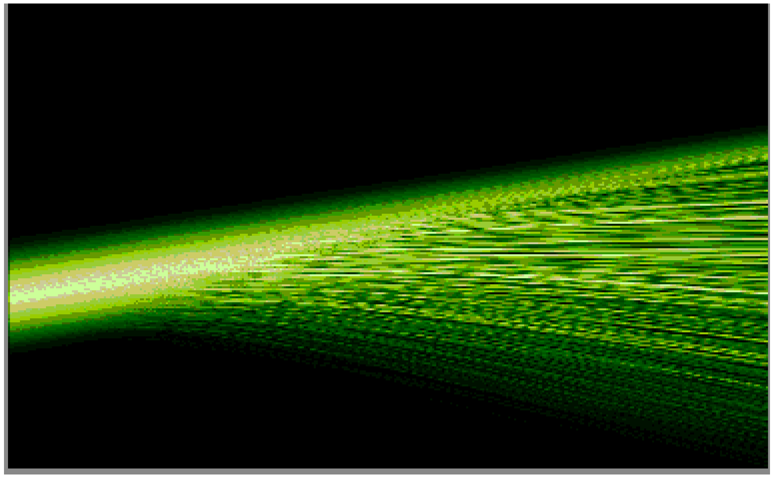
Optical 3D Fourier Transformation and Reconstruction with a Photorefractive crystal



Photorefractive fanning of Barium Titanate

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Physical Optics

4/26/2006

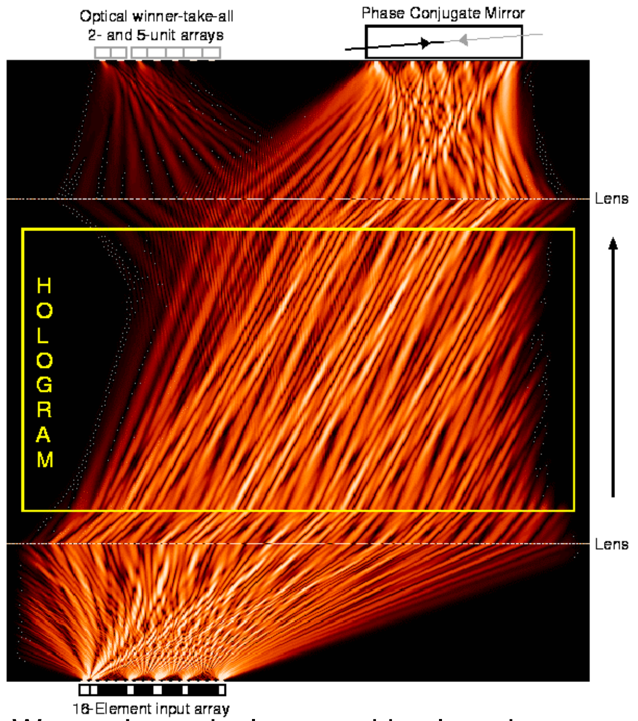
Agenda

- **Nonlinear optics background**
  * What is Nonlinear optics all about?
  * Why study yet another field?

- **Optical 3D Fourier transformation**
  * Design and analysis
  * Experimental results

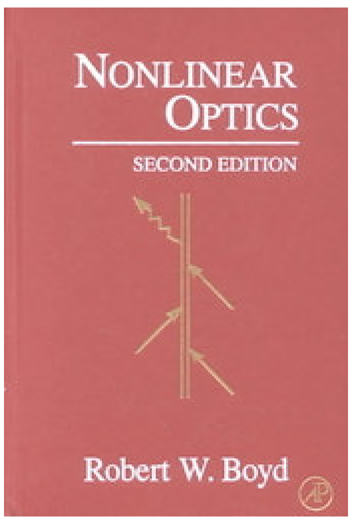
- **Potential of Nonlinear optics**
  * Well known applications

- **Conclusion**



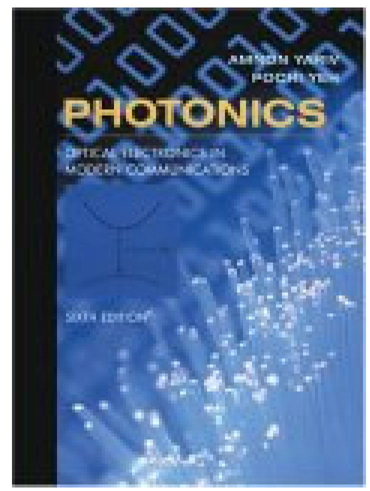
Prof. Kelvin Wagner's optical competitive learning system

Nonlinear optics background



Standard books:

- Nonlinear optics, R. Boyd
- Optical electronics, Yariv



What is Nonlinear optics all about?

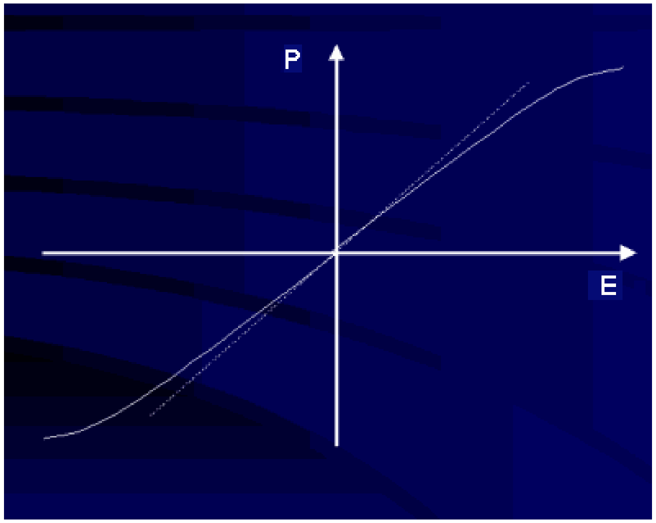
- Polarization in a nonlinear medium is a nonlinear function of the electric field.

$$P(t) \propto \chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \cdots$$
$$D = \varepsilon_0 E + P$$

- Hence, D is not linearly proportional to E in a nonlinear medium.

- Consequently, D (not E) is perpendicular to the direction of propagation k

- Typically observed at high light intensities.



Third order nonlinearity

Linear optics Vs Nonlinear optics

Linear optics	**Nonlinear optics**
Refractive index independent of light intensity	Refractive index varies with light intensity *(Kerr effect)*
Frequency of light is a constant	Frequency of light can be altered by passing through a medium *(Harmonic Generation)*
Photons do not interact	Photons do interact *(Optical Amplification)*
Obeys the principle of superposition	Damn superposition!

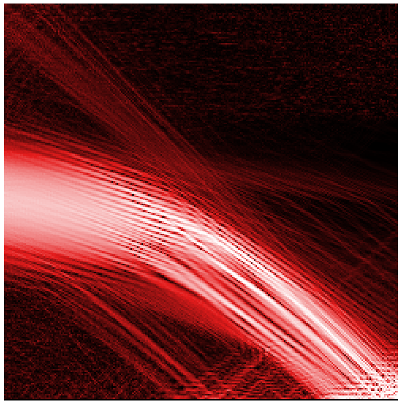
Why study yet another field?

- NLO is considered to be one of the challenging domains of optics (generally disliked by students and loved by professors ☺)

Some cool motivations:

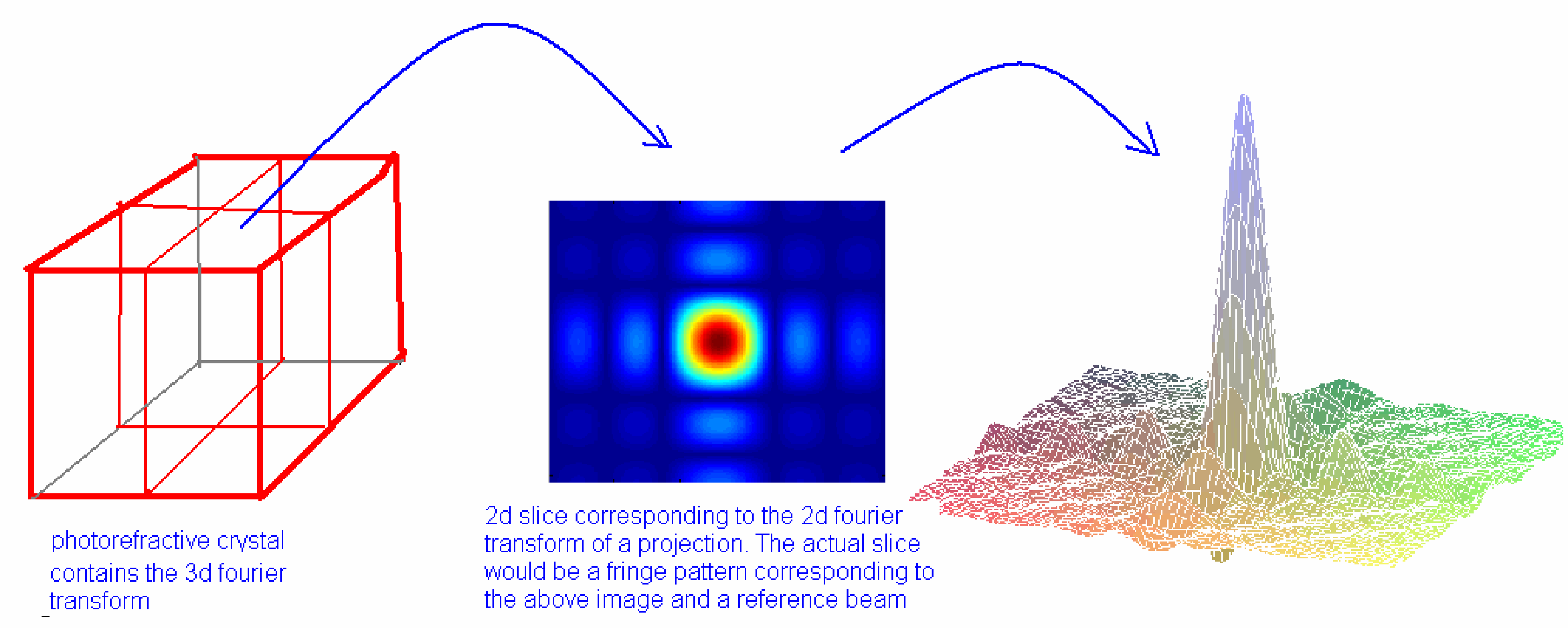
- In nonlinear optics, light can "disobey" the law of reflection!
- Sell IR and buy Green – where else is this possible?
- Imaging without a lens!
- Self focusing (shine light* on a crystal and focus it)

  * conditions apply
- Eliminate intra-cavity medium distortions in a resonator
- And finally, create 3D Fourier transforms and recover 3D objects at a later point of time. New!

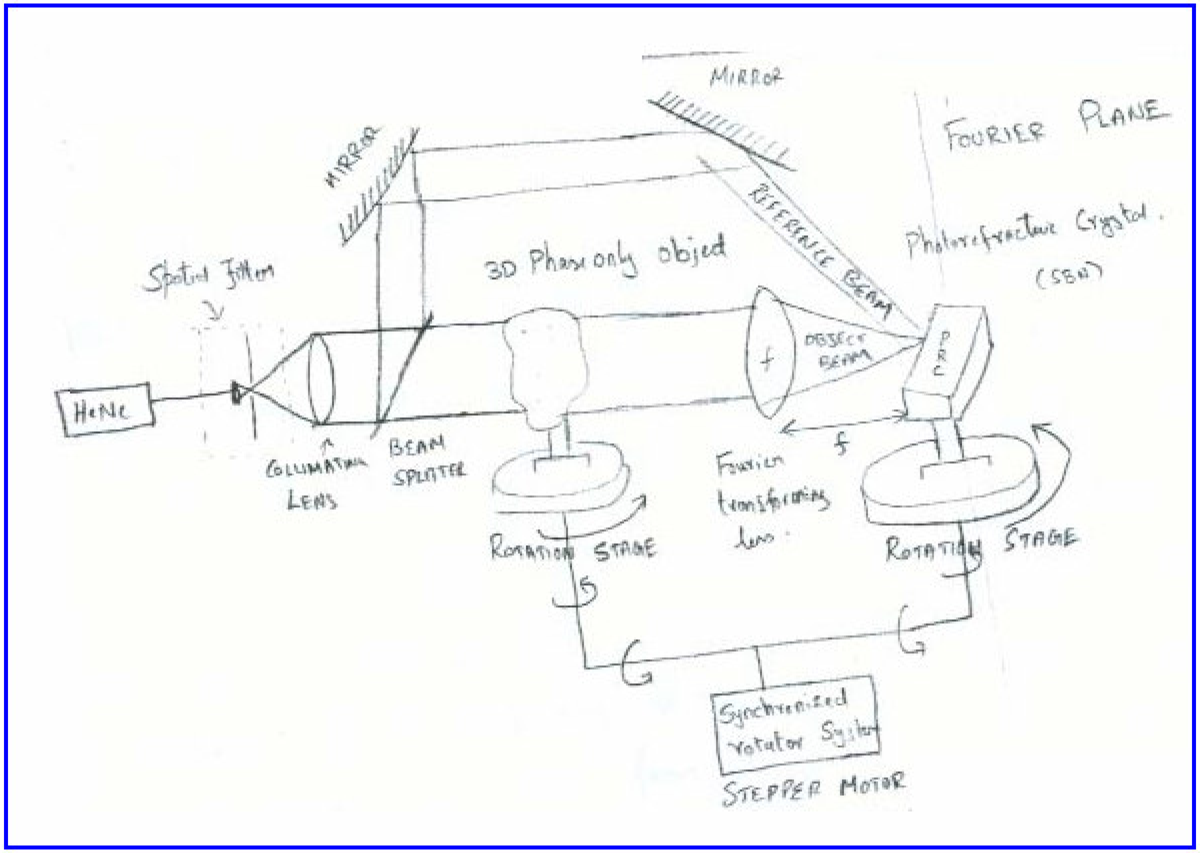


Self-pumped phase conjugation in Barium Titanate

Optical 3D Fourier Transformation

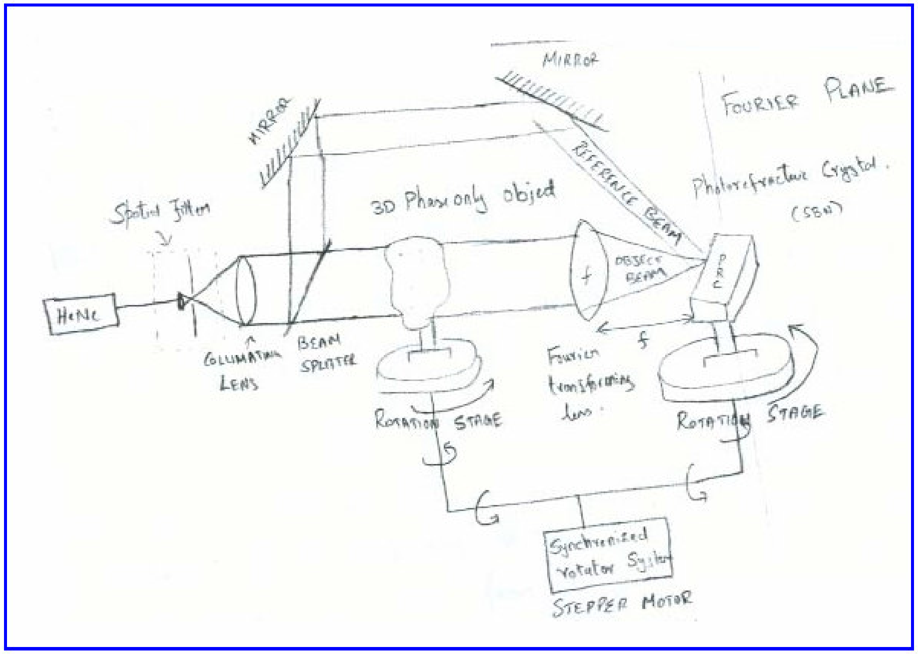


Setup for recording 3D Fourier Transform



Setup for recording 3D Fourier Transform

- Spatially coherent source
- Input to the Fourier transforming lens is a 2D projection of the 3D phase object.
- The photorefractive crystal sits on the fourier plane of the lens
- The object beam interferes with the reference beam, there by creating interference fringes, which is recorded inside the crystal as a 2D slice.
- Both the object and the crystal are synchronously rotated to record 2D FTs of multiple projections.

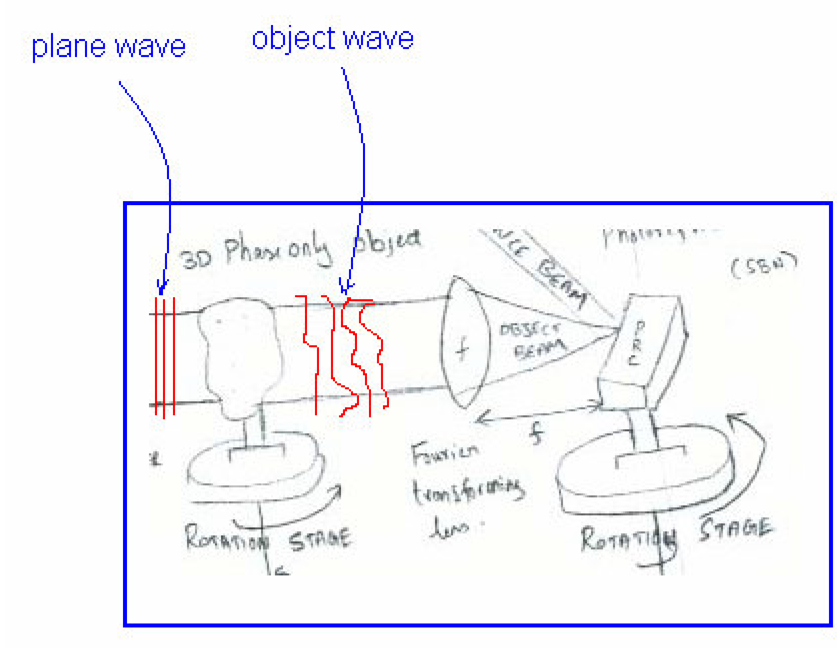


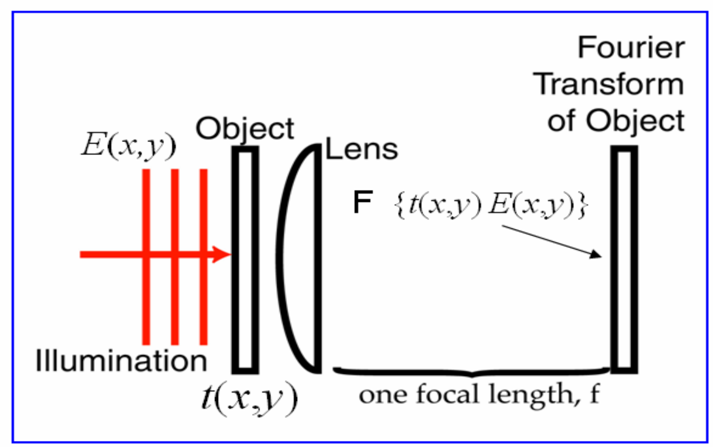
How does this work?

- The plane wave, after passing through the object, is not plane anymore!
- Different parts of the erstwhile plane wave are selectively delayed according to the thickness/refractive index of the object.
- How can a lens make a fourier transform?
  * Fraunhofer diffraction theory

$$E(x_1, y_1) \propto \iint \exp\left\{-i\frac{k}{f}(x_0 x_1 + y_0 y_1)\right\} t(x_0, y_0) E(x_0, y_0)\, dx_0\, dy_0$$

- If the object is placed in the front focal plane, the fourier transform is exact! Otherwise, it can be shown that there would be an additional phase curvature in the back focal plane.





How does this work?

- a(x,y) = object wave
- A(x,y) = reference wave
- I(x,y) = Intensity of the sum of object and reference waves

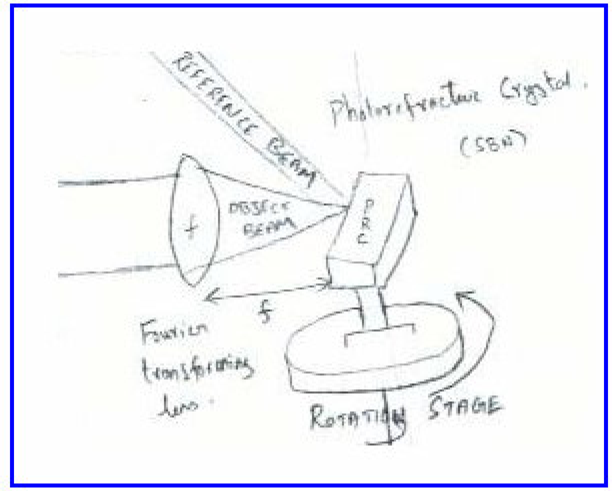
$$a(x, y) = |a(x, y)| \exp[-j\phi(x, y)]$$

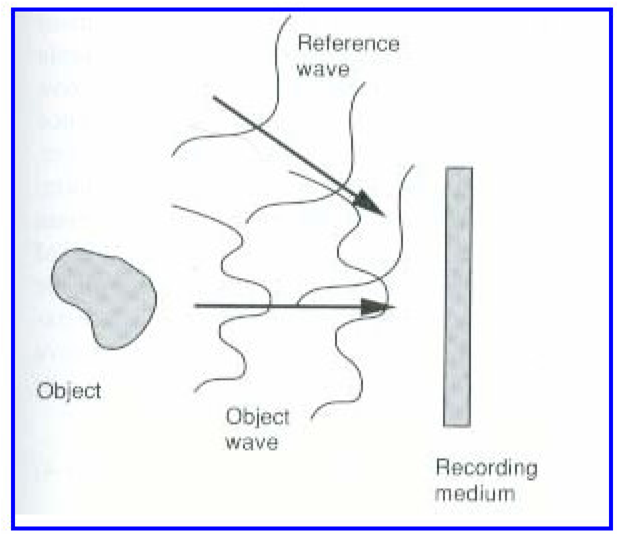
$$A(x, y) = |A(x, y)| \exp[-j\psi(x, y)]$$

$$\mathcal{I}(x, y) = |A(x, y)|^2 + |a(x, y)|^2 + 2|A(x, y)||a(x, y)| \cos[\psi(x, y) - \phi(x, y)].$$

- The important point is that, we record both amplitude and phase of the object beam!

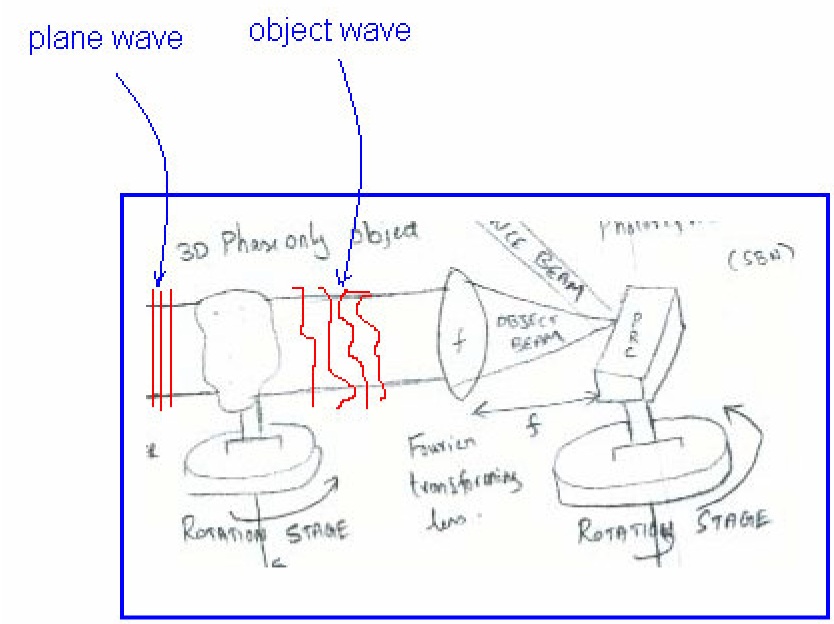
- Once recorded, the object beam can be reconstructed at a later point of time, by merely shining the reference beam on the recording medium (a.k.a hologram) *(more on this later..)*



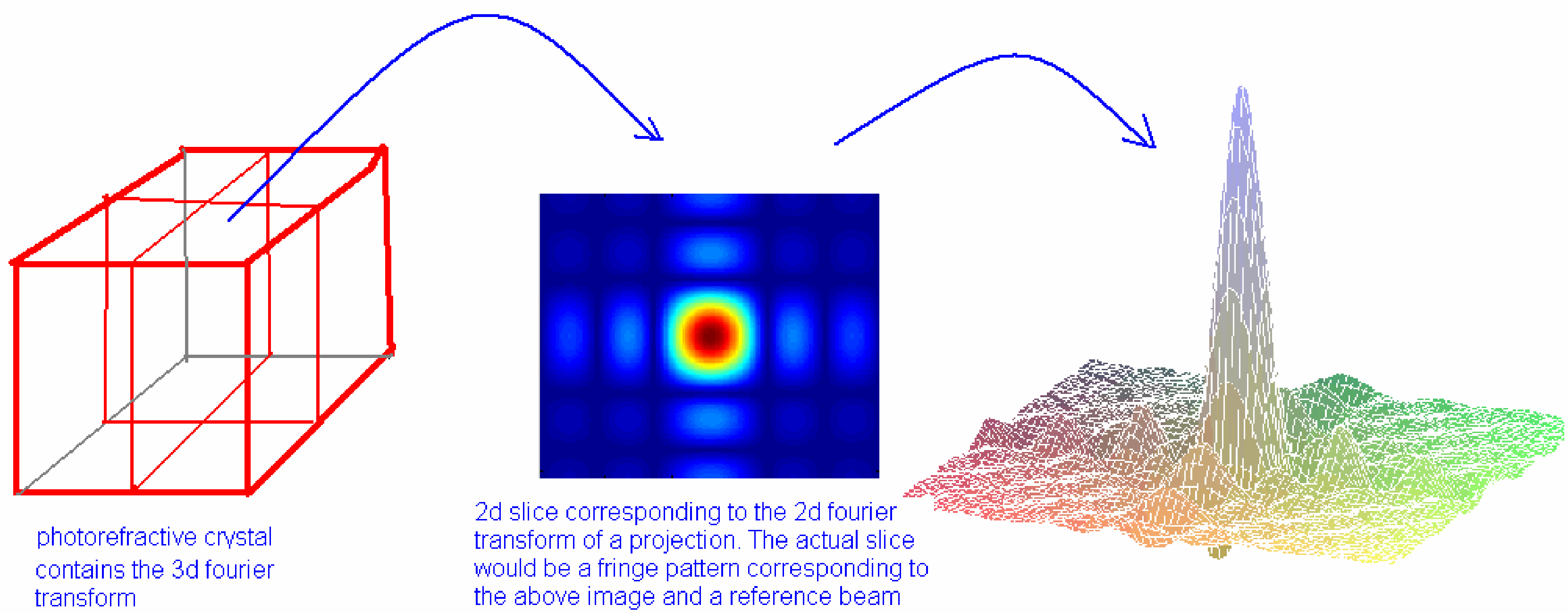


How does this work?

- So much for one recording the 2D fourier transform of one projection!
- Obviously, inorder to compeletely characterize a 3D object, we need to take multiple projections.
- This is done by rotating the object and the photorefractive crystal simultaneously.



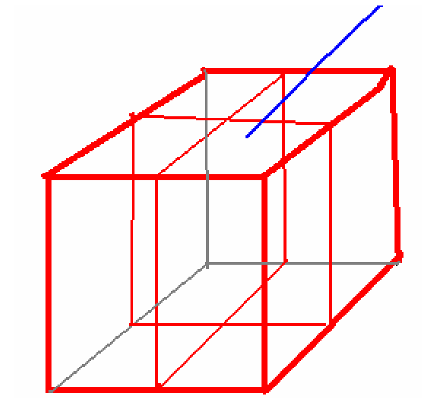
So, where is all this heading?



- At the end of the recording process, the crystal will have slices of 2D fourier transforms of different projections radially bisecting each other.

“ At the end of the recording process, the crystal will have slices of 2D fourier transforms of different projections radially bisecting each other”

So what? Where’s my 3D Fourier transform?

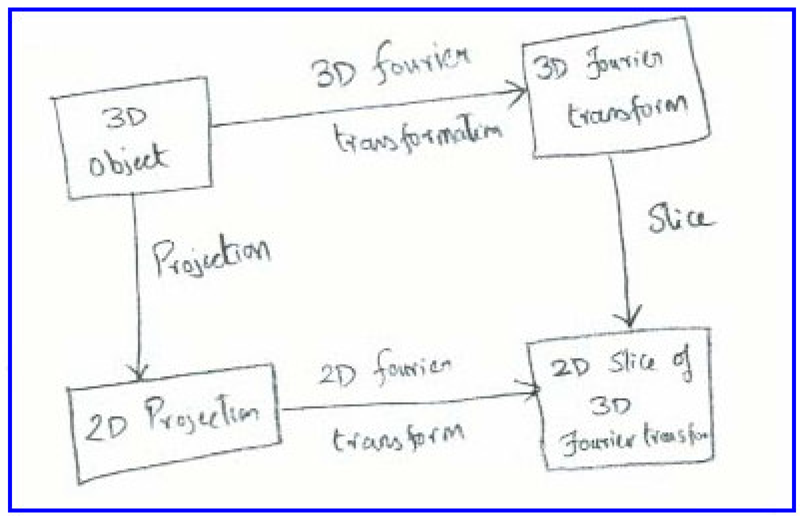


photorefractive crystal contains the 3d fourier transform

Fourier slice (Projection slice) theorem:

“2D slice of a 3D function’s Fourier transform is the Fourier transform of an orthographic integral projection of the 3D function”

What does this mean?



• We have the 2D fourier transforms of the projections arranged radially inside the crystal

• According to the theorem, what we have is indeed the 3D fourier transform!

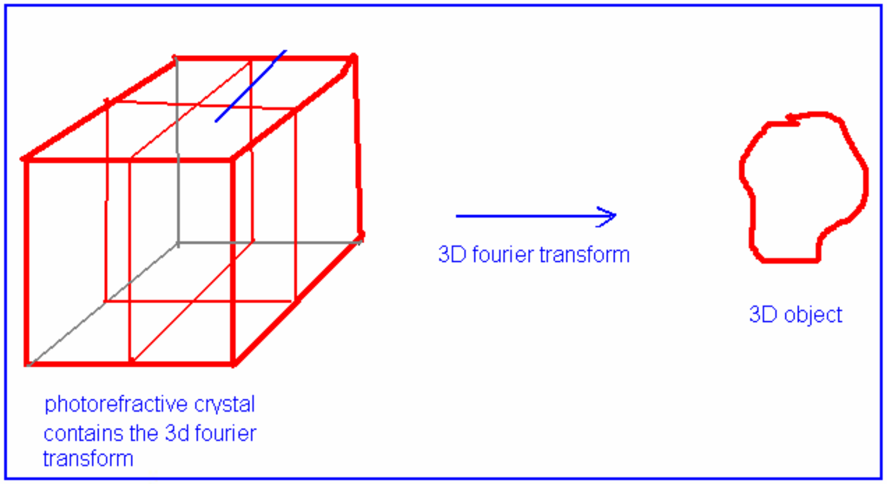
How to recover the 3D object back?

Born's approximation:
"If an object is weakly scattering, then, the scattered field of the object is actually the 3D fourier transform of the object"

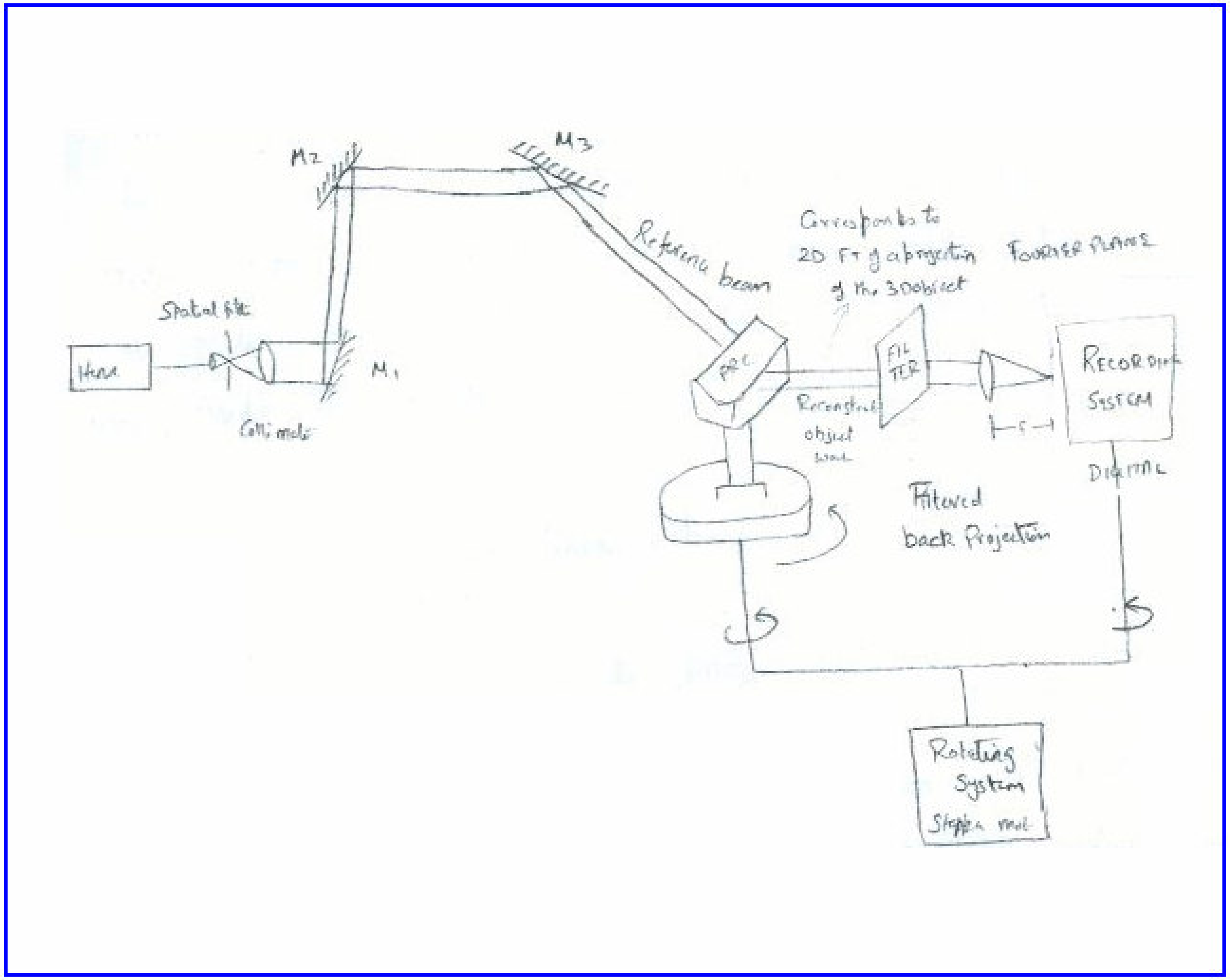
Fourier identity:
The fourier transform of the fourier tansform of a function is the function itself!

- So, if the born approximation is valid, the object can be essentially reconstructed by scattering.

- But, what if the weakly scattering approximation is not valid?

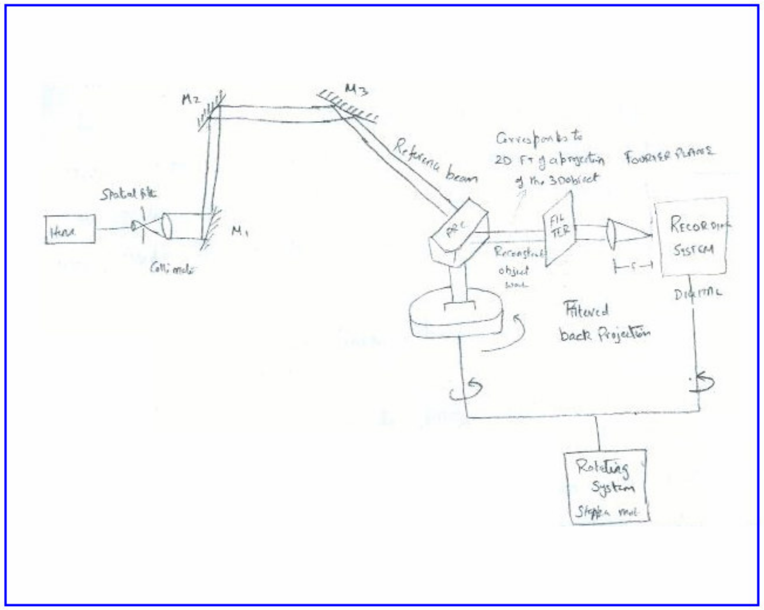


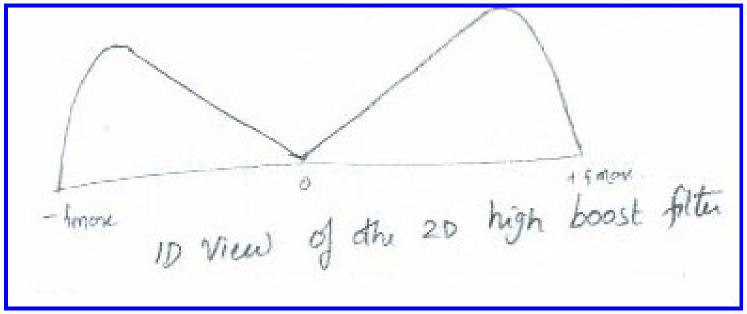
Optical reconstruction



Optical reconstruction

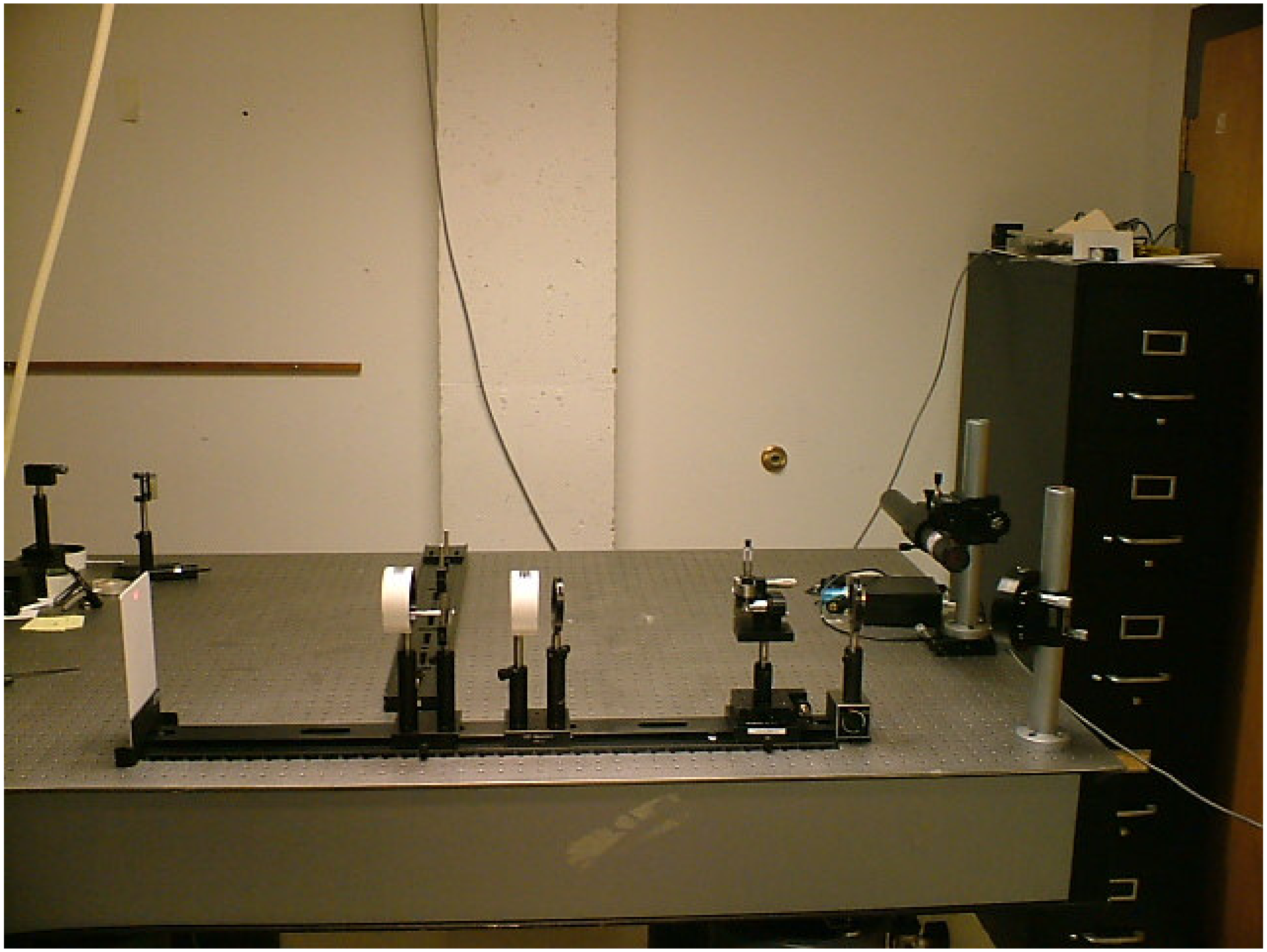
- Holographic reconstruction of the 2D fourier transform of projections
- Filter with a high boost spatial mask.
- The filtered back projection is obtained in the back focal plane of the Fourier transforming lens
- Used filtered back projection algorithm for recovering the object from projections.
- For each angle of the crystal, smear the filtered back projection (2D) in a 3D object matrix (rotated to the corresponding angle)





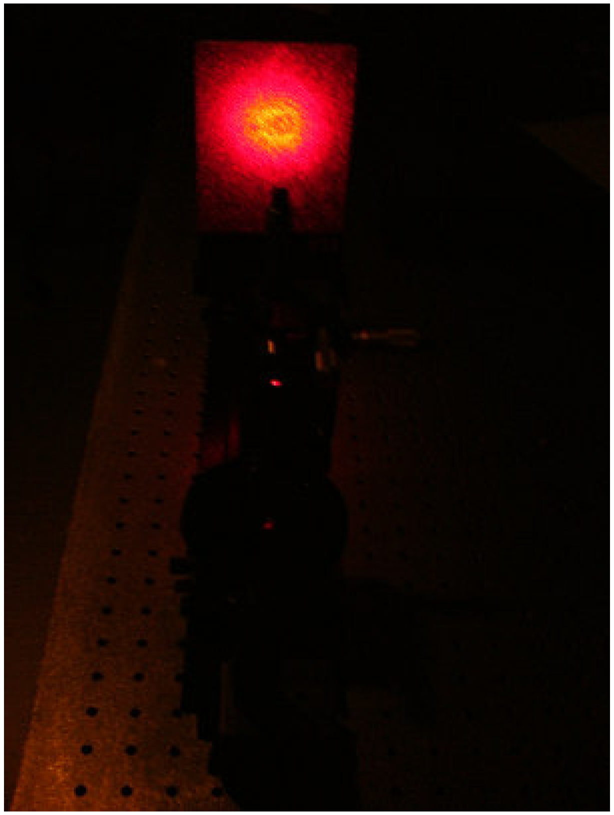
Experiments

Fourier transform setup

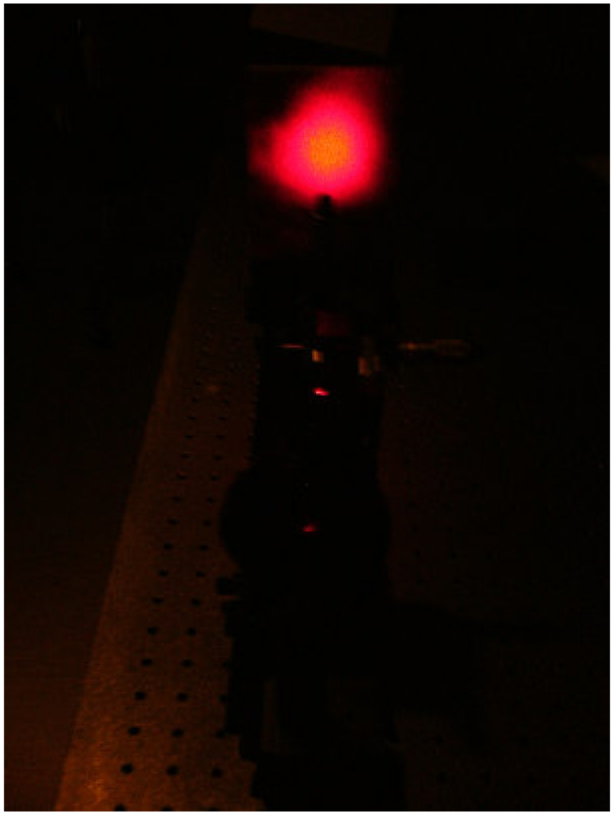


Experiments

spatial filtering



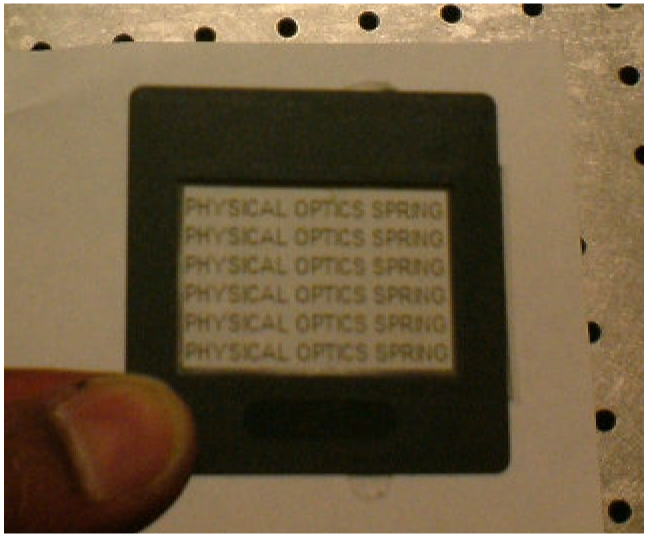
Before spatial filtering

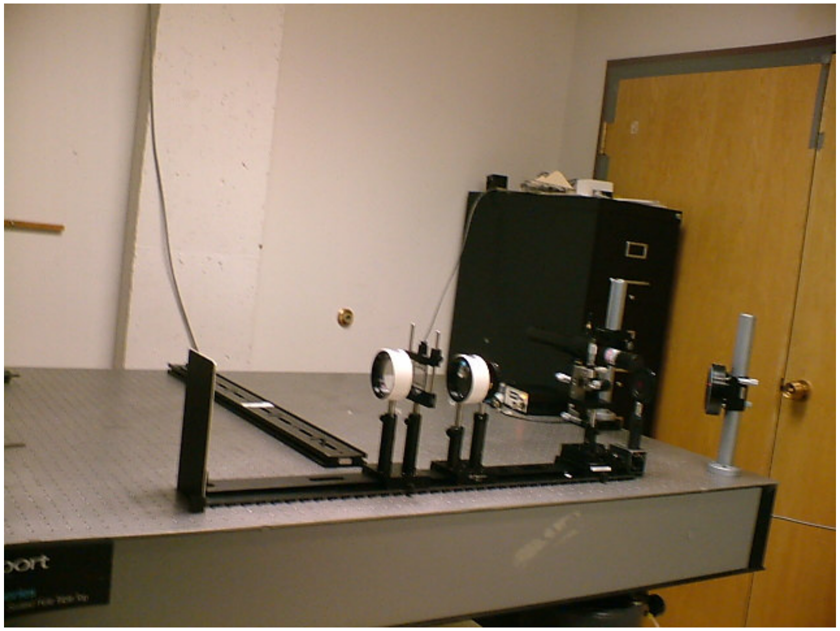


After spatial filtering

Experiments

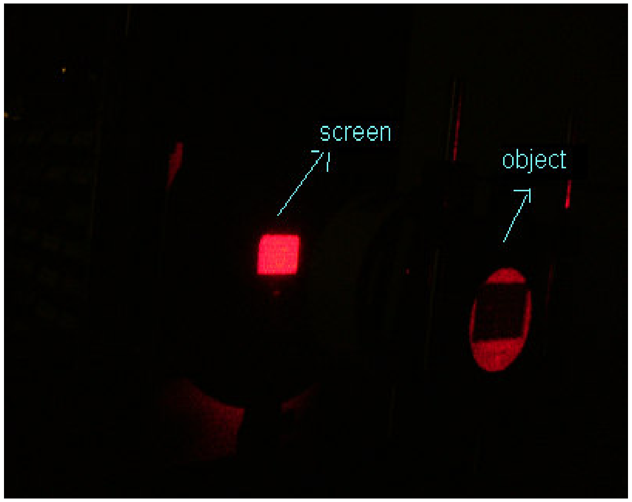
2D object used



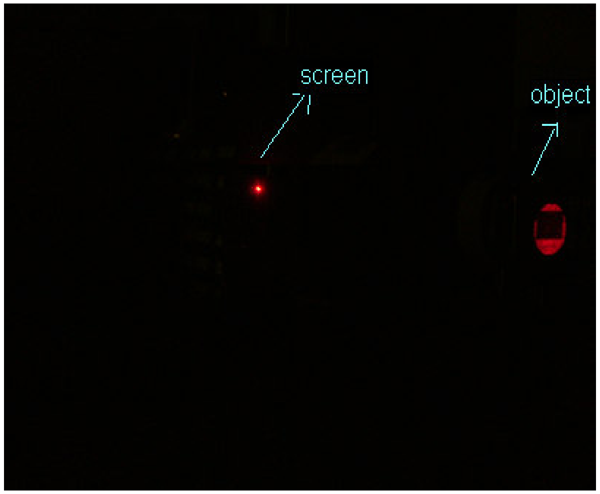


Experiments

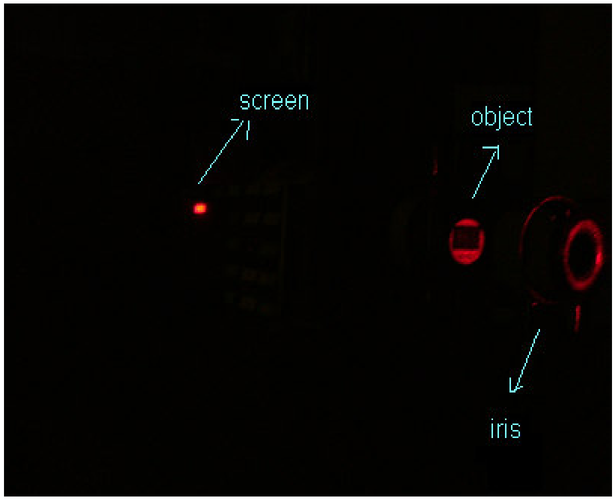
Fourier plane location



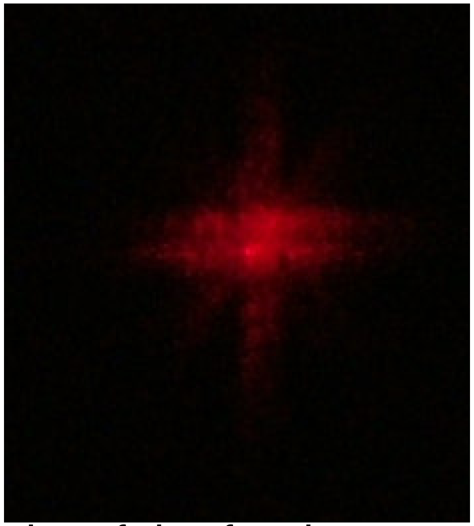
Before Fourier plane



Fourier plane



After Fourier plane

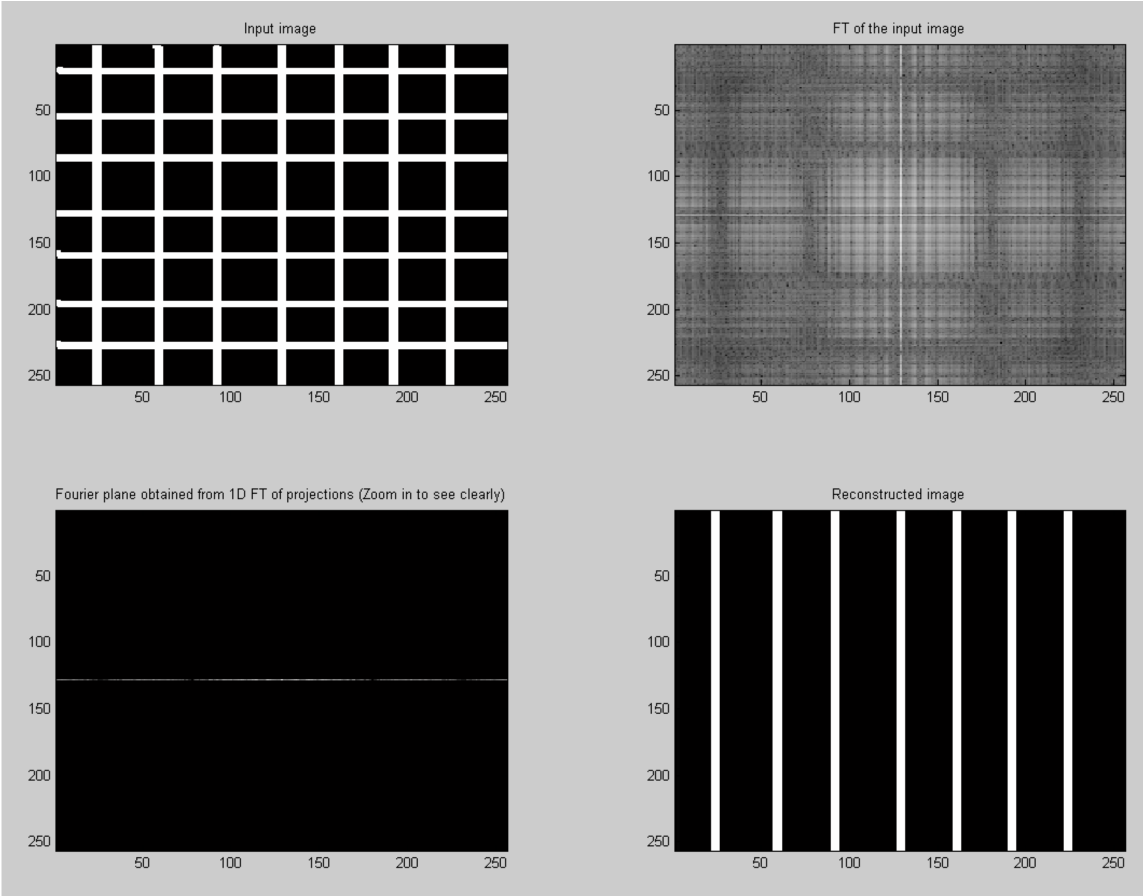

Intensity of the fourier transform

Experiments

3D Fourier Transformation

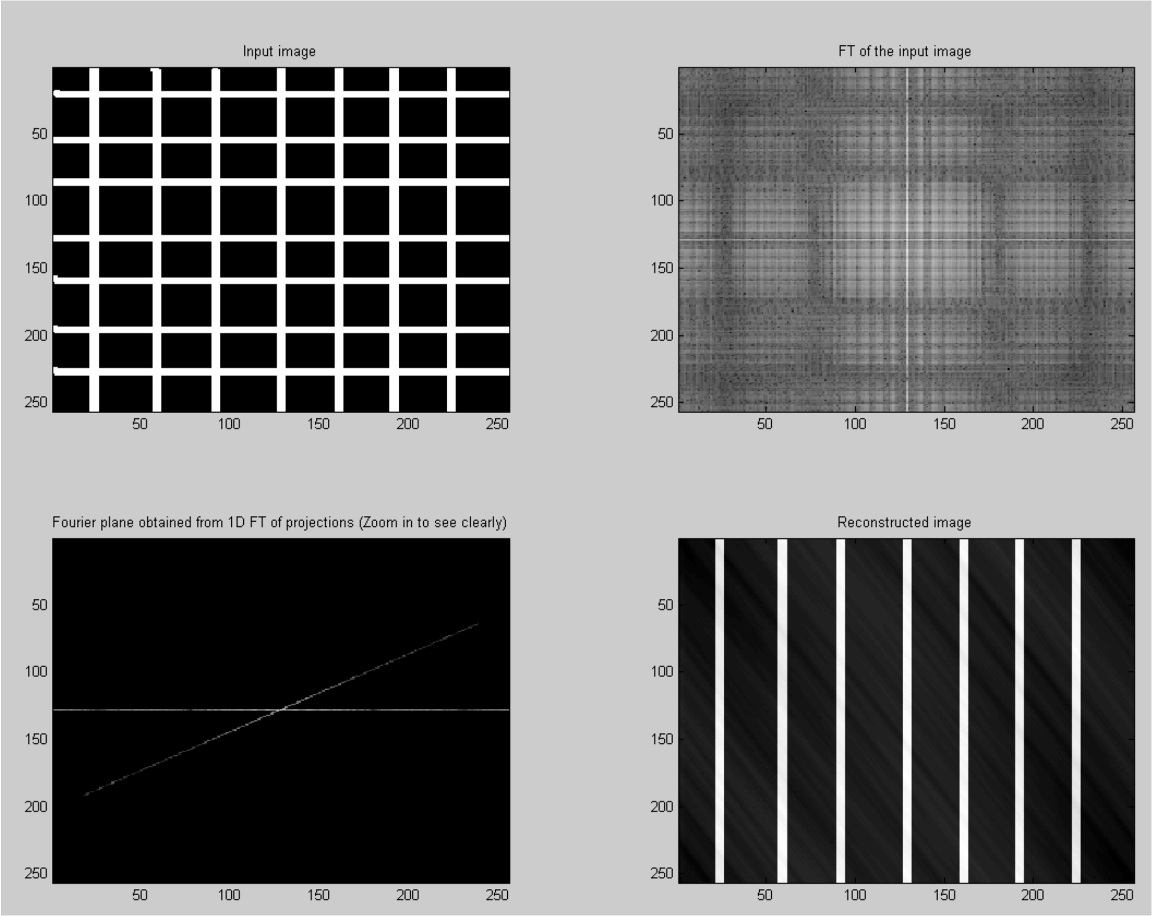
Simulations

Fourier Transformation
(theta = 0)



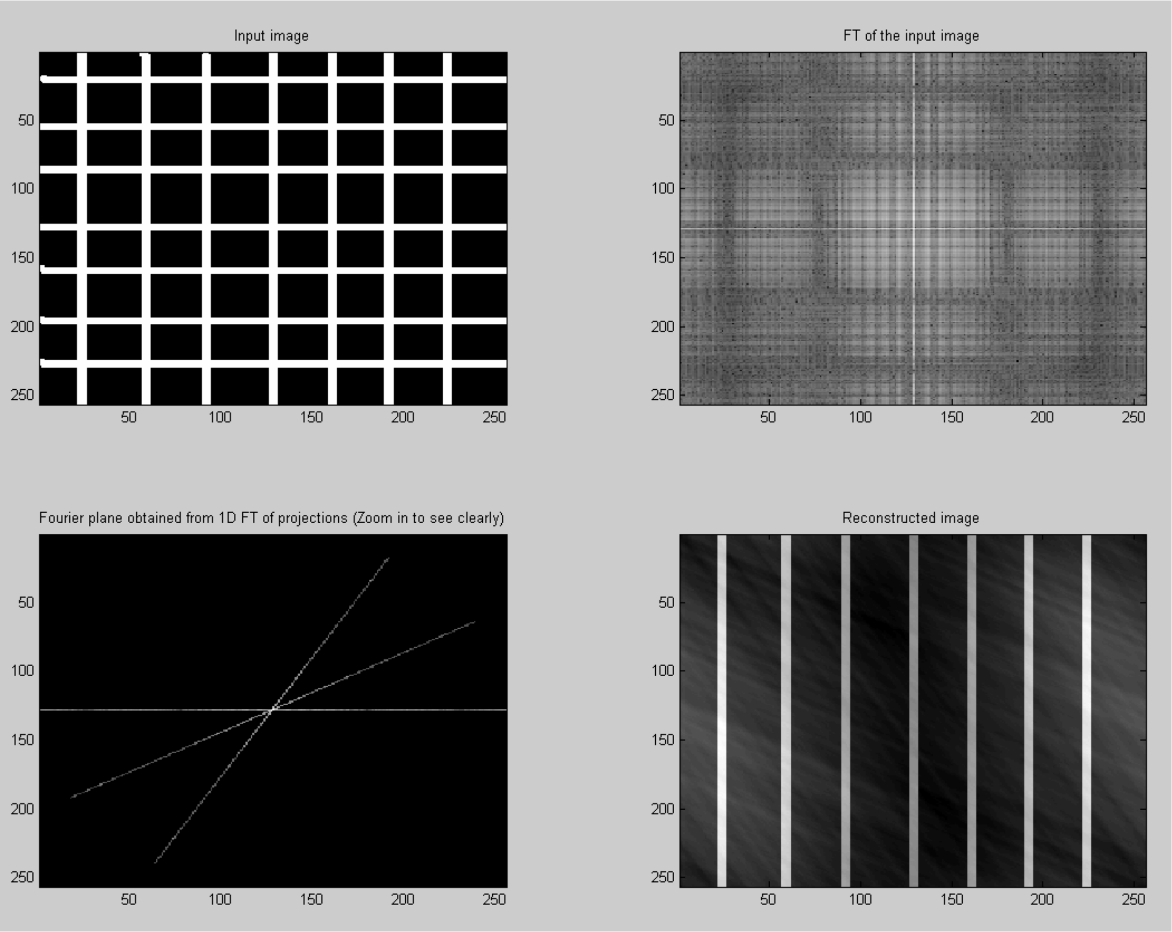
Simulations

Fourier Transformation
(theta = 30)



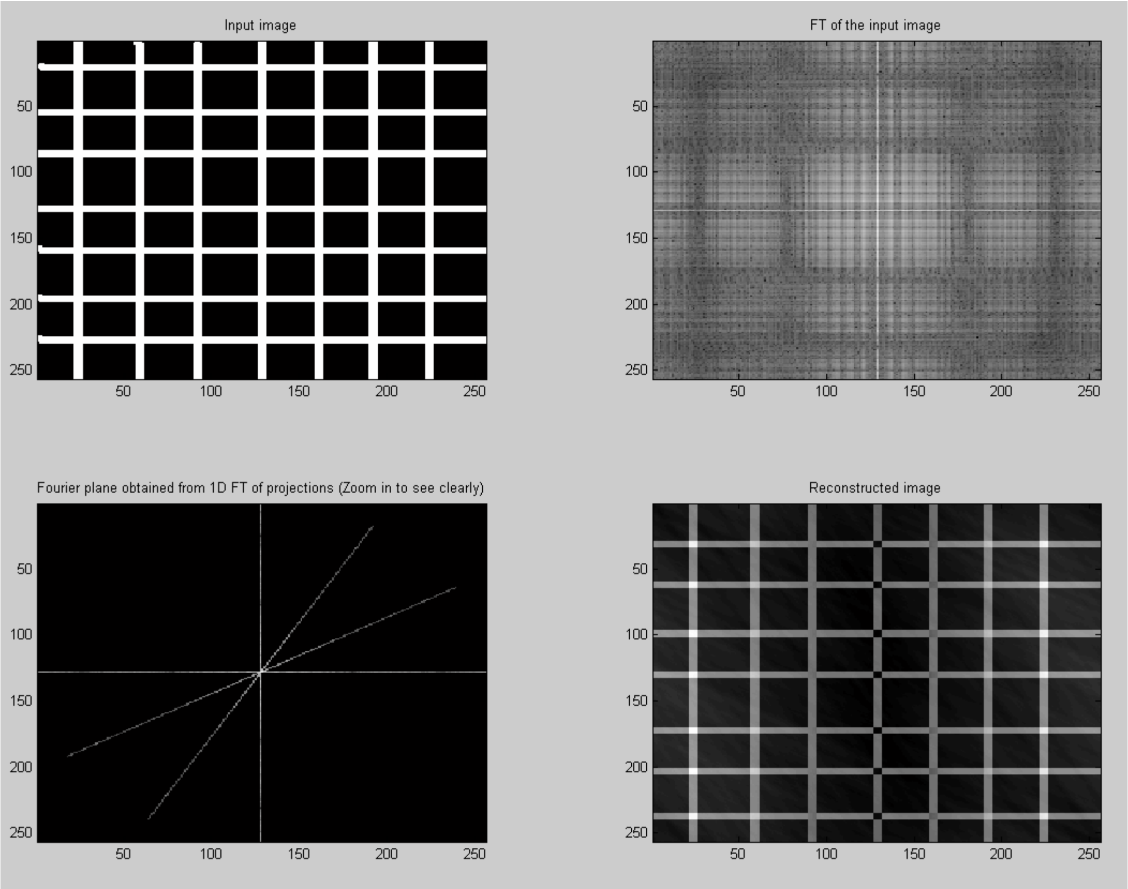
Simulations

Fourier Transformation
(theta = 60)



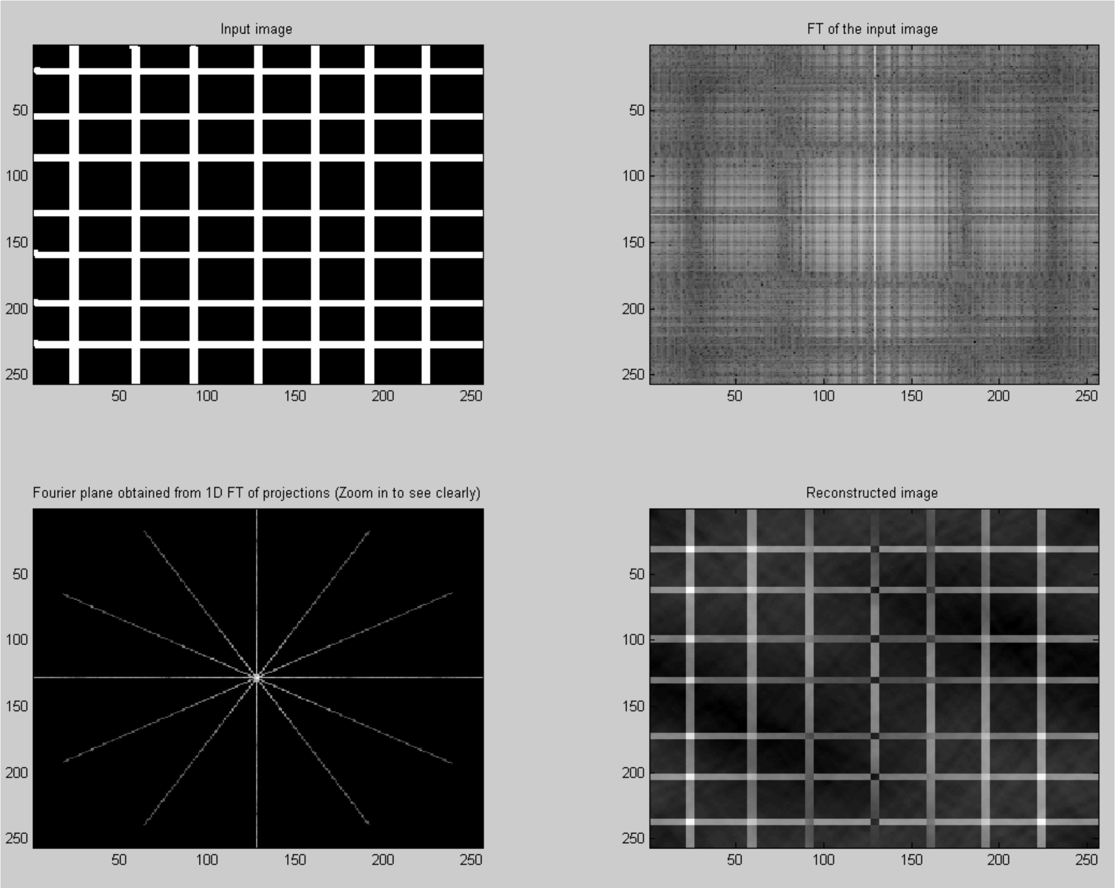
Simulations

Fourier Transformation
(theta = 90)



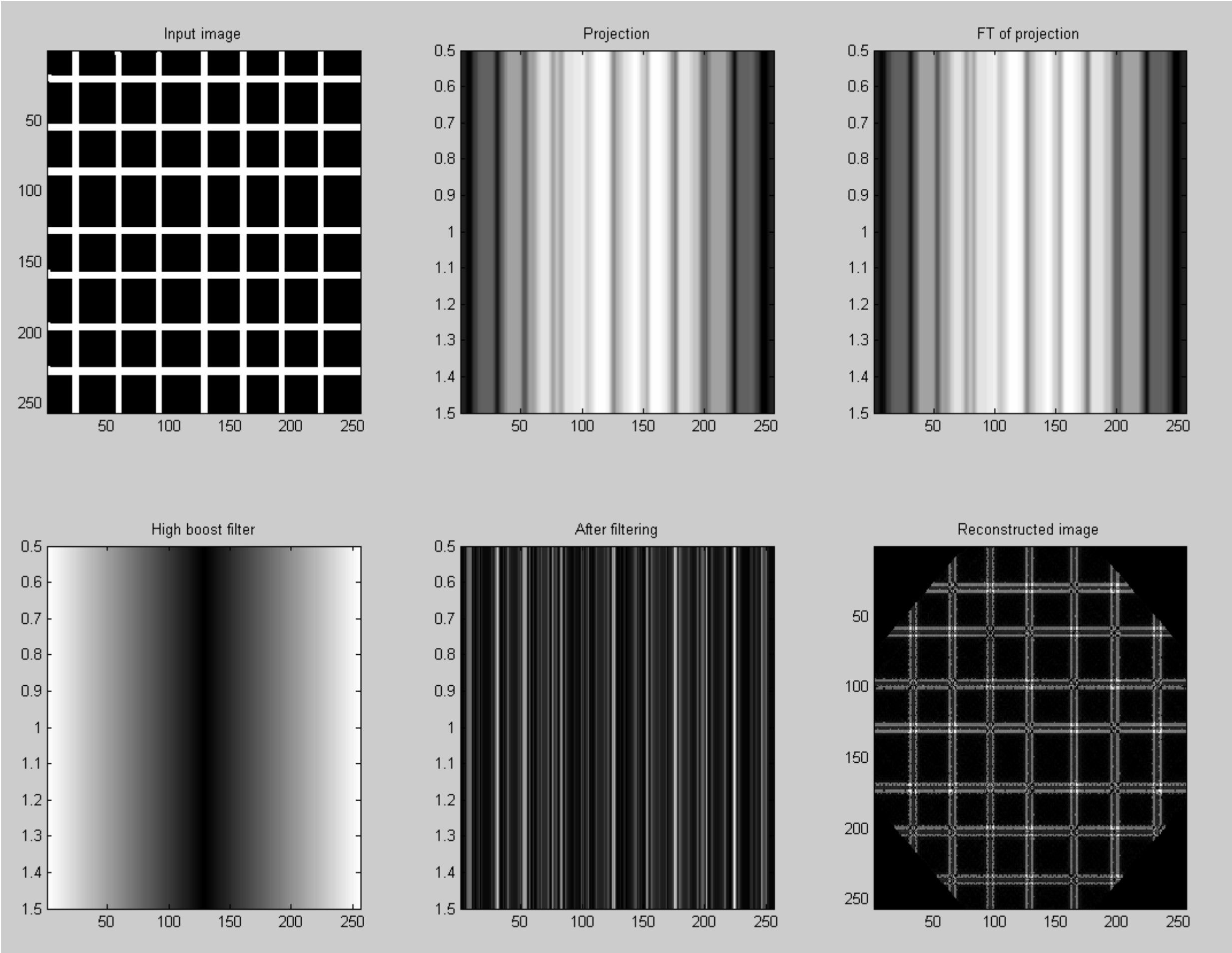
Simulations

Fourier Transformation
After rotations from 0 to 180 in steps of 30



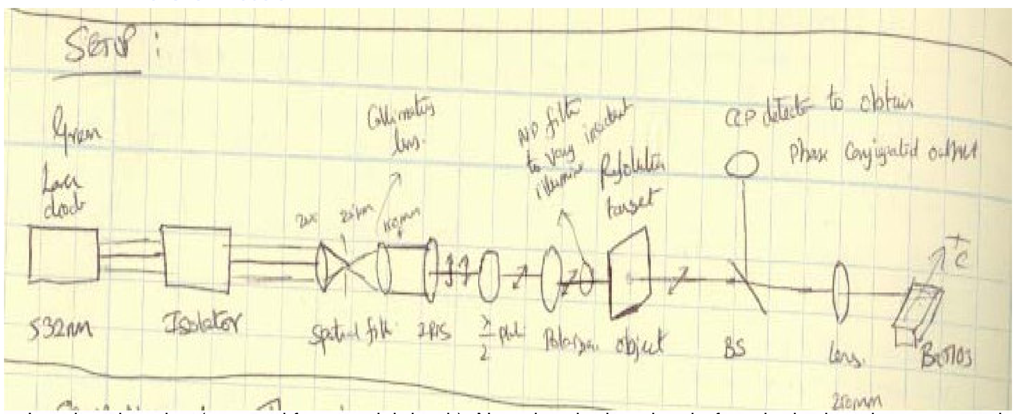
Simulations

Reconstruction using filtered back propagation
After rotations from 0 to 180 in steps of 30

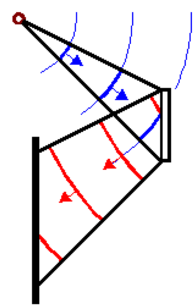


Potential of Nonlinear optics

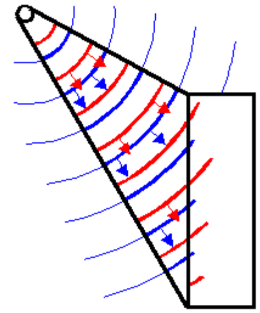
- Phase conjugate Mirrors retro reflect regardless of the angle of incidence.
- lensless imaging
- Self focusing
- Harmonic generation
- Elimination of intra-cavity medium distortions resonator



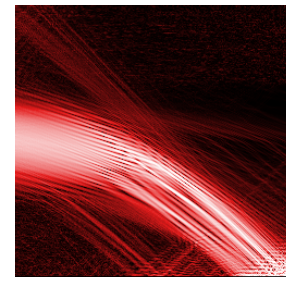
Lensless imaging (scanned from my lab book) Note that the lens just before the barium titanate crystal is used for focussing and not imaging



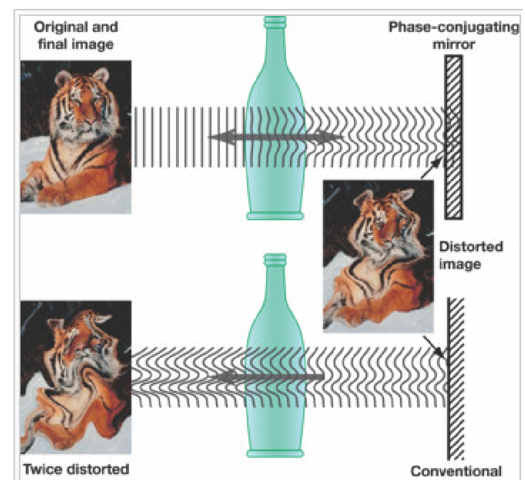
Ordinary mirror



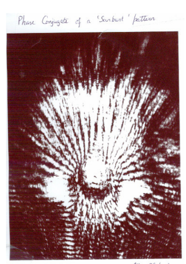
Phase conjugate mirror



Self-pumped phase conjugation in Barium Titanate

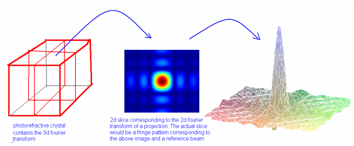


Distortion elimination in a cavity with a phase conjugate mirror

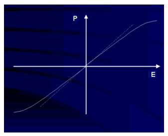


A real phase conjugate image that I imaged without a lens

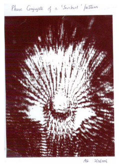
Project Contributions



- An optical way of recording 3D Fourier transforms, and reconstructing 3D objects back, was proposed. Experimental setup was discussed and MATLAB simulations were provided.



- An overview of Nonlinear Optics was discussed.



- Some key applications in use were analyzed.

Conclusion

- 3D Fourier transforms can be recorded and reconstructed optically.
- Experiments and simulations agree with theoretical predictions.
- Nonlinear optics opens up applications in information storage, harmonic generation and phase conjugation.

Acknowledgement

- Thanks to Prof. Carol Cogswell's ”Micro-Optical Imaging Systems Laboratory”, where most of this work was done.

References

- [1] Nonlinear optics, R. Boyd
- [2] Optical Electronics, Yariv
- [3] Applications of photorefractive crystals, SI stepnov, Rep prog phy (1994)
- [4] Principles of optics, Born and Wolf
- [5] Introduction to Fourier optics, Goodman
- [6] Fundamentals of photonics, Saleh and Teich
- [7] http://www.futureworld.dk/tech/ether/phasecon/phasecon.htm
- [8] http://en.wikipedia.org/wiki/Nonlinear_optics
- [9] Photorefractive crystals lab, Advanced Optics Lab, CU Boulder
  http://optics.colorado.edu/~kelvin/links/opticslab/pr01.pdf

Questions?

Interested in Nonlinear optics? Prof. Kelvin Wagner is teaching it in Fall 2006!

ECEN6016 – Nonlinear/Crystal Optics

- Thank You!