Journal Publication

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Curras,E (CSIC-UC) *et al*

04 August 2012

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025.

This work is part of AIDA Work Package 9: **Advanced infrastructures for detector R&D.**

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Influence of the Fiber Coating Type on the Strain Response of Proton-Irradiated Fiber Bragg Gratings

E. Currás, A. L. Virto, D. Moya, I. Vila, J. G. Carrión, M. Frövel, J. García-López, M. C. Jiménez, Y. Morilla, and F. R. Palomo

Abstract—We report on the effect of the fiber coating on the radiation sensitivity of Fiber Bragg Gratings (FBG). For the first time this type of study has been carried out using a 13.5 MeV proton beam up to a fluence of 3.3×10^{15} protons/cm² (total absorbed dose of 15 MGy). We observed a clear dependence of the radiation sensitivity on the coating, in particular, we have investigated the irradiation induced changes on the strain sensitivity; FBG strain coefficient remains stable for all the fiber within a 5%. This result demonstrates the suitability of FBGs as structural health and deformation monitors in the very hostile environment of the new generation of high-intensity particle physics proton colliders.

Index Terms—Draw tower gratings, fiber Bragg gratings, proton radiation effects, type II gratings.

I. INTRODUCTION

VERY recently, the use of fiber Bragg gratings (FBG) based sensors has been considered as an attractive technology for the structural and environmental monitoring of collider particle physics experiments [1]–[3]. The radiation effects on FBGs have been studied for more than one decade and the overall FBG radiation sensitivity is understood up to a reasonable level, including the dependence with the FBG fabrication process [4], [5].

On the other hand, the radiation cocktail of a collider particle physics experiment, where intense fluxes of high momentum protons, other charged hadrons and neutrons are common, differs quite significantly with respect to other more conventional radiation environments like space or nuclear installations. This may well be the reason why the radiation sensitivity of FBGs against protons has been less studied [6]. Our study aims to cover this specific lack of information and to increase the irradiation dose to the expected values of the future generation of

hadronic colliders. In addition, we explicitly focused our study on the radiation-induced change in the strain response of the FBGs under test.

The effect of the fiber coating on the gamma radiation sensitivity of FBGs has been already reported up to a moderate dose (40 kGy) with a clear conclusion: the radiation-induced Bragg wavelength shift (BWS) strongly depends on the coating material [7]. In [6], under proton irradiation (100 KGy maximum dose), the modification of the FBG temperature sensitivity is explained as a consequence of the thermo-optical effect but the authors did not make any attempt on understanding the influence of the coatings on the irradiation effects.

In our study, the main goal was to determine the effect of coatings on the strain sensitivity, on FBGs under proton irradiation. The linearity (k factor) of each FBG sensor against the strain was determined before and after the irradiation. Polyimide and ormocer are coatings that are bonded together to the glass fiber as the fiber is extruded (draw tower process), whereas acrylate coating is recoated after sensor writing.

We have investigated the effect of the proton irradiation on the strain response of the FBGs produced with all the above referred technologies and coatings. The large proton fluence required in this study corresponds to the expected values for the new generation of particle physics hadronic collider experiments.

II. EXPERIMENTAL ARRANGEMENT

A. Irradiation Arrangement

Seven arrays of FBG sensors were irradiated at the Centro Nacional de Aceleradores (CNA) at Seville [8] in the cyclotron external line where protons can be accelerated up to 18 MeV. In our arrangement the proton energy illuminating the FBG sensors was 13.5 MeV with a dispersion of about 160 KeV. The average proton flux was of 3.11×10^{11} protons/cm²s and a total fluence of 3.3×10^{15} protons/cm².

The irradiation was done in air with a room temperature of 20°C. Using circular V-grooves made in an aluminum plate, the fibers were held at a constant distance with respect to the proton beam axis, see Fig. 1. The proton beam profile has a cylindrical symmetry with a two-step radial intensity. The intensity of each step is uniform. The innermost step of the intensity distribution illuminates a circle with a radius of one centimeter, the second outer step illuminates an annular area with an internal and external radius of one and four centimeters respectively, its intensity is about 30% lower than the innermost step intensity. The

Manuscript received September 23, 2011; revised January 11, 2012, March 09, 2012; accepted March 26, 2012. Date of publication July 18, 2012; date of current version August 14, 2012. This work has been supported in part by the Spanish Ministry of Science and Innovation under the projects FPA2007-66387 and FPA2010-22163-C02-01.

E. Currás, A. L. Virto, D. Moya and I. Vila are with the Instituto de Física de Cantabria (CSIC-UC), 39005 Santander, Spain (e-mail: vila@ifca.unican.es).

J. G. Carrión and M. Frövel are with the Instituto Nacional de Técnica Aeroespacial (INTA) Composite Materials Department, 28850 Torrejón de Ardoz, Spain (e-mail: carrionmj@inta.es).

J. García-López, M. C. Jiménez and Y. Morilla, are with the Centro Nacional de Aceleradores (CNA), 41092 Sevilla, Spain (e-mail: fjgl@us.es).

F. R. Palomo is with the Electronic Engineering Dpt., School of Engineering, University of Sevilla, 41092 Sevilla, Spain (email: rogelio@gte.esi.us.es).

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Digital Object Identifier 10.1109/TNS.2012.2206049

Fig. 1. Layout of the fibers during irradiation; the table specifies the actual irradiated fiber length and fiber radial location.

Fig. 2. Experimental set-up used for this irradiation study; FBG 211 from fiber 21 was left outside the irradiation area. Different coatings are color coded.

fibers are disposed such that they are all inside this annular area, ensuring the uniform irradiation of the gratings.

The LET inside the FBG sensor was calculated using a detailed simulation of the proton interactions and transport [9]. Combining the calculated LET and the experimental calibrated fluence, an absorbed dose of 15 MGy(SiO₂) was estimated at an average dose rate of 6 MGy/h. The simulation confirmed also that protons are energetic enough to completely traverse the fiber section and thus preventing the proton implantation in the fiber which induces birefringence in the optical fiber and as a consequence the broadening of the FBG reflected peak [10].

A sketch of the experimental set-up used for this study is shown in Fig. 2, sensors were in air at room temperature. Although the room temperature during irradiation remained stable, the FBG's temperature is expected to increase due to the intense irradiation and the heat transfer between the FBG sensors and the aluminum plate holding the fibers. This holding plate acted as a thermal diffusor making a more uniform temperature distribution in the fibers area. However, a radial thermal gradient was present in the holder during the irradiation due to the proton beam induced heating of the inner part of the fiber holding plate. A thermal gradient of about seven degrees between the inner and the outer radius fiber was estimated using a detailed finite element simulation, see Fig. 3. This temperature difference is compatible with the wavelength shift difference measured between a FBG temperature reference sensor, attached at one edge of the support plate, and the innermost acrylate-coated FBG sensor

Fig. 3. Finite element simulation of the thermal distribution on the fiber holder during irradiation (in Celsius degrees). The estimated temperature at the edge of the plate presents an acceptable agreement with the reference temperature sensor readout.

under irradiation. The reference temperature sensor was outside the irradiated beam, its recorded temperature and location are shown in Fig. 3.

In addition, it turned out that the contact of the FBG gratings with the fiber holding plate was not the same for each sensors; this fact rendered the individual temperature compensation of each FBG grating unfeasible. The difference between the plate temperature and the gratings is expected to be of a few degrees.

TABLE I
PARAMETERS OF THE FBGS USED IN THE EXPERIMENT

Fiber code	Coating	Manufacture	# of FBGs
11	acrylate	re-coated, type I	2
21	polyimide	Draw Tower, type I	3
22	polyimide	Draw Tower, type I	3
02	ormocer	Draw Tower, type I	3
03	ormocer	Draw Tower, type II	1
04	ormocer	Draw Tower, type II	1
05	ormocer	Draw Tower, type II	1

The maximum temperature reached by the support is between eighty and ninety Celsius degrees—a temperature that may be found in the inner and forward parts of a hadronic collider experiment. The cool-down period, after the proton beam is stopped, is about one hour. This slow cooling profile is a trend common to all FBG sensors and it is driven by the large thermal inertia of the aluminum fiber holder, manifestly, the dominating effect over some possible short term annealing processes.

Given the above considerations, hereafter, we are going to constrain ourselves to discuss the radiation induced effects on the FBG gratings after applying a total fluence of 3.3×10^{15} protons/cm², once the thermal equilibrium was reached after shutting down the proton beam.

B. Selected Bragg Gratings

The FBG sensors were coated with three different materials: acrylate, polyimide and ormocer. Sensors have been coded with a three-digit number ABC where A identifies the coating type, B the fiber and C the FBG sensor in the fiber, (see Table I). The reflexion spectra of typical gratings for each kind of fiber coating are shown in Section III.

The acrylate coated sensors were manufactured by the Polytechnic University of Madrid (ETSIA) using a phase mask technique. As UV source a KrF excimer laser (Lumitronic Pulse-master 844), with a wavelength of 248 nm and a maximum pulse energy of 260 mJ, was used. The FBG grating is inscribed in a photosensitive Nufern fiber (GF1) [11]. The grating engraving process continues until a 99% of FBG reflectivity is achieved; subsequently, the fiber is recoated. Neither hydrogen loading nor post-inscription annealing of the fiber was done.

The polyimide and ormocer FBG sensors were manufactured by FBGS Technologies. The gratings were inscribed during the fiber drawing process (DTG gratings). A KrF excimer laser (Compex150 T, Lambda Physik, wavelength 248 nm) in connection with a Talbot interferometer is used to write the DTGs; a single laser pulse was applied [12]. For the case of type I gratings, the pulse energy of the laser is about 200 mJ with an energy density of about 0.8 J/cm², that is, below the destruction threshold of the core glass material. For type II gratings, the laser focusing was increased to achieve an energy density of about 2 J/cm² which is above the glass damage threshold [13]–[15]. When making this single-pulse engraving of FBGs, it is of paramount importance to use fibers with a high UV-photosensitivity; besides, the draw tower process prevents

Fig. 4. Device used for the measurement of the strain sensitivity of the irradiated FBG sensors.

the use of some technical tricks to enhance the fiber's photo-sensitivity as it is the hydrogen loading of the fiber. The fibers inscribed here were developed by the IPHT institute at Jena (Germany). The fiber preforms were designed with a Germania content of about 15 mol% and are made under special oxygen reduced collapsing conditions (helium atmosphere) [16].

The sensors were read out in situ during the irradiation using a MICRON SM125 interrogating unit with an accuracy of one picometre [17].

C. Test Stand for Strain Response Studies

For the strain sensitivity study, a dedicated set-up was built. At the end of a 600 mm carbon-fiber-reinforced polymer (CFRP) tube—designed to have a negligible thermal expansion coefficient—a micrometric stage was attached. The micrometric stage can move along the tube axis direction with a precision of ten micrometers.

The lay-up of the CFRP tube is eight unidirectional layers in 0° (longitudinal) and one layer of $\pm 45^\circ$ of high strength carbon fiber AS4 with 8552 epoxy matrix. The calculated thermal expansion coefficient of this lay-up is $-0.36 \cdot 10^{-6}/K$ using the commercial calculation software ESAComp. As a cross-check, tests were performed on tubes with a similar lay-up. In these tests, 1.5 m long tubes were heated to 60°C and 100°C and their deformation was measured with a mechanical micrometer. Thermal expansions coefficients between $-0.09 \cdot 10^{-6}/K$ and $-0.18 \cdot 10^{-6}/K$ were found.

During the measurement, one end of the optical fiber carrying the FBG sensor array was fixed to the free end of the carbon fiber tube while the other optical fiber end was clamped to the micrometric stage. The fiber was strung and pre-stressed in such a way that follows approximately the CF tube axis; therefore, the FBG sensors themselves are not in contact with the CF tube, just the ends of the fiber are fixed to the tube. Controlled strains can be created in the optical fiber by moving the micrometric stage. A photograph of the actual measurement device is shown in Fig. 4.

This arrangement allows us to produce a controlled strain in the fiber with a resolution of about two microstrains. Each fiber array was measured three times (without detaching the fiber from the carbon fiber tube) before and after the irradiation session to estimate the repeatability of the measurement procedure. The FBG sensor 211 was left outside of the proton beam area while the rest of the fiber sensors of the polyimide fiber 21 were on beam. Therefore, the change of the strain coefficient (k factor) of sensor 211 before and after the irradiation is an estimate of the systematic error associated to the measurement procedure. Systematic effects that may contribute to this

Fig. 5. Strain measurement output. Dependence of the BWS with the fiber strain before and after irradiation. For the fit of the k factor, in both cases, we have subtracted the initial FBG shift. Each point is an average of three measurements. The error bars are the RMS of these three measurements (multiplied by a factor of ten to make them visible).

TABLE II
BRAGG PEAK AMPLITUDE CHANGE AND WAVELENGTH SHIFT AFTER IRRADIATION

Sensor code	Coating	Initial Amp. dBm	Amp. Change, dB	Peak Shift, pm
111	acrylate	-22.51	-0.42	-3
112	acrylate	-20.48	-0.15	-14
211	polyimide	-25.19	-0.44	10
212	polyimide	-25.02	-6.05	140
213	polyimide	-54.58	-6.26	173
214	polyimide	-24.76	-7.16	175
221	polyimide	-24.20	-7.56	158
222	polyimide	-25.22	-6.92	175
223	polyimide	-25.12	-6.92	173
021	ormocer	-23.75	-6.23	308
022	ormocer	-24.07	-8.80	379
023	ormocer	-22.63	-5.00	334
03	ormocer	-17.81	-0.01	206
04	ormocer	-15.18	-0.03	307
05	ormocer	-27.51	-0.21	359

measurement are such as the reproducibility of the fiber fixing to the measuring device. Fig. 5 illustrates the typical linear dependence between the BWS and the fiber strain for FBG sensor 222 before and after irradiation and its corresponding fitted k factors.

III. RESULTS AND DISCUSSION

A. Radiation-Induced Bragg Peak Attenuation.

Table II summarizes the effect of the proton irradiation on the Bragg peak amplitude and wavelength of the FBG sensors under test after a total dose of 15 MGy. Concerning the peak attenuation, the most visible effect is the very slight decrease of the Bragg peak amplitude of Type-II FBG gratings (FBGs 03, 04 and 05), as illustration, see Fig. 6. Consequently, both, the change in the grating reflectivity and the radiation-induced attenuation (RIA) of the inscribed fiber are negligible for this

Fig. 6. Bragg peak for the ormocer coated Type II FBG sensor 04, before (blue) and after (red) irradiation. It is observed a large BWS but a very slight peak amplitude reduction.

Fig. 7. Reflected peak for the ormocer coated Type I FBG sensor 023, before (blue) and after (red) irradiation. A large BWS and Bragg amplitude reduction is observed.

Type-II FBGs. Since polyimide and ormocer coated fibers were manufactured using the same kind of photosensitive enhanced fibers from IPHT, the fiber's RIA must have a very minor contribution to the large Bragg peak amplitude decrease observed in the remaining type I FBGs fabricated in polyimide and ormocer coated fibers, Fig. 7 shows a typical Bragg peak before and after the irradiation. Hence, the amplitude decrease can only be explained as a change in the FBGs reflectivity for these fibers. Let's recall again that FBG 211 was outside the irradiation area, therefore it is the only polyimide type I FBG that does not present a significant Bragg peak attenuation. For acrylate-coated fibers, Fig. 8 shows the Bragg peak of FBG 111 before and after the irradiation; a minor effect of the irradiation on the Bragg peak amplitude for sensors inscribed in acrylate coated fibers was found.

The observed reflectivity change for each sensor matches the expectations: Type I FBGs manufactured in fibers with relatively high concentration of Germania (15 mol% in our case) are known to be more sensitive to the radiation-induced reflectivity reduction; on the other hand, reflectivity of type II FBGs is expected to be more radiation resistance since the damage of the glass core, inherent to this type of FBGs, can not be reverted by the irradiation. The acrylate-coated FBGs were inscribed using a method with a much longer engraving time (about 30 seconds);

Fig. 8. Bragg peak from the acrylate coated Type I FBG sensor 111 before and after the irradiation (slightly attenuated peak).

Fig. 9. Bragg Wavelength Shift during and after irradiation for three different Type I sensors and the FBG temperature reference sensor. The right side axis gives the corresponding temperature values for the temperature reference sensor.

in opposition to the single-pulse method (15 ns duration) employed for DTG engraving. Longer inscribing times allow for less Germania concentration in the fiber making the resulting FBG less prone to radiation induced changes in the reflectivity.

B. Radiation-Induced Bragg Wavelength Shift

We see that the fiber with the acrylate coating shows the best behavior in terms of BWS. Polyimide coated fibers behave systematically better than ormocer coated fibers. Fig. 9, shows the BWS of three representative FBGs made on fibers with different coatings during and after the irradiation.

The BWS of the FBG temperature reference sensor, also shown in Fig. 9, follows the acrylate-coated FBG response trend, the observed difference during the irradiation, as explained before, may be caused by the temperature gradient of few degrees between different points of the fiber's support. The response of the acrylate FBG sensor and the temperature reference FBG sensor is again the same once they cool down to room temperature.

Even for the FBGs with larger radiation-induced BWS (ormocer fibers) the relative change in the Bragg Peak is about 10^{-4} , a change that can still be explained by an alteration of the coating stress induced by the irradiation damage as it is argued in [7] where the total dose was in the range of 40 KGy.

TABLE III
CHANGES ON STRAIN COEFFICIENT

Sensor code	K , pm/ μ strain (before irradiation)	K , pm/ μ strain (after irradiation)	K variation (%)
111	1,13	1,07	-5,3
112	1,13	-	-
211	1,10	1,16	5,6
212	1,10	1,16	5,6
213	1,10	1,16	5,6
214	1,10	1,17	5,9
221	1,13	1,16	2,8
222	1,14	1,16	2,2
223	1,14	1,17	2,9
021	1,14	1,16	1,3
022	1,15	1,17	1,7
023	1,16	1,18	2,1
03	1,14	1,15	0,6
04	1,15	1,17	1,9
05	1,18	1,18	-0,1

The underlying mechanism behind the observed positive BWS is the irradiation-induced liberation of gases as a result of bond scission of the coating polymeric chains [18]. Depending of the out-diffusion rate of the radiolytic gas, part of it will be trapped within polymeric matrix and causes the coating to swell and hence bringing on a positive shift of the Bragg peak wavelength. A second radiochemistry process, simultaneous with the gas liberation, is happening in the fiber coating material: the linear polymeric network is replaced by a three-dimensional network caused by the creation of transversal covalence bonds between the polymer chains (radiation cross-linking). The polymer cross-linking process may introduce some modification of the mechanical properties of the coating, in particular to increase the Young modules (increase the coating rigidity) and to reduce its elongation (coating shrinking) [19]. During the irradiation, the first process dominates as it is indicated by the positive increase of the BWS. Once the irradiation ended a BWS annealing is expected since the liberated gas will tend to diffuse outside the fiber, while the coating cross-linking will stay stable, hence the relative contribution of the cross-linking effect will increase; this translates into a decrease of the BWS after the irradiation [5].

As it was explained in Section II.B the two acrylate-coated gratings out of fifteen under study were inscribed in a different kind of fiber. In addition, these two gratings endured an extra re-coating step unnecessary for the rest of DTG gratings. In spite of the different manufacturing process and fiber type, the radiation induced BWS seen by this fiber is expected to be dominated by the coating radiochemistry. To unambiguously probe the validity of this statement we have carried out a second proton irradiation of DTG acrylate-coated IPHT fibers similar to the DTG fibers used for the study reported here. In this second experiment whose analysis is not yet completed, we observed a radiation induced WBS which saturated around 40 KGy with a plateau value of about 30 pm. This result is just a confirmation of the previous study done in these same DTG type-I acrylate-coated

TABLE IV
SUMMARY OF THE RESULTS BY TYPE OF SENSOR

Coating	Manufacture	Attenuation, dB	Peak Shift, pm	K variation (%)
Acrylate	re-coated, type I	-0.28±0.19	-8.5±7.7	-5.3
Polyimide	DTG, type I	-6.81±0.56	165±14	4.2±1.7
ormocer	DTG, type I	-6.67±1.93	340±36	1.7±0.4
ormocer	DTG, type II	-0.08±0.11	290±78	0.8±1.0

gratings inscribed in a similar fiber where a saturation was observed on the radiation induced BWS with a plateau value of about 15 pm after a dose of 30 KGy [7].

C. Radiation-Induced Change on the Strain Coefficient

Concerning the change in the strain coefficient (see Table III), it is below the 6% for all the fibers; therefore, the observed change of the k factor is within the systematic error of the measurement procedure which is 5.6%, value which was estimated from the change of the k factor of the sensor 211 (5.6%). In addition, the fact that the observed changes of the k factor are similar for the sensors inscribed in a same fiber indicates that the observed change is dominated by the systematic error of the measurement. As a second conclusion, since the change of sensor 211 is identical to the change of the rest of the fiber 21 sensors, we can say that the irradiation did not introduce any non-uniformity in the strain distribution along the fiber.

IV. CONCLUSION

We have extended the existing FBG studies on irradiation induced effects to the MGy range for which we have confirmed the importance of the coating material on the FBGs radiation sensitivity. As shown in previous results, the acrylate coated-fiber appears to be the less sensible fiber to the radiation in terms of induced radiation wavelength shifts where the coating dimensions and its radiochemistry is the driving phenomena of the observed BWS. We also confirm that Type II fibers maintain an almost unaffected reflectivity after irradiation. The results pointed out again the importance of a more detailed study of the annealing processes and how they depend on the total dose and temperature.

The strain sensitivity of the FBGs sensors before and after the irradiation does not show any significant change. The change of the strain coefficient is compatible with the systematic error of the measurement procedure.

As a spin-off, we obtained a reproducibility study of the behavior of different gratings manufactured under the identical conditions, see Table IV for a summary of the results.

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