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Optical fiber ultrasonic sensor networks based on WDM and TDM

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Abstract. An optical fiber sensor network for ultrasonic measurement based on wavelength division multiplexing (WDM) and time division multiplexing (TDM) technology is presented. Each of the sensor probes is an optical fiber extrinsic Fabry-Perot interferometer (EFPI) which is composed of the fiber’s end face and the aluminum thin diaphragm. The sensors are arranged in different wavelength domains formed by a wavelength division multiplexer. Each wavelength division multiplexer, with a group of the sensors, is connected to one of the output ports of optical switch to realize TDM. The signal of each sensor is exported sequentially from a tunable narrowband optical filter (TNOF) that queries every sensor though scanning mode. The principle of the phenomenon of phase induced signal fade in interferometric fiber-optic sensors is also analyzed. Nicely, the detection method above implements the operation of anti-phase induced signal fade detection. The system is interrogated by broadband light source. The scanning range of TNOF is full of the bandwidth of the light source. The result of experiment in water show that the sensor sensitivity reaches -162dB(0dB=1rad/µPa), the frequency response range is from 10KHz to 5 MHz. The number of multiplexing sensors based on WDM and TDM reaches to 64.

Keywords: optical fiber sensor, WDM, TDM, Fabry-Perot interferometry, signal fade

1. Introduction
The detection of the ultrasound field pressure plays an important role in many fields. Optical fiber Fabry-Perot (F-P) interferometric sensor has a number of inherent advantages, including high sensitivity, immunity from electromagnetic interference, resistant to corrosion and small size, in application of ultrasound detection [1][2][3]. Array system based on various multiplexing technology is the current trend of research in ultrasound detection field [4], especially in optical fiber hydrophone.
field. At the same time, there is the phenomenon of phase induced signal fade in interferometric optical fiber sensors in measuring dynamic pressure signal. To implement anti-phase induced signal fade detection and multiplexing detection are the key points in measurement of ultrasound field. In this paper, we demonstrate an array structure of F-P interferometry sensors based on wavelength division multiplexing (WDM) and time division multiplexing (TDM) technology. And the anti-phase induced signal fade detection is implemented.

2. Structure of the networks
Figure 1 shows the total construction of the proposed array based on WDM and TDM methods. Sixty-four fiber F-P sensor probes are integrated in this trial. The input light for the system is a superradiance light emitting diode (SLD) broadband source (BBS) with 200nm full width at half maximum (FWHM). The injected light through the bidirectional optical switch (OS) is divided into eight beams by a coarse wavelength division multiplexer (CWDM) which has eight channels with 20nm interval. Thus, the every eight sensors in a group can all be interrogated within different optical spectrum, in which the sensors occupy different wavelength bands.

![Figure 1. WDM and TDM scheme of the ultrasonic measurement system](image)

All the reflected lights from the sensor elements are combined by a tunable narrowband optical filter (TNOF). The TNOF has a free spectrum range of 200nm, and the bandwidth is 0.1nm. A sawtooth-wave generated by processing circuit, as a linear-scanning voltage, is used to drive the TNOF. The output beam of the TNOF is a narrow band light with the information of interference signal come from sensor probes. And then the output beam detected by the PD is sampled and processed.

When the scan voltage is generated, the control signal is also exported to the optical switch from the signal processing circuit. These two signals together determine which probe the current signal waveform detected by PD corresponds to.

3. Principle of the probe
The optical fiber F-P sensor is composed of single mode fiber, silica glass tube and aluminum (Al) diaphragm, as shown in Figure 2. The inside diameter of the thick tube is 2mm, and its outside diameter is 4mm. The active diameter of Al diaphragm is equal to the inside diameter of the thick tube, 2mm obviously. The distance between Al diaphragm and the end face of single mode fiber ranges from several to several tens of micron, and it is the length of the F-P cavity.
Light is injected into the optical fiber and partially reflected by the end face of the fiber as the first beam of the interference light. The other beam emitted from fiber is reflected by the inside surface of the Al diaphragm. Then the two reflected beams propagate back into the same fiber and generate interference fringes. Affected by ambient pressure, the Al diaphragm will deform, that is to say the cavity length is in response to ambient pressure variation, thus resulting in a slight change of the optical path difference of the two beams. And then the output intensity which generates output voltage signal will change with measurand.

The diaphragm will be deflected whenever there is a differential pressure $\Delta P$ between inside and outside of the cavity. Supposing the cavity length is $d$, $\Delta d$ is the deflection of the diaphragm. With the assumption of uniform diaphragm thickness, small deflection, the deflection of Al diaphragm under pressure difference $\Delta P$ is expressed as [5]

$$\Delta d = \frac{3(1-\mu^2)(a^2-r^2)^2}{16Eh^3}\Delta P$$

(1)

Where $a$ is the radius of the diaphragm defined by the inner diameter of the thick silica tube, $r$ is any radial position leaving central point of the diaphragm, $h$ is the thickness of the diaphragm, $\mu$ is Poisson’s ratio of diaphragm material and $\mu=0.355$ for Al material, $E=7\times10^{10}\text{N/m}^2$ is modulus of elasticity of the aluminum material.

Based on the properties of aluminum diaphragm, the lowest natural frequency of the diaphragm can be theoretically calculated as follows [5]

$$f = \frac{\alpha}{4\pi} \sqrt{\frac{Eg}{3\omega(1-\mu^2)}}\left(\frac{h}{a^2}\right)$$

(2)

Where $\alpha$ is a constant related to the vibrating modes, and $\alpha=10.21$ for the lowest natural frequency, $g = 9.815 \text{ m/s}^2$ is the gravitational constant, $\omega$ is the mass density of the diaphragm material, $\omega=2.7\times10^3 \text{ kg/m}^3$ for Al material, and $a$, $h$, $E$, and $\mu$ are the same as the parameters in Eq.(1).

Can be seen from Eq.(1) and Eq.(2), the deflection of the diaphragm is proportional to pressure difference. And radius and thickness of the diaphragm are the key factors for sensitivity and frequency response of the sensor.

In order to further improve the sensitivity of the sensor, the thick silica tube is processed into tapered end, as shown in Figure 3. Then the efficient radius of the diaphragm increase to 1.5mm from 1mm, so the pressure sensitivity improves to 5 times of the original.

4. Anti-phase induce signal fading detection
If a sinusoidal phase modulated signal of the interferometric sensor with initial phase, $\varphi_0$, the interference intensity signal is

$$I = A + B \cos(\varphi_0 + \varphi_s + \varphi_n)$$

(3)

Where constants $A$ and $B$ are proportional to the input optical power, but $B$ also depends on the mixing efficiency of the interferometer; and $\varphi_s$ is the phase shift caused by the measured signal; $\varphi_n$ is phase shift for environmental effects.

The phase shift $\varphi_n$ caused by the environment is usually great signal of the low frequency and random fluctuations, but the measured signal is often weak signal. When there is a very small phase shift $\Delta \varphi_s$ caused by measured signal, the voltage converted from light intensity is

$$V = kA + kB \cos \Delta \varphi_s \cos(\varphi_0 + \varphi_n) - kB \sin \Delta \varphi_s \sin(\varphi_0 + \varphi_n)$$

$$\approx kA + kB \cos(\varphi_0 + \varphi_n) - kB \Delta \varphi_s \sin(\varphi_0 + \varphi_n)$$

(4)

Where $k$ is conversion factor. Since $\varphi_n$ varied very slowly, it can be treated as DC signal. So the voltage changes $\Delta V$ can be expressed as

$$\Delta V \approx -kB \Delta \varphi_s \sin(\varphi_0 + \varphi_n)$$

(5)

Therefore, when $\varphi_0 + \varphi_n = m\pi + \pi / 2$ or $\varphi_0 + \varphi_n = m\pi + 3\pi / 2$ (m is integer) with slowly drift of $\varphi_n$, the output signal will reach maximum. But, when $\varphi_0 + \varphi_n$ is close to $m\pi$, the output signal is about zero. This is the phenomena of phase induced signal fading of interferometric fiber-optic sensors.

In order to eliminate the signal fading and implement the signal stable examination, many methods of detecting signal have been proposed such as 3×3 coupler [6], phase generated carrier [7], phase-tracking technology [8].

In our design, it is to eliminate the signal fading automatically by introducing the TNOF and CWDM. The CWDM has the same operation principle as a coarse WDM that was used in fiber optic telecommunication. It is custom-made, and it is quite compatible with the optical fiber. The configuration of the CWDM and the spectra of the interference signal are shown in Figure 4.

![Figure 4. Interference spectrum and wavelength division interval](image)

The interference signal waveform of one of the sensors is shown in Figure 4. The whole scope of source wavelength is divided into eight beams with the channel interval of the CWDM, $\Delta \lambda = \Delta \lambda_i (i=1\ldots8)$, as shown in Figure 4. Each beam is corresponding to a sensor probe respectively. If
the TNOF is tuned in $\Delta \lambda_1$, probe 1 is activated while the other probes are not accessed, and the current of PD gives the output signal of probe 1. If the TNOF is moved into $\Delta \lambda_2$, the signal of probe 2 is detected, and so on.

The wavelength-period of the interference spectrum must be not less than 2 times of $\Delta \lambda$,

$$\lambda_a - \lambda_b \geq 2\Delta \lambda$$

(6)

Where $\lambda_a$ and $\lambda_b$ which are the peaks of the interference signal. When the TNOF scans within the scope of wavelength of the source, $\varphi_0$ is also to change continually. And then, the center wavelength of TNOF is always to achieve the orthogonal points to export the maximum of the signal when the TNOF scans in every channel of the CWDM. Even if there is disturbance from environment, it is also true. The voltage of orthogonal point is the value when $\varphi_0 + \varphi_a = m\pi + \pi / 2$ or $\varphi_0 + \varphi_a = n\pi + 3\pi / 2$.

The wavelength-period of the interference spectrum is inversely proportional to the cavity length of the sensor [9]. Therefore, we may control the period of interference signal by adjusting the cavity length of the F-P probe at first.

5. Experiments

The two wavelengths $\lambda_a$ and $\lambda_b$ are the peaks of the interference signal with $2\pi$ out of phase as shown in figure 4. Then the cavity length $d$ is

$$d = \frac{\lambda_a \lambda_b}{2(\lambda_a - \lambda_b)}$$

(7)

The relationship of the differential variables, $\Delta d$ and $\Delta \lambda$, is $\Delta d / \Delta \lambda = \Delta \lambda_b / \lambda_a$.

First we test the static pressure characteristic of the F-P sensor. We may indirectly obtain cavity length $d$ by the position of the peaks of the interference signal on the screen of spectroscopic instrument. The relationship between cavity length $d$ and outside pressure is shown as Figure 5. The static pressure response curve has been fitted by line $y=33.081-2.286x$, and the correlation coefficient is 0.998. The sensitivity of the sensor is 1.96$\mu$m/KPa of change quantity of cavity length. We can also work out the phase sensitivity of the sensor is -162dB(0dB=1rad/$\mu$Pa) at the wavelength, 1550nm.

![Figure 5. Static pressure response of the sensor](image1)

![Figure 6. signal and its frequency spectrum](image2)

We set up another experimental system to test the performance of the array of F-P diaphragm-based sensors for ultrasonic wave signal detection in a water tank. The ultrasonic vibration
signal is generated by a piezoelectric (PZT) transducer driven by an adjustable sine wave signal. The sensor probes receive underwater ultrasonic wave signal and transform the signal to light intensity signal, and the signal processing circuit transforms intensity signal to voltage signal. The output voltage signal waveform exported from one of the sensor and its frequency spectrum are shown in Figure 6.

Every sensor can receive the ultrasonic signal when the TNOF scans the corresponding passband of the CWDM. But the signal amplitude is variable with the center wavelength of the TNOF moving. When the center wavelength is at the orthogonal point of the interference signal, the amplitude is biggest. So the amplitude maximum should be treated as the normal amplitude of the signal detected by the sensor. The frequency range of the sensor sensing is from 10 KHz to 5MHz.

6. Conclusions
We have described a diaphragm-based miniature fiber-optic ultrasonic F-P sensor and the array detection system based on WDM and TDM technology. It has simultaneously implemented sensor multiplexing and anti-phase induced signal fade detection by using CWDM and a tunable narrowband optical filter. It is ideal for applications of acoustic and ultrasonic detection, such as hydrophone.

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