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Fiber loop ring down for static ice pressure detection

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ABSTRACT

We studied static ice pressure detection of hydraulic structures based on fiber loop ring down technology. Our detection system consists of a mode-locked laser, two 2×1 optical fiber couplers, a piece of single-mode fiber, the on-line micro-bend fiber sensor and a photo-detector. The static ice pressure was monitored based on measuring the change of the ring down time induced by external ice pressure on on-line micro-bend fiber sensor. We monitored the static ice pressure during ice growth and melting from −10 °C to 6 °C. The detection sensitivity is 0.00998/(μs·kPa). The proposed pressure sensing method has many advantages such as free from the fluctuation of the light power, simple structure, fast response and high sensitivity.

1. Introduction

Ice is a common phenomenon in high latitudes. Ice swelling pressure in heating process causes damages to the hydraulic structure such as piers, quay wall and embankment. When the water level changes, ice affected by the water level rise or fall causes damage to buildings and threatens people's property [1,2]. It is crucial to detect ice pressure in an effective and real-time manner. However, the ice pressure detection is always a problem due to the harsh climate and complex geographical environment. Seeking an efficient, accurate and real-time static ice pressure detection method in cold area has become an important research task.

Many methods have been used for ice monitoring, such as acoustic emission [3], satellite imagery [4], capacitance sensor [5] and sonar [6]. The prototype observation, model experiment and numerical simulation have also been proposed to study the static ice pressure [7–10]. Fiber sensor has been widely used because of its simple structure, high sensitivity, good resistance to electromagnetic interference, small volume and low cost. For instance, Jia et al. used a fiber Bragg grating (FBG) ice force sensor to measure the ice loading on bridge pier model [11]. Zhou et al. proposed both FBG and Brillouin optical time domain analysis (BOTDA) sensors to monitor the strain and damage characteristic of ice structures [12]. These sensors can be used for long-term monitoring the structures of ice and evaluating the safety. Zou et al. introduced a fiber-optic ice sensor with an oblique end-face of fibers [13]. Qin et al. proposed a special bellow fiber optic sensor to measure the static ice pressure automatically and continuously [14].

It is difficult to detect the ice pressure in harsh environment conditions. Fiber loop ring down (FLRD) sensor technology is especially attractive, because it only utilizes two fiber couplers and sensor unit for the sensing, such as pressure, temperature, gas, refractive index, and small volume of fluids [15–20]. FLRD sensors have advantages of real-time response, high sensitivity, low cost and free from the fluctuation of the light power.

In this paper, we present a detection system for the ice pressure on on-line micro-bend sensor based on optical FLRD system. The experimental setup of FLRD detection system is described in Section II. The experiments and results are analyzed in Section III, followed by a conclusion presented in Section IV.

2. The experimental setup

The experimental setup of the static ice pressure detection based on FLRD in hydraulic structures is schematically shown in Fig. 1(a). The mode-locked fiber laser consists of a 980-nm pump laser diode (LD), a 980/1550 nm wavelength-division-multiplexer (WDM), an erbium-doped fiber (EDF) with a length of 6.5 m, a single-mode fiber (SMF), an optical coupler (OC-1) with a coupling ratio of 90:10, a polarization controller (PC) and a polarization

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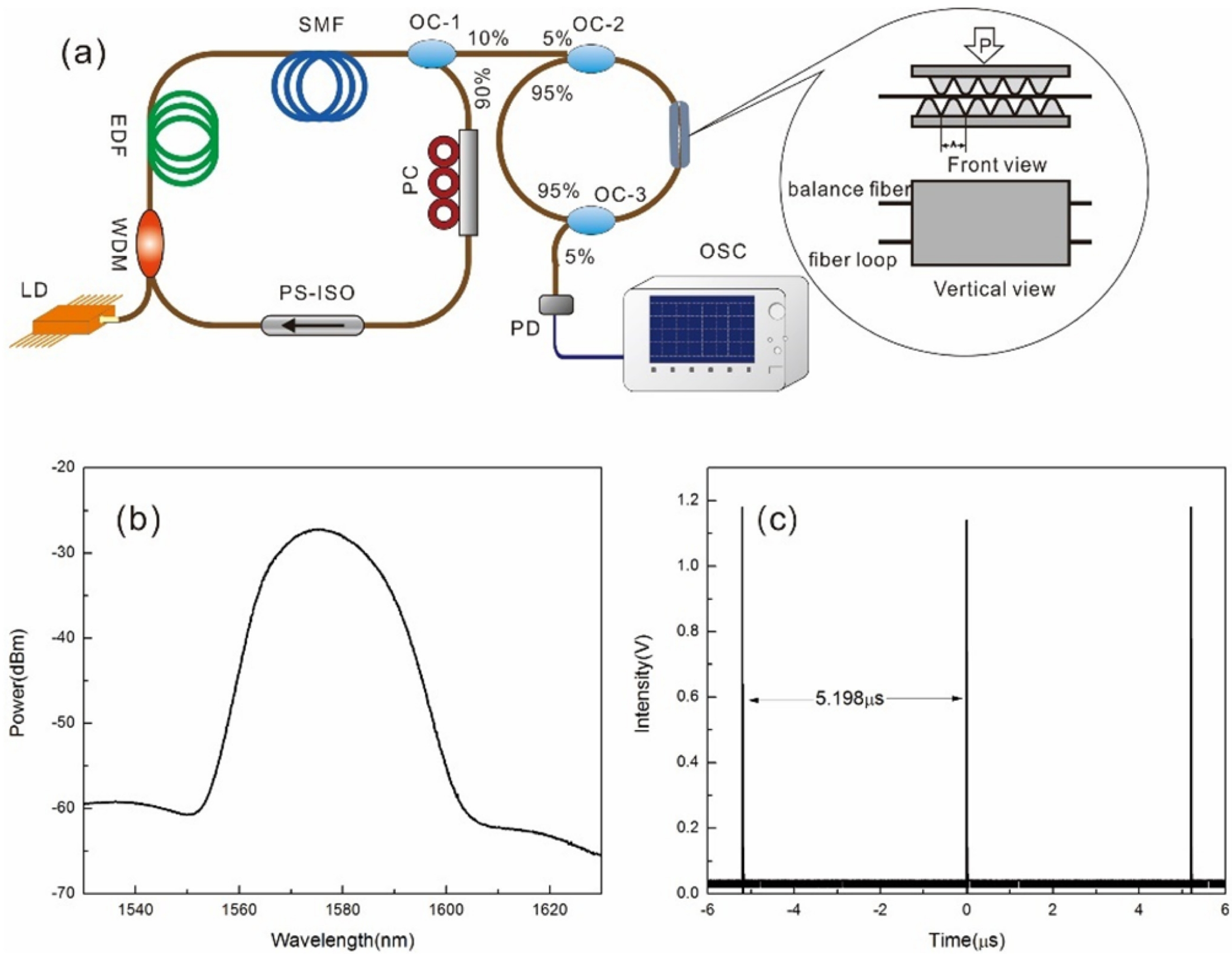

Fig. 1. (a) Experimental setup of the RLRD static ice pressure detection system. (b) The spectrum of the obtained mode-locked laser. (c) The oscilloscope trace of mode-locked laser.

sensitive isolator (PS-ISO). The spectrum and time series of the mode-locked fiber laser were obtained and plotted. The central wavelength shown in Fig. 1(b) is 1575 nm. The round-trip time shown in Fig. 1(c) is 5.198 μs, corresponding to repetition frequency of 192.4 kHz.

The proposed FLRD system consists of two 2 × 1 fiber couplers with the splitting rate of 95:5. The pulses generated by the mode-locked fiber laser are coupled into fiber loop by the fiber coupler (OC-2) and are coupled out by an output coupler (OC-3). The 95% of the output coupler (OC-3) remains in the fiber loop. The 5% of the output is detected by the photo-detector (PD) and the oscilloscope (OSC).

When a pulse travels in the fiber loop, the intensity output can be modeled by Wang et al. [21,22]. For the fiber loop ring down pressure sensor, the pressure is determined by the ring down time of the pulse. When the ice pressure P is applied to the sensor, a pressure-induced loss of the sensor occurs. The force-induced loss causes the change of the ring down time that can be expressed as:

$$\left(\frac{1}{\tau}-\frac{1}{\tau_0}\right)=kP, \tag{1}$$

where τ and τ_0 are the ring down time of the pulse attenuated to the $1/e$ of the light intensity in the force-induced loss and without load loss, respectively. k is the detection sensitivity related to round trip time of the loop and the sensor.

3. Experiment results

The pressure calibration experiments were done. We measured the pulse evolution without load and fitted it to an exponential decay curve of the pulse peak, as shown in Fig. 2. The ring down

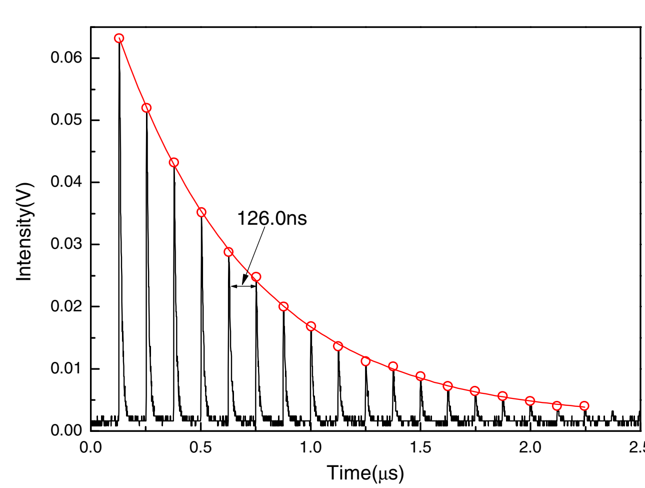

Fig. 2. Output signal in time-domain of FLRD system without load.