



Nonlinear Phase Contrast

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- Interpretation
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- Flow visualization
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Introduction

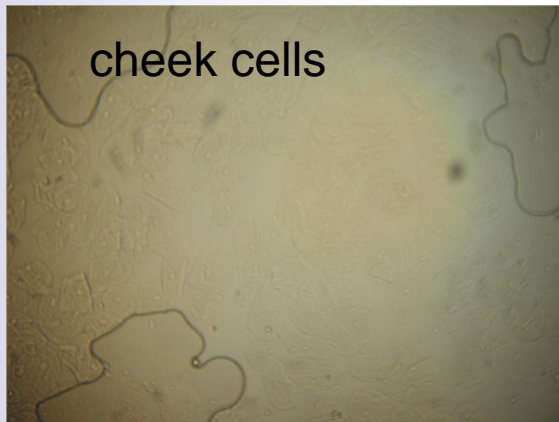


- **The imaging and visualization of phase objects wavefront disturbances and phase aberrations are of considerable interest in the field of optics**
- **In general phase disturbances cannot be viewed directly with a naked eye, then a method must be sought to extract the desired information indirectly**
- **Interferometry, spatial filtering and phase contrast techniques are the most common techniques to visualize such phase changes**
- **Here we proposed and demonstrated that a nonlinear common path interferometer (NLCPI) can be used to visualize phase disturbances**

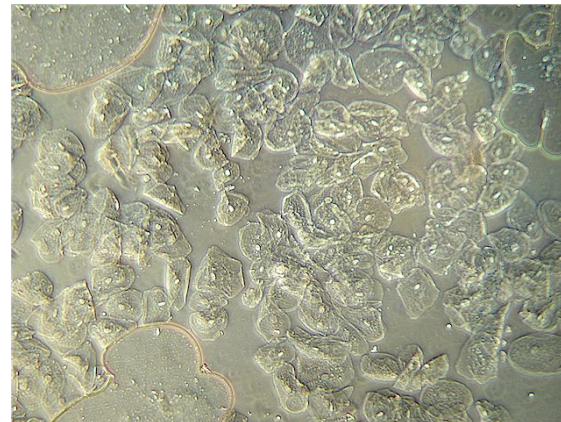
Introduction to phase contrast



- **Phase contrast microscopy is a contrast-enhancing optical technique that can be utilized to produce high-contrast images of transparent specimens**



Bright field microscope



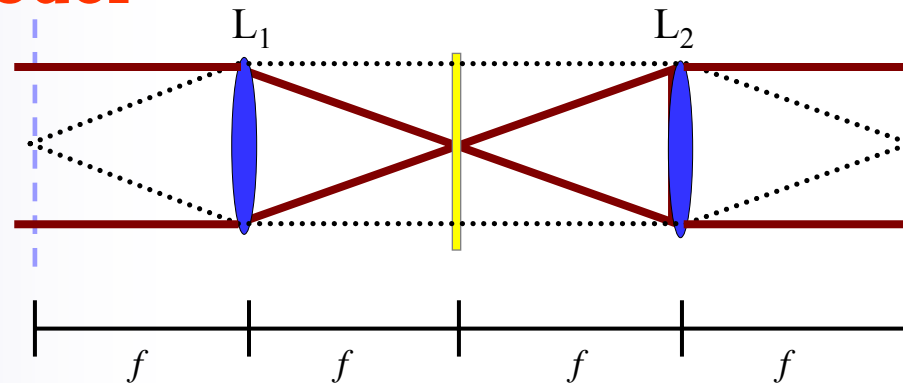
Phase contrast microscope

<http://www.microscope-microscope.org/advanced/phase-contrast-microscope.htm>

Zernike Phase-Contrast Microscope



Simplified model



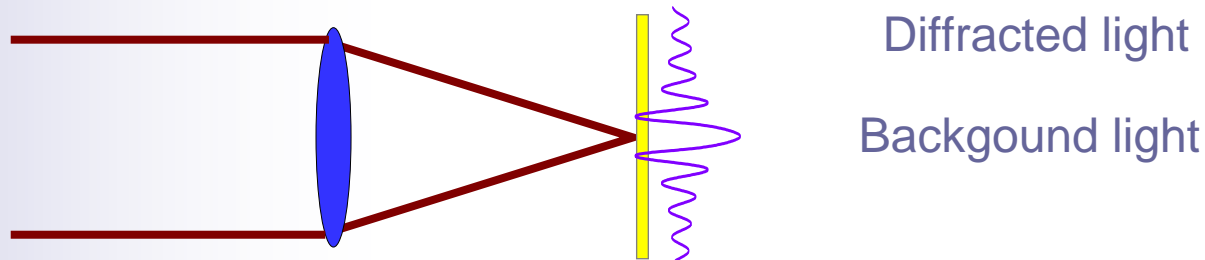
The transmittance of phase object with small phase variations

$$t(x, y) \approx \underbrace{e^{i\phi_0}}_{\text{Strong wave}} [1 + \underbrace{i\Delta\phi(x, y)}_{\text{Weak diffracted wave}}]$$

Strong wave **Weak diffracted wave**

Since the diffracted wave is in quadrature with the strong background, phase variations will not be observed!

Phase Filter



Zernike realized that a $\pi/2$ phase plate placed at the focal plane will break the quadrature and the intensity becomes:

$$I(x, y) = \left| e^{\pm i\pi/2} + i\Delta\phi(x, y) \right|^2 \approx 1 \pm 2\Delta\phi(x, y)$$

A linear relation between phase changes and intensity distribution is obtained i.e. phase changes can easily be quantified!

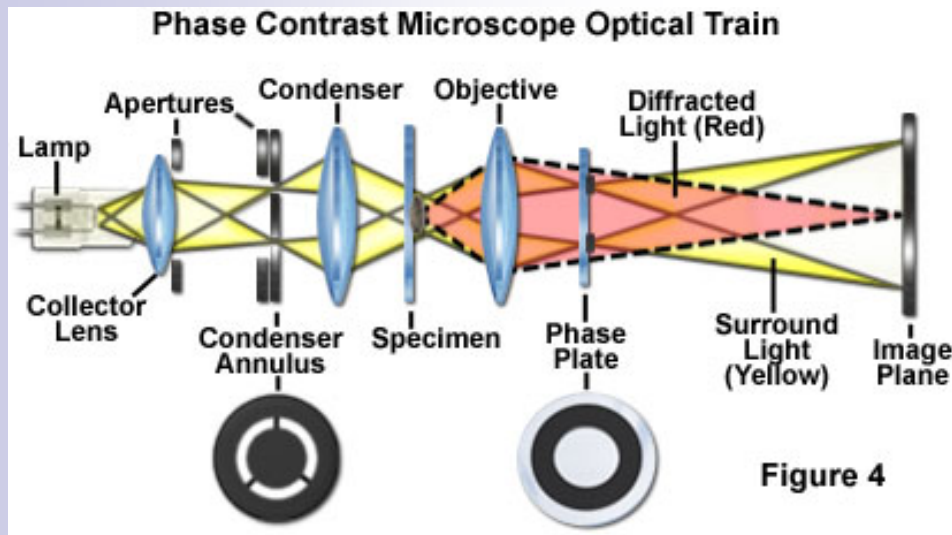
- F. Zernike, *Mon. Not. R. Astron. Soc.* **94**, 371 (1934).



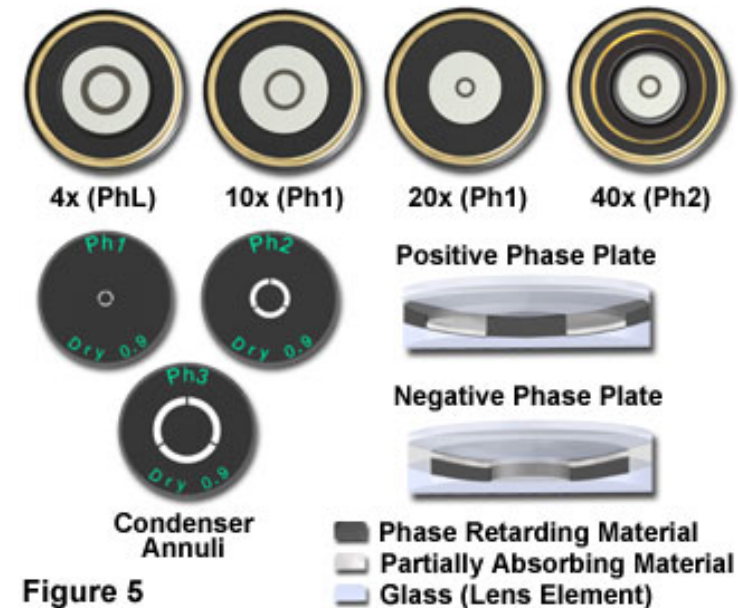
Phase Contrast Microscope



<http://www.microscopyu.com/articles/phasecontrast/phasehome.html>



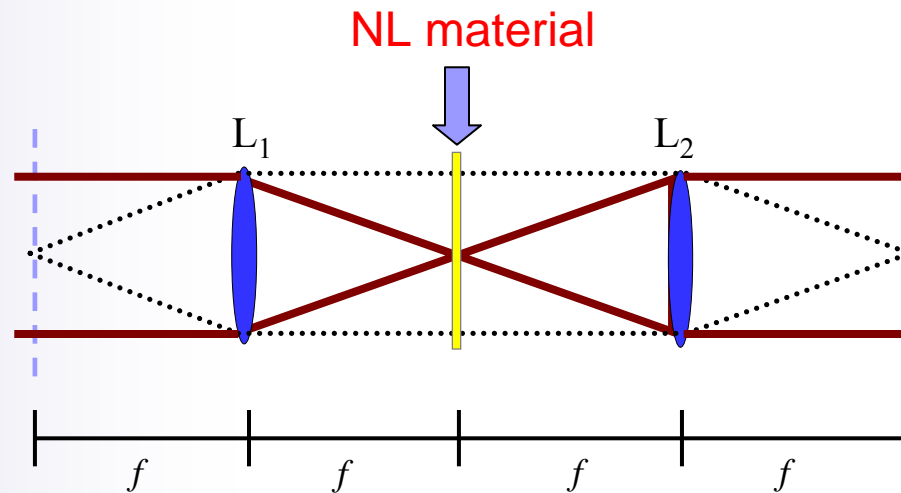
Objective Apertures and Phase Contrast Optics



Disadvantages

- Precise filter fabrication
- Hard to align
- Filter`s size is specimen dependent
- Filter`s size depends on optics used

Nonlinear Phase Contrast



What happens if we place nonlinear material on the Fourier plane of the system?

Self-induced phase filter!!!

Not any NL material it must be a Kerr (or Kerr-like)

M. D. Iturbe Castillo, D. Sánchez-de-la-Llave, R. Ramos García, Luis Ignacio Olivos-Pérez, L. A. González, M. Rodríguez-Ortiz. "Real-time self-induced nonlinear optical Zernike-type filter in a bacteriorhodopsin film". *Opt. Eng.* **40**, 2367-2368 (2003).

Nonlinear Refractive Index



Nonlinear optics is what happens when the polarization is the result of higher-order (nonlinear!) terms in the field:

$$P = \epsilon_0 \left[\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \dots \right]$$

$$n_0 = \sqrt{1 + \chi^{(1)}}$$

$$n = \sqrt{1 + \chi^{(1)} + \chi^{(3)} |E|^2} \approx n_0 + \chi^{(3)} |E|^2 / 2n_0 \quad \text{since } I \propto |E|^2$$

$$n \approx n_0 + n_2 I$$

$$\Delta n = \Delta n(I) = \begin{cases} n_2 I \\ \frac{n_2 I}{1 + I/I_{\text{sat}}} \end{cases}$$

Kerr

Saturable Kerr



Intensity dependence phase

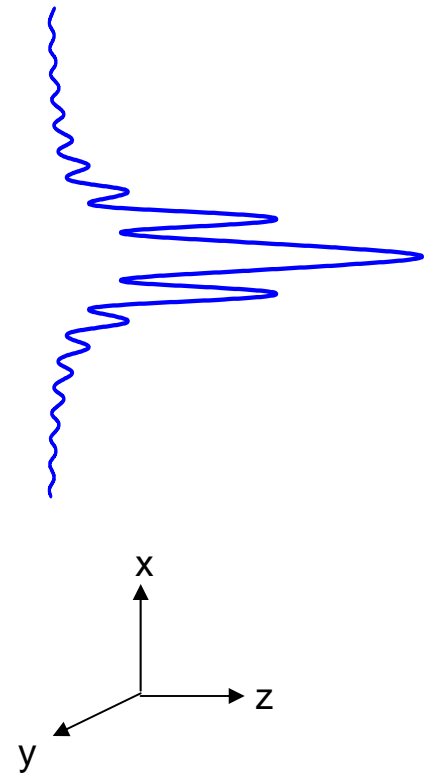


At the Fourier plane the spatial intensity distribution produces a spatially varying phase filter

$$\phi(x, y, d) = kd[n_0 + n_2 I(x, y)]$$

Since the NL material is placed on the Fourier plane, the filter is:

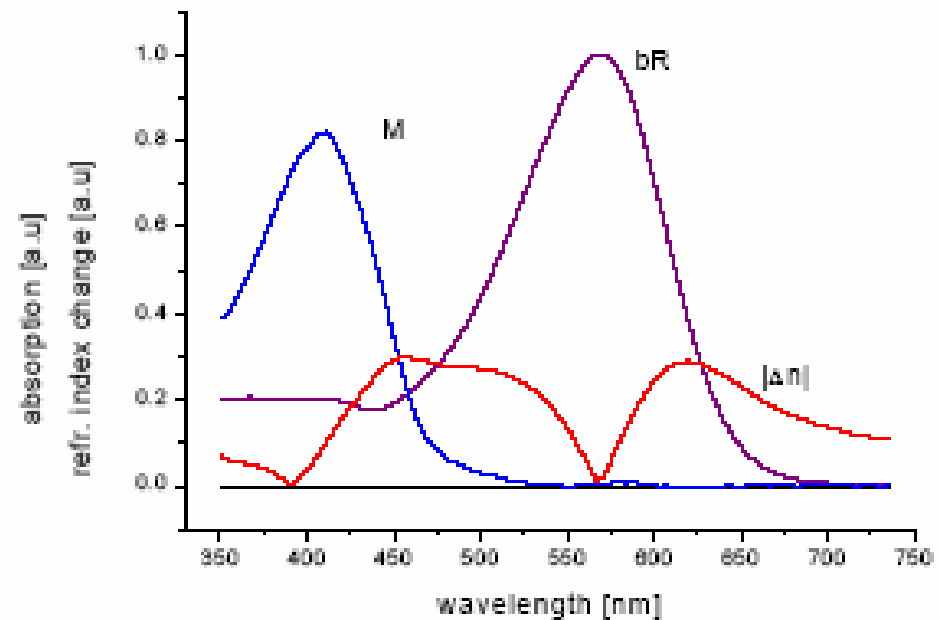
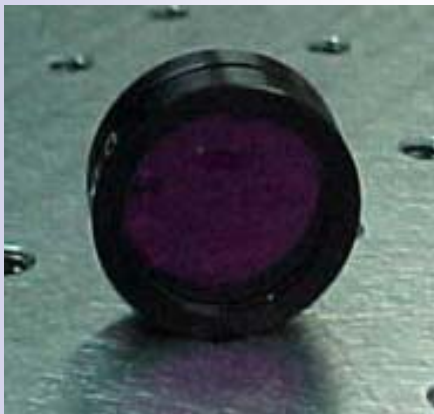
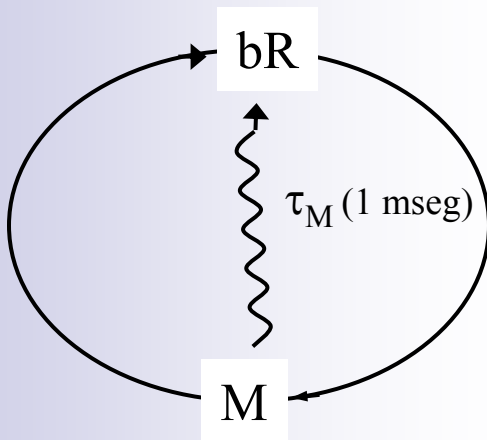
- Self-induced phase
- Self-aligned
- Real-time



Material: Bacteriorhodopsin



- Simplified model of the origin of the nonlinear effect in Br

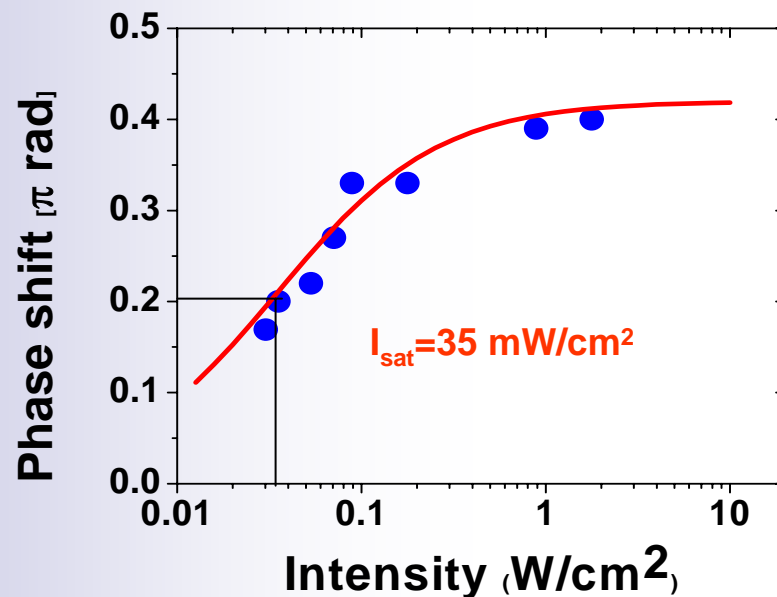


$$\Delta\phi = \frac{2\pi}{\lambda} d\Delta n(\lambda, I)$$

NLO Properties of Bacteriorhopsin



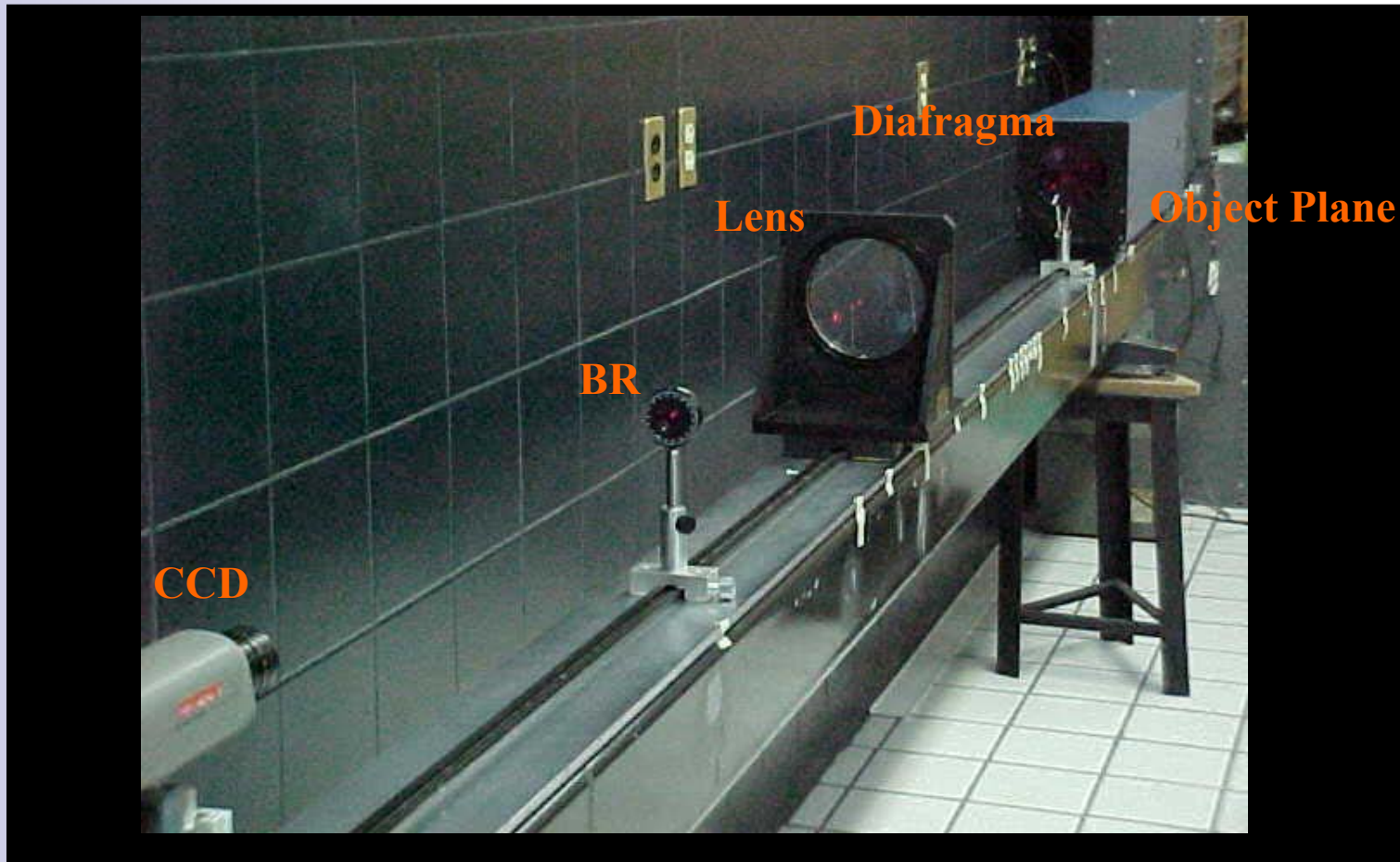
Phase changes were measured by using a Mach-Zender interferometer



$$n = n_0 + \frac{n_2 I}{1 + I/I_s}$$

Br is a high sensitivity material with low saturation intensity, suitable for Low power applications. **P~270 μ W**

Experiment

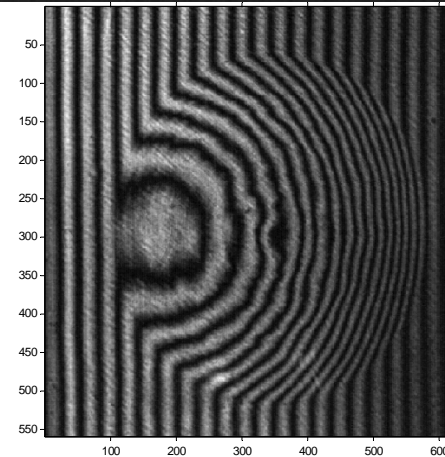
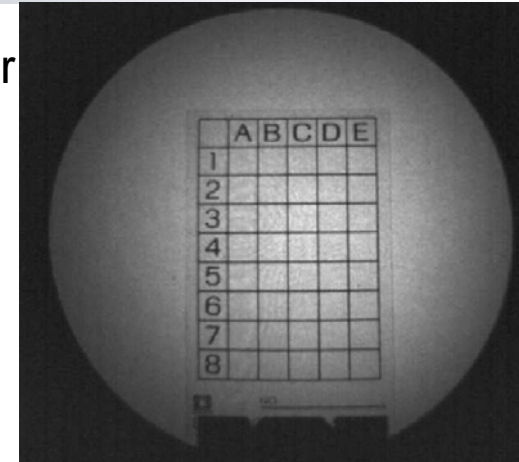
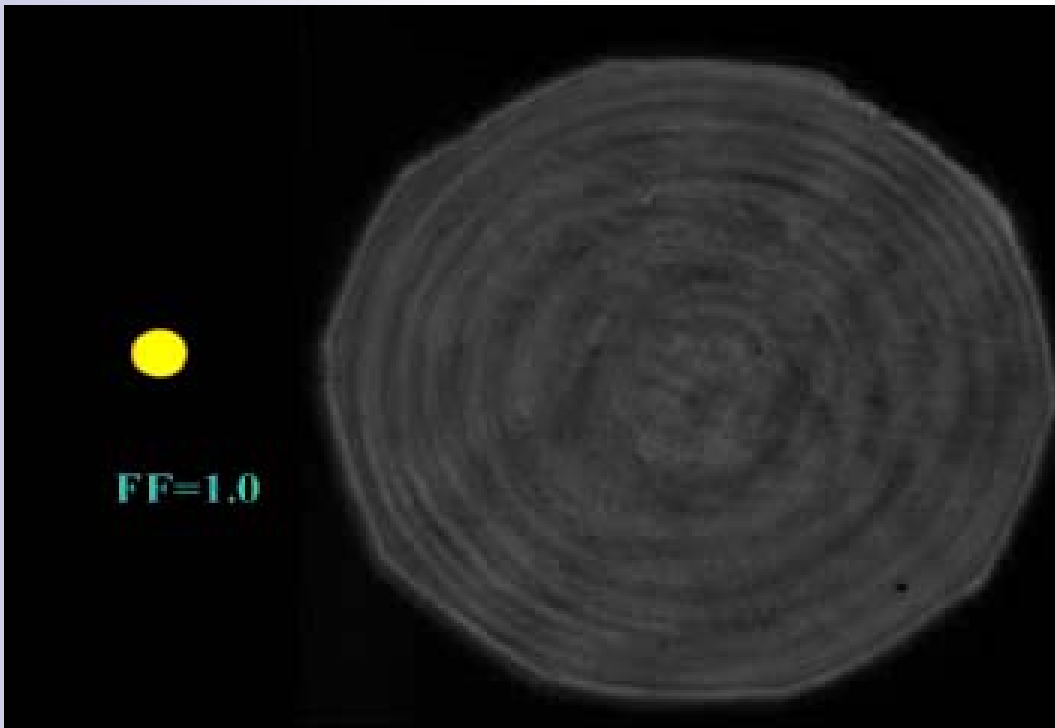


M.D. Iturbe-Catillo *et.al*, *Opt.Eng.* **40**, 11 (2002) 2367

But it doesn't work that well!!



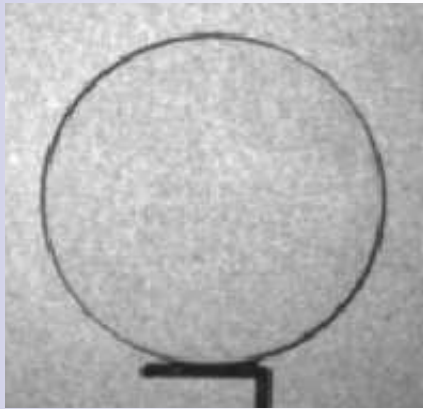
1 diopter PMMA oftalmic lens ablated with an excimer laser



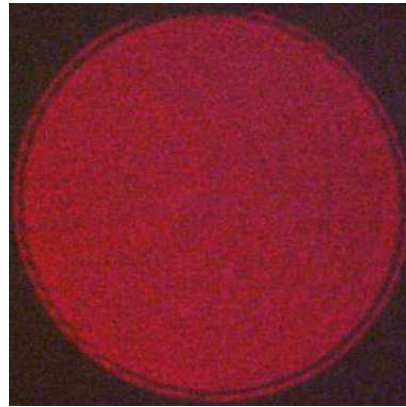
Fill Factor



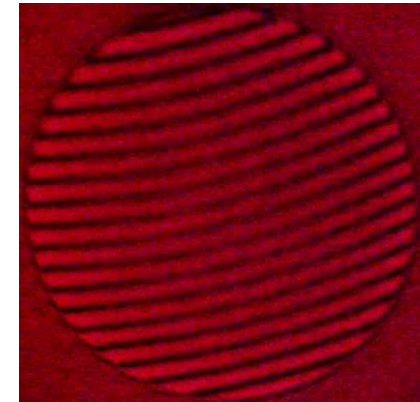
$$\rho = \frac{\text{Object area}}{\text{Total illuminated area}}$$



Reconstructed image
X NL filter



F=0.9

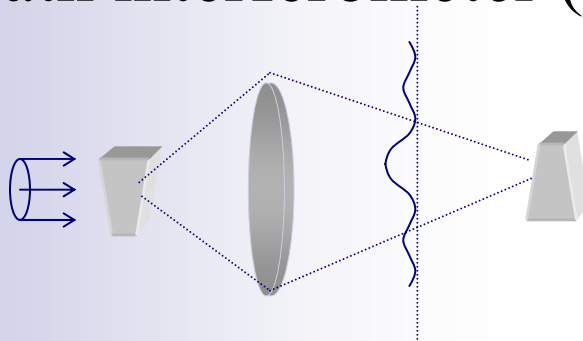


F=0.1

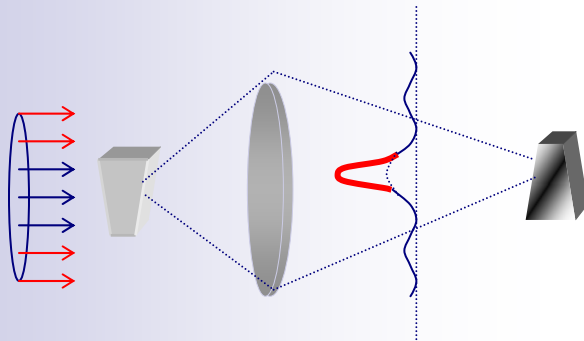
Interpretation



- Our results can be understood as a nonlinear common path interferometer (NLCPI)



For binary objects, the output distribution at the image plane is



$$g(x, y) = \left| \underbrace{e^{i\phi(x,y)}}_{\text{Object}} + \underbrace{(e^{i\alpha} - 1)(1 - \rho + \rho e^{i\phi(x,y)})}_{\text{Synthetic wave reference}} \right|^2$$

Sanchez-de-la-Llave, Iturbe Castillo, *Appl Opt.* **41**,14 (2002) 2067

J. Gluckstad and P. C. Mogensen, "Optimal phase contrast in CPI". *Appl. Opt.* **40** (2001) 268.

It works in real time!



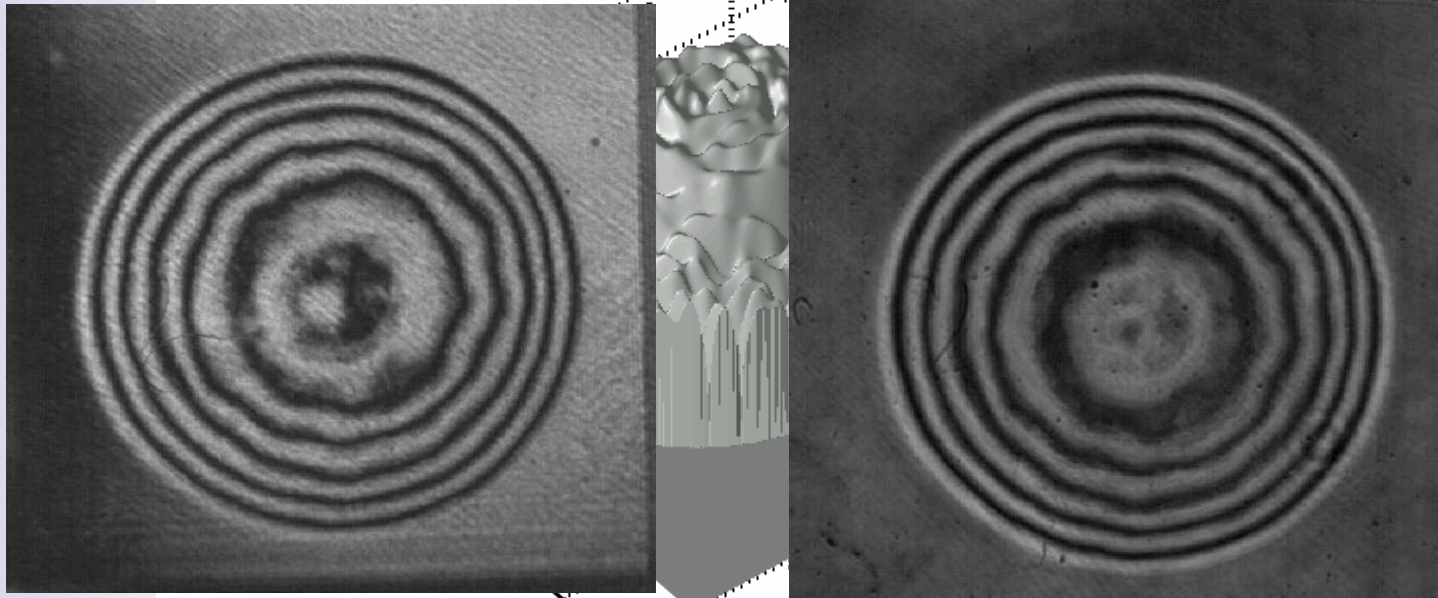
Treviño-Palacios, C. G., Iturbe Castillo, M. D., Sánchez-de-la-Llave, D., Ramos García, R., Olivos-Pérez, L. I., “Nonlinear common path interferometer: an image processor,” *Appl. Opt.* **42**, 5091-5095 (2003).



Interferometry vs NL Phase Contrast



- The same information can be extracted from both systems!



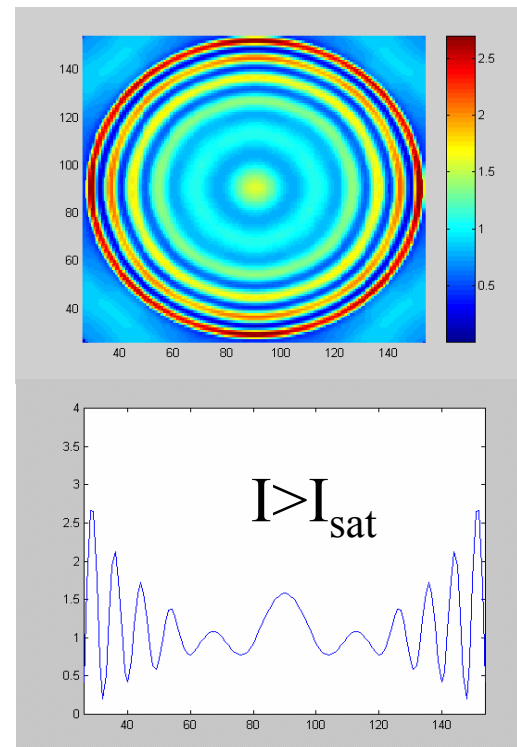
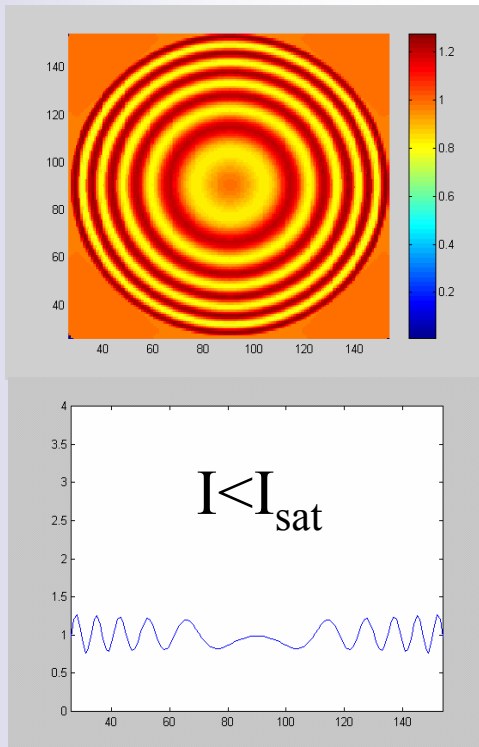
Mach-Zender

Nonlinear Common Path
Interferometer
(Phase Contrast)

Phase Contrast Simulations



Phase contrast is modeled by using a saturable Kerr media placed at the Fourier plane of the NLCPI



Distortion!!

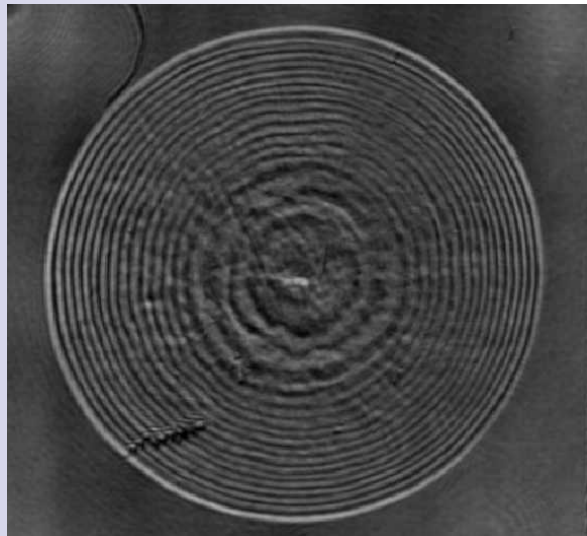
- H. Rehn and R. Kowarschik, , *Opt. Las. Tech.* **30**, 39 (1998).
- Treviño-Palacios, C. G., Iturbe Castillo, M. D., Sánchez-de-la-Llave, D., Olivos-Pérez, L. I., CLEO 2004



Larger than $\pi/2$ phase filter

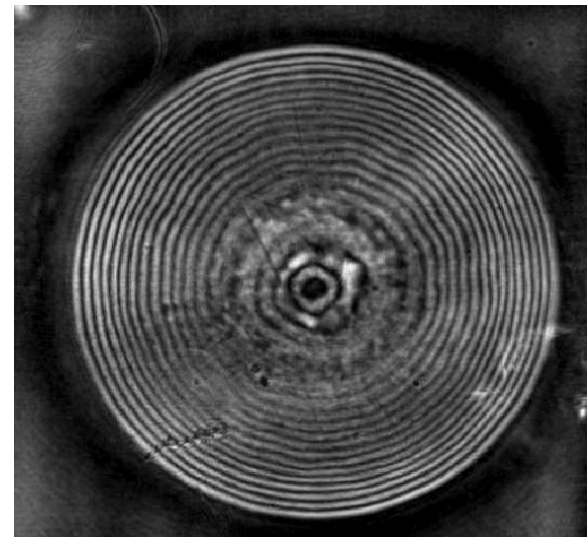


$\rho=0.1$



BR film

$$\Delta\phi = -0.4\pi$$

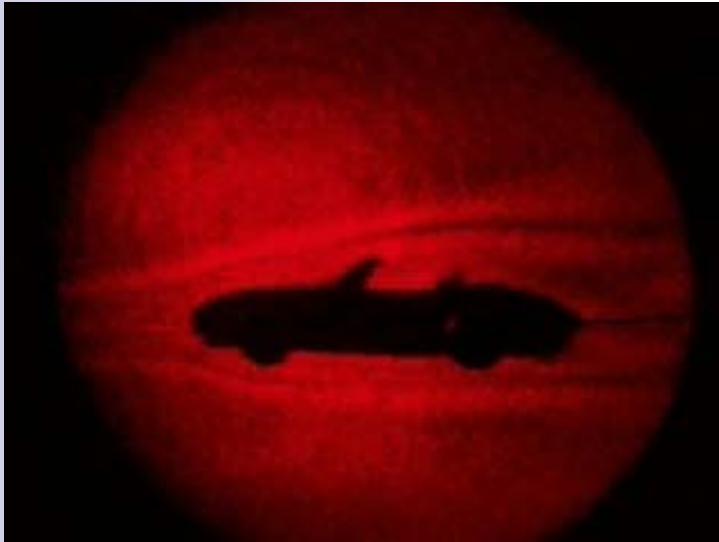


Acrylic

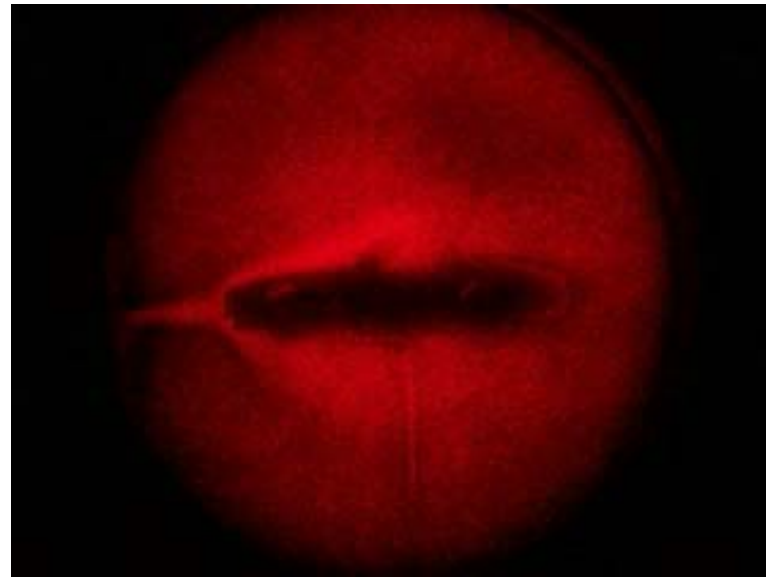
$$\Delta\phi = 6\pi$$

- Visibility improves with large phase filter

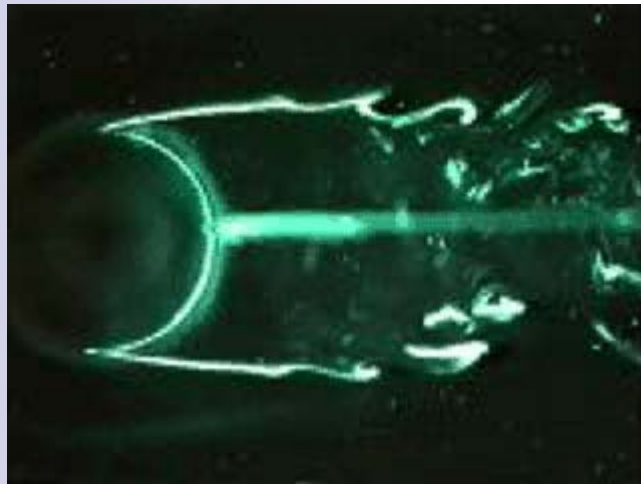
Dynamic Flow Visualization



- Real time flow visualization!



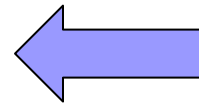
Dynamic Flow Visualization



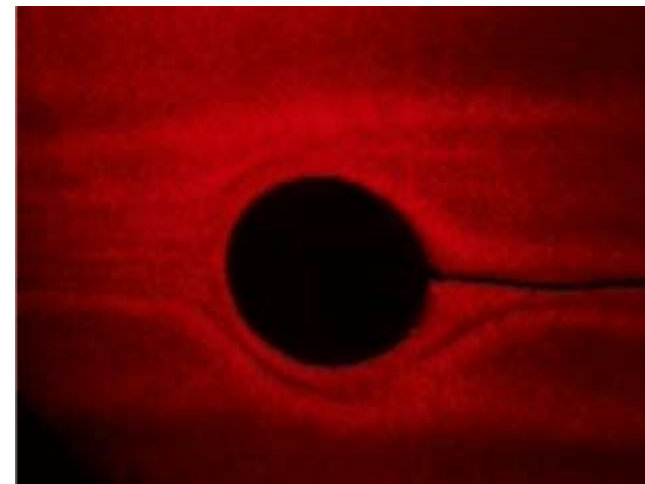
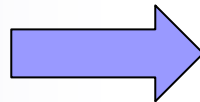
Cylinder

Trazer

Hessert Lab, Notre Dame U



Our NLCPI

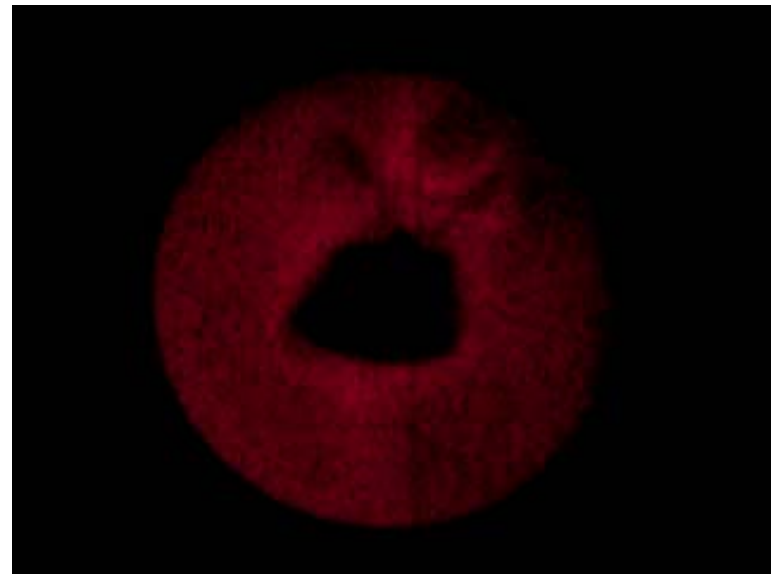


Dynamic Flow Visualization



$\Delta T \sim 17^\circ \text{C}$

$\Delta T \sim 20^\circ \text{C}$

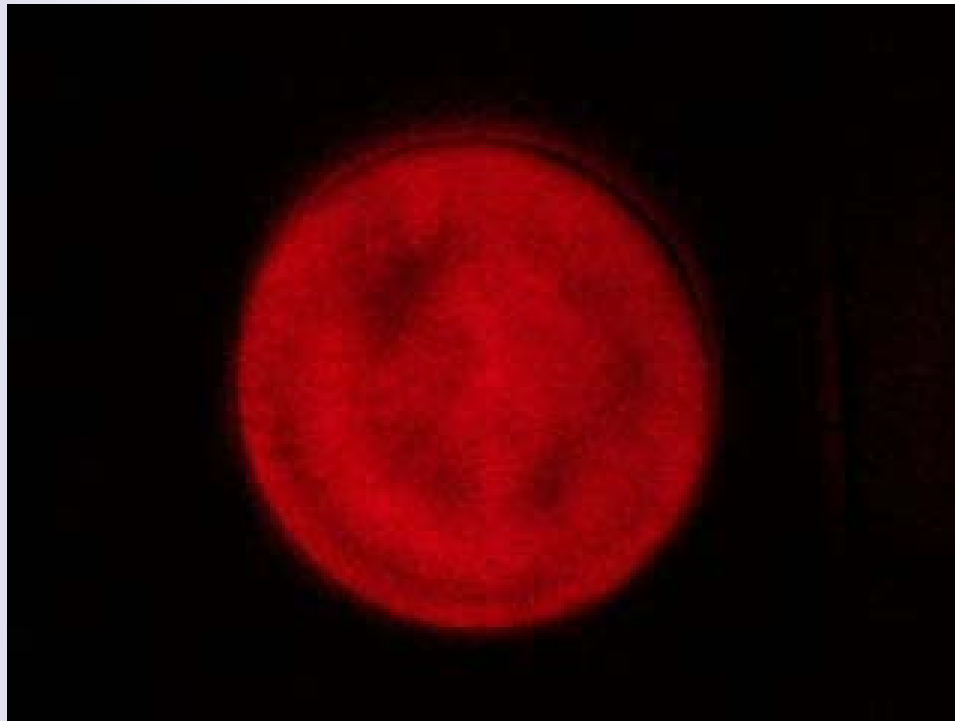


Our system can detect phase perturbations due to temperature induced air density changes

Dynamic Flow Visualization



- Adjusting the fill factor can increase the sensitivity of the system



**Laboratory
Turbulence**

Concluding remarks



- A single-lens optical processor was described. Easy to align
- The filter can be describe as a nonlinear common path interferometer
- The fill factor plays an important role on the quality of the phase contrasted images
- Real time operation allows dynamic visualization of flow
- NLCPI is a technique looking for real-world applications

The Team



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