Drift correction in a multichannel integrated optical Young interferometer

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We demonstrate that in a sensor based on a multichannel Young interferometer, the phase information obtained for different pairs of channels can be used to correct the long-term instability (drift) due to temperature differences between measuring and reference channels, the drift in the alignment of the setup, etc. Experiments show that the nature of a major part of the drift is such that the drift present in one of the channels can be determined by interpolation of the drift measured in the two adjacent channels. It is shown that a drift reduction of 10 times can be achieved as compared with the situation in which no correction is applied. We anticipate that these findings will permit the exploitation of the extreme sensitivity of interference-based sensors to a much greater extent. © 2005 Optical Society of America

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1. Introduction

Integrated optical sensors, especially interferometric ones such as the Young interferometer (YI),[1,2] Mach–Zehnder interferometer,[3] etc., are becoming increasingly sensitive thanks to optimization and improvement of the waveguide structure parameters. These sensors show an extremely high refractive-index resolution,[2,3] of the order of $\sim 10^{-8}$, which is equivalent to a protein mass coverage of ~ 30 fg/mm^2. Using such sensitive sensors makes possible the measurement of low concentrations of an analyte in solution when it is applied in the measuring window of the interferometer device. However, monitoring of a binding event, such as an immunoreaction, often requires a long time. In the latter case, the sensitivity of these devices is limited by so-called drift, which may be caused by temperature differences between reference and measuring channels, drift in the alignment of the setup, etc. Even when the measuring and reference channels are positioned relatively close to each other, a temperature drift cannot be completely avoided. The same holds for the drift in the alignment of the setup. As a consequence, the long-term stability (hours) of these devices with respect to a refractive-index change may be reduced by as much as order of magnitude,[1–3] as compared with the short-term stability (minutes). This is especially true with respect to monitoring of low analyte concentrations and low surface coverage of molecules, which require high resolution; here the drift strongly hampers high-resolution sensing and thus the accuracy of such measurements.

We present a method to reduce the uncertainty of the measured signal that is due to drift. We demonstrate that the drift decreases by a factor of ~ 10 when the drift-correction method is applied. Implementation of this correction technique is possible because of the unique properties of the multichannel integrated YI, designed such that the phase change for each possible channel pair can be measured simultaneously.

2. Multichannel Young Interferometer

We designed a four-channel integrated optical (IO) YI device, schematically presented in Fig. 1, that was fabricated by use of SiON technology.[4,5] The device

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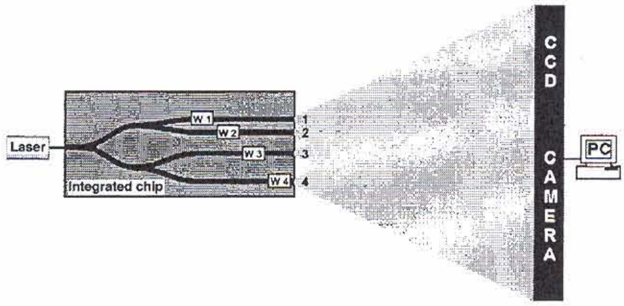

Fig. 1. Schematic presentation of the four-channel IO YI: W1, W2, W3, and W4, sensing windows in channels 1, 2, 3, and 4, respectively.

has the same waveguide parameters as the one described in Ref. 6.

In brief, the working principle of a four-channel YI is similar to that of a two-channel YI. In a two-channel YI, laser light is coupled to a guided mode of a channel waveguide and is then split into two channels: a measurement channel and a reference channel. At the end of the waveguide chip, the light is coupled out and the two output beams are overlapped to generate an interference pattern on a CCD camera. When the optical path-length difference between the two channels changes, the interference pattern shifts along the CCD camera. The shift is determined by a fast-Fourier-transform algorithm. If the YI is used as an immunosensor, the determined path-length differences, which are due to a change in the refractive index of the waveguide modes, are caused by protein adsorption at the waveguide surface. Proteins can access the waveguide surface only at the sensing windows where the waveguide surface is in contact with the sample solution. In a four-channel YI (see Fig. 1) there are four waveguide channels positioned at different distances from one another. The spatial frequency of the interference pattern is related to the distance between the channels, giving rise to different spatial frequencies and thus providing a means to determine all six optical path-length differences that occur among the four different channels. If a given phase change is introduced by a change in the refractive index in one of the channels, e.g., channel 2, then the phase change occurs for all channel pairs that involve channel 2.[2,6] In addition, drift introduces additional phase changes for each pair of channels. What we demonstrate in Section 3 is that the phase information measured for all channel pairs can be used to determine the refractive-index change introduced in a particular channel and, at the same time, to correct for the drift.

3. Drift-Correction Method

The correction method is based on the assumption that, for each of the two channel pairs, the ratio of the phase deviations due to the drift remains constant during a measurement, which may take several minutes to one hour. Based on this assumption and on consideration of only channels 1, 2, and 3 of the four-channel YI device, one can define the following equations:

$$\frac{\Delta\Phi_{12}^{\text{drift}}}{\Delta\Phi_{13}^{\text{drift}}} = C_{12,13},$$
$$\frac{\Delta\Phi_{23}^{\text{drift}}}{\Delta\Phi_{13}^{\text{drift}}} = C_{23,13}, \tag{1}$$

where $C_{12,13}$ and $C_{23,13}$ are constants and $\Delta\Phi_{12}^{\text{drift}}$, $\Delta\Phi_{23}^{\text{drift}}$, and $\Delta\Phi_{13}^{\text{drift}}$ are the phase changes caused by the drift between channels 1 and 2, 2 and 3, and 1 and 3, respectively. When a refractive-index change (signal) is introduced in channel 2, the phase changes measured among channels $\Delta\Phi_{12}^{\text{meas}}$, $\Delta\Phi_{23}^{\text{meas}}$, and $\Delta\Phi_{13}^{\text{meas}}$ can be written as

$$\Delta\Phi_{12}^{\text{meas}} = \Delta\Phi_{12}^{\text{signal}} + \Delta\Phi_{12}^{\text{drift}},$$
$$\Delta\Phi_{23}^{\text{meas}} = \Delta\Phi_{23}^{\text{signal}} + \Delta\Phi_{23}^{\text{drift}},$$
$$\Delta\Phi_{13}^{\text{meas}} = \Delta\Phi_{13}^{\text{drift}}, \tag{2}$$

where $\Delta\Phi_{12}^{\text{signal}}$ and $\Delta\Phi_{23}^{\text{signal}}$ are, respectively, the phase changes between channels 1 and 2, and 2 and 3 that are due to the refractive-index change introduced in channel 2. Combining Eq. (1) and Eq. (2), one can determine the drift-corrected phase changes $\Delta\Phi_{12}^{\text{signal}}$ and $\Delta\Phi_{23}^{\text{signal}}$ introduced by the refractive-index change in channel 2:

$$\Delta\Phi_{12}^{\text{signal}} = \Delta\Phi_{12}^{\text{meas}} - C_{12,13}\,\Delta\Phi_{13}^{\text{meas}},$$
$$\Delta\Phi_{23}^{\text{signal}} = \Delta\Phi_{23}^{\text{meas}} - C_{23,13}\,\Delta\Phi_{13}^{\text{meas}}. \tag{3}$$

4. Results

In Fig. 2(A) the values of $\Delta\Phi_{12}^{\text{meas}}$, $\Delta\Phi_{23}^{\text{meas}}$, and $\Delta\Phi_{13}^{\text{meas}}$ are shown, as measured in 1 h. No refractive-index change was introduced at any of the channels; pure water was continuously flown onto the sensing window of each channel to approach the conditions of a real measurement. Because no refractive-index change or binding event was taking place in any of the channels, the phase changes that result for each channel pair are caused only by drift. From these measurements we determined $C_{12,13}$ and $C_{23,13}$ by rationing the corresponding phase graphs, followed by averaging the values of the constants over the first 10 min: $C_{12,13} = 0.83$ and $C_{23,13} = 0.17$, the sum of which equals 1.0 as expected from Eq. (1). Using Eq. (3) we calculated the signals $\Delta\Phi_{12}^{\text{signal}}$ and $\Delta\Phi_{23}^{\text{signal}}$ (in this particular case both signals should be equal to zero). In Fig. 2(B) the drift-corrected phase changes, $\Delta\Phi_{12}^{\text{signal}}$ and $\Delta\Phi_{23}^{\text{signal}}$, are shown. Clearly, the method works over long time scales. These promising results are related in the fact that at least a major part of the drift for different pairs of channels are correlated with each other such that their ratio remains constant in time, as confirmed by the measurements.

Next the drift-correction method was applied to a measurement in which a refractive-index change of

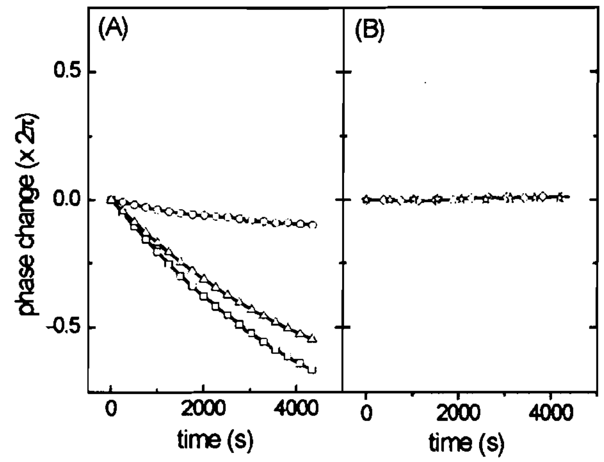

Fig. 2. (A) Phase changes $\Delta\Phi_{12}^{meas}$ (triangles), $\Delta\Phi_{23}^{meas}$ (circles), and $\Delta\Phi_{13}^{meas}$ (squares) observed in the four-channel IO YI when no refractive-index change is introduced in the channels; pure water is continuously flown onto the sensing window of each channel. (B) Drift-corrected phase change between channels 1 and 2, $\Delta\Phi_{12}^{signal}$ (stars), and between channels 2 and 3, $\Delta\Phi_{23}^{signal}$ (diamonds), using Eq. (3). The same vertical scale is used in both graphs.

1.5 × 2π was introduced in channel 2 only by flowing a 0.924-wt.% solution of glucose in water.[7] First, pure water was introduced into channel 2 at $t = 0$ s. At $t = 50$ s the flow was changed from water to a glucose solution, and at $t = 300$ s water was flown again into channel 2. Pure water was continuously flown into channels 1 and 3.

In Fig. 3 we show the results as well as the drift-corrected phase changes $\Delta\Phi_{12}^{signal}$ and $\Delta\Phi_{23}^{signal}$, as obtained from Eq. (3). The phase change measured between channels 1 and 3 is caused only by the presence of drift, $\Delta\Phi_{13}^{drift}$, because no refractive-index change was introduced in channel 1 or 3. The ratios $C_{12,13}$ and $C_{23,13}$ were determined based on the phase changes measured before the refractive-index change was introduced in channel 2 (during the time interval from 0 to 50 s). According to Fig. 3, the phase change due to the drift, still present after the correction, is ~10 times smaller than that observed when no correction is applied for $\Delta\Phi_{12}$ and $\Delta\Phi_{23}$. This improvement was also obtained when the refractive-index change was introduced in channel 1 or 3 (not shown).

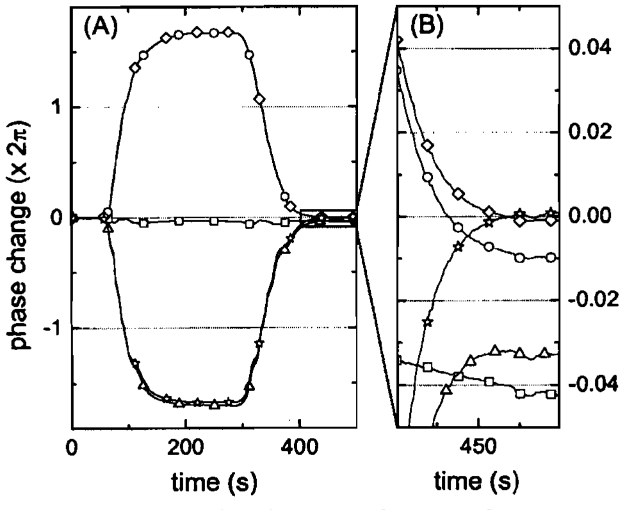

Fig. 3. (A) Response of the four-channel integrated YI sensor to a phase change of 1.5 × 2π introduced in channel 2 by flowing a 0.924-wt. % glucose solution: $t = 50$ s, change from water to glucose solution; $t = 300$ s, change from glucose solution to water. $\Delta\Phi_{12}^{meas}$ (triangles), $\Delta\Phi_{23}^{meas}$ (circles), and $\Delta\Phi_{13}^{meas}$ (squares) are the phase changes measured, and $\Delta\Phi_{12}^{signal}$ (stars) and $\Delta\Phi_{23}^{signal}$ (diamonds) are the drift-corrected phase changes. (B) Plot showing that the drift-corrected phase changes return to zero as expected.

5. Discussion and Conclusions

The experimental results presented give a clear indication that the proposed method provides a means to obtain a major reduction in drift. This means that the origin of the drift is such that $C_{12,13}$ and $C_{23,13}$ are constant during the experiment. The most likely explanation for this observation is that the optical path lengths of the different waveguide channels respond differently to temperature changes. These differences can originate from variations in the waveguide parameters (e.g., thickness, refractive index, length) across the IO chip. Another possible explanation is that the values for the observed ratios differ from chip to chip but are similar from experiment to experiment when the same chip is used.

In this paper we have shown that in a multichannel integrated YI, it is possible to correct phase changes that are due to temperature differences between measuring and reference channels and to other sources. Drift decreases by a factor of ~10 when the drift-correction method is applied. Implementation of this correction technique is possible because of the unique properties of the multichannel integrated YI, which is designed such that the phase change for each possible channel pair can be measured, thereby allowing implementation of the drift-correction method.

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