Polarization mode dispersion effects in embedded fiber optic strain sensors

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Abstract

The strain of an optical fiber, embedded in a composite laminated plate, was measured using radio frequency interferometry. While the response of a similar fiber glued to the plate was linear with the applied loading, the strain experienced by the embedded fiber exhibited significant fluctuations around the linear expected trend. This phenomenon is qualitatively described in terms of polarization mode dispersion associated with excess fiber birefringence, which was introduced during the manufacturing process of the laminated plate.

Keywords: strain sensors, smart structures, polarization mode dispersion

2. Introduction

The use of embedded optical fibers for strain measurements in composite structures has recently become a very active field of research for smart structures applications [1]. Strain in the structure is transferred to the optical fiber, where it induces a phase shift in the propagating optical signal. This phase shift is linearly proportional to the average applied strain. One widely investigated technique for detecting the strain-induced phase shift is optical interferometry [2]. Due to its high sensitivity, this technique, however, has one major drawback: commonly occurring strains (100-5000 microstrains) give rise to optical phase shifts of many radians, and fringe counting techniques must be utilized to extract the information from the optical signal. To overcome this impediment, fiber optic radio-frequency (RF) interferometry is used [3,4]. Here, the light is amplitude modulated at GHz frequencies before it is transmitted through the fiber. At the output of the fiber the light is detected and the result is electronically mixed with a reference at the same RF frequency. The outcome is a DC signal proportional to the cosine of the RF phase difference between the arms of the interferometer. With a proper choice of the RF frequency and, as long as the applied strain is small enough, this signal is linearly proportional to the average strain experienced by the embedded fiber.

In this paper we report strain measurements of a fiber embedded in a composite laminate, that was manufactured in a high pressure/high temperature process. RF interferometry was used and the performance of this interferometer was checked with a strained free fiber.

During the strain measurements in the embedded fiber we have observed the following phenomenon: Instead of increasing linearly with the applied straining force, the measured strain fluctuated around its actual value, as determined by a reference electrical strain gauge. With the aid of an additional experiment we have identified the cause of these fluctuations: variations in the state of polarization (SOP) during the straining process, together with the existence of significant birefringence within the embedded fiber, were translated via the interferometric mechanism into variations in the output signal.
After sketching the theory in Sec. 3, the experiment is described in Sec. 4, followed by a discussion (Sec. 5) and conclusions (Sec. 6).

3. Theory

When a free and/or embedded optical fiber is stressed, the optical field propagating within the fiber suffers a phase shift. This is the result of two major effects: The physical change in the fiber length and the change in the refractive index due to the strain-optic effect (the change in the propagation constant due to the change in the lateral dimensions of the waveguide can be ignored [5]). Aligning the z-axis of a cartesian coordinate system with the fiber (and in the embedded case, with the x-axes perpendicular to the laminate), we further assume that all the applied forces do not give rise to shear strains and that the principal (major) axes of the induced non-spherical optical index ellipsoid are parallel to the coordinate axes. Under these assumptions we expect the three non-zero strains to induce refractive index changes according to [6]:

\[
\begin{bmatrix}
\Delta \left( \frac{1}{n_x^2} \right) \\
\Delta \left( \frac{1}{n_y^2} \right) \\
\Delta \left( \frac{1}{n_z^2} \right)
\end{bmatrix} =
\begin{bmatrix}
p_{11} & p_{12} & p_{12} \\
p_{12} & p_{11} & p_{12} \\
p_{12} & p_{12} & p_{11}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z
\end{bmatrix}
\]

(1)

where \( p_{ij} \) are the Pockels constants, \( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are strains along the coordinate axes and \( n_x \), for example, is the refractive index for an optical wave polarized in the x-direction.

For a free fiber under longitudinal stress,

\[
\varepsilon_x = \varepsilon_y = -\mu \varepsilon_z = -\mu \Delta L / L
\]

(2)

where \( \mu \) is the Poisson ratio and \( L \) and \( \Delta L \) are, respectively, the fiber length and differential elongation. Substituting Eq. (2) into (1), the additional phase shift accumulated by the propagating wave as a result of the applied strain becomes [4]:

\[
\Delta \phi_{opt} = \frac{2\pi}{\lambda_o} (n \Delta L + L \Delta n) = \frac{2\pi L}{\lambda_o} n \left[ 1 - \frac{n^2}{2} p_{12} + \frac{n^2}{2} (p_{11} + p_{12}) \mu \right] \Delta L / L.
\]

(3)

Here, \( n \) is the unstrained refractive index of the fiber, and \( \lambda_o \) is the optical wavelength.

In the embedded case, when the laminate is under tensile stress parallel to the optical axis of the fiber, the values of \( \varepsilon_x \) and \( \varepsilon_y \) are no longer a function of only \( \varepsilon_z \), and they may have different values resulting in anisotropic phase shifts which are still proportional to \( \varepsilon_z \).
In a fiber-optic RF interferometer the light is amplitude-modulated with a sinusoidal signal at frequency $\omega_m$ (in the GHz range). When the fiber is under longitudinal stress, the phase of the modulating signal changes together with that of its optical carrier. The relation between the RF and optical phases is given by:

$$\Delta \phi_s = \frac{2\pi}{\lambda_0} K_s \varepsilon, \quad \Delta \phi_p = \frac{2\pi}{\lambda_0} K_p \frac{\Delta L}{L}. \quad (4)$$

Thus, the use of RF interferometry reduces the phase shift by as much as 5 orders of magnitude, resulting in a linear sensor response, rather than a periodic one.

4. Experiment

The average strain along an optical fiber was measured with a fiber-optic RF interferometer (Fig. 1). We used an RF source at 2.5 GHz to amplitude modulate a 1.3$\mu$m optical carrier. The modulated optical carrier was transmitted through a polyimide coated single mode optical fiber, which was subjected to increasing longitudinal strain. Three different cases were studied: First, we measured the strain in a free fiber, then we glued the fiber to the skin of a 60cm long, composite laminated plate, and finally we measured a fiber which was embedded within a similar plate. While in the first case the elongation was directly measured with a micrometer, in the latter two cases the strain was measured with the use of electronic strain gauges, that were glued to the plate skin. The plates were made of 4 plies of Graphite/Epoxy fabric and were glued to both sides of an Aluminum Honeycomb (Fig 2). The strain was applied to the plates using a four points loading configuration (Fig. 3), which ensured uniform distribution of the strain between the inner loading points (Fig 3 - inset).

Results: Figure 4 shows plots of the free fiber strain as measured by the sensor (ordinate) versus the actual value that was found by directly monitoring the fiber elongation (abscissa). To obtain strain values for the ordinate, the sensor output was processed via Eq. (3), assuming: $n = 1.467$, $p_{12} = 0.27$, $p_{11} = 0.121$, $\mu = 0.17$. 

![Figure 1: The experimental setup](Image)
The measurements were repeated several times and always followed straight lines with a slope of 0.94 (instead of 1), indicating that the actual parameters of the fibers are slightly different than those assumed above. Note that the different lines, while being parallel, are horizontally displaced from one another, due to the experimental uncertainty in the absolute determination of the zero strain point (abscissa). Similar results were obtained for the externally glued fiber (Fig. 5). Again the response was linear and the readings were in good agreement with the reference measurement taken by the centered strain gauge.
Strong deviations from linearity were observed in the case of the embedded fiber (Fig. 6). While the response of the strain gauge was linear as before, the strain as measured by the sensor fluctuated around it. The results were found to be highly sensitive to the polarization of the launched light. We installed a polarization controller just in front of the sample, and instead of increasing the
force continuously, we stopped at several points, and for the temporarily fixed stress took measurements of the strain for different settings of the polarization controller, namely, for different input states of polarization (SOP). The resulting response appears in Fig. 7, where it is clearly seen that the variations in the sensor output caused by the changes in the input SOP are of the same size as the fluctuations in Fig. 6.

5. Discussion

It is well known that deviations of the fiber core from circular symmetry, as well as internal or external stresses induce birefringence (i.e. a dependency of the refractive index on the SOP of the light) into an otherwise nonbirefringent fiber. The optical field, propagating in a birefringent fiber, can always be expressed as a weighted sum of two distinctive modes, each propagating at a different group velocity with weights that are simply the projections of the propagating field upon these two modes. This phenomenon is commonly called: Polarization Mode Dispersion (PMD) [7].

In the interferometric configuration of Fig. 1 the existence of two differently delayed modes is translated to polarization dependent output signal: if the input SOP is aligned with the faster mode the delay in the sample is minimized, while when aligned with the slower mode, the delay is maximized. Any other SOP results in some intermediate value. Since the interferometer output is proportional to this delay (for not too large strains), the existence of polarization mode dispersion can result in finite size fluctuations of the interferometer output.

![Figure 6: Sensor strain results for the embedded fiber](image-url)
6. Conclusions

A fiber optic RF interferometer strain sensor was described. Results of strain measurements in a free fiber, a fiber that was glued to the skin of a composite laminated plate and a fiber embedded in a similar plate were presented. While the responses of the sensor in the case of the free fiber and the glued fiber were linear as expected, strong fluctuations appeared for the embedded fiber. These fluctuations were attributed to the existence of polarization mode dispersion, which was induced in the fiber during the high temperature/high pressure embedding process. The unfortunate breaking of the embedded fiber prevented us from making further more direct investigations of this induced polarization mode dispersion. However, additional experiments with other samples confirmed that the polarization mode dispersion of the embedded fiber is much higher than that of the free fiber. These results, together with a more comprehensive analysis of the phenomenon will be published elsewhere.

These polarization-induced fluctuations must be eliminated before real practical use can be made of such embedded fiber-optic strain sensors. The use of high birefringence fibers, as well as launching unpolarized light into the sample are few of the solution paths that are currently under investigations.
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8. References