Method of hybrid multiplexing for fiber-optic Fabry–Perot sensors utilizing frequency-shifted interferometry

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Experimental and theoretical research on hybrid multiplexing for fiber-optic Fabry–Perot (F-P) sensors based on frequency-shifted interferometry is presented. Four F-P sensors multiplexed in a hybrid configuration were experimentally investigated. The location of each multiplexed sensor was retrieved by performing the fast Fourier transform, and the reflection spectrum of each sensor was also obtained in spite of the spectral overlap, which was consistent with the results measured by an optical spectrum analyzer. With theoretical modeling, the maximum sensor number of a two-channel hybrid multiplexing system reaches 26 with cross-talk of less than −50 dB and a maximum frequency-domain signal-to-noise ratio (SNR) of ∼25 dB, when the source power is 2 mW and the sensor separation is optimal, i.e., 40 m. And the sensor number is almost twice that multiplexed by a serial system under the same conditions. An SNR improvement of 3.9 dB can be achieved by using a Hamming window in a noise-free system compared with a Hanning window. In addition, we applied the experimental multiplexing system to a strain sensing test. The cavity lengths and cavity-length shifts of the four F-P sensors were demodulated, which was consistent with the actual situation. It provides a new feasible method to multiplex F-P sensors at large scale.

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1. Introduction

As a kind of high-precision interferometric fiber-optic sensors, Fabry–Perot (F-P) sensors have gained great attention and widespread use for their simple structure, easy manufacture, low cost, minimum cross sensitivity, and applicability for hostile environments [1–3]. Furthermore, F-P sensors can be used to build sensor networks by multiplexing, which can effectively reduce the system cost and realize multipoint and distributed sensing. Therefore, F-P sensor multiplexing technology has caused great interest from researchers all over the world [4–11]. Lots of F-P sensor multiplexing techniques have been developed, including wavelength-division multiplexing (WDM) [4,5], time-division multiplexing (TDM) [4,6], space-division multiplexing (SDM) [7,8], frequency-division multiplexing (FDM) [9,10], and coherence multiplexing (CM) [11,12]. However,
in the WDM scheme, different sensors must be arranged in different wavelength domains, and consequently the sensor number is limited by the optical source bandwidth. TDM requires a pulsed light source, a time-gated detector, and fast data acquisition equipment. In the SDM scheme, each sensor needs its own detector [7,8]. FDM requires sensor cavity lengths that are different from one another. The CM system has a complex structure, and its signal-to-noise ratio (SNR) sharply decays along with the increase of the sensor number.

As a novel fiber-optic sensor sensing technique, frequency-shifted interferometry (FSI) was proposed and quickly developed by the research group of Qian [13-17], and has many outstanding advantages. FSI needs only one CW light source, one low-speed data acquisition element, and one slow detector, compared with TDM, and the detector is a shared one, unlike SDM. It has a compact structure and high SNR compared to CM. Unlike FDM, FSI allows the cavity length of each sensor to be identical. Moreover, FSI allows spectral overlap and offers a more flexible wavelength window for sensors, unlike WDM.

In this paper, we proposed a novel method of hybrid multiplexing for optic fiber F-P sensors based on FSI. We experimentally investigated a two-channel multiplexing system constituted by four F-P sensors. This method resolved the location of each F-P sensor through fast Fourier transform (FFT). And it distinguished the reflection spectrum of each sensor from the overlapped spectra, which agreed with the measurement results of an optical spectrum analyzer (OSA). The experimental multiplexing system was also applied to a strain sensing test. We obtained the cavity lengths and cavity-length shifts of all F-P sensors. Further, we theoretically analyzed the relationship between crosstalk and sensor separation under different window functions in noise-free and noisy situations, and discussed the influencing factors of the maximum sensor number. It was found that crosstalk can be lowered by employing a low-noise source and a Hamming window, and the maximum number was mainly limited by the crosstalk, the source power, the maximum frequency-domain SNR, and the sensing range. The results show that the FSI scheme can improve the multiplexing capacity of F-P sensors to a larger extent and thus can significantly reduce the cost of the whole sensor system.

2. Principle

The principle of FSI was described in detail in [15], and a schematic diagram of the FSI-based hybrid multiplexing system for fiber-optic F-P sensors is depicted in Fig. 1. The hybrid multiplexing system includes $M$ channels of F-P sensor links, each of which is constituted by $N$ cascaded F-P sensors and respectively connected with the $M$ output ports of the coupler $C_2$. Since each F-P sensor serves as a reflection site, the frequency-shifted interferometer can be seen as an amalgamation of $M$-by-$N$ Sagnac loops, each containing an F-P sensor.

For a single reflection site, the differential intensity at the balanced detector (BD) is a cosine function of $f$ [15,16]; therefore, for the $m$th ($m = 1, 2, \ldots, or M$) channel sensor link, including $N$ reflection sites, the intensity is a summation of $N$ cosine functions, which can be given as [15]

$$I_m(\lambda, f) = \sum_{n=1}^{N} AK_{mn}(\lambda)I_0 \cos \left(\frac{4\pi n(L_0 + L_{mn}f)}{c}\right). \quad (1)$$

where $\lambda$ is the wavelength of the laser source, $f$ is the acoustic frequency of the AOM, $c$ is the speed of light, $n$ is the refractive index of fiber core, $L_{mn}$ is the location of F-P$_{mn}$ (i.e., the $n$th F-P sensor in the $m$th channel). $I_0$ is the initiative input light intensity at the coupler $C_1$, and $I_0 = P_s \cdot 10^{-0.1a_c}$, where $P_s$ is the output power of the tunable laser source (TLS), and $a_c$ is the circulator loss in decibels. $L_0$ is a distance constant contributed by the three lengths $L_a$, $L_b$, and $L_c$ in the interferometer loop as shown in Fig. 1, and $L_0 = (L_a + L_b - L_c)/2$. $A$ and $K_{mn}$ separately denote the transmission coefficient contributed by the elements before $C_2$ and that after $C_2$, which can be expressed as follows:

$$A = 4\kappa A\kappa B\gamma_1\gamma_2(1 - \gamma_1)(1 - \gamma_2) \cdot 10^{-\frac{2a_c}{10}}. \quad (2)$$

$$K_{mn}(\lambda) = \left\{ \prod_{i=1}^{n-1} \left[1 - R_{mn}(\lambda)\right] \right\}^{-1} \cdot 10^{-\frac{2n\alpha_{mn}}{10}} R_{mn}(\lambda), \quad (3)$$

where $\kappa_A$ and $\kappa_B$ are the transmission coefficients of path A and path B, $\gamma_1$ and $\gamma_2$ are the coupling ratios of $C_1$ and $C_2$, and $\alpha_c$ represents the unintended losses in decibels, for example, the loss caused by some external factors (draw, pressure, twist, etc.) [18]. In Eq. (3), the term in the big round bracket corresponds to the spectral features of the previous $n - 1$ sensors imposing to the latter sensor ($n > 1$), which is termed as the spectral shadowing effect [15]. $\alpha_f$ is the loss coefficient of the fiber, $L_{mn}$ is the location of the sensor F-P$_{mn}$ i.e., the distance between $C_2$ and F-P$_{mn}$, and $R_{mn}(\lambda)$ is the reflectivity of F-P$_{mn}$.

Because $M$ channels of F-P sensor links are parallel and independent from one another, the spectral
shadowing effect will not arise. Therefore, the total differential intensity \( I_{\text{total}}(\lambda, f) \) at the BD is a linear superposition of the intensity of the \( M \) channels, which can be described as

\[
I_{\text{total}}(\lambda, f) = \sum_{m=1}^{M} I_m(\lambda, f) = \sum_{m=1}^{M} \sum_{n=1}^{N} AK_{mn}(\lambda)I_0 \cos \left( \frac{4\pi n(L_0 + L_{mn}f)}{c} \right). \tag{4}
\]

For each wavelength \( \lambda \), if we linearly sweep the acousto-optic modulator (AOM) frequency \( f \) and operate the FFT on the differential signal, the location \( L_{mn} \) of each sensor can be retrieved from the FFT components \( F_{mn} \), which can be represented as \cite{14,15}

\[
L_{mn} = \frac{ct_{\text{sw}}}{2n\Delta f} F_{mn} - L_0, \tag{5}
\]

where \( \Delta f \) and \( t_{\text{sw}} \) are the sweep range and the sweep period of the AOM. If we also scan the wavelength of the laser source, we can reconstruct the reflection spectrum of each sensor. Since the reflection spectra are location-resolved, the reflection spectrum of each F-P sensor can be distinguished from the overlapped spectra.

3. Experiments and Results

Our experimental setup is demonstrated in Fig. 1, and the hybrid multiplexing structure of fiber-optic F-P sensors is composed of two channels, each containing two sensors, i.e., F-P_{11}, F-P_{12}, F-P_{21}, and F-P_{22}, respectively. Each F-P sensor we used was an extrinsic fiber-optic F-P interferometer, which was constituted by two fiber ends oppositely inserted into a hollow quartz tube. Among them, F-P_{11} and F-P_{12} were separated by \( \sim 42 \) m, and F-P_{21} and F-P_{22} were separated by \( \sim 45 \) m. In order to retrieve the locations of different sensors and avoid the interference of DC noise, we separately linked \( \sim 65 \) m fiber between F-P_{11} and C2, and \( \sim 176 \) m fiber between F-P_{21} and C2. According to Eqs. (1)-(4), the differential interference signal after being detected by the BD can be shown as

\[
I_{\text{total}}(\lambda, f) = A'K_{11}(\lambda)I_0 \cos \left( \frac{4\pi n(L_0 + L_{111})f}{c} \right) \nonumber \\
+ A'K_{12}(\lambda)I_0 \cos \left( \frac{4\pi n(L_0 + L_{122})f}{c} \right) \nonumber \\
+ A'K_{21}(\lambda)I_0 \cos \left( \frac{4\pi n(L_0 + L_{211})f}{c} \right) \nonumber \\
+ A'K_{22}(\lambda)I_0 \cos \left( \frac{4\pi n(L_0 + L_{222})f}{c} \right), \tag{6}
\]

where \( A' = A\rho G; \rho \) and \( G \) represent the responsivity and the gain of the BD. \( L_0 \) is \( \sim 1 \) m.

A LabVIEW program was developed and used to control the wavelength scan of the TLS and the AOM frequency sweep, and to acquire and process the data synchronously with each AOM frequency sweep \cite{14}. The TLS (Ando TLS-AQ4321D) was set at a resolution of 0.02 nm, an output power of \( \sim 2 \) mW, and a wavelength range from 1530 to 1610 nm. The AOM (Brimrose AMM-100-20-25-1550-2FP) was swept from 90 to 110 MHz at steps of 0.02 MHz with a step time interval of 1 ms. The output of the BD (New Focus Model 2117) was sent to a data acquisition board (NI USB-6361) with a sampling rate of 100 KHz and then processed by the computer.

Figure 2 demonstrates the FFT spectrum of a sampled signal at the wavelength of 1580.036 nm obtained by the FSI scheme. Four Fourier peaks are clearly shown in the spectrum, corresponding to the four F-P sensors, F-P_{11}, F-P_{12}, F-P_{21}, and F-P_{22}, which locate at 64.6, 107.0, 175.1, and 220.5 m, respectively. The peak at zero location was the residual DC signal caused by the incomplete offset of the signals at the two output ports of the BD \cite{14}. The fluctuations between the peaks were mainly induced by the system random noise, of which the average power was \( \sim 0.2 \) \( \mu \)W. In order to eliminate its influence, all of the FSI-measured spectra that are given in Figs. 3-5 were smoothed.

By scanning the TLS wavelength, the reflection spectra of the four multiplexed F-P sensors can be obtained from the FFT spectrum at every wavelength. Figure 3(a) clearly illustrates the reconstructed and location-resolved spectrum of each sensor measured by the FSI. For comparison, we measured the reflection spectra of these sensors in the same multiplexed layout using a super luminescent diode (SLED), a 3 dB coupler, and an OSA (Yokogama AQ6370C) with a 0.02 nm resolution, which are shown in Fig. 3(b). As can be seen, the OSA measurement result is the overlay of all sensor reflection spectra, from which we could not discriminate the individual spectrum of each F-P sensor. In contrast, the FSI scheme can distinguish the reflection spectrum of each F-P sensor despite the spectral overlap.

In order to experimentally verify whether the spectrum obtained by the FSI is really the reflection
spectrum of an F-P sensor, we employed the traditional OSA measurement method to acquire the spectrum of F-P\textsubscript{21}, and then compared it with the FSI measurement result. The two kinds of spectra are shown in Fig. 4, where the vertical variable used the logarithmic coordinate for facilitating the comparison. It can be seen that they almost overlapped, which confirms that the FSI method is feasible and correct for measuring the reflection spectrum of an F-P sensor.

A strain sensing experiment was conducted on the multiplexing system. Among the four F-P sensors, only the sensor F-P\textsubscript{22} was mounted on an equal strength beam. The reflection spectra after loading the strain can be obtained using the same methods and procedures as mentioned above. For the sake of facilitating a comparison between the reflection spectra before and after loading strain on F-P\textsubscript{22}, we drew out the individual spectrum of each sensor from the direct FSI measurement and drew them in the same figure, and the results are shown in Fig. 5. We can see that there are almost no wavelength shifts in the reflective spectra of the sensors F-P\textsubscript{11}, F-P\textsubscript{12}, and F-P\textsubscript{21} from Figs. 5(a)–5(c). However, shown from Fig. 5(d), there is an obvious shift in the spectrum of F-P\textsubscript{22}, which indicates that the strain will result in the wavelength shift of an F-P sensor. On the other hand, it can also be seen that the amplitudes of all the reflection spectra are more or less changed, especially for F-P\textsubscript{12}. This may be the reason that the polarization state of reflected light by sensors drifted during the FSI measurement [16]. According to these spectra measured by FSI, we can further demodulate the cavity length and cavity-length shift of each sensor, which normally carry the information of the parameters measured.

By the algorithm of discrete Fourier transform [19], we calculated the cavity lengths of F-P sensors before and after loading strain on F-P\textsubscript{22}, and consequently obtained their relative shifts, which are shown in Table 1. The relative cavity-length shifts of F-P\textsubscript{11}, F-P\textsubscript{12}, and F-P\textsubscript{21} were only 0.19%, 0.21%, and 0.11%; however, the variation of F-P\textsubscript{22} reached 7.6%, which was a magnitude greater than the others. This indicates that the loaded strain led to the cavity-length increase of F-P\textsubscript{22}; in a deeper sense, external parameter changes can be detected from the cavity-length shift of an F-P sensor. Note that there
were tiny cavity-length changes among F-P_{11}, F-P_{12}, and F-P_{21}, although no strain was loaded on them. This may be caused by the fluctuation of the ambient temperature and the calculation error of the demodulation algorithm, which was proven to be a few parts per thousand by simulation.

4. Discussion

A. Crosstalk

Crosstalk is an important indicator for evaluating the multiplexing system performance, which is defined as the ratio of the side-lobe amplitude of the previous Fourier peak at the site where the latter peak lies to the amplitude of the latter peak. The contributing factors to crosstalk include the spectral shadowing effect, windowing during the FFT process, and interference due to unintended reflections among sensors [15]. Because the F-P sensors we used are low-reflectivity and the sensor separation is larger than the laser coherence length, the unintended interference can be ignored. Therefore, the crosstalk between serial sensors is caused by the spectral shadowing effect and windowing, but the crosstalk between parallel sensors is only caused by windowing as no spectral shadowing effect occurs between these sensors. The window function is an important factor in our system. With the experimental parameters in Section 3, we simulated the crosstalk between two adjacent serial sensors under three window functions: rectangular, Hanning, and Hamming windows, which are shown in Fig. 6. As can be seen from Fig. 6(a), the crosstalk under the three window functions almost decreases with the increase of sensor separation, and that under the rectangular window is always the worst. When the sensor separation is less than 20 m, the crosstalk under a Hamming window is smaller than that under a Hanning window. However, when the separation is more than 20 m, the crosstalk by a Hanning window, in turn, is smaller than that by a Hamming window, and it decreases rapidly with the increase of sensor separation, but the crosstalk by the other two windows lowers very gently. When the system random noise mentioned in Section 3 is considered, the crosstalk can be shown in Fig. 6(b). Obviously, the crosstalk under the Hanning window and that under the Hamming window become nearly the same, and their values are higher than those with no noise [shown as in Fig. 6(a)], whereas the crosstalk under the rectangular window is still the worst. Therefore, Fig. 6 illustrates that the size of crosstalk depends on not only the sensor separation and types of window functions but also the system random noise. If a laser source with low noise, a proper window function (Hanning or Hamming), and the right sensor separation are chosen, the crosstalk can be effectively reduced. Figure 7 demonstrates the Fourier spectrum under a Hanning window and that under a Hamming window in two situations: without noise [shown as in Fig. 7(a)] and with the noise, mentioned in Section 3 [shown as in Fig. 7(b)]. As we can see, whether in the noise-free situation or in the noisy situation, the Fourier peak width of the FFT spectra under the Hamming window and the Hanning window are approximately equal, but the Hamming window has higher Fourier peaks and almost the same side lobes, which shows clearly that it has higher SNR. By calculation, the SNR under a Hanning window is 3.9 dB larger than that under a Hamming window in the noise-free situation. Considering the results above, we adopted the Hamming window during the experimental measurements.

B. Maximum Sensor Number

The quality of a multiplexing scheme and a multiplexing system mainly depends on the number of
sensors that can be multiplexed. The maximum sensor number is obtained by extracting the number of Fourier peaks whose amplitudes are higher than a specified threshold. Here the threshold is roughly set as the mean amplitude of fluctuations (include side lobes and the random system noise as mentioned in Section 3) at the bottom of a FFT spectrum. And in order to further weigh the performance of a multiplexing system, we define the maximum frequency-domain SNR as the ratio of the maximum Fourier peak to the standard deviation of its side-lobe amplitudes. Using the experimental parameters in Section 3, we constructed a two-channel hybrid multiplexing system and a serial system, set the source wavelength at 1580.036 nm, and changed the sensor separation under three source powers: 1, 2, and 3 mW. Note that for simplicity we set each F-P sensor with the same cavity length of 80 μm. Then we achieved the curves of the multiplexed sensor number and the maximum frequency-domain SNR, which are shown in Fig. 8. From it we can see some phenomena as follows:

First, when the source power remains unchanged, the sensor number multiplexed by a two-channel hybrid multiplexing system is approximately twice as much as that by a serial system. The sensor number curves of the serial system tends toward stability when the sensor separation is more than 10 m, and yet the number curve of the hybrid system gradually drops after an approximate stability; that is, there is an inflection point on its curve. This is caused by the restriction of crosstalk and the maximum multiplexing distance, i.e., the sensing range (∼2586 m according to Eq. (14) in [15]). When the sensor separation is less than 10 m, the crosstalk is so serious [as shown in Fig. 6(a)] that the Fourier peaks almost overlap and become difficult to distinguish. However, when the sensor separation increases to more than 10 m, the crosstalk is low enough to make a certain number of Fourier peaks set apart, which results in the near invariability of sensor number. However, the sensor separation could not be increased infinitely, because the product of the separation and its corresponding sensor number must be less than the sensing range. For a serial system, since the sensor number is small at the separation range from 10 to 150 m, the product is always small and the sensor number remains nearly unchanged, but for the hybrid multiplexing system, the sensor number is relatively high and the product can easily exceed the sensing range, so the sensor number decreases with the increase of the sensor separation after the separation exceeds a certain value, i.e., the inflection value. And the inflection value will decrease with the increase of the source power due to the increase of the source power.

Second, when the sensor separation is constant, the sensor numbers of the two systems both increase with the increase of the source power as the amplitudes of Fourier peaks all enlarge with the power. Third, because the amplitudes of the maximum Fourier peak and its side lobes change at nearly the same rate, the maximum frequency-domain SNR for different source powers is almost identical. And because the most previous sensor in a serial system and the one in a two-channel system have the same input light intensity, the two types of systems also have the same maximum frequency-domain SNR.
SNR. Consequently, for avoiding confusion, we just drew one of the maximum frequency-domain SNR curves in Fig. 8, which is the one marked with a black arrow under the source power of 2 mW. As we can see, the SNR curve rises sharply in the beginning separation range from 5 to 25 m, stabilizes in the range from 30 to 45 m, and then declines gradually after 45 m separation. Although the SNR at the separation of 25 m is the maximum, the crosstalk in the FFT spectrum is very high [as shown in Fig. 6(a)]. Therefore, the separation of 40 m is the best choice under satisfying the requirement for high SNR and low crosstalk.

As can be seen, when the source power is 2 mW, the wavelength is 1580.036 nm, and the sensor separation is 40 m, we can have 26 sensors in a two-channel hybrid multiplexing system and 13 in a serial system, with a crosstalk of less than −50 dB and a maximum frequency-domain SNR of ∼25 dB. In addition, we simulated the influence of the system noise on the multiplexed sensor number. The results show that when the source power remains constant the random volatility of the sensor number and the maximum frequency-domain SNR increase with the increase of the system noise, and vice versa, and the number and SNR are closer to the ideal values.

5. Conclusions

A novel multiplexing method of optic fiber F-P sensors based on FSI was proposed and demonstrated. Four F-P sensors were experimentally multiplexed to verify the proposed hybrid multiplexing system. The multiplexed location of each sensor was resolved by performing FFT. In spite of the spectral overlap, the reflection spectrum of each sensor was obtained by scanning the wavelength of the optic source, which agreed well with the measurement result of an OSA. By simulation, it was found that the crosstalk increases with the decrease of the sensor separation, and can be effectively suppressed by employing a low-noise laser source and a proper window function. An SNR improvement of 3.9 dB can be achieved by a Hamming window in a noise-free situation compared with a Hanning window. For such FSI-based multiplexing systems, the maximum sensor number is mainly constrained by crosstalk, the maximum frequency-domain SNR, the source power, and the sensing range. Among them, the multiplexed sensor number increases with the increase of the source power, and the number multiplexed by a two-channel hybrid system is nearly twice as large as that of a serial system. In the condition of meeting the requirements for high SNR and low crosstalk, the separation of 40 m is optimal. When we set the source power at 2 mW, the wavelength at 1580.036 nm, and the sensor separation at 40 m, we achieved 26 F-P sensors in a two-channel hybrid system with crosstalk of less than −50 dB and maximum frequency-domain SNR of ∼25 dB. In addition, the cavity lengths and strain-induced cavity-length shifts of the four sensors were experimentally obtained, which were consistent with the actual situation. In conclusion, the experiment and simulation results show that the FSI-based multiplexing scheme for F-P sensors is suited for large-scale sensor networks, and can find important applications in sensing the change and position of ambient physical or chemical parameters.

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