

Digital Speckle Pattern Heterodyne Interferometry: Computational Focusing Compared with Optical Focusing

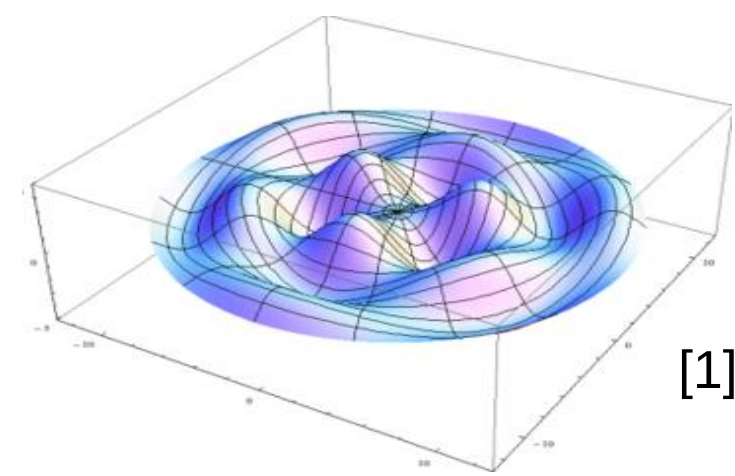
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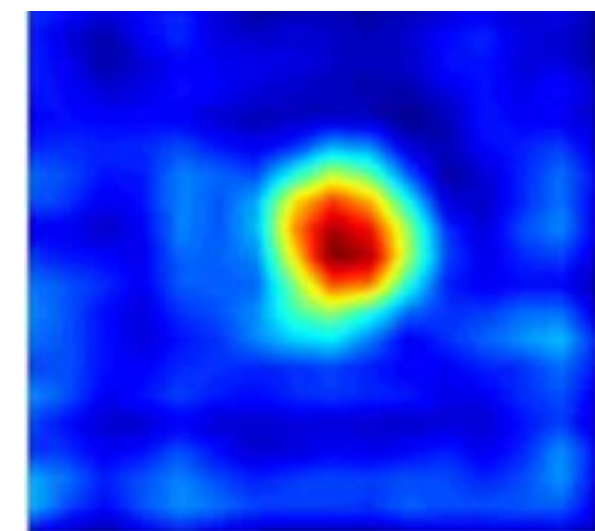
Motivation

- Many applications rely on the non-contact detection of single (multi) frequency motion (MHz) on a surface in a wide-field of view
⇒ Testing a wide array of microelectromechanical systems (MEMS)
⇒ Hidden target detection by excitation [2]

- The amplitude of vibration for many of these applications are on the order of picometers
- There is a need for scalable and cheap optical detectors for resolving the motion in a **wide-field** of view with **picometer level sensitivity**



[1]

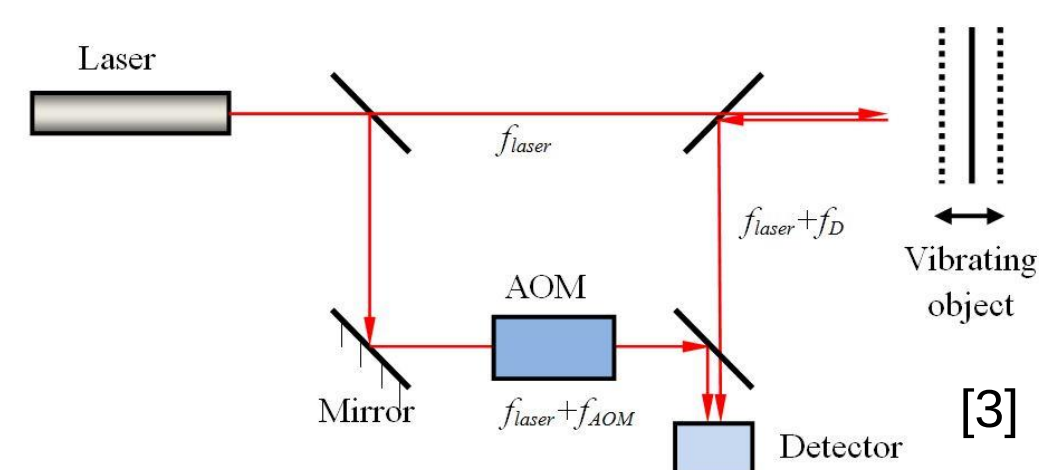


[2]

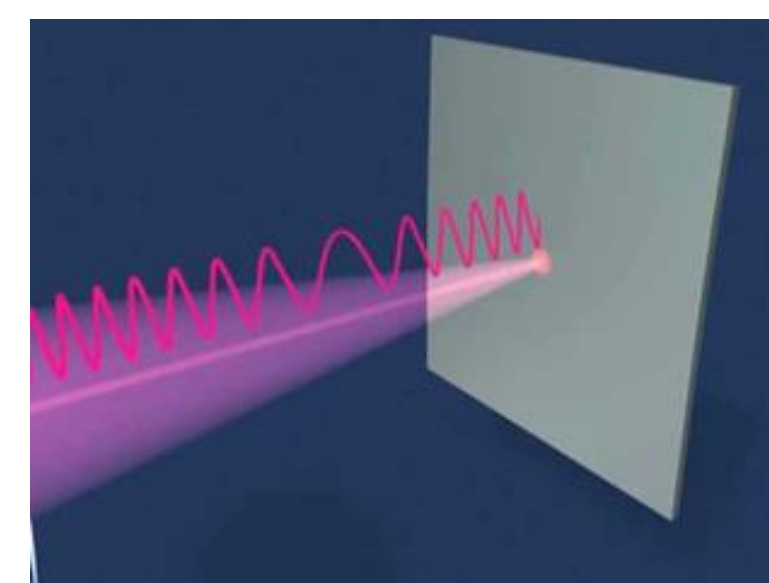
Related Work

- Standard interferometric measurement techniques rely on high temporal bandwidth photodiodes

Laser Doppler Vibrometer (LDV):



[3]



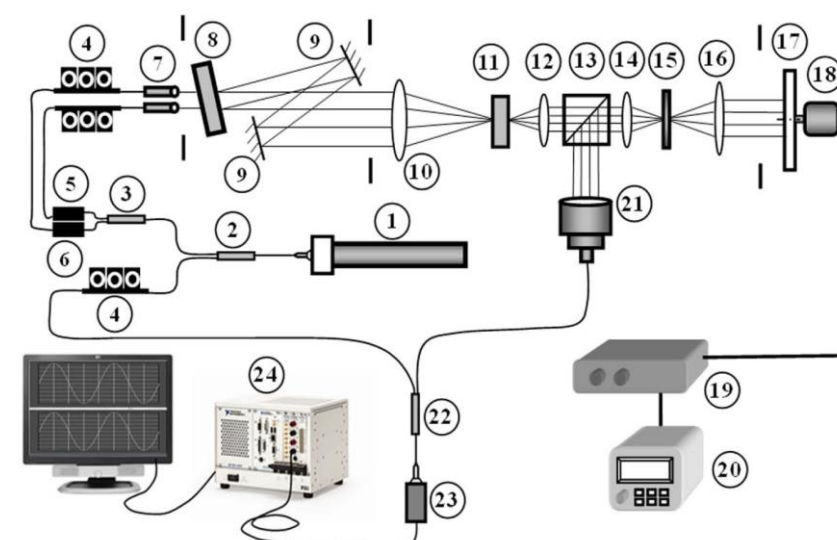
[4]

$$\varphi(t) = \frac{4\pi}{\lambda} x(t)$$

$$I_{tot} = |\sqrt{I_{ref}}e^{j\omega_L t} + \sqrt{I_{obj}}e^{j\omega_L t}e^{j\varphi(t)}|^2 = I_{ref} + I_{obj} + 2\sqrt{I_{ref}I_{obj}}\cos(\varphi(t))$$

Standard Approaches to Monitor a Wide-Field:

- LDV: Need scanning
- Spatial encoding in frequency: Bulky and complex



[5]

Heterodyne Detection with a CMOS Camera

- CMOS Camera as detector: **Scalable and Cheap!**
- Need to measure **MHz frequencies!**
- Temporal bandwidth of camera ~ Hz
- Heterodyne detection to **downconvert** to temporal bandwidth

Wide Field of View:

- Computational Focusing
- Optical Focusing with lens

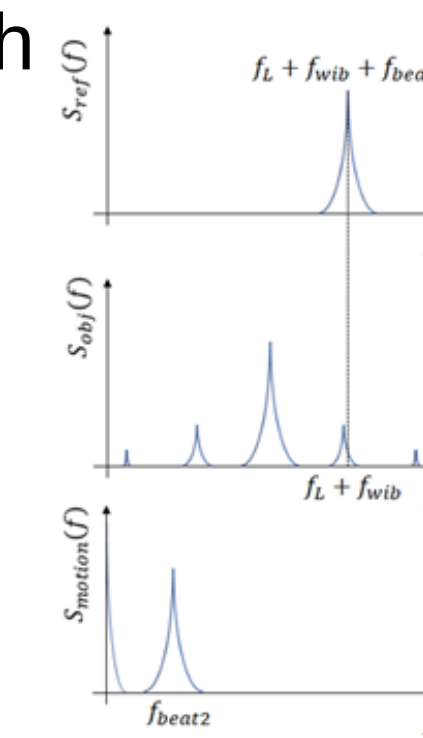
Jacobi-Anger Expansion:

$$\varphi(t) = \frac{4\pi}{\lambda} A_k \cos(\omega_{vib} t + \psi_k)$$

$$e^{jz \sin \theta} = \sum_{n=-\infty}^{\infty} J_n(z) e^{jn\theta}$$



[6]



Optical Configurations

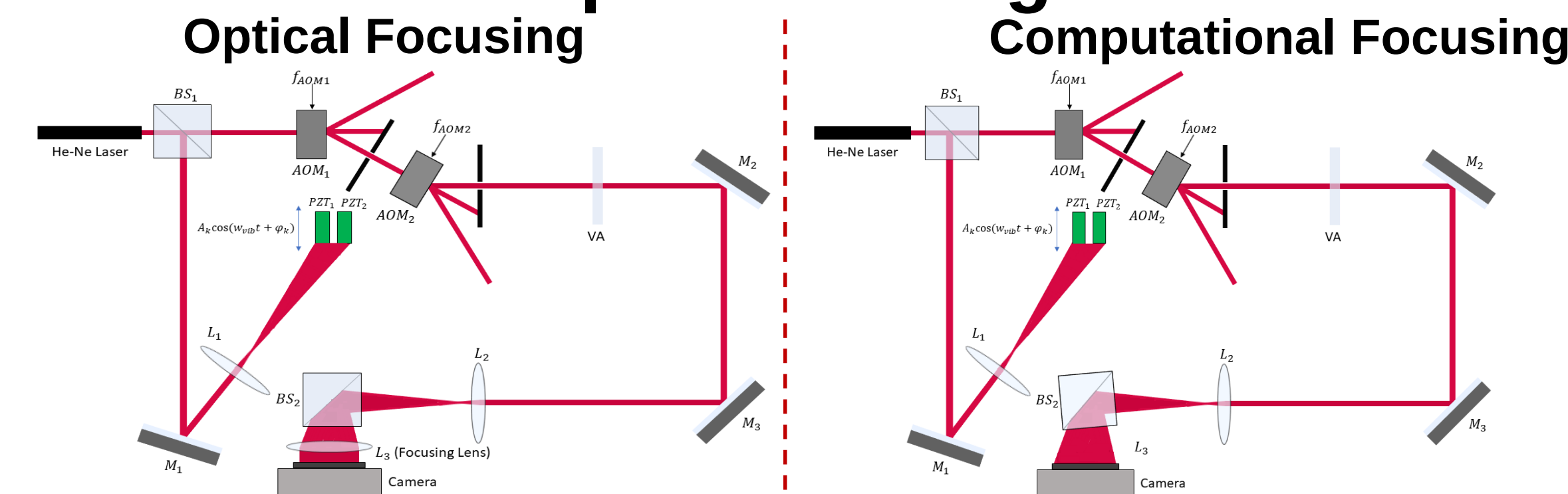


Image naturally formed by Focusing Lens L_3

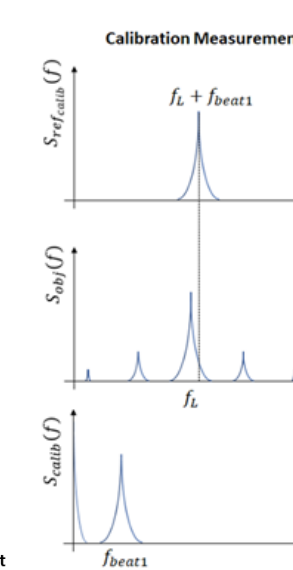
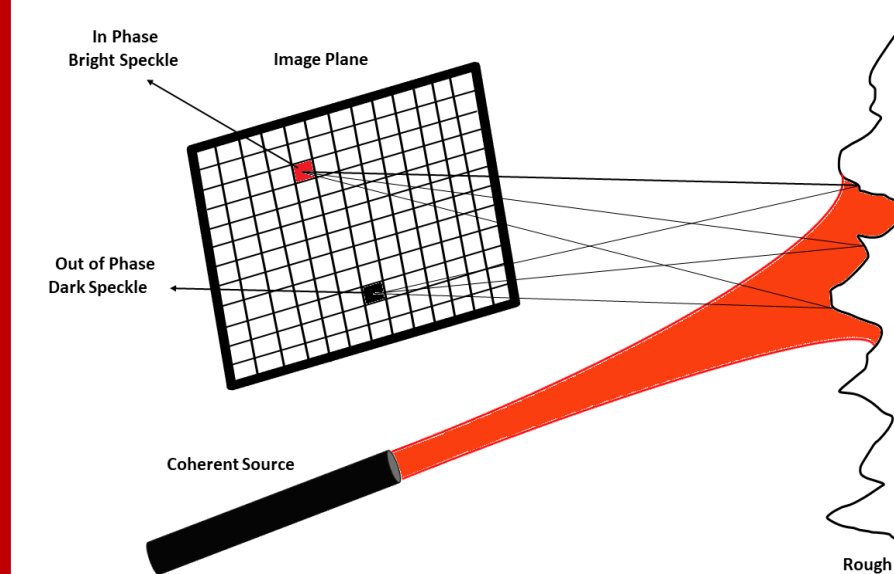
Backpropagation: Solve diffraction equation

$$F(k_x, k_y) = \mathcal{F}\{f(x, y)e^{\frac{jk}{2z}(x^2+y^2)}\}$$

Speckle Noise Removal

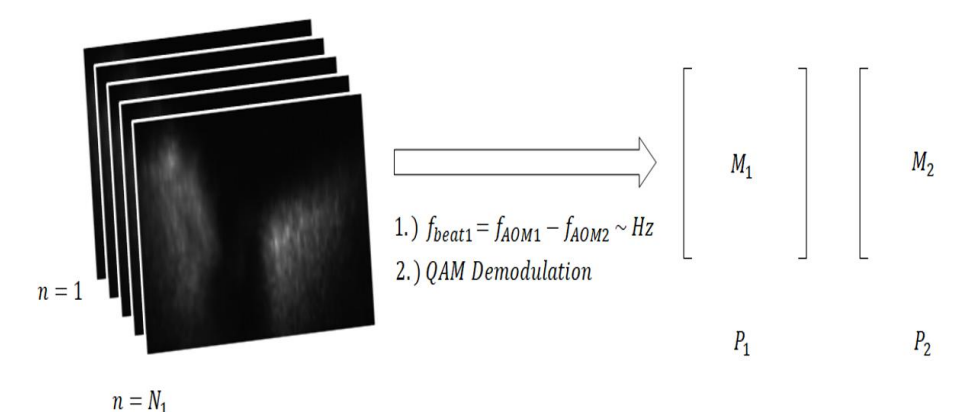
- Coherent Illumination: Speckle Noise!

$$I_{totxy} = I_{ref} + I_{objxy} + 2J_1\left(\frac{4\pi}{\lambda} A_k\right) \sqrt{I_{ref}I_{objxy}} \cos((\omega_{obj} - \Delta\omega)t + \theta_{xy} + \psi_k)$$



Speckle Amplitude

Speckle Phase

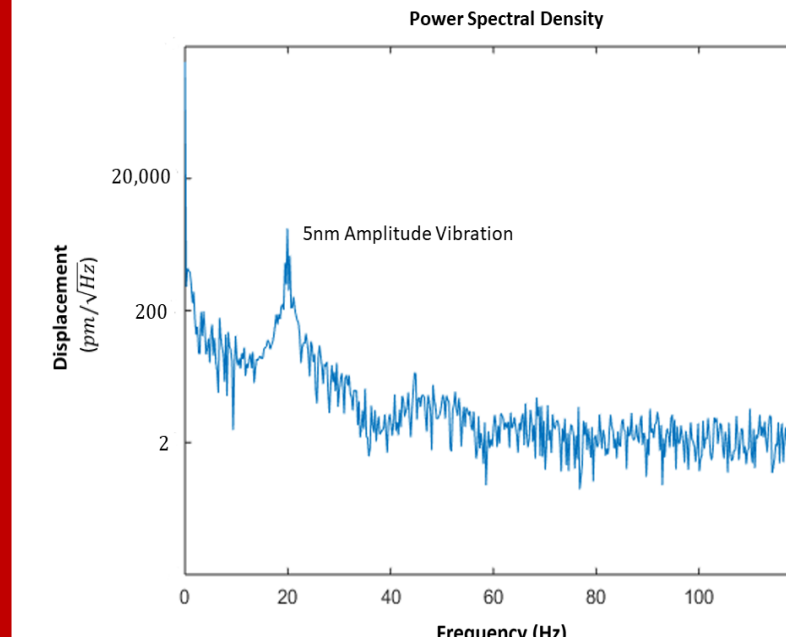
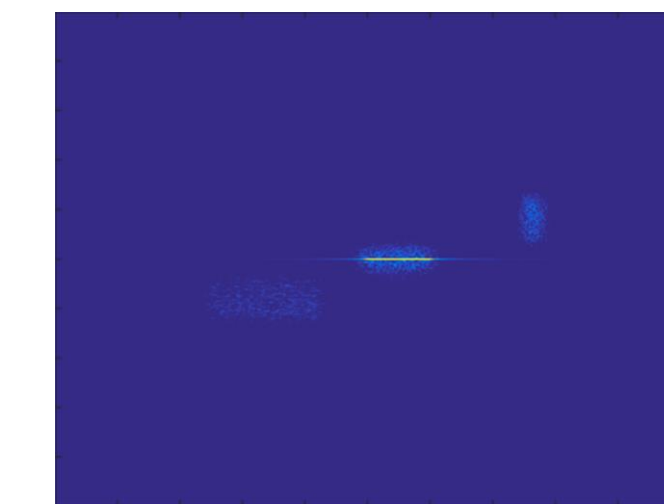


Computational vs Optical Focusing

- Equal Signal to Noise Ratio (SNR) assuming shot-noise limited measurements
- Computational Focusing**
 - Flexibility in depth of focus
 - Robustness to mechanical motion: Larger speckle autocorrelation size
- Optical Focusing**
 - Higher camera frame rate: Better frequency resolution
 - Lower computational complexity

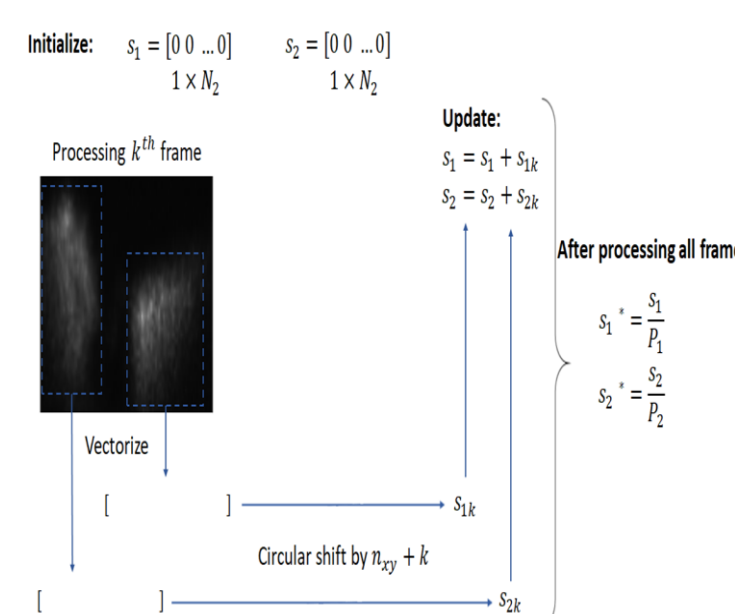
Experimental Results

Computational Reconstruction



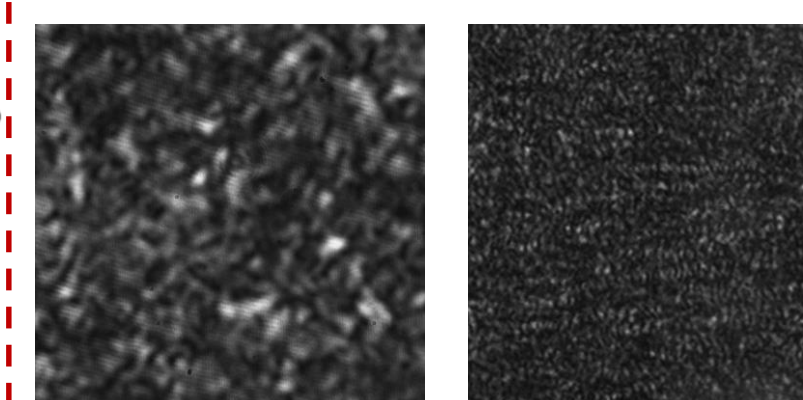
2pm/√Hz amplitude detection sensitivity!

Optical Focusing Frame Processing



Speckle Pattern

Without Lens With Lens



References

- [1] Bessel function. (2018, March 6). Retrieved from https://en.wikipedia.org/wiki/Bessel_function
- [2] Sabatier, J.M. (2001). Enhanced Equipment for Acoustic Detection of Buried Landmines
- [3] RESEARCH. From <http://holobright.com/research/>
- [4] Polytec: Introduction to 3-D Scanning Vibrometry
- [5] Fu, Y. (2011) Multipoint laser Doppler vibrometry with single detector: principles, implementations, and signal analyses. *Applied Optics*, 50(10), 1280.
- [6] Scientific CMOS Cameras. Retrieved from <https://www.photonicsonline.com/doc/scientific-cmos-cameras-pco-edge-0001>