Tunable Time Delays for Phased Array Antenna Systems

DARPA AOSP KICKOFF MEETING

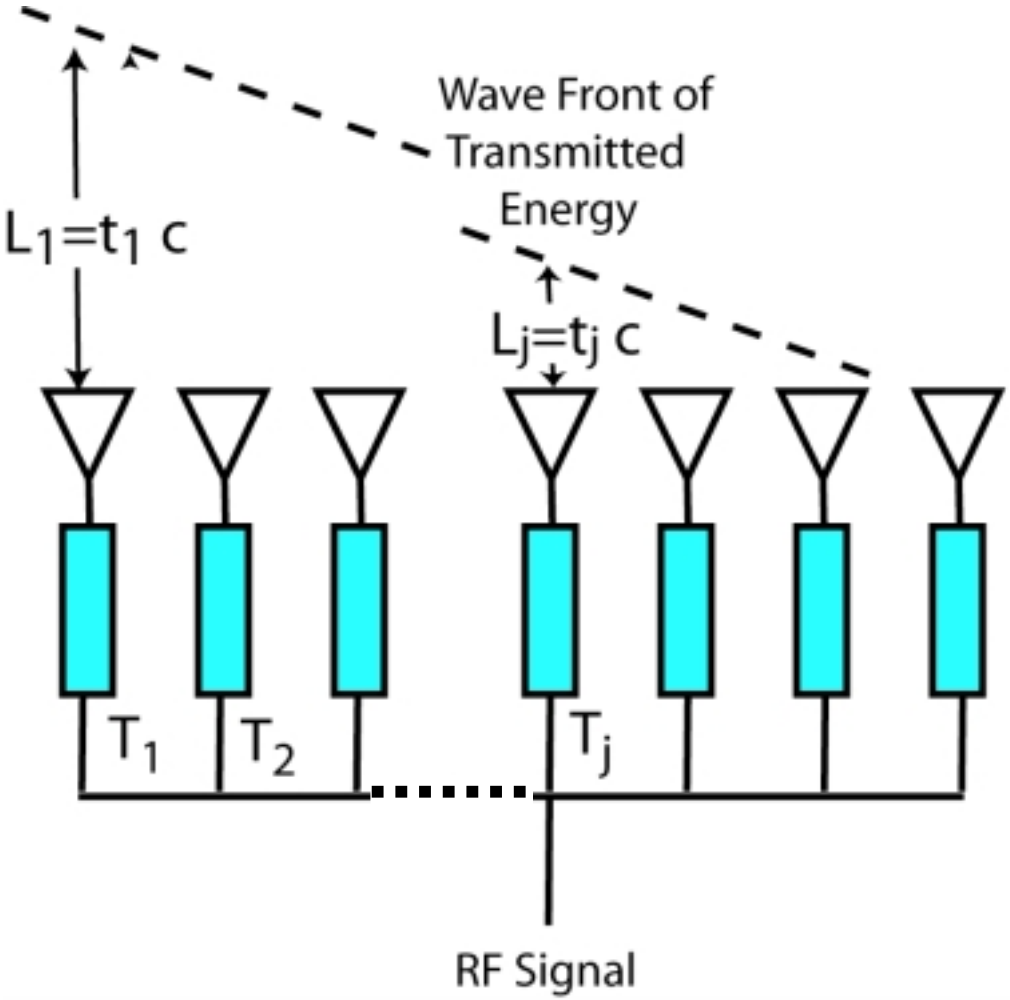
M. W. Geis, S. J. Spector, K. E Krohn, S. J. Deneault,
M. F. Marchant,L. M. Johnson, R. C. Williamson,
S. G. Johnson,M. L. Povinelli, R. Sinta, W. Mowers, and
T. M. Lyszczarz

August 7 & 8, 2002

Outline

- **Part I**
  - → **Program Goals**
  - **Basic Design of Optical Delay System**
  - **Tunable Optical Delay Architecture**
  - **Thermal Switch**
  - **Electro-Optic Organic Crystals, DAST**
  - **Low Loss Wave Guide Fabrication**
- **Part II**
  - **Tunable Delay Implementation**

Phased Array Antenna System Motivation



Optical Waveguide
Variable
True Time Delay

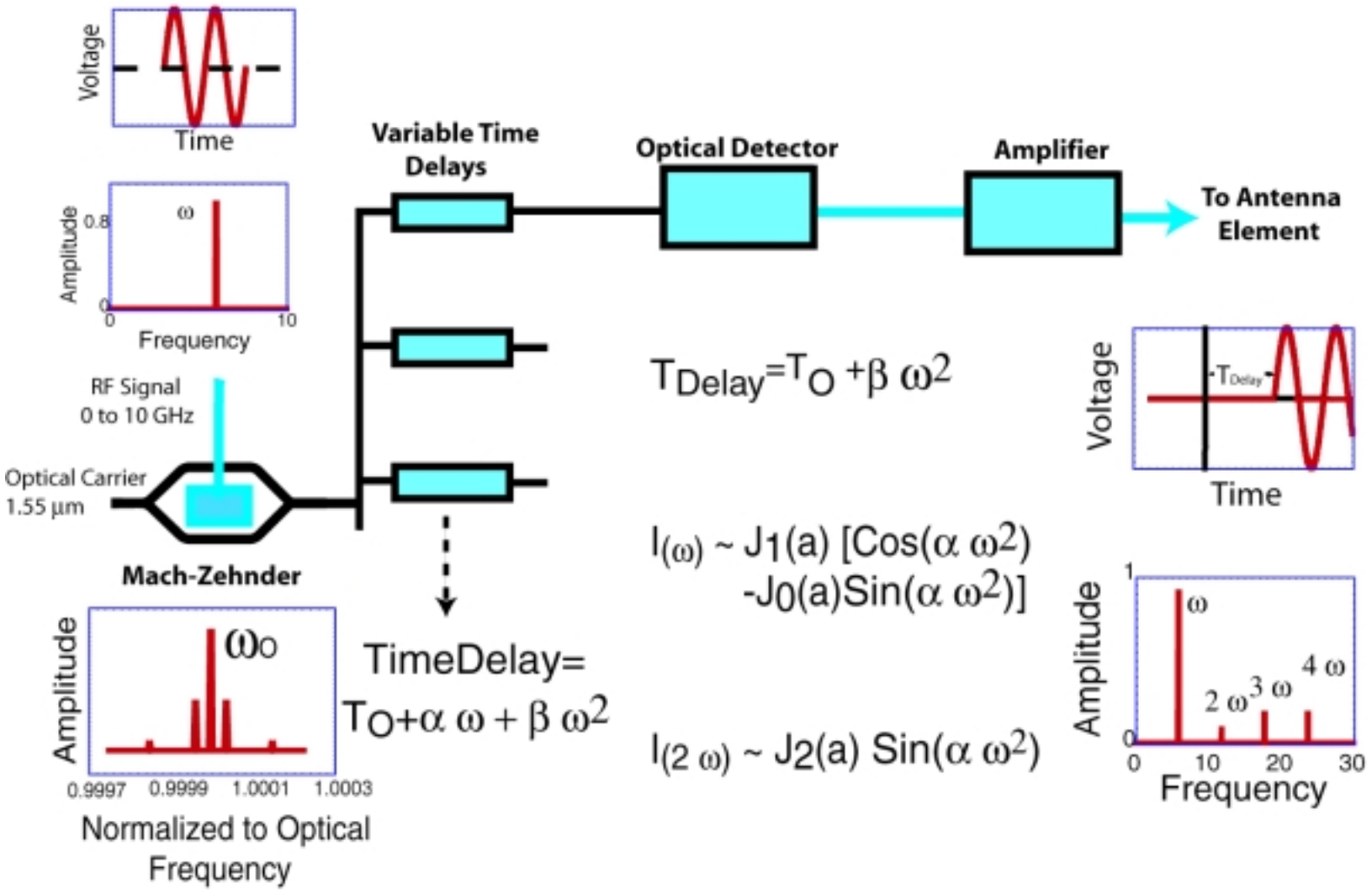
Program Goals

- **Year 1**
  - **Variable time delay ≤10 ns, 1 dB/ns loss, 20% thermal tuning**
  - **Design 3-D structures – IC fab, self assembly, …**
  - **Study alternative tuning techniques, eg electro-optic material**
- **Year 2**
  - **Integrate multiple waveguides, 1 μs tuning rate**
  - **Develop low loss waveguide, 10 ns delay, 0.1 dB/ns, 20% range**
    - **2-D photonic crystal**
  - **Fabricate 3-D structures**
  - **Demonstrate variable attenuator**
- **Year 3**
  - **Integrate variable attenuator – demonstrate fixed loss variable delay**
  - **Develop lower loss waveguide, 0.01 dB/ns loss, 50 ns delay, 20% tuning – 3-D photonic crystal**

Outline

- **Part I**
  - Program Goals
  - → **Basic Design of Optical Delay System**
    - **Dispersion Effect**
    - **Design Trade Offs**
      - **Bandwidth**
      - **Dispersion**
      - **Pointing Accuracy**
    - **Tunable Optical Delay Architecture**
    - **Thermal Switch**
    - **Electro-Optic Organic Crystals, DAST**
    - **Low Loss Wave Guide Fabrication**
- **Part II**
  - **Tunable Delay Implementation**

Variable Time Delay Unit



System Degradation by Dispersion

$$\text{Time Delay} = T_o + \omega\,\alpha + \omega^2\,\beta$$

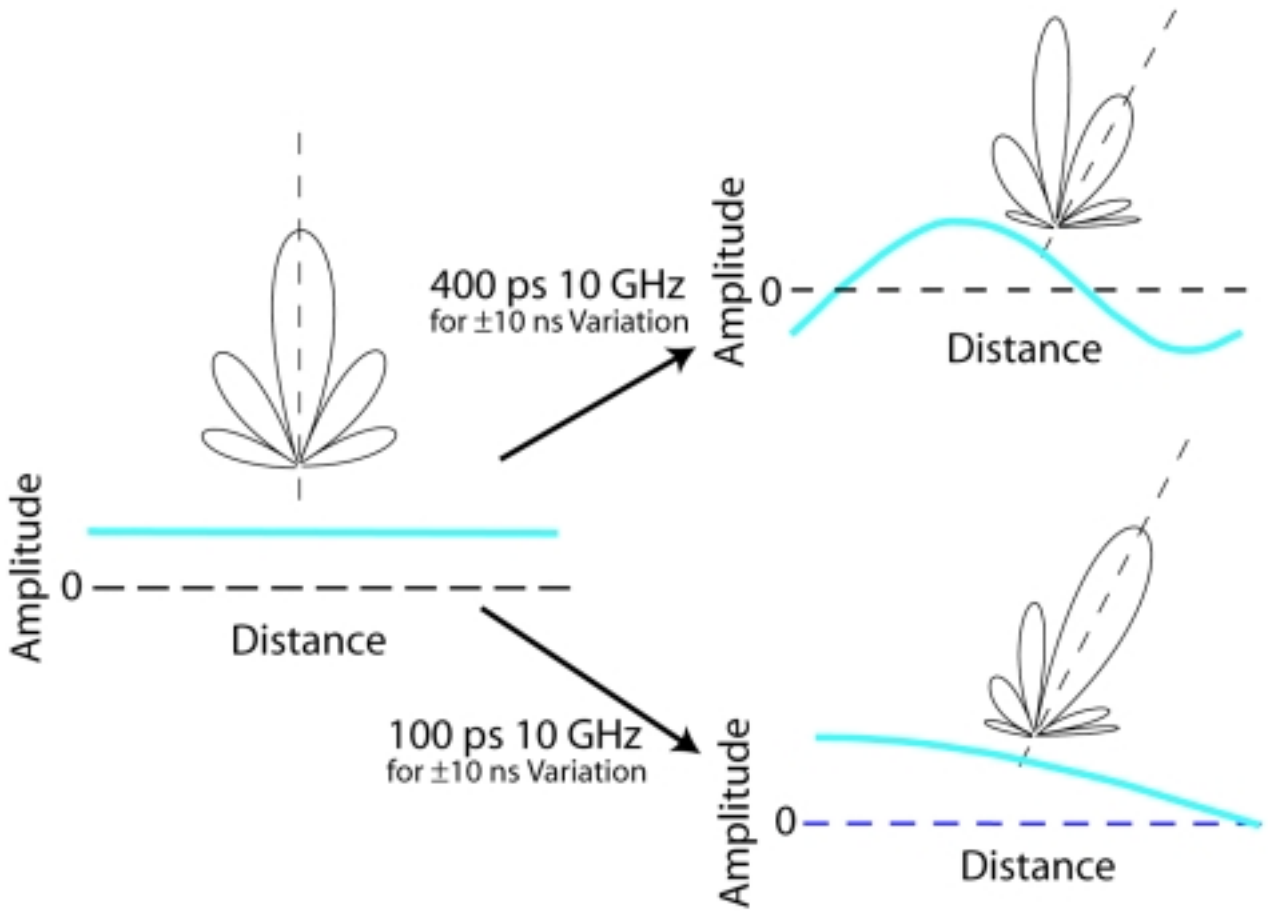
First Order Dispersion, α

- **Time Delay -> none**
- **Phase-> none**
- **Magnitude-> $\alpha\ \omega^2$**
- **Second Harmonic -> $\alpha\ \omega^2$**
- **Signal Distortion-> $\alpha\ \omega^2$**

Second Order Dispersion, β

- **Time Delay -> $\omega^2\ \beta$**
- **Phase-> none**
- **Magnitude ->none**
- **Second Harmonic ->none**

First Order Dispersion
Antenna Pointing and Power Distribution

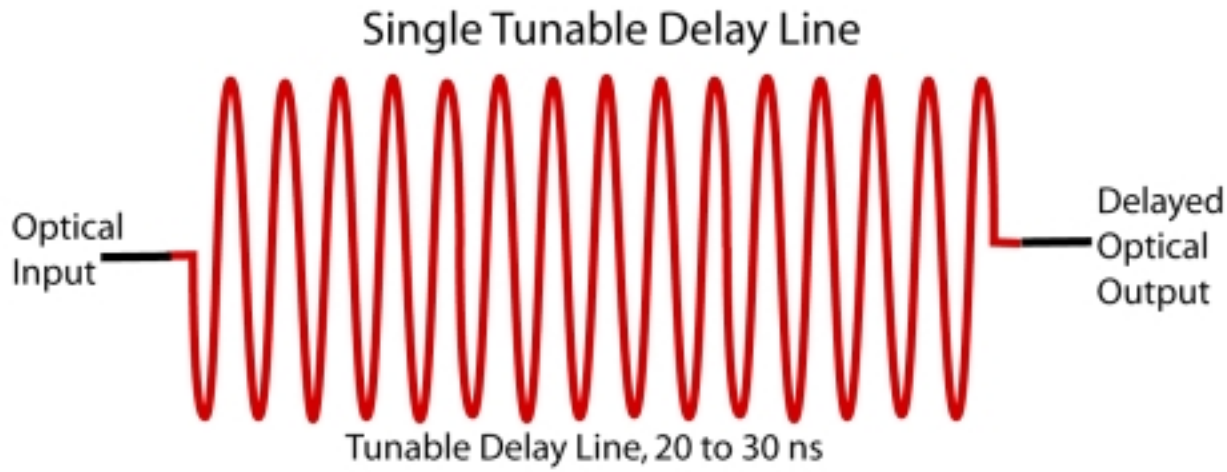


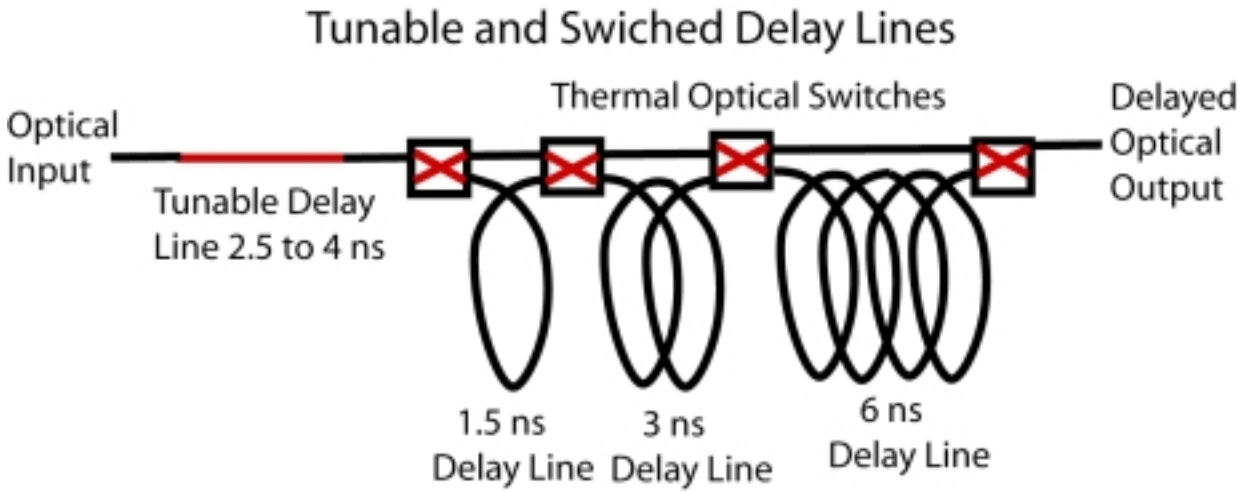
Commercial Chirped Fiber Grating 100 ps for 10 ns Delay Variation
Slow -Wave Photonic Crystals Systems 100 to 10 ps for 10 ns Delay Variation

Outline

- **Part I**
  - **Program Goals**
  - **Basic Design of Optical Delay System**
  - → **Tunable Optical Delay Architecture**
  - → **Thermal Switch**
  - **Electro-Optic Organic Crystals, DAST**
  - **Low Loss Wave Guide Fabrication**
- **Part II**
  - **Tunable Delay Implementation**

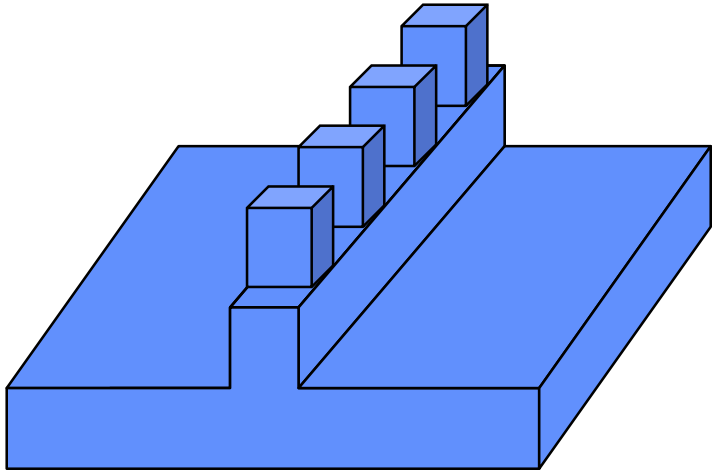
Tunable Time Delay Systems





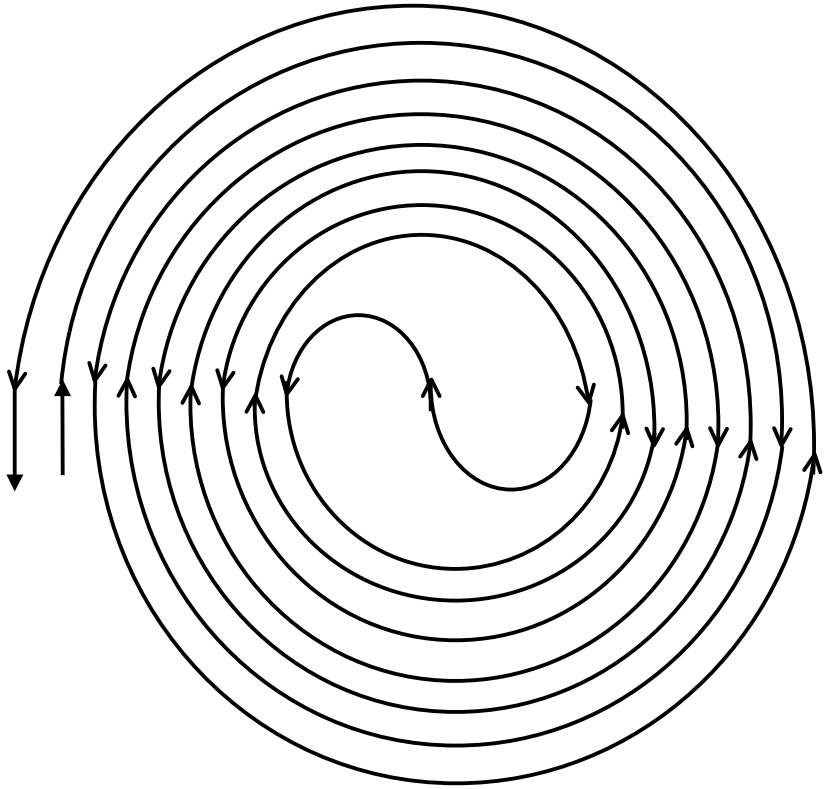
Variable Time Delay Structure
Rib Waveguide Etched in Silicon

Tunable Time Delay



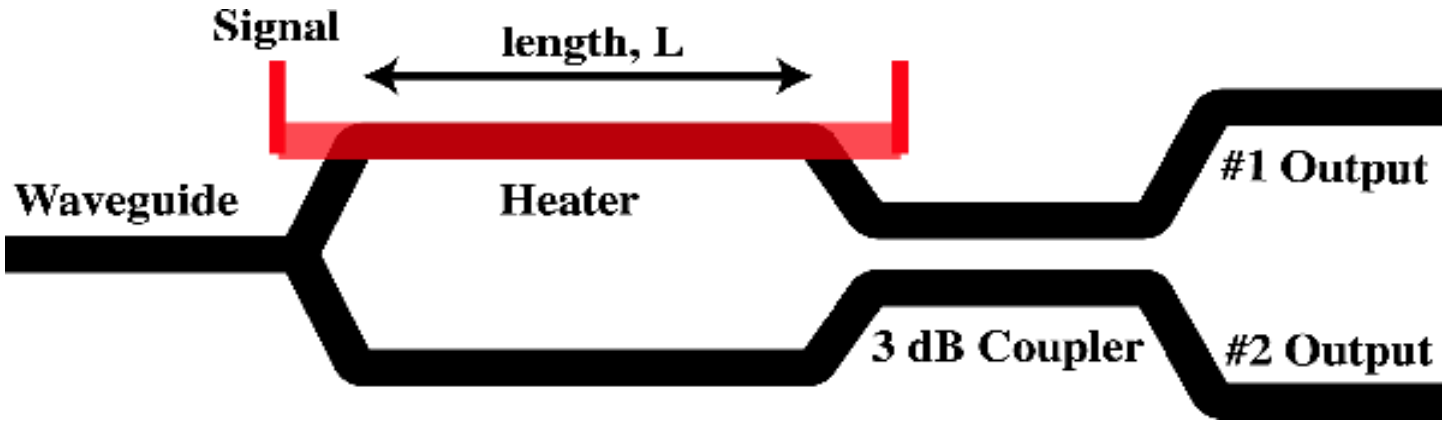
Photonic Bandgap
Slow Wave Structure

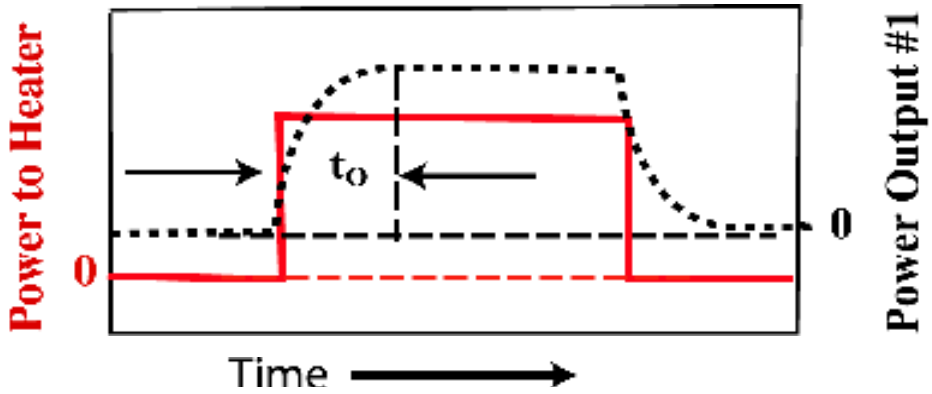
Fixed Time Delay



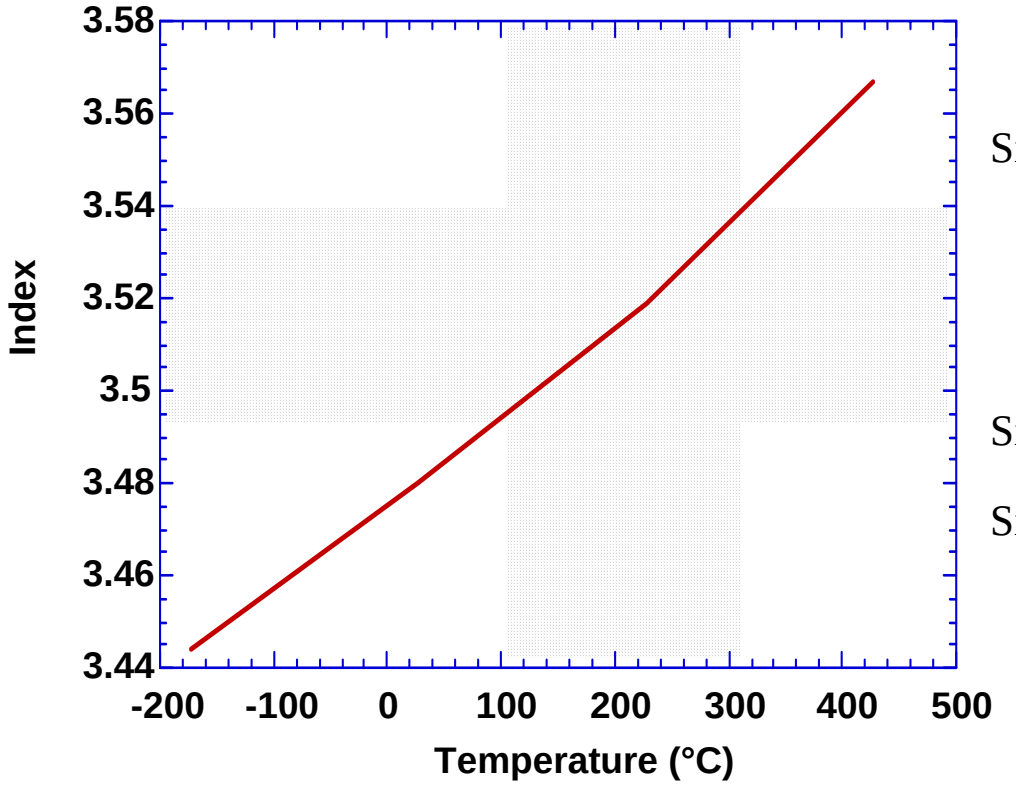
Compact Time Delay

Thermal Mach-Zehnder Optical Switch





Thermal-Optical Properties

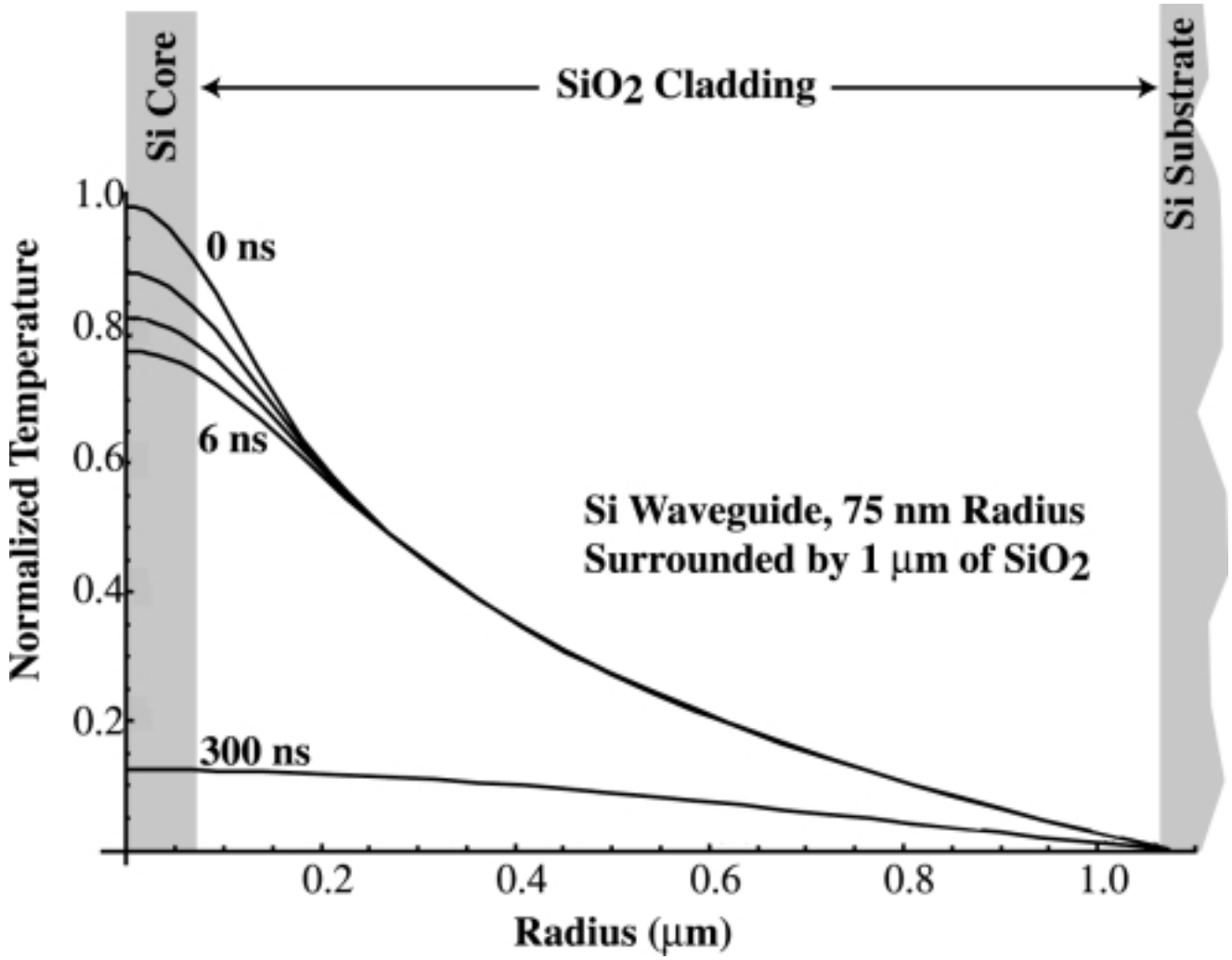


Silicon $\frac{dn}{dT} = 2x10^{-4} \ \ ^{\circ}C^{-1}$

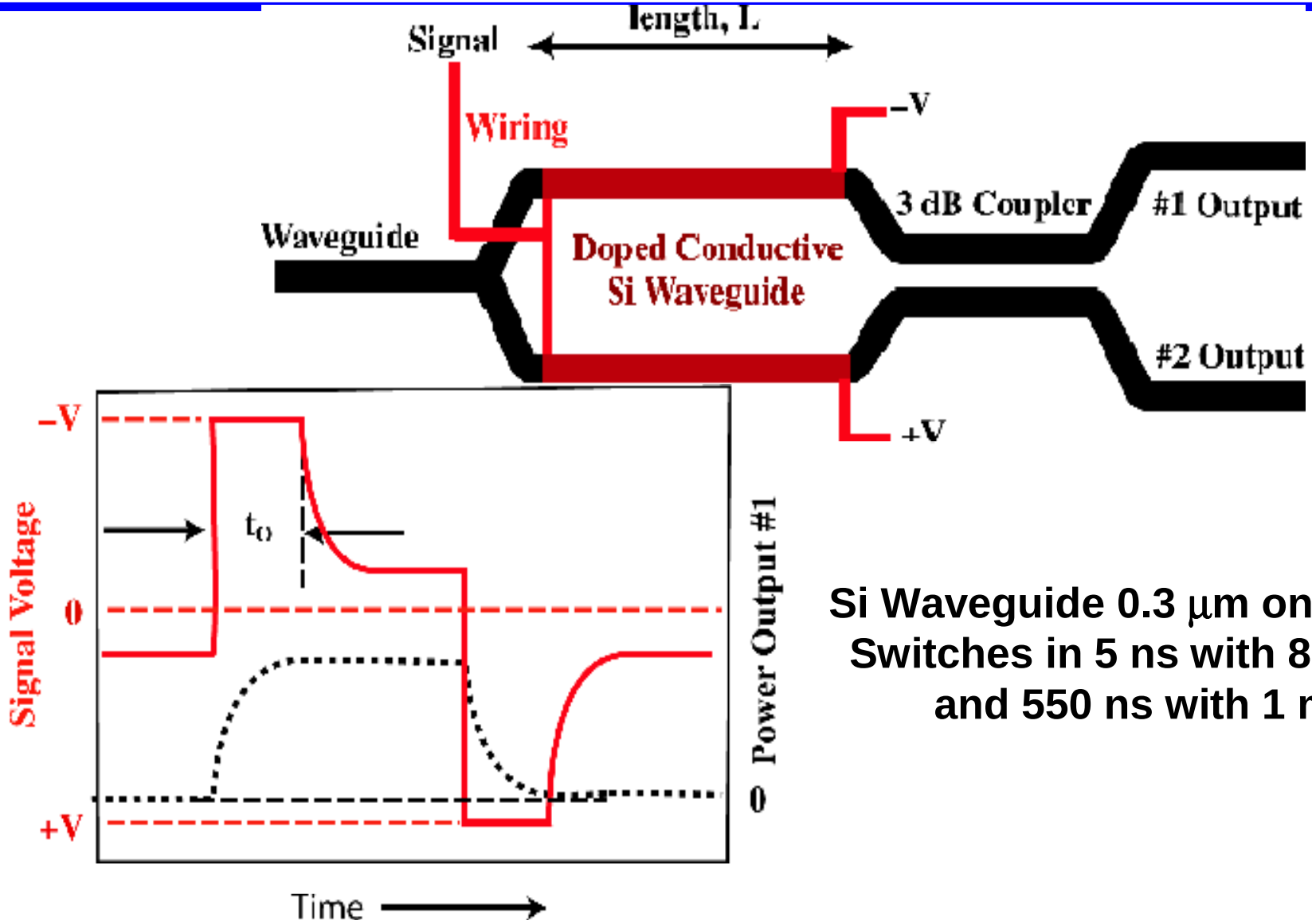
Silicon Dioxide and

Silicon Nitride $\frac{dn}{dT} \approx -1x10^{-5} \ \ ^{\circ}C^{-1}$

Si Waveguide Temperature Transients



Both Arms of Mach-Zehnder Heated

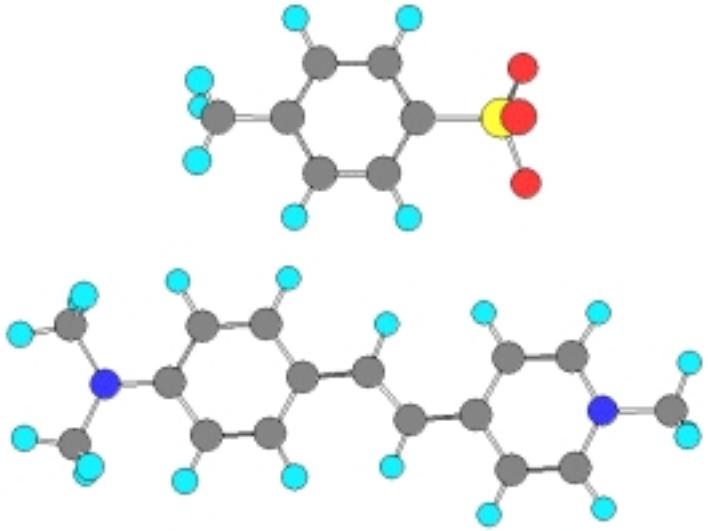


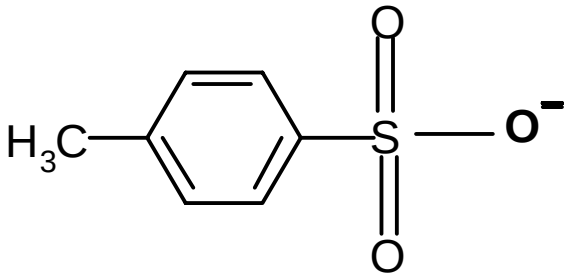
Si Waveguide 0.3 μm on a side, Switches in 5 ns with 85 mW, and 550 ns with 1 mW

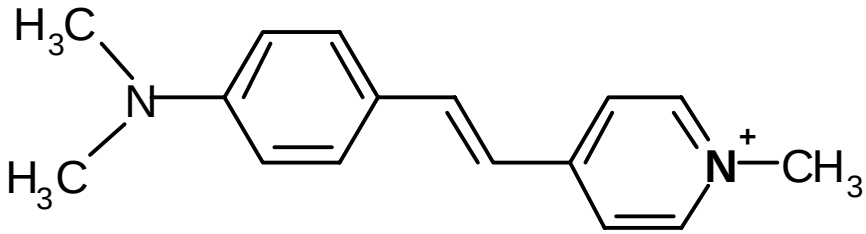
Outline

- **Part I**
  - Program Goals
  - Basic Design of Optical Delay System
  - Tunable Optical Delay Architecture
  - Thermal Switch
  - → **Electro-Optic Organic Crystals, DAST**
  - **Low Loss Wave Guide Fabrication**
- **Part II**
  - **Tunable Delay Implementation**

Electro-Optic Switch with DAST

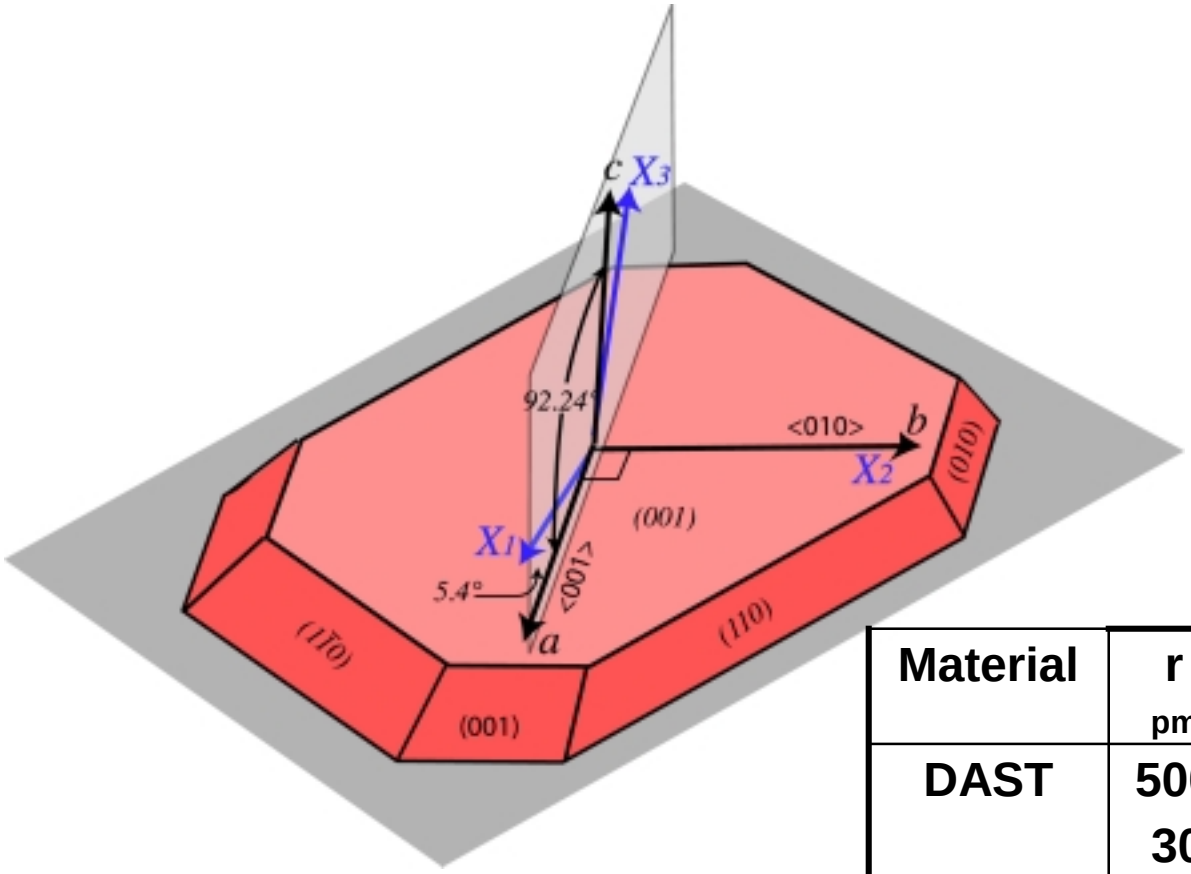






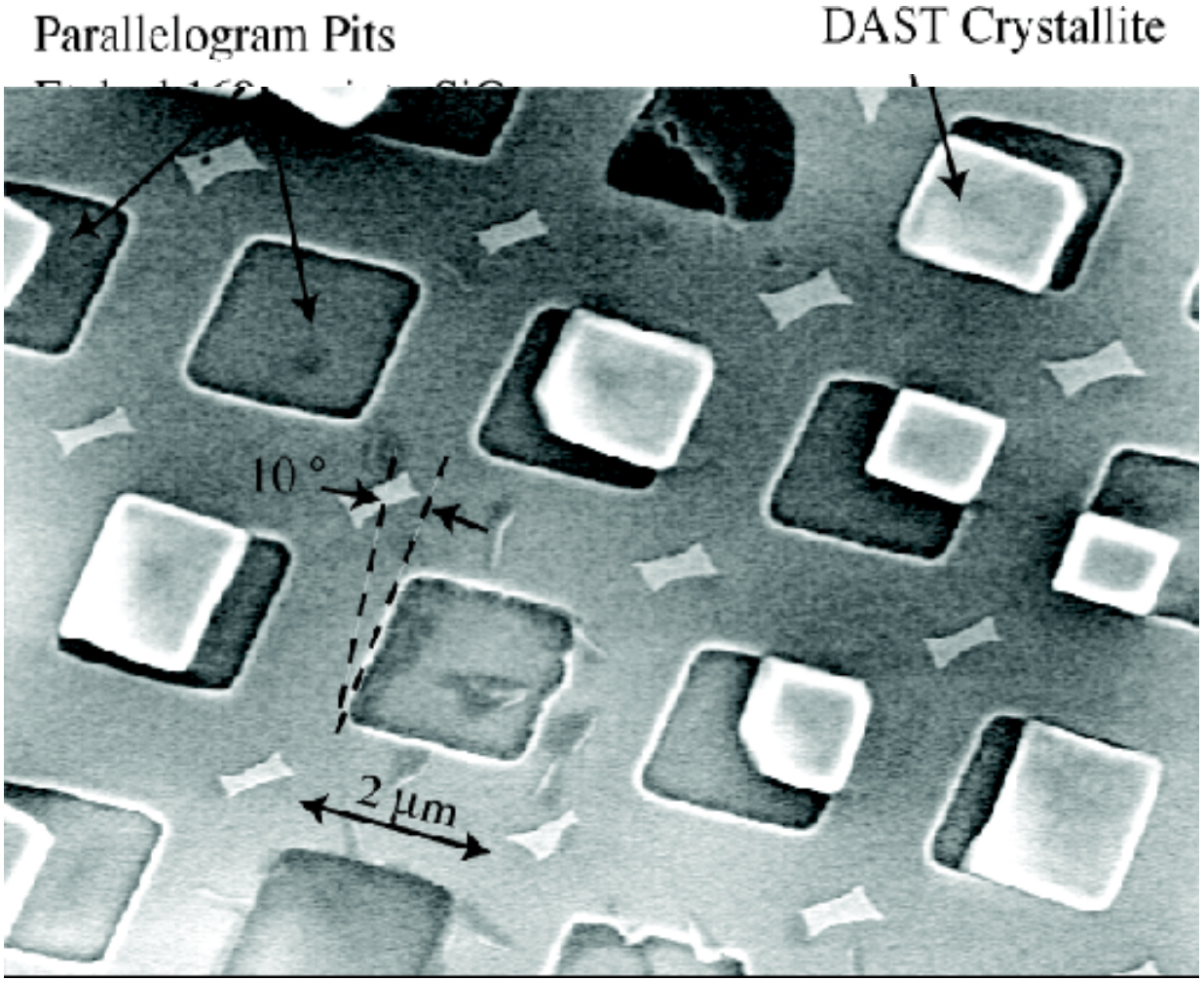
Dimethyl Amino 4-N-Methylstilbazolium Tosylate

Properties of DAST

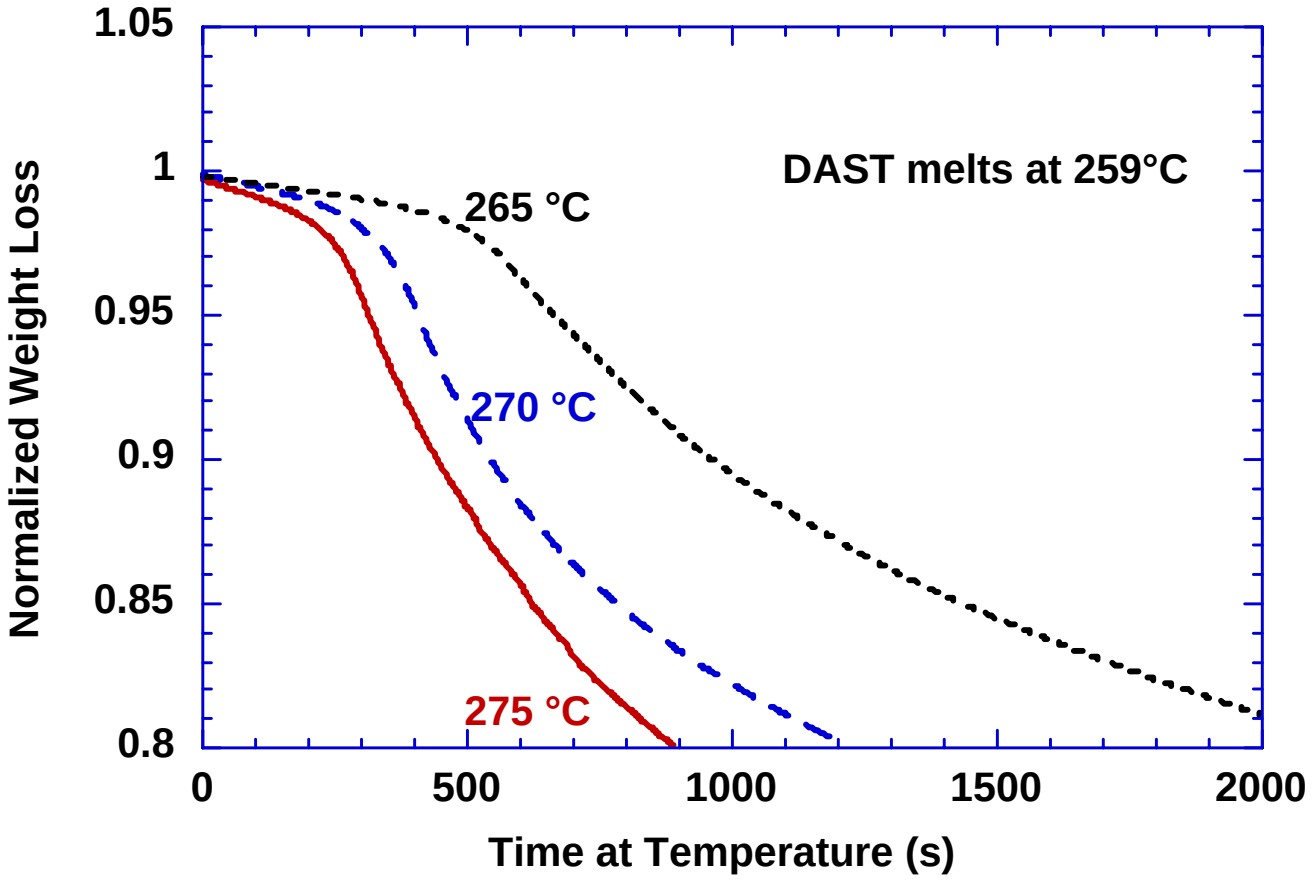


Material	r n^3 pm V-1	n_{RF}	n_{Op}	Max. T °C
DAST	500 to 3000	2.2	2.2	260
$LiNbO_3$	290	5.7	2.1	500 to 1000
Polymer	~290	~1.5	~1.5	~100

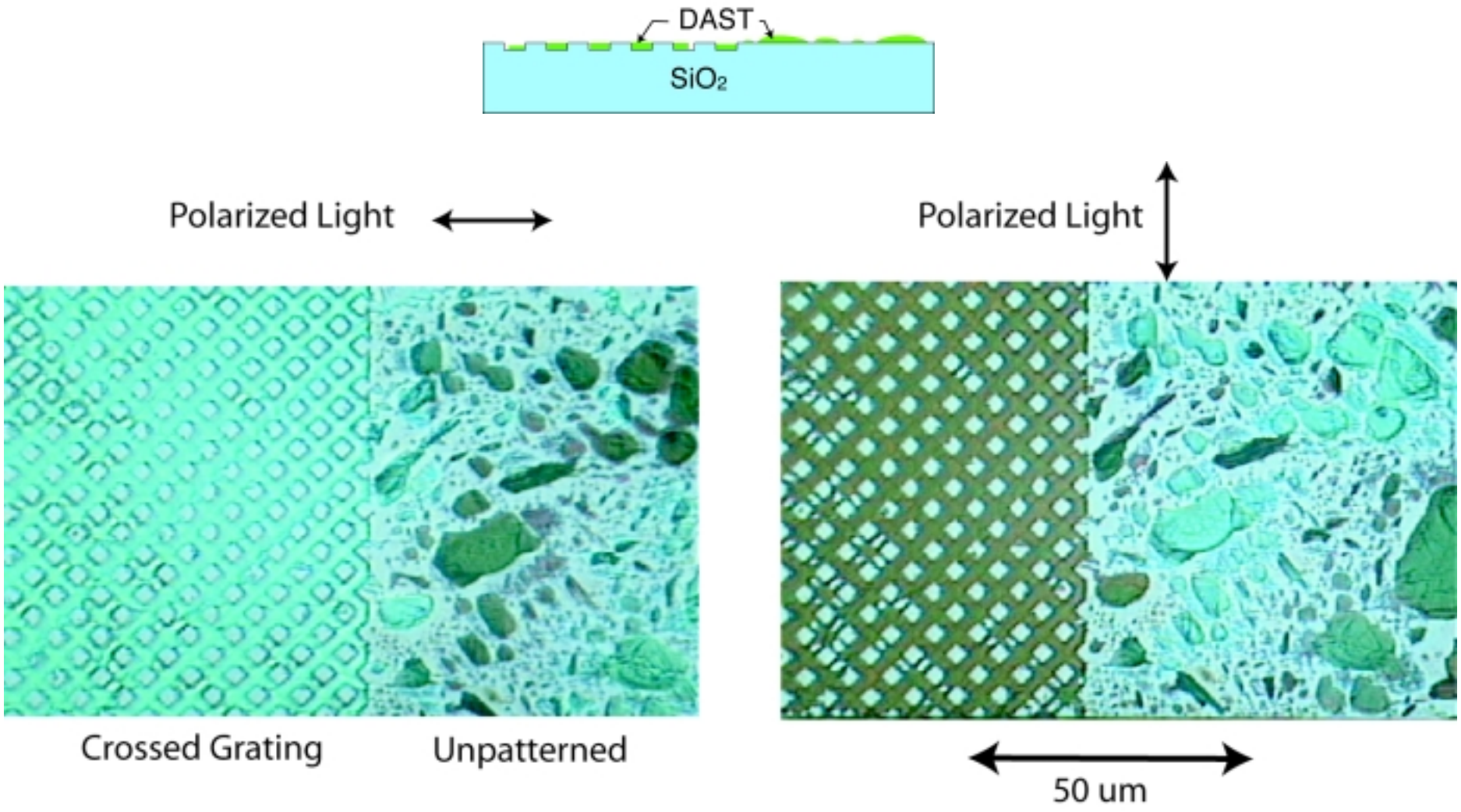
Crystal of DAST Oriented by Lithographic Structures



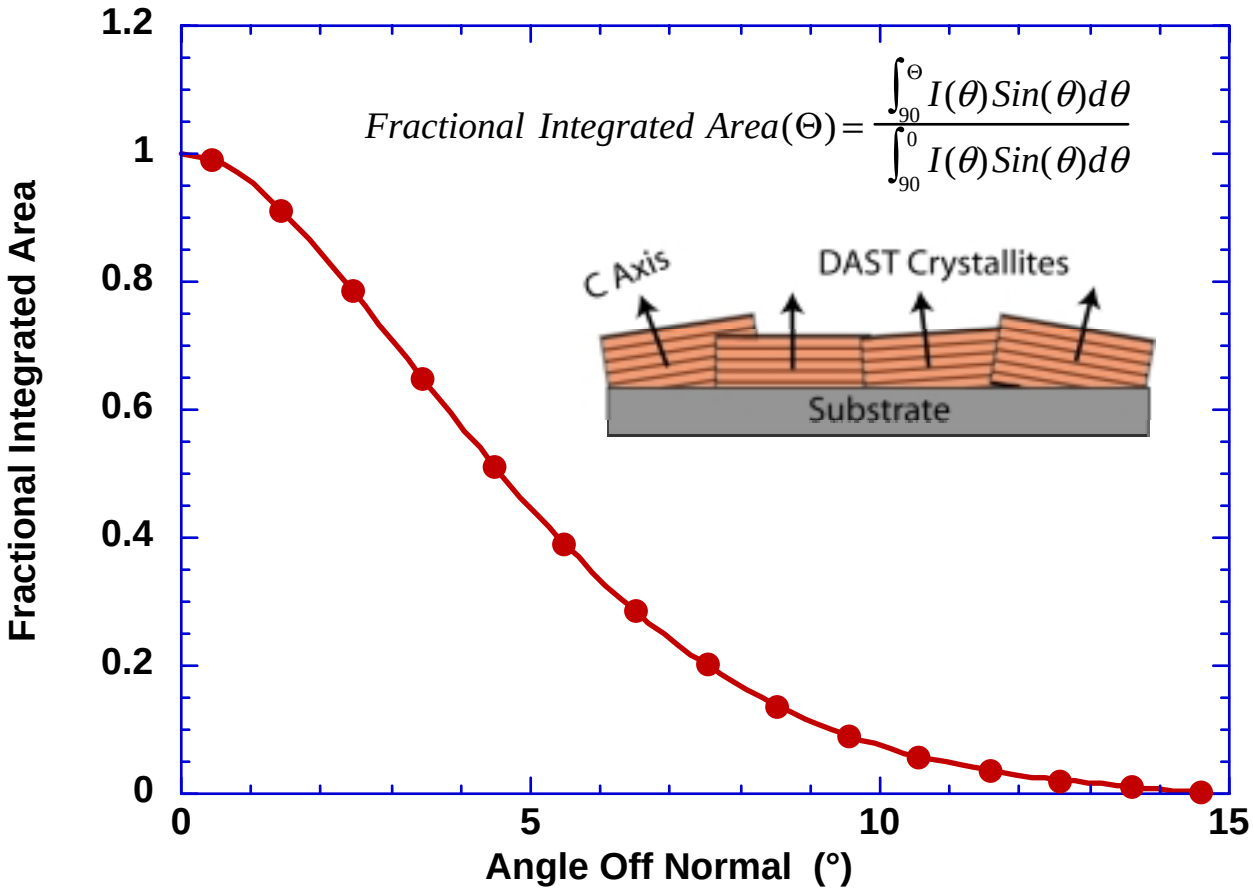
DAST Thermal Properties



Grating-Stabilized Crystal Growth

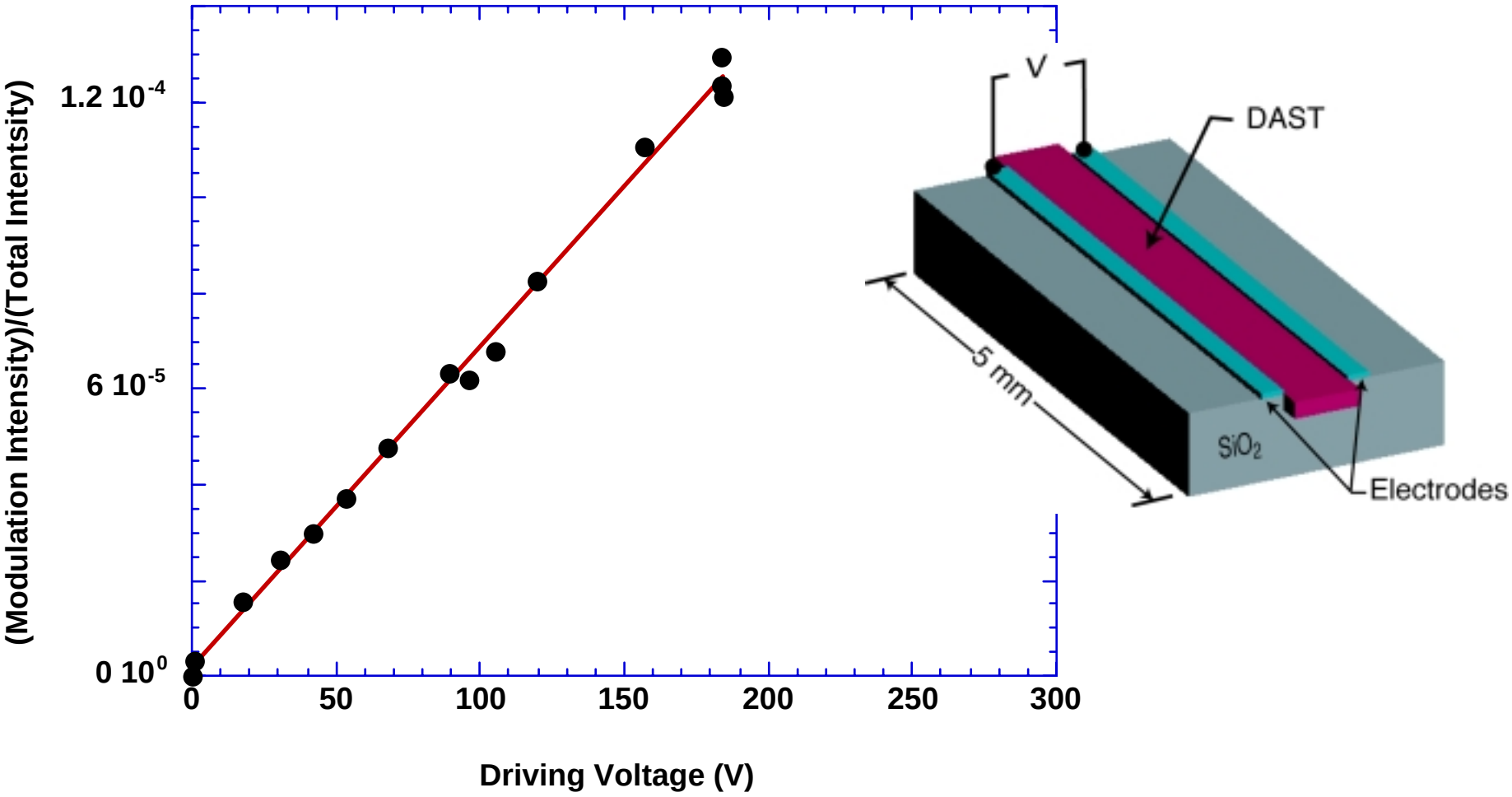


DAST C Axis Orientation

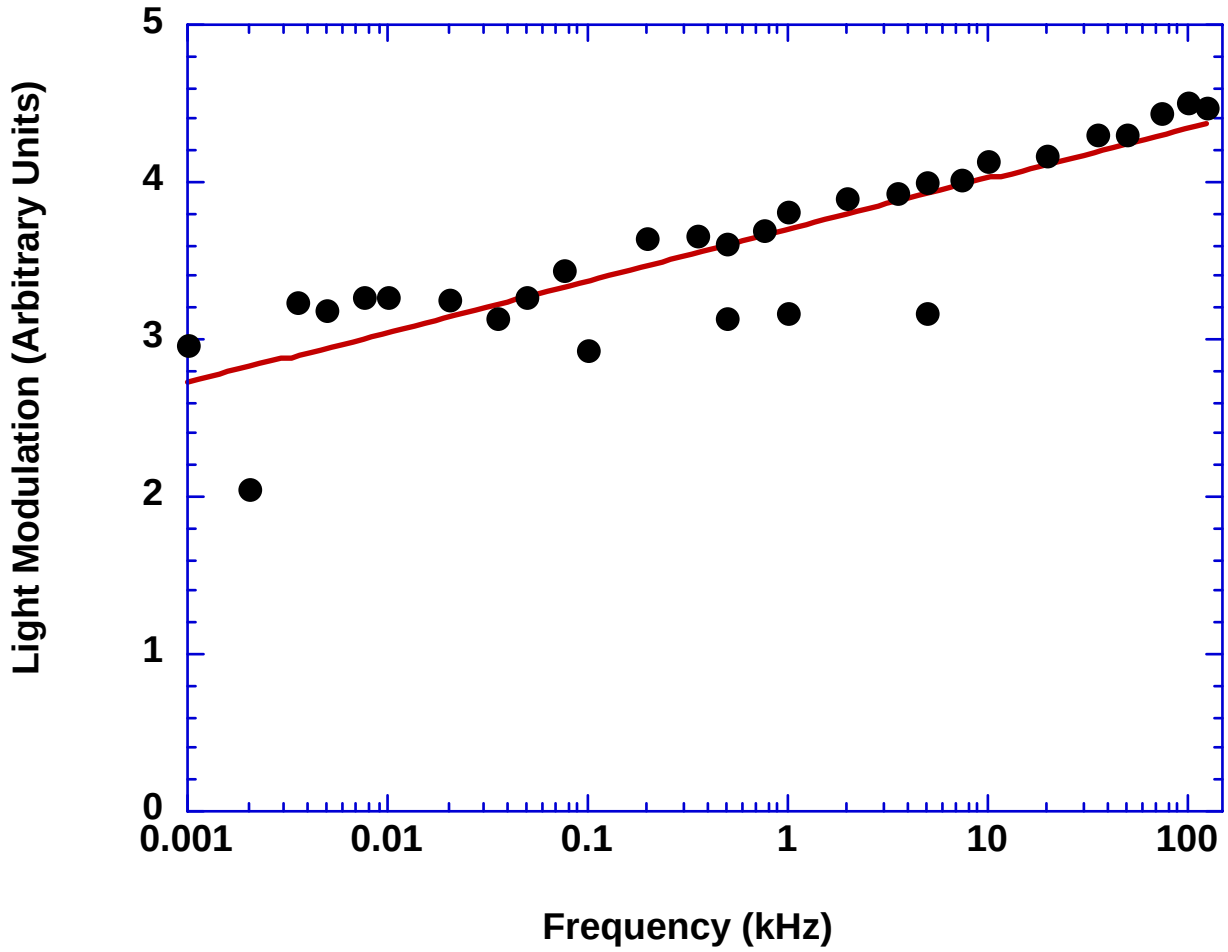


DAST Wave Guide

Modulation with DAST Waveguide



DAST Modulator Frequency Response

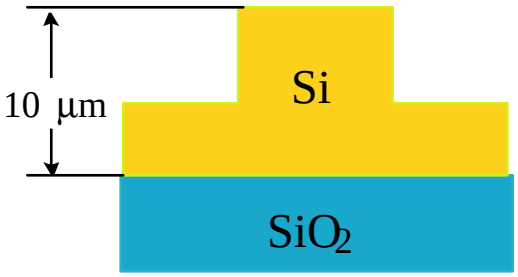


Outline

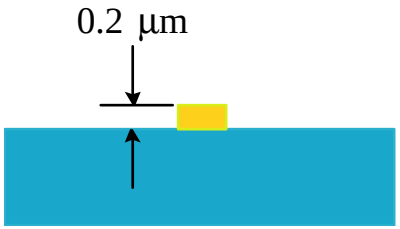
- **Part I**
  - Program Goals
  - Basic Design of Optical Delay System
  - Tunable Optical Delay Architecture
  - Thermal Switch
  - Electro-Optic Organic Crystals, DAST
  - → **Low Loss Wave Guide Fabrication**
- **Part II**
  - **Tunable Delay Implementation**

Waveguides

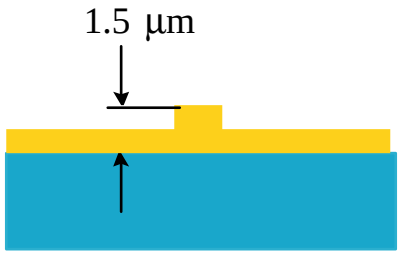
Rib:
- losses ~ 0.1 dB/cm
- bending radius ~ 5 mm
- efficient coupling from fibers



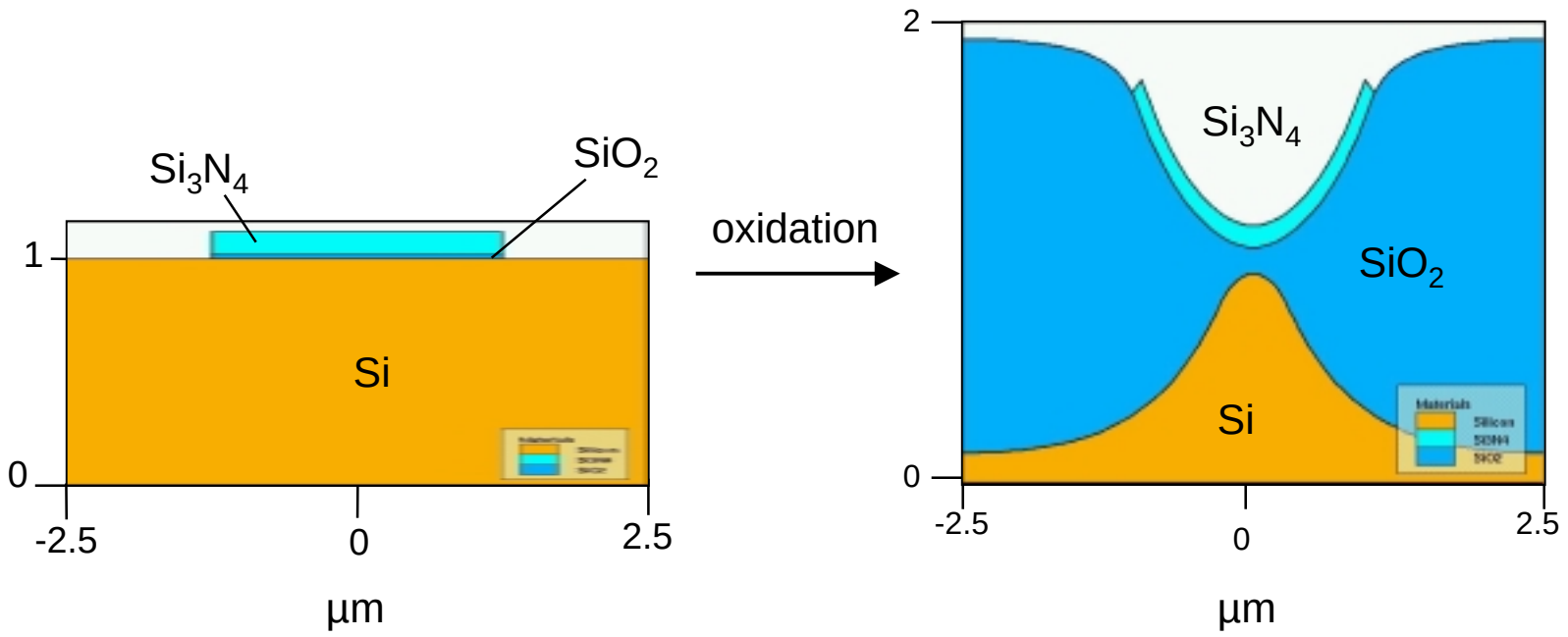
Strip:
- losses ~ 1-10 dB/cm
- bending radius ~ 5 μm



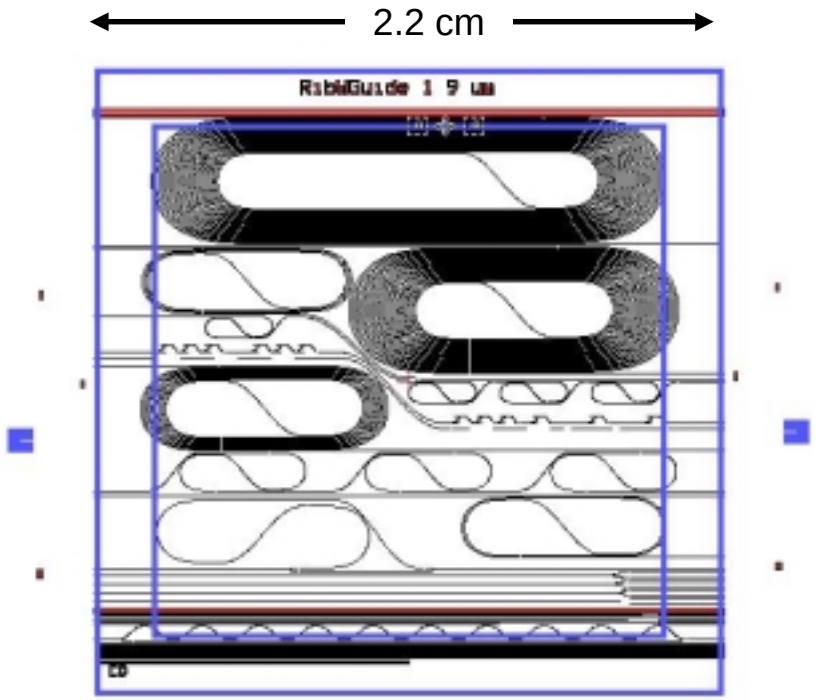
Small Rib:
- losses ~ ?? dB/cm
- bending radius ~ 0.3 mm



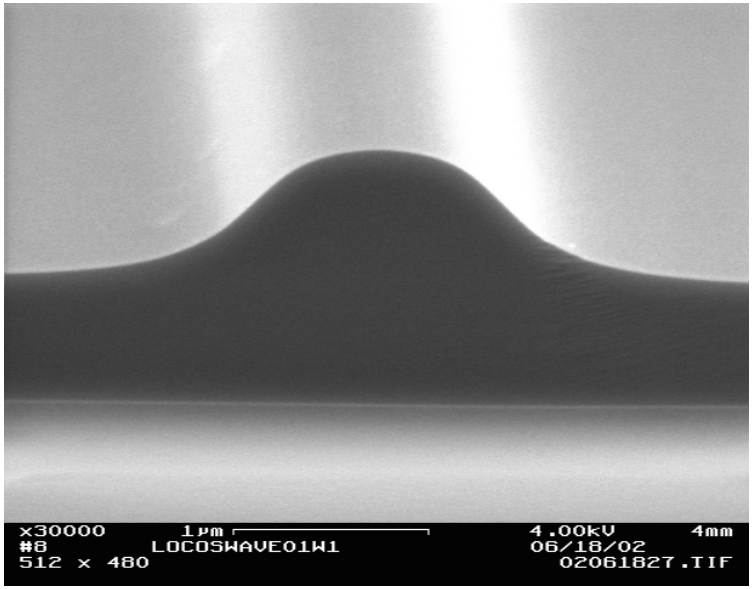
Local Oxide (LOCOS) growth simulations



Low-loss Rib Waveguides



Mask with test waveguide structures for measuring loss.
-Path lengths 2 to 90 cm,
0.2 to 10 ns
-Bending 10 μm to 1 mm



Cross-section of waveguide fabricated in SOI.
-Currently being tested.
-Profile is wider than expected. (Likely not single mode).

Initial Rib Waveguide Results

- **Optical Loss 0.05 to 0.1 dB/cm or 0.5 to 1 dB/ns**
- **Coupling Loss In and Out 2 to 10 dB, Average ~ 4 dB, Using Fiber Lens**

Summary

- **Modeled Variable Time-Delay Structures**
  - **First Order Dispersion Does Not Affect Time Delay or Pointing**
- **Modeled Thermal Si Waveguide Mach Zehnders**
  - **Fast, ~ 10 ns**
  - **Low Power, 1 mW**
- **Demonstrated Electro-Optic Modulation in DAST**
- **Made Low Loss Waveguides in Si**