Shape sensing with a smart elastic textile band containing pre-strained FBG sensors

Bastien Van Esbeen*[a], Damien Kinet[a], Corentin Guyot[b], Annick Depré[c], Rik Knoppers[d], Remco Nieuwland[d], Christophe Caucheteur[a]
[a]ERC Unit – Advanced Photonics, Boulevard Dolez 31, Mons Belgium;
[b]B-SENS, Boulevard Dolez 31, Mons Belgium;
[c]Elasta, Textielstraat 15, Waregem Belgium;
[d]Somni Corporation B.V., Rotterdamseweg 183C, Delft Netherlands

ABSTRACT

This paper reports on the development of a smart elastic textile band containing pre-strained fiber Bragg gratings (FBG) that was specifically designed with the ambition to dynamically measure the position of the backbone. To this aim, the textile band is 700 mm long and 60 mm wide. A piece of standard single-mode optical fiber, in which four fiber Bragg gratings were inscribed, is sewn on the band. Each FBG is glued on a 3D-printed pad in a pre-strained way, allowing the detection of FBG compression in addition to elongation. Measurements were performed on this sensing elastic band and the resulting sensitivity is a Bragg wavelength shift of 12 pm per mm of textile elongation. Validation tests were also carried out to highlight the sensitivity to compression and to show that the sensing system is capable of repeatability in a dynamic environment.

Keywords: Fiber Bragg grating, smart textile, fiber optic sensor, medical monitoring

1. INTRODUCTION

Because of their numerous intrinsic advantages (small size, immunity to electromagnetic interferences, robustness, wavelength-encoded information, capability of quasi-distributed sensing with a remote interrogator, etc.), fiber Bragg grating (FBG) sensors are preferred compared to classical solutions in an increasing number of practical applications. Strain, temperature and bending sensing remain the most prominent examples although the technology is even more developed for (bio)chemical sensing. Optical fibers and FBGs in particular are also very well suited for used within or right over a textile. Hence, medical applications find interest in fiber optics sensors embedded in textile[1–3], e.g. for respiratory monitoring[4–6].

Compared to the existing literature about smart textiles based on fiber optics sensors, this work presents a new design allowing the sensor to measure both elongation and compression of the textile. Since an FBG sensor at rest is only able of elongation sensing, this design was conceived in such a way that the fiber Bragg gratings are pre-strained.

This summary first defines an FBG and explains its working principle, then describes the optical fiber integration into the textile and the fabrication design. Afterwards, the outcomes of the sensing setup calibration in the lab are exposed. This calibration aims to determine the resulting sensitivity of the sensing system, i.e. the Bragg wavelength shift [pm] per unit of elastic textile elongation [mm]. Finally, validation tests were performed to confirm the good operation of compression sensing and of repeatability.

*bastien.vanesbeen@umons.ac.be

2. FBG THEORY

An FBG is a periodic and permanent modification of the core refractive index inside an optical fiber. This modulation constitutes a distributed mirror, reflecting a small portion of the incident light at the Bragg wavelength λ_B and every other wavelength is transmitted. An FBG is described by its grating period Λ, grating length L and refractive index modulation δn. The Bragg wavelength λ_B can be computed as

$$\lambda_B = 2(n_{\text{eff}} + \delta n)\Lambda \approx 2n_{\text{eff}}\Lambda \tag{1}$$

where n_{eff} is the effective core refractive index. If there is a variation of n_{eff} or Λ, a Bragg wavelength shift is observed, which can be used for axial strain, temperature or pressure sensing. The FBG sensitivity to strain and temperature is linear, typical values at 1550 nm are 1.2 pm/με and 10 pm/°C, respectively.

3. TEXTILE FABRICATION AND SENSOR INTEGRATION

The elastic textile band was manufactured by Elasta (Waregem, Belgium) and is 700 mm long and 60 mm wide. A scheme of the design is represented in Figure 1. A single-mode telecommunication-grade optical fiber composed of four Bragg gratings was sewn on the band, letting a few centimeters of loss fiber between the gratings so that it gets stretched when the textile elongates. Both ends of each grating are glued on a pad (one per grating), 3D-printed by Somni Corporation B.V. (Delft, Netherlands). This particular design basically aimed to achieve backbone monitoring, although the concept of pre-strained sensors in textile can be used for a large set of applications requiring strain sensing on warping surfaces.

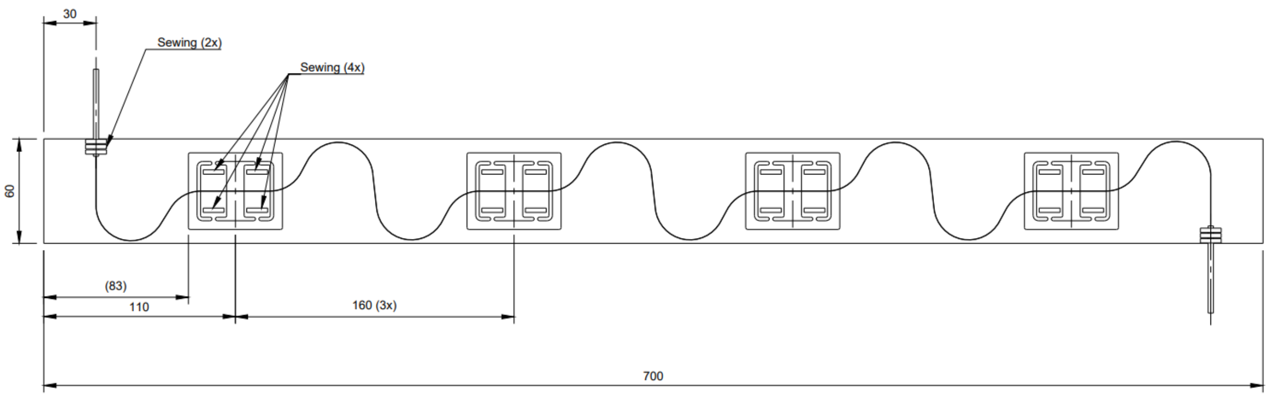

Figure 1. Scheme and sizes of the textile band design.

4. CALIBRATION MEASUREMENTS

The calibration consists in finding the Bragg wavelength shift per unit of textile elongation, i.e. the sensitivity of the whole sensing structure. Indeed, As the deformation of the fiber does not exactly follow that of the textile, due to the presence of the 3D-printed pad, the resulting sensitivity is decreased. The textile band was subject to a traction test in the *Civil Engineering and Structural Mechanics Department* of UMONS (Figure 2). Measurements were done by an FBG interrogator under development by B-SENS (Mons, Belgium), with a sample speed of 200 Hz. The Bragg wavelength shift Δλ was recorded for a textile elongation ΔL from 0 mm (rest state) to 90 mm by steps of 5 mm. The textile band was then released from 90 mm to 0 mm with the same step. The corresponding graph can be found in Figure 3. The resulting sensitivity is the slope of the linear fit of the data, leading to 12 pm/mm with a R^2 value of 0.94. It has to be noted that a limited hysteresis can be observed, due to the elastic behavior of the band.

Figure 2. Picture of the textile band during traction test.

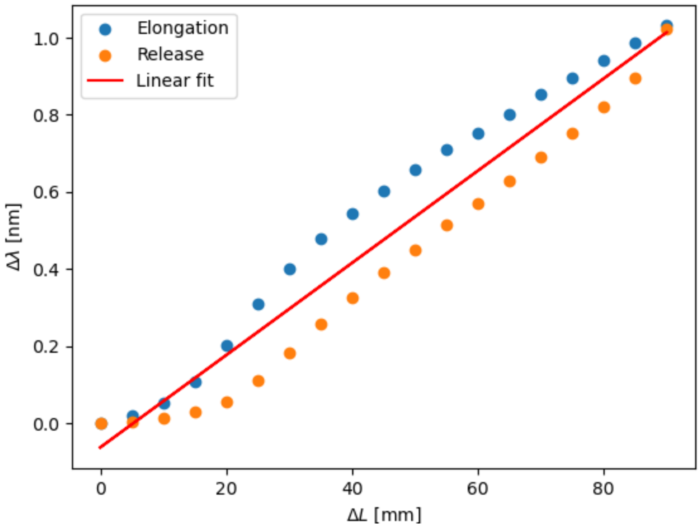

Figure 3. Bragg wavelength shift Vs textile elongation.

5. VALIDATION TESTS

5.1 Compression sensibility

In order to highlight the ability of the sensor to detect shrinkage in addition to elongation, an FBG of the textile was subject to a stretching of 7 seconds followed by a contraction of 10 seconds. The recorded Bragg wavelength versus time is represented in Figure 4. The sensor is at rest state between 0 and 6 seconds and between 26 and 35 seconds.

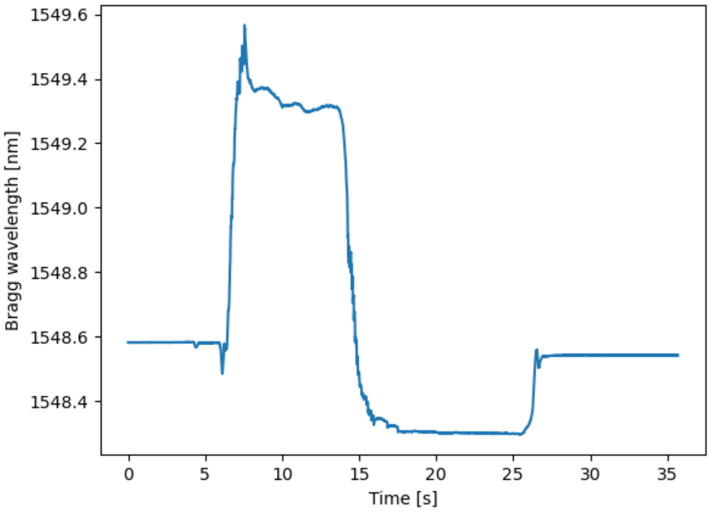

Figure 4. Bragg wavelength shifts versus time in the case of elongation and contraction applied to the textile band.

5.2 Repeatability

To demonstrate the good operation of the smart textile in a dynamic environment, ten traction cycles were applied from the rest state to an elongation of 90 mm. Each cycle lasted roughly 130 seconds (80 seconds of elongation, 50 of release).

Figure 5 shows the measured wavelength shift as a function of time. The operation of the sensor is very similar from one cycle to another. The red lines represent the highest level among the maxima and the lowest level among the minima. The mean of all the maxima is 1064.549 pm with a standard deviation of 2.463 pm. For the minima, the mean is -6.665 pm and the standard deviation 0.607 pm. This proves that the developed smart textile has a very accurate repeatability ability.

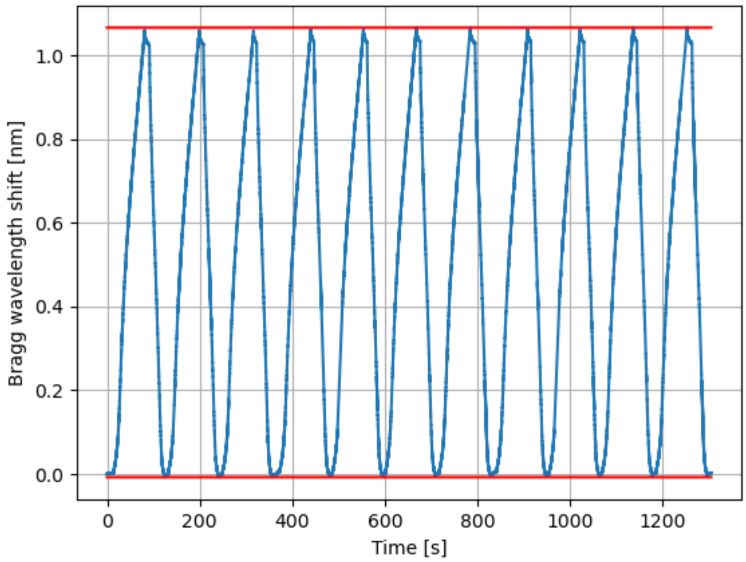

Figure 5. Bragg wavelength shift versus time for ten elongation-release cycles applied to the textile band.

6. CONCLUSION

In conclusion, this paper has demonstrated the development of a smart textile using pre-strained fiber Bragg gratings as sensors. The textile fabrication and the sensor integration in it was described. The design was imagined in a such way that the sensors are able to detect elongation as well as compression. The outcome of the calibration is a sensitivity of 12 pm/mm, based on a 700 mm long elastic band. Validation tests confirmed the compression sensitivity and the repeatability ability of the smart textile.

REFERENCES

[1] Quandt, B. M., Scherer, L. J., Boesel, L. F., Wolf, M., Bona, G. L. and Rossi, R. M., "Body-Monitoring and Health Supervision by Means of Optical Fiber-Based Sensing Systems in Medical Textiles," Adv Healthc Mater **4**(3), 330–355 (2015).

[2] Grillet, A., Kinet, D., Witt, J., Schukar, M., Krebber, K., Pirotte, F. and Depré, A., "Optical fiber sensors embedded into medical textiles for healthcare monitoring," IEEE Sens J **8**(7), 1215–1222 (2008).

[3] Lo Presti, D., Massaroni, C., Formica, D., Saccomandi, P., Giurazza, F., Caponero, M. A. and Schena, E., "Smart Textile Based on 12 Fiber Bragg Gratings Array for Vital Signs Monitoring," IEEE Sens J **17**(18), 6037–6043 (2017).

[4] Lo Presti, D., Romano, C., Massaroni, C., D'Abbraccio, J., Massari, L., Caponero, M. A., Oddo, C. M., Formica, D. and Schena, E., "Cardio-respiratory monitoring in archery using a smart textile based on flexible fiber Bragg grating sensors," Sensors (Switzerland) **19**(16) (2019).

[5] Massaroni, C., Saccomandi, P., Formica, D., lo Presti, D., Caponero, M. A., di Tomaso, G., Giurazza, F., Muto, M. and Schena, E., "Design and Feasibility Assessment of a Magnetic Resonance-Compatible Smart Textile Based on Fiber Bragg Grating Sensors for Respiratory Monitoring," IEEE Sens J **16**(22), 8103–8110 (2016).

[6] Ciocchetti, M., Massaroni, C., Saccomandi, P., Caponero, M. A., Polimadei, A., Formica, D. and Schena, E., "Smart textile based on fiber Bragg grating sensors for respiratory monitoring: Design and preliminary trials," Biosensors (Basel) **5**(3), 602–615 (2015).