Quantum Information Processing with 10^{10} Electrons ?

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People:

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- Peter Marzlin
- Jeremie Choquette

Informatics iCORE Circle of Research Excellence

Motivation

Quantum information processing realizations

Ions

Photons

Neutral Atoms

Solid State systems

NMR

Superconductors

Need for hybridization and interfacing of different technologies

Surface Plasmons ?

coherent charge density oscillations involving 10^{10} electrons

Outline

- What are surface plasmons: Introduction
- Excitation of surface plasmons at surfaces
- Entanglement and surface plasmons
- Surface plasmons in quantum information implementations

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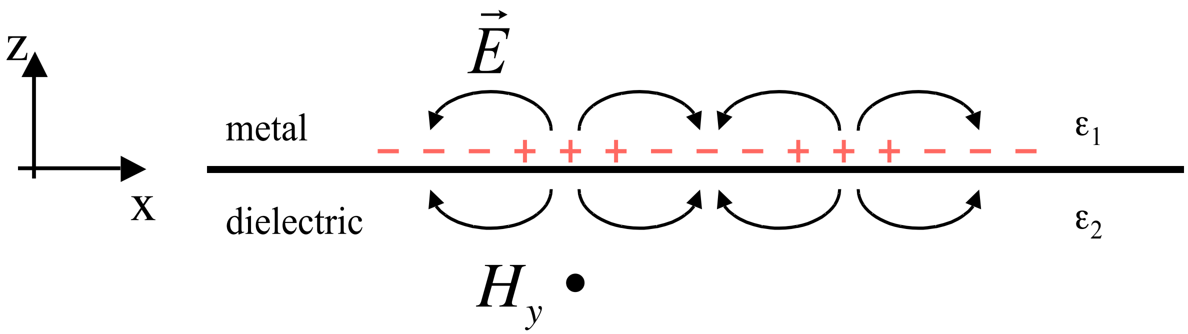
What are surface plasmons ?

- Electric field propagating at surface



$$\mathbf{E}_1 = \begin{pmatrix} E_{x1} \\ 0 \\ E_{z1} \end{pmatrix} \exp\left[i\left(k_{x1}x - k_{z1}z - \omega t\right)\right]$$

$$\mathbf{H}_1 = \begin{pmatrix} 0 \\ E_{y1} \\ 0 \end{pmatrix} \exp\left[i\left(k_{x1}x - k_{z1}z - \omega t\right)\right]$$

$$\mathbf{E}_2 = \begin{pmatrix} E_{x2} \\ 0 \\ E_{z2} \end{pmatrix} \exp\left[i\left(k_{x2}x + k_{z2}z - \omega t\right)\right]$$

$$\mathbf{H}_2 = \begin{pmatrix} 0 \\ E_{y2} \\ 0 \end{pmatrix} \exp\left[i\left(k_{x2}x + k_{z2}z - \omega t\right)\right]$$

- Maxwell Equations and continuity

$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon \mathbf{E}$ (linear medium)

$$\operatorname{div} \mathbf{D} = 0 \quad \rightarrow \quad \begin{aligned} E_{x1} &= E_{x2} \\ \varepsilon_1 E_{z1} &= \varepsilon_2 E_{z2} \end{aligned}$$

$$\operatorname{rot} \mathbf{H} - \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} = 0 \quad \rightarrow \quad \begin{aligned} H_{y1} &= H_{y2} \\ \frac{k_{z1}}{\varepsilon_1} H_{y1} &= -\frac{k_{z2}}{\varepsilon_2} H_{y2} \end{aligned}$$

$$\operatorname{div} \mathbf{B} = 0$$

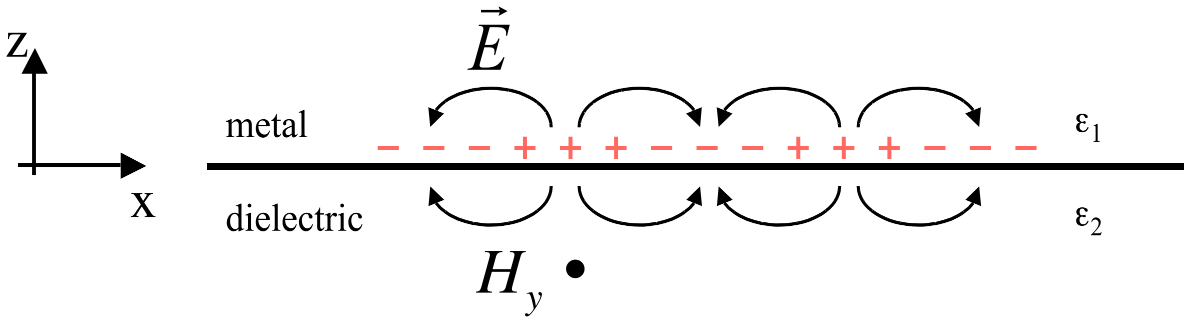
SP Dispersion relation

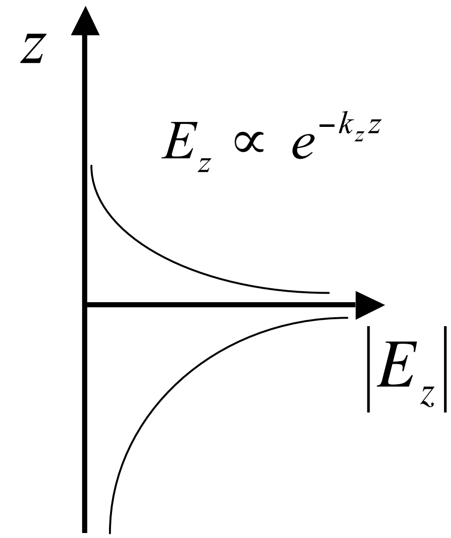
$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$

$$k_x^2 + k_{zi}^2 = \varepsilon_i \frac{\omega^2}{c^2}$$

What are surface plasmons ?

- Evanescent electric field propagating at surface





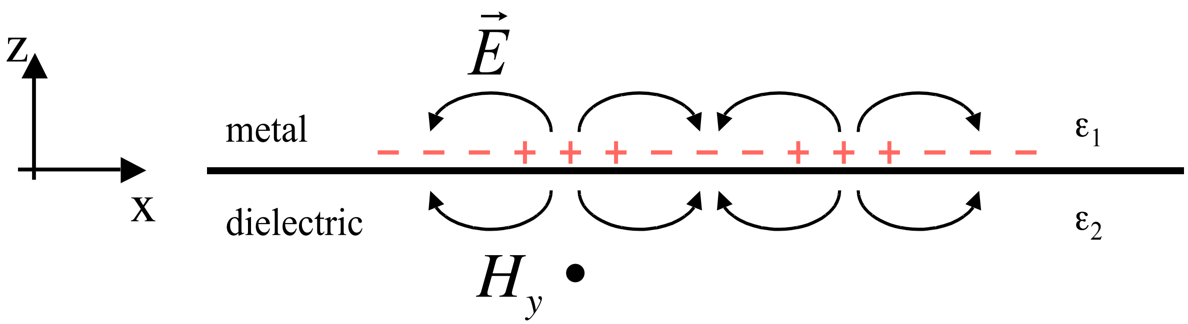
Surface Plasmon: Longitudinal charge density oscillations involving 10^{10} electrons

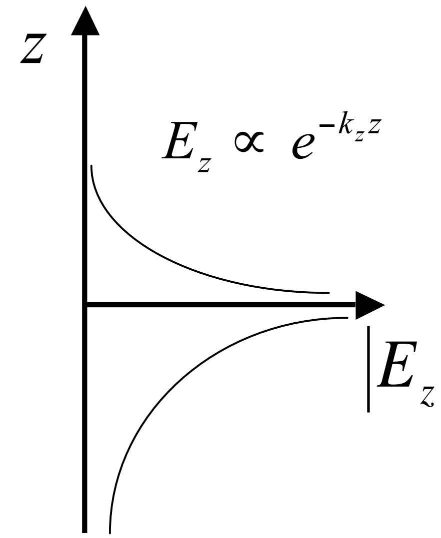
$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$

Surface Plasmon Polariton: Polaritons are quasiparticles resulting from strong coupling of electromagnetic waves with an electric or magnetic dipole-carrying excitation, in this case plasmons.

What are surface plasmons ?

- Evanescent electric field propagating at surface





$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}}$$

$\varepsilon_1 = \varepsilon_1' + i\,\varepsilon_1''$

ε_2 is real

$\varepsilon_1'' < |\varepsilon_1'|$

$$k_x' = \frac{\omega}{c}\left(\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1'+\varepsilon_2}\right)^{\frac{1}{2}}$$

$$k_x'' = \frac{\omega}{c}\left(\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1'+\varepsilon_2}\right)^{\frac{3}{2}}\frac{\varepsilon_1''}{2(\varepsilon_1')^2}$$

e.g.

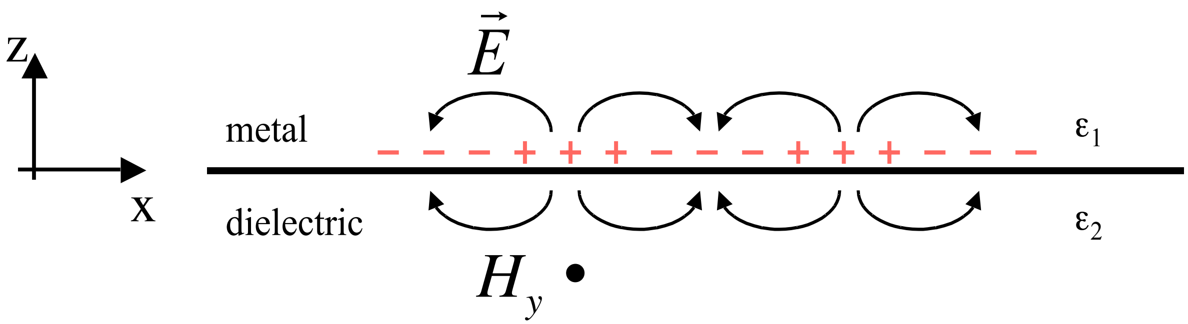
Ag $\varepsilon = -22.4 - 0.91i$

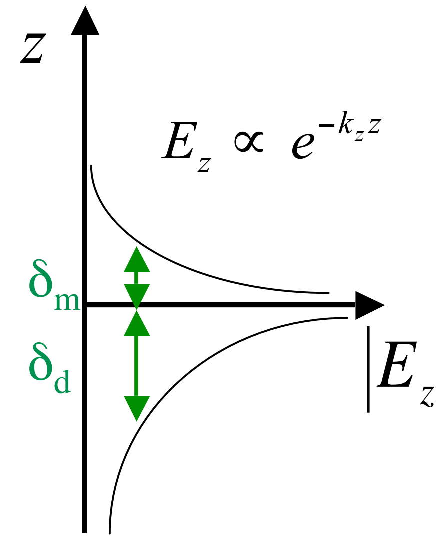
Au $\varepsilon = -23.0 - 0.77i$

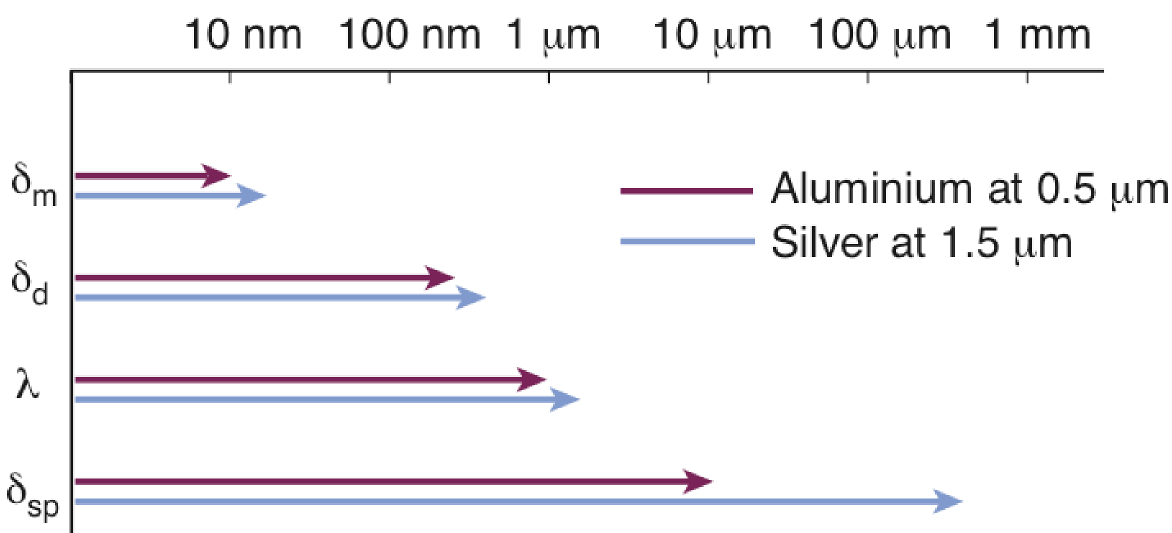
[also $\varepsilon(\omega)$]

What are surface plasmons ?

- Evanescent electric field propagating at surface







[Figures courtesy of Barnes et al., Nature 424, p824 (2003)]

$$\delta_{sp} \Leftrightarrow k_x'' = \frac{\omega}{c}\left(\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1' + \varepsilon_2}\right)^{\frac{3}{2}} \frac{\varepsilon_1''}{2(\varepsilon_1')^2}$$

Extremely short lifetimes for surface plasmons (10^{-15} s to 10^{-12} s)

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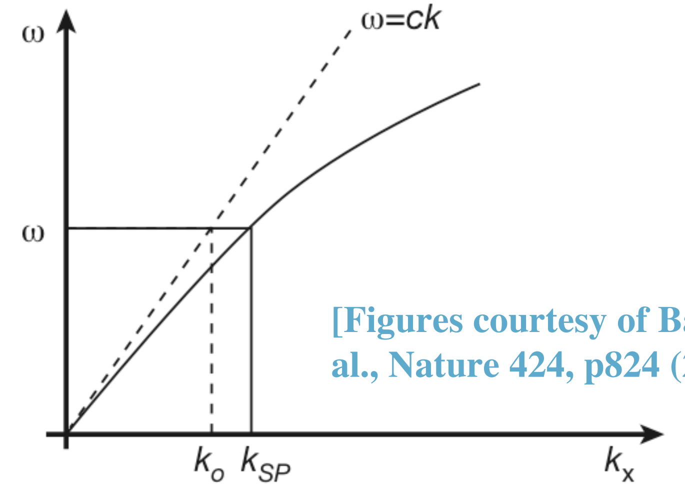
Excitation of Surface Plasmons

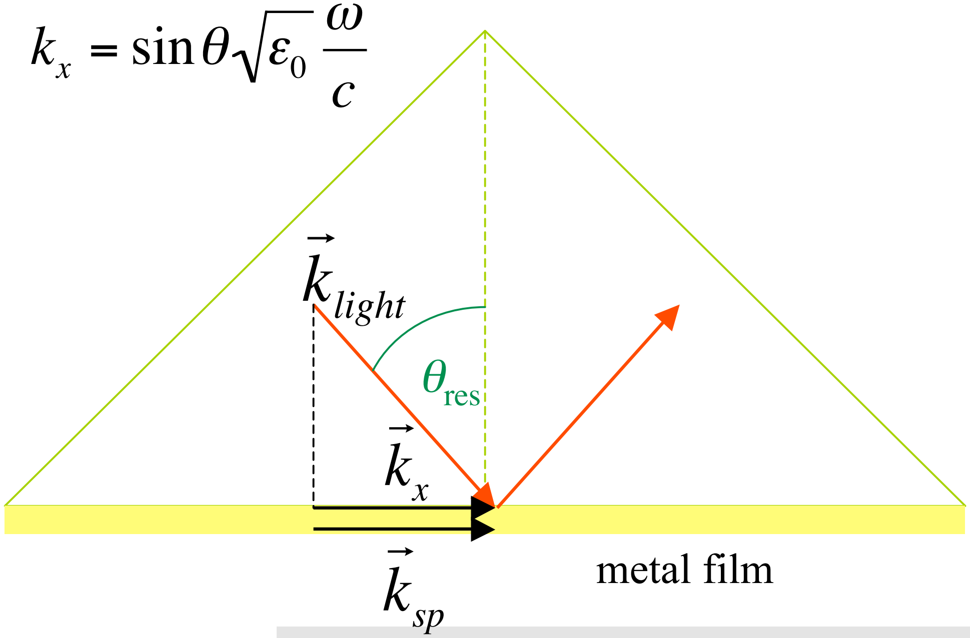
- Attenuated total reflection

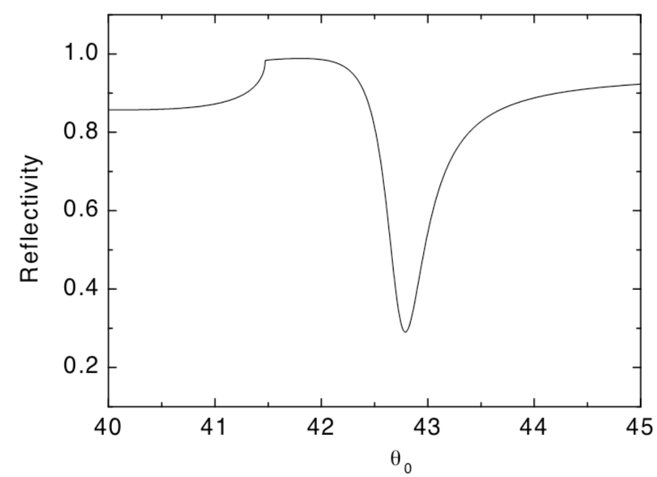
$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} < \frac{\omega}{c}$$



[Figures courtesy of Barnes et al., Nature 424, p824 (2003)]

$$k_x = \sin\theta\sqrt{\varepsilon_0}\,\frac{\omega}{c}$$





attenuated total reflection at surface plasmon resonance

[other figures courtesy of R. Stock, Thesis, UNM (2001)]

Excitation of Surface Plasmons

- Attenuated total reflection

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} < \frac{\omega}{c}$$

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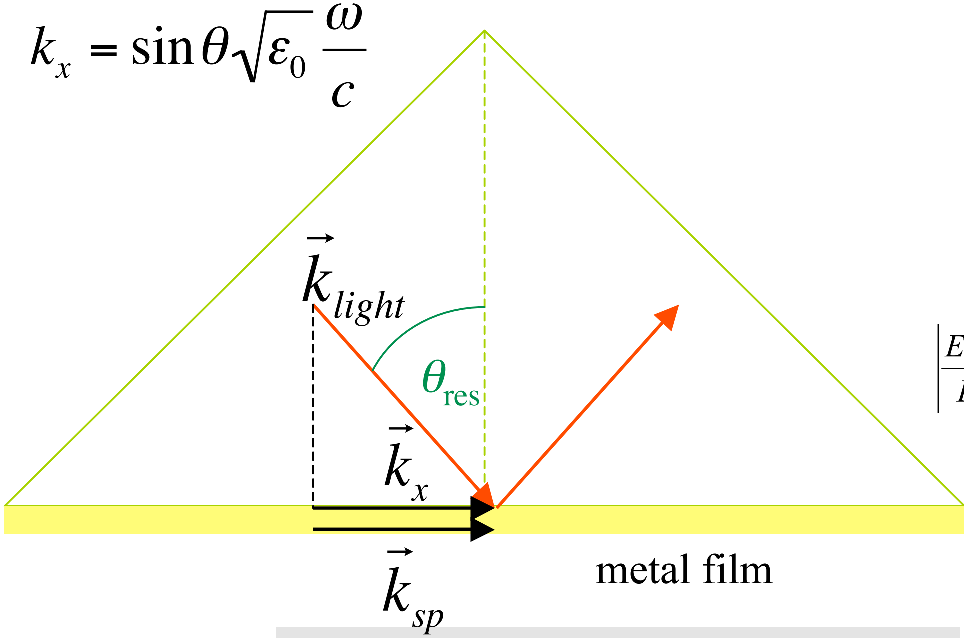
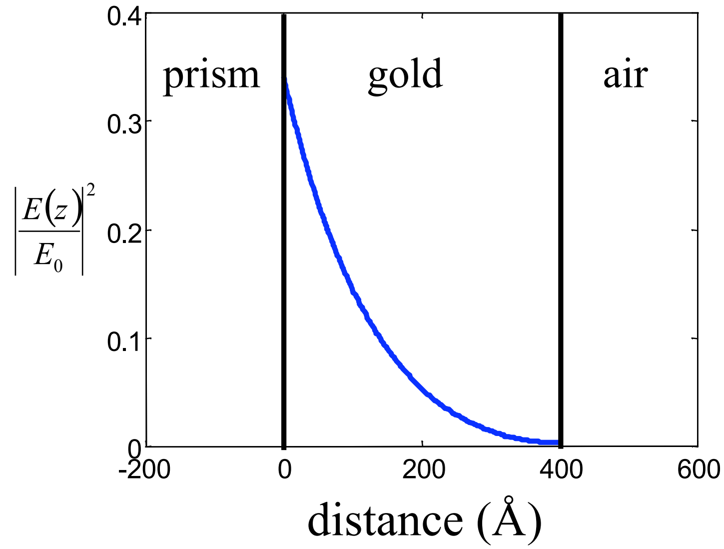
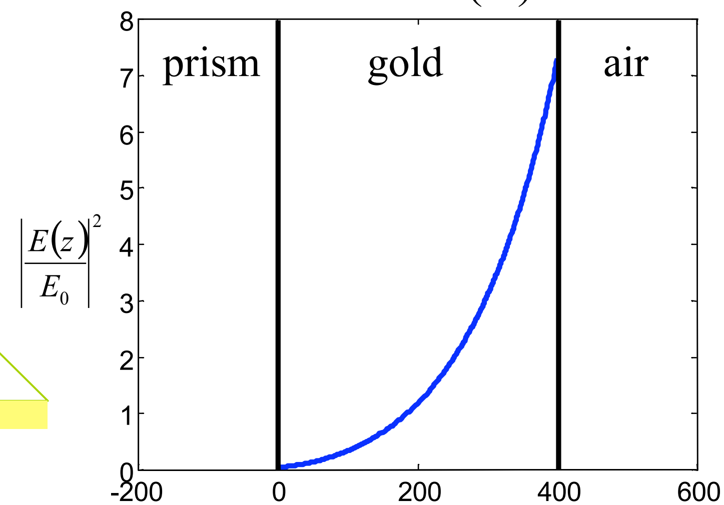




normal incidence



surface plasmon resonance angle

→ strong field enhancement effect due to surface plasmons

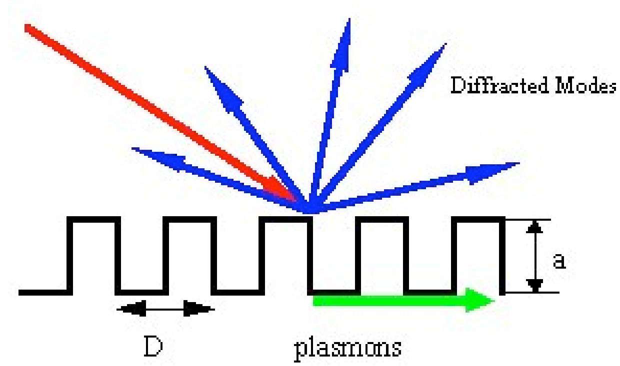
[Figures courtesy of R. Stock, Thesis, UNM (2001)]

Excitation of Surface Plasmons

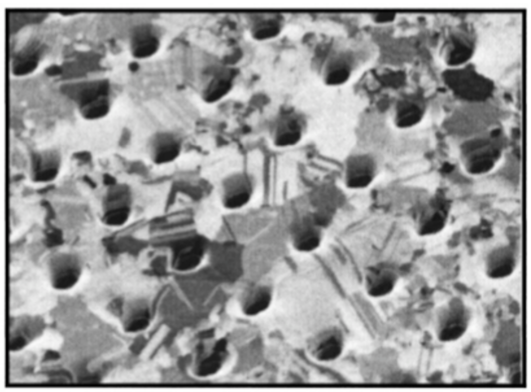
- Periodic structure

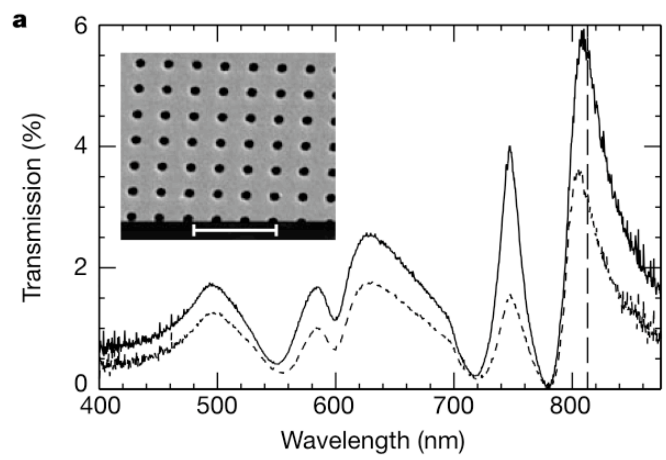
$$\vec{k}_{sp} = \vec{k}_x \pm m\vec{G}_x \pm n\vec{G}_y$$

$$\rightarrow \quad \sqrt{m^2 + n^2}\,\lambda = D\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$



- Periodic sub wavelength hole array



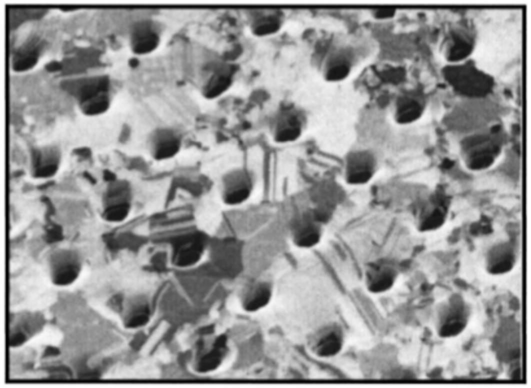


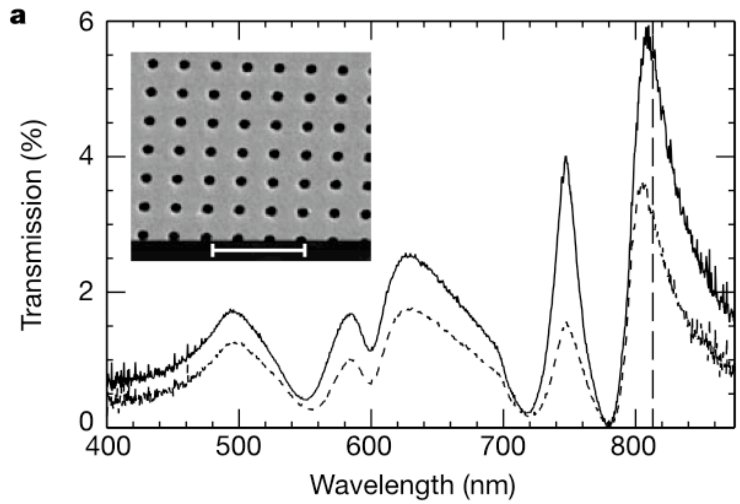
➡ versatile wavevector matching using periodic structures

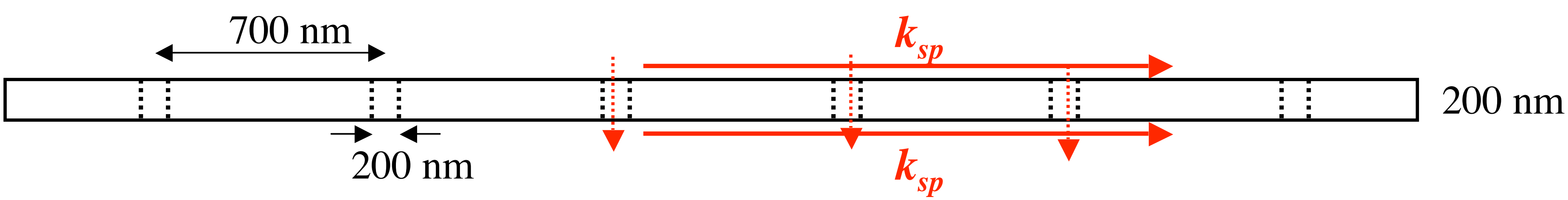
[Figures courtesy of Ghaemi et al., PRB 58, p6779 (1998) and Altewischer et al., Nature 418, p304 (2002)]

Excitation of Surface Plasmons

- Periodic sub wavelength hole array







Enhanced optical transmission through array of sub wavelength holes (compared to diffraction theory)

[Figures courtesy of Ghaemi et al., PRB 58, p6779 (1998) and Altewischer et al., Nature 418, p304 (2002)]

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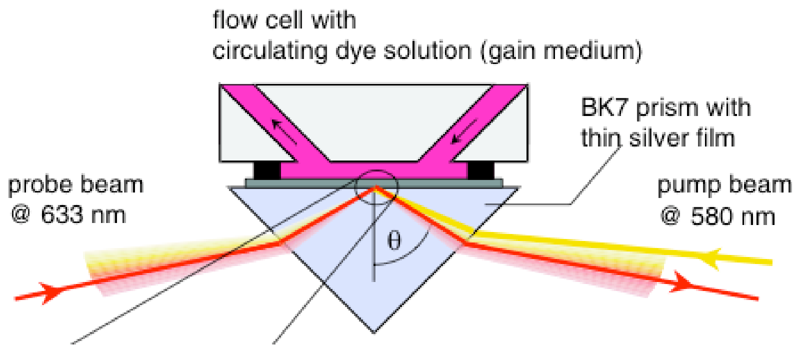
Implementations using Surface Plasmons

- Field enhancement effect
  - Surface enhanced spectroscopy
  - Strong coupling to waveguides
  - Biophotonics: Biological and chemical detectors (sensitivity to ε_2 at the surface)

- Nanoscale technology
  - Nano-optics and nano-circuitry on surfaces:
    - Mirrors (reflectivity> 90%)
    - Nanowires (waveguides) for plasmons
  - "Plasmonic" computer chips and other nanoscale technology
  - Data storage

- Quantum nature of surface plasmons
  - SPASERS (surface plasmon amplification by spontaneous emission of radiation)
  - Single photon light sources
  - Quantum information processing



Seidel et al., PRL 94, 177401 (2005)

Surface Plasmons and Entanglement

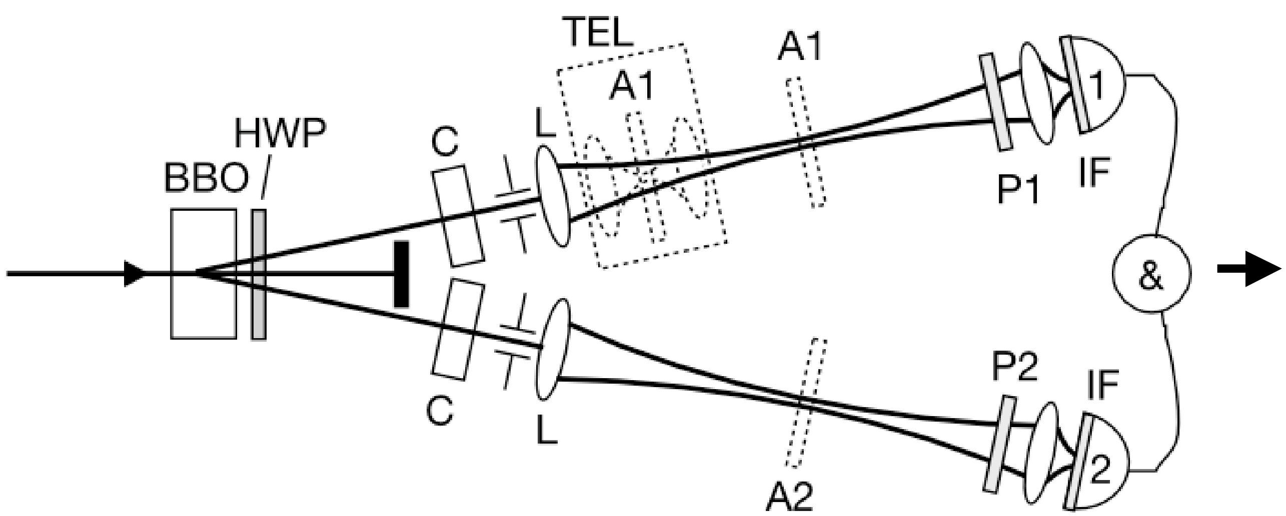
- Polarization entangled photons

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|X_1Y_2\rangle + e^{i\phi}|Y_1X_2\rangle\right)$$

- Experimental setup

Plasmon-assisted transmission of entangled photons

E. Altewischer, M. P. van Exter & J. P. Woerdman
Nature **418**, p304 (2002)



Coincidence detection after transmission through hole array

Surface Plasmons and Entanglement

- Experiment

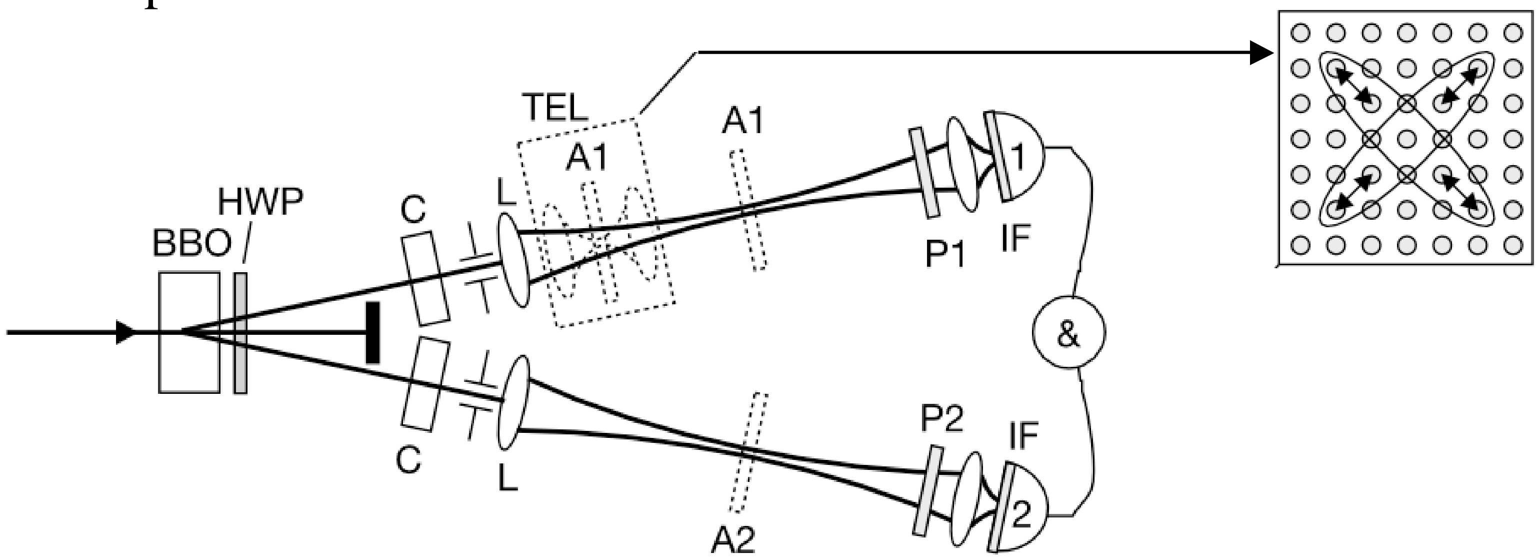


Table 1 Biphoton fringe visibilities

Experiment	R (s^{-1})	$V_{0°}$ (%)	$V_{45°}$ (%)
No arrays	32×10^3	99.3	97.0
Both arrays	55	97.1	97.2
Only array 1	1.6×10^3	99.4	97.1
Only array 2	1.0×10^3	97.5	96.8
Array 1, focussed	1.1×10^3	73	87

R, measured coincidence count rate; $V_{0°}$ and $V_{45°}$, measured visibility for one of the polarizers fixed at 0° and 45°, respectively.

Reduced visibility due "which-path" information in solid?

Surface Plasmons and Entanglement

- Which-path information: include state of solid

  E. Moreno, F.J. Garcia-Vidal, D. Erni, J. I. Cirac, L. Martin-Moreno
  PRL 92, 236801(2004)

$$|\Phi_{\rm in}\rangle = (|X_1 Y_2\rangle - |Y_1 X_2\rangle)/\sqrt{2} \otimes |S\rangle$$

$$\Downarrow$$

$$t_{X_1X_1}|X_1Y_2\rangle \otimes |S_{xx}\rangle + t_{Y_1X_1}|Y_1Y_2\rangle \otimes |S_{yx}\rangle - t_{X_1Y_1}|X_1X_2\rangle \otimes |S_{xy}\rangle - t_{Y_1Y_1}|Y_1X_2\rangle \otimes |S_{yy}\rangle$$

- Interaction models?

  a) all $|S_{ab}\rangle$ are orthogonal: solid and biphoton entangled

  → trace over solid: mixed state for biphoton, "which-polarization" information

  b) all $|S_{ab}\rangle$ are equal: no entanglement between solid and photon states

  → trace over solid: biphoton entangled depending on t_{ab}

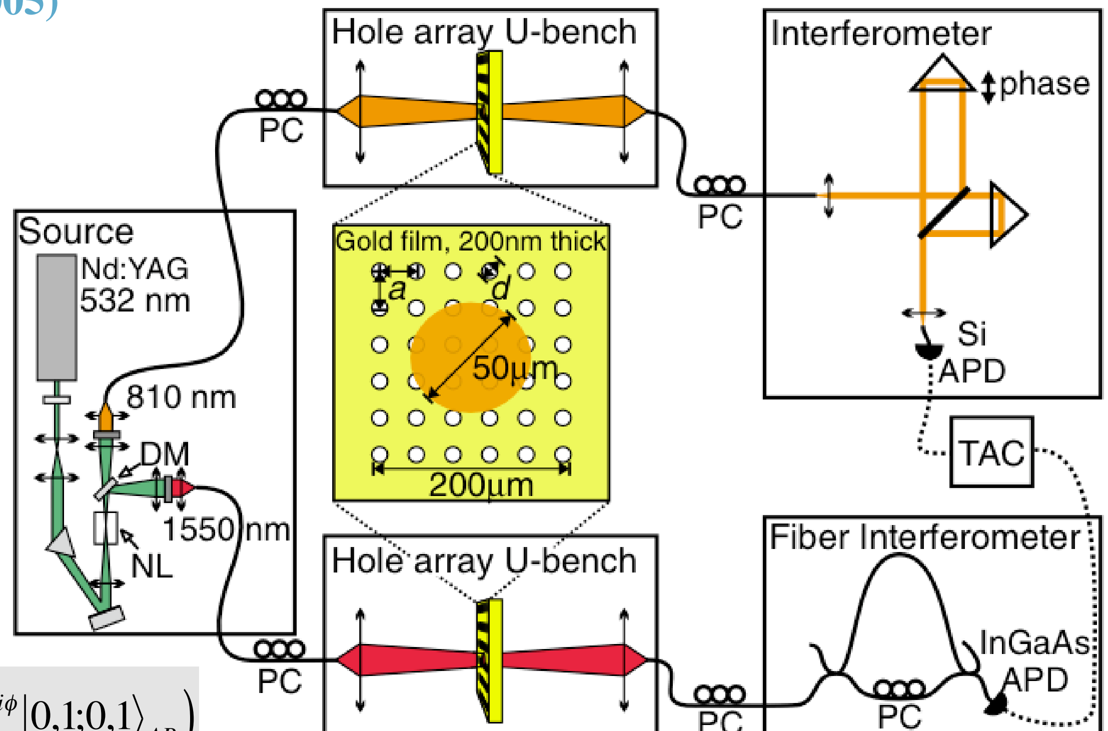
⇒

- Choose b): no which-path labels introduced in solid
- Observed visibilities can be explained by polarization dependent transmission of hole array

Surface Plasmons and Entanglement

- Energy-time entanglement

  S. Fasel, N. Gisin, H. Zbinden, D. Erni, E. Moreno, F. Robin
  PRL 94, 110501(2005)



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|1,0;1,0\rangle_{AB} + e^{i\phi}|0,1;0,1\rangle_{AB}\right)$$

→ energy-time entanglement especially robust against environmental disturbance

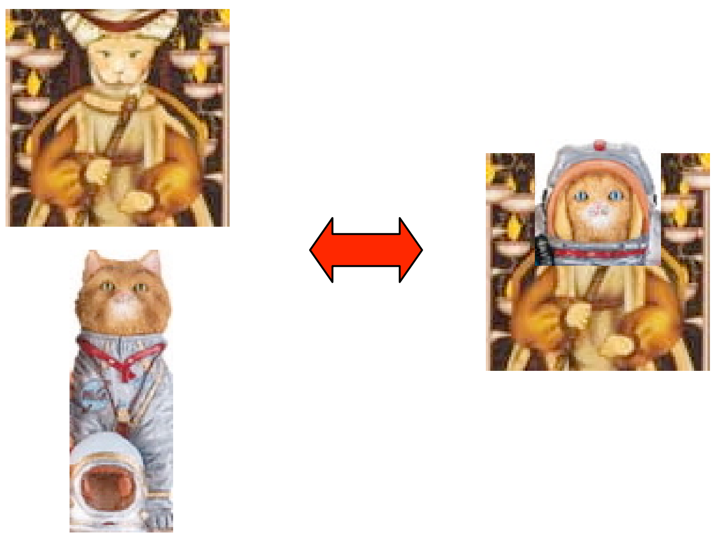
→ telecom wavelength particularly interesting for quantum communication

Surface Plasmons and Entanglement

- Energy-time entanglement

S. Fasel, N. Gisin, H. Zbinden, D. Erni, E. Moreno, F. Robin
PRL 94, 110501(2005)

→ macroscopic cat states (surface plasmons) living at different "epochs" that differ by more than the cats (surface plasmon) lifetime



Experiment	Reference visibility	Plasmon-assisted visibility	Transmittance
extraordinary transmission at 810 nm	$93 \pm 3\%$	$93 \pm 3\%$	11%
extraordinary transmission at 1550 nm	$97 \pm 3\%$	$96 \pm 5\%$	6%

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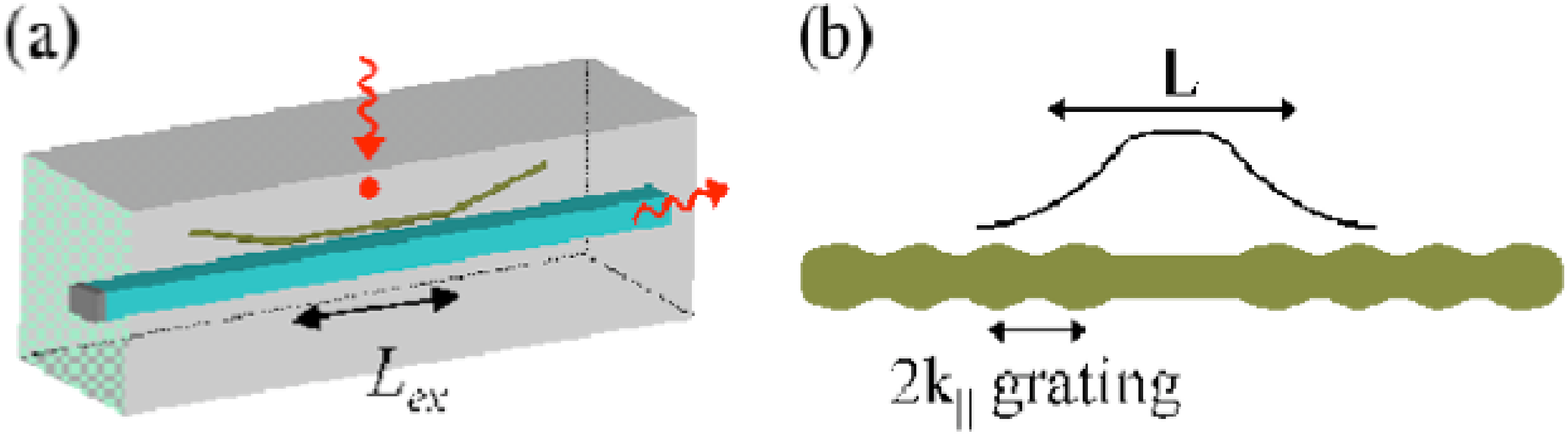
Surface Plasmons in Quantum Information

- Proposal: Cavity QED with Surface Plasmons

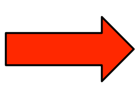
D. E. Chang, A. S. Sorensen, P. R. Hemmer, and M. D. Lukin
quant-ph/0506117



- efficient coupling of emitter (quantum dot, atom) to plasmon mode of nanowire
- evanescent coupling of nanowire to dielectric waveguide

→ single photon source

- plasmon cavity created by plasmon mirrors ($2k_{||}$ grating on surface) with reflectivity > 0.9



- field enhancement: stronger coupling and faster interaction times
- one photon sources

Surface Plasmons in Quantum Information

- Proposal: Cavity QED with Surface Plasmons

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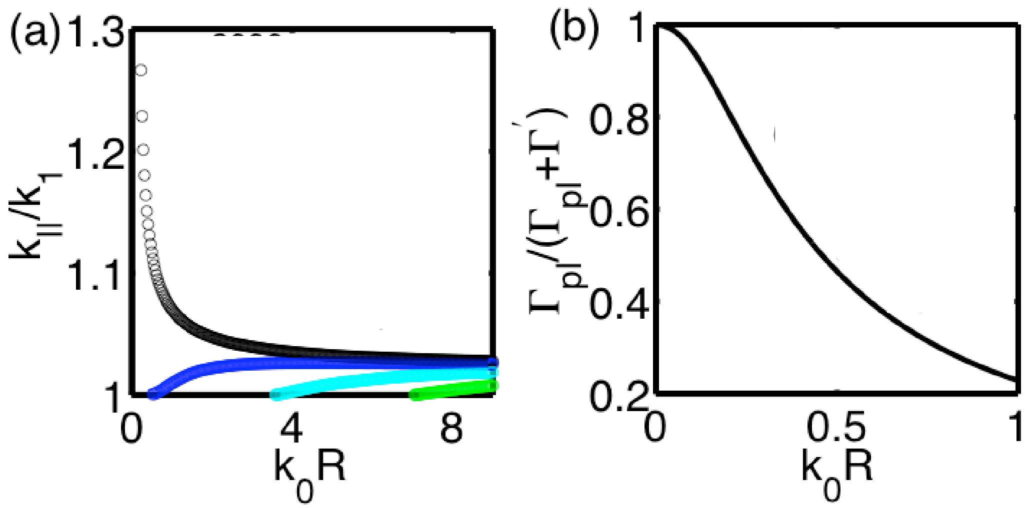
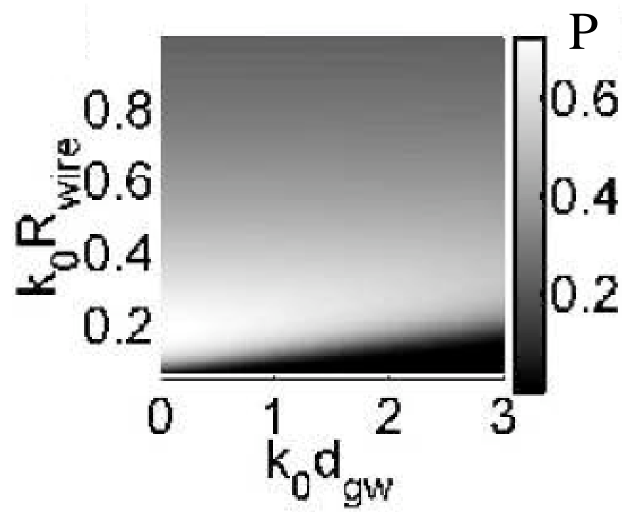
→ calculation of plasmons modes

→ efficiency of single photon generation





- fractional power emitted into fundamental plasmon mode
- one photon source efficiency: 0.7 (coupling to wire), 0.9 coupling to cavity

Summary

Summary

- Entanglement survives excitation and deexcitation of surface plasmons
- Applications for hybridization of different QIP implementations
- Problems:
  - Short Coherence time (usually < 10^{-12} s)
  - Limited spatial propagation (usually < 1 mm)

References

- General review: **J. Opt. A 5, S16-S50 (2003)**
- Surface Plasmons: **H. Raether: Surface Plasmons, Springer 1988**
- Entanglement experiments **Nature 418, 304 (2002)**
  - Theoretical analysis **PRL 92, 236801(2004)**
  - Time-energy entanglement **PRL 94, 110501(2005)**
- Hybrid proposal **quant-ph/0506117**