On the feasibility of using an optical fiber Bragg grating array for multi-point dose measurements in radiation therapy

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Abstract. Fiber Bragg gratings (FBGs) have proven to be a valuable dosimeter in nuclear environment where radiation doses reach up to a hundred of kiloGray (kGy). Multiple FBGs can be written in a single fiber to allow multi-point detection which would prove very useful for radiotherapy dosimetry. The purpose here is to adapt this already existing technology to provide a novel dosimeter for radiotherapy measurements. The proposed real-time dosimeter consists of twenty 4 mm-long FBGs, equally distributed over 20 cm. FBGs are written through the coating of a standard polyimide-coated silica fiber with the phase-mask technique and femtosecond pulses. The wavelength dependant variation of each FBG is recorded at 1 kHz with a commercially available interrogator. The use of gamma radiation (clinical radiotherapy accelerator) induces a linear shift (0.070 ± 0.006 pm/Gy) of the FBG’s reflected wavelength, which is independent of the dose rates (2.8-11.6 Gy/min) and the energy (6-23 MV). A statistical error of 0.03 pm is obtained on data points therefore limiting the detectable dose to 0.4 Gy. A dose profile of 6 and 23 MV radiotherapy accelerator is also measured. The presented FBGs dosimeter allows for real-time dose measurement in 2D and the small size of its detector makes it a versatile tool. The length and spacing of FBGs can be easily modified to increase both the spatial resolution and the amount of dose point.

1. Introduction
Fiber Bragg gratings (FBGs) are now common and versatile sensors used in a wide range of applications in the industries to measure pressure, stress or temperature. They can be used to detect leaks on a pipeline, but also measure the deformation of the wings of an airplane during flights [1-2]. A FBG is a periodic or quasi-periodic modification of an optical fiber core refractive index relative to its propagation axis. When light propagates through this periodic refractive index variation, it produces a reflection of a narrow bandwidth of light centered around the Bragg wavelength. A variation of temperature or strain applied to the FBGs sensors produce a reflected wavelength shift. Thus, the FBGs sensors determine the quantity of interest (pressure, stress, temperature, etc.) by measuring the reflected wavelength shift. FBGs sensor has also proven to be a useful dosimeter in nuclear environment where dose reach up to a hundred kGy [3]. In these conditions, radiation produces damages to the fiber glass, which modifies the fiber refractive index according to the Kramers-Kronig relation [4]. This results in a reflected wavelength shift that can be measured with a dedicated interrogator and correlated to the emitted...
radiation. Since many FBGs can be written in a single fiber, this dosimeter allows, by design, multi-
point detection. A single point prototype relying on post-irradiation thermo-optic properties of FBGs,
therefore preventing real-time use, was proposed with a reported minimum detection of 0.160 Gy [5].

Hence, the purpose here is to adapt this technology to provide an innovative real-time dosimeter
for radiotherapy measurements. For this proof-of-concept, an optical 20 points real-time dosimeter,
using fiber Bragg gratings, is proposed for clinical radiation dosimetry measurements. Preliminary
characterization of this dosimeter response to dose and dose rates is presented in this paper as well as
dose profile measurements.

2. Methods and materials

2.1. FBGs inscription

The FBGs are written by focusing 35 fs pulses at 800 nm (Coherent, Astrella) through the coating of a
standard 125 µm polyimide-coated fiber (OFS BF06160-02) by a short focal acylindrical lens [6]. A
custom e-beam phase mask with 20 uniform periods ranging from 1045 nm to 1091 nm was used to
write an array of 20 different 4-mm long FBGs along the fiber length. The FBGs are spectrally
distributed from 1516 nm to 1581 nm, with a separation of 3.4 nm between each peak.

2.2. Irradiation conditions

All irradiations were performed on a CLINACiX. Shifts in wavelength due to irradiation of the FBGs
by a 6 and 23 MV beam were recorded for a dose up to 20 Gy. A 6 Gy/min dose rate and 10 X 10 cm
field size were used unless otherwise noted.

2.3. Experimental set-up

The detector is made of twenty (20) 4mm-long FBGs, equally distributed over 20 cm. The detector is
fixed to a PMMA sheet to minimize environmental factor variation such as pressure applied on the
detector. The plastic sheet also ensures that the detector is tightly surrounded by diffusing material. The
wavelength shift of each FBG is recorded at 1 kHz with a commercially available interrogator (si155,
Micron Optics) and its sensing analysis software (ENLIGHT). The data points are averaged to have one
measure per second. As shown in figure 1, a diffusing material (solid water) is used and the detector is
placed at d_{max} (1.5 cm for 6 MV and 3.5 cm for 23 MV).

![Figure 1. Experimental set-up. As the laser beam spreads into the FBGs, the reflected wavelength is measured with the interrogator.](image-url)
3. Results and Discussion

3.1. Dose and dose rates dependence
A linear reflected wavelength shift is obtained upon irradiations. Using 21 dose measurements (3 trials of 7 FBGs), the mean signal slope is 0.070 pm/Gy and the standard deviation is 0.006 pm/Gy. Figure 2a shows the reflected wavelength shift of 1 grating produced by a 20 Gy irradiation. The standard error on data points is 0.03 pm, which, using the response to dose slope, leads to a detection limit of this early prototype of 0.4 Gy. This detection limit is far from the 0.01 Gy dose resolution required for radiotherapy applications [7], but we are currently working on material optimization to make the dosimeter more sensitive to radiation which will increase the detection limit. It should also be noted that a higher sampling frequency would decrease the statistical error therefore resulting in an increased detection limit.

The detector is dose rate independent (tested between 2.8 – 11.6 Gy/min) as shown in Figure 2b. The presented values are averaged from seven measurements, except for the 6 Gy/min dose rate for which we averaged the Bragg reflected wavelength shift for twenty-one irradiations. The error bar corresponds to one (1) standard deviation.

![Figure 2](image)

Figure 2. a) Bragg reflected wavelength shift in terms of dose and b) differential Bragg reflected wavelength produced by a 20 Gy irradiation (6 MV beam).

3.2. Dose profiles
A dose profile of 6 MV and 23 MV radiotherapy accelerator 10 x 10 cm beam is measured with a mean error of 6.3 ± 0.7 % and 7 ± 1 % on the central region (Figure 3). The signal variation can be explained by the fact that Bragg wavelengths are affected by temperature variation. We applied a temperature-based correction to minimize the impact of temperature variation on the detector response, but the method still needs improvements. The mean shift over 21 measurements (3 trials of the 7 FBGs in the central region) is 1.4 ± 0.1 pm for the 6MV beam and 1.4 ± 0.1 pm for the 23MV beam. Thereby, we conclude that the presented submillimeter-size detector is also energy independent between 6MV and 23 MV beams.
4. Conclusion
We propose a novel FBG-based dosimeter that supports real-time dose measurements in 2D. The submillimeter diameter (155 microns diameter) of the detector makes it suitable for in vivo dosimetry, as well as regular and small field measurements. It allows, by design, multi-point dose measurements with a spatial resolution of 4 mm, which make dose profile measurements possible. Moreover, it has a linear response to dose while being independent to dose rate and energy. It is also important to mention that length of FBGs and spacing can be customized and hence, the spatial resolution and the amount of dose points can be increased significantly, up to 50 with the current assembly. We now plan on developing a prototype with suitable spatial resolution for small field dosimetry.

5. Acknowledgements
This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery grants RGPIN #2019-05038 and Natural Sciences and Engineering Research Council of Canada (CG112389).

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