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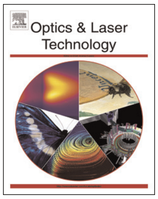

A hybrid fiber-optic sensing system for down-hole pressure and distributed temperature measurements

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ABSTRACT

A hybrid fiber-optic sensing technique, combining the extrinsic Fabry–Perot interferometer (EFPI) based pressure sensor with the incoherent optical frequency domain reflectometry (IOFDR) based distributed temperature sensor (DTS), is presented for down-hole measurements. By using a laser diode as the common light source, a highly integrated hybrid EFPI/DTS sensing system has been developed with a single fiber. With the injection current of the laser diode below lasing threshold, the broadband spontaneous emission light is used for EFPI based pressure sensing; while with the injection current above the threshold, the stimulated emission light is used for Raman based distributed temperature sensing. There is no overlap between the spectral range of the reflected light from the EFPI sensor and the spectral range of the Raman scattered light. Pressure and distributed temperature can thus be measured by using wavelength-division multiplexing (WDM) technology. Experimental results show that both the pressure and the distributed temperature are measured with little interference. Furthermore, the pressure measurement can be compensated by the measured temperature values.

1. Introduction

Down-hole conditions, such as pressure and temperature, are important for oil exploration and reservoir management [1,2]. However, traditional electronic sensors cannot work stably, under the conditions of high pressure and high temperature in the wellbore. Fiber-optic sensors have advantages of resistance to harsh environment, capability of distribution measurement, small size and high resolution [3,4]. Therefore, the widely used fiber-optic sensors, such as Raman distributed temperature sensor (DTS), fiber Bragg grating (FBG) sensor and the extrinsic Fabry–Perot interferometer (EFPI) sensor, have been installed for permanent monitoring of down-hole pressure and temperature [5–7].

For well logging with fiber-optic sensors, the main challenges are the long-term stability and the high cost compared with electronic sensors [8,9]. It is well known that hydrogen readily diffuses into the core of a standard fiber and creates a strong increase in optical background loss, under high temperature down-hole environment. In recent years, costly polyimide and carbon coated pure silica core fiber is applied for overcoming this problem. On the other hand, separated interrogators and fibers for DTS and EFPI sensor are often used, which make the monitoring system complicated and more costly. In order to optimize system structure and reduce system cost, a few multiplexed structures with FBG and EFPI sensors have been proposed [10–12], but they are all for single-point pressure and temperature measurement. An incoherent optical frequency domain reflectometry (IOFDR) setup combining with several multiplexed EFPI sensors has been proposed for quasi-distributed measurement [13]. However, static parameters could not be accurately measured by the EFPI sensors, due to the intensity demodulation mechanism. Moreover, the system is not applicable to distributed temperature measurement. In our early work, a multiplexed sensing system combining the EFPI based pressure sensor with the DTS has been presented using a wide bandwidth wavelength-division multiplexer (WDM) [8]. The system can realize accurate pressure and distributed temperature measurements of the wellbore with a single fiber. However, with this method, the WDM induced insertion loss would evidently spoil the resolution of both pressure and temperature measurements. Furthermore, two separated demodulation devices which use two light sources are needed.

In this paper, a highly integrated hybrid sensing system combining the EFPI sensor with the IOFDR based DTS is presented with a single light source and a single fiber. A laser diode is the common light source for demodulation. The pressure and distributed temperature can be measured alternatively by controlling the injection current of the laser diode.

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2. Principle

2.1. Principle of the EFPI based pressure sensor

The typical structure of the EFPI based pressure sensor is shown in Fig. 1. The fiber-optic EFPI sensor consists of two cleaved fiber endfaces joined in a silica capillary tube. The fibers and the tube are bonded by a CO_2 laser. The air gap between two fiber endfaces forms the Fabry–Perot cavity. The relationship between the cavity length change (Δd) and the applied pressure (p) can be expressed as [8,11]

$$\Delta d = \frac{L_g r_o^2}{E\left(r_o^2 - r_i^2\right)}(1 - 2\mu)p = k(T)\cdot p \tag{1}$$

where L_g is the effective sensor gauge length defined by the distance between the two bonding points, E is Young's modulus of the capillary material, μ is the Poisson ratio of the glass tube, r_o and r_i are the outer and inner radii of the capillary tube respectively. The proportionality coefficient k normally is a function of the ambient temperature T.

The EFPI sensor is sensitive to both the pressure and the ambient temperature, the cavity length can be expressed as [11]

$$d = a_1 pT + a_2 p + a_3 T + a_4 \tag{2}$$

where a_1, a_2, a_3 and a_4 are the coefficients which can be determined by a pressure and temperature calibration.

A broadband light source can be used for EFPI based pressure demodulation [14–16]. The interference signal can be described by [15]

$$I(\lambda) = 2I_s(\lambda)\left[1 + \gamma(d)\cos\left(\frac{4\pi d}{\lambda} + \pi\right)\right] \tag{3}$$

where λ is the wavelength of the light source, $I_s(\lambda)$ is the intensity distribution, d is the cavity length, and $\gamma(d)$ is the fringe visibility of EFPI. According to Eq. (3), the cavity length d can be demodulated by tracking the shift of the spectrum or measuring the frequency variation of the interference fringe.

2.2. Principle of the DTS

In the Raman-based DTS system, the temperature information is derived from the ratio $R(T)$ of anti-Stokes intensity (I_{aS}) to Stokes intensity (I_S), which can be expressed as [17]

$$R(T(z)) = \frac{I_{aS}(T(z))}{I_S(T(z))} = \kappa\frac{n_{aS}\lambda_S^4}{n_S\lambda_{aS}^4}\exp\left(-\frac{h\Delta\nu}{k_B T(z)}\right) \tag{4}$$

where λ_S and λ_{aS} are the wavelengths of Stokes and anti-Stokes scattered light, respectively, n_s and n_{as} are the refractive indexes at λ_S and λ_{aS} respectively, h is the Plank constant, $\Delta\nu$ is the Raman frequency shift in the fiber, k_B is Boltzmann's constant, $T(z)$ is the absolute temperature at the location of z, and κ is a calibration constant.

The location information can be obtained with two different signal detection mechanisms: optical time domain reflectometry (OTDR) [18] and IOFDR [19]. An IOFDR uses a continuous wave laser source which is sinusoidal amplitude modulated by a sequence of stepwise changed frequencies. The magnitude and phase of the backscattered light signal under each frequency can be measured. Subsequently, by carrying out an inverse Fourier transform with the measured frequency response of the backscattered light signal, the backscattered light trace which contains location information is obtained. According to Eq. (4), the distributed temperature can be demodulated by the Stokes and anti-Stokes backscattered traces. Benefiting from the narrow-band signal detection method, and the frequency modulated continued wave (FMCW) technology, the IOFDR has many technical advantages, such as higher signal-to-noise ratio (SNR), lower sample rate and longer working life of the laser [19,20].

2.3. Hybrid EFPI/DTS sensing technique

It is known that a laser diode emits broadband spontaneous emission light as the injection current below lasing threshold, and emits stimulated emission light as the injection current above the threshold. A broadband light can be used for demodulating the EFPI based pressure sensor, and a FMCW laser can be used for the IOFDR-based DTS. Therefore, by adjusting injection current, a single laser diode can be used as the light source for demodulating both the EFPI sensor and the DTS. The injection current of the laser diode changed with time is schematically shown in Fig. 2, where I_{th} represents the threshold current of the laser diode. The single-point pressure and distributed temperature can thus be measured alternatively.

For a DTS system, λ_S and λ_{aS} are usually tens of nanometers away from the center wavelength of the laser light (λ_0). Meanwhile, when measuring pressure, the reflected light from the EFPI sensor spreads a wavelength range of tens of nanometers with its center wavelength near λ_0. The spectral distribution of the hybrid EFPI/DTS sensing technique is schematically shown in Fig. 3. There can be no overlap between the spectral range of the reflected light from EFPI sensor for pressure measurement and the spectral range of the Raman backscattered light for distributed temperature measurement. Therefore, both the pressure and distributed temperature can be measured by using the wavelength-division multiplexing technology.

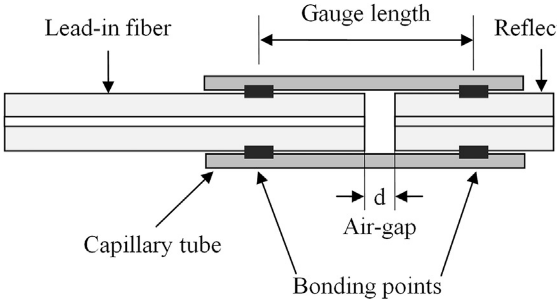

Fig. 1. Typical structure of the EFPI based pressure sensor.

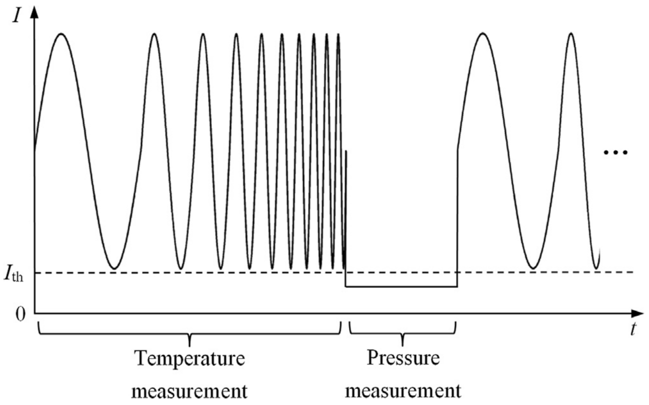

Fig. 2. Schematic diagram of the injection current changed with time.