A hybrid demodulation method based on coherent detection and pulse pair for distributed acoustic sensing is proposed. The Rayleigh backscattering light of pulse pair is coherent amplified by local reference light. A 3 × 3 fiber coupler is utilized to produce stable 2π/3 phase shift for phase extraction. The digital mixing of the beat signals of two pulses suppress the noise caused by phase drift and vibration on the local reference fiber. Several simulated acoustic waveforms are detected and retrieved. Experimental results show that the system has good linear response. And the equivalent strain of noise is as low as 0.4 με. © 2019 The Japan Society of Applied Physics
which shows well linear response ability. And signal-to-noise ratio achieves 31.3 dB when sinuous signal with 700 mV amplitude is being loaded. Then a triangle-amplitude-modulated sinusoidal signal is loaded and detected for forward verifying the ability of retrieving waveform.

Figure 1(a) is the proposed sensing system principle diagram. The light with an optical frequency of $f_0$ from a narrowband CW laser goes through a fiber polarization beam splitter, and is divided into two parts, the signal light and the local reference light. The signal light enters a DPMZM which is driven by an arbitrary waveform generator (AWG). The signal light is modulated into a pulse pair, whose two pulses are frequency shifted with $f_1$ and $f_2$, respectively. The pulse width is $W$ and pulses interval is $\tau$ while the repeat period is $T$, as shown in Fig. 1(b). The pulse pair is amplified by the Erbium-doped fiber amplifier. Then the amplified pulse pair is launched into the sensing fiber by a circulator. Generated RBS light goes through the circulator and interfere with the local reference light in a 3×3 fiber coupler. The interference light enters into three photodiodes (PDs) and are transformed into photonic current signals. Three analog high-pass filters (FIRs) connected to the PDs are used for removing the direct part of signals. The alternating part of the signals are sent to the data acquisition and processing system.

There exists a $2\pi/3$ phase difference between each arm of a 3×3 fiber coupler, thus the signals of the three ports and phase of the signals can be expressed as:

$$I_a = I_{a,d_1} + I_{a,d_2} = A(t)\sin \left[ 2\pi f_1 t + \phi_1(Z_1) \right] + B(t)\sin \left[ 2\pi f_2 t + \phi_2(Z_2) \right]$$

$$I_b = I_{b,d_1} + I_{b,d_2} = A(t)\sin \left[ 2\pi f_1 t + \phi_1(Z_1) + \frac{2\pi}{3} \right] + B(t)\sin \left[ 2\pi f_2 t + \phi_2(Z_2) + \frac{2\pi}{3} \right]$$

$$I_c = I_{c,d_1} + I_{c,d_2} = A(t)\sin \left[ 2\pi f_1 t + \phi_1(Z_1) - \frac{2\pi}{3} \right] + B(t)\sin \left[ 2\pi f_2 t + \phi_2(Z_2) - \frac{2\pi}{3} \right]$$

where, $Z_1$, $Z_2$ are the coordinates of P1 and P2 where the pulses returning, as shown in Fig. 1(c). $\phi_1(Z_1)$, $\phi_2(Z_2)$ are the phase difference between RBS generated by pulse probe and the reference local light; $\phi_{LO}$ is the local reference light phase which might be affected by the perturbation on the coupler arm; $\delta(t)$, $\delta(t + \tau)$ are the phase drift caused by laser phase noise.

Figure 2 shows the digital signal processing procedure. $I_{a,d_1}$, $I_{b,d_1}$, $I_{c,d_1}$ and $I_{a,d_2}$ are obtained with bandpass filters. $I_{a,d_2}$ is then used to mix with $I_{a,d_1}$, $I_{b,d_1}$, $I_{c,d_1}$, respectively. Low pass filters are applied to the mixed operation outputs. The digital signal processing results can be expressed as:

$$V_a = \frac{A(t)B(t)}{2} \cos \left[ 2\pi (f_1 - f_2) t + \Phi(Z_1) \right]$$

$$V_b = \frac{A(t)B(t)}{2} \cos \left[ 2\pi (f_1 - f_2) t + \Phi(Z_1) + \frac{2\pi}{3} \right]$$

$$V_c = \frac{A(t)B(t)}{2} \cos \left[ 2\pi (f_1 - f_2) t + \Phi(Z_1) - \frac{2\pi}{3} \right]$$
\[
\Phi(Z_j) = \phi_1(Z_j) - \phi_2(Z_j) \approx \frac{4\pi}{\lambda} \cdot nL + \delta(t) - \delta(t + \tau) \approx \frac{4\pi}{\lambda} \cdot nL,
\]

where \(\Phi(Z_j)\) is the differential phase. Since the refractive index of each fiber section \(n(z)\) is slow-varying along the sensing fiber, the refractive index between P1 and P2 is approximately a fixed value. The distance between P1 and P2 is \(L = \frac{ct}{2\lambda}\) as shown in Fig. 1(c). Considering the pulses interval \(\tau\) is usually lower than 500 ns, \(\delta(t) - \delta(t + \tau)\) can be negligible. Thus, the effects of \(\varphi_{LO}\) and \(\delta(t)\) are eliminated or suppressed in \(\Phi(Z_j)\). In the system using single pulse and time-delay fiber coupler interferometer, the arms of coupler should be protected carefully to weaken the perturbation of \(\varphi_{LO}\) which exists in the final demodulated phase and introduce noise. On the contrary, our method using pulse pair method suppresses \(\varphi_{LO}\) in data processing and avoids the noise caused by disturbance on the arms of fiber coupler. Then the differential phase is extracted by transformation of triangle function as follows:

\[
\Phi(Z_l) = \arctan \left( \frac{V_c - V_b}{\sqrt{3} V_a} \right) - \frac{2\pi}{3} (f_1 - f_2) t.
\]

The amplitudes \(A(t)\) and \(B(t)\) of the two signals are eliminated in (10). Thus, intensity difference of the two COTDR signals will not affect the demodulation result. An unwrapping algorithm is applied to solve the sudden change of inverse tangent function. When strain \(\varepsilon\) induced by acoustic event is applied to the fiber section between P1 and P2, the differential phase at \(Z_l\) coordinate \(\Phi(Z_l)\) changes compared with the original value. The differential phase variation \(\Delta\Phi(Z_l)\) caused by strain \(\varepsilon\) at \(Z_l\) coordinate can be expressed as:

\[
\Delta\Phi(Z_l) = \frac{4\pi L}{\lambda} \left\{ n - \frac{n^3}{2} [p_{12} - \mu(p_{11} + p_{12})] \right\} \varepsilon = S \cdot \varepsilon
\]

where \(S\) is the sensitivity coefficient, \(\mu\) is the material Poisson’s ratio; \(p_{11}, p_{12}\) are elements of elastic-optic coefficient matrix. For the fused silica, \(\mu = 0.170, p_{11} = 0.113, p_{12} = 0.252\). When the wavelength of light is 1550 nm, the sensitivity coefficient \(S = 94.4\ \text{rad/}\mu\varepsilon\) for 10 meter long \(L\). According to (10), the differential phase variation is directly and only proportional to the strain \(\varepsilon\) applied on the corresponding section of sensing fiber. Therefore, the acoustic waveform acted on the section between P1 and P2 can be retrieved by extracting and monitoring the differential phase variation at \(Z_l\) coordinate.

The sensing system is set up according to Fig. 1(a). A narrowband laser with a linewidth less than 3 kHz generated CW light with 1550.12 nm center wavelength and 40 mW power. The DPMZM (Photoline MXIQ-LN-40) has a sharp risetime which is lower than 25 ps. And it is driven by the dual-channel arbitrary waveform generator (AT-AWG-GS 2500) with 14 bit vertical resolution, 2.5 GS s\(^{-1}\) sampling rate and time-domain deviation between channels less than 10 ps. The generated pulse pair shifted frequency are \(f_1 = 80\ \text{MHz}\) and \(f_2 = 50\ \text{MHz}\) for satisfied the effective spectrum range and filtering requirements. The pulse width of two pulses are both \(W = 100\ \text{ns}\), while the interval between two pulses is set as \(\tau = 100\ \text{ns}\). The repeat period of pulse pair array is \(T = 25\ \text{us}\) which determining the sample rate for acoustic sensing is 40 kHz. The sensing fiber is connected by a 1040 meter long optical fiber, a commercial fiber stretcher and a 1000 meter long optical fiber in turn. The fiber stretcher is a 10 meter long fiber wound piezoelectric element which is utilized to simulate the fiber strain caused by acoustic signal. The typical stretcher constant of the fiber stretcher is 18\(\varepsilon\) = \(\text{V}^{-1}\). And a function waveform generator (Agilent33521A) is used to drive it. The bandwidth of the three PDs are all 150 MHz. The cut-off frequency of the high-pass filters is 25 MHz. The signals are received by a three-channel data acquisition with 12 bit ADC resolution and 1 GS s\(^{-1}\) sampling rate for each channel. The exact phase shift of 3 \(\times\) 3 fiber coupler are 118.5\(^\circ\), 0\(^\circ\) and \(-117.5\(^\circ\). And the errors caused by the difference from ideal phase shift is lower than the noise and can be ignored.

To verify the linear response performance of the proposed method, seven sinusuous signals with 100–700 mV amplitudes and 500 Hz frequency are loaded to the fiber stretcher in turn. And the amplitude of retrieved waveform for each signal is shown in Fig. 3(a). The left vertical axis shows the strain calculated from (10). And the results fit well with a linear function, with a slope obtained as \(20 \text{neV V}^{-1}\) (1.9 rad V\(^{-1}\)) and a goodness of fit \(R^2 = 0.9986\). This result shows that the amplitude of retrieved signal is linear with the amplitude of voltage signal loaded on fiber stretcher. According to the linear response of this commercial fiber stretcher, the proposed method can detect fiber strain which is caused by acoustic signal linearly. The power spectral density (PSD) of retrieved waveform when a sinusuous signal with 700 mV amplitude and 500 Hz frequency is applied on the PZT is shown in Fig. 3(b). The center frequency is 500 Hz which is consistent to the loaded signal. The SNR achieves 31.3 dB. And the main noise is round 50 Hz and the peak
The value of the noise is −28.1 dB. The equivalent strain of the −28.1 dB noise density is 0.4 nε. When sinuous signals with different amplitudes are applied in turn, the peak value of noise changes slightly while the peak value of signal and the SNR vary logarithmically with amplitude as shown in Fig. 3(c).

In order to verify the strain signal retrieval ability, an amplitude modulation (AM) simulated acoustic signal is applied.
applied to the sensing fiber. The Carrier signal is a sinusoidal signal with the frequency 500 Hz. The AM signal is a triangular-wave with the frequency 25 Hz. The maximum amplitude of signal is 700 mV. Figure 4(a) shows the spatial-temporal domain differential phase signals from 700 to 1300 m. It can be recognized that there is a retrieved signal at the location 1040–1050 m which is consistent with actual location of fiber stretcher. The part of spatial-temporal domain differential phase which is enclosed by a red dotted line is zoomed and plotted three-dimensionally as shown in Fig. 4(b). A vibration signal with modulated amplitude can be recognized. The location information and general waveform characters of signal is detected correctly.

Then temporal domain signal of the retrieved signal is further shown in Figs. 4(c), 4(d). The green points are the detected results and the red curve is the fitting curve of the retrieved results. The center frequency and the AM frequency of fitting curve are 500 and 25 Hz, which is consistent with the loaded signal. And the fitting factor $R^2$ is 0.9968. And the partial enlargement graph Fig. 4(d) shows directly that the waveform of signal applied on the sensing fiber is well retrieved with little distortion.

A hybrid demodulation method for DAS is proposed. A 3 x 3 fiber coupler is utilized for coherent amplifying the RBS and producing stable $2\pi/3$ phase differences for phase extraction. A pulse pair containing two pulses with different frequency is injected into the sensing fiber for producing interfering signals with different frequency and malposed phase information. The noise caused by phase drifting and vibration on the local reference arm are recoded by digital mixing the two interfering signals. The proposed scheme measures triangle AM sinusine and sinusinus acoustic signals simulated by a PZT actuator placed at 1050 m. This scheme has well ability of linear amplitude response. The measurement result SNR of sinusinus with 700 mV voltage achieves 31.3 dB. In conclusion, this differential phase COTDR shows well ability of recovering the signal for DAS.

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