Quasi-distributed strain sensing with white-light interferometry: a novel approach

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An optical fiber ring is used to generate multiple reference waves in a multiplexed fiber-optic Michelson-type sensor array. The array consists of N sensing segments connected in series along a single optical fiber path and is interrogated with a white-light interferometric technique. Experimental results with a two-sensor array are presented. © 2000 Optical Society of America

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There has been considerable interest recently in the development of fiber-optic sensors based on white-light interferometry.[1] The use of such a technique for distributed strain or temperature sensing in advanced composite or other structural materials has been discussed in several recent papers.[2–5] Fiber-optic Michelson sensor arrays are of particular interest for such applications because a number of reflective-type sensors networked in either a serial or a parallel topology can be interrogated by use of a common path-length reference variable, thus keeping the system cost down. Several schemes have been reported for multiplexing this type of sensor. These include coherence turning,[6,7] time division[8], spatial division,[9] duplicate fiber-optic switching[2] and $1 \times N$ star coupler[3] multiplexing. In this Letter we report the results of applying a fiber ring resonator as a common reference for an array of serial-connected strain sensors. Compared with the approaches reported in Refs. 2, 3, 7, and 9, this multiplexing approach is simple and low cost. The system can operate either in a tracking mode (for a single sensor) or in a scanning mode (for either a single-sensor or a multiple-sensor array). In the latter case a high-resolution scanning translation stage is required for measurement of the strain-induced optical path changes that occur in the sensing regions.

In a Michelson white-light interferometer, light from a LED is split into two arms: a sensing arm with its optical path sensitive to, for example, strain, and a reference arm with its path length varied in a controlled manner. The return light from the two arms is combined at the same splitter and detected by a photodetector. If the path length of the variable reference is made to be equal to that of the sensing arm, an interferogram is generated. The path-length variation that is due to applied strain can then be obtained by measurement of the path length of the reference arm that corresponds to the center of the interferogram. This technique can be utilized as a powerful tool for the measurement of deformations and strain experienced by optical fibers.

The quasi-distributed sensor system shown in Fig. 1 is based on the aforementioned basic principle. In this sensor system the sensing arm consists of N sensing segments (N sensors) connected in series with partial reflectors between the adjacent sensors. A fiber ring is used as a multireference wave generator, and each wave has a unique delay that is related to the number of times that the wave has traveled around the fiber ring. The lengths of the sensing segments are chosen to be approximately equal to half of the length of the fiber ring. This arrangement allows each of the reflected waves from the partial reflectors to be approximately matched in path length to one of the light waves generated from the fiber ring. A scanning mirror mounted on a step-motor positioning system fine tunes the path length of the reference waves to match that of the reflected waves.

Assume that the fiber length between the coupler and the first partial reflector is L_1 and the gauge lengths of the fiber sensors are $l_1, l_2, \cdots, l_N$. If the reflectors are of low reflectivity and the multiple reflections occurring in the system can be neglected, there

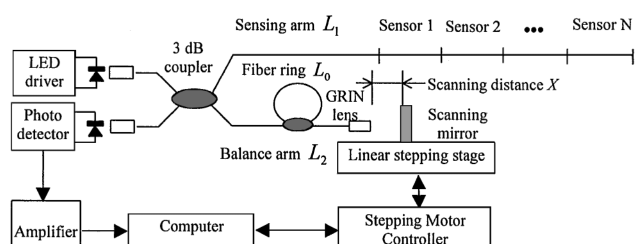

Fig. 1. Configuration of the quasi-distributed fiber-optic strain sensor system: GRIN, graded index.

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will be $N + 1$ reflected waves returning from the sensing arm. The optical path length of the kth reflected wave is

$$2n\left(L_1 + \sum_{i=1}^{k} l_i\right), \tag{1}$$

where $k = 0, 1, \ldots N$ and n is the effective refractive index of the fiber. If the fiber length of the reference arm (excluding the fiber ring) is L_2 and the length of the fiber ring is L_0, the return waves from the reference arm containing the fiber ring will have the following path length:

$$2nL_2 + 2X + nkL_0\,, \tag{2}$$

where $k = 0, 1, 2, \ldots N$ and X is the distance between the graded-index lens and the scanning mirror. If L_2 is made slightly shorter than L_1 (say, 3–5 mm shorter) and $l_1, l_2, \cdots, l_N$ are chosen to be different from but approximately equal to $L_0/2$, it is be possible to adjust X over a small range to match the optical path of the kth reflected wave from the sensing to that of the reference wave, i.e.,

$$2N\left(L_1 + \sum_{i=1}^{k} l_i\right) = 2nL_2 + 2X_k + nkL_0\,, \tag{3}$$

where X_k is the distance between the graded-index lens and the scanning mirror at the center of the kth interferogram (zero-order fringe). If $|n(l_i - l_j)|\,(i \neq j)$ and $|n(l_i - L_0/2)|$ are further chosen to be larger than the coherence length of the light source, solutions X_k for different k will be different, corresponding to the interferograms produced by nonoverlap of the different sensing and referencing waves. The difference $Y_k = X_k - X_{k-1}$ can be obtained from Eq. (3) and expressed as

$$Y_k = nl_k - \frac{nL_0}{2}\,. \tag{4}$$

If l_k is changed to $l_k + \Delta l_k$ as a result of a strain or load applied to sensor k, the measured change in Y_k (i.e., ΔY_k) can be related to the applied strain by

$$\Delta Y_k = n\Delta l_k = nl_k\epsilon_k\,, \tag{5}$$

where $\epsilon_k = \Delta l_k/l_k$ is the strain applied to sensor k. If the value of X_k $(k = 0, 1, \ldots N)$ is known, the strain applied to all the sensors can be recovered by using Eq. (5).

To calculate the intensity received by the photodiode of the fiber-optic sensing system, we assume that the light intensity from the LED source launched into the fiber is I_0 and that a 3-dB coupler splits this light intensity into two branches. In the sensing branch the light intensity is $I_0/2$. At each fiber end surface, the light wave partly reflects and partly transmits. If the reflectivity is R when the light wave undergoes each of the reflections between the two fiber ends, the transmitted light and the reflected light intensity are then proportional to $I_0(1 - R)/2$ and $I_0R/2$, respectively, as shown in Fig. 2.

Note that all the losses included connection-part insertion losses and other losses, but reflective losses are δ_i for sensor number i. For convincing calculations, let $\alpha_i = 10^{-\delta_i/10}$; then the reflected light intensity arriving at the detector of the kth sensor can be calculated as

$$I_S(k) = \begin{cases} \dfrac{I_0}{4}R\alpha_0 & k = 0 \\ \dfrac{I_0}{4}R\alpha_0\left\{\displaystyle\prod_{i=1}^{k}[\alpha_{i-1}(1 - R)]\right\}^2 & k = 1, 2, \cdots \end{cases}\,. \tag{6}$$

Under the condition of perpendicular incidence, the reflectivity of the fiber end surface is given by the Fresnel formula $R(n - 1/n + 1)^2$, where n is the index of the fiber core, a typical value of which is 1.46, and the typical losses of the fiber connection parts was estimated as 0.5 dB.

To determine the relationship of the kth sensor signal-to-noise ratio, we introduce a minimum signal-to-noise value required by the interferometer for identification of the central fringe. This value can be defined as[10]

$$\mathrm{SNR}_{\min}(\mathrm{dB})|_k = -20\lg[\Delta I_s(k)_{01}]\,, \tag{7}$$

where $\Delta I_s(k)_{01}$ is the normalized intensity difference between the central fringe and the largest side fringe.

A two-sensor system (Fig. 1; $N = 2$) with $l_1 \approx l_2 \approx L_0/2 \approx 104$ mm was constructed and tested for strain measurement in a test specimen. The sensors were made from single-mode fibers with 9/125-μm core/cladding diameter and a 40-μm-thick polymer coating. The system is powered by a 1310-nm LED source with a drive current of 50 mA, and the output optical power is 38.6 μW. The specimen was designed to have a shape as shown in Fig. 3, with a width ratio of the two uniform parts of 2:1. If the specimen were under longitudinal tension, the strain experienced by the two parts would ideally be of a ratio of 1:2. The sensing fiber was attached to the plastic test specimen with epoxy,

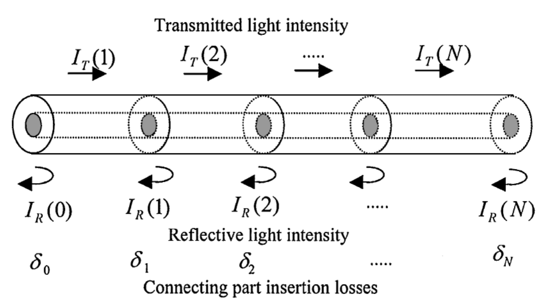

Fig. 2. Model of calculation of the light intensities of the fiber-optic sensor part.

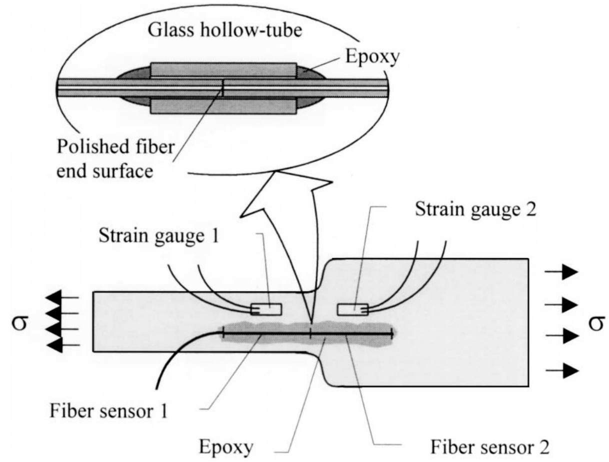

Fig. 3. Test specimen.

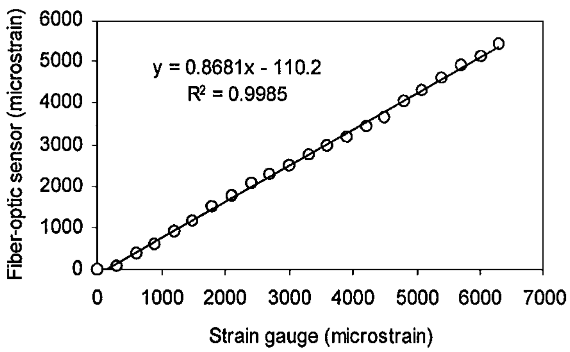

Fig. 4. Calibration of the fiber-optic sensors.

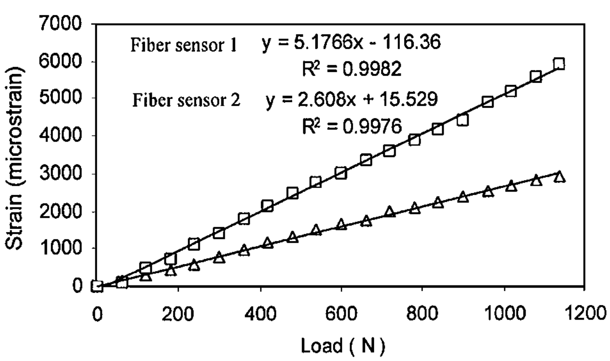

Fig. 5. Experimental results: strain values of the fiber sensors as functions of applied load.

as shown in Fig. 3. If the matrix-glass fiber bond were perfect, the strain measured by the fiber sensor would be the same as the local strain experienced by the specimen. However, as the fiber that we used had a thick polymer coating, which is far less rigid than the glass fiber and the surrounding matrix material (epoxy), it was expected that measured strain would be slightly different from the true strain experienced by the specimen.[11] Calibration was therefore performed by comparison of the experimental data from the fiber sensors with those from precision strain gauges (Measurements Group, Inc., CEA-06-125UN-350), which were placed near the two fiber sensors as shown in Fig. 3. A linear relation $\epsilon_{\text{fiber}} = \kappa\epsilon_{\text{strain gauge}}$ was obtained as shown in Fig. 4. The response ratios were 0.8681 and 0.8719 for fiber-optic sensors 1 and 2, respectively. The average value of the calibration factor for the two fiber-optic sensors with a gauge length of 104 mm is $\kappa = 0.87$. The strain values of the fiber sensors as functions of applied load are plotted in Fig. 5. The test results show that the ratio of the strain measured by the two fiber-optic sensors is 1:1.93, which is close to the expected value of 1:2. The true strain experienced by the specimen can be calculated by division of the fiber sensor output value by the calibration factor κ.

In summary, a novel quasi-distributed fiber-optic sensor system based on white-light interferometry has been demonstrated. The sensor has a Michelson-type architecture, with the sensing arm formed by a number of sensing segments connected in series, and the reference arm consists of a fiber ring and a scanning mirror. We can scale the gauge length of the sensing segments up or down by simply scaling the loop length of the ring resonator. We can also apply the system to a network of sensors with multiple branches by matching the path lengths of the branches to those of the reference waves generated from the ring resonator.

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