Fiber in-line Fabry–Pérot interferometer for simultaneous measurement of reflective index and temperature

Xiaoqi Ni (倪小琦), Ming Wang (王鸣)*, and Dongmei Guo (郭冬梅)

Jiangsu Key Laboratory on Opto-Electronic Technology, School of Physical Science and Technology, Nanjing Normal University, Nanjing 210023, China

*Corresponding author: wangming@njnu.edu.cn

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A fiber in-line Fabry–Pérot interferometer is presented. The sensing head consists of a micro ellipsoidal air cavity and a small section of solid-core photonic crystal fiber. The reflective index (RI) and temperature can be interrogated simultaneously through a fast Fourier transform and by tracing the dip wavelength shift of the reflective spectrum. Experimental results show that the RI amplitude and wavelength sensitivities are 5.30/RIU and 8.46 × 10⁻¹ nm/RIU in the range from 1.34 to 1.43, and the temperature amplitude and wavelength sensitivities are 6.8 × 10⁻⁴ °C and 2.48 × 10⁻³ nm/°C in the range from 15°C to 75°C, respectively. Easy fabrication, a simple system, and simultaneous measurement make it appropriate for dual-parameter sensing application.

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both dips as $\lambda_1$ and $\lambda_2$, we calculated that the length of the air cavity is about 19.1 $\mu$m by using

$$L = \frac{\lambda_1 \lambda_2}{2n(\lambda_2 - \lambda_1)},$$

which is almost the same as the measured value (18.85 $\mu$m). However, the other cavity was formed when a certain length of PCF remained after cleaving. The reflective spectra consist of an envelope and a high-frequency fringe spectrum whose frequency varies with the length of the remaining PCF. In order to find out where the fringe spectrum comes from, we analyzed the schematic diagram of the sensing head and the propagation of the light.

As shown in Fig. 3, after being reflected by the air cavity, the rest of the incident light is coupled to the PCF through the collapsed region. Lots of higher modes are excited at the beginning of the PCF, including the cladding modes. But the cladding modes vanish gradually through the propagation distance due to the power dissipation. As a result, the guided modes propagating in the PCF are the core modes, including the high-order modes. They are reflected by the PCF end face cleavage, and are coupled to the SMF again through the collapsed region. Taking the interference between the fundamental mode (LP$_{01}$) and the high-order mode (LP$_{31}$) into consideration, we calculated that the FP cavity should be 412 mm ($n = 3.51 \times 10^{-2} \mu$m) when the interference spectrum is the same as the one dotted in red in Fig. 2. But it was not coincident with the experimental result (9 mm). So we inferred that the fringe spectrum was caused by the silica cavity ($L_2$), which was composed of the collapsed region and the PCF, as illustrated in Fig. 3. With $n = n_{\text{silica}} = 1.457$, we calculated that the cavity length should be 9.99 mm, which was well coincident with $L_2$ in the experiment (9.78 mm).

There are three reflection surfaces in the sensing head, as follows: SMF-air, air-silica, silica-surrounding with power reflection coefficients of $R_1$, $R_2$, and $R_3$, respectively. $R_1$ and $R_2$ are equal to $(n_0 - 1)^2/(n_0 + 1)^2 = 0.034$, $R_3 = (n_0 - n_{\text{Liq}})^2/(n_0 + n_{\text{Liq}})^2$, with $n_0$ being the RI of pure silica and $n_{\text{Liq}}$ being the RI of the measured solution. The total reflected field from the sensor is given approximately by the sum of the first-order reflected fields from the three surfaces. The total contribution from the high-order reflections is less than 0.1% because of the low reflection coefficients and therefore can be neglected. So the normalized reflection spectrum $R(\lambda)$ is obtained as follows:

$$R(\lambda) = \left| \frac{E_r}{E_i} \right|^2 = R_1 + (1 - \alpha)^2(1 - R_1)^2R_2 + (1 - \alpha)^2(1 - \gamma)^2(1 - R_1)^2(1 - R_2)^2R_3 - 2\sqrt{R_1 R_2}(1 - \alpha)(1 - R_1)\cos(4\pi L_1/\lambda) - 2\sqrt{R_1 R_3}(1 - \alpha)(1 - \gamma)(1 - R_1)(1 - R_2) \times \cos[4\pi (L_1 + n_0 L_2)/\lambda] + 2\sqrt{R_2 R_3}(1 - \alpha)^2(1 - \gamma)(1 - R_1)^2(1 - R_2) \times \cos(4\pi n_0 L_2/\lambda),$$

where $E_1$ is the incident wave field, $E_r$ is the reflected wave field, $\alpha$ and $\gamma$ are the diffraction loss factors of air cavity and silica cavity, respectively. A phase shift of $\pi$ takes place at the reflection surface of air and fiber because light is reflected from an optically dense medium to a thinner medium. As a result, if the refractive index of the solution to be measured ($n_{\text{Liq}}$) is bigger than $n_0$, there is also a $\pi$ phase shift at the reflection surface of the PCF. From Eq. (2), we find out that the reflection coefficient $R_3$, which depends on $n_{\text{Liq}}$, only affects the amplitude of $R(\lambda)$. So when the sensor is dipped into different solutions, the fringe contrast of the reflective spectrum will change, whereas the phase will remain unchanged.

The reflective interference spectrum is simulated with the parameters $L_1 = 18.75 \mu$m, $L_2 = 1531 \mu$m, $n_0 = 1.457$,
Amplitude is defined as the peak near the frequency of about 1.8 nm, which is depicted in Fig. 3, from which we can see that the reflective spectrum mainly consists of a low-frequency envelope and a high-frequency waveform. To analyze the characteristics of the interference pattern, the wavelength spectrum was Fourier transformed to a spatial frequency. The reflective spectra with \(n_{\text{Liq}}\) in the range from 1.33 to 1.45 were analyzed after a Fast Fourier Transform (FFT).

Taking the parameter “Amplitude” as the Y axis, the FFT results in the spatial frequency domain are shown in Fig. 5. Amplitude is defined as \(\sqrt{\text{Re}^2 + \text{Im}^2}/n\), where \(\text{Re}\) and \(\text{Im}\) are the real and imaginary part of the FFT data, and \(n\) is the number of sample points, respectively.

From Fig. 5, we can see that the first several peaks in the spatial frequency domain, which correspond to interferences in the air cavity, do not change with \(n_{\text{Liq}}\). But the peak near the frequency of about 1.8 nm\(^{-1}\), which corresponds to interferences in the cavity of silica, decreases when \(n_{\text{Liq}}\) increases. The relationship between the amplitude peak \((P)\) near the frequency of about 1.8 nm\(^{-1}\) and the RI of the solution is depicted in Fig. 6, from which we can see that the simulated \(P\) has a linear relationship with \(n_{\text{Liq}}\).

Given that the RI of a material itself exhibits a dependence on temperature, RI sensing cannot be carried out reliably without the simultaneous measurement of temperature. When temperature changes, the dip wavelength \((\Delta \lambda_{\text{dip}})\) of the reflective optical spectrum will shift and the amplitude peaks of the frequency spectrum will also change. If both parameters are perturbed simultaneously by the RI and temperature, the variation of the dip wavelength \(\Delta \lambda_{\text{dip}}\) caused by the temperature and RI can be expressed as \((\Delta \lambda_{\text{dip}}) = K_{\lambda,T} \Delta T + K_{\lambda,RI} \Delta RI\),

where \(K_{\lambda,T}\) is the sensitivity coefficient of the temperature and the unit is nm/°C, and \(K_{\lambda,RI}\) is the sensitivity coefficient of RI and the unit is nm/RIU. The variation of the amplitude peak \((\Delta P)\) of the FFT results caused by the variation in temperature and RI can be expressed as

\[
\Delta P = K_{P,T} \Delta T + K_{P,RI} \Delta RI,
\]

where \(K_{P,T}\) is the sensitivity coefficient of the temperature with units of °C, and \(K_{P,RI}\) is the sensitivity coefficient of RI with units of /RIU. The equation of the sensitivity matrix can be written as

\[
\begin{bmatrix}
\Delta \lambda_{\text{dip}} \\
\Delta P
\end{bmatrix} =
\begin{bmatrix}
K_{\lambda,T} & K_{\lambda,RI} \\
K_{P,T} & K_{P,RI}
\end{bmatrix}
\begin{bmatrix}
\Delta T \\
\Delta RI
\end{bmatrix},
\]

The equation of the sensitivity matrix can be transposed as

\[
\begin{bmatrix}
\Delta T \\
\Delta RI
\end{bmatrix} = \frac{1}{D}
\begin{bmatrix}
K_{P,RI} & -K_{\lambda,RI} \\
-K_{P,T} & K_{\lambda,T}
\end{bmatrix}
\begin{bmatrix}
\Delta \lambda_{\text{dip}} \\
\Delta P
\end{bmatrix},
\]

where \(D = K_{\lambda,T} K_{P,RI} - K_{P,T} K_{\lambda,RI}\), and \(K_{\lambda,T}\), \(K_{\lambda,RI}\), \(K_{P,T}\), and \(K_{P,RI}\) are regarded as constant values and can be determined by measuring the temperature and wavelength response separately for \(\Delta \lambda_{\text{dip}}\) and \(\Delta P\). The temperature and RI variations can thus be evaluated by Eq. (6).

Several all-fiber optical FPIs with different lengths of air cavity and PCF were fabricated. Two reflective spectra in the air at 10°C are shown in Fig. 7, with parameters as follows: for sensor1, \(L_1 = 15.6\) μm, \(L_2 = 925\) μm; for sensor2, \(L_1 = 6.2\) μm, \(L_2 = 1400\) μm. The solid line represents the reflective spectrum of sensor1 and the dotted line represents sensor2. To calibrate the sensor, we immersed sensor1 into the prepared sugar solution with different RI, and we found that the fringe contrast of the reflective spectrum decreases with RI. The FFT results of the reflective spectra with different RIs are shown in Fig. 8.

Subsequently, the sensor was placed in an oven and the temperature was twice increased from 15°C to 75°C and then decreased to 15°C.

Assuming \(\Delta P_{\text{RI}}\) is the difference between the measured \(P\) in the air and in different solutions, \(\Delta RI\) is the difference

Fig. 5. Simulated FFT results of spectral responses with different \(n_{\text{Liq}}\).

Fig. 6. Simulated relationship between the \(P\) and RI of the solution.
between the RI of the solution and the air, the experimental \( \Delta P \) were dotted in Fig. 9. Assuming \( \Delta P_T \) is the difference of the measured \( P \) at different temperatures and at 10°C, the experimental \( \Delta P_T \) values were marked with square points in Fig. 9. After linear fitting, we found that the parameter \( \Delta P \) increases almost linearly with \( \Delta RI \), with the sensitivity of 6.80 x 10^-4 /°C. Consequently, the parameters \( K_{P,T} \)

and \( K_{P,RI} \) in Eq. (5) are 6.80 x 10^-4 /°C and 5.30/RIU, respectively. In this Letter, the solution samples were characterized through an Abbe refractometer.

The relationship between \( \Delta \lambda_{dip} \) and \( \Delta RI \), together with the relationship between \( \Delta \lambda_{dip} \) and \( \Delta T \) were explored in this Letter. The reflective spectra of the sensor after a low-pass filter with a cutoff frequency of 0.15 Hz at temperatures of 15°C, 20°C, and 25°C were shown in Fig. 10. The dip wavelength shifts to short wavelength with the increase of temperature. Assuming \( \Delta \lambda_{RI} \) is the wavelength shift caused by \( \Delta RI \), the experimental \( \Delta \lambda_{RI} \) were dotted in Fig. 11. Assuming \( \Delta \lambda_T \) is the wavelength shift caused by \( \Delta T \), the experimental \( \Delta \lambda_T \) were marked with square points in Fig. 11. After linear fitting, we found out that the parameter \( \Delta \lambda_{dip} \) increases almost linearly with \( \Delta RI \), with a sensitivity of 8.46 x 10^{-1} nm /RIU and \( \Delta \lambda_{dip} \) also increases linearly with \( \Delta T \) with a sensitivity of 2.48 x 10^{-3} nm /°C. Consequently, the parameters \( K_{\lambda,T} \) and \( K_{\lambda,RI} \) in Eq. (5) are 2.48 x 10^{-3} nm /°C and 8.46 x 10^{-1} nm /RIU, respectively, and Eq. (5) can be written as follows:

\[
\begin{bmatrix}
\Delta \lambda_{dip} \\
\Delta P
\end{bmatrix} =
\begin{bmatrix}
2.48 \times 10^{-3} & 8.46 \times 10^{-1} \\
6.80 \times 10^{-4} & 5.30
\end{bmatrix}
\begin{bmatrix}
\Delta T \\
\Delta RI
\end{bmatrix}.
\]

(7)
Equation (6) can be written as

\[
\begin{bmatrix}
\Delta T \\
\Delta RI
\end{bmatrix} = \begin{bmatrix}
4.05 \times 10^2 & -6.55 \times 10^{-4} \\
-5.25 \times 10^{-3} & 2.00 \times 10^{-6}
\end{bmatrix}\begin{bmatrix}
\Delta \lambda_{dip} \\
\Delta P
\end{bmatrix}.
\] (8)

Equation (8) can be applied to simultaneously determine the surrounding RI and temperature, as long as the wavelength shift $\Delta \lambda_{dip}$ and $\Delta P$ are measured.

In conclusion, a simple optical sensor is proposed and demonstrated that can be used to simultaneously measure RI and temperature. The sensing head is made by splicing a small section of PCF with SMF, with an ellipsoid air cavity reserved. The interference model is analyzed theoretically and verified experimentally. $\Delta P$ from the FFT analysis and $\Delta \lambda_{dip}$ of the envelope after the FFT low-pass filter can be measured. An amplitude sensitivity of 5.30/RIU after the FFT and a wavelength sensitivity of $8.46 \times 10^{-1}$ nm/RIU are experimentally achieved over the RI range from 1.34 to 1.43. For temperature measurements, an amplitude sensitivity of $6.80 \times 10^{-4}$/°C and a wavelength sensitivity of $2.48 \times 10^{-3}$ nm/°C are achieved. Easy fabrication, low cost, good temperature compensation, and dual-parameter measurement make it appropriate for practical applications.

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