Polarization mode dispersion reduction in spun large mode area silica holey fibres

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Abstract: We report the fabrication of the first 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.

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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

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one pair of degenerate orthogonally polarized modes [1]. However, in practice, all real fibers exhibit a degree of asymmetry. This 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 now assumes different phase and group velocities. For certain applications, particularly many device and sensor applications in which it is desirable to maintain polarization, it is desirable to accentuate waveguide asymmetry to maximize the mode splitting and thereby improve the discrimination/isolation between the two modes. However for other applications, notably data transmission, it is necessary to develop techniques to reduce the effects of the mode splitting along the fiber length.

The way to do this with conventional fiber technology is to introduce spin into the fiber during the draw that can couple light between the two polarization modes and which thereby eliminates (in a path average sense) any underlying structural asymmetry sampled by light propagating within the core [2,3]. In order for this technique to be effective, the fiber typically needs to be spun around 10 times faster than the intrinsic local beat-length [4]. Various strategies for spinning the fiber during the draw have now been developed ranging from simple unidirectional spinning as implied above, through to more recent systems that apply periodic variation of the amplitude, sign and period of the spinning [5]. 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 form birefringence [6] - with <0.5 mm beat lengths possible. Given the complexity of the holey fiber fabrication process, one might imagine that this fibre type might be more prone than conventional fibres to structural asymmetry. Despite this, little attention has been paid thus far as to how low a PMD value might reliably be achieved in holey fibres. Some PMD characterization in large mode area (LMA) holey fibers has been reported [7,8] and although low PMD was indeed observed in one 100m length of fiber [7], no comments were provided regarding the fabrication of this fiber and whether the low PMD arose by chance, or through some modification of the standard fabrication process itself.

In this paper we report what we believe to be the first demonstration of the application of the spinning technique to holey optical fibers. Our results show that the spinning approach is fully compatible with the holey fiber drawing process and that significant reductions in PMD levels can indeed be achieved using this technique. 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 transmission fibers.

2. Fabrication

In order to test the possibility of PMD reduction in LMA fibers we attached a rotating chuck onto the preform feed mechanism of our fiber draw tower. The chuck allowed us to rotate holey fiber preforms within the fiber draw furnace at speeds of up to 2000 revolutions per minute (rpm), although in the experiments reported herein the rotation rate was restricted to the 0-810 rpm range. We constructed a stacked LMA holey fiber for these experiments that comprised a hexagonal stack of 7 rings of silica capillaries surrounding a central solid rod, all of which were arranged within a jacket tube. The grade of silica used was Heraeus F300 throughout. The preform was designed to provide LMA holey fibers with a nominal specification in terms of Λ and d/Λ of 12 μm and 0.45 respectively.

Three fibers were sequentially drawn from the same perform during a single drawing run at rotation speeds of 0, 400 and 810 rpm. In all cases the temperature of the draw furnace was 1990 ºC, the preform feed speed was set at 1.7 mm/minute and the fiber draw speed set at 10 m/minute. Given these draw parameters the spin periods for drawing at 400 rpm and 810 rpm are 2.5 cm and 1.23 cm respectively**.** Fiber samples were taken once the drawing process had stabilized subsequent to the changes in preform rotation rate. The fiber samples were wound

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onto spools with a diameter of ~15 cm in an identical fashion, without overlap of the fiber, for storage and measurement purposes.

Table 1. Parameters of the LMA HFs

Fibre sample	Rotation rate (rpm)	L[m]	Λ [μm]	d/Λ	eccentricity (*e*)	Spin period [cm]
A	0	75	12.2	0.52	0.035	—
B	400	47	11.9	0.49	0.007	2.5
C	810	78	11.7	0.40	0.034	1.23

Table 1 summarizes the key parameters for the three fiber samples - length of fiber *L*, the hole-to-hole spacing Λ, the normalized hole diameter *d/*Λ, the eccentricity of the core region (the eccentricity of the core is defined as $e=1-d_{min}/d_{max}$ where d_{min} and d_{max} are the minimum and maximum distances between two diagonal air-holes surrounding the core) and the spin period**.** The corresponding cross-sectional scanning electron micrograph (SEM) images of the fiber samples are shown in Fig. 1.

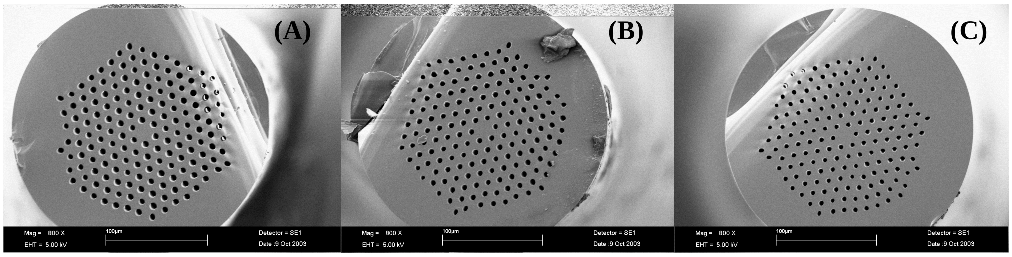

Fig. 1. Scanning electron micrograph image of the fiber samples A,B,C.

As can be seen from the SEMs, very good fiber structure is retained both for the case of spun and non-spun fiber, although it is to be noted that the precise structural parameters of the fibers vary from sample to sample. At this stage we cannot confirm whether these small changes are due to the spinning motion of the preform itself or due to other changes (e.g., thermal/pressure build-up/gas-flow) associated with the dynamics of feeding the spinning preform into the furnace. Although more detailed studies will be required in order to decouple the various factors influencing the detailed structure as a function of the spin rate/draw conditions, the key finding is that we can produce rapidly spun holey fibers with high-quality well-defined structure.

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 1.53-1.57μm. Thus, before making any PMD measurements, we conducted mode characterization experiments to see whether this was the case. Fortunately, our experiments showed that each of the fibers is effectively single-mode in practice, which we attribute to the fact that any higher order modes are very leaky, and so any radiation launched into these possible modes is readily stripped out.

We first assessed the intrinsic birefringence of the non-spun fiber A using a crossed polarizer technique with a polarized broadband source with a 100nm bandwidth at a wavelength of 1.06μm. The broadband polarized light was coupled into the HF aligned at~45 degrees relative to a principal axis of the fiber and the output analyzed as a function of wavelength through a second polarizer. The output spectrum exhibits oscillations due to the fiber birefringence and by measuring the spectral distance between two consecutive dips or peaks the group birefringence of the fiber can be evaluated. Unfortunately, due to the relatively short length and relatively low birefringence of this fiber the spectral bandwidth of our source was not broad enough to fully resolve two peaks. However, by estimating the oscillation period from the limited fraction of the spectral modulation cycle that we could measure with our limited bandwidth source we were able to determine the group birefringence. We were then able to estimate the intrinsic (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 $(d(\Delta\beta)/d\lambda)$ and hence the relatively large margin of error in our measurement. The resulting beat length estimate is of the order of ~3-5 m, which is around two orders of magnitude longer than the spin periods of the two spun samples. Note that the ellipticity data in Table 1 indicates that the fiber samples A and C have comparable, and relatively high, eccentricity compared to sample B, which means that one might expect the 'intrinsic birefringence' of structure B to be slightly lower than that of fiber A, and that of structure C to be roughly comparable to that of fiber A.

We then measured the DGD of all three 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 [9]. Note that fiber A and spun fiber C have essentially identical lengths and are spooled 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. It is though to be appreciated that a quantitative description and measurement of PMD depends critically on whether one is working in the short fiber length (deterministic) or long fiber length (statistical) measurement regime. This ultimately requires some knowledge of the effective polarization coupling length within the fiber. Our fiber samples were tightly wound onto a relatively small diameter storage spool for the DGD measurements and we thus expect significant 'quasi-random' polarization mode coupling to occur along the fiber's length and the fiber to thus have a relatively short effective coupling length. In what follows we shall then assume that we are in the long fiber length regime and shall for convenience express all PMD measurements in the appropriate length normalized units ($ps/km^{1/2}$)[10]. It is though to be appreciated that we have not yet been able to make a direct measurement of the polarization coupling lengths for these spooled fiber samples and that the absolute values of PMD quoted within this paper should be treated with some caution at this stage. Further studies will be required to address the issues of mode-coupling and PMD statistics in due course.

In Fig. 2 we plot the results of the differential group delay as a function of wavelength for the three HFs. The mean DGD values averaged over the wavelength are also reported in Table 2. The wavelength dependence of the DGD ($\delta_\tau(\omega)$) is low for all three HFs analyzed since the lengths of the HFs measured are relatively short and the scanned wavelength range is not that large, however clear and useful conclusions can still be drawn.

The key result is obtained by comparing the results of measurements on samples A and C. Since the fibers have exactly the same length we can immediately assert that a twenty-fold reduction in the mean DGD is obtained. Although from Table 1 the structural parameters of the samples A and C are slightly different in terms of d, Λ and ε, and such differences would

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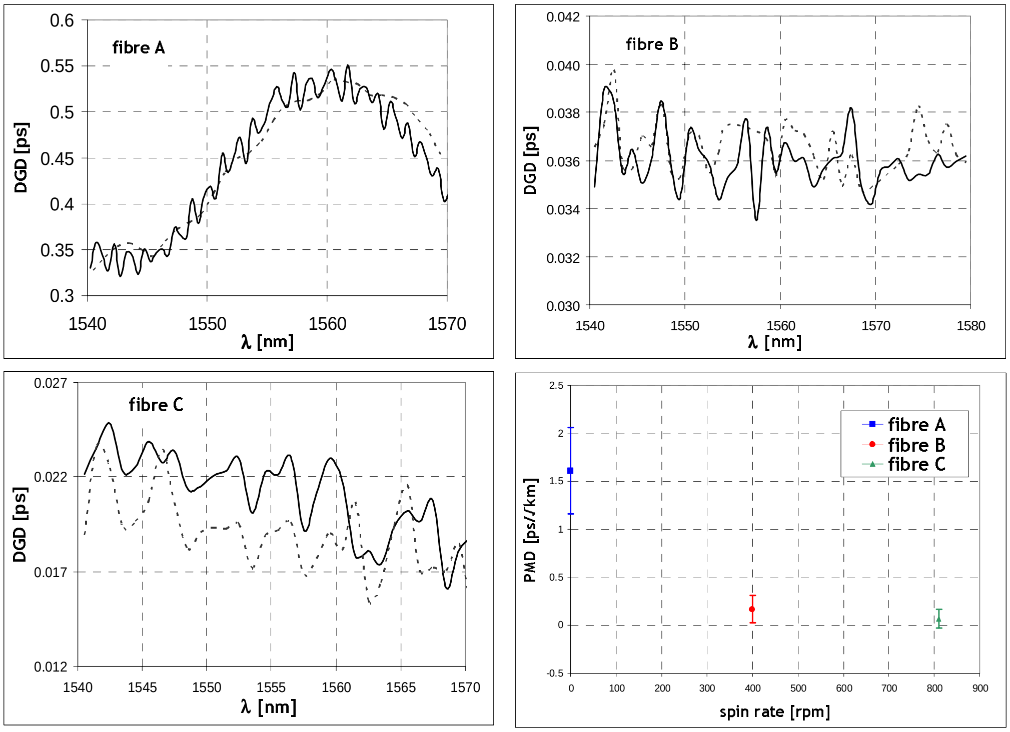

Fig 2. DGD of the samples A (up left), B (up right) and C (bottom left) as a function of wavelength. Bottom Right: Accuracy limitation of the measured PMD values

be expected to contribute to a difference in inherent birefringence, we do not consider the level of structural variation observed to be able to account for the large decrease in DGD for the non-spun/spun structures. We thus conclude that spinning is the primary cause of the observed DGD reduction.

The PMD value Δτ is defined as the rms value of the DGD, i.e.:

$$\Delta\tau(\omega_1,\omega_2)^2 = \frac{1}{\omega_2-\omega_1}\int_{\omega_1}^{\omega_2}\delta_\tau(\omega)^2\,d\omega\,. \tag{1}$$

The accuracy limitation to the PMD measurement is then expressed by [11]:

$$\Delta\tau_{meas} = \overline{\Delta\tau}\left(1 \pm \frac{\alpha}{\sqrt{\overline{\Delta\tau}\,\Delta\omega}}\right), \tag{2}$$

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 α≈0.9.

In Table 2 the mean DGD and PMD values normalized to the square root of the lengths of the fibers are summarized. The values are averaged over different measurements. In Fig. 2 (bottom right) the same PMD values are plotted with respect to the spin rate. The error bars displayed in the plot refer to the PMD measurement uncertainty calculated via Eq. (2) 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 C 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 C 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	75	0	444	1.611	28
B	47	400	36	0.167	84
C	78	810	20	0.071	132

Finally, we can compare the average PMD values of the two fibers spun at different rates. From Table 2 it is seen that the PMD appears to scale in rough proportion to the spin rate as theoretically expected for spin rates that are fast relative to the inherent fiber birefringence [12]. It is though to be appreciated that the measurement errors are large here for such low values of PMD and that we have ignored the possible effects of residual frozen-in torsional stress associated with unidirectional spinning [13], which might be appreciable for these fibers given the relatively rapid number of spin periods per ‘inherent beat length’.

4. Conclusions

We have demonstrated that it is possible to apply perform spinning to the production of holey fibres. We have 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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