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Design and characterization of a curvature sensor using fused polymer optical fibers

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This Letter demonstrates the application of polymer optical fibers (POFs) damaged by the fiber fuse effect to curvature sensing and dynamic angular monitoring. The curvature sensing performance using the fused-POF is compared to POF without the fuse effect. Both POFs are submitted to angles of up to 90 deg in flexion/extension cycles with angular velocities ranging from 0.48 rad/s to 5.61 rad/s. The fused POF is found to show higher performance with respect to sensitivity, correlation coefficient with linear regression, and hysteresis. For instance, at the angular velocity of 0.48 rad/s, the fused POF shows >3 times higher sensitivity and significantly lower hysteresis than those of the non-fused POF. In addition, the fused POFs have lower cross-sensitivity and hysteresis variations on the tests with different angular velocities. These results indicate that the fused POFs are potential candidates to develop curvature sensors with various advantages over non-fused POFs, for applications such as gait analysis and wearable robotics.

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Optical fiber sensors have been used to measure various physical parameters, such as temperature [1], strain [2], pressure [3], refractive index [4], and curvature [5], among others. In addition to silica optical fibers, polymer optical fibers (POFs) have also been used for sensing purposes. Although POFs generally suffer from higher optical propagation losses, they have some advantages over silica fibers, which include a non-brittle nature, higher strain limits, flexibility in bending, and fracture toughness [6]. By exploiting these advantages, numerous kinds of POF sensors have been developed for the past several decades. They are, for instance, based on short and long period gratings [7,8], interferometry [9], Brillouin scattering [10], and intensity variations [11].

A catastrophic fiber fuse effect is a self-destruction process of an optical fiber [12], where high-power light causes an optical discharge under certain conditions, such as tight bending or damaged connection. POFs are generally composed of various materials, such as polymethyl methacrylate (PMMA), polycarbonate, Zeonex, thermoplastic olefin polymer of amorphous structure, and cyclic transparent optical polymer (CYTOP), where these materials are further discussed in [13]. From all these types of POFs, the fiber fuse effect has been observed only in the CYTOP-based POF [14,15]. The POF fuse was initiated with the amplified signal from a laser diode at 1546 nm to 200 mW using an erbium-doped fiber amplifier. One extremity of the POF was connected to a silica single-mode fiber, whereas the other end was covered with 0.5-μm alumina powder for the fuse ignition [14].

In silica glass fibers, periodical voids are created inside the core after the fuse effect [12]. Although many sensing applications of these voids in fused silica fibers have been reported [16,17], fused POFs are yet to be further explored for sensing applications. Unlike the case of the silica fiber fuse, light can still propagate through the fused POFs, but with a high attenuation of ~1.4 dB/cm [15]. In addition, the mechanical characterization of the fused POFs [18] indicates that they have some advantages over the same type of non-fused POFs for elastic deformation sensing applications (strain, curvature, etc.), especially when the deformation is dynamically applied.

In this work, we report, for the first time, to the best of our knowledge, the development of a curvature sensor using a fused POF. This sensor is based on the light power attenuation when the POF is under curvature. In this sensor, one of the mechanisms for light power attenuation is the variations of the refractive index induced by the increased stress, via the stress-optic effect (changes in the refractive index with increasing stress) [11]. Therefore, the POF material properties play a major role in the sensor performance. In order to compare the performances (such as sensitivity, hysteresis, and correlation coefficient with linear regression) of the fused-POF-based sensor with the non-fused ones, curvature tests with different angular ranges and velocities were conducted similarly in both POFs.

Figure 1 schematically shows the experimental setup for evaluating the curvature sensing performance of fused and non-fused POF samples. The sample lengths were both set to 5 cm, as the propagation loss of the fused POF is relatively high. The light source was a low-cost laser with a central wavelength at 650 nm with 5 mW power, where it is also possible to employ light emitting diodes (LEDs) such as the one presented in [19]. The power of the POF-transmitted light was converted into an electrical signal using a photodiode (IF-D91, Industrial Fiber Optics, USA) with a trans-impedance amplifier. The acquisition was made at a sampling rate of 200 Hz using a data-acquisition board (USB-6008, National Instruments, USA). The angle and the angular velocity were controlled using a direct current (DC) motor, and the reference angle was measured using a potentiometer-based goniometer with angle and angular velocity uncertainties of ~0.1 deg and ~0.01 rad/s, respectively.

We performed annealing of the fused and non-fused POF samples before their installation in the setup. Annealing of POFs (thermal treatment process) is an effective method to suppress the measurement hysteresis [20] and increase their sensitivity to mechanical parameters [21]. In the annealing process, POFs are generally kept at a temperature that is close to, but lower than, their glass transition temperature for several hours [20]. In this experiment, both POF samples were placed inside a thermostatic chamber (Ethik Technology, Brazil) at 95°C for 48 h (note that the glass transition temperature of CYTOP-based POFs is higher than 100°C). In addition, in order to increase the measurement sensitivity and linearity, which is defined as the determination coefficient with linear regression (R^2), lateral sections were machined in both the POF samples through abrasive removal of material to create sensitive zones with a length of ~14 mm and a depth of ~0.1 mm [5].

After the sample preparation, curvature tests were conducted in the angular range from 0 deg to 90 deg. To evaluate the sensitivity, R^2, and hysteresis, the angular velocity was kept constant. Subsequently, additional tests were performed to evaluate the sensitivity and hysteresis. The angular interval was the same, but different angular velocities, ranging from 0.48 rad/s up to 5.61 rad/s, were applied.

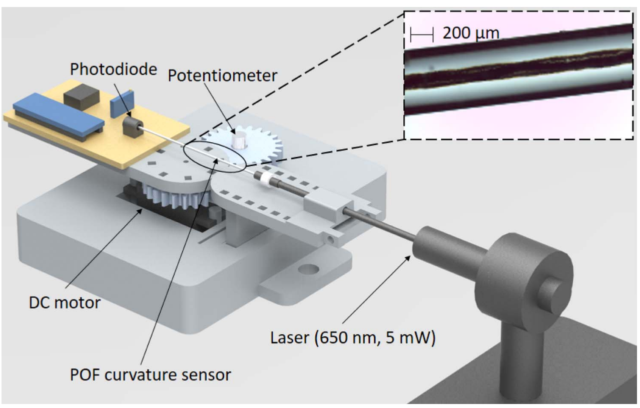


Fig. 1. Experimental setup for evaluating the curvature sensing characteristics of fused and non-fused POF samples. The inset is a microscopy photograph of the fused POF.

First, for fused and non-fused POF samples, the transmitted powers were plotted as a function of angles from 0 deg to 90 deg at a constant angular velocity of 0.48 rad/s (Fig. 2). The vertical axis was normalized so that the optical power at 0 deg became 1. With the increasing angle, both POF samples showed optical power attenuation, but the angle sensitivity of the fused POF was 0.0067 deg^{-1}, which was >3 times larger than that of the non-fused POF (0.0019 deg^{-1}). In addition, the R^2 between the measured data and its linear regression for the fused POF was 0.999, which was much closer to 1 (perfectly linear) than that of the non-fused POF (0.995). The higher sensitivity of the fused POF may be attributed to its higher optical propagation losses. Also, the higher R^2 of the fused POF may be originated from its highly linear relationship between stress and strain, when compared with the non-fused POF [18].

Subsequently, in order to evaluate the hysteresis, both POF samples were submitted to flexion and extension cycles, at an angular velocity of 0.48 rad/s, in order to obtain the sensor response with the lowest influence of the angular velocity. The measurements were repeated for three cycles, to show the sensor repeatability, and the averaged values were used. The results for non-fused and fused POFs are shown in Figs. 3(a) and 3(b), respectively. The hysteresis (defined as the highest normalized distance between the flexion and extension curves [22]) of the fused POF was 0.01% (within the detectable minimal limit), which was much lower than that of the non-fused (0.21%). Note that this value is two orders of magnitude lower than that reported for PMMA-based POF at this angular velocity (~1.2%) [5]. The reason for this difference may be related to the higher R^2 of the stress–strain curve of the fused POF [18]. Another reason may be the fact that the fused POF shows lower Young's modulus dependence with the frequency variations than the non-fused POF [18].

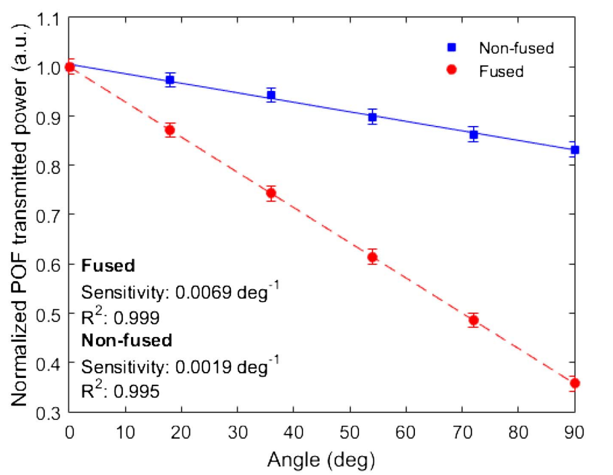
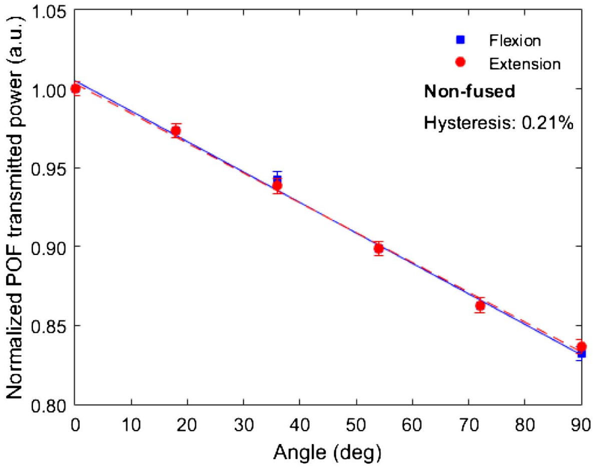
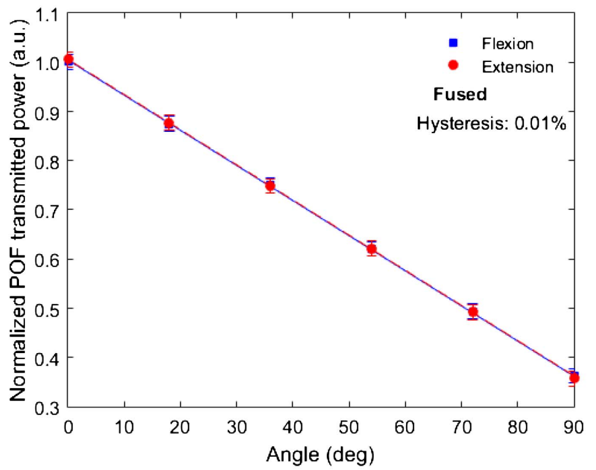


Fig. 2. Angle dependencies of the normalized transmitted power for fused (red) and non-fused (blue) POFs at a constant angular velocity of 0.48 rad/s. The points are the measured data, and the lines are the linear fits.



(a)



(b)

Fig. 3. Normalized transmitted power as a function of the angle for flexion/extension (blue/red) cycles for the: (a) non-fused and (b) fused POFs. The angular velocity was 0.48 rad/s. The points are the measured data, and the lines are the linear fits.

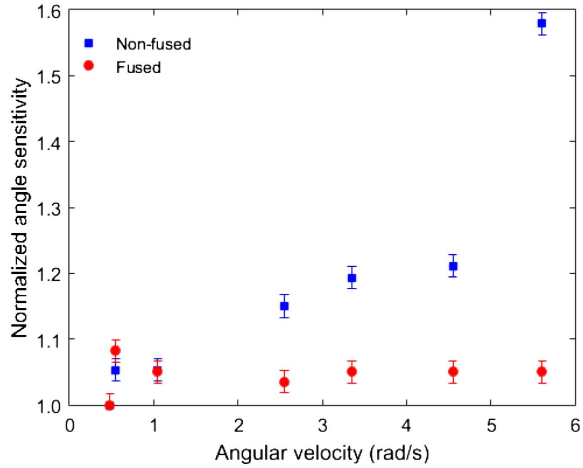


Fig. 4. Normalized angle sensitivities plotted as functions of angular velocity for non-fused (blue) and fused (red) POFs.

Next, the influence of flexion/extension cycle frequency on the angle sensitivity of the POF samples were analyzed by changing the angular velocities (0.48 rad/s, 0.55 rad/s, 1.05 rad/s, 4.55 rad/s, and 5.61 rad/s made in the range between 0 deg and 90 deg, whereas 2.55 rad/s and 3.35 rad/s performed in the range of 0 deg to 50 deg due to experimental limitations). Since the power-attenuation mechanism of the POFs includes the stress-optic effect [11], the variations in the Young's modulus [18] can lead to stress variations, which result in different attenuation characteristics. Hence, if the material properties of the POF change with the frequency or, in this case, angular velocity, there may be a cross-sensitivity of the angle sensitivity with respect to the angular velocity.

Figure 4 shows the angle sensitivity dependencies on the angular velocity for fused and non-fused POFs. The vertical axis was normalized so that the sensitivity (absolute value) became 1 at 0.48 rad/s, and the error bars represent the propagation of the experimental uncertainty due to the materials employed in the setup. Such uncertainty is about 2% of the measured values. The sensitivity of the non-fused POF clearly increased with the increase of the angular velocity, whereas the sensitivity of the fused POF remained relatively unchanged and did not show a significant variation. The reason for this behavior is the low variation of the fused POF Young's modulus, with the increasing strain-applying cycle frequency, when compared with the same POF without the fuse effect [18]. Such lower variations in the Young's modulus lead to lower variations of the refractive index with increasing angular velocity, resulting in the lower cross-sensitivity. Therefore, from the viewpoint of a stable operation without the influence of the cross-sensitivity, the fused POF is preferable to the non-fused POF (especially for the applications at angular velocities higher than ~1 rad/s). This feature is particularly advantageous in gait analysis applications, where the human knee develops a high variation of its angular velocity (~3.5 rad/s [5]), which will lead to errors in the angle measurement if the sensor presents a high angular velocity cross-sensitivity. Similarly, lower limb exoskeletons work in a range of angles that requires a sensor with lower cross-sensitivity. Therefore, the fused POF application as curvature sensor for movement analysis and in wearable robotics provides practical advantages when compared with the non-fused POFs.

Finally, the hysteresis dependencies on the angular velocity were also investigated for the fused and non-fused POFs (Fig. 5). Once again, the error bars represent the propagation of the experimental uncertainty (below 2% of the measured values). With an increasing angular velocity, the hysteresis of the non-fused POF clearly increased, whereas that of the fused POF was negligibly low in the whole range of tested angular velocities. Even the highest hysteresis obtained for the fused POF was as low as 0.04% (when the angular velocity was 0.55 rad/s). The lower variations in the hysteresis of the fused POF can also be attributed to the lower differences in the Young's modulus. These experimental results indicate that fused POFs have many advantages over standard non-fused POFs, and as so, are a promising candidate for intensity-variation-based curvature sensing.

In summary, we characterized the fused and non-fused POFs as intensity-variation-based curvature sensors. The flexion/extension cycle tests revealed that the fused POF exhibited higher

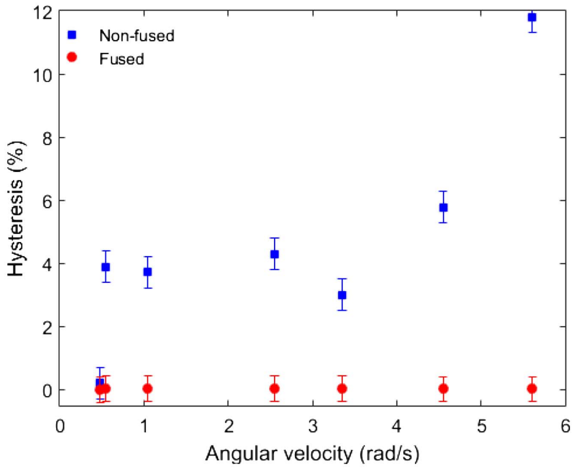


Fig. 5. Hysteresis dependencies on angular velocity for non-fused (blue) and fused (red) POFs.

sensing performance in all the measured parameters, including higher angle sensitivity, higher R^2, and lower hysteresis than those of the non-fused POF. In addition, measurements at different angular velocities showed that the fused POF has lower cross-sensitivity and lower hysteresis than those of the non-fused POF. It is also worth mentioning that multiple curvature sensors can be used if additional photodetectors are employed or by using multiplexing techniques. Thus, the presented results demonstrate that fused POFs will be of significant use in developing low-cost curvature sensors with high sensitivity and stability.

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REFERENCES

1. R. da Silva Marques, A. R. Prado, P. F. da Costa Antunes, P. S. de Brito André, M. R. N. Ribeiro, A. Frizera-Neto, and M. J. Pontes, Sensors **15**, 30693 (2015).
2. M. C. J. Large, J. Moran, and L. Ye, Meas. Sci. Technol. **20**, 34014 (2009).
3. K. Bhowmik, G.-D. Peng, Y. Luo, E. Ambikairajah, V. Lovric, W. R. Walsh, and G. Rajan, J. Lightwave Technol. **33**, 2456 (2015).
4. A. R. Prado, A. G. Leal-Junior, C. Marques, S. Leite, G. L. de Sena, L. C. Machado, A. Frizera, M. R. N. Ribeiro, and M. J. Pontes, Opt. Express **25**, 30051 (2017).
5. A. G. Leal-Junior, A. Frizera, and M. J. Pontes, J. Light. Technol. **36**, 1112 (2018).
6. C. A. F. Marques, D. J. Webb, and P. Andre, Opt. Fiber Technol. **36**, 144 (2017).
7. C. A. F. Marques, R. Min, A. Leal Junior, P. Antunes, A. Fasano, G. Woyessa, K. Nielsen, H. K. Rasmussen, B. Ortega, and O. Bang, Opt. Express **26**, 2013 (2018).
8. M. P. Hiscocks, M. A. van Eijkelenborg, A. Argyros, and M. C. J. Large, Opt. Express **14**, 4644 (2006).
9. R. Oliveira, T. H. R. Marques, L. Bilro, R. Nogueira, and C. M. B. Cordeiro, J. Lightwave Technol. **35**, 3 (2017).
10. H. Lee, N. Hayashi, Y. Mizuno, and K. Nakamura, J. Lightwave Technol. **35**, 2306 (2017).
11. A. G. L. Junior, A. Frizera, and M. J. Pontes, Opt. Laser Technol. **93**, 92 (2017).
12. S. Todoroki, *Fiber Fuse: Light-Induced Continuous Breakdown of Silica Glass Optical Fiber* (Springer, 2014).
13. Y. Luo, B. Yan, Q. Zhang, G.-D. Peng, J. Wen, and J. Zhang, Sensors **17**, 511 (2017).
14. Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura, and S. I. Todoroki, Appl. Phys. Lett. **104**, 043302 (2014).
15. Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura, and S. I. Todoroki, Sci. Rep. **4**, 4800 (2014).
16. P. F. C. Antunes, M. F. F. Domingues, N. J. Alberto, and P. S. André, IEEE Photon. Technol. Lett. **26**, 78 (2014).
17. C. Díaz, C. Leitão, C. Marques, M. Domingues, N. Alberto, M. Pontes, A. Frizera, M. Ribeiro, P. André, and P. Antunes, Sensors **17**, 2414 (2017).
18. A. Leal-Junior, A. Frizera, M. J. Pontes, P. Antunes, N. Alberto, M. F. Domingues, H. Lee, R. Ishikawa, Y. Mizuno, K. Nakamura, P. André, and C. Marques, Opt. Lett. **43**, 1754 (2018).
19. A. Sultangazin, J. Kusmangaliyev, A. Aitkulov, D. Akilbekova, M. Olivero, and D. Tosi, IEEE Sens. J. **17**, 6935 (2017).
20. W. Yuan, A. Stefani, M. Bache, T. Jacobsen, B. Rose, N. Herholdt-Rasmussen, F. K. Nielsen, S. Andresen, O. B. Sørensen, K. S. Hansen, and O. Bang, Opt. Commun. **284**, 176 (2011).
21. A. Pospori, C. A. F. Marques, D. Sáez-Rodríguez, K. Nielsen, O. Bang, and D. J. Webb, Opt. Fiber Technol. **36**, 68 (2017).
22. K. Kalantar-Zadeh, *Sensors: An Introductory Course* (Springer, 2013).