Sensing system with Michelson-type fiber optical interferometer based on single FBG reflector

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A sensing system, with Michelson-type fiber optical interferometer based on single fiber Bragg grating (FBG) as the reflector, is demonstrated. The system used a frequency-matched ring fiber optical laser as the source. The closed Michelson-type fiber optical interferometer system will be helpful in simplifying the developed interferometric sensor by replacing the double reflectors with only one FBG reflecting the double-side light. The basic sensing properties of the system are demonstrated, with a fiber optic piezoelectric ceramic transducer embedded in the arm of the interferometer simulating the sensing signal.

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As a simple fiber optic component, fiber Bragg grating (FBG) has been used frequently as a sensor, filter or reflector[1−4], etc. Meanwhile, the Michelson-type fiber optical interferometric sensor has achieved a high level of development in the acoustic, electric, and magnetic field sensors because of its simple and low-cost structure as well as multiplexing advantages. The Michelson-type interferometer has been widely applied with Faraday rotating mirrors (FRMs) or polarization maintaining fiber reflectors particularly in the fiber optic hydrophone system[5,6]. At present, further research is aimed at simplifying fiber optical interferometric sensors.

A simple research has been performed. This is concerned with replacing the two reflectors with two FBGs, which must have the same properties under the same environment[7]. The use of FBG as partial reflector and wavelength division multiplexer along the same fiber is an important topic for study. This kind of structure has been developed extensively, and it has become the main structure in the fiber optical hydrophone multiplexing array[8]. According to Ref. [9], the sensing principle of the FBG embedded in the ring has realized the novel demodulation of FBG sensor, based on the use of an amplified spontaneous emission (ASE) source. However, realizing the scheme is difficult because of the required accurate balance for the fiber optical paths beside the FBG. Additionally, the sensing principle of FBG has just been studied recently. One kind of structure, a FBG embedded in a loop interferometer, has also been studied as a comb filter[10].

In this letter, we propose a simplified Michelson fiber optical interferometer with only one FBG serving as double direction light reflector and a frequency-matched fiber optical laser as the source of the interferometer.

The structure of the system is shown in Fig. 1. A ring fiber optical laser (RFOL)[11] has been used as the source in the system. RFOL has a stable output and very narrow line-width, the wavelength of which depends on a saturated absorber and a FBG at the end of the absorber. Consequently, the wavelength would always be located in the flat peak of the FBG. When we obtained another FBG (named as reflecting FBG) with the same property as those of the FBG in the RFOL, the wavelength of the laser has been shown to be located in the flat peak of this reflecting FBG when the temperature around the system environment does not change quickly.

Thus, this reflecting FBG can be used in a fiber ring, which is combined by the two output ports of a 2 × 2 fiber optical coupler (see Fig. 1). The light from the RFOL passes through an optical isolator and injected in the 2 × 2 coupler. To simplify the deduction process, we assume that the 2 × 2 coupler has no loss, and its splitting ratio is 1:1. The light from port 3 passes through a fiber optic piezoelectric ceramic transducer, which serves as a phase modulator, to simulate the signal from external effects, such as acoustic pressure, magnetic field induced strain, etc. Lastly, the lights from ports 3 and 4 reach the counter side of the reflecting FBG. As described above, the two beams are almost fully reflected. A new kind of non-balanced Michelson fiber optical interferometer with a narrow-width RFOL source is obtained. We call the interferometer as a closed Michelson fiber optical interferometer (CMFOI) with single FBG reflector. The interference signal can be obtained by a photo detector at the end of port 2 of the coupler.

Theoretically, the light output at the detector can be shown as

$$I_{\text{out}} = I_0 R(1 + \cos \Delta\phi) = I_0 R[1 + \cos(2\phi_{\text{s}} + 2\phi_0)], \quad (1)$$

where I_0 is the light power at the port 1 of the 3-dB coupler, R is the reflective ratio of the FBG as a reflector (the wavelength of the laser is located at the flat peak of the reflecting spectrum of the FBG), ϕ_{s} is the phase signal produced by the phase modulator, $2\phi_{\text{s}}$ is the parameter that will be measured by the interferometer, and $2\phi_0$ is

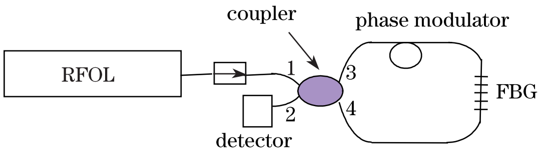

Fig. 1. Simplified system construction.

the initial phase difference between light path 1 and light path 2. Light path 1 is illustrated as follows: port 1 → port 3 → FBG reflecting → port 3 → port 2. Light path 2 is depicted as follows: port 1 → port 4 → FBG reflecting → port 4 → port 2. We assume that the FBG produces the same phase delay when the counter directional lights are reflected.

Evidently, when R is not equal to 1, there will be another set of two paths of light that passes through the FBG which mixes with the interference signal. Path 3 is described as follows: port 1 → port 3 → FBG passing → port 4 → port 2. Path 4 is illustrated as follows: port 1 → port 4 → FBG passing → port 3 → port 2. The lights of the four paths must be considered together. The complex mode amplitudes of the lights of the four paths are added together, the sum is multiplied by its conjugation, and the real part of the result is the light output at the detector.

We illustrate the phase delays of the four paths of light as follows: path 1: $2L_1 - \pi/2 - P_{\text{FBG\_R}}$, path 2: $2L_2 - \pi/2 - P_{\text{FBG\_R}}$, path 3: $L_1 + L_2 + P_{\text{FBG\_P}}$, path 4: $L_1 + L_2 - \pi + P_{\text{FBG\_P}}$. L_1 is the phase delay from coupler port 3 to FBG, L_2 is the phase delay from coupler port 4 to FBG, $P_{\text{FBG\_R}}$ is the phase delay when light is reflected from FBG, $P_{\text{FBG\_P}}$ is the phase delay when light passes through FBG, and $\pi/2$ is the phase delay of the coupler which should also be considered. The coherence between paths 1 and 2 is the main of the interferometer. The coherence between paths 3 and 4 is ignored because it is a Sagnac interferometer with very short ring length. The coherence between path $i(i = 1,\ 2)$ and path $j(j = 3,\ 4)$ is dramatically cancelled out when the coupler is a realistic 3-dB component, as we have assumed.

The result at the detector can be deduced by

$$\begin{aligned} I_{\text{out}} = {} & I_0 R + I_0 R\cos(2\phi_{\text{s}} + 2\phi_0) + I_0(1-R) \\ & + I_0(1-R)\cos(\pi) + I_0\sqrt{R(1-R)} \\ & [\cos(\Delta L - P - \pi/2) + \cos(\Delta L + P + \pi/2) \\ & + \cos(\Delta L - P + \pi/2) + \cos(\Delta L + P - \pi/2)] \\ = {} & I_0 R[1 + \cos(2\phi_{\text{s}} + 2\phi_0)]. \end{aligned} \tag{2}$$

Thus, ϕ_0 is the DC part of $L_1 - L_2$ and ϕ_{s} is included in the AC part of $L_1 - L_2$. $\Delta L = L_1 - L_2$, $P = P_{\text{FBG\_R}} + P_{\text{FBG\_P}}$. In this equation, the phase delay due to the light passing through or being reflected by the FBG is always constant, although it may change with the reflective ratio. This means that it has also been discharged. The FBG is not sensitized on the sensing stain, hence, its effect can also be ignored. The losses of the coupler, passing fiber, and the FBG are all ignored in the above derivation.

Only when the coupler is not a realistic 3-dB component can the coherence between path $i(i{=}1,\ 2)$ and path $j(j = 3,\ 4)$ be not fully discharged. Consequently, the coherence becomes a noise to the detecting signal. However, the effect is minimal.

The detected signal is inputted to a computer to process the digital phase generation carrier PGC modulation/demodulation. The modulating frequency on the frequency-matched RFOL is 12.5 kHz. The method is detailed in an earlier study[12]. Finally, the demodulated signal could be obtained through the computer, which composes a simulating sensing system. Figure 2 shows the response of the system when a 1-V peak to peak signal with 1-kHz frequency is added to the fiber optical phase modulator.

The linear response is also measured by changing the signal amplitude with a frequency of 1 kHz. The result is shown in Fig. 3. As calculated, the linearity has reached 0.99994.

The frequency response of the system is also measured with the stable electric signal input on the piezoelectric fiber optical phase modulator, as shown in Fig. 4. The frequency response consistency of the system is excellent, with fluctuations of no more than 0.3 dB over a range of 100 Hz to 2 kHz.

Finally, we have measured the background noise of this fiber optical sensing system, with only one FBG as reflector. As shown in Fig. 5, the noise of the system is always below −100 dB (0 dB re 1 rad/Hz$^{1/2}$) when the frequency is higher than 400 Hz. This is well within the

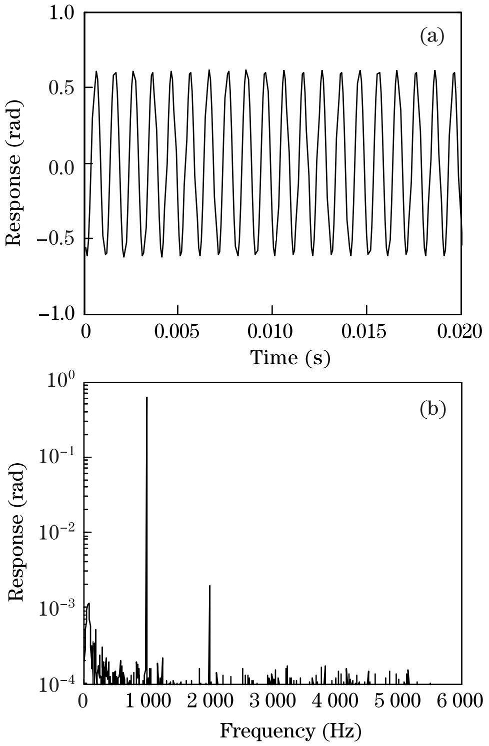

Fig. 2. Response of the fiber optical sensing system. (a) Time domain result; (b) frequency domain result.

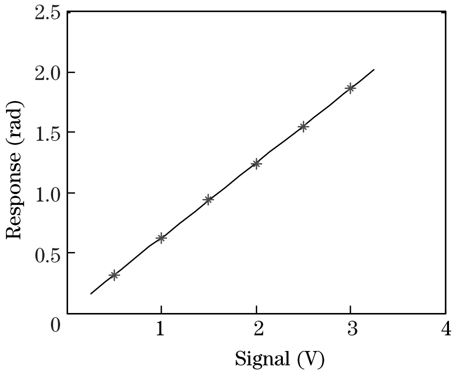

Fig. 3. Linear response result.

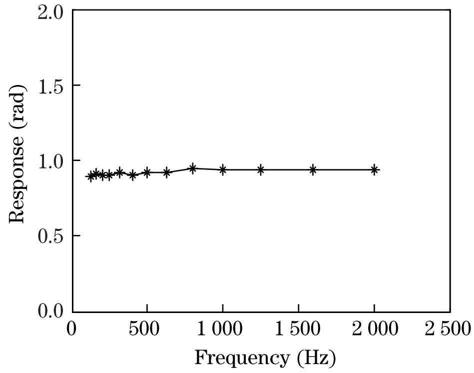

Fig. 4. Frequency response result.

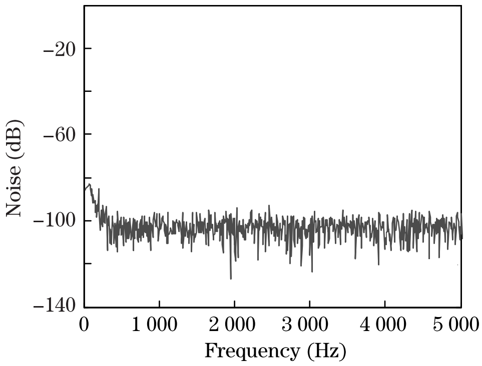

Fig. 5. Background noise of the system.

values in the usual fiber optical sensor with digital PGC technology.

In conclusion, the Michelson-type fiber optical interferometer sensing system with single FBG as reflector can work very well with the frequency-matched RFOL source. This is helpful in simplifying the traditional Michelson-type fiber optical interferometer as fiber optical hydrophone or magnetic field fiber optical sensor, as well as in other applications. Overall structure can be made small and compact through total assembly line fabrication technology and other processes. Frequency matching is important for the system in normal applications, which can be solved by using the same batch of FBG in the RFOL and the CMFOI sensing system or choosing FBGs in detail. The different temperatures around the laser and the sensing system would be the causes of the shortcoming of the system. However, this can be solved with temperature control on the RFOL. After all, temperature control is always necessary for an advanced fiber laser. Nevertheless, further work should be implemented to identify all the problems in the new and simplified CMFOI sensing system with one FBG as the reflector. The theory and experiments show the presence of a slight amount of influent from the residual interference in the system. With regard to FBG sensing, bared FBG is, in fact, not overly sensitive to acoustic pressure signal and vibrating signal. Based on the current study, bared FBG can also be protected from the sensing signal with the use of some package technologies.

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