# Affordable High-Frequency Interrogation of Optical Fiber Speckle Sensors with Event-Based Cameras

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## Motivation

Speckle-based optical fiber sensors offer exceptional sensitivity to external perturbations, making them valuable for dynamic sensing. However, traditional camera-based interrogation methods suffer from limited frame rates and dynamic range, particularly at high frequencies. Event-Based Vision Sensors (EVS) represent a novel alternative, capable of detecting rapid intensity changes with microsecond resolution and low latency. This work explores the use of EVS to interrogate multimode fiber speckle patterns modulated by acoustic vibrations, enabling affordable and high-speed sensing beyond the capabilities of conventional imaging systems.

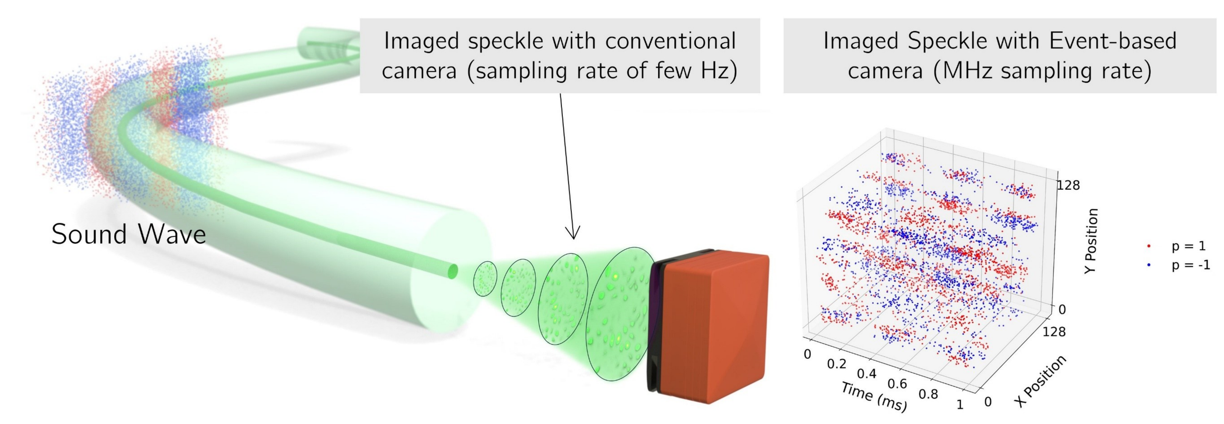



Figure 1. Schematic representation a comparison between speckle-based sensor interrogation using conventional cameras (left) or using event-based cameras (right). Perturbations induced on the fiber translate into speckle changes that can be imaged by a standard camera or by an event-based camera. An event-based camera is used for interrogation, with asynchronous event detection enabling faster interrogation than conventional CMOS or CCD sensors.

## Theoretical considerations

Considering sufficiently small perturbations $\delta_i$ at N positions denoted $x_i$, the intensity pattern $\boldsymbol{I}$ can be computed as

$$\boldsymbol{I}(\delta_1, \dots, \delta_N) \approx \boldsymbol{I_0} + \sum_{i=1}^{N} (\partial_{\delta_i} \boldsymbol{I}) \delta_i + O(\delta_i^2, \delta_i \delta_j)$$

And the deformations at each point can be determined by

$$\begin{bmatrix} \delta_1 \\ \vdots \\ \delta_N \end{bmatrix} \approx [\boldsymbol{I}(\delta_1, \dots, \delta_N) - \boldsymbol{I_0}] \cdot \frac{(\partial_\delta I)^+}{\|(\partial_\delta \boldsymbol{I})^+\|^2}, \text{with } \partial_\delta I \equiv \begin{bmatrix} \partial_{\delta_1} I \\ \vdots \\ \partial_{\delta_N} I \end{bmatrix}$$

The optimal interrogation mode, $\partial_\delta \boldsymbol{I}$, can be determined using a data-driven approach optimizing a feature-wise linear layer model with a loss-function

$$\mathcal{L} = \sum_{i=1}^{N} \frac{\sigma_i^2(\emptyset) + \beta}{\sigma_i^2(\Delta)}$$

Variance of the reconstructed signal with no stimulus

Regularization term to control uniformity of tensor weights

Variance of the reconstructed signal with stimulus

## Experimental implementation

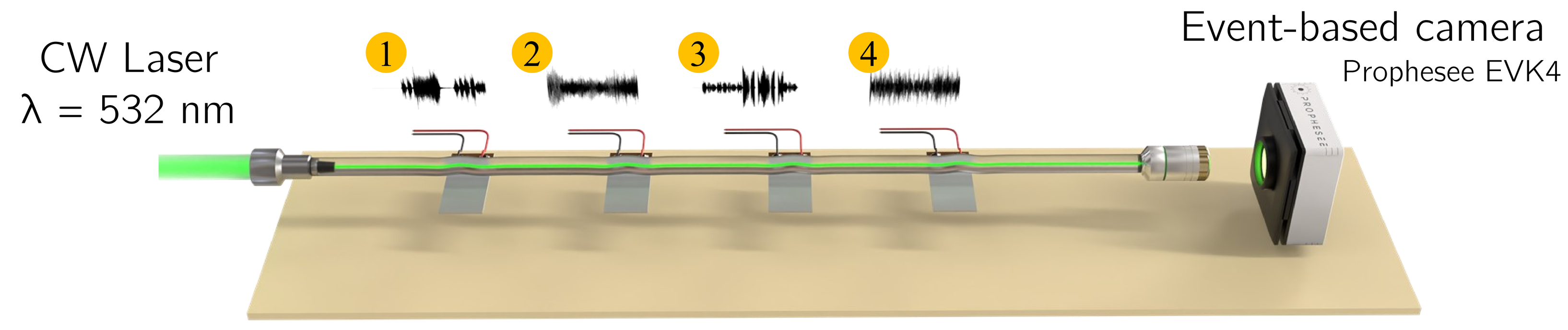
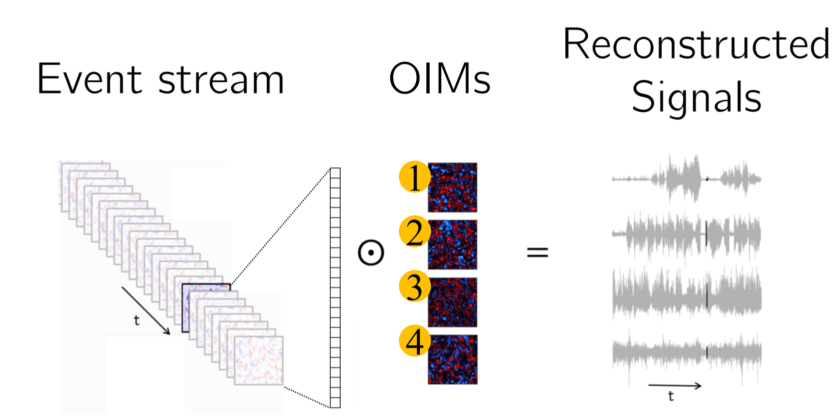


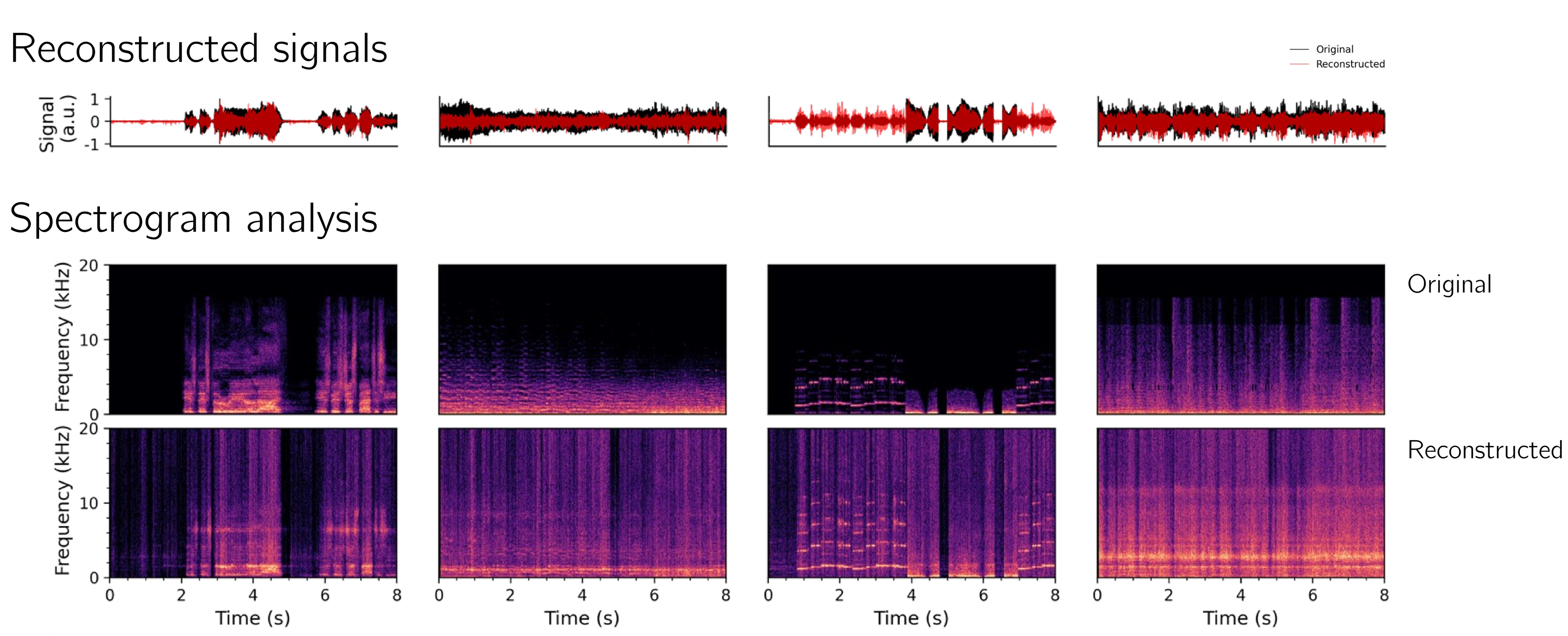

Figure 2. Schematic representation of the sensing setup composed of a 532nm laser coupled into a multimode optical fiber (OM1, 62.5 µm core), with a fiber section (~2 cm) in direct contact with the piezoelectric actuators. The speckle output is imaged by an event-based camera (Prophesee EVK4).

The optimal interrogation modes were determined by applying known perturbations at each point separately using a PyTorch-based model to isolate and reconstruct the deformation signals.




## Multipoint acoustic sensing

For a proof-of-concept, 4 different perturbations were simultaneously applied at each piezoelectric actuator, and speckle variation was recorded with the event-based camera.




Spectral Coherence Index

| Original Signal \ Reconstructed Signal | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 0.29 | 0.01 | 0.01 | 0.00 |
| 2 | 0.01 | 0.43 | 0.02 | 0.00 |
| 3 | 0.02 | 0.07 | 0.32 | 0.00 |
| 4 | 0.01 | 0.01 | 0.00 | 0.31 |

Audio Reconstructions

The results demonstrate strong signal separability and reconstruction fidelity. Spectral coherence index confusion matrix was used for quantification of reconstruction fidelity and crosstalk between interrogation modes.

Figure 4. (top) Reconstructed signals corresponding to each OIM and its comparison to the input signal; (bottom) Spectrograms of each signal and its comparison to the original signal, it can be observed that each reconstructed signal preserves the distinct spectral and temporal signatures of its input; (right) spectral coherence index confusion matrix as a metric for the spectral similarity between the original and reconstructed signals, and crosstalk between OIMs.

## Concluding Remarks

The results show an unexplored potential of EVS for high-speed optical fiber sensing, particularly in scenarios requiring rapid interrogation of complex intensity patterns such as acoustic vibrations. This proof-of-concept lays the foundation for future applications in optical metrology, structural health monitoring, and dynamic sensing, providing a compact, low-cost, and high-speed alternative to conventional detection methods.

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