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Distributed fiber sensing system with wide frequency response and accurate location

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ABSTRACT

A distributed fiber sensing system merging Mach–Zehnder interferometer and phase-sensitive optical time domain reflectometer (Φ-OTDR) is demonstrated for vibration measurement, which requires wide frequency response and accurate location. Two narrow line-width lasers with delicately different wavelengths are used to constitute the interferometer and reflectometer respectively. A narrow band Fiber Bragg Grating is responsible for separating the two wavelengths. In addition, heterodyne detection is applied to maintain the signal to noise rate of the locating signal. Experiment results show that the novel system has a wide frequency from 1 Hz to 50 MHz, limited by the sample frequency of data acquisition card, and a spatial resolution of 20 m, according to 200 ns pulse width, along 2.5 km fiber link.

1. Introduction

Distributed optical fiber sensing system (DOFS) has great potential in industrial application due to its wide range of advantages, like real-time long-distance monitoring, immunity to electromagnetic and simple construction. In the early applications, limited by the signal to noise rate (SNR), only static measurement, like temperature or static strain, can be detected. With the development of DOFS, dynamic process can be detected through optical interference process. In dynamic process detection, not only the wide frequency detection, but also the accurate location, are required.

During the past years, the DOFS mainly includes optical fiber interferometer sensors and optical backscattering based sensors. The interferometer sensors acquire the dynamic information by integration the phase-modulated signal and generally use two interferometers to determine the location of the dynamic event. Many demonstrations have been reported through combing different interferometers (Mach–Zehnder interferometer (MZI), Sagnac interferometer, and Michelson interferometer) [1–8]. In Ref. [1], a merged Sagnac–Michelson interferometer sensor is proposed to detect the time-varying disturbance such as strain and temperature. In Ref. [2], a modified Sagnac/Mach–Zehnder interferometer is proposed and achieves 5 m measurement accuracy along 200 m sensing fiber. In Ref. [3], 102 m spatial resolution is achieved along 4012 m fiber link by using dual Michelson interferometer. Due to the different variations caused by optical phase and optical polarization between the two interferometers, the location accurate and repeatability of the twin-interferometers are not satisfied. However, the detected frequency range is usually wide and mainly limited by the sample frequency of data acquisition card (DAQ). On the other hand, DOFS based on optical backscattering, such as polarization–OTDR [9], phase-sensitive OTDR [10], and Brillouin OTDR [11], has been demonstrated and provides better location accuracy. However, limited by the weak backscattering signal and relatively lower pulse repeat rate, the frequency response of the optical backscattering based sensor is not satisfied.

Wide frequency response and accurate location are often required simultaneously for monitoring request, such as monitoring leakage of high-pressure and high-temperature oil and gas pipelines and monitoring crash of material for structure health. Notice that the interferometer sensor has wide frequency and optical backscattering based sensor has accurate location, it would be an effective way to merge them in one DOFS. In Ref. [12], a modulated-pulse based distributed vibration sensing method by merging interferometer and phase-sensitive OTDR is proposed. 5 m of spatial resolution is achieved along 1064 m sensing fiber. The lowest frequency response is 10 Hz and the highest frequency response is 3 MHz. The major limitation of this system is the SNR deterioration caused by the modulated pulses and the low intensity value of the interference signal decreases the detectable frequency response. Another combination structure of interferometer

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and phase-sensitive OTDR is proposed in Ref. [13]. By using a time division multiplexing strategy (TDM), the signal intensity of interferometer is improved and the highest detectable frequency rises to 6.3 MHz along 1150 m sensing fiber. The limitation is the signal of interferometer is separated by the OTDR traces and the low frequency response is limited.

In this paper, we propose a novel DOFS combining MZI and phase-sensitive OTDR using wavelength division multiplexing strategy (WDM) and we apply heterodyne detection to avoid the SNR deterioration caused by overlap. A laser with 1549.900 nm wavelength is used to constitute the MZI and another laser with 1550.204 nm wavelength is used to constitute the phase-sensitive OTDR. Location information and frequency response are acquired by Rayleigh backscattering traces and interference waveforms respectively. Experiment results show that the maximum detected response of piezoelectric transducer (PZT) is almost 50 MHz, limited by the 100 MHz sample frequency of DAQ, and the lowest detected response of PZT can be 1 Hz or lower, limited by the sample length of interferometer waveform. As the pulse width is 200 ns, the spatial resolution is 20 m along 2.5 km sensing fiber.

2. Principle

The setup of the DOFS is shown in Fig. 1. A CW light from Laser 1 with 1550.204 nm wavelength and 3 kHz line-width is divided into 2 part through a 1:99 optical coupler (OC1). The 1% part light is sent to OC2 and acts as a local light. The 99% part light is modulated into pulses by an acoustic–optic modulator (AOM) with a frequency shift of 200 MHz. Then the pulses are amplified by an Erbium-doped fiber amplifier (EDFA1), and the spontaneous radiation created by EDFA1 is filtered by a fiber Bragg grating (FBG1). The amplified pulses launch into the sensing fiber and the backscattering light comes back through a circulator (Cir.2). The backscattering light is then amplified by EDFA2. The reflection band of FBG2 is only 0.292 nm, from 1550.040 nm to 1550.332 nm. Thus, the backscattering light will be reflected and meet the local light at OC2, producing the signal of phase-sensitive OTDR with a beat frequency of 200 MHz. Then the light intensity is detected by a balanced detector with 400 MHz output bandwidth. The conditioning circuit moves the center frequency from 200 MHz to 20 MHz and make sure the signal can be sampled by DAQ1 with 100 MHz sample frequency. Laser 2 is the same as Laser 1, and the only difference is the wavelength, which is adjusted to 1549.900 nm. We should note that the Laser 2 can be replaced by Laser1 with an intensity electro-optic modulator (EOM) with a 38 GHz drive frequency to shift the frequency of the light from Laser 1. The CW light of Laser 2 then divides into 2 parts through a 50:50 optical coupler (OC3). One part propagates through the sensing fiber, Cir2, EDFA2 and Cir3, and then reaches to FBG2. As the reflect band of FBG2 is from 1550.040 nm to 1550.332 nm, which not includes the 1549.900 nm, the 1549.900 nm light wave will past through FBG2 and go to OC4, meeting the other part light from the reference fiber. Then the MZI waveform is formed at OC4 and detected by detector 2, an InGaAs detector. The spectrograph is used to observe the light spectrum at OC4.

As the Laser 2 is also a narrow line-width laser, whose wavelength is not included in the reflect band of FBG2, the FBG2 will barely reflect its light wave. Considering that the CW light from Laser 2 propagates forward in sensing fiber, which is strong, and the phase-sensitive OTDR signal is backscattered, which is much lower, the heterodyne detection is used to help isolate these two kinds of light. The Raleigh backscattering light will meet the local light at OC2 and form a beat light. The beat frequency is due to the light frequency shift caused by AOM, which is 200 MHz in our setup. When some optical light of Laser 2 is reflected by FBG2, it will also mix with the local light at OC2 and form a beat signal of 38 GHz. Because the frequency bandwidth of the detector is only 400 MHz, the 38 GHz beat signal cannot be detected and it only forms the DC component at the balanced detector. Thus, only the information of the phase-sensitive OTDR trace will be amplitude-modulated into the 200 MHz carrier signal and detected by the balanced detector. After the high pass filter in conditioning circuit, the DC component will be removed. Hence, the SNR of phase-sensitive OTDR will not be deteriorated by the MZI light.

On the other aspect, the phase-sensitive OTDR part will have some influence in the MZI part. Although the wavelength of Laser 1 includes in the reflect band of FBG2, the backscattering light from Laser 1 will not be totally reflected. The leakage light from FBG2 will then enter into the detector 2, leading to a periodical noise in MZI waveform. However, the light reached at OC4 from Laser 2 is much stronger than the leakage light of FBG2 from Laser 1, and the noise caused by the leakage of phase-sensitive OTDR trace can be omitted. There is only one exception. If there is a strong attenuation point in the sensing fiber, such as a fiber connector with 3 dB attenuation, the instantaneous reflected pulsed will be acquired by detector 2 because its strong light intensity even past through FBG2. This will cause a leap in the MZI waveform. Fortunately, the leap will be periodical and can be easily removed.

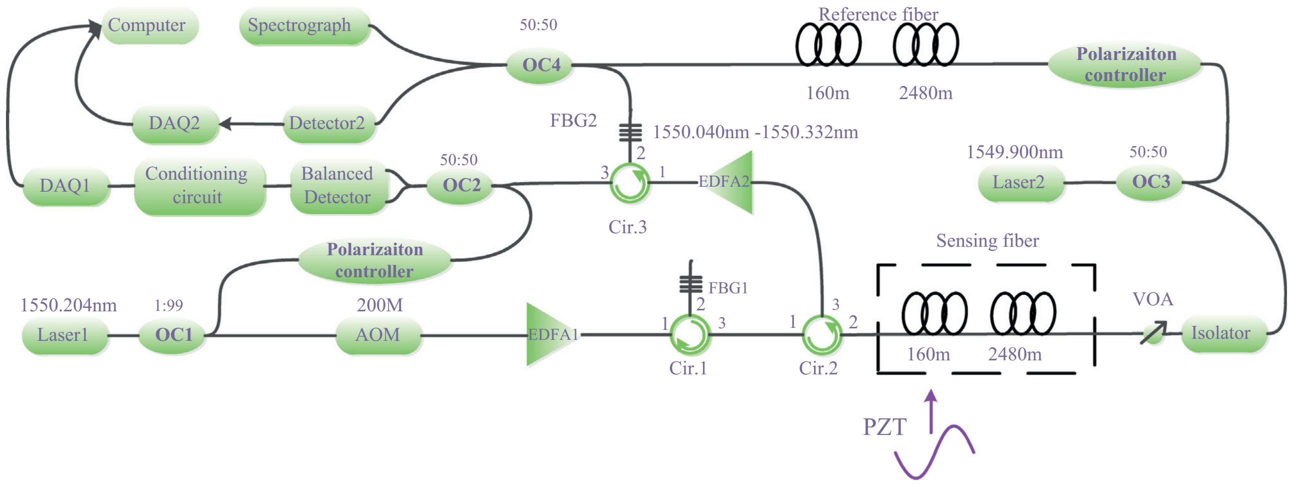

Fig. 1. The setup of the distributed vibration sensing system.