IBM

Zurich Research Laboratory

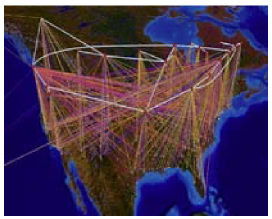
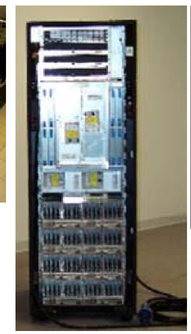
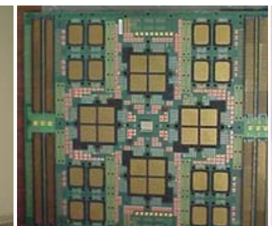
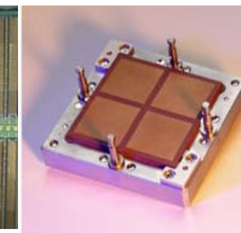
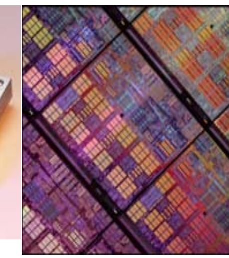
Hybrid Photonic Nano-Structures for Lasing and Switching Applications

Nikolaj Moll, Rik Harbers, Selim Jochim, Stephan Gulde, Rainer F. Mahrt and Bert J. Offrein

June 28, 2006

www.zurich.ibm.com

Optical Interconnect Hierarchy

	WAN, MAN-level Internet, GRID	**Lab & Campus-level** LAN, SAN	**System-level** intra-rack & rack-to-rack	**Board-level** module-to-module	**module-level** chip-to-chip	**Chip-level** on-chip
						
Distances	**Multi-km**	**10-2,000 m**	**0.3-1 m**	**0.1-0.3 m**	**5-100 mm**	**0.1-10 mm**
# Lines	**1s**	**1s-10s**	**100s**	**1000s**	**10,000s**	**100,000s**
Technologies	**Internet protocol, SONET, ATM**	**LAN/SAN Standards (Ethernet, InfiniBand, Fibre Channel)**	**Design-specific system buses, new standards (InfiniBand)**	**Design-specific, some standards (PCI/PCI-X/3GIO)**	**Design-specific**	**Design-specific**
Optics Use	**Ubiquitous since 80s or early 90s**	**Common since late 90s: Fiber standards in Enet, IB, FC**	**Coming in 2006-2010, with investment**	**Possibly cost-effective vs. copper in 2010-2015**	**Later**	**Even later, if ever**
			The Next Steps		**The Future**	

Outline

- Organic photonic crystal lasers

  Laser structures with TiO_2 feedback layer

  Interferometrically Defined Laser Structures

- All-optical switching in organic micro-cavities

  Cavity pump-and-probe measurements

Outline

- Organic photonic crystal lasers
  - Laser structures with TiO_2 feedback layer
  - Interferometrically Defined Laser Structures
- All-optical switching in organic micro-cavities
  - Cavity pump-and-probe measurements

Motivation

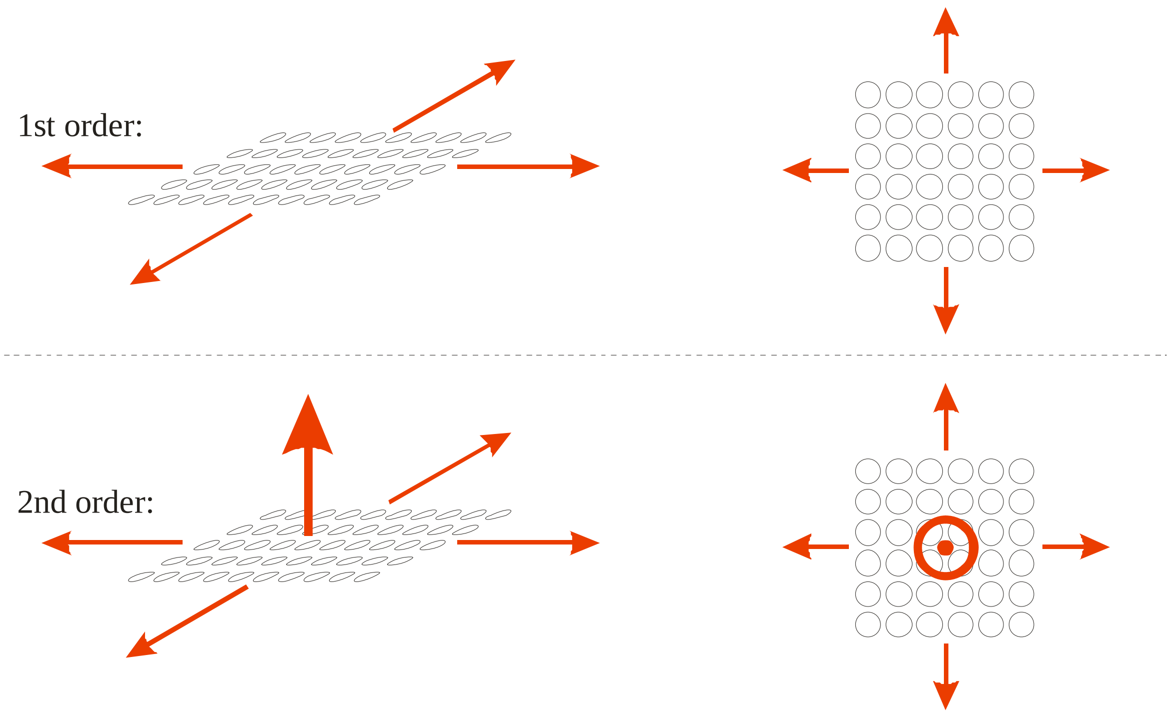
Why organic photonic crystal lasers?

- Potentially cheap alternative to conventional edge-emitting and VCSEL lasers
- Broad gain spectrum
- Flexible wavelength selection
- Possibility to integrate into optical integrated circuits

Distributed Feedback in a 2D Grating / Photonic Crystal

First order: Emission in-plane

Second order: Emission in-plane and/or ***directional*** vertical emission



Outline

- Organic photonic crystal lasers

  Laser structures with TiO_2 feedback layer

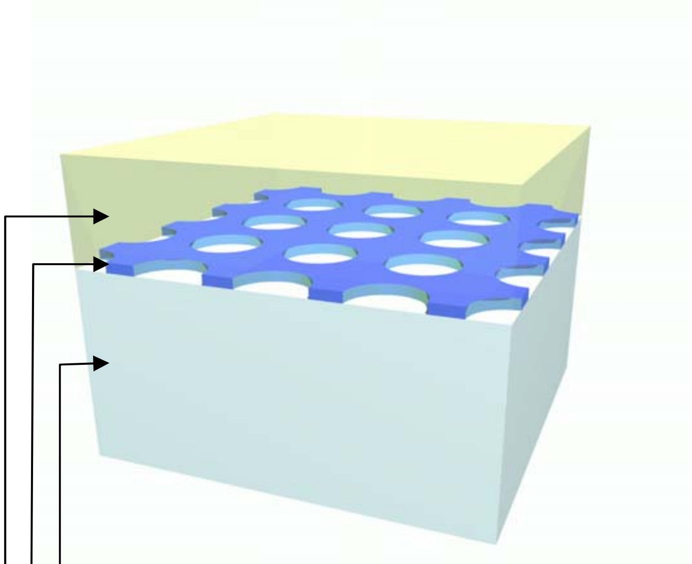
  Interferometrically Defined Laser Structures

- All-optical switching in organic micro-cavities

  Cavity pump-and-probe measurements

Enhanced coupling in distributed feedback structures

- Photonic crystal structures featuring a *TiO_2 layer* enhancing the feedback
  - Higher index contrast than with a SiO_2 – polymer interface
  - Larger confinement in the waveguide

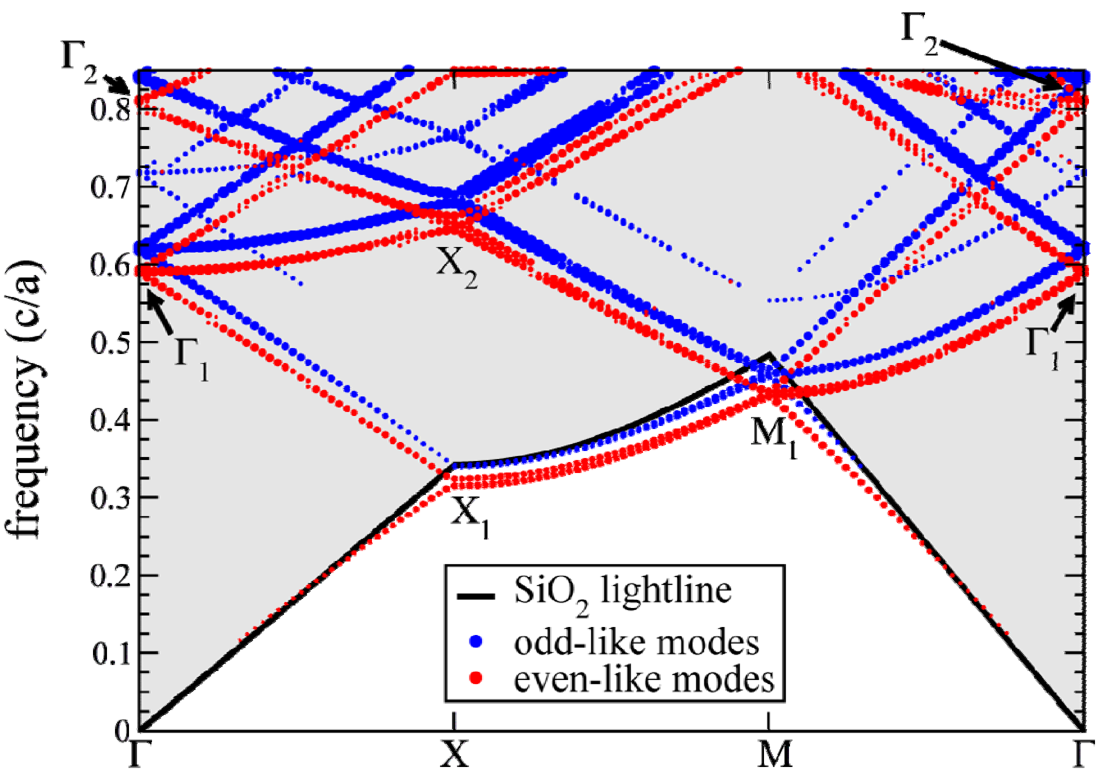


SiO_2: n=1.46

TiO_2: n=2.5, t = 35nm

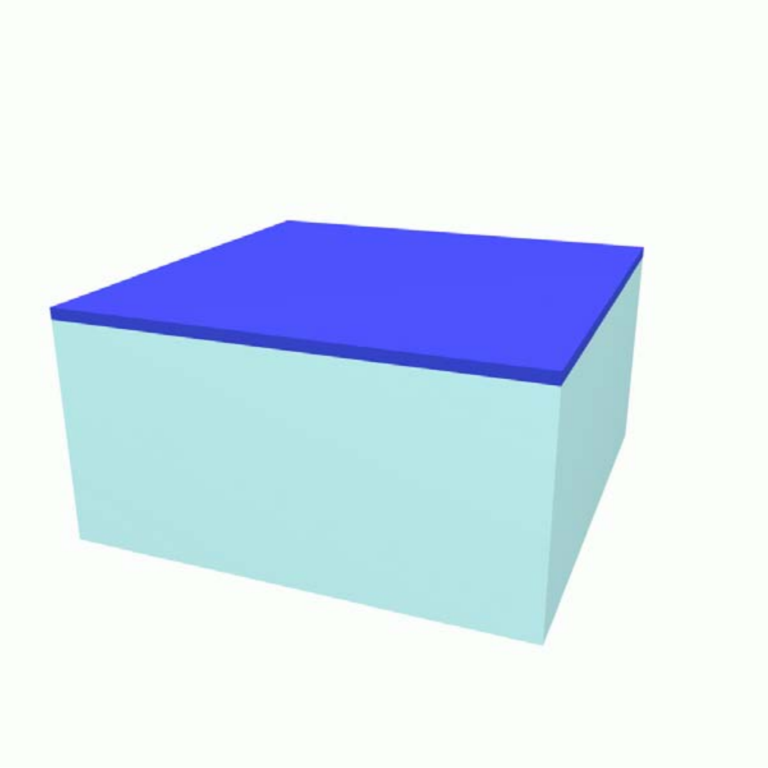
Poly: n=1.75, t = 250nm

For λ=490nm, a=295nm



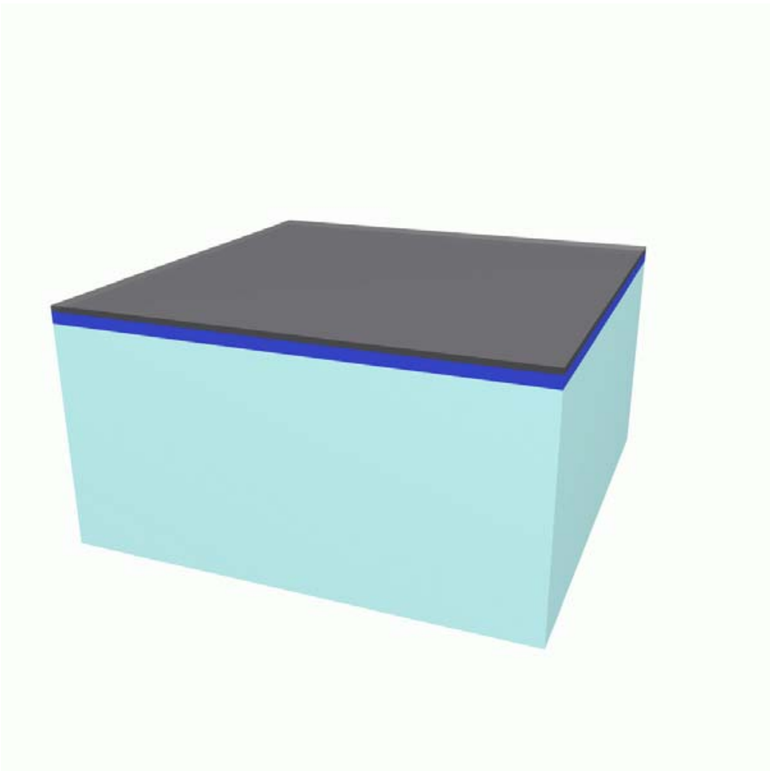
Fabrication

- Depositing the TiO_2 using sputtering Ti in O_2



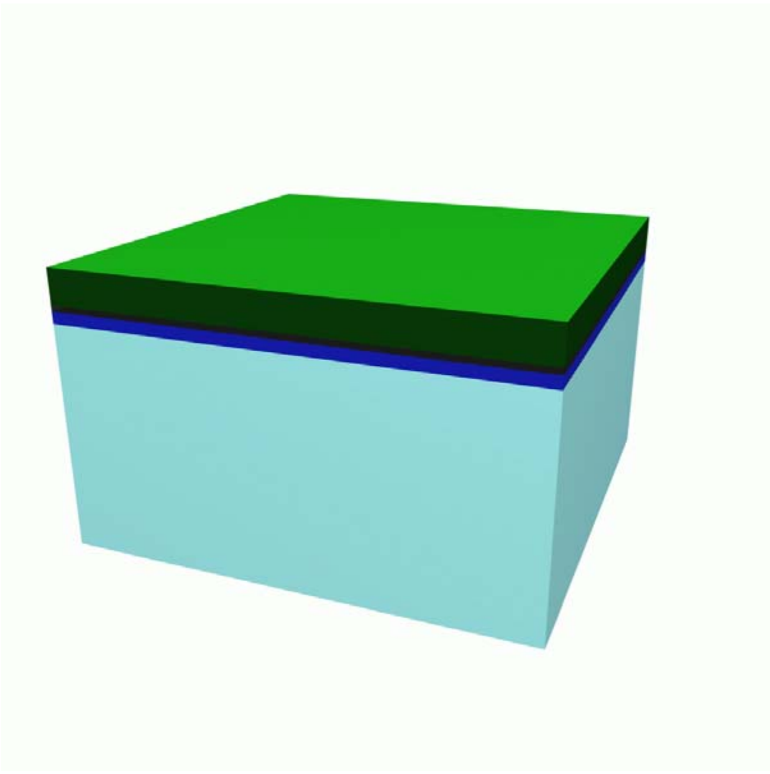
Fabrication

- Depositing the TiO_2 using sputtering Ti in O_2
- Depositing the Chrome etchmask using sputtering



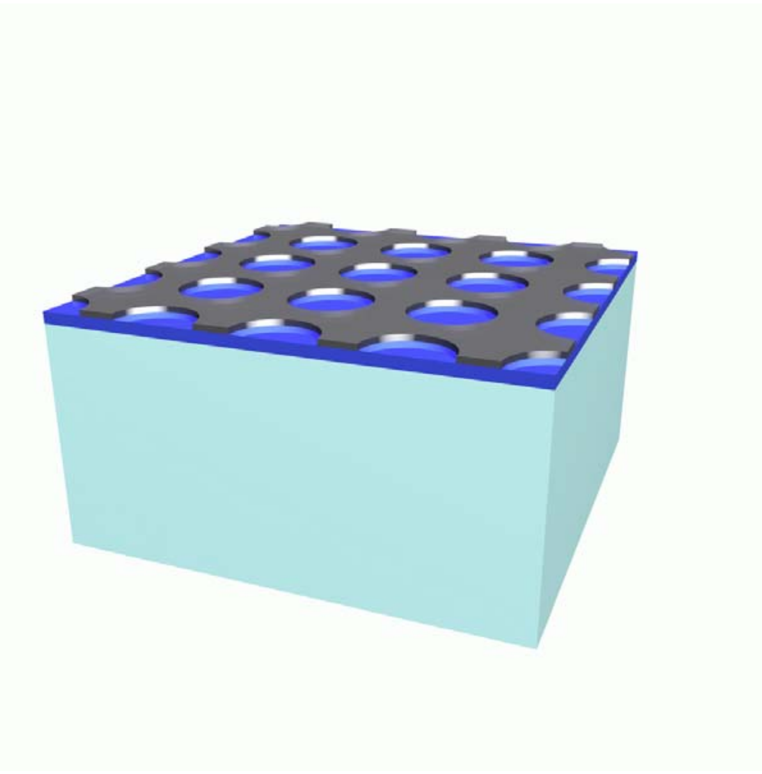
Fabrication

- Depositing the TiO_2 using sputtering Ti in O_2
- Depositing the Chrome etchmask using sputtering
- Spincoating PMMA and structuring using electron beam litho



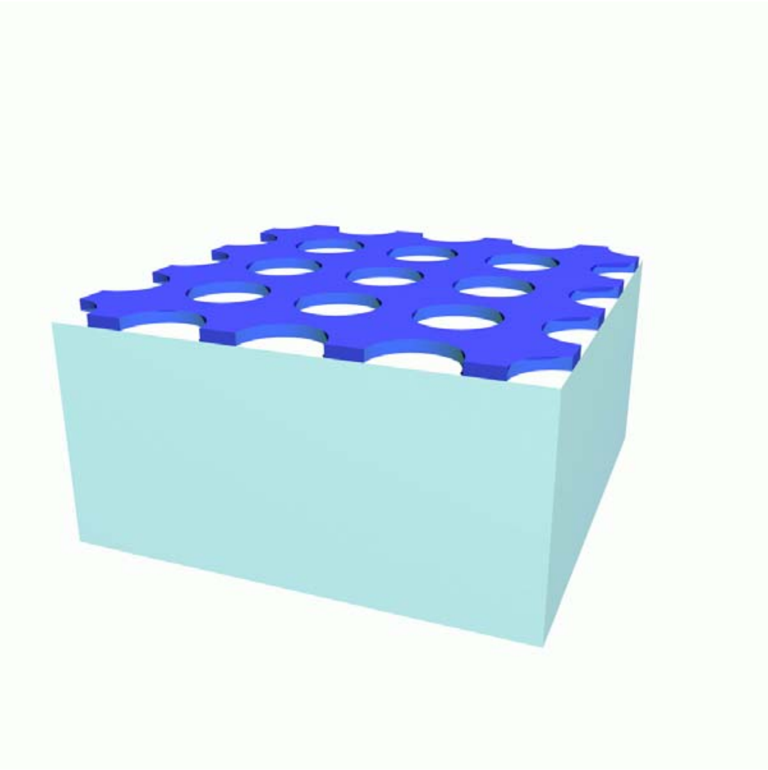
Fabrication

- Depositing the TiO_2 using sputtering Ti in O_2
- Depositing the Chrome etchmask using sputtering
- Spincoating PMMA and structuring using electron beam litho
- Structuring the Cr mask using ion milling



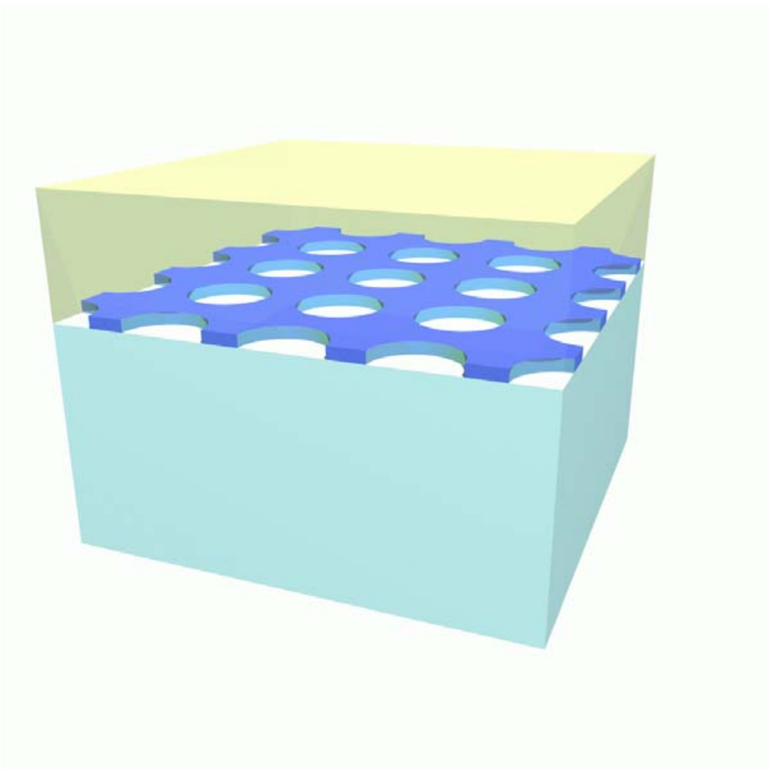
Fabrication

- Depositing the TiO_2 using sputtering Ti in O_2
- Depositing the Chrome etchmask using sputtering
- Spincoating PMMA and structuring using electron beam litho
- Structuring the Cr mask using ion milling
- Etching the TiO_2 using RIE



Fabrication

- Depositing the TiO_2 using sputtering Ti in O_2
- Depositing the Chrome etchmask using sputtering
- Spincoating PMMA and structuring using electron beam litho
- Structuring the Cr mask using ion milling
- Etching the TiO_2 using RIE
- Spin-coating of the gain material

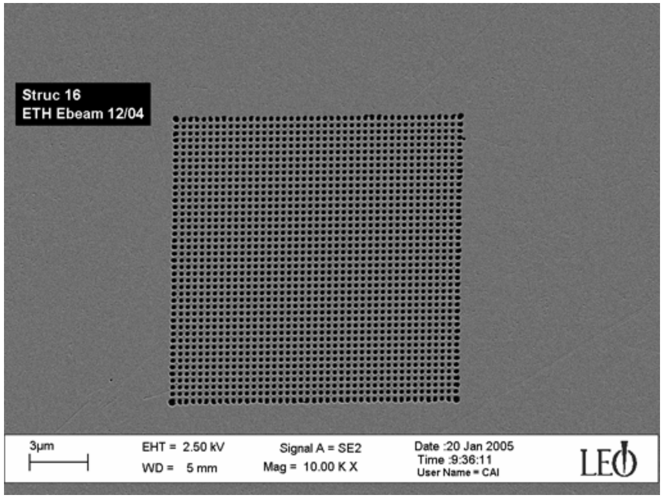


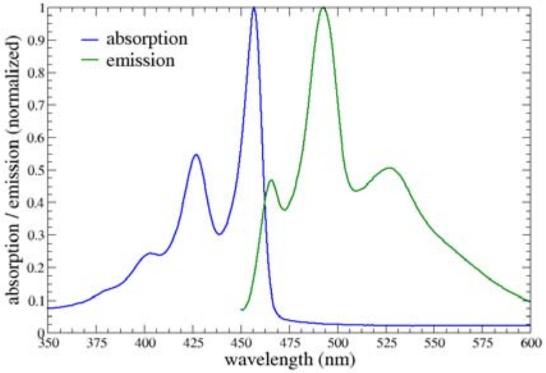
Characterization – Chip layout and material properties

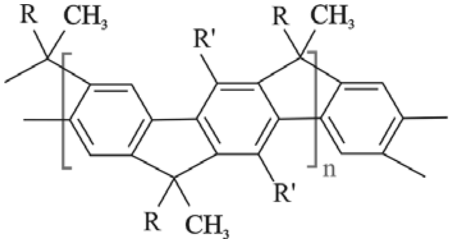
- Devices are photonic crystal pads of ~ 100μm x 100μm down to 15μm x 15μm

Easily deposited using spin-coating

Gain maximum around 494nm

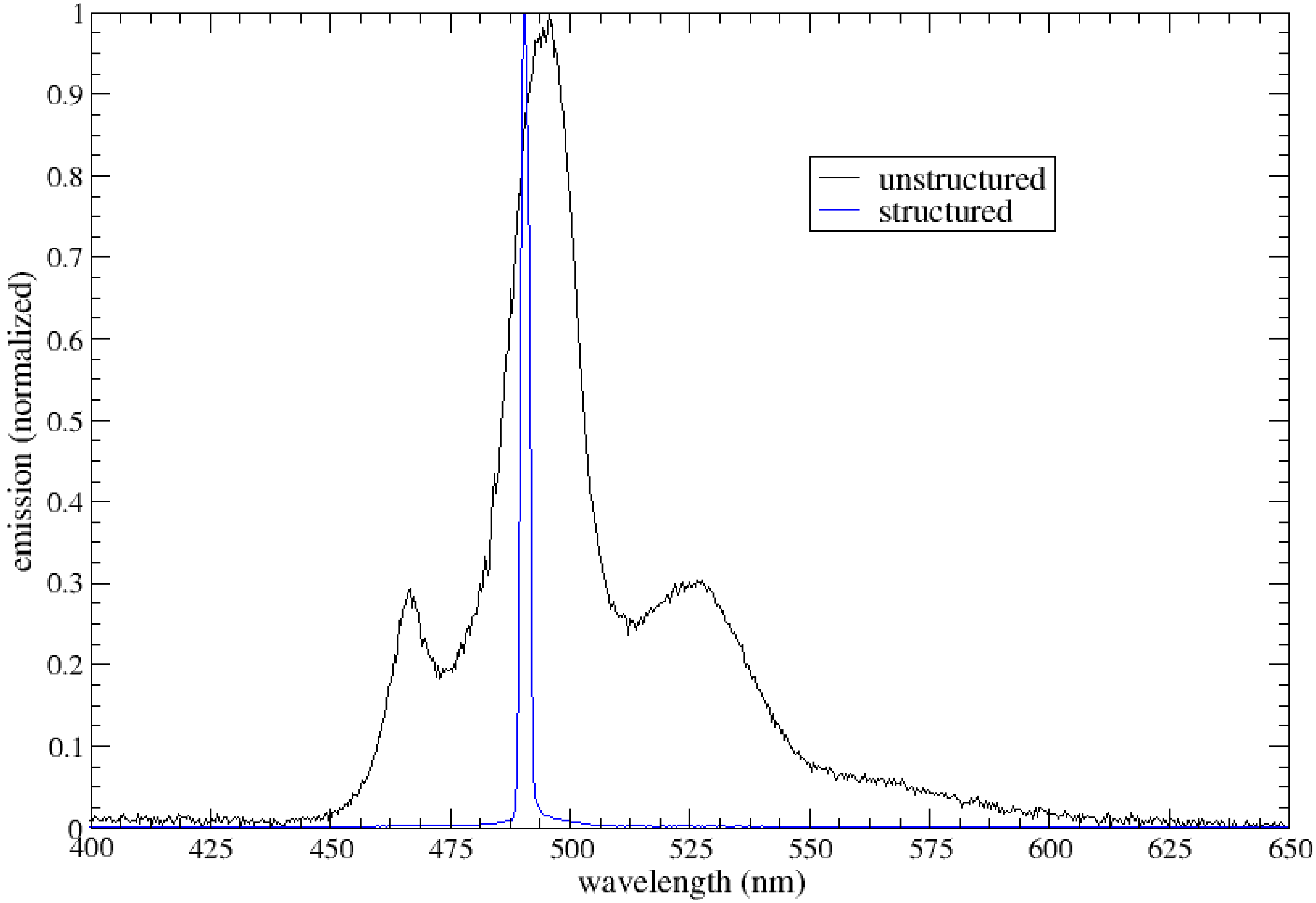




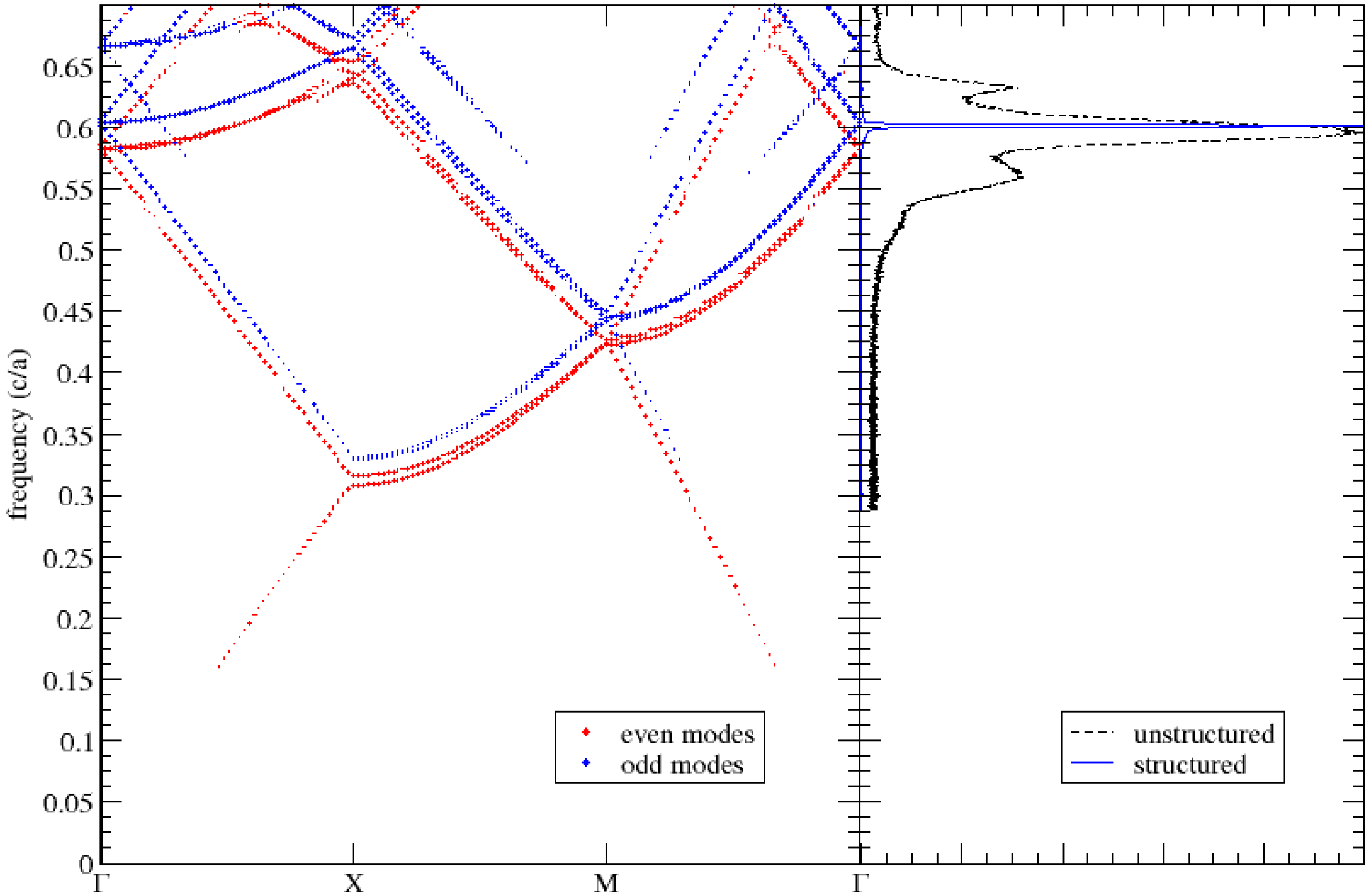


$R = 1,4\text{-}C_6H_4\text{-n-}C_{10}H_{21}$
$R' = \text{-n-}C_6H_{13}$

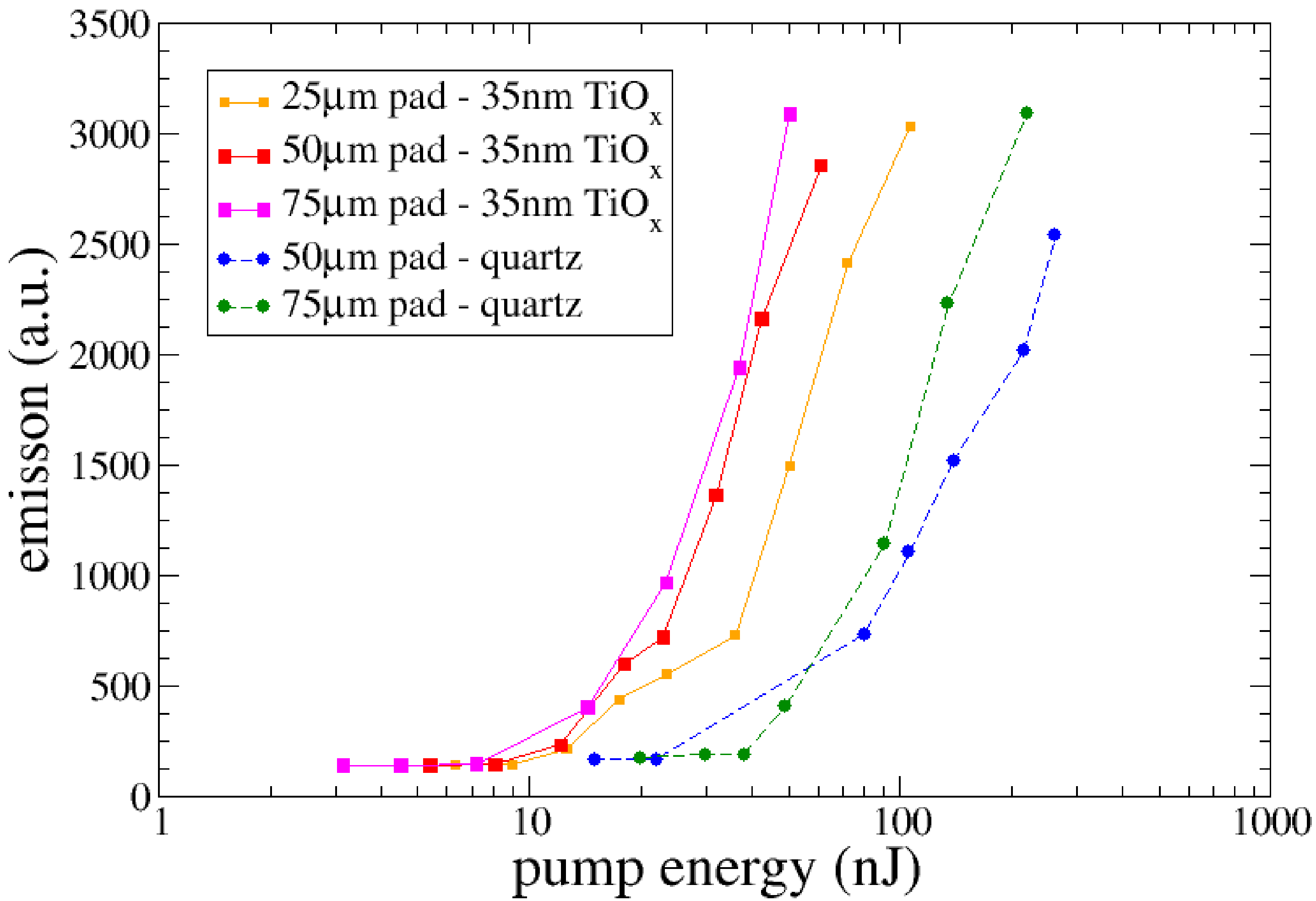
Lasing of 2D Photonic Crystals Structures



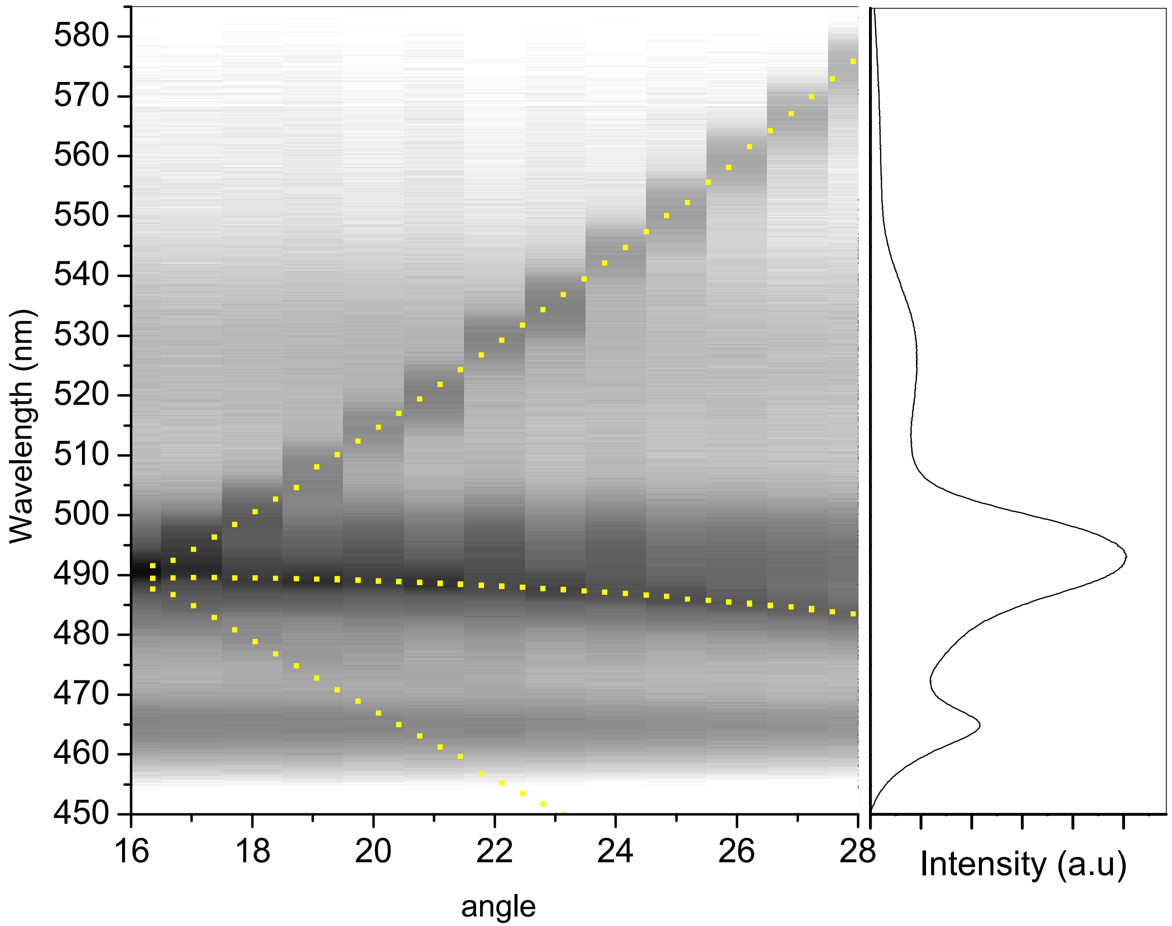
Comparison with Band Structure Calculations



Lasing Threshold of 2D Photonic Crystals Structures



Experimental band-diagram mapping below threshold



Outline

- Organic photonic crystal lasers

  Laser structures with TiO_2 feedback layer

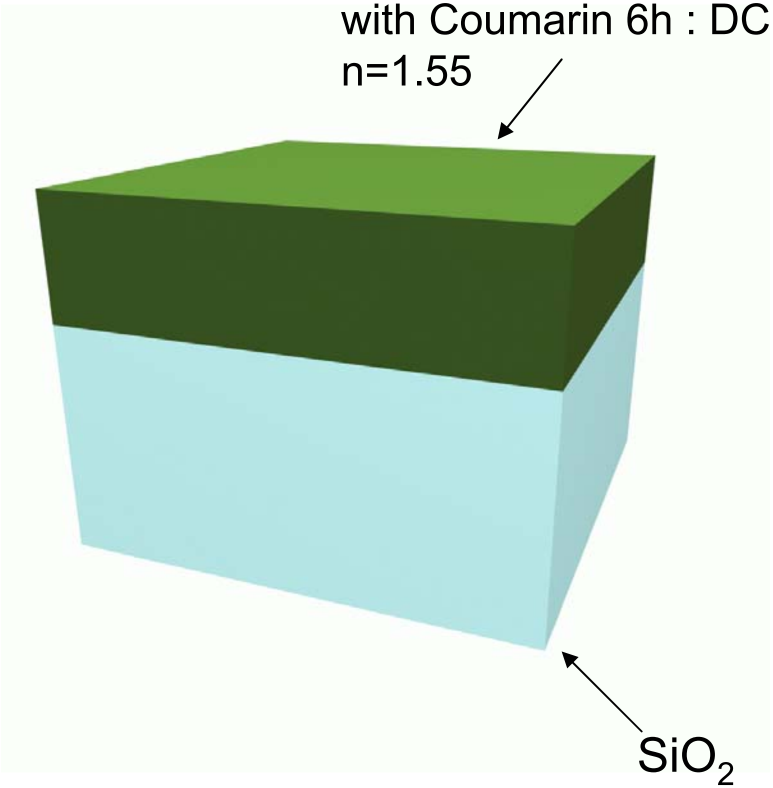
  Interferometrically Defined Laser Structures

- All-optical switching in organic micro-cavities

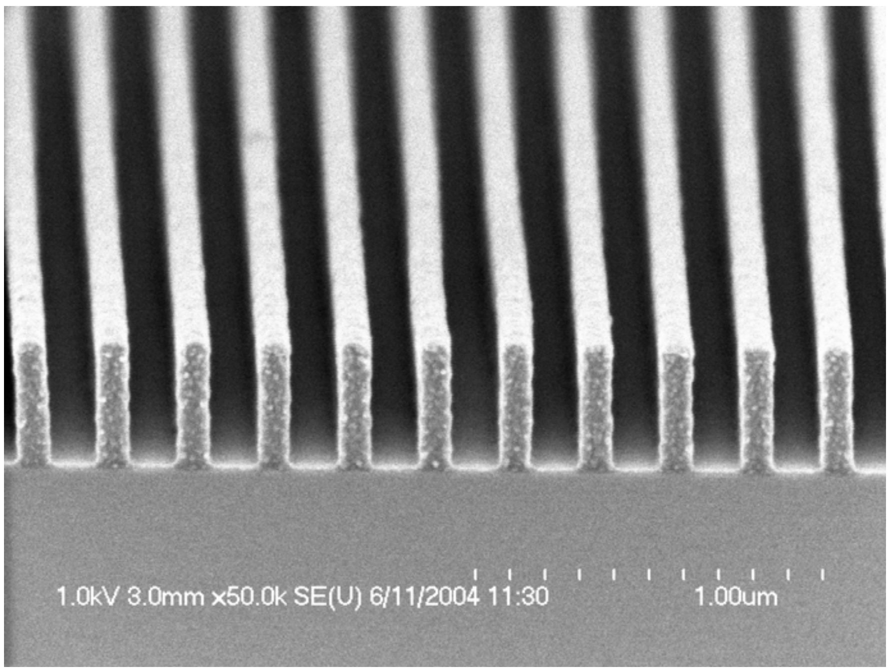
  Cavity pump-and-probe measurements

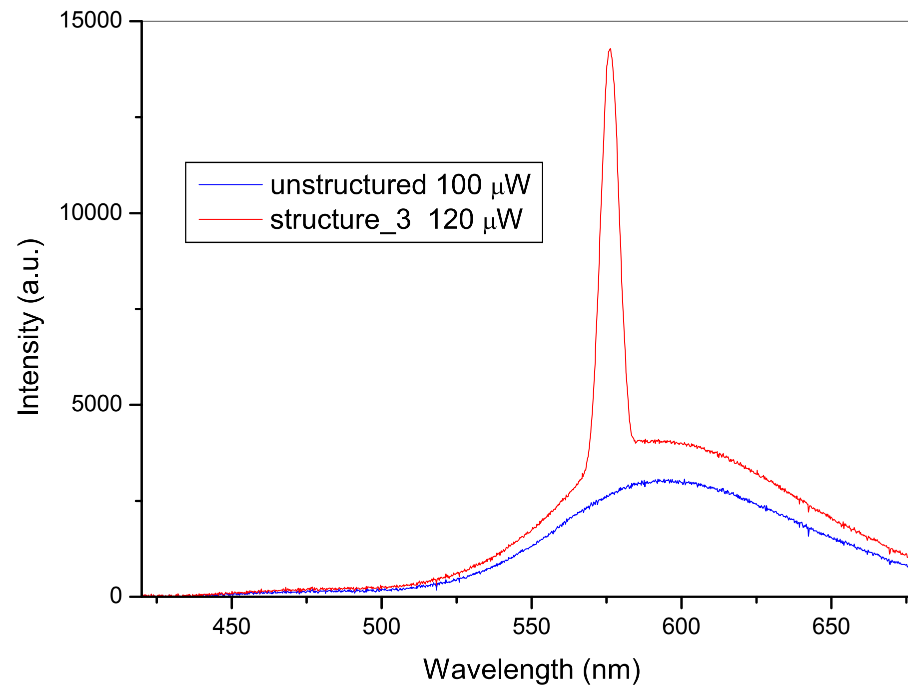
Interferometrically Defined Laser Structures

- Direct structuring of the gain material using Almaden Research Center's *Laser Interferometer Lithography* setup
- Advantages:
  - → Relatively easy fabrication
  - → High index contrast air – polymer
  - → Very regular periods
- Disadvantages:
  - → Low index of the waveguide material
  - → Hard to control hole dimensions



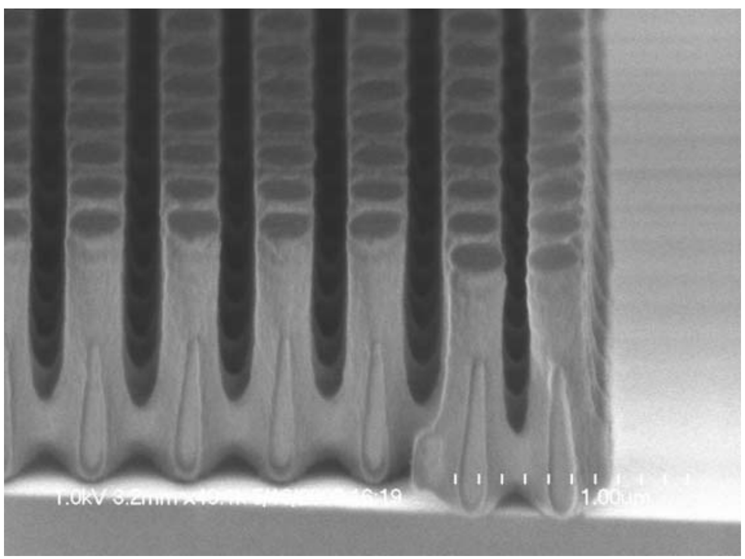
Stimulated emission from Interferometrically Structured Samples

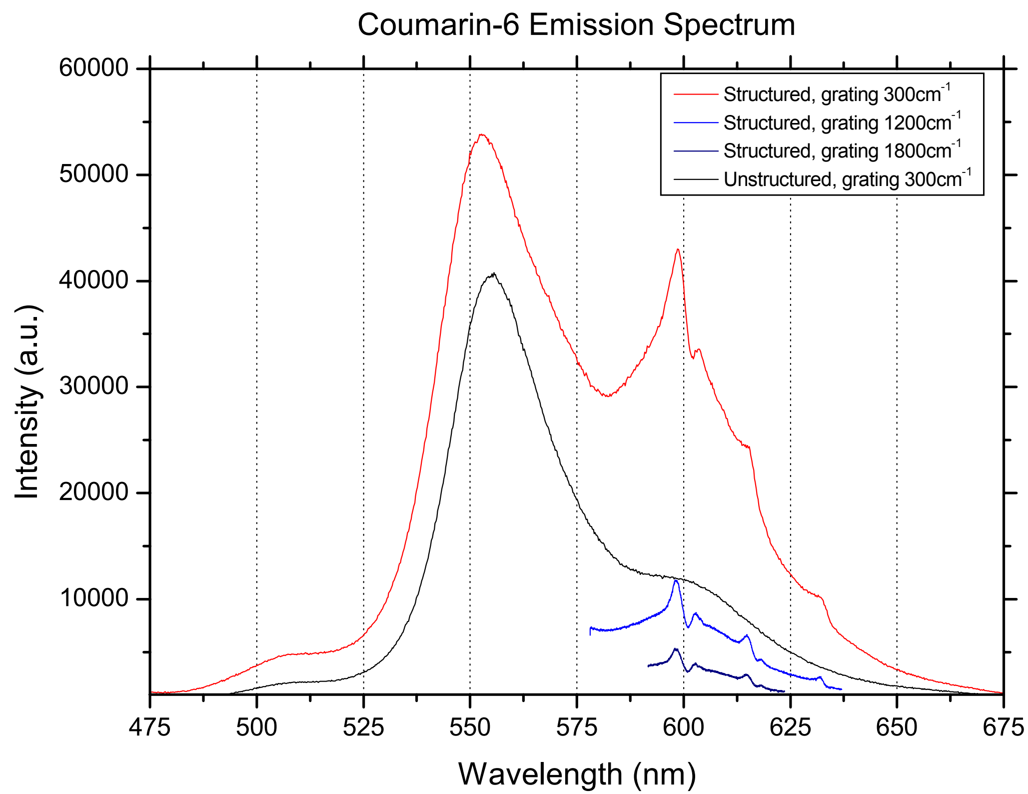




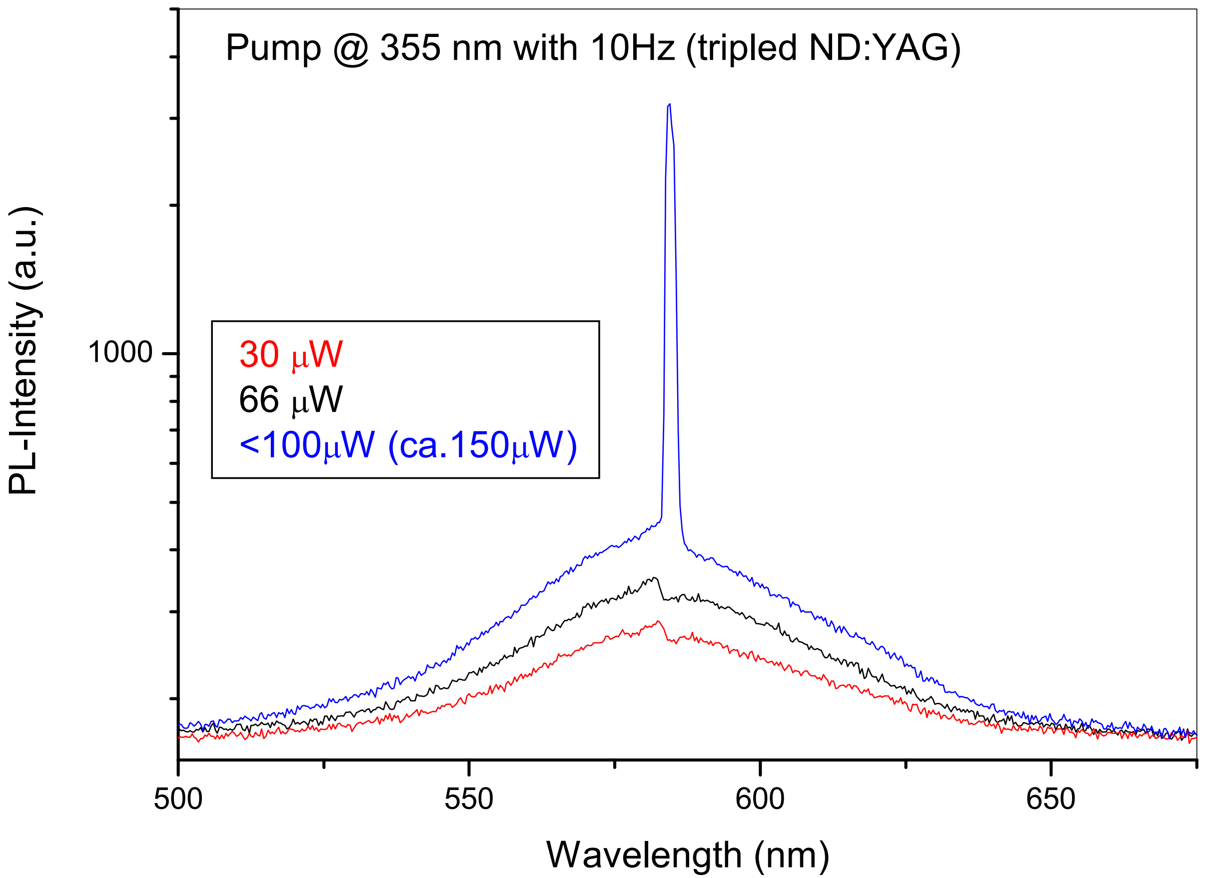
Holographically fabricated structures

- Resist doped with a laser dye is structured using holography – Rods of resist



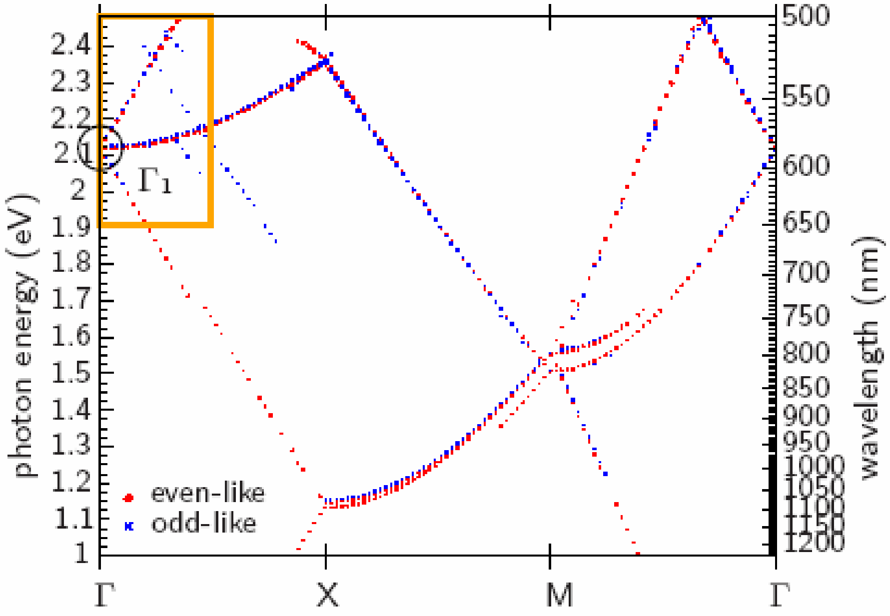


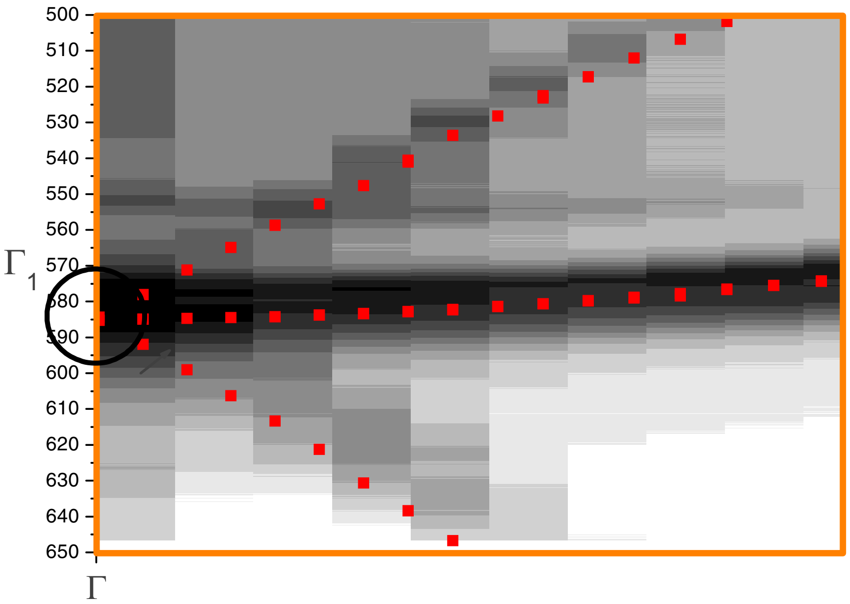
Lasing of Interferometrically Defined Structures



sample from 23/11/2004 (email John) site number "1"

Band-Diagram Theory & Experiment





R.Harbers et al, APL, in press

Summary

- Distributed feedback through photonic crystals fabricated in TiO_2 or in photo-resist
- The lasing threshold can be lowered by incorporating a high index TiO_2 layer
- Leads to smaller devices
- Next step: Electrically pumped organic lasers

Outline

- Organic photonic crystal lasers

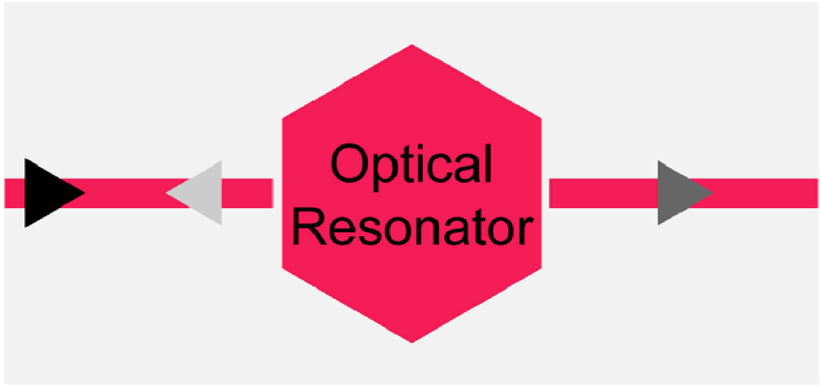
  Laser structures with TiO_2 feedback layer

  Interferometrically Defined Laser Structures

- All-optical switching in organic micro-cavities

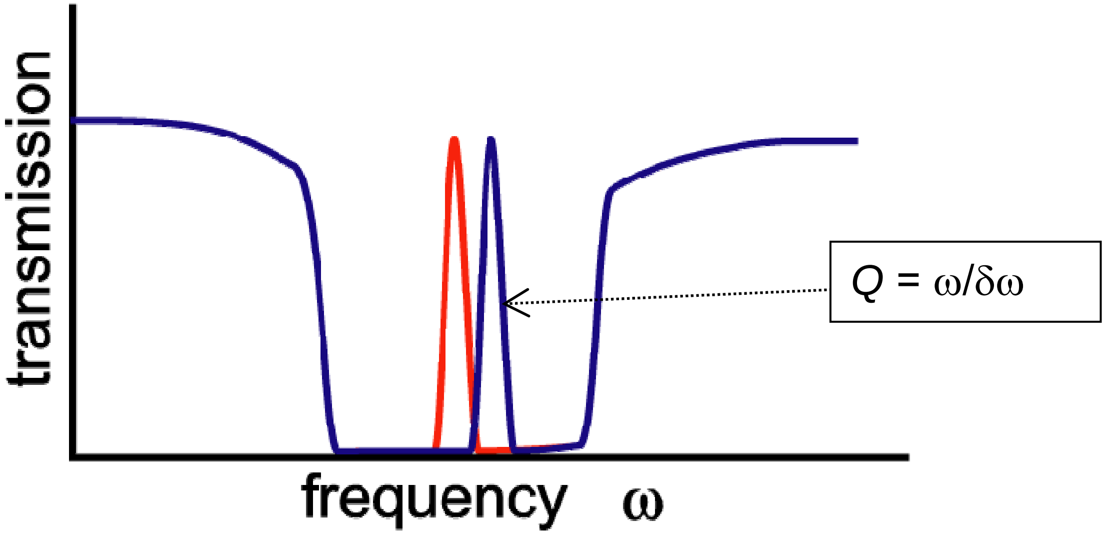
  Cavity pump-and-probe measurements

All-Optical Switch



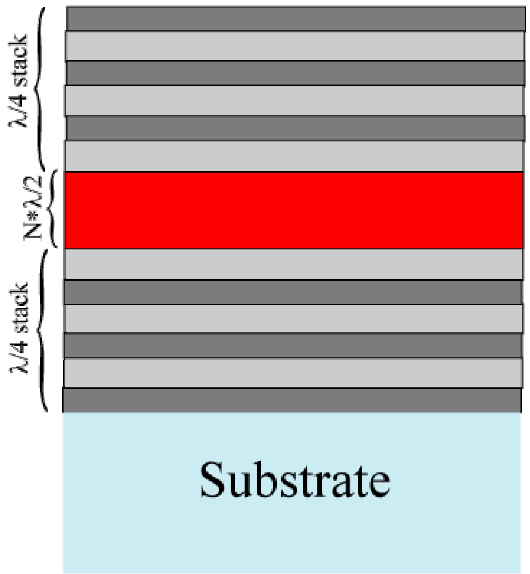
Kerr effect:

$n = n_0 + n_2 I$



Fabrication Technology for Hybrid Cavities

- Sputtering of dielectric $\lambda/4$ mirror stacks, for example Si/SiO_2 (infrared), or TiO_2/SiO_2 (visible)
- spin coating, thermal deposition of organic thin films
- Room temperature process works with most materials



Critical parameters: → Reproducible thickness of films
→ Quality of high-index films

Outline

- Organic photonic crystal lasers

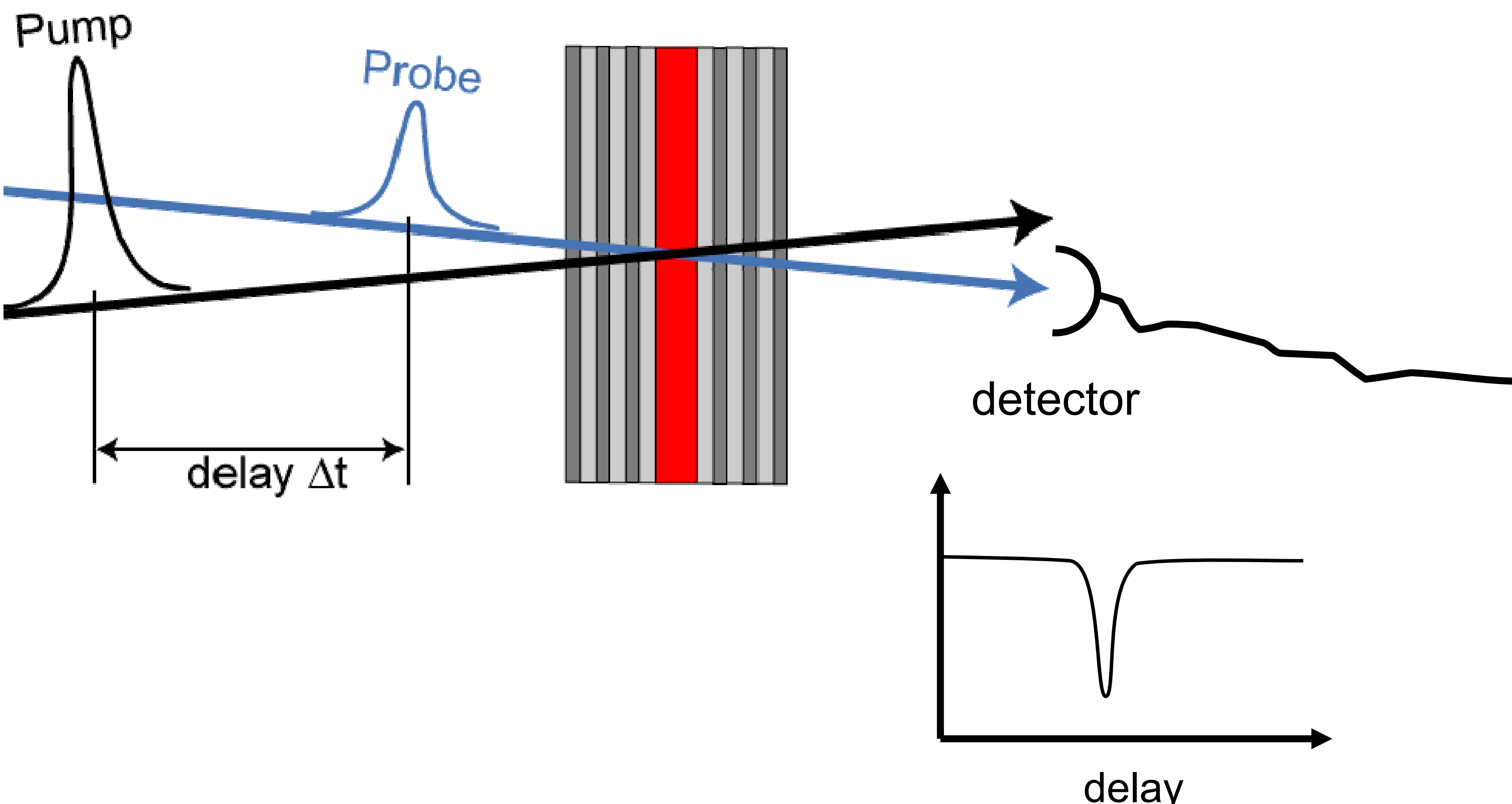
    Laser structures with TiO_2 feedback layer

    Interferometrically Defined Laser Structures

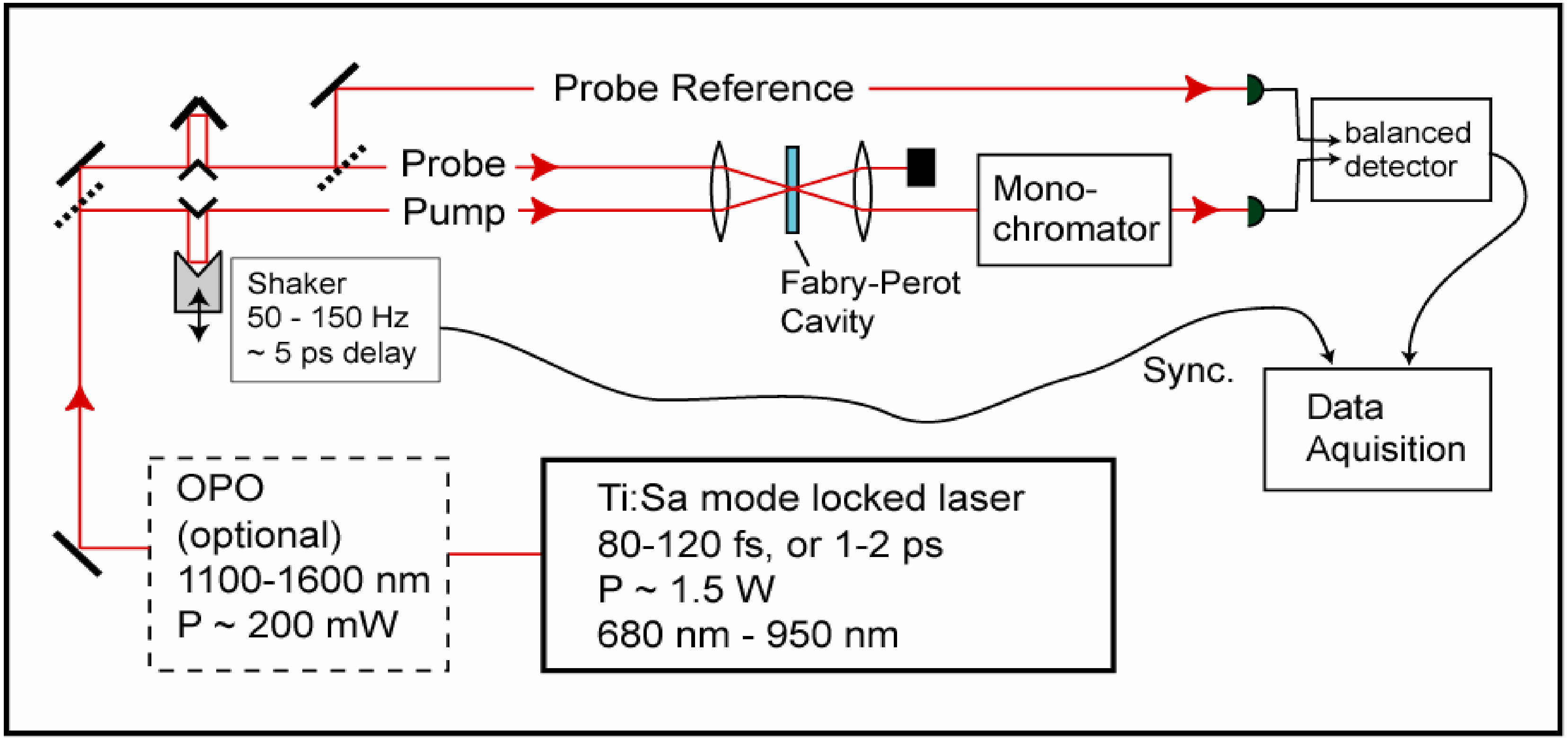
- All-optical switching in organic micro-cavities

    Cavity pump-and-probe measurements

Cavity Pump & Probe, Concept



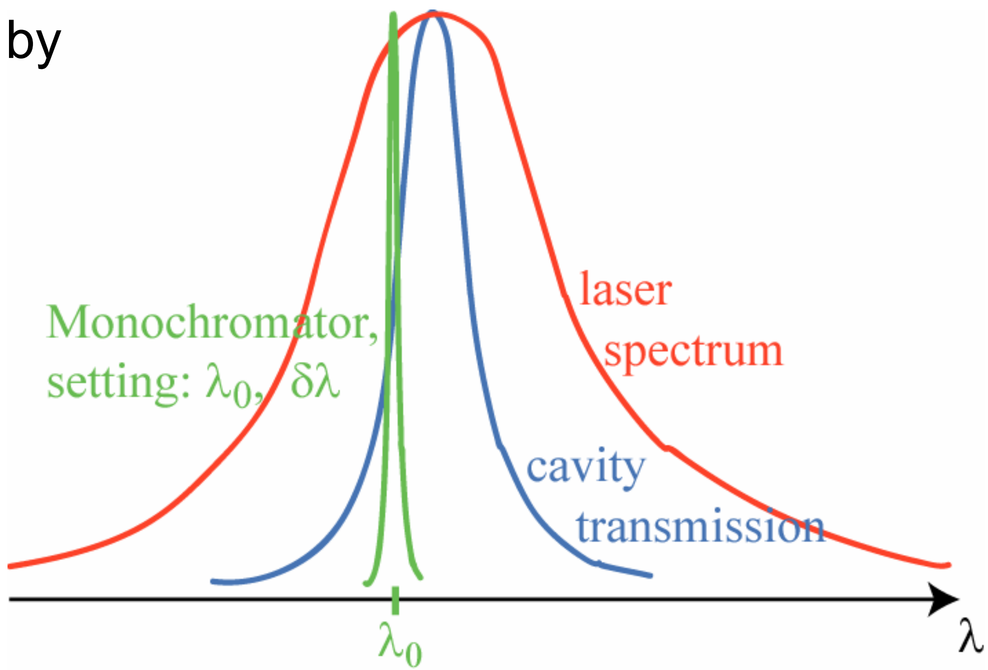
Femtosecond Pump & Probe Setup



Femto-Second Pump & Probe technique

Laser spectrum much wider than cavity transmission

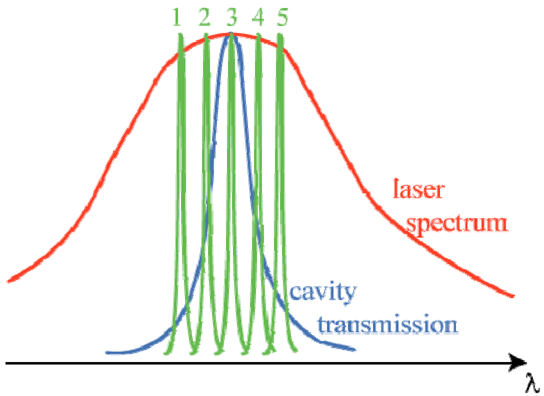
Wavelength selected by monochromator



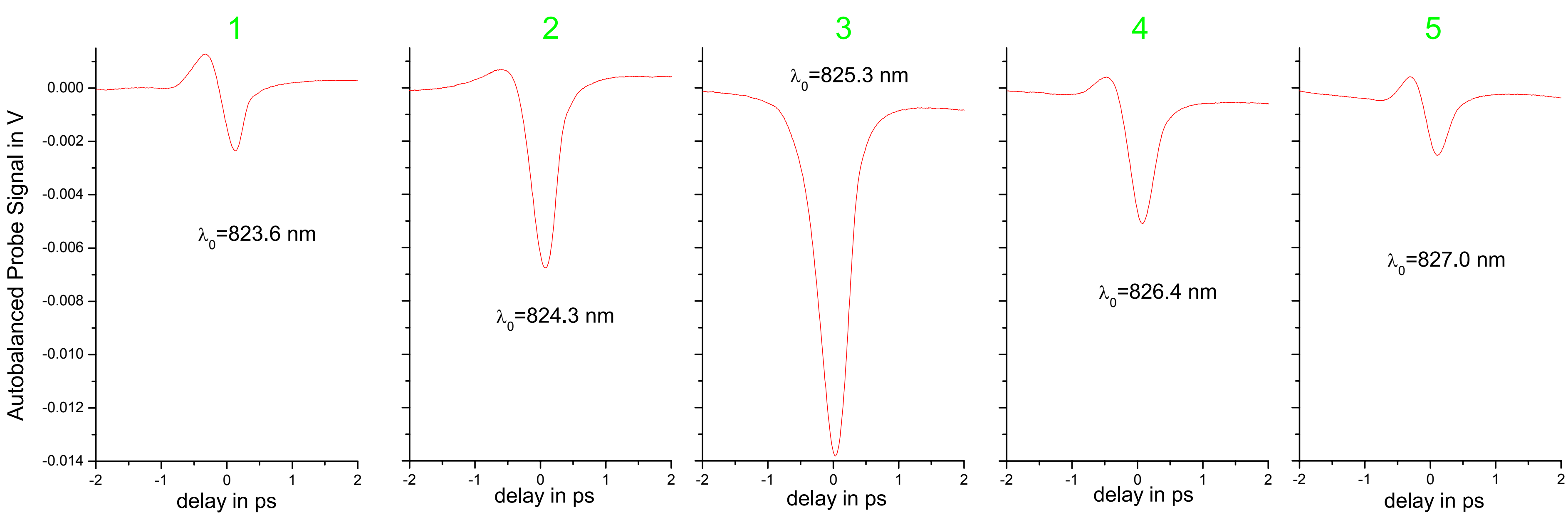
Cavity is always exposed to the same laser field!

Femtosecond Pump & Probe, Example Signals

C60 cavity,
λ_C= 825.3 nm, $\Delta\lambda_C$= 2.0 nm,
$\Delta\lambda_L \approx$ 2.0 nm,
Monochromator: $\delta\lambda$ = 0.6 nm

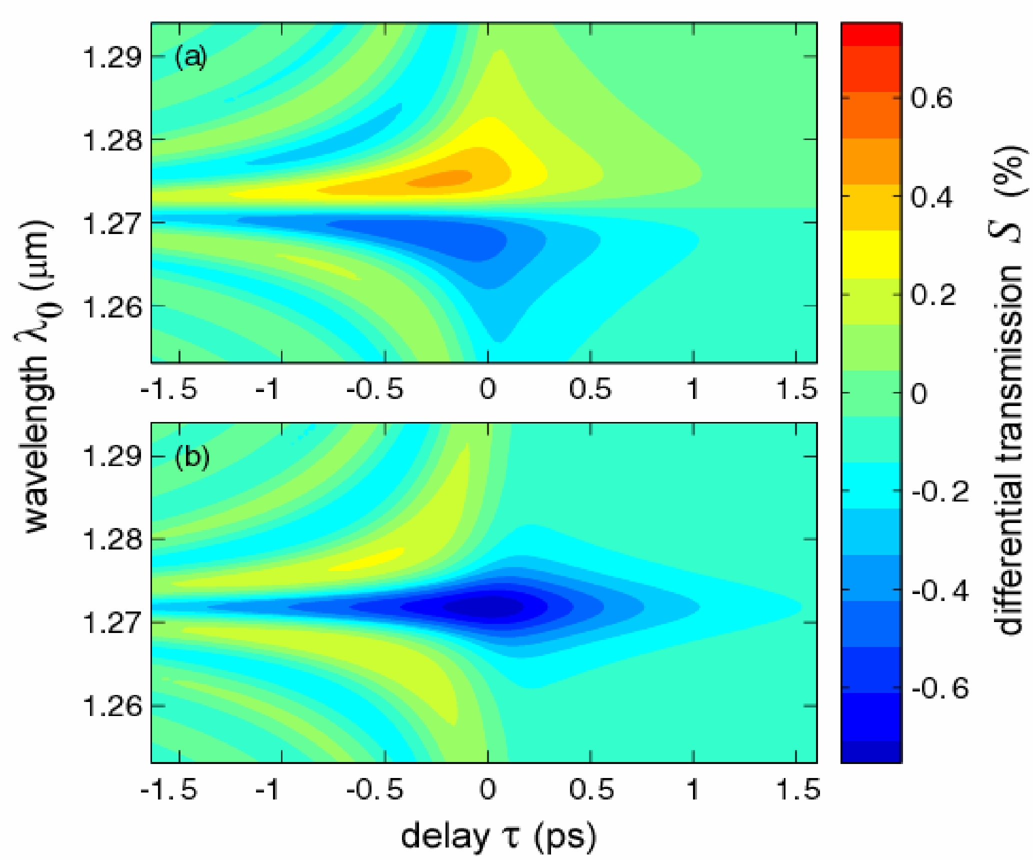


Almost purely absorptive



Numerical Simulations Confirm Experimental Behavior

differential
transmission



assume instantaneous nonlinearity:

only nonlinear refraction n_2

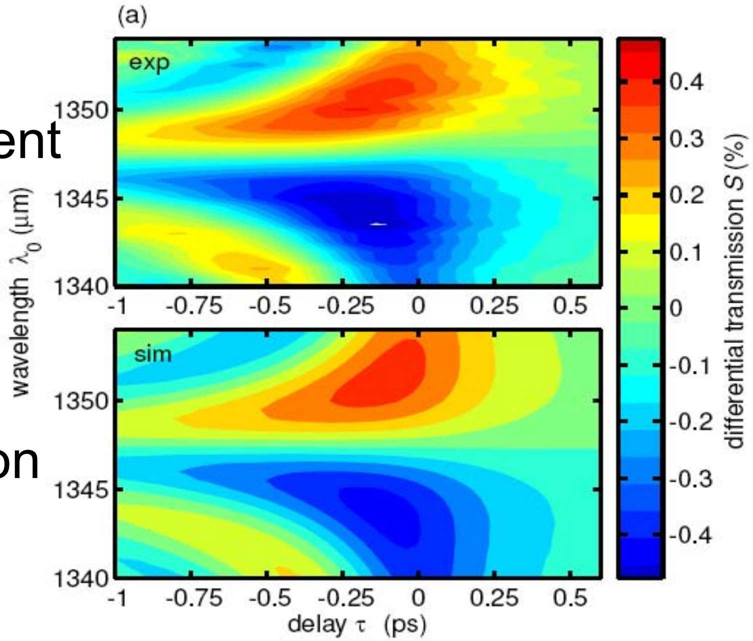
only nonlinear absorption α_2

Femtosecond Pump & Probe, Example Fits

C_{60}, infrared

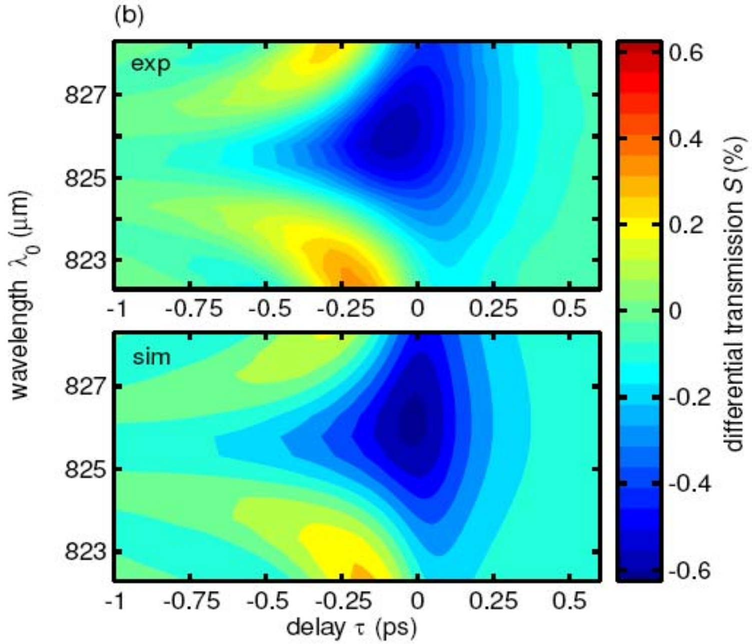
Experiment

Simulation



mostly refractive

C_{60}, near infrared



mostly absorptive

Excellent agreement with simulation: ⇒ Nonlinearity in C_{60} is instantaneous

All-Optical Switching: Figures of Merit

linear absorption

$$W \quad \frac{n_2 I}{\alpha \; \lambda}$$

nonlinear absorption

$$T \quad \frac{\alpha_2 \lambda}{n_2}$$

condition for bistability:

$$W \quad 1$$

$$T \quad 1$$

intensity dependent:
→ can be fulfilled through device optimization/intensity

independent of intensity:
→ a true material constraint!

Obtained Material Parameters

(Infrared wavelength range 1300-1400nm)

Material	n_2 (cm²/TW)	α_2 (cm/GW)	Figure of merit T
C_{60}	0.06	0.8	**1.6**
C_{70}	0.04	0.5	1.75
MEH-PPV	0.1	10	12
Si	0.015	1.45	12
C_{60}-PU	< 0.006	-	-

so far: C_{60} is the most promising material

"exotic" materials did not meet expectations

Summary and Conclusion

- Pump & probe measurements on Fabry-Perot micro-cavities
- Reliable characterization of nonlinear materials for all-optical switching
- Still missing: suitable nonlinear organic material
- Without nonlinear materials with much larger n_2 (10-100x) and good figure-of-merit T no integrated devices are feasible

Thank You.

Supported by European project:

Phoenix