

High-speed nanometer-resolved imaging vibrometry and velocimetry

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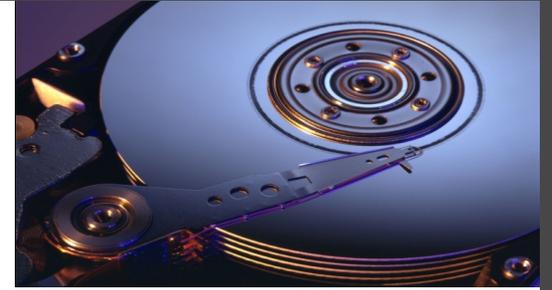
Jalali Lab at UCLA

PDV Workshop

November 3-4,2011 Livermore

www.photonics.ucla.edu

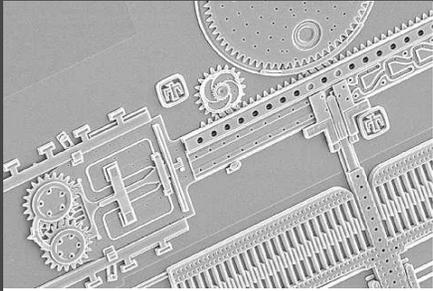
Applications of vibrometry & velocimetry



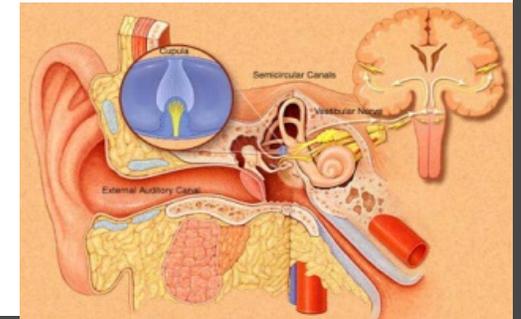
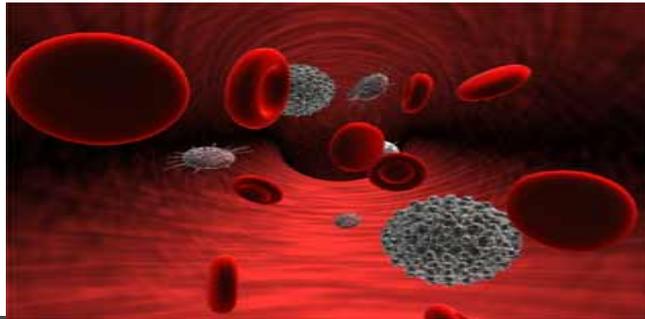
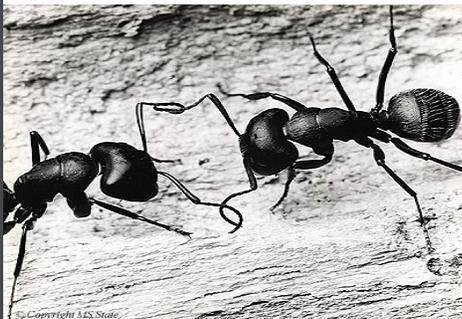
- Industrial applications
 - Inspection of aircraft components
 - Diagnosis of automotive structural dynamics and brake performance
 - Hard disk drive diagnostics
 - Performance of musical instruments and loud speakers
- Military applications
 - Detection of buried landmines



Applications of vibrometry & velocimetry

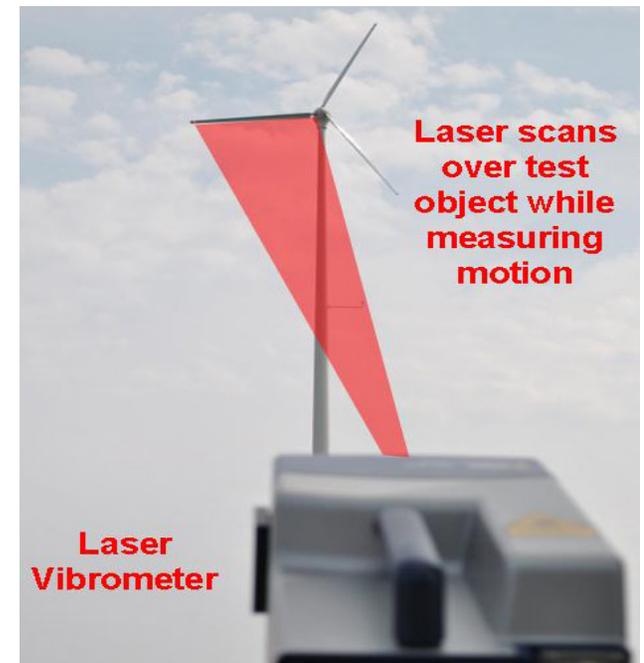


- Scientific applications
 - Inspection of microelectromechanical (MEMS) devices
 - Monitoring of fluid dynamics in aerospace and naval applications
 - Insect communication
- Biomedical applications
 - Non-invasive quantification of blood flow
 - Eardrum diagnostics



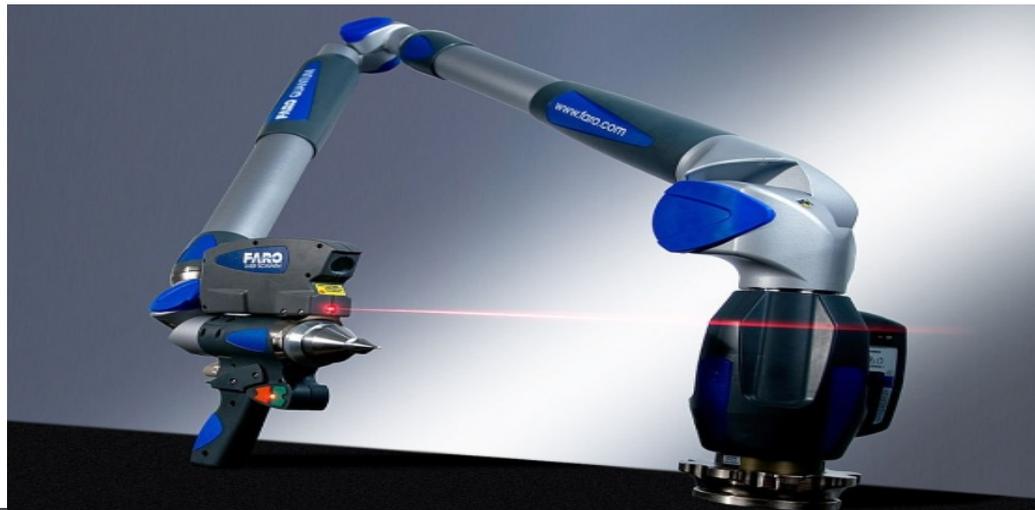
Limitations of conventional laser vibrometers

- Conventional laser vibrometers are unable to perform *imaging-based vibrometry* at high speeds because their operation builds on single-point measurements and relies on **beam scanning** for multi-dimensional laser vibrometry.



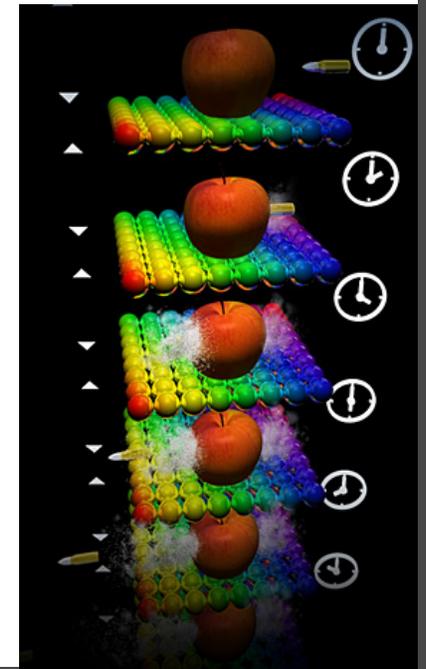
Limitations of conventional laser vibrometers

- Currently, the maximum scan rates provided by conventional laser vibrometers (e.g., galvanometric mirror scanners and acousto-optic deflectors) are **~100 kHz in 1D** (line scans) and **~1 kHz in 2D** (raster or spiral scans).
- We demonstrate a laser vibrometer that achieves imaging-based surface vibration measurements with nanometer-scale axial resolution at **~100 times higher scan rates** than the conventional methods.



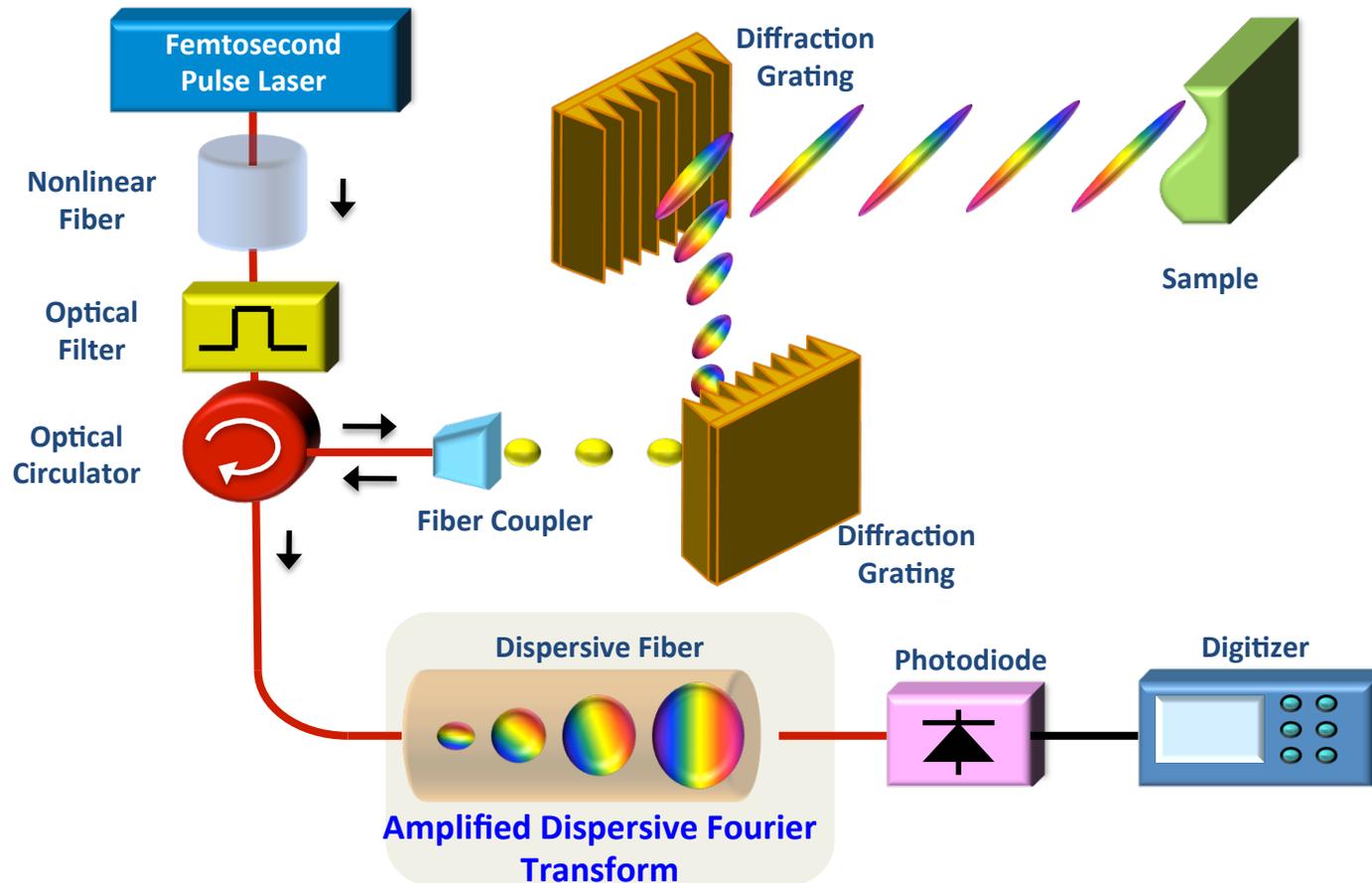
Serial time-encoded amplified imaging/microscopy (STEAM)

- Developed by Photonics lab at UCLA
- Known as **the world's fastest camera**
- Equipped with the first built-in optical image amplifier that overcomes the trade-off between sensitivity and speed (at high frame rates, fewer photons are detected, resulting in reduced sensitivity)
- STEAM offers:
 - Frame rate: **~10s of million frames/second**
 - Shutter speed: **~10s of picoseconds**
 - Optical image gain: **~30 dB (~1000 times)**
- Based on **spectrally encoded imaging** and **Amplified Dispersive Fourier Transform (ADFT)**



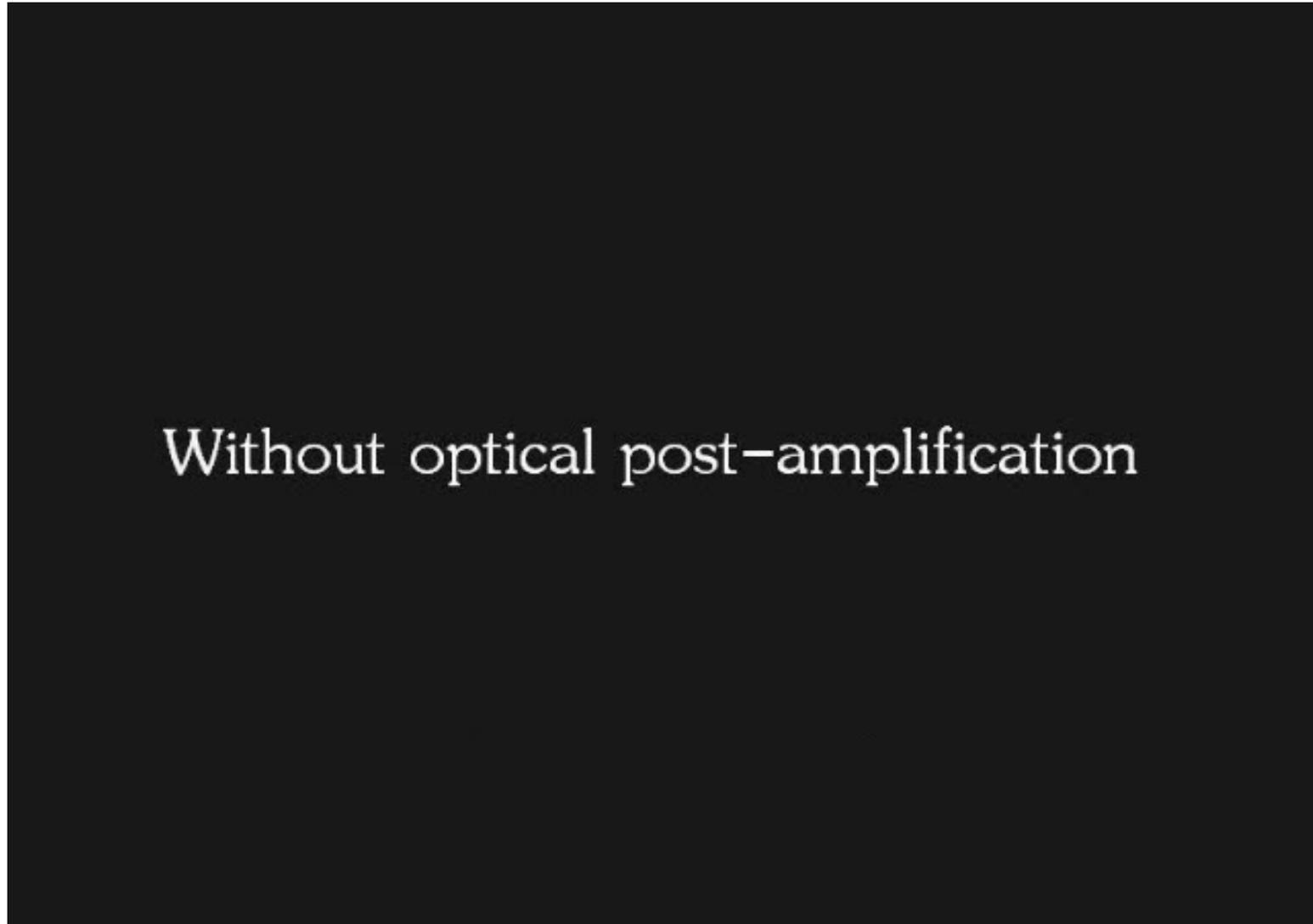
[1] K. Goda, K. K. Tsia, and B. Jalali, "[Serial time-encoded amplified imaging for real-time observation of fast dynamic phenomena.](#)" *Nature* 458, 1145 (2009)

Schematic of STEAM

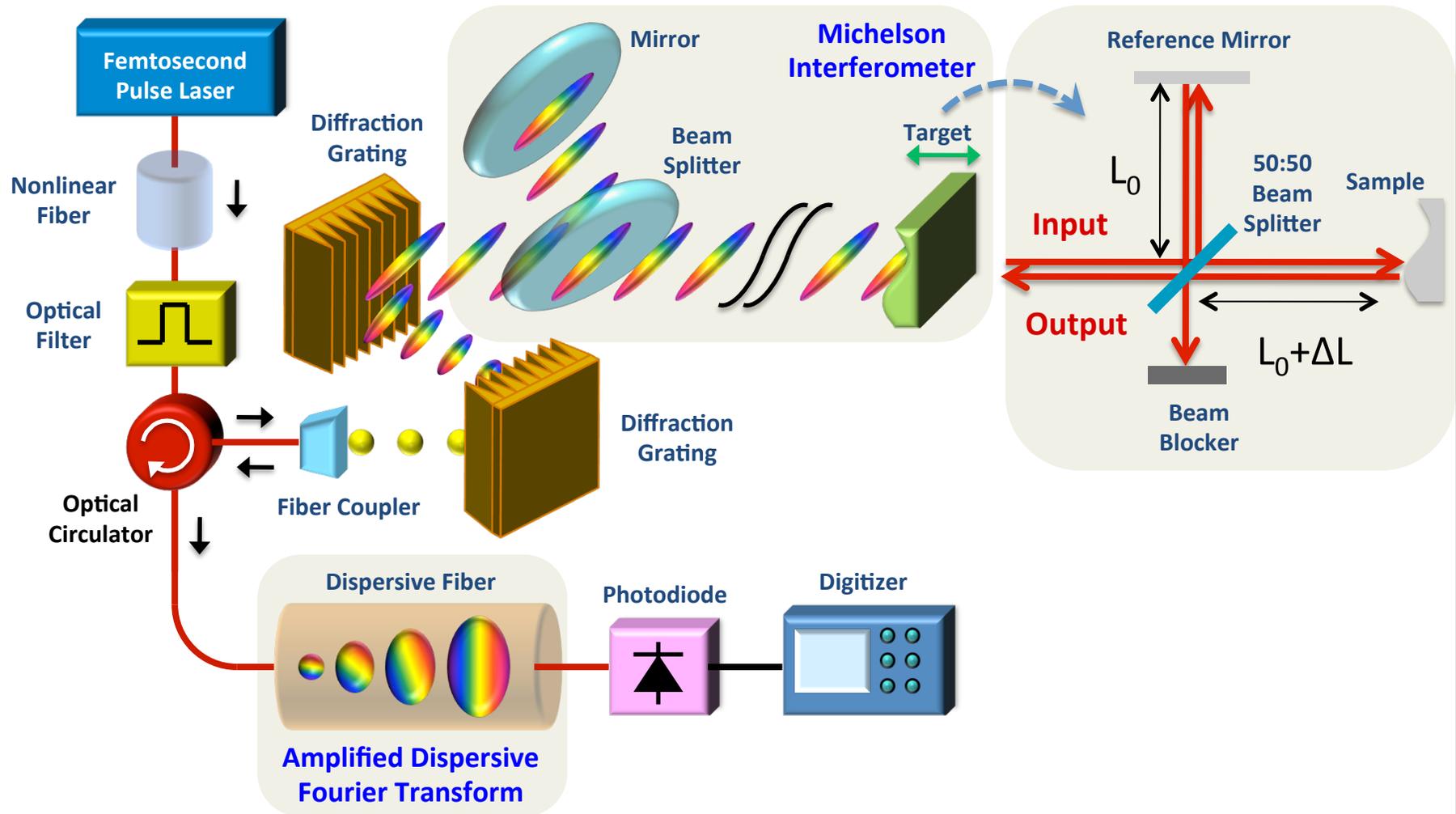


- Frame rate = pulse repetition rate
- No need for mechanical scanning
- Single photodiode; no need for a CCD/CMOS camera

Video of STEAM operation principle



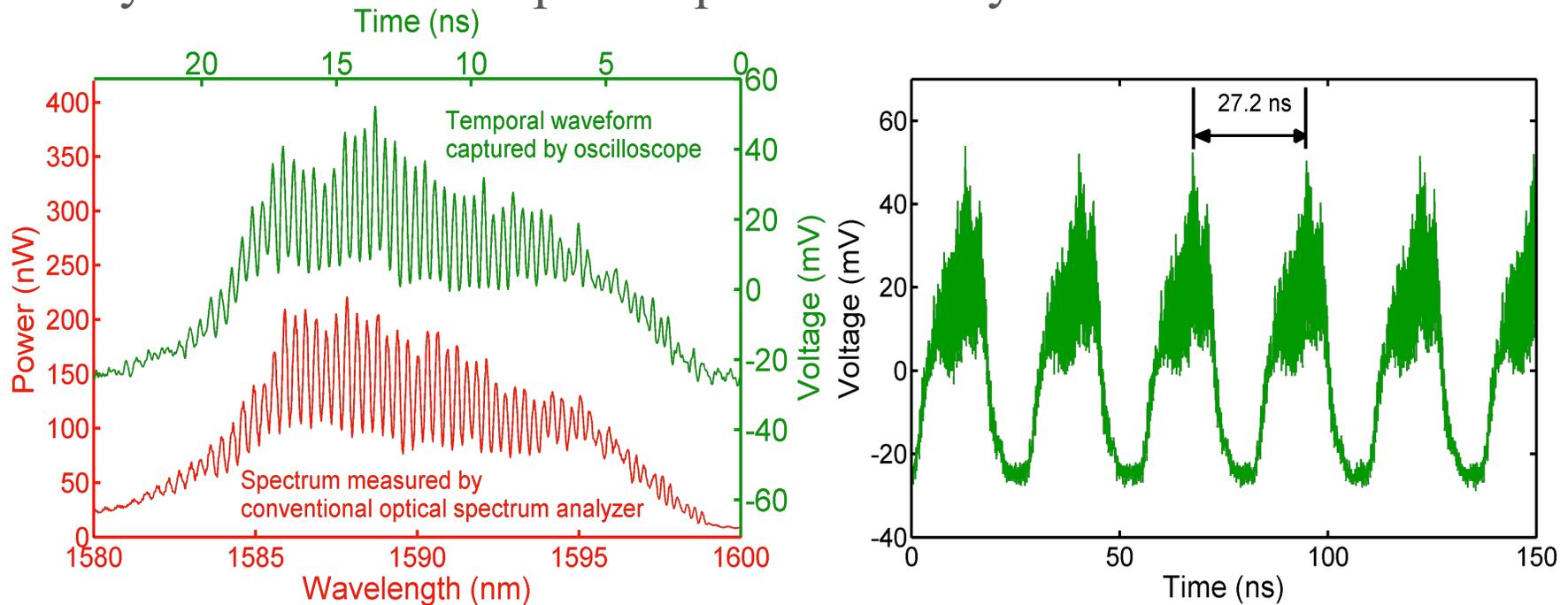
STEAM vibrometer & velocimeter



[2] Ata Mahjoubfar, et al, "[High-Speed Nanometer-Resolved Imaging Vibrometry & Velocimetry](#)," *Applied Physics Letters*, Vol. 98, Iss. 10 (2011)

Signal processing

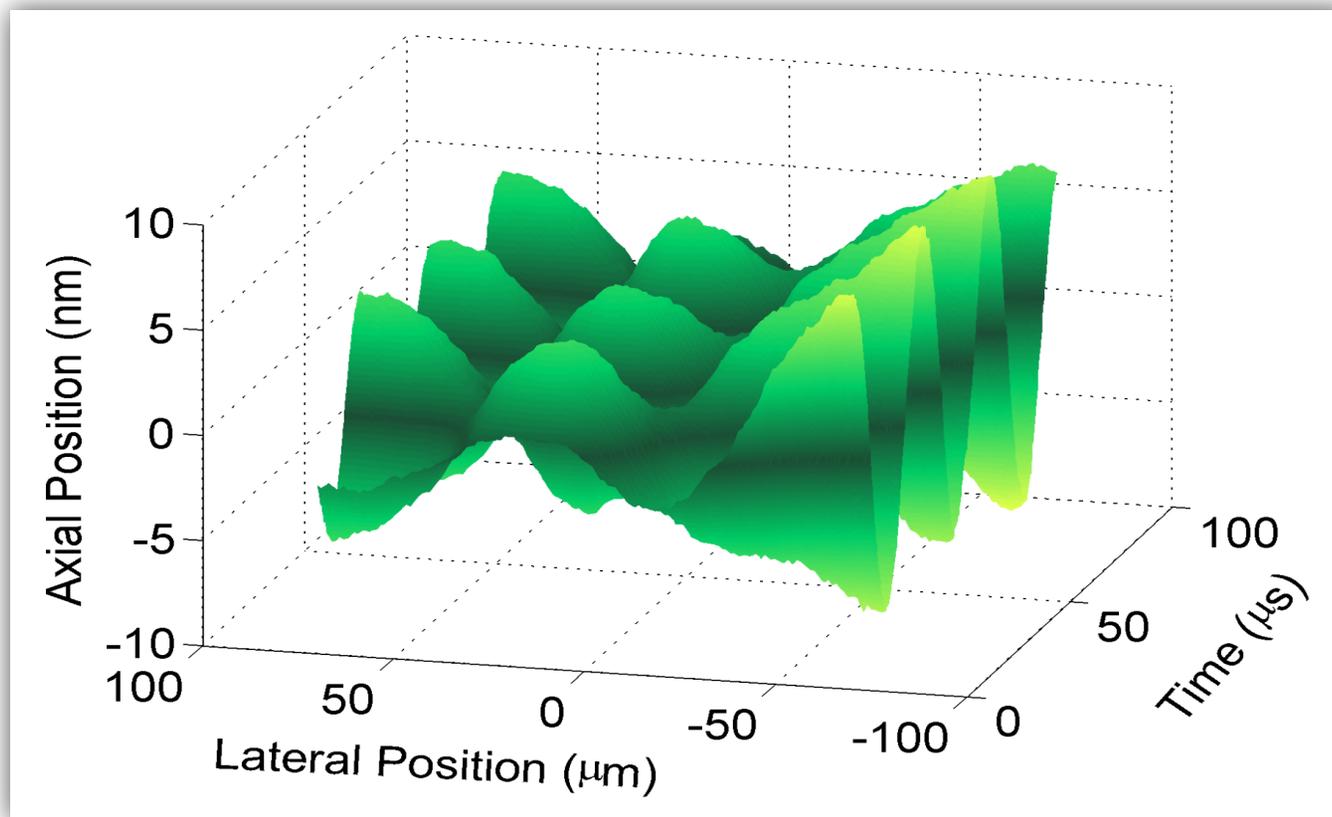
- The temporal waveform of a single interfered pulse captured by the photodiode is very similar to the optical spectrum measured by a conventional optical spectrum analyzer.



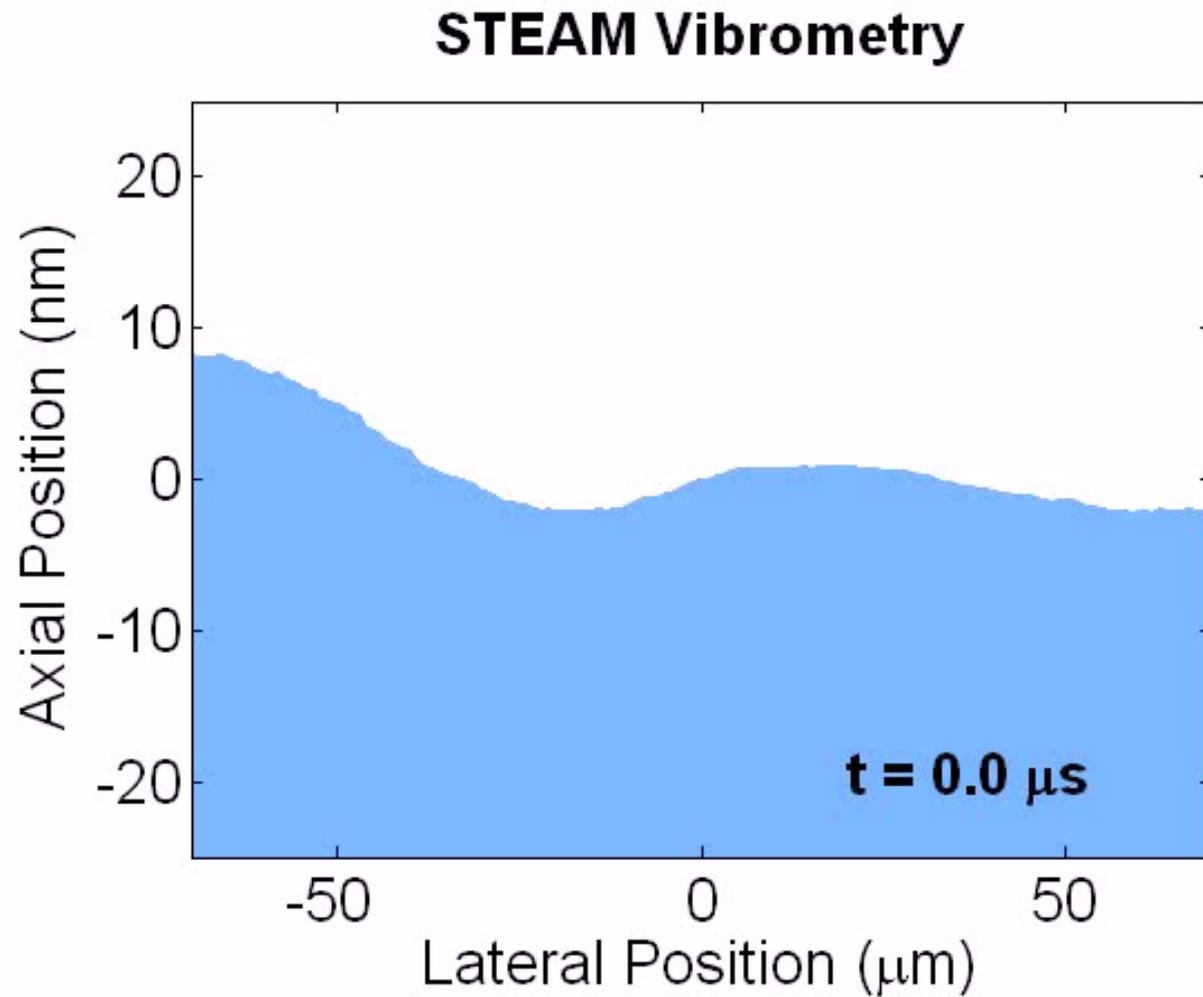
- Hilbert transformation is applied in the digital domain to each spectrally interfered pulse to obtain the axial information of the target at multiple points along the 1D line.

Experimental results of STEAM vibrometry

- Surface vibration for a 30 kHz acoustic wave with ~ 1 nm axial resolution, ~ 170 resolvable points, and 30 ps dwell time (no blurring) at 36.7 MHz scan rate (freezes the motion).

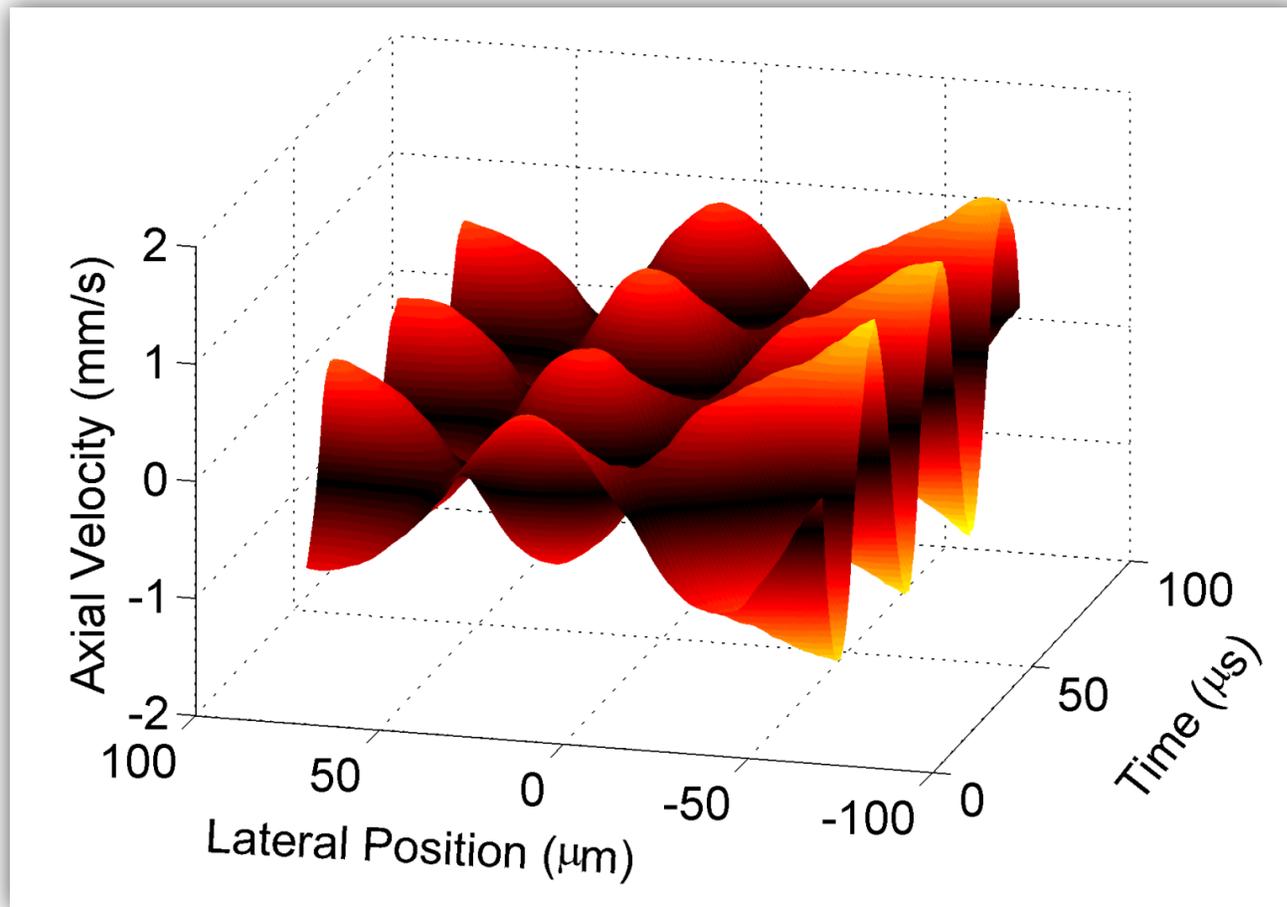


Video of STEAM vibrometry

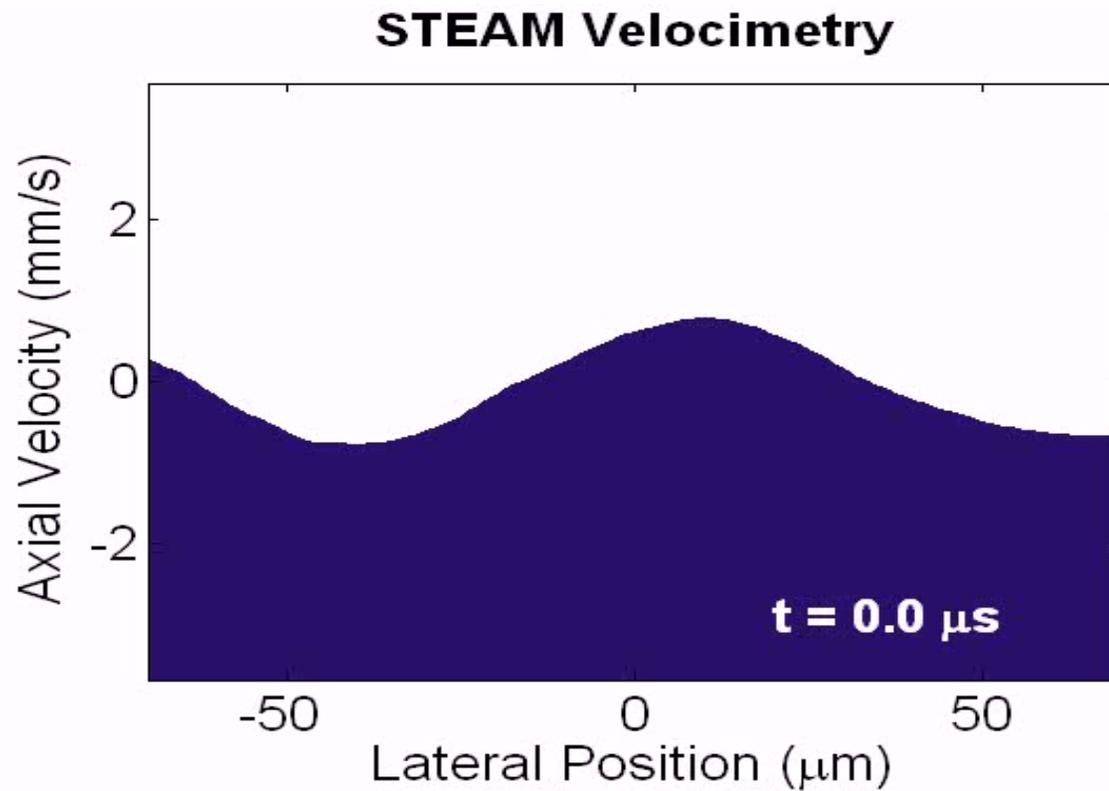


Experimental results of STEAM velocimetry

- The superior temporal resolution of this method enables multi-dimensional velocimetry as the velocity of the surface can be obtained from the axial position of the surface.



Video of STEAM velocimetry



Summary

- Serial Time-Encoded Amplified Microscopy/Imaging (STEAM) is the world's fastest imaging technique.
- We demonstrate a laser vibrometer:
 - Imaging-based
 - 1 nanometer axial resolution
 - 36.7 MHz scan rates
- Surface velocity measurement enabled by high scan rate vibrometry.
- Vibrometry and Velocimetry of 30 kHz acoustic vibration was shown.

Thanks for your attention!

Question?

STEAM vibrometry & velocimetry resolution

- The number of image pixels on the target is found from the total dispersion in the dispersive fiber ($D = -1200$ ps/nm), the optical bandwidth ($\Delta\lambda = 20$ nm) of the laser pulses, and the sampling rate of the digitizer ($f_{dig} = 50$ GS/s):

The diagram shows the equation $N_{pxl} = D\Delta\lambda f_{dig} = 1200$. Three blue boxes with arrows point to the variables: 'Dispersion' points to D , 'Bandwidth of the optical pulses' points to $\Delta\lambda$, and 'Sampling rate of the digitizer' points to f_{dig} .

$$N_{pxl} = D\Delta\lambda f_{dig} = 1200$$

- The number of resolvable points is limited by the spectral resolution of the ADFT process:

The diagram shows the equation $N_{res} = \frac{\Delta\lambda}{\lambda} \sqrt{\frac{D \cdot c}{2}} ; 170$. A blue box labeled 'Speed of light' has an arrow pointing to the c term in the square root.

$$N_{res} = \frac{\Delta\lambda}{\lambda} \sqrt{\frac{D \cdot c}{2}} ; 170$$

- The axial resolution is given by the bit depth of the digitizer ($n = 8$):

$$0.5 \sin(4\pi \cdot \Delta L / \lambda) = 2^{-n} \Rightarrow \Delta L = 0.99 \text{ nm}$$

A blue box labeled 'Bit depth of the digitizer' has an arrow pointing to the 2^{-n} term in the equation above.

Bit depth of the digitizer