System Simulation of a GLV Projection System

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Grating Light Valve

Incident Reflected

Down ribbons

Diffracted Incident Diffracted

Up ribbons

Ribbons

\( \frac{1}{4} \lambda \)

O\textsuperscript{th} Mode

\( \pm 1\text{st} \) Mode

\( \pm 3\text{rd} \) Mode

Silicon Light Machines: http://www.siliconlight.com
What is required for an accurate GLV model?

- **Mechanical Models**
  - Accurate bending of the anchored ribbons

- **Electrical Models**
  - Voltage applied between ribbon and substrate
  - Electrostatic attraction between ribbons and substrate

- **Optical Models**
  - Support diffraction and small feature size

Efficient multi-domain CAD tool to support system-level evaluation of mechanics, electronics, and optics and their interactions in a single simulation framework.
PWL Fast Solvers for Electrical and Mechanical Domain

Modified Nodal Analysis

Nodal Analysis (Template base formulation):

Support for: Electronic → Spice like Netlists
Mechanical → Structural Netlists
Micro-Mechanical Modeling

- General motion equation for a mechanical structure
  \[ F = [K][U] + [B][\dot{U}] + [M][\ddot{U}] \]

- 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

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

\[ S_G = A^T S_L A \]

- \( A = \) Translation Matrix
- \( S_G = \) Global Matrix
- \( S_L = \) Local Matrix
Electrostatic Characterization: Nodal Modeling

- Analyze each elemental beam (ie., node) separately

- Each node is an inclined flat capacitor

- Electro-static torque over each node

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

\[
F_i = \left( \frac{\varepsilon w V^2}{l} \right) \frac{(y_i - y_{i-1})^2}{\phi_i^2 y_i y_{i-1}}
\]
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 $\gg \lambda$
  - Distance to observation plane $\gg \lambda$

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

Direct Integration: $O(N^4)$
Efficient Optical Simulation: Angular Spectrum Technique

- 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

- CMOS Amplifier
- PWL Source
- Message Splitter
- Optical GLV (with graphical output)
- Detection Placement
- Detector Placement
- Plane Wave Source
- Mechanical GLV

Electrical
- PWLsource
- Message Splitter
- Scope Output

Mechanical
- PW_MechGLV

Optical
System Simulation - Electrical

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

![Circuit Diagram]

60 µs switching time
System Simulation - Mechanical

- **GLV**
  - 4 ribbons
    - 60 \( \mu \text{m} \times 5 \mu \text{m} \)
    - 1.5 \( \mu \text{m} \) thick
    - \( \text{Si}_3\text{N}_4 \): density = 3290 Kg/m\(^3\), Young’s modulus = 290x10\(^9\) N/m\(^2\)
    - Air gap is 0.65 \( \mu \text{m} \)
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

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<th>Mode</th>
<th>Chatoyant Modal Frequency</th>
<th>ANSYS Modal Frequency</th>
<th>%Error</th>
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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

Normalized Power Efficiency vs. Distance Between Lens and Detector Plane

Optical Efficiency (au)

Distance between Lens and Detector Plane (um)

Red • Green • Blue

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