Large OPD Extrinsic Fabry Perot Interferometers using Thermally Expanded Core Fiber

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1. Introduction

Extrinsic Fabry Perot Interferometers (EFPI) Sensors have been extensively used for the monitoring of strain and temperature into smart materials and structures[1]. For these applications, the Fabry-Perot cavity used is usually formed by an air gap of few tens of microns located between the extremity of an input single-mode fiber and the reflective extremity of another fiber, either single-mode or multimode. Such gap values provide in fact a good compromise between strain sensitivity, temperature sensitivity and optical performances of the sensor.

For some other applications, like position or linear displacement sensors, the constraints of implementation are not exactly the same and can incite to use larger working distances (for instance one millimeter or more) between the extremity of the single mode fiber and the surface of the reflecting part (fiber, mirror or metallic surface). In such a case, the light power reflected by the surface and back coupled into the core of the input single mode fiber can be very low (typically, less than 0.3% at a wavelength of 1300 nanometers), which makes poorer the intrinsic performances of the distance sensor.

The use of collimating optics is a possible way to increase the working range of such interferometric sensors, but the tolerances applicable to the angular position of the reflecting surface become very stringent and unachievable in most of the cases. An efficient solution can be provided by the replacement of the Fabry-Perot arrangement by a Michelson device, which uses a reference arm and cube corner reflectors instead of plane mirror surfaces[2], but this method leads to larger probe size and more expensive sensor systems.

It is the reason why we have imagined to use single-mode Thermally Expanded Core (TEC) fibers[3] to increase the usefull range of EFPI position sensors to one millimeter or more, without any penalty onto the performances, the size and the cost of the distance probe.

2. Fundamental properties of single-mode TEC Fibers

TEC fibers are fabricated by heating single-mode fibers locally at a temperature comprised between 1300°C and 1600°C with a micro burner (propane/oxygen flame). The duration of this heat treatment varies from 2 minutes up to 60 minutes. This temperature increase induces a radial diffusion of the dopants of the fiber core from the center to the periphery, and, as a consequence, an enlargement of the Mode Field Diameter. The heating region being finite, the longitudinal profile of the fiber core becomes tapered, as shown at the Figure 1.

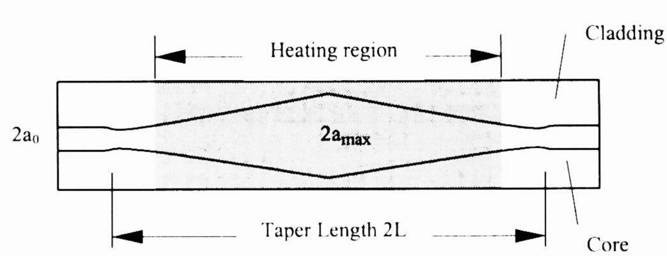


Figure 1 – Schematic illustration of a TEC fiber

This fiber is finally cut in two parts, symmetrically with respect to the center of the heating region, in order to obtain a component whose the untreated extremity can be easily spliced to a standard single-mode fiber, while the enlarged mode field extremity can be used as a part of a low loss connector.

By using the phase-front transformer model[4], it is possible to compute the intrinsic transmission T_0 of the TEC fiber shown at the Figure 1. We found :

$$T_0 = \left[1 + \left\{ \gamma_{\max} (\gamma_{\max} - 1) \frac{\pi n_0 w_0^2}{\lambda L / 2} \right\}^2 \right]^{-1} \tag{1}$$

where n_0 is the refractive index of the cladding of the fiber, w_0 the fundamental Mode Field Radius (MFR), λ the wavelength, L half the taper length and γ_{max} the maximum core expansion ratio (which is in practical identical to the maximum MFR expansion ratio w_{max}/w_0).

For maximum MFR expansion ratio comprised between 2 and 3, the intrinsic loss of such TEC fibers remains below 0.1 dB for Taper Length greater than 12 mm, which allows the manufacturing of EFPI position sensor of small size (L < 6 mm).

3. EFPI Sensors using TEC Fibers : Theoretical analysis

A schematic description of a distance sensor using TEC/EFPI probe is shown at the Figure 2.

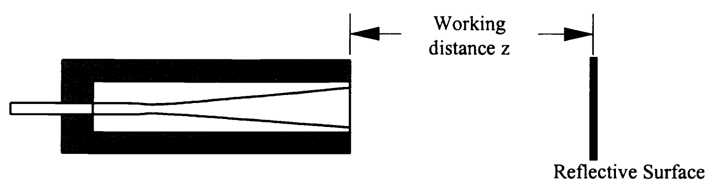


Figure 2 – TEC Fiber EFPI Probe

This probes includes only a TEC fiber and a metallic sleeve to allow its stable and firm fixation in front of the reflective surface.

The optical behavior of the EFPI probe can be described in first approximation by restricting to two the number of reflected waves, i.e. :

- the wave reflected by the silica/air interface at the output of the TEC fiber (reflection coefficient ρ equal to 3,4%)
- the wave reflected by the metallic surface and back-coupled into the same TEC fiber (effective reflection coefficient ηR, where η is the coupling efficiency and R the reflection coefficient of the surface).

In this approximation, the optical transfer function of the probe can be expressed as follows

$$P_R(z, \lambda) = T_0^2 P_0 \left\{ \rho + (1-\rho)^2 R\eta(z) - 2(1-\rho)\sqrt{\rho R \eta(z)} \cos \frac{4\pi z}{\lambda} \right\} \tag{2}$$

where P_0 is the incoming light power, P_R the reflected light power, T_0 the intrinsic transmission of the TEC fiber, z the distance between the extremity of the TEC fiber and the reflective surface and $\eta(z)$ the back coupling efficiency defined by[5] :

$$\eta(z) = \left[1 + \left[\frac{\lambda z}{\pi \gamma_{\max}^2 w_0^2} \right]^2 \right]^{-1} \tag{3}$$

By introducing the normalized working distance $\tilde{z} = z / \gamma_{max}^2$, the optical transfer function of a TEC/EFPI probe can be rewritten as follows :

$$P_R(\tilde{z}, \lambda) = P_0 \Re(\tilde{z}) \left\{ 1 + m(\tilde{z}) \cos \frac{4\pi\gamma_{max}^2 \tilde{z}}{\lambda} \right\} \qquad (4)$$

where $\Re$ is the mean coefficient of reflection of the probe and m the index of modulation of the interferometric signal.

The variations of these two last quantities versus the normalized distance $\tilde{z}$ are plotted on the Figure 3 and show that TEC fibers with expansion ratio of 3 allows to manufacture high quality displacement sensors with working distance up to 5 mm.

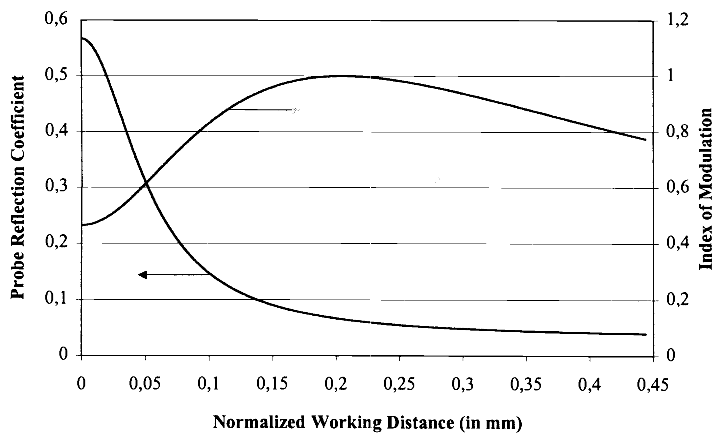


Figure 3 – Main Optical Characteristics of a TEC/EFPI Probe

4. Experimental results

We have purchased TEC fibers manufactured by KYOCERA FineCeramics S.A., single-moded at 1.3 µm and characterized by a Mode Field Diameter around 20 µm (standard products are commercially available at 1.55 µm with expansion ratio between 2 and 3).

The experimental set-up used to perform the optical characterization of the TEC/EFPI probes is described at the Figure 4. It allows to determine the absolute values and the variations of both quantities defined in the previous theoretical section (mean coefficient of reflection, index of modulation).

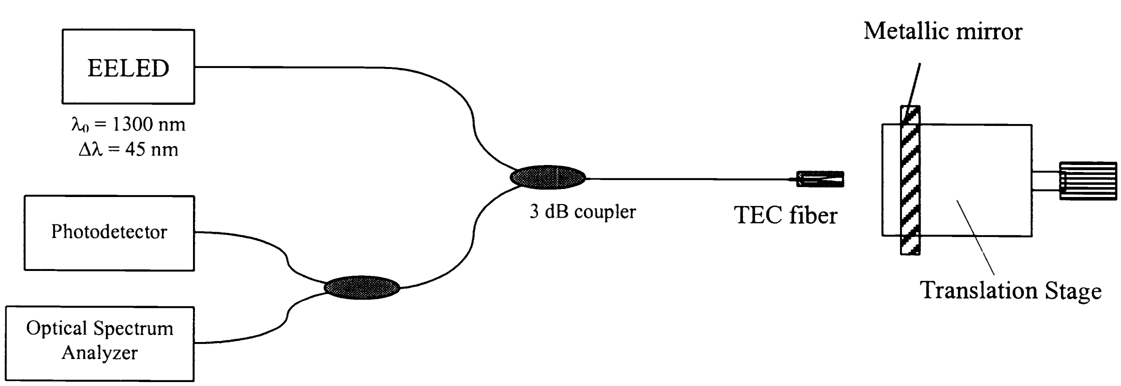


Figure 4 – Experimental set-up

The reflecting surface used here is a flat Invar surface (reflection coefficient around 65% at 1.3 μm) and its position is checked continuously with a .1 μm accuracy electronic displacement sensor .

The Figure 5 shows the variations of the quantity H(z) defined by

$$H(z) = \sqrt{(P(0) - P(z))/(P(z) - P(\infty))} \tag{5}$$

where P(z) is the amount of light power received on the detector when the distance between the extremity of the TEC fiber and the metallic mirror is equal to z.

By combining relations (2) and (3), it is easy to demonstrate that, for working distances greater that the coherence length of the source, H(z) shall be linear with respect to z, the slope being equal to $\lambda / \pi\gamma_{\max}^2 w_0^2$.

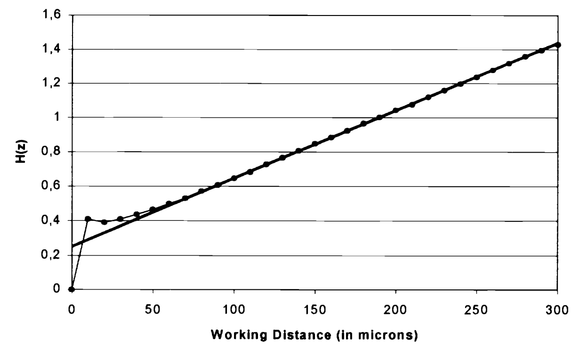
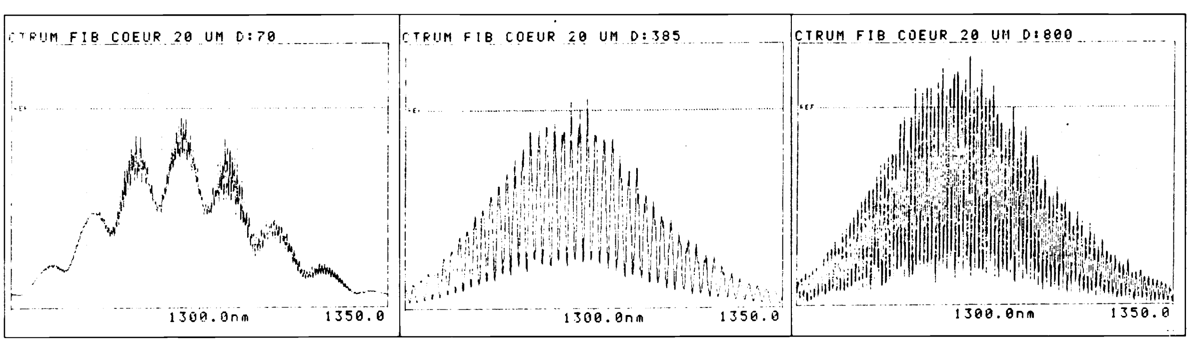


Figure 5 – Experimental results : Variations of the H parameter with the working distance z

The quality of the linear relationship experimentally obtained between H and z for distances greater than the coherence length of the EELED, i.e. 40 μm (black dots : experimental data – black line : linear fitting) confirms that the mode profile at the output of the TEC fiber is always single-moded and allows us to determine the value of the expansion ratio, i.e. 2.2 assuming a 4.65 μm initial MFR.

Figures 6a to 6c show the shape of the spectral profile of the light power reflected by this displacement sensor for three specific working distances, i.e. 70 μm, 315 μm and 800 μm. The index of modulation reached for so large OPD values (for instance 1,6 mm for the Figure 6c) makes the proof that TEC/EFPI probes with expansion ratio between 2 and 3 can be used as accurate displacement sensors even at working distance chosen in the 1-5 millimeters range, and be demodulated through coherence reading with a scanning receiver interferometer.



Figures 6 – Spectrum of the light power reflected by TEC/EFPI probe

5. Conclusion

Single-mode Thermally Expanded Core Fibers provide a efficient mean to extend the working range of EFPI displacement sensors in the 1-5 millimeters range. The only constraint applicable to the manufacturing of such components remain the excess loss level, while absolutely no requirements are needed on the repeatability of the MFD value of the expanded region (which is naturally not the case for the low loss connectors applications).

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