Small form-factor PANDA type HiBi fiber for sensing applications

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ABSTRACT

For intrinsic fiber optic sensors such as interferometric fiber optic gyroscopes that use polarization maintaining fibers, performance of the fibers that constitute the sensing coils is a key issue. In general, requirements include small form-factor, good bend performance, tight tolerances on fiber geometry and ability to maintain a single polarization state. Currently, bow-tie or elliptical clad type high birefringence fibers are used in such sensors. This paper deals with the development and characterization of small form-factor (80 μm) PANDA style high birefringence fibers for sensing applications at different wavelengths of interest. The rationale and advantages of the new design are discussed along with geometrical and optical characteristics of one new fiber. Performance data of the fiber in terms of cross-talk variation in the -55 to + 85°C temperature range are presented.

Keywords: Polarization maintaining, HiBi, PANDA, Gyroscope fiber, Beat length, Cross-talk

1. INTRODUCTION

All-fiber or intrinsic fiber optic sensors (FOS) are those in which the optical fiber itself acts as the sensing element by modulating the light under the influence of the externality to be measured. The quantities that can be modulated and carry the information include optical power (amplitude/intensity sensors), wavelength (spectroscopic sensors), phase (interferometric sensors) and polarization (polarimetric sensors).[1] Interest in intrinsic FOS is increasing rapidly because of the numerous advantages offered by such sensors. Some of the key advantages include: (a) small size and weight, (b) low power consumption, (c) ability to withstand corrosive and high temperature environments, (d) immunity from electromagnetic interference, (e) biocompatibility, (f) large distance between signal generation/ detection and signal treatment sites, and (g) high sensitivity, dynamic range and resolution.[2] Interferometric type intrinsic FOS are by far the most important. Here the measurand changes the effective optical path length of the light beam in the optical fiber resulting in a phase shift that is accurately measured using interferometric techniques. Interferometric type intrinsic FOS have the potential for extremely high performance in sensing rotation, acceleration, acoustics, electric and magnetic fields, strain, temperature, pressure and current. Sagnac interferometers which may be used as a rotation sensor to replace existing gyroscopes have the potential to become one of the highest value applications of intrinsic FOS with markets valued at several hundreds of millions of dollars.[3-4]

For certain intrinsic FOS, it is very important to maintain the state of polarization of light along the fiber length and in the presence of micro- and macro-bending (such as interferometric fiber optic gyroscope, IFOG). Also, small changes in pressure, temperature or wavelength alter the polarization state in a predictable manner. These changes can be detected interferometrically leading to highly sensitive sensors with a large dynamic range and good resolution. All such applications demand the use of high quality polarization maintaining (PM) fibers. Such PM high birefringence (HiBi) fibers also find utility in basic all-fiber functional components such as couplers, polarizers, depolarizers, modulators, controllers, filters and isolators.

Small form-factor (reduced cladding size) HiBi fibers are becoming increasingly important in the FOS arena because they allow component miniaturization. The reasons behind this drive towards miniaturization are two-fold: (a) space saving with associated cost reduction, and (b) potential new fiber optic applications that are yet to be explored.[5] Indeed the advantages of small form-factor fibers are well known in FOG applications, where 80 μm diameter fiber is now a standard. In this case, the space savings from winding are substantial. Also important is the increased number of windings per layer that are achieved with smaller diameter fibers.

This paper describes a small form-factor PANDA style HiBi fiber that Nufern has developed to address the fiber optic sensors market in general and IFOG market in particular. This fiber is designated as Nufern PM850G-80. The technology choices that were made and the fiber design issues are discussed. Quantitative data on geometrical and optical characteristics of the fiber are presented to assess the suitability of this fiber for use in FOS in general and in IFOGs particularly.

2. PANDA Style HiBi FIBER FABRICATION AND CHARACTERIZATION

2.1 Fabrication

PANDA style HiBi fibers rely on residual stress anisotropy across the core as a result of differences in thermal expansion coefficient ($\Delta\alpha$) between the circular stress members and the core and the cladding. The composition, location and geometry of the stress members determine the birefringence of the fiber. The compositional design of stress members and the geometrical design of the HiBi fibers were established using an internally developed multi-stepped linked model. This model predicts the index of refraction and the expansion coefficients of the glass based on composition of the deposited glass. These parameters in turn are used as inputs to predict the birefringence based on geometrical considerations.

The main steps involved in the fabrication of PANDA style HiBi fibers are illustrated schematically in Figure 1.[6] This methodology allows the fabrication of stress members to be decoupled from the fabrication of the preform with associated advantages. A high quality synthetic quartz tube is used to deposit the germanium doped glass via the MCVD method. The tube is then collapsed into a rod and further processed such that when drawn the fiber has the required core and cladding dimensions. In a separate step, circular stress elements of desired composition are fabricated via MCVD. Two holes of the desired dimension are drilled in the preform, diametrically opposite to each other on either side of the core. The two circular stress members are inserted into the holes and incorporated into the preform. The preform with the stress members is then drawn to 80 μm size with a dual layer acrylate coating.

2.2 Characterization

The fiber was characterized with respect to optical features, geometry and polarization maintaining properties. For optical features, the fiber was characterized with respect to cut-off wavelength, mode field diameter and attenuation. For geometry, the fiber was characterized with respect to cladding/coating diameters, cladding/coating non-circularity, core/cladding off-set and coating concentricity. Finally polarization maintaining properties of the fiber were characterized with respect to beat length/birefringence and cross-talk/h-parameter.

Fiber beat length was measured on less than 0.5 m lengths of fiber using a GN Nettest S18 dispersion measurement system which uses a wavelength scanning technique known as the fixed analyzer method. Fully polarized light launched into the fiber is passed through a polarizer (the analyzer) that is fixed at the exit end. The output power is then recorded as a function of wavelength. A reference scan is then taken without the analyzer so that power fluctuations due to non-PMD related effects are taken into account. In fibers with weak mode coupling, such as PM fibers, the scan of the effective power with wavelength has a periodic intensity variation with a series of maxima and

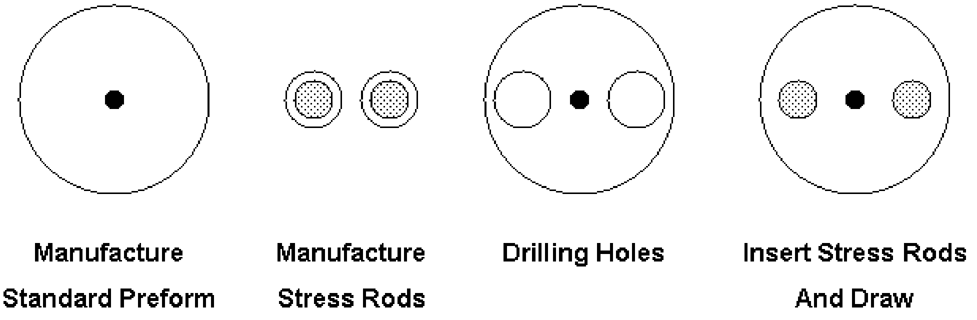

Figure 1. Schematic illustration of the steps involved in the fabrication of PANDA style HiBi fiber.

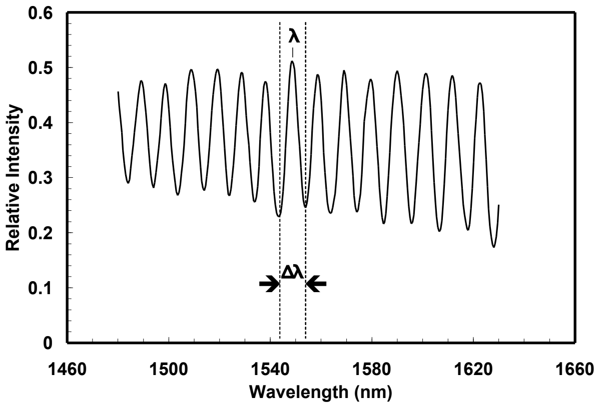

Figure 2. Relative intensity vs. wavelength plot to obtain Δλ for calculating the beat length (L = 0.285 m).

minima as shown in Figure 2. Beat length can be calculated for any wavelength from the spacing between the intensity peaks using the following equation:

$$L_b = L\,(\Delta\lambda/\lambda) \tag{1}$$

where L_b is the beat length, L is the length of fiber, λ is the wavelength and Δλ is the peak spacing. Birefringence (B) is related to beat length via the following equation.

$$B = \lambda/L_b \tag{2}$$

The polarization cross-talk measurement was performed in accordance with TIA/EIA-455-193 (FOTP-193).[7] A system comprising of high quality crystal polarizers, low birefringence optics and computer controlled precision alignment system provided repeatable cross-talk measurements below -45 dB. Measurements were made on 100 m long sections of fiber, looped into 254 mm diameter coils. The h-parameter is related to the cross-talk (CT) via the following equation.

$$h = (10^{CT/10})/L \tag{3}$$

3. RESULTS AND DISCUSSIONS

3.1 HiBi Fiber Designs

In this paper the term HiBi is used for fibers that support two orthogonal polarization modes. Of all the different HiBi fibers, only three designs based on the stress induced birefringence namely, PANDA, bow-tie and elliptical cladding, are commonly used. The three designs are illustrated in Figure 3. Each of these designs has different advantages relating to uniformity of the stress distribution, maximum attainable birefringence and ease of fabrication. For each design, optimum parameters for the size and the position of the stress regions can be determined. Analytical models to predict the birefringence of the three fiber designs have been developed.[8-10] Beside the geometrical variables illustrated in Figure 3, these models consider the stress optic coefficient, elastic modulus, Poisson's ratio, thermal expansion coefficient of glass and softening temperature of glass as input parameters.

The models were used to calculate the birefringence induced in the three fiber types as a function of the asymmetry factor, (a-b)/(a+b). For comparison purposes, values of b, r and $\Delta\alpha\Delta T$ (thermal expansion mismatch level) were kept constant. The value of $\Delta\alpha\Delta T$ used is characteristic of high boron content glass typically used for stress members. The results are presented in Figure 4a. For the bow-tie fiber, the angular scope of the fan-shaped regions (ϕ) was fixed at

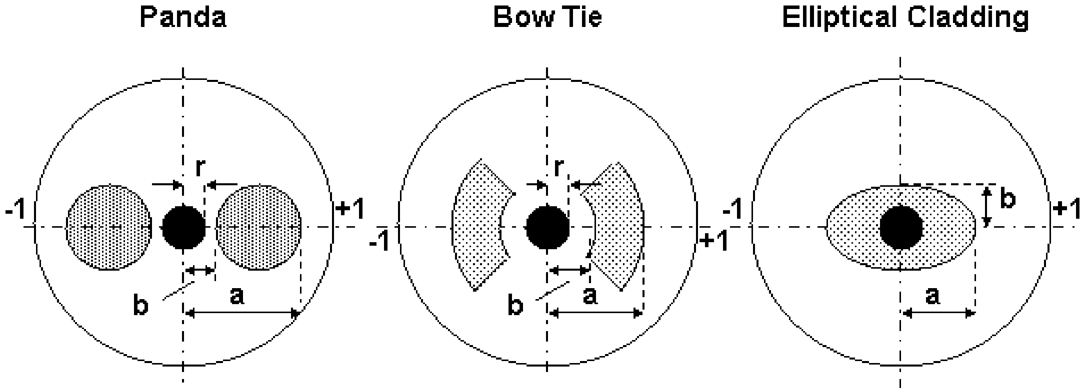

Figure 3. Stress inducing HiBi fiber designs. Dimensions a, b and r are normalized with respect to fiber radius, R.

90° to provide maximum birefringence.[10] For a given geometry and composition of the stress regions, three facts are apparent. First, for all the fibers, birefringence increases initially with increasing asymmetry factor followed by a decrease. The reasons for this behavior have been explained elsewhere.[8-11] Second, bow-tie fiber yields the highest maximum birefringence followed by PANDA and elliptical clad style fibers. Therefore, simply on the basis of maximum achievable birefringence, bow-tie design is most favorable followed by PANDA and elliptical clad style fibers. It must also be noted that only maximum achievable birefringence values are of interest. Finally, the maxima in birefringence occurs at the lowest asymmetry factor for bow-tie, followed by PANDA and elliptical clad style fibers. This again suggests that bow-tie design is most forgiving followed by PANDA and elliptical clad designs. These results do not imply that high stress levels are better utilized in bow-tie fiber as compared to PANDA and elliptical clad style fibers. A better measure of stress utilization in the three designs is the ratio of the birefringence to the area of the stress regions. This comparison is illustrated in Figure 4b where birefringence per unit stress area in the three fiber types is plotted as a function of the asymmetry factor. The results indicate that if a and b are chosen to provide maximum birefringence in each fiber (all other factors being identical), elliptical clad design provides best utilization of stress induced area followed by PANDA and bow-tie type designs. To obtain large birefringence, high levels of stress are necessary inside the fiber. Attainment of such high stress levels creates problems during manufacturing and therefore, it is important to utilize the stresses in an efficient manner.

Among the three HiBi fiber designs, bow-tie fiber is the best and elliptical cladding fiber is the worst from the maximum achievable birefringence perspective. Similarly, bow-tie fiber is the worst and elliptical cladding fiber is the best from the view point of efficient usage of stress areas. It appears that from both points of view, PANDA style fiber offers the optimum performance. PANDA design has a number of other significant advantages over the other two

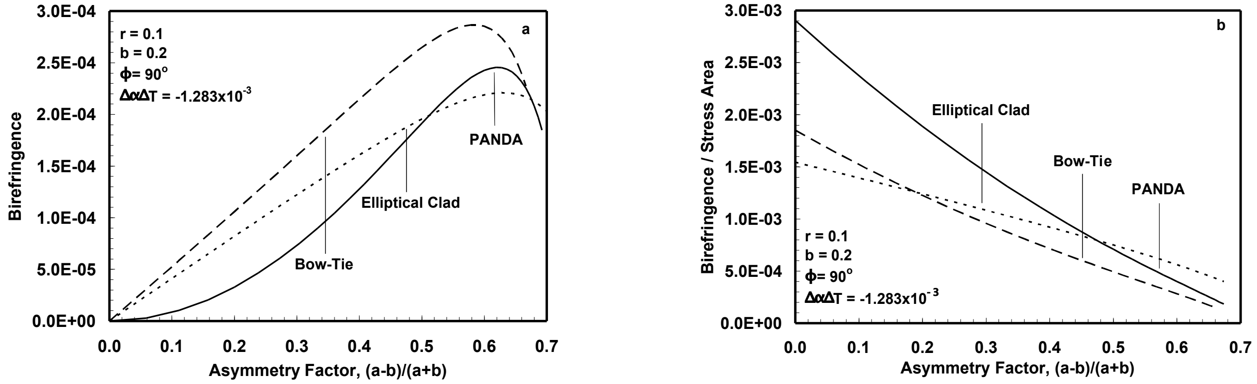

Figure 4. Comparison of birefringence and stress utilization in the stress inducing HiBi fiber designs.

designs. In PANDA style HiBi fiber manufacturing, both the preform and the stress member fabrication steps are decoupled thereby providing independent control of the fiber polarization properties and its other optical characteristics. Furthermore, fairly large stress inducing members can be fabricated which increase the preform size making the process eminently suitable for scale-up. Typically, PANDA design can yield 50-100 km of fiber per preform whereas bow-tie and elliptical clad designs yield 15-20 km of fiber per preform. The fact that under identical conditions PANDA design yields lower birefringence than bow-tie design (Figure 4a) is not a significant impediment. Birefringence can be increased by simply changing the composition of the stress members to yield higher thermal expansion coefficient mismatch ($\Delta\alpha\Delta T$) with the surrounding cladding. PANDA design offers a significant advantage over bow-tie design in incorporating new glass compositions into the design because of the independent control over the preform and the stress member fabrication steps. If new stress member compositions are incorporated, PANDA style fibers can provide the same or even larger birefringence than bow-tie fibers. This is illustrated in Figure 5. For the PANDA fiber, as the composition of the stress members changes to provide higher thermal expansion coefficient mismatch, the maximum birefringence increases. For a 15% increase in $\Delta\alpha\Delta T$ above the traditional boron stress member composition, birefringence of the PANDA style fiber increases to that of the bow-tie fiber. Glass compositions that provide much higher values of $\Delta\alpha\Delta T$ have already been developed at Nufern. Based on the above arguments, PANDA style HiBi fiber is the preferred technology of choice for high volume production.

3.2 Fabrication

As discussed above, PANDA design offers several advantages over other HiBi fiber manufacturing technologies. However, like other fiber designs such as bow-tie, PANDA design also offers one practical disadvantage in the sense that it imposes a limit on the maximum achievable birefringence. Modeling studies indicate that to maximize birefringence, the stress elements must be brought close to the core.[11] As the stress elements come close to the core, the stress field begins to interfere with the mode field resulting in the degradation of the optical properties of the fiber. In this context, bow-tie design is more forgiving because it involves stress regions that can be deposited close to the core as opposed to PANDA design that involves stress regions resulting from drilling of holes in the preform in the vicinity of the core and inserting stress rods in the holes. Since in PANDA design stress elements have to be kept farther apart, a high birefringence cannot be achieved for a given size and traditional composition of the stress elements. To manufacture the fiber under consideration, a new stress member glass composition was developed that resulted in a $\Delta\alpha\Delta T$ value of $3.294\text{x}10^{-3}$ which is approximately 250% larger than the $\Delta\alpha\Delta T$ value provided by the traditional boron doped glass ($1.283\text{x}10^{-3}$). Based on the new stress member composition, maximum birefringence in 80 µm PANDA fiber at b= 0.2 is predicted to be $6.25\text{x}10^{-4}$ at an asymmetry factor of 0.619. This corresponds to a beat length of approximately 1 mm at 633 nm.

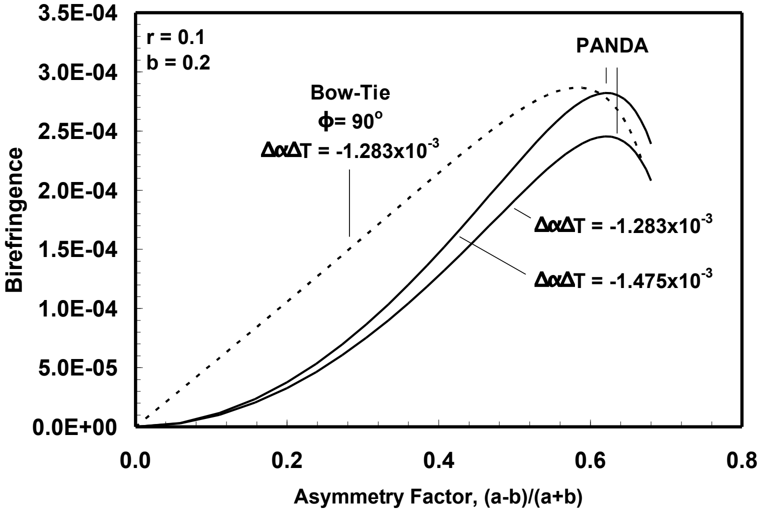

Figure 5. Birefringence of PANDA style fiber as a function of thermal expansion coefficient mismatch.

Nufern has fabricated a series of PANDA style reduced cladding (80 μm) HiBi fibers for use at different wavelengths. In order to show the uniformity of the optical and the geometrical characteristics of these fibers, data are presented for one of the fibers (PM850G-80) as a test case.

3.3 Optical and Geometrical Characteristics

The Nufern PM850G-80 fiber having a nominal NA of 0.165 is designed to operate at a nominal wavelength of 850 nm and has a cut-off wavelength of 730 ± 50 nm. Known lengths of fiber were cut from the master spool (containing several kilometers of fiber) and re-spooled onto smaller spools for testing. Six smaller spools were made containing different lengths of fiber consuming the entire master spool. Optical and geometrical properties were measured at both ends of each fiber spool. The average data values are presented in Figure 6. The solid lines have no significance other than to show trends. Here the length along the fiber is normalized with respect to the total length of fiber in the master spool to protect some valuable information. It is quite obvious that optical (attenuation and mode field diameter) and geometrical parameters (cladding and coating diameters) of the fiber are held to very tight tolerances along the entire length of the fiber drawn from a given preform. A few other geometrical parameters were also measured and the data are summarized in Table 1. Again, the table indicates that geometrical properties of the fiber exhibit minimum variation along the entire length of the drawn fiber. The small fiber diameter, tight tolerances on attenuation, mode field diameter, cut-off wavelength, fiber diameter and particularly the coating diameter are of paramount importance to FOS manufacturers because they directly affect sensor performances.

3.4 Polarization Maintaining Properties

In general, polarization maintaining characteristics of HiBi fibers are described in terms of: (a) beat length or birefringence, and (b) cross-talk or mode coupling parameter, h. Beat length or birefringence are measures of the magnitude of difference in the propagation constants of the two orthogonal linear polarization modes (LP_{01}^{x} and LP_{01}^{y}). High birefringence and small beat length come from asymmetric distribution of thermal stresses. In an ideal HiBi fiber, the two polarization modes are perfectly preserved. However, in actual practice the power between the two polarization modes gets coupled. Cross-talk or h-parameter is a measure of the extent of this power coupling which limits the fiber length over which polarization is maintained. Whereas beat length or birefringence may be considered an intrinsic property of the fiber, cross-talk or h-parameter may be considered as an extrinsic property. It is desirable to have smaller values for all the properties except for the birefringence for which high values are desirable. It is also important to have minimum variation in these properties along the fiber length.

As mentioned earlier, known lengths of fiber were removed from the master spool and re-spooled onto smaller spools for testing. Polarization maintaining characteristics of the Nufern 850G-80 HiBi fiber as a function of normalized fiber length in the spool are presented in Figure 7. As before, the solid lines have no significance other than to show trends. It is obvious that polarization maintaining properties vary marginally over the entire length of the master

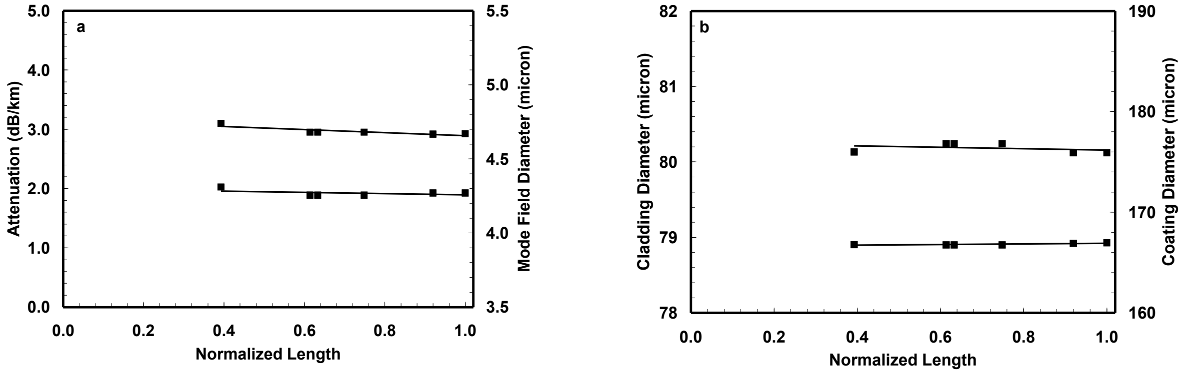

Figure 6. Properties Nufern 850G-80 fiber: (a) Optical (attenuation and mode field diameter) properties, and (b) geometrical (cladding and coating diameters) properties.

Table 1. Geometrical characteristics of Nufern PM850G-80 fiber.

Parameter	Value Range
Cladding non-circularity (%)	0.36 – 0.49
Coating non-circularity (%)	0.04 – 0.39
Core/clad concentricity (μm)	0.18 – 0.42
Coating concentricity (μm)	0.60 – 2.50

spool. The average beat length of the PM850G-80 fiber is 1.20 mm at 850 nm corresponding to a beat length of 0.89 mm at 633 nm. Currently, gyro quality bow-tie type HiBi fibers exhibit beat lengths of less than 1 mm at 633 nm. The PANDA style gyro quality HiBi fiber being considered here certainly meets the beat length requirement expected out of gyro fiber. Delivering the necessary beat length coupled with the remarkably tight tolerances on other optical and geometrical features makes this fiber very competitive for gyro coils that are intended to operate at 850 nm.

The average cross-talk/100 m for the PM850G-80 fiber in loose coil condition is -29.1 dB. Cross-talk is seriously affected by extrinsic factors such as bending, coiling, etc. that originate from handling of the fiber. For sensor applications like IFOG where a large length of fiber is wound over a relatively small diameter spool, cross-talk is likely to degrade with respect to the loose coil configuration. Although the measured cross-talk (in loose coil configuration) is reasonably low, it is imperative to know how the cross-talk would change under actual fiber deployment conditions.

3.5 Polarization Crosstalk and Temperature

The fiber under consideration in this paper is intended primarily for gyro sensing coil applications. The cross-talk of the fiber in the form of loose coils (10 inch diameter spools) is radically different from the cross-talk when the fiber is wound in the form of the gyro coil. Fiber coating defects, coil diameter, fiber tension, coil defects such as crossovers and coil temperature are some of the factors that affect polarization cross-talk. To assess the cross-talk of the fiber under conditions that simulate gyro deployment environment, 100 m length of fiber was helically wound onto a 40 mm diameter aluminum spool (15 mm flange spacing) under 15 grams of tension. For our fiber, this corresponds to nine layers with each layer containing ninety turns. Since the coil was helically wound, defects like crossovers exist. The fiber in the coil was then tested for cross-talk at various temperatures in the customary -55°C to +85°C range. For this purpose a fully automated and specially designed environmental chamber was used that allowed for continuous data acquisition. The results are presented in Figure 8. The coil was subjected to seven temperature cycles (each lasting for about 7 hours during which temperature changed from 25°C to a low of -55°C, then to a high of 85°C and finally returning to 25°C). Before drawing any conclusions from the data, it must be understood that actual gyro coil spools are not made of aluminum but rather of some low thermal expansion coefficient material. High thermal expansion coefficient of aluminum poses a problem with interpreting the data at the high temperature end of the thermal cycle.

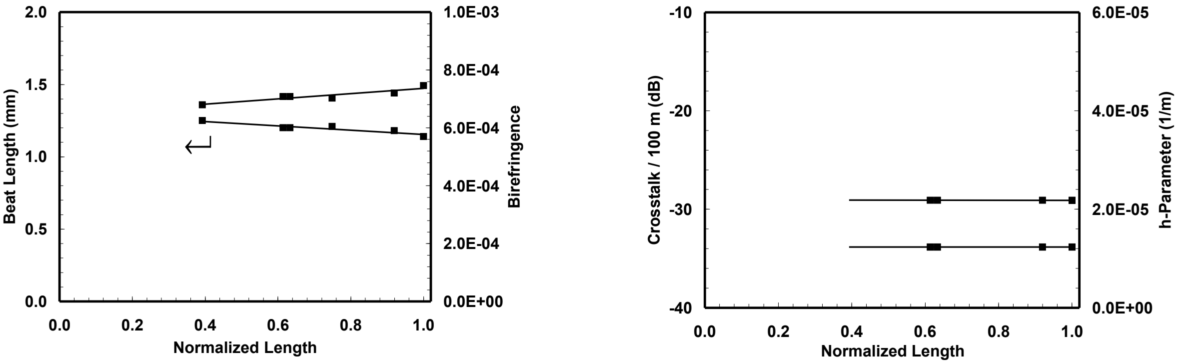

Figure 7. Variation in the polarization maintaining properties of the PM850G-80 fiber versus fiber length. Beat length is at the operating wavelength of 850 nm. Crosstalk is for loose coil.

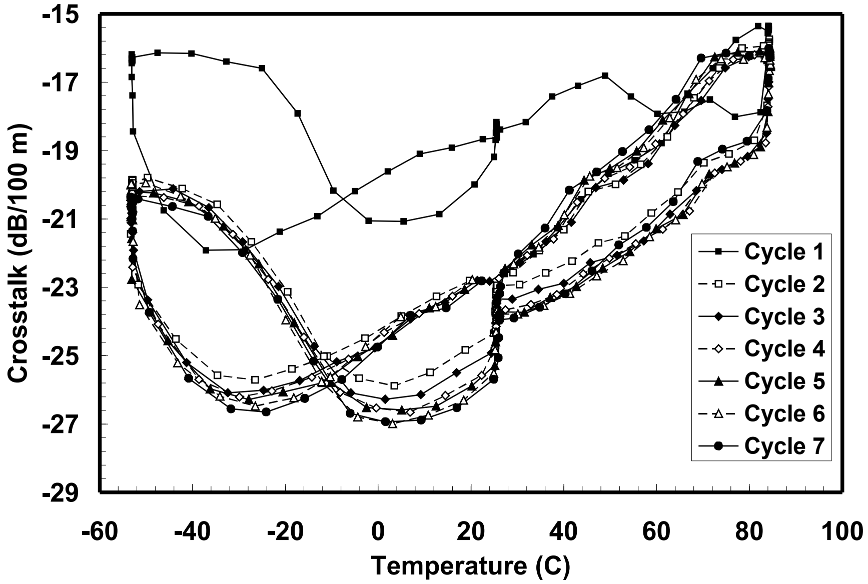

Figure 8. Crosstalk of the PM850G-80 fiber in the coil versus temperature.

This is due to the fact that as the temperature increases and as the aluminum spool expands, the fiber tension increases resulting in cross-talk degradation. Therefore too much emphasis should not be paid on the high temperature end of the data in Figure 8. At the lower temperature end of the thermal cycle, thermal expansion of aluminum becomes much less of an issue and therefore, interpretation of data is more appropriate.

Several facts are immediately noticeable from perusal of Figure 8. First, room temperature cross-talk of the 100 m long fiber degraded significantly upon coiling from the initial value of -29.1 dB in case of loose coil (Figure 7b). This degradation can be attributed to higher tension and coil defects like crossovers. Second, after completion of the seven thermal cycles and as temperature returned to 25°C, the cross-talk improved to some extent. This behavior is most likely due to the fact that thermal cycling relieved the crossovers and perhaps other spooling related issues that lead to poor cross-talk. The question arises as to how many thermal cycles are needed for the cross-talk to settle down. This answer is also provided by Figure 8. Most of the changes in cross-talk occur during the first thermal cycle (subsequent cycles have roughly the same profile). Since the improvement in cross-talk after the first cycle is due to spooling issues, it further emphasizes the importance of good spool winding. If the winding is good to start with, the cross-talk performance would be much better from the start. Third, cross-talk performance worsens as the magnitude of coil temperature deviation from room temperature increases. As mentioned earlier, cross-talk degradation at higher temperatures is due to thermal expansion of the aluminum spool that increases the fiber tension in the coil. The magnitude of this change in actual gyro coil would be much smaller because of the low thermal expansion coefficient of the spool material relative to aluminum. Cross-talk degradation at lower temperature is due to contraction of coating on the fiber that applies non-uniform stress in the fiber. This performance can also be improved by using a lower glass transition temperature coating. Finally, cross-talk versus temperature curves exhibit hysteresis behavior.

3.6 Comparison of Properties

To assess the suitability of PANDA style HiBi fiber (PM850G-80) in gyro applications, it would be informative to compare the properties of this fiber relative to a relevant gyro grade bow-tie fiber and elliptical cladding fiber. Such a comparison is given in Table 2. Data for bow-tie and elliptical clad fibers are taken from published literature.[12-13] The table indicates that the PANDA style gyro fiber is similar to bow-tie and elliptical clad fibers in all respects. The table clearly illustrates the point that PANDA style gyro fibers can perform equally well as gyro grade bow-tie and elliptical clad fibers and can meet all the specifications ascribed to such commercially available fibers.

Table 2. Properties of PANDA, bow-tie and elliptical clad gyro grade HiBi fibers.

Cut-o

Parameters	**PANDA PM850G-80 (Typical)**	**Bow-Tie HB800G**	**Elliptical Clad FS-PM-4611**
Operating Wavelength (nm)	850	830	820
Cut-off Wavelength (nm)	690 - 730	680 - 780	< 780
Numerical Aperture	0.15 - 0.18	0.14 - 0.18	0.13
Mode Field Diameter (μm)	4.2	4.2	5.3
Attenuation @ Operating Wavelength (dB/km)	3.0	< 5	< 5
Cladding Diameter (μm)	80.0 - 80.4	79 - 81	80
Coating Diameter (μm)	166.6 - 167.1	166 - 184	165
Core-Clad Concentricity (μm)	0.18 - 0.42	< 0.5	-
Beat Length at 633 nm (mm)	< 1.4 (Typical 0.9)	< 1.5	< 1.66
h-Parameter (1/m)	$1.23\text{x}10^{-5}$	-	$< 5\text{x}10^{-5}$
Coating Type	Dual Layer, UV acrylate	Dual Layer, UV acrylate	-

4. CONCLUSIONS

There is a growing need for small form-factor, HiBi fibers for applications in demanding sensing areas that cover the entire wavelength range of interest. To that end, Nufern has developed high performance PANDA style HiBi fibers for use at different wavelengths. PANDA design is preferred over other designs due to the fact that this design is optimal with respect to getting high birefringence and efficient utilization of stress regions. The results show that by proper choice of stress rod composition, polarization properties comparable to, if not better than, those of bow-tie and elliptical clad fibers can be achieved. In addition, since the manufacture of core and stress rods is fully decoupled in PANDA type design, significant benefits can be realized in terms of uniformity, consistency and preform scale-up for volume manufacturing. Hence, PANDA design is well suited for high performance, low cost, HiBi fibers for high precision FOG and other fiber optic sensors.

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