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A Panda fiber temperature sensor up to 900°C

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Abstract: The use of Panda-type polarization-maintaining (PM) fiber for the localized sensing of high temperatures was analyzed with simulations and experiments up to 900°C. Accuracy and repeatability of the results started to decline above 800°C. Fused silica optical fiber melts at 1700°C, which sets an ultimate limit for measurable temperatures. In practice, optical fiber birefringence restricts the maximum temperature to 1060°C where PM fiber loses its ability to maintain polarization. Three sensor fibers (4, 5 and 10 cm long) were spliced at 45° angles to input/output fibers and calibrated in an oven from room temperature to 850–900°C temperature range. Two superluminescent light-emitting diodes (SLEDs) were coupled together as a broadband light source. Birefringence-induced change of the polarization in the sensor fiber was measured with a polarization splitter and an optical spectrum analyzer (OSA) as a function of the wavelength. Temperature-dependent birefringence generates a sinusoidal reflection spectrum from the input polarization mode to the orthogonal output polarization mode. Temperature changes could be concluded from variations in these spectra. Finally, a small fusion device, NORTH, at DTU, Denmark was successfully used as a testbed to make sure that the sensors can handle transportation and the instrumentation required for vacuum operation and still produce sensible data from a harsh environment.

Keywords: Optics; Plasma diagnostics - probes; Polarisation

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Contents

1 Introduction

One potential use for fiber optical sensors is high temperature measurement in harsh radiation environments such as found near burning hydrogen plasma in a fusion power plant. Fusion reactions produce high energy neutron fluxes, and through water and material activation, gamma radiation. They pose serious issues for semiconductors and insulators found in electronic measurement equipment and thermal cameras. In fiber optic measurements, the electronics can be placed far away in shielded environment, while only the optical fiber itself needs to be routed to the location of interest. High radiation dose rates will increase the attenuation of PM fiber [1]. However, a spectroscopic measurement system, based on polarization, is expected to tolerate even a relatively large increase in attenuation and this optical fiber darkening may only affect in the long term. The sensor concept demonstrated here could be also used in other high temperature applications that could have high electromagnetic fields.

Polarization-maintaining optical fibers can maintain the polarization state of transmitted light. This is based on birefringence that has been produced with tension structures inside the fiber. The thermal expansion coefficient of the tension structures is different from the core and cladding of the silica fiber, so that they create tension when the fiber cools down after the high-temperature fiber-drawing process. Birefringent fiber then has slightly different refractive indices for the two perpendicular polarization states and this birefringence is temperature dependent. PM fiber birefringence has been used for low temperature sensing already in the beginning of the 1980's when PM fibers were developed. Eickhoff used mode interference with a 2.15 m long fiber having $\Delta n = 7.35 \times 10^{-5}$ birefringence [2]. He measured 50°C temperatures with a helium-neon laser at 633 nm wavelength. Corke spliced a 30 cm long Bow-tie type sensor fiber to the same type 90 m long PM fiber [3]. The polarization axis of the sensor fiber was rotated 45° to excite both polarization states in the sensing fiber. The sensor end was silver coated and the signal was measured in reflection mode. The sensor was heated in a furnace to 160°C, and a helium-neon laser was also here as the light source. Zhang and Lit compared commercial Panda, Bow-tie and elliptical PM fibers in temperature and strain sensing [4]. Temperature sensitivity was defined cooling a 10 cm long fiber part from +100°C to -10°C and strain was measured stretching 67 cm long fibers from zero to 300 µm. Panda was the most efficient temperature sensor and Bow-tie the best strain sensor. Panda and Bow-tie were almost as good in both sensor types, but elliptical type PM fiber had the lowest sensitivity in both cases. Zhang et al. tested temperature measurement accuracy with a Panda PM fiber and a Sagnac interferometer setup [5]. They sputtered a silver film at the end of the sensor fiber and got ~80% reflectivity for the reflection mode measurement. They heated the sensor in a water bath between 40–60°C and demonstrated 1.46 nm/°C sensitivity with < 10 cm long sensor.

Coviello et al. showed 1000°C temperature measurements with photonic crystal (PC) PM fibers [6]. This sensor needs thermal treatment at 1000°C to get constant and repeatable operation. After the thermal treatment, PC-PM fiber sensor operates like a two-mode interferometer, because the fiber splicing region excites two core modes. Rong et al. reached an even higher 1100°C temperature with PC-PM fibers [7]. They also utilized higher-order modes in the measurements and got 12.3 pm/°C sensitivity with 6 cm long PC-PM fibers.

Panda PM fibers have two circular tension structures made from boron oxide doped (B_2O_3) silica (SiO_2) glasses [8]. The temperature behavior of bare boron oxide is challenging to high temperature applications. Fajans and Barber reported already in 1952 that boron oxide has vitreous, crystalline and liquid states [9]. Vitreous states are below 300°C, crystalline boron oxide has a melting point already at 450°C and liquid states start around 500°C. Golubkov and Onushchenko investigated sodium borosilicate glasses [10]. Vitrification temperatures for their sodium borosilicate glasses were 490–581°C and transition temperatures from super-cooled liquid to solid non-crystalline states were about 50°C lower. Marrone et al. measured birefringence of a borosilicate-doped Bow-tie type PM fiber up to 1060°C [11]. They mentioned that the nominal softening temperature of borosilicate doped fiber is 780°C, but they noticed thermal hysteresis between 400°C and 600°C. Marrone and Davis also measured lower limits for boron doped PM fibers in liquid nitrogen [12]. They presented that boron doped PM fibers can be linear temperature sensor from −200°C to +400°C. Thermal hysteresis of PM fibers was reduced by Ourmazd et al. with thermal anneling [13]. They demonstrated "on-line" temperature treatment during normal fiber drawing process with 1 m long furnace with four temperature zones: 550, 500, 450 and 400°C.

A birefringence change based sensor is not the only fiber optic high temperature sensor. There is a few options that all have still some drawbacks or limitations. Fiber Bragg gratings (FBG) have been used to as high temperature sensor. Li et al. used hydrogen doped optical fibers with 800 nm femtosecond laser irradiation to make gratings over 1000°C [14]. FBG have benefit to put several FBGs to the same even kilometer long optical fiber from few centimeter to kilometer range distance from each other, but optical fiber cabling should also work in this high temperature environment. These high temperature FBGs are also much more expensive than PM fibers. Fiber optic pyrometer is able to measure thermal radiation from hot specimen. Fu et al. showed multi-wavelength pyrometer based sensor for blackbody and hot metals with 1200°C [15]. This sensor is especially good for remote high temperature measurements. The challenge is the emissivity of the sample that should be known accurately. Distributed temperature measurement that is based on the Rayleigh backscattering

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is also used to fiber optic high temperature measurements. This technique makes possible to measure temperature and position along the fiber. Wood et al. heated Corning's SMF-28e+ single mode optical fiber to 1000°C and they define the maximum operational temperature to 650°C [16]. The optical fiber cabling is the major challenge with this long high temperature sensor, because just bare fiber survives in high temperatures. Even kilometers range distance with one meter accuracy is the main benefit to this type temperature sensor but point type parallel measurements are difficult. A short probe type Panda PM fiber sensor is easier for parallel multipoint instrumentation and this way optical fiber length in high temperature can be minimized.

In this work, Panda PM fibers were used for the first time for a high temperature application over the thermal hysteresis temperatures 400–600°C showed earlier [11]. The PM fiber sensors were calibrated up to 900°C with a repeated thermal treatment. This scientifically proved the ability of spliced Panda fibers to measure temperatures accurately and locally at least up to 800°C. Over 400°C temperatures were then measured inside NORTH tokamak to prove the practical feasibility of the Panda fiber sensors in harsh environments. Instrumentation of the optical fiber based temperature sensor inside fusion equipment was done for the first time. This system could be used in large tokamaks to monitor wall temperatures behind the tiles of the plasma chamber or instrument ports. Parallel sensors make it possible to define a temperature distribution on the wall. Plasma temperature 10–20 eV (1 eV $\approx$ 11600 K) measurements [17] are not possible, because the optical fibers melt already at 1730°C [18] and PM fibers lose birefringence around 1060°C like Marrone showed [11]. Vacuum feedthrough to the tokamak, bare glass fiber handling without any protective coatings, preheating and calibration in the oven, and temperature measurements in the tokamak were the main technical challenges of this work. The measurement system could still be improved with faster test equipment and also the polarization maintaining fiber rotation could be monitored by measurement [19] during the sensor fiber splicing to get exact 45° angle rotation. Currently the rotation angle is measured mechanically to get equal intensity to both polarization states. Angle measurement would lead to more accurate temperature values with the PM fiber sensor.

2 Methods

2.1 Fiber sensor and measurement setup

Two Panda PM fibers (figure 1a) from OZ Optics were spliced together with a fiber splicer. The sensor fiber was turned 45° with respect to the input/output fiber to split the light from the slow axis mode of the input fiber evenly to both polarization modes of the sensor fiber (figure 1b). Sensor fibers were used in reflection mode without any reflective coatings, because those coatings would burn away in the high temperature fusion application. The protective fiber coatings were also totally removed from the sensor fiber and 30 cm from the input/output fiber, starting from the splicing point. Birefringence causes the two polarization modes to propagate at different velocities in the sensor fiber. The resulting phase difference between the polarizations changes linearly as a function of fiber length and it is inversely proportional to the wavelength (λ). This creates sinusoidal transmission (or reflection) spectra (on frequency scale) to the two polarization modes of the output fiber.

Two superluminescent light emitting diodes (SLED) S5FC1021P (1310 nm, 12.5 dBm, 85 nm bandwidth) and S5FC1550P-A2 (1550 nm, 2.5 dBm, 90 nm bandwidth) from Thorlabs were coupled

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together with a PM fiber coupler to form a broadband light source. Both SLED light sources were coupled to the slow axis of the Panda fiber (figure 1b). Ando AQ-6315A Optical spectrum analyzer (OSA) was used as a detector. A polarization splitter coupled the light source to the slow-axis of the input/output fiber and then separated the back-reflected fast axis light to the OSA. The measurement span was 1175–1675 nm with 10 nm resolution to get a sufficient measurement speed. A LabVIEW program acquired the reflection spectrum from the OSA and calculated the corresponding temperature from calibration data.

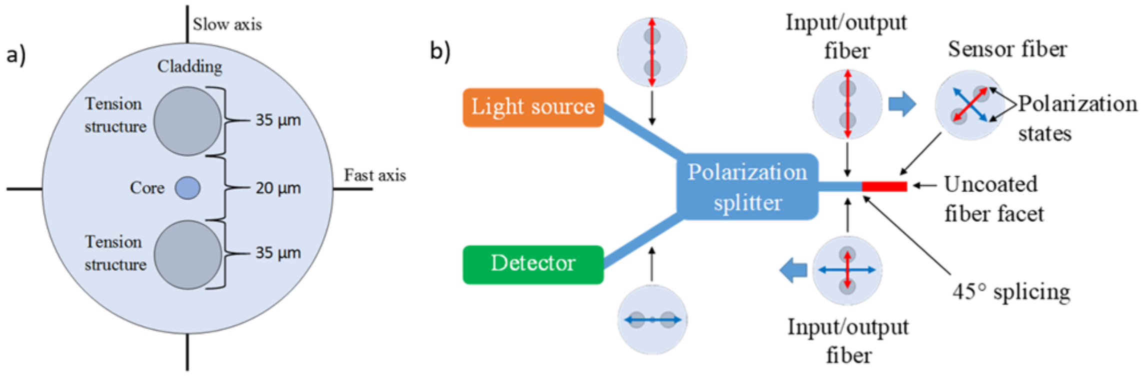

Figure 1. a) Panda PM fiber structure and b) measurement setup for PM fiber sensor.

2.2 Measurement interface on NORTH tokamak

A steel capillary with 1.6 mm outer diameter and 1.1 mm inner diameter was used to protect the optical fiber in the vacuum feedthrough (figure 2a). The optical fiber was glued with Araldite rapid epoxy to the steel capillary to make a vacuum seal between the fiber and the capillary. The glue was put on an outer connector end of the steel capillary. Swagelok connectors (SS-100-1-2BT) were drilled and welded to the tokamak's 4.5″ outer diameter flange (F0450X000N) from Kurt J. Lesker Company (figure 2b). The flange was connected to a bellow that can be moved 20 cm towards the tokamak's plasma chamber [17]. It was possible to get the PM-fiber sensor inside the plasma chamber (figure 2c).

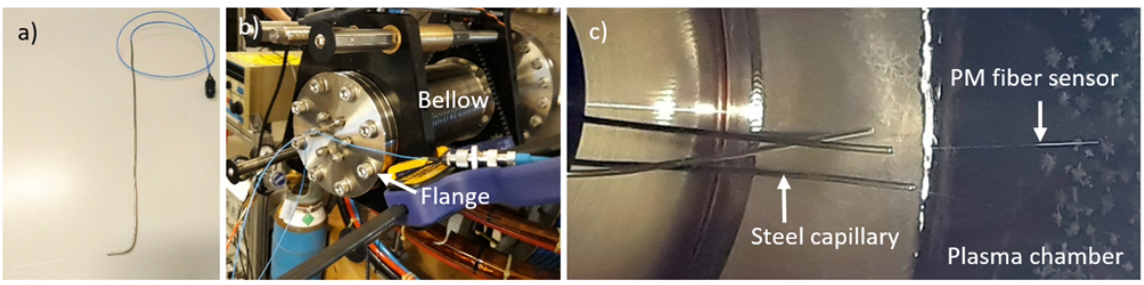

Figure 2. a) Panda PM fiber sensor, b) bellow with flange and c) PM fiber sensors inside NORTH.

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2.3 COMSOL modeling for the Panda PM fiber at high temperatures

To explain the experimental results, we modelled the temperature dependence of the Panda fiber's optical characteristics in COMSOL Multiphysics. We divided the calculation to two parts: a linear elastic modelling of temperature-induced stress and strain, and an electromagnetic simulation to find the propagation constants of the two orthogonal polarization modes. We considered the geometric parameters of the fiber as shown in figure 1a. The composition of the core material of the fiber is GeO_2-doped SiO_2. The Panda elements (stress elements) are made from sodium borosilicate (a composition of sodium (Na), SiO_2 and B_2O_3), while the cladding is considered to be pure silica material. The Young's modulus and Poisson ratio of each material are assumed to be those of pure silica, while the coefficient of thermal expansion of the stress elements is different (see table 1). The length of the fiber is much longer than the cross-section of the fiber, so we modeled only the cross-section of the fiber by ignoring the strain in the longitudinal direction [20]. The refractive indices of the materials were taken from Guan [20]. We considered the initial stress in our fiber as 450×10^6 N/m^2 to match the simulation results with our experimental data. It should be noted that there exists a vitrification process within the sodium borosilicate occurring around 480°C [10], which gives rise to a sharp discontinuity in the thermal expansion coefficient of the material. We have taken this into account by using a piecewise thermal expansion coefficient for: 2.05×10^{-6} 1/K at temperatures lower than 480°C and 3.32×10^{-6} 1/K above.

The two-dimensional simplified model of the PM fiber follows the stress birefringence relationship as given by Guan [20]:

$$B = N_x - N_y = C(\sigma_x - \sigma_y), \tag{2.1}$$

where C is the relative stress-photoelastic coefficient of the material and can be calculated as $C = a - b$, where a and b are stress-photoelastic coefficients of the material. σ_x, σ_y are in plane stress in X and Y direction respectively, and B is the birefringence. This equation gives the birefringence at each point in the cross section of the fiber, while the mode birefringence is calculated as the difference between the effective indices of the fundamental modes in the slow and fast axis of the PM fiber.

Table 1. Material parameters used in the modelling. The parameters have been measured at 20°C.

Parameters used for modeling	SiO_2 Cladding	GeO_2/SiO_2 Core	$B_2O_3-SiO_2$ stress elements
Young's modulus E_i (Pa)	78.3×10^9	78.3×10^9	78.3×10^9
Poisson ratio ϑ_i	0.18	0.18	0.18
Thermal expansion coefficient (TEC) α (1/K)	0.54×10^{-6}	0.54×10^{-6}	$2.05 \times 10^{-6}, T < 480$°C $3.32 \times 10^{-6}, T > 480$°C
Stress-optic coefficient a (1/ Pa)		0.65×10^{-12}	
Stress-optic coefficient b (1/ Pa)		4.2×10^{-12}	

3 Results

3.1 Sensor calibration

Two SLED light sources give an approximately 500 nm wide measurement range. Figure 3 shows this light source spectrum and a back-reflected spectrum from the PM fiber sensor. The lowest curve is the difference between those two and it is used for birefringence calculation.

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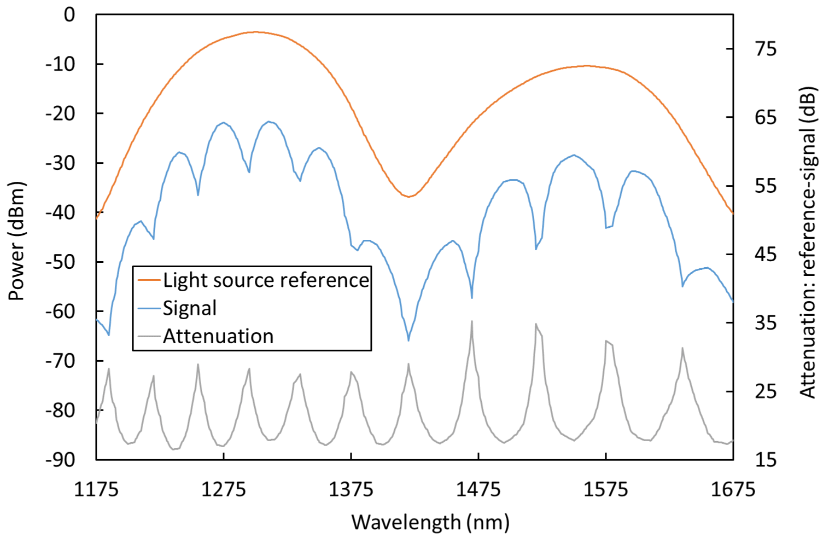

Figure 3. Wavelength spectrum at room temperature for a 4 cm long sensor.

Birefringence can be calculated from the phase difference in the wavelength spectrum in figure 3:

$$\frac{\Delta nL}{\lambda_1}2\pi - \frac{\Delta nL}{\lambda_2}2\pi = m2\pi \tag{3.1}$$

$$\lambda_2 \Delta nL - \lambda_1 \Delta nL = m\lambda_1\lambda_2 \tag{3.2}$$

$$\Delta n(\lambda_2 - \lambda_1) = \frac{m\lambda_1\lambda_2}{L} \tag{3.3}$$

$$\Delta n = \frac{m\lambda_1\lambda_2}{\Delta\lambda L}, \tag{3.4}$$

where Δn is birefringence, L sensor length, m peak number difference, λ_1 and λ_2 peak wavelengths [21, 22].

Birefringence change is totally different, when it is heated first time as Marrone et al. and Ourmazd et al. showed with boron doped silica stress structures for Bow-tie type PM fiber [11, 13]. We measured the same kind of behavior with Panda type PM fiber. Birefringence values were calculated with equation (3.4). In a first heating period there is a "knee" type thermal hysteresis between 400–700°C. After a few heating and cooling periods this thermal hysteresis disappears, but the turning point in birefringence at 500–600°C still exists.

The attenuation curve from figure 3 was converted into a frequency spectrum. Peak spacing is constant over the frequency range and temperature can be calibrated as a function of the peak spacing. A scanning speed of the optical spectrum analyzer ($\sim$ 1 Hz) limits the temperature accuracy. It is possible to get even more accurate temperature calibration if temperature is calibrated to one fixed peak, but a much faster spectrum measurement system would then be needed.

At least five heating and cooling periods from room temperature to maximum temperature are needed (figure 4), before the sensor can be calibrated. Extra internal stress will relax and temperature behavior will stabilize. In figure 4, the first six cooling periods of a four centimeters long fiber are illustrated. The slower and more stable cooling period was used for calibration. The temperature distribution in the oven is unclear during the fast and uneven heating period. Marrone et al. mentioned

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that softening temperature for borosilicate stress structure is 780°C [11]. Measured temperature curves have still some variations above this softening temperature after six heat treatment cycles. Because of this temperature accuracy is of the order of < 10° below 780°C and > 10° above 780°C.

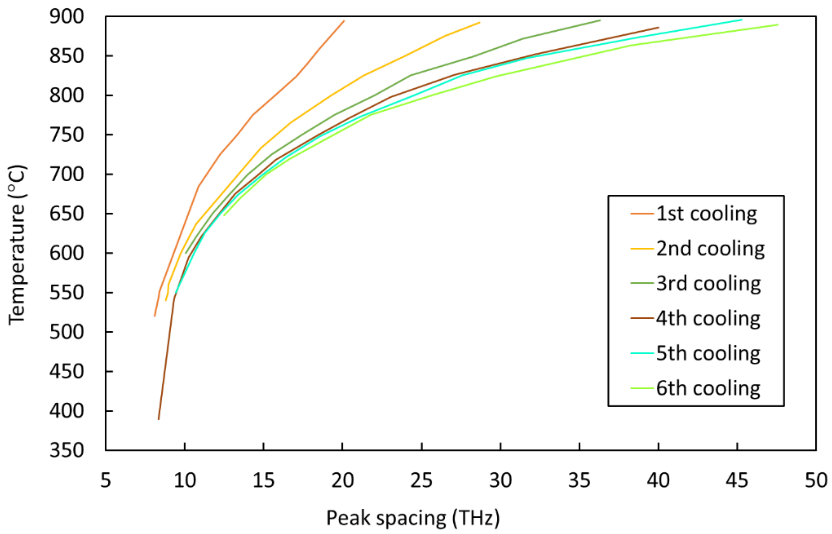

Figure 4. Heat treatment for PM fiber sensor.

Calibration curves were defined for three different sensor lengths: 4, 5 and 10 cm. Sensors were calibrated from room temperature to 850–900°C. Temperatures over 800°C are less accurate due to borosilicate's softening. The different sensor lengths provide different temperature measurement ranges. Longer sensor lengths are needed for higher temperatures where the birefringence of the sensor fiber becomes lower. All calibrated sensors 4, 5 and 10 cm have the same birefringence

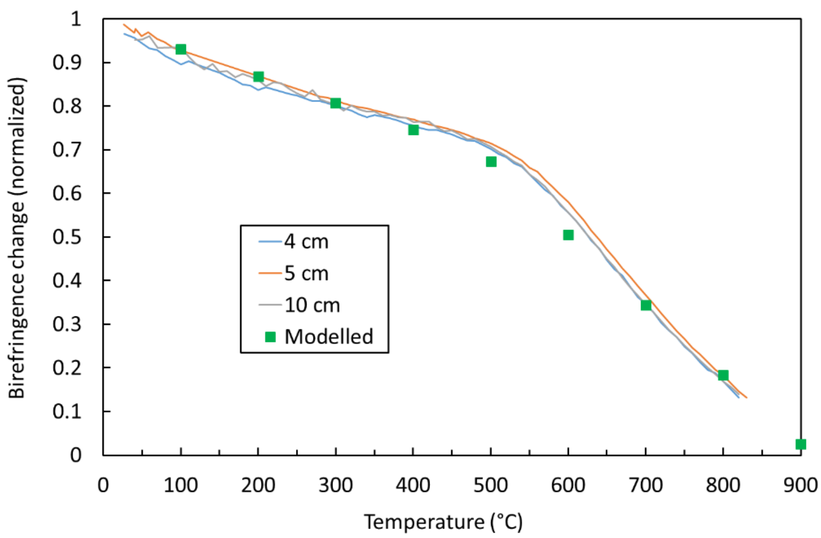

Figure 5. Measured and modelled birefringence change for the Panda PM fiber.

behavior as a function of the temperature in figure 5. These birefringence curves were normalized, so that comparison with the modelled results would be easier. The material parameters used in the simulation may differ from the real ones. The room temperature birefringence value for calibrated sensors was about 5.4×10^{-4}.

3.2 Panda PM fiber temperature modelling

We performed the mode analysis of the PM fiber to calculate the stress induced birefringence for a temperature range from 100°C to 900°C. The normalized modelling results matched quite well with our experimental data as shown in figure 5. The almost piecewise linear nature of the curve is accounted for by the vitrification process of sodium borosilicate, which we took into account as described in section 2.3. Birefringence change comes mainly from a temperature induced mechanical stress. Additionally, the sodium borosilicate vitrification makes discontinuation to thermal expansion coefficient and a turning point to the birefringence. The matching between the experimental and theoretical curves near the turning point could be further improved by taking into account the smooth, nonlinear variation of the thermal expansion coefficient of sodium borosilicate in this temperature range.

3.3 Measurements on the NORTH tokamak

As part of the feasibility investigation, the annealed and calibrated sensors were inserted inside the steel capillaries and transported to the NORTH tokamak (experimental small fusion device in Denmark). Several sensors were inserted (one by one) inside the tokamak vacuum chamber through a port with the ability to move the sensor from the edge all the way to the center of the plasma as needed. In order to mount these sensors inside the tokamak, we developed a basic sensor assembly with vacuum feedthroughs as detailed before. In addition, LabVIEW software was written for converting the spectral measurements into temperature using the calibration data collected from the laboratory oven measurements. This allowed recording the temperature of the optical fiber in real time using a laptop.

We found that all the tested sensors survived the air and road transportation from Finland to Denmark and produced reasonable data when installed inside the tokamak vacuum chamber even though the optical fibers with 125 µm diameter required very careful handling. Figure 6 shows temperature measurements obtained during pulsed plasma discharges. During the seven-second long plasma discharges the steel capillary, immersed in the plasma, is heated up to 350–430°C after which it cools down through radiation and conduction for a few hundreds of seconds before the next, nearly identical, discharge. In other words the long cooling period is not due to plasma physics or slow sensor response but is due to thermal inertia. We can see that our sensors measure the temperature consistently. The non-physical negative temperature signal during plasma ignition is not understood but is likely due to the strongly varying magnetic field ramp up at plasma startup. Note that in the envisaged real life application multiple fibers would be embedded in parallel just inside the front face of a plasma facing tile to allow radially resolved temperature measurements. The sensor would thus measure the temperature on the surface of the tile facing the plasma. Here steel capillary was used because the NORTH tokamak plasma is not hot enough to cause significant temperature increase at the vessel walls.

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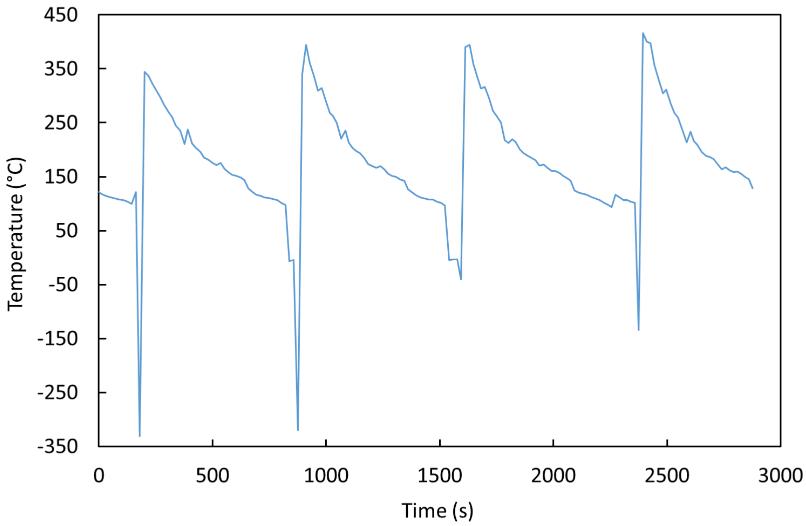

Figure 6. Four consecutive seven-second long plasma pulses measured with 4 cm PM fiber sensor in steel capillary.

4 Conclusions

Temperature measurements with Panda type PM fiber sensors inside a tokamak environment were demonstrated on NORTH tokamak. Two different sensor lengths 4 and 5 cm were tested. Maximum measured temperature with a steel capillary cover were in the range 350–430°C. While these tokamak tests did not yet try to reproduce a realistic application of this sensor, they did validate the proof of concept to measure wall temperatures behind the tiles in large tokamaks. More work is obviously needed to assess and improve the sensor stability, accuracy, temporal resolution, assembly, etc. However, these tests showed that the concept is promising and there should not be any critical issues that would prevent the development of a radiation and electromagnetic noise resistant, fusion power plant compatible, high temperature sensor capable of measurements up to 900°C for the first time with a standard Panda PM fiber. Nuclear industry has also a broader need for high temperature measurements in harsh environment with electromagnetic noise resistant optical sensor. Panda PM fiber sensor is a new possibility to fulfill those instrumentation needs in this demanding environment.

Acknowledgments

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