A fiber micro-vibration sensor based on single-mode fiber ring laser

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A new micro-vibration sensor based on single-mode fiber ring laser is put forward. The Mach-Zehnder interferometric (MZI) detection technique is presented for interrogating laser frequency shift due to the measurand (piezoelectric transducer (PZT) is used to simulate the micro-vibration) induced laser cavity strain from both single- and multi-mode lasers. In the experiment, compared with multi-mode laser sensors, the single-mode laser sensor is proved to be a sensor with high resolution. When the PZT is driven by the analog signal (0.03 rad near 2 kHz), the signal-to-noise ratio (SNR) of output signal from the single-mode laser sensor is close to 55 dB and the sensitivity of the sensor is about 5×10^{-5} rad/Hz$^{1/2}$.

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In recent years, the study on optical fiber laser sensor is mainly focused on the fiber Bragg grating laser sensor (FBGLS). Since Meltz *et al.* demonstrated that fiber Bragg gratings (FBGs) can be used for fiber sensors[1,2], the study of fiber grating laser sensors has made a great progress for more than ten years[3,4]. However, the gratings of FBGLS are affected easily by outside temperature variation[5]. When uneven temperature produces an effect on the resonant cavity, the laser will show mode-hopping and the sensor cannot detect the measurand fidelity. The single-longitudinal-mode fiber ring laser produces stable narrow linewidth[6] and the outside temperature variation has little influence on the laser. This kind of fiber laser can constitute the sensing probe of fiber sensor to measure the micro-vibration signal.

A resonant cavity of length L_{FL} allows resonances at frequencies $\nu_{\mathrm{FL}} = kc/nL_{\mathrm{FL}}$ for integer values of k, where c is the speed of light in vacuum and n is the refraction index of the fiber core. The strain ε on the laser cavity of length L_{FL} induces a change in the cavity length of ΔL_{FL}, $\varepsilon = \Delta L_{\mathrm{FL}}/L_{\mathrm{FL}}$, leading to a frequency shift $\Delta\nu_{\mathrm{FL}}$ in the output laser according to

$$\Delta\nu_{\mathrm{FL}} = -\frac{\Delta L_{\mathrm{FL}}}{L_{\mathrm{FL}}} \cdot (1 - P_{\mathrm{e}}) \cdot \nu_{\mathrm{FL}}, \tag{1}$$

where P_{e} is an effective strain optical coefficient and usually considered as a constant which depends on the photoelastic properties of the fiber. At the 1550-nm wavelength, P_{e} is 0.21[7]. If λ is the center wavelength of output laser, $\alpha = 2\pi \cdot \frac{\Delta L_{\mathrm{FL}}}{\lambda}$ is the analog signal volume of piezoelectric transducer (PZT), from Eq. (1), we can get

$$\Delta\nu_{\mathrm{FL}} = -\alpha\frac{\lambda}{2\pi L_{\mathrm{FL}}}(1 - P_{\mathrm{e}}) \cdot \nu_{\mathrm{FL}}. \tag{2}$$

For a single-mode fiber ring laser, the Mach-Zehnder interferometer (MZI) phase bias Φ_{MZ} is dependent on the output optical frequency ν_{FL} and the interferometer optical path difference (OPD) $= nL_{\mathrm{MZ}}$ (where L_{MZ} is the fiber path difference between the fiber arms) according to the relationship

$$\Phi_{\mathrm{MZ}} = \frac{2 \cdot \pi \cdot n \cdot L_{\mathrm{MZ}}}{c} \cdot \nu_{\mathrm{FL}}. \tag{3}$$

Then,

$$\Delta\Phi_{\mathrm{MZ}} = \frac{2 \cdot \pi \cdot n \cdot L_{\mathrm{MZ}}}{c} \cdot \Delta\nu_{\mathrm{FL}} = -\alpha \cdot \frac{nL_{\mathrm{MZ}}}{L_{\mathrm{FL}}}(1 - P_{\mathrm{e}}). \tag{4}$$

So changes in the laser frequency induced by the cavity strain give rise to a modulation in the output phase shift.

The above description is for the single-longitudinal-mode laser sensors. For multi-longitudinal-mode laser sensors, the laser frequency is $\nu^i_{\mathrm{FL}} = k_i c/nL_{\mathrm{FL}}$ where the integer k_i takes on different values for different longitudinal modes, i is the order of the longitudinal mode. From Eqs. (1) and (2), we can know

$$\Delta\nu^i_{\mathrm{FL}} = -\frac{\Delta L_{\mathrm{FL}}}{L_{\mathrm{FL}}} \cdot (1 - P_{\mathrm{e}}) \cdot \nu^i_{\mathrm{FL}} = -\alpha_i\frac{\lambda_i}{2\pi L_{\mathrm{FL}}}(1 - P_{\mathrm{e}})\,\nu^i_{\mathrm{FL}}. \tag{5}$$

Equation (4) can be modified to $\Delta\Phi^i_{\mathrm{MZ}}$ for the ith laser longitudinal mode as

$$\Delta\Phi^i_{\mathrm{MZ}} = \frac{2 \cdot \pi \cdot n \cdot L_{\mathrm{MZ}}}{c} \cdot \Delta\nu^i_{\mathrm{FL}} = -\alpha_i \cdot \frac{nL_{\mathrm{MZ}}}{L_{\mathrm{FL}}}(1 - P_{\mathrm{e}}), \tag{6}$$

where $\alpha_i = 2\pi \cdot \Delta L_{\mathrm{FL}}/\lambda_i$ is the analog signal volume for the ith laser longitudinal mode. From Eqs. (4) and

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(6), it can be seen that for multi-mode laser, the output signal will comprise multiple component interference signals arising from each laser mode.

In this letter, two kinds of multi-mode fiber laser sensors are presented. Figure 1 shows the experimental setup of a multi-longitudinal-mode fiber laser sensor with a read-out interferometer for detecting the micro-vibration induced laser wavelength/frequency shifts. The pump source is a 980-nm laser diode (LD). We wind a section of fiber (about 15 cm long) in the laser resonator around the PZT driven by a sine signal source. Homodyne demodulation[8,9] is adopted with phase generated carrier (PGC)scheme to restore signals. In order to avoid polarization-induced fading, a complete set of polarization system is presented. The polarization system consists of polarization maintaining couplers (PMCs), the erbium doped polarization maintaining fiber (PM-EDF), and a 980/1550 nm polarization maintaining wavelength division multiplexer (PM-WDM).

In this system, the MZI OPD is about 80 m. The pump laser and MZI devices are exposed in the air. As there is fierce mode competition in the fiber ring laser, the mode-hopping is obvious. Lots of output signal waveforms are superposed together and the amplitude is badly unstable even though the ring laser works near the threshold point[10], as shown in Fig. 2.

Based on the setup shown in Fig. 1, another system is presented, as shown in Fig. 3. There are a circulation in resonant cavity and a FBG (bandwidth nearly 1 nm) in the circulation reflection arm. The bandwidth of FBG is much smaller than the laser gain spectrum width (nearly 30 nm). The cavity mode spacing is $\Delta\nu_{\mathrm{FL}} = c/nL_{\mathrm{FL}}$ and is about 10 MHz (a resonant cavity length of about 20 m). The presence of an intra-cavity selective element restricts the cavity resonance to a finite number of laser

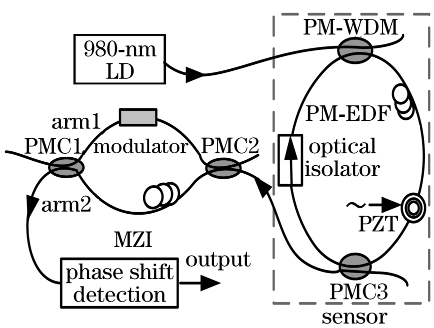

Fig. 1. Setup for multi-mode sensor based on a simple fiber ring laser.

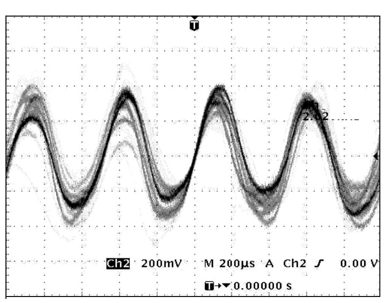

Fig. 2. Oscilloscope display of the output signal with the setup of Fig. 1.

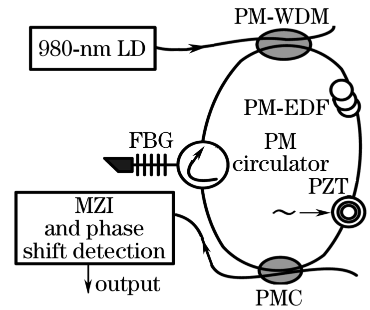

Fig. 3. Setup for multi-mode sensor based on a fiber ring laser and a FBG.

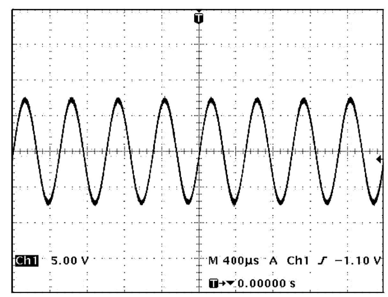

Fig. 4. Oscilloscope display of the output signal with the setup of Fig. 3.

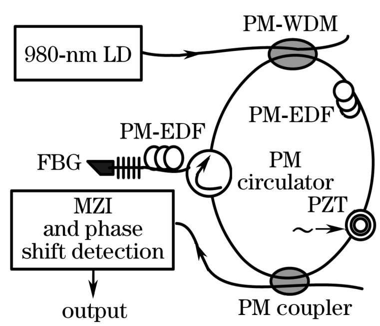

Fig. 5. Setup for single-mode sensor based on a fiber ring laser.

modes. Meanwhile, the bandwidth of the PGC demodulation circuit is less than 1 MHz and the lasing harmonic components are automatically filtered by the demodulation circuit. Therefore, this system can restore the analog signal as shown in Fig. 4. However, mode competition still exists and the stability of output signal lasts not more than 1 min. In order to pick up the micro-vibration signal fidelity, we designed a single-mode fiber sensor.

The single-longitudinal-mode narrow linewidth fiber laser is used for a probe of sensing system[11,12]. Figure 5 shows the basic form. In the laser cavity, the reflecting arm is composed of the PM-EDF and a FBG. Because this PM-EDF is unpumped, a self-written grating which is equal to a transmitted grating is formed by the standing wave interference when the condition of saturable absorption is satisfied[13]. Therefore, the mode-hopping is suppressed, and stable single-mode operation is realized. The PZT is driven by the 0.03-rad analog signal near 2 kHz shown in Fig. 6(a). The signal can be restored as shown in Fig. 6(b) via the read-out interferometer and the PGC demodulation circuit. The stability of output

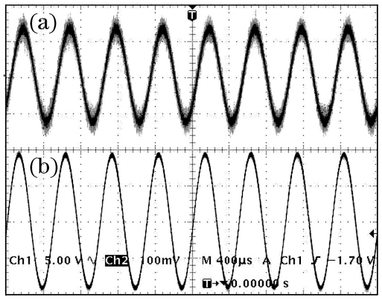

Fig. 6. Oscilloscope display of (a) analog signal and (b) output signal.

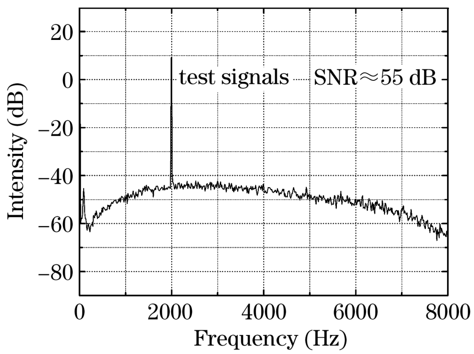

Fig. 7. Spectral response of the MZI to the single-frequency fiber laser output with a cavity modulation signal of 0.03 rad at 2 kHz.

signal can be maintained and the signal-to-noise ratio (SNR) is close to 55 dB, as shown in Fig. 7. The sensitivity of the system is about 5×10^{-5} rad/Hz$^{1/2}$.

For multi-mode fiber laser sensors, due to the mode competition, the output signal is unstable, so that the sine signal cannot be restored accurately. In contrast, single-longitudinal-mode laser sensor can produce stabilized output signal and bring high SNR and high sensitivity. Because fiber ring laser is used for the sensing probe, the output optical power is high, which enhances the capability of remote sensing.

In summary, we have provided a new structure for detecting dynamic micro-vibration with high sensitivity. The sensitivity of the system is about 5×10^{-5} rad/Hz$^{1/2}$. It shows great potential for the pickup of micro-vibration signal fidelity.

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