

Supplemental Information

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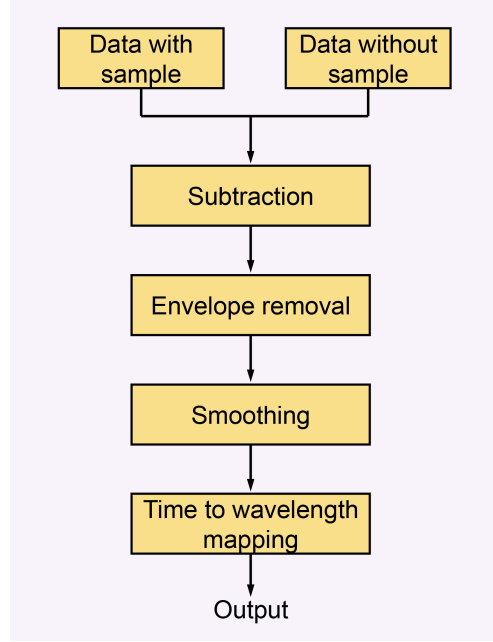
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1 Digital signal processing

A key consideration in our system is the presence of various noise sources, which include intensity noise from the mode-locked laser, shot noise from the photodetector, quantization noise from the analog-to-digital converter (ADC), and amplified spontaneous emission (ASE) noise from the amplifier. Among these, ASE noise is the dominant contributor to the overall noise floor. The accumulation of noise and the broadening of the optical pulse envelope after passing through the amplifier loop multiple times (N turns) can severely degrade the signal quality. Therefore, it is crucial to mitigate these effects in order to recover the original absorption spectra accurately. To address this challenge, we employ advanced digital signal processing (DSP) techniques to reconstruct spectral information from data that suffers from a low signal-to-noise ratio (SNR) (see Fig. 3a, right column; Fig. 3c in the main text). As depicted in Supplementary Figure 1, the processing algorithm follows a systematic, multi-step procedure to enhance signal fidelity: (1) Initially, we acquire waveforms both with and without the sample, and subtract the two in order to eliminate the coarse envelope and common-mode noise; (2) Any residual envelope artifacts are further refined and removed, followed by smoothing to suppress high-frequency noise; (3) Finally, the time axis is mapped to wavelength using dispersion relations. Notably, if analog differential detection is employed, both ASE noise [1] and the optical envelope [2] can be suppressed before digitization. Thus, the effective number of bits (ENOB) of the ADC

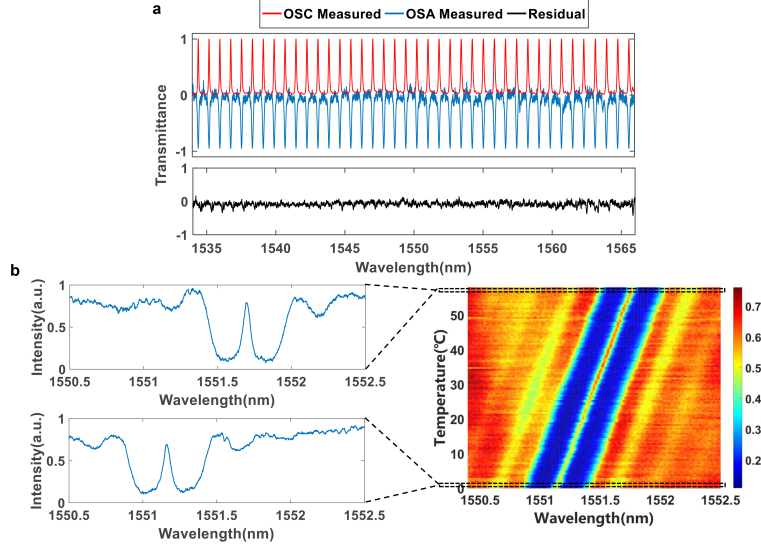
can be fully utilized, leading to a significant improvement in the overall sensitivity of the system.



Supplementary Figure 1. Flow diagram for signal processing in digital domain.

2 Results of temperature sensing

To enhance wavelength calibration accuracy, we retrieve the real-time spectra of a flat-top comb filter by averaging 180 time-stretch waveforms. The resulting spectrum is plotted as the red line in Supplementary Figure 2(a). For comparison, conventional frequency-domain measurements are recorded using an industrial optical spectrum analyzer (OSA) (Advantest Q8384) with a resolution of 10 pm. The error between the two spectra is calculated and shown as the black line in Supplementary Figure 2(a). As demonstrated, the spectrum measured by our method is in excellent agreement with the reference spectrum, validating the accuracy of our calibration. To highlight the practical utility of this technique for long time measurements, we use a temperature-sensitive PS-FBG. A large tunable-range temperature control stage is employed to introduce dynamic temperature variations in 10 minutes. The corresponding transmission spectrum is displayed in Supplementary Figure 2(b). Temperature changes induce thermal expansion or contraction of the fiber, which alters the period of the PS-FBG and consequently shifts the wavelength of the reflected light. By tracking the center wavelength of the PS-FBG, we can effectively monitor the effects of temperature variations. As shown in Supplementary Figure 2(b), the center wavelength shifts to longer values as the temperature increases, following a linear relationship.



Supplementary Figure 2. (a) Wavelength precision evaluation. Comparison of normalized spectra obtained using the proposed reconfigurable spectroscopy (red line) and an OSA (blue line). The comb filter, with a dispersion of -25.49 ns/nm and a refresh rate of 152 kHz, was used as the sample. The black line at the bottom represents the residual difference between the two spectra. (b) Single-shot measurement spectra of a PS-FBG with a bandwidth of 50 pm, as a function of environmental temperature (right). Detailed spectra at temperatures of 0°C and 60°C are shown on the left, captured over a 10-minute interval.

Specifically, the reflected wavelength moves from 1551.16 nm to 1551.70 nm as the temperature rises from 0°C to 60°C . This indicates that the center wavelength shifts by 9 pm per degree Celsius. Notably, these measurements are captured in real-time with an acquisition speed of 152 kHz, demonstrating the technique's high temporal resolution in long term measurements.

References

- [1] Campbell, J.C., Sun, W., Lu, Z., Itzler, M.A., Jiang, X.: Common-mode cancellation in sinusoidal gating with balanced ingaas/inp single photon avalanche diodes. *IEEE Journal of Quantum Electronics* **48**(12), 1505–1511 (2012)
- [2] Ordouie, E., Jiang, T., Zhou, T., A. Juneghani, F., Eshaghi, M., G. Vazimali, M., Fathpour, S., Jalali, B.: Differential phase-diversity electrooptic modulator for cancellation of fiber dispersion and laser noise. *Nature communications* **14**(1), 6065 (2023)