
NSU / Michigan / Purdue / Cornell
Active and Functional Metamaterials
Meta-PREM
M. A. Noginov
$$$ DMR 1205457
Meta-PREM

Vision:

(1) To become the world's leader in understanding, controlling and utilizing fundamental physical properties of *active* and *hyperbolic* MMs.

(2) Make the Partnership one of the key players in the development of a new generation of scientists and engineers, in particular from underrepresented minority groups, specializing in MMs.

Mission:

(1) Broadening participation of underrepresented minority students in Materials Science and Engineering and enhancing their traineeship and educational experiences,

(2) Creating a world-class research center at NSU.

Graduate Education: strengthen, broaden participation

- 18 Graduate Students in PREM research:
  - 8 Females , 4 African Americans
- Monthly 4-campus group meeting presentations
- 4 NSU student*trip to U. Michigan (fall/spring)
- Summer Plans:
  - 2.5-day Career Prep Workshop @ NSU co-fund, July
    - 35 M.S./Ph.D. MS&E + 25 other STEM M.S. stud.
    - video share with partners
  - Graduate student mentoring skills training

Undergraduate Research & Education: recruit into Mats. Sci., specially AA

- 8 NSU ugrads in PREM research (fall/spring)
  - 4 females, 5 African Americans, 2 Africans
- 11 NSU Summer Ugrad Researchers (2013)
  - 4 females, 6 African Americans, 1 Hispanic
  - 2 Cornell U., 6 NSU, 1 LSU, 1 Savannah St., 1 NCA&T
  - 3 workshops to be vc'ed from U. Michigan
- 400/500 Nanoscience course, fall submission
  - Interdisciplinary, broad, exciting => recruiting.

High School Outreach & Partnership: sustain collaboration, recruit into STEM

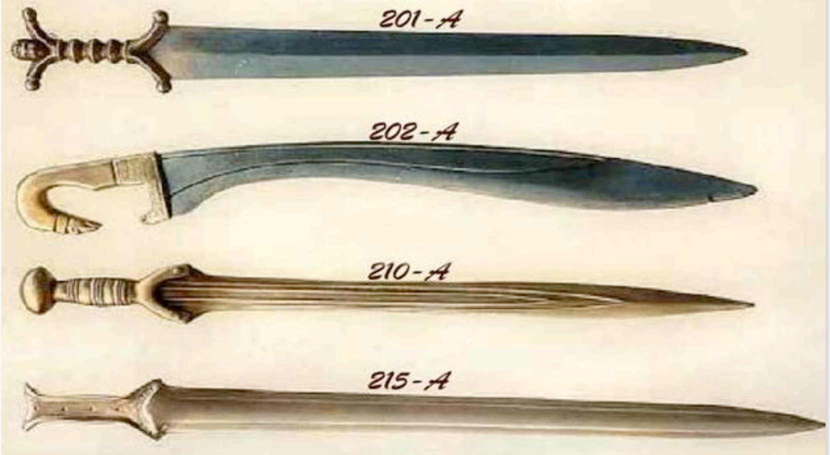
- Targeting 3 local schools:
  - Science and Math Academy – OLHS
  - International Baccalaureate – PAHS
  - Urban, disadvantaged, AA-serving – BTWHS

- Activities:
  - Fall Materials Science Day @ NSU (Dec. 2012, 35 s/t)
  - Spring Materials Science Day @ HS (May 2013, 40 st.)
  - Paid summer Research Program (4 weeks, 5 students)

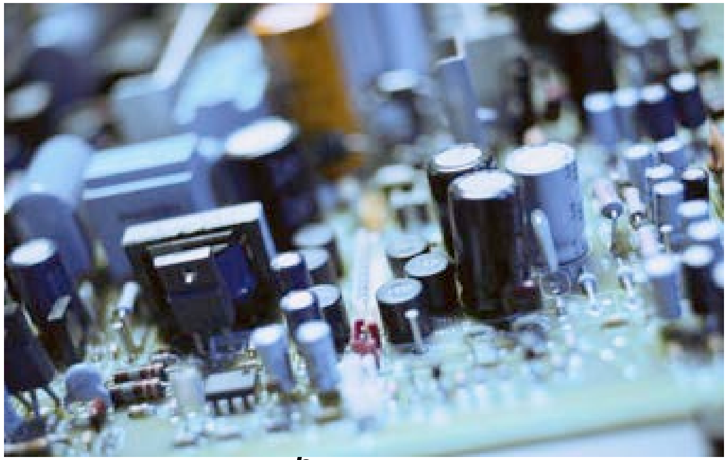
- Broader Outreach:
  - Nanomaterials seminar @ HS (120 students+parents)
  - U.S. Natl. Chemistry Olympiad (35 students, 9 schools)

Materials determine technological development of the civilization

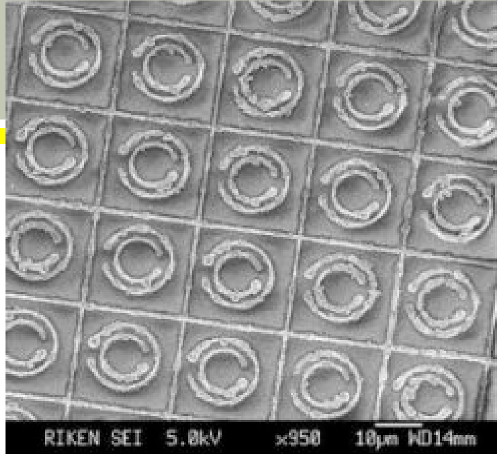
Stone Age



Bronze Age

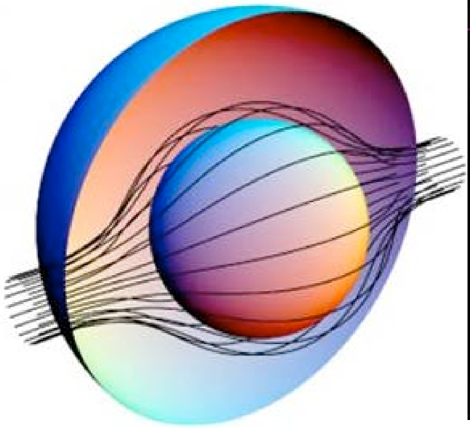


Metamaterials

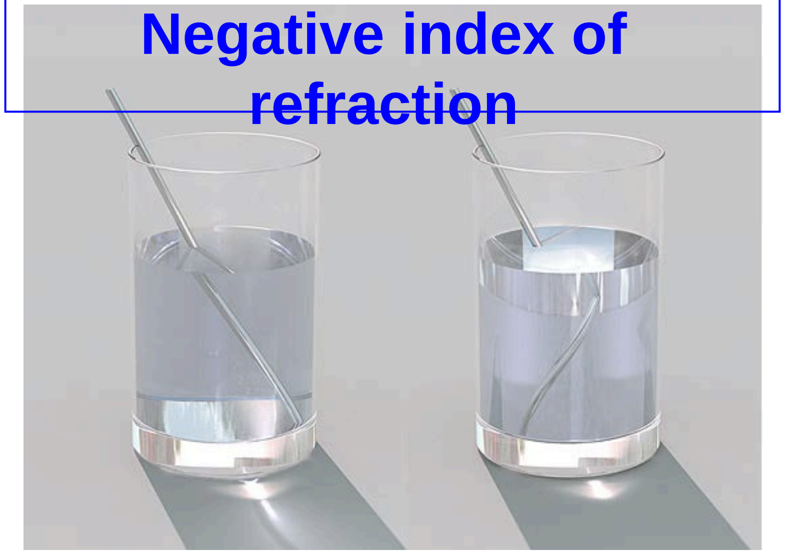


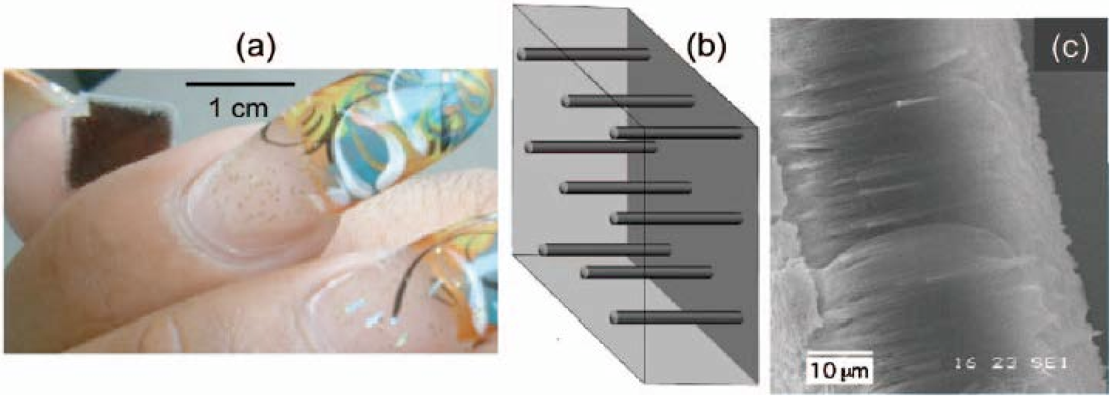
- Turn of the 21st century - invention of a new materials platform - metamaterials
- Unparalleled properties and dream applications

Optical cloak



Negative index of refraction

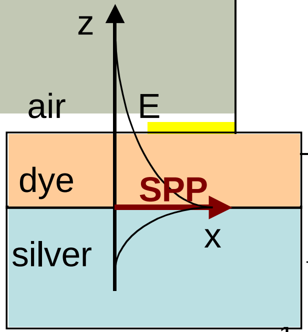


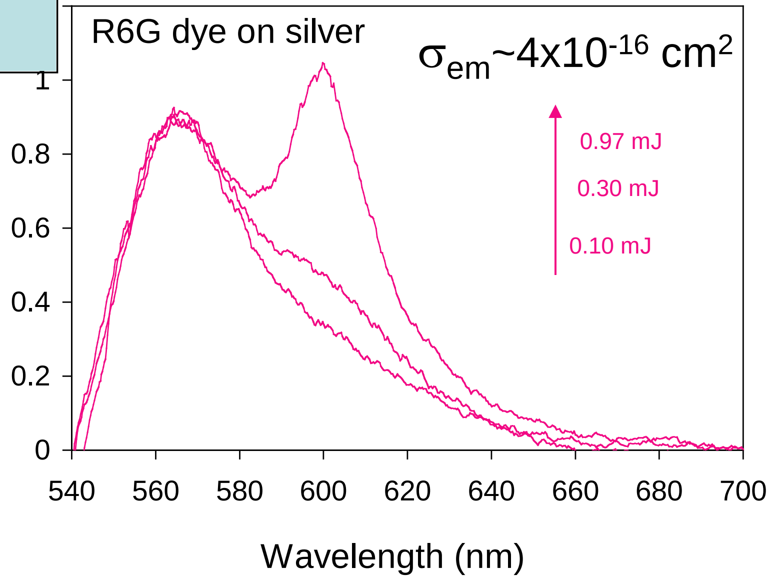


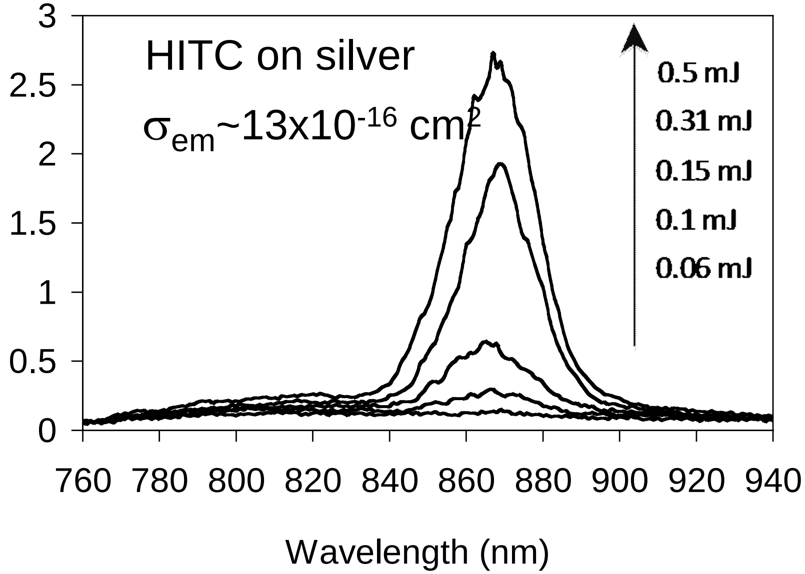
NSU: largest reported in the literature bulk optical metamaterial

[Appl. Phys. Lett. 2009]

Toward active metamaterials: Stimulated emission of surface plasmon polaritons







SPP Loss

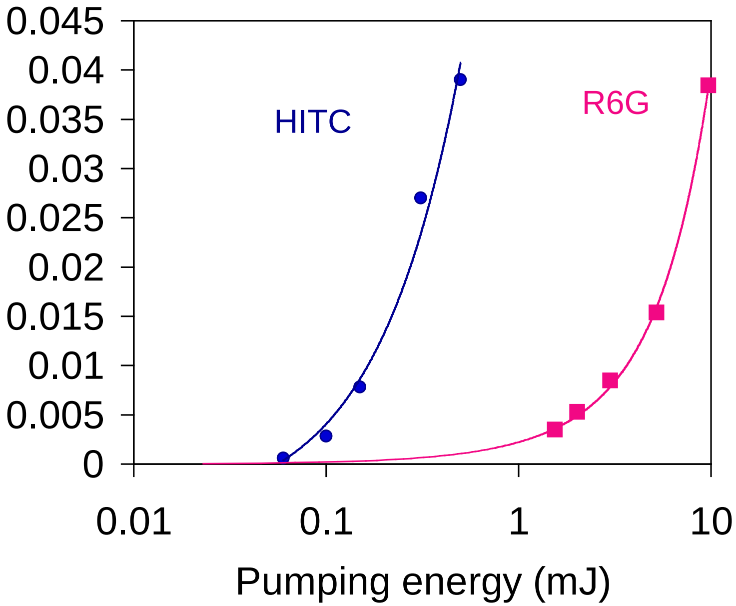
$$\gamma_i = \frac{\omega}{2c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{3/2}\left(\frac{\varepsilon''_m}{\varepsilon_m^2} + \frac{\varepsilon''_d}{\varepsilon_d^2}\right)$$

[Noginov, Podolskiy … OE 2008]

Threshold conditions:

$$600\ \text{nm}:\ \varepsilon_m = -16\ \Rightarrow\ \varepsilon''_d = 0.0087;\ \text{gain} = 607\ \text{cm}^{-1}$$

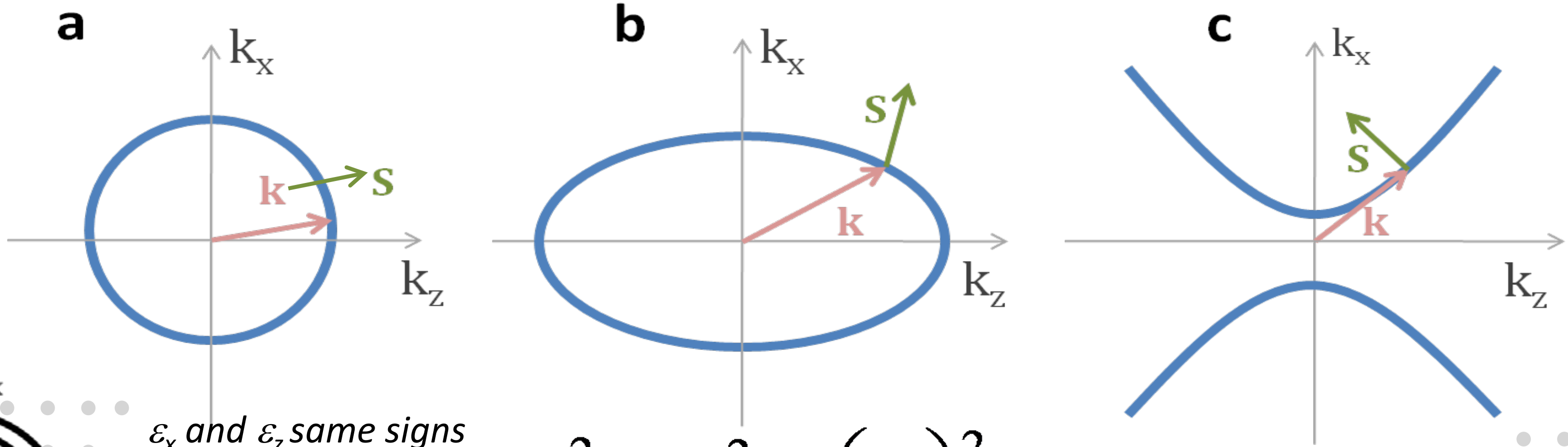
$$870\ \text{nm}:\ \varepsilon_m = -38\ \Rightarrow\ \varepsilon''_d = 0.0018;\ \text{gain} = 84\ \text{cm}^{-1}$$

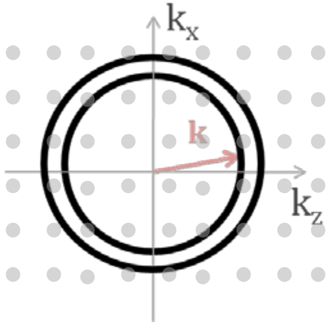


Metamaterials with hyperbolic dispersion

Indefinite media – [Smith, Schurig, PRL (2003)] **Hyperbolic Dispersion – [Jacob,…Narimanov, OE (2006)]**

Isotropic — Anisotropic — Hyperbolic

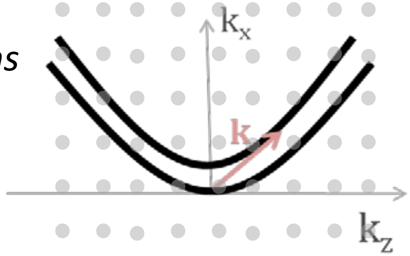




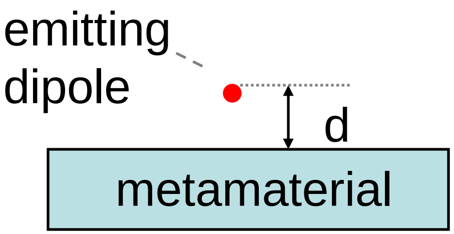
ε_x and ε_z same signs

$$\frac{k_z^2}{\varepsilon_x} + \frac{k_x^2}{\varepsilon_z} = \left(\frac{\omega}{c}\right)^2$$

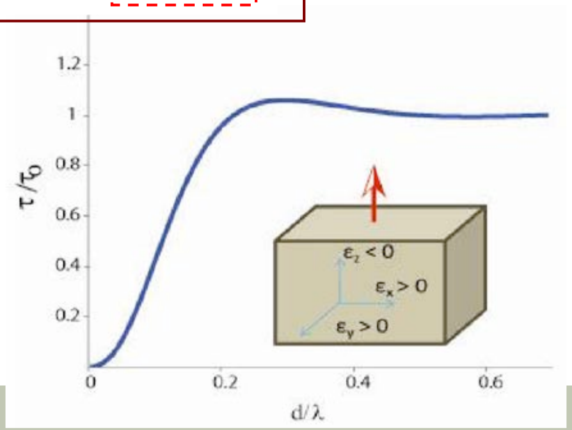
ε_x and ε_z opposite signs



Fermi's golden rule: $$R_s = \frac{2\pi}{\hbar} \left| \langle \Psi_f | H_{\rm int} | \Psi_i \rangle \right|^2 n(\varepsilon_f).$$

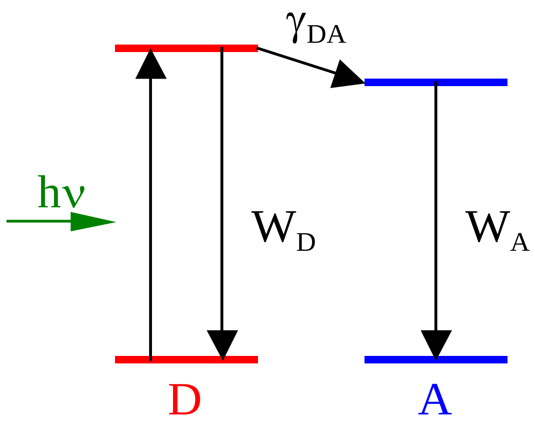


Spontaneous emission life-time



[Jacob, Smolyaninov, Narimanov (2009)]

Förster Energy Transfer



In solid solutions, at dipole-dipole interaction, and random distribution of acceptors:

$$I(t) = I_0 \exp\left(-(A+W)t - \gamma\sqrt{t}\right)$$

$$\gamma \approx 6.28 R_0^3 N / \sqrt{\tau_0} \quad (\tau_0^{-1} = A+W)$$

$$R_0 = \sqrt[6]{\frac{3}{2(2\pi)^5}\frac{\eta_0}{n^4}\int F(\bar{\nu})\sigma(\bar{\nu})\frac{d\bar{\nu}}{\bar{\nu}^4}}$$

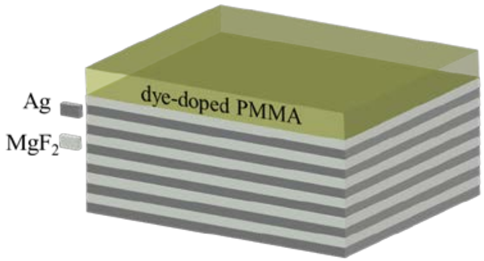
– The distance at which the rate of energy transfer is equal to that of spontaneous emission.

Our system

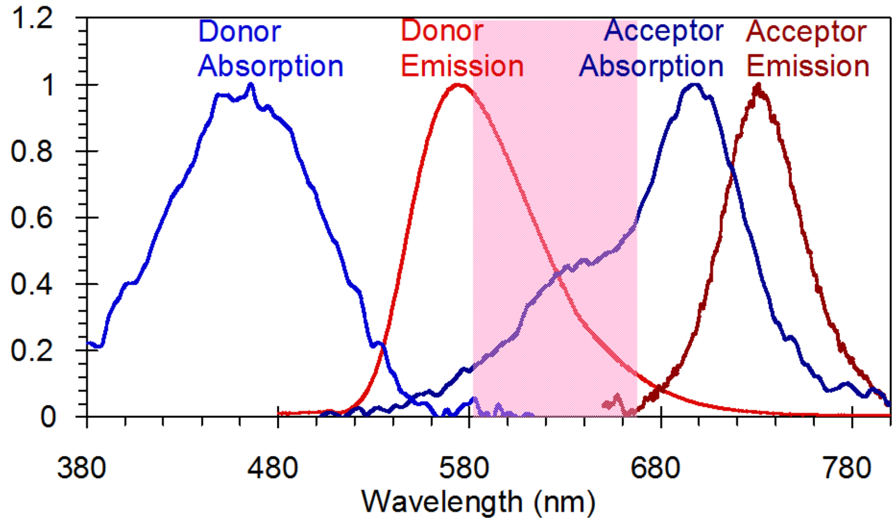
Donors: DCM molecules

Acceptors: DOTC molecules

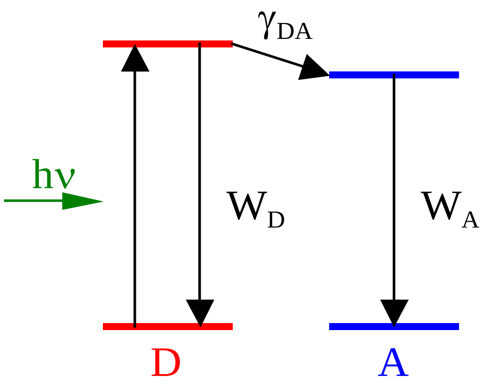
Embedded into <100nm PMMA films deposited onto different substrates.



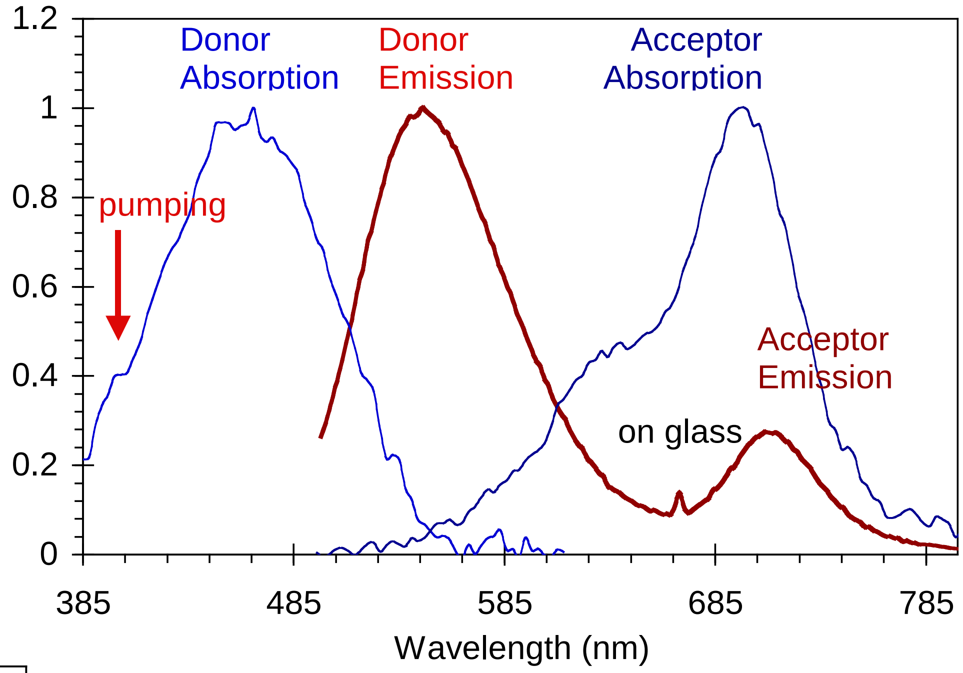
Good overlap between emission of donors and absorption of acceptors.



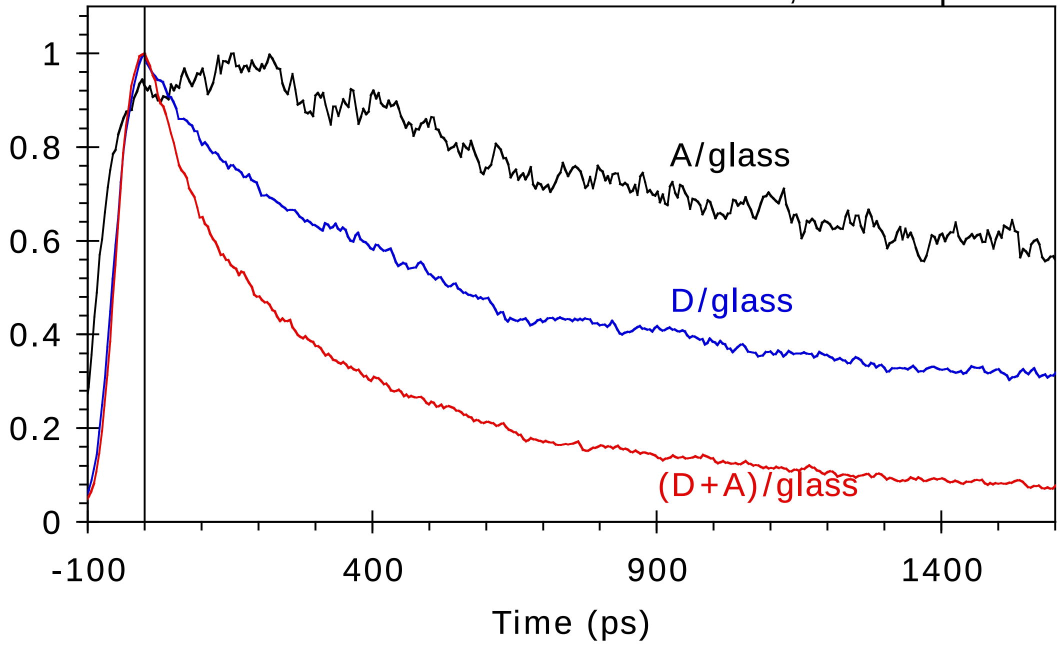
Förster Energy Transfer on Top of Glass

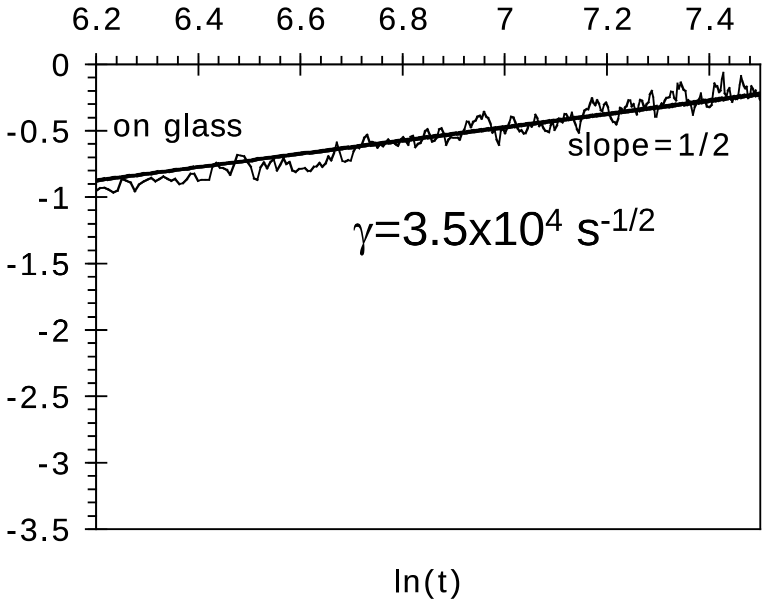


$$\frac{I_{(D+A)}}{I_D} \propto \frac{\exp\left(-At-\gamma\sqrt{t}\right)}{\exp\left(-At\right)} \Rightarrow \exp\left(-\gamma\sqrt{t}\right)$$

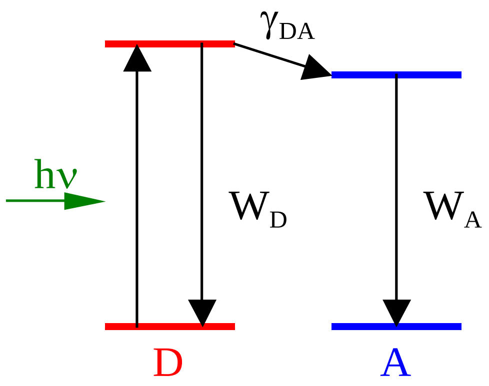


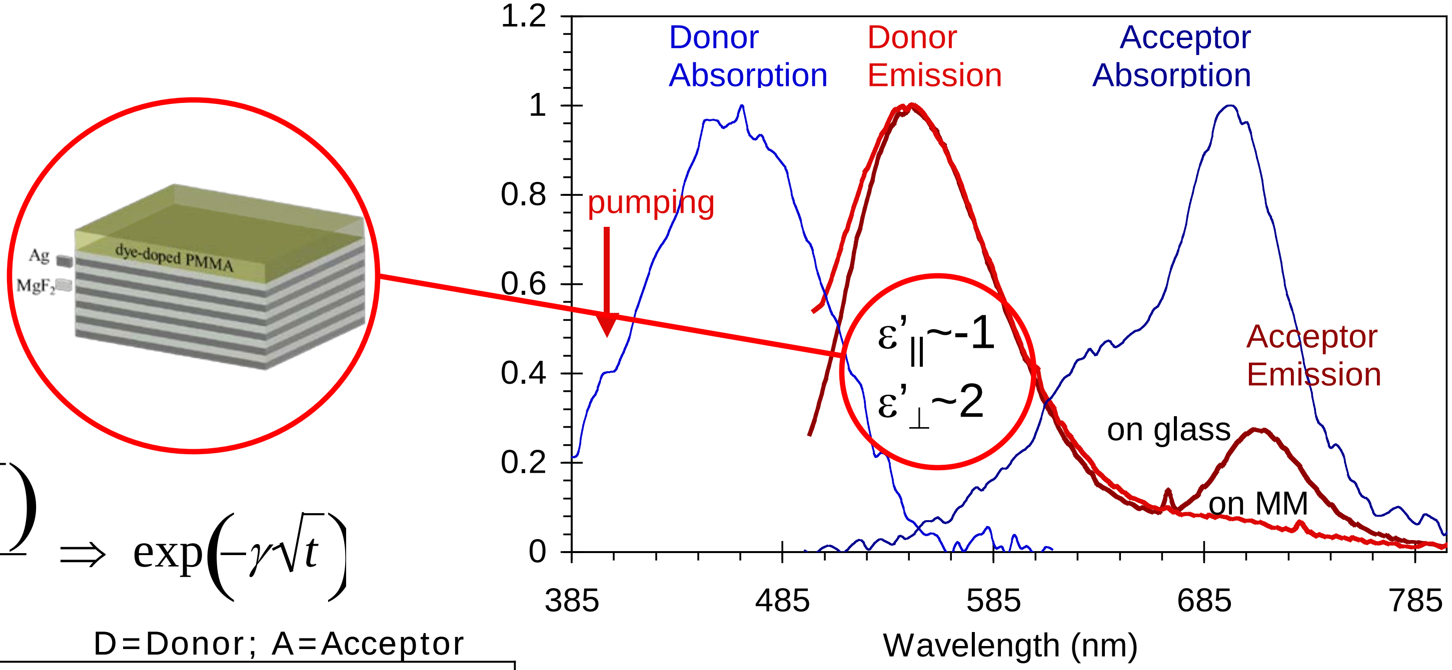
D=Donor; A=Acceptor





Förster Energy Transfer on top of HMMs and Metals





$$\frac{I_{(D+A)}}{I_D} \propto \frac{\exp\left(-At-\gamma\sqrt{t}\right)}{\exp\left(-At\right)} \Rightarrow \exp\left(-\gamma\sqrt{t}\right)$$

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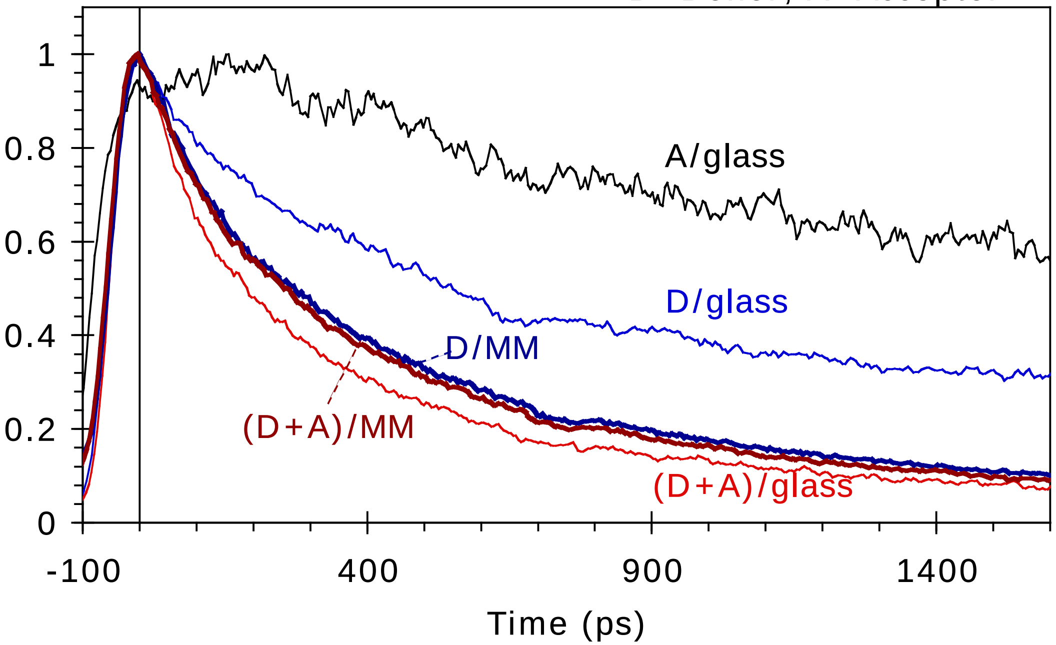
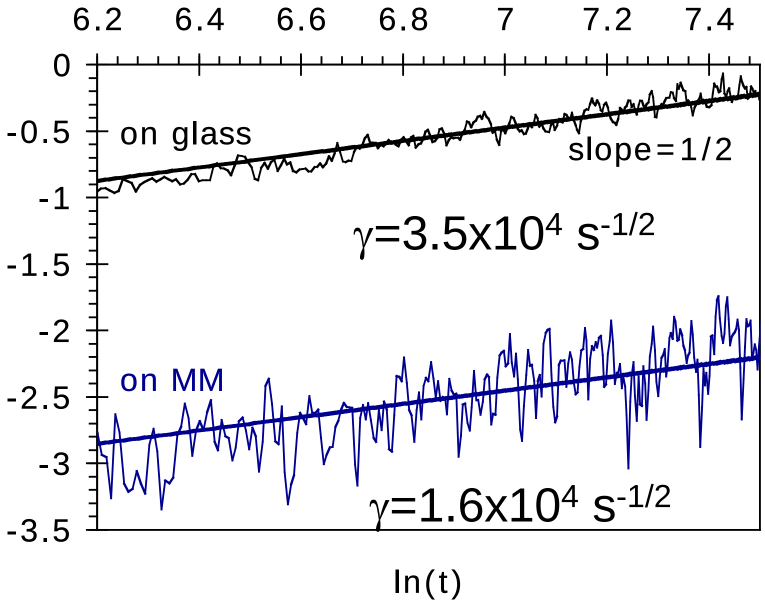
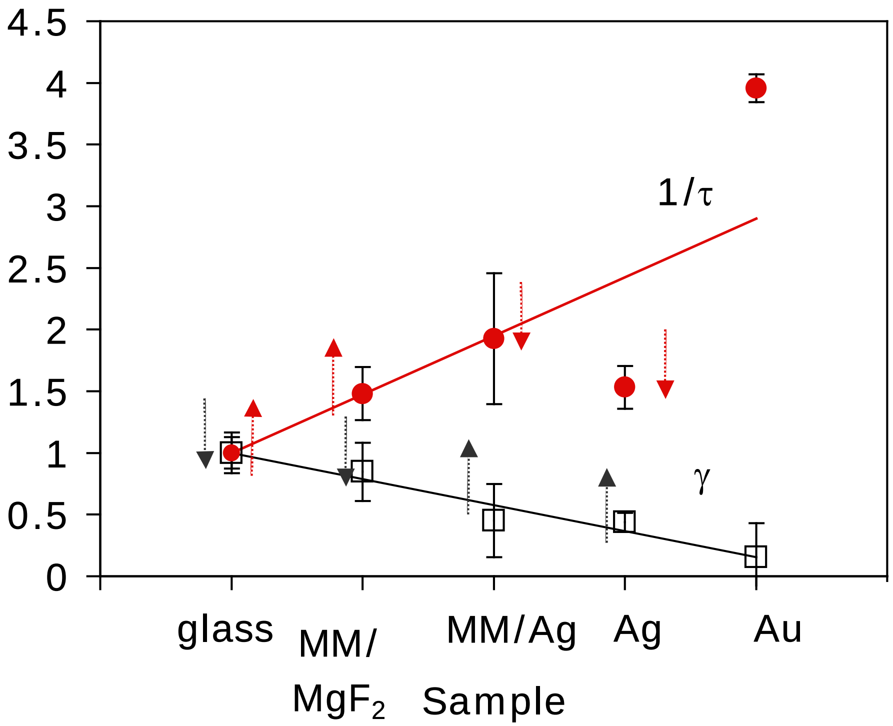




High Density of States Inhibits Förster Energy Transfer



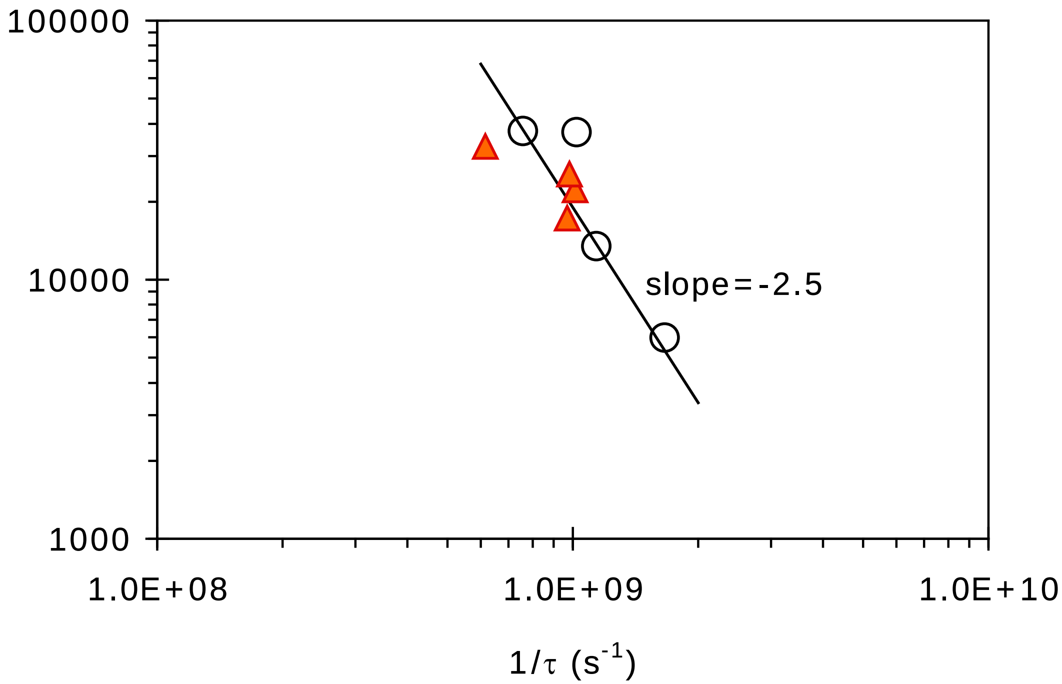
Same environments, which enhance emission decay rate, inhibit Förster energy transfer.

$$\gamma \approx 6.28 R_0^3 N / \sqrt{\tau_0} \quad (\tau_0^{-1} = A + W)$$

$$R_0 = \sqrt[6]{\frac{3}{2(2\pi)^5} \frac{\eta_0}{n^4} \int F(\bar{v})\sigma(\bar{v}) \frac{d\bar{v}}{\bar{v}^4}}$$

If $A >> W$ and $A \propto n \Rightarrow \gamma \propto n^{-1.5}$

Slope of γ *vs* A is -2.5



Absorption, Scattering… What else?

- **Effect of ε on various spectroscopic and quantum processes**

√ • **Spontaneous emission rate** $\alpha \sqrt{\varepsilon}\left(\frac{\varepsilon+2}{3}\right)^2$

• **Absorption coefficient (gain / stimulated emission)** $\alpha \frac{1}{\sqrt{\varepsilon}}\left(\frac{\varepsilon+2}{3}\right)^2$

√ • **Reflection/ Scattering**

√ • **Forster resonance energy transfer (dipole-dipole)**

•Transfer rate $R_0^6 \ \alpha \ \frac{1}{\varepsilon^2}\left(\frac{\varepsilon+2}{3}\right)^4$

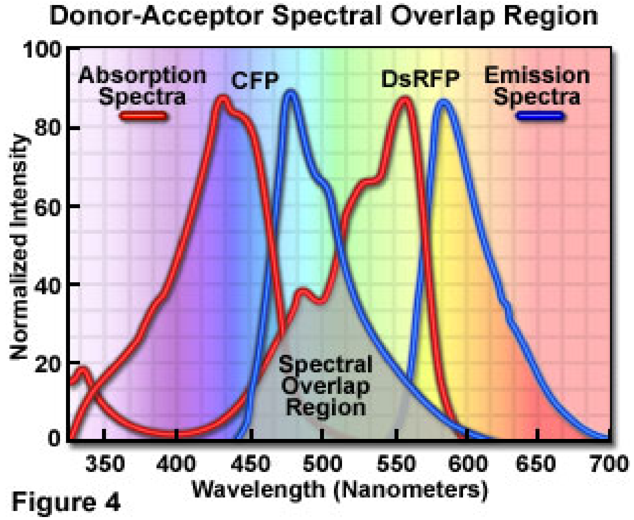


Figure 4

http://www.olympusconfocal.com/applications/fretintro.html

• **Wetting**

$$\gamma(1+\cos\theta)=W_{ad}=\left|\frac{c}{h^8}-\frac{A}{12\pi h^2}\right|;\quad A=\frac{3}{16\sqrt{2}}\frac{(\varepsilon-1)^2}{(\varepsilon+1)^2}\hbar\omega$$

• **Non-linear optical effects**

$$\chi^{(2)} \ \alpha \ \left(\frac{\varepsilon_{2\omega}+2}{3}\right)\left(\frac{\varepsilon_{\omega}+2}{3}\right)^2$$

$$\chi^{(3)} \ \alpha \ \left(\frac{\varepsilon_{2\omega}+2}{3}\right)\left(\frac{\varepsilon_{\omega}+2}{3}\right)^3$$

• **Chemical redox reactions (Marcus theory)**

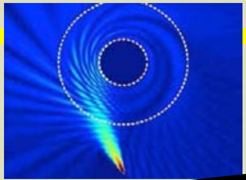
$$k_{act}=Ae^{-\frac{\Delta G}{RT}};\quad G\propto\left(\frac{1}{\varepsilon}-\frac{1}{\varepsilon_{\omega=0}}\right)$$

•**Raman/SERS**

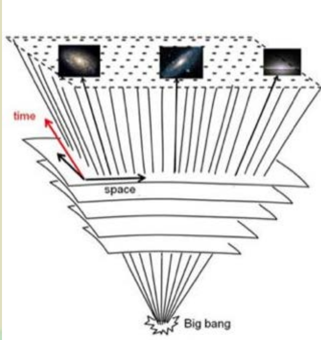
Hyperbolic metamaterials roadmap

Manipulating Emission Lifetimes

Black holes, big bang



[Narimanov, Kildishev; Cheng,...Cai arxiv 2010]



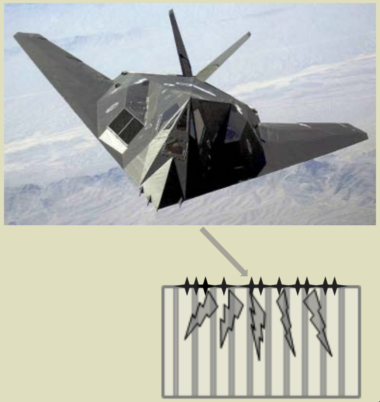
[Smolyaninov, Hung, arxiv 2011]

Single photon gun

High frequency broadband LEDs

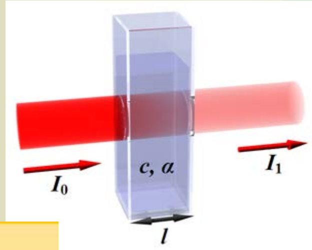
Stealth technology

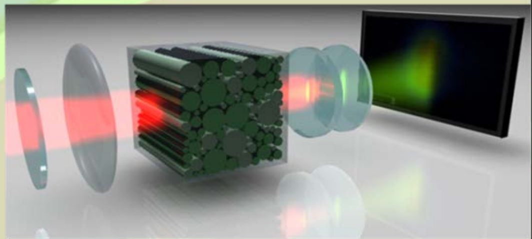
Darker than Black



Perfect absorbers – solar cells

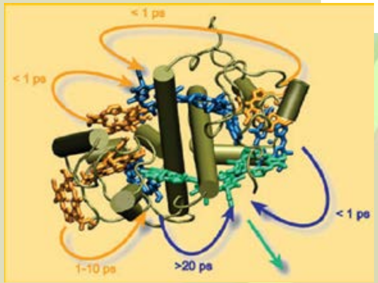
Enhanced NLO ($\chi^{(2)}, \chi^{(3)}$)





http://donll.upc.edu/research-topics/nonlinear-phenomena-in-materials-and-photonics

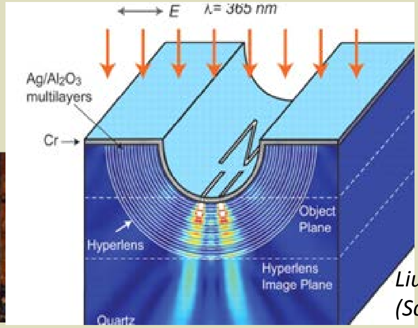
Optical Enhancements



D. Andrews, Laser Photonics Rev. 2011

Enhanced Energy Transfer (Bio-medical, solar harvesting)

Imaging



Liu, ...Zhang, (Science) 2007

Cloaking

Sub-wavelength imaging