A Fast Optical Propagation Technique for Modeling Micro-Optical Systems

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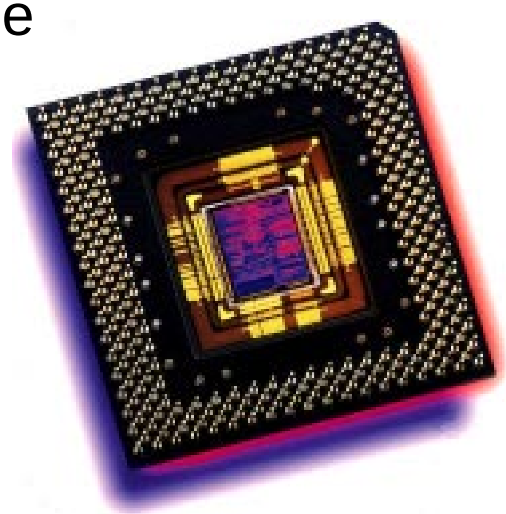
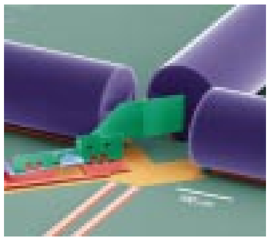
Overview

- Multi-domain micro-systems
- System-level CAD for mixed-signal, multi-domain systems
- Optical propagation
- Angular spectrum technique
- GLV simulation and analysis
- Summary and future work

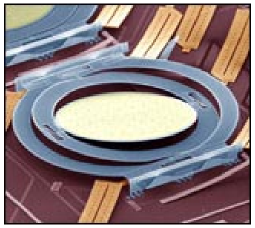
Optical Microsystems

- Applications: switching, projection, scanning, display, printing, sensing, modulating, and data storage
- Optics is good for information transport
  - High parallelism and small skew
  - High speed with low crosstalk
  - Low power and low latency
  - Fan-in/fan-out and permutations
- Electronics is good for computation
- Micro-mechanics is good for interactions with the “real world”
  - Sensing, actuating, switching

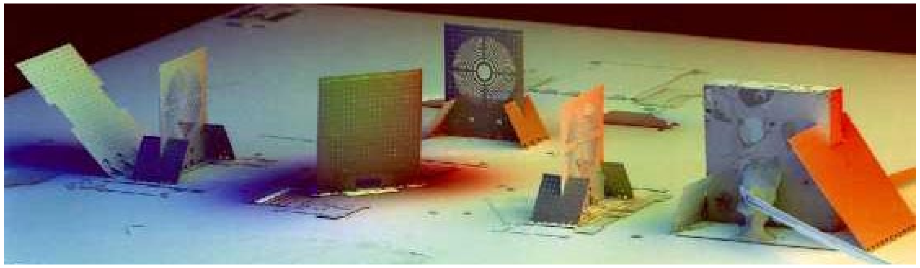




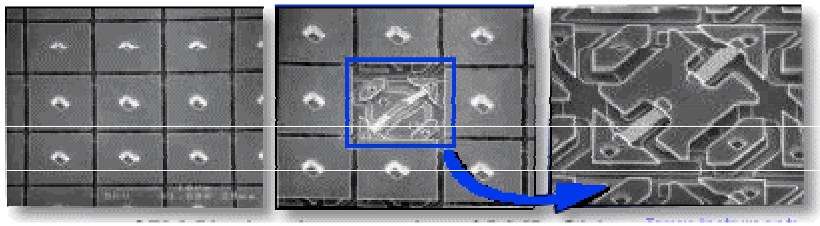
Bell Labs



Lucent



UCLA - Integrated Free-Space Optical Disk Pickup Head



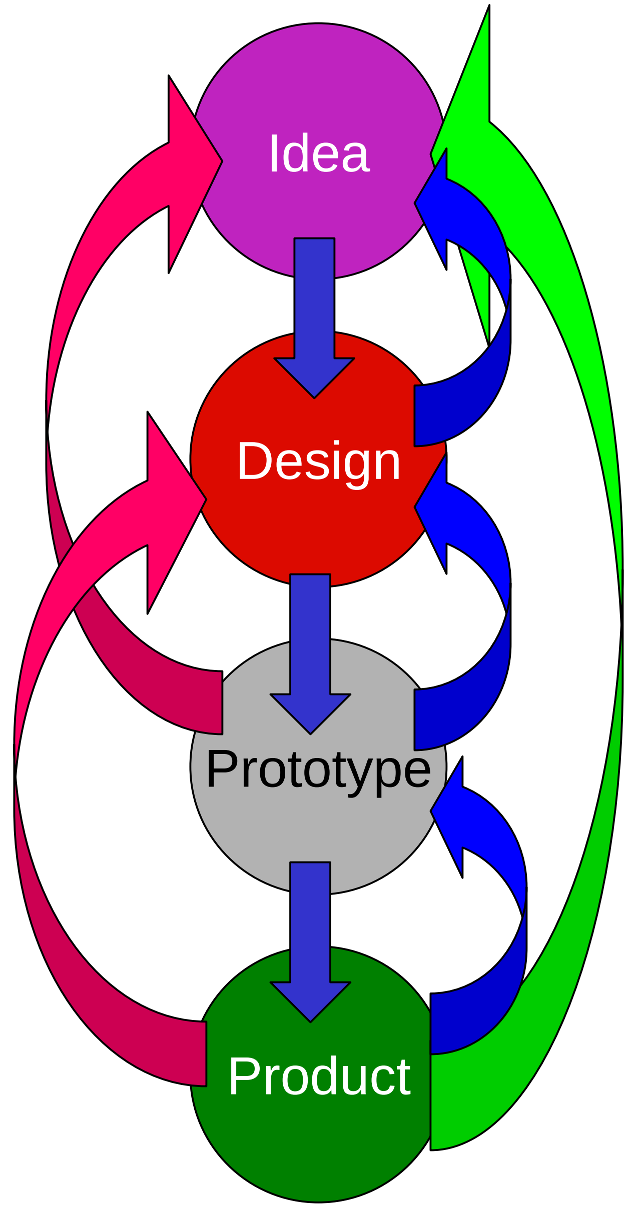
Texas Instruments - DMD

Mixed-Signal, Multi-Domain CAD

- CAD for optical MEM systems
  - Reduce costly prototyping
  - Test feasibility and effectiveness
  - Perform architecture vs. technology trade-offs

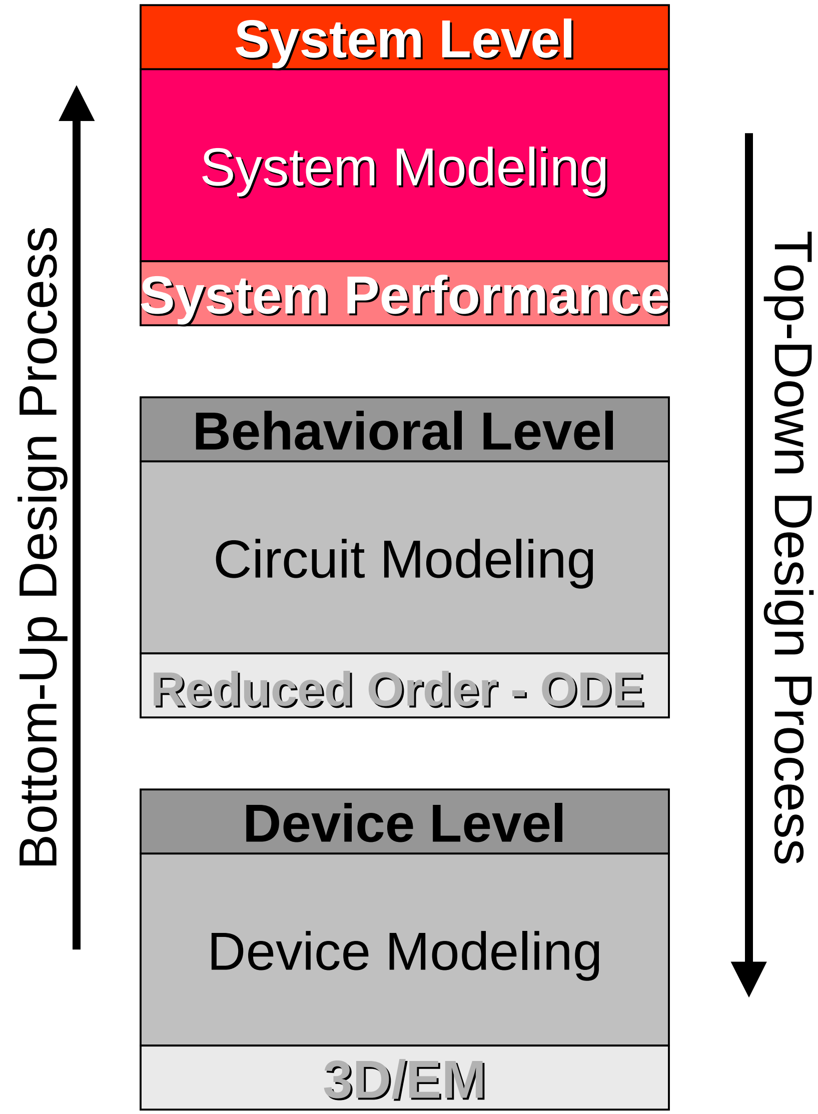
Goal: reduce the time-to-market and find the unexpected design flaw

- Difficulties
  - Mixed domains & interactions
    - *Optical*
    - Electrical
    - Mechanical
  - Modeling levels
    - Device
    - Behavioral
    - *System*



System-Level Simulation

- Ensemble of component behavioral models
- Fast solvers at component/ behavioral level
- Domain specific signal propagation models
- Global discrete event dataflow
- Ensemble performance measures:
  - BER
  - optical/electrical crosstalk
  - insertion loss
  - packaging/alignment tolerances
  - thermal effects
  - etc.

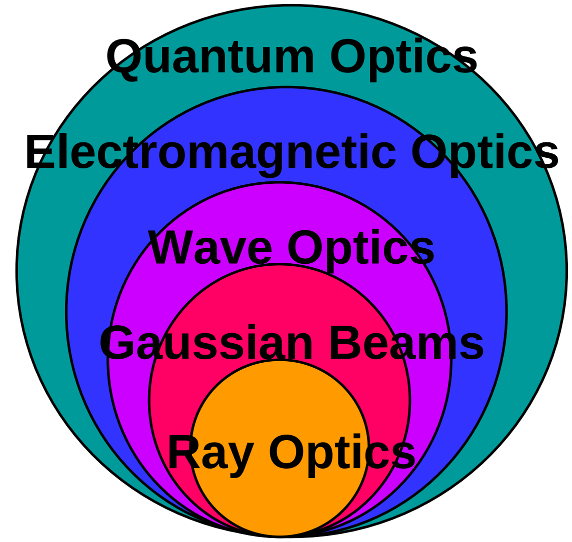


Optical Propagation Models

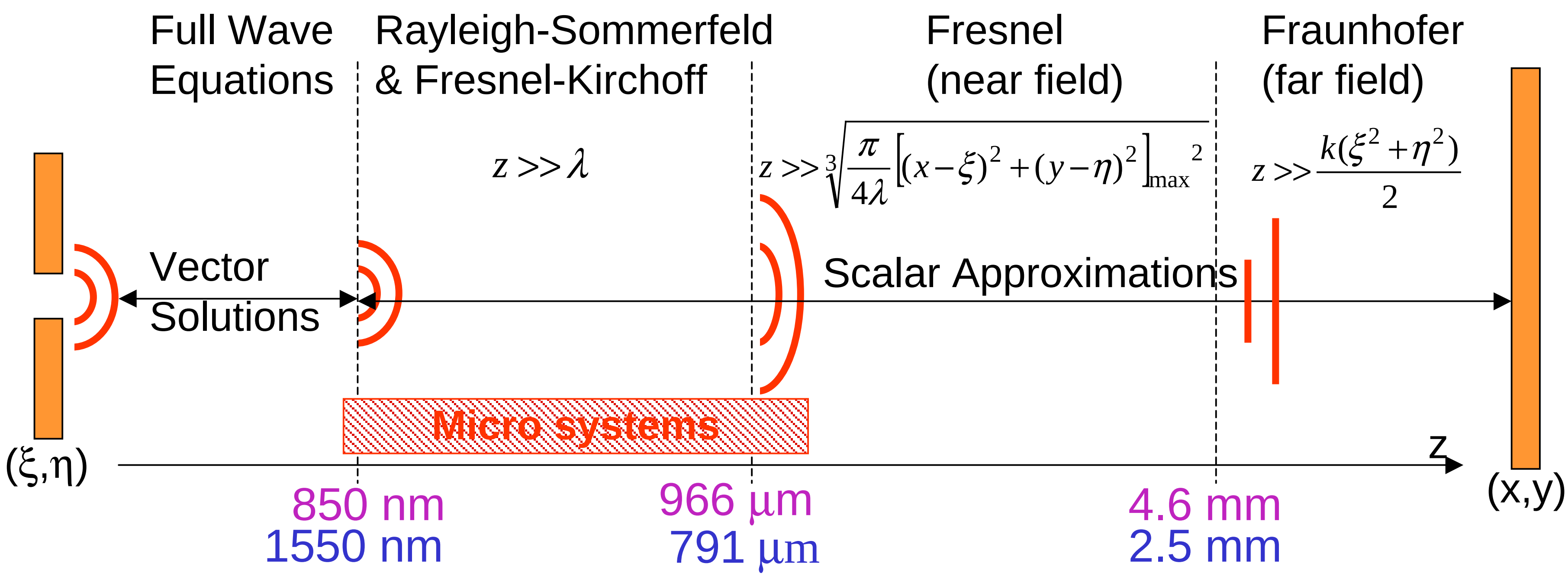
Increased Computation Speed

Increased Accuracy

- Geometric Ray Propagation
  - Positions and angles
  - No optical signal characterization
- Gaussian Propagation
  - 8 scalar parameters - z0, x, y, λ, etc.
  - Fast computation - no explicit integration at each component
  - Limited diffraction compensation
- Scalar Diffraction Propagation
  - Fraunhofer, Fresnel, Rayleigh-Sommerfeld
  - 2D complex wavefront
  - Propagation by summation of wavefronts
- Full-Wave Propagation
  - Finite Difference, Finite Element, Rigorous Coupled Wave, Boundary Integral
  - Computationally intensive



Validity of Scalar Models



Examples: 50 μm Aperture, 200 μm Observation, λ=850 nm, λ=1550 nm

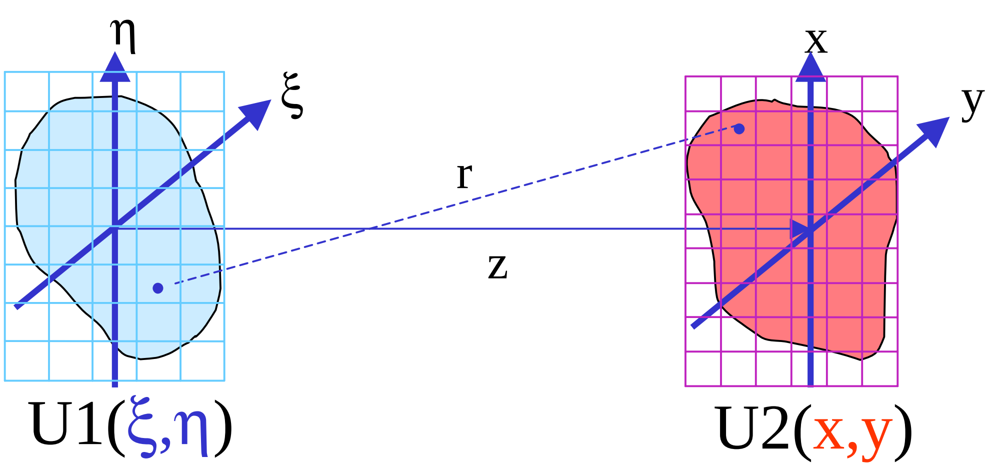
- Fraunhofer Approximation - Assume planar wavefronts
- Fresnel Approximation - Assume parabolic wavefronts
- Rayleigh-Sommerfeld Formulation - Spherical wavefronts

Rayleigh-Sommerfeld Formulation

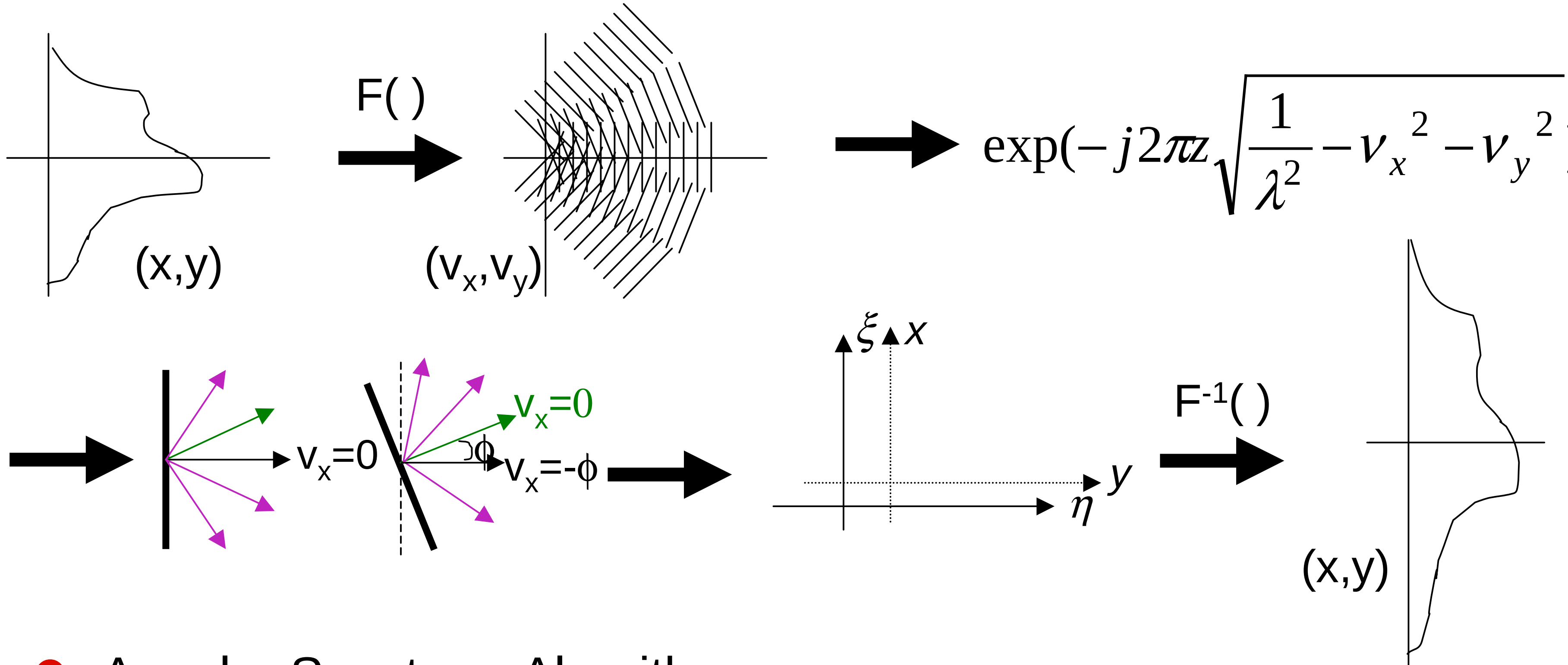
- Rayleigh-Sommerfeld Formulation
  - Diffractive component >> λ
  - Distance to observation plane >> λ

$$U2(x,y) = \frac{z}{j\lambda} \iint U1(\xi,\eta) \frac{e^{jkr}}{r^2} \partial\xi \partial\eta$$

- Implementation
  - Huygens-Fresnel principle
  - Direct Integration
    - Computational Order: $O(N^4)$



Rayleigh-Sommerfeld: Angular Spectrum



$$\exp\left(-j2\pi z\sqrt{\frac{1}{\lambda^2}-\nu_x^{\;2}-\nu_y^{\;2}}\right)$$

- Angular Spectrum Algorithm:
  - Decompose wavefront into sum of angled plane waves using FFT
  - Multiply with phase function for propagation
  - Map spatial frequencies into tilted coordinate system
  - Use Fourier shifting theorem for offset plane
  - Sum plane waves into wave function with inverse FFT

Angular Spectrum and the Rayleigh-Sommerfeld Formulation

- Rayleigh-Sommerfeld Formulation:

$$U2(x,y,z) = -\frac{1}{2\pi}\iint U1(\xi,\eta,0)\times\frac{\partial}{\partial z}\frac{e^{-jkr}}{r}\partial\xi\partial\eta$$

- Equivalently:

$$U2(x,y,z) = \frac{1}{2\pi}\iint U1(\xi,\eta,0)\times\frac{e^{-jkr}}{r}\frac{z}{r}(jk+\frac{1}{r})\partial\xi\partial\eta$$

$$r = \sqrt{z^2+(\xi-x)^2+(\eta-y)^2} \qquad k = \frac{2\pi}{\lambda}$$

- Convolution: Complex wavefront & propagation through free-space:

$$U2(x,y,z) = U1(\xi,\eta,0)\otimes\frac{1}{2\pi}\frac{\partial}{\partial z}\frac{e^{-jkr}}{r}\partial\xi\partial\eta$$

Angular Spectrum and the Rayleigh-Sommerfeld Formulation

- Convolution in the Spatial Domain is Multiplication in Frequency Domain:

$$U2(x,y,z) = F^{-1}\{F\{U2(x,y,z)\}\}$$

$$U2(x,y,z) = F^{-1}\left\{F\{U1(\xi,\eta,0)\}\times F\left\{\frac{1}{2\pi}\frac{\partial}{\partial z}\left[\frac{e^{-jkr}}{r}\right]\right\}\right\}$$

- The FFT of the complex wavefront is performed….

$$F\{U(\xi,\eta,0)\} = \iint U1(\xi,\eta,0)\times\exp(-j2\pi(\nu_x\xi+\nu_y\xi))\partial\xi\partial\eta$$
$$= A_0(\nu_x,\nu_y,0)$$

- …and is multiplied to the Free-Space transfer function

$$F\left\{\frac{1}{2\pi}\frac{\partial}{\partial z}\left[\frac{e^{-jkr}}{r}\right]\right\} = \exp(-j2\pi z\sqrt{\frac{1}{\lambda^2}-\nu_x{}^2-\nu_y{}^2})$$

Spatial Frequencies

- Spatial frequencies describe the propagating plane waves

$$A(v_x, v_y, 0) = \iint U(x, y, 0) \exp[-j2\pi(v_x x + v_y y)]\, \partial x \partial y$$

- Plane waves of the form (in 3D):

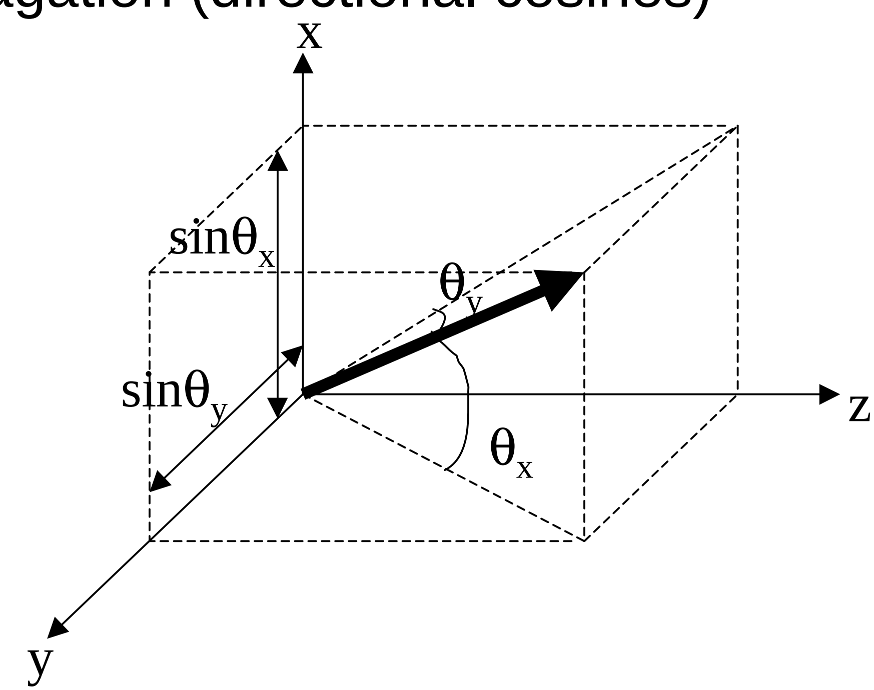
$$\exp[-j2\pi(v_x x + v_y y + v_z z)]$$

- Determine the direction of propagation (directional cosines)

$$v_y = \sin\theta_y / \lambda$$

$$v_x = \sin\theta_x / \lambda$$

$$v_z = \sqrt{(\frac{1}{\lambda})^2 - v_x^2 - v_y^2}$$

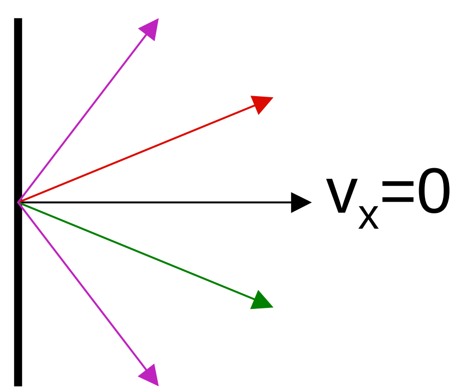


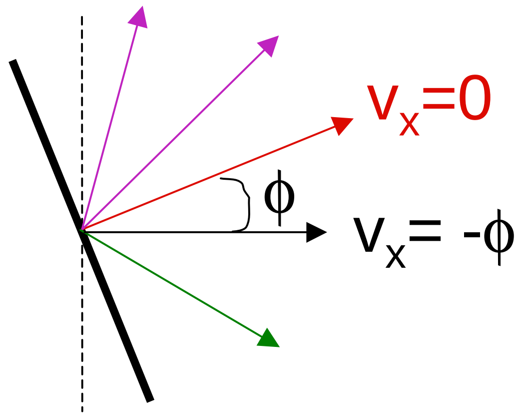
Tilted Planes

- When aperture and observation planes are not parallel:
  - Re-mapping of spatial frequencies
    - Valid since phase accumulation term does not change
- Re-mapping of spatial frequencies
  - Use well-known coordinate transfer matrices

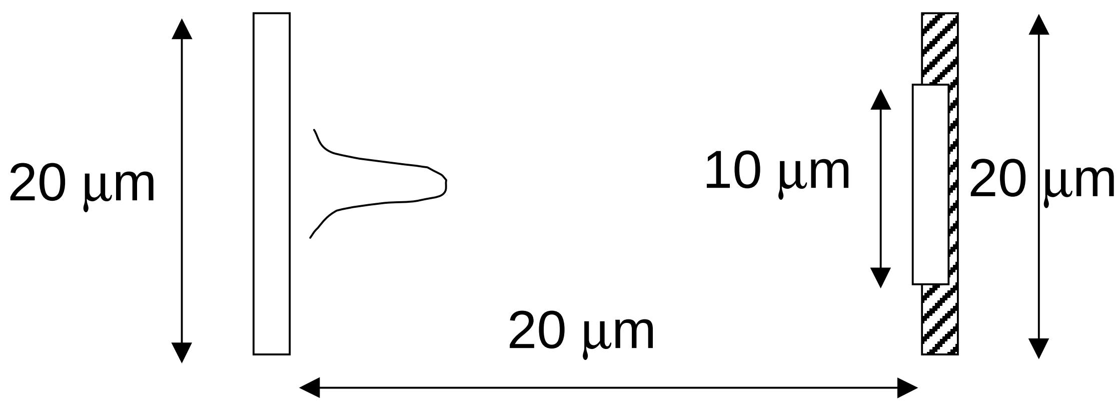
$$(x, y, z)^T = R(\xi, \eta, z')^T \qquad (v_x, v_y, v_z) = R(v_x', v_y', v_z')^T$$

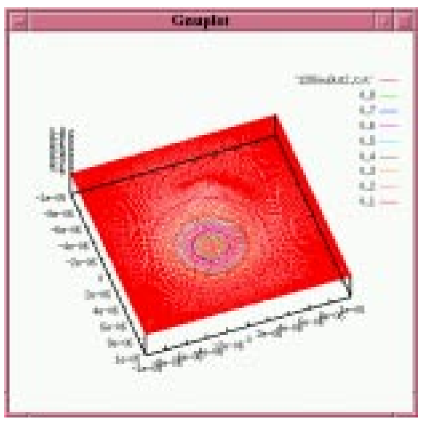
$$R_{y-axis} = \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix} \qquad R_{x-axis} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \qquad R_{z-axis} = \begin{bmatrix} \cos\rho & \sin\rho & 0 \\ -\sin\rho & \cos\rho & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



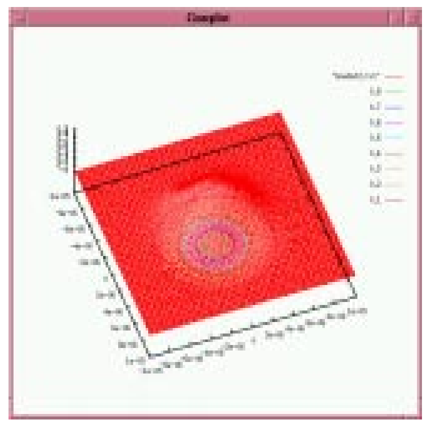


Computation Speed Comparison





Direct Integration(256x256)



FFT(256x256)

System Parameters:

VCSEL (Gaussian Source):
- 5 μm waist
- 1550 nm wavelength
- 20 μm bounding box

Distance:
- 20 μm

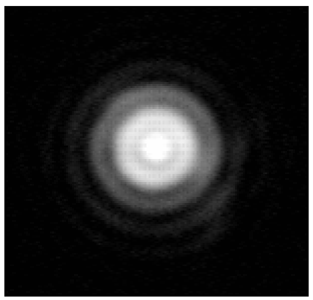
Detector:
- 10 μm square detector
- 20 μm bounding box

	Fast Fourier Transform					Direct Integration (Gaussian Quadrature)				
N (mesh side)	32	64	128	256	512	32	64	128	256	512
Computation (sec)	0.03551	0.1067	0.2744	1.8886	4.9675	1.8134	29.3992	455.841	7080	116480
% Power Error	0.13%	0.03%	0.01%	0.00%	0.00%	4.62%	0.97%	1.19%	0.14%	0.00%

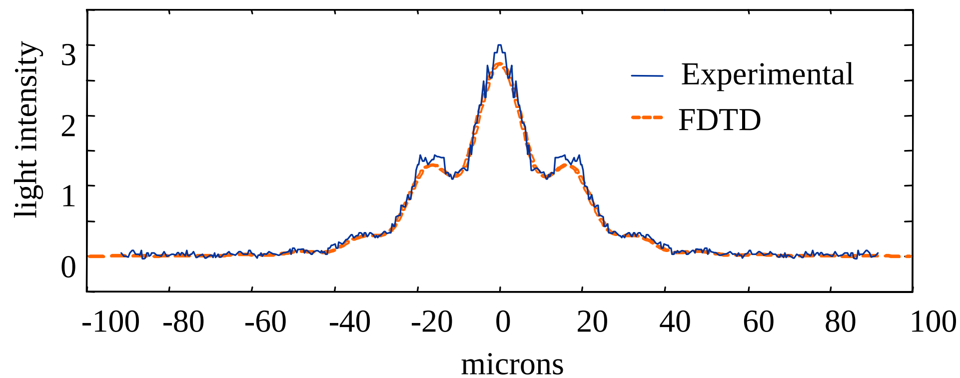
Experimental Validation

- Measure diffracted field 1.5mm past a 71 mm precision pinhole (l=632.8nm)
  - Prather, University of Delaware
- Model using FDTD to validate electromagnetic code
  - Prather, University of Delaware
- Model using scalar theory

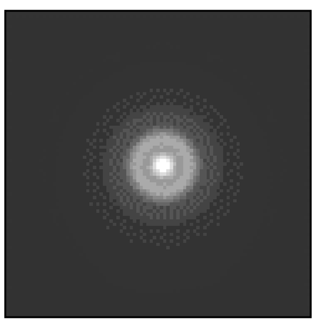
Experimental



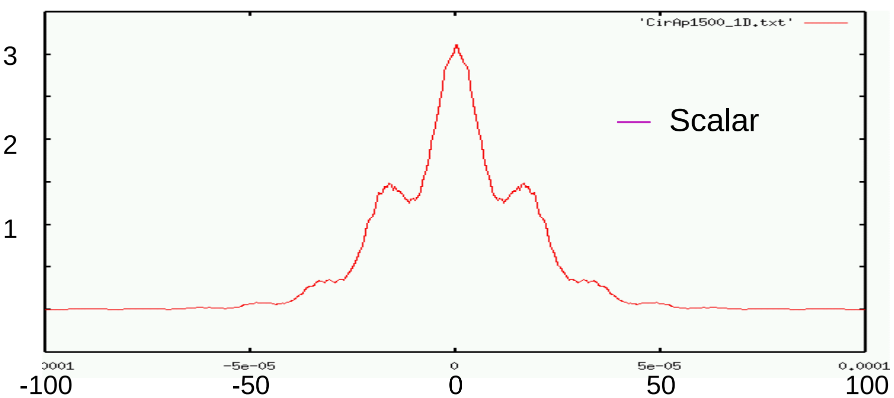
-100 100



Scalar

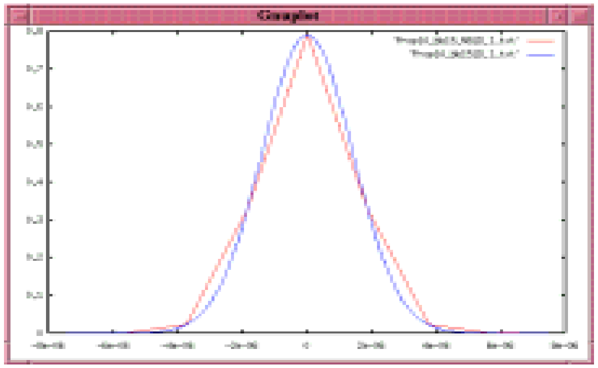


-100 100

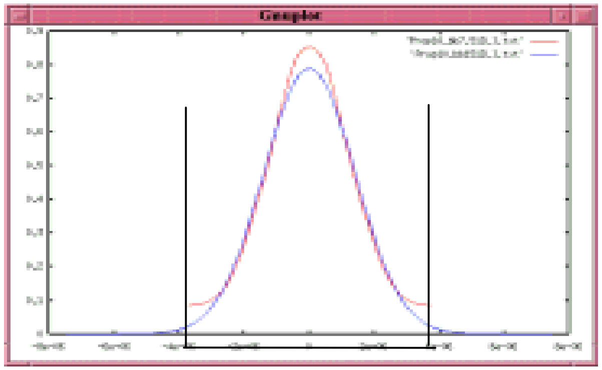


Error Analysis of Angular Spectrum

- Continuous Fourier transform theory
  - Angular spectrum method is exact Rayleigh-Sommerfeld solution
- Discrete Fourier transform theory
  - Continuous angular spectrum function is discretized
  - Errors are possible
- Common Errors:
  - Aliasing:
    - sampling too low to capture high frequencies
    - higher orders falsely placed in lower orders
  - Truncation:
    - signal cut-off on edges
- Errors Result in:
  - “Reflection” off of window
  - Undersamping



Aliasing



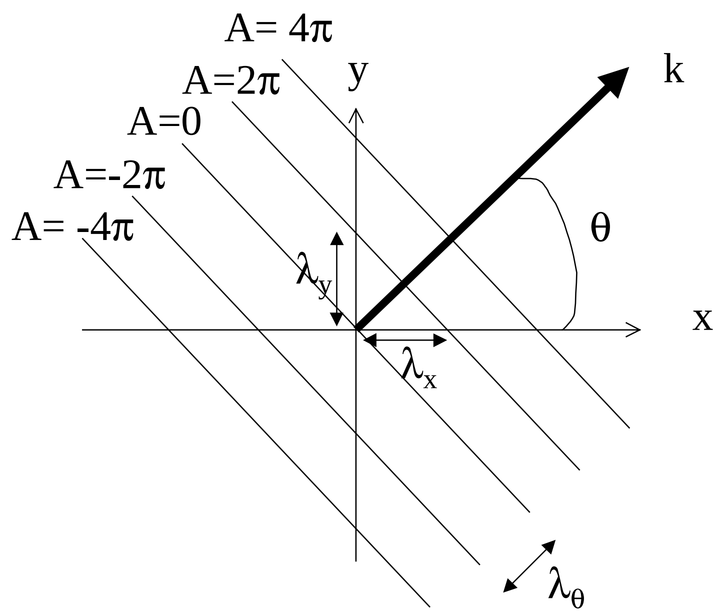
Truncation

Sampling of Angular Spectrum

- Fourier transform of x-y plane
  - Plane waves: $\exp^{-j(v_x x+v_y y)}$
  - Constant phase lines: $A = v_x x + v_y y$
  - Angle: $\theta_k = \tan^{-1}(\frac{\lambda_x}{\lambda_y}) = \tan^{-1}(\frac{v_y}{v_x})$
  - Spatial wavelength

$$\lambda_\theta = \frac{1}{\sqrt{\frac{1}{\lambda_x^2}+\frac{1}{\lambda_y^2}}} = \frac{1}{\sqrt{v_x^2+v_y^2}}$$

  - Angular spatial frequency $k = \sqrt{v_x^2+v_y^2}$



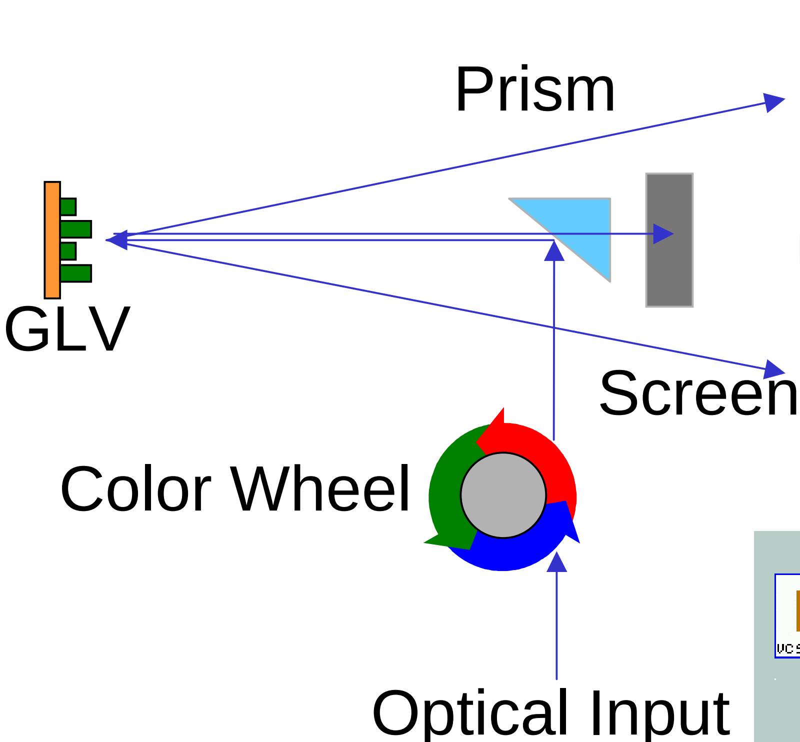
- For Plane waves propagating ±90° (half circle)

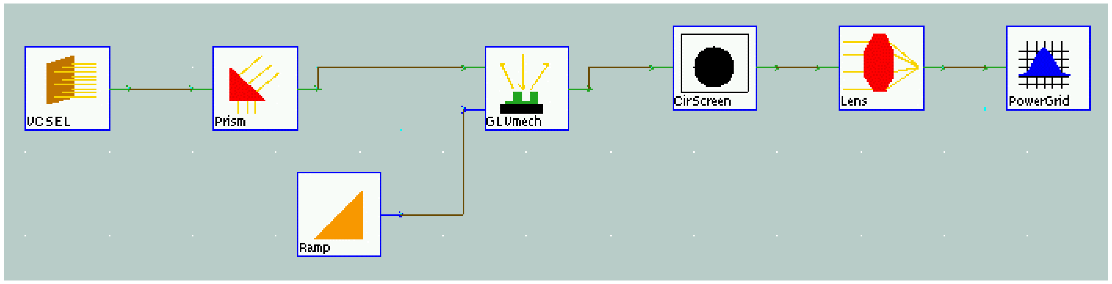
$$v_{x,y} = \frac{\sin\theta}{\lambda} = \frac{\sin\frac{\lambda}{2}}{\lambda} = \frac{1}{\lambda} \qquad \lambda_\theta = \frac{1}{\sqrt{\frac{1}{\lambda^2}+\frac{1}{\lambda^2}}} = \frac{1}{\sqrt{\frac{2}{\lambda^2}}} = \frac{\lambda}{\sqrt{2}}$$

- Using Sampling Theorem: $\Delta x, \Delta y \le \frac{\lambda_{min}}{2} = \frac{\lambda}{2\sqrt{2}}$

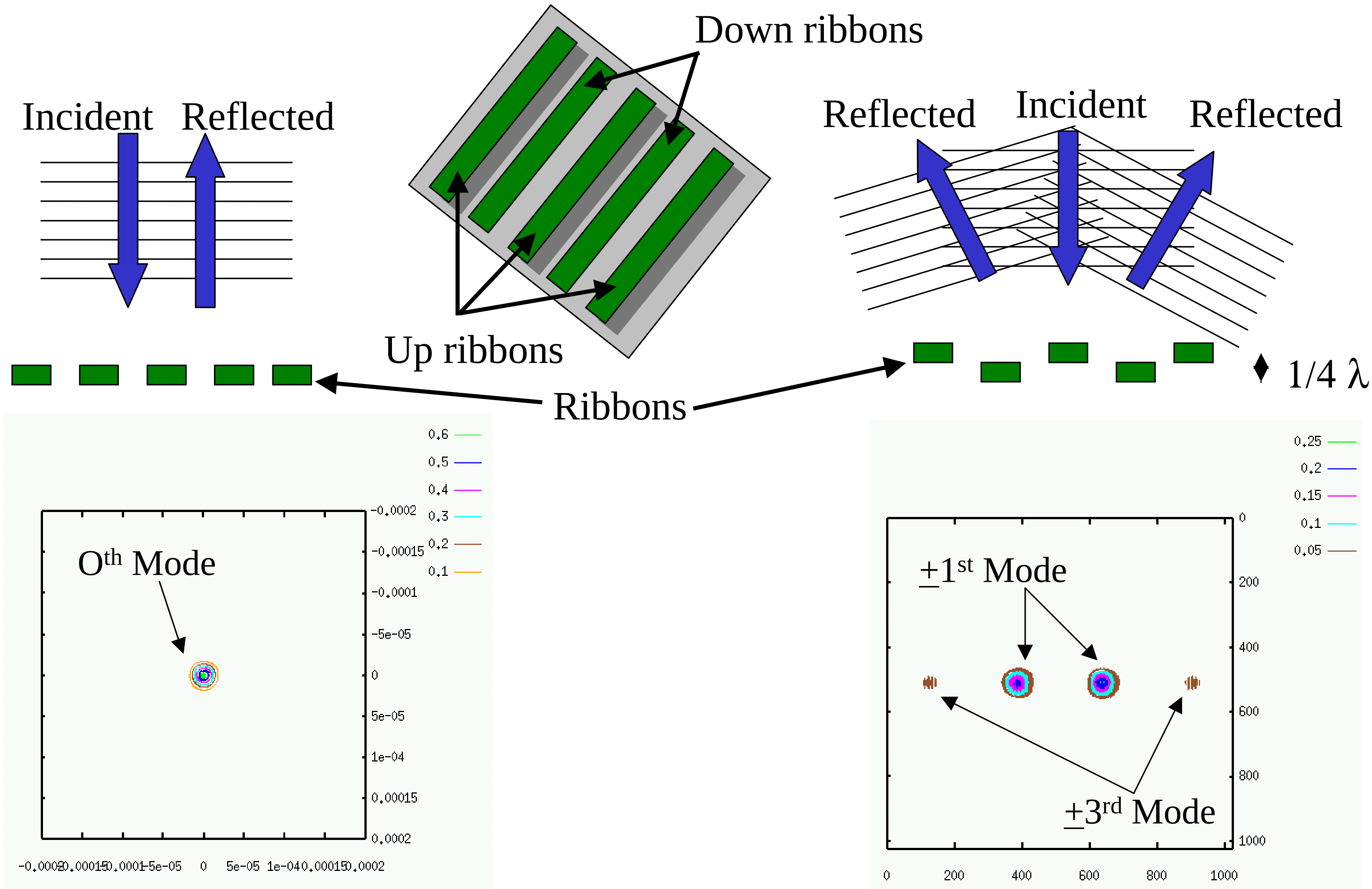
System-Level Simulation: Digital Projection System

- Digital Projection System using Grating Light Valve
  - If pixel is “on”, light is reflected off GVL at an angle, propagating through the lens to the focal plane
  - If pixel is “off”, light is reflected straight off GVL into the absorbing screen

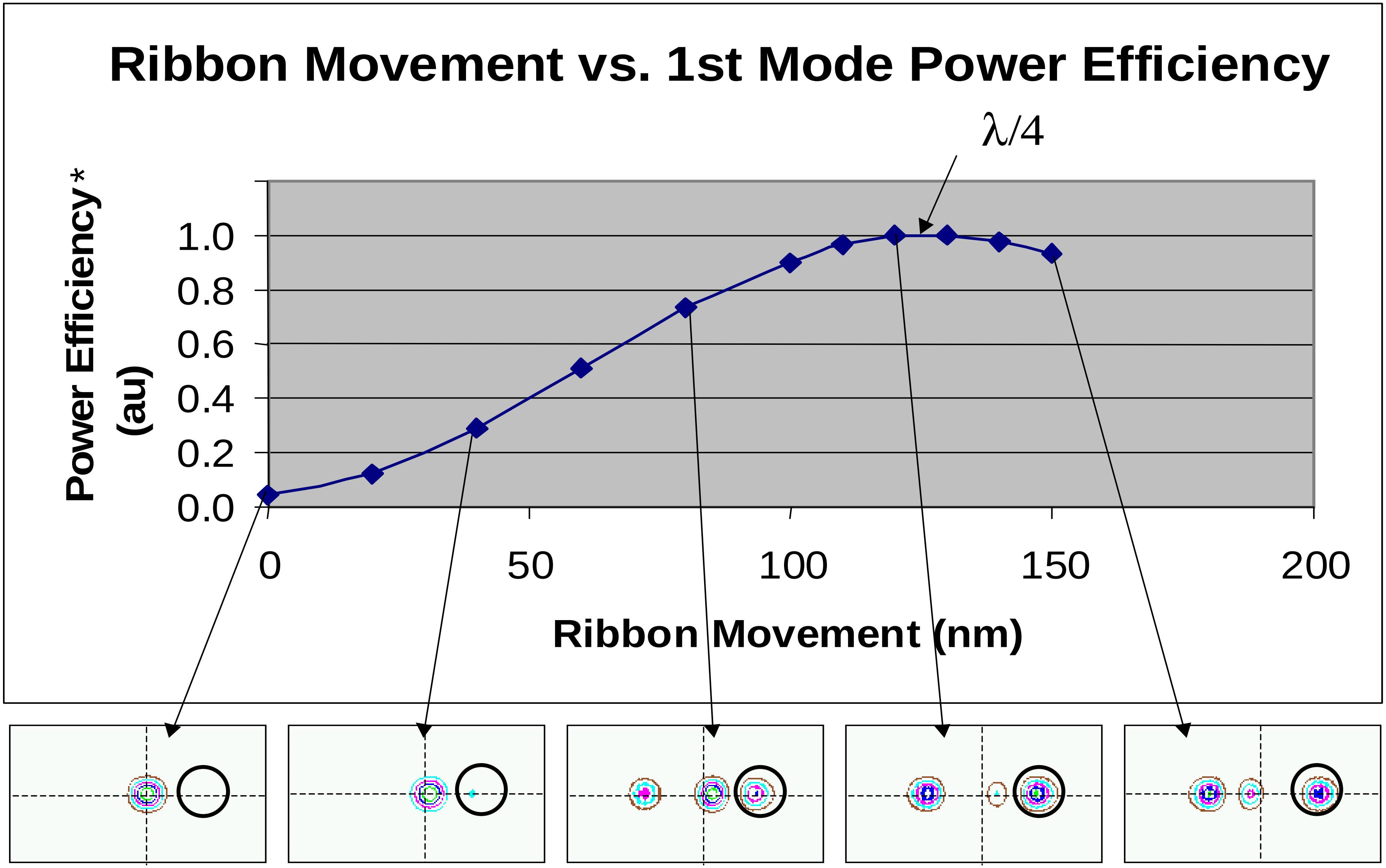




Grating Light Valve (GLV)

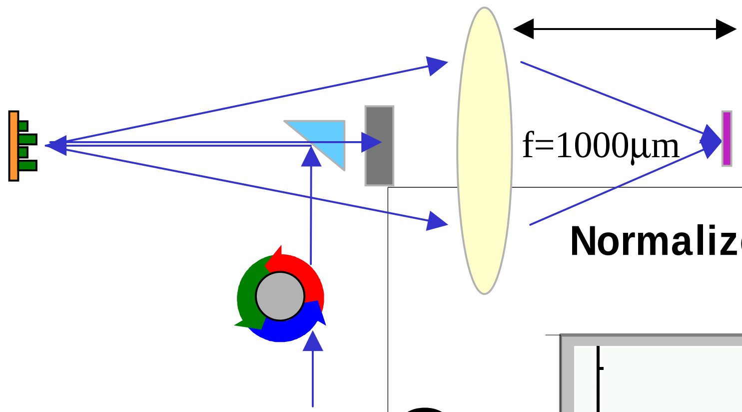


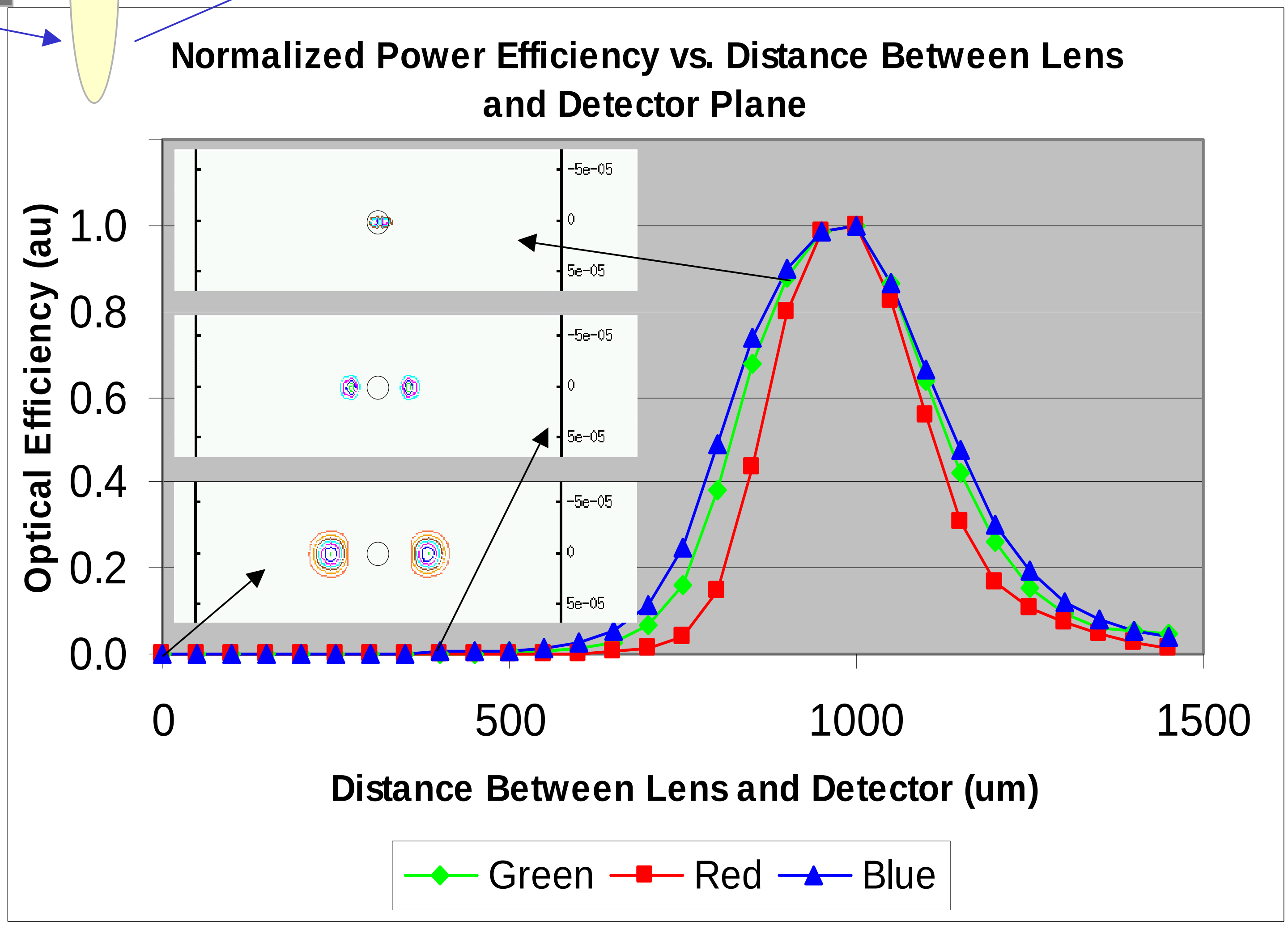
Ribbon Movement vs. Power Efficiency



*Encircled energy (12.5 μm radius) in the +1 mode

Multi-Wavelength Simulation





Summary and Future Work

- Optical micro-systems and system-level CAD
- Rayleigh-Sommerfeld Formulation required for accurate optical propagation modeling
- Angular spectrum method
  - Reduce $O(N^4)$ Direct Integration to $O(N^2 \log N)$ FFT
  - Convolution of the complex wavefront and free-space transfer function
  - Achieve the speed of the Fraunhofer approximation, with the accuracy of the Rayleigh-Sommerfeld formulation
- System-level simulations and validation
- Future work
  - Further error prediction
  - Determine limitations of Rayleigh-Sommerfeld scalar technique for optical micro-systems