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Distributed acoustic mapping based on interferometry of phase optical time-domain reflectometry

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ABSTRACT

We demonstrate the design and characterization of a distributed optical fiber sensing system based on Michelson interferometer of the phase sensitive optical time domain reflectometer (φ-OTDR) for acoustic measurement. Phase, amplitude, frequency response and location information can be directly obtained at the same time by using the passive 3×3 coupler demodulation. In order to simulate sound profiles of seismic or hydroacoustic imaging, experiments on detection of multiple piezoelectric transducers (PZT) are carried out. The result shows that our system can well demodulate different acoustic sources with different intensities.

1. Introduction

Distributed optical fiber sensors offer the capability of measuring at thousands of points simultaneously, using a simple, unmodified optical fiber as the sensing element. Distributed optical fiber sensors have been mainly investigated not only for static measurements, such as temperature or static strain [1–3], but also for dynamic process including time-varying signals, involving a walking person, leakage of pipelines, vibration of engines, and crack of bridges or cranes [4,5]. It has been extensively studied and adopted in industrial applications during the past decades.

Up to now, distributed optical fiber measurements mainly include optical fiber interferometer sensors and optical backscattering based sensors. Interferometer sensors acquire distributed information by integration of the phase modulation signal, and usually two interferometers are used to determine position, including combining the Sagnac to a Michelson [6], modified Sagnac/Mach–Zehnder interferometer [7], twin Sagnac [8]/Michelson [9,10]/Mach–Zehnder [11] interferometers, and adopting a variable loop Sagnac [12,13]. Due to the differences between two correlated signals caused by noises or changes of polarization state, the spatial resolution of these twin interferometers is not satisfied, and only one random event can be positioned. Another distinguished technique is the use of optical backscattering based sensors. A promising technique is phase sensitive optical time domain reflectometer (φ-OTDR) by using a narrow line-width laser has been demonstrated [14,15]. Another system based on Polarization-OTDR (POTDR) has achieved 10 m spatial resolution in 1 km sensing range, while the detected frequency response is 5 kHz [16]. Brillouin based dynamic strain sensors have been researched recently [17]. Recently a hybrid interferometer-backscattering system is demonstrated [18], but the interferometer and the backscattering parts are working separately.

A major limitation of those distributed sensors above is that they are incapable of determining the full vector acoustic field, namely the amplitude, frequency and phase, of the incident signal, which is a necessity for seismic imaging. Measuring the full acoustic field is a much harder technical challenge to overcome but, in doing so, it is possible to achieve high resolution seismic imaging and also make other novel systems, for example a massive acoustic antenna.

In this paper, we demonstrate the design and characterization of a distributed optical fiber sensing system based on Michelson interferometer of the φ-OTDR for acoustic measurement. Phase, amplitude, frequency response and location information can be directly obtained at the same time. Experiments on detection of multiple piezoelectric transducers are carried out. The result shows that our system can well describe the different acoustic sources with different intensities. Our system offers a versatile new tool for acoustic sensing and imaging, such as through the

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formation of a massive acoustic camera/telescope. The new technology can be used for surface, seabed and downhole measurements all using the same optical fiber cable.

2. Interferometry of the φ-OTDR

To get the distributed information along a fiber, Rayleigh backscattering from the fiber material is detected, and changes can be seen in different medium properties such as discontinuities in the fiber or coupler. Normally, φ-OTDR techniques, where the system is probed with narrow coherent light pulses with direct detection [19,20], is used. Here we add a Michelson interferometer to the output of the φ-OTDR. Fig. 1 shows the schematic configuration of the Michelson interferometor of the φ-OTDR. The Rayleigh scattering signal is injected into a classical Michelson interferometer comprised of a coupler and two Faraday rotation mirrors (FRM) with the half arm length of *s*. The interference signal at every certain time contains not only the information of the corresponding position in the detection fiber but also the phase changes within an arm length of 2*s* after this position for demodulation.

To have a better and direct understanding of the, we use the one-dimensional impulse-response model of the backscattering from a fiber [21]. When we launch a coherent light pulse with a pulse width *w* and an optical frequency *f* into a fiber at $t=0$, we obtain a backscattered wave $E_{bs}(t)$ at the input end of the fiber that is given by

$$E_{bs}(t) = \sum_{m=1}^{N} e_m \cos\left[2\pi f(t - \tau_m)\right] \exp\left(-\alpha\frac{c\tau_m}{n_f}\right) rect\left(\frac{t-\tau_m}{w}\right) \quad (1)$$

where e_m and τ_m are the amplitude and the delay of the *m*th scattered wave, *N* is the total number of scatterers, α is the fiber attenuation constant, *c* is the velocity of light in a vacuum, n_f is the refractive index of the fiber, and $rect[(t-\tau_m)/w]=1$ when $0 \le [(t-\tau_m)/w] \le 1$, and is zero otherwise. The delay τ_m corresponds to the distance l_m from the input end to the *m*th scatterer through the relation $\tau_m=2n_f l_m/c$. The term $rect[(t-\tau_m)/w]$ accounts for the change in the scattering volume seen as the pulse propagates.

After the Michelson interferometer, the delayed wave $E_d(t)$ at the input end of the fiber is

$$E_d(t) = \sum_{n=1}^{N} e_n \cos\left[2\pi f(t - \tau_n - \tau_s)\right] \exp\left[-\alpha\frac{c\tau_n}{n_f}\right] rect\left(\frac{t-\tau_n-\tau_s}{w}\right) \quad (2)$$

where *s* is the half arm length of the Michelson interferometer, $\tau_s=2n_f s/c$ is the delay introduced by the interferometer. Therefore the optical power $I(t)$ associated with the backscattered and delayed wave is given by

$$\begin{aligned} I(t) &= [E_{bs}(t) + E_d(t)] \bullet [E_{bs}(t) + E_d(t)]^{*} \\ &= \sum_{m=1}^{N} e_m^2 \exp\left(-2\alpha\frac{c\tau_m}{n_f}\right) rect\left(\frac{t-\tau_m}{w}\right) \\ &\quad + \sum_{n=1}^{N} e_n^2 \exp\left[-2\alpha\frac{c\tau_n}{n_f}\right] rect\left(\frac{t-\tau_n-\tau_s}{w}\right) \\ &\quad + 2\sum_{m=1}^{N}\sum_{n=1}^{N} e_m e_n \cos\phi_{mns} \\ &\quad \exp\left(-\alpha\frac{c(\tau_m+\tau_n)}{n_f}\right) rect\left(\frac{t-\tau_m}{w}\right) rect\left(\frac{t-\tau_n-\tau_s}{w}\right) \end{aligned} \quad (3)$$

where $\phi_{mns}=4\pi f n_f(l_n-l_m)/c+4\pi f n_f s/c$.

The quantity ϕ_{mns} denotes the phase difference between the backscattered waves from the *m*th and *n*th scatterers with the half arm length *s*. Therefore, the interference term $I(t)$ is a function of *f*, *w*, n_f, and ϕ_{mns}. Moreover, ϕ_{mns} depends on the acoustic response in the fiber, and hence $I(t)$ changes with them. Using this feature, we can measure the distributed acoustic responses by analyzing the measured backscatter power.

3. 3 × 3 demodulation method

For signal processing and demodulation part, here we use a simple Michelson interferometer (Fig. 2) made by a circulator, a 3 × 3 coupler and two FRMs [22]. The half arm length of the Michelson interferometer is *s*. Among the variety of fiber optical modulation–demodulation schemes, this approach based on the 3 × 3 coupler is based on passive components. Since no carrier wave is included in the modulating process, the accuracy requirement for the laser source is lowered. In general, its working mechanism is to produce modulated signals with certain phase shift for different arms. The demodulation principle is much simpler, and the burden carried by the demodulation calculation is reduced.

Theoretically, there is a 120° phase shift between two adjacent arms. Accordingly, the outputs of the three arms can be expressed as

$$\begin{aligned} I_1 &= D + I_0\cos[\phi(t)] \\ I_2 &= D + I_0\cos\left[\phi(t) - \frac{2\pi}{3}\right] \\ I_2 &= D + I_0\cos\left[\phi(t) - \frac{4\pi}{3}\right] \end{aligned} \quad (4)$$

where *D* and I_0 are constants, $\phi(t)=\phi_s+\phi_n+\phi_0$. ϕ_s, ϕ_n and ϕ_0 are respectively the signals to be detected, the noise and the intrinsic phase of the system. All three inputs I_1, I_2 and I_3 are equivalent for the demodulation process. For each point on the detection fiber, ϕ_s is obtained after the demodulation process shown in Fig. 3. It can directly demodulate all the information from the signal detected at the same time without any Fourier transformations.

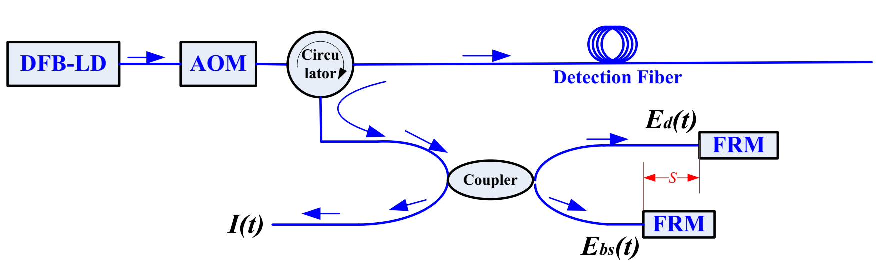

Fig. 1. Schematic diagram of the Michelson interferometer of the φ-OTDR with the half interferometer arm length *s*.