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Cryogenic Temperature Profiling of High Power Superconducting Lines using Local and Distributed Optical Fiber Sensors

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This contribution presents distributed and multi-point fiber-optic monitoring of cryogenic temperatures along a superconducting power transmission line down to 30 K and over 20 m distance. Multi-point measurements were conducted using fiber Bragg gratings sensors coated with two different functional overlays (epoxy and PMMA) demonstrating cryogenic operation in the range 300 – 4.2 K. Distributed measurements exploited optical frequency-domain reflectometry to analyze the Rayleigh scattering along two concatenated fibers with different coatings (acrylate and polyimide). The integrated system has been placed along the 20 m long cryostat of a superconducting power transmission line, which is currently being tested at the European Organization for Nuclear Research (CERN). Cool-down events from 300 K to 30 K have been successfully measured in space and time, confirming the viability of these approaches to the monitoring of cryogenic temperatures along a superconducting transmission line. © 2015 Optical Society of America

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The assessment of advanced technologies and devices designed to operate in cryogenic environment in several fields of applications, such as aerospace vehicles, superconducting magnets and high energy physics experiments [1-2], is leading to an increasing interest in the development of accurate cryogenic sensors with long-term robustness and reliability to assure good operation and safe working conditions of the equipment. To date resistive sensors represent the standard technology commonly used to meet the requirement of monitoring wide temperature ranges from room temperature down to ultra-low temperature in harsh environment and extreme working conditions. However, some of their limitations typically associated to their sensitivity to the magnetic field and the amount of electrical wires needed for their operation, may be efficiently overcome implementing fiber optic based monitoring systems which rely on appealing advantages like small size, light weight and electromagnetic interference immunity.

The application of fiber optic sensors (FOS) at cryogenic temperature is however not straightforward. Among the fiber optic technologies considered so far, the most promising one for low temperature monitoring is based on fiber Bragg Grating (FBG). Bare silica FBG sensors are not effective for cryogenic applications because of the thermo-optic and thermo-elastic coefficients of silica becoming negligible below 50 K [3]. This makes the FBG's characterization at cryogenic temperature and its development as a cryogenic sensor not well assessed yet. In particular experiments conducted down to 2.2 K [4] highlighted the need to consider additional coatings able to transduce temperature variation into measurable strain [5].

In this prospective, considerable efforts have been carried out by many research groups to select the material and the thickness of the coatings that ultimately determine the performance of the final device. Several materials and coating techniques have been explored in order to realize coated FBG thermal sensors operating at cryogenic temperature [6]. The material selection mainly focuses on the thermal expansion coefficient (CTE) of the host material (coating material) in order to achieve a good thermo-mechanic response (thermal apparent strain) from the grating, also at temperatures where the pure thermal effect of silica starts to be negligible. Besides maximizing the CTEs values at cryogenic temperatures, the selected coating material must also exhibit a good adhesion to the fiber, which is fundamental to assure a good strain transfer. Moreover, the geometry and thickness of the host material derive from considerations related to adequately transfer the strain from the host material to the optical fiber avoiding residual radial and longitudinal stresses, which can compromise the quality of the reflection spectrum of the embedded grating. Metal coatings reported in [7], namely aluminum, copper, lead and indium, have extended the range of operation of the FBG to 15 K, reaching a total wavelength shift of 6.28 nm, 7.08 nm, 9.41 nm and 10.06 nm respectively. Nevertheless, the use of polymers like Teflon (19 nm at 77 K [8]) and PMMA (11.7 nm at 30 K [9]) enables the highest thermal sensitivity, being their CTEs at cryogenic temperatures from 2 to 5 times larger than that of the considered metals [8].

Besides point-sensor technology, also distributed optical fiber sensors have been considered for cryogenic temperature monitoring. The use of Raman or Brillouin scattering in this field has found the main limitations in a sever lack of sensitivity and a highly non-monotonic behavior, respectively [10]. Differently, distributed FOSs based on Rayleigh scattering have found preliminary successful applications [11-13].

We recall for completeness that Rayleigh-based distributed measurements are conceptually similar to FBG-based ones. The main difference is that while the FBG generates a selective reflection spectrum because of its ordered structure, the reflection spectrum generated by Rayleigh backscattering looks like a random signal, since it is originated from silica amorphous structure [14]. Nevertheless, by comparing the spectra reflected by a fiber section at two different times, it is possible to understand if that section has experienced a variation of temperature and/or strain, just as with an FBG. Owing to the random nature, however, it is difficult in practice (although not impossible in principle) to relate an absolute Rayleigh reflected spectrum to an absolute temperature and strain condition. Therefore, only variations of strain and/or temperature can be reliably measured. In any case, the relationship between the measured spectral shift and the applied strain/temperature variation depends on the characteristics of the fiber and its coating, and hence needs to be calibrated.

Despite being affected by the same decrease in thermal sensitivity that affects FBGs, just as FBG Rayleigh scattering does not loose sensitivity to strain at cryogenic temperatures. Therefore, appropriate coatings can impact the thermo-mechanical behavior of the fiber preserving high sensitivity [12]. However, differently from FBG sensors, for which the coating can be chosen over several alternatives in agreement with the specific needs and requirements, in the case of distributed sensing economic considerations suggest limiting the choice to commercially available fibers [11].

In this work we report the implementation of a hybrid system which combines the multi-point sensing capability of coated FBGs with distributed Rayleigh measurements for cryogenic temperature monitoring along a 20 m long cryostat of a superconducting power transmission line. Experiments have been carried out in the cryogenic test facility at the European Organization for Nuclear Research (CERN), where superconducting links are being developed in the framework of the Luminosity Upgrade of the Large Hadron Collider (HL - LHC). This upgrade will require new technologies and solutions to feed the magnets from surface, or radiation free underground areas, down to the 100 m deep tunnel, displacing the power converters to remote locations. To this aim, a novel superconducting power transmission line (hereafter SC-link) is under study. The link is made of high temperature superconductors, has a length ranging from 300 m to 500 m, and works at the He gas temperature between 5–30 K [15]. Temperature monitoring over long distance is therefore required to localize possible sections where the He cooling may results insufficient to assure safe operation of the superconducting cable below its critical temperature (transition temperature from resistive to superconducting state).

The FBG used in this experiment have been coated with epoxy and PMMA, which have shown good thermal expansion down to [16]. Four FBG sensors with 10 mm grating length have been coated using reactive casting and a polymeric precursors highly compatible with silica to enhance the surface wetting before the polymerization. Two sensors (hereinafter named “B62” and “B57”) have been coated with PMMA and two with epoxy (“A55” and “A65”); the final dimensions of the coatings is about 2.5 × 5.0 × 25.0 mm (height × width × length) [16].

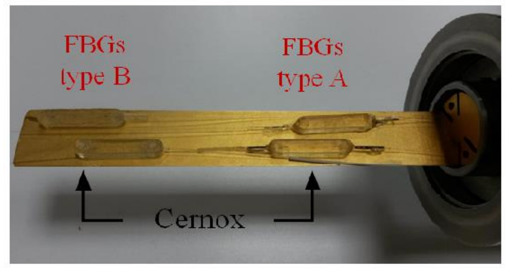

Fig. 1. Cryo-cooler set up and FBGs location on the platform.

The FBG sensors have been calibrated in a closed cycle refrigerator system composed of a pulse tube and a cryogen free cryostat, where the samples are cooled in He gas inside a variable temperature insert (VTI) of 50 mm inner diameter [17]. The sensors have been laid down free of any stress on a gold – coated copper platform (24 mm width and 132 mm length) at the same locations of 2 reference resistive sensors (CERNOX™ Lake Shore), installed inside the platform at 100 mm from each other [see Fig. (1)]. The optical connection with the interrogator (Micron Optics sm125) has been achieved by a dedicated vacuum-tight feed-through.

The reflection wavelengths of each FBG sensor have been measured every 10 seconds during 9 controlled cool-down from 300 to 4.2 K, each lasting about 6 hours allowing an accurate calibration.

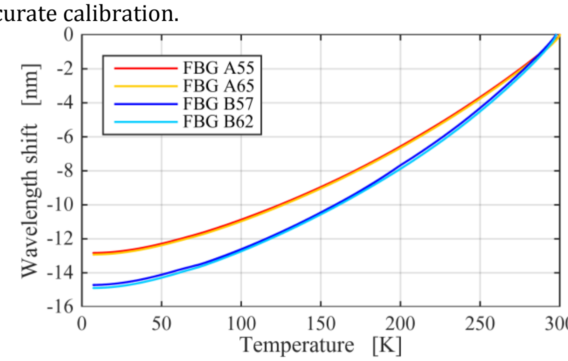

Fig.2. Characteristic curves of the FBGs.

The measurements showed a very good repeatability of the spectral responses: at 30 K the standard deviation of the wavelength shift is 25 pm for type “B” sensors and 10 pm for type “A” sensors. The characteristic curves of all the four FBG sensors are shown in Fig. 2. In response to a temperature variation from 298 to 4.2 K, the reflection wavelength of FBGs “B62” and “B57” shifted by –14.9 nm and –14.7 nm, respectively. Similarly, in the range 300 to 4.2 K the wavelength shifts of FBGs “A55” and “A65” were –12.83 nm and –12.92 nm, respectively.

The wavelength shift vs. temperature curves of the FBG sensors have been fitted with a sixth degree polynomial. For all the FBG sensors, the residuals of the interpolation are less than 0.5 K in the range 15 – 300 K and less than 2 K for temperature below 15 K. The resulting sensitivities obtained differentiating the polynomial fitting curves ($S_T= d\lambda/dT$) are reported in Fig. 3 for the FBGs "B57" and "A55"; the curves are the same also for the FBGs "B62" and "A65". In particular, the sensitivity is 16 pm/K at 30 K for type "B" FBGs, and 14 pm/K for type "A" FBGs, and decreases to about 2 pm/K at 7 K for type "B" and about 1 pm/K at 9 K for type "A".

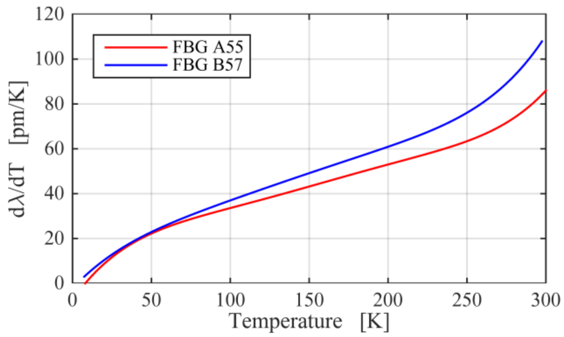

Fig.3. FBG sensitivity curves.

These calibration curves have been used to both perform the temperature monitoring in the SC-link with the FBG, and to calibrate the bare fibers used for the distributed measurements, whose calibration could not be performed in the cryo cooler due to a lack of space in the VTI.

The schematic of the cryostat of the SC-link is showed in Fig. 4. The cryostat is connected on one side to the feed-box, from where the He gas is injected into the line, and on the other side to an instrumentation volume, from where all the sensors installed inside the cryostat can be accessed using ultra-vacuum-tight feed-through. The four calibrated FBG sensors and two bare fibers with different coatings (acrylate and polyimide) for distributed measurements have been installed along the cryostat, protected by a Kapton (DuPont™) loose tube conveniently perforated in order to allow the He gas to freely flow inside [18]. The FBG sensors have been concatenated in two separate arrays [see Fig. 4]. FBGs B57, A55, A65 and B62 have been placed at 0, 7, 14 and 20 m, respectively, from the end of the cryostat on the side of the optical feed-through. The bare-fiber link for distributed monitoring was made by splicing together about 10 m of polyimide-coated single-mode fiber (OFS GEOSIL-SM; coating thickness 15 μm) and almost as much of acrylate-coated single-mode fiber (Pirelli FreeLight with double-layer coating as typical for telecommunication fiber; total thickness 62.5 μm). The splice between the two fibers was about at the center of the cryostat [see Fig. 4].

The wavelength shift of the FBG sensors has been measured every 5 minute with a Micron Optics sm125 unit. Distributed measurements have been performed at the same rate using a Luna Inc. OBR 4600 [14]. The SC-link has been cooled down to 30 K in about 9 hours; the resulting variation of temperature vs. time measured by the 4 FBGs sensors is shown in Fig. 5, confirming the ability of these sensors to monitor temperature variations down to cryogenic levels. These data have been used also to calibrate the frequency response of the bare fibers. As can be seen in the schematic of the Kapton tube in Fig. 4, there are two FBG sensors in correspondence of each of the two fibers. Since the fibers properties are uniform, we should expect that the two FBGs provide the same calibration curve for the corresponding fiber.

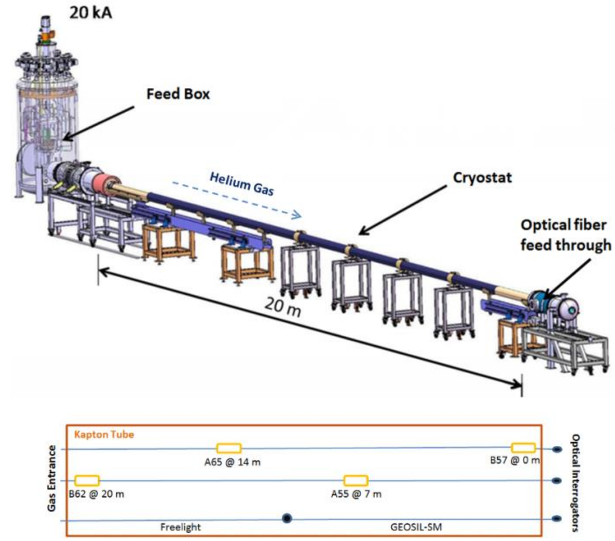

Fig.4. SC-link test station at CERN (drawing R. Betemps) and FBGs locations along the 20 m length Kapton tube

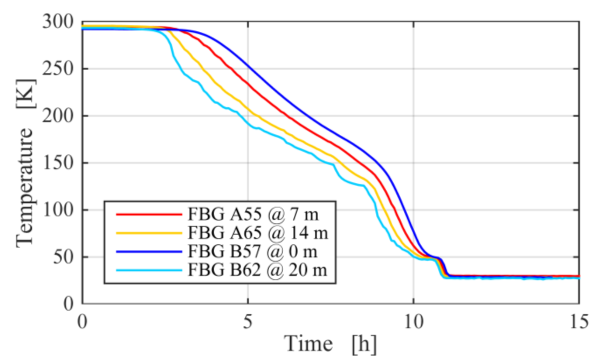

Fig.5. FBGs temperature vs. time during the SC – Link cool-down.

This is indeed confirmed in practice as shown in Fig. 6, where the Rayleigh-shift vs. temperature is plotted for each fiber and each of the two corresponding FBG sensors. In particular, the reported Rayleigh-shift has been measured on a 5-cm-long section of fiber at the location of the corresponding FBG location; the agreement of the two curves for each fiber is very good, confirming the quality of the measurements. The figure also shows that, for the same temperature variation, the polyimide-coated fiber generates a much lower Rayleigh-shift compared to the acrylate-coated ones. These differences are mainly due to the different coating materials and their thickness, and are in agreement with previously reported measurements [10]. The calibration curve of each fiber has been estimated averaging the temperature vs. Rayleigh-shift curves obtained from each FBG. Similarly to what done for the FBGs, the calibration curves have been fitted with sixth degree polynomials; the residuals of the interpolations are below about 2 K over the whole range. The sensitivities of the fibers have been evaluated by differentiating the polynomials; results are shown in Fig. 7. In particular, the sensitivities at 60 K are about 2.5 and 9.5 pm/K for the polyimide and the acrylate-coated fiber, respectively, whereas at 30 K they drop to about 0.4 and 4 pm/K.

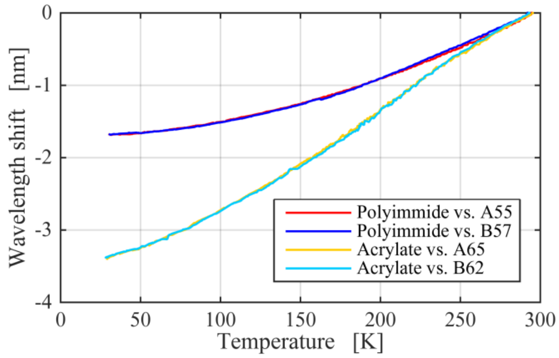

Fig. 6. Calibration curve of the two fibers with respect to each FBG. Curves for the same coating are almost overlapped.

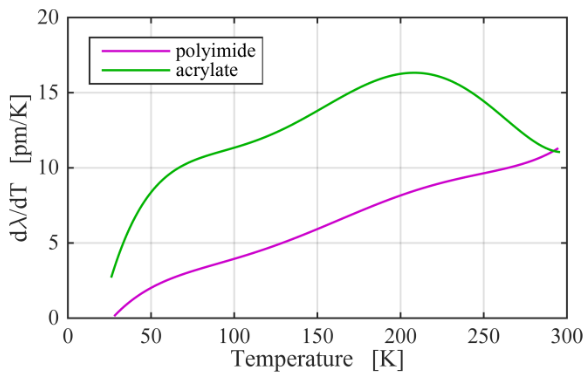

Fig. 7. Sensitivity curves of the two bare fibers.

After the bare fibers have been calibrated at the position of the FBG sensors, it has been possible to measure the temperature variation along the whole SC-link, as shown in Fig. 8 for different measurement times; as before, data have a spatial resolution of 5 cm. The temperature profiles are consistent with the fact that the cold He gas was entering from the far end of the SC-link. A remarkable result is also the agreement of the temperatures measured by the two fibers near the splice position (less than 1.5 K of difference on the whole range); this confirms the consistency and quality of the measurement. It can also be noted that at lower temperature the blue curves become noisier due to the reduced sensitivity of polyimide coated fiber at lower temperature. Differently the rough oscillations reported for both fibers at higher temperature are not due to noise, but are likely caused by small inhomogeneity of coating diameter, as suggested in [10], and/or uncontrolled installation issues, as for example the Kapton tube being not as loose as intended.

In conclusion, the reported results confirm that proper coating materials and fabrication techniques make the FBGs suitable and reliable sensors for cryogenic temperature monitoring in a wide range 300 - 4.2 K. Moreover, although further investigations are needed to increase the thermal sensitivity and coating effects, Rayleigh-based sensor results to be a viable solution for distributed monitoring at cryogenic temperature. The experimental results reported here demonstrate the feasibility of the distributed and multi-point fiber-optic monitoring over 20 m down to 30 K.

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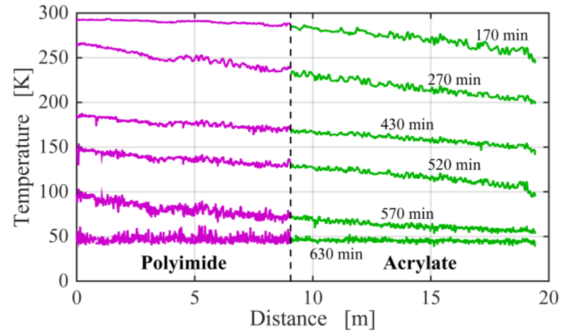

Fig. 8. Temperature variation along the SC-link at 6 different times during the cool-down.

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