Photoelectricity Signal Processing Circuit of Interferometric Fiber-Optic Pressure Sensor

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ABSTRACT

We have designed an intensity-demodulated sensing system based on Fabry-Perot interferometric sensor for pressure measurement. The structure of the sensing probe has been presented. The sensing system is interrogated by broadband source. For compensating drift of the source power and fluctuation in fiber attenuation, the light beam is separated into two channels by a fiber Bragg Grating, the transmitted light used as reference signal and the reflected light used as sensing signal. In order to improve the signal-to-noise ratio(SNR) of the detection system, the input light is modulated by pulse signal, and the low noise preamplifier is given. The more important factor to improve the SNR is that a synchronization integrator is employed to construct a narrow band filter to restrain noises and disturbances. It has better performance with a narrow band noise filter rather than the general RC active bandpass filter. The sensing signal and the reference signal are transformed into DC voltage signal from AC voltage signal after they passed the synchronization integrator circuit. Subsequently the division operation of the sensing signal and the reference signal is implemented. At last a linear output model is established. The system has advantages of fast response, strong ability and low cost. The dynamic range of the sensor is from 0 to 400KPa, and the resolution reaches to 200Pa.

Keywords: Optical fiber sensor, Fabry-Perot interferometer, Pressure, Signal-to-noise ratio, Synchronization integrator

1. INTRODUCTION

Compared with conventional sensors, Optical fiber sensor has many advantages such as high sensitivity and resolution, immunity from electromagnetic interference, resistant to corrosion and good electrical insulation. Among various types of optical fiber sensors, optical fiber Fabry-Perot interferometric sensor is an important branch[1]. Because of its simpleness, ingeniousness and low costs, it has been doing extensive research in many fields. Pressure measurement[2][3][4] is the basic application of the sensors. In many cases, the useful signal is even less than the noise from the environmental disturbance and the device itself. So we should take effective measures for noise reduction, design the system of weak signal detection circuit to improve the resolving power and signal-to-noise ratio(SNR).

2. PRINCIPLE OF THE SENSOR

2.1 Structure of the sensor

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The structure of optical fiber Fabry-Perot interferometric sensor is shown in Fig. 1[3]. The sensor is composed of a hollow fused silica tube and single mode fibers (SMF). By plugging optical fibers into the silica tube, an optical fiber extrinsic Fabry-Perot interferometer is produced within the silica tube. Interference is happened by the two beams reflected from the two end faces of the fibers, SMF1 and SMF2, shown in Fig. 1. The distance between the two end faces of optical fibers ranges from tens to hundreds micron, and it is called cavity length. The length of the silica tube L is called the gauge of the sensor.

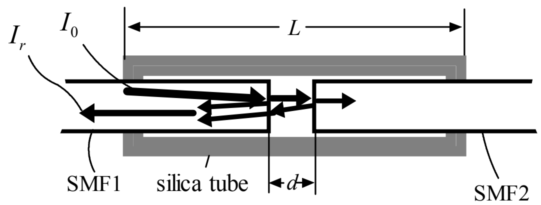

Fig. 1. Structure of the sensor probe

Light, I_0, is injected into SMF1 and partially reflected by the end face. The reflection index of SMF1 end face, R_1, higher than bare fiber end face because the end face is electroplated by a piece of metal reflected film on it. The other beam emitted from SMF1 is reflected by the end face of SMF2 and then coupled into SMF1. The two reflected beams generate interference fringes in SMF1. Under general conditions, the reflection index of the tip of SMF2 is higher than SMF1, namely $R_2 > R_1$. In this case, the contrast of the interference fringes will reach a higher value.

2.2 Pressure response principle

Affected by external pressure, the silica tube will deform, thus resulting in a slight change in the length of the cavity. When there is a differential pressure ΔP between inside and outside of the tube, the variable quantity of cavity length Δd under pressure difference ΔP is expressed as[5]

$$\Delta d = \frac{\Delta P L r_o^2}{E(r_o^2 - r_i^2)}(1 - 2\mu) \quad (1)$$

Where L is the length of the tube, r_i is inside radius of the tube and r_o is its outside radius, μ is Poisson's ratio of tube material and μ=0.17 for silica material, E=7.3×10^{10}N/m^2 is modulus of elasticity of the silica material.

From Eq.(1), we can see the variable quantity of the cavity length is proportional to pressure difference and the tube length is the key factors for sensitivity of the sensor. In our sensor configuration, r_i=63μm, r_o=0.9mm, L=5cm.

2.3 Measurement system

The pressure measurement system setup can be seen in Fig. 2. The input light for the system is a broadband source(BBS) such as a light-emitting diode(LED), a superluminescent diode(SLD) or an amplified spontaneous emission(ASE) source. The fiber Bragg grating(FBG) is used as a narrow band filter which can provide sensing signal and reference signal to compensate error due to power drift of the source and fluctuation in fiber attenuation[6]. The light transmitted through the FBG, as the reference light signal, is directly detected by photodiode 1(PD1) and the light reflected by FBG, as the sensing light signal, is detected by PD2. The two light signals are transformed into current signals by photodiodes. After combined treatment of the two current signals in the signal processing circuit, the final result is given.

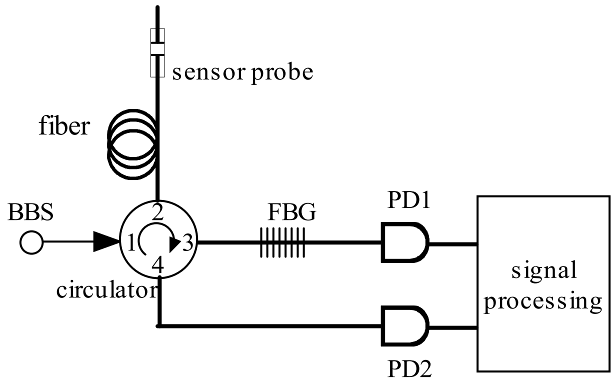

Fig. 2. Scheme of the measurement system

3. CIRCUIT DESCRIPTION

In this section the system design and practical considerations to be taken into account for measurement circuit are presented. SNR is the main improvement in the design of the full system.

3.1 Function of the circuit

The measurement circuit is designed to convert optical signal to voltage signal and then the analog voltage signal is transformed to digital signal by A/D converter to implement other function such as memory and display. In order to improve the system SNR, we have used a low noise preamplifier to amplify the weak signal, converted the DC signal to AC signal to avoid operating point shift, and used a synchronous integrator to limit noise bandwidth. The block diagram of the circuit is shown in Fig. 3.

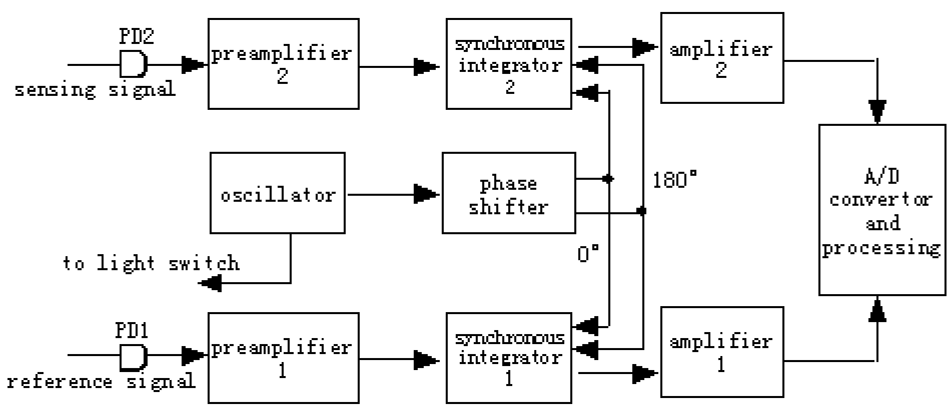

Fig. 3. Signal processing scheme

The square wave signal generated by oscillator is separated into two paths: the first is to control the light switch to provide light pulse signal, the second is split into two channels of contrary phase wave to control the two electronic switches of the synchronous integrator. After the sensing signal and the reference signal were processed by the two similar circuits which include preamplifier, synchronous integrator and amplifier, they are converted into digital signal and make division operation in the last block as shown at the right side in Fig. 3.

3.2 Preamplifier circuit

Since the light intensity to the photodiode is less than the level of μW, it is necessary to amplify the signal from the sensor with a very high-gain preamplifiers. Nevertheless, if the gain is very high, most tiny noises are amplified simultaneously and interfere seriously with the output signal. Therefore, in our design, we should restrain any noise generated by the photodiode and operational amplifier.

The high-sensitivity photodiode with the responsivity of 0.8 A/W and the dark current of 50 nA is selected. The light signal is transformed into current signal by the photodiode, so the preamplifier should be a current-voltage type circuit, namely transimpedance amplifier, as shown in Fig. 4.

The noise figure is the key factor to the preamplifier, especially for high gain amplifier. The operational amplifier(OA) of AD8572 has ultralow offset, drift and bias current. And it is autozeroing amplifier with Analog Devices' new topology. With an offset of only 1 μV, drift of 0.005 μV/℃ and voltage noise density of 51 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$, the AD8572 is perfectly suited for applications where error sources cannot be tolerated.

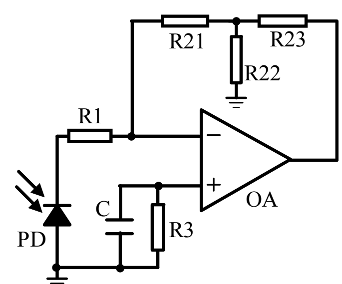

Fig. 4. Photoelectric detection circuit

In order to achieve a higher gain, the feedback resistor value should be a great, but when the feedback resistance to a certain large value, the stability of resistance will lower and its noise become larger; moreover, when the feedback resistance is close to the order of the input resistance of OA, the amplification factor of the circuit will be unstable. The feedback resistor should not therefore take a big value. Here using T-resistor network instead of single feedback resistor is shown in Fig. 4.

The equivalent resistance of the T-resistor network is:

$$R_F = (R_{21} + R_{23})(1 + \frac{R_{21} // R_{23}}{R_{22}}) \tag{2}$$

For example, when R_1=5KΩ and G=1000, then the feedback resistor should be 5MΩ, that is R_F=5MΩ. To take $R_{21}=R_{23}$=100KΩ and R_{22}=2KΩ, then the equivalent resistance R_F can be obtained from the Eq.(2), is 5.2 MΩ. In this way, the 100KΩ and 2KΩ resistors played a role of 5.2MΩ resistor.

3.3 Synchronous integrator circuit

Synchronous integrator is a kind of synchronous filters which has the strong anti-interference ability resulting in able to extract weak signal under intense noise background. It continuously samples the voltage parameters at the same phase point of the each cycle of periodic signal to achieve the accumulation of the signal voltage. The arithmetic mean value of the voltage given from synchronous integrator is proportional to instantaneous value of the signal, but the average value of noise was zero. Therefore the Synchronous integrator might enhance the SNR greatly.

Suppose the input signal is V_{si}, the output is V_s. After V_{si} has been accumulated m times by the synchronous integrator, V_s is expressed:

$$V_s = \sum_{i=1}^{m} V_{si} = m\overline{V_{si}} \tag{3}$$

Where $\overline{V_{si}}$ is the average of the input signal voltage.

Suppose the input of random noise voltage is V_{ni}. After multiple accumulating, the noise output V_n is also random, as:

$$V_n = \frac{1}{m}\sum_{i=1}^{m} V_{ni} \tag{4}$$

The noise voltage of $V_{ni}(i=1,2,3,\ldots,m)$ has the same distribution. When $V_{ni}(i=1,2,3,\ldots,m)$ belongs to normal distribution, its mathematical expectation is zero and the variance is the noise power P_{ni}.

$$E(V_n) = \frac{1}{m}\sum_{i=1}^{m} E(V_{ni}) = 0 \tag{5}$$

$$P_n = D(V_n) = E(V_n - E(V_n))^2 = E(V_n)^2 = \frac{1}{m^2}\sum_{i=1}^{m} D(V_{ni}) = \frac{P_{ni}}{m} \tag{6}$$

Then the SNR of the output signal is:

$$\frac{P_s}{P_n} = \frac{\overline{V_{si}}^2}{P_{ni}/m} = m\frac{\overline{V_{si}}^2}{P_{ni}} \tag{7}$$

Obviously, the signal can accumulate effectively after sampling many times because it has the correlation. But the noise accumulation effect is on difference because it is random. The SNR may be m times of the original after m times accumulation.

The frequency of input signal has no relation with the parameter of R and C which only affects the noise bandwidth. The equivalent noise bandwidth nearby fundamental frequency is expressed as[7]:

$$\Delta f = \frac{1}{4RC} \tag{8}$$

The synchronous integrator circuit is shown as Fig. 5. The electronic switch, CD4016, is controlled by the square wave pulse generated by oscillator. The bigger of integration time constant RC, the stronger of capability to restrain noise. In the circuit, R=100KΩ, C=10uF, the equivalent noise bandwidth is only 0.25Hz calculated from Eq.(8). Can be seen that synchronous integrator circuit significantly limited the noise bandwidth, it largely improved SNR.

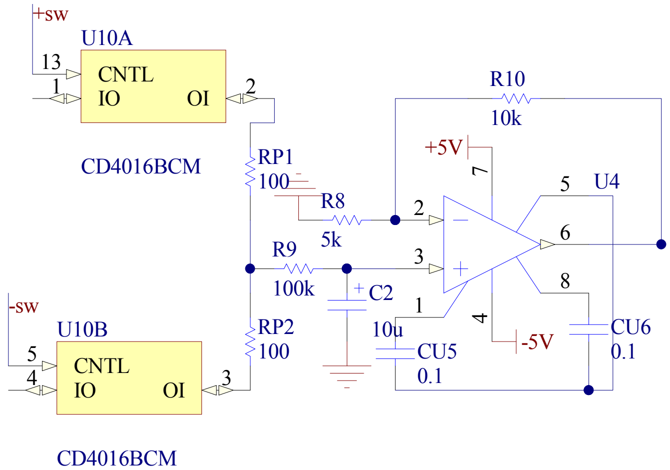

Fig. 5. Synchronous integrator circuit

In order to improve the output voltage of the synchronous integrator, the high level and low level of the input signal were all sampled and accumulated. So the signal had been separated into two channels with contrary phase behind preamplifier. Certainly the two signals with contrary phase should be sampled by the pulses with contrary phase too, +*sw* and –*sw*, as shown in Fig. 5.

4. PRESSURE MEASUREMENT

The system configuration used to analyze the pressure responds characteristic has been set up. The sensor head is placed in a pressure tank. The pressure within the tank is generated by hydraulic machine that includes a pressure gauge. The static pressure response of the measurement system is shown in Fig. 6.

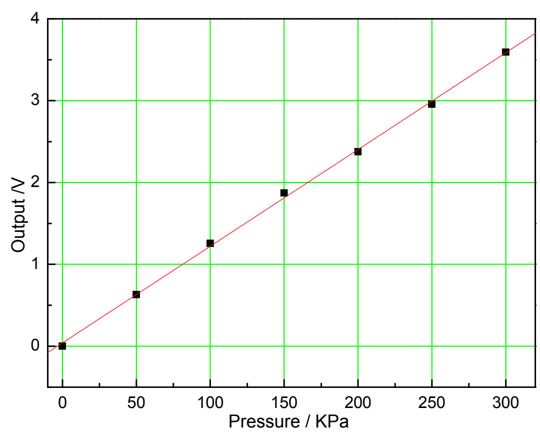

Fig. 6. Pressure measurement curve

From Fig. 6, the output voltage signal is proportional to the pressure around the sensor head. And the actual measured dynamic range of the sensor is from 0 to 400KPa. The curve has been fitted by line y=0.0394+0.0118x, and the correlation coefficient is 0.9995. The sensitivity of the sensor is 12mV/KPa and resolution is 200Pa.

5. CONCLUSION

This paper presents an interferometric–intensity-based extrinsic Fabry-Perot fiber sensor that interrogated by broadband light source and its signal processing circuit. We have taken effective measures for noise reduction and designed the system of weak signal detection circuit to have improved the SNR. The system has high resolution and fast response. The experimental testing of the pressure sensor with measurement ranges of 0–400KPa has the relative resolution as high as 0.05% of full scale. Its sensitivity reaches to 12mV/KPa. It is ideal for measuring pressure of liquid or gas.

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