System Simulation of a GLV Projection System

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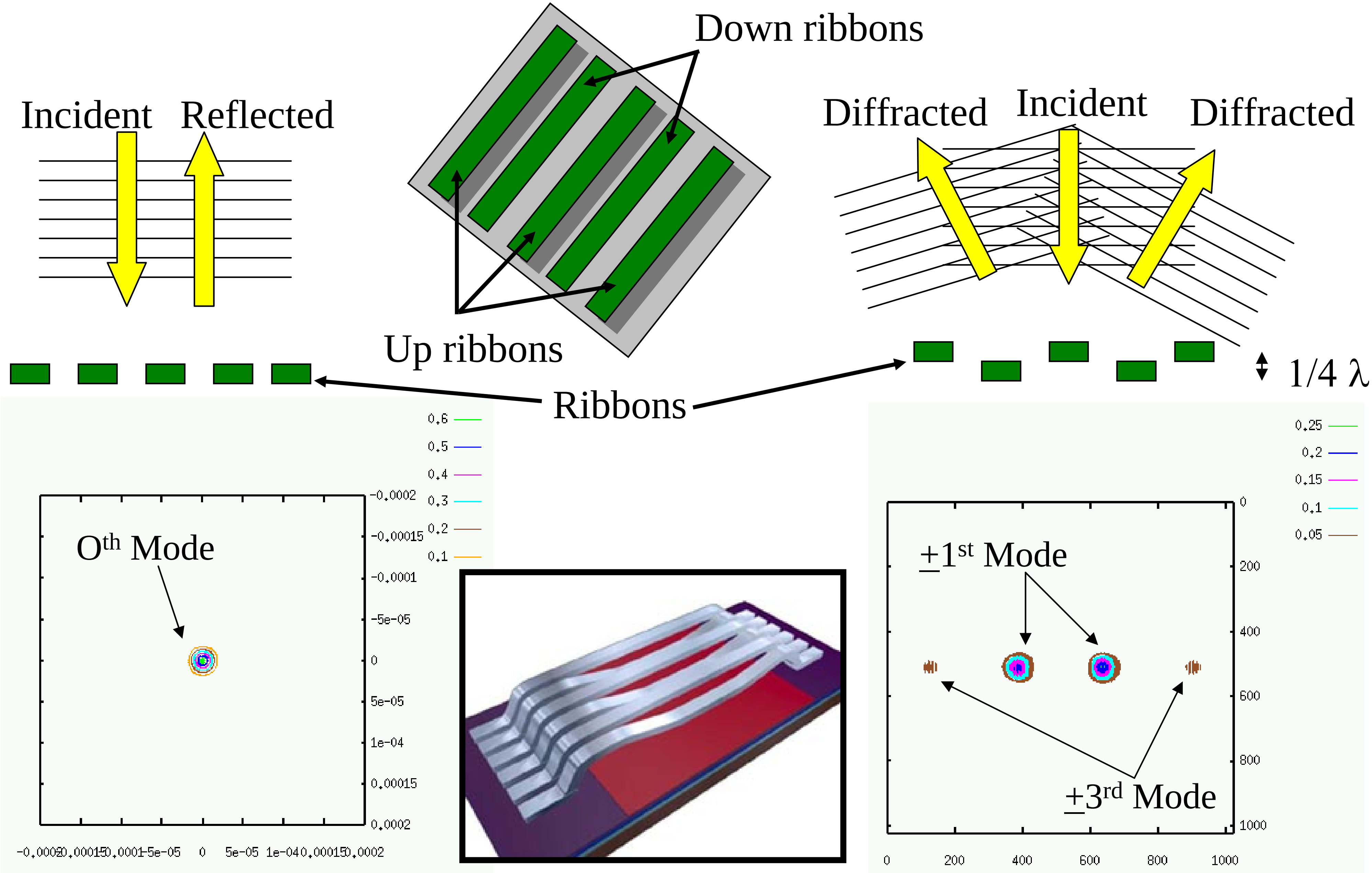
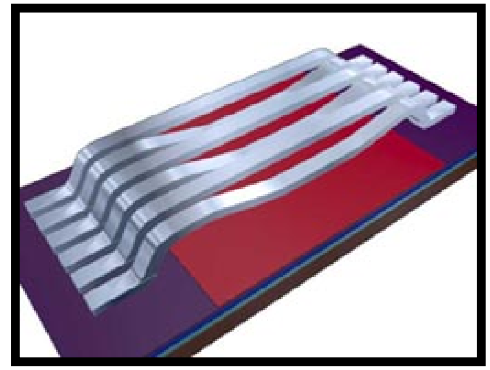
Grating Light Valve



Silicon Light Machines: http://www.siliconlight.com

What is required for an accurate GLV model?

- Mechanical Models
  - Accurate bending of the anchored ribbons



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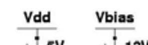
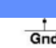
- Electrical Models

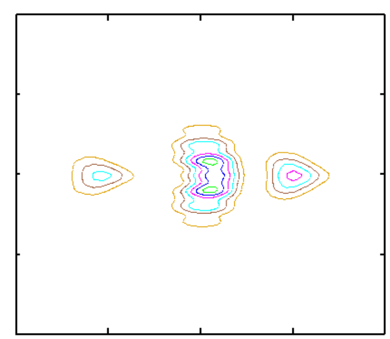


Efficient multi-domain CAD tool to support system-level evaluation of mechanics, electronics, and optics *and* their interactions in a single simulation framework

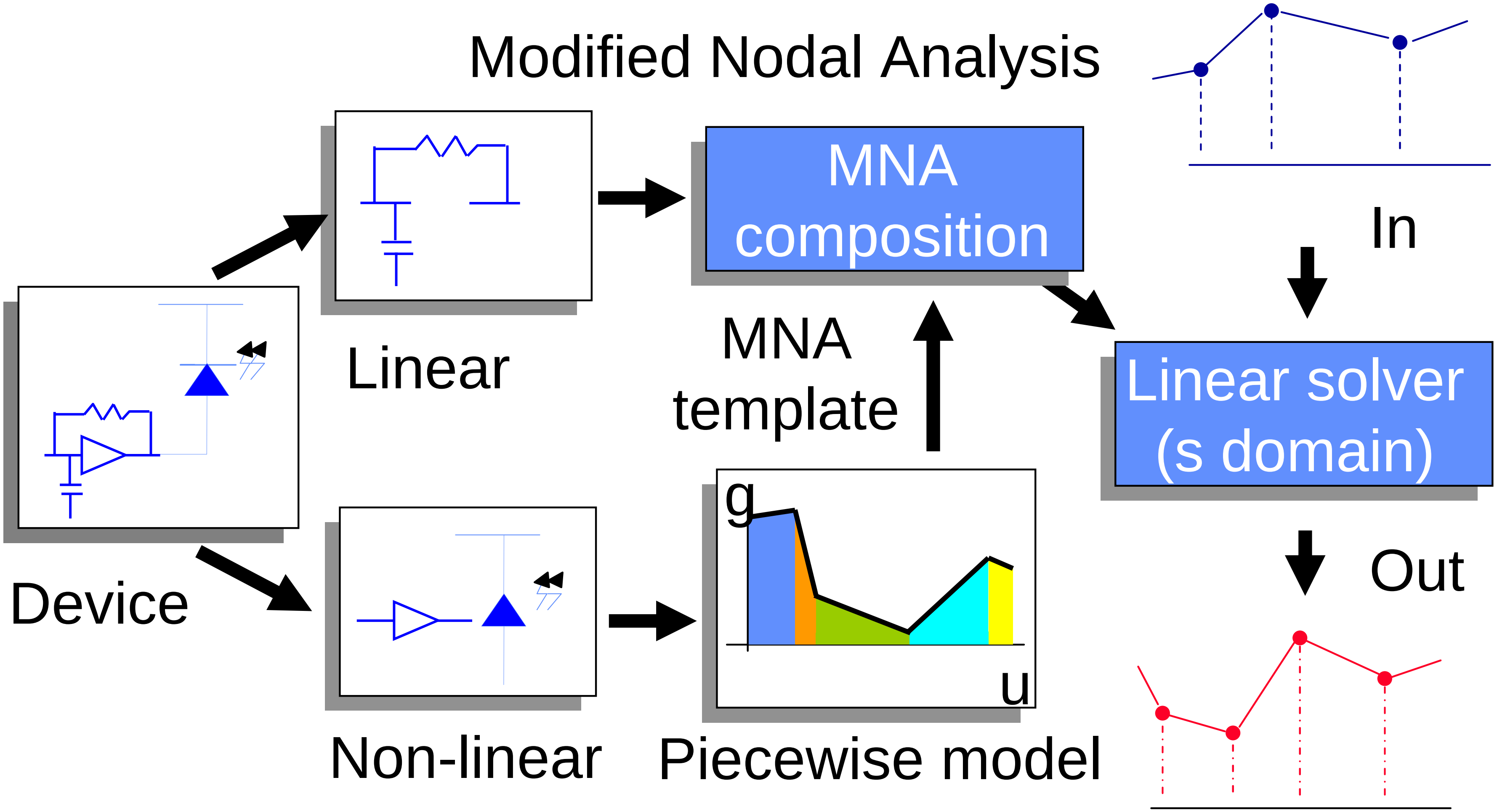
substrate



- Optical Models
  - Support diffraction and small feature size



PWL Fast Solvers for Electrical and Mechanical Domain



Nodal Analysis (Template base formulation) :

Support for: Electronic → Spice like Netlists
Mechanical → Structural Netlists

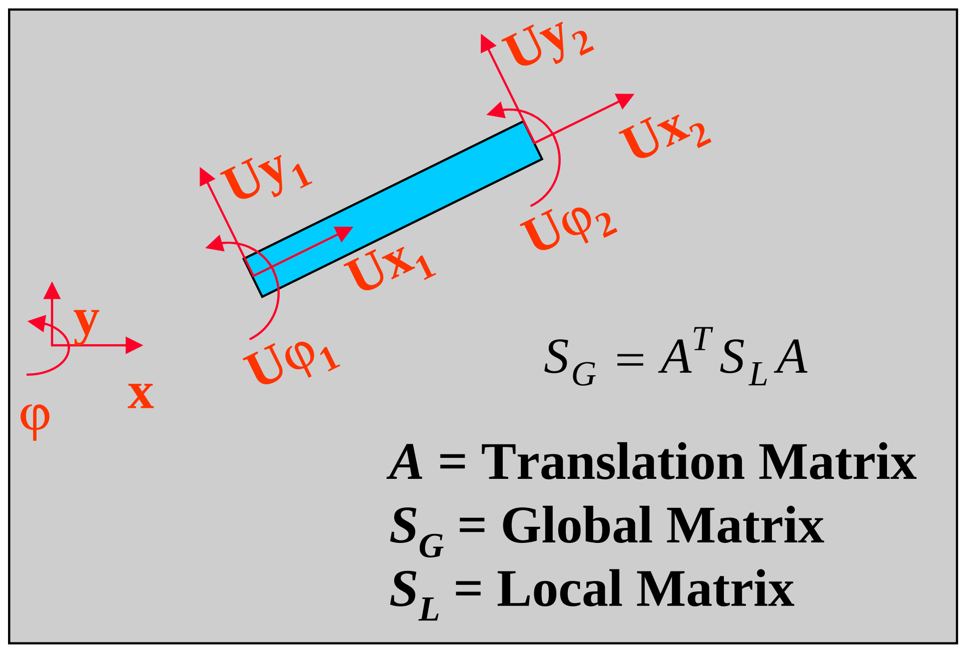
Micro-Mechanical Modeling

- General motion equation for a mechanical structure
- Reduction to standard ODE form applying Duncan's state transformation
- Templates for every basic element (e.g. beam)
- Translation from local to global reference using "translation matrix"
- Piecewise linear solver over global ODE representation

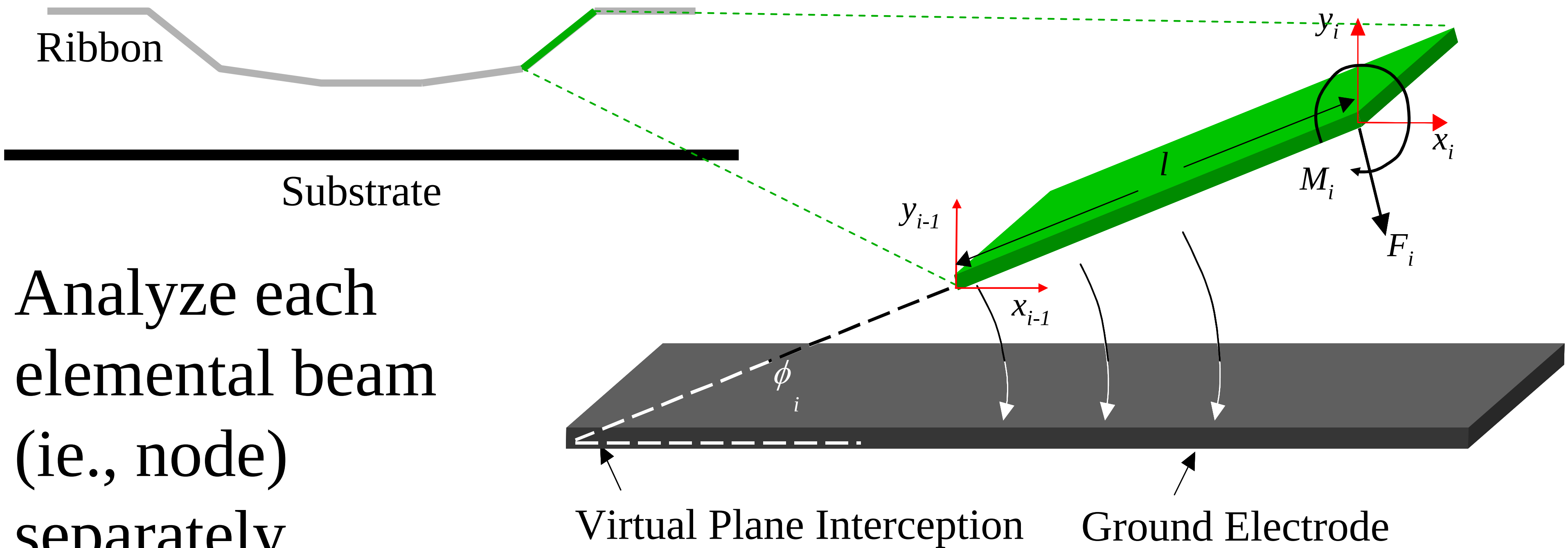
$$F = [K][U] + [B][\dot{U}] + [M][\ddot{U}]$$

$$\begin{bmatrix} 0 & M \\ M & B \end{bmatrix} \begin{bmatrix} \ddot{U} \\ \dot{U} \end{bmatrix} + \begin{bmatrix} -M & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} \dot{U} \\ U \end{bmatrix} = \begin{bmatrix} 0 \\ I \end{bmatrix} F$$

$$X = \begin{bmatrix} \dot{U} \\ U \end{bmatrix}; \quad [Mb]\dot{X} + [Mk]X = [E]F$$



Electrostatic Characterization: Nodal Modeling



- Analyze each elemental beam (ie., node) separately
- Each node is an inclined flat capacitor

$$F_i = \left(\frac{\varepsilon w V^2}{l}\right)\frac{(y_i - y_{i-1})^2}{\phi_i^{\,2} y_i y_{i-1}}$$

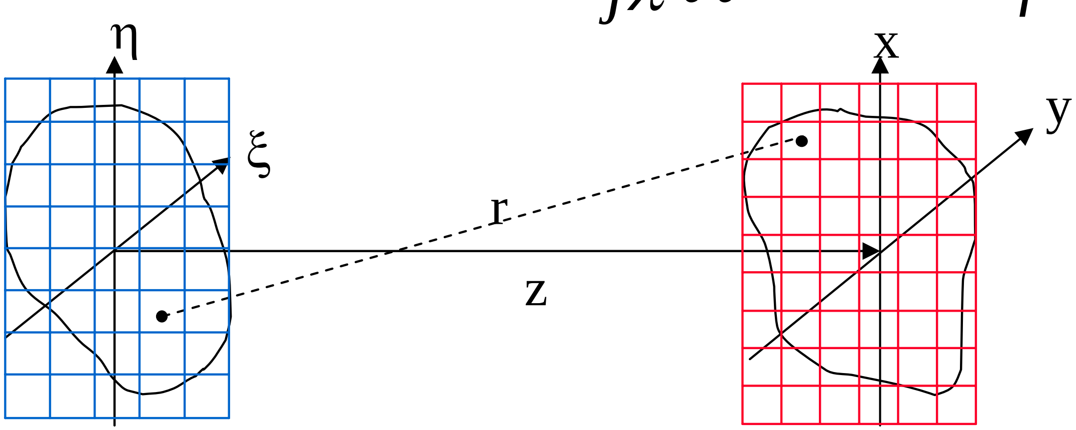
- Electro-static torque over each node

$$M_i = F_i \frac{\Delta x_i}{l} x_{i-1} + F_i \frac{\Delta x_i}{l}\frac{\Delta x_i}{\Delta y_i} y_{i-1}\left(\frac{y_i}{\Delta y_i}\ln\left(\frac{y_i}{y_{i-1}}\right) - 1\right) + F_i \frac{y_i}{l} y_{i-1} \ln\left(\frac{y_i}{y_{i-1}}\right)$$

Optical Model: Rayleigh-Sommerfeld Formulation

- Scalar Diffraction - Rayleigh-Sommerfeld Formulation
  - Common optical propagation techniques (Fraunhofer, Fresnel) are not valid for optical MEM systems
  - Diffractive component >> λ
  - Distance to observation plane >> λ

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

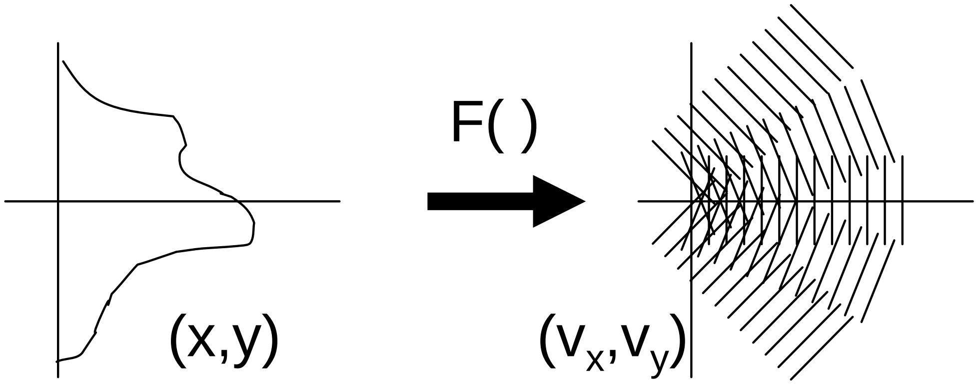


U1(ξ,η)

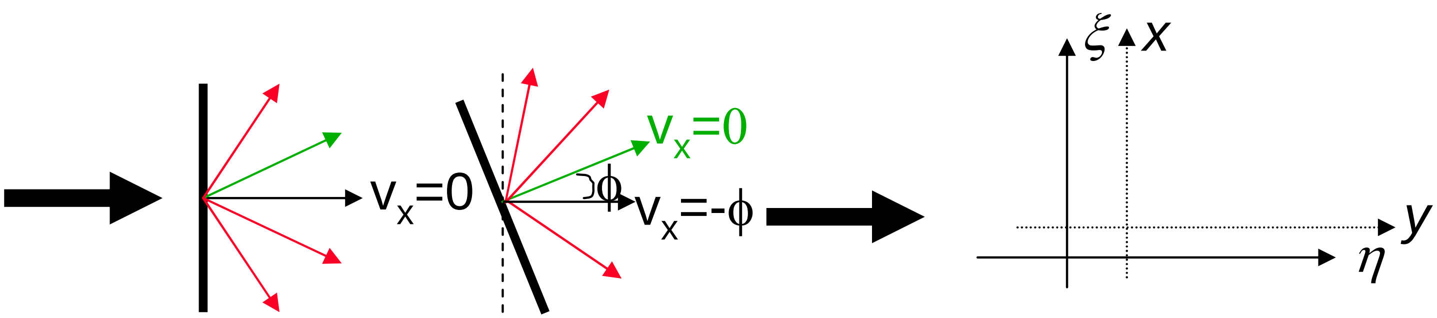
U2(x,y)

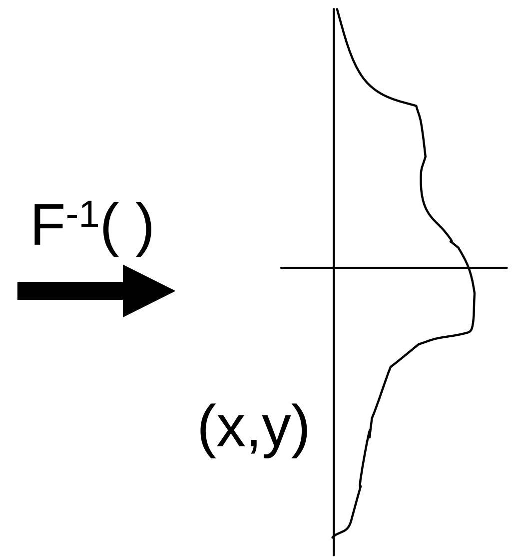
Direct Integration:
$O(N^4)$

Efficient Optical Simulation: Angular Spectrum Technique



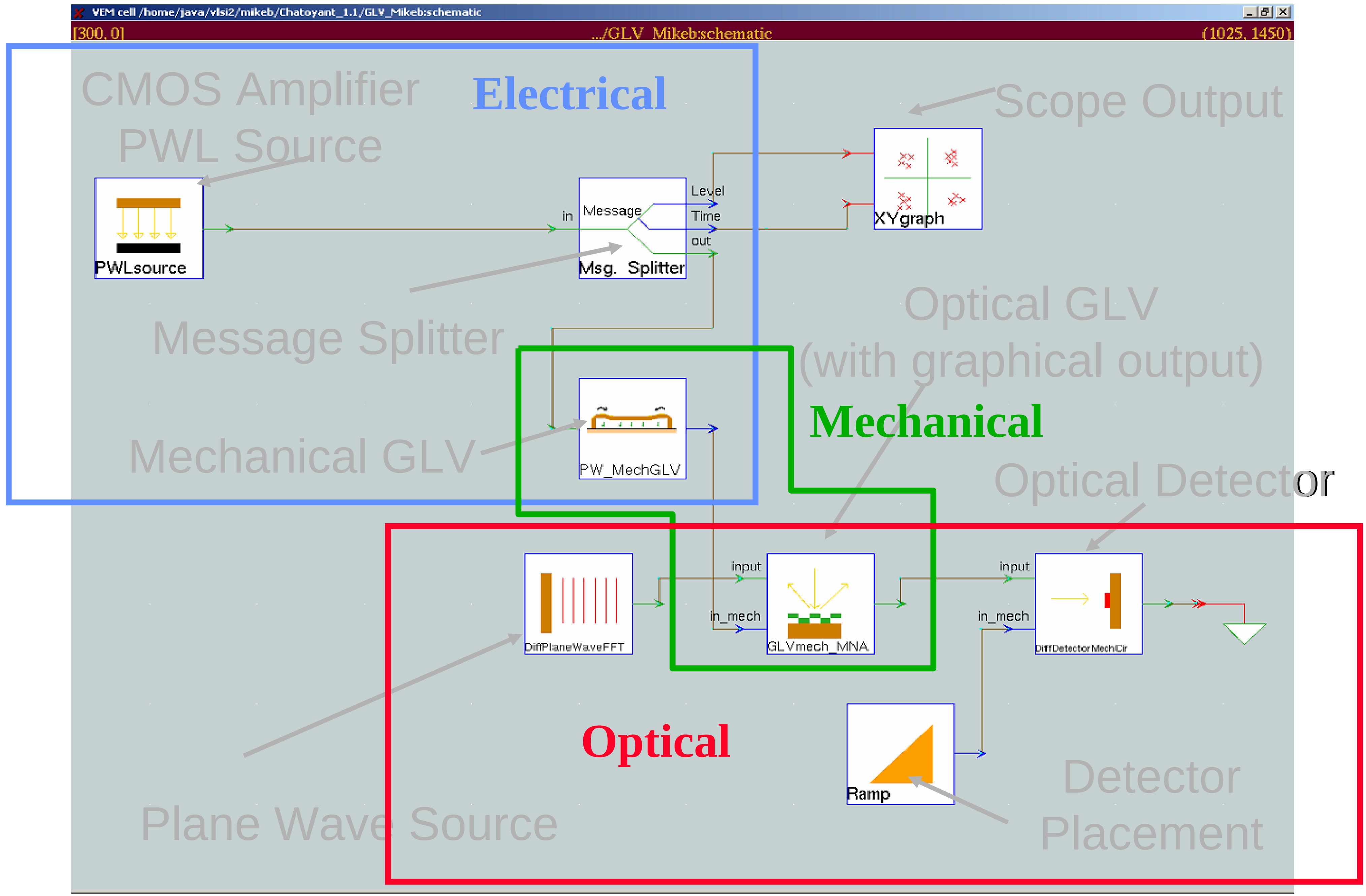
$$\exp\left(-j2\pi z\sqrt{\frac{1}{\lambda^2}-\nu_x{}^2-\nu_y{}^2}\right)$$





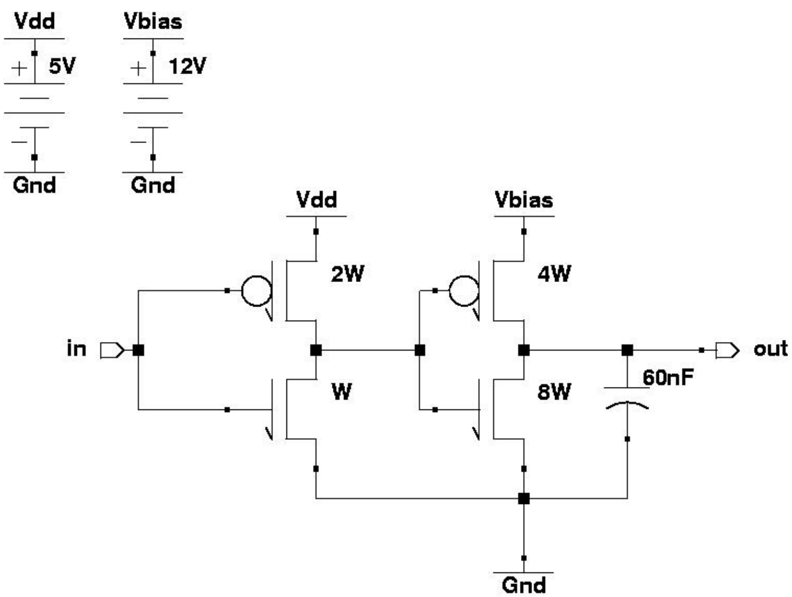
- Angular Spectrum Algorithm $O(N^2 \log N)$:
  - Decompose wavefront into sum of angled plane waves using FFT
  - Multiply free-space transfer function
  - Map spatial frequencies into tilted coordinate system
  - Use Fourier shifting theorem for offset plane
  - Sum plane waves into wave function with inverse FFT

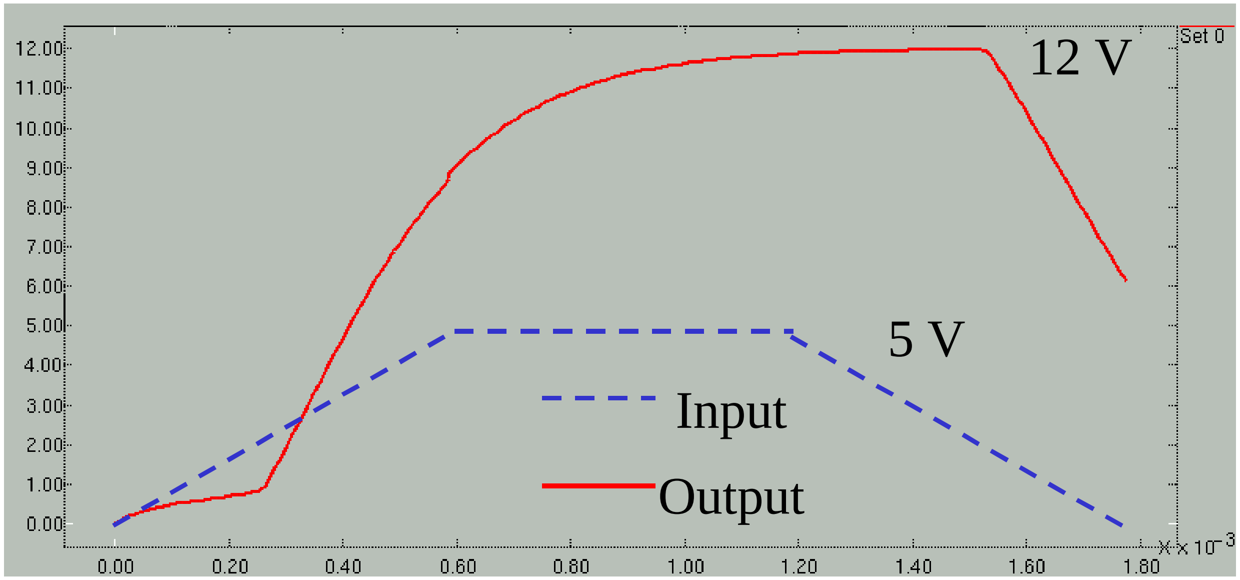
GLV System Simulation within Chatoyant



System Simulation - Electrical

- Electrical Driver
  - Electrostatic attraction: voltage applied between ribbon and substrate
  - 2 stage CMOS amplifier

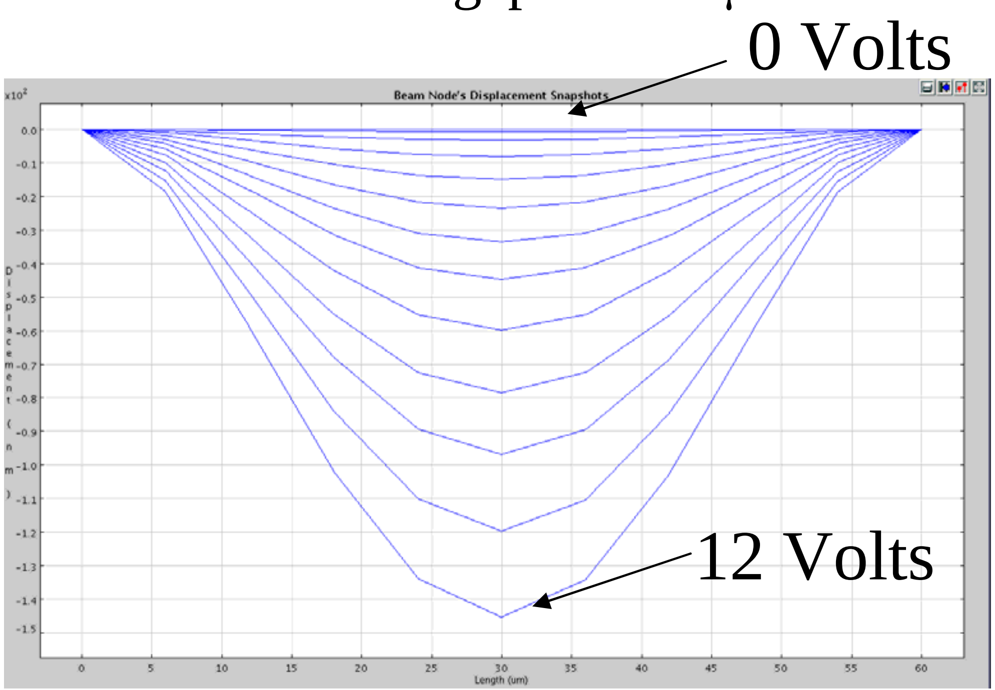




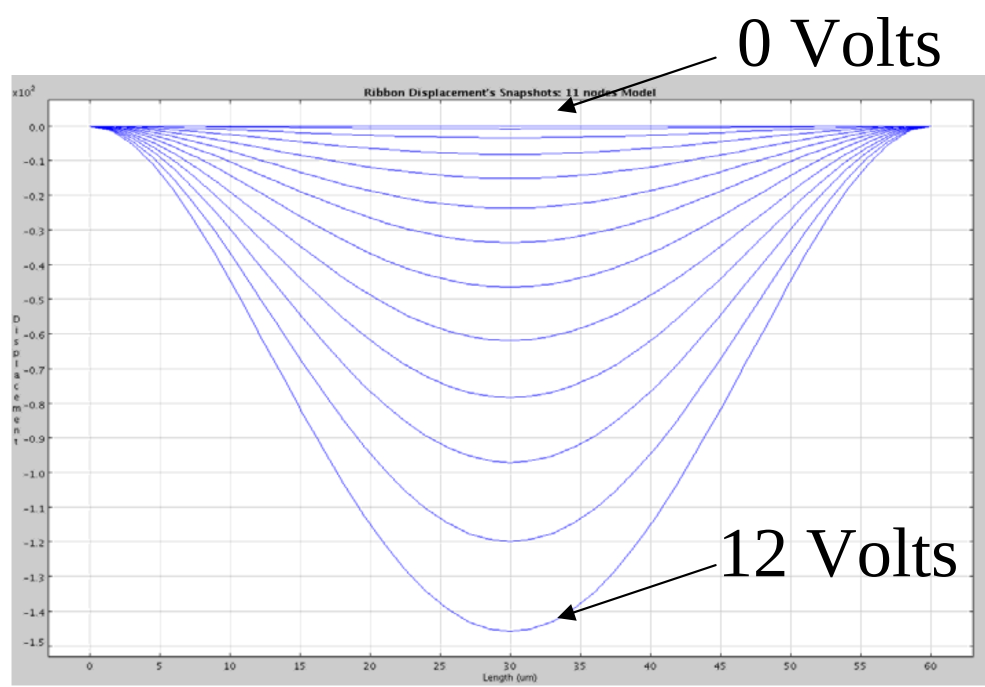
60 μs switching time

System Simulation - Mechanical

- GLV
  - 4 ribbons
    - 60 μm x 5 μm
    - 1.5 μm thick
    - Si_3N_4: density = 3290 Kg/m^3, Young's modulus = 290x10^9 N/m^2
    - Air gap is 0.65 μm



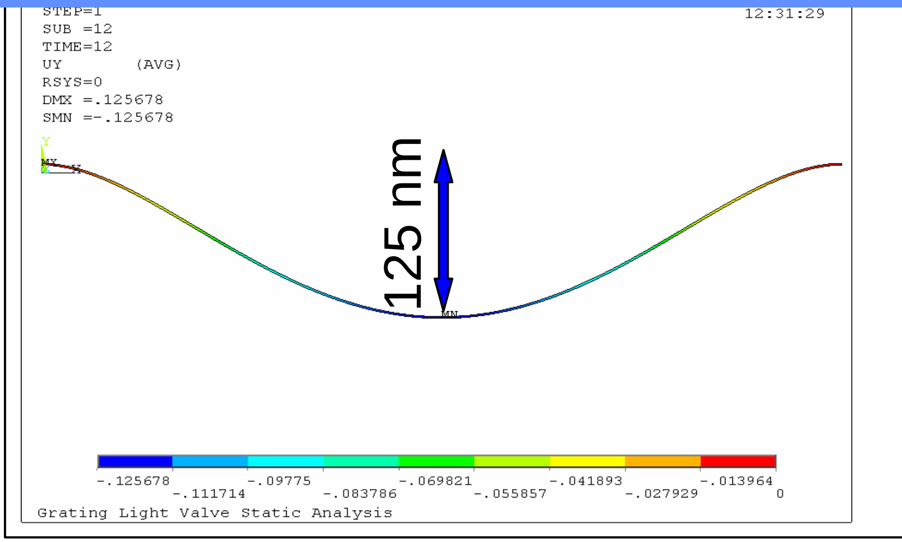
11 Node Ribbon Model

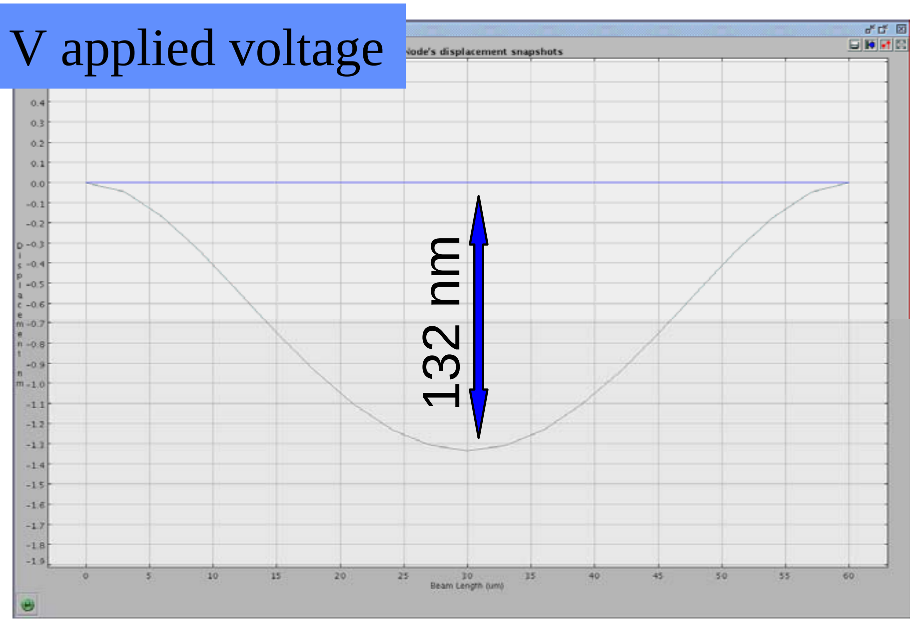


41 Node Ribbon Model

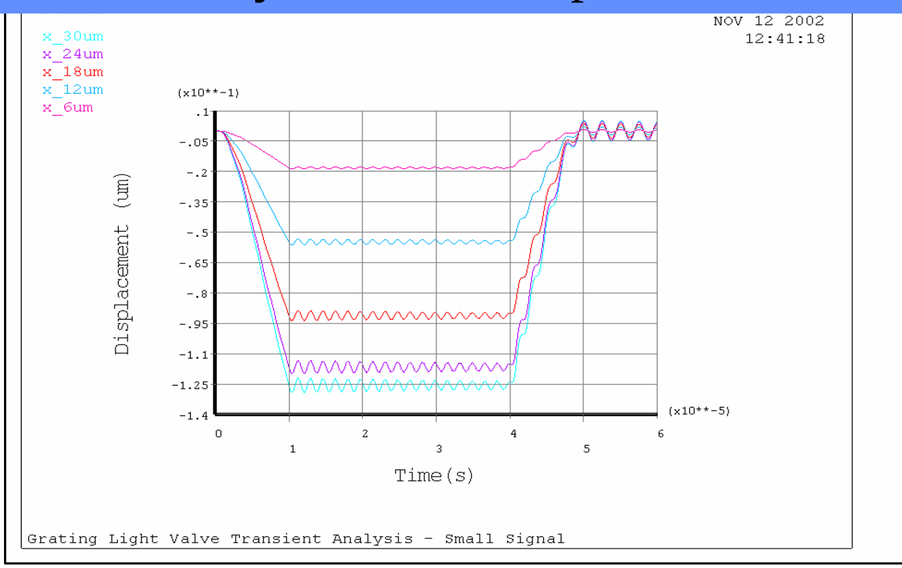
Mechanical Comparison with Ansys

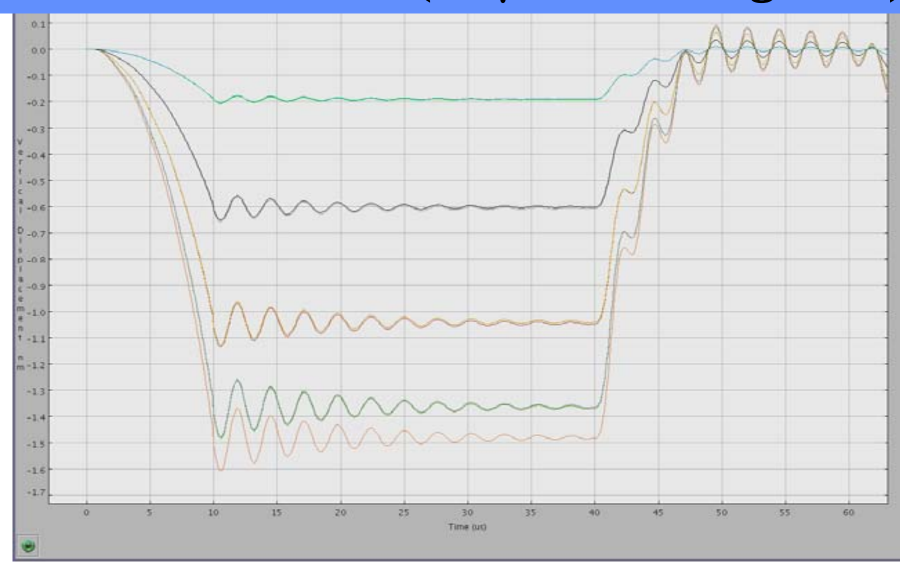
Static Analysis: Ribbon deformation due to 12 V applied voltage





Transient Analysis: Nodal displacements in 11-node ribbon model (**60 µs switching time)**





Chatoyant and ANSYS Modal Analyses

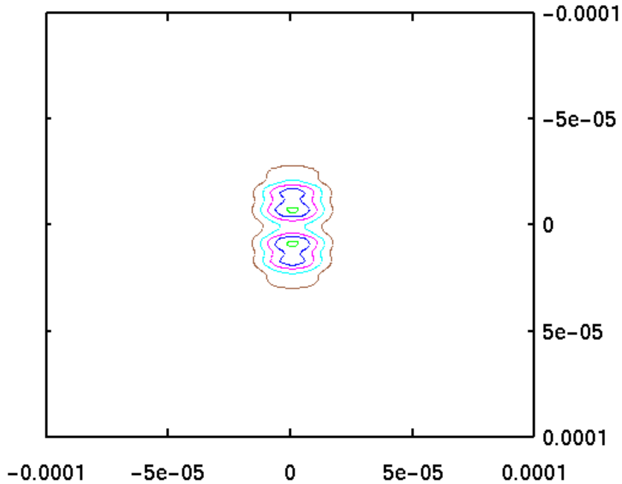
	Chatoyant	ANSYS	%Error
Mode	Modal Frequency	Modal Frequency	
1	4.02081E+05	4.02120E+05	0.0097
2	1.10845E+06	1.10840E+06	-0.0045
3	2.17312E+06	2.17280E+06	-0.0147
4	3.59267E+06	3.59140E+06	-0.0353
5	5.36796E+06	5.36430E+06	-0.0682
6	7.50006E+06	7.49120E+06	-0.1181
7	9.99083E+06	9.97200E+06	-0.1885
8	1.28431E+07	1.28060E+07	-0.2889
9	1.60610E+07	1.57740E+07	-1.7869
10	1.96502E+07	1.95340E+07	-0.5913

Largest Percent Error is seen in the 9th Mode: -1.7869%

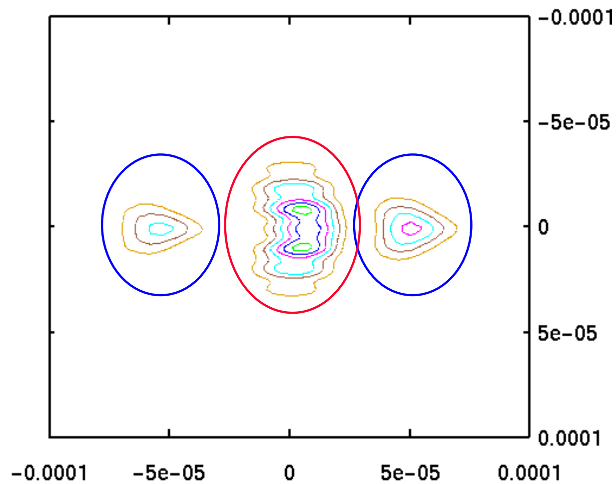
System Simulation - Optical

- GLV
  - Modeled as phase grating
  - Pulled down ribbons experience phase difference of:

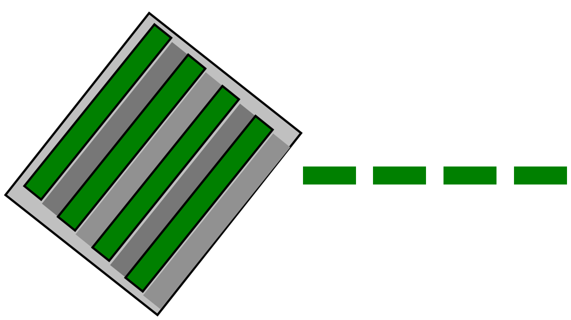
$$U_{DR} = U\exp(jkd \cdot 2)$$

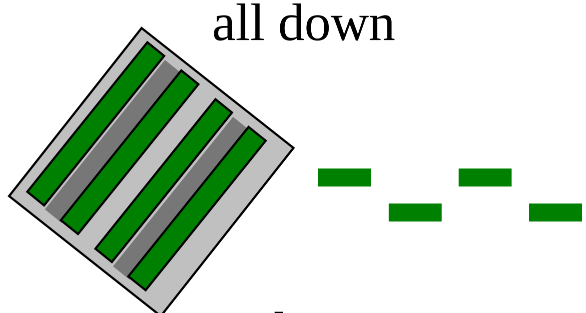


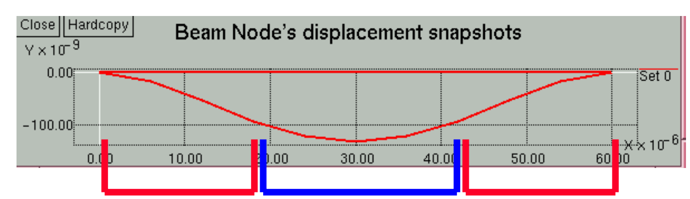
Ribbons all up



Alternating curved ribbons all down

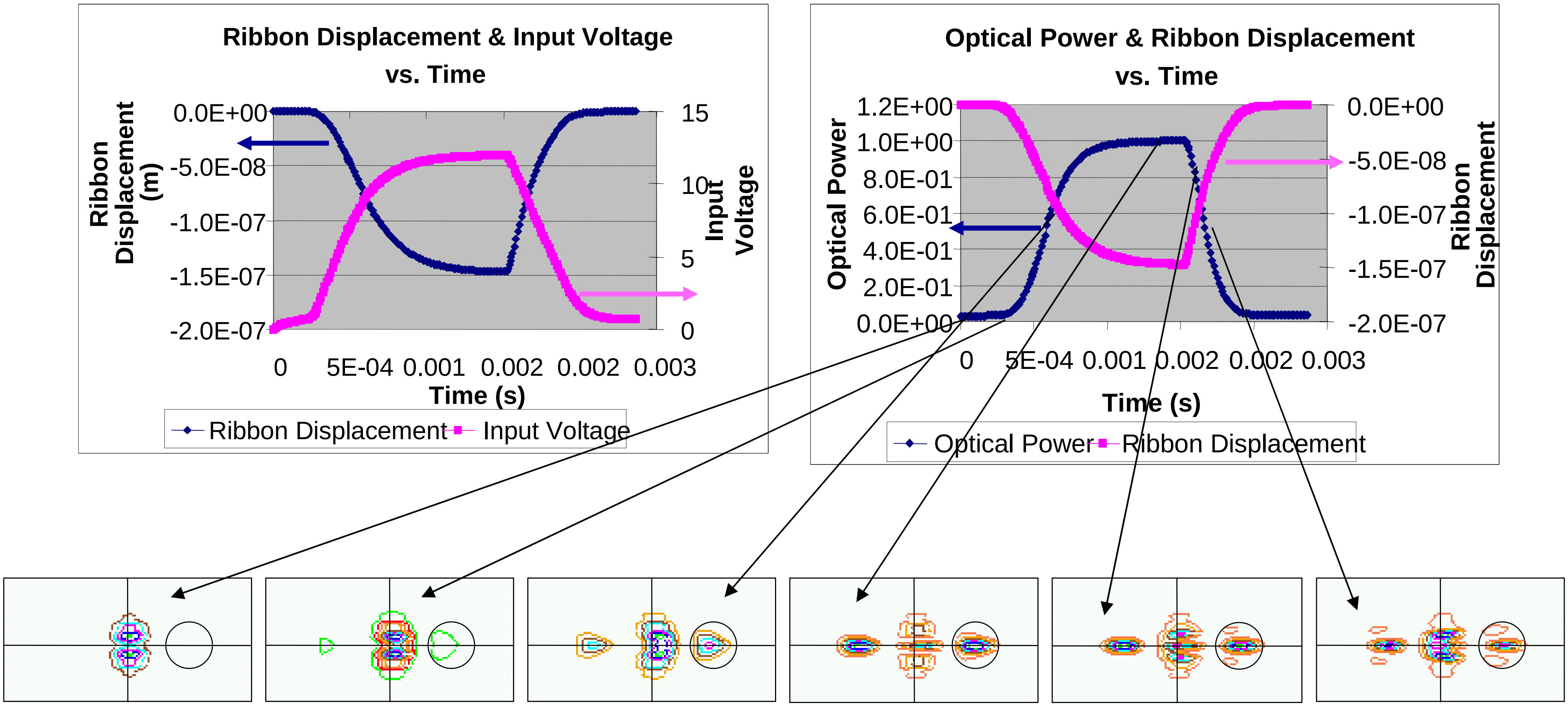






Only ~20 μm create square well diffraction pattern

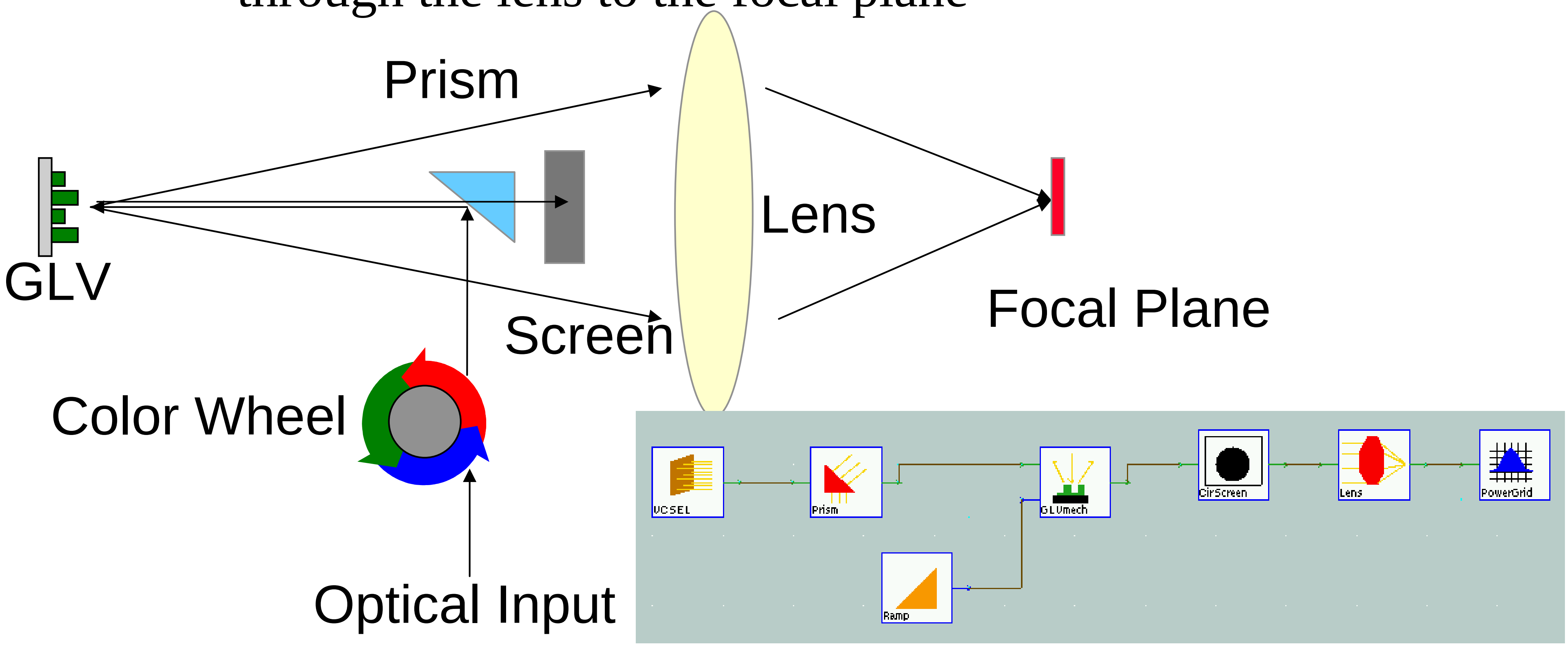
Multi-Domain System-Level Simulation



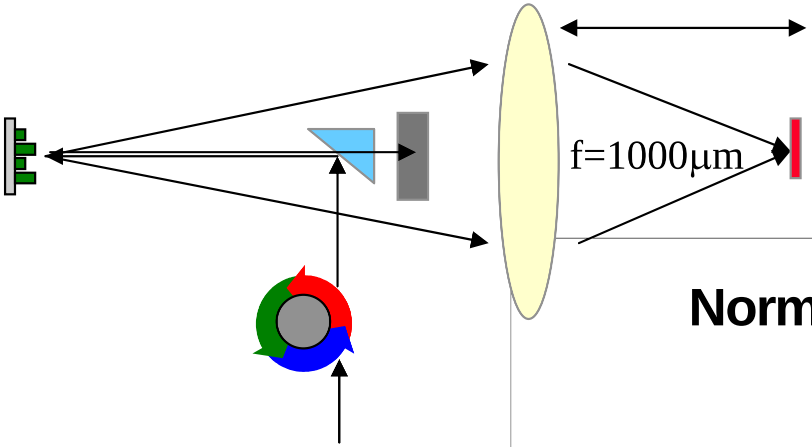
- Circular detector placed on +1 mode
- Normalized power detection

System-Level Simulation: Digital Projection System

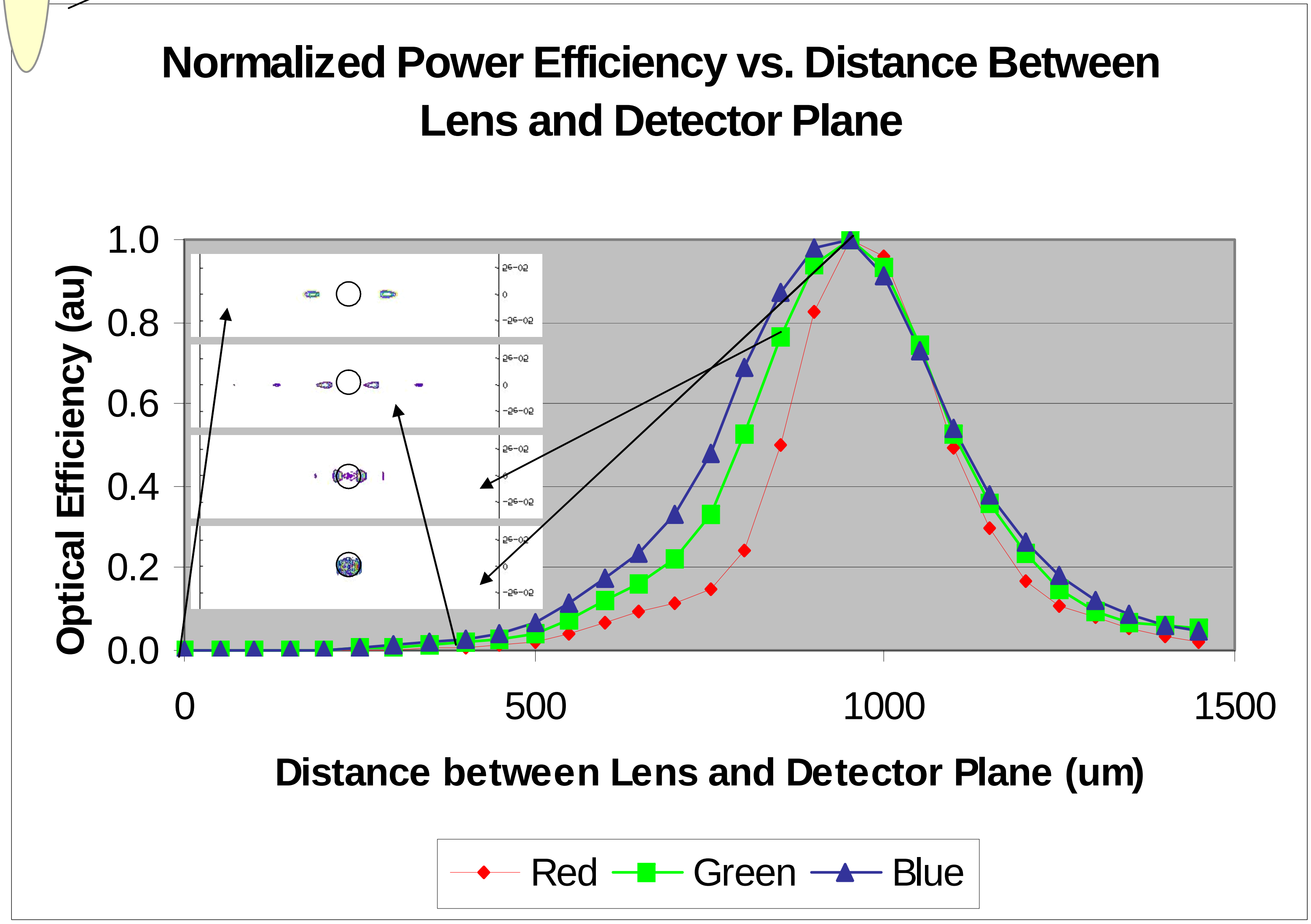
- Digital Projection System using Grating Light Valve
  - If pixel is "off", light is reflected straight off GVL into the absorbing screen
  - If pixel is "on", light is diffracted at an angle, propagating through the lens to the focal plane



Multi-Wavelength Simulation



- Alternating Ribbons are pulled down
- Pixel in “on” mode



Conclusions and Future Work

- Presented system-level simulations of GLV
- Fast behavioral models for electronics and mechanics using MNA
- Efficient and accurate optical simulation using angular spectrum technique
- Multi-domain, system-level analysis in single simulation framework
- Trade-off simulation accuracy for simulation speed
- Future Work:
  - Verification
  - Simulation of larger systems