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High-sensitivity pressure sensors based on mechanically induced long-period fiber gratings and fiber loop ring-down

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A transverse pressure sensor with high-sensitivity based on a mechanically induced long-period fiber grating (MLPFG) and fiber loop ring-down technique is presented. When a MLPFG is spliced into a fiber loop, an extra loss is introduced, which leads to a decrease of the ring-down time. The results demonstrate that the difference between the reciprocals of the ring-down time with and without pressure increases exponentially with increasing the pressure in the range of 0–23.4 MPa. This sensor shows good repeatability, and the least detectable pressure is only 0.0068 MPa which is about 18 times less than detecting the output light intensity directly.

1. Introduction

Long-period fiber grating (LPFG) is one of the optical filters that couple the fundamental mode to the forward-propagating cladding modes. The coupled cladding modes decay rapidly as they propagate along the fibers owing to scattering and absorption in the fiber coatings, which result in notches in the transmission spectra. LPFG can be made by creating periodical refractive index variation along the fiber with a typical period of several hundred micrometers. Traditionally, it is produced in hydrogen loaded germanosilicate fiber by exposing the cores to ultraviolet (UV) light. Alternatively, LPFG can be also made by periodically and locally heating the fiber with CO_2 laser pulses, electric arc discharge, etching the cladding and ion implantation. Recently, it has been proposed to induce LPFG mechanically, for example, by pressing the fiber with a periodically grooved plate [1], a coiled spring [2], arrayed metal wires [3] or winding a nylon string around the fiber periodically [4]. Mechanically induced long-period fiber gratings (MLPFGs) have been fabricated in almost any type of fibers, such as standard single mode fiber [1–4], microstructured polymer fiber [5], holey fiber [6] or liquid crystal photonic bandgap fiber [7]. Many applications of the MLPFGs have been already found in tunable fiber ring laser [8,9], band-pass [10] and gain equalization [11] filters, as well as twist [12] and load [13] sensors.

For transverse pressure sensing, one can measure the wavelength shift of the LPFG written by UV light [14], but an expensive optical spectrum analyzer must be used for demodulating. One can also detect the output light intensity from a LPFG written by high-frequency CO_2 laser pulses [15], with which the pressure sensitivity can reach to -0.078 dB(MPa)$^{-1}$ in the range of 0–47.2 MPa and the least detectable pressure is about 0.12 MPa. Fiber loop ring-down (FLRD) [16] is a sensitive technique that has been used for pressure [17], temperature [18], strain [19] and refractive index [20,21] sensor. We have presented a way to improve the sensitivity of the pressure sensor by etching its cladding and using FLRD technique [22]. But the etched fiber is easy to be broken, thus some special encapsulation ways must be taken. When a LPFG is introduced into the fiber loop, the LPFG transmission spectrum will shift with the pressure, which leads to a loss change for a given laser wavelength in the fiber loop [23]. But a variable optical attenuator, an EDFA and a FBG tunable filter are needed in order to compensate the large loss induced by the LPFG. And each original single loss-peak may split into two sub-peaks [14]. While the MLPFG with a small loss can be easily induced by applying a small pressure, which will simplify the measurement setup and improve the sensitivity. In this paper, we present a new type of pressure sensor with high-sensitivity based on MLPFG and FLRD techniques. It's realized by splicing a MLPFG into a fiber loop. When the pressure is applied, notches are produced in the MLPFG's transmission spectrum, and an extra loss is introduced in the loop, which leads to a decrease of the ring-down time.

2. Principles

When a standard single mode fiber is laterally pressed by a periodically grooved plate, its refractive index is modulated

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periodically due to photoelastic effect, so a MLPFG is formed. In the MLPFG, the fundamental mode is coupled to the ith cladding mode at the resonant wavelength λ_c defined by the phase-matching condition. The pressure induced coupling loss S is given by [3]

$$S = \frac{\sin^2\left[\kappa_g l\sqrt{1+\left(\delta/\kappa_g\right)^2}\right]}{1+\left(\delta/\kappa_g\right)^2}, \tag{1}$$

where, l is the length of the grating; $\delta=(\beta_{01}-\beta^{i}_{clad}-2\pi/\Lambda)/2$ is the detuning parameter, Λ is the grating period, β_{01} and β^{i}_{clad} are the propagation constants of the fundamental and the ith cladding mode, respectively; $\kappa_g=\pi\Delta n_{eff}/\lambda$ is the coupling constant of the grating, Δn_{eff} is the pressure induced refractive index variation of the fiber and can be described by [24]

$$\Delta n_{eff} \approx -\frac{n^3(1+\nu)}{\pi DY}\left[(1+2\nu)p_{11}+(2\nu-3)p_{12}\right]\frac{F}{l}, \tag{2}$$

where, p_{11} and p_{12} are the photoelastic coefficients, respectively; Y is the Young's modulus; ν is the Poisson's ratio; F is the force applied along the fiber axis in the region of l, and D is the fiber diameter.

For a fiber loop composed of two fiber couplers and a single mode fiber, a pressure induced loss S will be introduced when a MLPFG is spliced into the loop. The variation of the ring-down time is then described by [17]

$$\frac{1}{\tau}-\frac{1}{\tau_0} = \frac{c}{n_{eff}L}S, \tag{3}$$

where, τ and τ_0 are the ring-down times with and without pressure, respectively; c is the light speed in vacuum; n_{eff} is the effective refractive index of the fiber core; L is the length of the loop.

From Eq. (3) we can see that the term $(1/\tau-1/\tau_0)$ increases linearly with the loss S. Over coupling effect [1] does not occur under small pressure condition and F/l is determined by measuring τ and τ_0. F/l can be converted to an equivalent pressure P by $P=F/A$, where A estimates as the area of a rectangular shape with a width of one tenth of the fiber diameter (250 μm when the coating is still remained) and a length l [17,22,23].

3. Experimental setup

A MLPFG was realized in standard single mode fiber by placing them between a periodically grooved plate and a flat plate. The grooved plate with 60 periodic V-grooves was made by wire cut on a brass block. The V-grooves had a period of 0.58 mm, a duty circle of 48%, and a depth of 0.2 mm, so the length of the grooved plate was 34.52 mm. The flat plate weighted 61 g was made of aluminum. The grooved plate was fixed on a rotary stage to adjust the rotational angle θ of the grooved plate with respect to the fiber, so the period of the MLPFG Λ could be tuned according to the expression $\Lambda=0.58/\cos\theta$, while l was determined by the interaction length of the plates. The pressure P was applied by adding weights on the flat plate. The transmission spectra of the MLPFG were monitored by a broadband source (EXFO FLS-2300B) and an optical spectrum analyzer (ANDO AQ6317C) in the range of 1530–1610 nm.

Fig. 1 shows the experimental setup for pressure sensing based on MLPFG and FLRD techniques. The fiber loop estimated 1 km was composed of two 2×1 commercially available single mode fiber couplers with a split ratio of 99:1 and a long segment of SMF-28. A pigtailed distributed feedback laser diode (DFB LD) with a maximal output power of 20 mW and a spectral bandwidth of 1 MHz was used as the laser source. It was driven by a LD controller to control the output power and the wavelength precisely. Its central wavelength λ could be tuned from 1548.3 nm to 1552.1 nm by tuning the

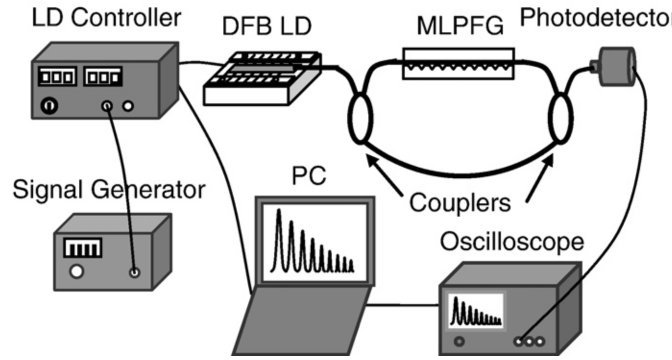

Fig. 1. Experimental setup for pressure sensing based on MLPFG and FLRD techniques. DFB LD: distributed feedback laser diode; LD controller: laser diode controller; MLPFG: mechanically induced long-period fiber grating.

temperature, and its input current was set to 107 mA and modulated by a series of pulse waves (1KHz, 2 V, duty cycle is 0.2%) to produce an optical pulse train with a pulse width of 2 μs. The optical pulse train was coupled into the loop, and the output optical signals were detected by an amplified InGaAs photodetector. The output voltage signals of the detector were sampled and averaged for 64 times by a digital oscilloscope. A LabVIEW program was used to control the measurement and process the results.

4. Results and discussions

Fig. 2(a) gives the transmission spectra of the MLPFG without a dummy fiber when the pressure increases from 0 to 34.8 MPa in steps of 1.12 MPa, and the inset shows the relationships between its transmission losses and the pressure at the wavelengths of 1548.56 nm, 1552.08 nm and 1558.72 nm, respectively. We can see that with increasing pressure applied on the fiber, the coupling from the fundamental mode to the cladding mode increases accordingly. The loss-peak of the grating grows to 2.9 dB, while λ_c decreases from 1559.5 nm to 1558.4 nm. If the pressure is removed, the MLPFG disappears and the fiber recovers its original transmission spectra. The out-of-band loss decreases to less than 0.65 dB by exerting pretension in the fiber. But if the tension is large enough, the out-of-band loss increases to 1.7 dB, while the loss-peak is almost the same. When a dummy fiber with the same type is placed in parallel with the MLPFG for balance in the MLPFG-making process, each of the fibers bears half of the pressure, and the transmission spectra of the MLPFG are shown in Fig. 2(b). In order to get the same loss-peak, about twice pressure should be applied on the flat plate than there is no dummy fiber, so the MLPFG distorts more heavily and the out-of-band loss increases quickly, while there is no notch until larger pressure is applied. For this reason, in the following experiments, the dummy fiber is not used and the MLPFG bears the whole pressure.

Fig. 3 shows the transmission spectra of the MLPFG with different periods under applying a pressure of about 44.2 MPa. The period is adjusted by changing the angle θ between the normal of V-grooves and the fiber from 0° to 13°. From Fig. 3 we can see that λ_c increases from 1559 nm to 1589 nm leading to a tunable range of about 30 nm.

The transmission losses of the MLPFG at 1552.08 nm are measured by using an optical fiber power meter. The relationships between the transmission losses and the pressure are shown in Fig. 4. The measurement is repeated 5 times. From Fig. 4 we can see that in the range of 0–130 MPa the transmission losses increase quickly until over coupling effect occurred, the losses reach to as high as 8 dB when P increases to 84.8 MPa, after that the losses begin to decrease slowly. We also find that the 2nd to 5th measurement results are identical and more sensitive than the 1st one; it is likely that the fiber is distorted slightly after applying the pressure as high as 130 MPa. The 2nd to 5th measurement results in the range of 22.8–78.8 MPa are