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Distributed Quantitative Vibration Demodulation with Direct Detection based Phase-sensitive OTDR Assisted by Acousto-Optic Phase Shifting Technique

*Shuaiqi Liu, Feihong Yu, Weijie Xu, Mang I Vai, Liyang Shao **

Email: shaoly@sustech.edu.cn

ABSTRACT

Quantitative demodulation of the external vibration is demonstrated with a direct-detection based Phase-sensitive OTDR system. An acousto-optic modulator is utilized for both probe pulse generation and optical phase shifting simultaneously. The fiber under test is probed with a phase shifted double pulse pair scheme, with the relative phase difference periodically shifted with a π/2 step. The optical phase information is retrieved using the self-interferenced signal of the Rayleigh backscattered light with direct-detection receiver only. Experimental results show good consistence between the phase demodulation results and the applied vibration amplitude under a cost-effective system configuration.

Principle of Operation

Fig. 1 illustrates the working principle of dual-pulse Φ-OTDR. The two probe pulses, pulse A and pulse B, are launched into the FUT sequentially, with a temporal delay of Δt. The RBS traces generated by the two pulses are interfered with each other and detected by the photodiode PD. The resultant self-interferenced intensity signal I(t) can be expressed by:

$$I(t) = \left|E_{RBS,A}(t)+E_{RBS,B}(t)\right|^2 = \left|E_{RBS}(t)\right|^2 + \left|E_{RBS}(t-\frac{\Delta t}{2})\right|^2 + 2\sqrt{\left|E_{RBS}(t)\right|^2\left|E_{RBS}(t-\frac{\Delta t}{2})\right|^2}\cdot\cos(\Delta\varphi(t)+\theta_0) \quad (1)$$

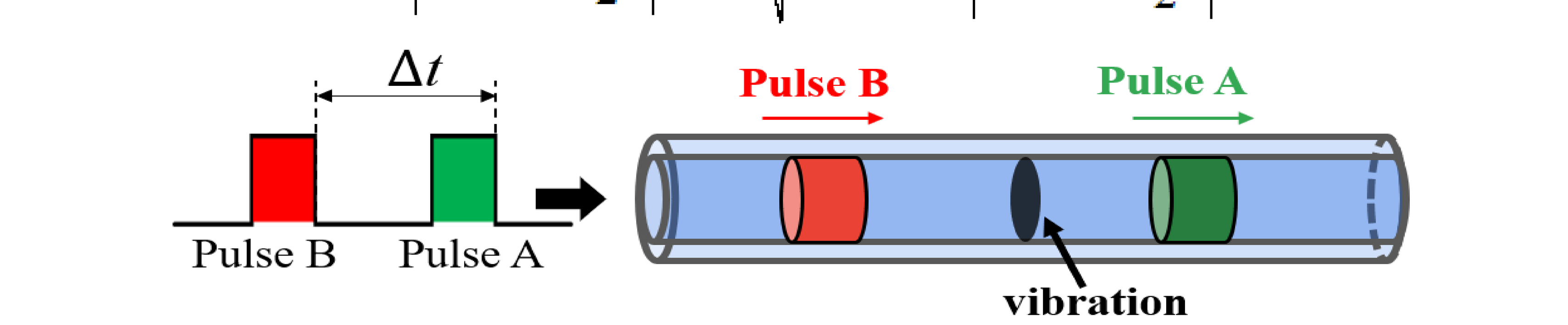

Fig. 1. Operation Principle of Dual Pulse Φ-OTDR and the generation of self-interferenced RBS signal

Therefore, by introducing a phase shift of $\Delta\theta_i = i\cdot\pi/2$ between pulse A and B of the i-th probe pulse pair, the i-th and (i+1)-th RBS trace can be expressed by:

$$I_i(t) = I_{DC}(t) + I_{AC}(t)\cdot\cos(\Delta\varphi(t)+\theta_0+\Delta\theta_i)$$
$$I_{i+1}(t) = I_{DC}(t) - I_{AC}(t)\cdot\sin(\Delta\varphi(t)+\theta_0+\Delta\theta_i) \quad (2)$$

And the differential phase is easily obtained as:

$$\Delta\varphi(t) = \arctan\left(\frac{-\hat{I}_{i+1}(t)}{\hat{I}_i(t)}\right) - \Delta\theta_i - \theta_0 \quad (3)$$

We proposed to achieve simultaneous probe pulse generation and pulse phase shifting with a single acousto-optic modulator (AOM). By switching the on-off state of the acoustic wave, the optical intensity of the incident beam is modulated to generate optical pulses; whilst by modulating the initial phase of the acoustic wave, the initial optical phase of the probe pulse is modulated accordingly as shown in Fig 2.

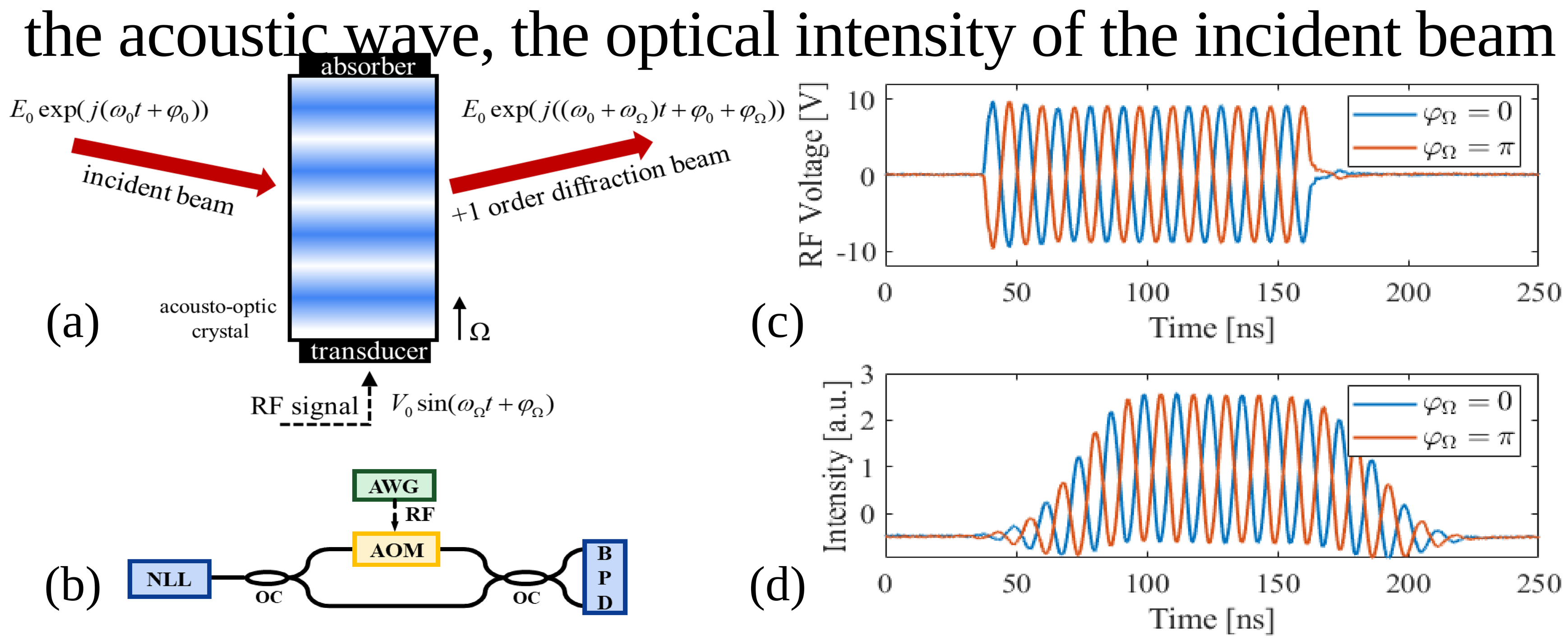

Fig. 2. (a) Schematic diagram of the basic working principle of an AOM. Ω: acoustic wave. (b) Experimental setup for testing the phase shifted pulsing method based on AOM. (c) The waveforms of two RF pulse signal, with initial phases φ_Ω of 0 (blue) and π (red) respectively. (d) The waveforms of the optical pulses corresponding to RF pulses with φ_Ω=0 (blue) and φ_Ω=π (red) after beating with the reference light.

RESULTS

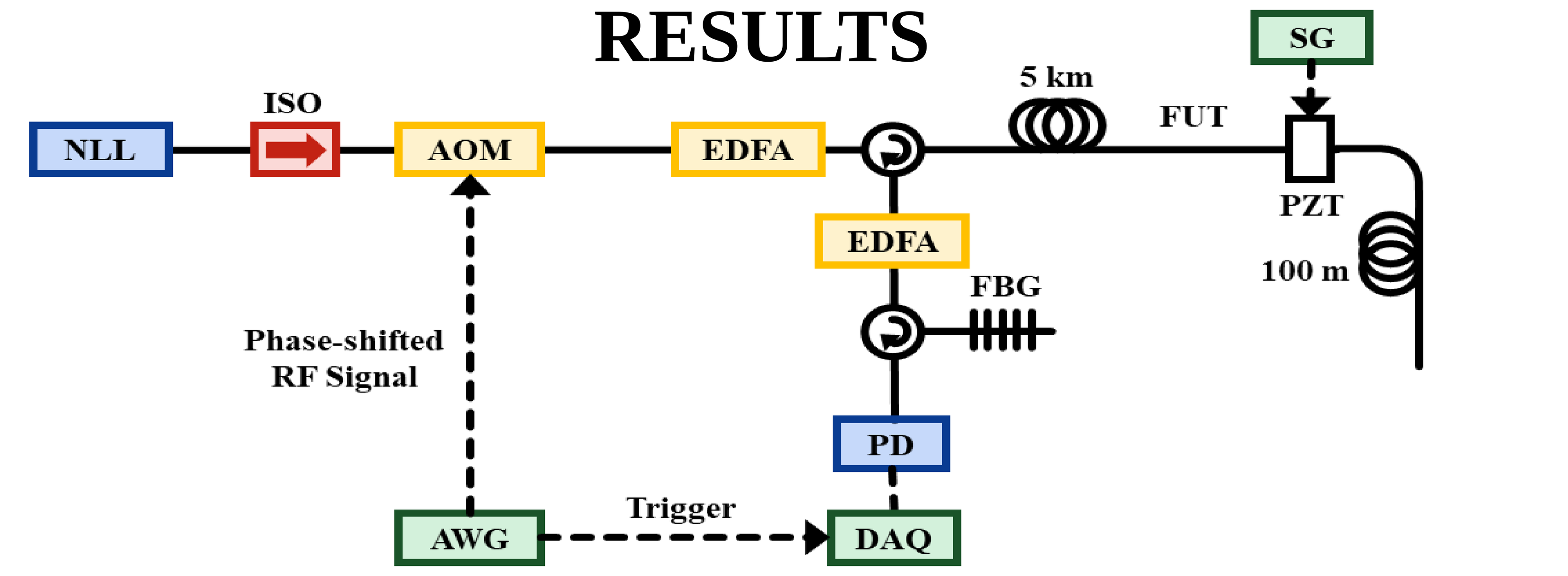

Fig. 3 Experimental Setup

The experimental setup is illustrated in Fig. 3. In this configuration, the repetition rate of the dual-pulse probe is set as 16 kHz. The pulse width of the two pulses are 100 ns, while the temporal delay Δt between the two pulses is chosen as 200 ns. The system gauge length L is approximately 10 meters.

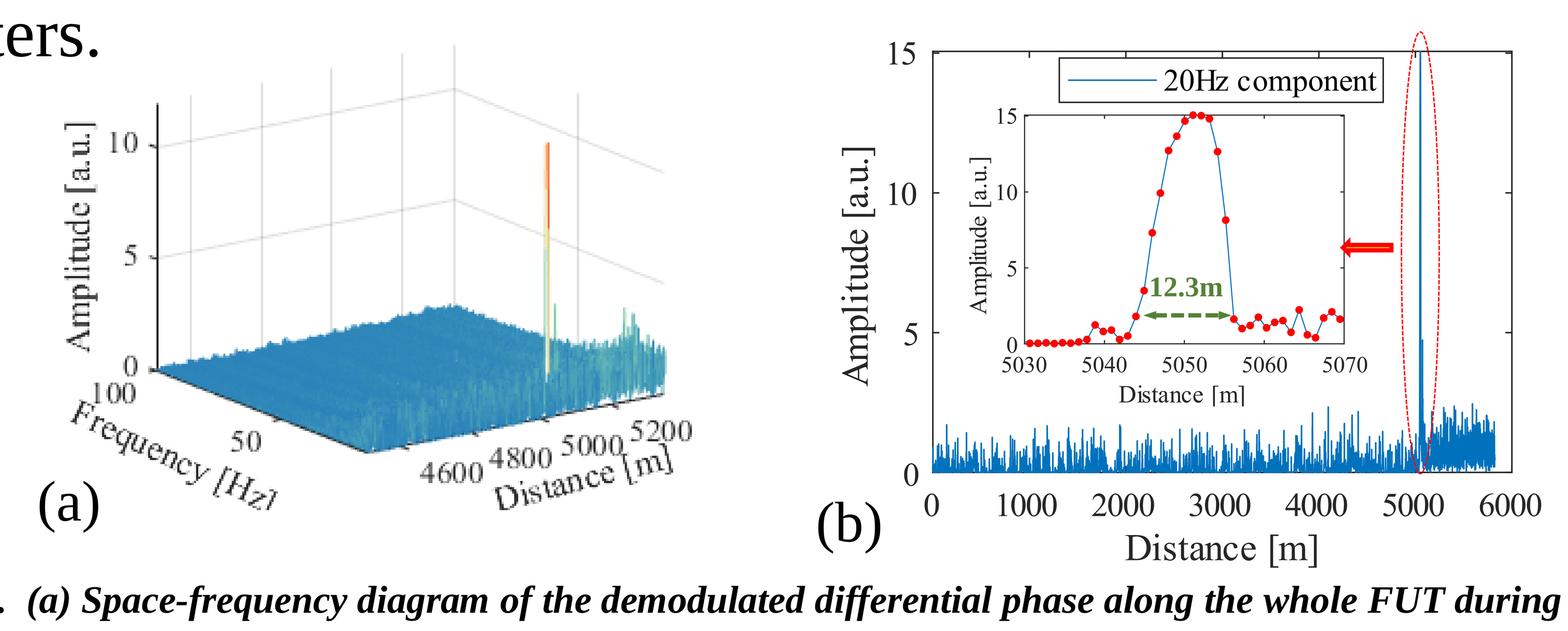

Fig. 4. (a) Space-frequency diagram of the demodulated differential phase along the whole FUT during 3 second sampling period with 20-Hz vibration applied at ~5km position of the FUT. (b) Amplitude of the 20 Hz frequency component of the differential phase signal along the FUT. The inlet is a zoomed-in view at the vibration location.

First, a 20-Hz sinusoidal signal is applied to the PZT placed about 5 km away from the FUT injection port. As illustrated in Fig. 4, a spatial resolution of 12.3 meters is achieved with the proposed method. Next, a 1-Hz vibration is accurately reconstructed with 31.3 dB SNR, as shown in Fig. 5.

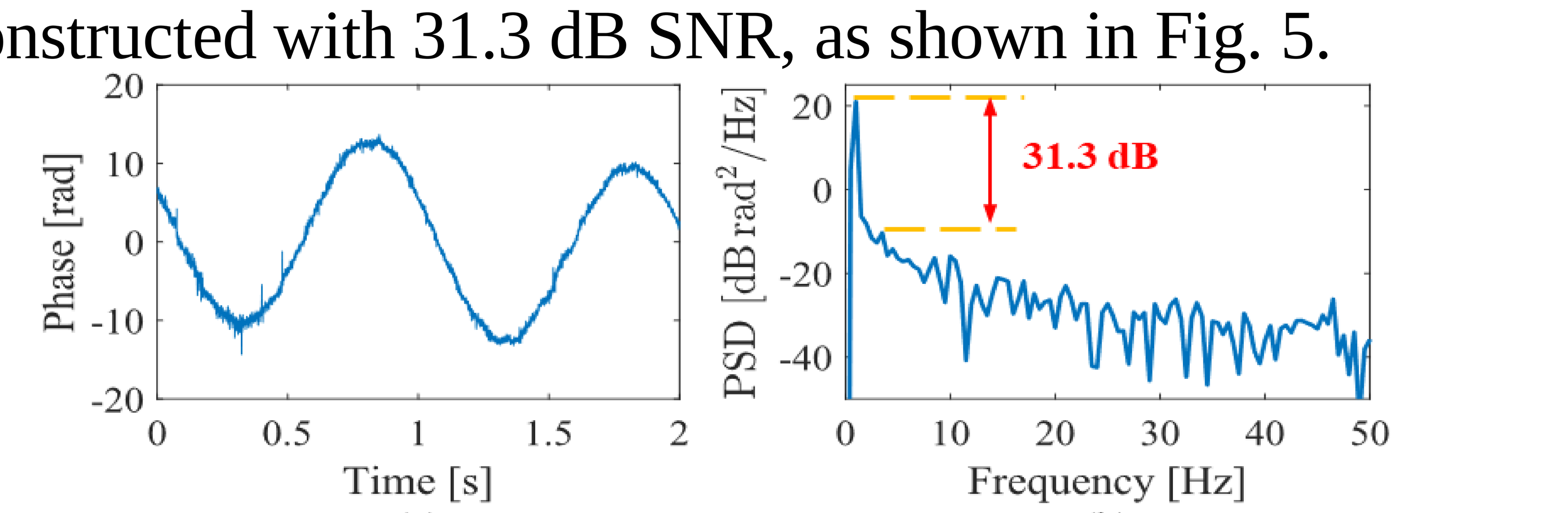

Fig. 5. (a) Differential phase waveform of a 1 Hz vibration; (b) The corresponding power spectrum density.

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