of Fig. 3. The same figure highlights that the 1550 nm RIA in the Ge-doped fiber is higher than in the Ge-free one. Among the analyzed samples, the most radiation-resistant is the F-doped fiber, whose RIA saturates around 70 dB/km at the γ-dose of 10 MGy.

Unlike most of the absorption bands in the UV-visible region of the spectrum, the origin of the IR-RIA is not clear yet; only very few studies deal with this IR band. Chernov [17] attributed to self-trapped holes a NIR-band peaked at a wavelength longer than 1500 nm. Since we record only the tail of an IR band, we cannot determine the spectral parameters of this absorption band to confirm its attribution. Moreover, from the shape of the absorption around 600 nm we cannot affirm the presence of another band peaked at 660 nm and associated to the same defects [18].

The RIA limits the OFS performance; indeed, even if the FBG-based sensor allows only localized measurements, more gratings can be written in series inside a same fiber to determine the sensing parameter in different points along the fiber length, e.g. about ten gratings could be written along 100 m long fiber for civil nuclear applications. Concerning the gratings, the important condition that must be verified is not to overlap the spectral ranges in which the peak of each FBG can vary, for example the peaks' positions must be spaced few nm, if the gratings are temperature sensors working from RT to 100 °C. The fiber, instead, must be characterized by a reduced RIA value to allow the signal transmission along the whole fiber length and then the monitoring of all the gratings written in the same sample. As an example, we take into account a 100 m long fiber inside which ten gratings are written at a space distance of 10 m from each other and an acquisition system with an optical budget of 10 dB. At an irradiation dose of 10 MGy, the signal will be attenuated at the fiber end by 24 dB for the Ge-doped fiber, which means that it will propagate for less than half distance, i.e. 41 m, and therefore only the first four gratings will be tested. For the F-doped fiber, instead, the signal attenuation along the whole fiber length will be around 7 dB and all the sensors could be checked at the total dose of 10 MGy.

Secondly, we performed the irradiation tests on gratings and pointed out that fs-FBGs are less sensitive to radiation than classical UV-gratings. The main cause is the H_2-loading of the fiber before the grating inscription with UV light; nevertheless, it is necessary to make the fiber more photosensitive. The increase of the radiation-sensitivity with the hydrogenation has been already observed [19] and associated with the radiolytic rupture of OH-bonds [20].

Even if the BWS induced in the UV-FBG is higher than in the fs-gratings, it shows a saturating behavior, whereas the peak shift of the fs-FBGs does not seem to saturate up to 1 MGy accumulated dose. The main radiation effect on the peak of these gratings is a blue-shift. A comparable behavior was observed by Henschel *et al.* on similar fs-FBGs [8]: the BWS induced at the accumulated dose of 1 MGy is between -10 pm and $+15$ pm, lower than in our case. Apart the inscription conditions, one of the main causes of this difference is probably related with the different irradiation conditions: we used a higher dose-rate than in the experiment performed by Henschel *et al.* in their paper, 50 Gy/s against 2 Gy/s. For the classical UV-FBGs, Fernandez *et al.* have inferred that the higher dose-rate, the bigger the radiation-induced BWS [21]. Assuming the same behavior for the fs-FBGs, the higher dose-rate should be the cause of the larger BWS here reported. Moreover, we have to note another important difference between our fs-gratings and those reported in literature: ours did not withstand any thermal treatments after inscription. The effect of a pre-irradiation thermal treatment on the radiation-response is not clear yet and it depends on several parameters, as those of the inscription and of the treatment itself. By comparing the radiation-induced BWS of our gratings with those of Henschel *et al.* [8], it is likely that the annealing changes the dose and BWS values at which the shift direction occurs, and it could also reduce the BWS.

To try to understand the differences of both used inscription techniques, thanks to the confocal micro-luminescence, we studied the defects induced in the fiber by the grating inscription process. Independently of the writing laser source, the induced defects are mainly concentrated in the core region, indeed during the grating inscription the laser is focused into the fiber core. The light focalization that is simple for UV lasers becomes more complicated for the fs-gratings, because of the critical alignment between laser and fiber. This operation is realized by connecting one fiber end to a spectrometer working in the visible spectral domain to record online the emitted spectra with PL bands of defects induced by the IR-radiation inside the fiber and optimizing the interaction between incoming laser and fiber. During this procedure, the laser power is fixed at a lower value than during the inscription in order to avoid possible structural modifications of the fiber.

Figs. 6 and 7 showed the differences: the UV light generates defects only in a symmetrical area around the fiber core zone, whereas the defects produced by the fs IR-radiation are present in the fiber core and in an area along the laser direction. This asymmetry has been already observed for the fs-FBGs by Troy *et al.* [22]. Nevertheless, we took advantages of this asymmetry to study the structural changes induced by the fs laser, by easily comparing two small regions of the fiber (area of 5 μm $\times$ 5 μm) at the same distance from the core center but whose one was irradiated and the other was not. This lets us highlight the D_2 band increase induced by the fs IR-laser. Several research groups studied the effects induced by femtosecond IR laser in silica [23] and demonstrated that they are consistent with a densification process; indeed the main induced changes in the Raman spectra are the shift to higher frequencies and the width decrease for the main 440 cm^{-1} band and the intensity increase for the D_2 band. No result has been presented in literature, to our knowledge, about the effects of the fs IR-radiation on fibers. In our case, a radiation influence on the D_2 band is clearly observed in Fig. 8; but, because of the low signal-to-noise ratio, it is not possible to know if the radiation causes other small changes, as a shift of the main band, confirming the hypothesis of densification, or if the D_2 band increase is the only one and it is due to an increase of the stress inside the fiber. However, what is important to note is that structural modifications of the glass or stress redistribution can be induced during the fs-FBG writing and they could be crucial to determine the influence of radiation or thermal treatment on the grating response. For example, whereas a pre-irradiation thermal treatment increases the radiation sensi-

TABLE II
RADIATION-INDUCED ERROR

FBG	Temperature error at 1 MGy dose
UV-Ge	+14 °C
fs-Ge	−2.2 °C
fs-F	−2.3 °C
fs-PSC	−0.7 °C

Error on the temperature measurement by using the FBGs as temperature sensors in radiative environments at the accumulated dose of 1 MGy.

tivity of the UV-gratings by restoring precursors, as observed by Gusarov *et al.* [20], a different temperature effect on the radiation-resistance could be obtained for the fs-gratings, depending on its effects on the structure or stress distribution. For this reason, a study of the radiation resistance of the fs-FBGs as a function of the temperature of a pre-irradiation annealing has been recently realized by our research group [24].

Based on the above discussion, the research on radiation-resistant gratings is still of interest: very low values of the radiation-induced BWS must be obtained to use the gratings in harsh environments as strain or temperature sensors, because the BWS entails an error on the sensing parameter measurement. For example, for our gratings, if they are used as temperature sensors, the BWS induced at 1 MGy dose corresponds to an error of around 2 °C on the temperature measurement for the worst gratings, as reported in Table II. Moreover, this error is reduced to less than 1 °C for the grating written in the PSC fiber.

V. CONCLUSION

In this work we show the preliminary study that has to be performed to determine and identify both the adapted fiber and the Bragg grating photo-inscription conditions to realize a strain and/or temperature sensor suitable for a harsh environment. The F-doped SMF showed the lowest RIA value at 1550 nm among the analyzed samples at an accumulated dose of 1 MGy. The choice of a Ge-free fiber promotes the fs-radiation, as the one we used operating at 800 nm, for the grating inscription. On the contrary of the RIA, no strong dependence of the fs-FBGs' radiation sensitivity on the fiber composition was observed. Moreover, the blue-shift of the Bragg peak at 1 MGy dose corresponds to an error on the temperature measurement lower than 2.5 °C.

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Authors' biographies not available at the time of publication.