Polaritons in microstructured materials

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2010 11 11

Content

- Introduction
- Piezoelectric superlattice

  Piezoelectric transducer

  Polariton　　Superlattice vibration
- Polariton in a plasmonic crystal
- Conclusions

Polariton

1978)

(1980) phonon-polariton)

(1991):

2001

Phonon-Polariton:

Exciton-polariton

……

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·38 (2009) 8

Polariton is a mixed state of photon and polarization wave

The polariton represents an interactive relationship between the light energy and the material polarization that it induces.

Light within a material is no longer just an optical field, it is now intimately linked with the optical response of the material, the mode is a polariton rather than a photon.

PRB 54, 6227 (1996)

Electrons Dispersion of refractive index

Ions Infrared absorption etc.

Piezoelectric effect: related to ions displacement

POLARITON

1951: Proposed the phenomenon in an ionic crystal

Strong coupling exists between EM wave and transverse optical phonon!

K. Huang, *Proc. R. Soc. London A* **208**, 352 (1951)

1958: Coined the word "polariton"

J.J.Hopfield, PR 112, 1555(1958)

It is of interesting to note that the term “polariton” was originally coined by Hopfield to designate the **“uncoupled polarization field particles”** of the medium. The term was, however, **misconstrued by Russian investigators as designating the coupled polarization excitation-photon modes**, and through extensive use in the Russian literature polariton has become the generic name for the coupled modes.

“The polarization field “particles” analogous to photons will be called “polaritons.” (Excitons will be shown to be one kind of polariton…. Optical phonons are another example of polaritons.)

J.J.Hopfield, PR 112, 1555(1958)

The propagating state for these energies and wave vectors can no longer be described as a phonon or a photon, but is a mixture of these two elementary excitations know as a polariton.

C.H.Henry, J.J.Hopfield, Phys.Rev.Lett.15, 964(1965)

Exciton Polaritons

- If a light field and an exciton overlap, they affect each other.
- Light is an EM-field, and EM-fields affect charged particles, thus changes the behavior of the electron and the hole that make up the exciton.
- The charged particles create electric-fields, the exciton in turn affects the way the light behaves.
- If we match the energy of the light and excitons they become "entangled", and seem to become a pair of new and different objects. These are "polaritons".

Surface polaritons

Modes that propagate along an interface with the amplitudes of the fields decreasing normal to the interface.

Surface polaritons are classified by the mechanism by which light is bound to the surface:

- Light modes bound to the surface through interactions between the photons and the free-electron gas in a metal are called electron-gas-driven polaritons or plasmon polaritons.

- Light bound to the surface through interactions between photons and phonons are called phonon-driven polaritons or phonon polaritons.

Quantum-well polariton

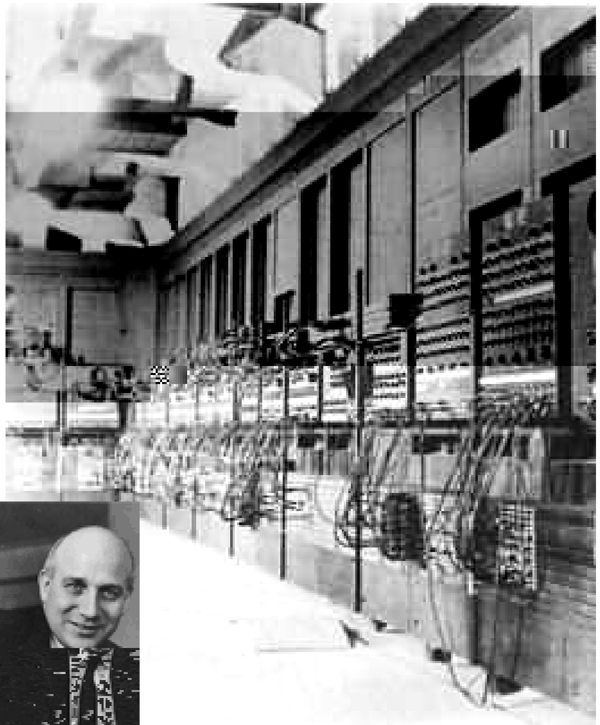
It is the quantum-mechanical combination of the light in an optical-cavity and an exciton in a quantum-well.

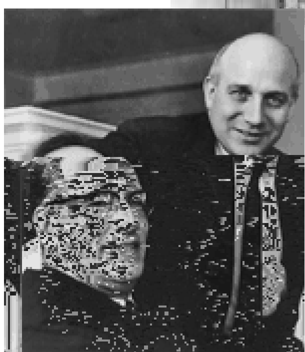
Phonon polaritons

- Transverse optical-phonon polariton
- Longitudinal optical-phonon polariton???

In an ionic crystal, impossible!

But in a piezoelectric superlattice, possible!





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1947, Bardeen *et al.*

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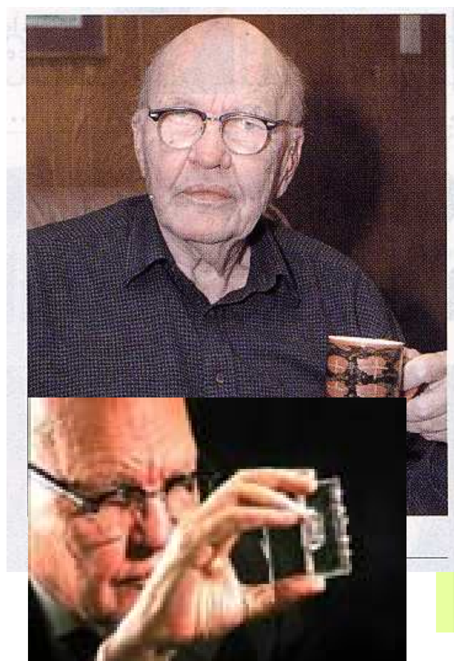
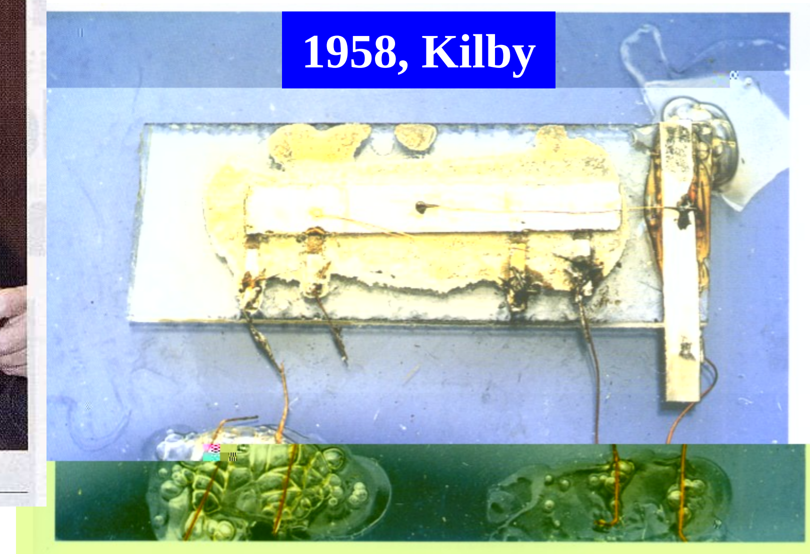
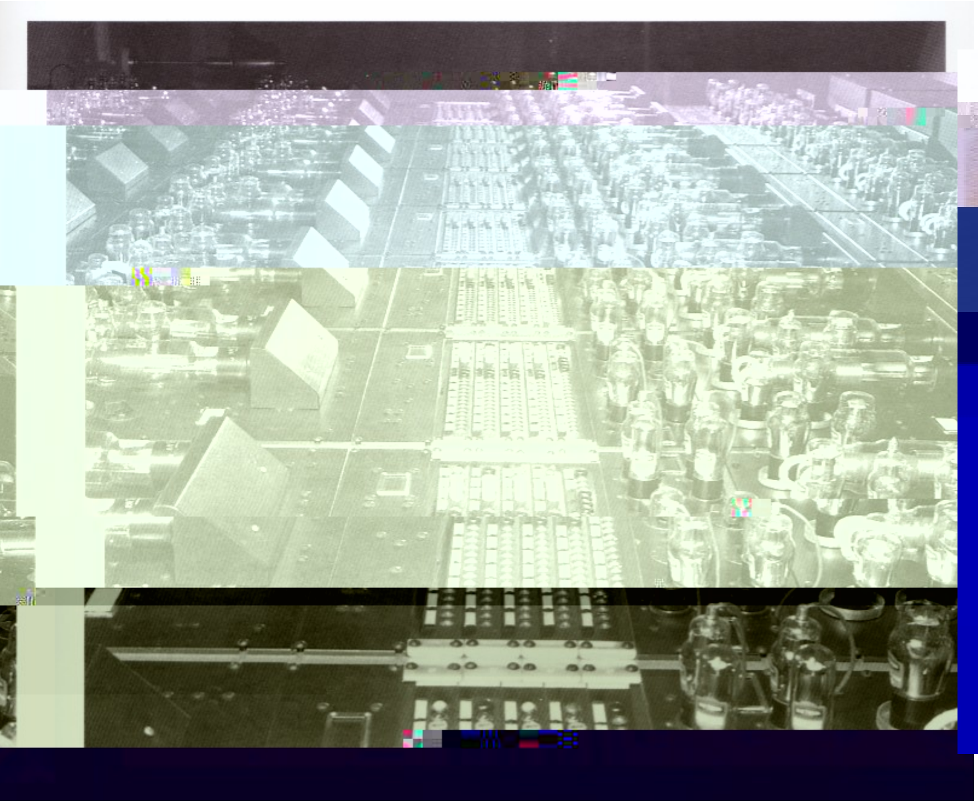
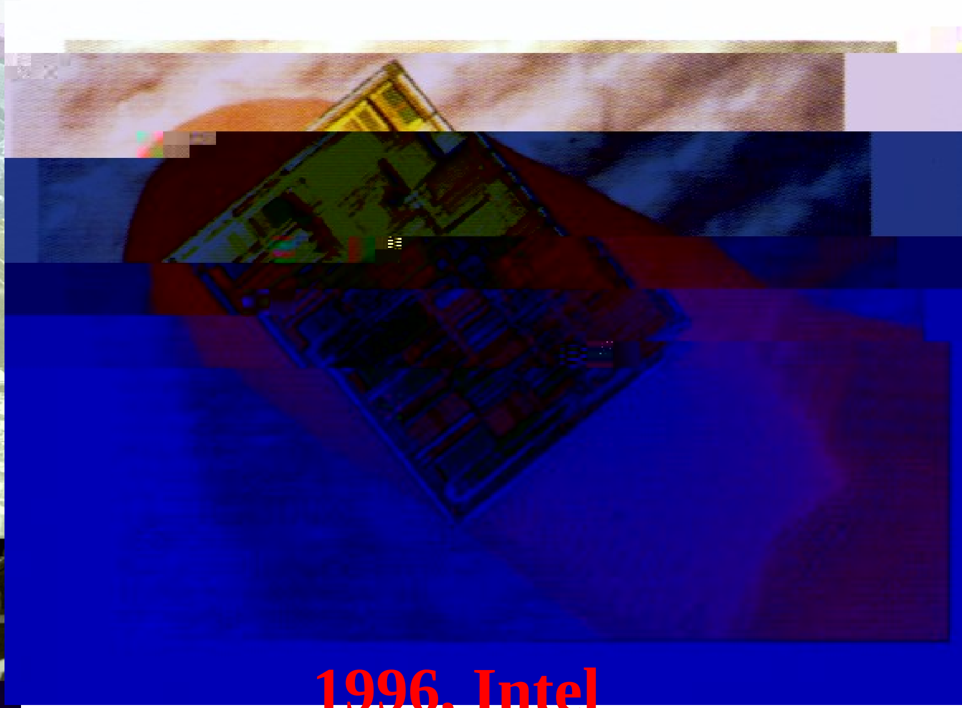


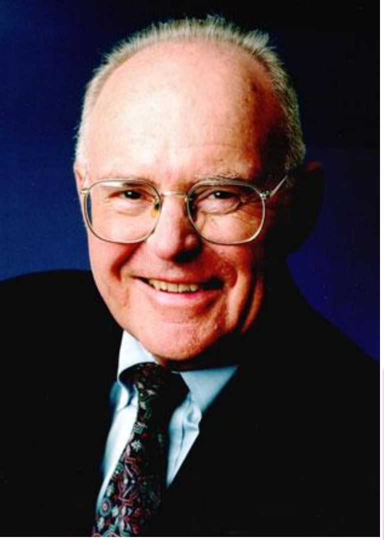


(Intel) " - "
Moore Noyce more noise( ),





1996, Intel



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Intel

1965

1975 " " " "

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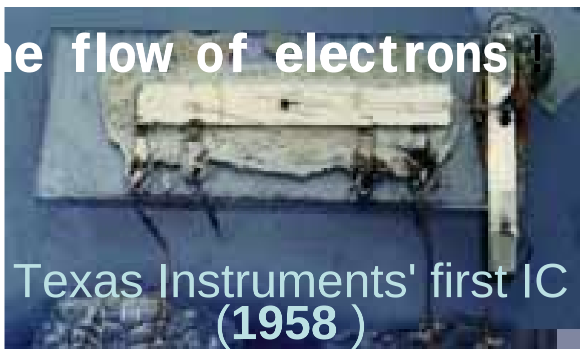
- Photonic Crystal
- Left-handed Material
- Cloaking
- QPM Material

Thousand years ago, we built "fences"

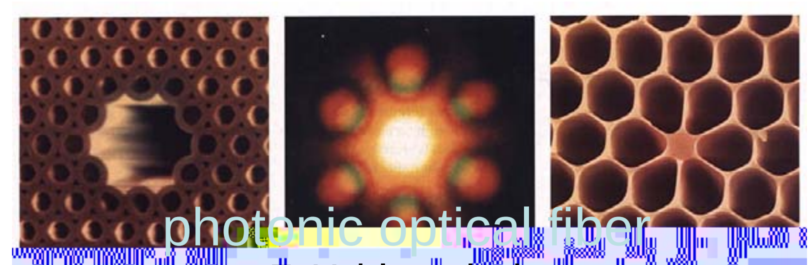
…to control animals !

Not far back, we made "wires" and "integrated circuits"

…to control the flow of electrons !



Texas Instruments' first IC (1958)



photonic optical fiber

E. Yablonovitch, *Scientific American* 285, 47-55 (2001)

In the new century, we design photonic band gap materials "Photonic Crystals"

…to control the flow of light (photons).

Integrated optical circuits and all-optical computers

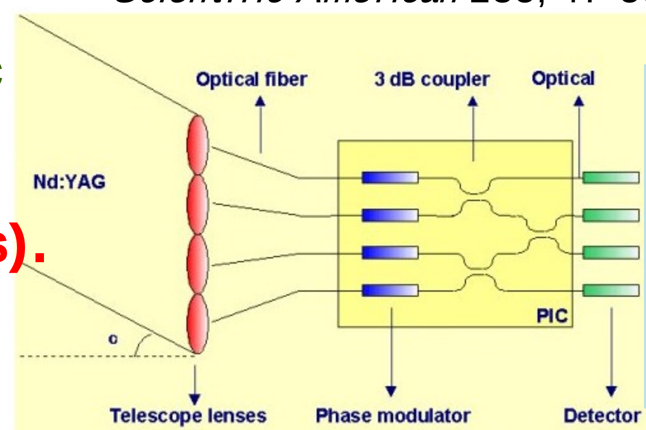


Figure 1: Functional layout

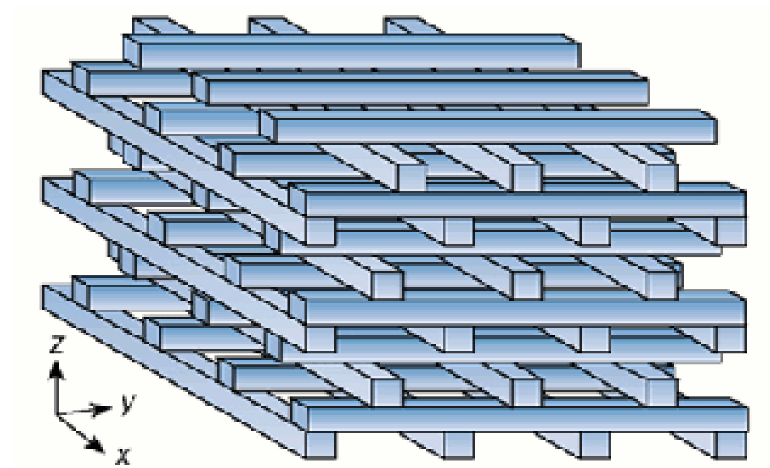
Photonic Integrated Circuits for Optical Phase Control
ETH Zürich (Switzerland) 2006

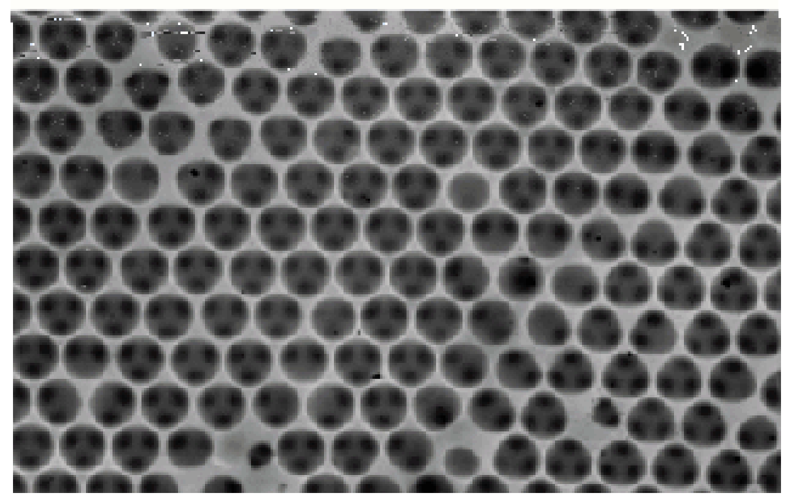
:

Yablonovitch

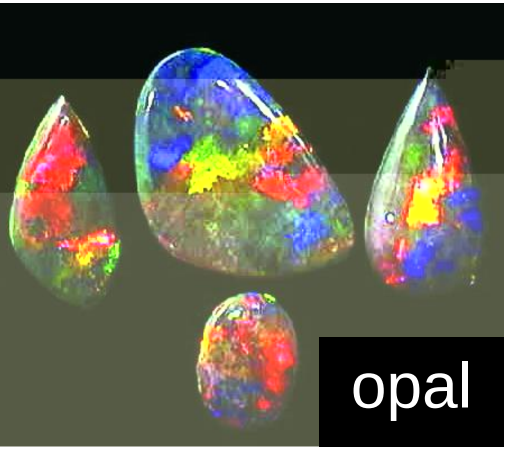
John

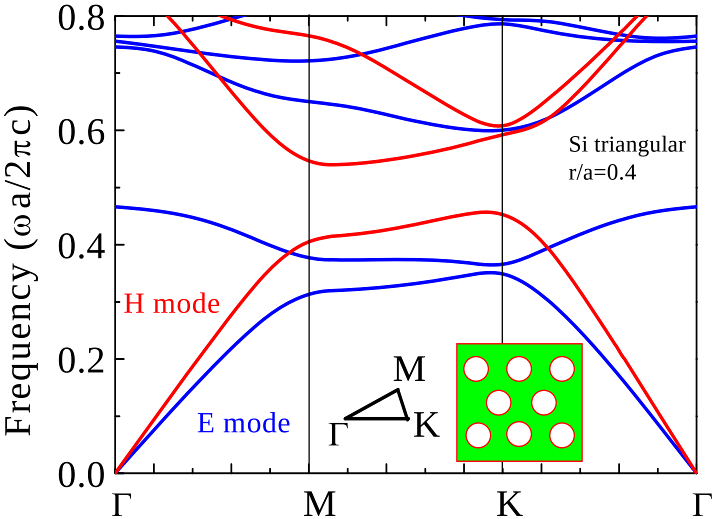
1987

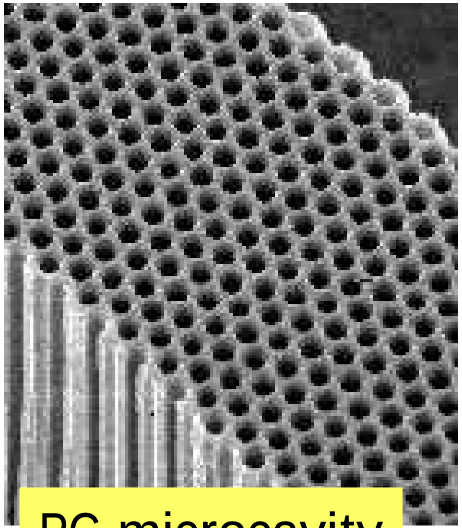


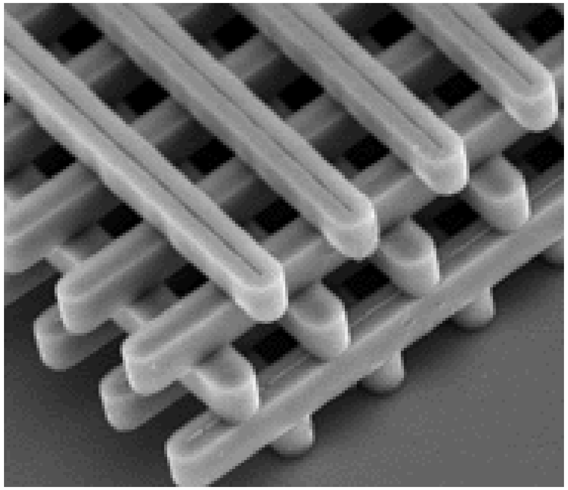


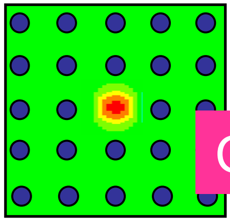
Photonic crystal

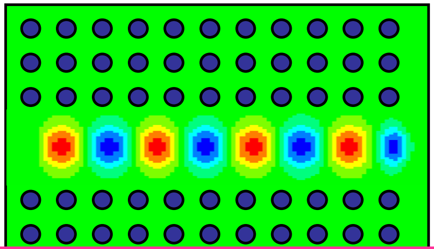


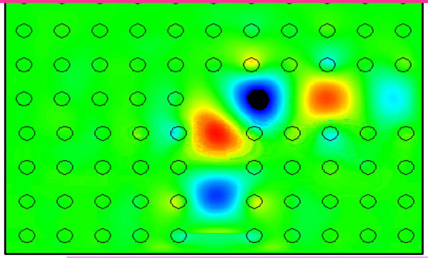












Control the flow of photons

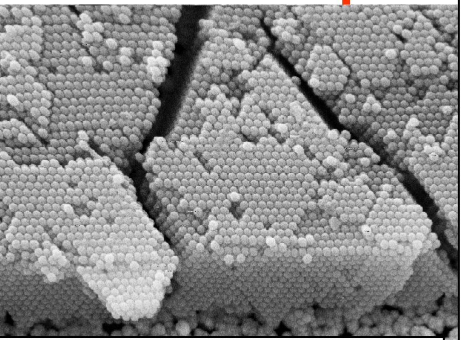
PC microcavity
PC waveguide
PC …

→ Optical IC → Optical chip → Photonic revolution

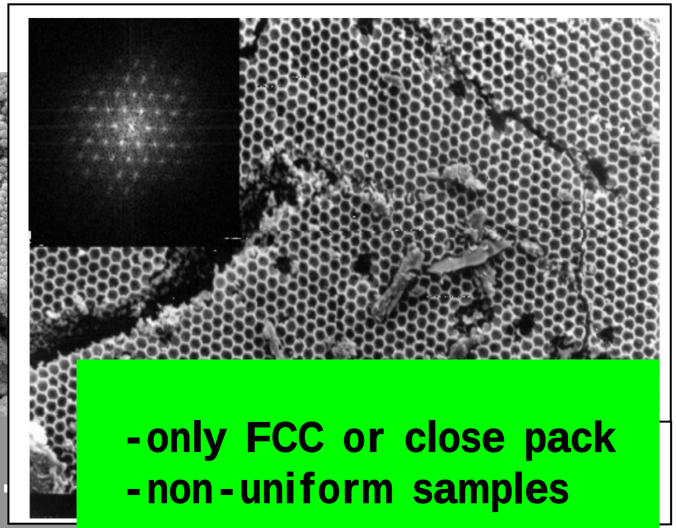
Photonic Band Gap Materials

Contemporary fabrication methods:

Artificial Opals

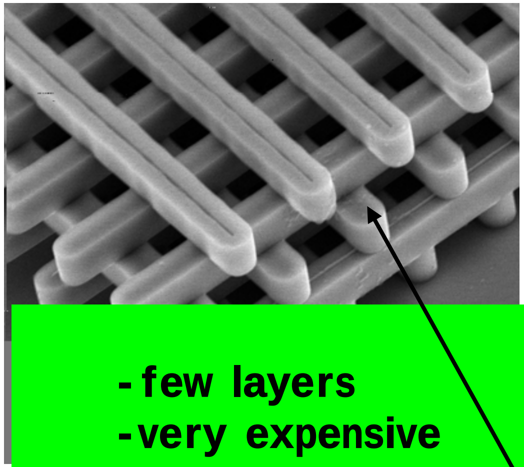


Y. Jiang, et al., J. of Phys. Condens. Mat. **15**, 5871-5879 (2003). **(HKUST)**



- only FCC or close pack
- non-uniform samples

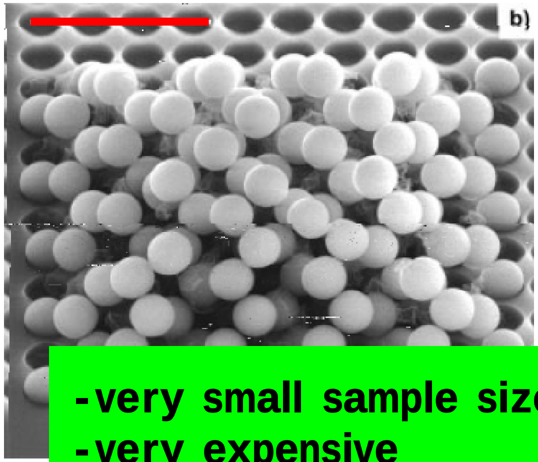
Layer-by-layer Lithography



- few layers
- very expensive

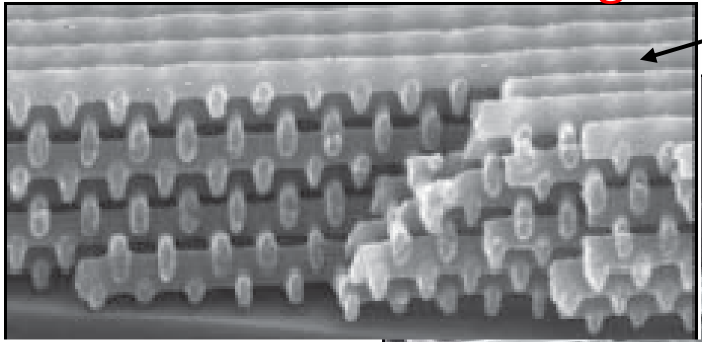
Woodpiles

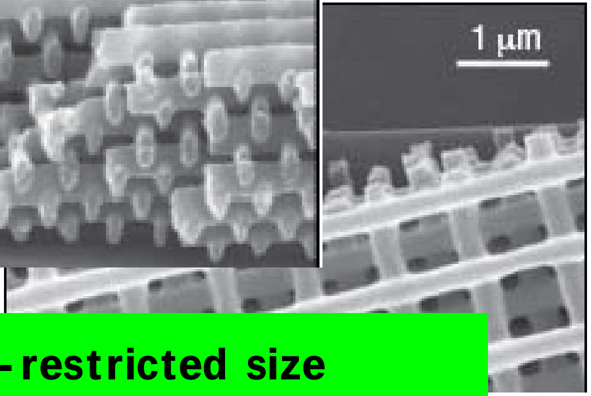
Nano-robotic Manipulation



- very small sample size
- very expensive
- long time

Direct Laser Writing





- restricted size
- relatively expensive
- long time

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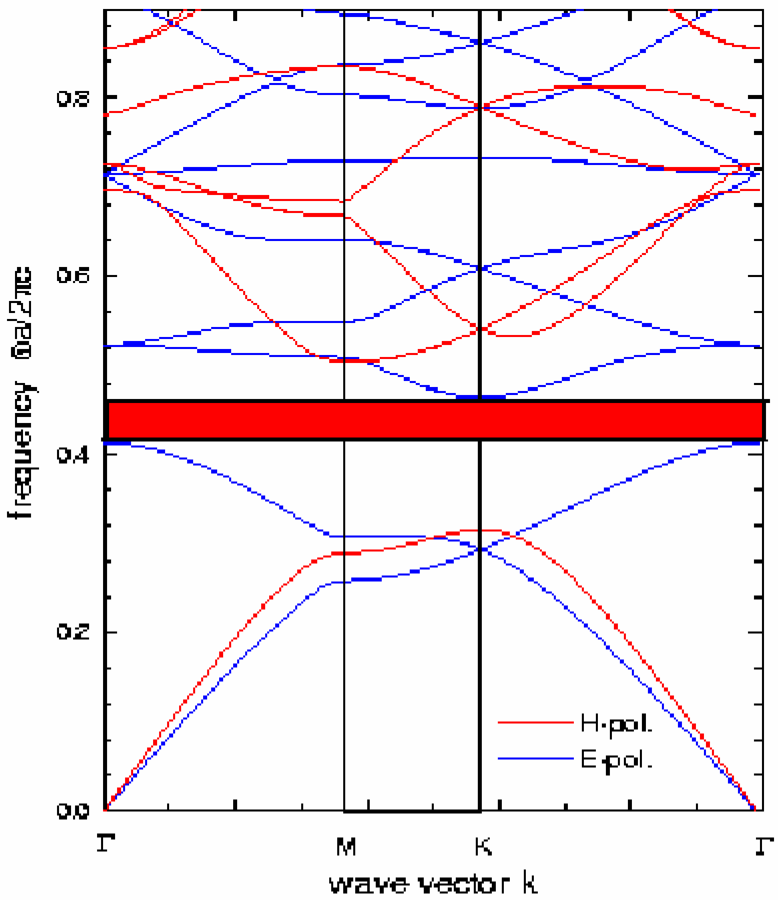

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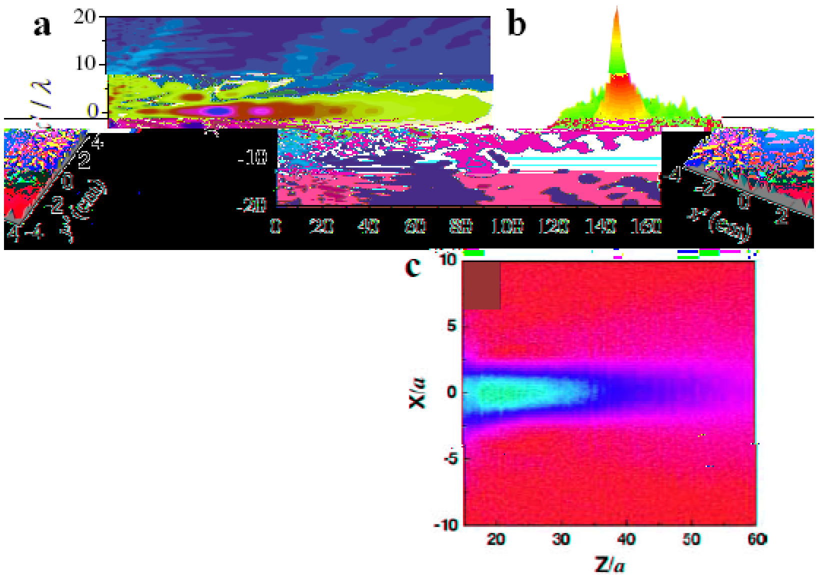
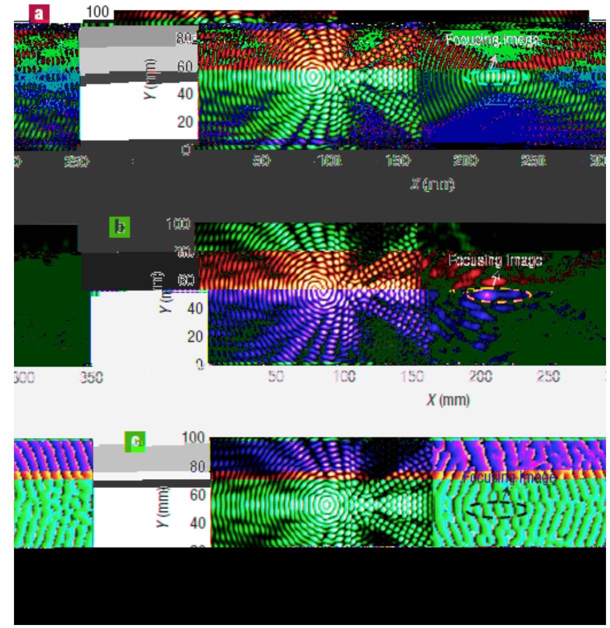
ü $V_p \sim \omega(k)/k$

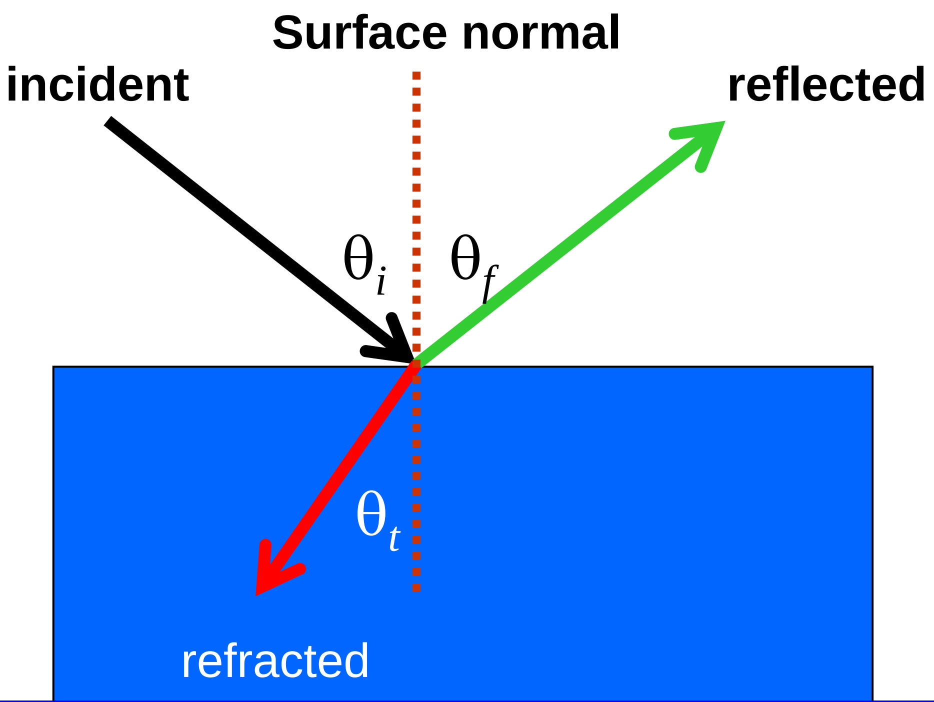
ü $V_g \sim \partial\omega/\partial k$





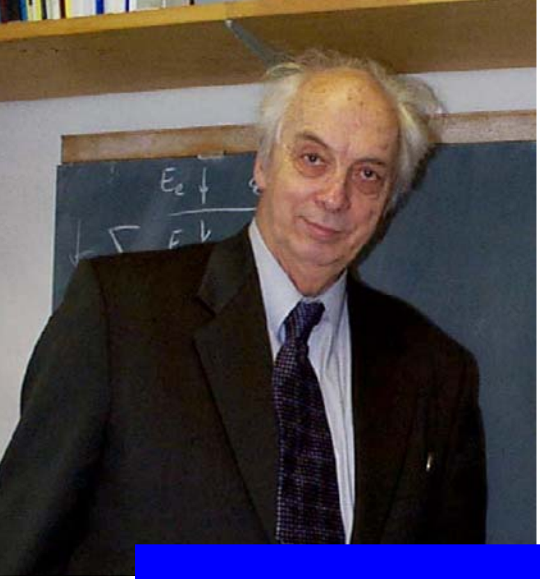
Phys. Rev. Lett. 93, 024301 (2004).
Phys. Rev. B 71, 054302 (2005).
Phys. Rev. B 73, 054302 (2006)
Appl. Phys. Lett. 85, 341 (2004)
Nature Mater. 6,744 (2007)

Left-handed material



A LHM would have dramatically different propagation characteristics stemming from the sign change of the group velocity, including reversal of both the Doppler shift and Cherenkov radiation, anomalous refraction, and even reversal of radiation pressure to radiation tension.

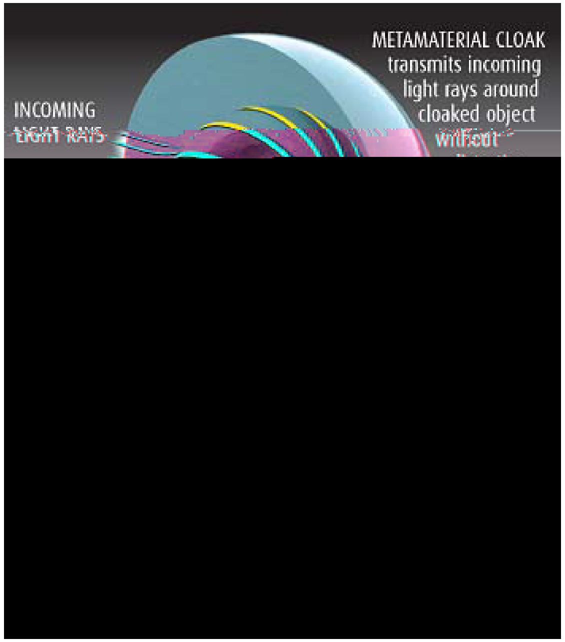
A composite medium, based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires, that exhibits a frequency region in the microwave regime with simultaneously negative values of effective permeability and permittivity.

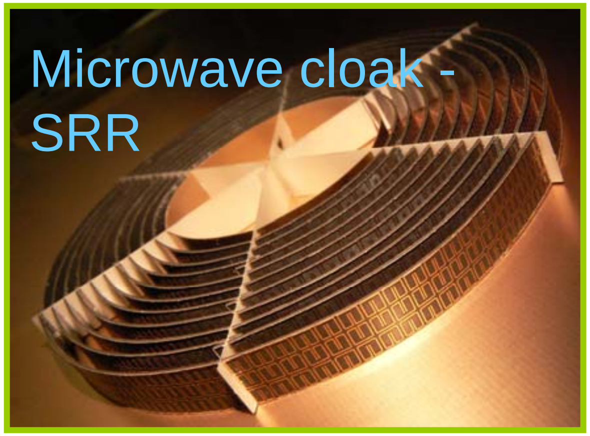


Left-Handed Materials → Negative Refractive Index

Electromagnetic waves will only propagate in a medium that has a real index of refraction, $n_{\text{eff}}(\omega) = \sqrt{\varepsilon_{\text{eff}}(\omega)\mu_{eff}(\omega)}$. If either $\varepsilon_{\text{eff}}(\omega)$ *or* $\mu_{eff}(\omega)$ is negative, then $n_{\text{eff}}(\omega)$ is imaginary, and there will be no transmission through a thick sample. If, however, both $\varepsilon_{\text{eff}}(\omega)$ *and* $\mu_{eff}(\omega)$ are less than zero, electro-magnetic waves will propagate through the medium, but the negative root must be chosen for $n_{\text{eff}}(\omega)$, and the group and phase velocities will be antiparallel.

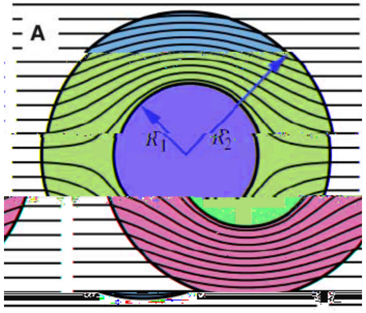
Metamaterial for EM Cloaking

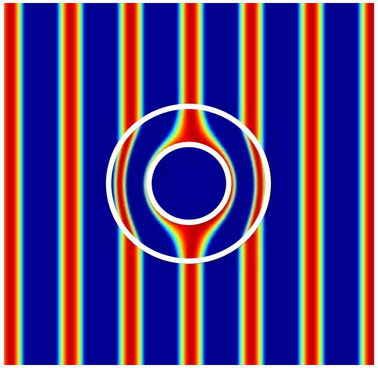




Microwave cloak - SRR

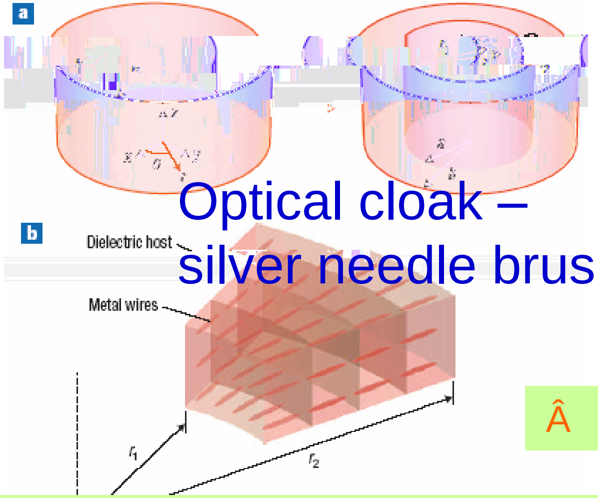
Â Smith & Pendry, *Science* 314, 977 (2006)





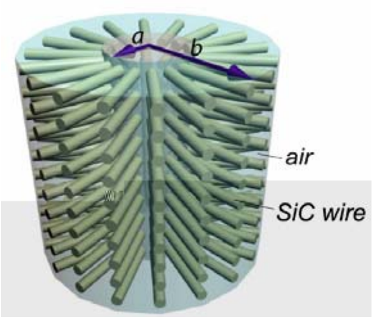
Â Pendry *Science* 312, 1780 (2006).

Â U.Leonhardt *Science* 312, 1777(2006).



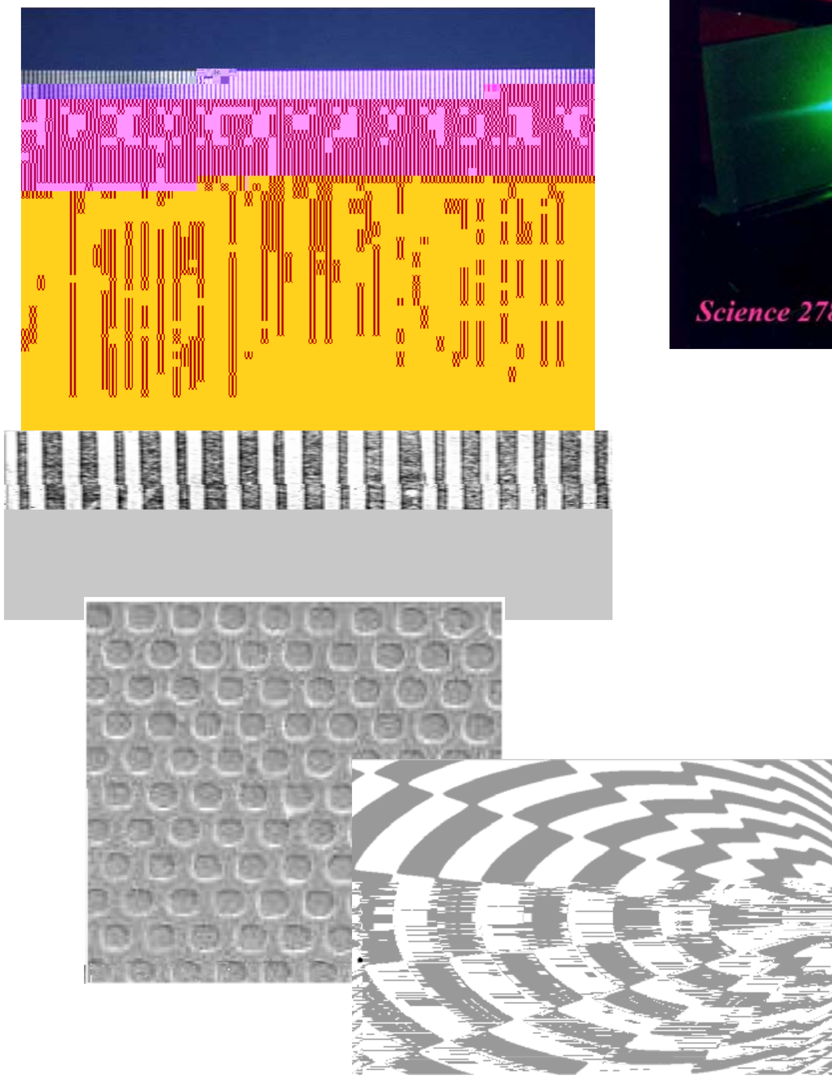
Optical cloak – silver needle brush

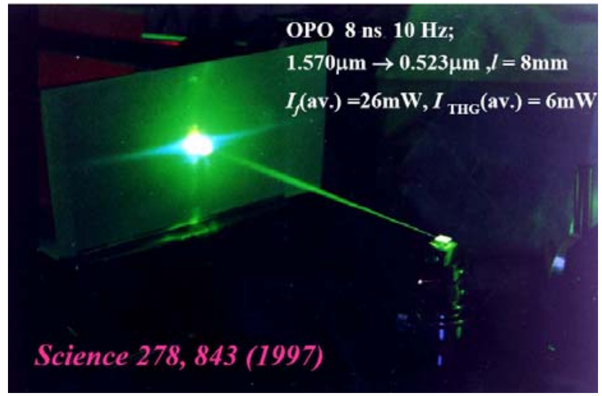
Â *Nat. Photonics*, 1, 224(2007).

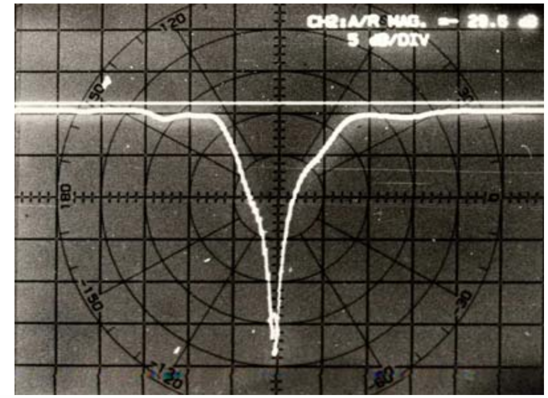


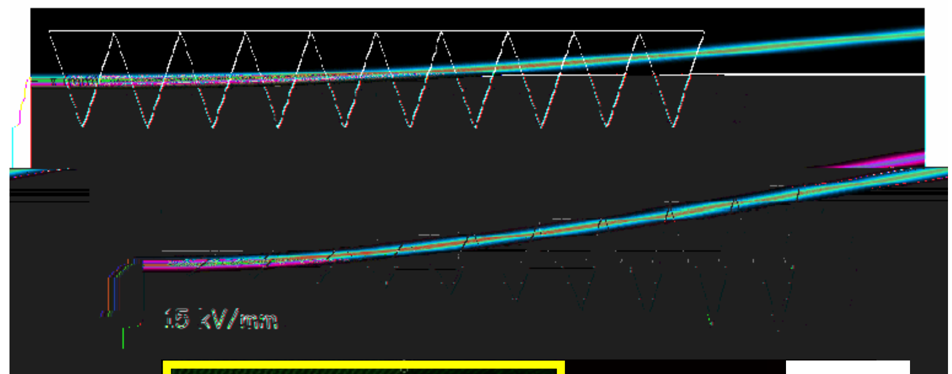
Â *Opt. Express*, 16, 2008.

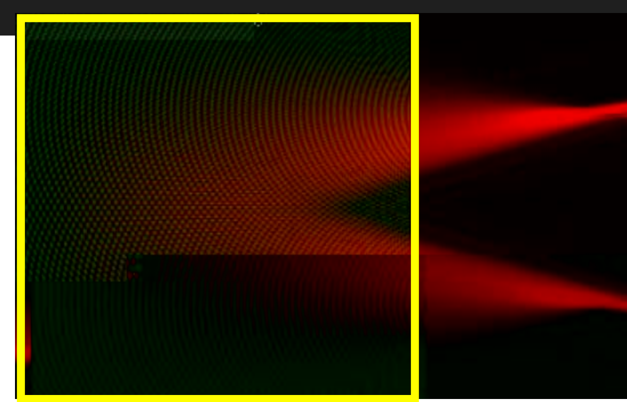
Ferroelectric domain structures
nonlinear optical, piezoelectric, electrooptic





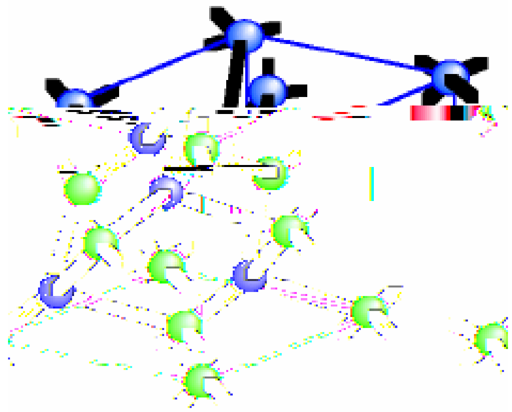


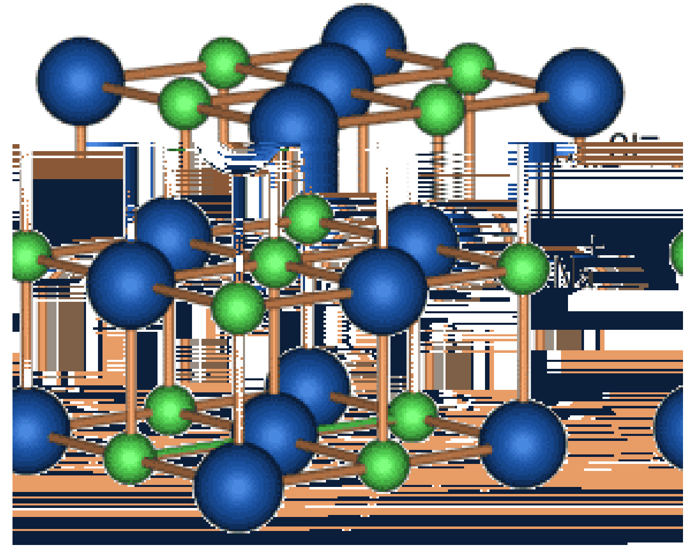




…Researchers no longer just study the rich variety of materials provided by nature but have rather become creative designers who tailor optical properties at will, leading to qualitatively new and unprecedented behavior….

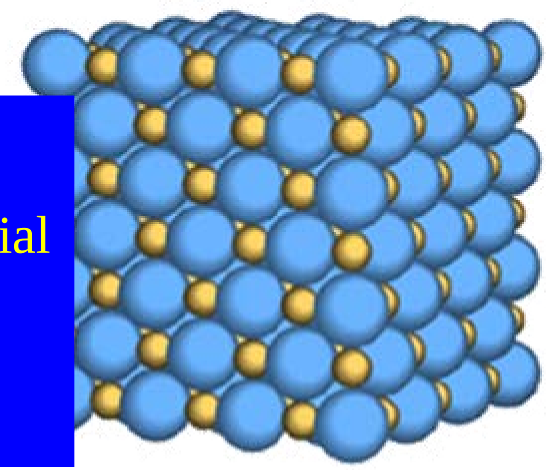
Science 313, 502 (2006)





NaCl

- Photonic Crystal
- Left-handed Material
- Cloaking
- QPM Material



In a sense, every material is a composite, even if the individual ingredients consist of atoms and molecules. …… it is only a small step to replace the atoms of the original concept with structure on a larger scale.

IEEE TRANS. on MICROWAVE THEO. AND TECH.47, 2075 (1999)


朝韩停止“三八线宣传战”

“ ”

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Content

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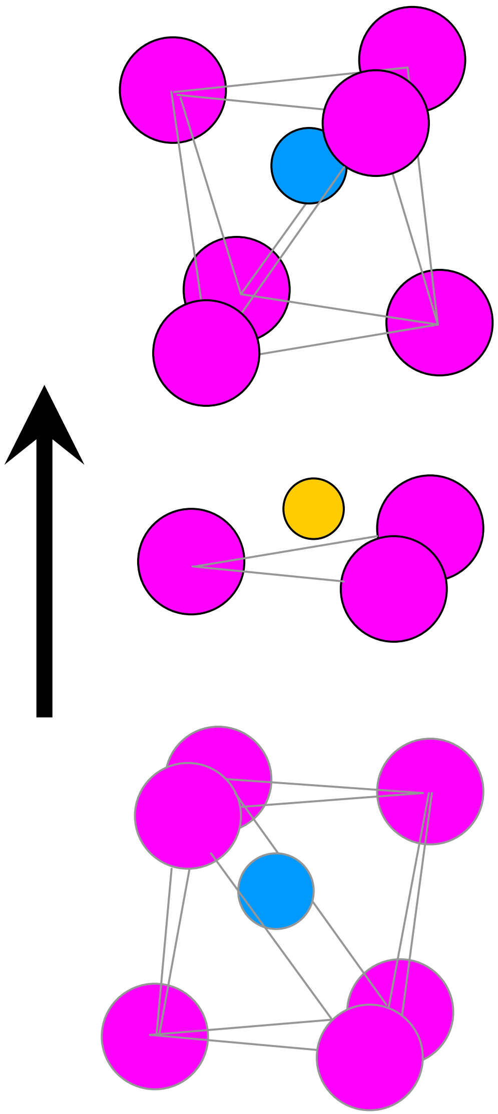
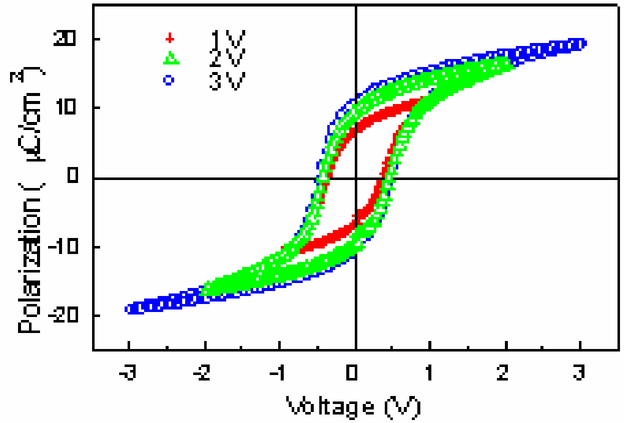
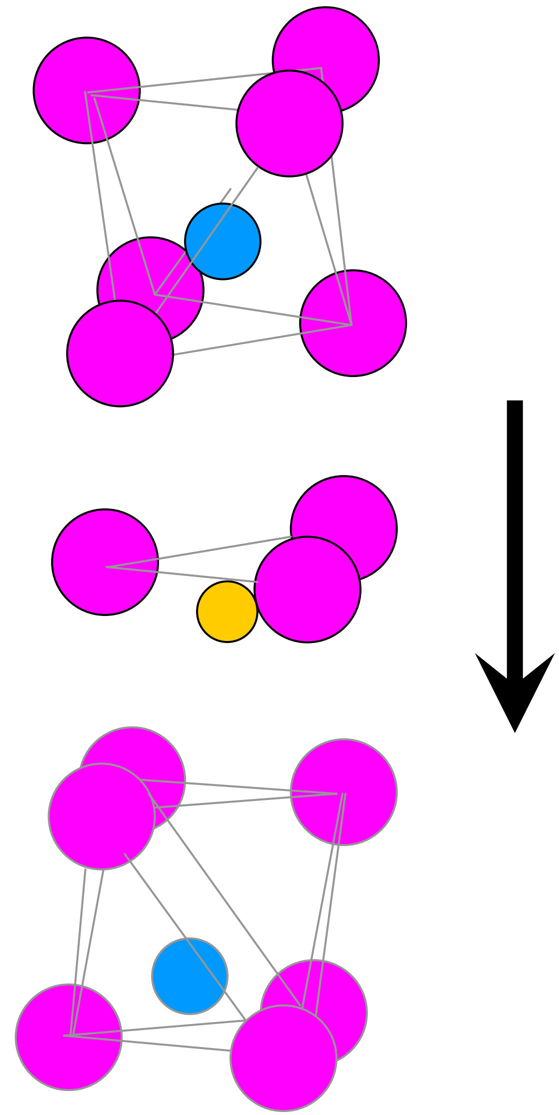
    Piezoelectric transducer

    Polariton   Superlattice vibration
- Polariton in a plasmonic crystal
- Conclusions



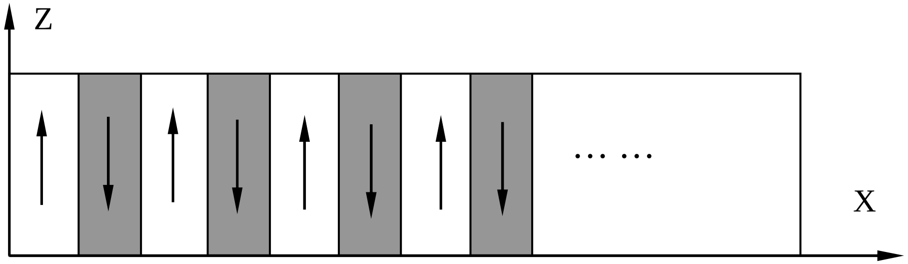




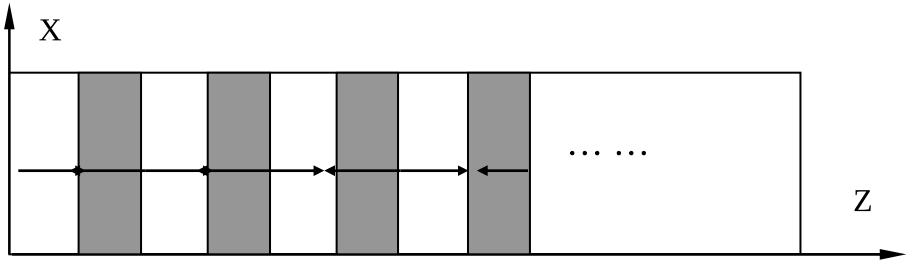
A ferroelectric crystal is a material the direction of whose spontaneous polarization can be changed by an external electric field.

$LiNbO_3$

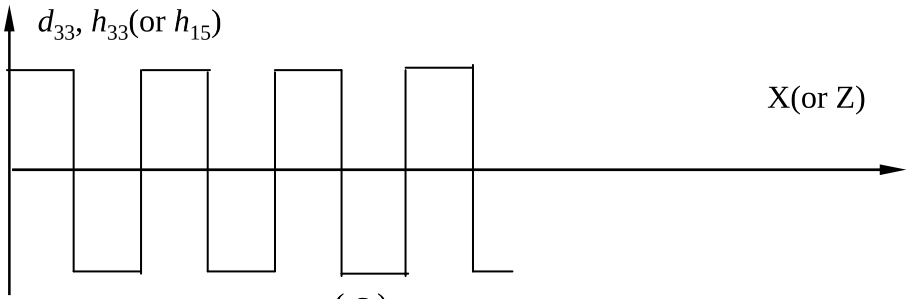
Patterned Ferroelectric Domain Structures



(a)

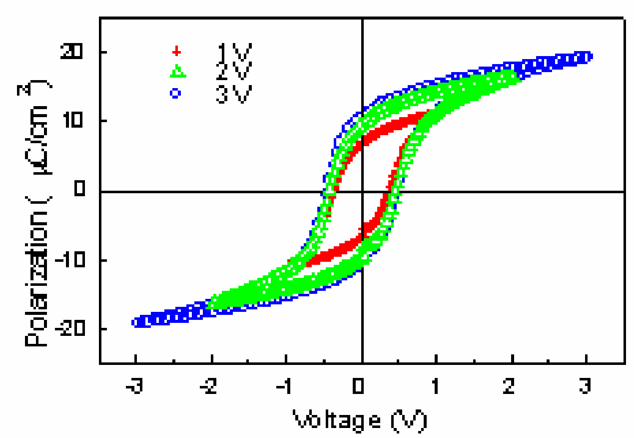


(b)



(c)

Physical properties modulated
Second-nonlinear optical, piezoelectric and electrooptic coefficients



A ferroelectric crystal is a material the direction of whose spontaneous polarization can be changed by an external electric field.

How to prepare a domain structure?

Growth striation method

Room temperature poling

Direct electron beam writing

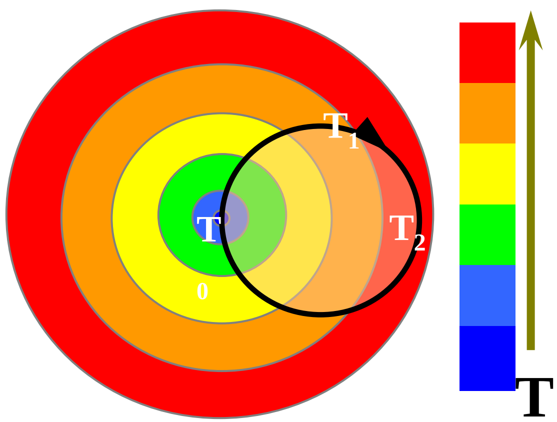
Atomic force microscopy

Scanning probe microscopy

focused ion beam

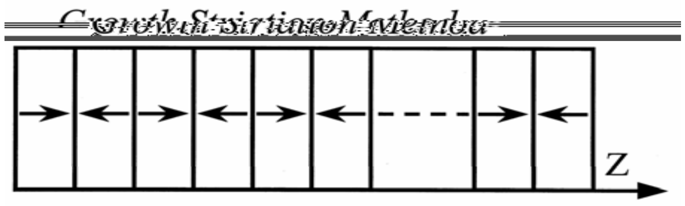
Growth Striation Method

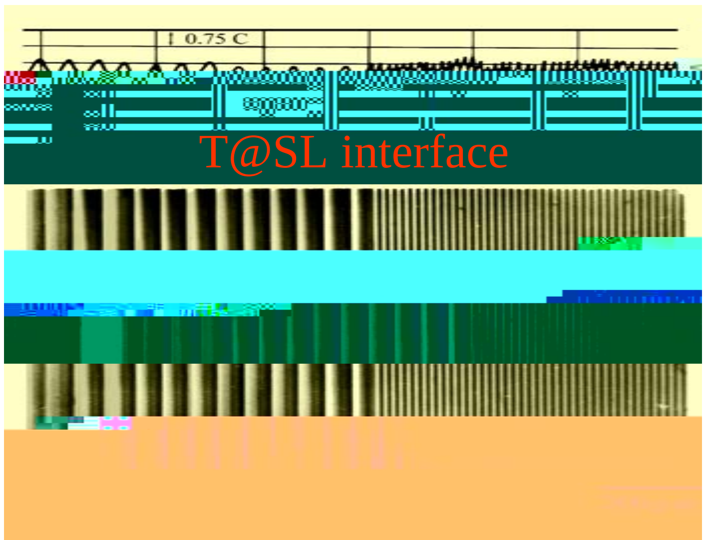
Temperature field



Periodic temperature fluctuation Ą periodic impurity concentration Ą periodic space charge field Ą periodic ferroelectric domain

First realized by Feng and Ming et al. in LN by the growth striation method



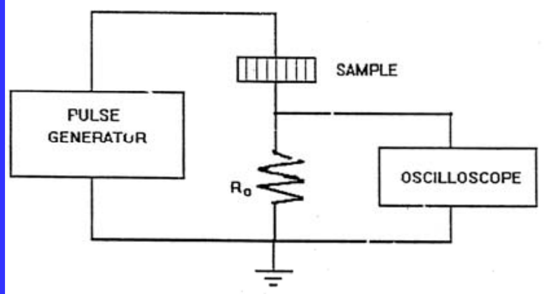


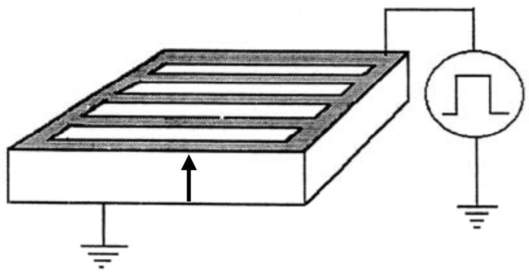
Temperature fluctuations measured on the solid-liquid interface and the corresponding surface rotational growth striations in a LN crystal

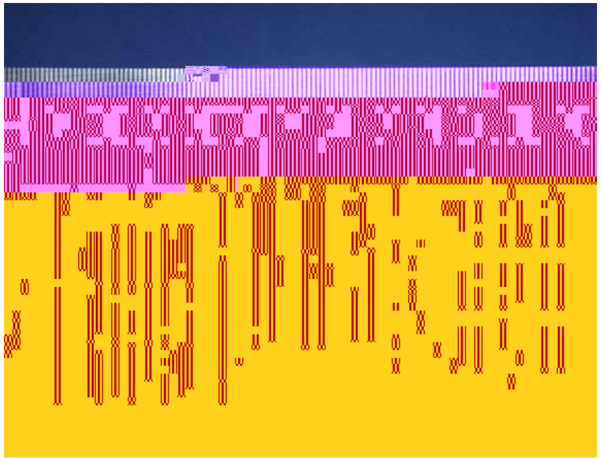
Ming et al., J.Mater.Sci.17, 1663 (1982)

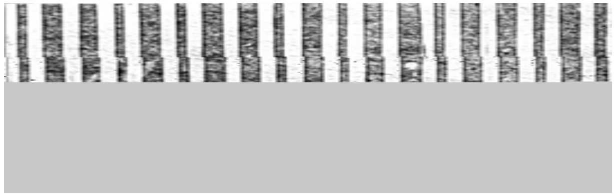
Room temperature poling

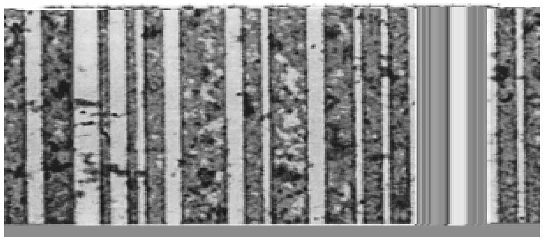
The room temperature poling technique: attracted much attention due to its capability to fabricate, when combined with photolithography, domain structures with any pre-designed patterns.











Schematic setup for domain engineering and optical micrographs of some samples with modulated ferroelectric domains

Physics of Dielectric: polarization

1. Electronic: arises from the displacement of the electron shell relative to a nucleus by E field
2. Ionic: comes from the displacement of a charged ion with respect to other ions by E field
3. Piezoelectric material: polarization due to strain
4. Orientational polarization

$$P \propto \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$$

QPM: Nonlinear optical effect

The light field is a harmonic function, such as $E\cos(\omega t)$. Trigonometric identitie allow a power

$$T_1 =$$

Piezoelectric effect: Acoustic transducer & Polariton

$$P_2 = -e_{22}(x)S_1 + \varepsilon_0(\varepsilon_{11}^S - 1)E_2$$

Content

- Introduction
- Piezoelectric superlattice

  Piezoelectric transducer

  Polariton   Superlattice vibration
- Polariton in a plasmonic crystal
- Conclusions

Piezoelectric effect

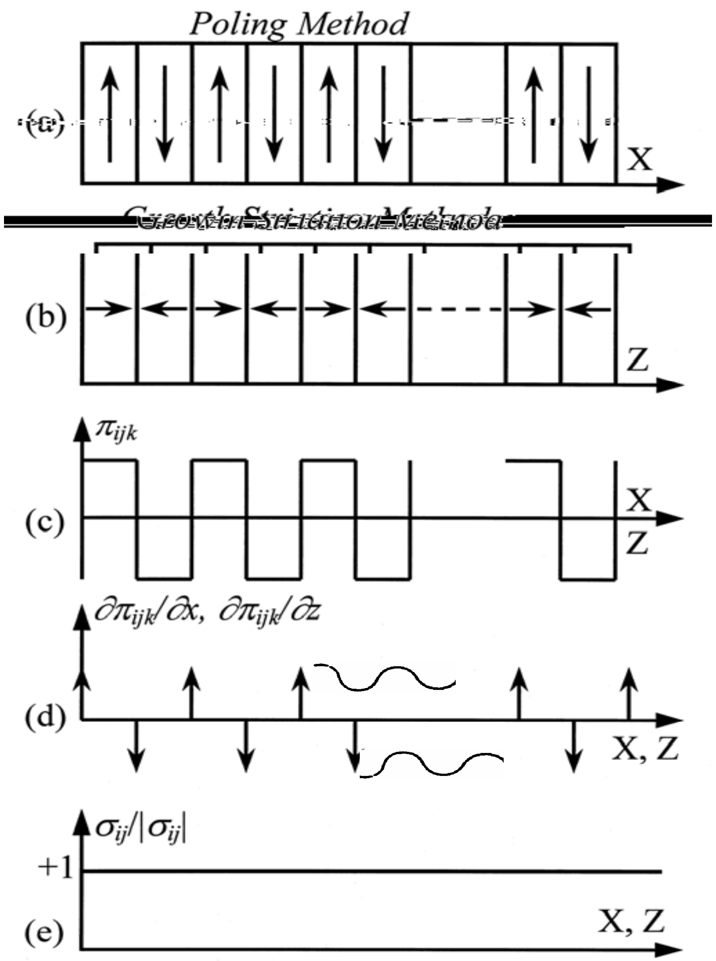
A piezoelectric material is a material that becomes electrically polarized when it is strained or that becomes strained when placed in an electric field.

Piezoelectric effect

that becomes strained when placed in an electric field.

Piezoelectric transducer

$$\frac{\partial^2 u_3}{\partial t^2} - \left(\frac{C_{33}^D}{\rho}\right)\frac{\partial^2 u_3}{\partial z^2} = D_3 \frac{\partial h_{33}}{\partial z}$$



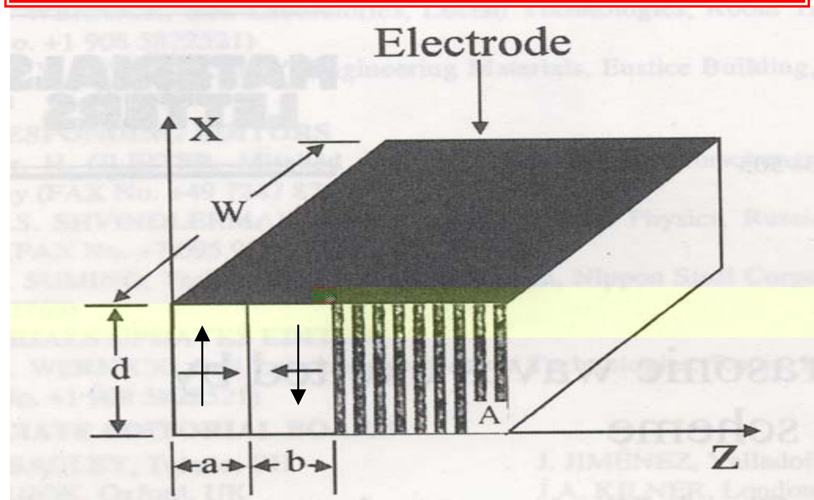
Domain walls → δ sources → Elastic waves → Constructive interference → Resonance

Physical basis for the ultrasonic excitation

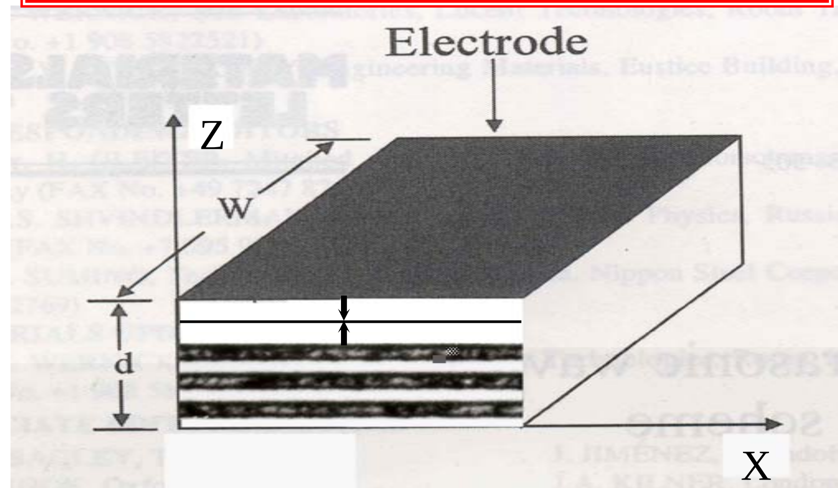
Resonance freq. depends on structure's periodicity, not on its total thickness.

Piezoelectric transducer

Crossed-field Scheme:
Electric field and propagation vector perpendicular



In-line field Scheme:
Acoustic propagation vector parallel to the applied electric field



High Frequency(GHz)

Resonators
Acoustic filters
Transducers

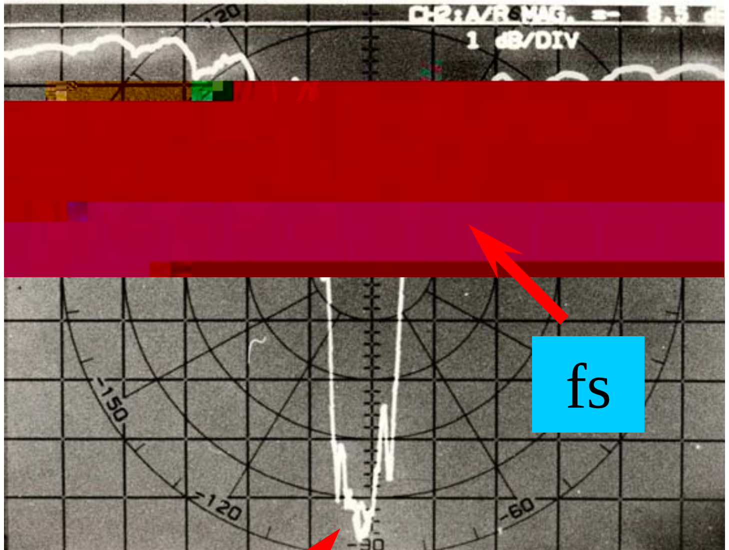
Resonator

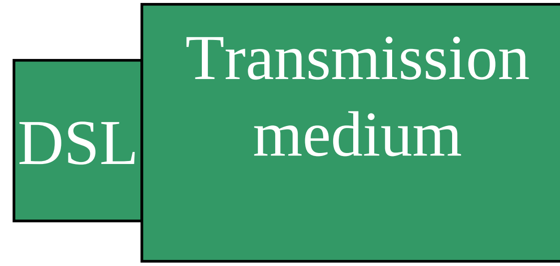
$$T(z=0)=T(z=N(a+b))=0$$

Transducer

$$T(z=0)=T(z\rightarrow\infty))=0$$

Piezoelectric transducer





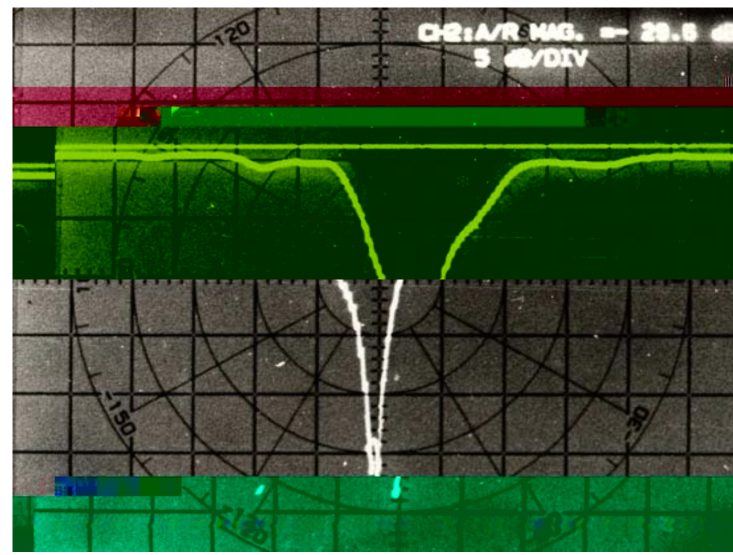
S: Satellite-like

$$f_{main} = v/(a+b)$$

$$(fs)^m = m f_{main}/2N$$

$$m = \pm 1, \pm 3, \pm 5 \ldots$$

N: Periods

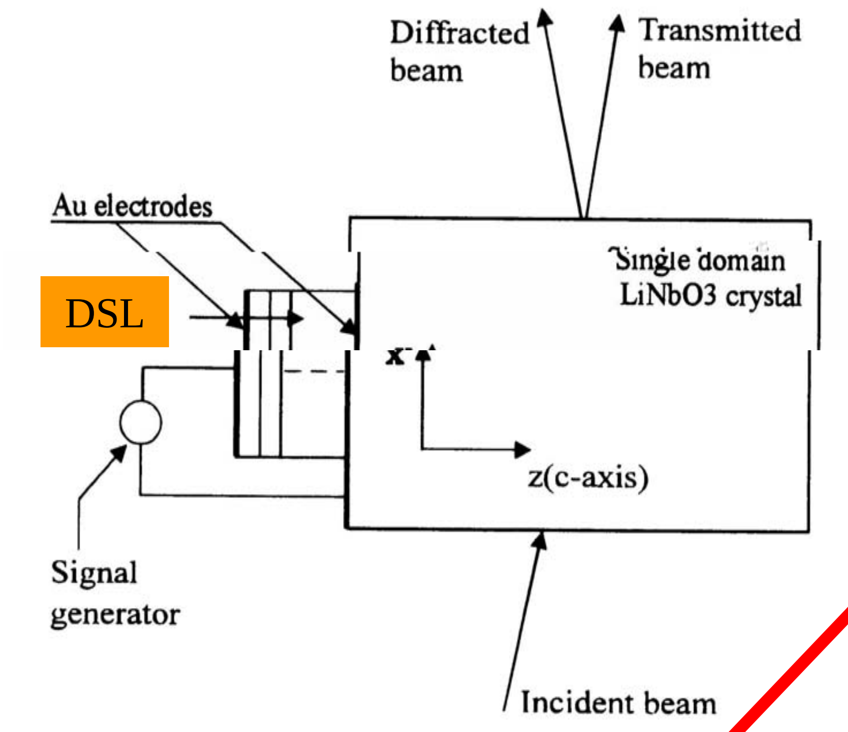


APL53, 1381 & 2278 (1988); JAP72, 904 (1992) & 79, 2221(1996)

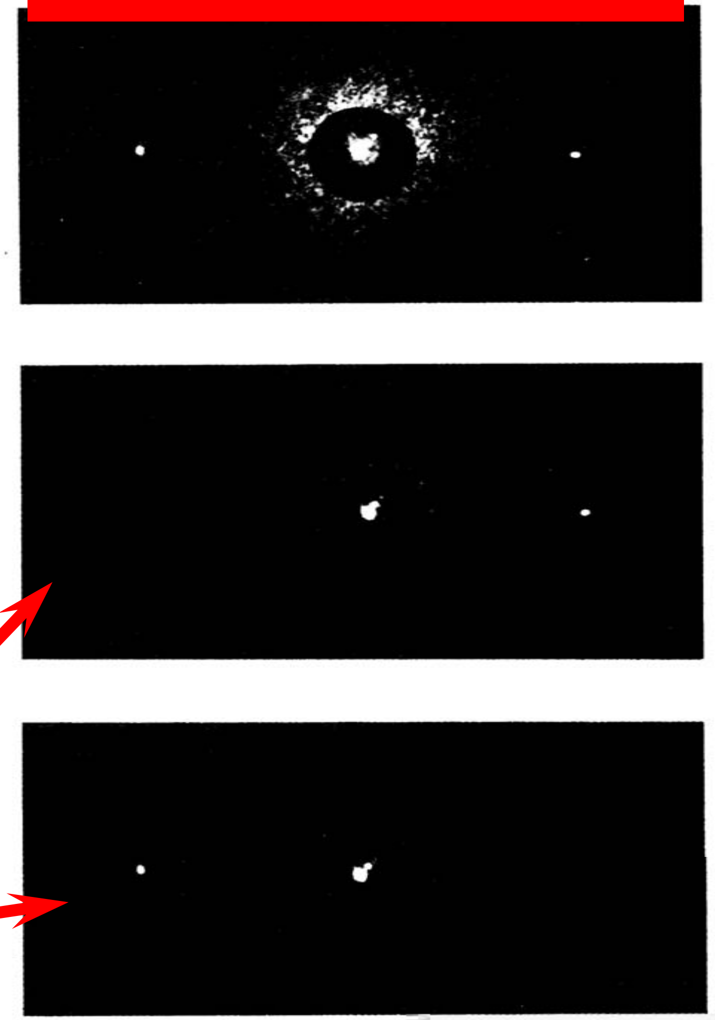
Acoustooptic Interaction

Bragg Angle

$$\sin \theta_B = \lambda_{Light} / (2n\Lambda_{Acoust})$$



Normal incidence



Incident at Bragg angle

Content

- Introduction
- Piezoelectric superlattice

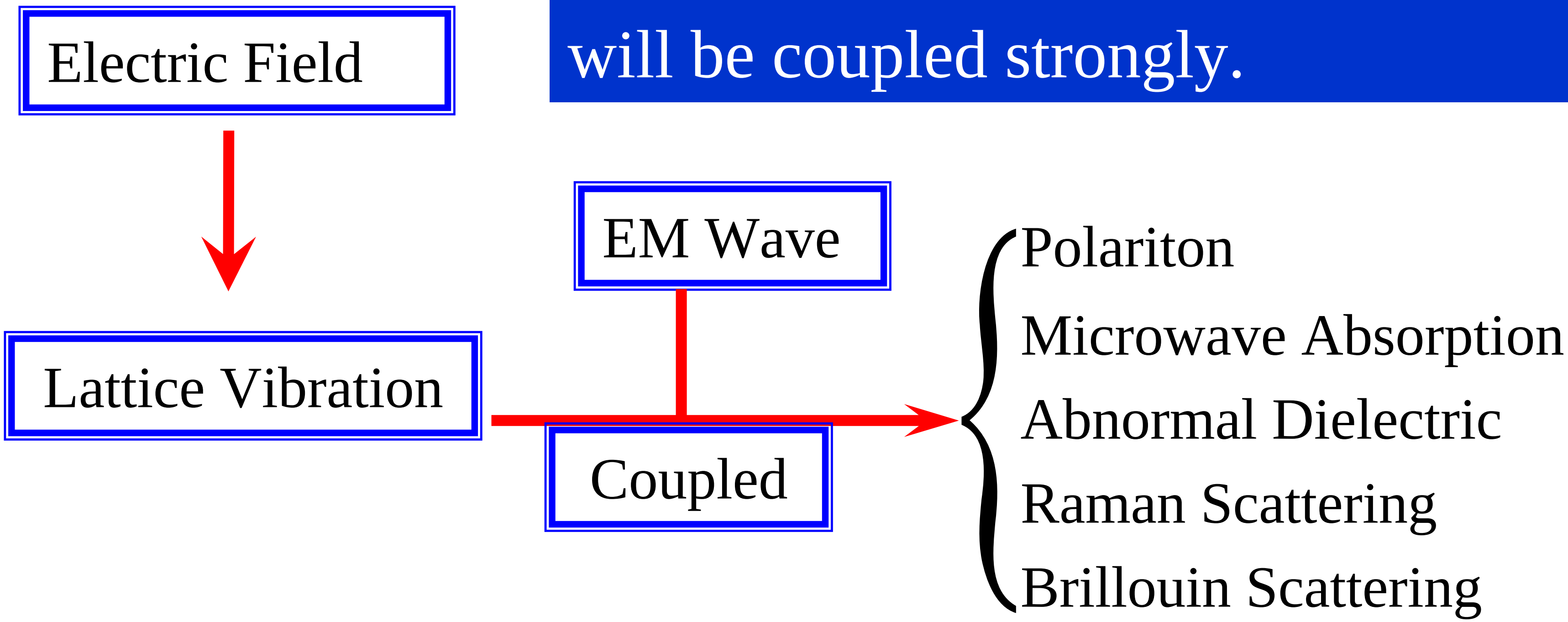
    Piezoelectric transducer

    Polariton   Superlattice vibration
- Polariton in a plasmonic crystal
- Conclusions

Piezoelectric effect

A piezoelectric material is a material that becomes electrically polarized when it is strained or that becomes strained when placed in an electric field.

In a piezoelectric material, the superlattice vibrations will induce electrical polarization. The laterally electrical polarization in turn will emit EM waves that interfere with the original EM wave. In such a case, lattice vibration and the EM wave will be coupled strongly.



Polariton

Polariton in piezoelectric superlattices

EM wave coupled strongly with

- **Transverse superlattice vibration**

  Science 284, 1822(1999)

- **Longitudinal superlattice vibration**

  PRL90, 053903 (2003) (Theoretical)
  PRB 69, 085118 (2004) (Exp.: periodic)
  APL 85, 3531 (2004) (Exp.: Quasiperiodic)

- **Piezoelectric-induced coupling of polaritons**

  PRL 94, 117401 (2005) (Theoretical)

Polariton

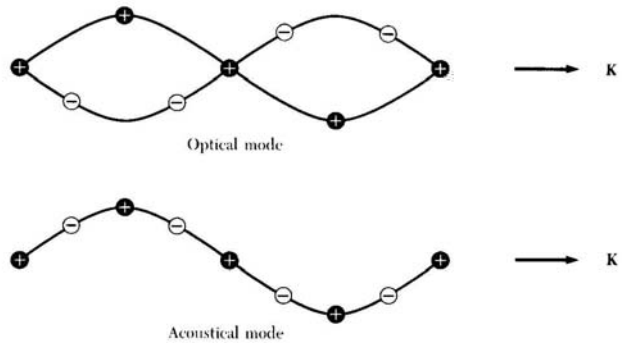


Figure 10 Transverse optical and transverse acoustical waves in a diatomic linear lattice, illustrated by the particle displacements for the two modes at the same wavelength.

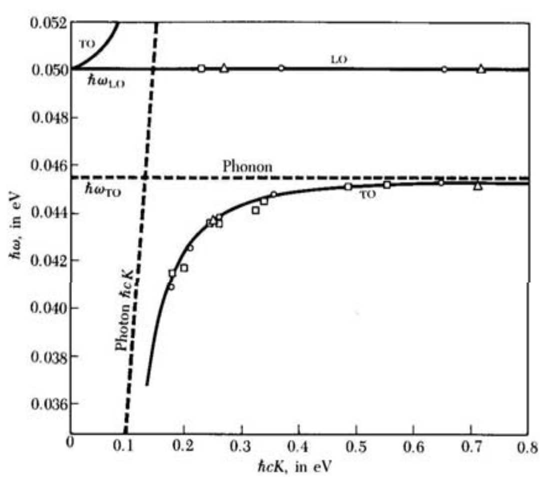
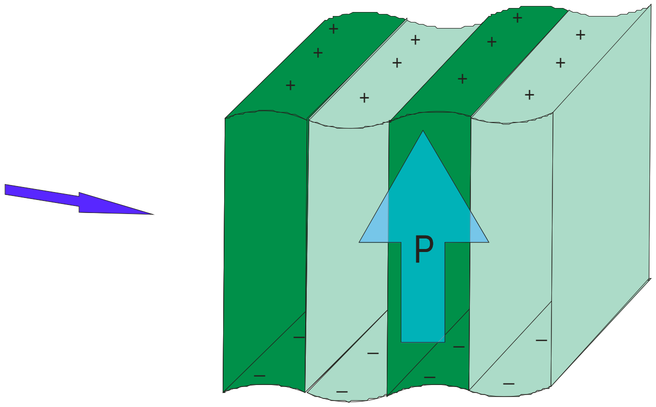
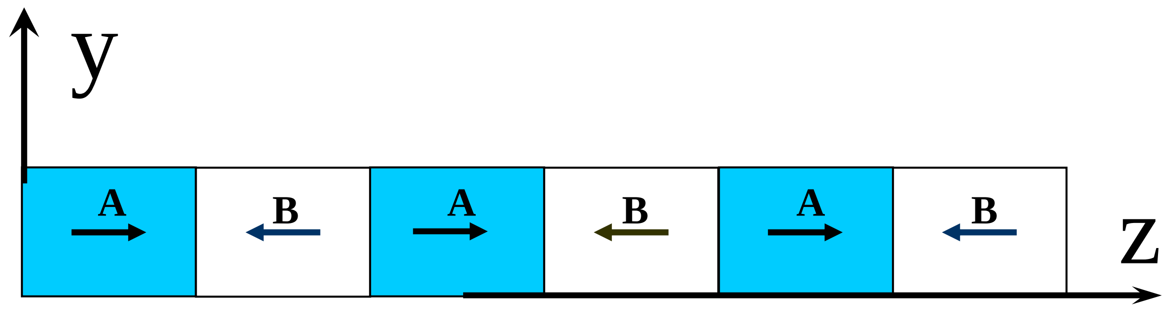


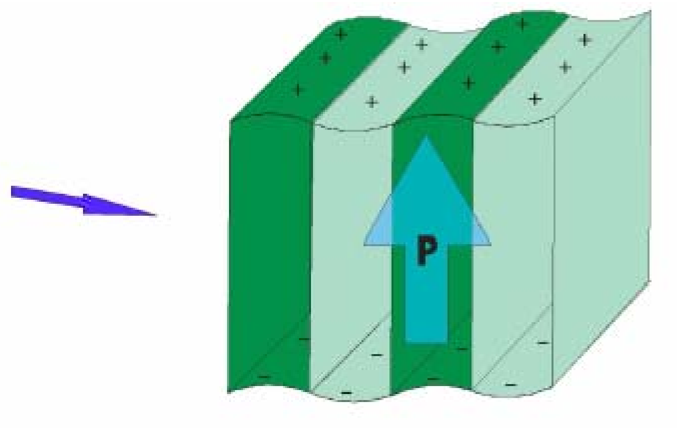
Figure 11 A plot of the observed energies and wavevectors of the polaritons and of the LO phonons in GaP. The theoretical dispersion curves are shown by the solid lines. The dispersion curves for the uncoupled phonons and photons are shown by the short, dashed lines. (After C. H. Henry and J. J. Hopfield.)

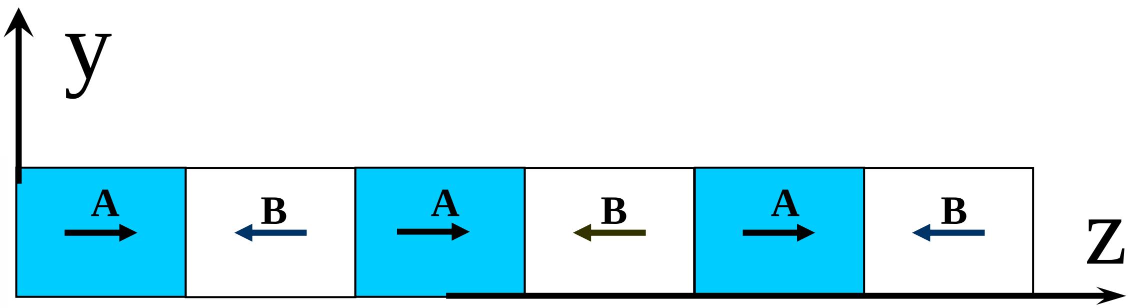
For lattice vibrations belonging to the transverse optical branches, the atoms carrying opposite charges vibrate against each other. This type of vibration can be excited by the electric field of a light wave.


P


y
A
B
A
B
A
B
Z

Piezoelectric equations



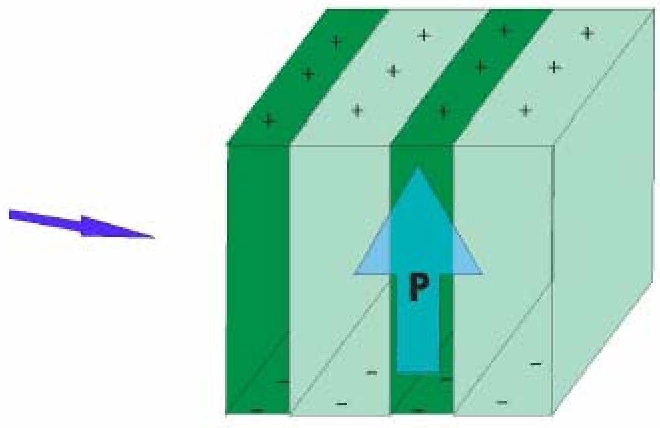


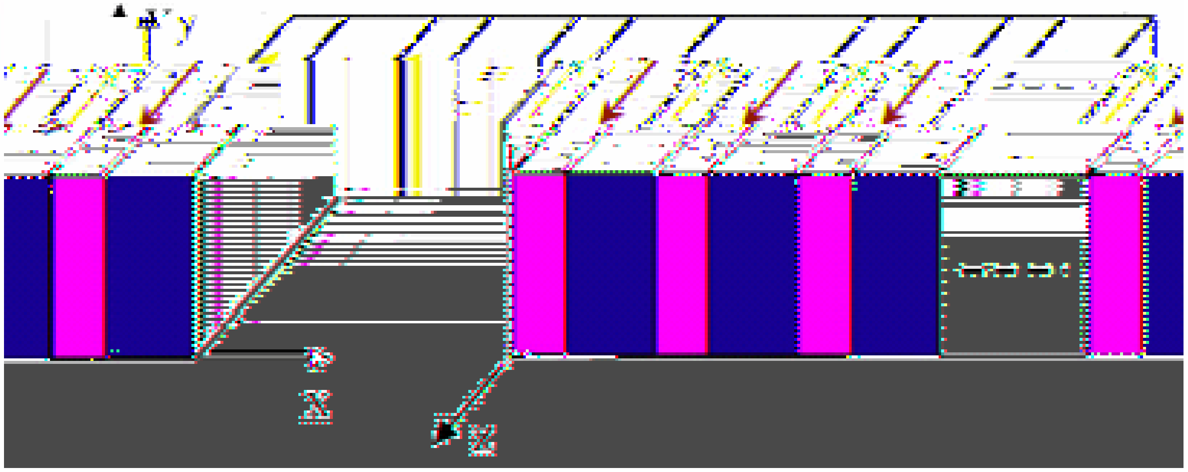
$$T_4 = C_{44}^E S_4 - e_{15}(x) E_2$$
$$P_2 = e_{15}(x) S_4 + \varepsilon_0 (\varepsilon_{11}^S - 1) E_2$$

A transverse acoustic wave propagating along the *z*-axis will be excited.

For this configuration, EM wave couples strongly with transverse superlattice vibration.

Piezoelectric equations



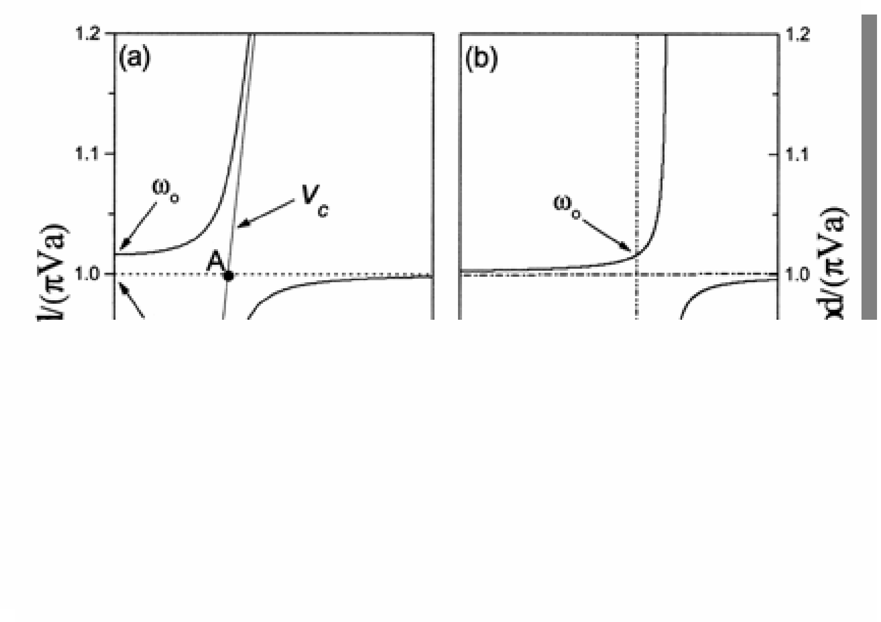


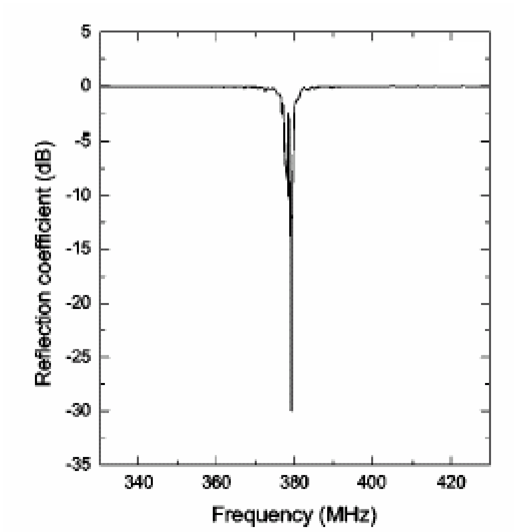
$$T_1 = C_{11}^E S_1 + e_{22}(x)E_2$$

$$P_2 = -e_{22}(x)S_1 + \varepsilon_0(\varepsilon_{11}^S - 1)E_2$$

For this configuration, a longitudinal superlattice vibration propagating along the *x*-axis will be excited.

Polariton





- At resonance, both energy conservation and momentum conservation are fulfilled.
- The photon-phonon coupling entirely changes the character of the propagation.
- Strong coupling induces a gap where EM waves are highly reflected.

PRL90, 053903 (2003)

$$\ddot{W}_2 = b_{11} W_2 + b_{12} E_2$$

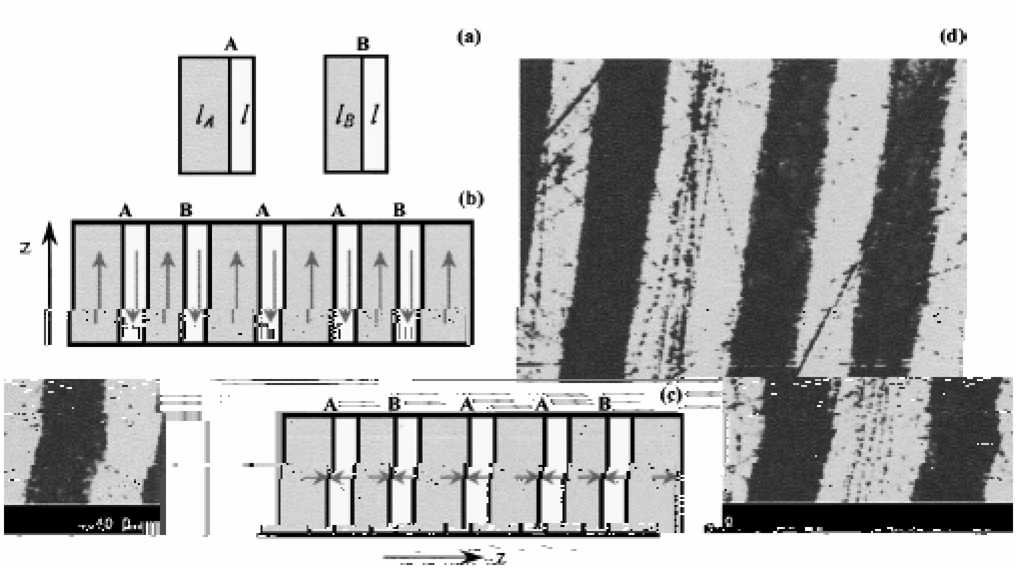
$$P_2 = b_{21} W_2 + b_{22} E_2$$

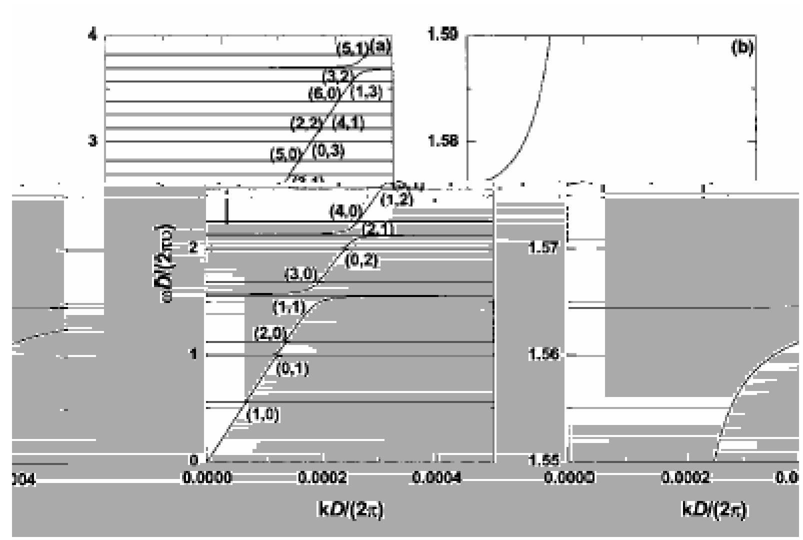
$$b_{11} = -\omega_m^2, \qquad b_{22} = \varepsilon_0(\varepsilon_{11}^S - 1),$$

$$b_{21} = \frac{4e_{15}}{\Delta}\sqrt{\frac{2}{\rho}}\,\sin(mD\pi) \qquad b_{12} =$$

$$U_2 \, W_2 = i\sqrt{2}\rho \, e^{\ldots}$$

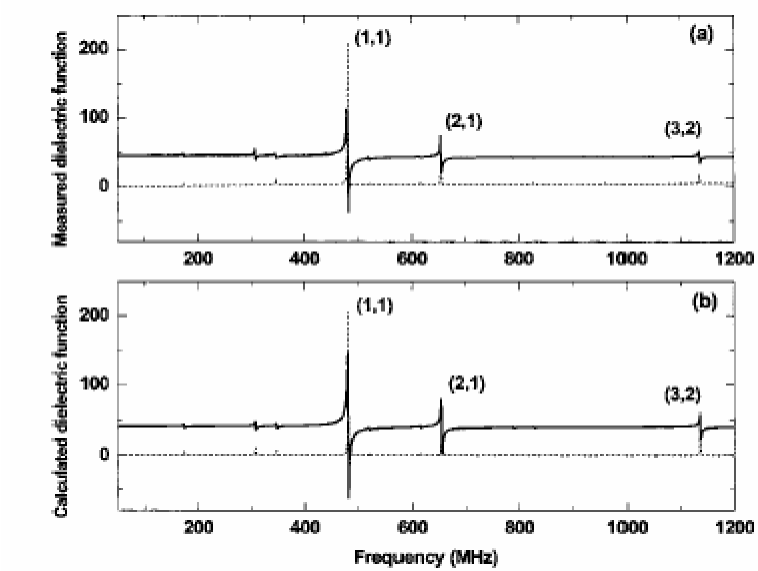
Polariton: Quasiperiodic structure





Polariton dispersion

Dielectric funct.



APL 85, 3531 (2004)

Piezo-coupling of polaritons

$$\begin{pmatrix} D_2 \\ D_3 \end{pmatrix} = \varepsilon_0 \begin{pmatrix} \varepsilon_{22}(\omega) & \varepsilon_{23}(\omega) \\ \varepsilon_{23}(\omega) & \varepsilon_{33}(\omega) \end{pmatrix} \begin{pmatrix} E_2 \\ E_3 \end{pmatrix}$$

$$\varepsilon_{22}(\omega) = \varepsilon_{11}^S + \frac{8e_{22}^2/d^2\rho\varepsilon_0}{\omega_L^2 - \omega^2 - i\gamma\omega}$$

$$\varepsilon_{23}(\omega) = -\frac{8e_{22}e_{31}/d^2\rho\varepsilon_0}{\omega_L^2 - \omega^2 - i\gamma\omega},$$

$$\varepsilon_{33}(\omega) = \varepsilon_{33}^S + \frac{8e_{31}^2/d^2\rho\varepsilon_0}{\omega_L^2 - \omega^2 - i\gamma\omega}$$

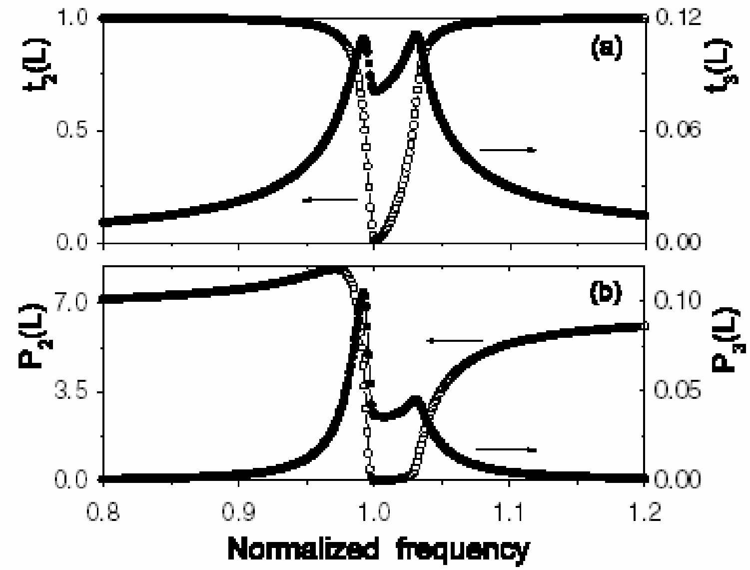


FIG. 3. Variation of the electric fields (a), and the PFD (normalized to $\frac{1}{2}\varepsilon_0 c|E_{20}|^2$) (b) with the frequency. The energy is transferred between E_2 and E_3 due to piezoelectric-induced coupling.

- **Two polariton modes**
- **Coupling related to piezo-effect**
- **Due to coupling, one mode has gap, the other one no gap**
- **Periodicity <<EM wavelength, subwavelength structure**

PRL 94, 117401 (2005)

Content

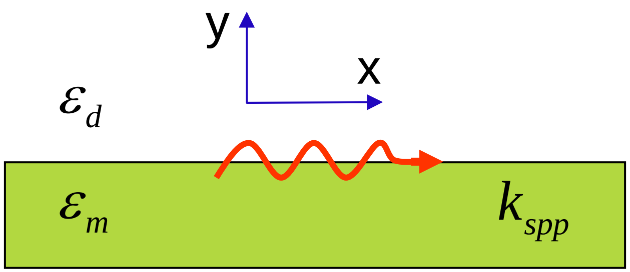
Plasmonic materials & Surface plasmon polariton

- Surface plasmon polariton (SPP)—**light on the metal surface**

Generally, the electrons cannot pass through an insulator, and the light cannot propagate in a metal:

$$k = (\omega / c)\sqrt{\varepsilon_m},$$

$$\varepsilon_m = 1 - \omega_p^2 / \omega^2$$

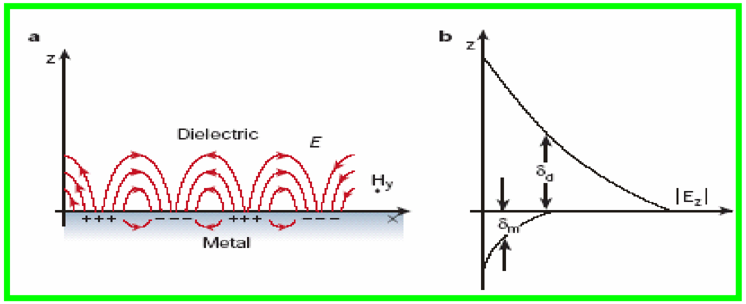


At the metal surface:

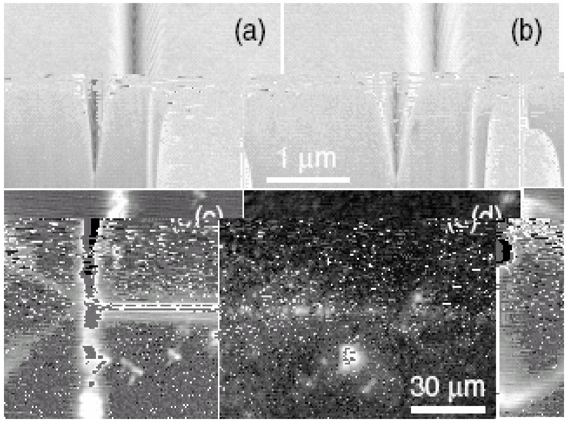
$$k_x = \sqrt{k_0^2 \varepsilon_m - k_y^2} > 0 \quad (k_y = i|k_y|)$$

- **SPP is a wave** that propagates along the metal surface but evanescent on either side, where the photons couple strongly with the surface charges.

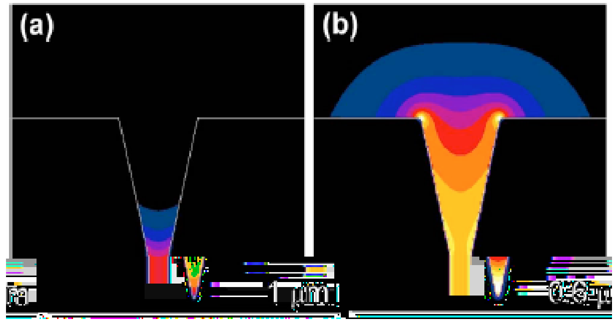
$$k_{spp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$

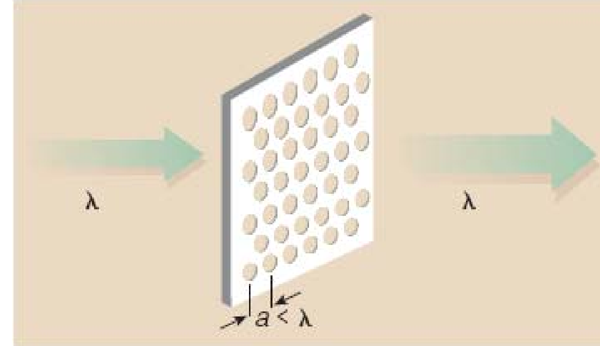


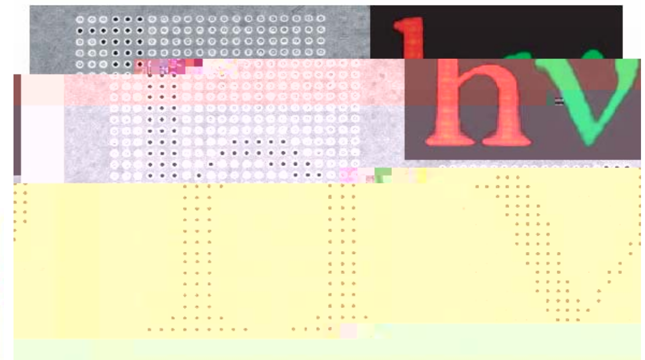
Novel effects & potential applications

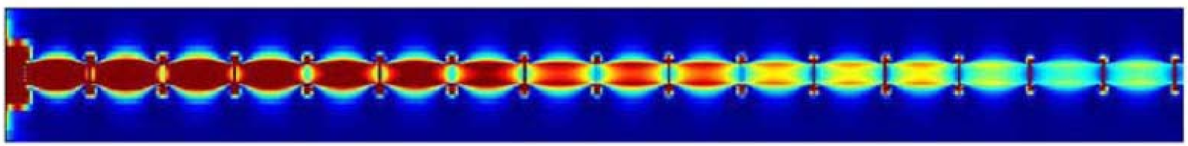


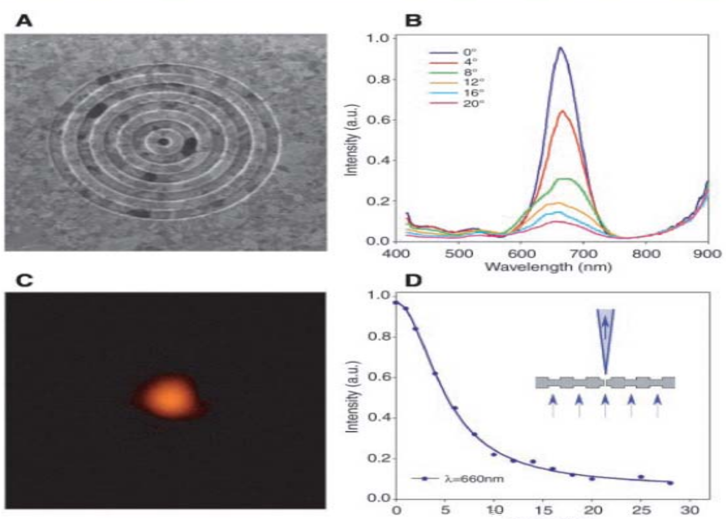
• Plasmonic waveguides

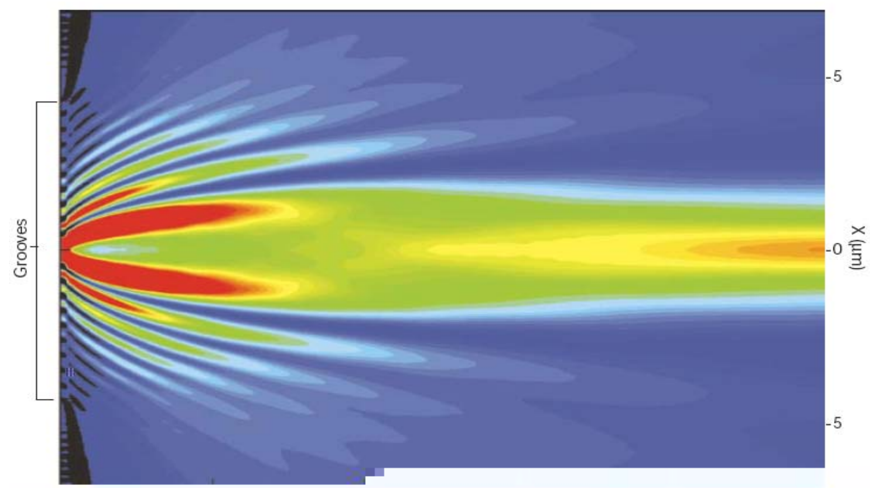






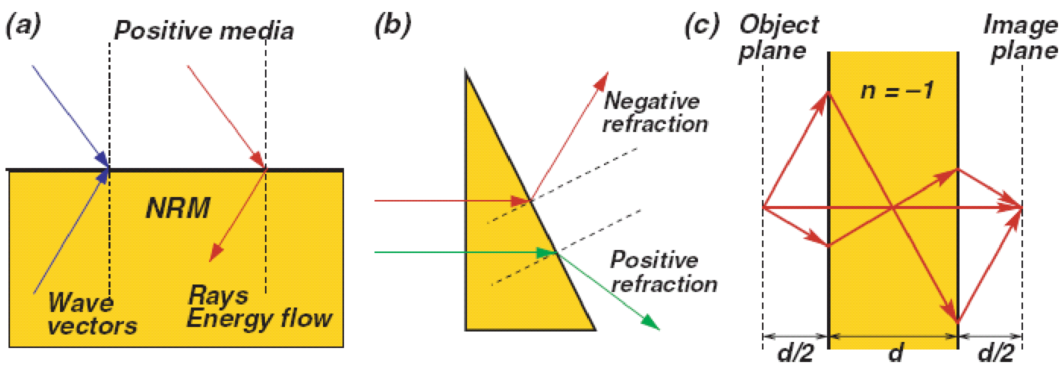


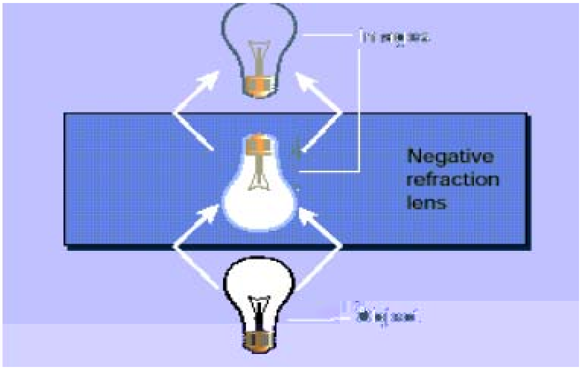


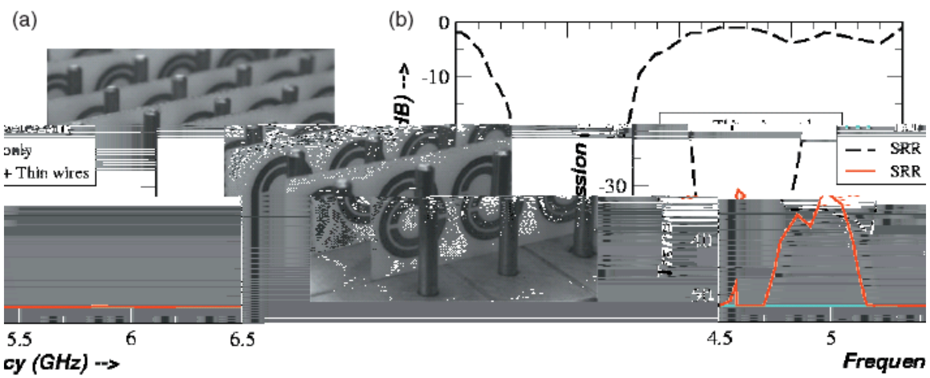


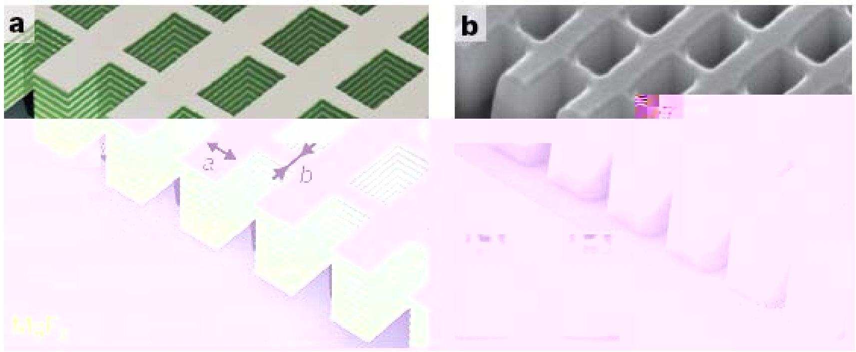
• Plasmonic transmission [Nature 391, 667 (1998) & Science 297, 820 (2002)]

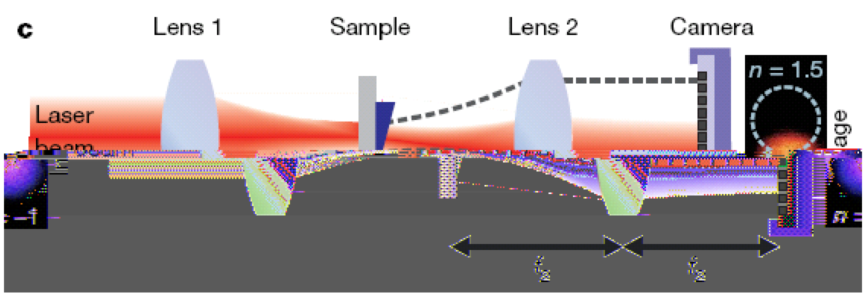
Novel effects & potential applications











Science 292, 77 (2001)

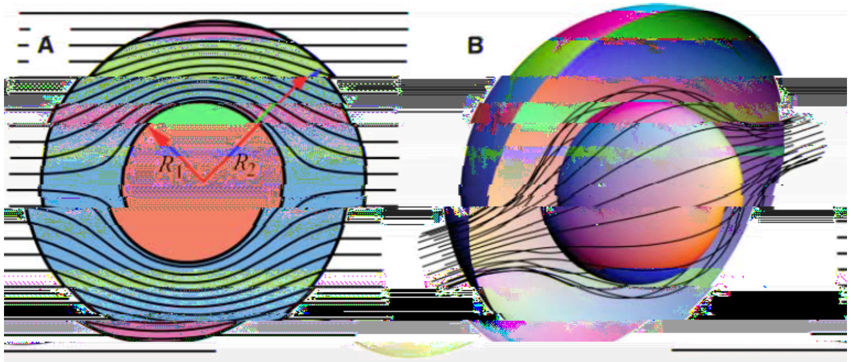
Nature 455, 376 (2008)

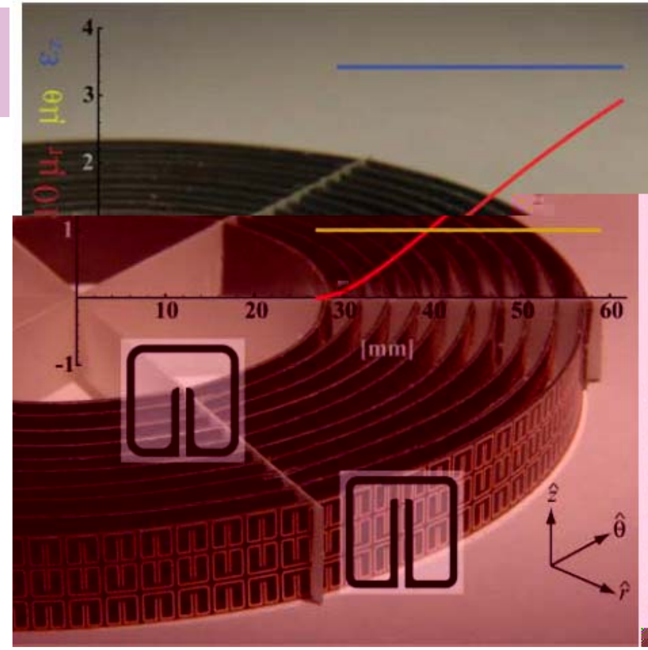
- **Negative refraction (perfect lens)**

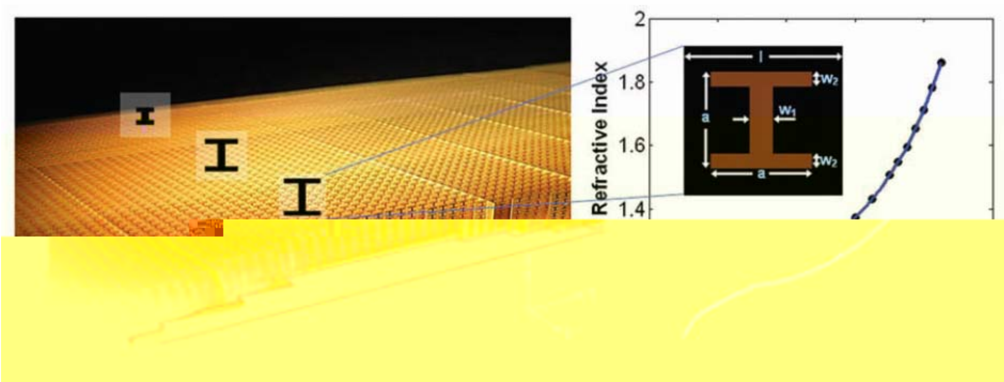
Metallic wire + SRR (microwave band)

Multilayer fishnet structure (optical freq.)

Novel effects & potential applications

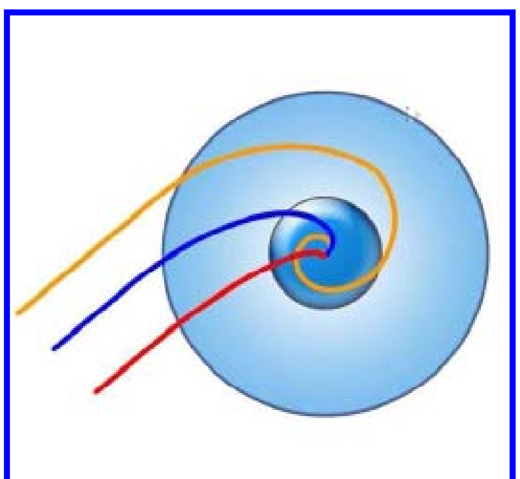




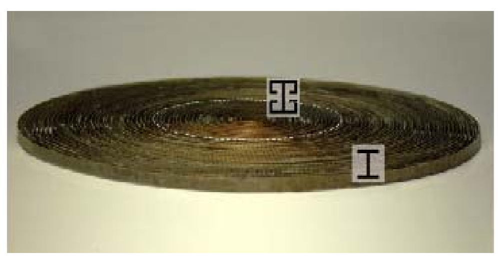


Science 2006 & 2009

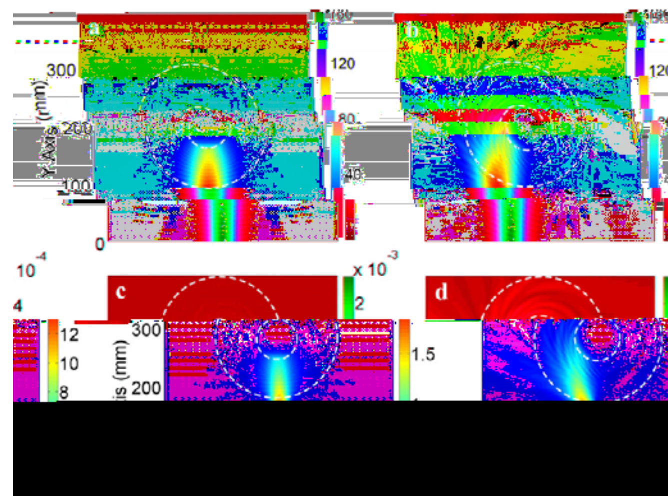
• **Cloaking with metamaterial**



N.J.Phys.12, 063006 (2010)

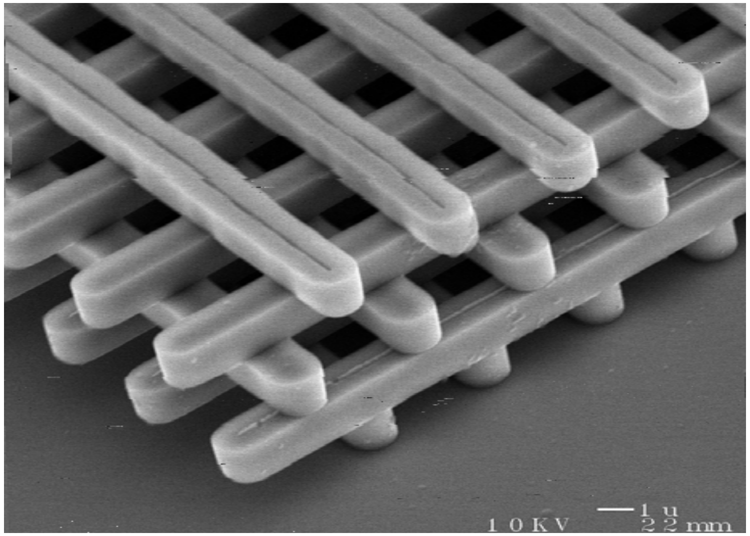


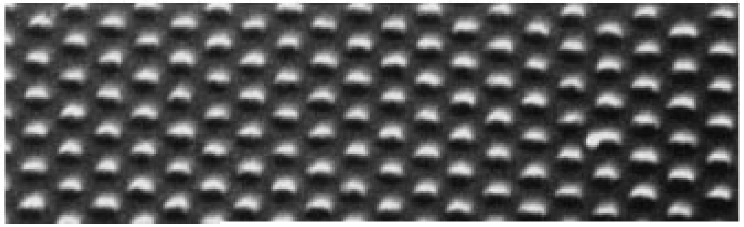
• **Optical black hole**



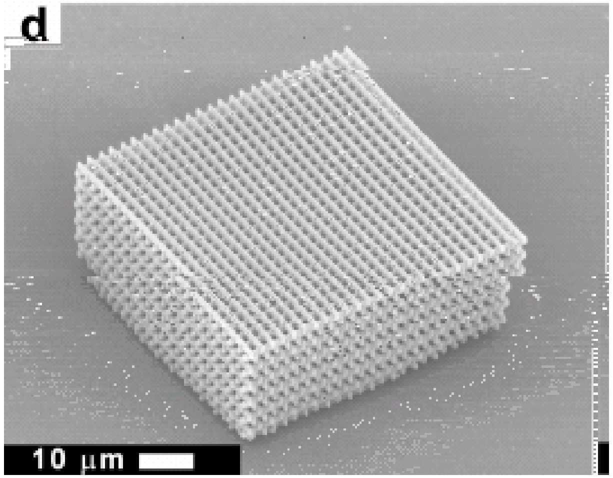
•Long-wavelength optical properties of a plasmonic crystal

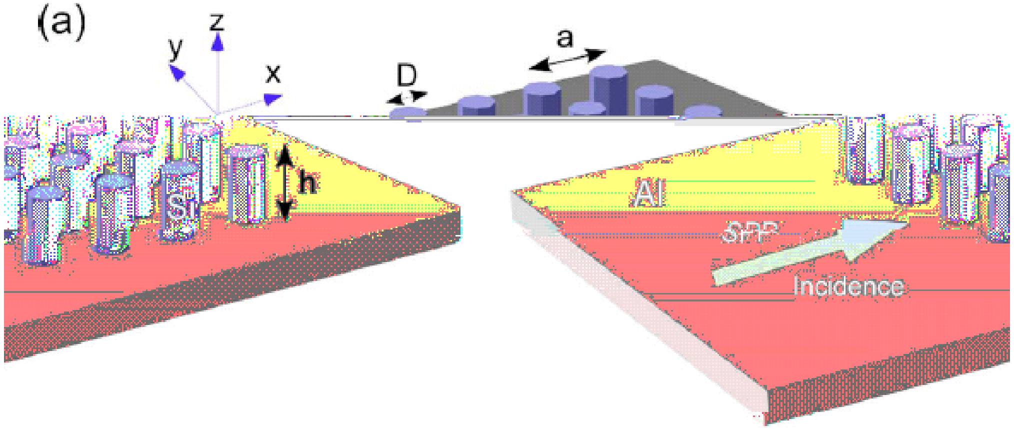
Stop band by Bragg reflection: photonic stop band





3D metal-dielectric PC



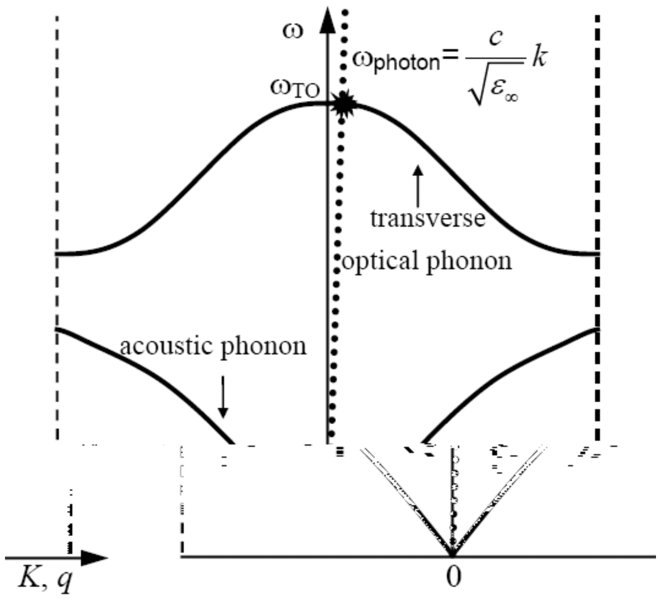


Kitson et al., Phys.Rev.Lett. 77, 2670 (1996)

Feng et al., Appl.Phys.Lett. 93, 231105 (2008)

Stop band by coupling effect: polaritonic stop band

Ionic crystal



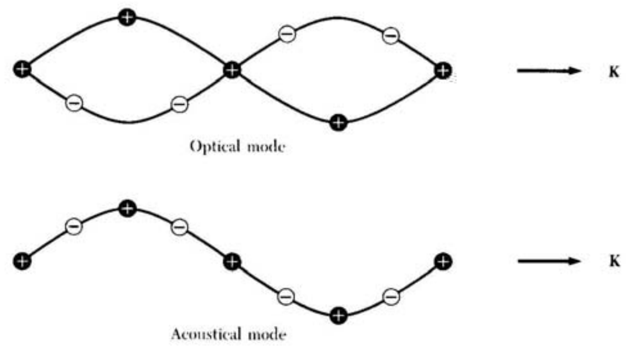
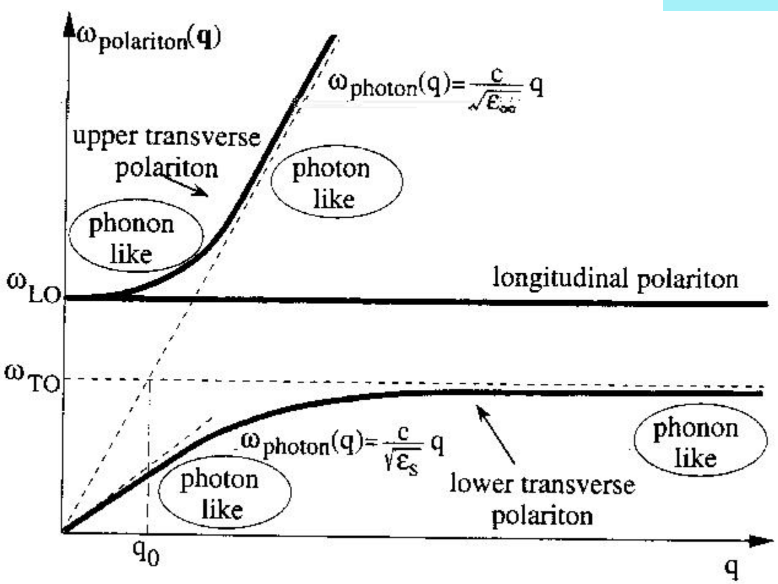


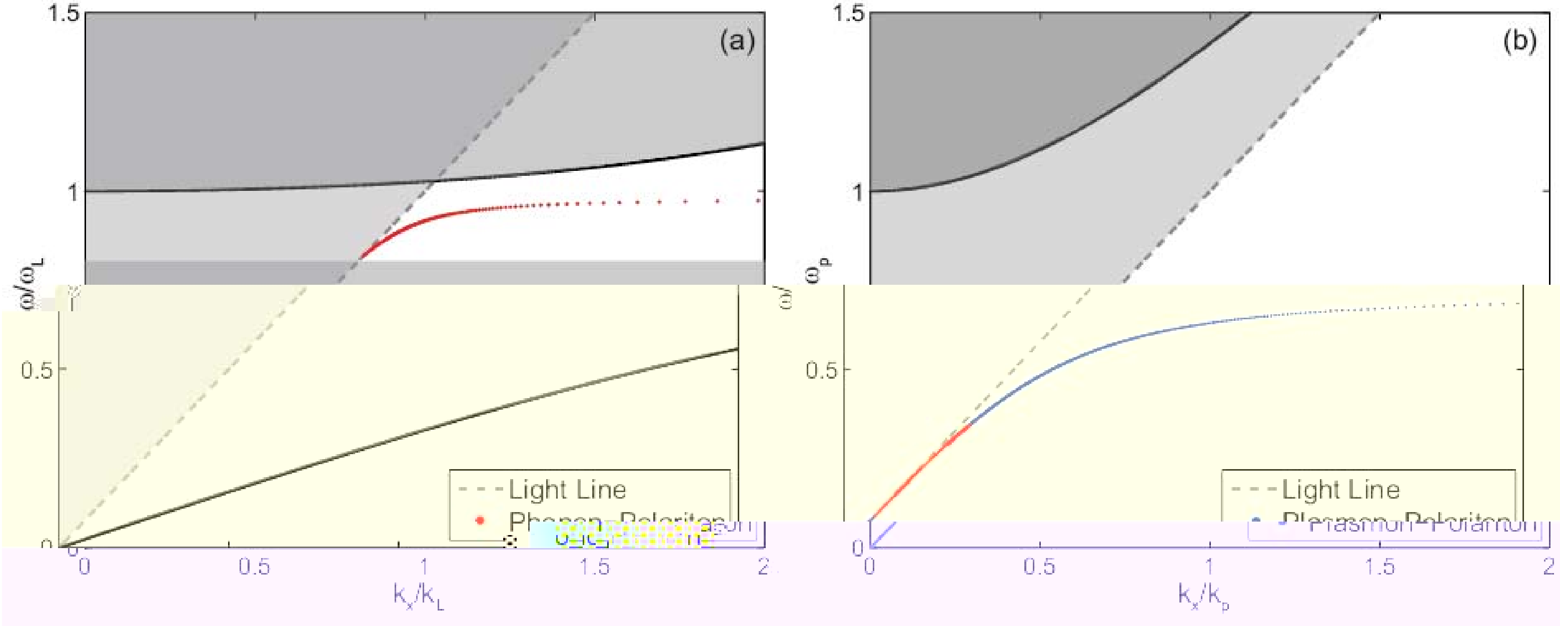
Figure 10 Transverse optical and transverse acoustical waves in a diatomic linear lattice, illustrated by the particle displacements for the two modes at the same wavelength.



Polariton is a mixed state of photon and polarization wave

In an ionic crystal, the strong coupling between the photons and transverse optical phonons leads to phonon polariton and a stop band.

Similarities between ionic and plasmonic crystals



$$k_{\mathrm{SPP}}(\omega) = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1(\omega)\varepsilon_2}{\varepsilon_1(\omega)+\varepsilon_2}},$$

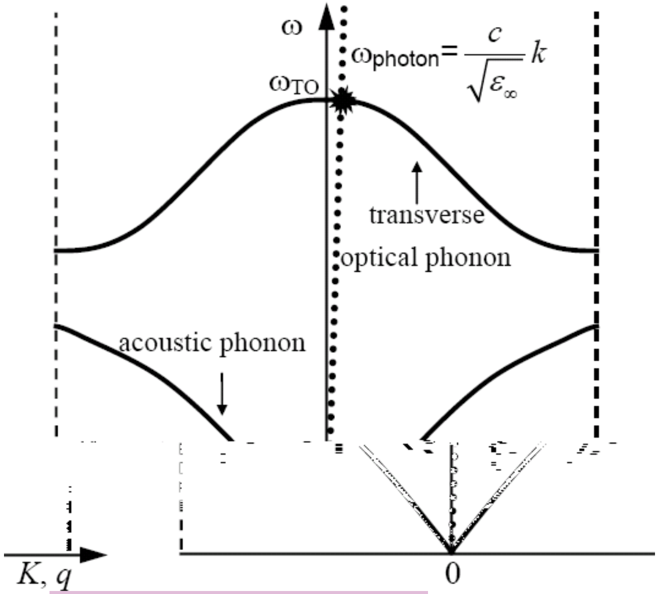
$$\varepsilon_1(\omega) = \varepsilon_\infty \frac{\omega_L^2 - \omega^2 + i\gamma\omega}{\omega_T^2 - \omega^2 + i\gamma\omega},$$

$$\varepsilon_1(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega+i\gamma)}.$$

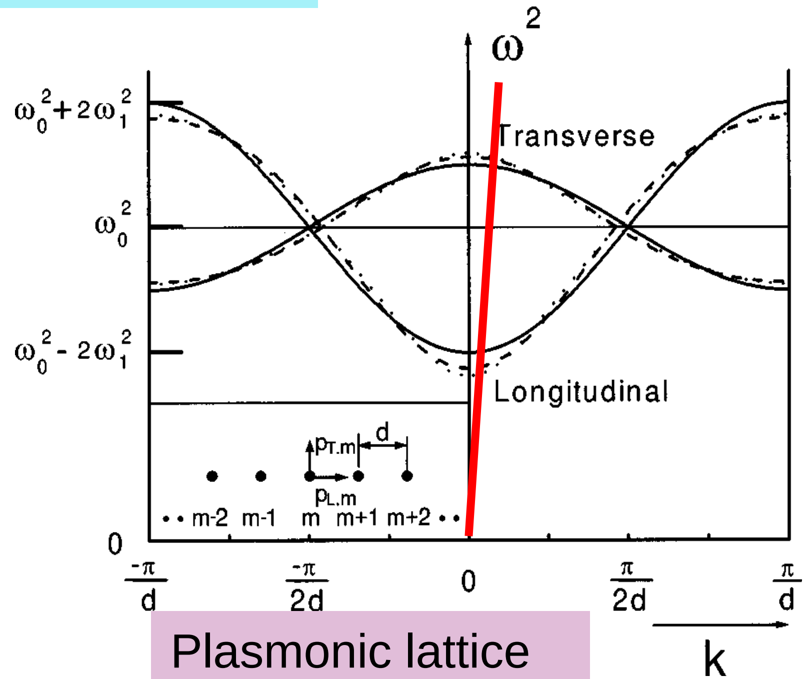
Surface modes: Surface phonon polariton & surface plasmon polariton

Enhanced transmission through perforated films ***[PRB 75, 075422 (2007)]***

Similarities between ionic and plasmonic crystals



Ionic lattice



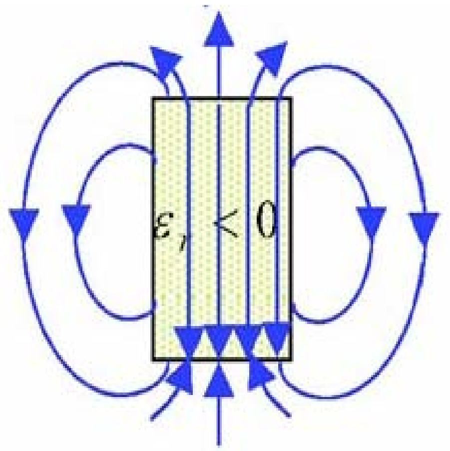
Plasmonic lattice

Ionic crystals	Plasmonic crystals
Lattice vibration	Plasma oscillation
Dipole moments	Dipole moments
Transverse optical waves	Transverse plasmon waves

Therefore, because of strong coupling between light and transverse plasmon wave (vibrations of free electrons), a bulk polariton mode can be present in a PC.

How to understand the electronic motion/plasmon resonance in the gold nanorod?

A) AC resistance



$$\nabla \times H = J + \frac{\partial P}{\partial t} + \varepsilon_0 \frac{\partial E}{\partial t} = \frac{\partial D}{\partial t},$$

$$D = \varepsilon_0 \varepsilon_m E,$$

$$\varepsilon_m = \varepsilon_\infty + \frac{i\sigma}{\varepsilon_0 \omega} = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}.$$

Conduction current is dominant in a metal!

$$m\ddot{r} = -eE - \gamma m \dot{r} \quad \Rightarrow \quad J = -nev = \sigma E \quad (\sigma = \frac{\sigma_0}{1 - i\omega\tau}, \quad \sigma_0 = \frac{ne^2\tau}{m})$$

$$R = \frac{1}{\sigma}\frac{l}{s} = \frac{1 - i\omega\tau}{\sigma_0}\frac{l}{s}$$

$$= \frac{l}{\sigma_0 s} - i\omega \frac{\mu_0 l}{k_p^2 s}$$

$$= R_0 - i\omega L_0$$

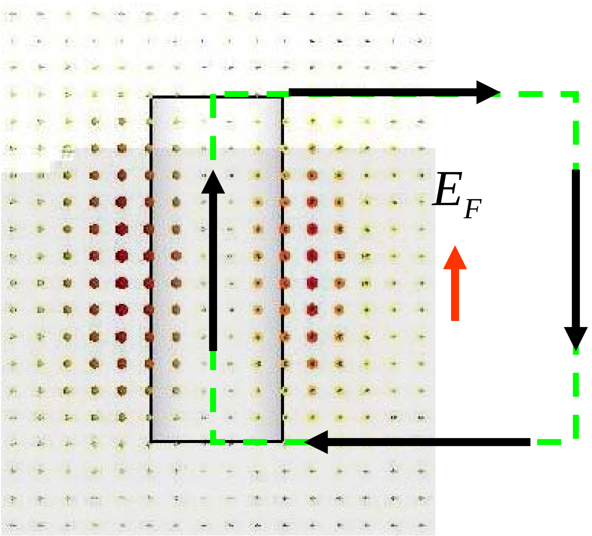
The electron mass/inertia plays a role of inductance!

$$W_e = \frac{1}{2}(nsl)mv^2$$

$$= \frac{1}{2}(nsl)m\left(\frac{I}{nes}\right)^2 = \frac{1}{2}L_0 I^2$$

$$L_0 = ml/ne^2 s = \mu_0 l / k_p^2 s.$$

B) Faraday inductance



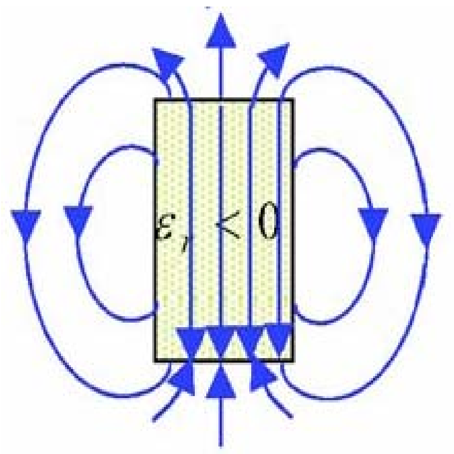
$$W_M = \frac{1}{2} L I^2 \quad \Rightarrow \quad L \approx \frac{\mu_0 l}{2\pi} \ln \frac{l}{2r_0}.$$

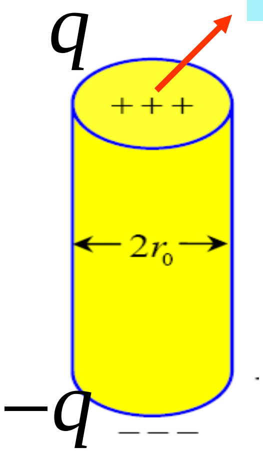
$$\mathcal{E}_F = E_F l = \oint E_F \cdot dl = -\frac{d\phi}{dt}$$

$$L = \phi / I \approx \frac{\mu_0 l}{2\pi} \ln \frac{l}{2r_0}.$$

$$E_F = -\frac{\partial A}{\partial t} \propto \frac{\partial I}{\partial t}$$

C) Capacitance





q / α

$$W_E = q^2 / 2C.$$

$$U_+ = -U_- = \frac{q/\alpha}{2\pi\varepsilon_0\varepsilon_d r_0}$$

$$C = \frac{q}{\Delta U} = \alpha\pi\varepsilon_0\varepsilon_d r_0.$$

Circuit theory:

$$\mathcal{E} = IZ \quad \Rightarrow \quad El = I(R - i\omega L - \frac{1}{i\omega C})$$

$$p \approx ql = \frac{\varepsilon_0 A}{\omega_0^2 - \omega^2 - i\eta\omega} E$$

Newton's equation:

$$m\ddot{z} = -e(E + E_C + E_F) - \gamma m \dot{z}$$

$$= -e(E - \frac{q}{Cl} - \frac{L}{l}\ddot{q}) - \gamma m \dot{z}$$

$$(q = -nesz)$$

$$(m + \sigma L)\ddot{z} = -(\sigma / C)z - \gamma m \dot{z} - Ee.$$

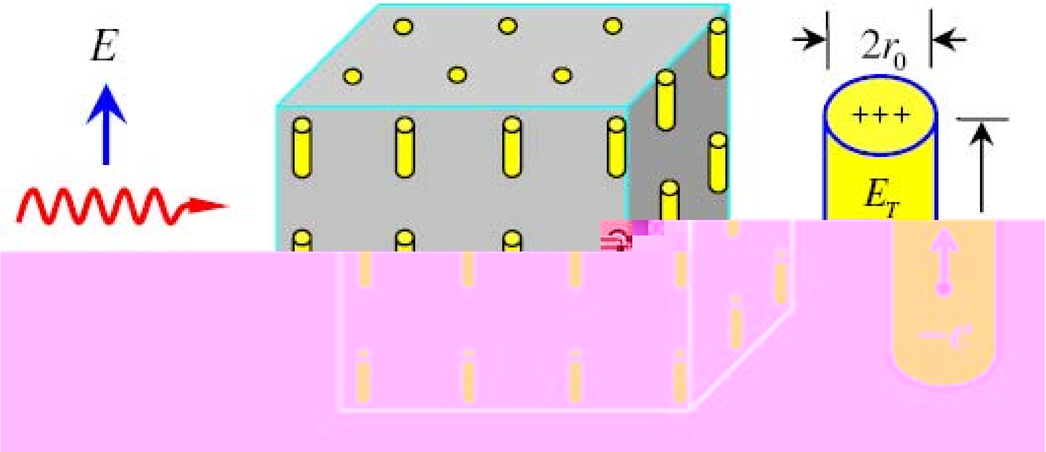
$$(\sigma = ne^2 s / l)$$

- **The free electrons act as forced harmonic oscillators (an effective restoring force & an increased electron mass)!**
- **The self-inductance plays a role of electron inertia!**

(The electron mass/inertia plays a role of inductance!)

OK!

Bulk plasmon-polariton in a plasmonic crystal composed of gold nanorod particles



$$\ddot{W} = -(\omega_o^2 - \frac{Q^2}{3\varepsilon_0\varepsilon_d M\Omega})W + \frac{Q}{(M\Omega)^{1/2}}E,$$

$$P = \frac{Q}{(M\Omega)^{1/2}}W + \varepsilon_0(\varepsilon_d - 1)E.$$

$$\ddot{W} = b_{11}W + b_{12}E,$$

$$P = b_{21}W + b_{22}E.$$

- We proposed that the HK equation, which was established originally for an ionic crystal where a strong coupling between the photons and lattice vibrations is present, may be extended to the plasmonic lattice (in the long-wavelength limit).

- Starting from the classical motion equation of free electrons, the governing equation for the plasmonic crystal has been deduced, showing indeed the same format as Huang's Equation.

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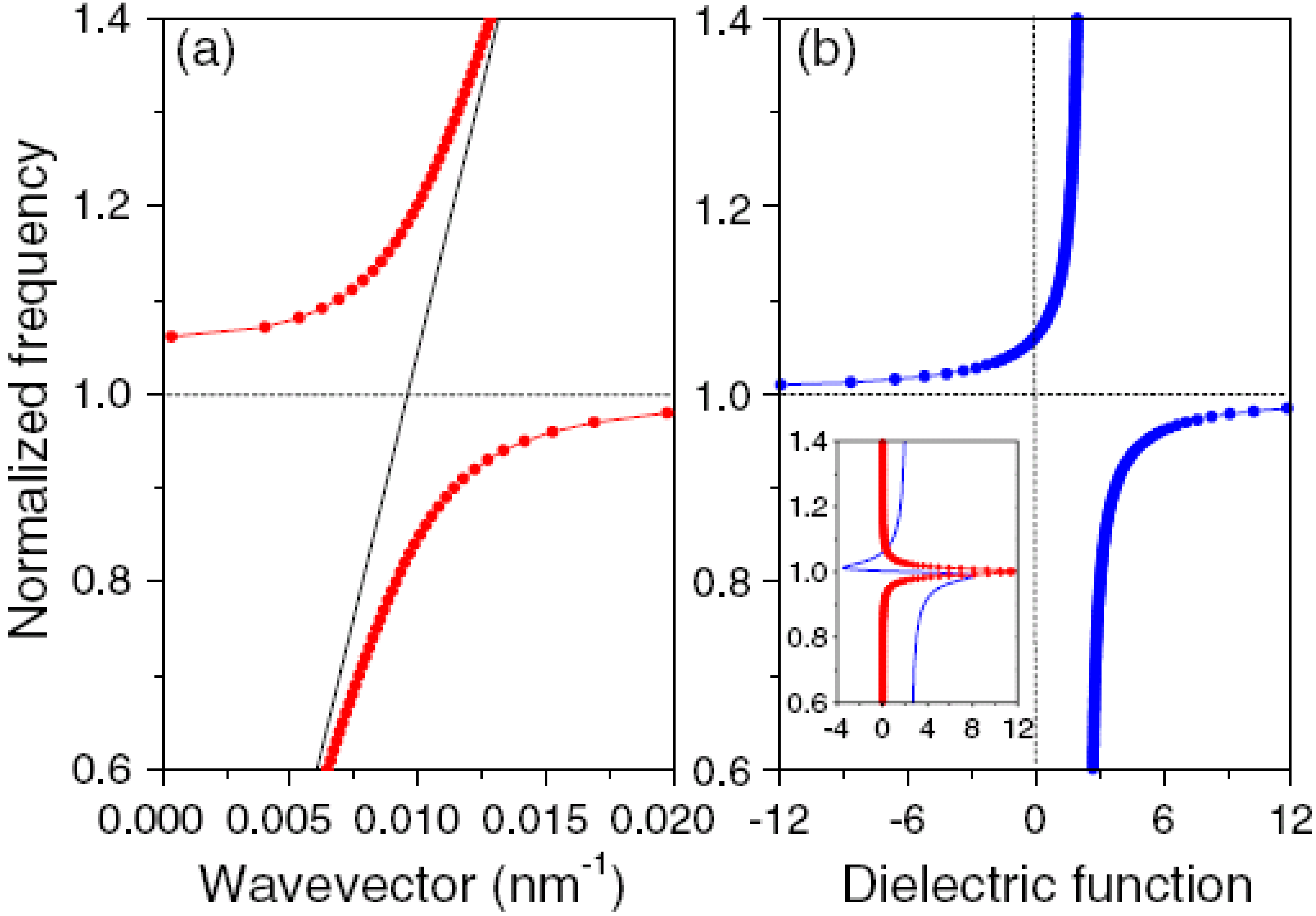
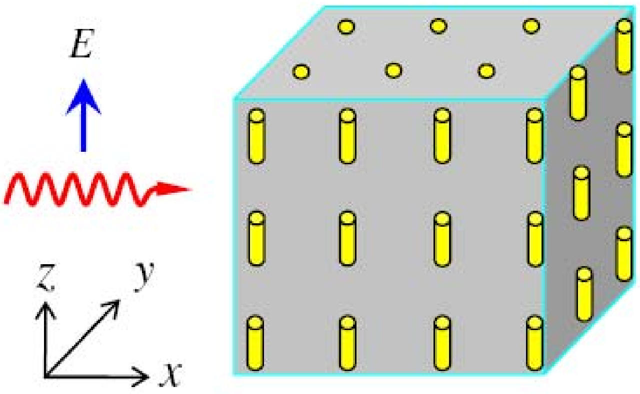


Because of the strong coupling, a polaritonic stop band is created.

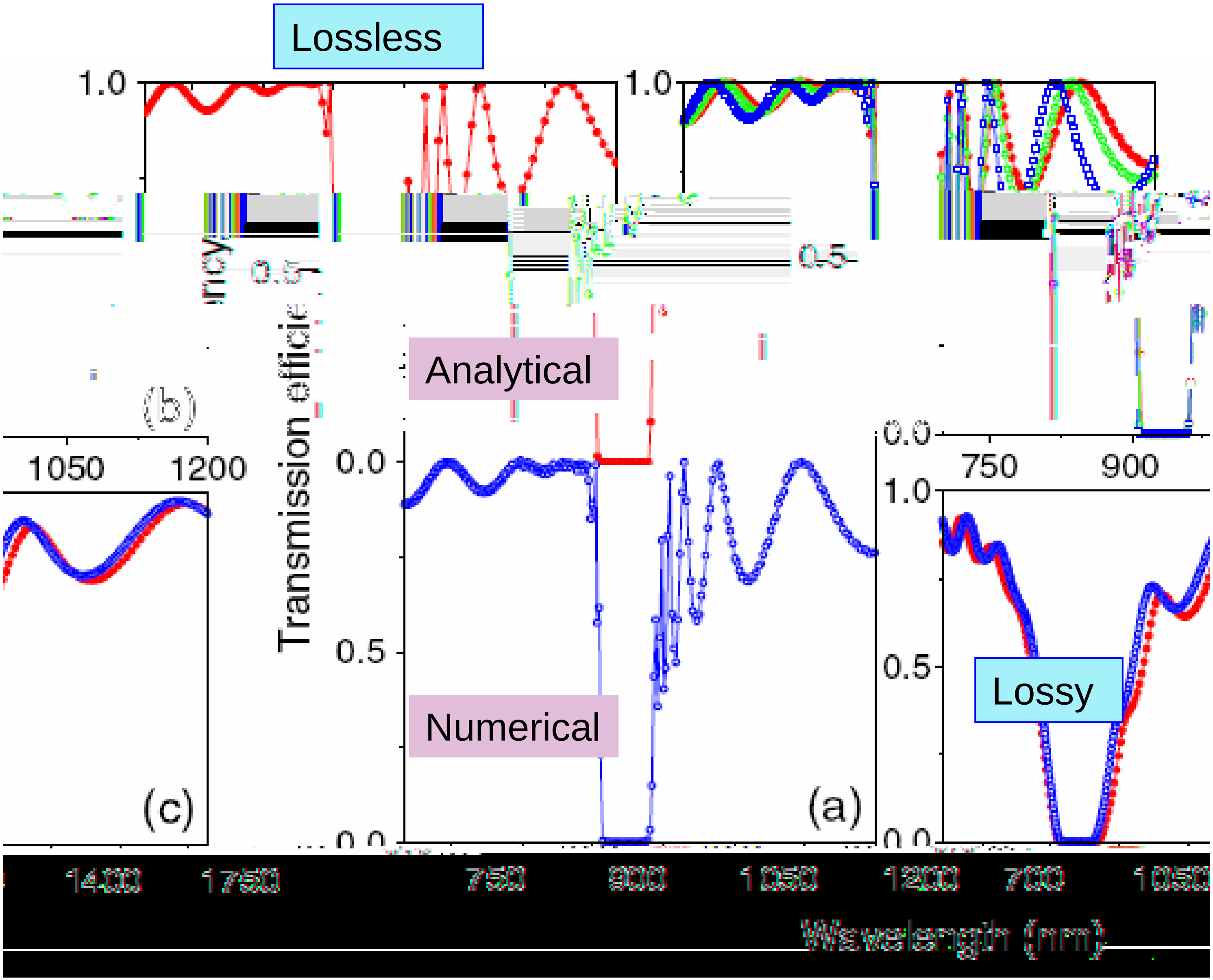
Analytical result vs numerical simulations

$$t = \left| \frac{4k_0 k \exp(ikh)}{(k_0+k)^2 - (k_0-k)^2 \exp(2ikh)} \right|^2 .$$

$$\frac{c^2 k^2}{\omega^2} = \varepsilon_d + \frac{fm/m_{eff}}{\omega_s^2 - \omega^2}\,\omega_p^2 ,$$



- To demonstrate the polariton effect, we have calculated the transmission spectrum of a plasmonic crystal film both analytically and numerically.
- The lattice constant is 80nm, the permittivity of host medium is 2.25, and the length and diameter of nanorod is 40nm and 10nm respectively (the film thickness is 1600nm, 20 unit-cell thick.



Lossless
Analytical
Numerical
Lossy
(a)
(b)
(c)
1.0
0.5
0.0
750
900
1050
1200
1400
1750
700
1050
Wavelength (nm)

conclusions

- Polariton: a mixed state of photon and polarization wave
- Stop band:

  by Bragg reflection: photonic stop band

  by coupling effect: polaritonic stop band

Thank you for your attention!