Dispersion and its Compensation

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Contents

Dispersion compensation in…

- Optical communication
- Photonic crystal fiber
- Photonic crystal waveguide

Extreme of dispersion in…

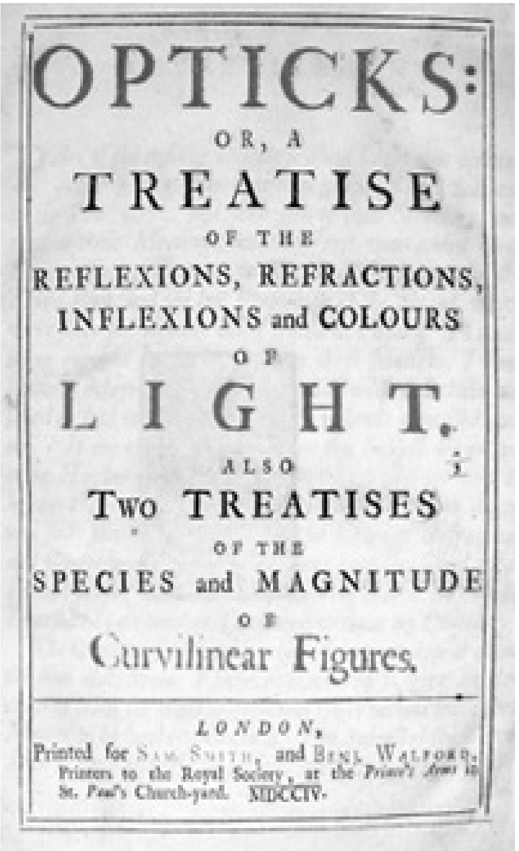
- Slow Light / Stop Light

Dispersion properties in…

- Surface plasmon polaritons & meta-material

Concluding remarks

Newton

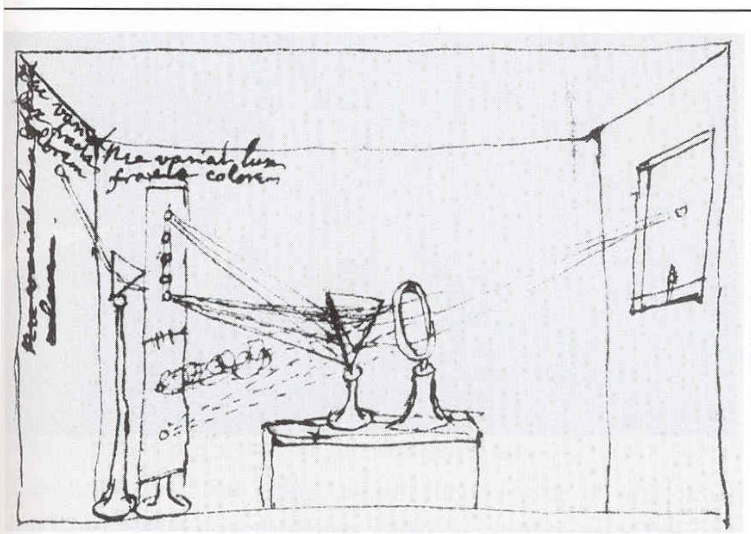


OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the *Prince's Arms* in
St. *Paul's* Church-yard. MDCCIV.

Isaac Newton

(1642-1727)

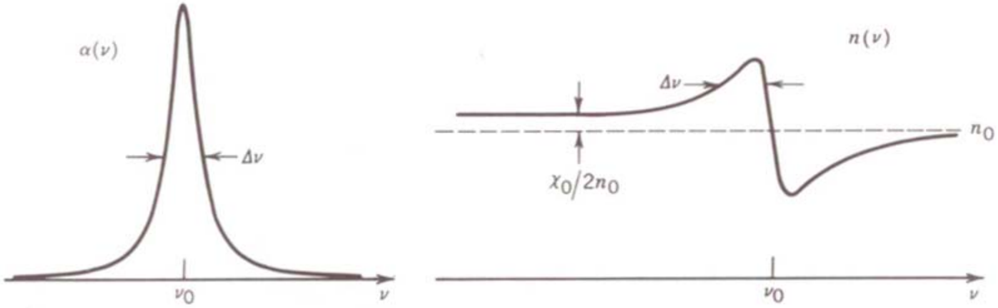


A sketch (left) from Newton's 1672 notebook shows sunlight entering through the window at right, passing through a triangular prism, and splitting into a spectrum of colors. One of the earliest known studies of optics (the science of light and vision) was done by Islamic mathematician Ibn al-Haytham (965–1040), also known as Alhazen. His sketch of lenses is below.

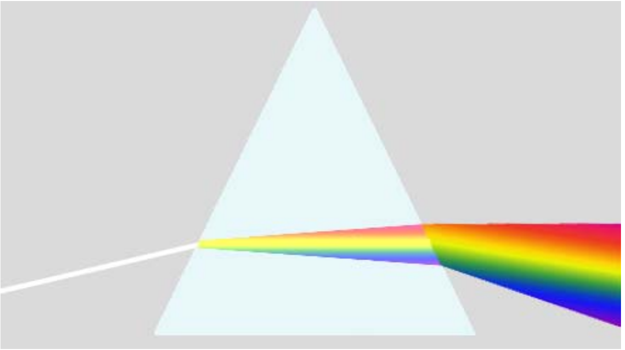
J. Hakim, The Story of Science - Newton at the Center, Smithsonian Books, Washington DC, USA, 2005.

Dispersion

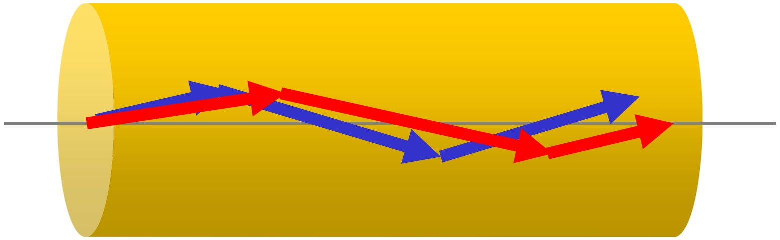
- Dispersion : a phenomenon due to a dependence of the wave's speed on its wavelength that causes the separation of a wave into spectral components with different wavelengths.
  - Chromatic Dispersion
    - Material Dispersion
    - Waveguide Dispersion
  - Modal Dispersion



Spatial dispersion



Temporal dispersion



Control of dispersion

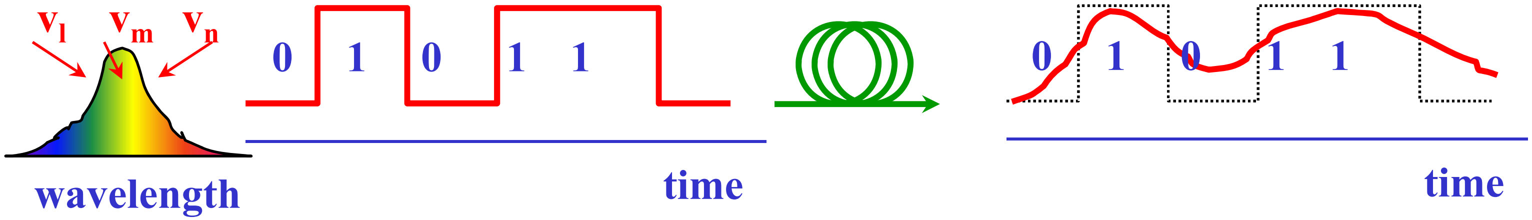
Dispersion compensation / mitigation – removing dispersion

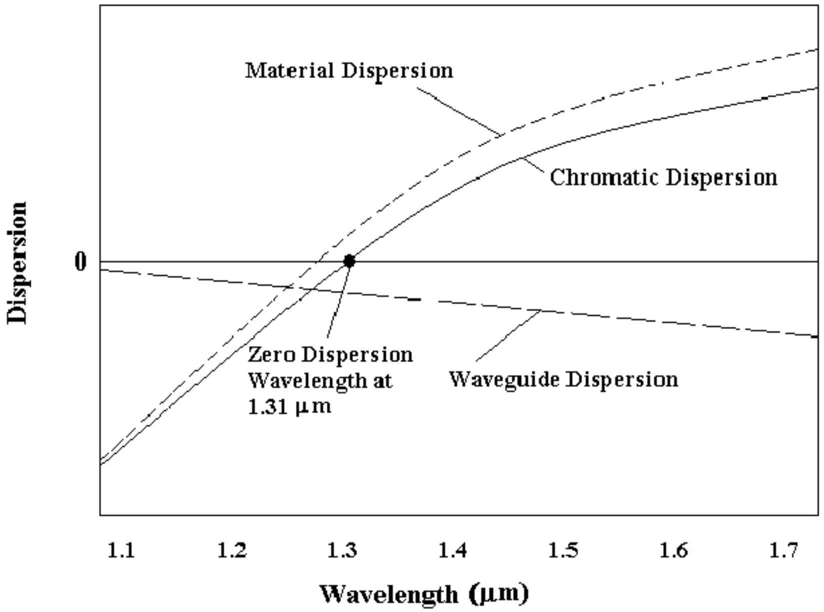
- Optical communication
- Photonic crystal fiber
- Photonic crystal waveguide

Dispersion control – using dispersion

- Photonic crystal fiber
- Photonic crystal waveguides
- Slow light / stop light
- Pulse compression
- Surface plasmon polaritons & meta-material

Chromatic dispersion in optical fiber





$$\upsilon(\lambda) = \frac{c_0}{n(\lambda)} \approx \frac{c_0}{n_0(\lambda_0) + \frac{\partial n}{\partial \lambda}\delta\lambda + \frac{1}{2}\frac{\partial^2 n}{\partial \lambda^2}\delta\lambda^2}$$

$$\frac{\partial n}{\partial \lambda} \sim \text{chromatic dispersion}, \; \frac{\partial^2 n}{\partial \lambda^2} \sim \text{dispersion slope}$$

$$L_D = \frac{1}{D \cdot B \cdot \Delta\lambda} \propto \frac{1}{B^2}$$

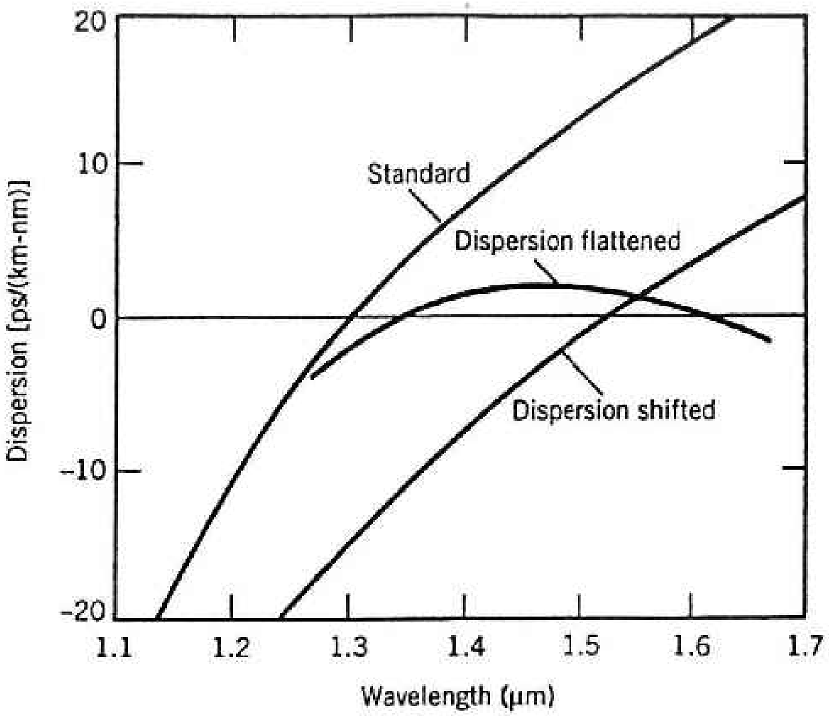
L_D : dispersion limited distance, B: bit rate

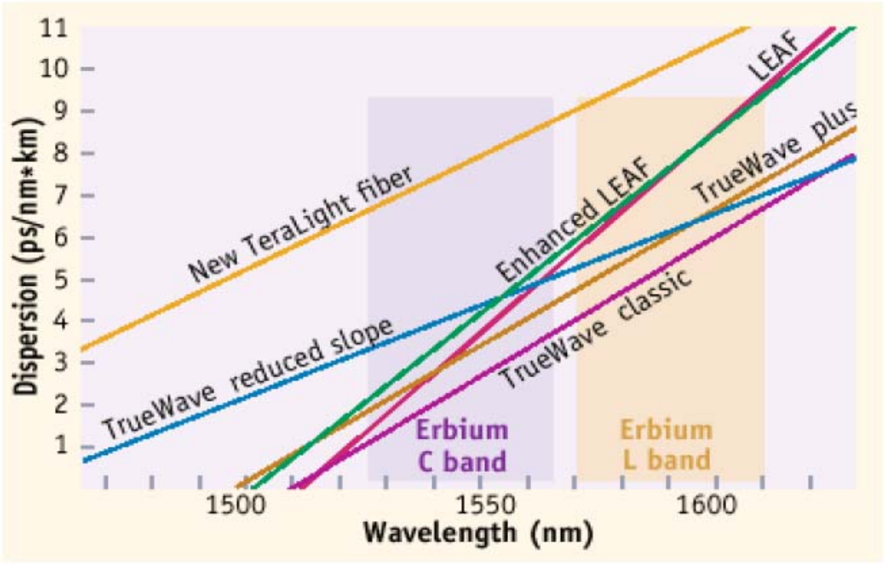
L_D : ~ 900 km (2.5 Gbit/s)
60 km (10 Gbit/s)
4 km (40 Gbit/s)

SMF D ~ +17 ps/(nm· km) at 1550 nm

⇒ varies according to optical path and environment

Dispersion engineering in optical fiber





Legacy fibers SMF-28 has dispersion of 17 ps/nm-km @ 1550 nm

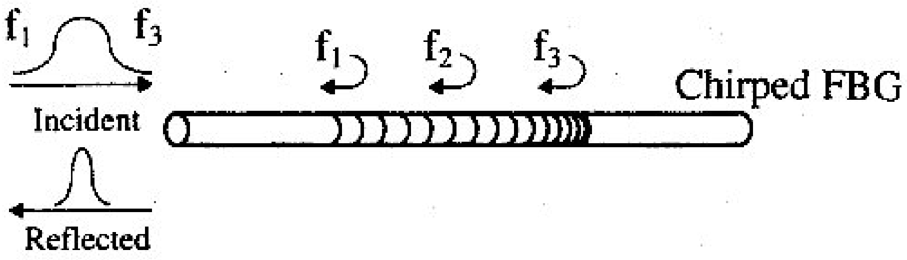
Need for dynamic chromatic dispersion compensation

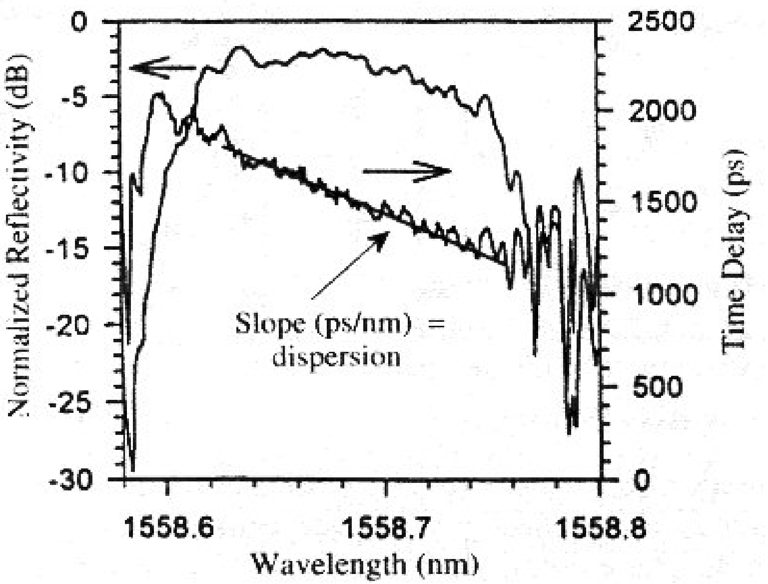
For 40 Gb/s (or more) transmission,

- Communications link will not work if the compensation value does not exactly match the fiber within a few percent of the required dispersion value.
- Dispersion changes with temperature since the zero-dispersion wavelength of fiber changes with temperature at a typical rate of 0.03 nm/^{o}C.
- Inventory management
- Reconfigurable optical networking

A. E. Willner, *IEEE LEOS Annual Meeting*, TuI1, 2002.

Dispersion Compensation with Chirped Fiber Bragg Gratings





CFBGs reflect different frequency components at different locations within the grating.

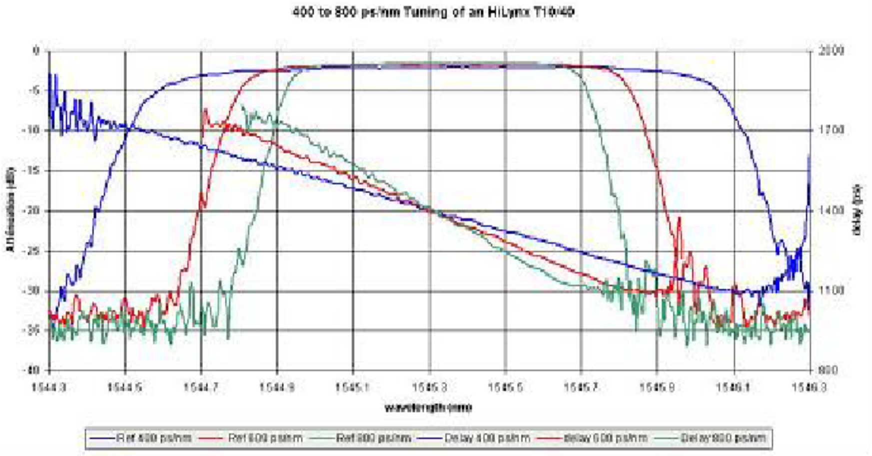
They can be used for dispersion compensation when the time delay for the grating is the inverse of the delay caused by dispersion of a transmission line.

Normalized reflectivity and time delay for a linearly CFBG.

Oscillatory and random ripple should be minimized for the best system performance.

I. Kaminow and T. Li, *Optical Fiber Communications IV B*, Academic Press (2002).

Commercialized Tunable CFBG for CD Compensation
- Highwave Optical Technologies



Optical Specifications	**Units**	**HiLynx T10** (10 Gbit/s systems)	**HiLynx T10/40** (10 and 40 Gbit/s systems)
Dispersion tuning range	ps/nm	700 to 1300	400 to 800
Channel Bandwidth (BW)	GHz	Up to 40	Up to 80
Insertion loss (including a circulator)	dB	< 2 dB	
Insertion loss Ripple	dB	< 0.5 dB	
Raw Group Delay Ripple (over full T° range)	ps	< +/-20 ps	< +/-15 ps
Group Delay Ripple (100 pm smoothing avg.)	ps	< +/- 5 ps	< +/- 3 ps
PDL (averaged in BW)	dB	< 0.1 dB	
PMD (averaged in BW)	ps	< 0.5 ps	

Electronic dispersion compensation (EDC)

5120-km RZ-DPSK transmission at 10 Gb/s without optical dispersion compensation

D. McGhan *et al*., *IEEE Photon. Technol. Lett*., 18 (2), pp. 400-402, 2006

Electro-optic modulator in transmitter

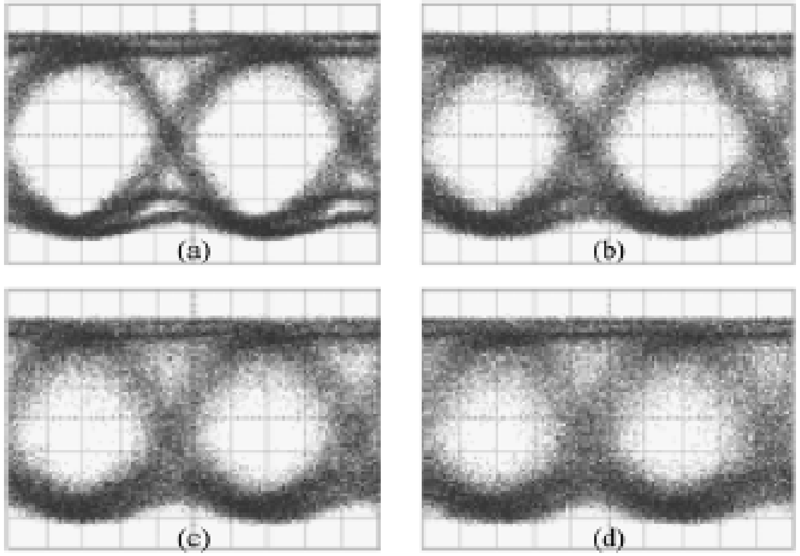


Fig. 4. Eye diagrams at receiver after propagation on G.652 fiber: (a) back-to-back (0 ps/nm), (b) 1600 km (25 760 ps/nm), (c) 3200 km (51 520 ps/nm), and (d) 5120 km (82 433 ps/nm).

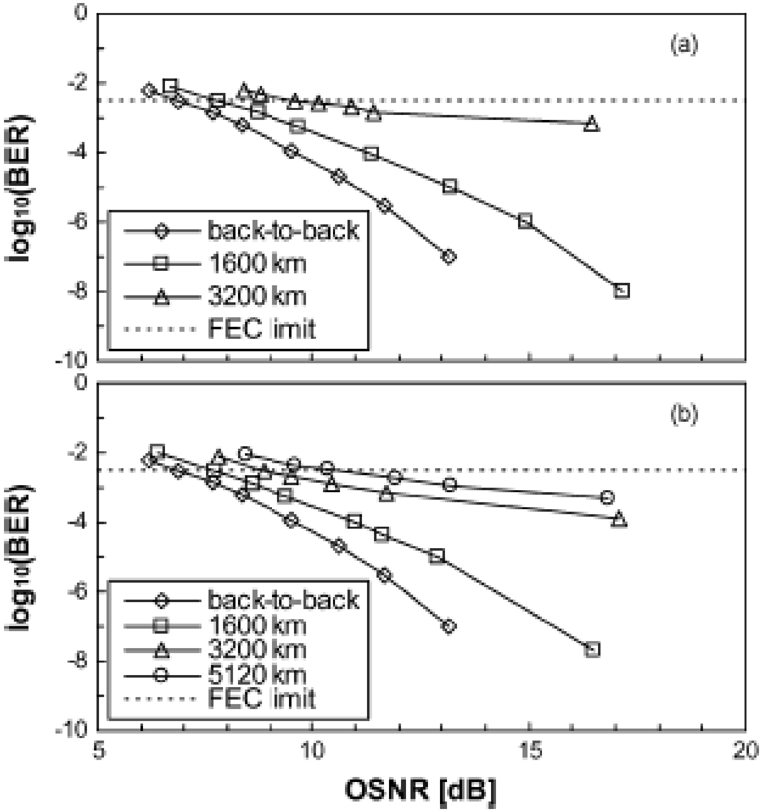
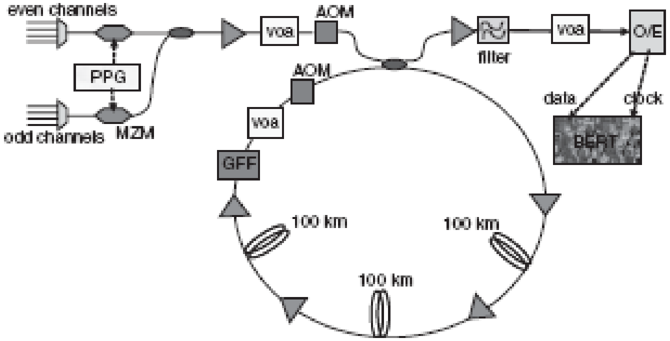


Fig. 5. BER as function of OSNR in 0.1-nm resolution bandwidth. Average launch power: (a) −5 and (b) −7 dBm.

EDC, without optical compensation

1500 km transmission over NZ-DSF without in-line or post-compensation of dispersion for 38 x 10.7 Gbps channels

J. D. Downie *et al*., *Electron. Lett*., 42 (11), pp. 650-652, 2006.



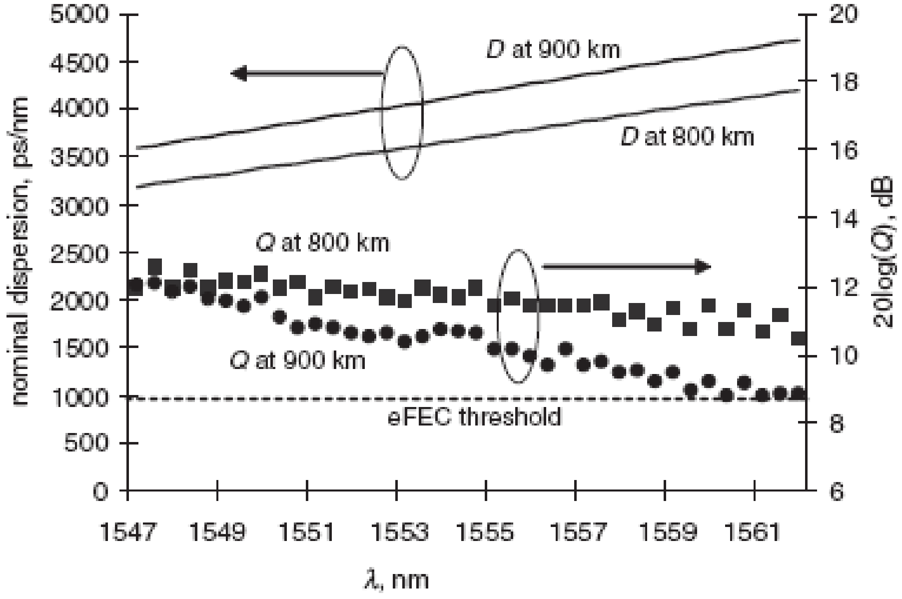


Fig. 2 *Accumulated dispersion and signal Q values at 800 and 900 km*

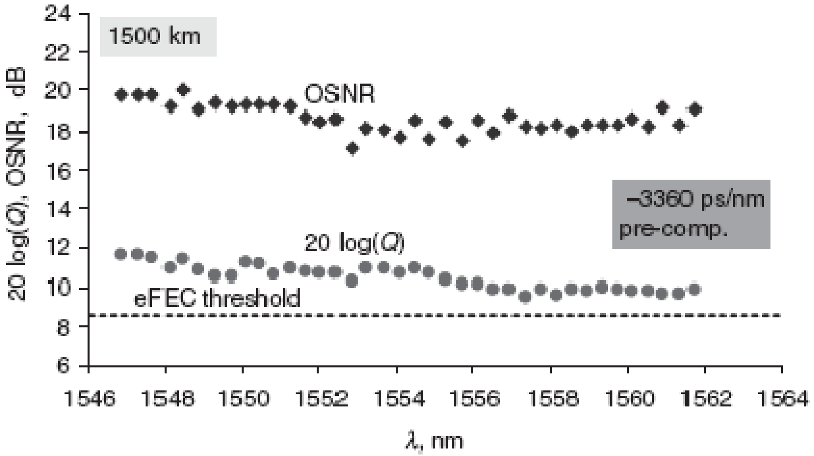


Fig. 3 *OSNR and Q values after transmission over 1500 km*

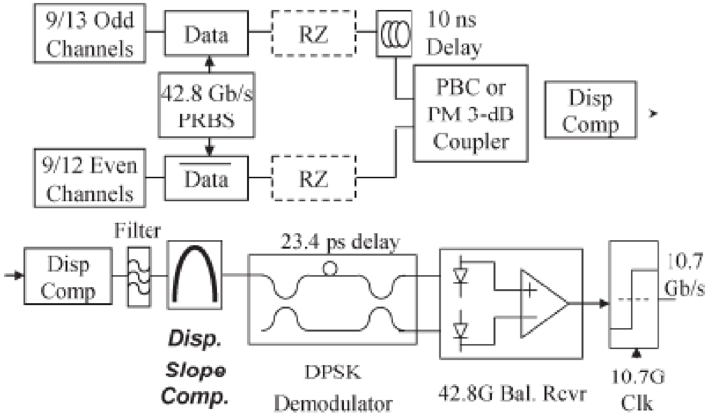
900km transmission w/o optical compensation

1500km transmission with DCF compensation

EDC, receiver dispersion slope compensation

Transmission of 40-Gb/s WDM signals over transoceanic distance using conventional NZ-DSF with receiver dispersion slope compensation

J.-X. Cai *et al*., *J. Lightwave Technol*., 24 (1), pp. 191-200, 2006



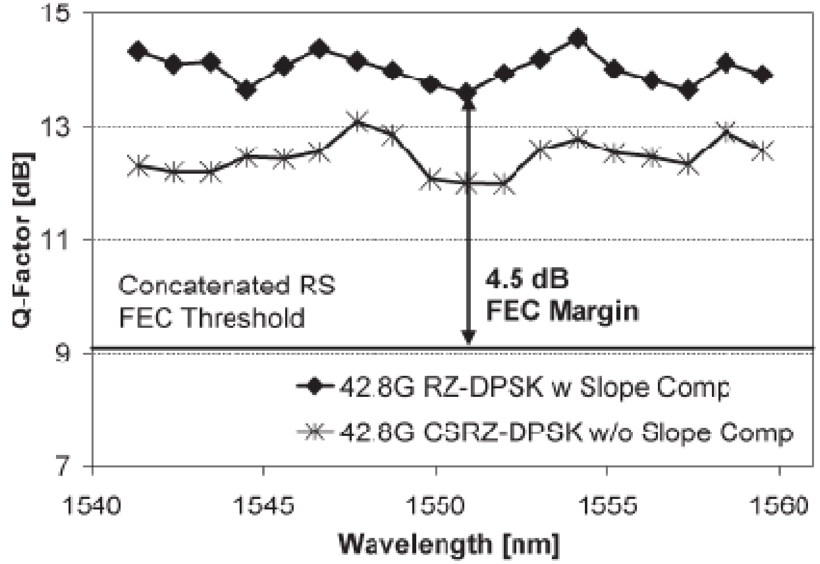


Fig. 6. Q-factors for 42.8-Gb/s RZ-DPSK (with slope compensation) and CSRZ-DPSK (without slope compensation) after 6250 km.

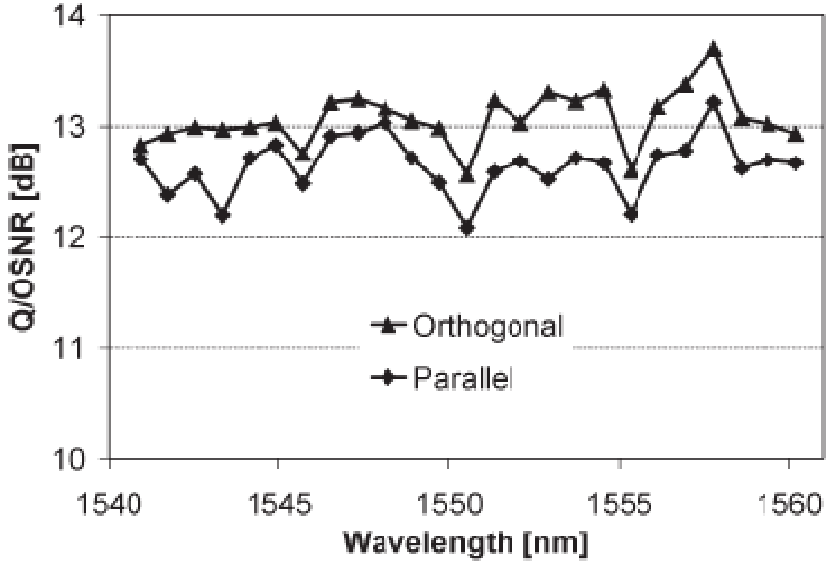
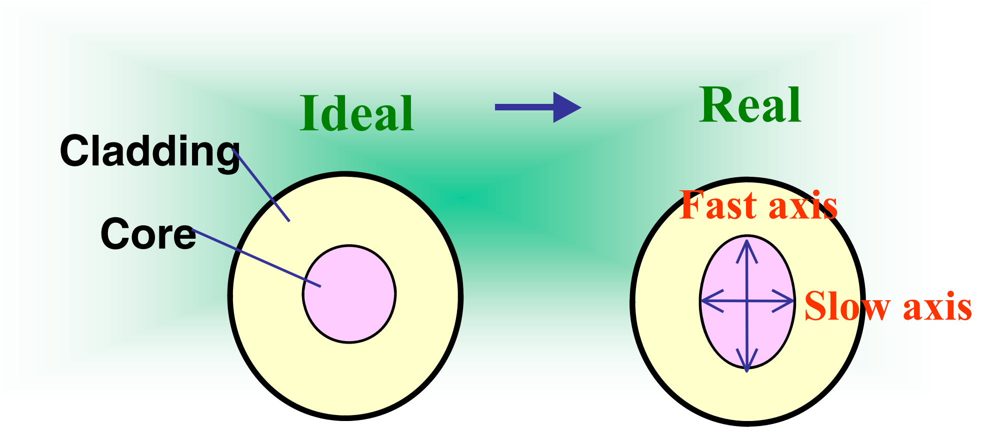
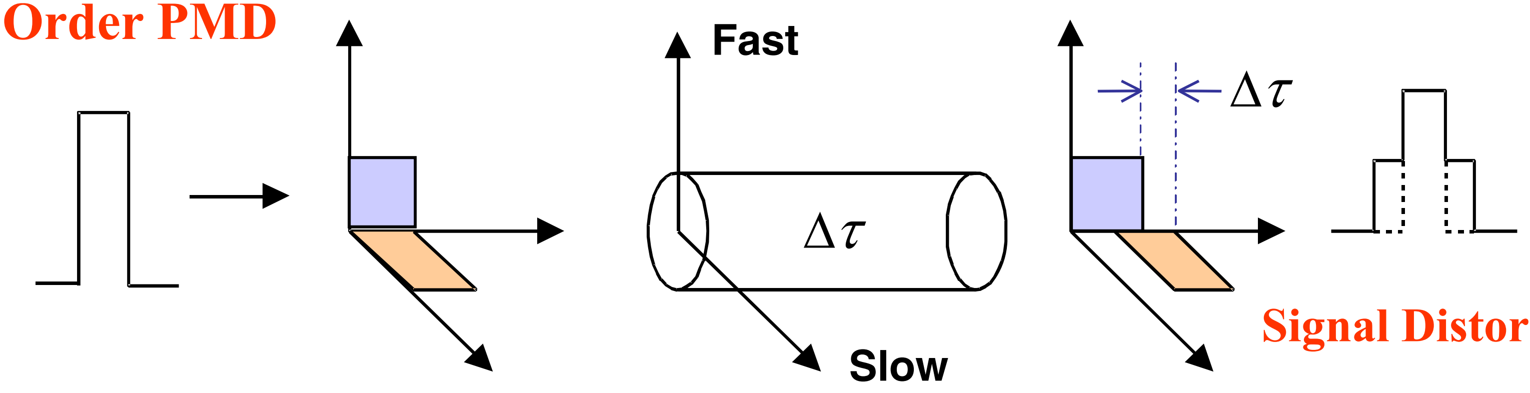


Fig. 18. Comparison of parallel and orthogonal launch (CSRZ-DPSK, 100-GHz channel spacing, 25 × 40 Gb/s over 6250 km).

Polarization mode dispersion (PMD)

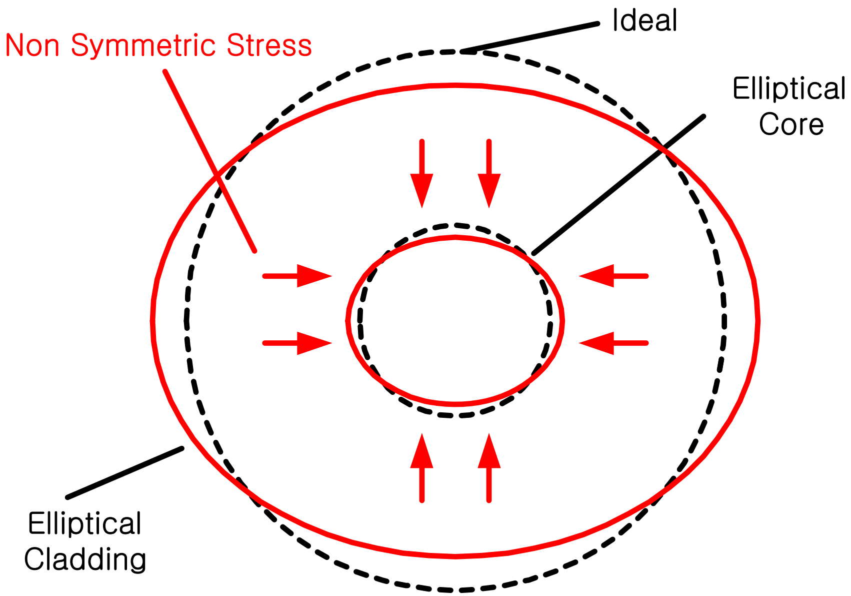


1st Order PMD

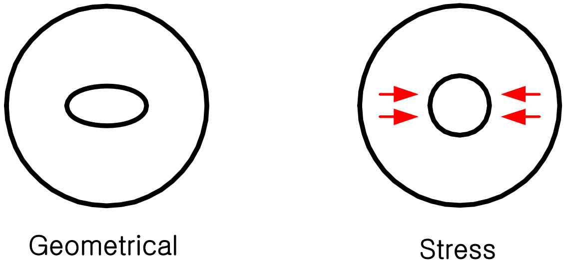


Signal Distortion!!

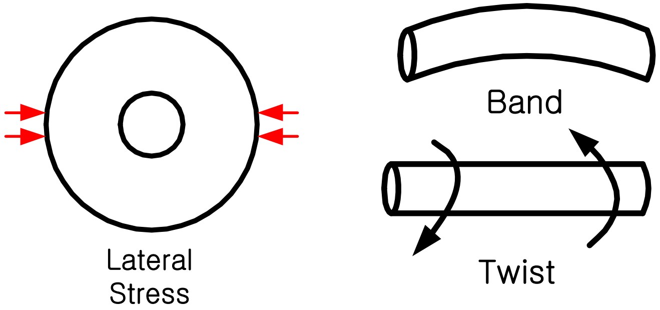
Causes of birefringence



- Intrinsic : Oval waveguide

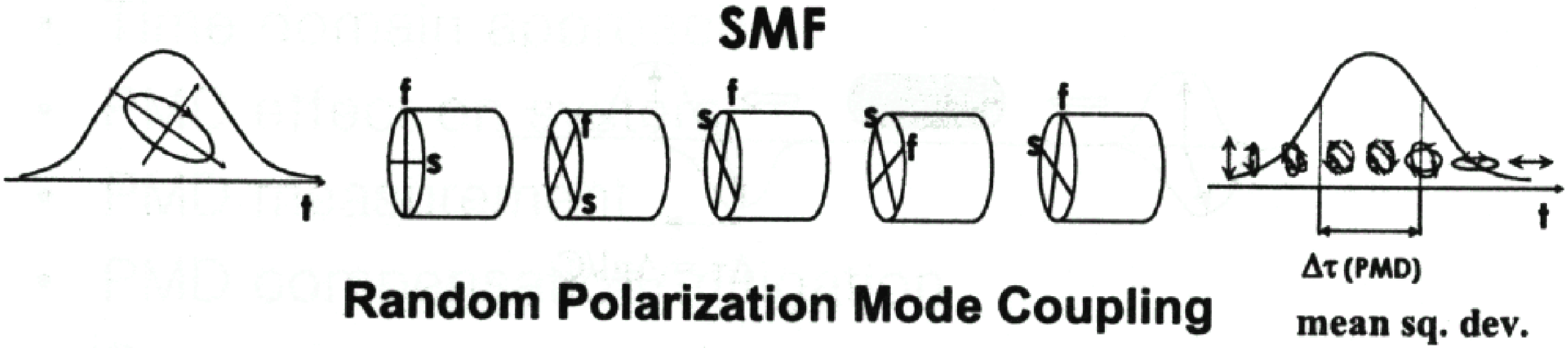


- Extrinsic : Mechanical stress



Realistic model of fiber PMD

- Multiple concatenation of randomly oriented birefringent elements

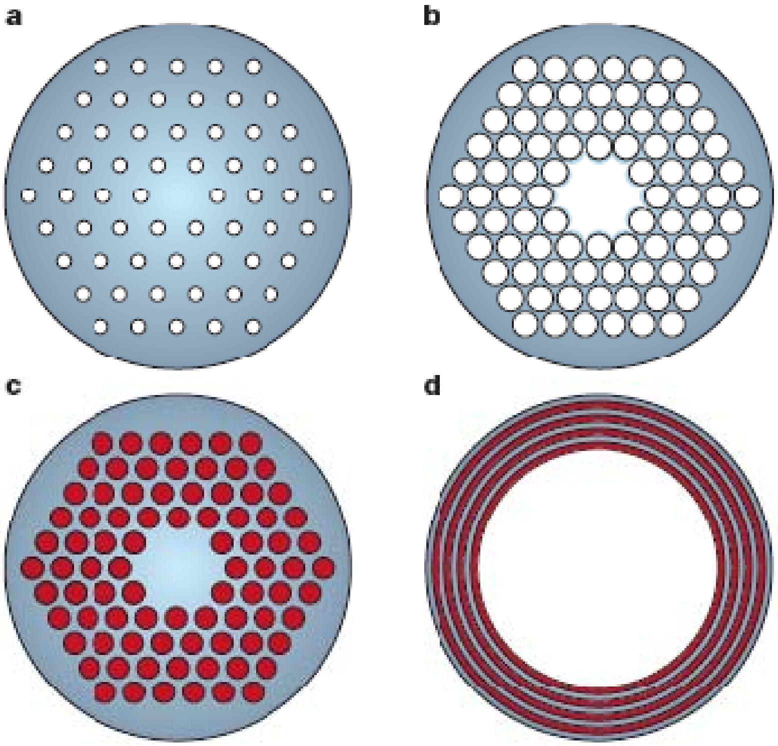


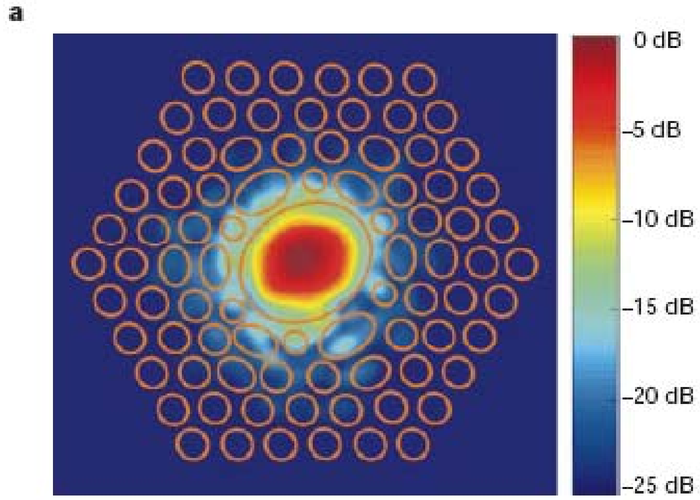
Random Polarization Mode Coupling

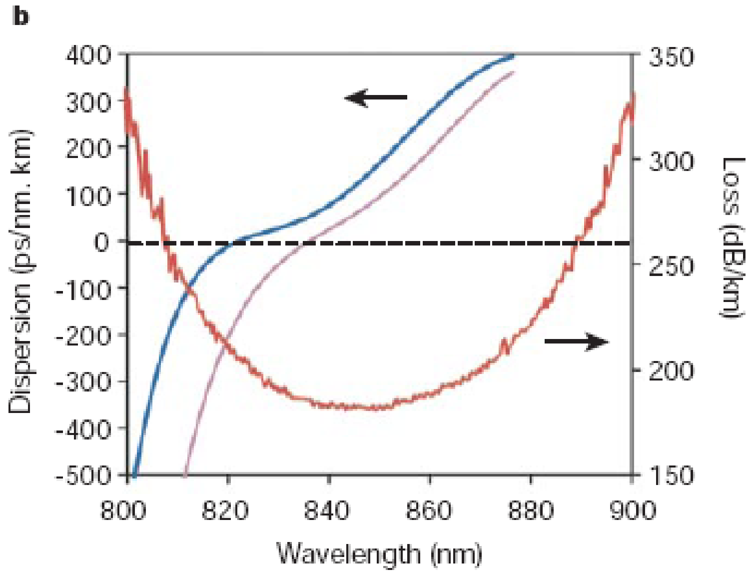
Photonic crystal fiber (PCF)

Photonic crystal fibers

J. C. Knight, *Nature*, 424, pp. 847-851, 2003.



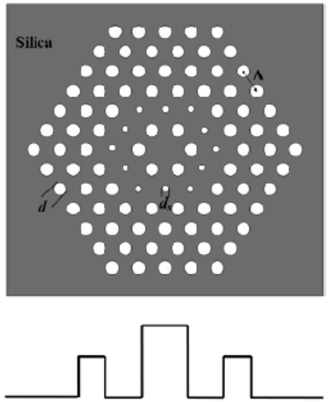


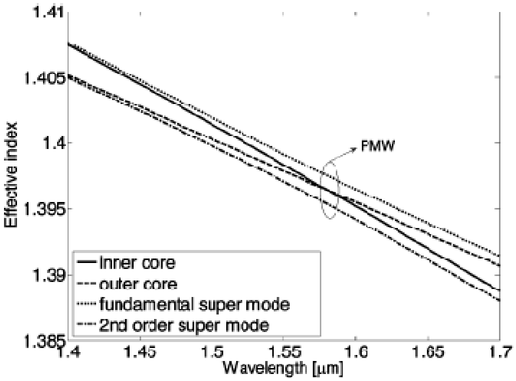


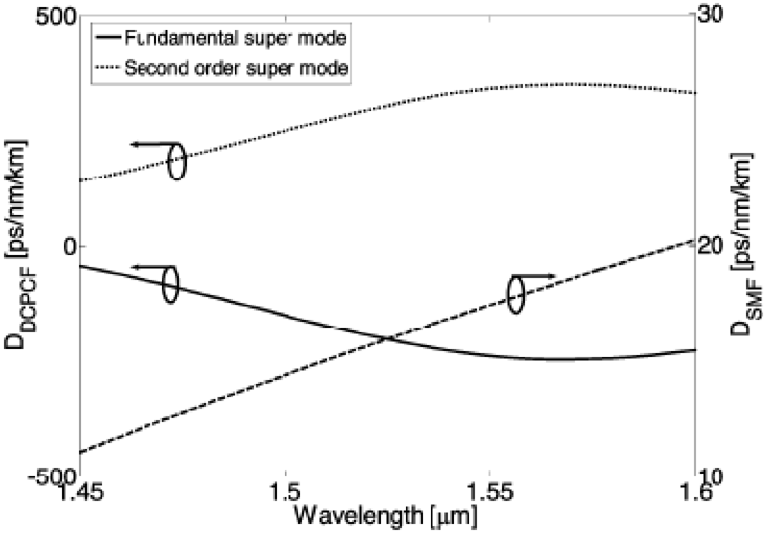
Dispersion compensation with PCF

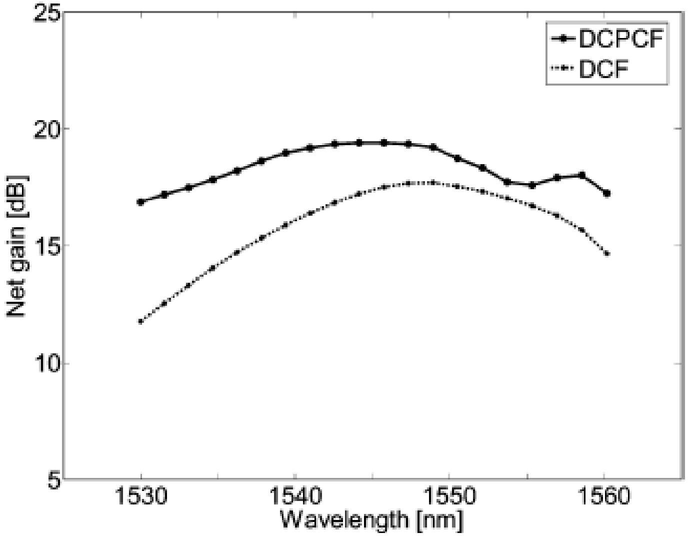
A novel design for dispersion compensating photonic crystal fiber Raman amplifier

S. K. Varshney *et al*., *IEEE Photon. Technol. Lett*., 17 (10), pp. 2062-2064, 2005.









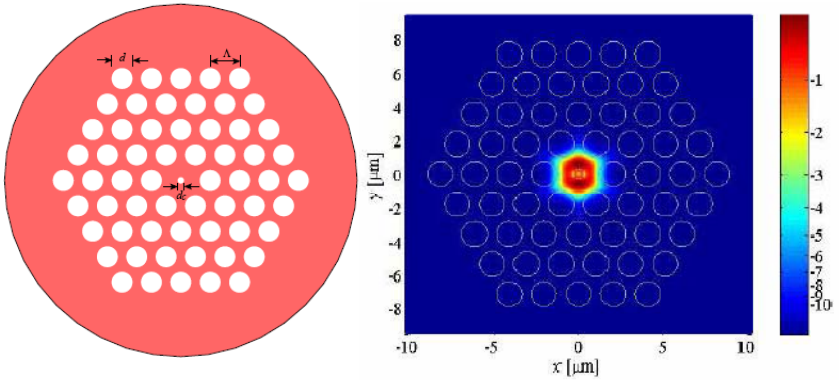
Highly-negative dispersion for the fundamental mode

Flattened gain by Raman amplification

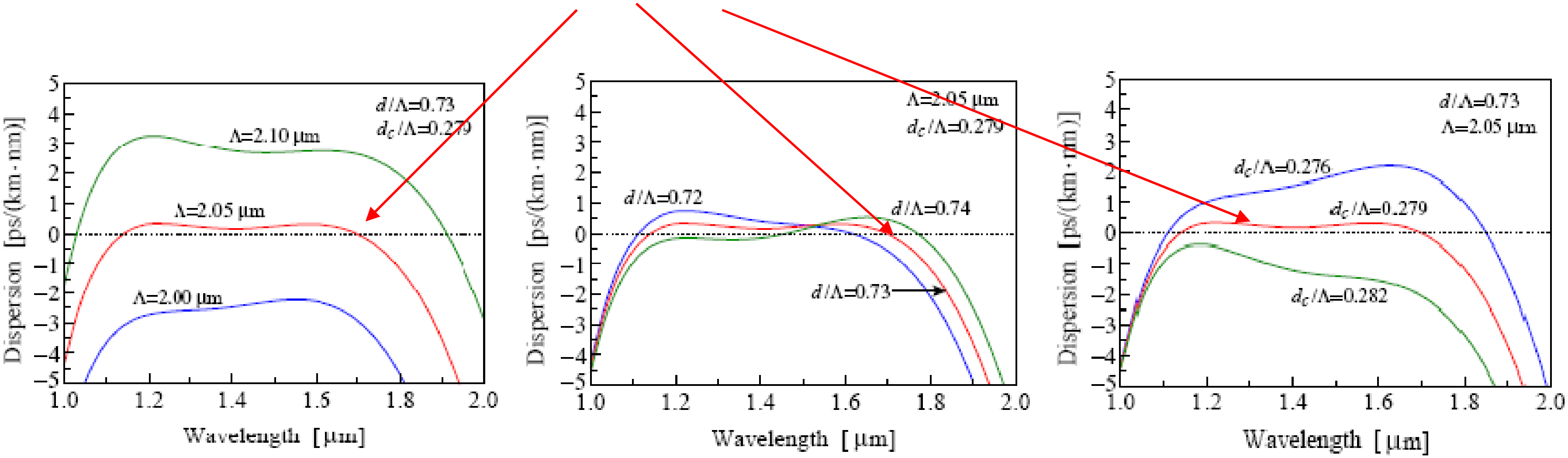
Dispersion compensation with PCF

Ultra-flattened chromatic dispersion controllability using a defected-core photonic crystal fiber with low confinement losses

K. Saitoh *et al*., *Opt. Express*, 13 (21), pp. 8365-8371, 2005.



Optimally-flattened-dispersion



Lattice constant variation

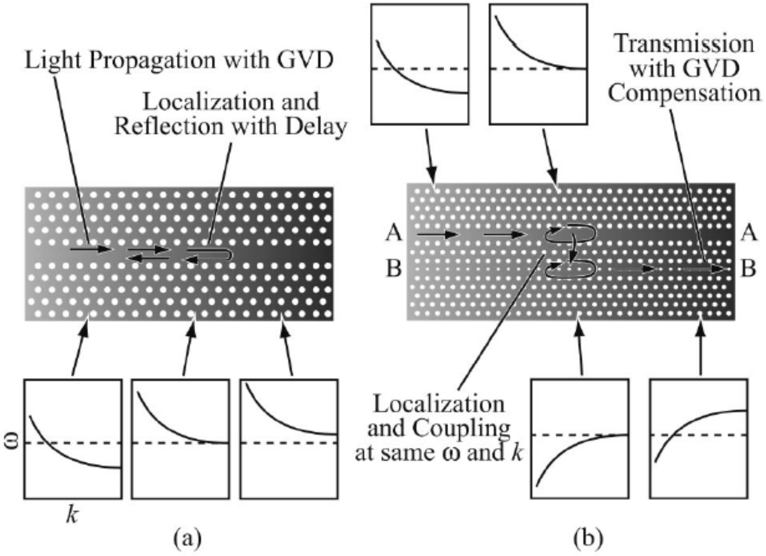
Cladding diameter variation

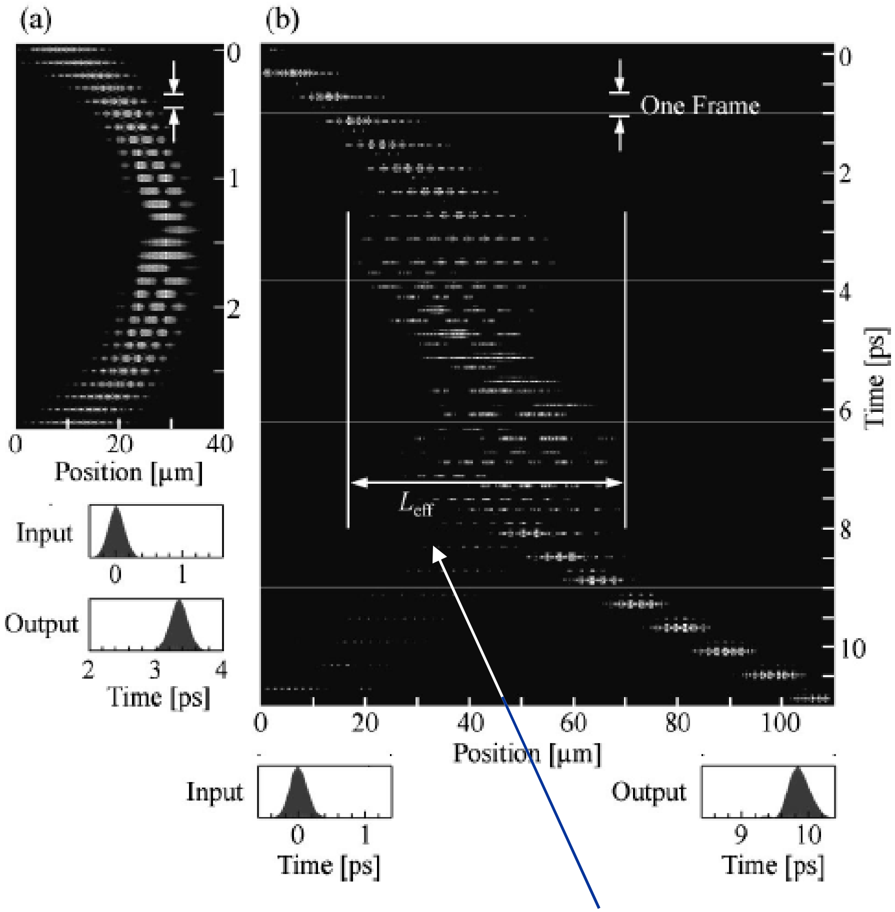
Core diameter variation

Group delay device: dispersion control

Dispersion-controlled optical group delay device by chirped photonic crystal waveguides

D. Mori and T. Baba, *Appl. Phys. Lett.*, 85 (7), pp. 1101-1103, 2004.





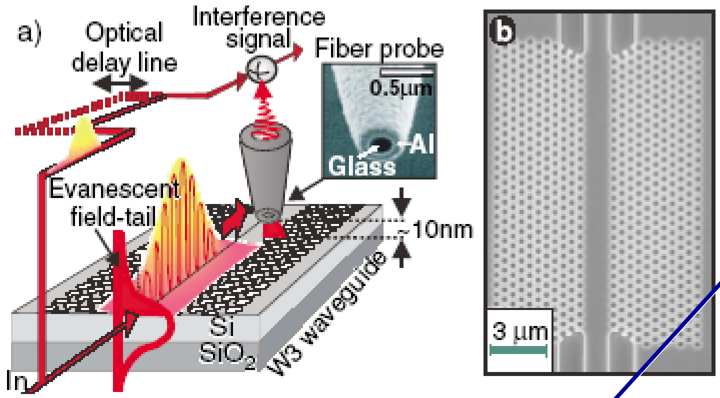
$L_{eff} = 45\mu m$

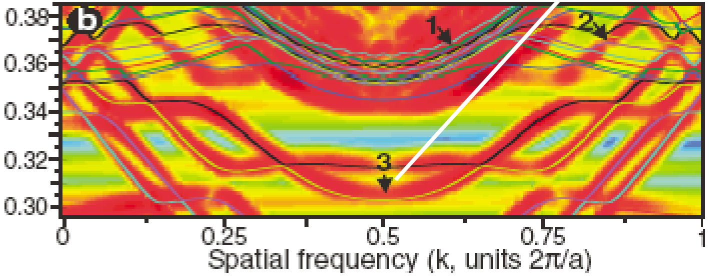
Delay device by slowing

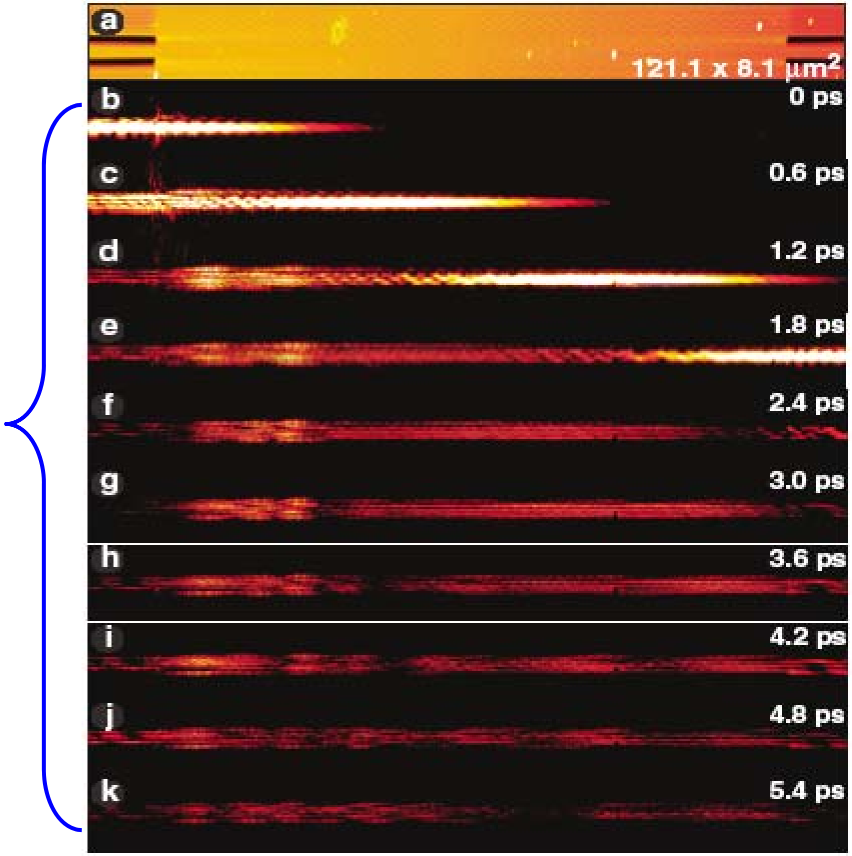
Slow light & strong dispersion

Real-space observation of ultraslow light in photonic crystal waveguides

H. Gersen *et al*., *Phys. Rev. Lett*., 94, 073903, 2005.





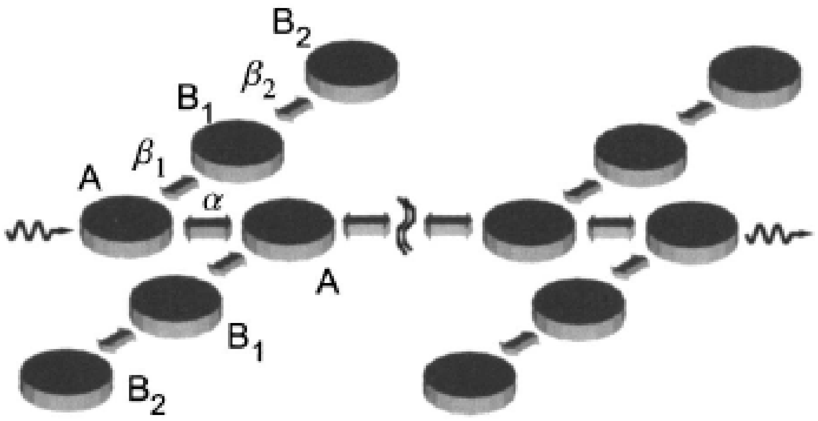


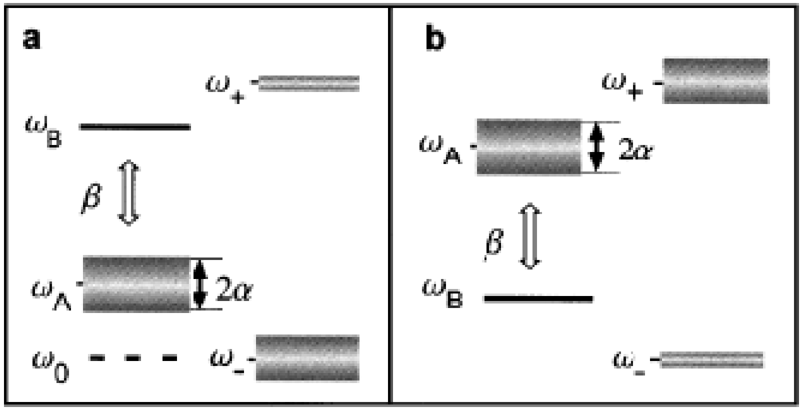
Real-space observation (< c/1000)

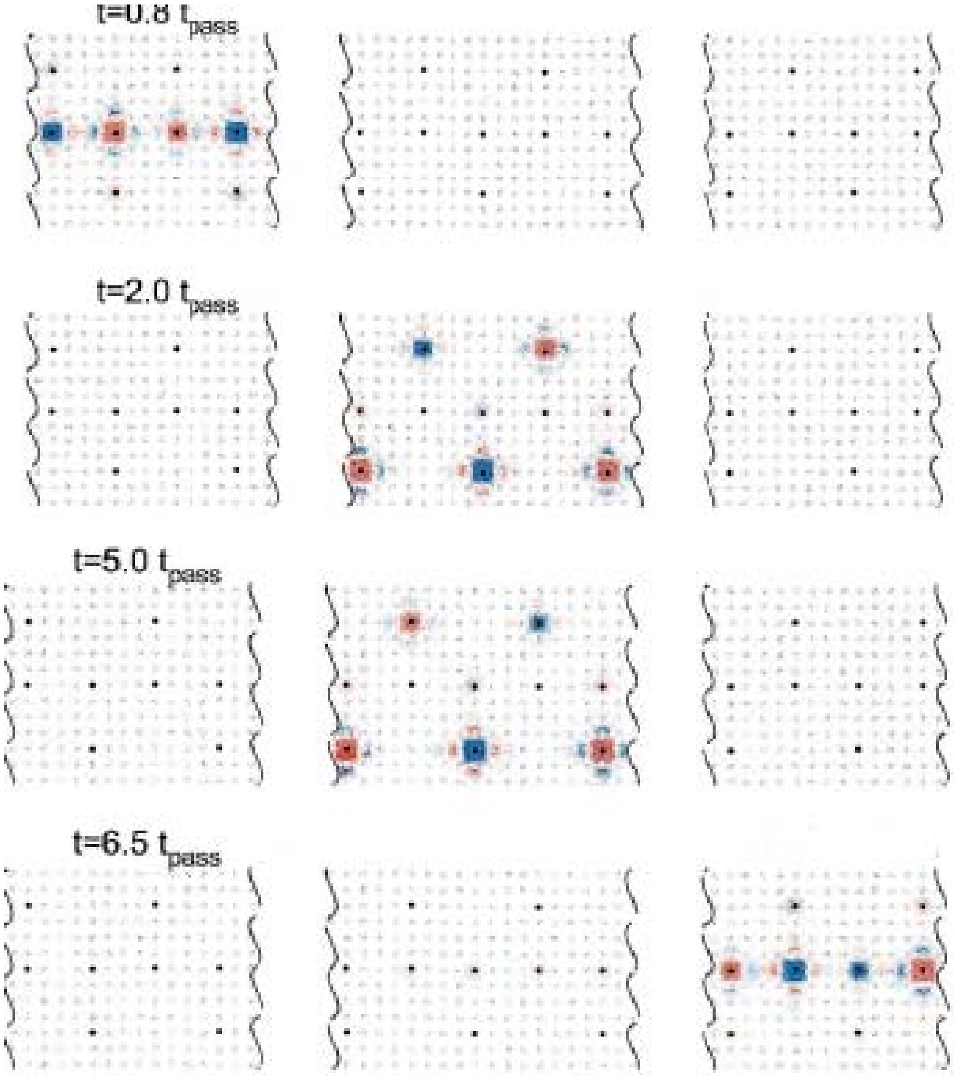
Slow & stopping light

Stopping light all optically

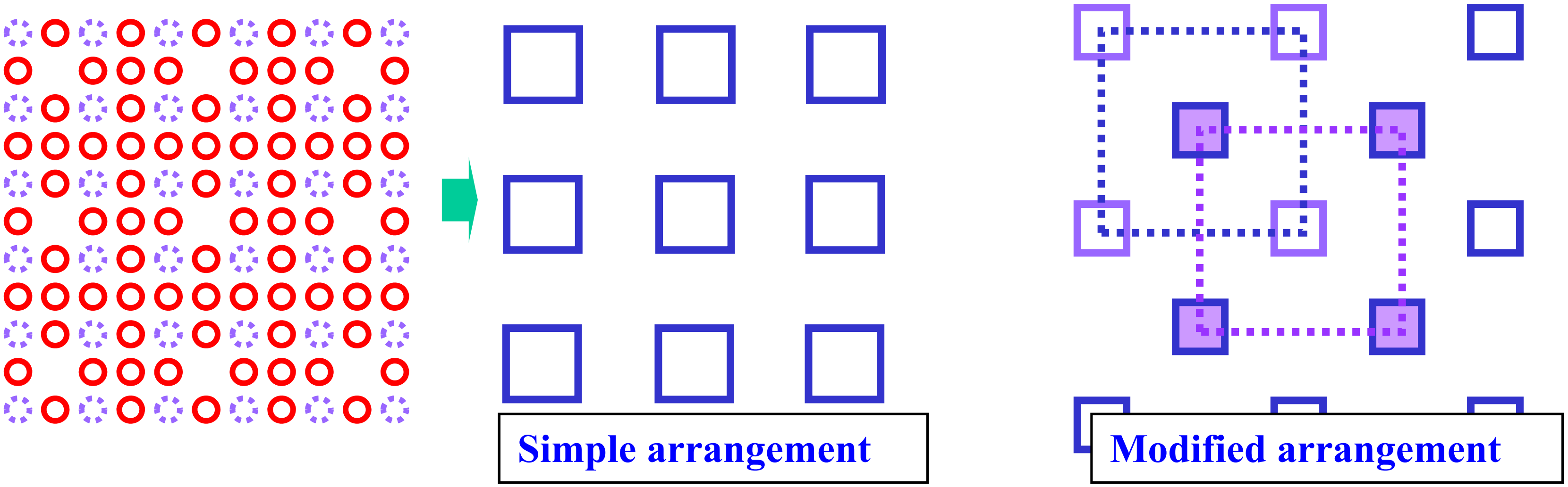
M. F. Yanik and S. Fan, *Phys. Rev. Lett.*, 92, 083901, 2004.







Coupled photonic crystal resonator array (CPCRA)



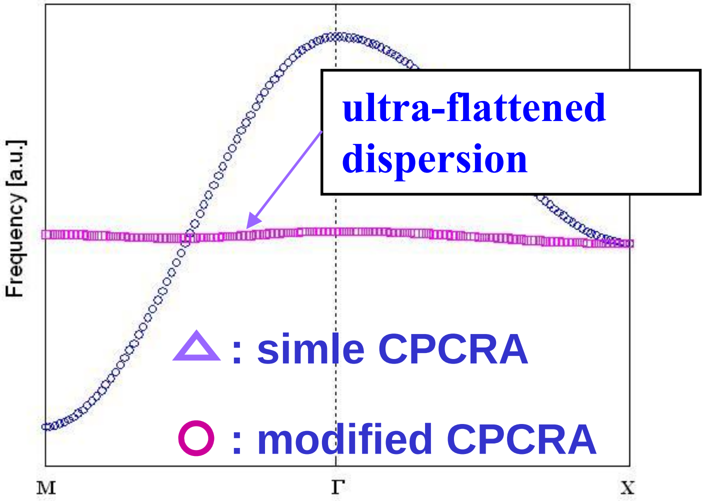
Simple arrangement

Modified arrangement

$$\omega_k^l \cong \Omega_l[1-\frac{\Delta\alpha^{l,l}}{2}+ \kappa_{1,0}^l\cos Rk_x+\kappa_{0,1}^l\cos Rk_z+\kappa_{1,1}^l\cos R(k_x+k_z)+\kappa_{1,-1}^l\cos R(k_x-k_z)]$$

$$v_{g,x}=v_{g,z}=-\Omega_l R\kappa_{1,0}^l\sin Rk_x$$

$$v_{g,d}=-\Omega_l\frac{R}{\sqrt{2}}[\kappa_{1,0}^l\sin Rk_x+\kappa_{0,1}^l\sin Rk_z]\approx-\Omega_l\sqrt{2}R\kappa_{1,0}^l\sin Rk_x$$

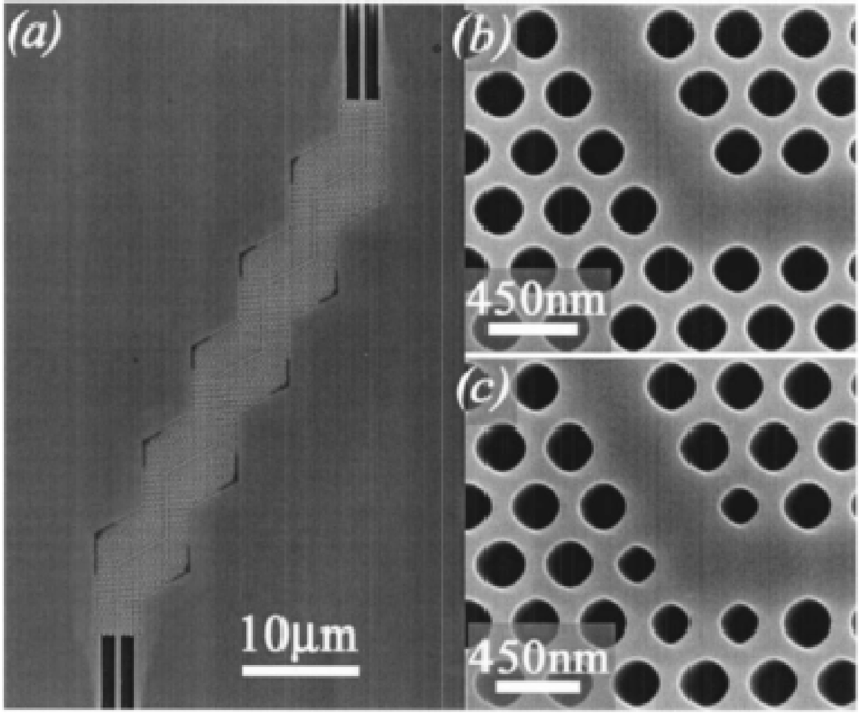


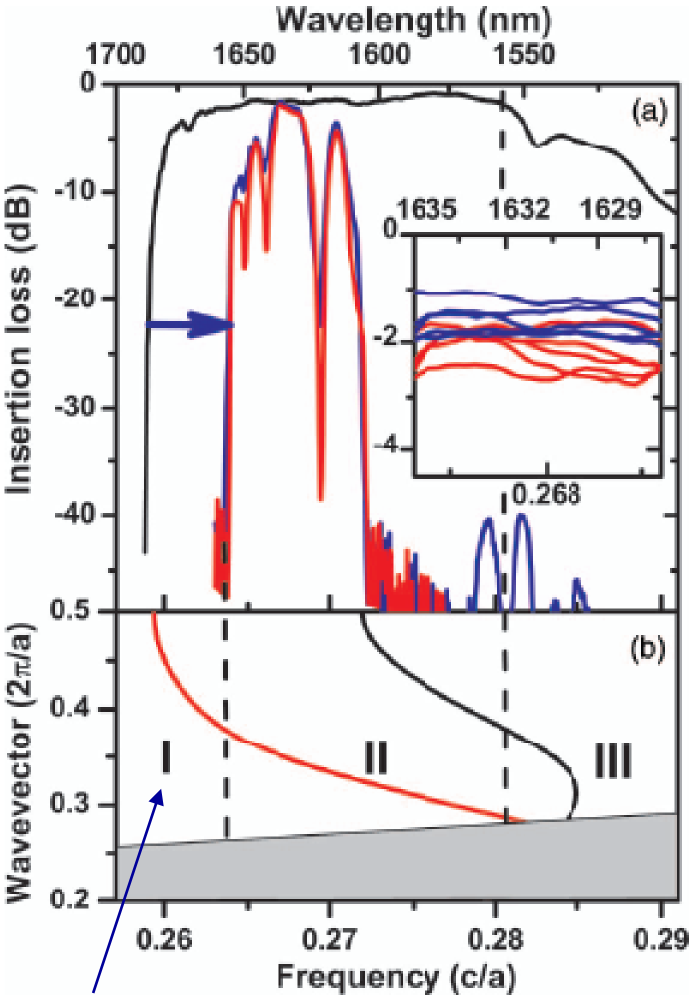
ultra-flattened dispersion

Slow & stopping light

Transmission of slow light through photonic crystal waveguide bends

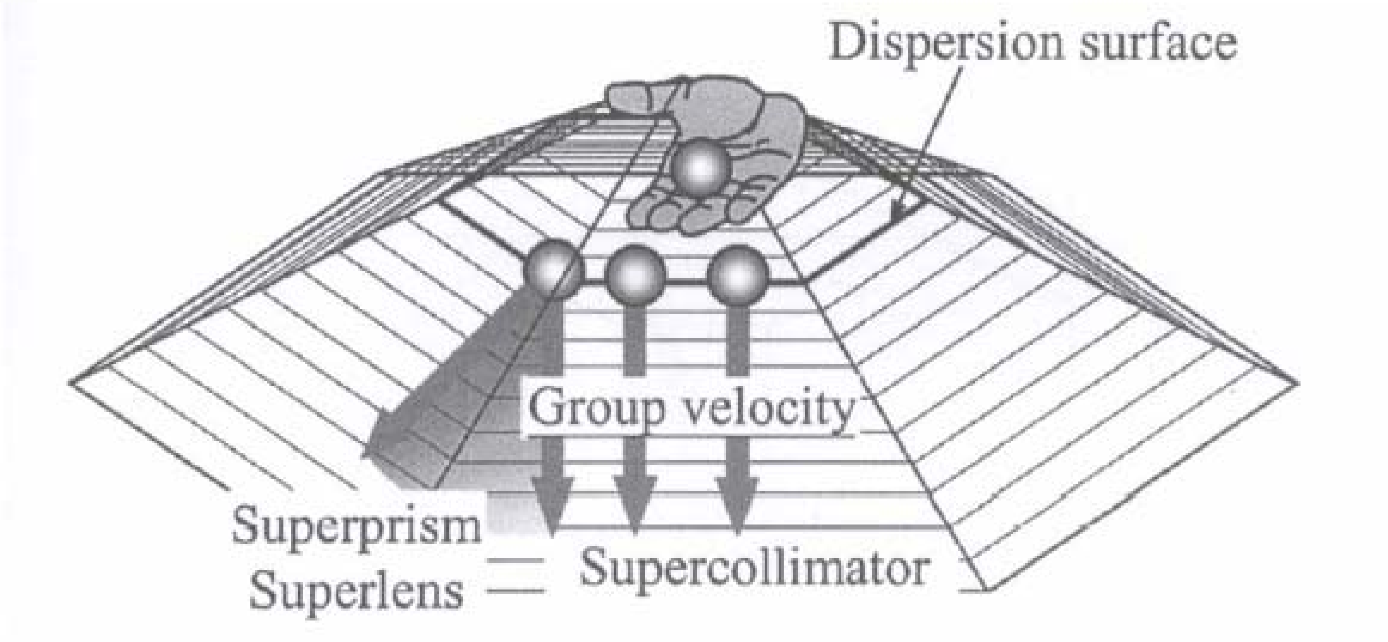
S. Assefa *et al*., *Opt. Lett*., 31 (6), pp. 745-747, 2006.





slow light regime

Dispersion surface



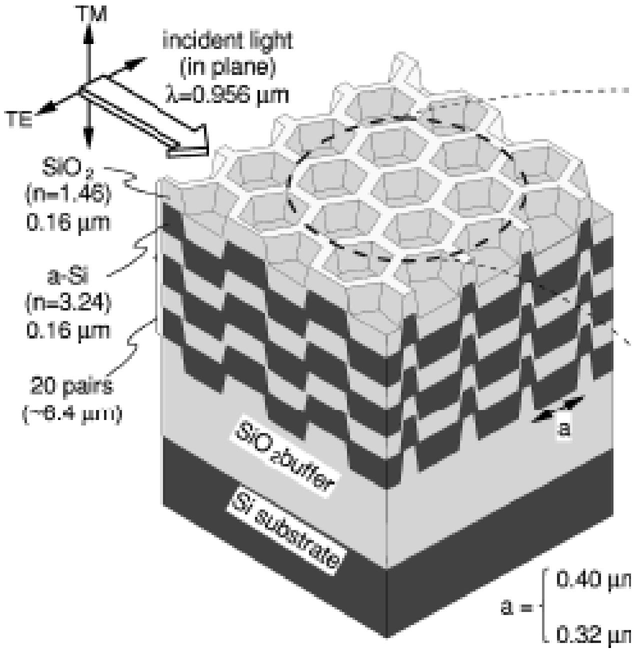
Energy propagation

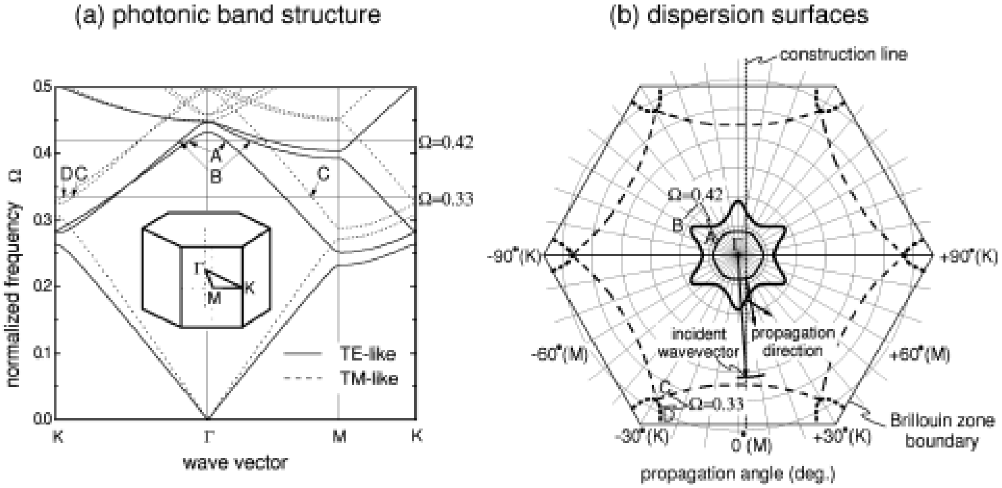
$$v_g = \partial\omega / \partial\vec{k}$$

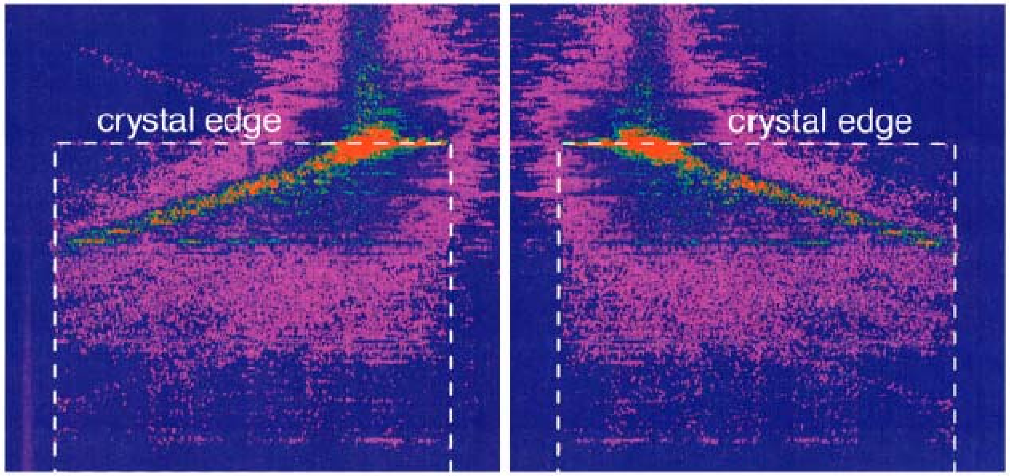
Superprism effect of photonic crystal

Superprism phenomena in photonic crystals

H. Kosaka *et al.*, *Phys. Rev. B*, 58 (16), R10096, 1998.



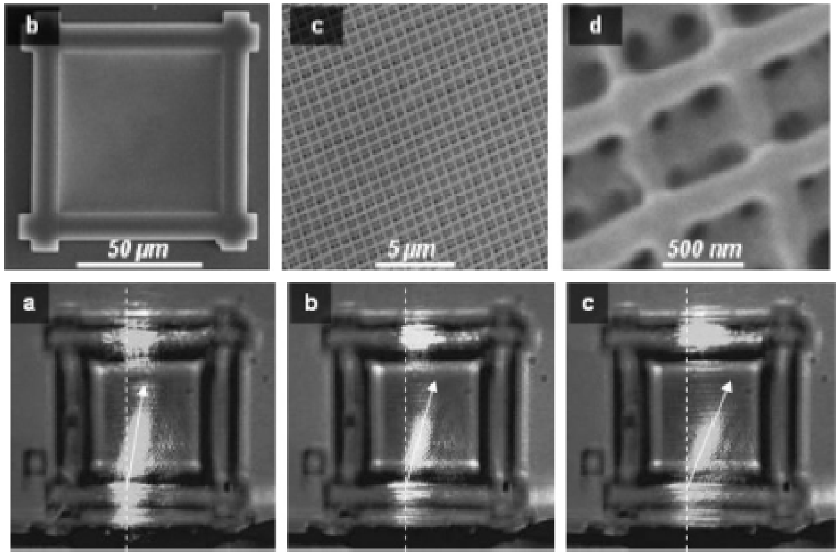


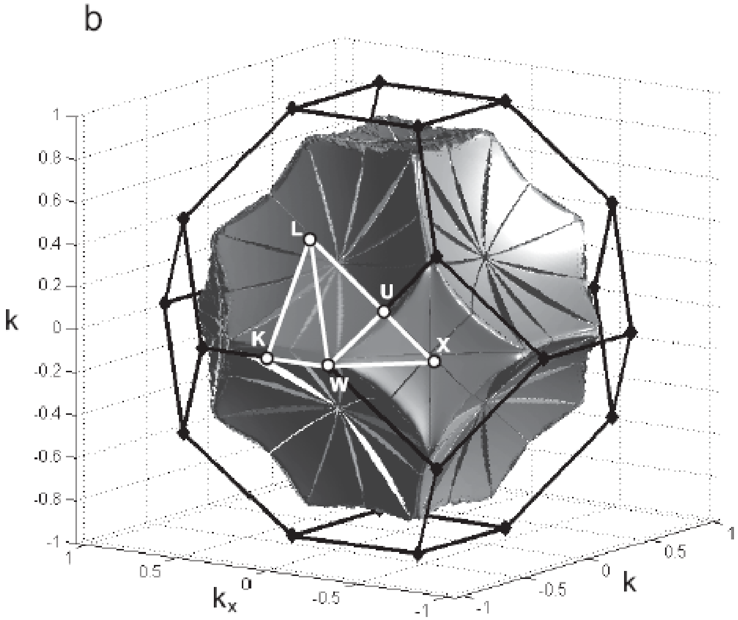


Polymeric superprism

Experimental evidence for superprism effects in three-dimensional polymer photonic crystals

J. Serbin and M. Gu, *Adv. Materals*., 18, pp. 221-224, 2006.

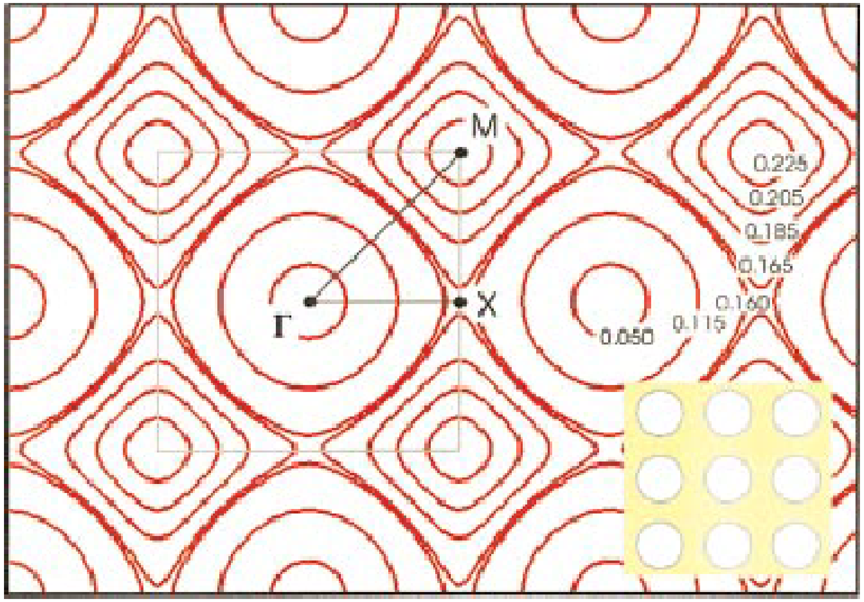




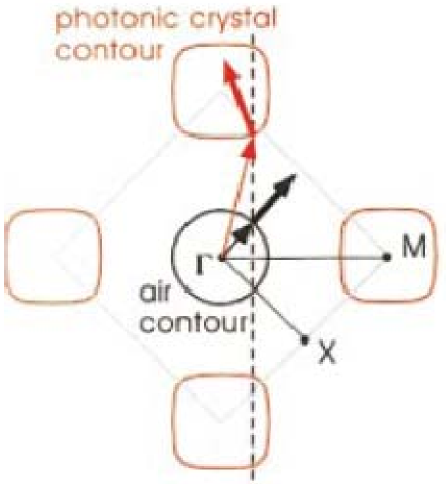
All-angle negative refraction

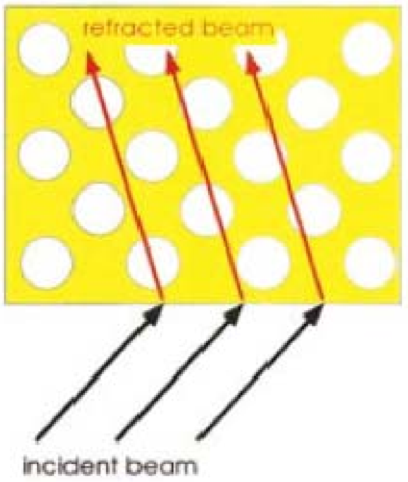
All-angle negative refraction without negative effective index

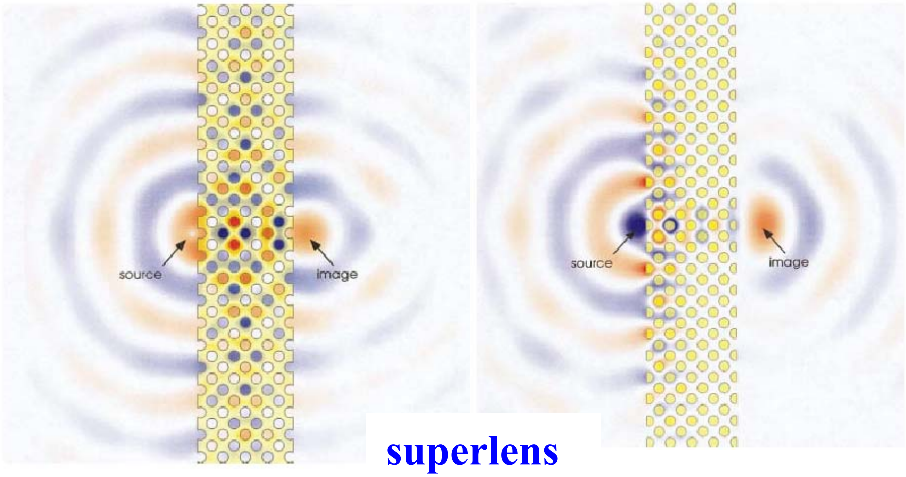
C. Luo *et al*., *Phys. Rev. B*, vol. 65, 201104, 2002.



$\partial^2 \omega / \partial k_i \partial k_j$

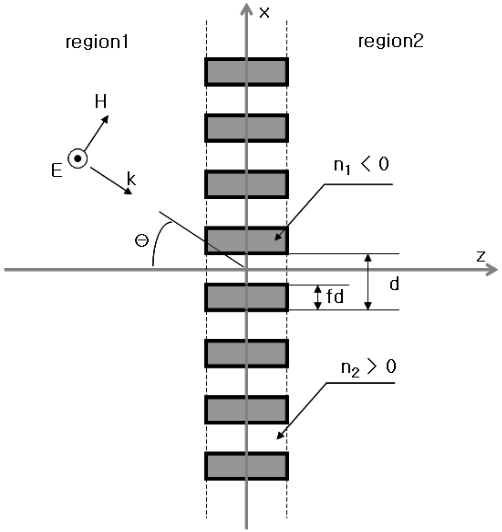


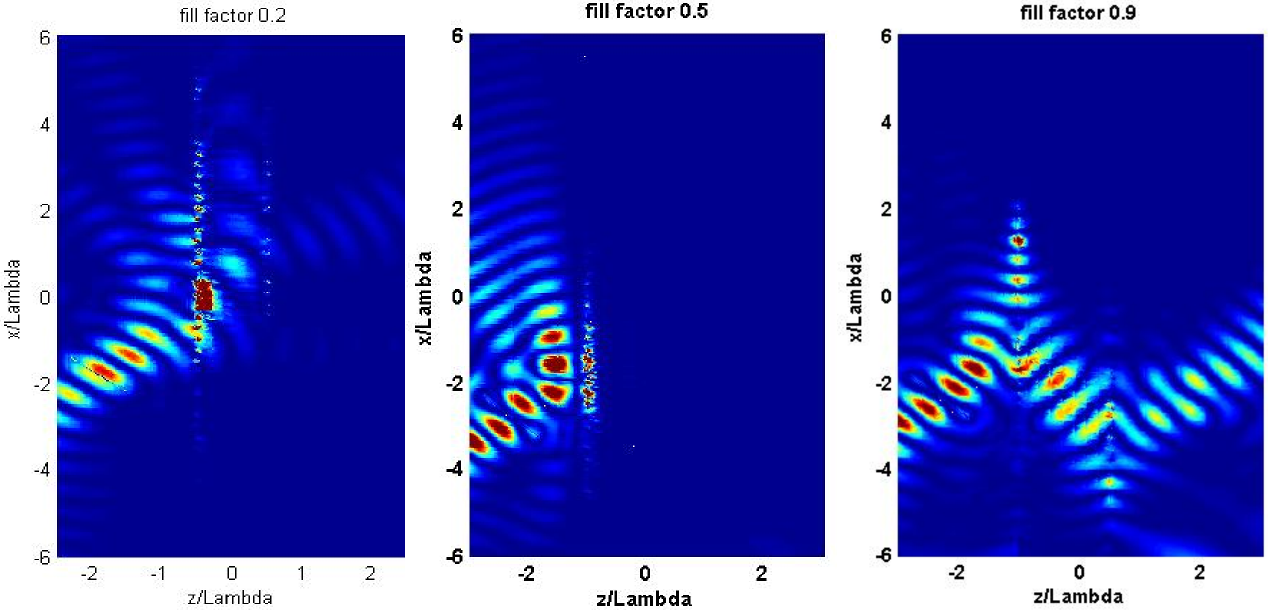




superlens

Negative refraction in meta-material





Positive (below 1)

Zero

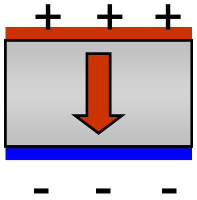
Negative

$$\cos(\alpha_0 d) = \cos[\gamma_1 (1-f)d]\cos[\gamma_2 fd] + \frac{1}{2}\left(\frac{\sigma_2\gamma_1}{\sigma_1\gamma_2} + \frac{\sigma_1\gamma_2}{\sigma_2\gamma_1}\right)\sin[\gamma_1(1-f)d]\sin[\gamma_2 fd]$$

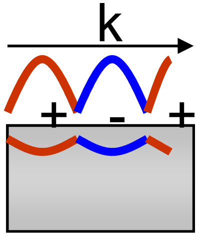
Surface plasmon polaritons

What is a plasmon?

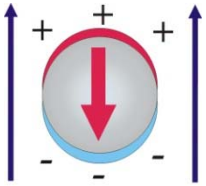
- “Plasma-oscillation”: density fluctuation of free electrons



Bulk plasmon



Surface plasmon



Confined plasmon in nanoparticle

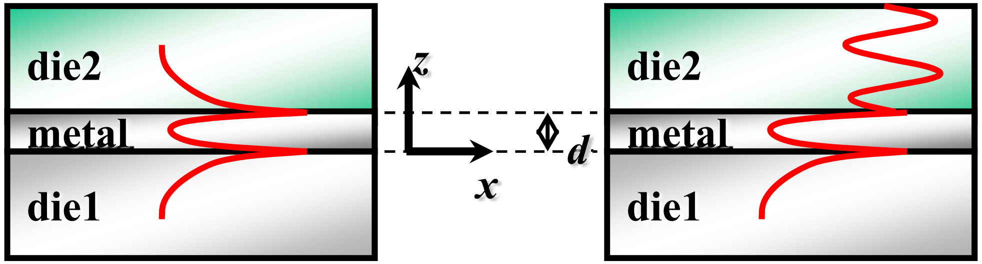
The Lycurgus Cup (glass)
British Museum
4th century A.D.

Green when illuminated from outside and red when illuminated from within the cup due to very small amounts of gold powder about 40 parts per million)

“Labors of the Months”
Norwich, England
ca. 1480

The ruby color is attributed to gold nanoparticles.

Dispersion relation of surface plasmon polariton



bound mode **radiation mode**

- Dispersion of SP

$$k_{SP} = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}$$

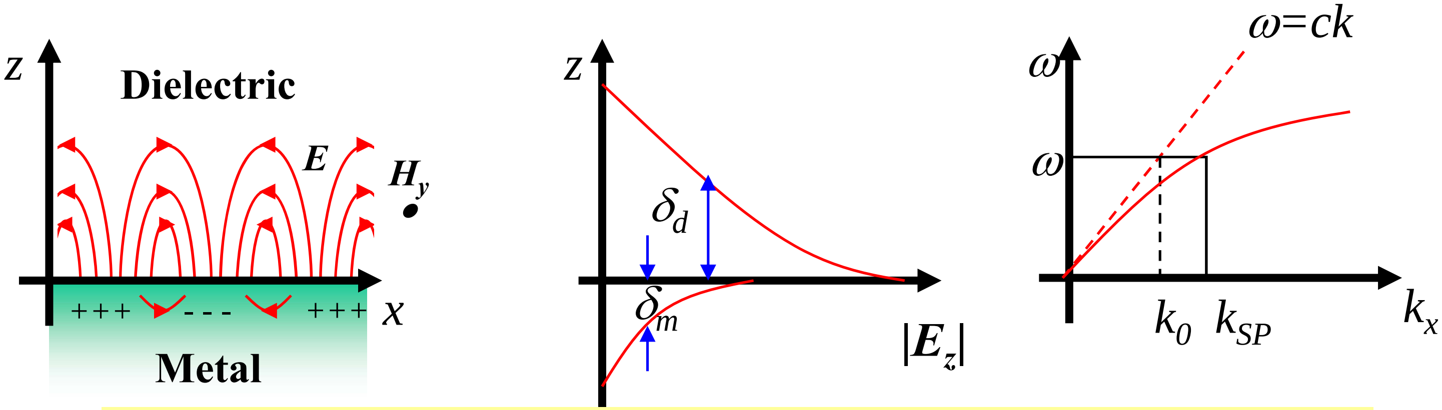
ex) for silver-air interface, $k_{sp} = 1.03k_o$

- Propagation length, δ_{SP}

$$\delta_{SP} = \frac{1}{2k''_{SP}} = \frac{c}{\omega} \left(\frac{\varepsilon'_m + \varepsilon_d}{\varepsilon'_m \varepsilon_d} \right)^{3/2} \frac{(\varepsilon'_m)^2}{\varepsilon''_m}$$

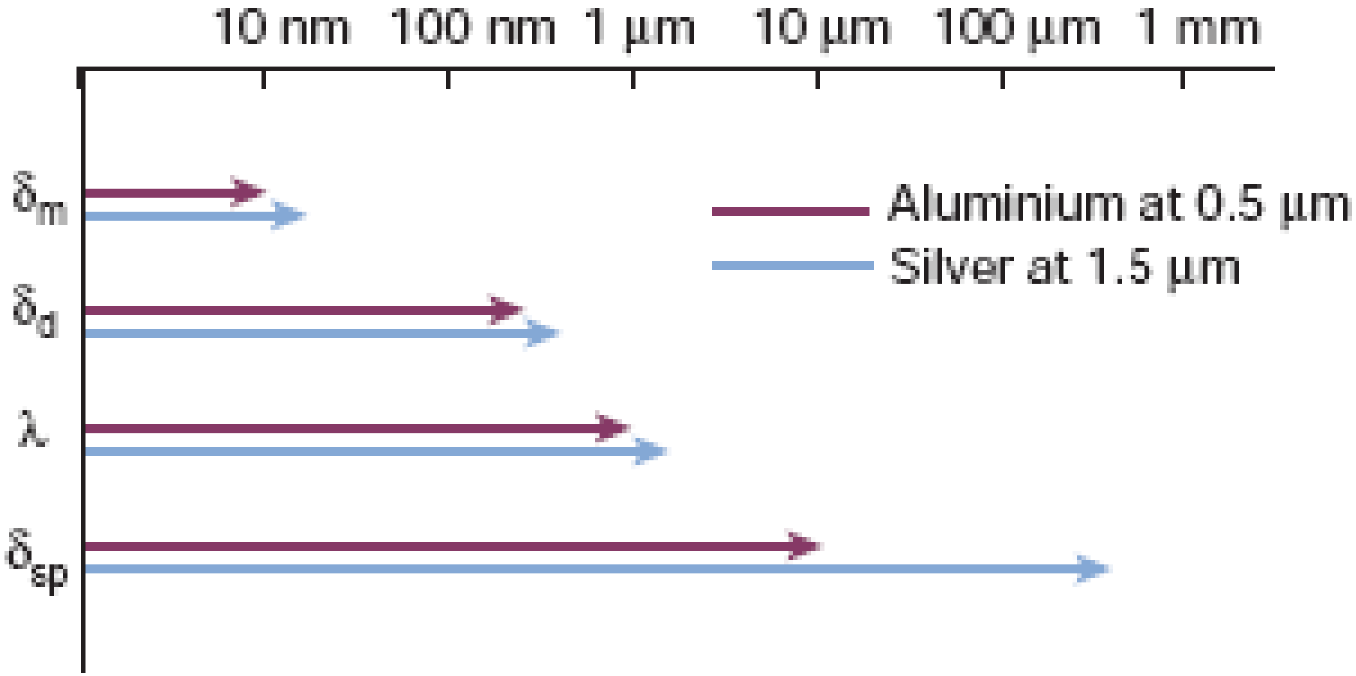
ex) for silver-air interface, $\delta_{SP} = 20\ \mu\text{m}$

$$\left(\frac{\varepsilon_m k_{z1}}{\varepsilon_1 k_{zm}} + 1 \right) \left(\frac{\varepsilon_m k_{z2}}{\varepsilon_2 k_{zm}} + 1 \right) = \left(\frac{\varepsilon_m k_{z1}}{\varepsilon_1 k_{zm}} - 1 \right) \left(\frac{\varepsilon_m k_{z2}}{\varepsilon_2 k_{zm}} - 1 \right) \exp(-2k_{zm} d)$$



Surface charges, evanescent fields, and dispersion curve for SP mode

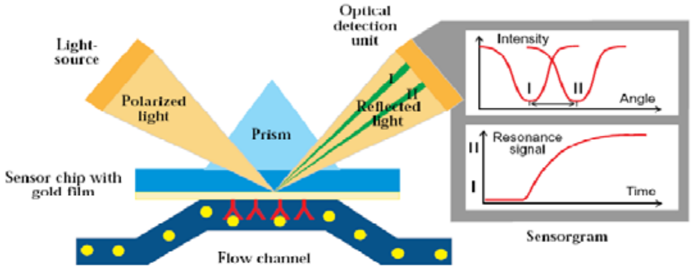
Surface plasmom

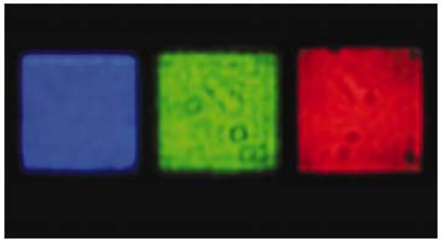


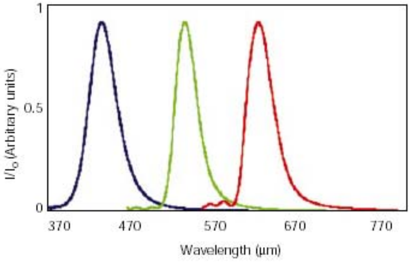
Surface plasmon applications

❑ SPP Applications

- Surface sensitive techniques, SPR microscopy
- SPR technologies and a wide range of photonic ICs.
  - Waveguides of surface plasmons
  - Surface plasmon Bragg reflectors
  - Bio- and flow-sensors using SPR
  - L ht transmission enhancement
  - er beam shaping

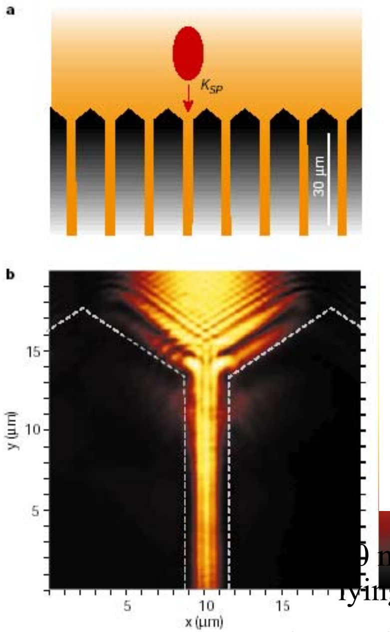


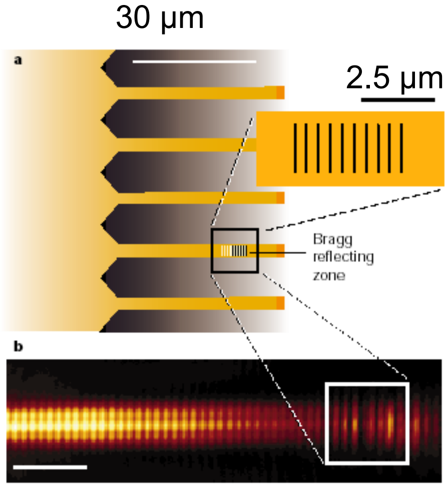




Ag Film with hole arrays
(Period = 300, 450, 550nm
Hole diameter=155,180,225nm)

A. Degiron et al. *Appl. Phys. Lett.* **81,** 4327 (2002).



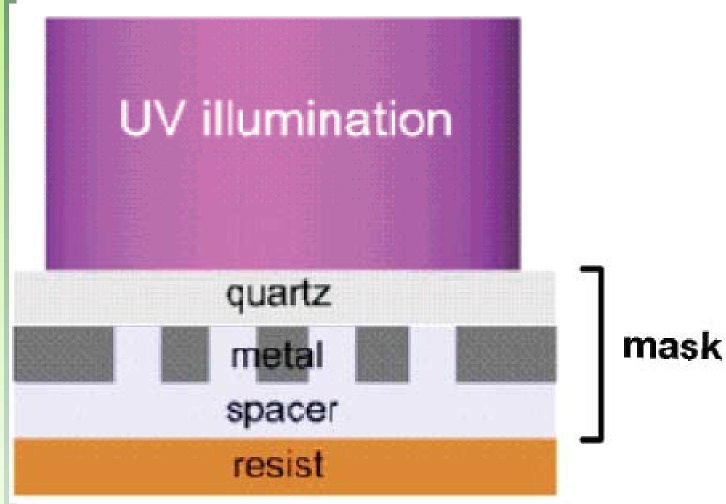


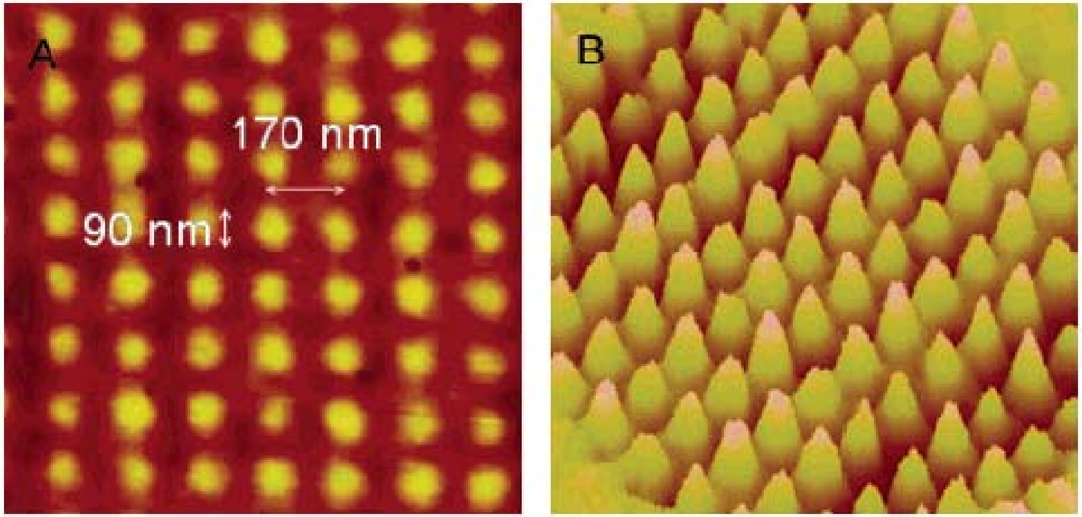
0 nm thick, 2.5 μm wide gold stripe lying on a glass substrate

J. C. Weeber et al., *Phys. Rev. B* **64**, 045411(2001).

Plasmonic nanolithography

W. Srituravanich, N. Fang, C. Sun, Q. Luo, and X. Zhang,
Nano Letters, 4 (6), pp. 1085-1088, 2004.





Metal mask : 90nm holes, 170nm period

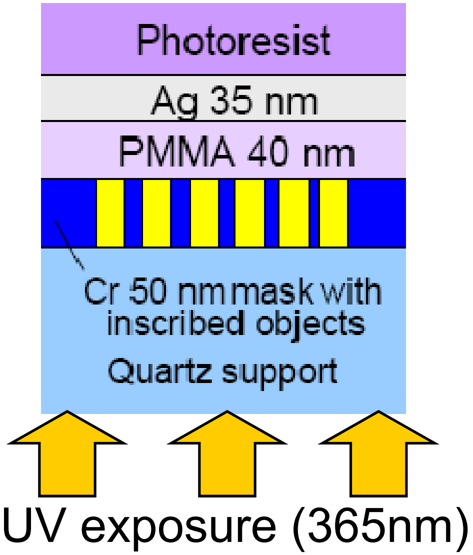
Surface plasmons

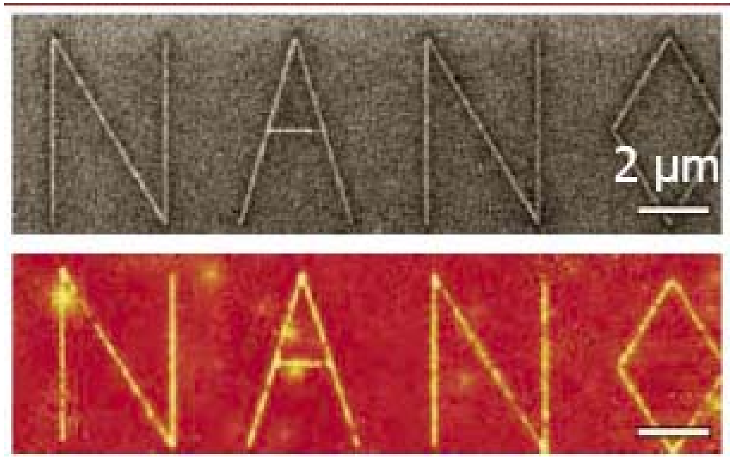
1. Much shorter wavelength compared to the excitation light wavelength
2. E-field intensity of surface plasmons can be boosted by several orders of magnitude compared to the excitation light

Resonant surface plasmon couplings (SuperLens)

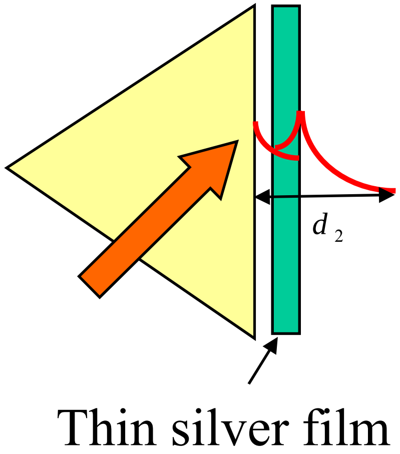
Superlens-based nanopatterning

- A flat plane of NRM behaves as superlens and amplifies evanescent waves in near-field through a series of plasmon resonances.
- This allows super-resolutions below diffraction limit.
- Experimentally achieved improvements in UV range: 5-10x beyond the operating wavelength
- Applicable for direct imaging of evanescent modes, thus for immediate recognition of analytes
- Also applicable for nanopatterning through subwavelength contact lithography





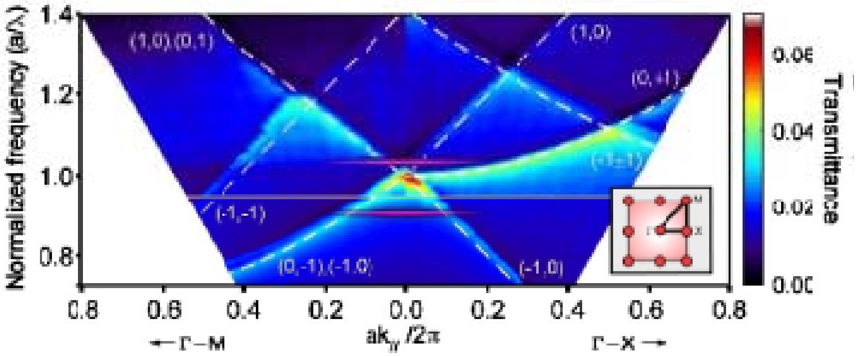
X. Zhang (UC Berkeley)



Femto-second surface plasmon

Propagation of femtosecond surface plasmon polariton pulses on the surface of a nanostructured metallic film, space-time complex amplitude characterization

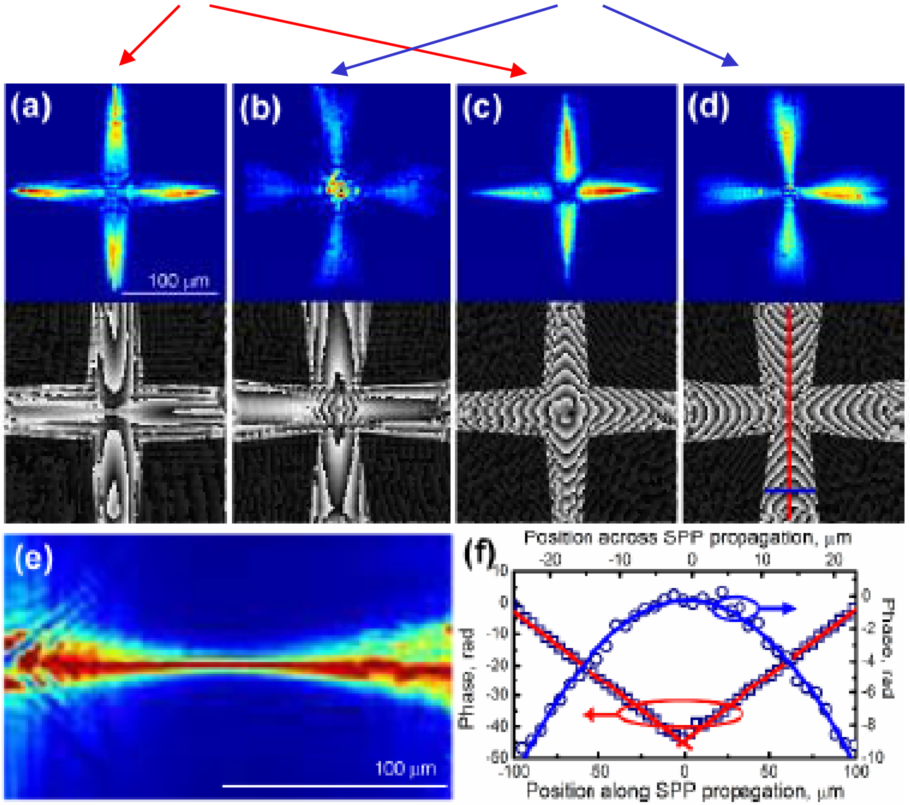
R. Rokitski *et al*., *Phys. Rev. Lett*., 95, 177401, 2005.



transmittance from nanohole array

converging

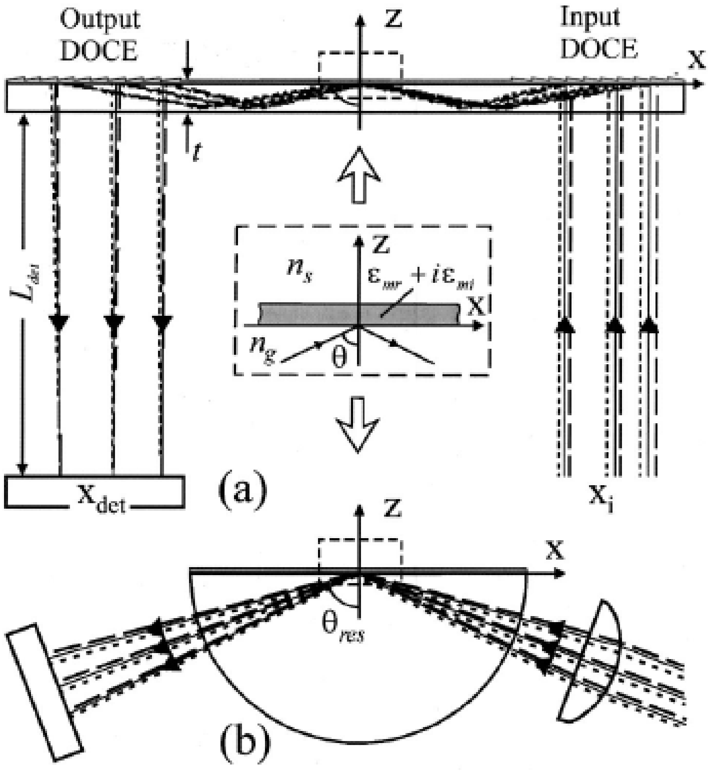
diverging

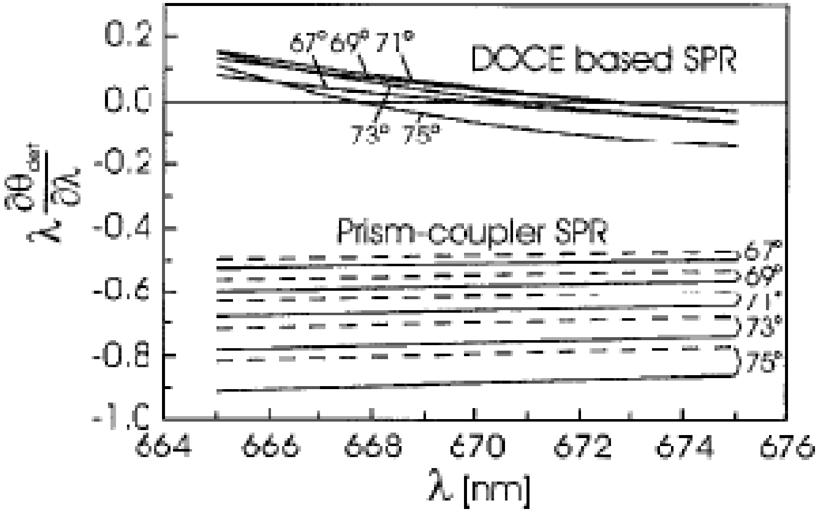


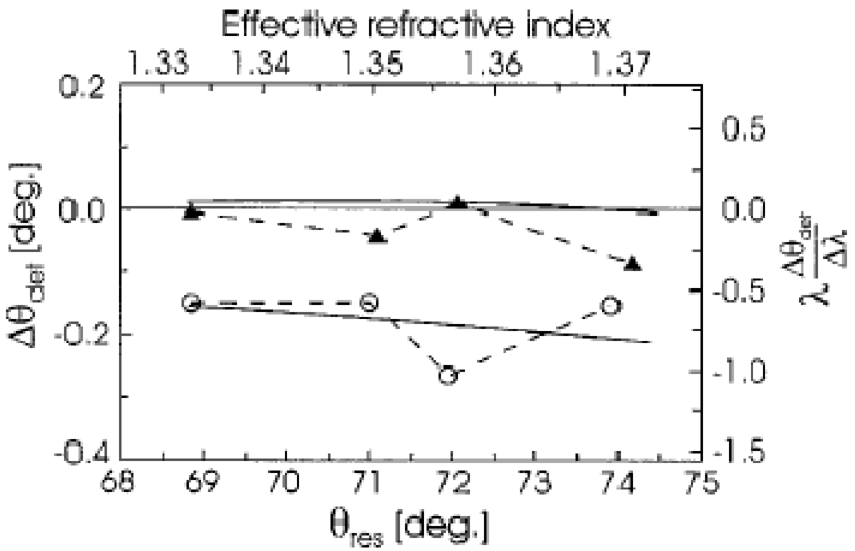
Surface plasmon biosensor

Optical biosensor with dispersion compensation

W. Zong *et al*., *Opt. Lett*., 30 (10), pp. 1138-1140, 2005.





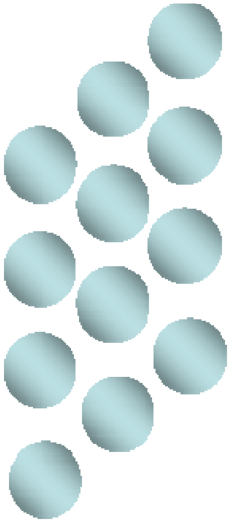


Comparison of simulation methods

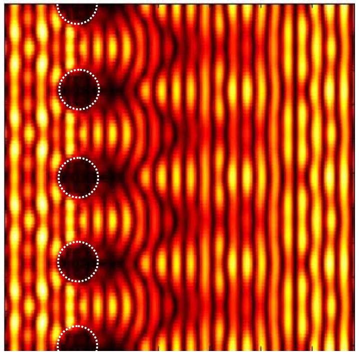
	FDTD	RCWA	PFMA
Domain	Space	Frequency	Frequency
Field representation	Finite-difference method	Piles of truncated 2D-pseudo-Fourier series	Truncated 3D-pseudo-Fourier series
Structure modeling	Mesh-structure	Staircase approximation & piles of 2D-Fourier series	3D-Fourier series (no staircase approximation)
Aperiodic structure Analysis	Yes	No (If using PML, yes)	No (If using PML, yes)
Evanescent field analysis	No (Cannot separate)	Yes	Yes
Modal analysis	No	No	Yes
Computation cost	Very huge	Large	Huge

RCWA examples

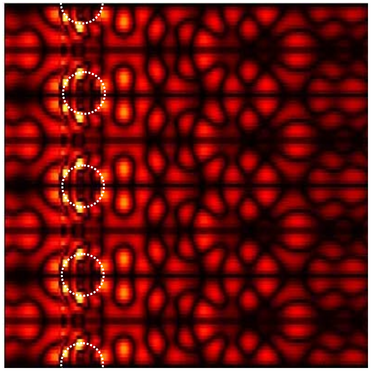
3D micro-metal-sphere structure (15 level staircase approximation)



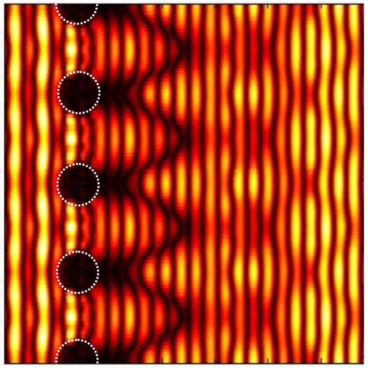
E_x

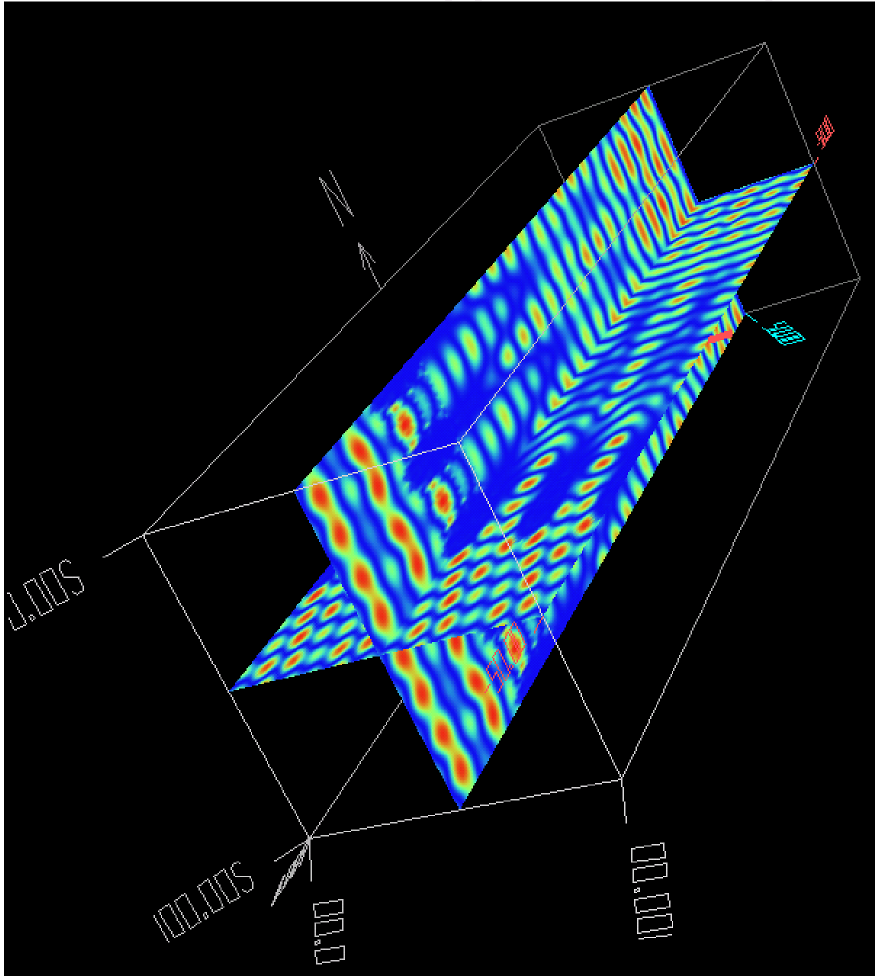


E_z



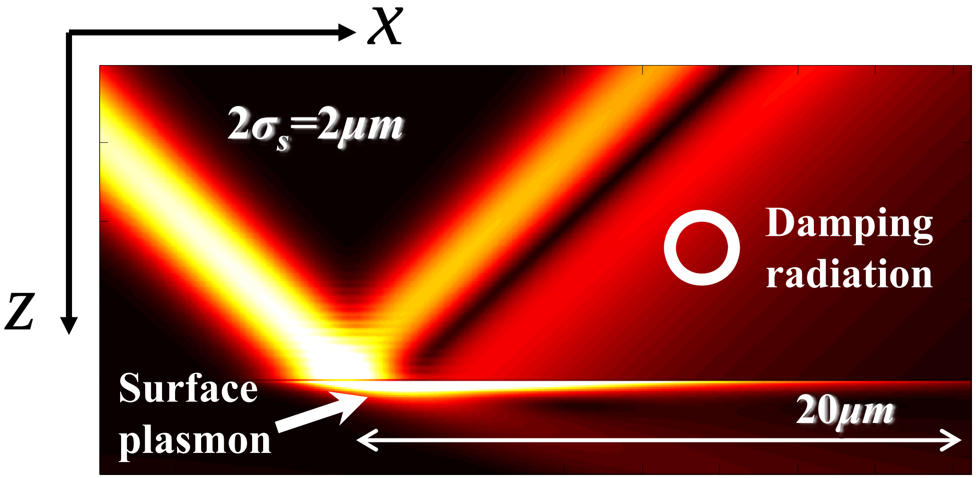
E_y



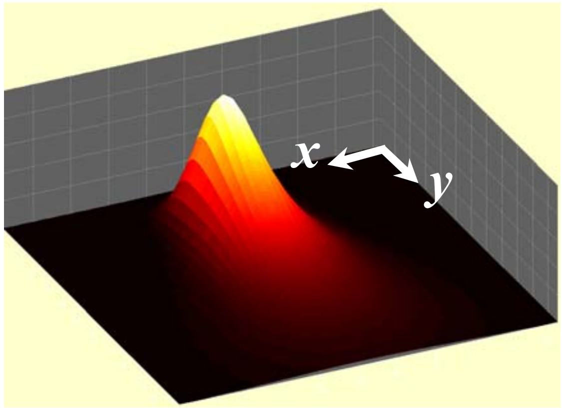


Surface plasmon excitation

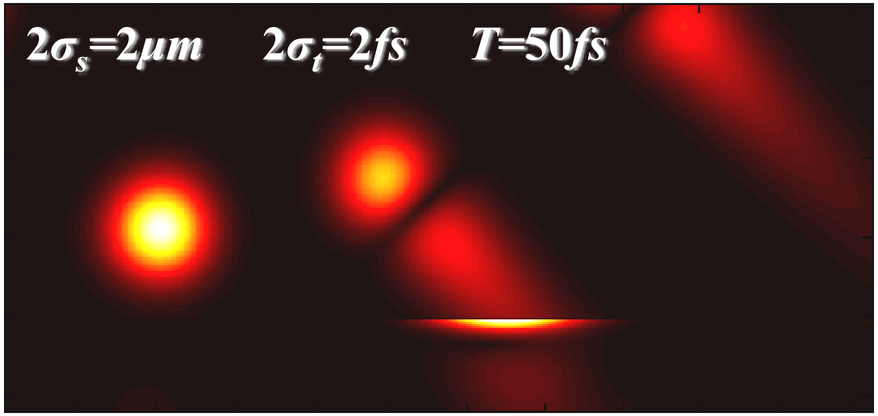
Finite metal slab structure



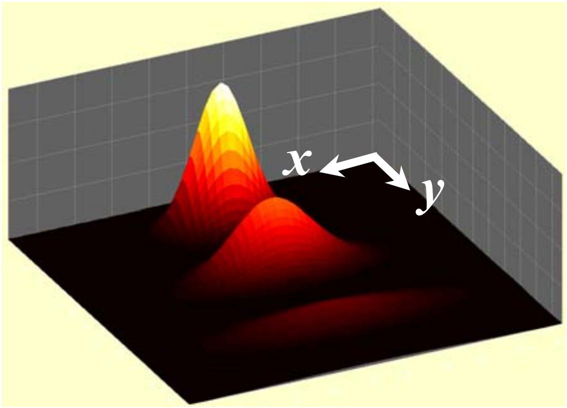
Surface plasmon excited by Gaussian beam



At metal surface

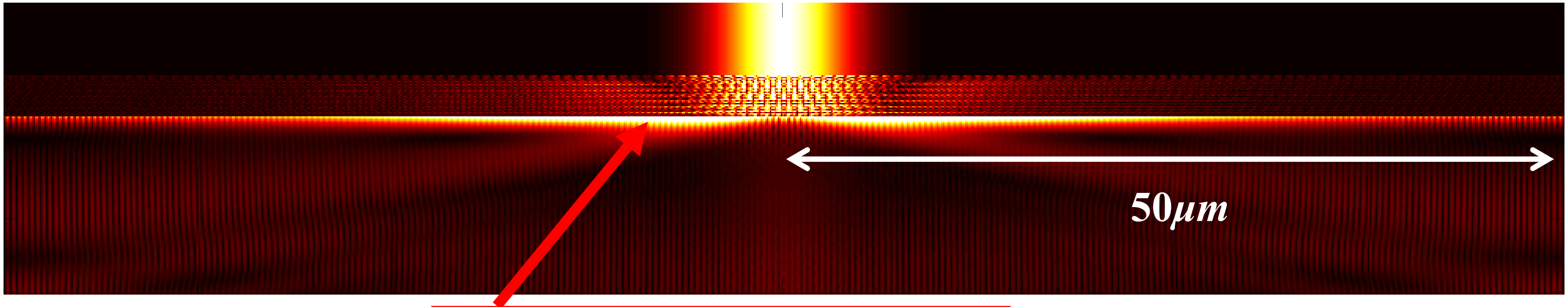


Surface plasmon excited by Gaussian pulse beam

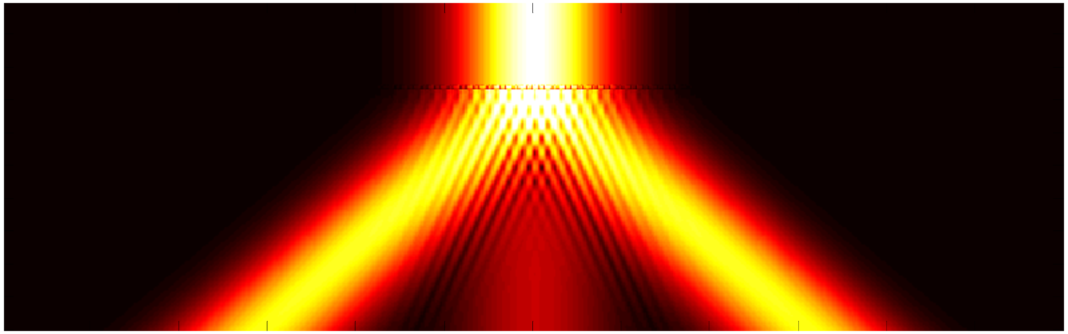


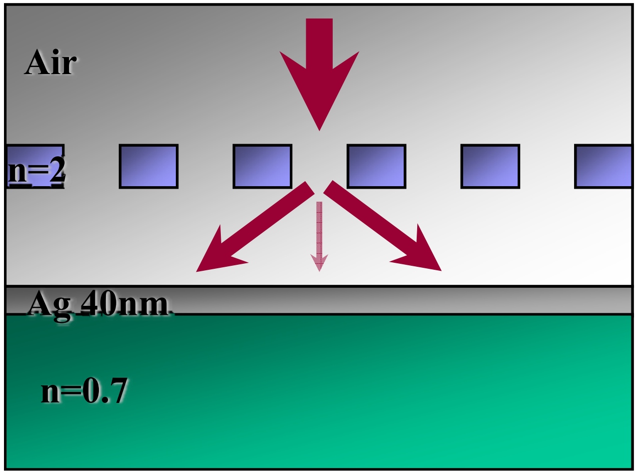
At metal surface

Surface plasmon excitation by grating coupler



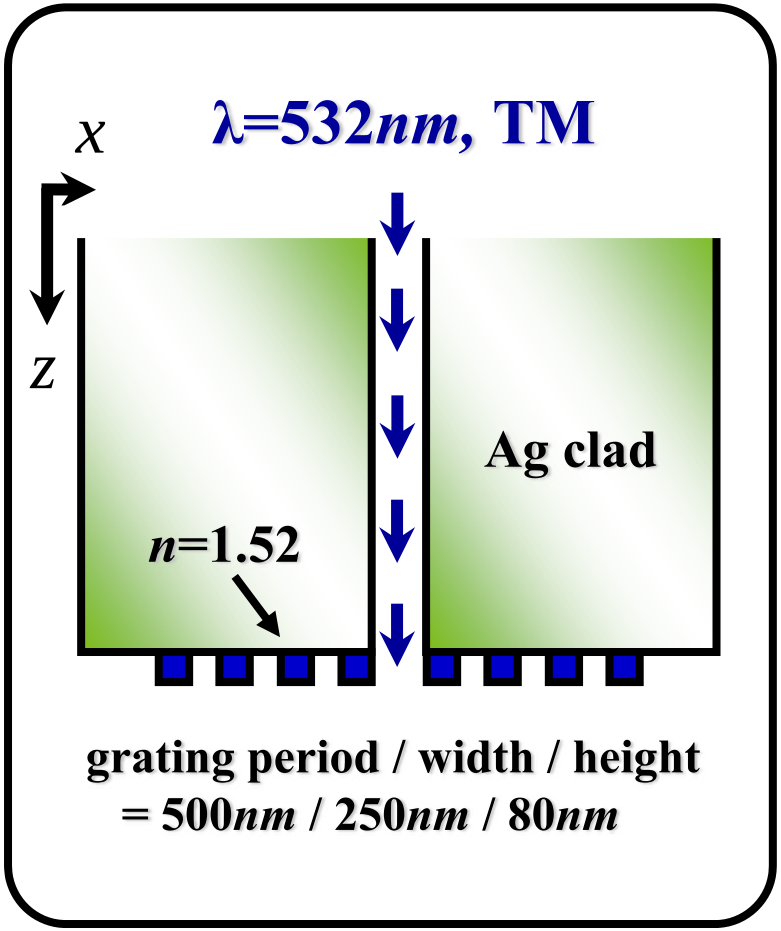
Regenerated surface plasmon



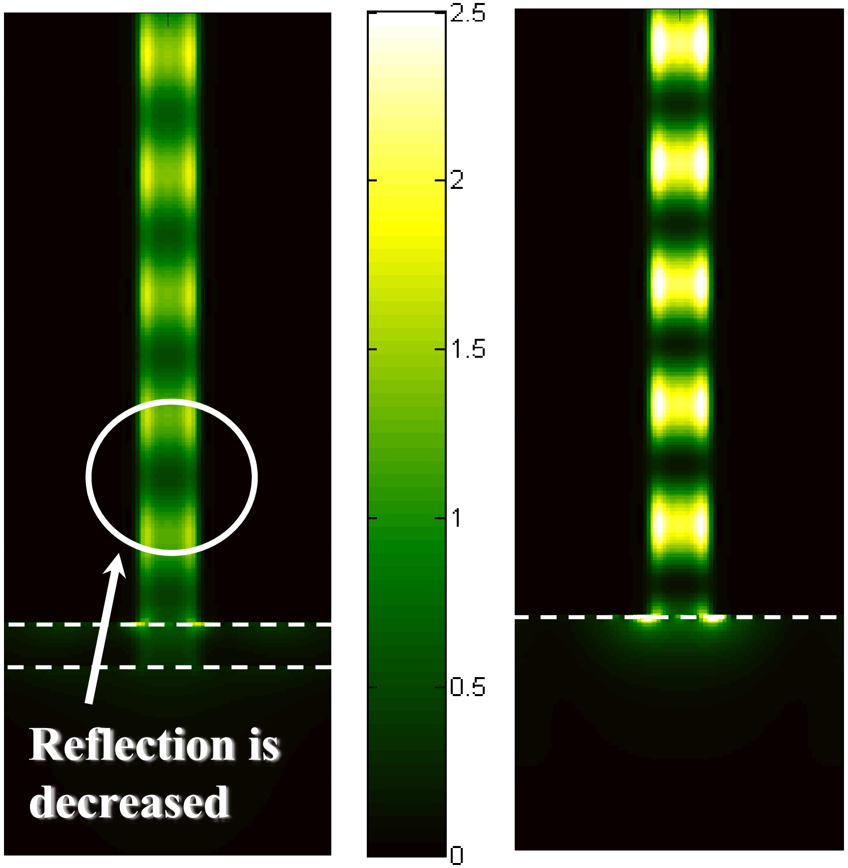


Metal-gap waveguide

Metal-gap waveguide with bottom surface grating



grating period / width / height
= 500*nm* / 250*nm* / 80*nm*



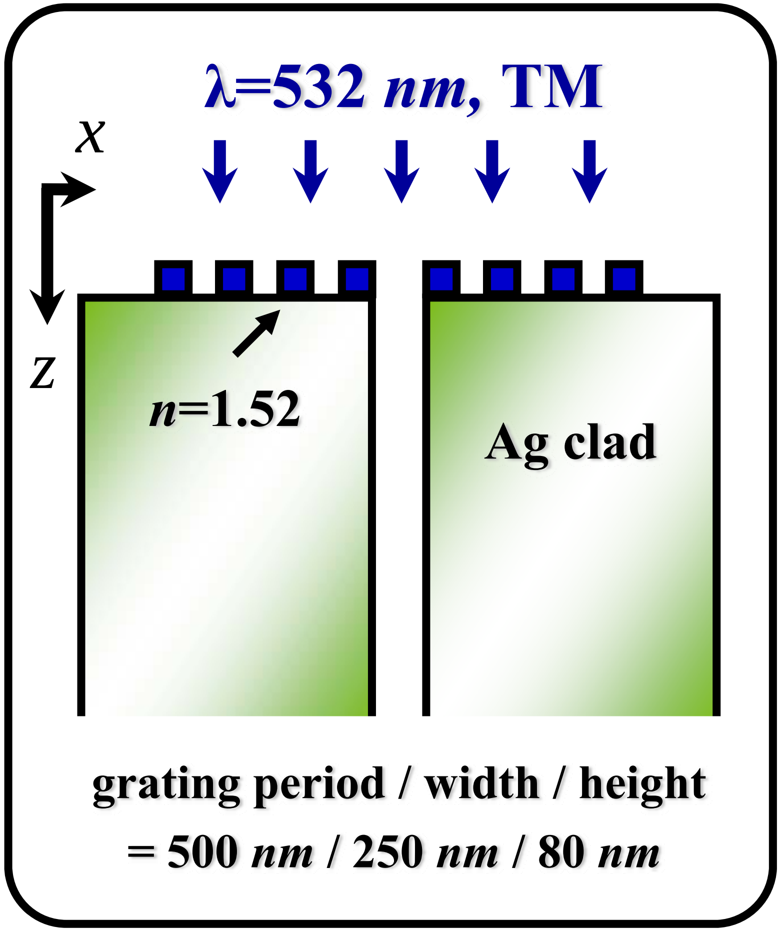
Reflection is decreased

surface grating

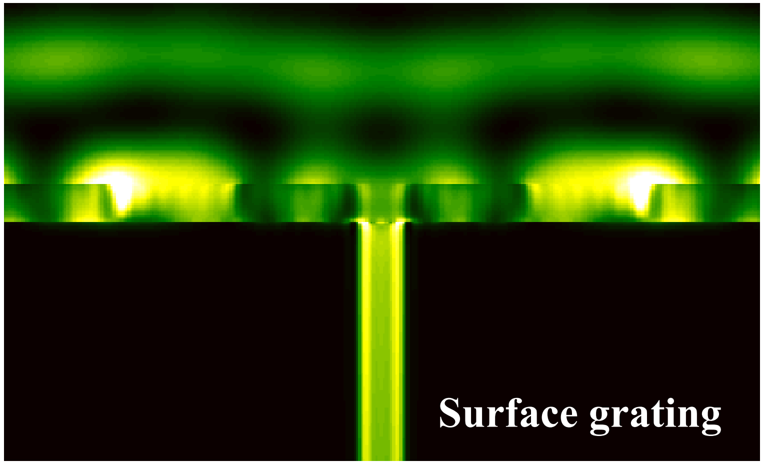
flat surface

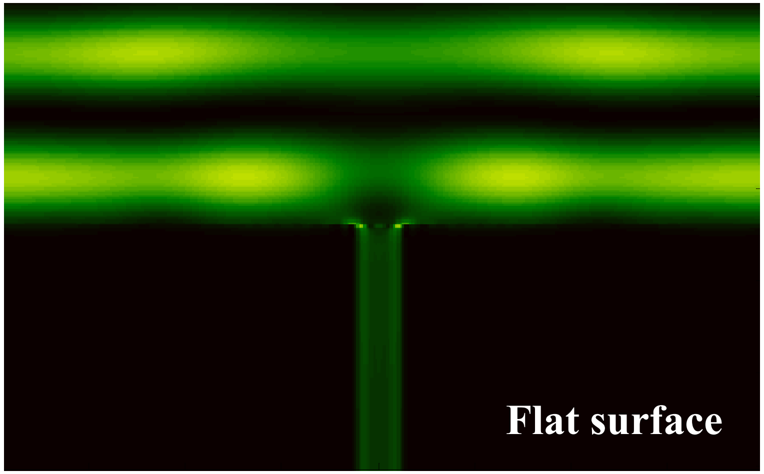
Metal-gap waveguide

Metal-gap waveguide with upper surface grating



grating period / width / height
= 500 *nm* / 250 *nm* / 80 *nm*

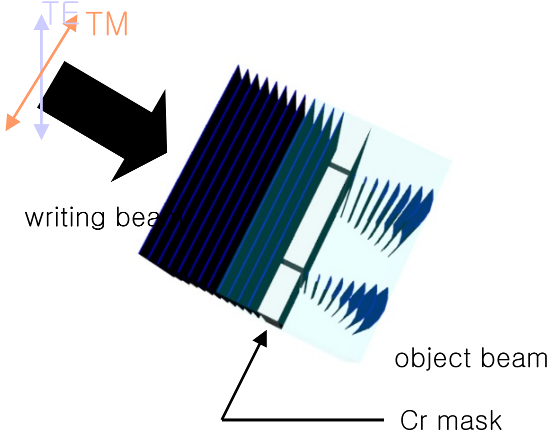

Surface grating

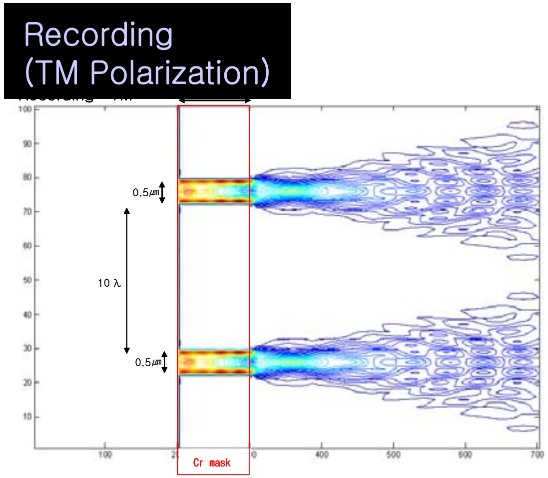

Flat surface

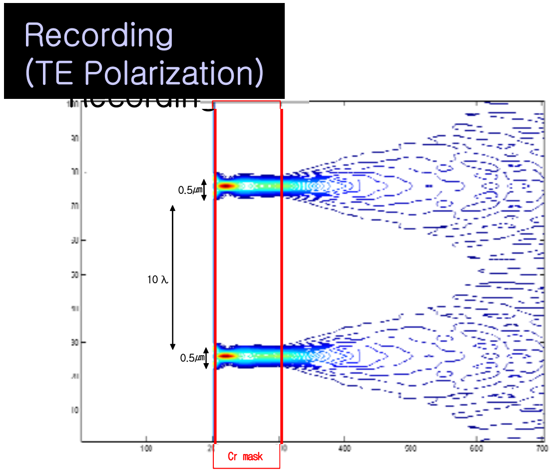
Holographic lithography

- **TIR holography simulation – rigorous electromagnetic analysis**

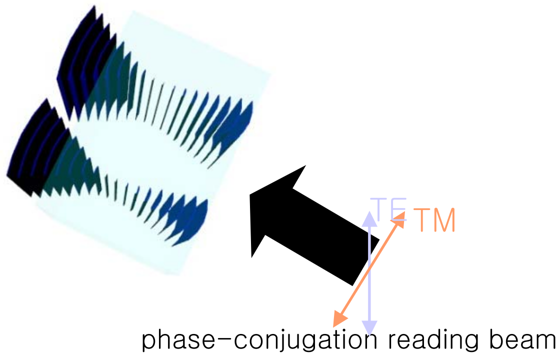
Recording

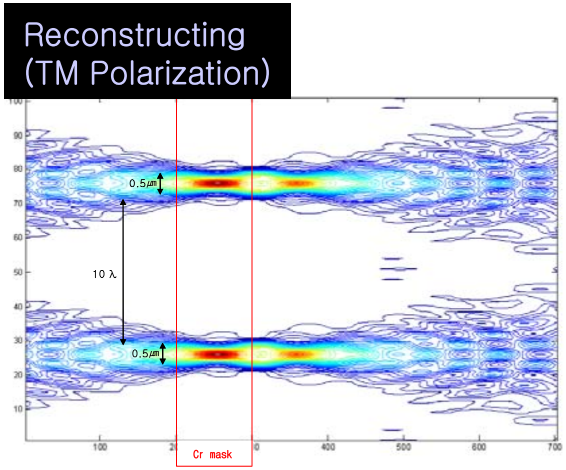


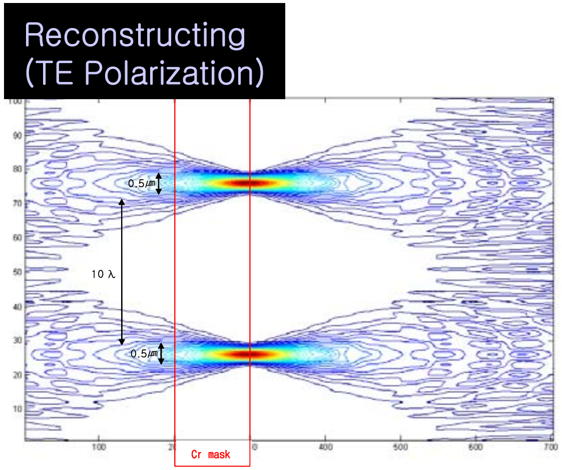

Recording
(TM Polarization)


Recording
(TE Polarization)

Reconstructing

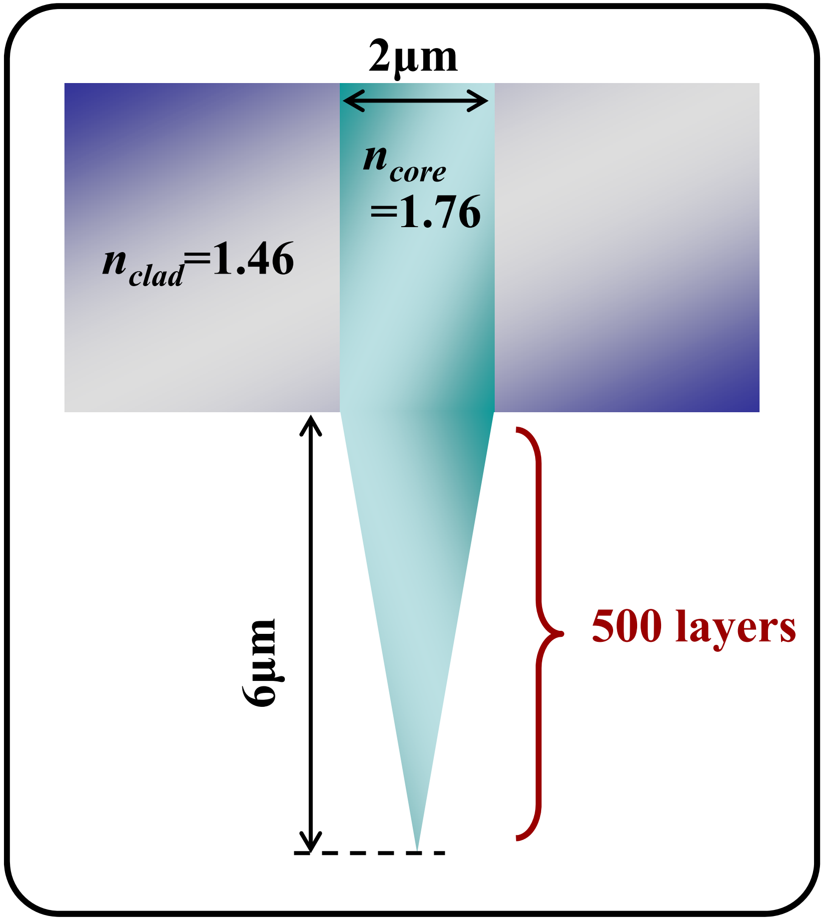


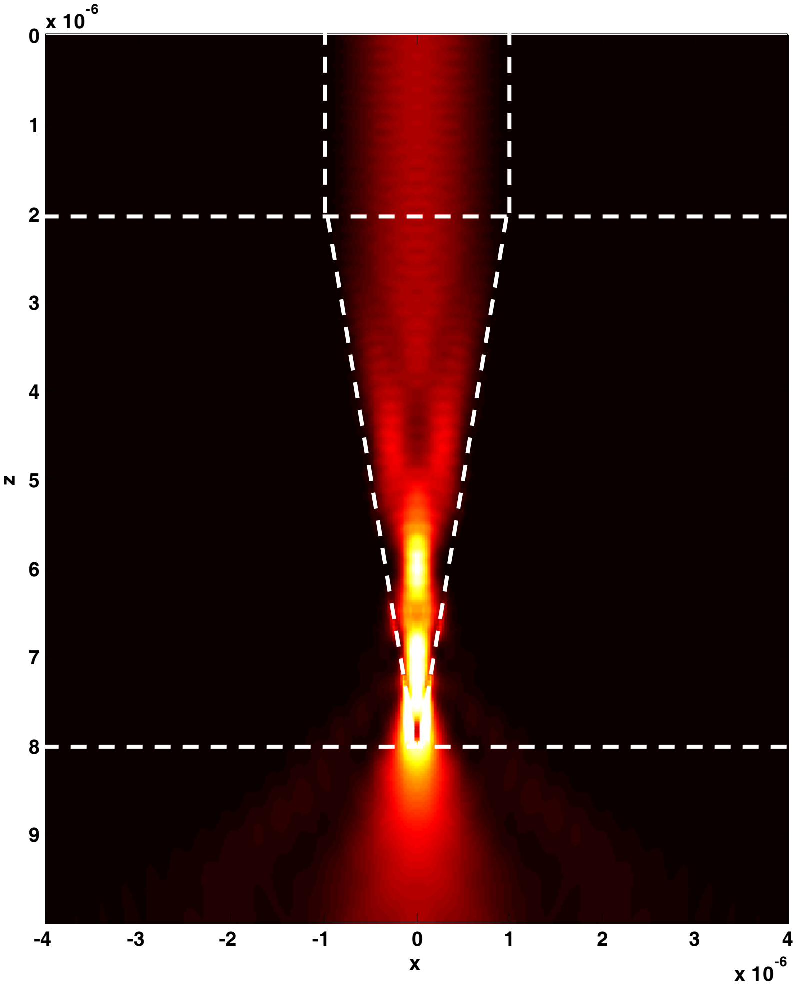

Reconstructing
(TM Polarization)


Reconstructing
(TE Polarization)

RCWA analysis of near field around a tip

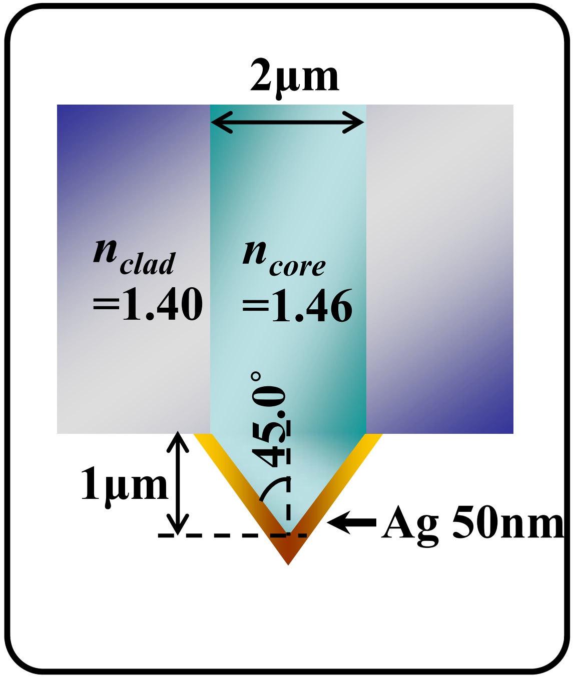
- **Dielectric tip structure**



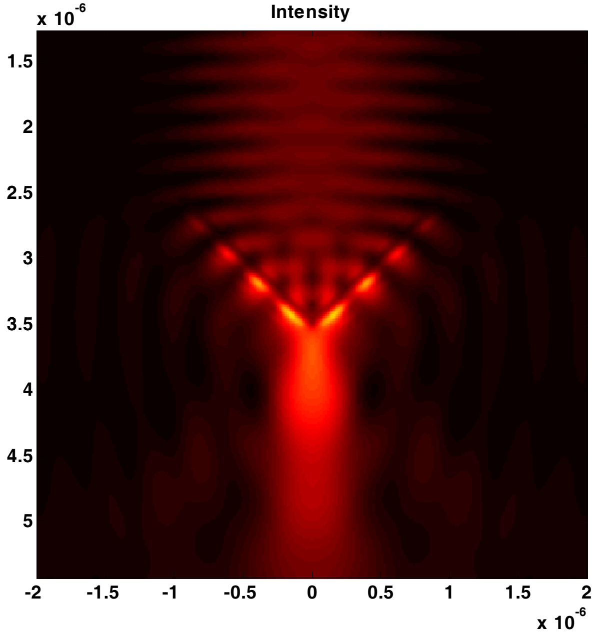


RCWA analysis of near field around a tip

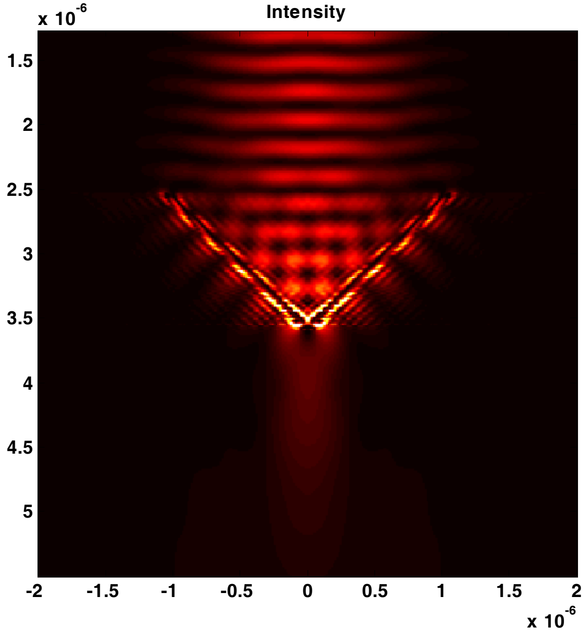
- **Metal coated tip structure**



500 layers staircase approximation



Without metal coating



With metal coating

Perspectives : Plasmonics

❑ **Transistor gate size : ~ 50 nm, Light wavelength: ~1,000 nm**

❑ **Plasmonics? – Surface plasmon-based photonics**

❑ **Challenges (E. Ozbay, Science, vol. 311, pp. 189-193, 2006)**

- **Demonstrate optical frequency subwavelength metallic wired circuits with propagation loss comparable to conventional waveguides**
- **Develop highly efficient plasmonic organic and inorganic LEDs with tunable radiation properties**
- **Achieve active control of plasmonic signals by implementing electro-optic, all-optical, and piezoelectric modulation and gain mechanisms to plasmonic structures**
- **Demonstrate 2D plasmonic optical components, including lenses and grating couplers, that can couple single mode fiber directly to plasmonic circuits**
- **Develop deep subwavelength plasmonic nanotithography over large surfaces**

Concluding remarks

- **Brief review on recent research trends on the dispersion and its compensation**