The Abdus Salam International Centre for Theoretical Physics

2223-21

Winter College on Optics in Imaging Science

31 January - 11 February, 2011

On breaking the Abbe diffraction limit in Optical Nanopatterning & Nanoscopy

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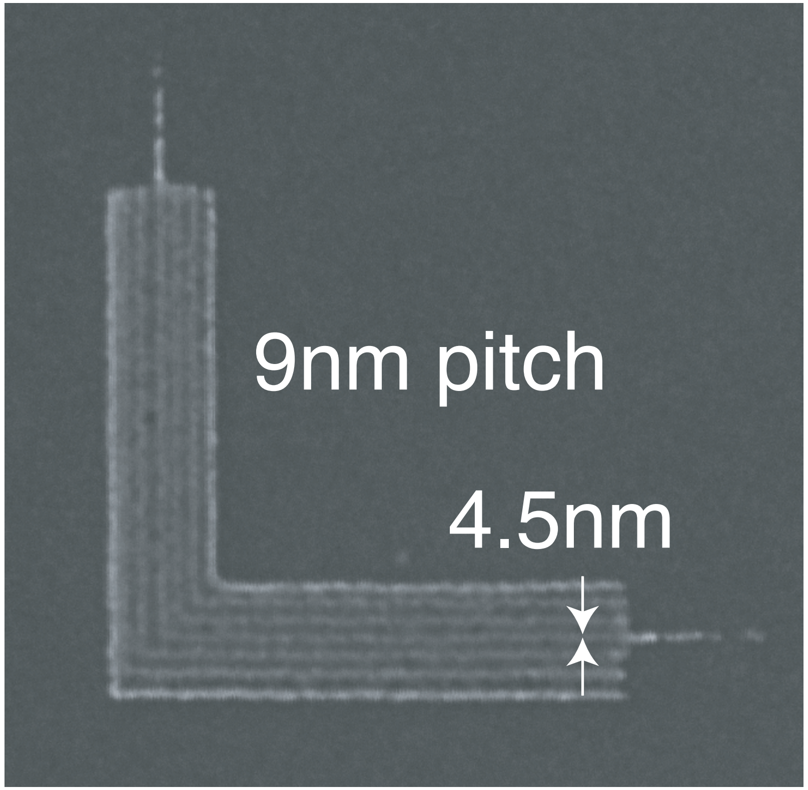
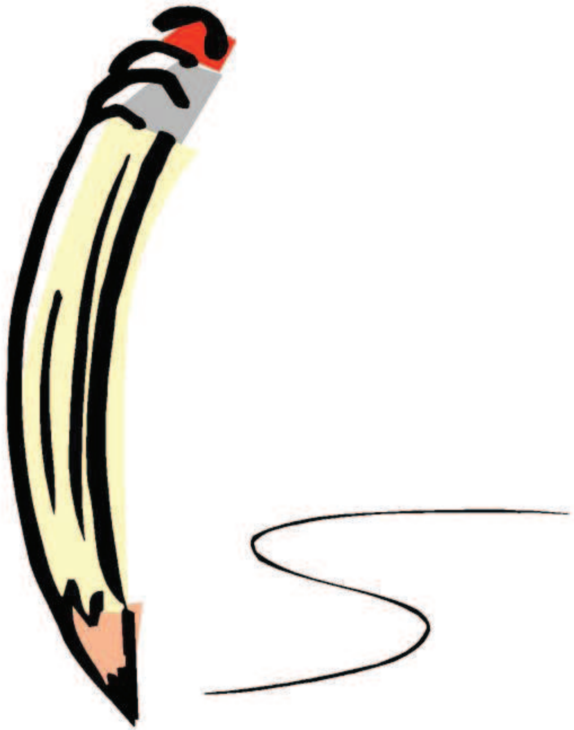
MIT

Complex geometries at the nanoscale are typically patterned via Scanning-electron-beam Lithography (SEBL)

10nm HSQ patterned on a
30kV Raith-150 two.

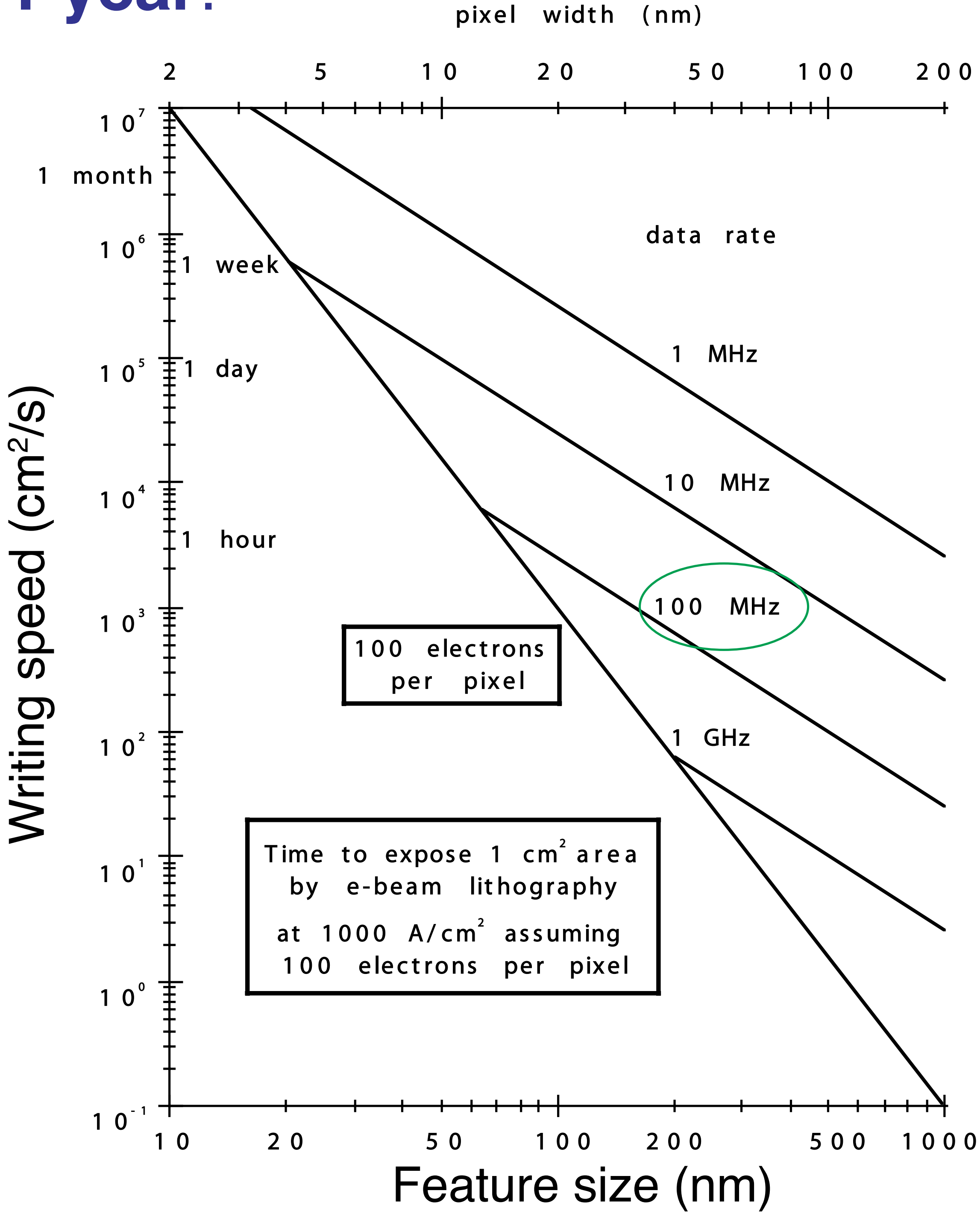


J. K. W. Wang & K. K. Berggren, *J. Vac. Sci. Technol. B*, 25, 2025 (2007).



This is analogous to a (very sharp) “pencil” drawing an image.

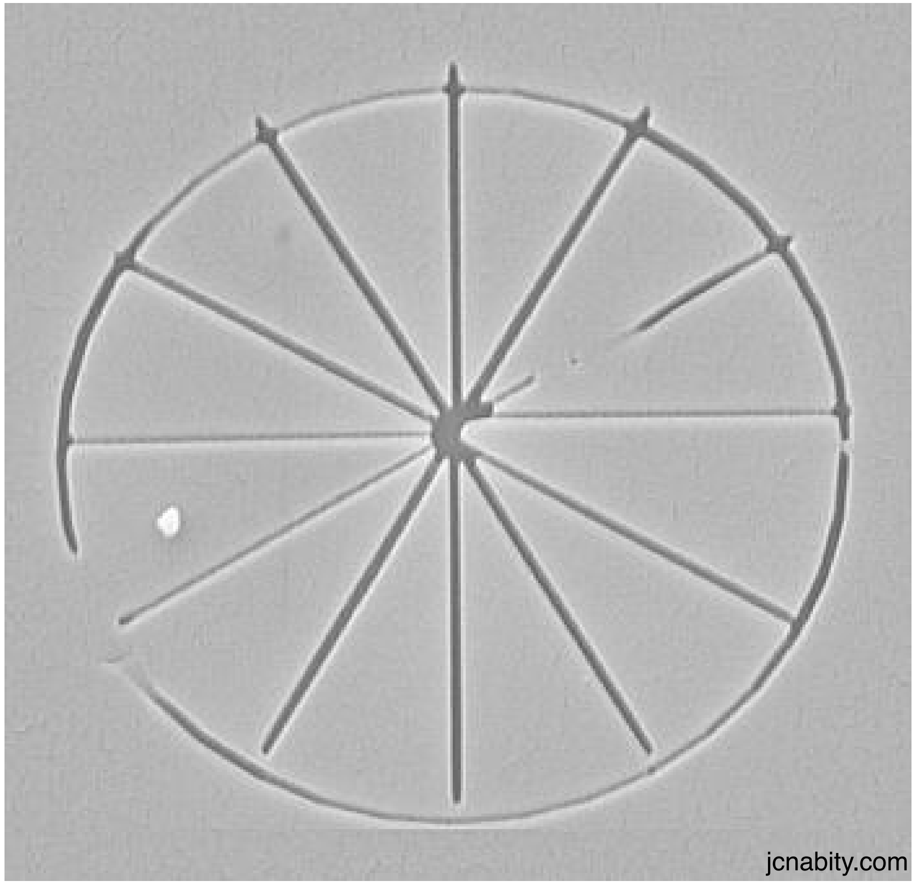
Time for SEBL to pattern a 150mm wafer with 10nm features ~ **1 year**!



Courtesy of H. I. Smith (MIT)

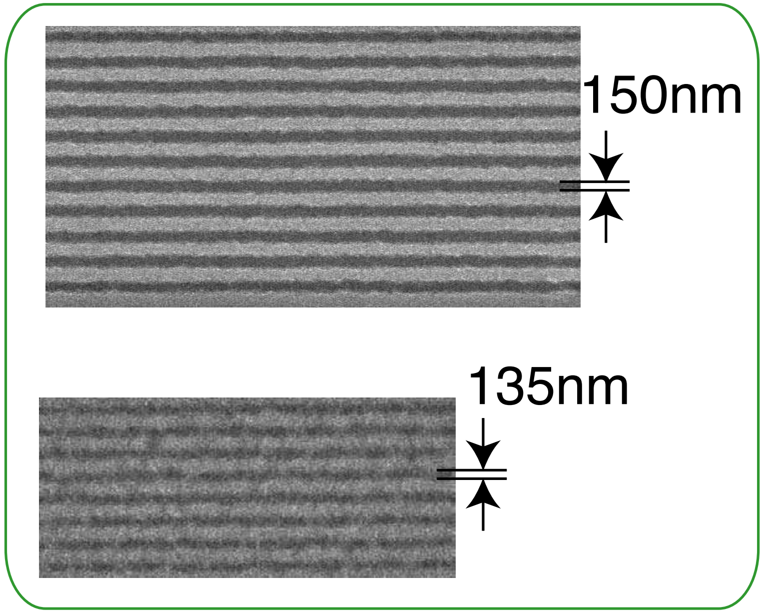
Electrons are deflected by stray electric & electromagnetic fields leading to pattern distortion

Distortions in a spoke-wheel pattern

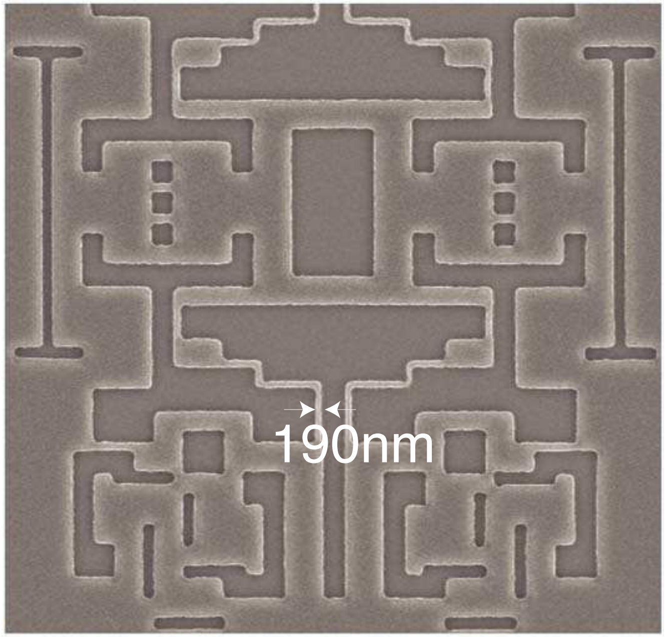


Photons avoid these problems

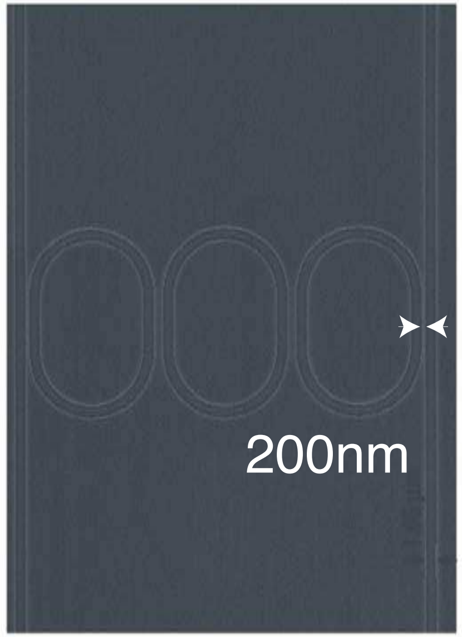
Gratings



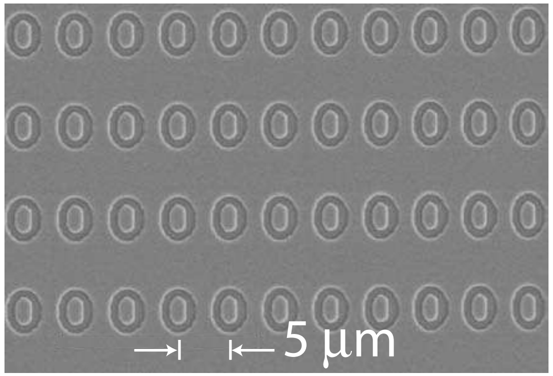
Photomask layout



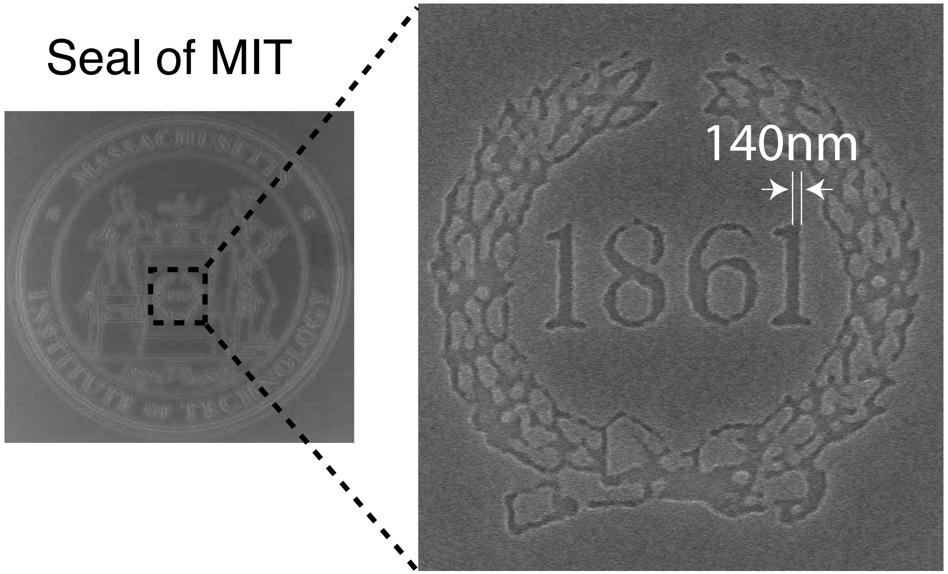
Integrated Optics



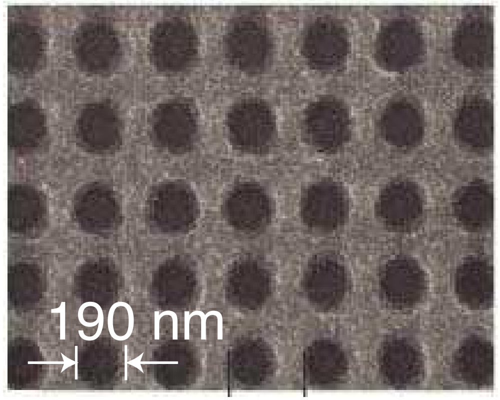
Micromagnetics



Seal of MIT

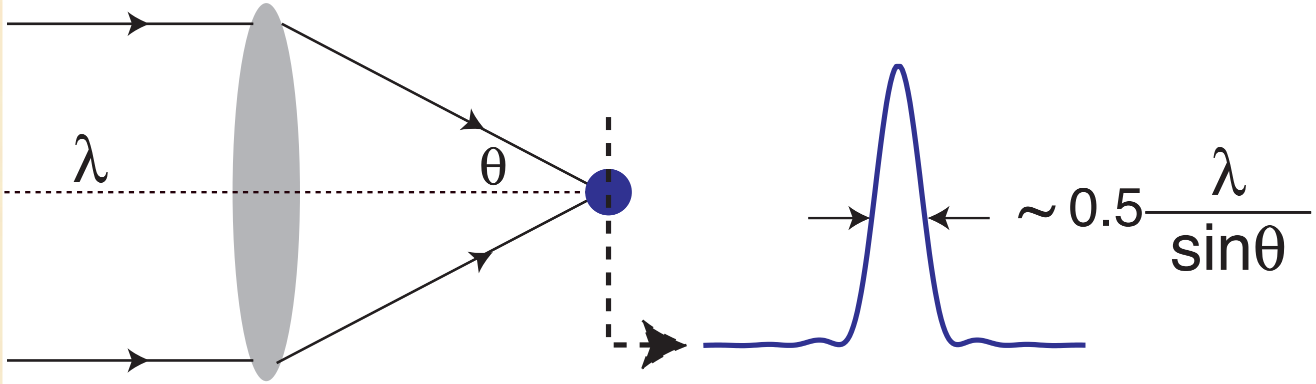


Photonic Device



R. Menon, A. Patel, D. Gil & H. I. Smith, Mat. Today, 26-33, Feb. (2005).

Patterning with photons can be fast & accurate
But they suffer from diffraction

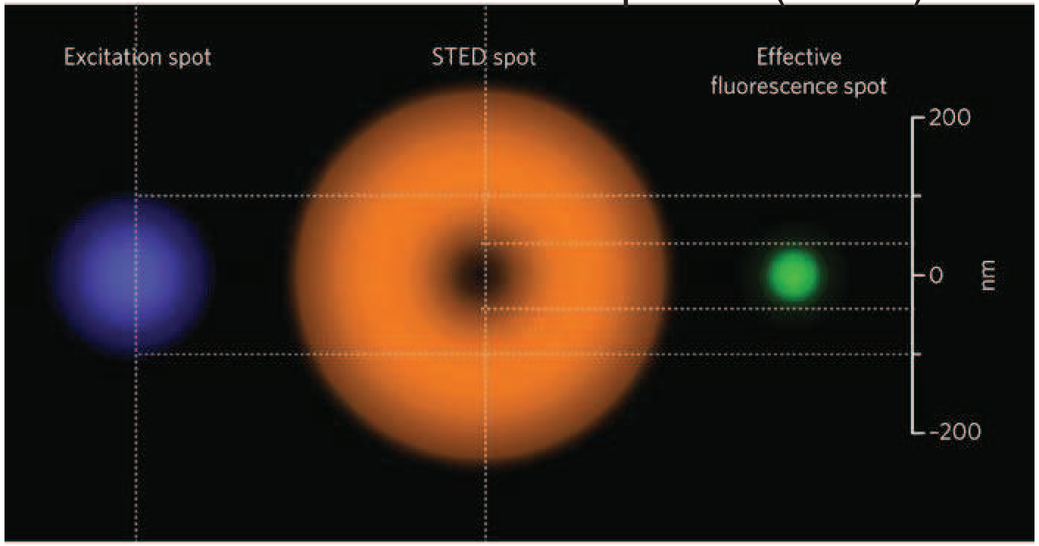


λ	Abbé limit
633nm	317nm
405nm	203nm
193nm	97nm
13.5nm	7nm

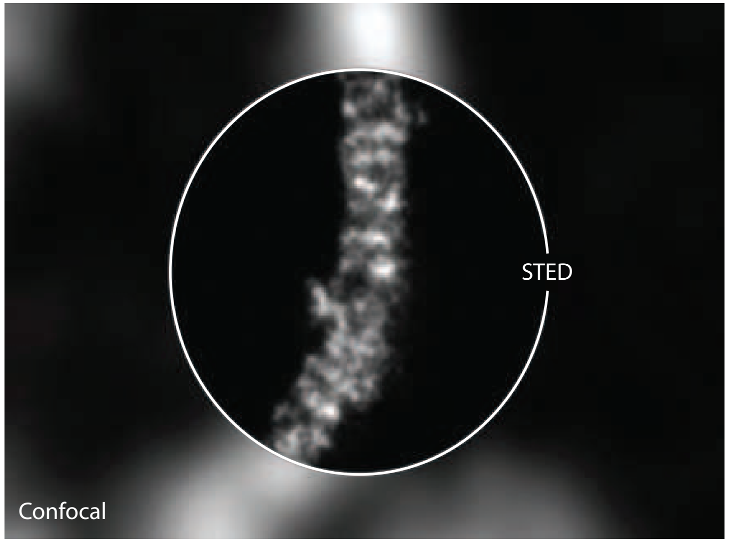
UV (ionizing)
Complex,
expensive sources

Superresolution using Fluorescence

STimulated Emission Depletion (STED)

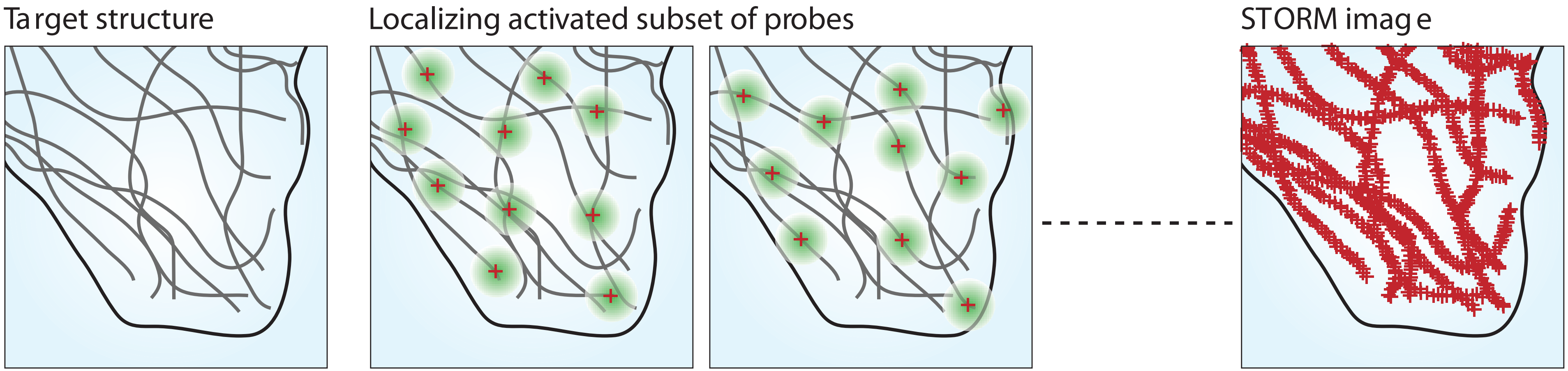


Folds of the mitochondrial inner membrane



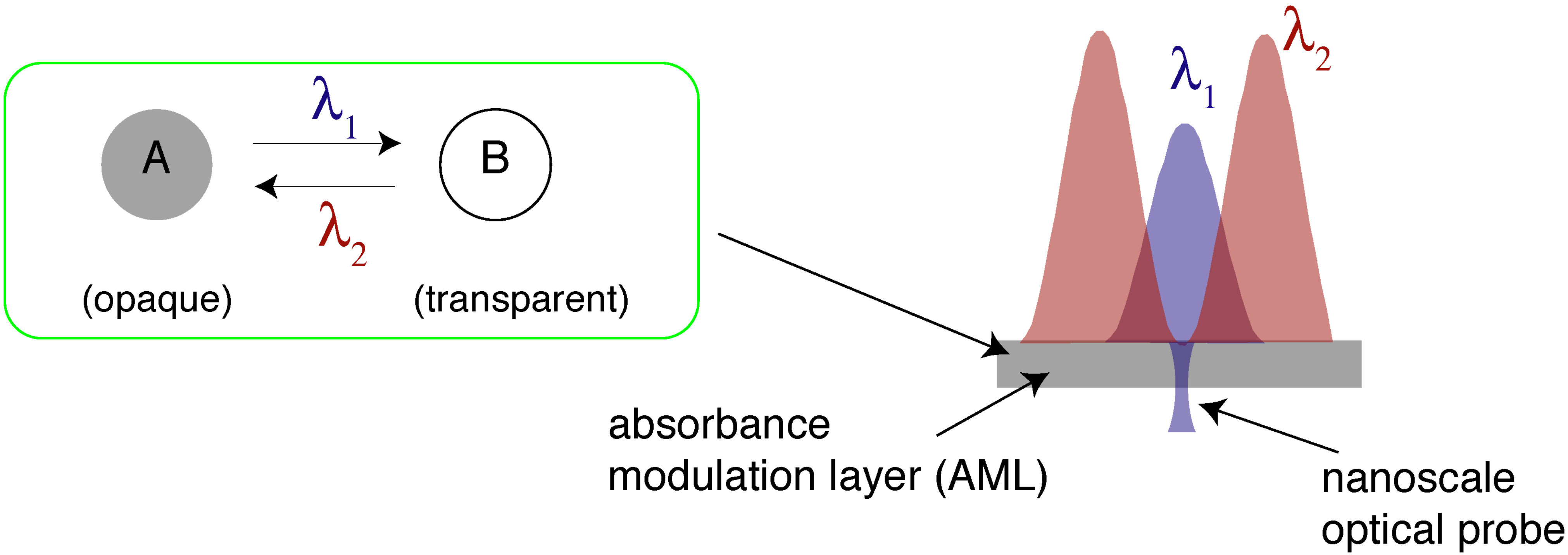
T. A. Klar, *et. al, PNAS* 97, 8206 (2000).

STochastic Optical Reconstruction Microscopy (STORM)



X. Zhuang, *Nat. Photonics*, 3, 365 (2009).

Absorbance Modulation: Exploiting Wavelength-selective chemistry to overcome the Diffraction limit



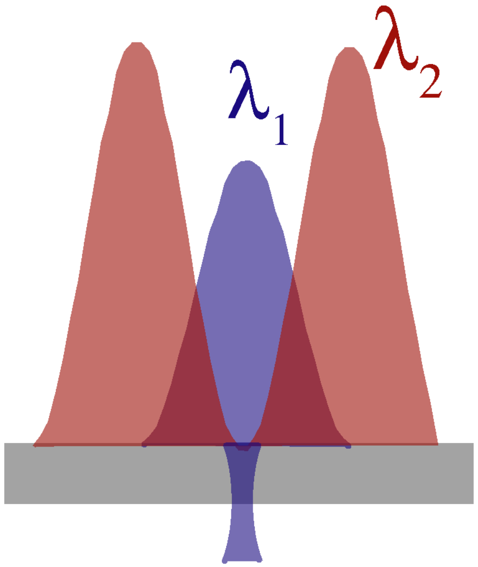
Focal ring at λ_2 in competition with round spot at λ_1 creates a localized sub-wavelength aperture.

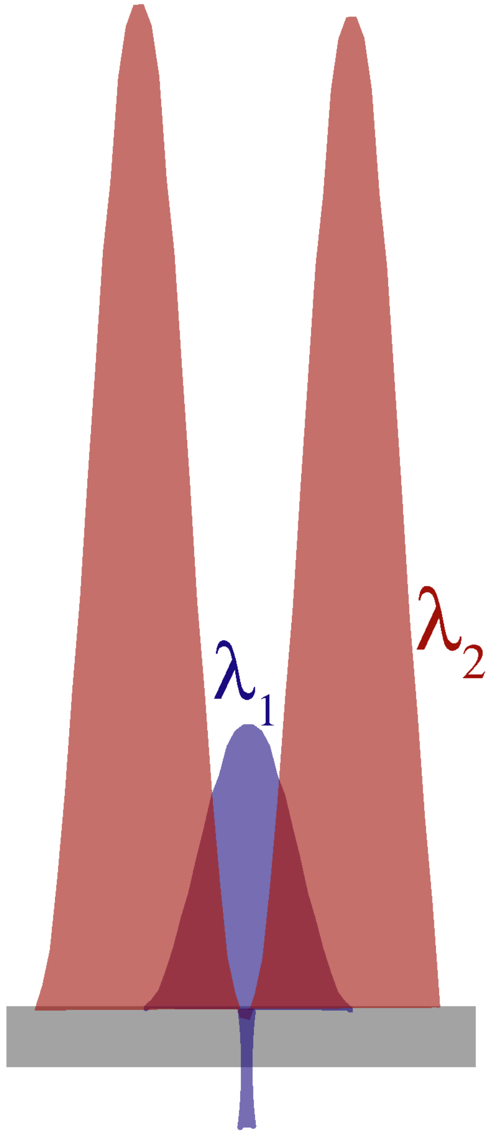
Light at λ_1 penetrates through this aperture forming a nanoscale probe

T. L. Andrew, H-Y. Tsai, **R. Menon**, Science, 324, 917 (2009),
H-Y. Tsai, G. W. Wallraff, **R.Menon**, Appl. Phys. Lett. 91(9), 094103 (2007)
R. Menon, H-Y. Tsai & S. W. Thomas, III, Phys. Rev. Lett. 98, 043905 (2007).
R. Menon, H. I. Smith, JOSA A, 23, 2290 (2006).

“Squeezing” the Nanoscale Optical Probe

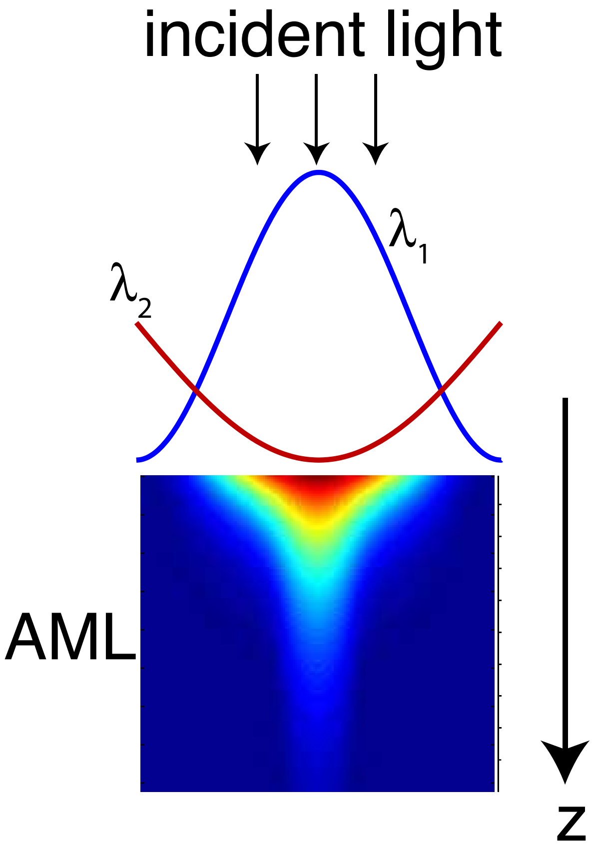
Increasing power density at λ_2 relative to λ_1
“squeezes” the transmitted “spot”





Nanoscale Optical Probe → nanopatterning, nanoscopy & nanoscale trapping

Modeling Absorbance Modulation

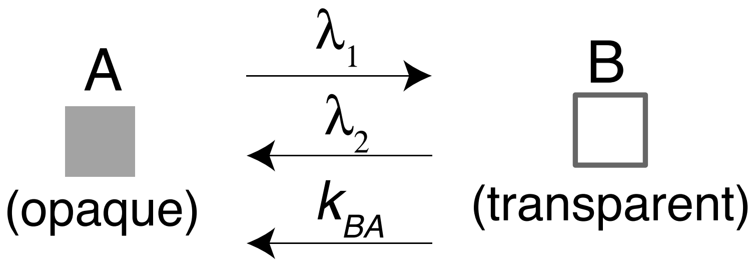


Photon Transport Equations

$$\frac{\partial I_1}{\partial z} + \frac{1}{c}\frac{\partial I_1}{\partial t} = -\left(\varepsilon_{1A}[A] + \varepsilon_{1B}[B]\right) I_1$$

$$\frac{\partial I_2}{\partial z} + \frac{1}{c}\frac{\partial I_2}{\partial t} = -\left(\varepsilon_{2A}[A] + \varepsilon_{2B}[B]\right) I_2$$

Rate Equation



$$[A]_0 = [A] + [B]$$

$$-\frac{\partial [A]}{\partial t} = [A] I_1 \varepsilon_{1A} \phi_{1AB} + [A] I_2 \varepsilon_{2A} \phi_{2AB} - [B] I_2 \varepsilon_{2B} \phi_{2BA} - [B] I_1 \varepsilon_{1B} \phi_{1BA} - [B] k_{BA}$$

Photostationary Approximation

Photon Transport Equation ⟶ Beer-Lambert Law

$$\frac{\partial I_1}{\partial z} = -\left(\varepsilon_{1A}[A] + \varepsilon_{1B}[B]\right) I_1 \qquad \frac{\partial I_2}{\partial z} = -\left(\varepsilon_{2A}[A] + \varepsilon_{2B}[B]\right) I_2$$

Rate Equation ⟶ Dynamic Equilibrium

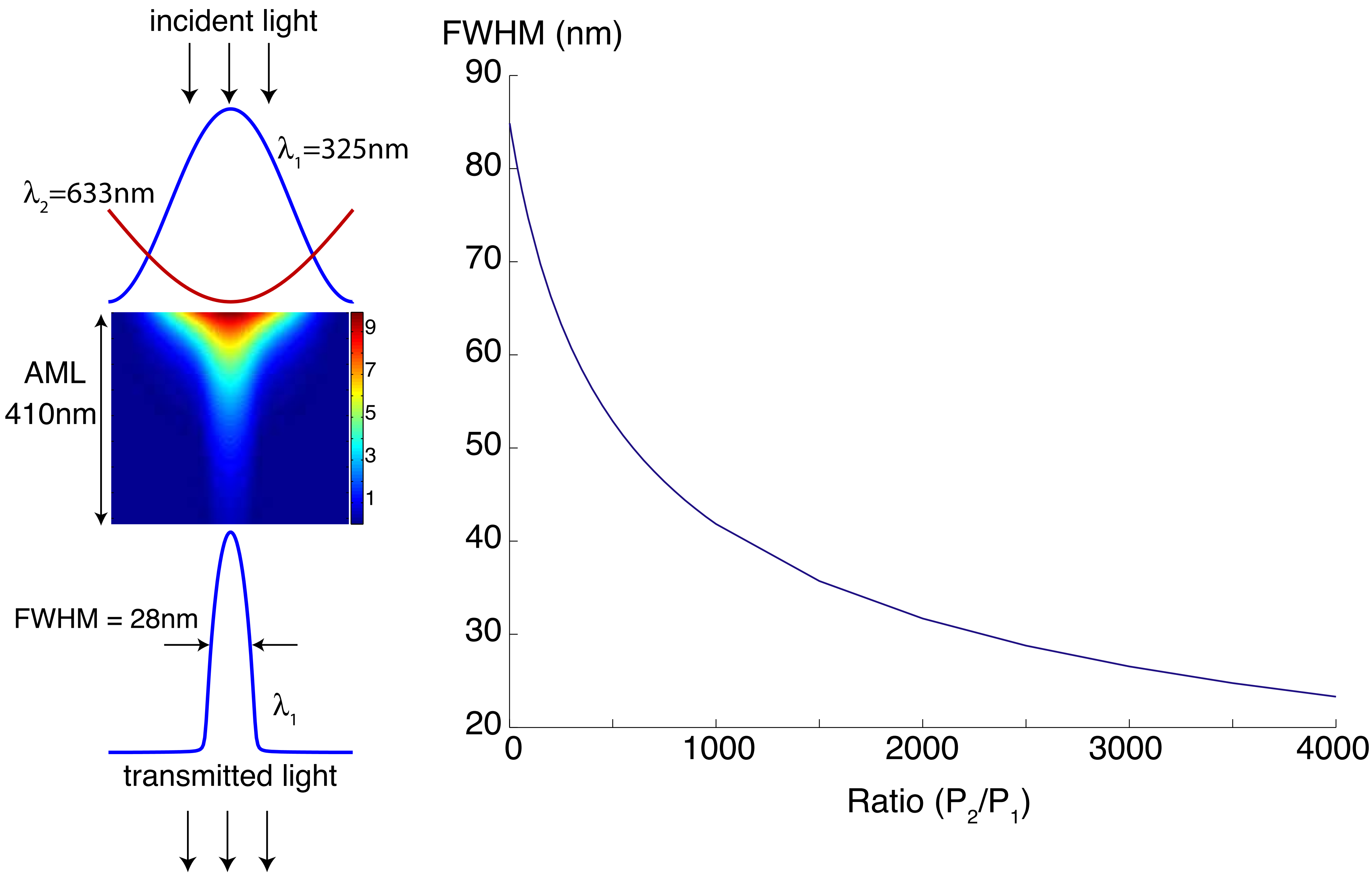
$$[A] I_1 \varepsilon_{1A} \phi_{1AB} + [A] I_2 \varepsilon_{2A} \phi_{2AB} - [B] I_2 \varepsilon_{2B} \phi_{2BA} - [B] I_1 \varepsilon_{1B} \phi_{1BA} - [B] k_{BA} = 0$$

Thermal Stability

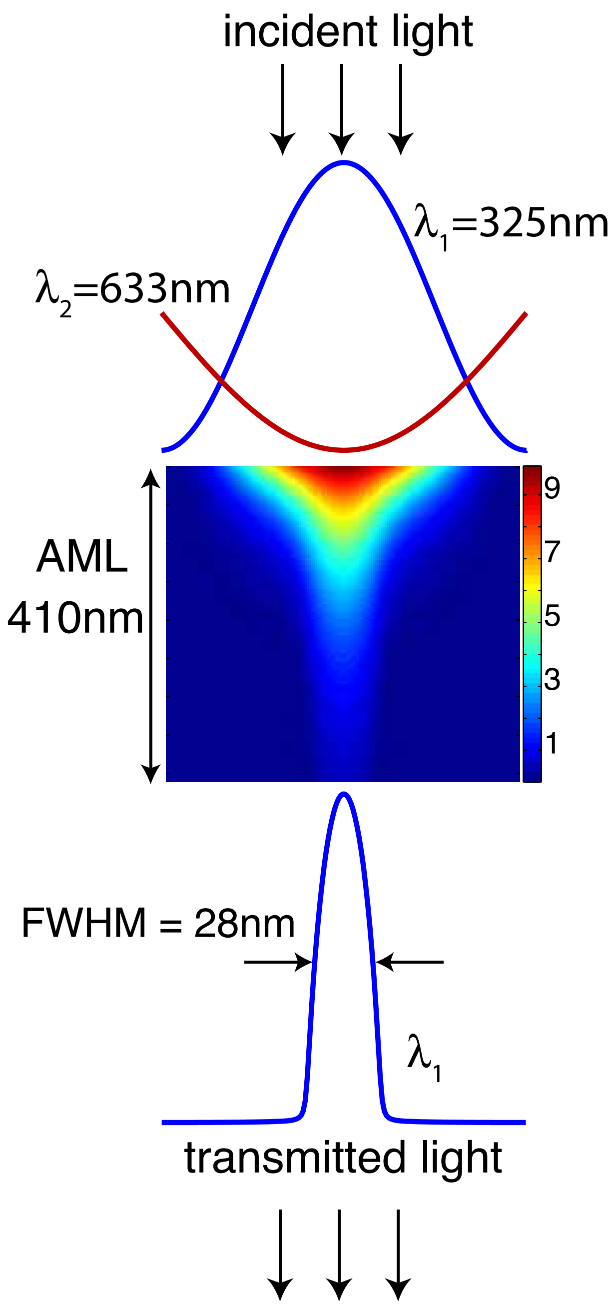
$$[A] I_1 \varepsilon_{1A} \phi_{1AB} + [A] I_2 \varepsilon_{2A} \phi_{2AB} - [B] I_2 \varepsilon_{2B} \phi_{2BA} - [B] I_1 \varepsilon_{1B} \phi_{1BA} - [B] k_{BA} = 0$$

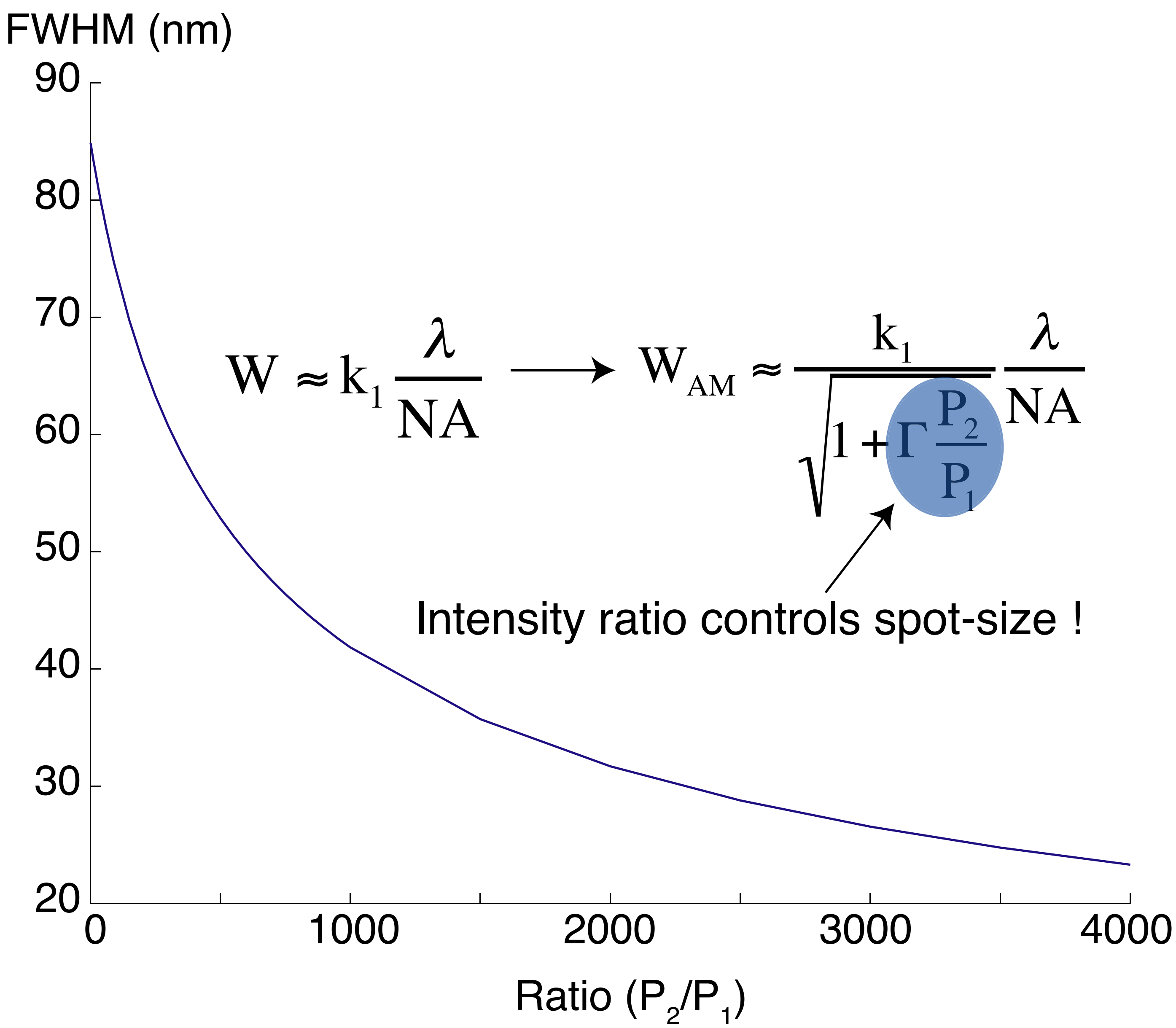
$\frac{I_2}{I_1}$ controls "squeezing" ⟶ large "effective" nonlinearities at low power levels !

Scaling towards macro-molecular resolution



New Scaling Law

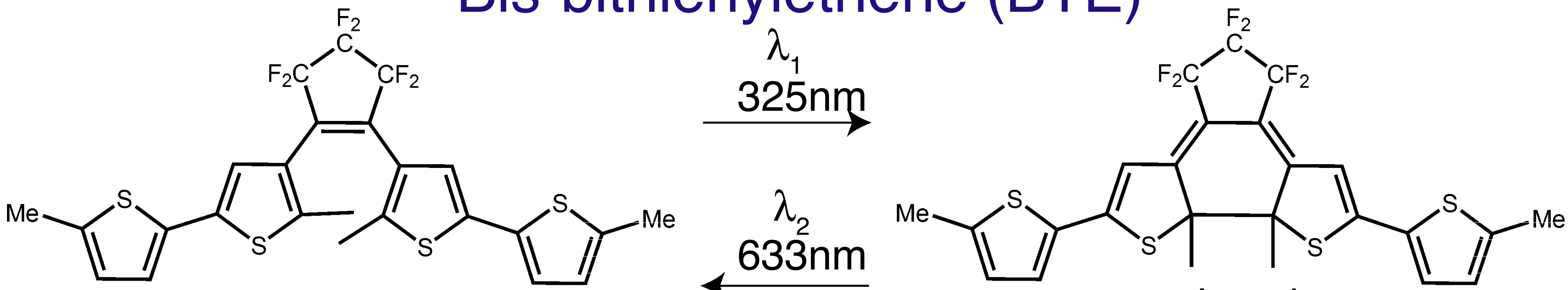




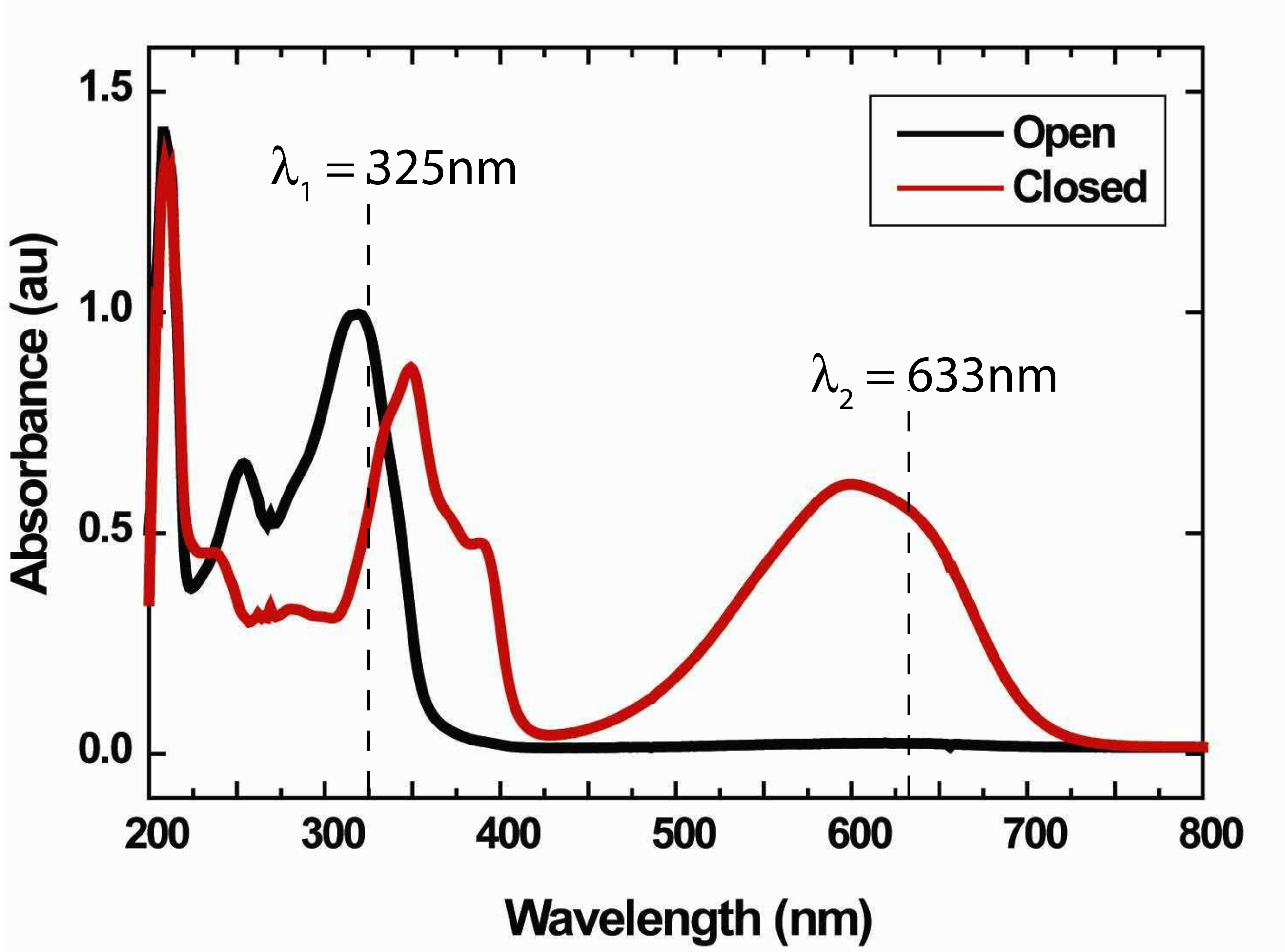
$$W \approx k_1 \frac{\lambda}{NA} \longrightarrow W_{AM} \approx \frac{k_1}{\sqrt{1 + \Gamma \frac{P_2}{P_1}}} \frac{\lambda}{NA}$$

Photochromic molecules of the diarylethene family

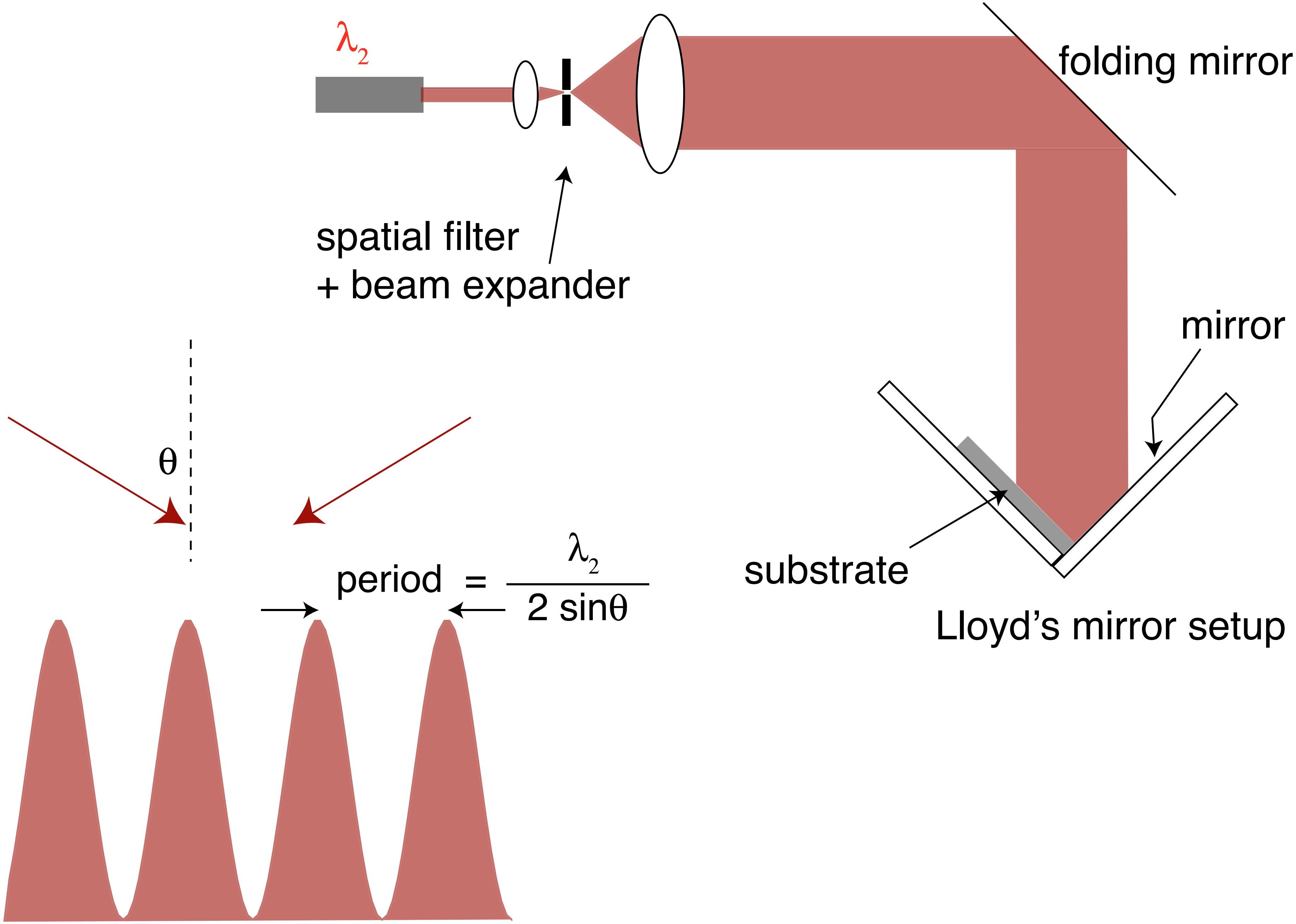
Bis-bithienylethene (BTE)



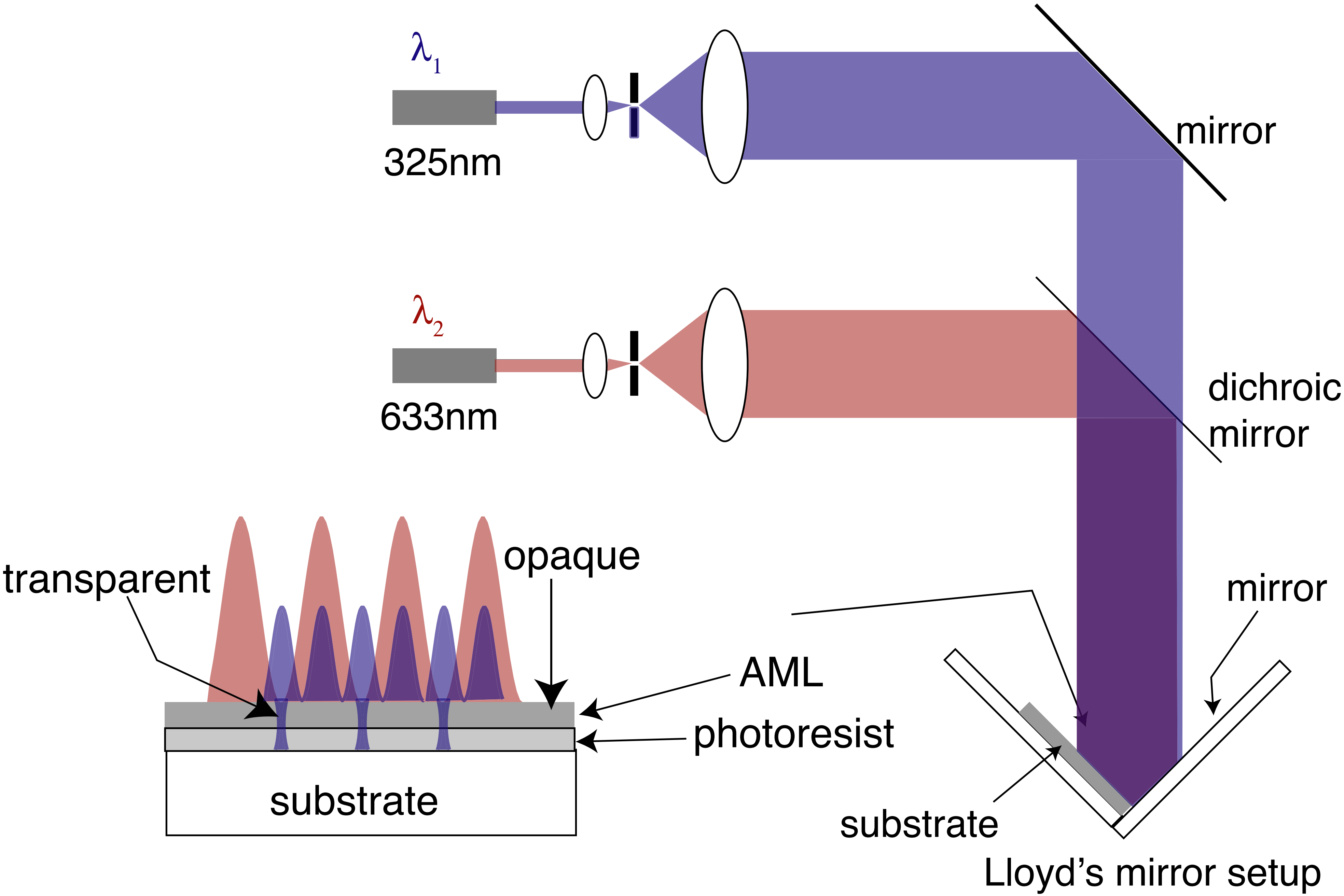
UV-Vis Spectra



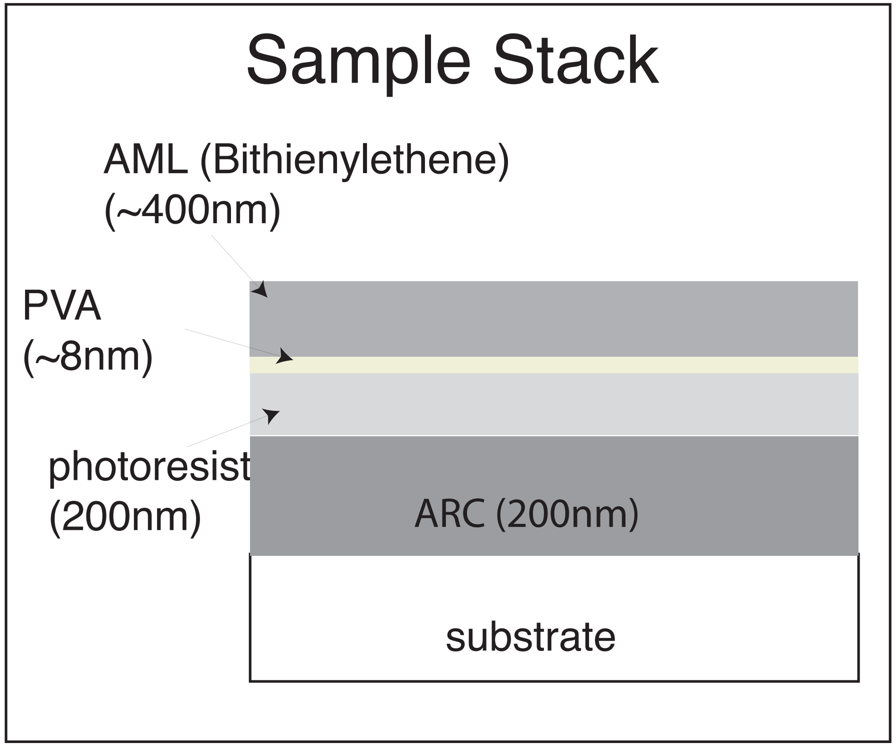
Lloyd's Mirror Interferometer : Working Principle

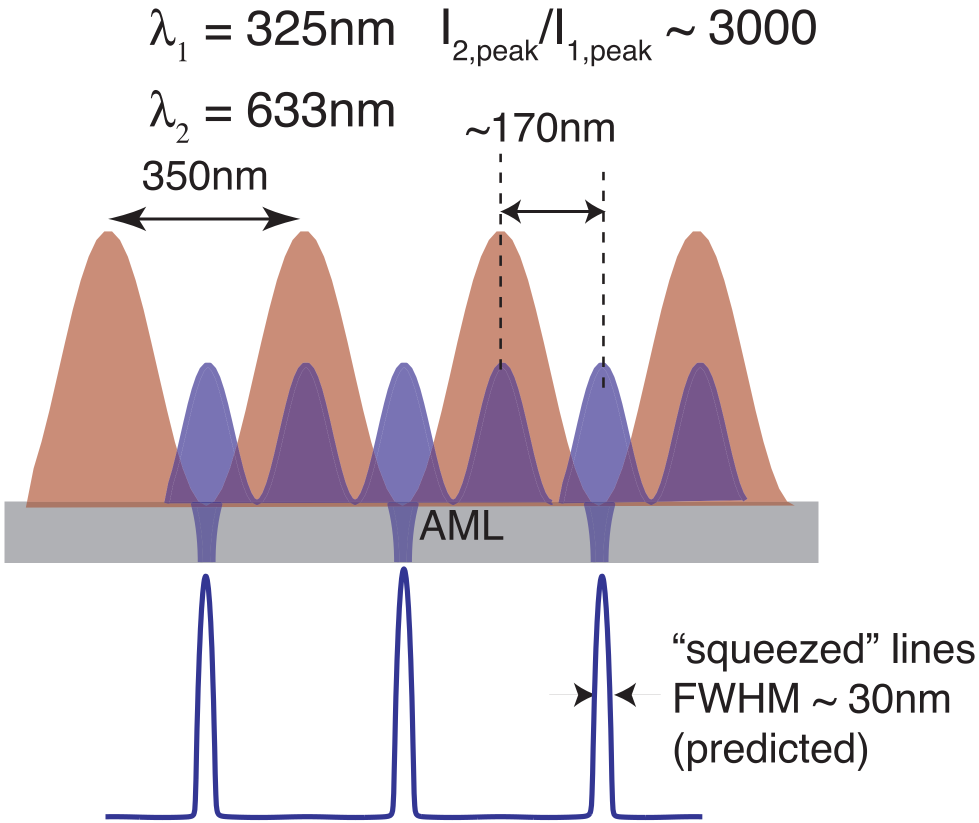


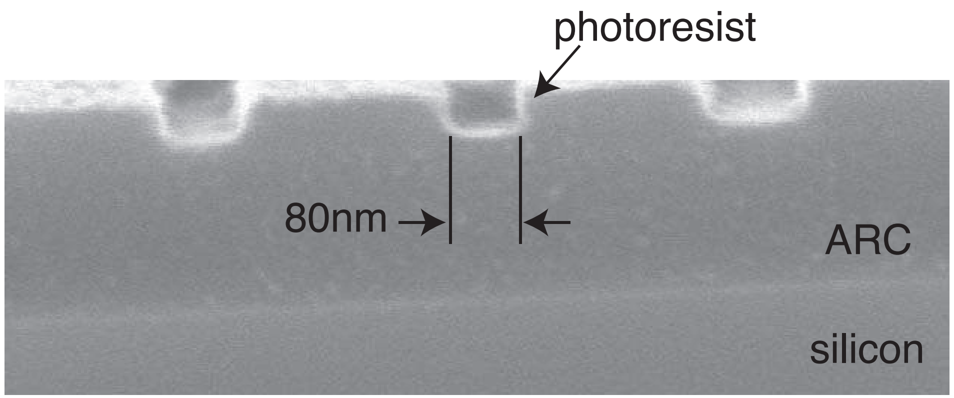
Lloyd's Mirror Interferometer for preliminary demonstration of Absorbance Modulation

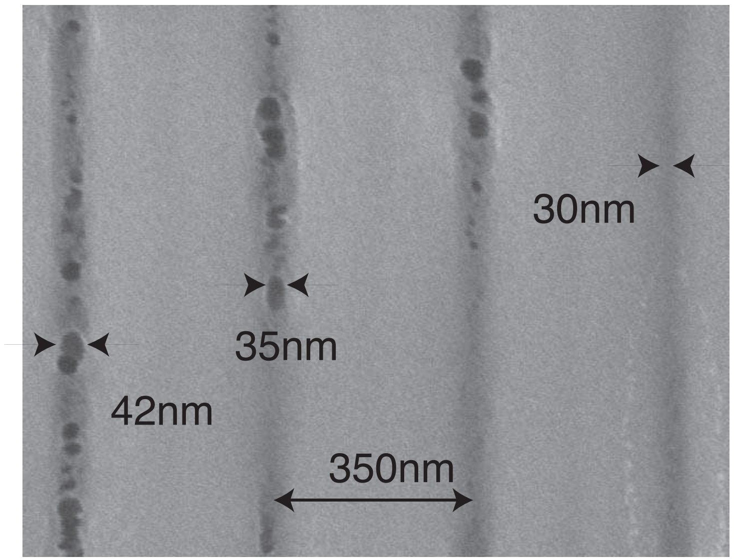


Patterning beyond the diffraction limit ($<\lambda_1/10$)



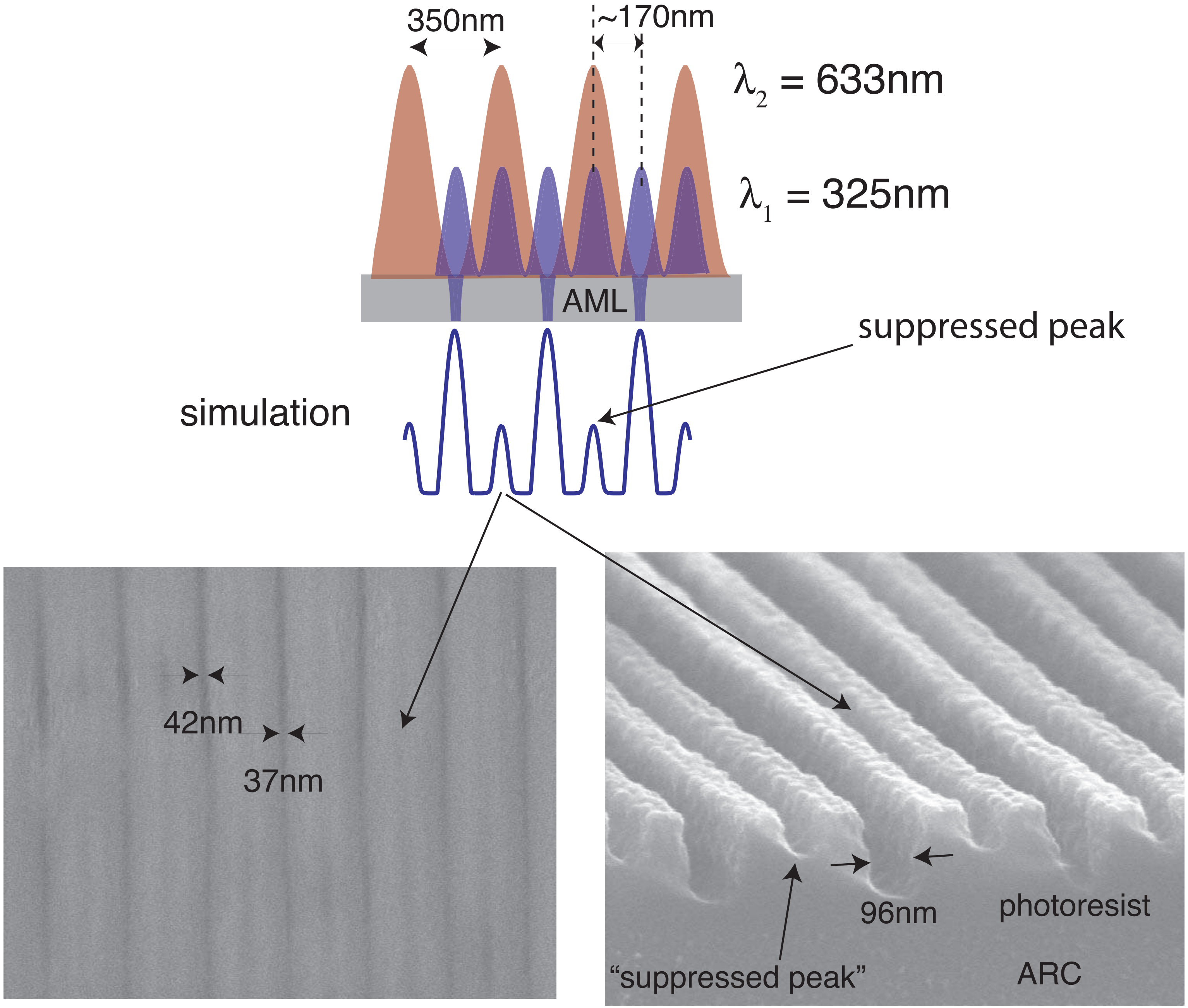






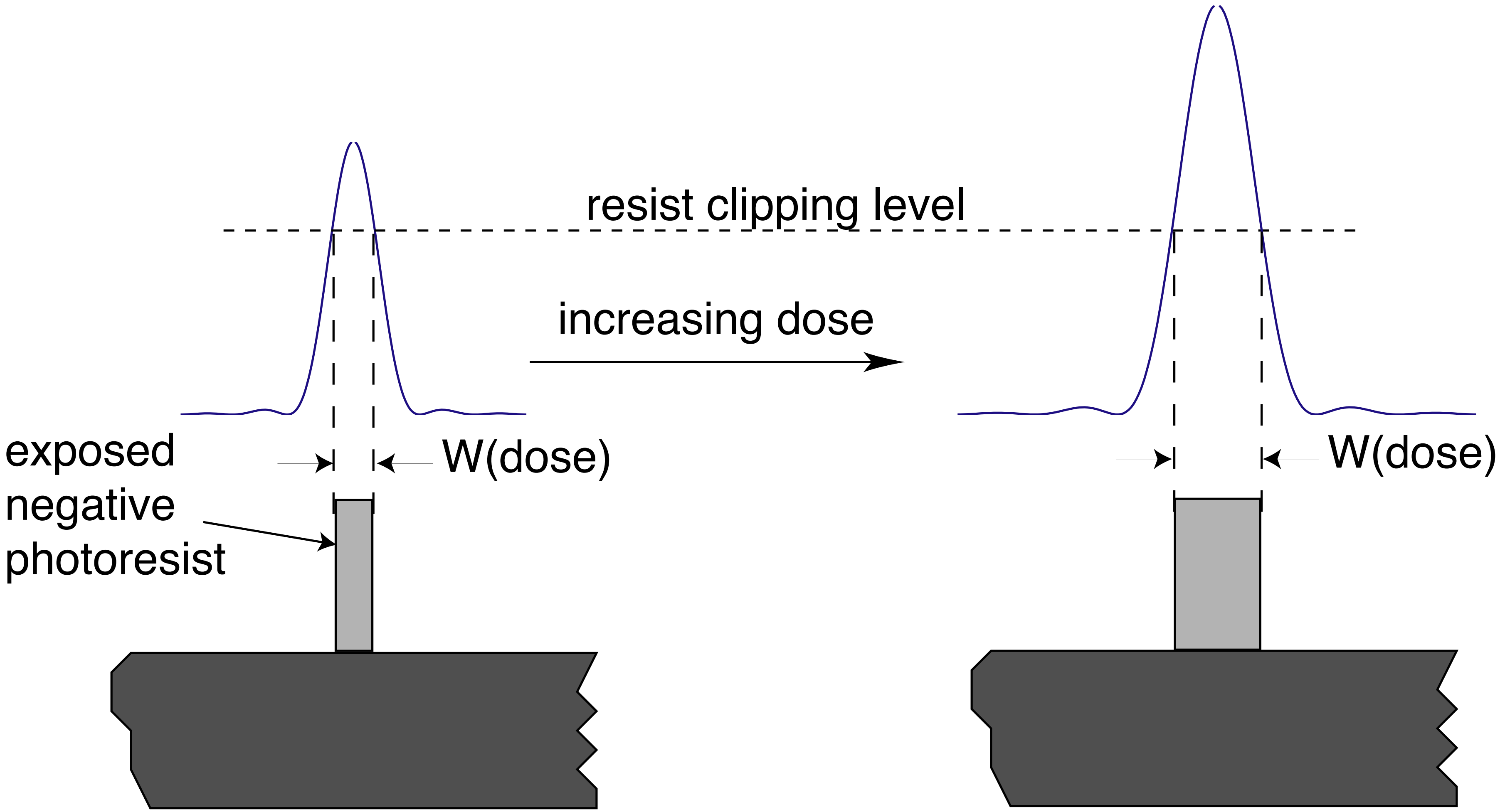
T. L. Andrew, H-Y. Tsai & R. Menon, *Science*, 324, 917 (2009).

Patterning beyond the diffraction limit ($<\lambda_1/10$)



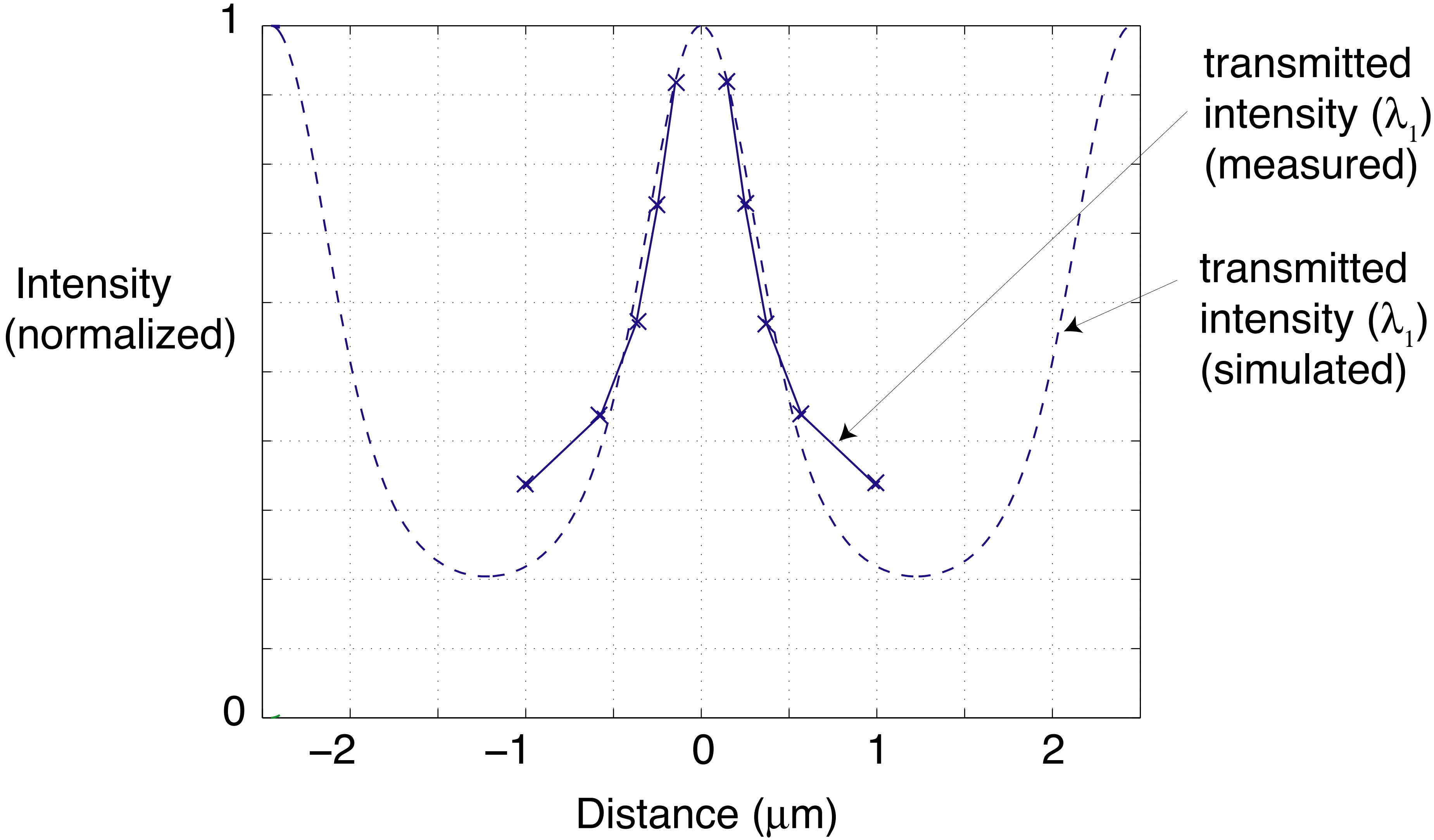
T. L. Andrew, H-Y. Tsai & R. Menon, *Science*, 324, 917 (2009).

Mapping the Line-Spread Function (LSF)



R. Menon, *et. al. J. Opt. Soc. Am. A*, 23(3), 567 (2006)

Quantitative verification of Absorbance Modulation



R. Menon, *et. al. Phys. Rev. Lett.*, 98, 043905 (2007)