Magnons and Plasmons

Ferromagnetic magnons - simple cubic

The dispersion relation in one dimension:

$$\hbar\omega = 4J\left|S\right|\left(1-\cos(ka)\right)$$

The dispersion relation for a cubic lattice in three dimensions:

$$\hbar\omega = 2J\left|S\right|\left(z-\sum_{\vec{\delta}}\cos(\vec{k}\cdot\vec{\delta})\right)$$

The magnon contribution to thermodynamic properties can be calculated similar to the phonon contribution to the thermodynamic properties.

Magnons

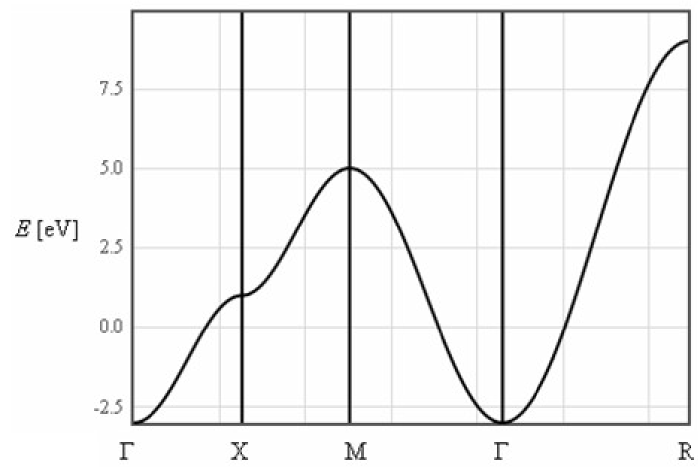
$$\hbar\omega = 2J\left|S\right|\left(z - \sum_{\vec{\delta}} \cos(\vec{k}\cdot\vec{\delta}) \right)$$

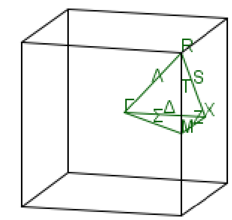
Dispersion relation is mathematically equivalent to tight binding model for electrons.

There is a maximum frequency analogous to the Debye frequency.

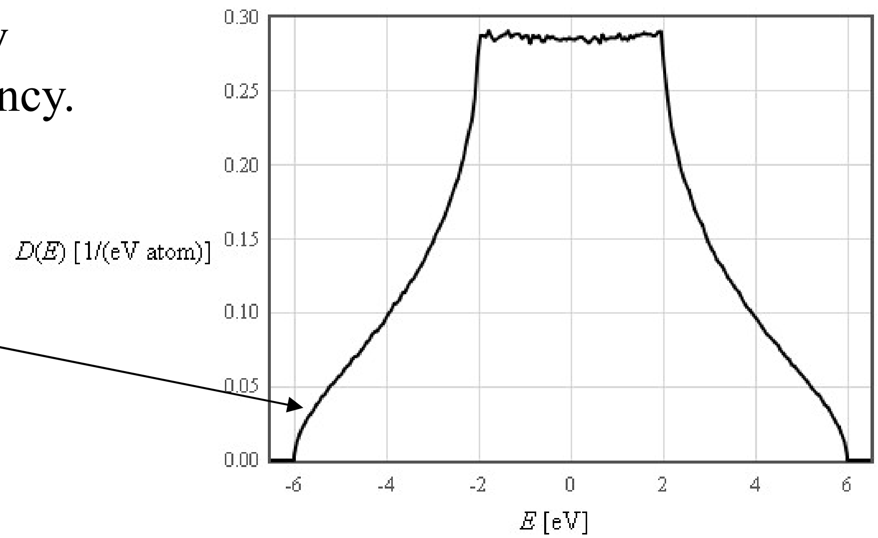
simple cubic 3-D

$$E = \varepsilon - 2t\left(\cos(k_x a) + \cos(k_y a) + \cos(k_z a)\right)$$





$\sqrt{\omega}$



Long wavelength / low temperature limit

Dispersion relation: $\hbar\omega \approx 2JSk^2a^2$

The density of states: $D(\omega) \propto \sqrt{\omega}$

Magnons are bosons: $\langle n_k \rangle = \dfrac{1}{\exp\left(\dfrac{\hbar\omega_k}{k_B T}\right) - 1}$

$$u = \int_0^\infty \frac{\hbar\omega D(\omega) d\omega}{\exp\left(\dfrac{\hbar\omega_k}{k_B T}\right) - 1} \propto T^{5/2}$$

$$c_v \propto T^{3/2}$$

Magnons

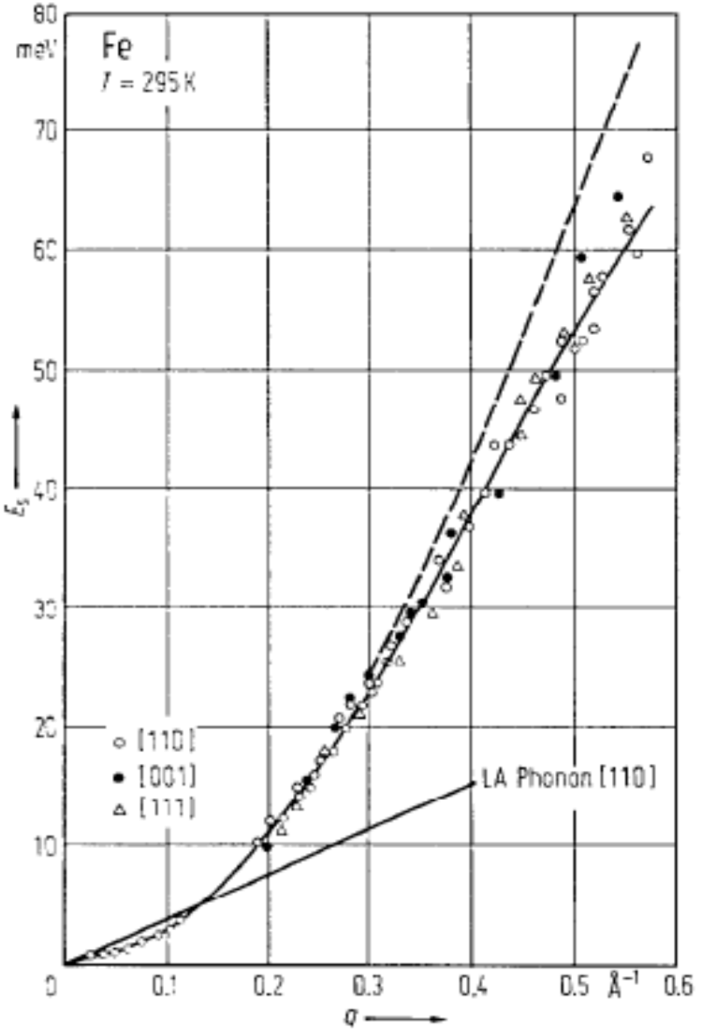


Fig. 1. Constant-E scan TAS-measured spin wave dispersion relation for various directions in a single crystal of Fe at 295 K. The dashed line corresponds to the Heisenberg model with $D = 281$ meV Å^2 and $\beta = 1.0$ Å^2 [68 S 3], see also [73 M 1].

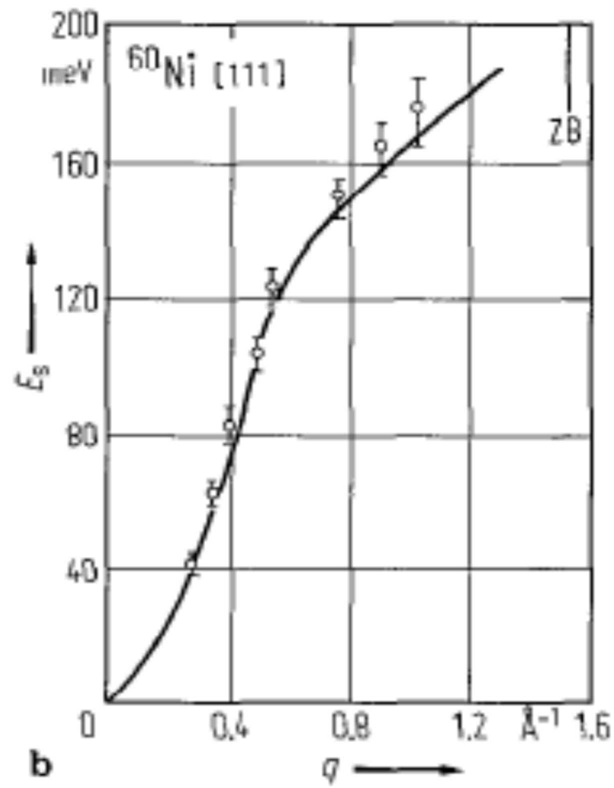
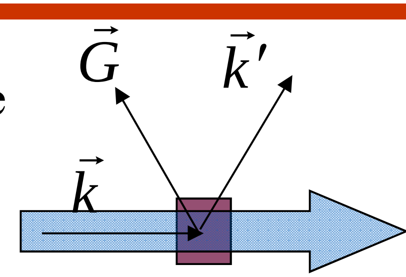


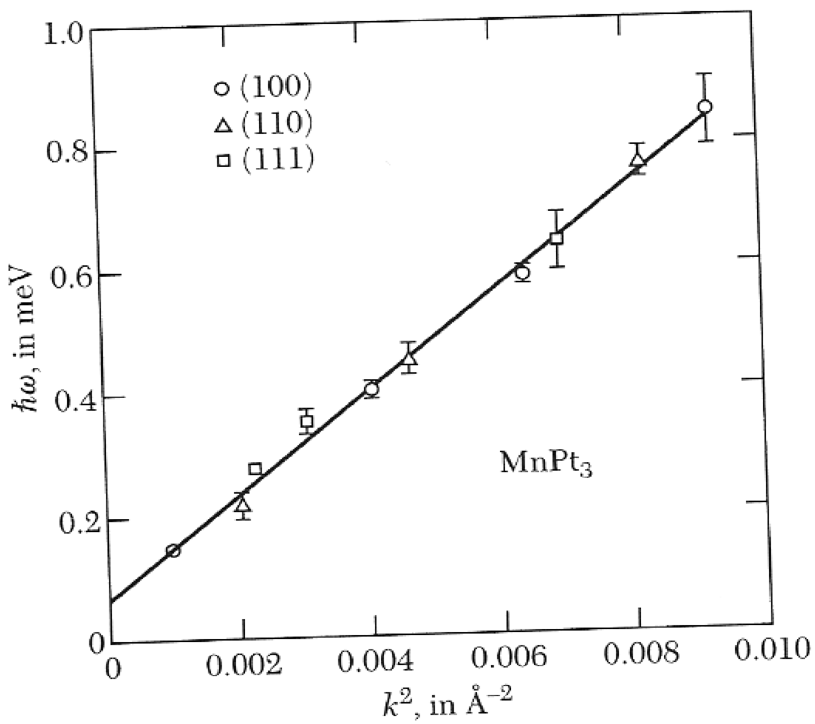
Fig. 6b. Room-temperature spin wave dispersion curve for the [111] direction of ^{60}Ni. ZB shows the position of the zone boundary [85 M 1]. The solid curve is from calculations [85 C 1, 83 C 1].

Neutron magnetic scattering

Neutrons can scatter inelastically from magnetic material and create or annihilate magnons

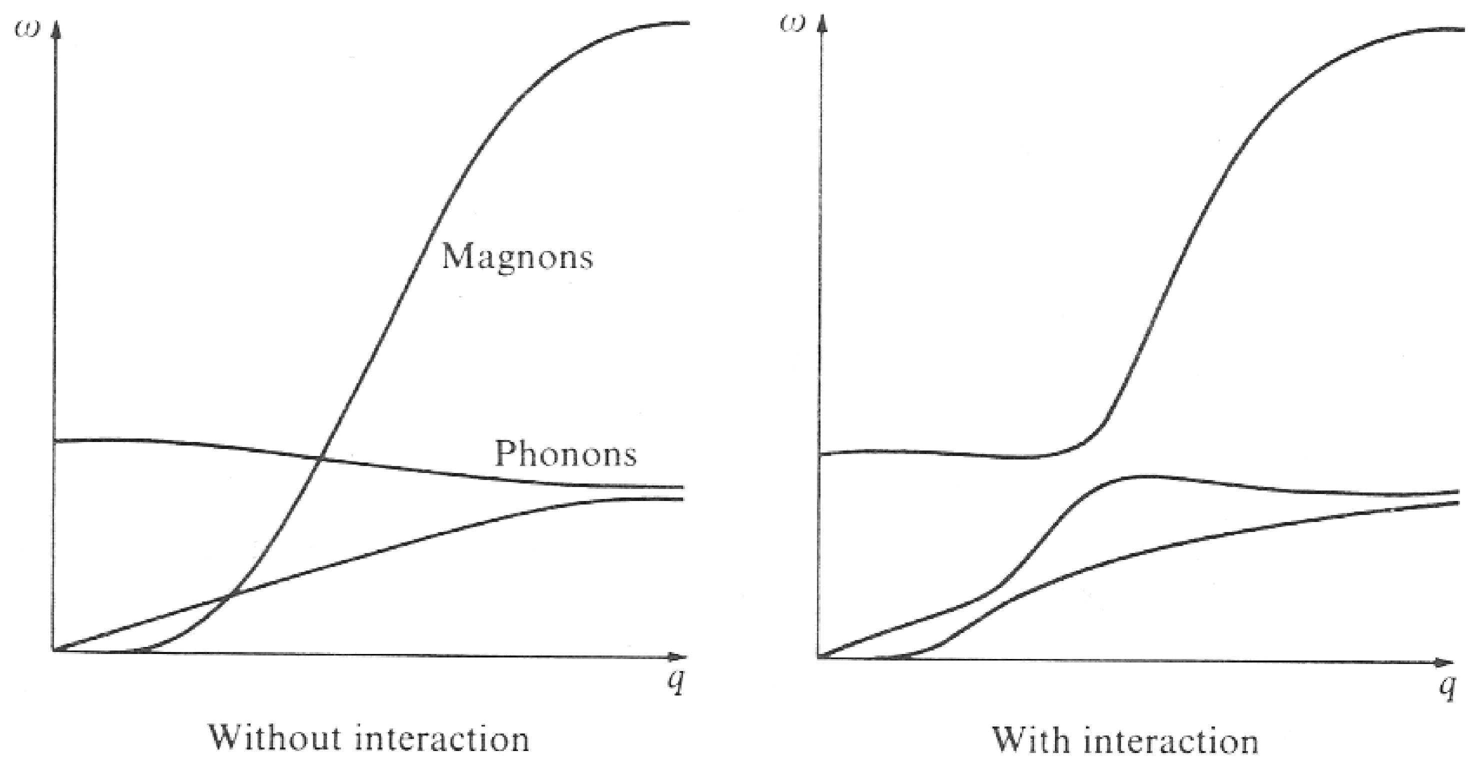


$$\vec{k}_n = \vec{k}_n{}' + \vec{k}_{magnon} + \vec{G}$$



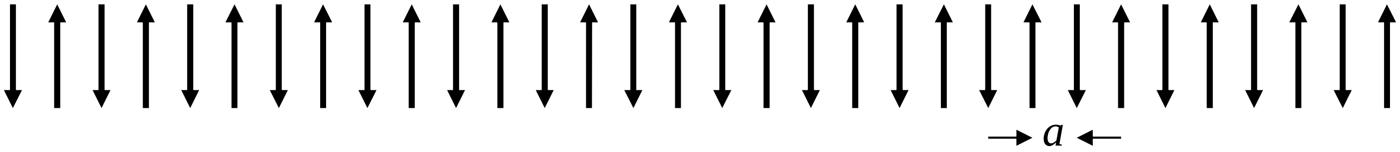
$$\frac{\hbar^2 k'^2}{2m_n} \pm \hbar\omega_{magnon} = \frac{\hbar^2 k^2}{2m_n} + \cancelto{0}{\frac{\hbar^2 G^2}{2m_{crystal}}}$$

Fig. 5.7 Schematic magnon and phonon dispersion curves. The magnon curve has been compressed by a factor of order 10 for illustrative purposes.



From: *Solid State Theory*, Harrison

Antiferromagnet magnons



$$\hbar \frac{dS_p^{Ax}}{dt} = 2J\,|S|\left(-S_p^{By} - 2S_p^{Ay} - S_{p-1}^{By}\right)$$

$$\hbar \frac{dS_p^{Ay}}{dt} = -2J\,|S|\left(-S_p^{Bx} - 2S_p^{Ax} - S_{p-1}^{Bx}\right)$$

$$\hbar \frac{dS_p^{Bx}}{dt} = 2J\,|S|\left(S_{p+1}^{Ay} + 2S_p^{By} + S_p^{Ay}\right)$$

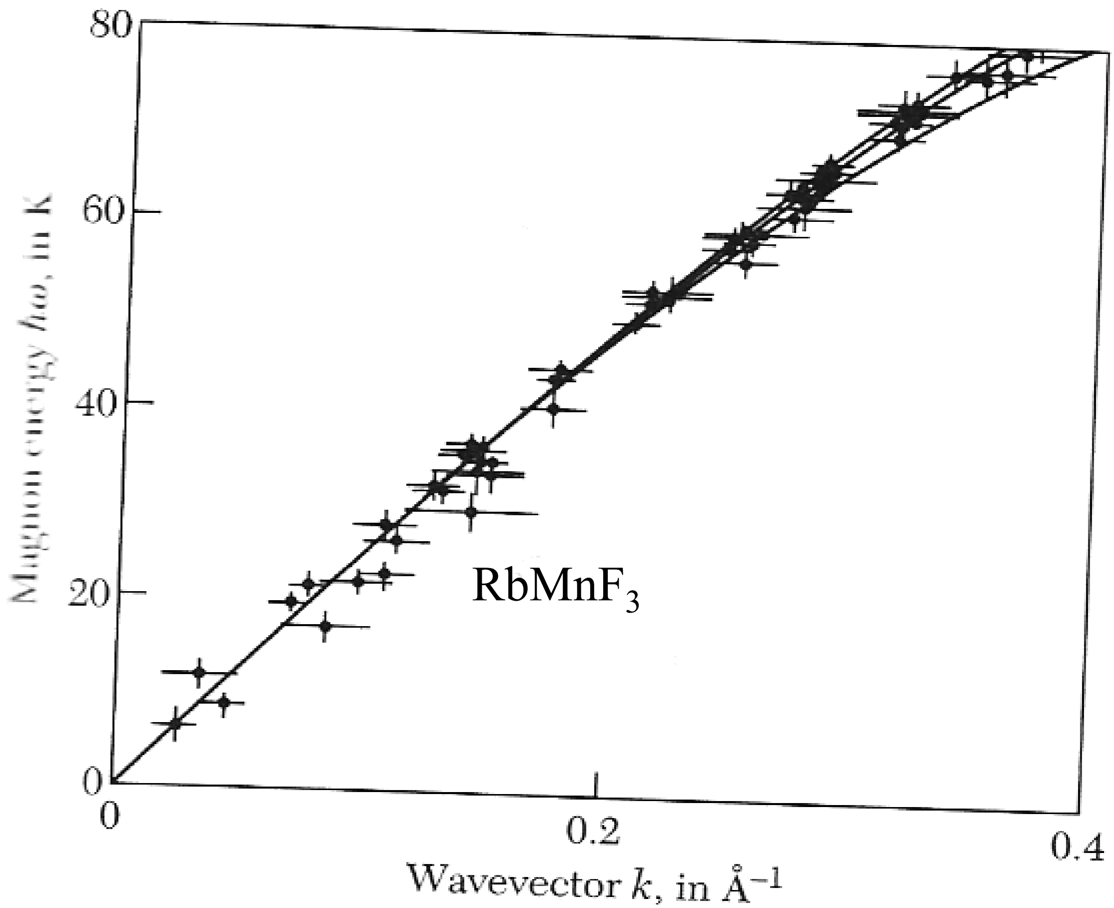
$$\hbar \frac{dS_p^{By}}{dt} = -2J\,|S|\left(S_{p+1}^{Ax} + 2S_p^{Bx} + S_p^{Ax}\right)$$

$$\hbar \frac{dS_p^{Az}}{dt} = 0 \qquad \hbar \frac{dS_p^{Bz}}{dt} = 0$$

$$\begin{pmatrix} S_p^{Ax} \\ S_p^{Ay} \\ S_p^{Bx} \\ S_p^{By} \end{pmatrix} = \begin{pmatrix} u_k^{Ax} \\ u_k^{Ay} \\ u_k^{Bx} \\ u_k^{By} \end{pmatrix} \exp\left[i\left(2kpa - \omega t\right)\right]$$

Antiferromagnet magnons

$$\hbar\omega = 4|J|S|\sin(ka)|$$



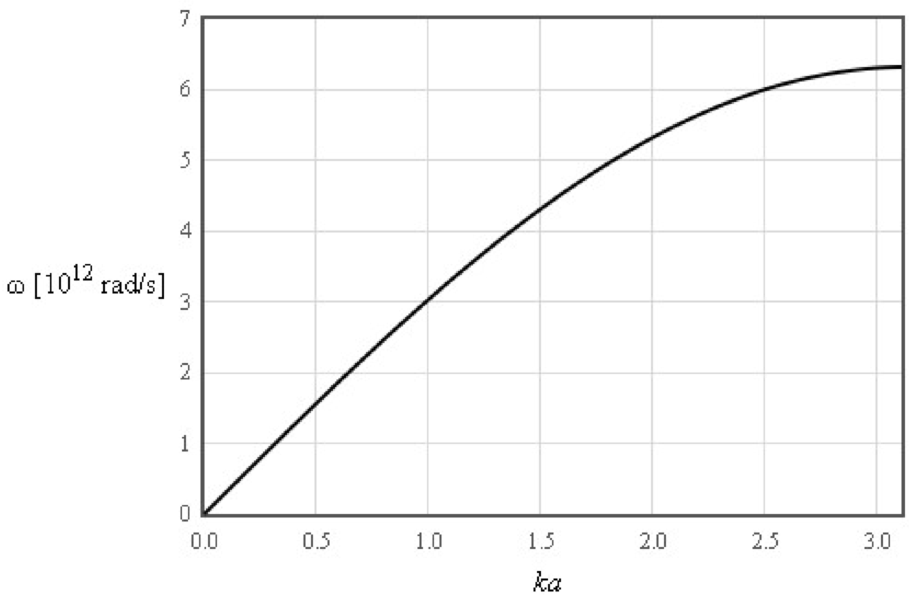
Brillouin zone boundary is at $k = \pi/2a$

Antiferromagnet magnons

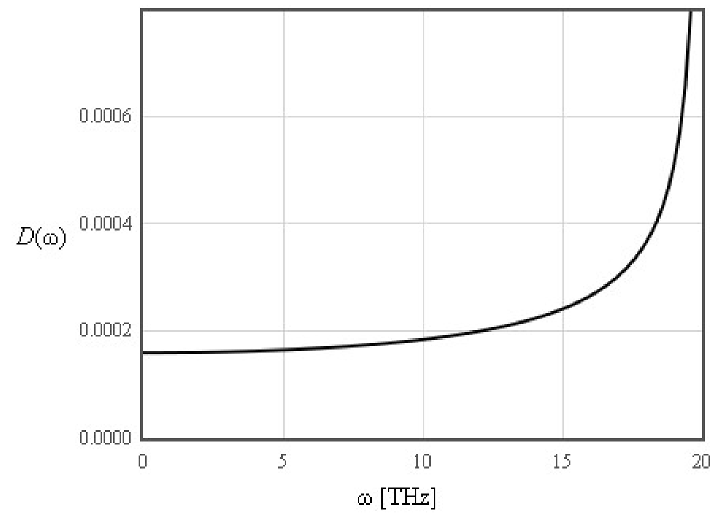
$$\hbar\omega = 4\left|J\right|S\left|\sin(ka)\right|$$

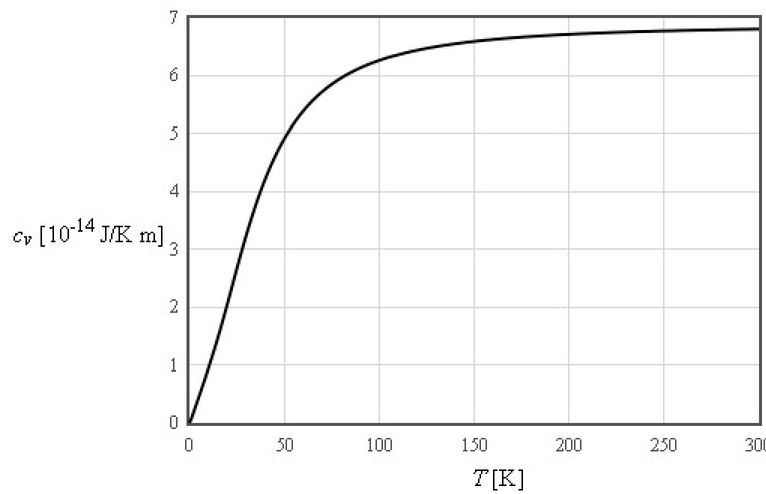
Mathematically equivalent to phonons in 1-d

$$\omega = \sqrt{\frac{4C}{m}}\left|\sin\left(\frac{ka}{2}\right)\right|$$



$$D(\omega) = \frac{1}{\pi a\sqrt{\frac{C}{m}}\sqrt{1-\frac{\omega^2 m}{4C}}}$$

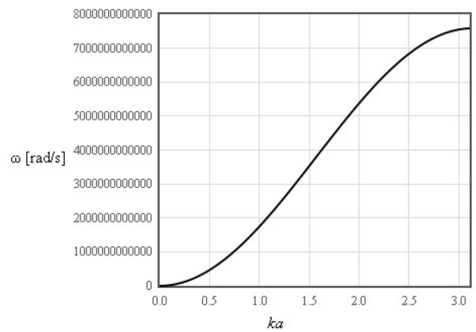
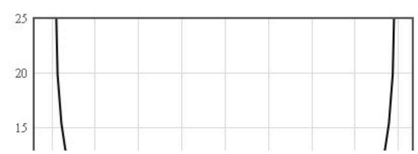




Student project

Make a table of magnon properties like the table of phonon properties

Magnons

	1-D ferromagnetic magnons	1-D antiferromagnetic magnons	3-D low temperature limit	
Equations of motion in mean field theory				
Eigenfunction solutions	$\begin{pmatrix} S_p^x \\ S_p^y \end{pmatrix} = \begin{pmatrix} u_k^x \\ u_k^y \end{pmatrix} \exp\left[i\left(kpa - \omega t \right) \right]$			
Dispersion relation	$\hbar\omega = 4JS\left(1 - \cos(ka)\right)$  Calculate ω(k)			
				$D(E)$

Fe bcc
Ni fcc
Co hcp

1 student / column

Longitudinal plasma waves

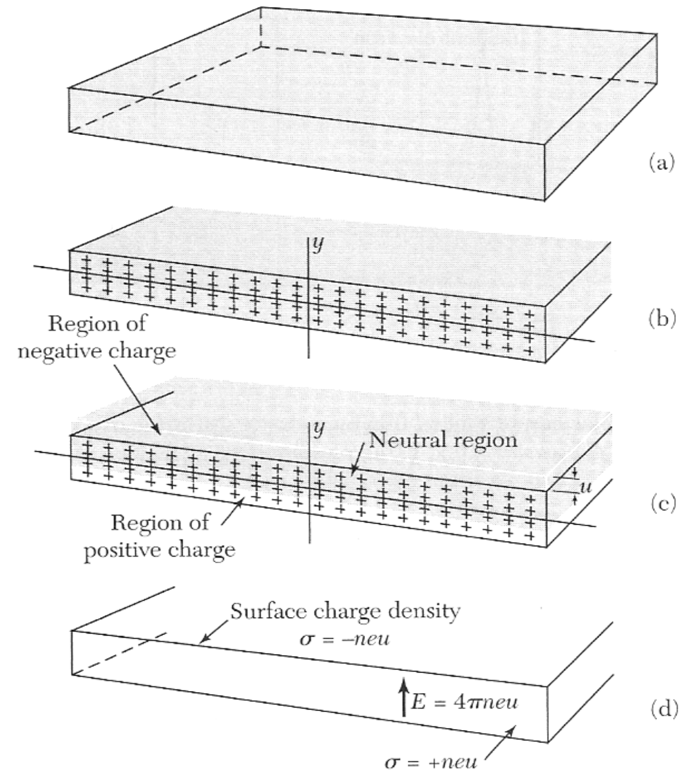
$$nm\frac{d^2y}{dt^2} = -neE$$

$$E = \frac{ney}{\varepsilon_0}$$

$$nm\frac{d^2y}{dt^2} = -\frac{n^2e^2y}{\varepsilon_0}$$

$$\frac{d^2y}{dt^2} + \omega_p^2 y = 0$$

Plasma frequency $$\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_0}}$$

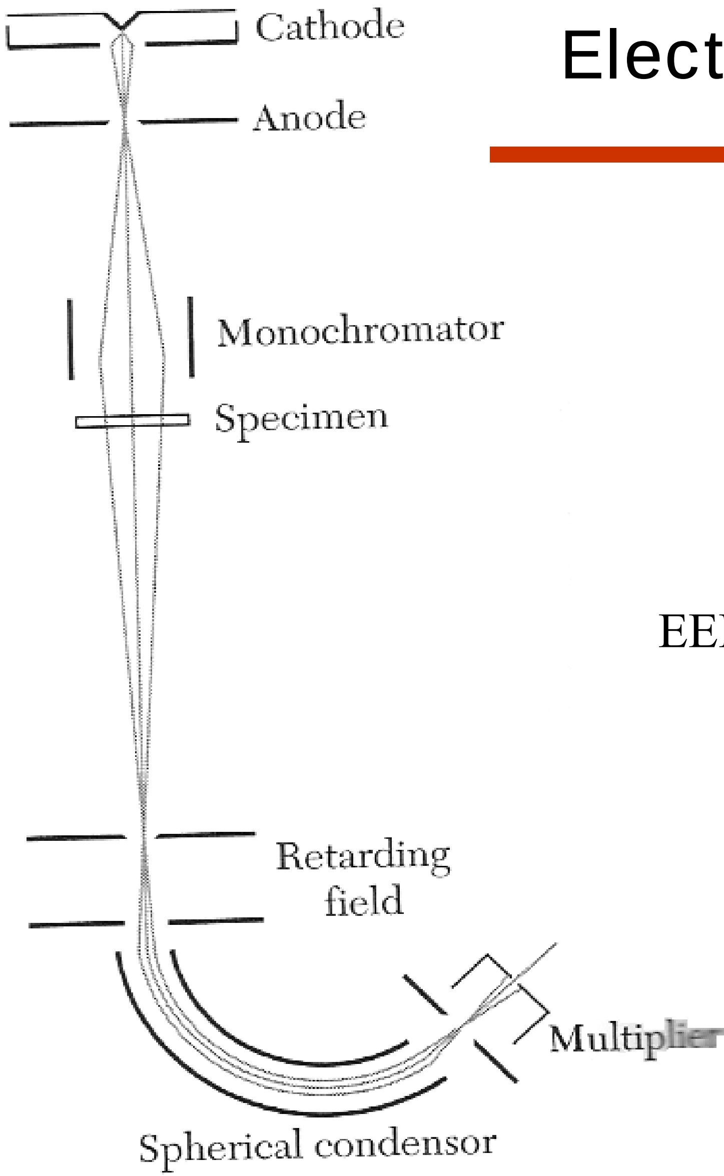


Kittel

There is no magnetic component of the wave.

Plasma waves can be quantized like any other wave

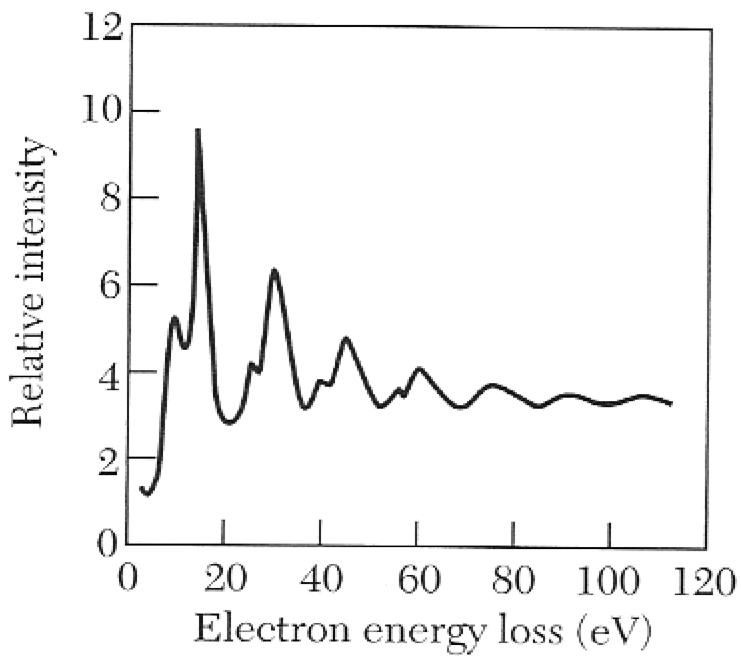
Electron energy loss spectroscopy

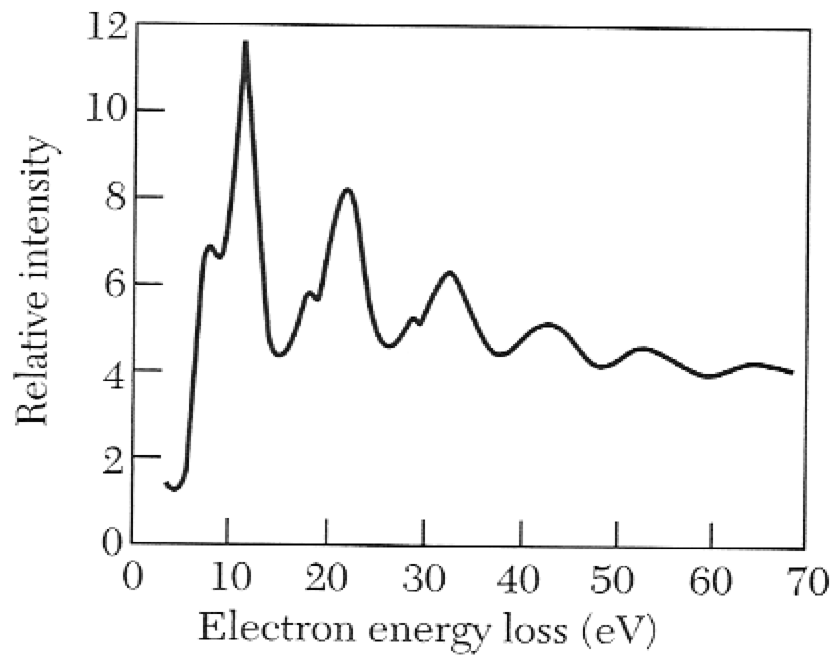


$$\Delta E = n\hbar\omega_p$$

EELS is often used to measure phonons

Electron energy loss spectroscopy





Aluminum

Plasmons 15.3 eV

Surface plasmons 10.3 eV

Magnesium

Plasmons 10.6 eV

Surface plasmons 7.1 eV

Transverse optical plasma waves

The dispersion relation for light

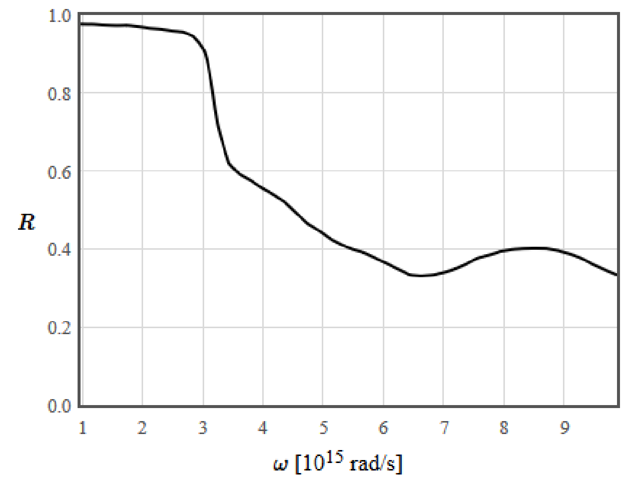
$$\varepsilon\varepsilon_0\mu_0\omega^2 = \frac{\varepsilon\omega^2}{c^2} = k^2$$

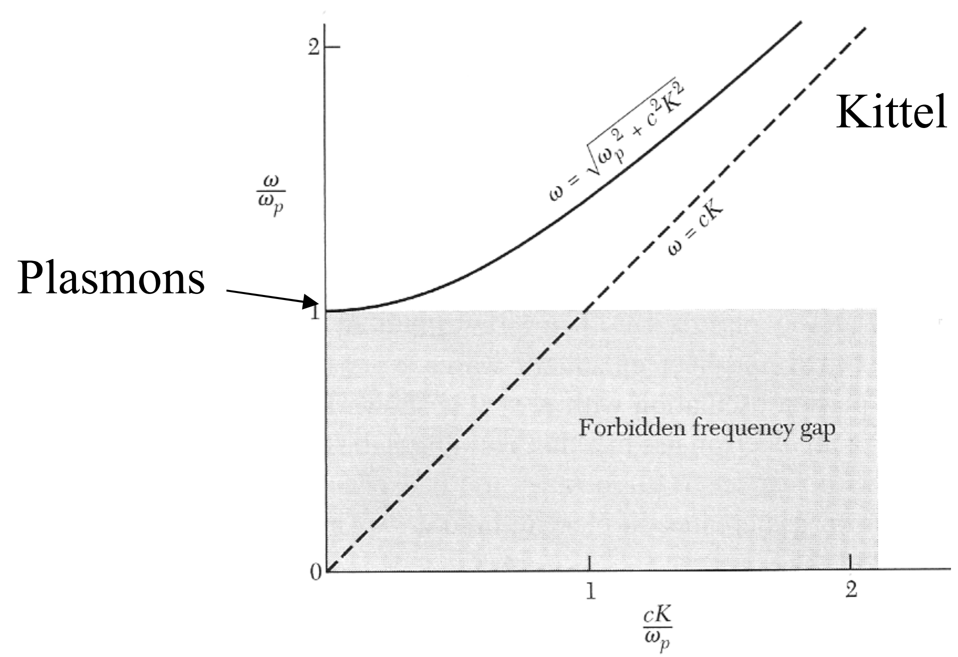
For a free electron gas

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\left(1 - \frac{\omega_p^2}{\omega^2}\right)\omega^2 = c^2k^2$$

$$\omega^2 = \omega_p^2 + c^2k^2$$

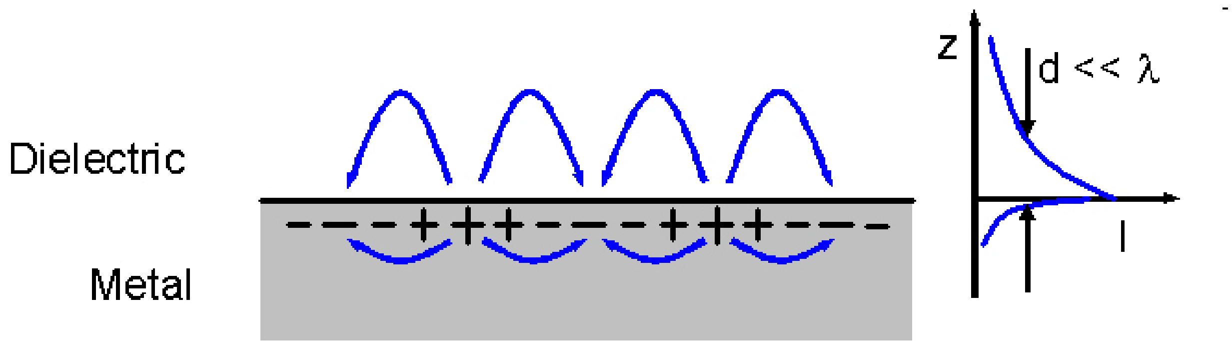




Surface Plasmons

Waves in the electron density at the boundary of two materials.

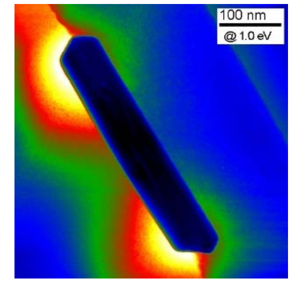
Surface plasmons have a lower frequency that bulk plasmons. This confines them to the interface.



Surface Plasmons

High-resolution surface plasmon imaging of gold nanoparticles by energy-filtered transmission electron microscopy

PHYSICAL REVIEW B 79, 041401 R 2009



Surface plasmons on nanoparticles are efficient at scattering light.

Green and blue require different sized particles.

Nature Photonics

LETTERS

Organic plasmon-emitting diode

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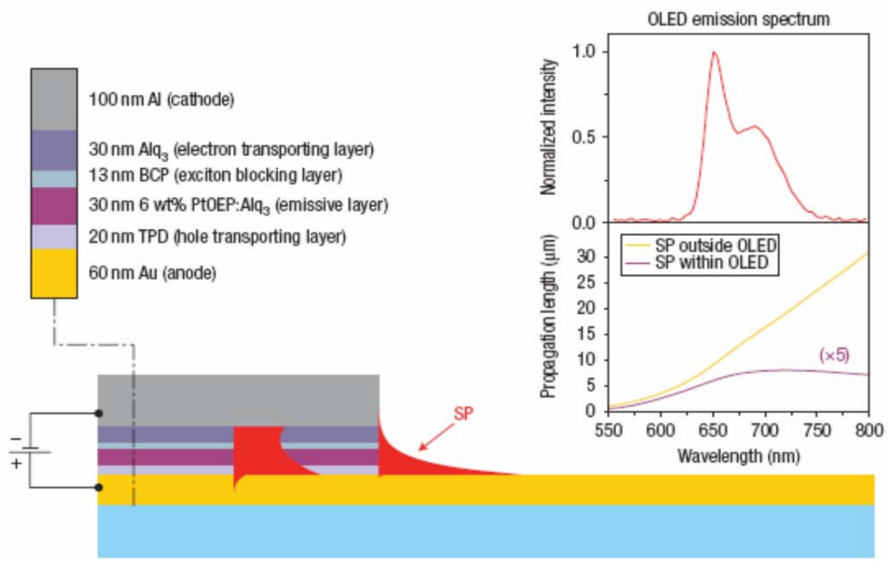
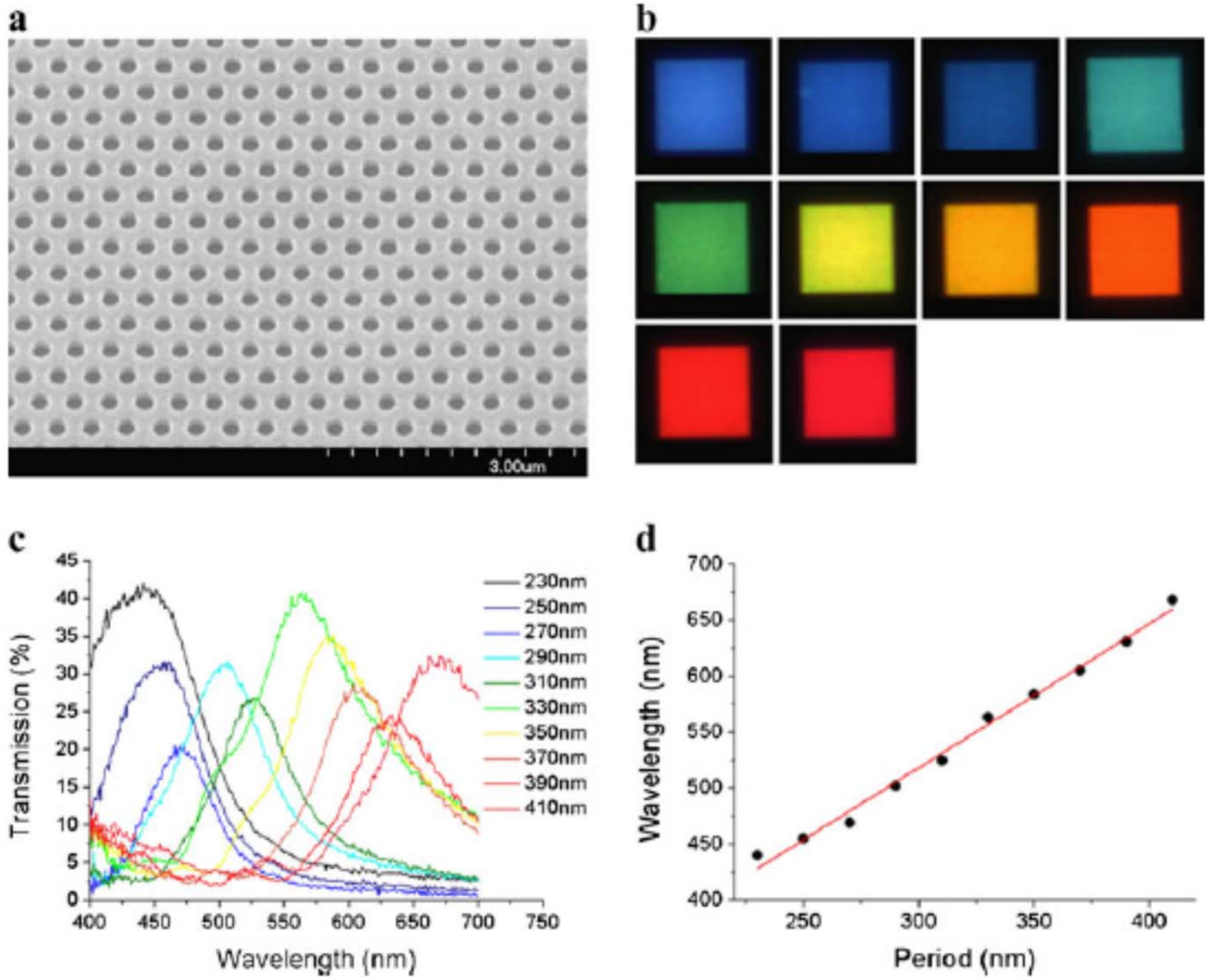
Surface plasmons are hybrid modes of longitudinal electron oscillations and light fields at the interface of a metal and a dielectric[1,2]. Driven by advances in nanofabrication, imaging and numerical methods[3,4], a wide range of plasmonic elements such as waveguides[5,6], Bragg mirrors[7], beamsplitters[8], optical modulators[9] and surface plasmon detectors[10] have recently been reported. For introducing dynamic functionality to plasmonics, the rapidly growing field of organic optoelectronics[11] holds strong promise due to its ease of fabrication and integration opportunities. Here, we introduce an electrically switchable



Surface plasmons are used for biosensors.

Plasmon filter

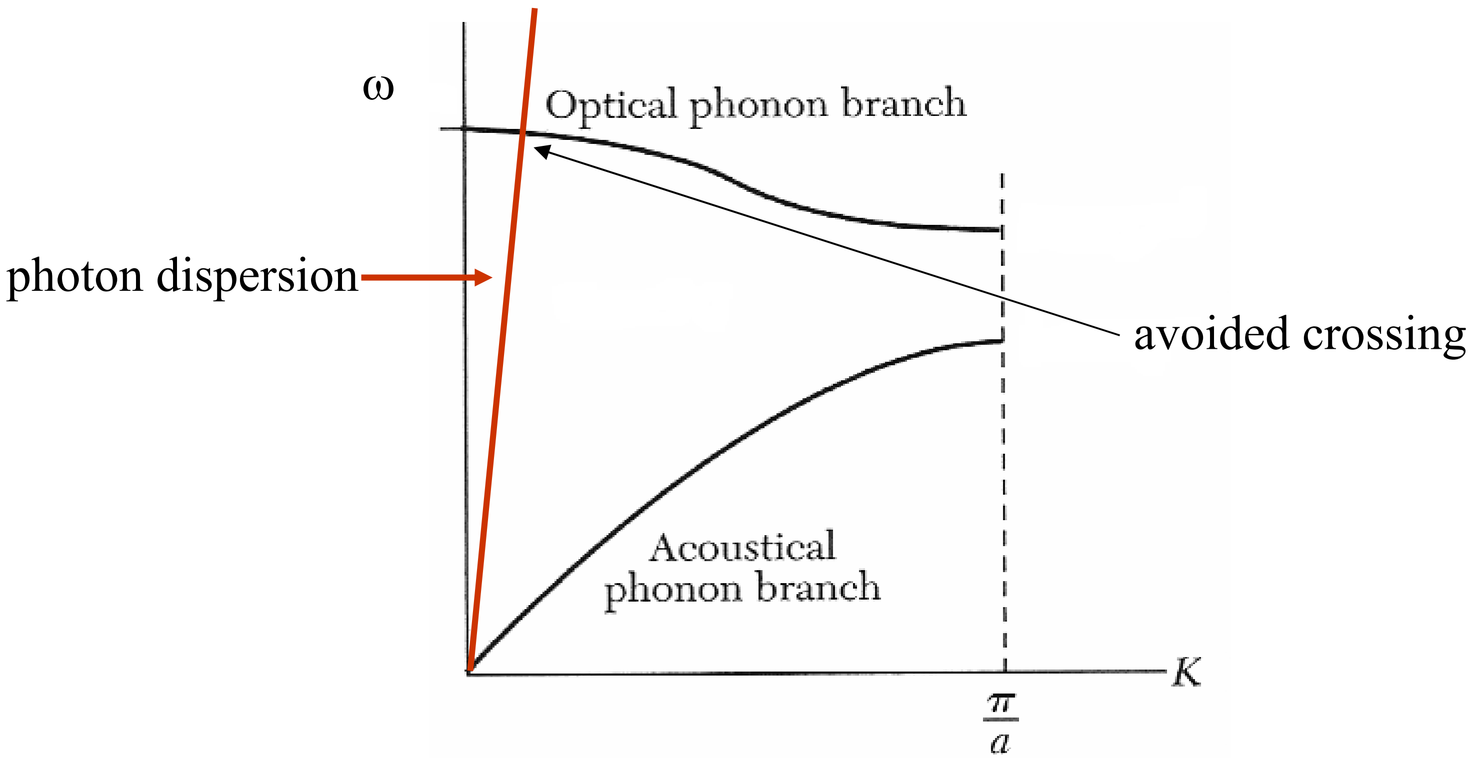


Plasmon modes on the other side of the metal films are excited.

http://web.pdx.edu/~larosaa/Applied_Optics_464-564/Lecture_Notes_Posted/2010_Lecture-7_SURFACE%20PLASMON%20POLARITONS%20AT%20%20METALINSULATOR%20INTERFACES/Lecture_on_the_Web_SURFACE-PLASMONS-POLARITONS.pdf

Polaritons

Transverse optical phonons will couple to photons with the same ω and *k*.



Light Bragg reflects off the sound wave; sound Bragg reflects off the light wave.