White-light interferometric fiber-optic strain sensor from three-peak-wavelength broadband LED source

Libo Yuan

A white-light fiber-optic interferometer working in the spatial domain, using a special three-peak-wavelength LED as a light source and one of the two arms of the Michelson interferometer as a strain sensor, is presented. Based on the Gaussian spectrum distribution function, a simple spectrum-decomposing method is used to describe the special three-peak-wavelength LED source. Experimental and theoretical analyses show that this special three-peak-wavelength LED source can be used in white-light interferometry to simplify the problem of central-fringe identification. A white-light Michelson fiber-optic strain-sensing system that uses a tapered cantilever beam is described. Experimental results show that the strain measured by the fiber-optic sensor is linear and always less than the surrounding matrix.

Key words: Fiber optic, strain sensor, white-light interferometer, broadband light source, fiber coating, Michelson interferometer, LED source, three-peak-wavelength LED light source.

1. Introduction

Since its invention in the 1880’s, the Michelson interferometer has been used to measure small spatial displacements. Standard laboratory experiments demonstrate methods for making such measurements either by fringe counting or by zero-path-length determination with white-light fringe. There is a fundamental difficulty that arises in all interferometers that use monochromatic or long-coherence-length light sources, which is a limited unambiguous operating range equivalent to an optical path length of $2\pi$ rad. To overcome this problem, recently a fiber-optic white-light Michelson interferometer has been employed to study temperature and absolute displacement measuring. In a white-light interferometer, the signal processing requires the position of the central fringe in the central set fringe packet to be accurately determined. It is possible that the intensity difference between the central fringe and its adjacent side fringe is too small to be distinguished owing to noise in the system.

The difficulty here is that some ambiguity may exist in fringe identification. Some authors proposed using two or three multimode laser diodes with different wavelengths as combination sources to solve this problem. In this work, a white-light fiber-optic Michelson interferometer as a strain sensing system is described in which a special three-peak-wavelength broadband LED is used to improve and simplify the central-fringe identification. In this experiment, a length of fiber is used as a strain sensor, and the fiber coating is not stripped. For practical applications, a coating is used to protect the brittle fiber against breakage and subsequent failure. Therefore the effects of the coating and the sensor gauge length are taken into account, and a series of tests are performed for evaluating the sensor’s performance.

2. Spectrum Structure of Three-Peak-Wavelength Broadband LED Light Source

For the broadband three-peak-wavelength LED light source (ABB HAFO, type 1A279-High-Performance LED), the spectrum distribution is given in Fig. 1.

The three-peak-wavelength spectrum can be considered to be the sum of three independent Gaussian distribution spectra in terms of the noncoherent
determined at terms are the relative intensity values for each peak, spectrum can be expressed as photon-emitting superposition principle. Then the actual spectra.

where \( k_{i0} = \frac{2\pi}{\lambda_{i0}} \), \( \lambda_{i0} \) \( (i = 1, 2, 3) \) are the central wavelengths of the peaks of the spectrum. The \( G_{i0} \) terms are the relative intensity values for each peak, determined at \( \lambda = \lambda_{i0} \), the \( \xi_i \) terms are the spectrum coefficients of the LED itself, and

\[
L_{\xi i} = \frac{\lambda_{i0}^2}{\Delta \lambda_i} \quad (i = 1, 2, 3),
\]

is the coherent length for each peak of the source.\(^{10}\) Here \( \Delta \lambda_i \) represents the full width at half-maximum for each peak.

The parameters of the type 1A279 LED source are given in Table 1, and the three independent Gaussian spectra compared with the actual spectra are shown in Fig. 1.

### 3. White-Light Michelson Fiber-Optic Interferometer from a Three-Peak-Wavelength Source

The fiber-optic Michelson interferometer operates by a well-established technique.\(^4\) Two beams are reflected and recombined in a Michelson configuration, shown in Fig. 2. When the optical-path difference between these two beams falls to within the coherence length of the source, a white-light fringe pattern is produced (see Fig. 3). The central fringe, which is located in the center of the fringe pattern and has the highest amplitude, corresponds to the exact optical path of these two beams.

Consider arbitrary monochromatic light that comes from the three-peak-wavelength continuous distribution spectrum \( G(k) \), let the wave number be \( k \); the monochromatic light intensity is given by Eq. (1). Then the output optical intensity of the fiber-optic Michelson interferometer can be calculated as

\[
G(k, x) = \alpha R_2 G_1(k) + \alpha R_3 G_2(k) + 2\alpha [R_2 G_1(k) R_3 G_2(k)]^{1/2} \cos(kx),
\]

where \( x \) is the optical-path difference introduced by the interferometer, \( \alpha \) is the \( 2 \times 2 \) fiber-optic coupler insertion loss coefficient defined as \( \alpha = (\text{total output optical power}/\text{input optical power}) \), \( R_1 \) is the reflectivity of sensing-arm-fiber end surface, and \( R_2 \) is the reflectivity of the compensation-arm reflective mirror. \( G_1(k) \) and \( G_2(k) \) are the intensities coupled into the sensing arm and the compensation arm, respectively.

### Table 1. Parameters of the Type 1A279 Three-Peak-Wavelength LED Source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength</td>
<td>( \lambda_{i0} )</td>
<td>788 nm</td>
<td>Spectral width (FWHM)</td>
<td>( \Delta \lambda_{i} )</td>
<td>35 nm</td>
<td>Coherent length</td>
<td>( L_{\xi i} )</td>
<td>17.74 ( \mu ) m</td>
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<tr>
<td>Spectral width (FWHM)</td>
<td>( \lambda_{i0} )</td>
<td>788 nm</td>
<td>Spectral width (FWHM)</td>
<td>( \Delta \lambda_{i} )</td>
<td>35 nm</td>
<td>Coherent length</td>
<td>( L_{\xi i} )</td>
<td>2.877</td>
</tr>
<tr>
<td>Coherent length</td>
<td>( \lambda_{i0} )</td>
<td>788 nm</td>
<td>Spectral width (FWHM)</td>
<td>( \Delta \lambda_{i} )</td>
<td>35 nm</td>
<td>Coherent length</td>
<td>( L_{\xi i} )</td>
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<tr>
<td>Spectral coefficient</td>
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<td>2.877</td>
<td>Spectral coefficient</td>
<td>( \xi_{i} )</td>
<td>2.877</td>
<td>Spectral coefficient</td>
<td>( \xi_{i} )</td>
<td>2.963</td>
</tr>
<tr>
<td>Relative intensity coefficient</td>
<td>( G_{i0} )</td>
<td>0.370 ( \mu ) W/( \mu ) m</td>
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<td>( G_{i0} )</td>
<td>0.296 ( \mu ) W/( \mu ) m</td>
</tr>
</tbody>
</table>

Fig. 2. Fiber-optic Michelson white-light interferometer with three-peak-wavelength LED light source.

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Let \( k_i = k - k_{i0} \) and then Eq. (6) becomes
\[
I(x) = \alpha^2 R \sum_{i=1}^{3} G_{i0} \left\{ \frac{L_{ci}}{2\pi k_i} \exp\left( -\frac{L_{ci}^2 (k - k_{i0})^2}{2\xi_i^2} \right) \right\} \times \{1 + \cos[(k_i + k_{i0})x]\} dk_i
\]
\[
= \alpha^2 R \sum_{i=1}^{3} G_{i0} \left\{ \frac{L_{ci}}{2\pi k_i} \exp\left( -\frac{L_{ci}^2 k_i^2}{2\xi_i^2} \right) \right\} \times \{1 + \cos(k_i x)\} \exp\left( -\frac{\xi_i^2 x^2}{2L_{ci}^2} \right) \left[ \cos\left( \frac{2\pi x}{\lambda_{i0}} \right) \right] \]  
\]
Substituting the data given by Table 1 into Eq. (7) and taking into account the coupler insertion losses \( \alpha = 0.95 \) and the reflectivity parameter \( R = 91\% \), we can calculate theoretically the normalized interference fringe pattern as shown in Fig. 3(b). The theoretical fringe pattern and the experimental result are compared in Figs. 3(c) and 3(d).

To compare the normal LED light source and quantify the case of central-fringe identification for different kinds of LED light source in the interferometric system, a \( SNR_{\text{min}} \) value, i.e., a minimum signal-to-noise ratio required by the interferometer to identify the central fringe is introduced and can be defined as
\[
SNR_{\text{min}}(dB) = -20 \log(\Delta I_{0n}), \tag{8}
\]
where \( \Delta I_{0n} \) is the normalized intensity difference between the central fringe and the largest side fringe.

According to Eq. (8), the \( SNR_{\text{min}} \) values obtained from simulation are 38.7 dB in Fig. 3(a) (for normal LED with peak wavelength 0.86 \( \mu \)m, spectral width \( \Delta \lambda = 40 \) nm, spectral coefficient \( \xi = 2.91 \)) and 24.4 dB in Fig. 3(b). The experimental \( SNR_{\text{min}} \) values obtained were 42.0 and 26.9 dB in Figs. 3(c) and 3(d), respectively. It is shown that to improve the identification of the central fringe, using the special three-peak-wavelengths LED light source is better than using the normal one, and it is simpler than a combination of two\(^6\) or three\(^9\) LEDs.

4. Optical Characteristics of the Fiber-Optic Strain Sensor

When optical fibers are used as embedded sensors, their ability to monitor strain in the surrounding matrix depends, among other things, on the bonding characteristics between matrix and fiber. In fact, the fiber cannot be subjected to any deformation without shear-strain transfer at the matrix–fiber interface. The deformation of the fiber induces changes in optical-signal transmission through the fiber. The fiber's optical-path change with gauge length \( 2L \) caused by the deformation can be expressed as
\[
\Delta x = 2[n \Delta L(\varepsilon) + \Delta n(\varepsilon)L], \tag{9}
\]
where \( \Delta x \) can be measured by displacement of the scanning mirror. The first term \( \Delta L(\varepsilon) \) in Eq. (9) represents the physical change of length produced by the strain; it is directly related to axial strain \( \varepsilon \) through the expression

\[
\Delta L(\varepsilon) = L\varepsilon. \tag{10}
\]

The second term, which is the change in optical path owing to a change in the refractive index of the fiber core, is given by

\[
\Delta n(\varepsilon) = -\frac{1}{2} n^2 [(1 - \mu)p_{12} - \mu p_{11}] \varepsilon, \tag{11}
\]

where \( \mu \) is the Poisson’s ratio of the fiberglass material and \( p_{ij} \) are the elements of the optic-tensor strain for a homogeneous isotropic material.

Combining these expressions, we have

\[
\Delta x = 2nL\varepsilon - n^2 [(1 - \mu)p_{12} - \mu p_{11}] L\varepsilon = 2n_{\text{eff}} L\varepsilon, \tag{12}
\]

where \( n_{\text{eff}} \) represents the effective refractive index of the fiber core. For the silica materials at wavelength \( \lambda = 1300 \text{ nm} \), the parameters are \( n = 1.46 \), Poisson ratio \( \mu = 0.25 \), and photoelastic constants \( p_{11} \approx 0.12 \), \( p_{12} \approx 0.27 \) (Ref. 12). Using these data, we can calculate the effective refractive index as \( n_{\text{eff}} \approx 1.19 \).

Therefore the correspondence strain subjected to the glass fiber can be measured by

\[
\varepsilon = \frac{\Delta x}{2n_{\text{eff}} L}. \tag{13}
\]

If a perfect matrix–fiber polymer coating and coating–glass fiber (including core and cladding) bonds of identical mechanical characteristics (homogeneous cross section) and uniform strain is applied to the matrix and the fiber, then every part of the fiber would be equally sensitive to the imposed strain field. That is, the strain in the glass fiber would be equal to the strain in the surrounding matrix. However, in reality, the stress is always directly applied on the matrix rather than the fiber, so that the strain in the glass fiber is subjected to shearing at the interface between the glass and the coating. This coating has to be in equilibrium under the interfacial shearing stresses only, and the polymer coating is far less rigid than the fiberglass and the surrounding matrix materials (e.g., epoxy and concrete). Therefore the layered cross section is expected to affect the performance of the fiber sensor. Thus the strain measured by the fiber can be written as

\[
\varepsilon = K(L)\varepsilon_H, \tag{14}
\]

where \( \varepsilon_H \) represents the strain of the host material and \( K(L) \) is the coefficient that is dependent on the fiber gauge length \( 2L \) and the mechanical properties of the fiber-coating material. It is expected that \( K(L) < 1 \) according to the above discussion.

5. Experimental Results

The experiment setup is illustrated in Fig. 4. The light from the three-peak-wavelength LED is split into two arms by a 3-dB single-mode coupler. The sensing-arm end of the single-mode fiber has a coated surface with reflectivity 87%, while the measuring arm end terminates in a gradient-index (GRIN) lens. A scanning mirror with reflectivity 94% is mounted on the motor drive linear positioning stage and is perpendicular to the GRIN lens. (Taking into account the coupling losses between the GRIN lens and

Fig. 4. Experimental setup.

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the mirror, we find that $R_1 = \eta R_2 = R$. Here $\eta$ is the coupling coefficient. The InGaAs photodetector receives signals from both the sensing arm and the measuring arm, which are reflected by the reflective coated fiber end and the mirror, respectively.

A tapered cantilever beam was employed in the experiments. A short length, $2L$ (approximately 35–175 mm), of optical fiber was attached to the tapered cantilever beam with epoxy. A resistance-strain gauge for calibrating the fiber sensor was attached to the beam next to the optical fiber, as shown in Fig. 4. Because of the tapered geometry of the beam, end displacement creates a constant strain field along the beam length. Because the end of the cantilever beam is displaced a distance $d$, the strain is subjected to the fiber, and then the optical path changes. Therefore the central fringe of the white-light interference pattern is shifted. A recognizer program running on a personal computer is used to identify the central fringe of optical fiber was attached to the tapered cantilever-beam surface are recorded by the resistance-strain gauge. The test results are shown in Fig. 5. It can be seen that the cantilever-beam strain measured by resistance-strain gauge measurement $\varepsilon_H$ is proportional to the strain measurement given by fiber-strain sensor $\varepsilon$. For different gauge lengths of the same kind of fiber, the relationship curve of the coefficient $K(L)$ in Eq. (14) versus fiber-optic gauge length $2L$ is given by a series test shown in Fig. 6.

6. Conclusions
It has been shown that a three-peak-wavelength broadband LED source can be used to simplify greatly central fringe identification in white-light interferometry. This technique is effective and simple. A white-light Michelson fiber-optic strain-sensing system was demonstrated that used the special LED source. The experimental results showed that the strain measured by the fiber-optic sensor is linear and, because of its polymer coating, is always less than the surrounding matrix strain for the sensing fiber that is embedded in the host material. The relation curve of coefficient $K(L)$ is given by a series test. It ascertains the validity of structural strains from measurements made by optical fiber.

References