Surface plasmons

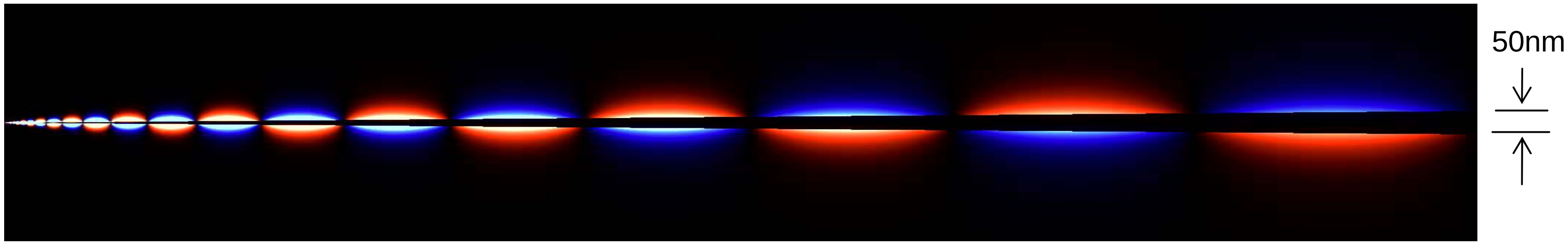
- **Basics :**
  - **Dispersion relation of surface plasmons**

- **References**

"Metal Optics"
Prof. Vlad Shalaev, Purdue Univ., ECE Department,
http://shay.ecn.purdue.edu/~ece695s/

"Surface plasmons on smooth and rough surfaces and on gratings"
Heinz Raether(Univ Hamburg), 1988, Springer-Verlag

"Surface-plasmon-polariton waveguides"
Hyongsik Won, Ph.D Thesis, Hanyang Univ, 2005.



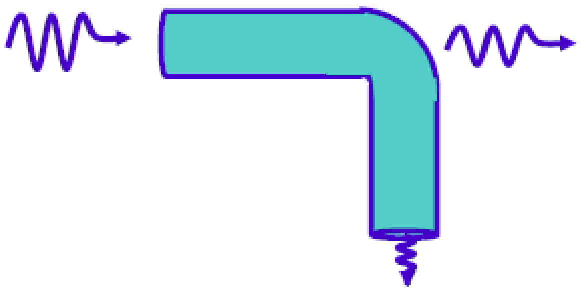
Metal Optics: An introduction

Majority of optical components based on dielectrics

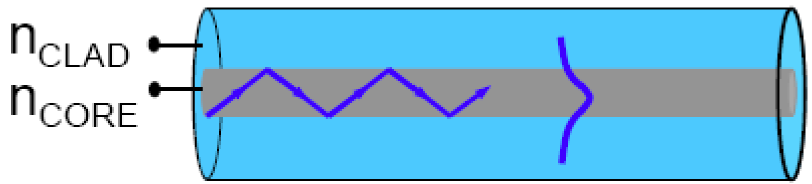
- High speed, high bandwidth (ω), but…
- Does not scale well ⇨ Needed for large scale integration

Problems

Bending losses



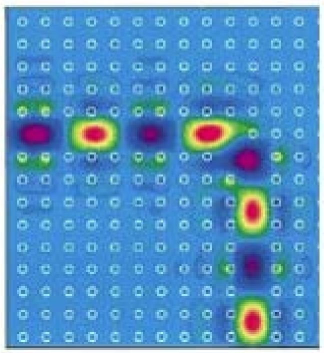
Diffraction Limit



Optical mode in waveguide > $\lambda_0/2n_{CORE}$

Solutions ?

Some:



J. D. Joannopoulos, et al, Nature, vol.386, p.143-9 (1997)

Some fundamental problems!

⇩

Photonic functionality based on metals?!

What is a plasmon?

What is a plasmon ?

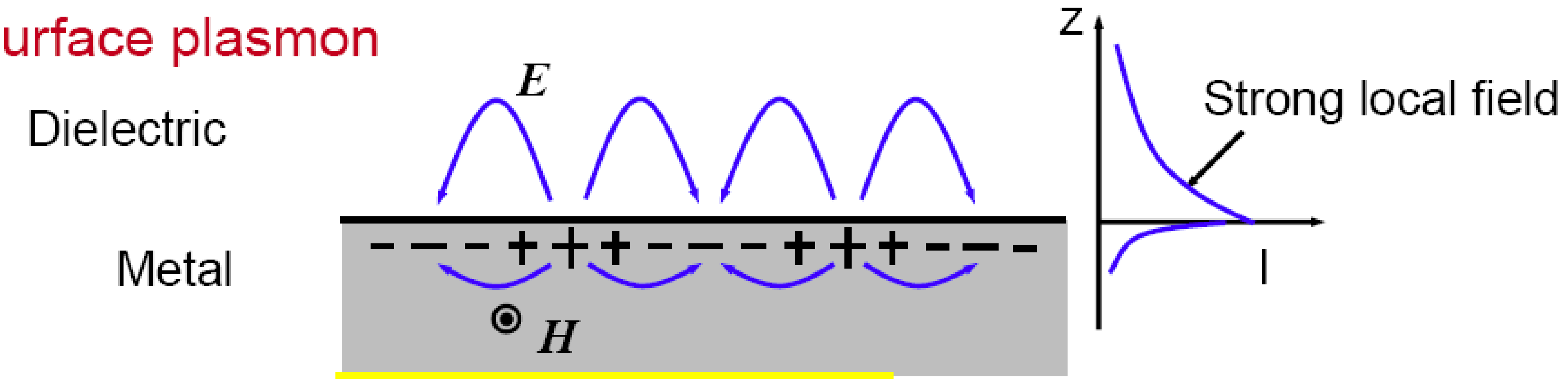
- Compare electron gas in a metal and real gas of molecules
- Metals are expected to allow for electron density waves: plasmons

Bulk plasmon

- Metals allow for EM wave propagation above the plasma frequency

They become transparent!

Surface plasmon

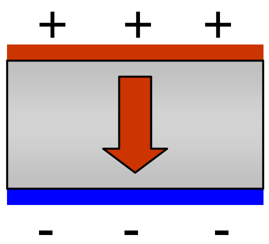


Note: SP is a TM wave!

- Sometimes called a surface plasmon-polariton (strong coupling to EM field)

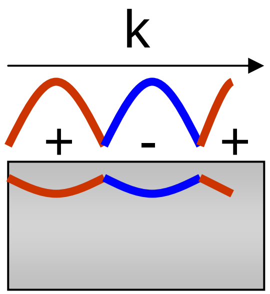
Plasmon-Polaritons

Plasma oscillation = density fluctuation of free electrons

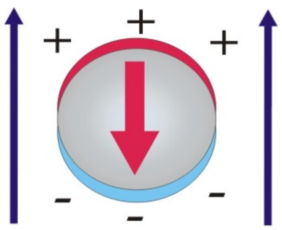


Plasmons in the bulk oscillate at ω_p determined by the free electron density and effective mass

$$\omega_p^{drude} = \sqrt{\frac{Ne^2}{m\varepsilon_0}}$$



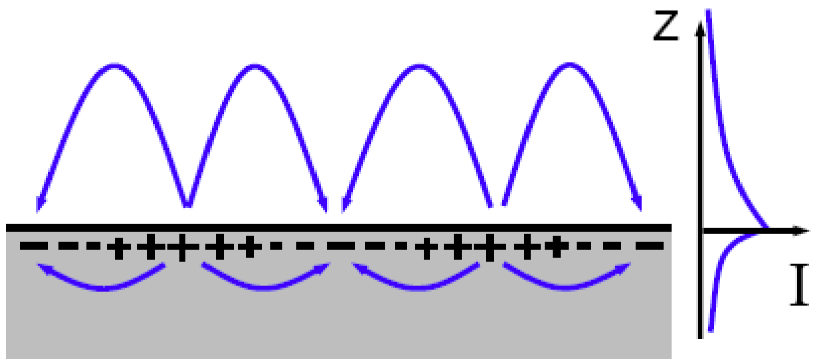
Plasmons confined to surfaces that can interact with light to form propagating "surface plasmon polaritons (SPP)"



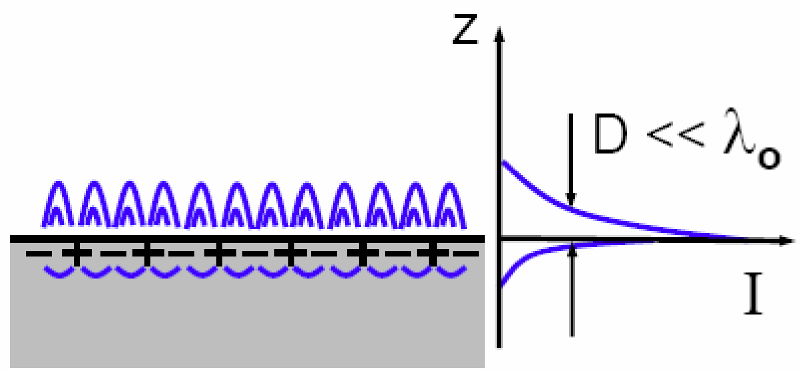
Confinement effects result in resonant SPP modes in nanoparticles

$$\omega_{particle}^{drude} = \sqrt{\frac{1}{3}\frac{Ne^2}{m\varepsilon_0}}$$

Local field intensity depends on wavelength



Long wavelength
(small propagation constant, k)



Short wavelength
(large propagation constant, k)

Characteristics plasmon-polariton
- Strong localization of the EM field
- High local field intensities easy to obtain

Applications:
- Guiding of light below the diffraction limit (near-field optics)
- Non-linear optics
- Sensitive optical studies of surfaces and interfaces
- Bio-sensors
- Study film growth
- ……

Dielectric constant of metal : Drude model

$$\varepsilon_{EFF}(\omega) = \varepsilon_B + i\frac{\sigma(\omega)}{\varepsilon_o \omega}$$

$$= \varepsilon_B + i\frac{1}{\varepsilon_o \omega}\left(\frac{\sigma_o}{1 - i\omega\tau}\right) = \varepsilon_B + i\frac{\sigma_o(1 + i\omega\tau)}{\varepsilon_o \omega(1 + \omega^2\tau^2)}$$

$$= \left(\varepsilon_B - \frac{\omega_p^2\tau^2}{1 + \omega^2\tau^2}\right) + i\left(\frac{\omega_p^2\tau^2}{\omega\tau + \omega^3\tau^3}\right)$$

where, $\omega_p^2 = \frac{\sigma_o}{\varepsilon_o \tau} = \frac{ne^2}{\varepsilon_o m_e}$: bulk plasma frequency ($\sim 10eV$ for metal)

Plasma frequency ▶

Dielectric constant at $\omega \approx \omega_{visible}$

Since $\omega_{vis}\tau >> 1$ ➡

$$\boxed{\varepsilon_{EFF} = \varepsilon_B - \frac{\omega_p^2}{\omega^2} + i\frac{\omega_p^2}{\omega^3\tau}}$$

Bound electrons

Free electrons

Ideal case : metal as a free-electron gas

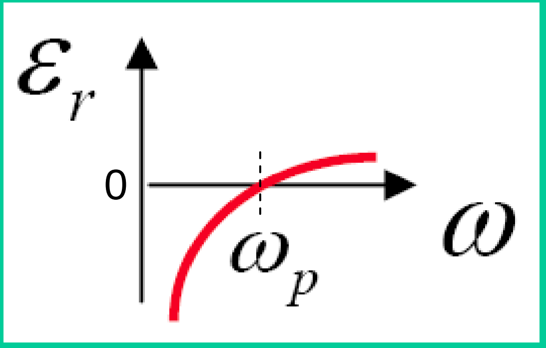
Dielectric constant of a free electron gas

- no decay ($\gamma \rightarrow 0$: infinite relaxation time)
- no interband transitions ($\varepsilon_B = 1$)

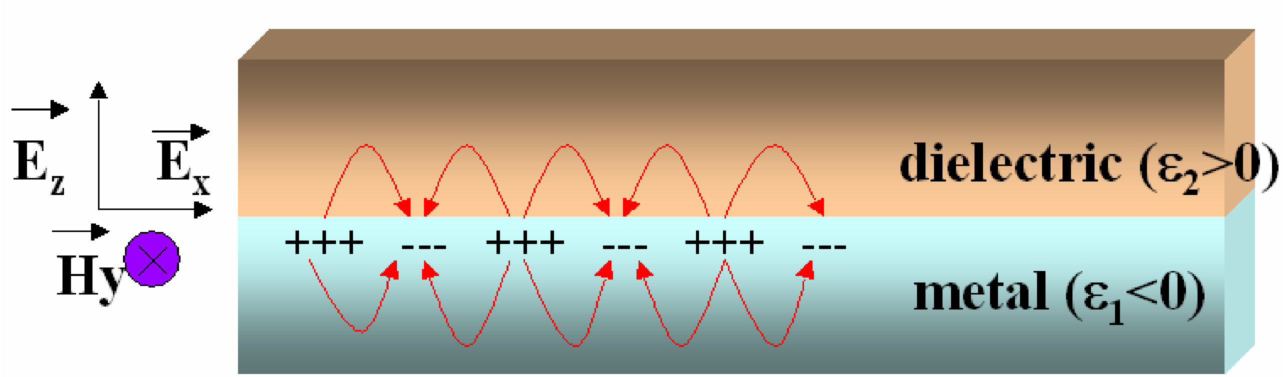
$$\varepsilon_{EFF}(\omega) = \varepsilon_B + i\frac{\sigma(\omega)}{\varepsilon_o \omega}$$

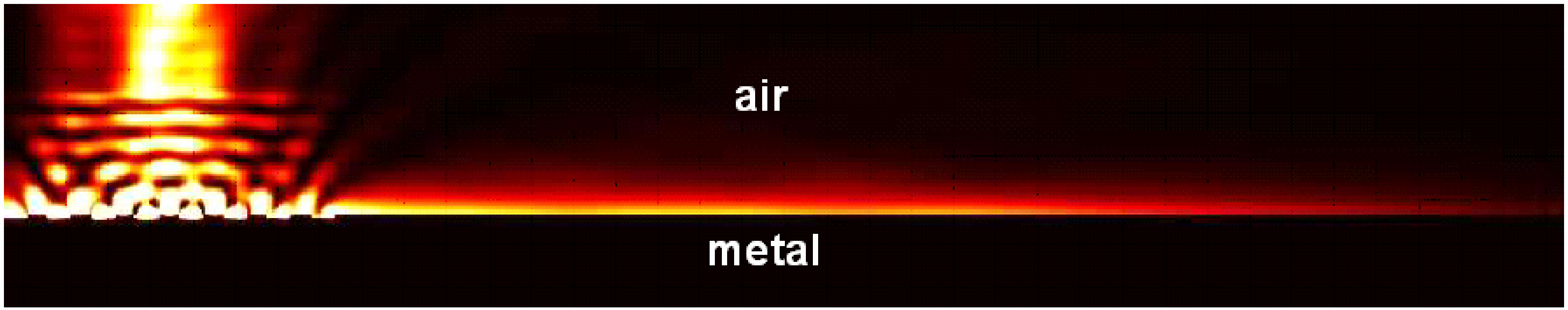
$$= \left(\varepsilon_B - \frac{\omega_p^2\tau^2}{1+\omega^2\tau^2}\right) + i\left(\frac{\omega_p^2\tau^2}{\omega\tau+\omega^3\tau^3}\right) \xrightarrow[\varepsilon_B=1]{\tau\to\infty} \varepsilon_{EFF} = \left(1-\frac{\omega_p^2}{\omega^2}\right)$$

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



Surface-plasmons on dielectric-metal boundaries





Dispersion relation for EM waves in electron gas (bulk plasmons)

Determination of dispersion relation for bulk plasmons

- The wave equation is given by: $$\frac{\varepsilon_r}{c^2}\frac{\partial^2 \boldsymbol{E}(\boldsymbol{r},t)}{\partial t^2} = \nabla^2 \boldsymbol{E}(\boldsymbol{r},t)$$

- Investigate solutions of the form: $$\boldsymbol{E}(\boldsymbol{r},t) = \mathrm{Re}\left\{\boldsymbol{E}(\boldsymbol{r},\omega)\exp\left(i\boldsymbol{k}\cdot\boldsymbol{r} - i\omega t\right)\right\}$$

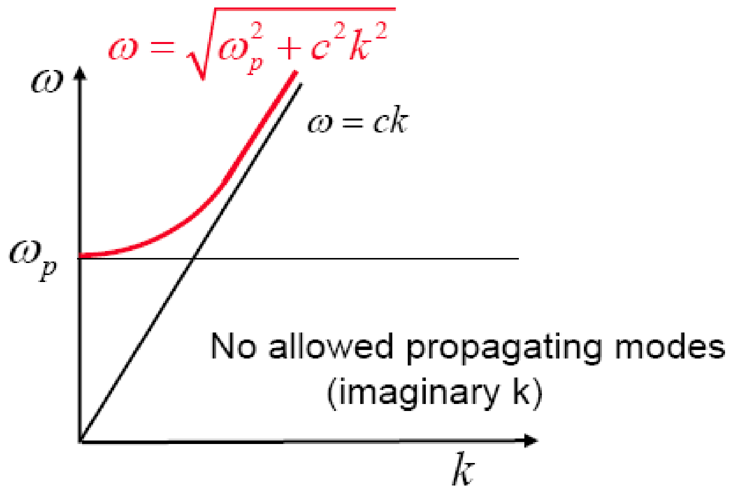
$$\Rightarrow \quad \omega^2 \varepsilon_r = c^2 k^2$$

- Dielectric constant: $\varepsilon_r = 1 - \dfrac{\omega_p^2}{\omega^2}$

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

- Dispersion relation:

$$\boxed{\omega = \omega(k)}$$



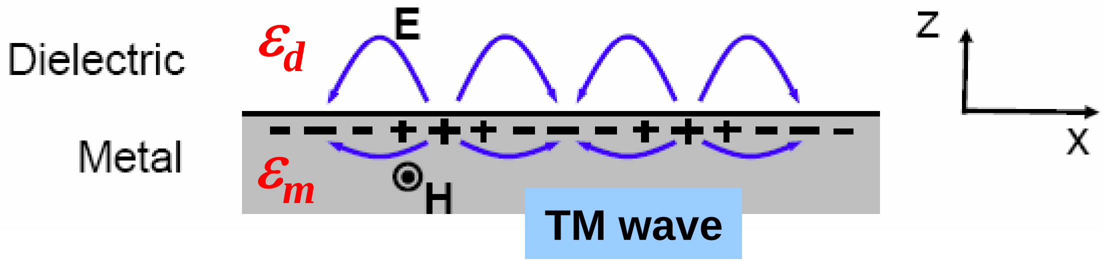
Note1: Solutions lie above light line

Note2: Metals: $\hbar\omega_p \approx 10$ eV; Semiconductors $\hbar\omega_p < 0.5$ eV (depending on dopant conc.)

Dispersion relation for surface plasmons

Solve Maxwell's equations with boundary conditions

- We are looking for solutions that look like:



- Mathematically:

Z > 0
$$\begin{cases} \boldsymbol{H}_d = \left(0, H_{yd}, 0\right) \exp i\left(k_{xd}x + k_{zd}z - \omega t\right) \\ \boldsymbol{E}_d = \left(E_{xd}, 0, E_{zd}\right) \exp i\left(k_{xd}x + k_{zd}z - \omega t\right) \end{cases}$$

Z < 0
$$\begin{cases} \boldsymbol{H}_m = \left(0, H_{ym}, 0\right) \exp i\left(k_{xm}x + k_{zm}z - \omega t\right) \\ \boldsymbol{E}_m = \left(E_{xm}, 0, E_{zm}\right) \exp i\left(k_{xm}x + k_{zm}z - \omega t\right) \end{cases}$$

- Maxwell's Equations in medium i (i = metal or dielectric):

$$\nabla \cdot \varepsilon_i \boldsymbol{E} = 0 \qquad \nabla \cdot \boldsymbol{H} = 0 \qquad \nabla \times \boldsymbol{E} = -\mu_0 \frac{\partial \boldsymbol{H}}{\partial t} \qquad \nabla \times \boldsymbol{H} = \varepsilon_i \frac{\partial \boldsymbol{E}}{\partial t}$$

- At the boundary (continuity of the tangential E_x, H_y, and the normal D_z):

$$E_{xm} = E_{xd} \qquad H_{ym} = H_{yd} \qquad \varepsilon_m E_{zm} = \varepsilon_d E_{zd}$$

Dispersion relation for surface plasmon polaritons

- Start with curl equation for $\boldsymbol{H}$ in medium i

$$\left.\begin{aligned} \nabla\times\boldsymbol{H}_i &= \varepsilon_i\frac{\partial\boldsymbol{E}_i}{\partial\boldsymbol{t}} \\ \text{where}\quad \boldsymbol{H}_i &= \left(0, H_{yi}, 0\right)\exp i\left(k_{xi}x + k_{zi}z - \omega t\right) \\ \boldsymbol{E}_i &= \left(E_{xi}, 0, E_{zi}\right)\exp i\left(k_{xi}x + k_{zi}z - \omega t\right) \end{aligned}\right\} \Rightarrow$$

$$\left(\frac{\partial H_{zi}}{\partial y}-\frac{\partial H_{yi}}{\partial z},\frac{\partial H_{xi}}{\partial z}-\frac{\partial H_{zi}}{\partial x},\frac{\partial H_{yi}}{\partial x}-\frac{\partial H_{xi}}{\partial y}\right)=(\underline{-ik_{zi}H_{yi}},0,ik_{xi}H_{yi})=(\underline{-i\omega\varepsilon_i E_{xi}},0,-i\omega\varepsilon_i E_{zi})$$

$$k_{zi}H_{yi}=\omega\varepsilon_i E_{xi} \Rightarrow \left\{\begin{aligned} k_{zm}H_{ym} &= \omega\varepsilon_m E_{xm} \\ k_{zd}H_{yd} &= \omega\varepsilon_d E_{xd} \end{aligned}\right.$$

- $E_{//}$ across boundary is continuous: $E_{xm} = E_{xd}$

$$\Rightarrow \frac{k_{zm}}{\varepsilon_m}H_{ym} = \frac{k_{zd}}{\varepsilon_d}H_{yd}$$

- $H_{//}$ across boundary is continuous: $H_{ym} = H_{yd}$

Combine with: $\frac{k_{zm}}{\varepsilon_m}H_{ym} = \frac{k_{zd}}{\varepsilon_d}H_{yd}$

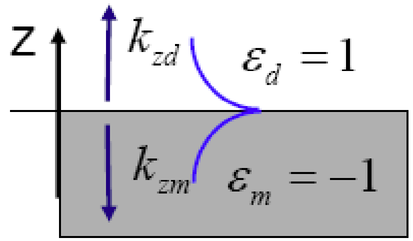
$$\Rightarrow \boxed{\frac{k_{zm}}{\varepsilon_m} = \frac{k_{zd}}{\varepsilon_d}}$$

Dispersion relation for surface plasmon polaritons

Relations between k vectors

- Condition for SP's to exist: $\dfrac{k_{zm}}{\varepsilon_m} = \dfrac{k_{zd}}{\varepsilon_d}$

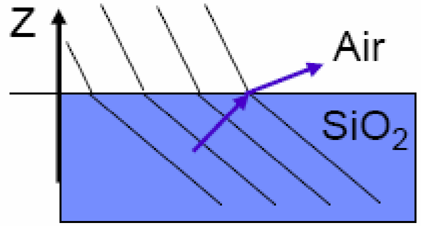
Example



- Relation for k_x (Continuity $E_{//}$, $H_{//}$) : $k_{xm} = k_{xd}$

true at any boundary

Example



- For any EM wave: $k^2 = \varepsilon_i \left(\dfrac{\omega}{c}\right)^2 = k_x^2 + k_{zi}^2$, $where\ k_x \equiv k_{xm} = k_{xd}$

- Both in the metal and dielectric: $k_{sp} = k_x = \sqrt{\varepsilon_i \left(\dfrac{\omega}{c}\right)^2 - k_{zi}^2}$

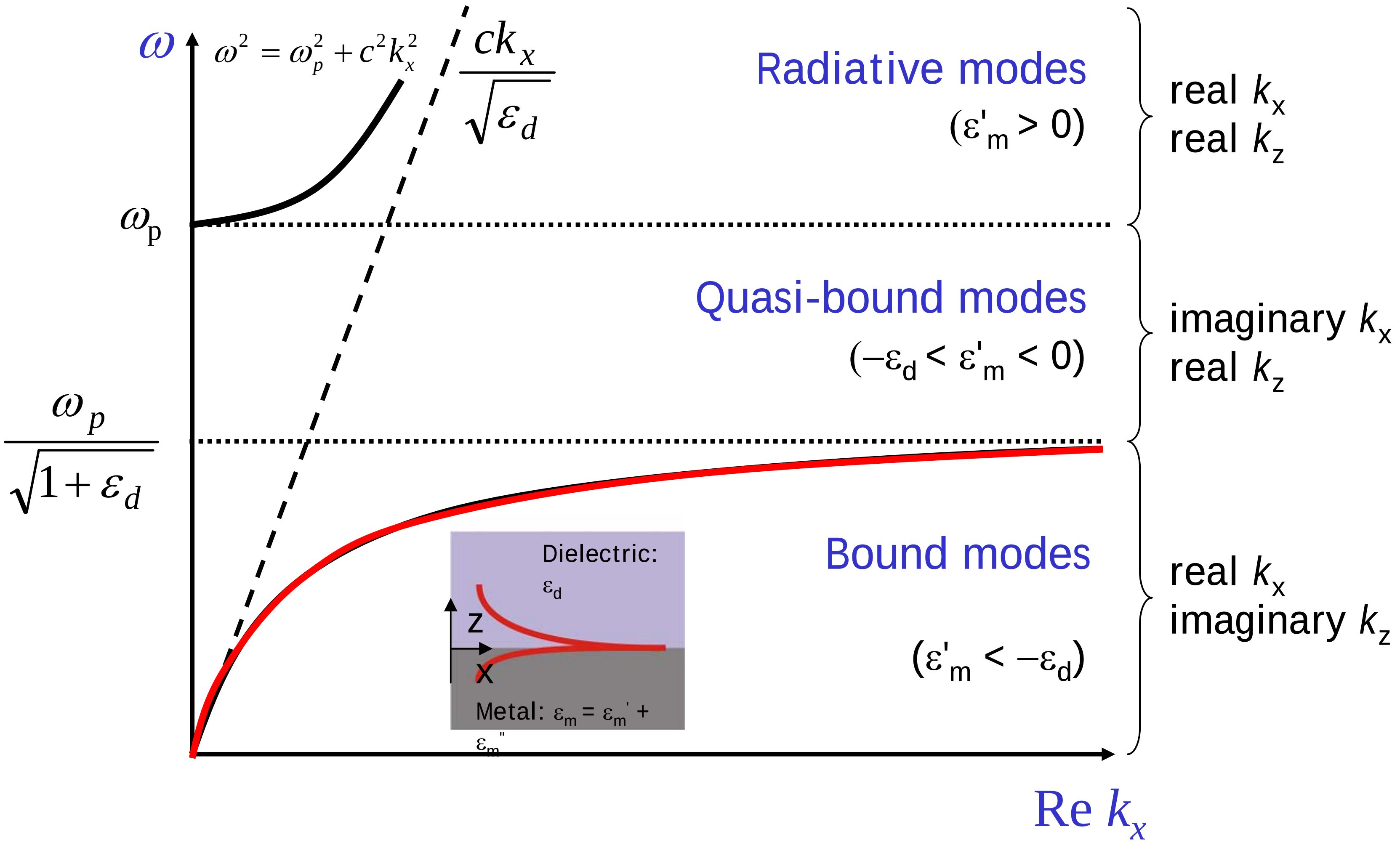
$$\left.\begin{array}{l} k_{sp} = k_x = \sqrt{\varepsilon_i \left(\dfrac{\omega}{c}\right)^2 - k_{zi}^2} \\ \dfrac{k_{zm}}{\varepsilon_m} = \dfrac{k_{zd}}{\varepsilon_d} \end{array}\right\} \Rightarrow$$

SP Dispersion Relation

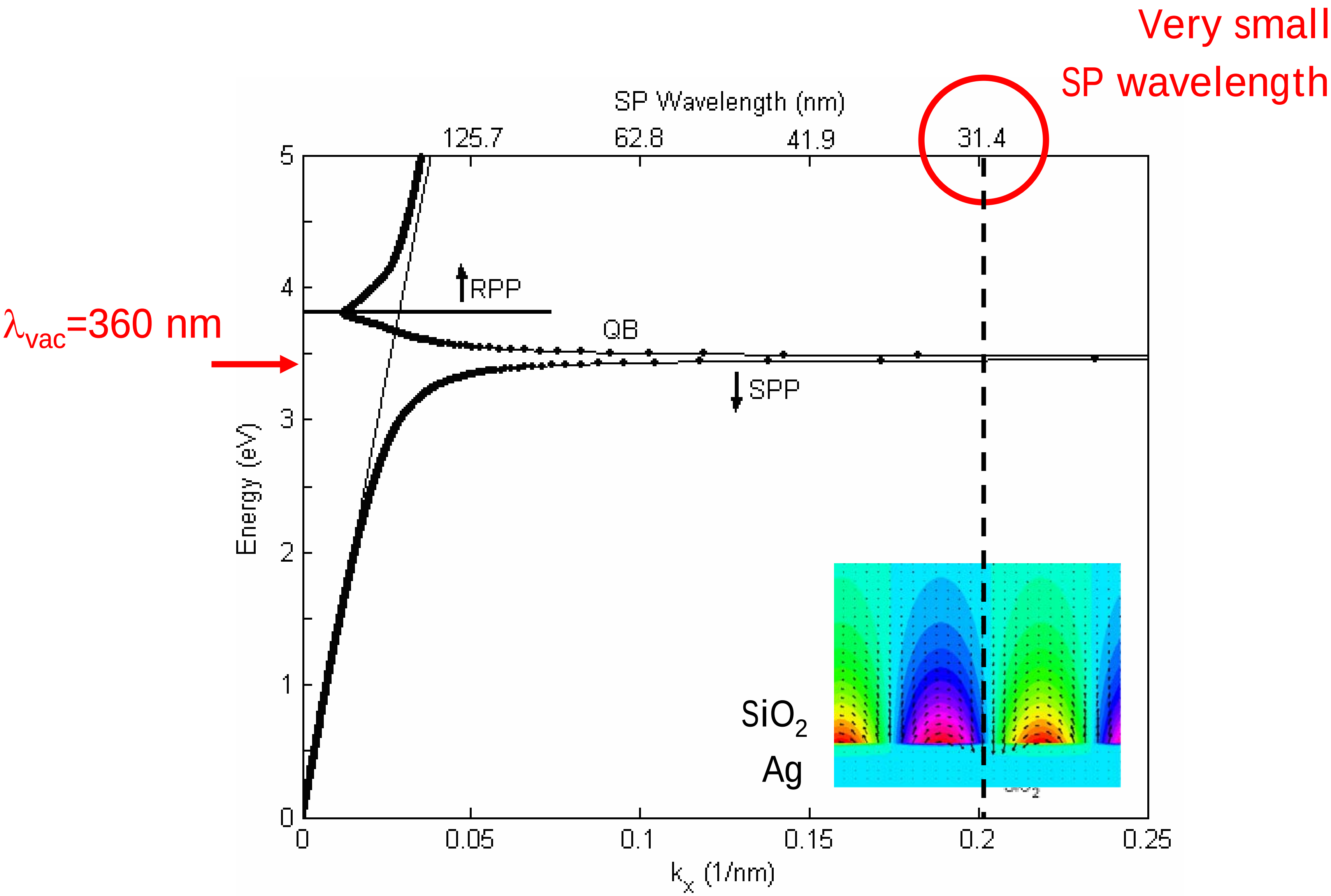
$$\boxed{k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}}$$

Surface plasmon dispersion relation

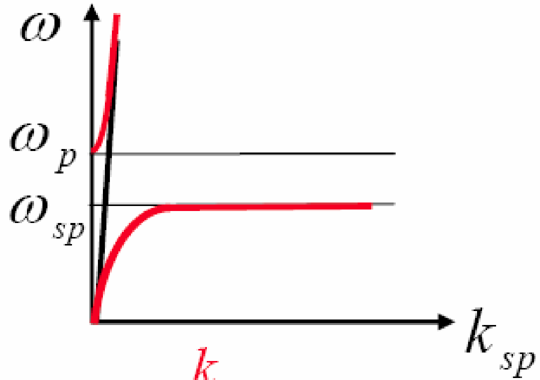
$$\boxed{k_x = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}} \qquad k_{zi} = \frac{\omega}{c}\left(\frac{\varepsilon_i^2}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$$



X-ray wavelengths at optical frequencies !!



Excitation of surface plasmons

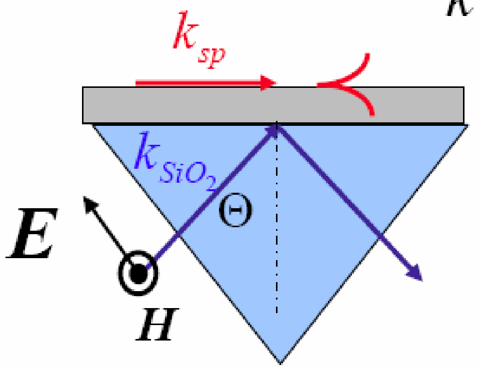


The dispersion relation for surface plasmons

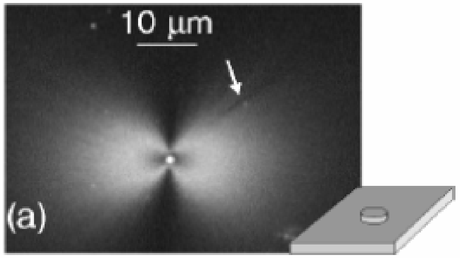
- Useful for describing plasmon excitation & propagation

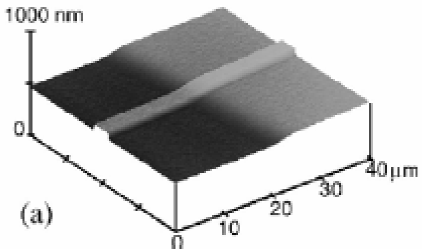
Coupling light to surface plasmon-polaritons

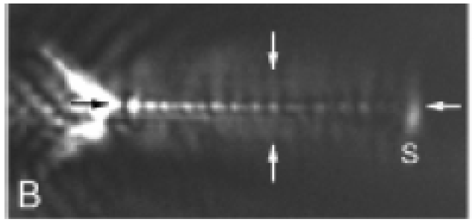
- Using high energy electrons (EELS)
- Kretchman geometry $$k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$$

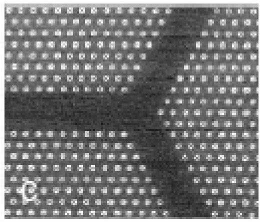


- Grating coupling
- Coupling using subwavelength features
- A diversity of guiding geometries





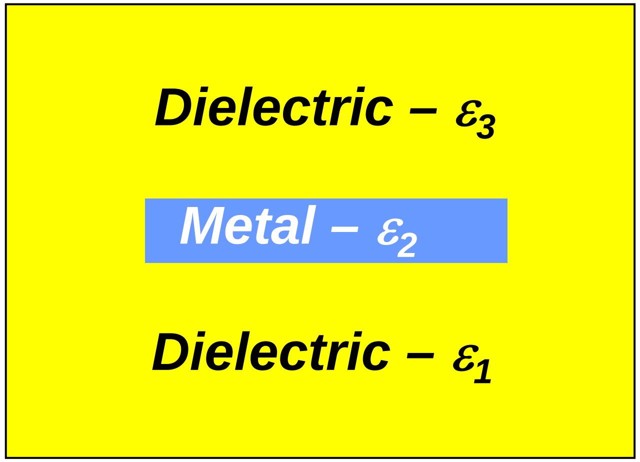




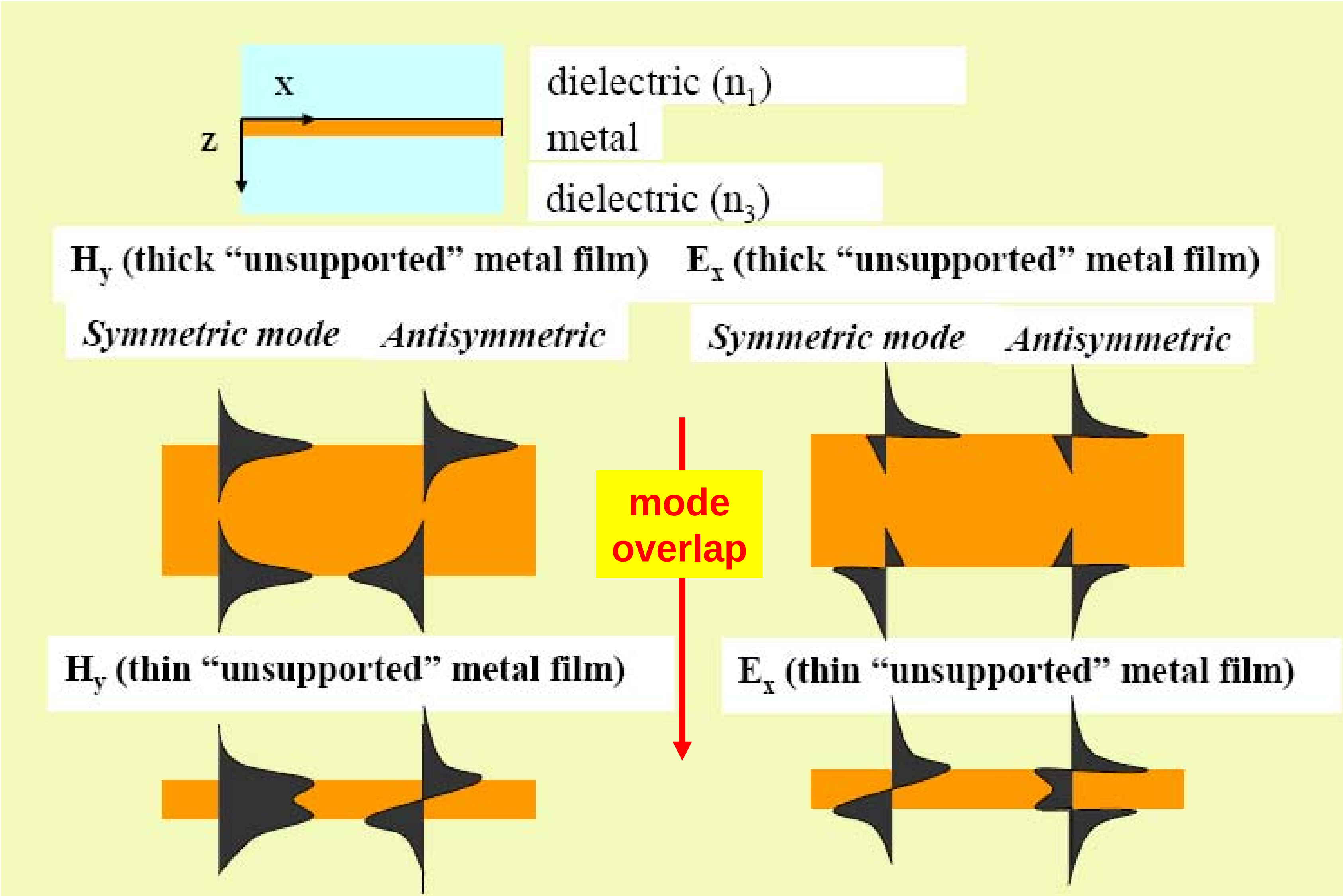
Surface-plasmon-polariton waveguides

Ssurface plasmon polaritons

propagating along very-thin(~ 10 nm) metal strips

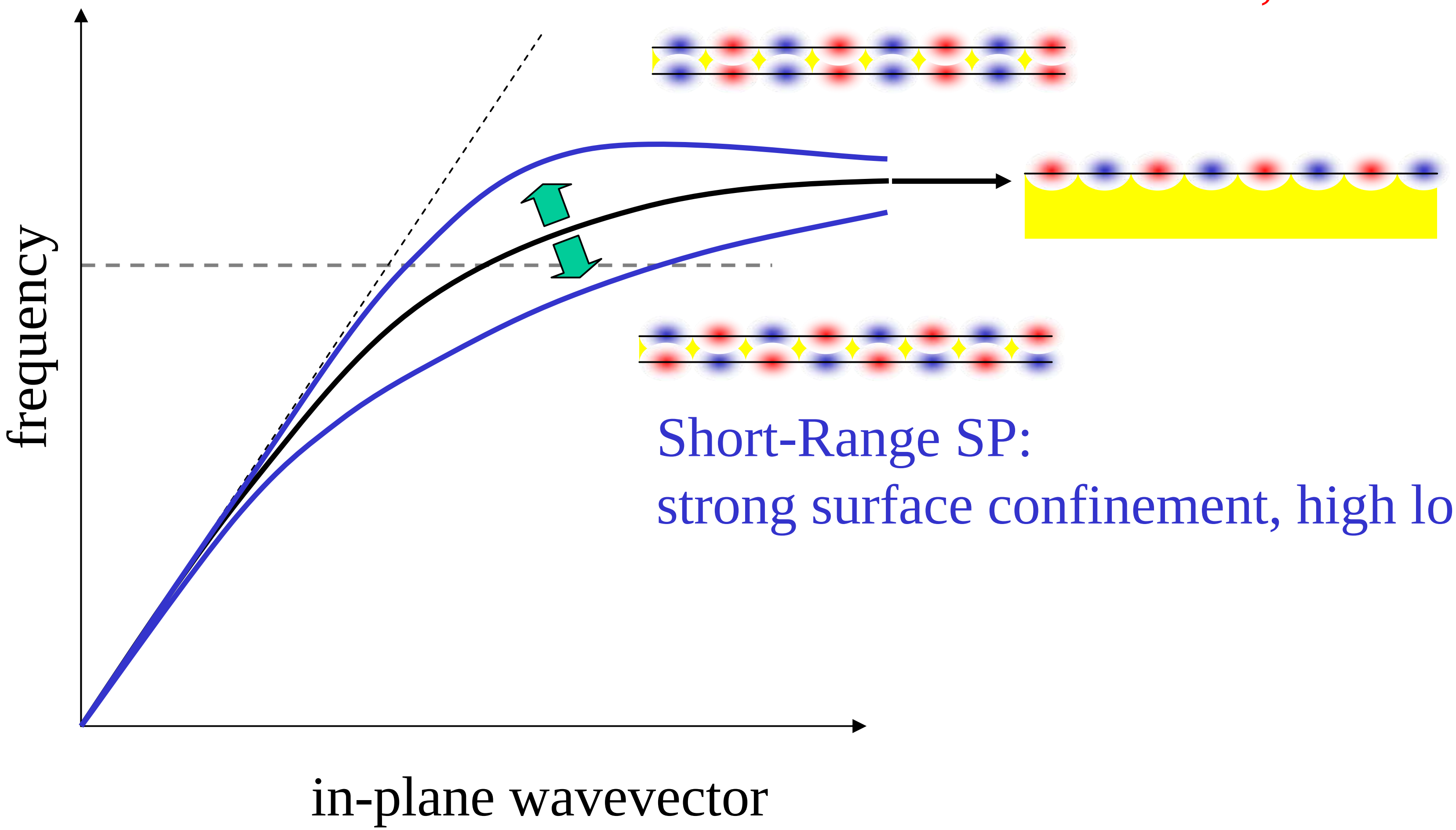


When the film thickness becomes finite.



Possibility of Propagation Range Extension

Long-Range SP:
weak surface confinement, low loss



Short-Range SP:
strong surface confinement, high loss

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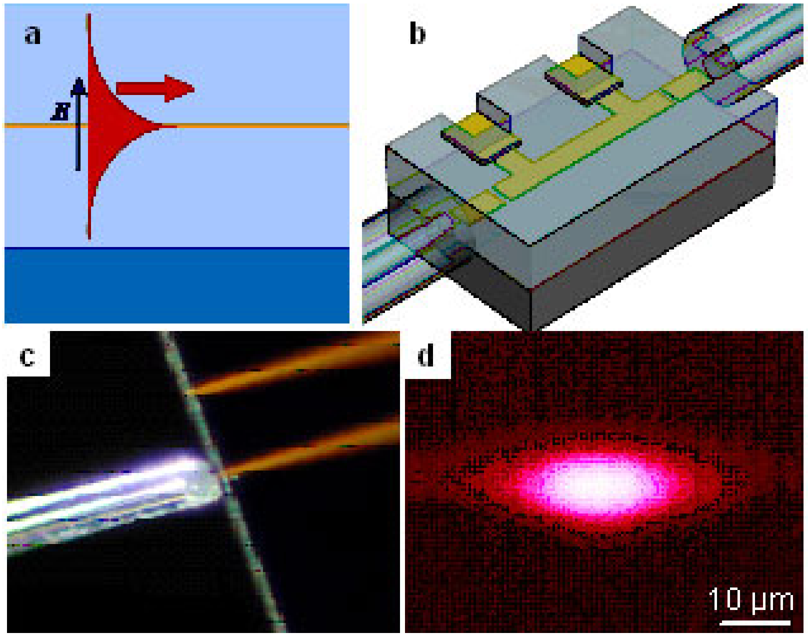
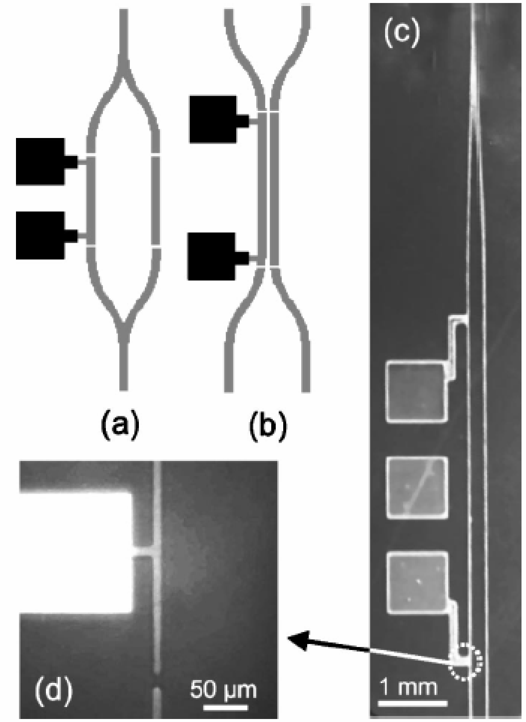
5834 Appl. Phys. Lett., Vol. 85, No. 24, 13 December 2004

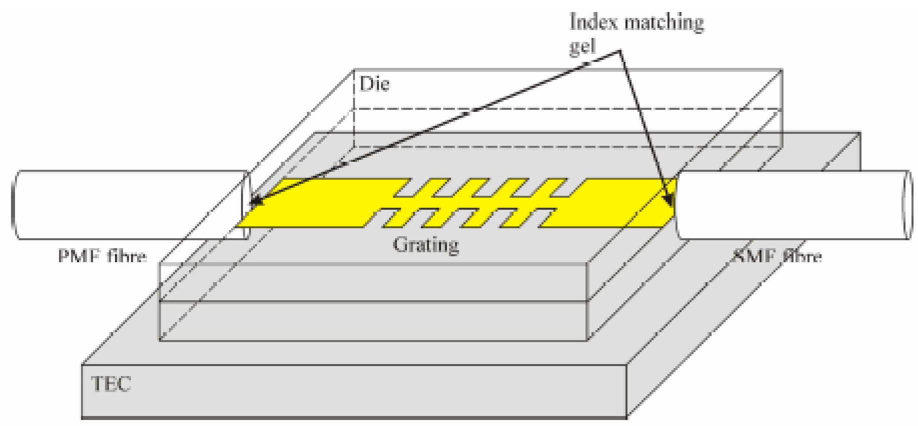


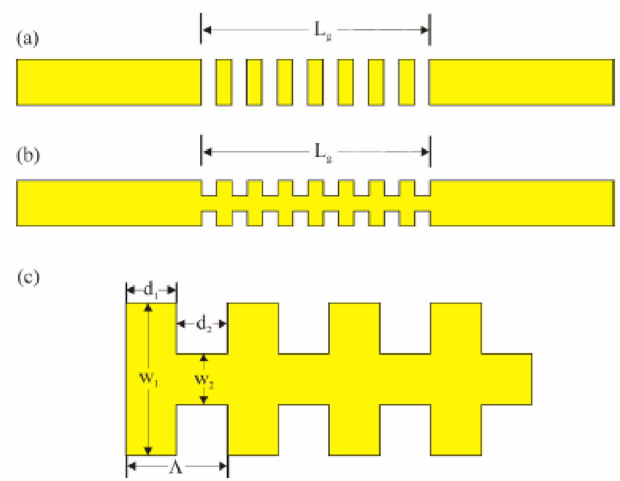


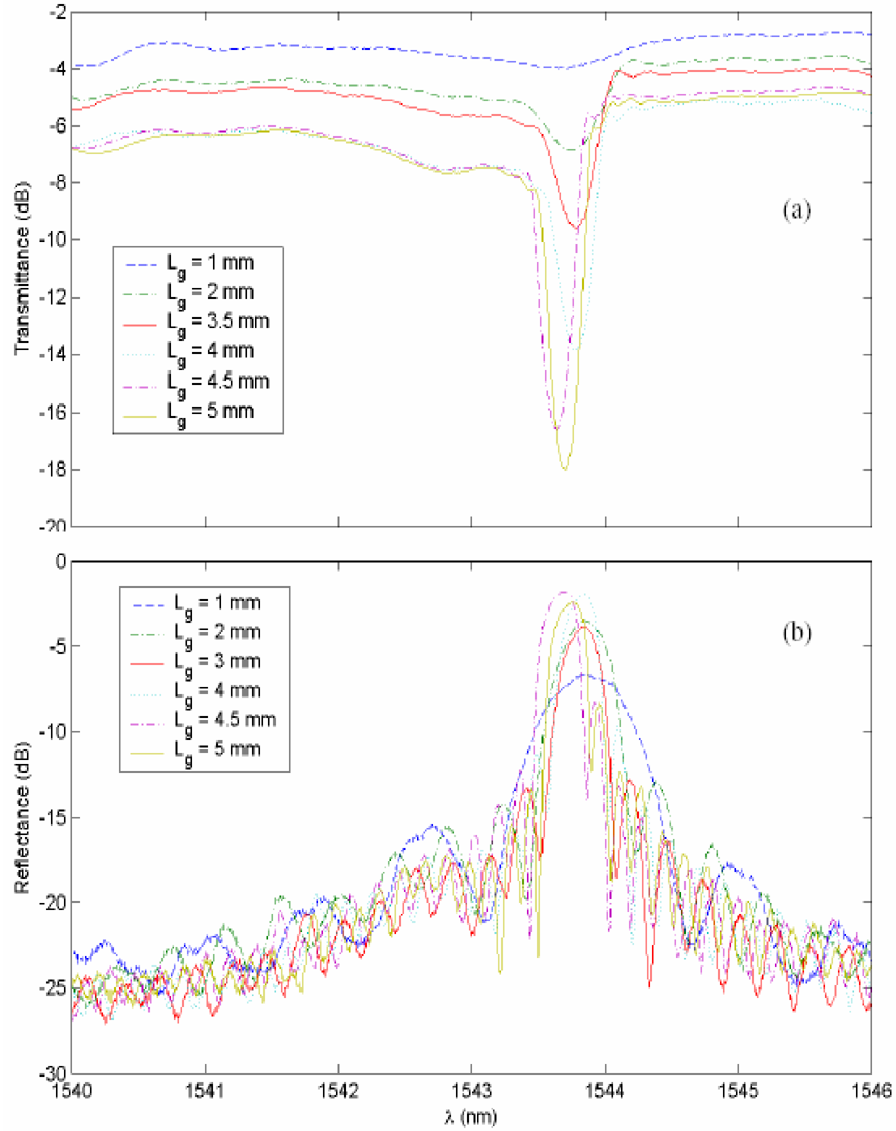
Several 1 cm long, 15 nm thin and 8 micron wide gold stripes guiding LRSPPs
3-6 mm long control electrodes
low driving powers (approx. 100 mW) and high extinction ratios (approx. 30 dB)
response times (approx. 0.5 ms)
total (fiber-to-fiber) insertion loss of approx. 8 dB when using single-mode fibers

Demonstration of Bragg gratings based on long-ranging surface plasmon polariton waveguides

Pierre Berini
13 June 2005 / Vol. 13, No. 12 / OPTICS EXPRESS 4674







Compact Z-add-drop wavelength filters for long-range surface plasmon polaritons

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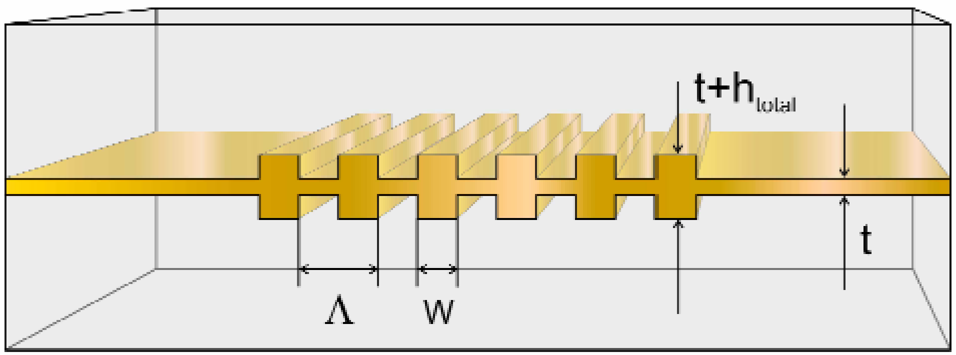
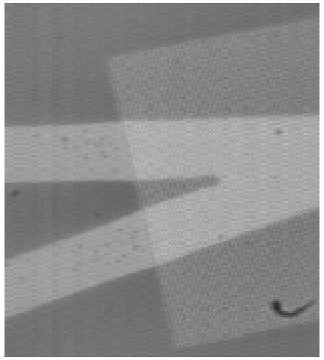
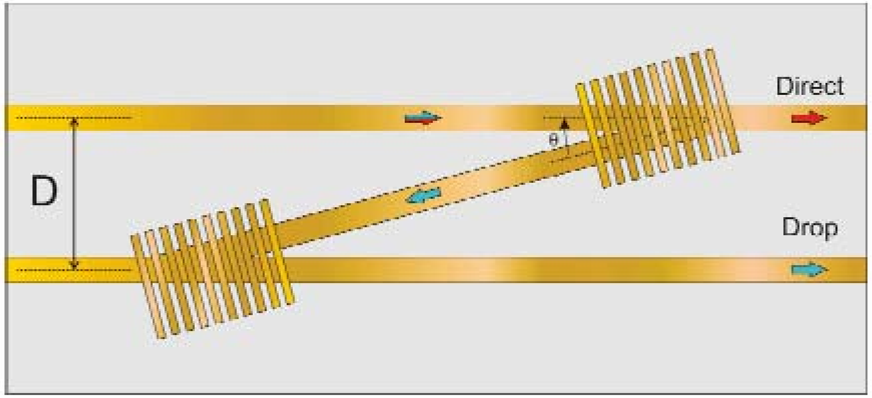
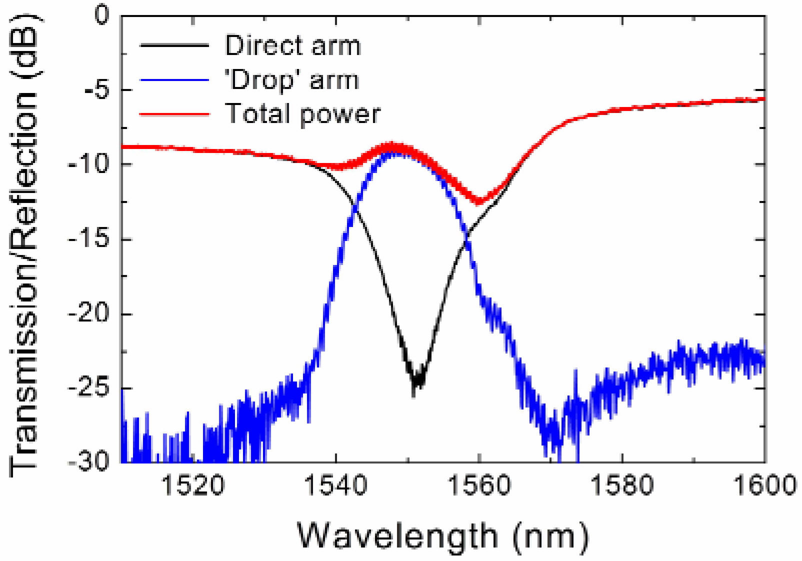
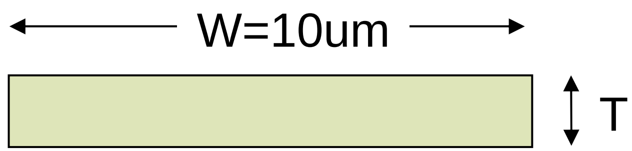


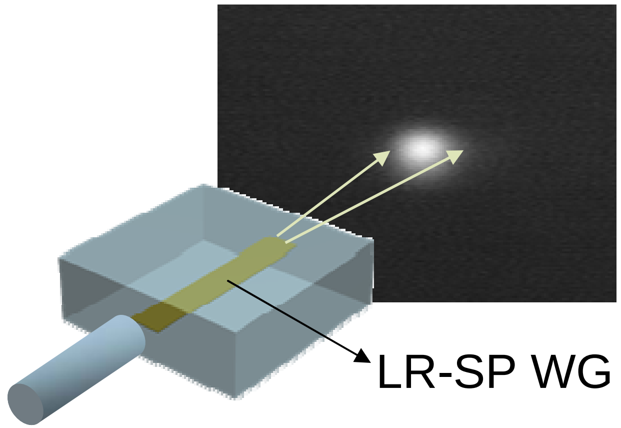


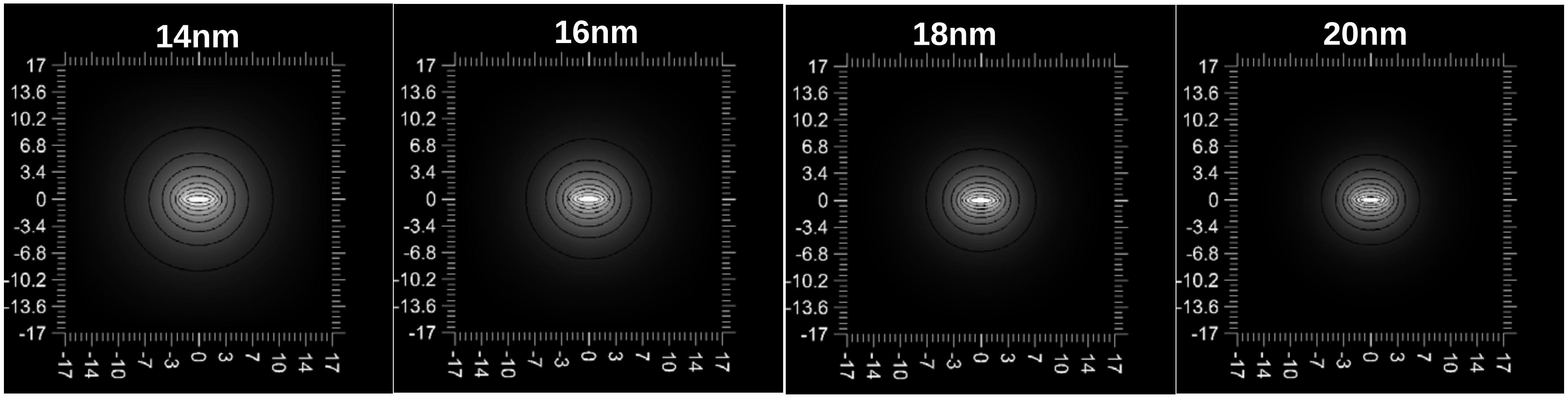




Fundamental symmetric mode of a metal stripe : thickness (T)







Metal	Resistivity ($\mu\Omega$-cm)	Real (ϵ)	Imaginary (ϵ)	Attenuation (dB/mm)
Al	2.83	-253.93	-46.08	0.89
Au	2.35	-131.95	-12.65	0.41
Ag	1.62	-86.64	-3.1	0.11

Table 1 : Resistivity and dielectric constant values for Al, Au, and Ag, along with theoretical attenuation at 1550 nm for a 4 μm wide waveguide of thickness of 20 nm embedded in SiO_2.

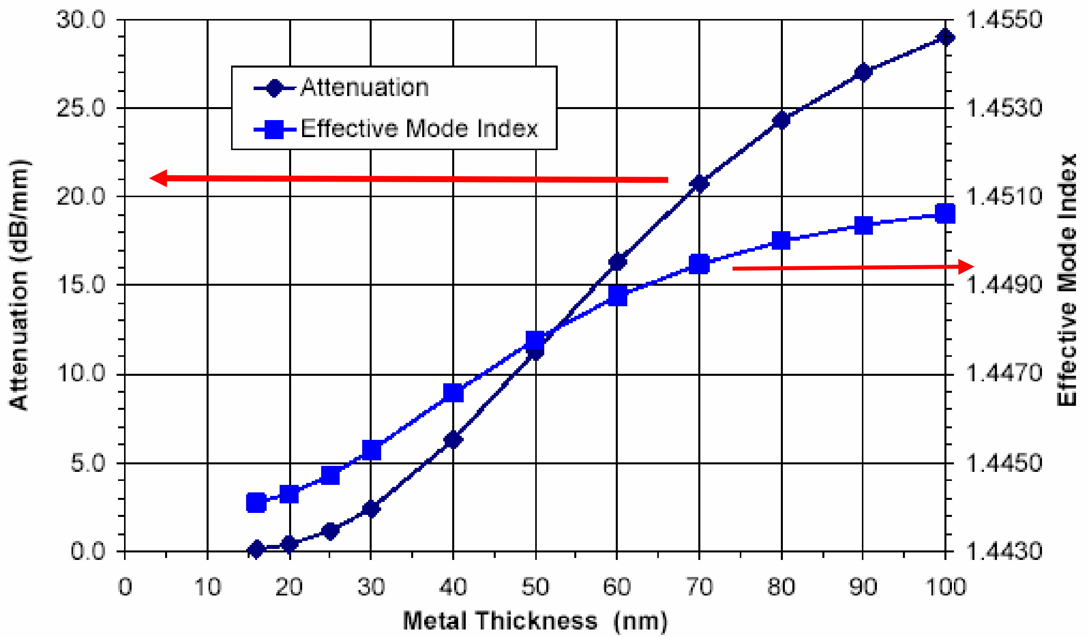
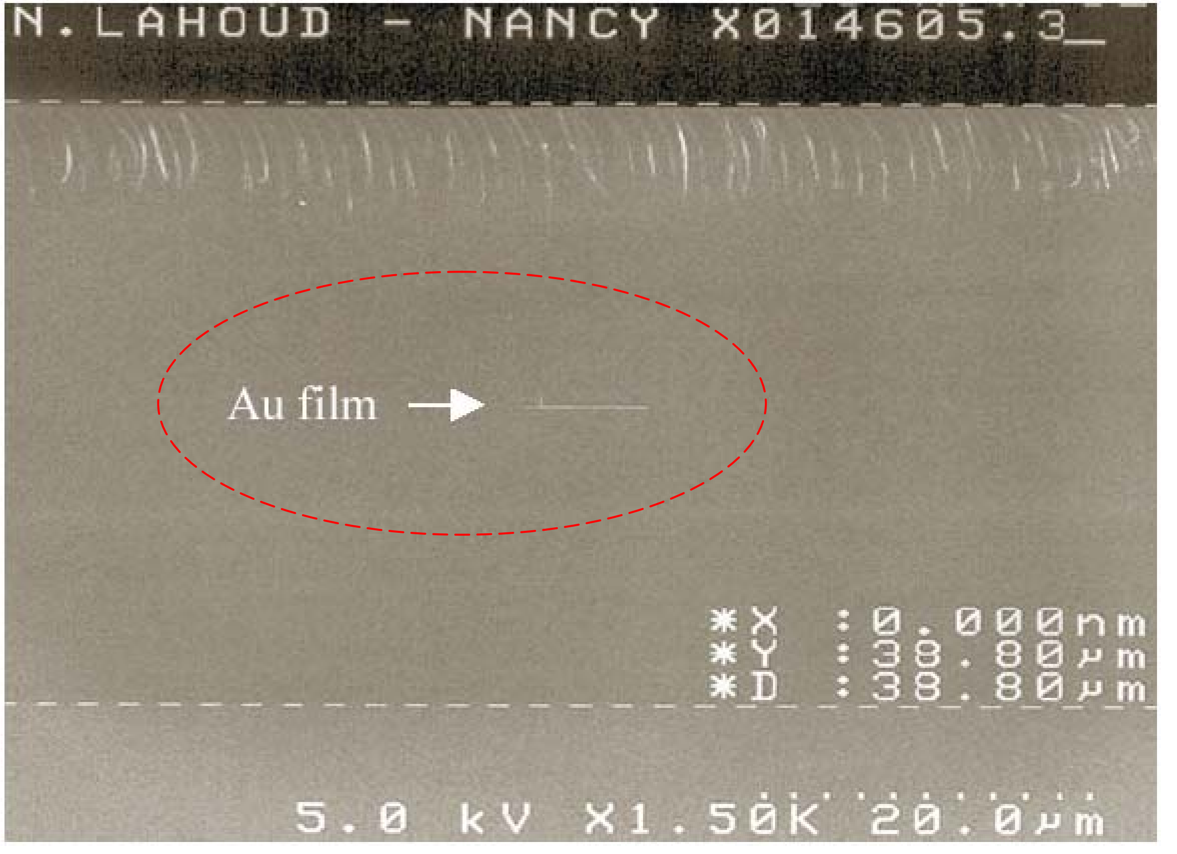


Figure 2 - Mode attenuation and effective index as a function of metal thickness for a 4 μm wide gold MWG cladded with oxide. The data presented in Figure 1 is a subset of the data presented here.

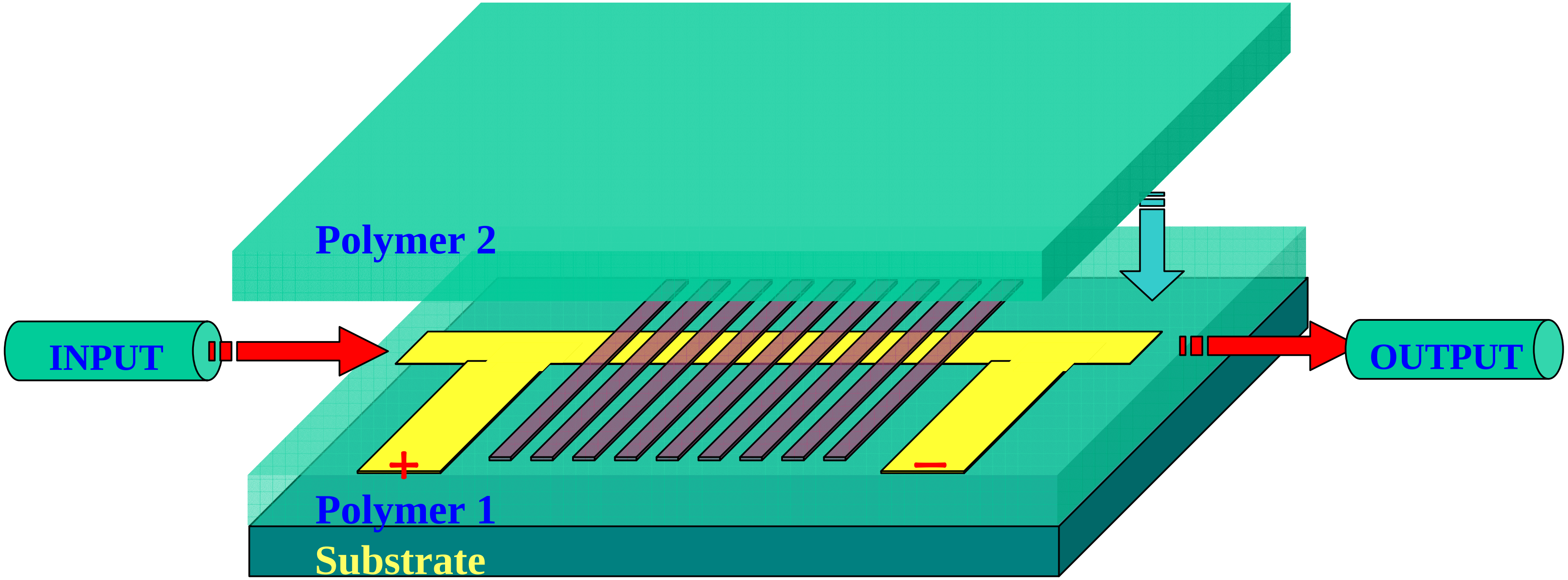
P. Berini, PhotonicWest 2005.

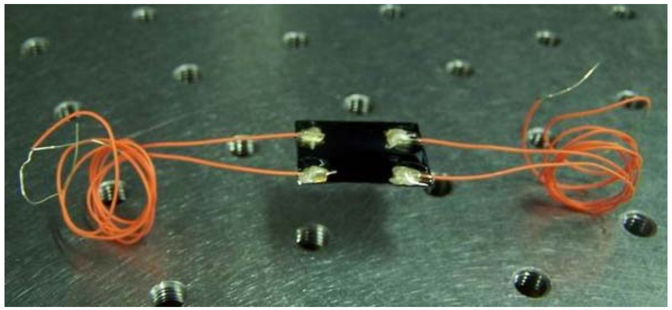


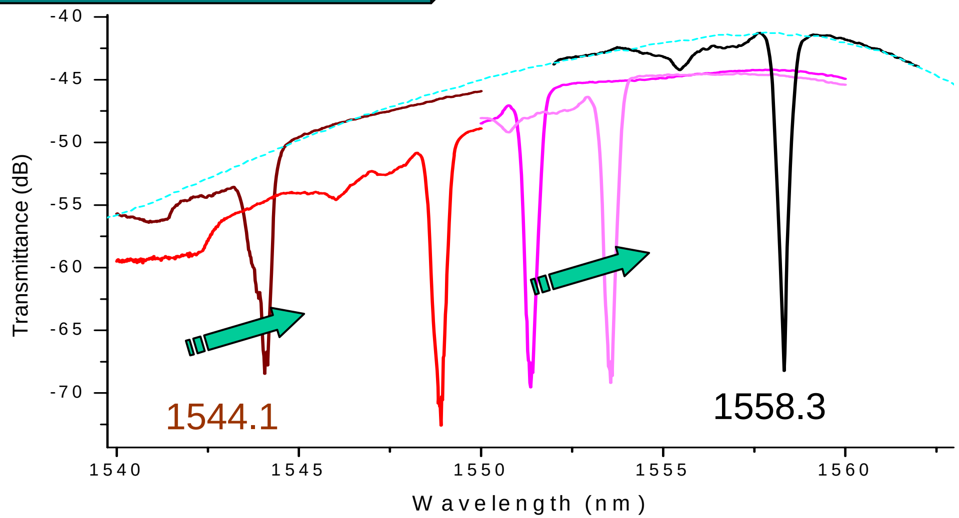
Cross-sectional FESEM image of a fabricated metal waveguide showing a thin Au film (bright horizontal line) embedded in about 40 μm of SiO_2.

(Spectalis Co.)

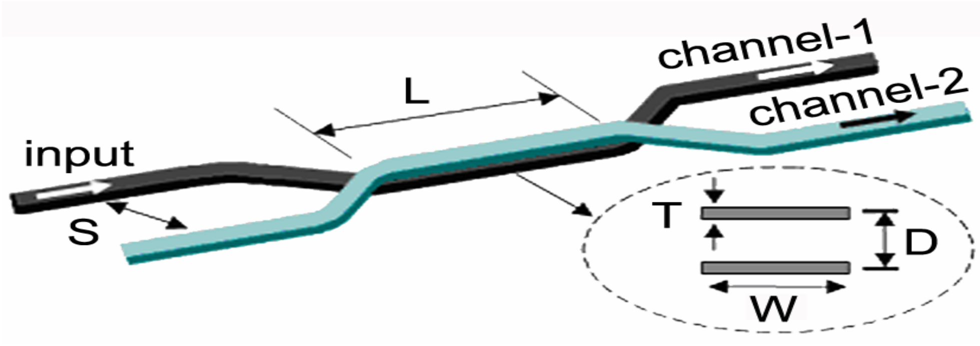
Tunable Wavelength filter by direct heating a metal wire

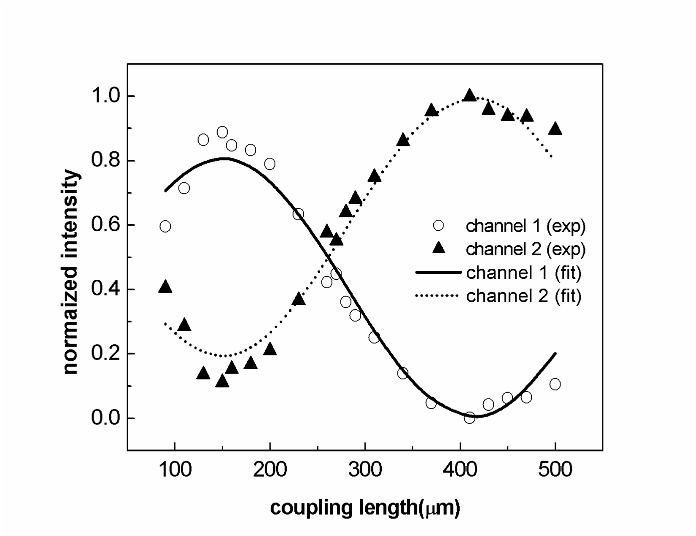


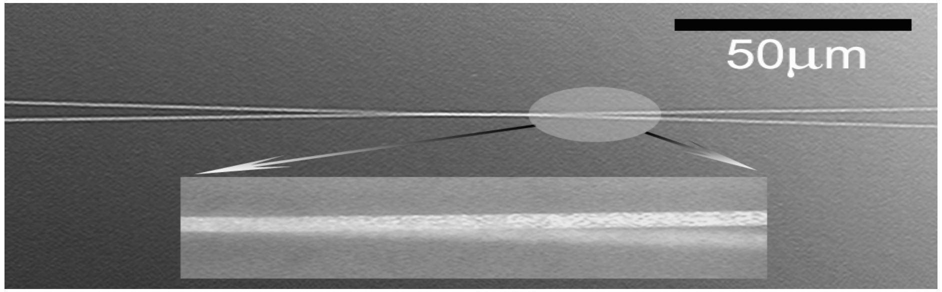


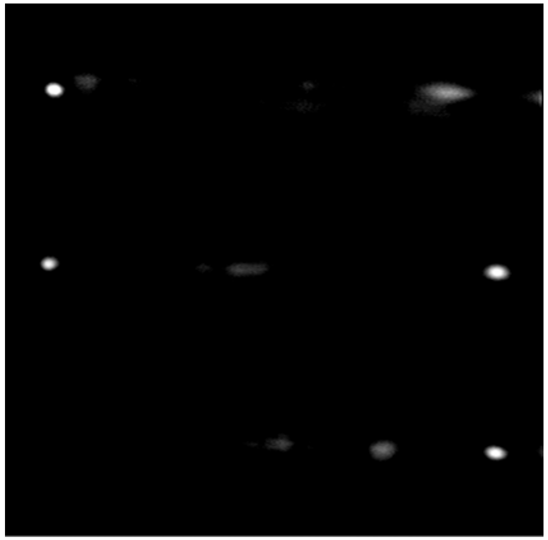


Vertical directional couplers





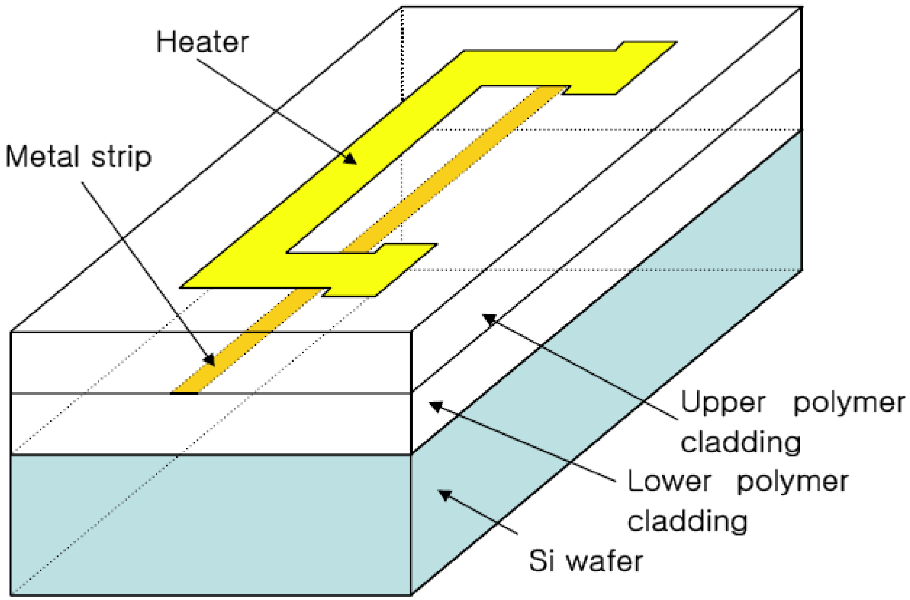


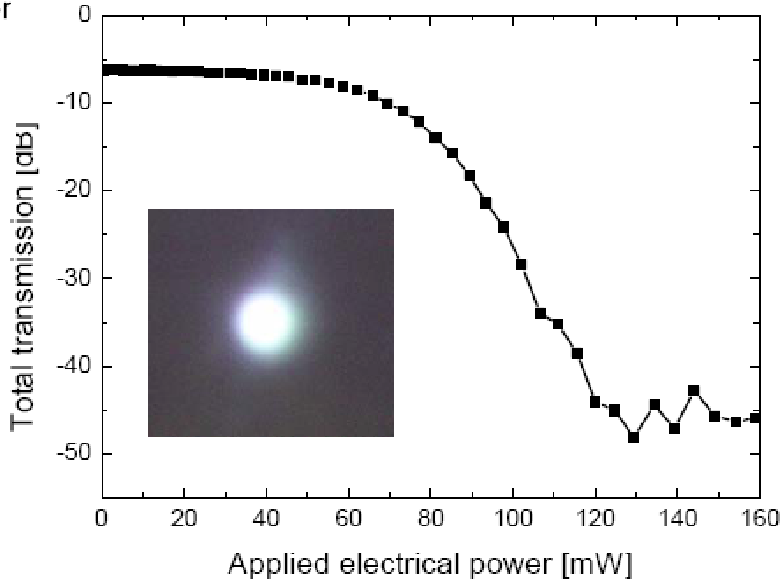


H. Won, APL vol.88, 011110 (2006)

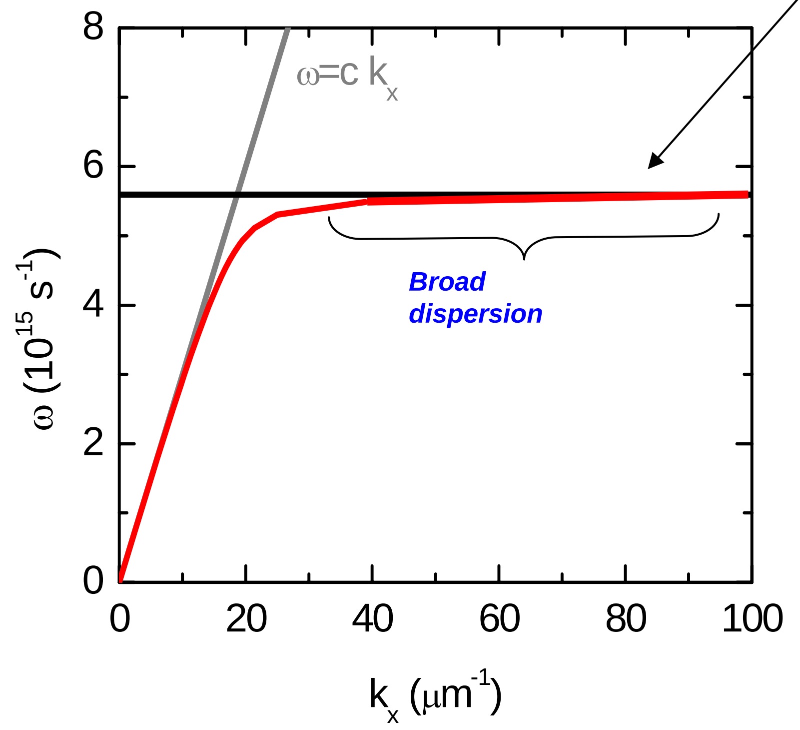
Variable optical attenuator based on LR-SPP

Submitted to EL, S. Park & S. Song





Localized Surface Plasmons : Nanofocusing and Nanolithography



At large k_x $(\varepsilon_1' \rightarrow -\varepsilon_2)$, $\hat{z}_i \approx \dfrac{1}{k_x}$.

$$E_z = \pm i E_x \ (air : +i,\ metal : \text{-}i)$$

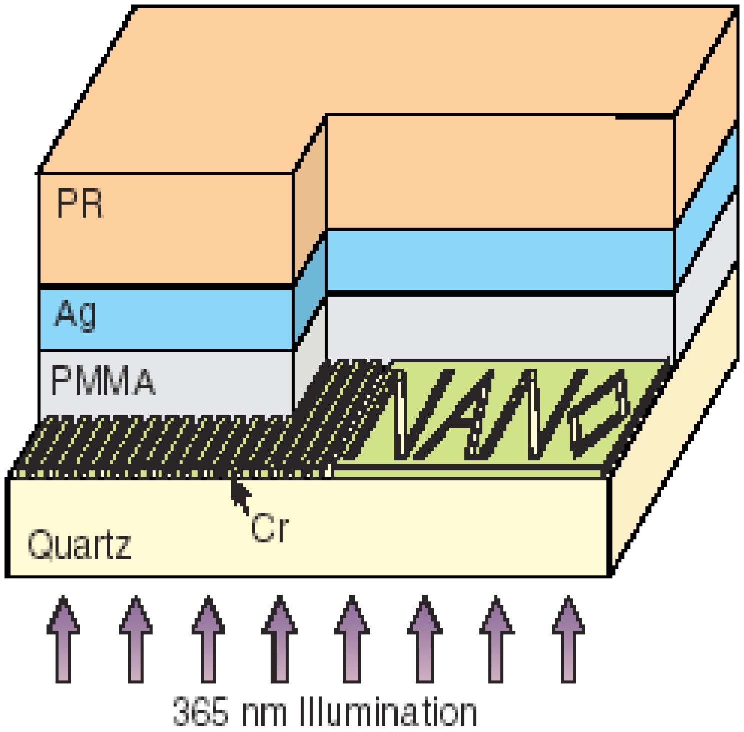
Strong confinement at the interface

→ Nano focusing

1686 23 MARCH 2007 VOL 315 SCIENCE

Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects

Zhaowei Liu,* Hyesog Lee,* Yi Xiong, Cheng Sun, Xiang Zhang†



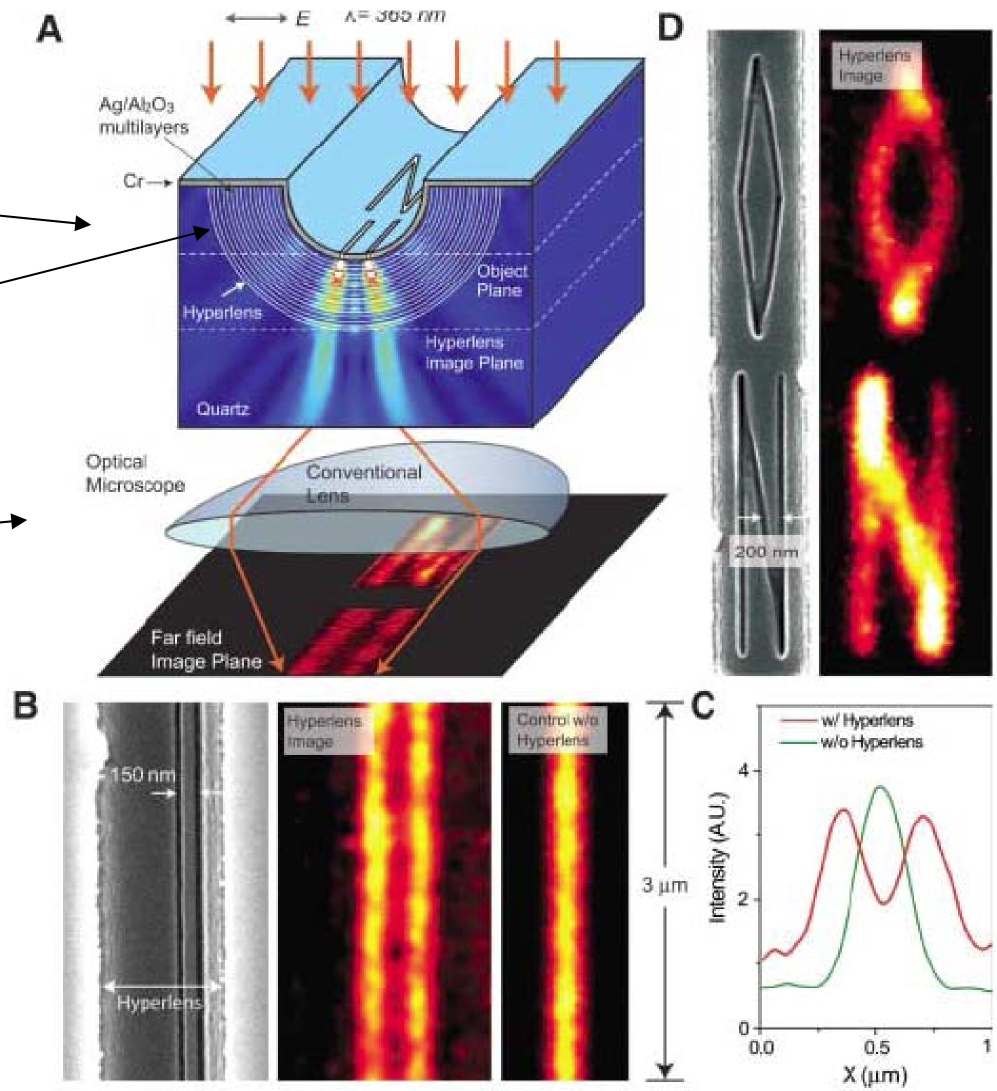


Fig. 1. Optical superlensing experiment. The embedded objects are inscribed onto the 50-nm-thick chrome (Cr); at left is an array of 60-nm-wide slots of 120 nm pitch, separated from the 35-nm-thick silver film by a 40-nm PMMA spacer layer. The image of the object is recorded by the photoresist on the other side of the silver superlens.

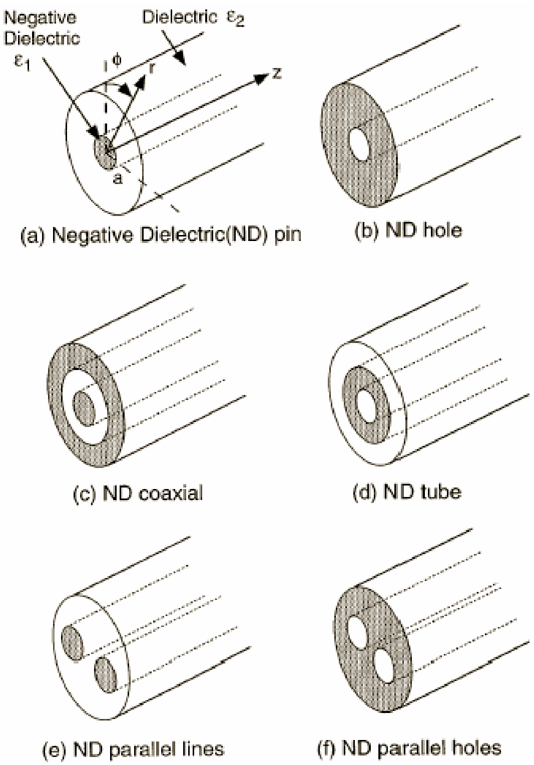
Propose metal nanowires.

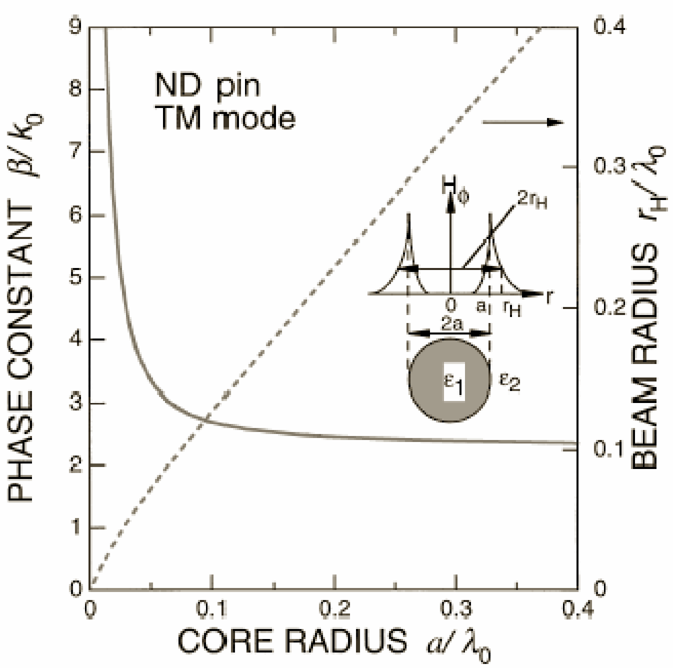
April 1, 1997 / Vol. 22, No. 7 / OPTICS LETTERS 475

Guiding of a one-dimensional optical beam with nanometer diameter

Junichi Takahara, Suguru Yamagishi, Hiroaki Taki, Akihiro Morimoto, and Tetsuro Kobayashi

Department of Electrical Engineering, Faculty of Engineering Science, Osaka University, Toyonaka, Osaka 560, Japan

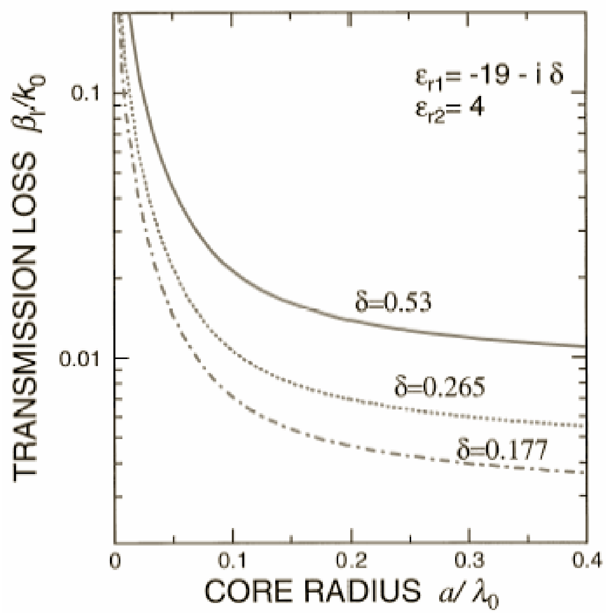




Beam radius -> zero!

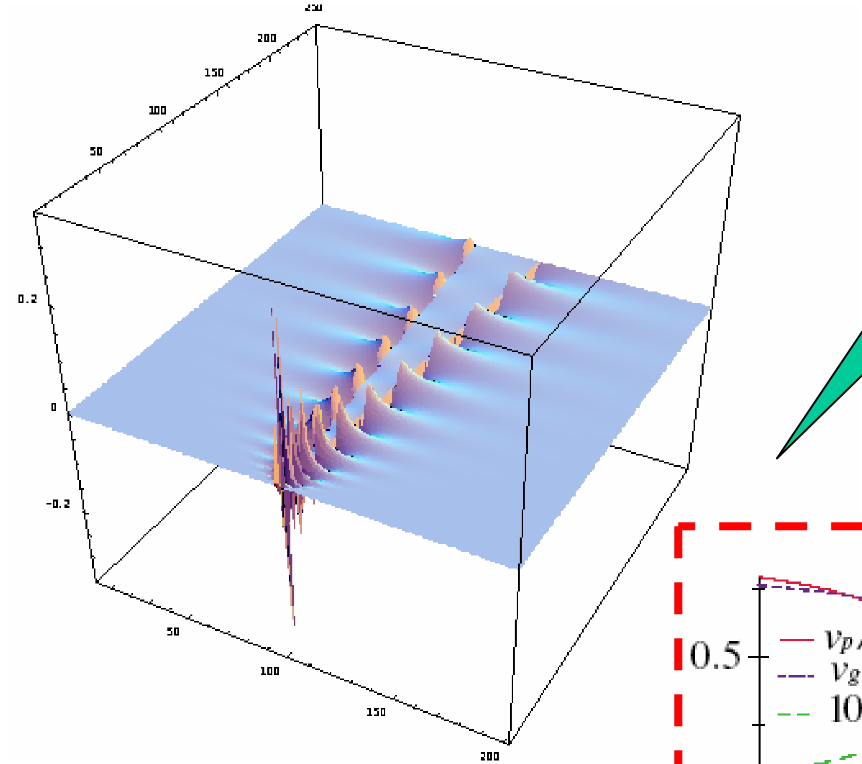
Propagation Loss (asymmetric mode)

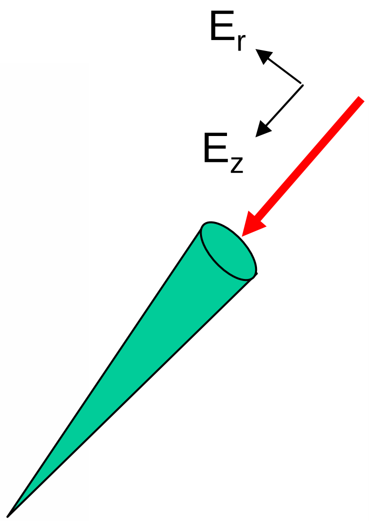
High



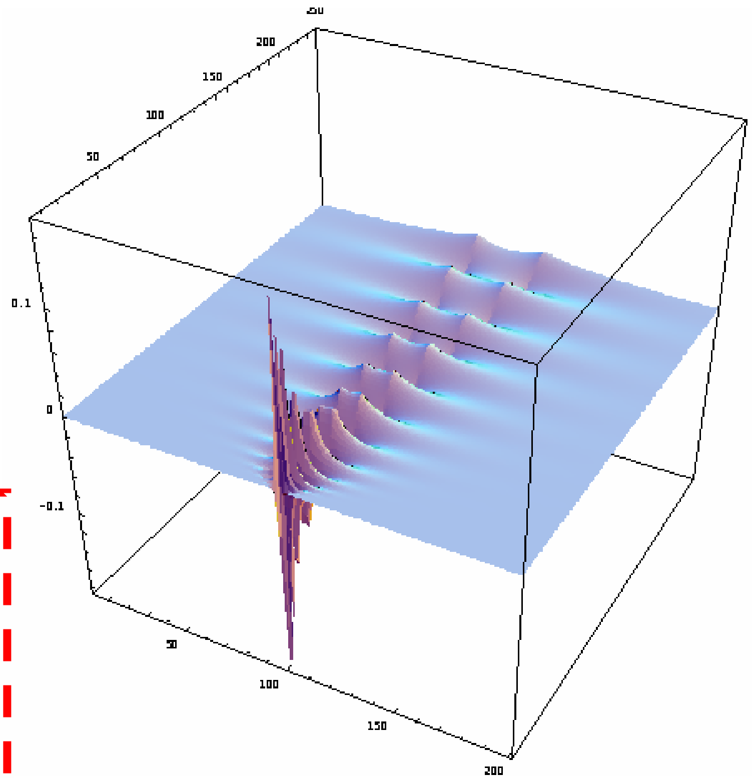
Asymmetric mode : field enhancement at a metallic tip

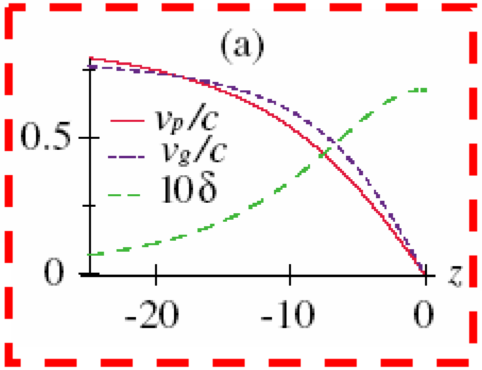
E_r

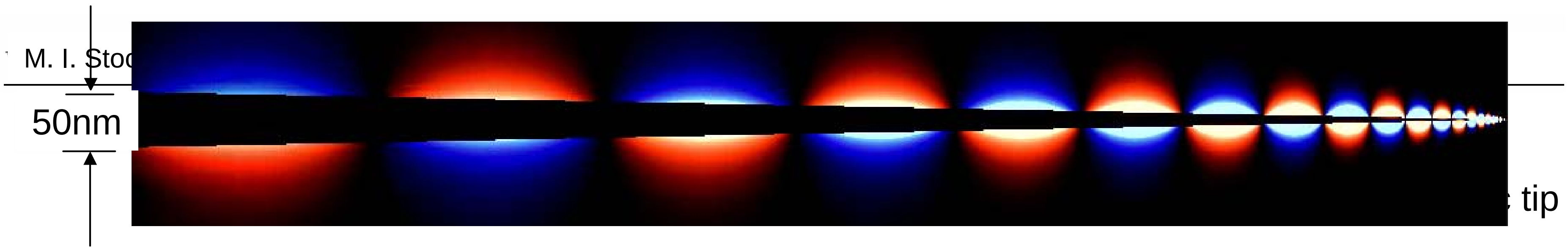




E_z







2007/5/1 ~

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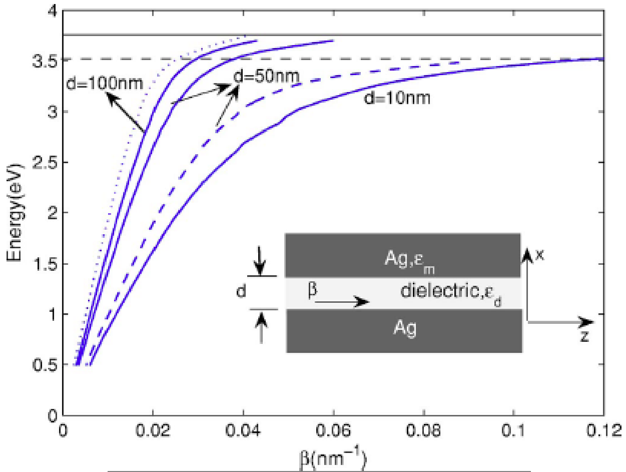
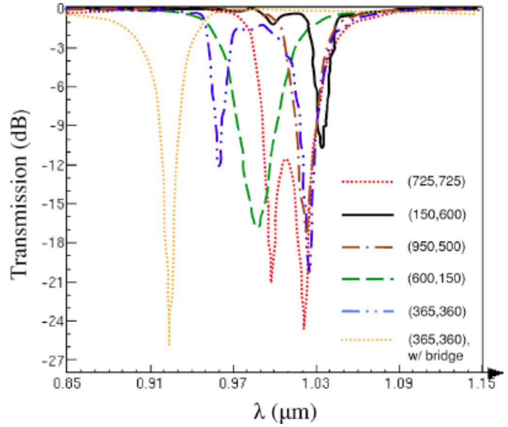
Nanoscale surface plasmon based resonator using rectangular geometry

Amir Hosseini and Yehia Massoud[a)] *Rice University, Houston*

an optical range resonator based on single mode metal-insulator-metal plasmonic gap waveguides.
A small bridge between the resonator and the input waveguide can be used to tune the resonance frequency.

FDTD with the perfectly matched layer boundary conditions

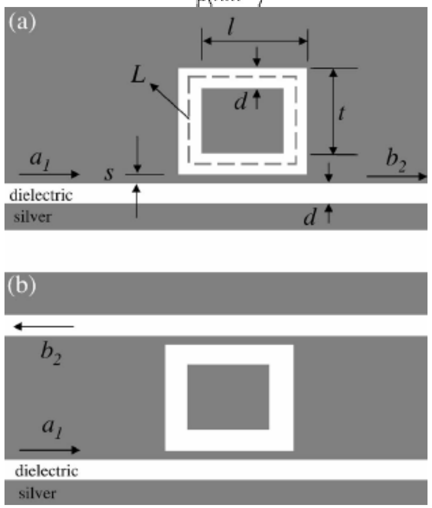




The transmission ($T=|b_2/a_1|^2$) through the input waveguide is given by

$$T=\frac{\alpha^2+|t|^2-2\alpha|t|\cos(\theta+\phi)}{1+\alpha^2|t|-\alpha|t|\cos(\theta+\phi)}, \quad (1)$$

where α and $|t|$ represent the ring internal attenuation and the coupling coefficient, respectively, i.e., $\alpha=1$ means no internal loss, and $\theta=(2\pi/\lambda_g)L$.[10] At resonance $(\phi+\theta=2N\pi)$,



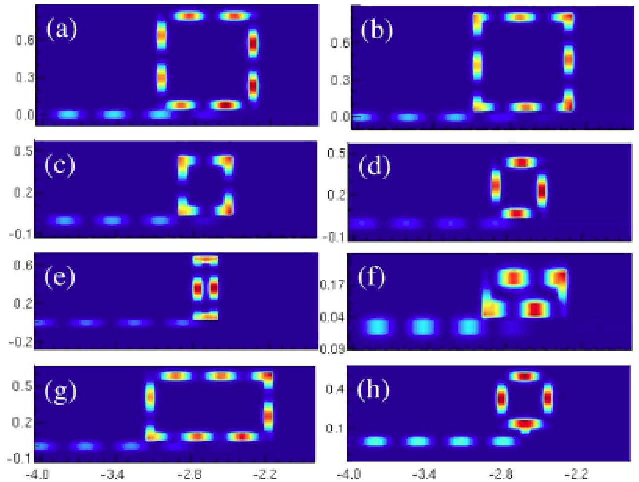


FIG. 4. (Color online) Field profile ($|Hz|^2$) for different (l,t) values in nm:

Nano Lett., Vol. 7, No. 6, 2007 1698

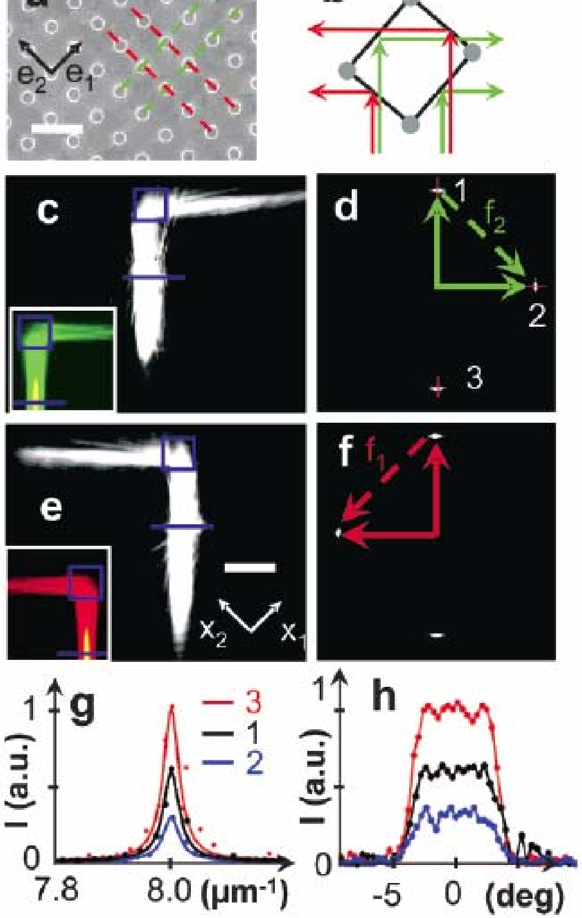
Plasmonic Crystal Demultiplexer and Multiports

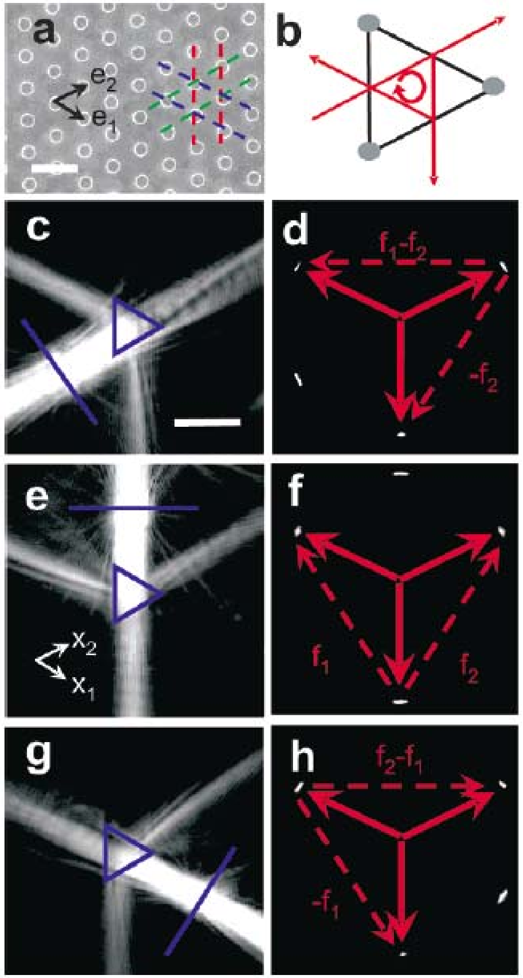
A. Drezet,* Daniel Koller, Andreas Hohenau, Alfred Leitner, Franz R. Aussenegg, and Joachim R. Krenn *Graz, Austria*

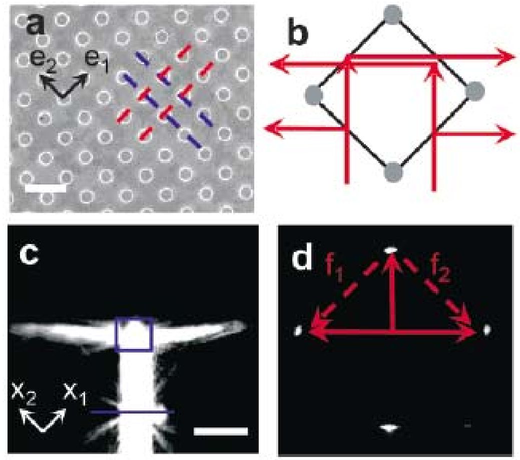
the realization of two-dimensional optical wavelength demultiplexers and multiports for surface plasmons polaritons (SPPs) based on plasmonic crystals, i.e., photonic crystals for SPPs.

50 nm thick gold
(200 nm diameter, 50 nm height

800 and 750 nm



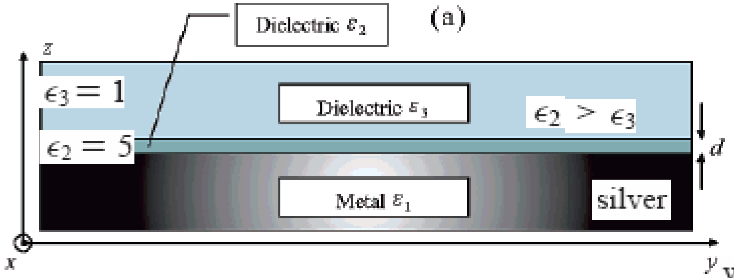




Nano Lett., Vol. 6, No. 11, 2006 **2604−2608**

Slow Propagation, Anomalous Absorption, and Total External Reflection of Surface Plasmon Polaritons in Nanolayer Systems

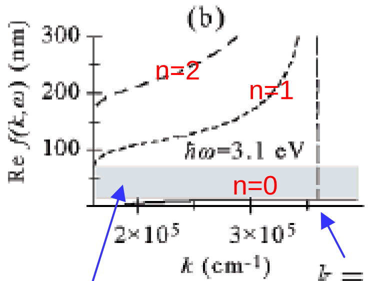
Mark I. Stockman* *Georgia State University*



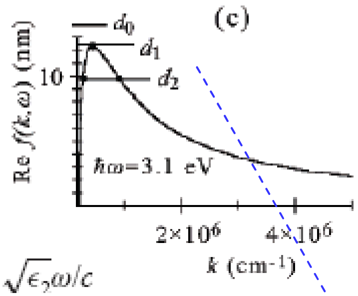
$$\epsilon_1(\omega_2) + \epsilon_2 = 0, \quad \hbar\omega_2 = 3.02 \text{ eV}$$

$$\epsilon_1(\omega_3) + \epsilon_3 = 0 \quad \hbar\omega_3 = 3.68 \text{ eV}$$

when the frequency $\omega_3 > \omega > \omega_2$.



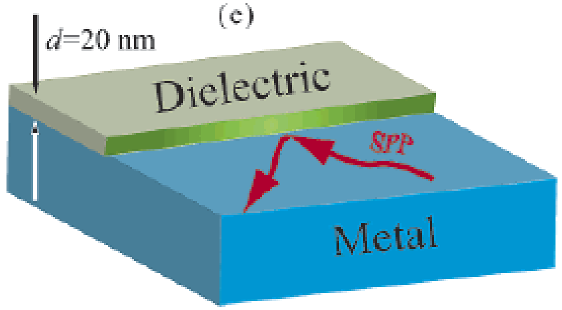
$k = \sqrt{\epsilon_2}\omega/c$



SPPs can propagate for a very thin layer ($d \to 0$)

when d increases,
the situation eventually changes to resemble an infinite layer of dielectric 2 over the metal where the SPP propagation is impossible.

→ total external reflection



the gap d for which there is no surface plasmon polariton propagation.

$d_1 = 12$ nm $\quad d_u = 82$ nm for $\omega = 3.1$ eV

$$d = f(k,\omega)$$

$$f(k,\omega) = \frac{1}{\epsilon_2 v_2}\left\{-\mathrm{Arctan}\left[\frac{v_2(u_1+u_3)}{u_1u_3 - v_2^2}\right] + n\pi\right\},$$

$n = 0, 1, 2, \ldots$, where

$$u_i = \frac{1}{\epsilon_i}\sqrt{q^2 - \epsilon_i}, \quad v_i = \sqrt{\epsilon_i - q^2}, \quad k = \frac{\omega}{c}q$$

$d_0 > d_1 = 12$ nm, there are no propagating SPPs.

$d = d_1 = 12$ nm a bifurcation point

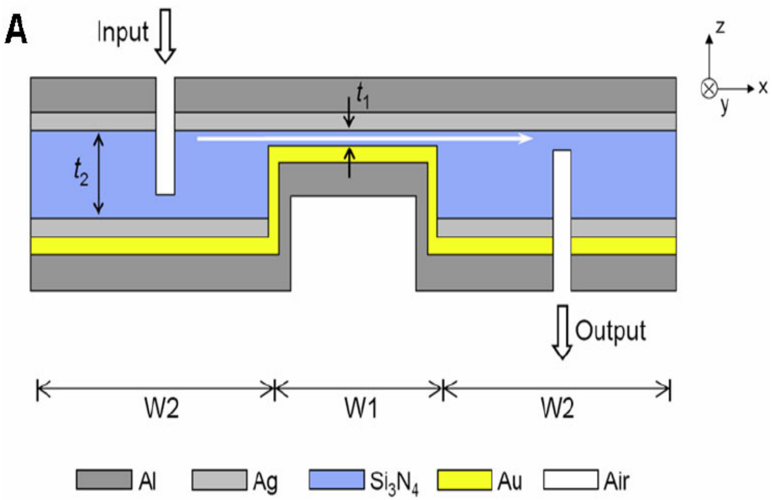
$d_2 < d_1 = 12$ nm, two solutions. a long wavelength (small k),
a short wavelength (large k)

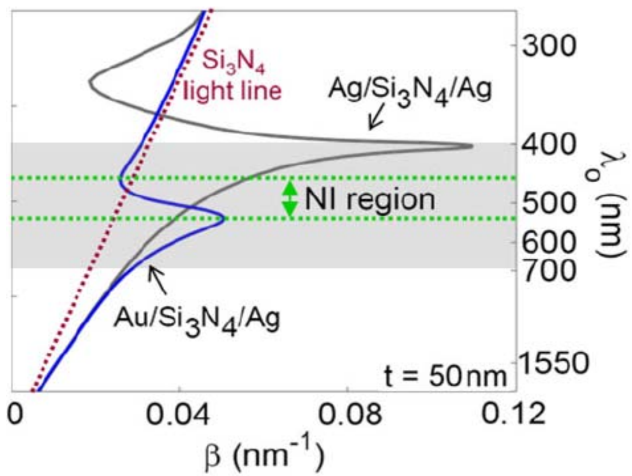
Sciencexpress / www.sciencexpress.org / 22 March 2007 / Page 1 / 10.1126/science.1139266

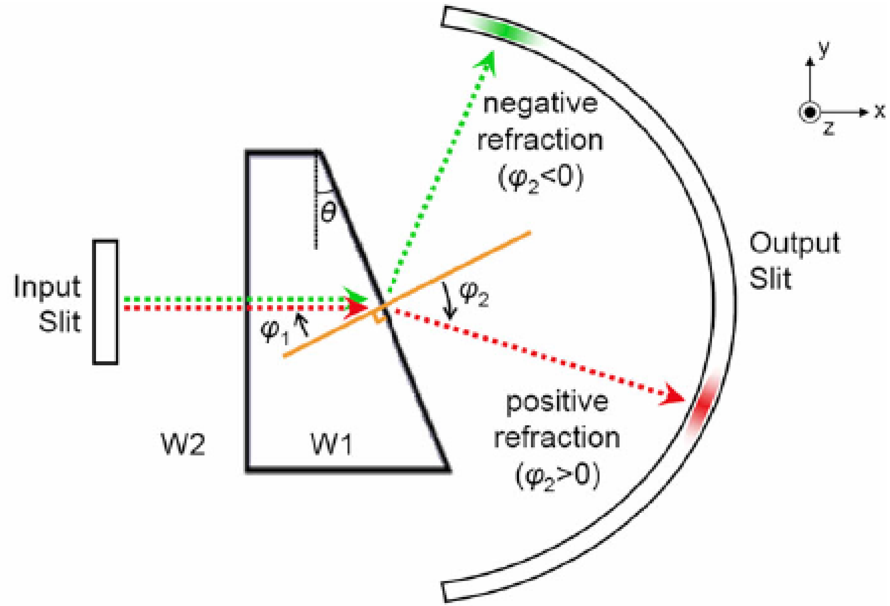
Negative Refraction at Visible Frequencies

Henri J. Lezec,[1,2]*† Jennifer A. Dionne,[1]* Harry A. Atwater[1]

[1]Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA. [2]Centre National de la Recherche Scientifique, 3 rue Michel-Ange, 75794 Paris Cedex 16, France.







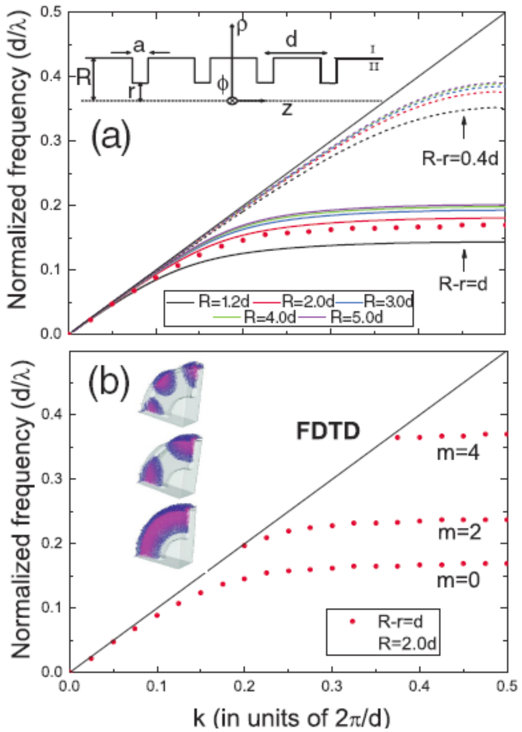
PRL 97, 176805 (2006)

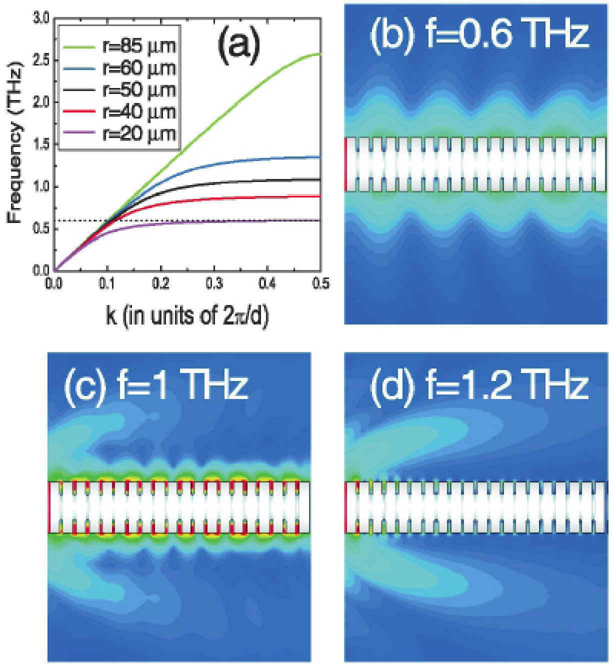
Terahertz Surface Plasmon-Polariton Propagation and Focusing on Periodically Corrugated Metal Wires

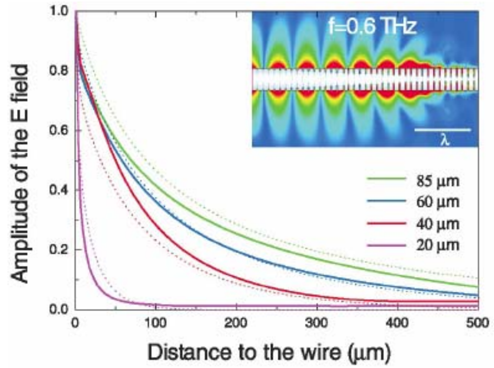
Stefan A. Maier,[1,*] Steve R. Andrews,[1] L. Martín-Moreno,[2] and F. J. García-Vidal[3,†] *University of Bath, United Kingdom*

we show how the dispersion relation of surface plasmon polaritons (SPPs) propagating along a perfectly conducting wire can be tailored by corrugating its surface with a periodic array of radial grooves.
Importantly, the propagation characteristics of these spoof SPPs can be controlled by the surface geometry, opening the way to important applications such as energy concentration on cylindrical wires and superfocusing using conical structures.

$$\sum_{n=-\infty}^{+\infty} S_n^2 \frac{g}{q_n}\frac{K_1(q_nR)}{K_0(q_nR)}\frac{N_0(gR)J_0(gr)-N_0(gr)J_0(gR)}{N_0(gr)J_1(gR)-N_1(gR)J_0(gr)}=1,$$







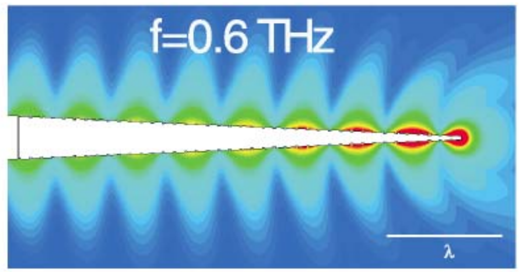


FIG. 4 (color). Superfocusing on a corrugated cone of length 2 mm, with constant $h = 5\ \mu m$ and $d = 50\ \mu m$. R is reduced from 100 to 10 μm. The plot shows the magnitude of the **E** field on a logarithmic scale spanning 2 orders of magnitude.

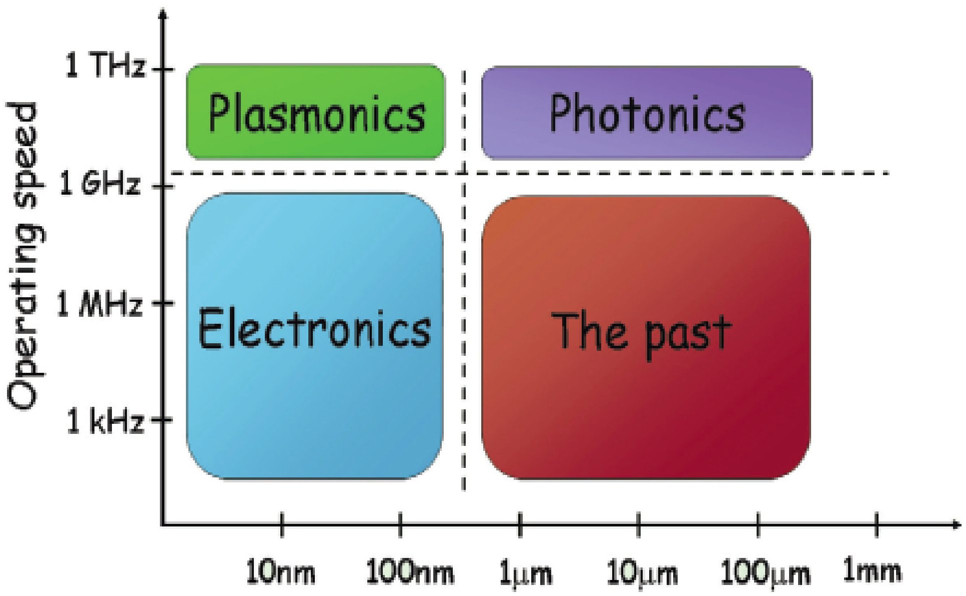
Summary : Plasmonic Photonics

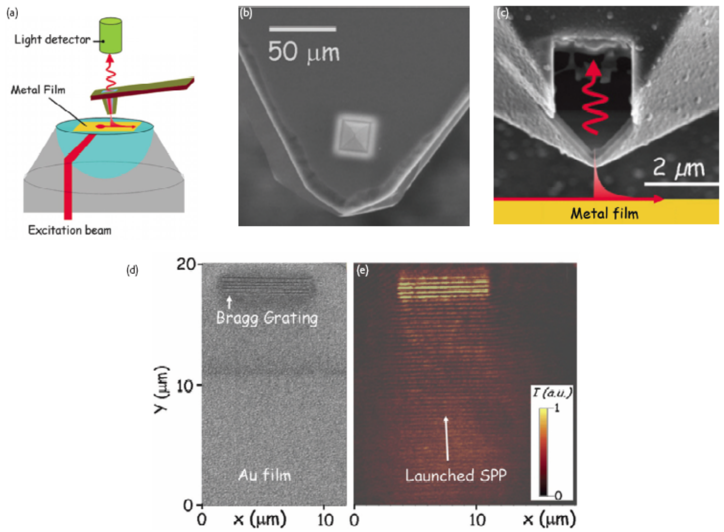
20 materialstoday JULY-AUGUST 2006 | VOLUME 9 | NUMBER 7-8

Plasmonics: the next chip-scale technology

Rashid Zia, Jon A. Schuller, Anu Chandran, and Mark L. Brongersma* Stanford University

Plasmonics is an exciting new device technology that has recently emerged.
A tremendous synergy can be attained by integrating plasmonic, electronic, and conventional dielectric photonic devices on the same chip and taking advantage of the strengths of each technology.





Plasmonic devices, therefore, might interface naturally with similar speed photonic devices and similar size electronic components. For these reasons, plasmonics may well serve as the missing link between the two device technologies that currently have a difficult time communicating. By increasing the synergy between these technologies, plasmonics may be able to unleash the full potential of nanoscale functionality and become the next wave of chip-scale technology.

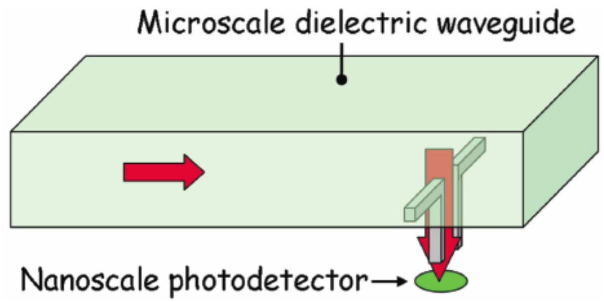


Fig. 7 Schematic of how a nanoscale antenna structure can serve as a bridge between microscale dielectric components and nanoscale electronic devices.