiber B strongly suggests that very low PMD values will ultimately be achievable for holey fibers using suitably optimized spinning techniques.

Table 2.:Summary of PMD measurements with uncertainties

Fiber sample	L[m]	Spinning rate [rpm]	<DGD> [fs]	PMD [ps/√km]	PMD uncertainty %
A	125	0	513	1.805	23
B	125	600	39.7	0.127	88

4. Conclusions

We have demonstrated that it is possible to apply preform spinning to the production of holey fibres. We have also demonstrated PMD reduction in spun large mode area holey fibres and shown that significant PMD reduction can be achieved. We consider this to be an important result in establishing the practicality of using HF technology as a transmission medium in future optical communication networks and for HF based device development.

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