A strain reflection-based fiber optic sensor using thin core and standard single-mode fibers

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\textbf{A B S T R A C T}

We propose and demonstrate a fiber optic strain sensor based on a simple splice between a thin core fiber and a piece of conventional single-mode fiber. Mode dispersion generates an interference reflection spectrum sensitive to strain and temperature. The sensor offers a competitive strain sensitivity of 2.4 pm/\mu m, good linearity (R\textsuperscript{2} = 0.9969), and a cursory repeatability analysis yielded variation. The thermal studies indicate minimal cross-sensitivity (2.9 \mu m/\degree C). The sensor offers a simple implementation without any intricate manufacturing.

1. Introduction

Optical fiber strain sensors have been proposed and demonstrated for some decades [1–3]; Different approaches were developed for various applications in which strain measurement is necessary with high precision, such as in structural health monitoring [4], robotics [5] and biomedical applications [6]. One of the first approaches demonstrated for strain estimation uses Fiber Bragg Gratings (FBG) [1]; usually, the sensitivity of these devices is less than 1.3 pm/\mu m [7]. This sensitivity can be improved by combining FBGs and interferometric devices [8,9]. However, intricate fabrication processes are required for these. Another well-known technique to estimate strain is related to optical fiber tapers [10,11]; these devices show similar sensitivity to FBGs. Furthermore, the sensitivity can be further improved by combining these elements with other all-fiber optical filters [12]. Unfortunately for both FBGs and tapers, the combination that enhances the strain sensitivity also increases the thermal sensitivity, and as a consequence, cross-talk can be present [13]. Another approach consists purely of optical fiber interferometers. These devices are fabricated by combining optical fibers with different geometries and characteristics, fiber optic strain sensors based on Fabry–Perot [14], Sagnac [15], Michelson [16], and Mach–Zehnder [17] configurations have been proposed. Here again, the need for special fibers and sophisticated splicers has limited mass production. Therefore, there is a need for high-sensitivity fiber optic strain sensors based on conventional fabrication processes and available optical fibers.

We propose a reflection-based fiber optic strain sensor. The device is fabricated by splicing a thin core fiber and a piece of single-mode fiber. The simple fabrication process does not require any sophisticated elements. The sensor offers a competitive sensitivity (2.4 pm/\mu m), good linearity (R\textsuperscript{2} = 0.9920), high repeatability, and a simple fabrication process. Furthermore, the thermal analysis shows minimal cross-talk (2.9 \mu m/\degree C).

2. Fabrication process and principle

The reflective interferometric optical fiber structure is shown in Fig. 1. At the end of an optical fiber Corning HI1060FLEX, a section of Plasma Fibre with similar characteristics to an SMF-28 optical fiber is spliced. The splice was made using a commercial arc splicer Fitel S-174 H in SMF automatic mode operation (see inset of Fig. 1). The HI1060FLEX fiber has a core diameter of 3.4 \mu m, and the SMF-28 fiber has a core diameter of 9.3 \mu m. Then, this splice generates a core diameter mismatch point. Consequently, the initial core mode propagating in the Corning HI1060FLEX excites a cladding mode at the splice point that travels along the SMF-28 fiber section.

It is essential to mention that the SMF-28 coating is not removed, except for a concise section, at the splice point and the end of the fiber. Therefore, the cladding energy is affected by the coating/cladding interface. Part of the cladding mode arrives at the flat end-face of the SMF-28 fiber and is back-reflected and coupled back into the HI1060FLEX's core at the splice point. The intensity of the final reflected signal (I\textsubscript{c}) is determined by interference between the core (I\textsubscript{1}) and the cladding (I\textsubscript{2}) modes as:

\begin{equation}
  I_c = I_1 + I_2 + 2(I_1I_2)\exp(0.5)\cos(4\phi)
\end{equation}

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where the phase difference of the interference is determined by:

$$\Delta \varphi = 4\pi (n_{co} - n_{cl}) L_{eff} / \lambda$$  \hspace{1cm} (2)$$

where $n_{co}$ and $n_{cl}$ are the effective refractive index of the dominant core and cladding modes, respectively, $L_{eff}$ is the effective length, and $\lambda$ is the free-space wavelength. According to Eq. (1), the minima in the spectrum can be described by:

$$\lambda_{dip} = 4(n_{co} - n_{cl}) L_{eff} / (2k + 1)$$  \hspace{1cm} (3)$$

where $k$ is a positive integer value, if the effective refractive index of either mode incurs a change, the wavelength of the interference minimum will be shifted. Additionally, using two consecutive minima points, the Free Spectral Range (FSR) can be computed by:

$$FSR = \frac{\lambda_{dip} \cdot \lambda_{dip}}{2 \cdot (n_{co} - n_{cl}) \times L_{eff}}.$$  \hspace{1cm} (4)$$

As can be appreciated, the splice mismatch point will generate the interfering modes, as a consequence this section governs the interferometer’s response; The interfering modes are exited due to the modal profile differences between the thin core fiber and the conventional single-mode fiber. Then, by using the overlap integral, it is possible to estimate the modal coupling power fraction ($W_{TCF,SMF28}$) for a specific cross-section ($\sigma$) [18,19]:

$$W_{TCF,SMF28} = \left( \int_{\sigma} \left| E_{TCF} \right|^2 \exp(2) ds \right) \times \left( \int_{\sigma} \left| E_{SMF28} \right|^2 \exp(2) ds \right) \exp(1/2).$$  \hspace{1cm} (5)$$

This expression considers the electric field of the thin core fiber ($E_{TCF}$) and the electric field of SMF28 ($E_{SMF28}$), and their boundary conditions need to be linked to the $\sigma$ (core or cladding). By using this expression will be possible to determine que energy at cladding that generates the interference. It is important to recall that the coupled energy will be reflected at the end of the SMF28 by Fresnel relation. Here, the flat end-face needs to be perpendicular to the axis of the fiber because any slight angle will break the symmetry and minimize the reflected modes [20].

### 3. Sensing setup and analysis of sensor parameters

#### 3.1. Experimental strain sensing setup

The sensors were characterized using the setup shown in Fig. 2. Light from a Broad Band Source (BBS) is launched into an Optical Fiber Coupler (OFC), where a part is directed to the reflective interferometric optical fiber structure, and the spectrometer monitors the reflection signal.

#### 3.2. Analysis of reflection-based fiber optic parameters

The interference spectrums of some reflection-based interferometers are shown in Fig. 3a. Besides, multiple sensors were fabricated using
different SMF-28 lengths (see Table 1). The subscript indicates the length range: a~19 cm, b~33 cm, and c~50 cm. In this work, 12 samples were fabricated with similar effective lengths to validate the fabrication process.
As can be appreciated in Fig. 3b, as the length is increased, the FSR of the interference fringes decreases. The FSR depends on the effective refractive index difference between the modes generated at the splicing point [21]. This difference depends on the cut-off frequency and the core dimensions difference [22]. It is important to mention that cladding modes can be excited in different ways, such as forming an L-angle [23] or a balloon shape [24–28]. In those cases, the effective refractive index in the transition region influences the interference spectrum, and therefore the effective length is not necessarily the physical length of the interferometer. Furthermore, the refractive index of the coating has a significant impact on the effective refractive index of the cladding mode [27,29].

Additionally, when the effective length is similar, the FRS is similar (see Fig. 3b). Overall, an increase in the length corresponds to...
Fig. 8. (a) Interference wavelength shifting of $E_{1b}$ as the strain increases, (b) Sensitivity analysis of samples with similar FRS ($E_{1b}$, $E_{2b}$, and $E_{3b}$), (c) Four consecutive round analysis of peak 949.3 nm in the $E_{1b}$ interference spectrum, (d) Hysteresis analysis of $E_{1b}$.

Table 2

| Parameter                        | SMF-28 | HI1060FLEX |
|----------------------------------|--------|------------|
| Core diameter                    | 9.3 μm | 3.4 μm     |
| Cladding diameter                | 115.7 μm | 121.6 μm  |
| Refractive index value – Core    | 1.4670 | 1.4680a    |
| Refractive index value – Cladding| 1.4470 | 1.4528a    |

*Considering nominal value by the fabricant.

These high order modes have confinement of 99.8% and 99.9%, and their strongest intensity distribution ensures their propagation in the SMF-28 section. These modes cover a significant sensing area; as a result, it can be expected a good sensitivity to the external perturbations. The above simulations are computed at the splice point where the coating is removed.

4. Numerical analysis

A Mode Lumerical simulation of the SMF-28 and HI1060FLEX cross-sections are computed to analyze the modal distribution and the modal coupling power fraction. This model provides information about the light intensity distribution and the effective refractive index under the parameters presented in Table 2.

In Fig. 4, the normalized magnitude of the electric field intensity at the cross-section of the SMF-28 and the HI1060FLEX fibers can be visualized using the color distribution, where the blue and red represent the lower and the highest electric field intensity, respectively. The simulation indicates that $L_{P_{01}}$ mode intensity distribution can be expected considering the propagation wavelength of 950 nm and the parameters of Table 2. Furthermore, by using Eq. (5), the $L_{P_{01}}$ coupling power fraction ($W_{TCP_{SMF-28}}$) at the SMF-28 is 29.70%. As a result, the rest of the energy goes to the cladding region. The simulation at the SMF-28 cross-section indicates that the strongest modes can be expected at the cladding with effective refractive indices of 1.44697 and 1.44693 (see Fig. 5).

5. Experimental results and discussion

5.1. Strain analysis

The strain response is analyzed by setting the interferometers between the translation stages T1 and T2 (see Fig. 2). Then, by applying...
The strain analysis indicates that the sensitivity increases as the length of the SMF-28 increases; here, the FSR range decreases. When a micro-displacements at T1, the strain is controlled. The strain response is analyzed considering the length of the samples. The first samples to be analyzed are samples with an FSR close to 10 nm (a~19 cm). For instance, the spectrum strain response of sample E2, is presented in Fig. 7a. As the strain increases, the spectral modulation is shifted to shorter wavelengths, and the maximum shift is 4.5 nm; then, a sensitivity close to 1.7 pm/με is achieved. As the polymer coating is stressed, the material’s refractive index is altered, and it is assumed that the wavelength shifting is related to the effective refractive index change of the cladding mode at the cladding/coating interface. The sensitivity of interferometers with an FSR of 10 and 9 nm are compared in Fig. 7b; here, a minima point shows a very similar pattern, and their sensitivities are similar (E1 = 1.6 pm/με, E2 = 1.7 pm/με and E3 = 1.7 pm/με). The samples also show good linearity, around R² = 0.98. Repeatability is analyzed and shown in Fig. 5c. Four strain cycles were applied, and a maximum variation of 0.41 nm was found at 1250 με. Additionally, hysteresis is analyzed by measuring increasing and decreasing strain where no path variation is observed (see Fig. 7d).

The samples with a FSR close to 4 nm (b~33 cm) are secondly studied. For these samples, the distance between T1–T2 is increased to hold the interferometers, then T1 is used to control the strain. The strain response of sample E2b, is presented in Fig. 8a. The same wavelength shift direction as a function of strain is observed. Fig. 8b compares the sensitivity of this sample to samples with similar FSR (7 nm). An average shift of 8.5 nm yielding similar sensitivities (E1b = 2.3 pm/με, E2b = 2.1 pm/με, and E3b = 2.0 pm/με). Again, we find good linearity with maximum linearity presented by E3b, of R² = 0.9930. Repeatability analysis of E1b, shows an absolute error of 61 με in 1739 με (see Fig. 8c). This sample also presents no path variation in the hysteresis analysis (see Fig. 6d).

A third study is carried out on samples with an FSR around 4 nm (c~50 cm), yielding a maximum shift of 6.8 nm (see Fig. 9a) and sensitivities: E1c = 2.3 pm/με, E2c = 2.4 pm/με, and E3c = 2.4 pm/με (see Fig. 9b). In this case, the T1–T2 distance is also increased. However, the length of the interferometers limits the section where the strain applied is over an SMF-28 fiber section. The repeatability analysis shows minimal error (1.04% με) at 434με (see Fig. 9c). The hysteresis analysis shows minimal variation around 0.6 nm (see Fig. 9d).

5.2. Thermal analysis

The thermal analysis is conducted on samples E4a, E4b, and E4c, in this samples the length of the interferometers increases in a linear manner. These samples were fixed over Corning PC-420D hotplate; the temperature was increased from 20 °C to 100 °C, and a thermocouple monitored the temperature. The hotplate dimensions limit the temperature exposure of the SMF-28 section for samples with a length longer than 20 cm. The sample E4a showed a wavelength shift of 1.85 nm (see Fig. 10a). As a result, a sensitivity of 23.1 pm/°C is achieved. The wavelength shifting is related to the modal cladding effective refractive index variation at the coating/cladding interface. As the length of the fiber increases, the shift decreases; for instance, E4b shows a shift of 1.30 nm (see Fig. 10b) or a sensitivity of 16.2 pm/°C. In Fig. 10c, the lowest sensitivity around 7 pm/°C can be observed (E4c); and correspond to the maximum length of the SMF-28 (52 cm), where it is essential to mention that the temperature variation is applied only in the middle of the reflection-based optical fiber interferometer (as a consequence of the hotplate dimensions).

5.3. Discussion

The strain analysis indicates that the sensitivity increases as the length of the SMF-28 increases; here, the FSR range decreases. When a
Fig. 10. Thermal dip wavelength response for temperature variation of (a) $E_{4a}$, (b) $E_{4b}$ and (c) $E_{4c}$.

### Table 3

Comparative sensitivity chart with prior and recent works.

| Ref. | Sensitivity (pm/$\mu$) | Range ($\mu$) | Year |
|------|------------------------|---------------|------|
| [31] | 1.89                   | 0–4000        | 2019 |
| [9]  | 2.14                   | 0–1250        | 2019 |
| [32] | 2                      | 0–450         | 2020 |
| [33] | 2                      | 0–1800        | 2020 |
| [34] | 1.20                   | 0–1000        | 2021 |
| [35] | 1.5                    | 50–150        | 2021 |
| [36] | 1.57                   | 0–800         | 2022 |
| [37] | 1.05                   | 0–2000        | 2022 |
| This Work | 2.4                    | 0–2500        | 2022 |

A small FSR is used to monitor strain, ambiguity about the position can occur, however, signal processing techniques can be used to separate the measurements of different minima [30]. Furthermore, the thermal studies show that the cross-sensitivity can be decreased if the length of the SMF-28 increases. The minimal cross-sensitivity of around 2.9 $\mu$/°C is presented for samples with an FSR of approximately 4 nm. This response is related to the long coating region that avoids thermal influence, where the strain measurement is not compromised. As can be appreciated in Table 3, this simple technique provides high strain sensitivity than other strain fiber optic sensors.

### 6. Conclusion

A sensitive fiber optic strain sensor operated in reflection mode is experimentally demonstrated. The sensor is fabricated by splicing a section of SMF-28 to the end of a thin core fiber. The reflection-based optical fiber structure generates an interference spectrum in which the FSR decreases as the length of the SMF-28 increases. This effect was demonstrated by fabricating 12 probes with a linear increment of the SMF-28 fiber length. The sensors exhibit a linear wavelength-shift response as the strain is increased. This wavelength shift is related to the effective refractive index change of the cladding mode at the coating/cladding interface. As the strain sensitivity goes from 1.3 pm/$\mu$ to 2.4 pm/$\mu$, this sensitivity variation is related to the SMF-28 fiber length increment. The samples with high sensitivity show good repeatability with minimal errors, and according to the hysteresis analysis, almost zero path variation is presented. This sensitivity is competitive when compared to prior works. Furthermore, the thermal analysis indicates minimal cross-sensitivity (2.9 $\mu$/°C) for the probes with a large section of SMF-28. While considering the elements involved and the fabrication process, the sensing setup is versatile and can be easily implemented for remote sensing applications.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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