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Digital Phase-Sensitive Holography for Numerical Shock-wave Distortion Cancellation

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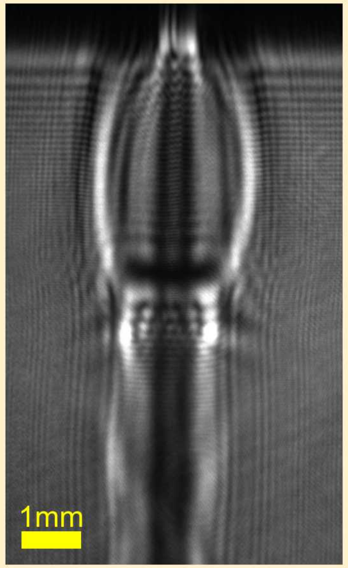
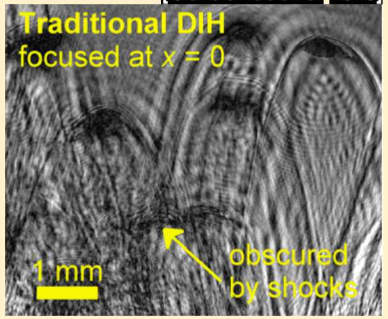
Motivation

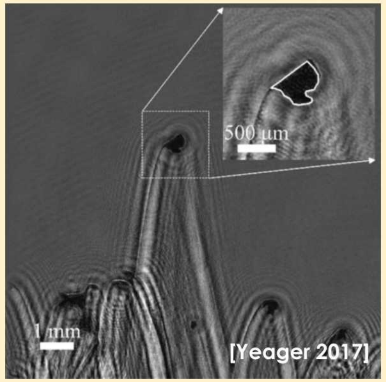
Problem Statement

- Shock-wave and density gradient distortions limit ability to accurately investigate objects in extreme environments
- Single-shot acquisition is necessary to allow for time-resolved measurements

[Guildenbecher 2018]



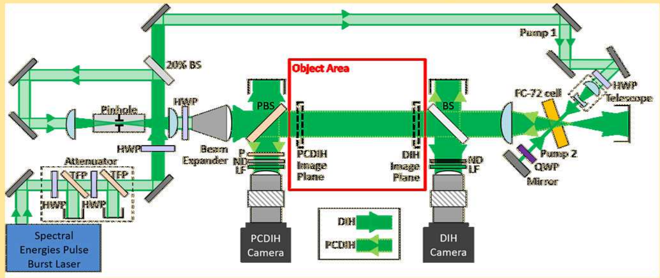


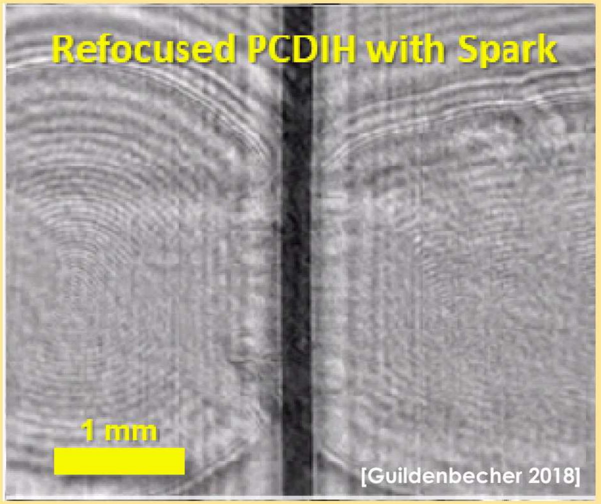


Existing Approaches

- Phase conjugate digital in-line holography (PCDIH) using phase conjugate mirrors to physically remove phase before image is taken

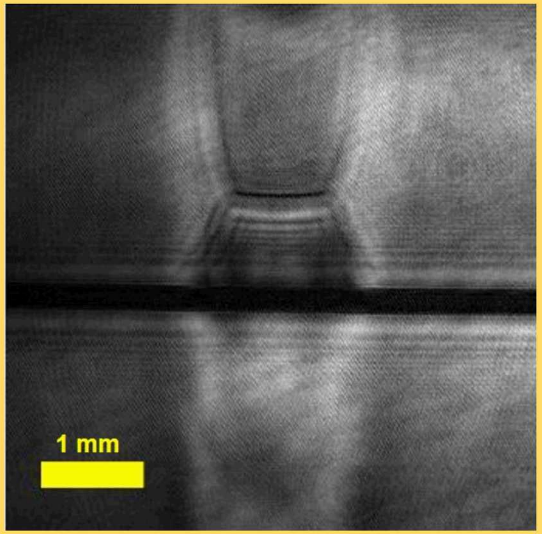
[Mazumdar 2019]





Proposed Solution

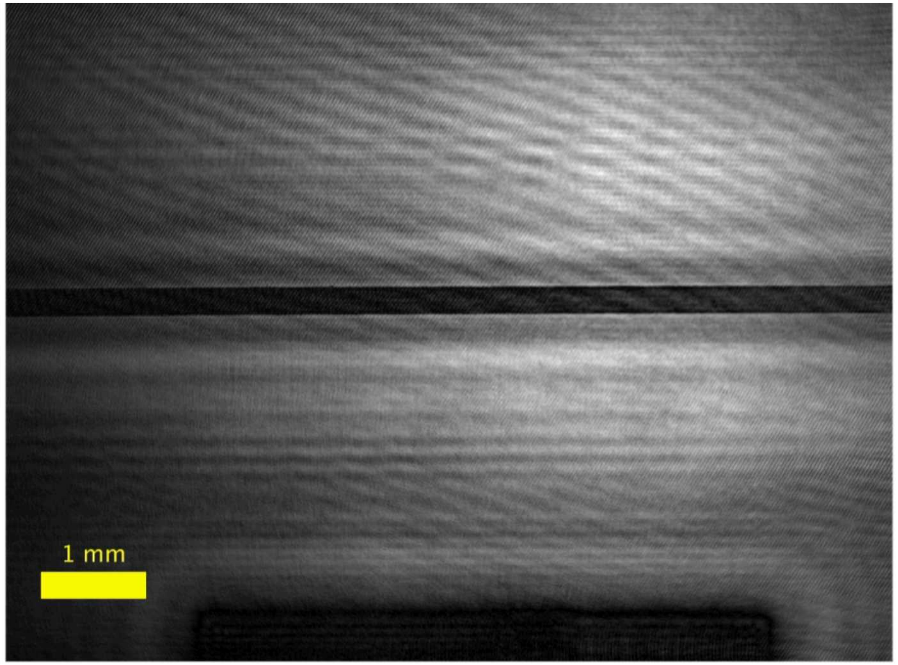
- Numerical Distortion Cancellation of digital holograms (NDC-DH)
- Use post-aquisition processing to numerically remove the phase distortions from the hologram

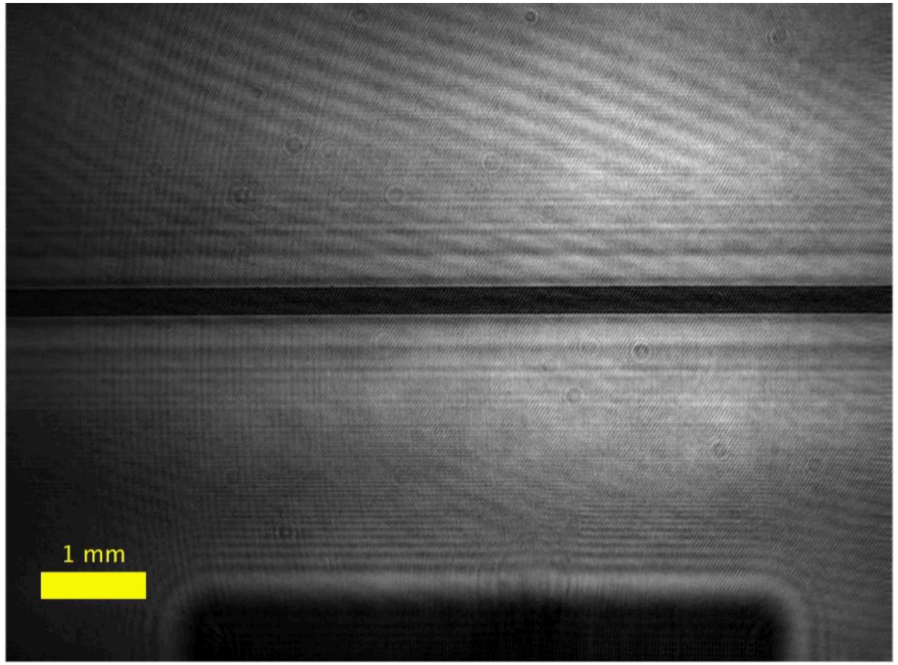


- This method allows for instantaneous capture of a hologram
- Eliminates the need for more powerful lasers and four-wave mixing

Overview

- Allow for tracking of 3D fragments through shockwave distortions in extreme supersonic, hypersonic or extreme environments
- Use a single-shot technique to numerically remove a phase distortion from a single hologram





Digital In-line Holography (DIH) Background

- Records an image's wave front rather than its projected image
- A raw hologram is collected at the imaging plane (z_h) as:

$$h(x, y) = |E_t(x, y, z_h)|^2$$

- Holograms are numerically refocused using

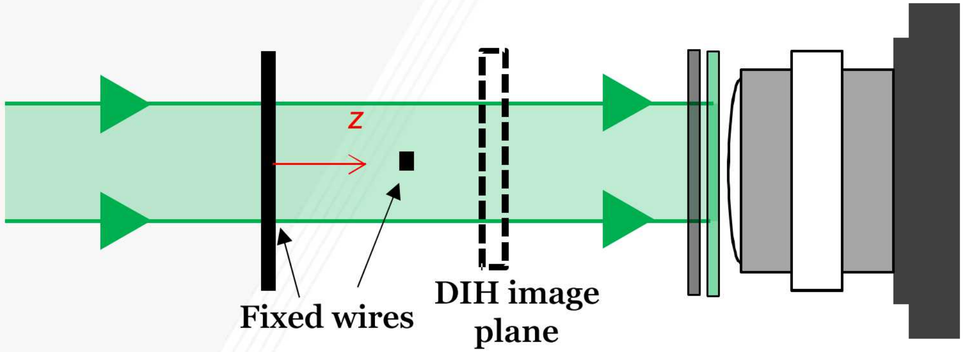
$$E_h(x, y, z) = [h(x, y)E_r^*(x, y)] \otimes g_b(x, y, z)$$

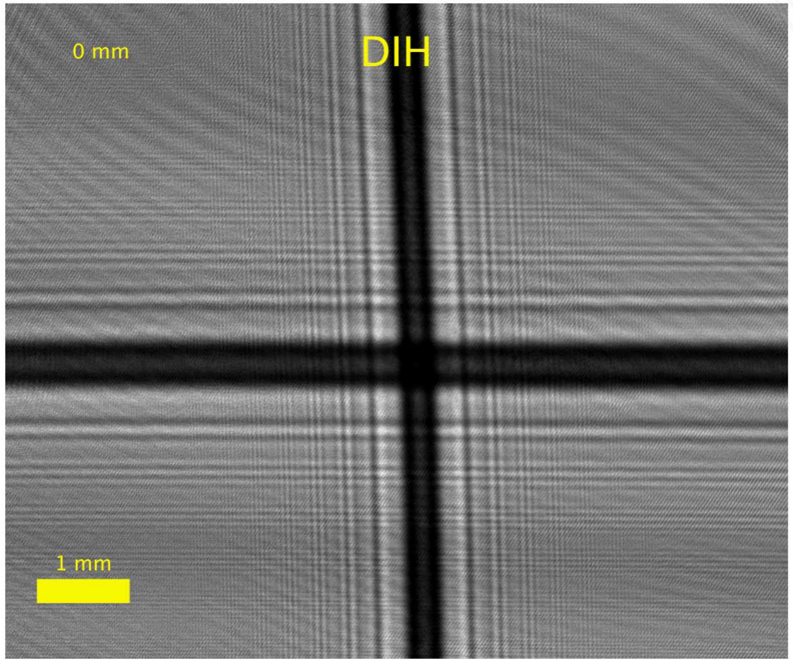
where,

$$g_b = FT^{-1}(G^*) \text{ and } G = e^{\frac{2\pi iz}{\lambda}\sqrt{1-(\lambda x)^2-(\lambda y)^2}}$$

- The amplitude is determined from

$$A_h = |E_h|$$

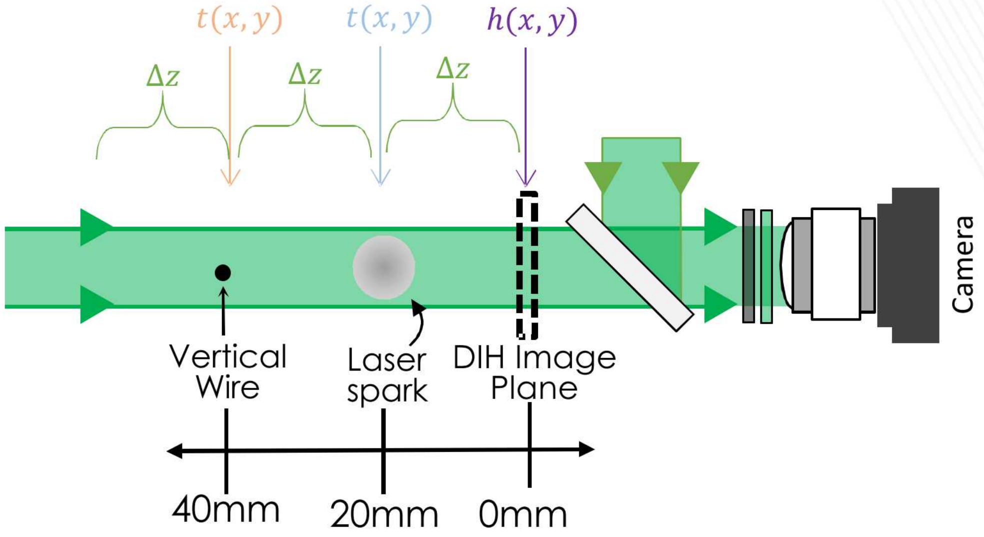


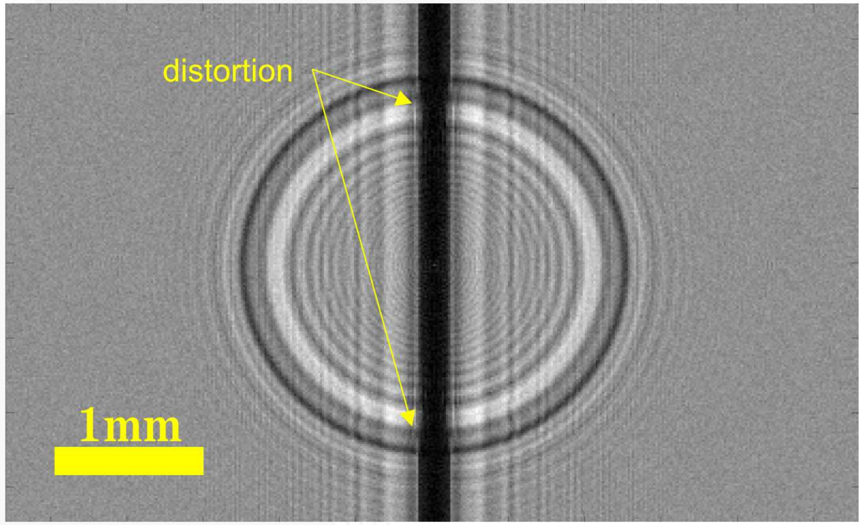


- The hologram is refocused to an object plane by finding the point with max edge sharpness and minimum amplitude
- DIH allows for 3D tracking of particles using successive frames
- Limited by the effects of phase distortions

Hologram Simulations

- Computer generated hologram simulating a DIH setup
- Allows for adjustment of parameters to test various scenarios
- Provide verification of algorithms and phase removal methods





The DIH image at the plane of the wire (*z=40mm*), the wire is seen to have distortions at the top and bottom of the shockwave.

Coherent light $E_r(x,y) = \mathrm{A_r}(\mathrm{x},\mathrm{y})\mathrm{e}^{\mathrm{ikz}-\mathrm{i}\omega t}$

Diffraction Propagation $E_t(x,y,z) = (E_r(x,y) \cdot t(x,y)) \otimes g_f(x,y,z)$,
where $ig_f = FT^{-1}(G)$ and $G = e^{\frac{2\pi i z}{\lambda}\sqrt{1-(\lambda x)^2-(\lambda y)^2}}$

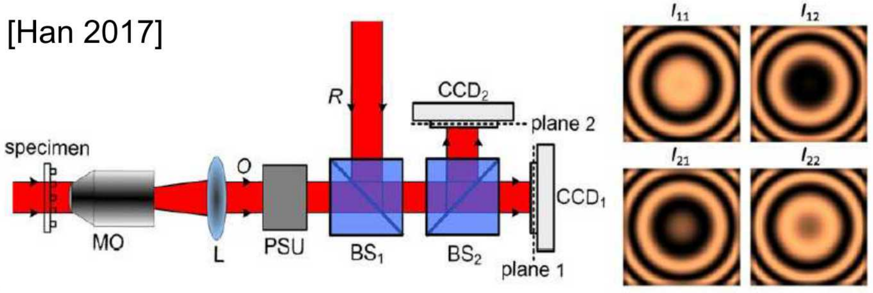
Interaction with object $t(x,y) = e^{-a(x,y)+i\phi(x,y)}$

Spherical shock-wave phase delay $\phi(x,y) \approx 2\pi R(n_{gas} - n_{air})/\lambda\sqrt{1 - z^2/R^2}$

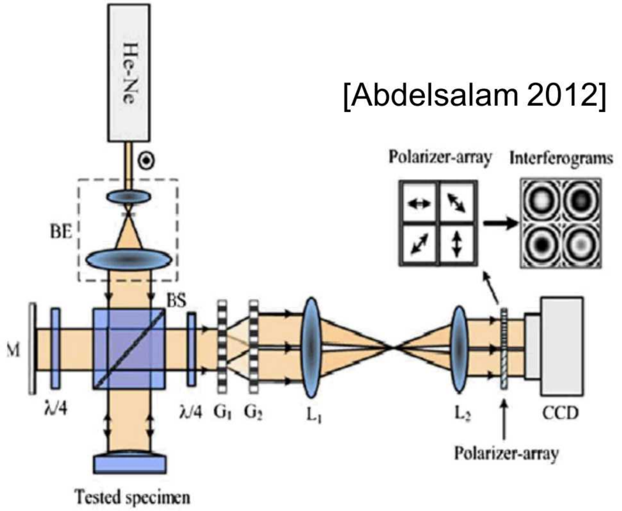
Phase Measurement vs. Phase Cancellation Techniques

- **<u>Phase measurement</u>** techniques are typically used in microscopy
- **<u>Phase cancellation</u>** of arbitrary distortions have not been explored
- Techniques Attempted:
  - Two-step Phase-shifting Digital Phase Holography
  - Single-Shot Polarization Phase-Shifting
- Used to obtain reconstructed object images and calculated phase

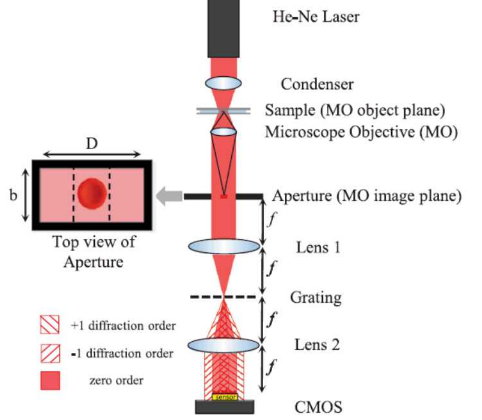
[Han 2017]

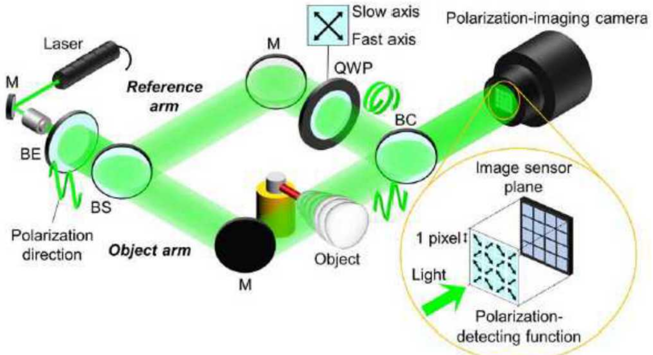


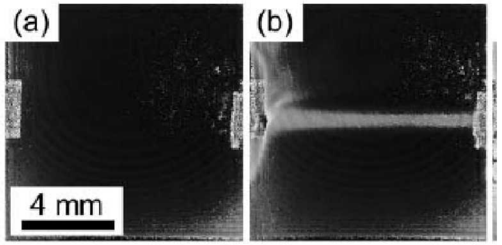
[Abdelsalam 2012]



[Hossein 2019]







[Kakue 2011]

Two-step Phase-shifting Digital Phase Holography

1. Generate four interferograms

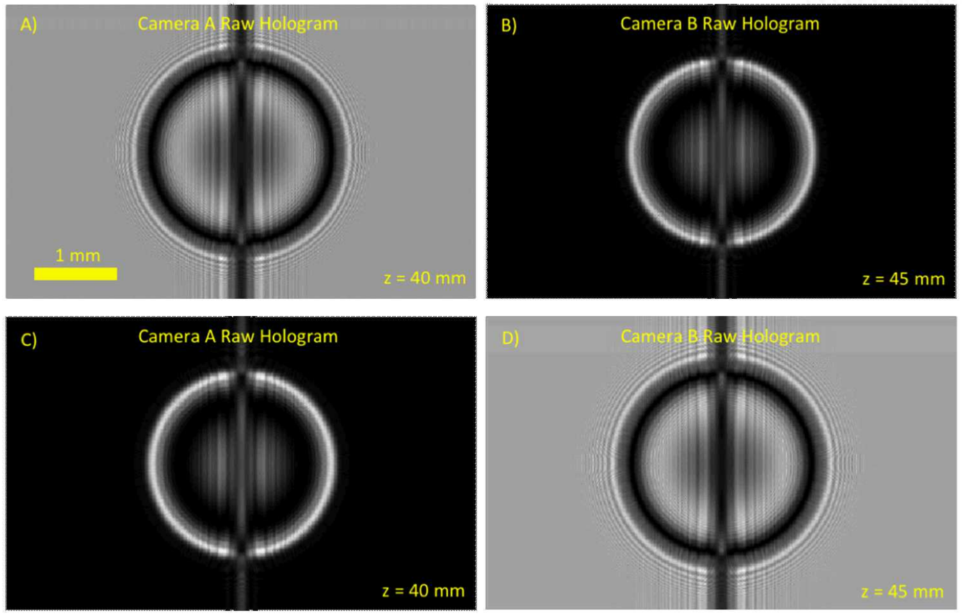
$$I_{1a} = |O_{z_1}|^2 + |R|^2 + O_{z_1} * R^* + O_{Z_1}^* * R$$
$$I_{1b} = |O_{z_1}|^2 + |R|^2 - O_{z_1} * R^* - O_{Z_1}^* * R$$
$$I_{2a} = |O_{z_2}|^2 + |R|^2 + O_{z_2} * R^* + O_{Z_2}^* * R$$
$$I_{2b} = |O_{z_2}|^2 + |R|^2 - O_{z_2} * R^* - O_{Z_2}^* * R$$

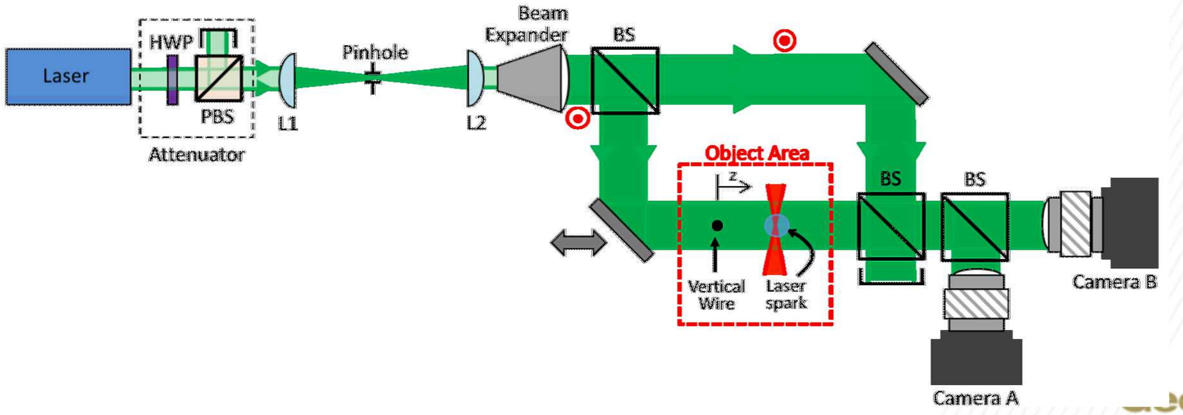
2. Apply the following equation

$$FT(OB_{calc}) = \frac{FT\{I_{2a} - I_{2b}\}G(-z_1) - FT\{I_{1a} - I_{1b}\}G(-z_2)}{2(G(z_2 - z_1) - G(z_1 - z_2))}$$

$$G(z) = e^{(\frac{2\pi i z}{\lambda})\sqrt{1-(\lambda u)^2-(\lambda v)^2}}$$

3. Find the inverse Fourier transformation to find the object wave





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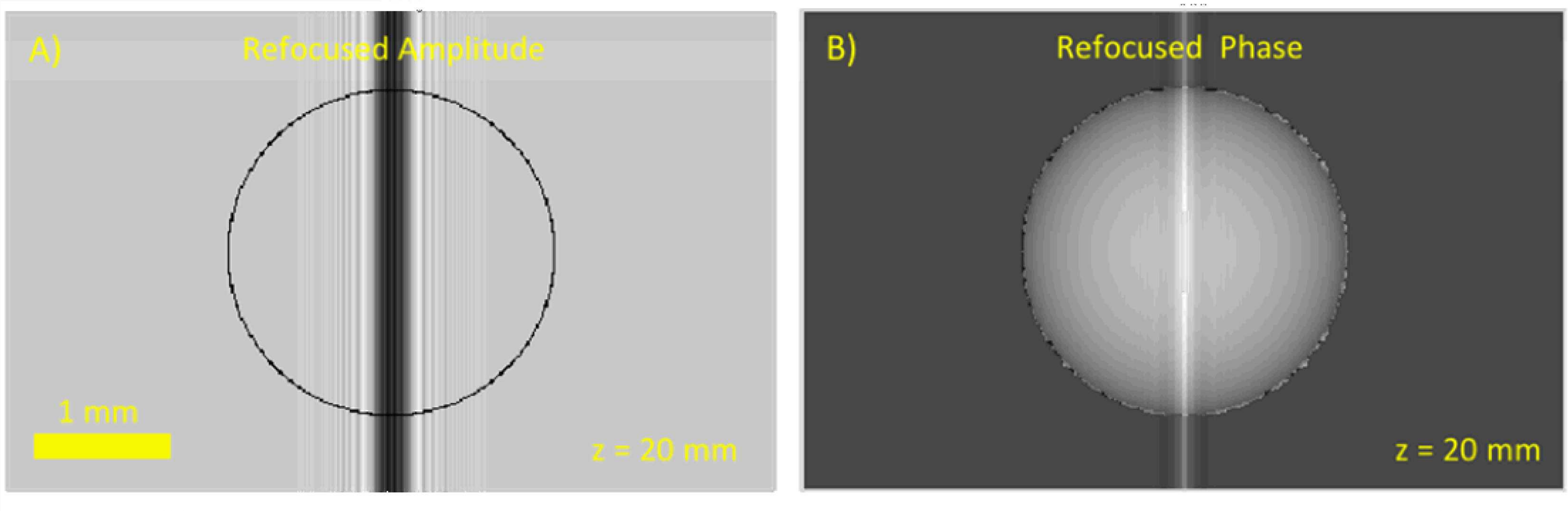
Two-Step Phase-Shifting Results

- The calculated amplitude and phase refocused to the plane of the shock
- Requires either two shot system or four cameras
- Impractical to implement as single shot system



Single-Shot Polarization Phase-Shifting

1. Generate four interferograms

$$I_n = \left|\left(OB * e^{ni\frac{\pi}{2}}\right) + R\right|^2$$

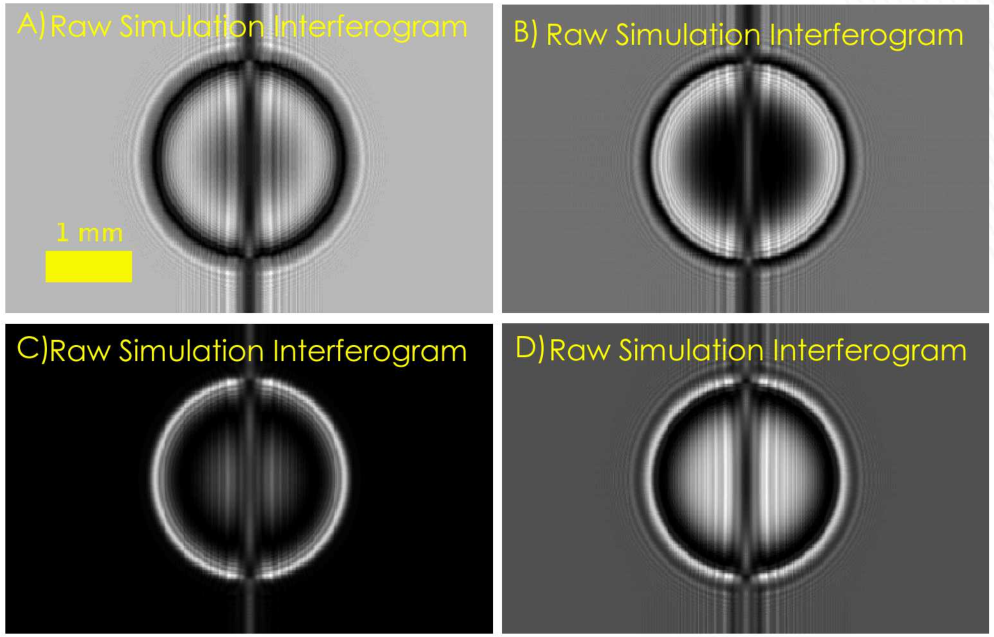
- *n= 0,1,2,3, R= Reference Image, and OB= Object Image*
- Intensity of the image at the imaging plane separated by a phase shift of $\frac{\pi}{2}$

2. Calculate phase

$$\Phi = \tan^{-1}\left(\frac{I_0 - I_\pi}{I_{\pi/2} - I_{3\pi/2}}\right)$$

3. Calculate reconstructed object image

$$OB_{calc} = (I_0 - I_\pi) - i\left(I_{\frac{\pi}{2}} - I_{\frac{3\pi}{2}}\right)$$



a) n= 0, b) n=1, c) n=2, d) n=3

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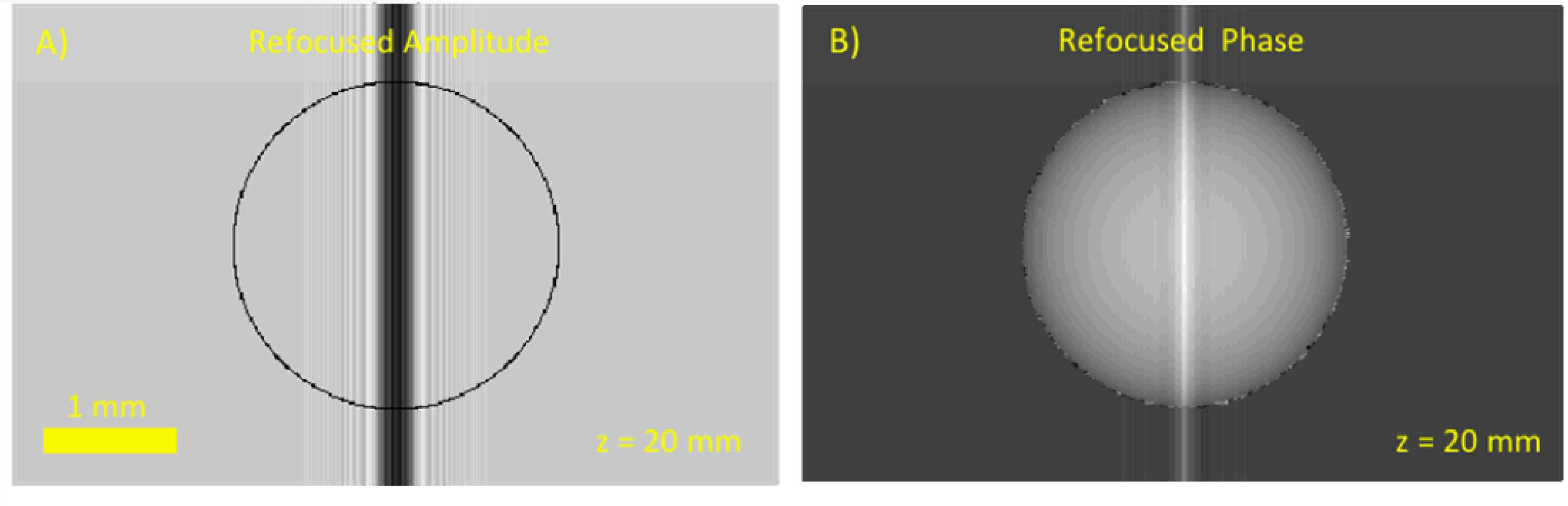
Single-Shot Polarization Results

- The image of both amplitude and phase have been numerically refocused to the center of the shockwave
- Includes both the phase of the shock wave distortion and the wire



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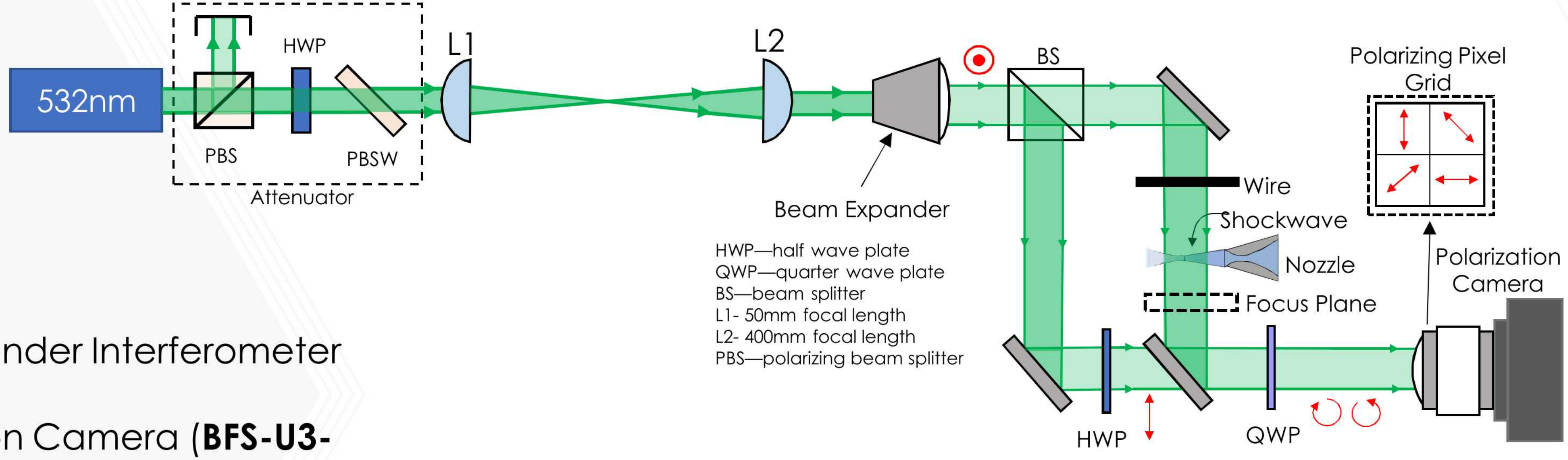
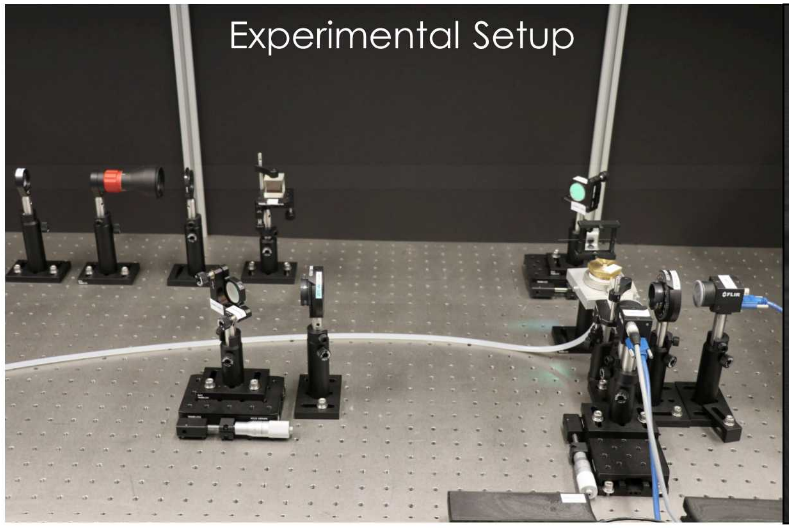
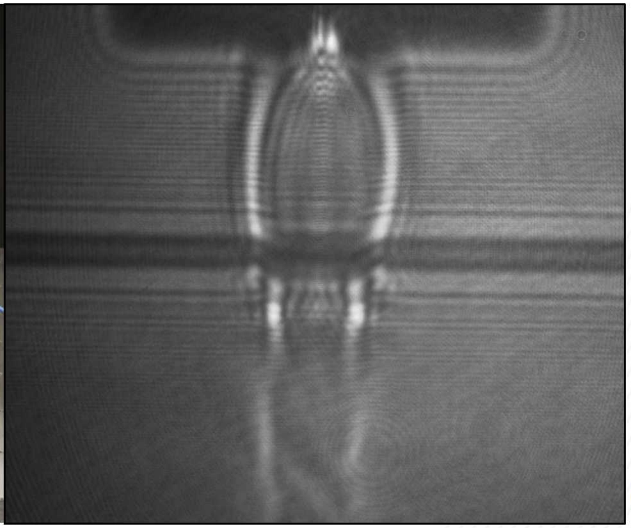
Experimental Setup

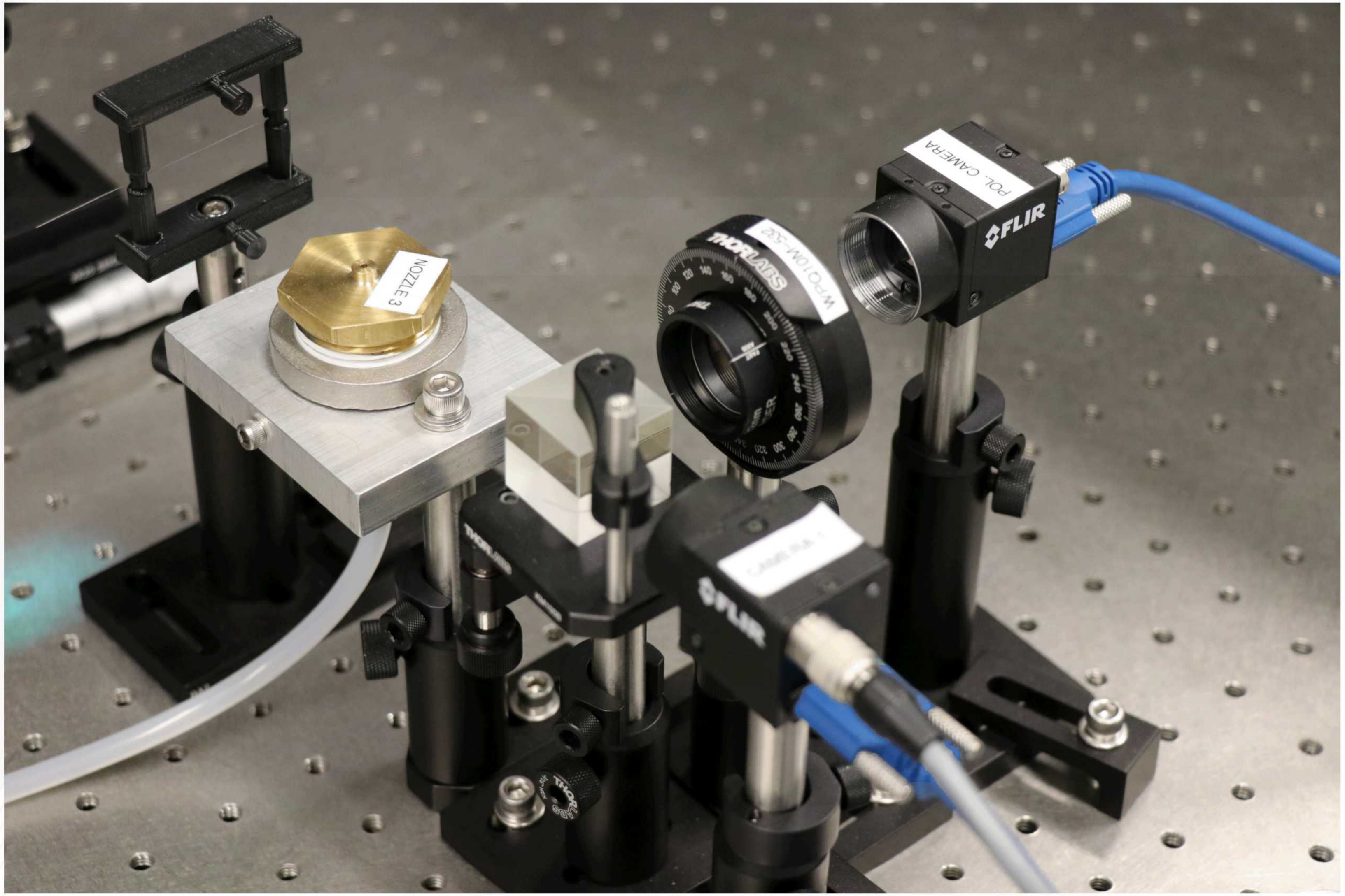


- Mach-Zehnder Interferometer setup
- Polarization Camera (**BFS-U3-51S5P-C USB3 Blackfly® S**)
- Diffraction pattern of each object is the result of the propagation of light
- Air jet nozzle (1.5 mm diameter, underexpanded, design Mach number of 1) produces stationary shock-waves
- Stationary shock produces distortions to the wire





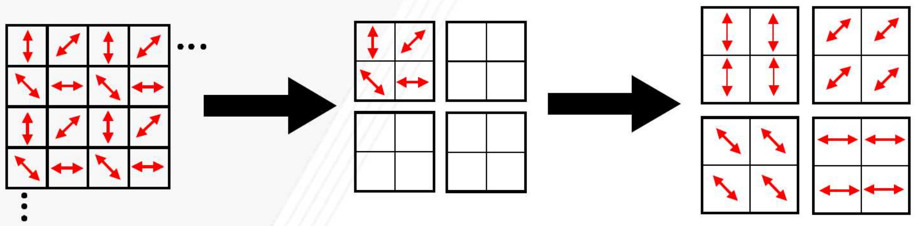
Photos of Setup

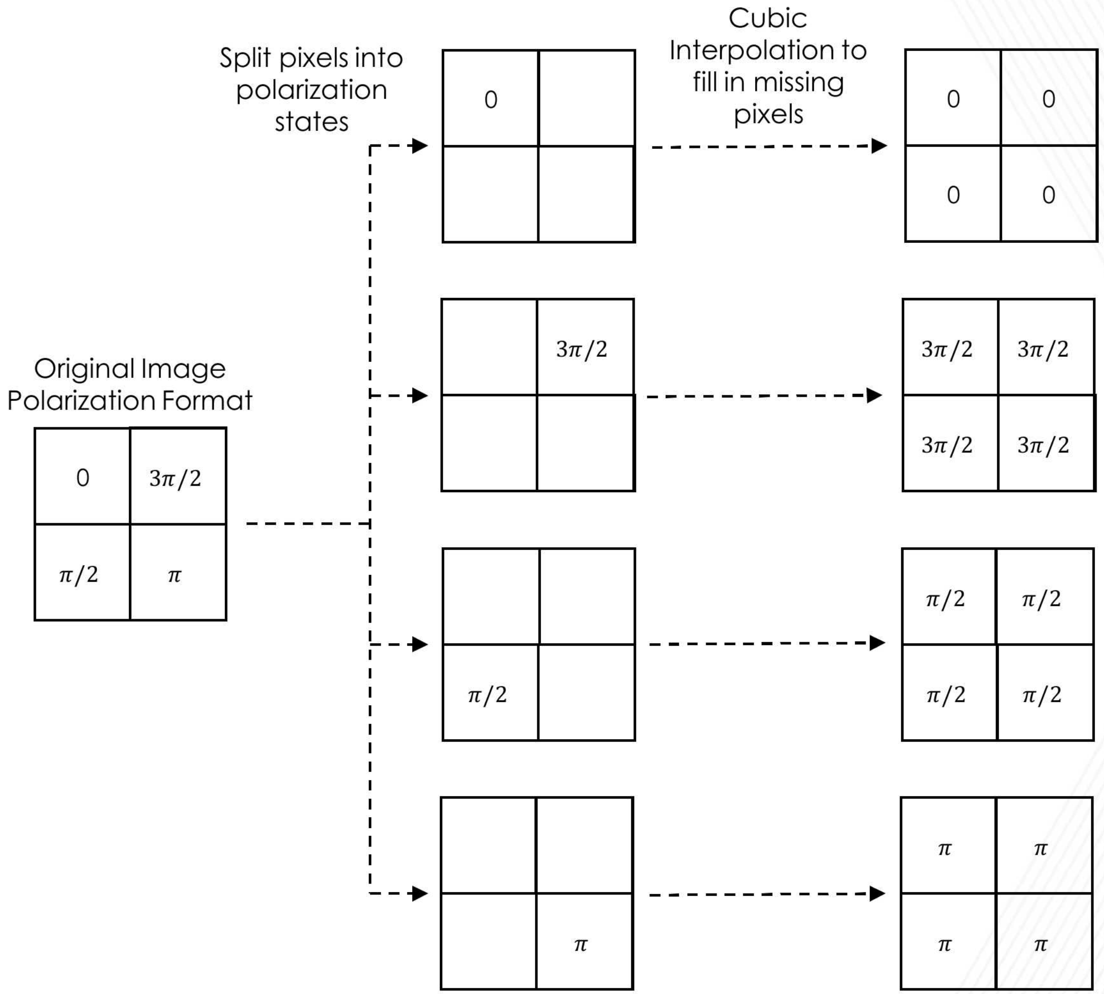


Polarizing Image Camera

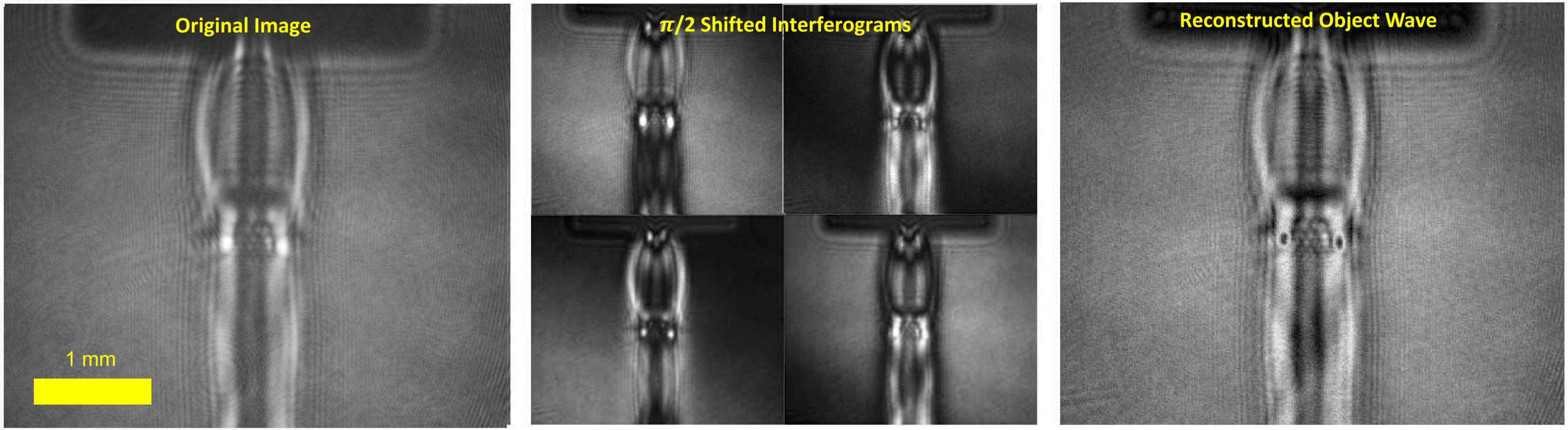
- Polarization sensor splits the different polarized light into 4 pixels of 0, $\pi/2$, π, and $3\pi/2$.

- Extract pixels from one specific polarized state and then perform cubic interpolation to fill in the missing pixels.





Experimentally Generated Image



Phase Cancellation Techniques

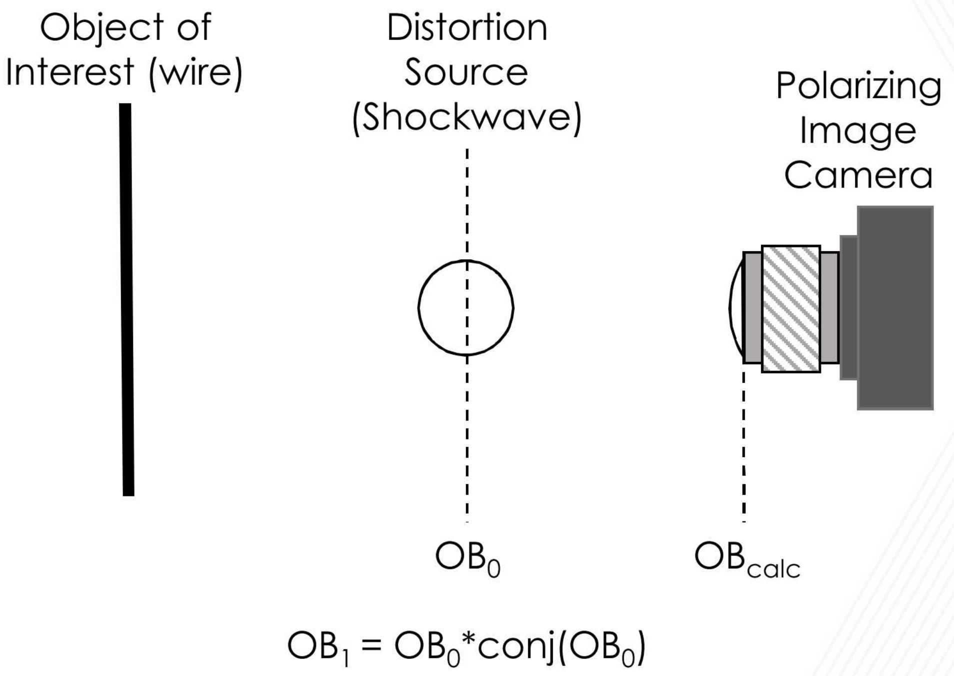
- $OB_{calc} = \left(I_{\frac{\pi}{4}} - I_{\frac{3\pi}{4}}\right) - i\left(I_0 - I_{\frac{\pi}{2}}\right)$

<u>Conjugate Multiplication</u>:

- $OB_1 = OB_0 * conj(OB_0)$

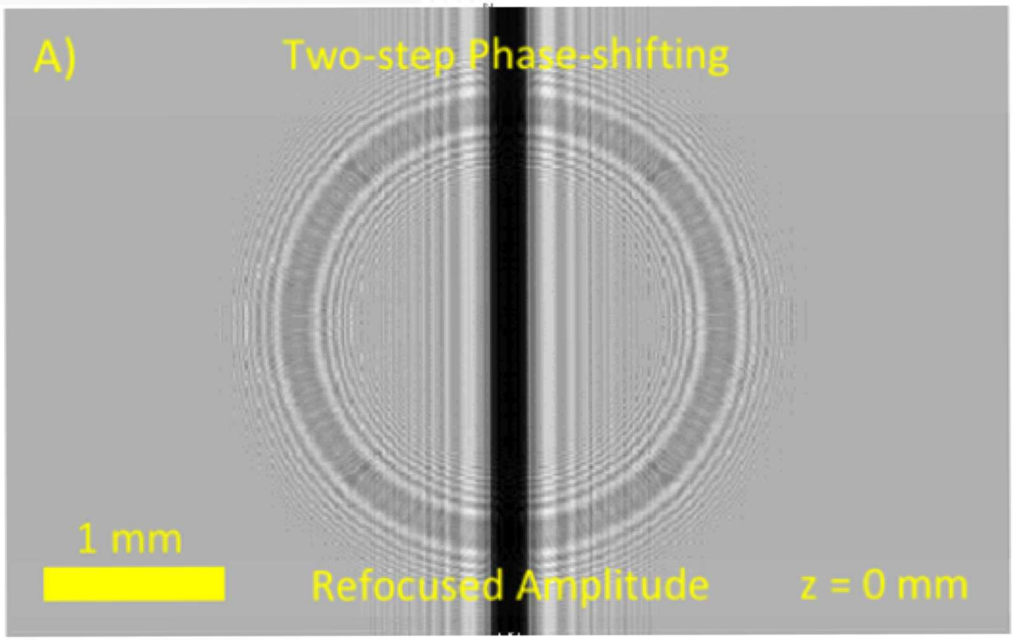
<u>RIP-Phase Holography</u>:

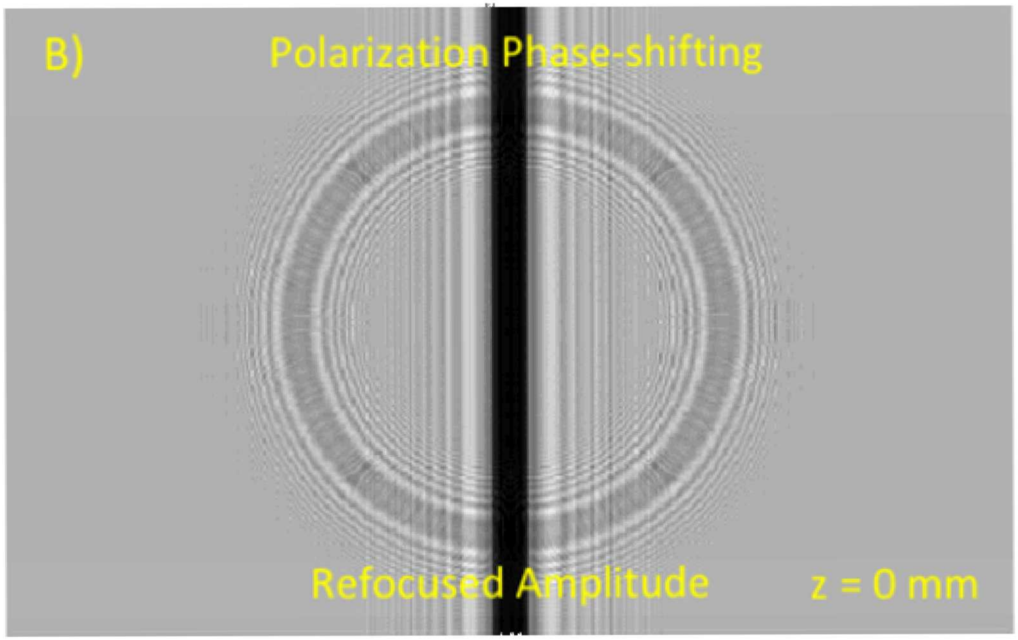
- Recalculated Intensity Propagation Phase Holography
- Propagate calculated intensity to the plane of the phase disturbance
- Numerically refocus to wire



Conjugate Multiplication

- Simulation results of conjugate multiplication using both calculated object images
- Distortions successfully removed

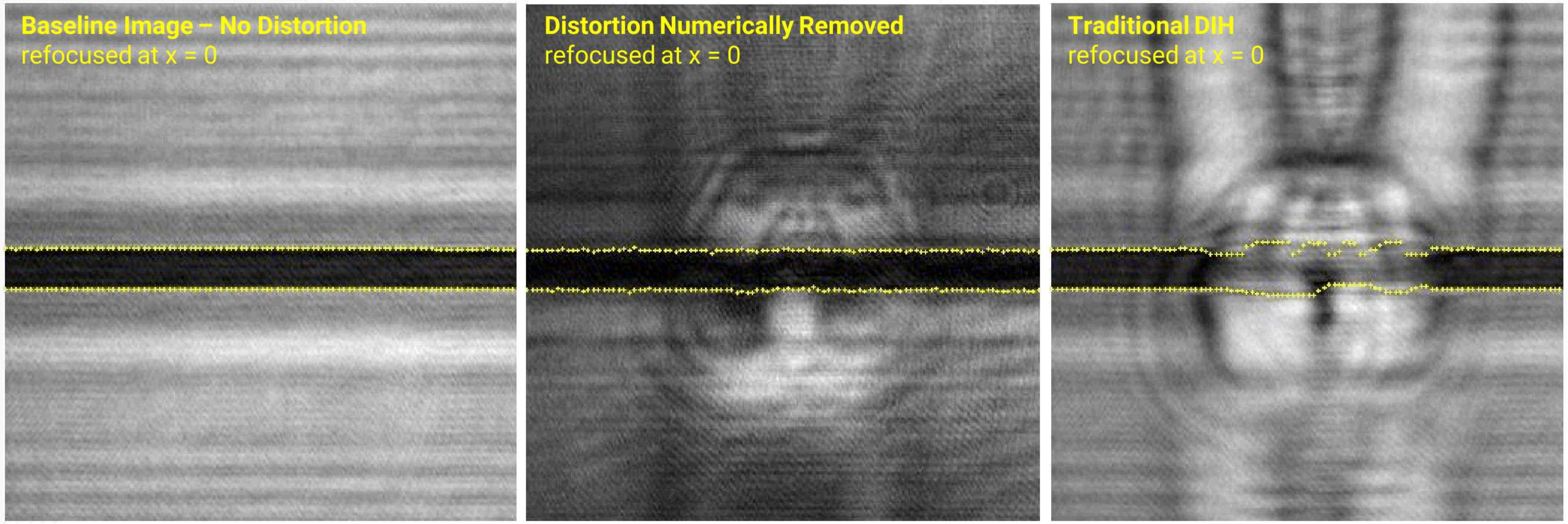




Quantitative Wire Tracking Results

Calculated wire edge standard deviation from the baseline image

	Top Wire Std. [µm]	Bottom Wire Std. [µm]
DIH	22.1	17.3
Numerical removal	8.5	6.8



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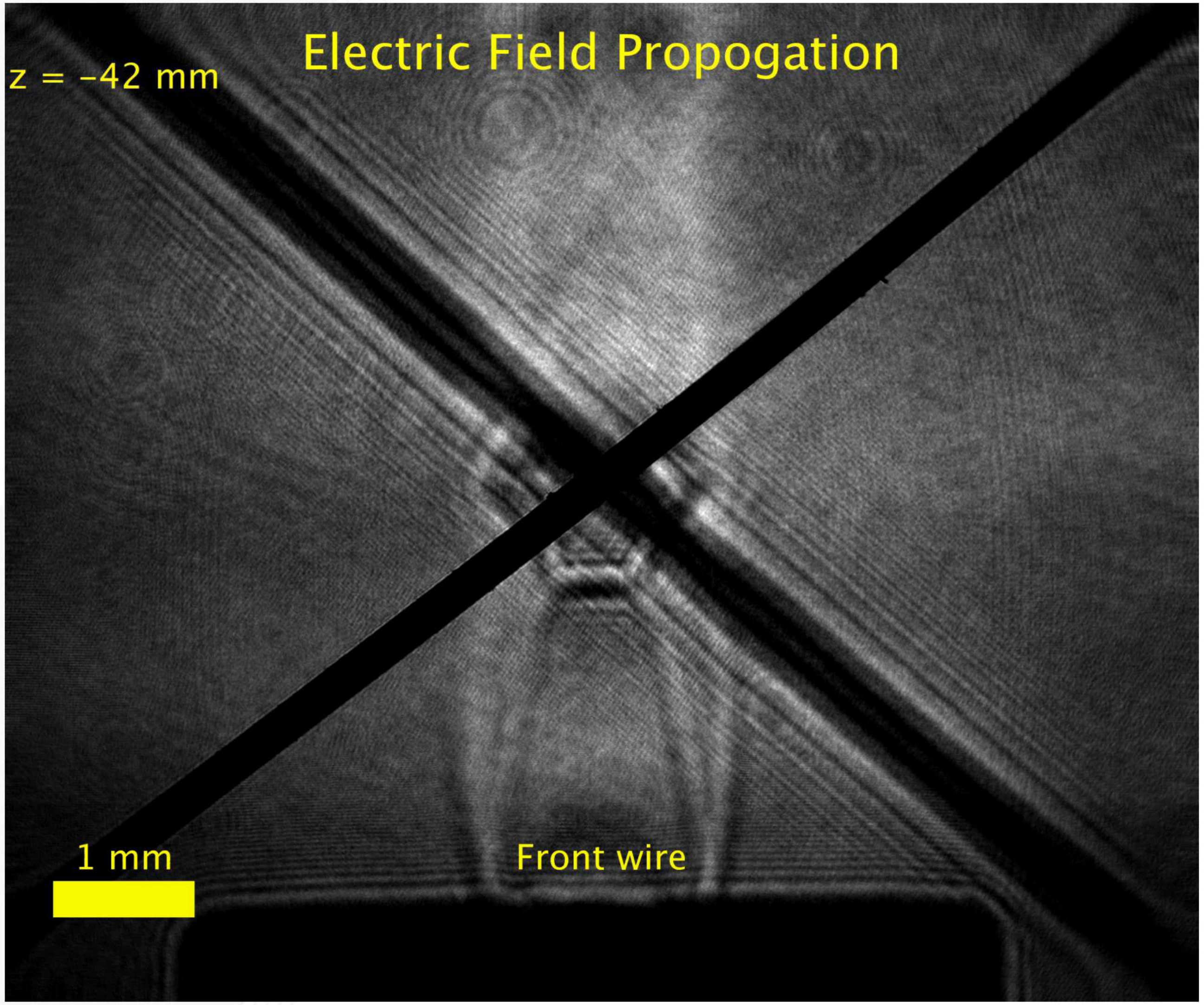
Current Results

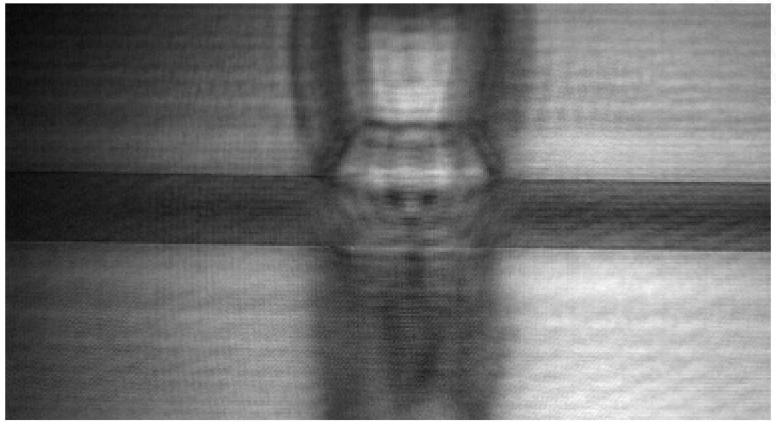


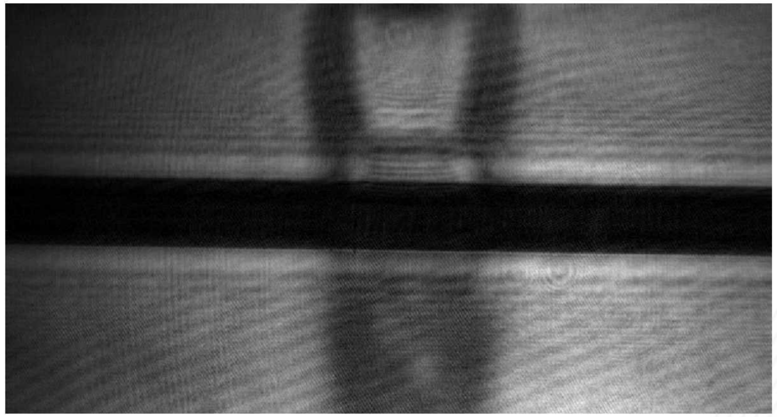
- Phase-sensitive holography benefits
  - Cancels phase distortions
  - Linear process, easier to implement and requires less laser power than PCDIH
  - Creates clearer images of shock-wave edges
- Other effects
  - Can also be used to measure phase distortions
  - Twin-image generation at shock-wave plane

Conclusion

- Polarization camera enables single-shot setup
- Intensity Propagation and conjugate multiplication can eliminate phase disturbances

- Future Simulation Work:
  - Phase before and after
  - Multiple phase distortions
  - Particle fields
  - Reduce the removal of object phase





Acknowledgements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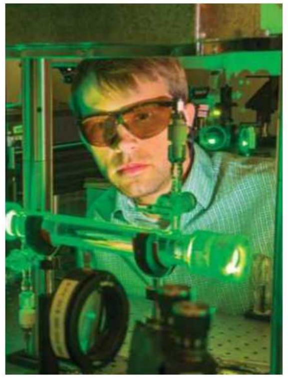
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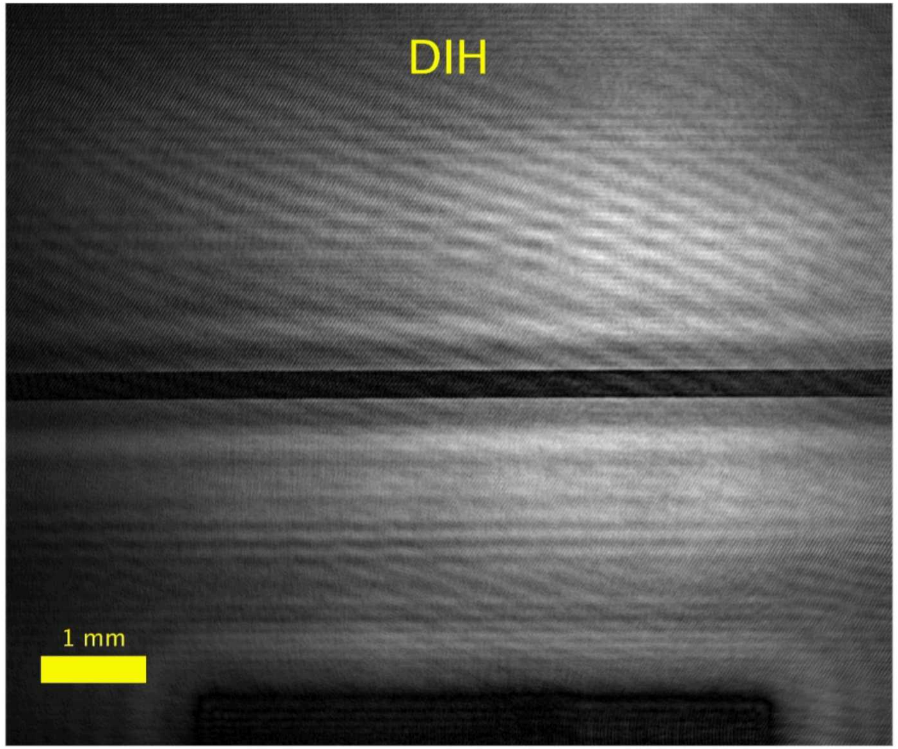
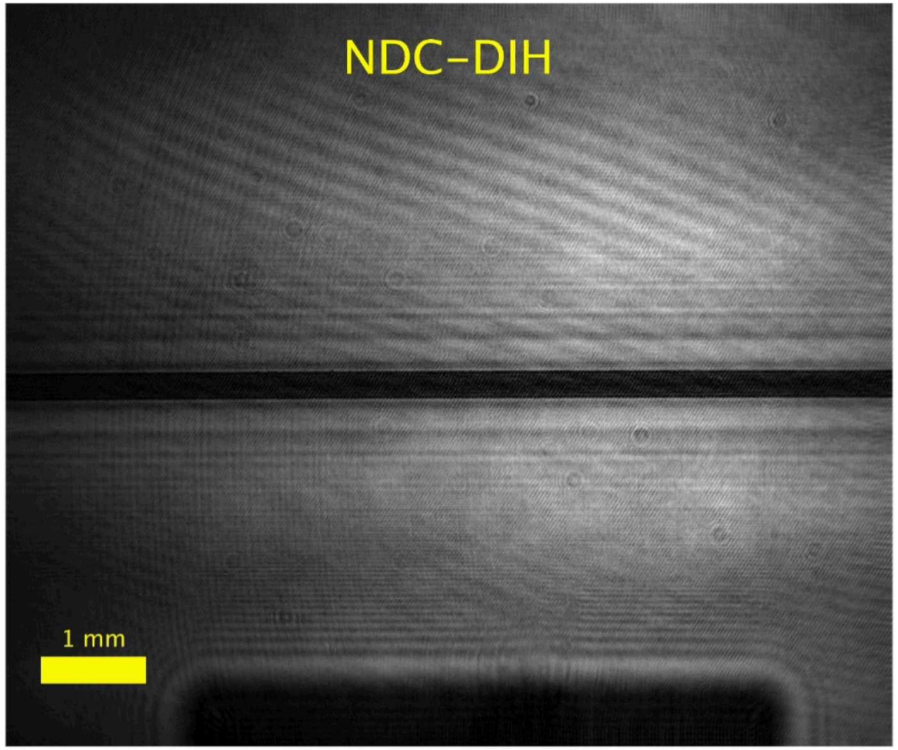
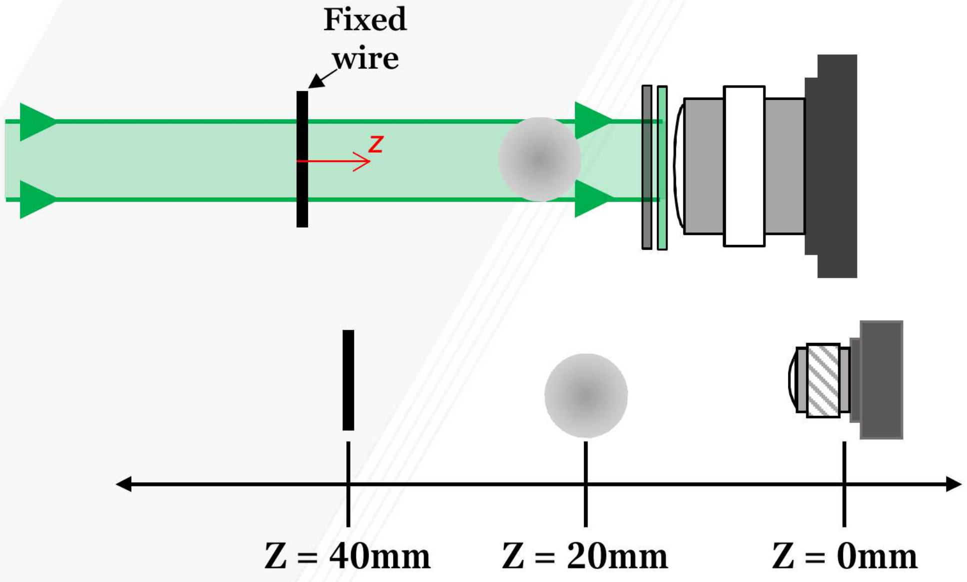
Questions?

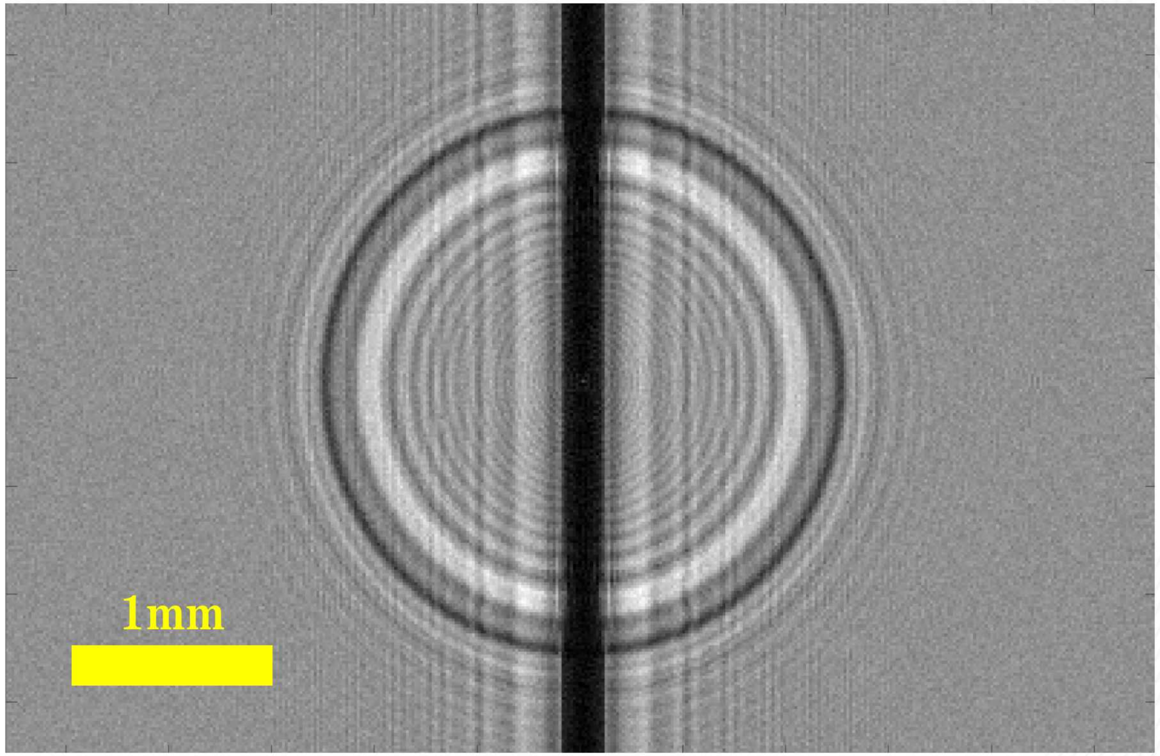




DIH Simulation

- Computer generated hologram simulating a DIH setup seen below
- Allows for adjustment of parameters to test various scenarios
- Provide verification of algorithms and phase removal methods





The DIH image at the plane of the wire (*z=40mm*), the wire is Seen to have distortions at the top and bottom of the shockwave.