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An enhanced distributed acoustic sensing system based on the interactions between microstructures

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Abstract. Acoustic field could be quite useful in structure health monitoring (SHM). Here we present an enhanced distributed acoustic sensing (DAS) system by implanting microstructures into the sensing fibre. Taking advantage of the interactions between nearby microstructures, the acoustic field could be reconstructed with high fidelity and signal-to-noise ratio (SNR) even at the rear end of 42.2km long sensing fibre. The experimental results have shown that the proposed sensing system has a linear intensity response of $R^2=0.9988$, while its frequency response band ranges from 8Hz to 1kHz.Purely distributed sensing along the optical fibre has been obtained even with discretely implanted microstructures for the proposed system, which offers a dependable option for acoustic field monitoring.

1. Introduction

High accuracy monitoring of acoustic field could be quite useful in structure health monitoring (SHM) [1-3]. Recently the distributed acoustic sensing (DAS) system has attracted a significant amount of research attention, owing to its outstanding advantages of long sensing range, high sensitivity, fast response, accurate location, immunity to electromagnetic interference and fully distributed sensing ability [4-8].

Valuable work has been made to improve the performance of DAS. Juarez utilized a continuous-wave Er3+ doped fibre Fabry-Perot laser and an electro-optic modulator to improve the sensing range to 12km[4]. The erbium-doped fibre amplifier (EDFA) can significantly boost the input power launched into the sensing fibre[9, 10], but the sensing range of EDFA-based DOFS would be limited by rapidly accumulated nonlinear effects along the fibre[11], which severely degrades the coherence of the probe signal. Then the distributed optical fibre amplifier based on Raman or Brillouin pump was applied in DOFS[12-15] to gain the probe light along the entire sensing fibre, and the sensing range could be improved up to 175km[12]. However, the complexity of the sensing system is increased which may lead to the degradation of flexibility in practical applications. To further improve the signal-to-noise ratio (SNR), microstructures have been induced to the sensing fibre. C. Wang et al. combined ultra-weak fibre Bragg gating (UWFBG) with phase-sensitive optical time domain reflectometry ($\Phi$-OTDR) for acoustic measurement and achieved a sensitivity of -158dB[16]. F. Zhu et al. embedded UWFBG array at the end of sensing fibre and $\mu$e level dynamic strain has been captured[17]. X. C. Wang et al. have proposed an enhanced polarization optical time domain reflectometry (P-OTDR) for vibration monitoring based on UWFBG. The SNR of system was improved by 11dB[18]. However, the microstructures in these cases just acted as a substitution for the Rayleigh scattering points within the sensing fibre to provide higher and more stable reflectivity.

In this paper, we proposed a new DAS scheme based on self-heterodyne detection. Taking advantage of the interaction between nearby microstructures, the acoustic field could be fully reconstructed with high fidelity and SNR without the help of additional demodulation structure.

2. Principle and Experimental Setup

Fig.1(a) presents the experimental setup of the proposed system. A 1550.12nm narrow linewidth laser (ROJ Orion Laser Module) was selected as the light source, whose linewidth was 3.7kHz. The continuous-wave (CW) of laser was separated into two paths by an optical coupler (OC). Then the CW waves were shaped by two acoustic optical modulators (AOM) into narrow probe pulses with frequency shift of 150MHz and 80MHz. The repetition period and width of the probe pulses...
were 500μs and 80ns, respectively. There was a time delay $\tau=100$ns between these two pulses. The two pulses were combined by OC2 and amplified by an EDFA. Optical filter was inserted to minimize the amplifier spontaneous emission (ASE). The probe pulses passed through a circulator (Cir) and launched into the sensing fibre through 1550nm port of the wavelength division multiplexer (WDM).

More than fifty microstructures were implanted at the end of 41.711km sensing fibre as wideband weak reflection surfaces, generating reflected light waves that were much stronger than Rayleigh back-scattering (RBS). The Raman pump was a Raman Fibre Laser (KEOPSYS) emitting at 1450nm with the maximum output power of 5W. The reflected light waves back from the sensing fibre first went through a small-signal-EDFA and another optical filter, and then emitting at 1450nm with the maximum output power of 5W. The reflected light waves back from adjacent microstructures. Therefore, at the time of $t_2$, the electric field of reflected light $E_{R1}$ will be delayed by $2L_{2}$ pulse and would be reflected. The electric field of reflected light $E_{R1}$ can be written as:

$$E_{R1} = E_1 \cos[(\omega_0 + \omega_1) t + \phi_0]$$

(1)

Where, $E_1$ is the amplitude of the reflected light from $M_0$, $\phi_0$ is the initial phase. When the dual pulse propagating forward, pulse 1 will arrive at $M_2$ at the time of $t_2$ and would be reflected as well. At this point, $E_{R1}$ arrives at $M_2$ and interferes with $E_{R2}$. The acoustic field could induce fibre length variation $\Delta L$ to the sensing fibre, thus creating phase change $\Delta \phi$ between the reflected light waves from adjacent microstructures. Therefore, at $t_2$, the electric field of reflected lights generated by $M_1$ and $M_2$ can be written as:

$$E_{R1} = E_1 \cos[(\omega_0 + \omega_1) t + \phi_1 + \frac{4\pi n}{\lambda}(L + \Delta L)]$$

(2)

$$E_{R2} = E_2 \cos[(\omega_0 + \omega_2) t + \phi_2]$$

(3)

The AC component of the photocurrent generated by the interference signal can be expressed as:

$$I(t) \propto 2E_1 E_2 \cos[(\omega_2 - \omega_1) t + \frac{4\pi n}{\lambda}(L + \Delta L + \Delta \phi)]$$

(4)
The frequency of this beating signal is $\omega_{IF}$, which is the difference between $\omega_1$ and $\omega_2$. $\varphi_{12}$ is the initial phase difference between the two reflections. The relationship between $\Delta L$ and $\Delta \varphi$ can be written as:

$$\Delta \varphi = \frac{4\pi n}{\lambda} \Delta L$$

(5)

After phase demodulation, we can derive $\Delta \varphi$, and the corresponding fibre length variation $\Delta L$ can be obtained linearly according to Eq. (5).

3. Results and Discussion

In the experiment, the microstructures were realized with on-line manufactured Ultra Weak Fibre Bragg Grating (UWFBG) of 0.01% (-40dB) reflectivity. The interval between adjacent UWFBGs was 10m. The pulse width was 80ns to cover a region that was narrower than the interval of adjacent UWFBGs. The amplitude profile of obtained beating signal is shown in Fig. 2 (a). Since Raman amplifying was induced, the magnitude of RBS was getting stronger at first along the fibre and reached its maximal around 15km. Then the signal slowly decreased all the way to the UWFBG region. As shown in Fig. 2 (b), the reflected waves from UWFBGs region within the red dash line, were much stronger light waves than the RBS, which makes it possible to reconstruct the acoustic field even at the rear end of the sensing fibre with high SNR. The reflection from a given UWFBG could be distinguished from its nearby reflections, thus the interaction between adjacent UWFBGs could be analysed one by one clearly.

Fig. 2 The obtained beating signal. (a) The entire amplitude profile of beating signal. (b) The zoomed amplitude profile near the UWFBGs region.

To evaluate the performance of the proposed system, a sinusoidal signal of 50Hz was applied on PZT to create periodical vibration. The voltage of the driving signal was 5V. The reconstructed acoustic signal in both time and frequency domains are given in Fig. 3, which is of high fidelity. No obvious high order harmonics of the vibration signal were observed. A SNR of 36dB could be obtained between the peak value of vibration signal and far end noise floor as shown in Fig. 3 (b).

Fig.3 The reconstructed signal (a) The time domain (b) The frequency domain

To verify the linear response property of the proposed system, the voltage applied on the PZT was swept from 0.5V to 10V while its frequency was fixed at 50Hz. Fig. 4(a) exhibits the waveform of the reconstructed acoustic signal at PZT after signal conditioning under different magnitudes. The reconstructed acoustic signal remained the shape of sinusoidal wave without distortion as the stretching of PZT was increased. In Fig. 4(b), the blue points were the measured amplitude of vibrations induced by PZT and the red dash line was the fitting result. The R-square of the fitting line was 0.99881, which confirmed a high level of linearity. Experiment has been made to further investigate the frequency response range of the proposed system. The repetition period of pulse was 500us, corresponding to the highest detectable frequency of 1 kHz according to the Nyquist rule of sampling. We tuned the frequency of the driving signal applied on PZT while its amplitude was fixed at 1V. For each frequency point, 500 consecutive traces were recorded for Fast Fourier
Transform (FFT). Fig. 4(c) shows the power spectrums obtained under different frequency points. The peak values were nearly of the same level all through the range from 8Hz to 1kHz.

The proposed system presents an innovative view of the usage of microstructures in the enhancement of a DAS system. Taking advantage of the interaction process between nearby microstructures, the distribution of acoustic field along the sensing fibre could be fully captured. The reconstruction of acoustic field is equivalent to the measurement of optical path variation induced by external disturbance, and finally converted into the observation on phase change of reflected light waves from adjacent microstructures all along the sensing fibre. By comparing the signals before and after UWFBGs as shown in Fig. 2, the SNR enhancement was approximately 18dB. That means the sensing fibre length would be improved by nearly 45km considering a round trip attenuation ratio of 0.4dB/km. The spatial resolution of the proposed system was mainly determined by the interval between adjacent UWFBGs. Higher spatial resolution could be obtained if the interval between UWFBGs is reduced. Purely distributed sensing along the optical fibre was achieved even with discretely implanted microstructures for the proposed system, which offers a dependable option for long range distributed acoustic sensor enhancement.

4. Conclusion
We present an enhanced DAS system based on the interactions between microstructures implanted into the optical sensing fibre. The acoustic field could be reconstructed with high fidelity even at the rear end of 42.2km long sensing fibre. The experimental results have shown that the proposed sensing system has a linear intensity response of $R^2=0.9988$, while its frequency response band ranges from 8Hz to 1 kHz.

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