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A hybrid sensing system for simultaneous Raman-based distributed and FBG-based quasi-distributed measurements

Ke Chen, Xinlei Zhou, Wei Peng, Qingxu Yu*

School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian, Liaoning 116023, PR China

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ABSTRACT

A hybrid sensing technique, combining the incoherent optical frequency domain reflectometry (IOFDR) based Raman distributed temperature sensor (DTS) with high-reflective fiber Bragg grating (FBG) sensors, is presented for simultaneous distributed and quasi-distributed measurements. By using a laser diode as the common light source, a highly integrated hybrid Raman/FBG sensing system has been developed with a single fiber. The stimulated emission light and the spontaneous emission light of the laser diode are used for DTS and FBG interrogations, respectively. There is no overlap between the spectral range of the Raman backscattered light and the spectral range of the reflected lights from the FBG sensors. The distributed and quasi-distributed measurements can thus be achieved simultaneously by using the wavelength-division multiplexing (WDM) technique. Experimental results show that, both the distributed temperature and the quasi-distributed temperature or dynamic strain can be measured with little interference. Furthermore, the hybrid system shows the capability of high-capacity multiplexing for FBG sensors.

1. Introduction

Fiber-optic sensors have been used in scientific and industrial applications, with the advantages such as small size, light weight, high resolution and immunity to electromagnetic interference [1,2]. Among them, Raman-based distributed temperature sensor (DTS) and fiber Bragg grating (FBG) sensor are the most widely used fiber-optic sensors for distributed and quasi-distributed measurements, respectively [3,4].

The combination of DTS and FBG sensor is demanded in many applications. For structural health monitoring, quasi-distributed FBG sensors are installed for strain and vibration measurement [5,6]. However, FBG is also sensitive to the ambient temperature. In order to diminish the impact of the cross-sensitivity effect, an auxiliary temperature sensor, such as DTS, has been introduced for temperature compensation [7,8]. Besides, for fiber-optic downhole monitoring, DTS combined with FBG based pressure sensor can be used for oil exploration and reservoir management [9–11]. However, in practical applications, separated interrogators and fibers for DTS and FBG sensor are often used, which makes the monitoring system complicated and costly.

A hybrid Raman/FBG scheme has been proposed for distributed temperature and discrete dynamic strain measurements [12–14]. In this scheme, broadband low-reflective FBGs with a single narrowband light source and a shared receiver were employed. However, the static temperature or strain could not be accurately measured by FBG sensors, due to the intensity demodulation mechanism and wavelength shift of the light source. Meanwhile, the measured distributed temperatures at the location of the FBGs are affected by the reflected lights from the FBG sensors.

In this paper, a novel highly integrated hybrid sensing system combining the incoherent optical frequency domain reflectometry (IOFDR) based Raman DTS with high-reflective FBG sensors is presented with a single light source and a single fiber. The laser diode is the common light source for interrogation. The stimulated emission light of the laser diode is used for Raman based distributed temperature measurement. Simultaneously, the spontaneous emission light of the laser diode is used for FBG based quasi-distributed static or dynamic measurement.

2. Principle

2.1. Principle of the IOFDR-based DTS

The IOFDR technique can be used to obtain the position information by detecting the backscattered light [15,16]. Specifically, the

* Corresponding author. Fax: +86 411 84708379.
E-mail address: yuqx@dlut.edu.cn (Q. Yu).

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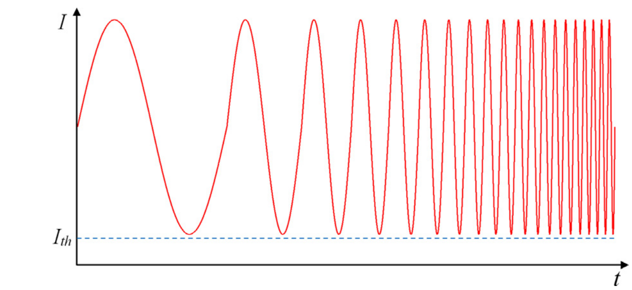

Fig. 1. Schematic diagram of the injection current changed with time.

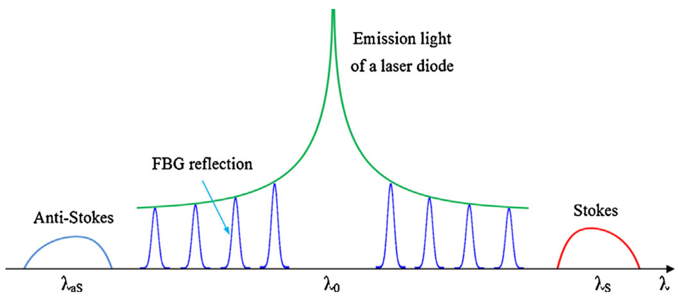

Fig. 2. Spectral distribution of the hybrid Raman/FBG sensing technique

light source (usually a laser diode) is sinusoidal amplitude modulated by a sequence of stepwise changed frequencies, which are typically from tens of kHz to tens of MHz. The injection current of the laser diode changed with time is schematically shown in Fig. 1, where I_{th} represents the threshold current of the laser diode. By carrying out an inverse Fourier transform with the measured frequency response of the backscattered light signal, a physical property as a function of position can be determined.

In a Raman-based DTS system, the temperature information can be derived from the ratio between the power of the anti-Stokes (P_{aS}) and the Stokes (P_S) backscattered light, as given by [17,18]:

$$\frac{P_{aS}(T(z))}{P_S(T(z))} = \kappa \frac{n_{aS}\lambda_S^4}{n_S\lambda_{aS}^4} \exp\left(-\frac{h\Delta\nu}{k_B T(z)}\right) \quad (1)$$

where λ_S and λ_{aS} are the wavelength of Stokes and anti-Stokes scattered light, n_s and n_{aS} are the refractive index 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.

2.2. Hybrid Raman/FBG sensing technique

It is known that a laser diode emits both stimulated emission light and spontaneous emission light simultaneously, with the injection current above the laser threshold. The frequency modulated continued wave (FMCW) laser can be used for the IOFDR-based DTS, and the broadband spontaneous emission light can be used for FBG interrogation. Therefore, a single laser diode can be suggested to be the common light source for demodulating both the DTS and FBG sensor.

The spectral distribution of the hybrid Raman/FBG sensing scheme is schematically shown in Fig. 2. For a DTS system, attributed to the broadened Raman scattered spectrum in optical fiber, λ_S and λ_{aS} are usually tens of nanometers away from the center wavelength of the laser light (λ_0) [19]. Meanwhile, the spontaneous emission light of the laser diode spreads a wavelength range of tens of nanometers with its central wavelength near λ_0. Within this range, FBG sensors can be wavelength-division multiplexed except a few nanometers near λ_0. Furthermore, there can be no overlap between the spectral range of the Raman backscattered light and the spectral range of the reflected lights from FBG sensors. Therefore, by using wavelength-division multiplexing technique, the hybrid Raman/FBG sensing scheme provides a new approach for simultaneous distributed and quasi-distributed measurements.

3. Experimental setup

The experimental setup of the hybrid Raman/FBG sensing system is schematically shown in Fig. 3. A laser diode (LD) (Oclaro, Inc.), with a center wavelength of 1064.3 nm and a threshold current of 31.7 mA, is used as the common light source. The fiber under test is composed of a 2.23 km G652 single-mode fiber (SMF) and two discrete sensing points. Each sensing point exists an apodized high-reflective FBG whose reflectivity is as high as 99%. Specifically, FBG1 (λ_B = 1041 nm) is applied a dynamic sinusoidal strain by a piezoelectric actuator (PZT). FBG2 (λ_B = 1081 nm) and the end fiber are placed into a temperature-controlled chamber (TCC) for static temperature measurement. The capability of quasi-distributed measurement is expected to be verified by the two FBGs.

The distributed temperature is measured with the IOFDR technique. The laser diode is modulated with stepwise increased frequencies by a driver circuit. A splitter with a coupling ratio of 1:99 splits 1% of the incident light, which is detected by a photodiode (PD), for measuring the initial phase. The Raman backscattered lights are filtered out by two band-pass filter wavelength-division multiplexers (WDM). Specifically, one WDM, with a center wavelength of 1030 nm and a pass band width of 10 nm, filters the anti-Stokes light. Another WDM, with a center wavelength of 1120 nm and a pass band width of 10 nm, filters the Stokes light. Moreover, in order to eliminate the interference of Rayleigh noise, the isolation of the WDM pass port at 1064 nm is more than 70 dB. The filtered Raman lights are detected by an avalanche photodiode (APD) module. Finally, the distributed temperature is demodulated by a signal processing unit.

Simultaneously, the spontaneous emission of the laser diode is used as the light source for FBG interrogation. The incident light is launched into the fiber and passes two filter WDMs. The broadband spontaneous emission light, modulated by the two FBG sensors, is then reflected back again by the filter WDMs, and is guided out via an optical circulator. A Rayleigh filter, which is a band-pass filter with a center wavelength of 1064 nm, filters out the relatively intense Rayleigh scattered light to prevent the charge-coupled device (CCD) based spectrometer from saturating and spectral crosstalk [20]. The remained reflected light is coupled into a fiber optic spectrometer (Ocean Optics HR2000). Finally, the measured spectrum is processed by a computer.

4. Experimental results and discussion

4.1. Emission spectrum of the laser diode

The laser diode, which is sinusoidal amplitude modulated, emits an average power of ~40 mW. The emission spectrum of the hybrid Raman/FBG interrogator has been measured by an optical spectrum analyzer (OSA) (ANDO AQ6317C), as shown in Fig. 4. It shows that the wavelength ranges of the spontaneous emission light mainly cover from 1040 nm to 1060 nm and from 1070 nm to 1110 nm. Meanwhile, the power spectral density (PSD) is greatly decreased near the wavelengths of 1030 nm and 1120 nm. The lost lights are guided out by the two band-pass Raman WDMs.