QUANTUM PLASMONICS

WINTER SCHOOL ON QUANTUM PHYSICS AND QUANTUM INFORMATION
Palacký University, Olomouc, Czech Republic | Jan 2014

MARK TAME

UNIVERSITY OF KWAZULU-NATAL

CENTRE FOR QUANTUM TECHNOLOGY

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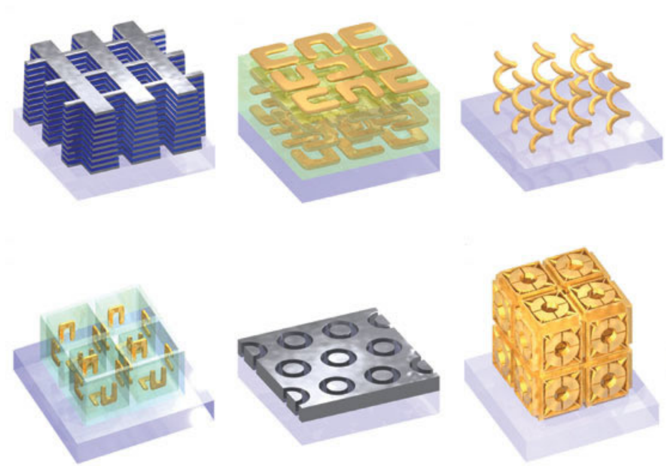
INVESTMENTS IN EDUCATION DEVELOPMENT

Lecture 1 - outline

1. **Introduction** — History — Applications
2. **Basics** — EM structure — Types of excitations: SPP, LSP
3. **Early work** — Quantum optics fundamentals — Quantum size effect
4. **Recent work** — Waveguides, sources and switches — Metamaterials
5. **Future directions** — Media: metals, graphene, superconductors — Hybridization, quantization

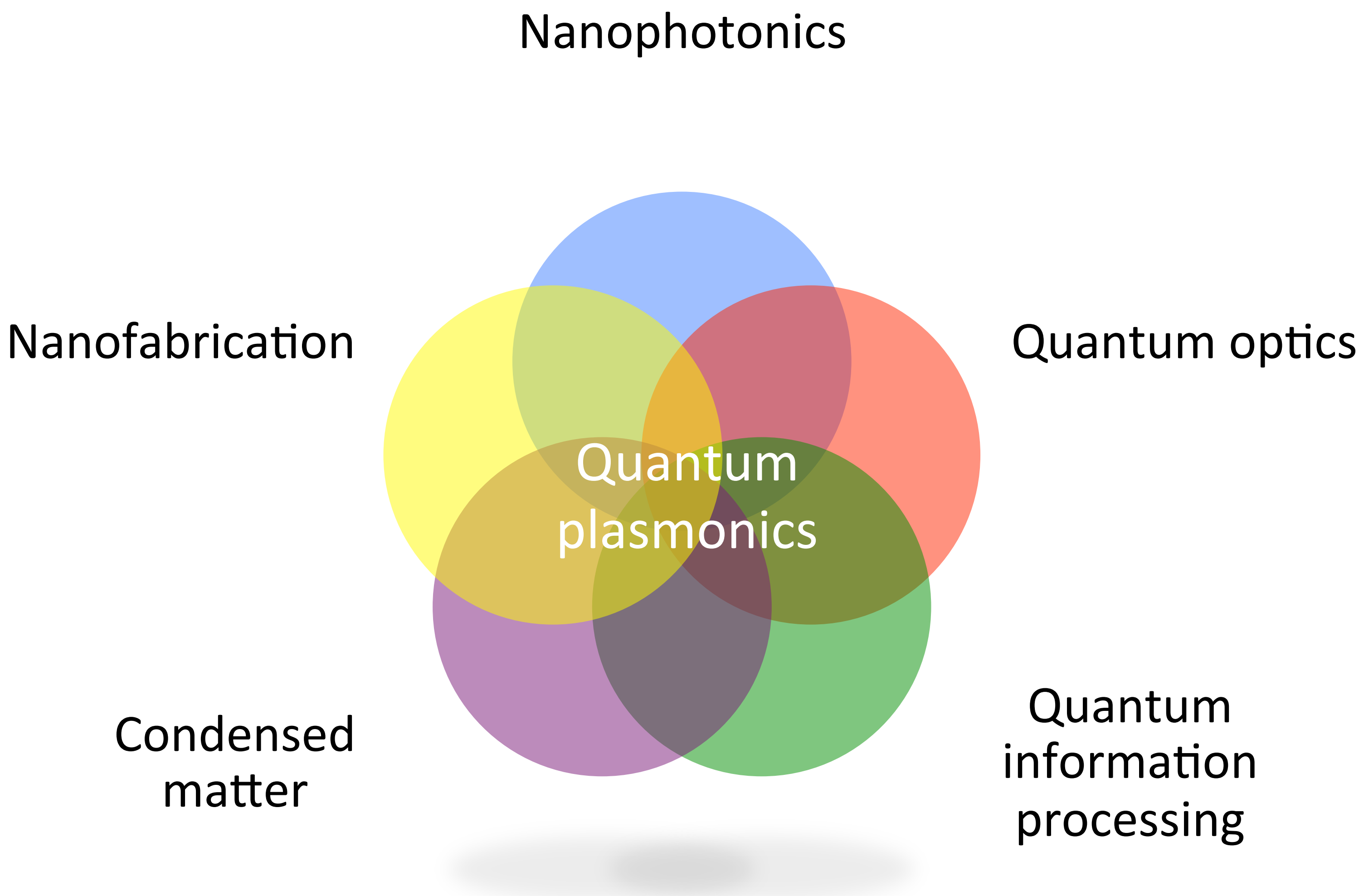

1
Introduction
History
Applications

Nanophotonic circuitry



Nanophotonic materials

1 Introduction | History | Applications



1902 — Robert Wood observes power loss in light reflected off metal grating surfaces

1907 — Jonathan Zenneck introduces mathematics for surface plasma waves, studying the transmission of radio waves

1947 — Ugo Fano produces the first explanation of Wood's power loss: surface plasma waves are introduced

1956-1958 — David Pines introduces quantized plasma oscillations in bulk metals - "plasmons"
Rufus Ritchie studies electron energy loss in thin films – "surface plasmons"
John Hopfield introduces "polariton" for coupled oscillations of bound electrons and light in media

1968 — Andreas Otto, Erich Kretschmann and Heinz Raether present methods for the optical excitation of surface plasmon polaritons

This is a **major advancement**, making experiments easily accessible to many researchers (see bar chart)

2002 — The quantum optics and plasmonics communities develop a keen interest in using surface plasmon polaritons for quantum applications

Now

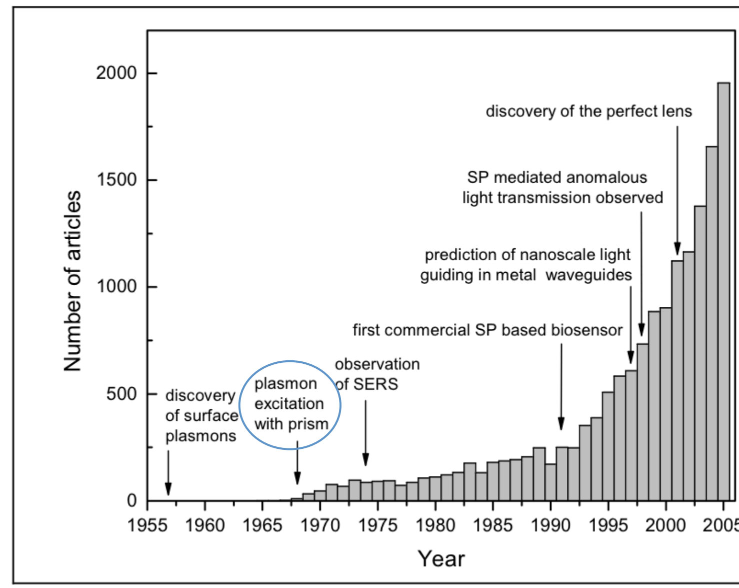
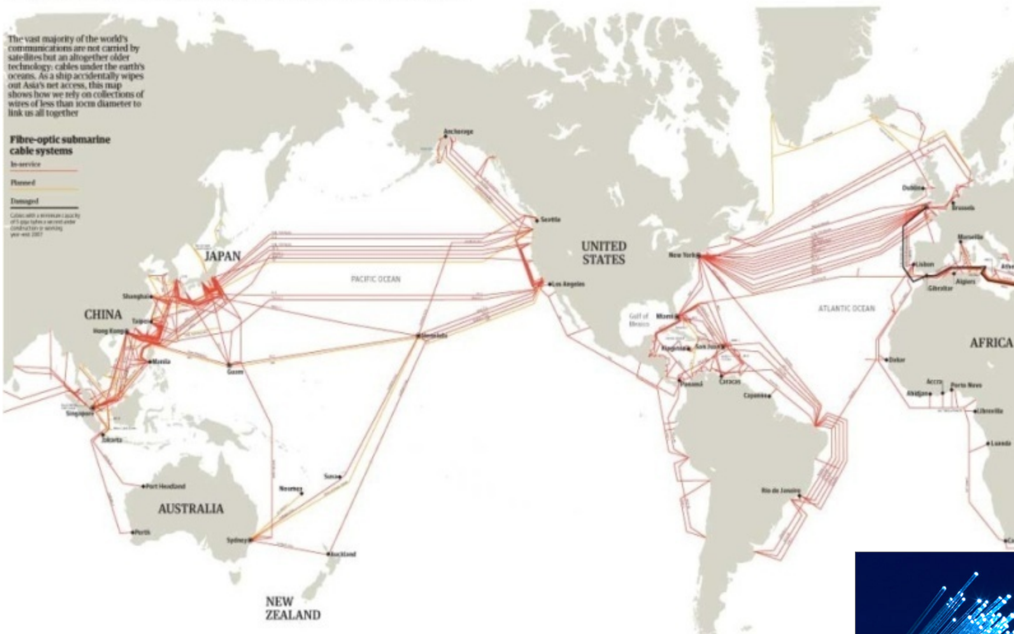


Figure 1-1. The growth of the field of metal nanophotonics is illustrated by the number of scientific articles published annually containing the phrase "surface plasmon" in either the title or abstract (based on data provided on www.sciencedirect.com)

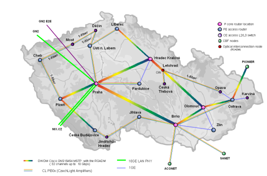
1 Introduction | History | Applications

The internet's undersea world

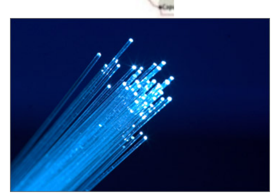


10^3
macroscale

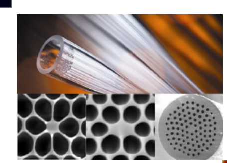
South Africa



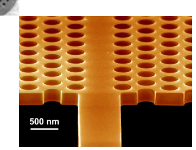
Czech Republic



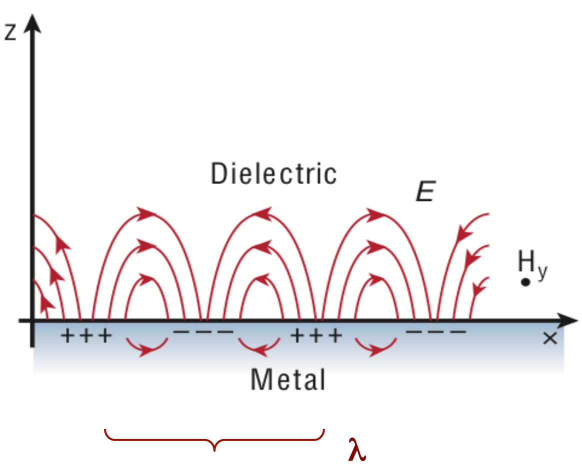
10^{-3} m
mesoscale



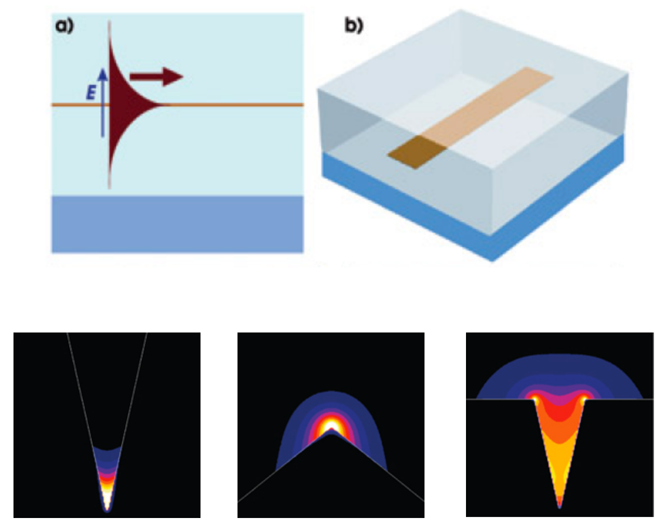
10^{-6} m
microscale



10^{-9} m
nanoscale



Barnes, Dereux and Ebbesen, Nature 424, 824 (2003)



Gramotnev and Bozhevolnyi, Nature Photonics 4, 83 (2010)

1

Introduction

History

Applications

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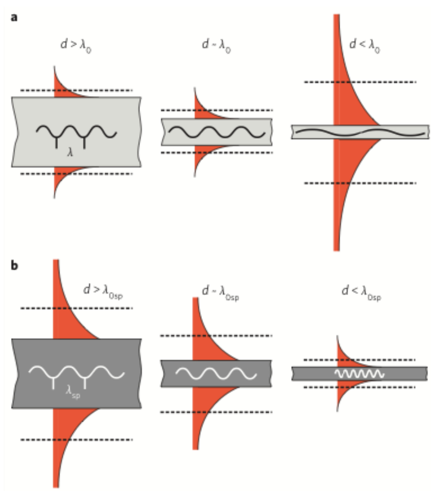
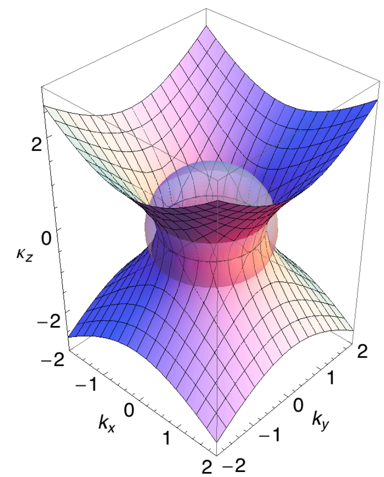
1 Introduction | History | Applications

Takahara et al., Opt. Lett. 22, 475 (1997)



Dielectric optical fibre



$$k_x^2 + k_y^2 + k_z^2 = (nk_0)^2 = \epsilon\mu(\frac{\omega}{c})^2$$

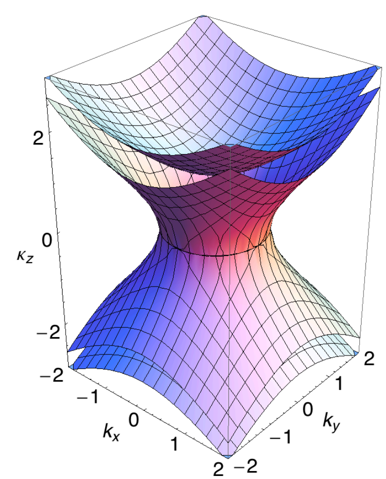
$$k_x^2 + k_y^2 - \kappa_z^2 = \epsilon\mu(\tfrac{\omega}{c})^2$$

Fourier reciprocity relation

$$\Delta x \geq \frac{2\pi}{\Delta k_x} = \frac{\lambda_0}{2n}$$

$$\delta_D \geq \frac{\lambda_0}{2\pi n} \rightarrow w \gtrsim \frac{\lambda_0}{2n}$$

metal



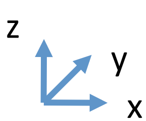
$$k_x^2 + k_y^2 - \kappa_z^2 = \epsilon\mu(\tfrac{\omega}{c})^2$$

$$\Delta x, \Delta y \geq \frac{\lambda_0}{2n}\sqrt{1 - \frac{\epsilon}{|\epsilon_{ND}|}}$$

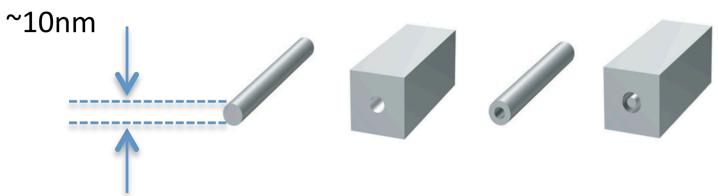
(1) sub-diffraction confinement of light

$$\delta_{SPP} < \frac{\lambda_0}{2\pi n} < \frac{\lambda_0}{2n}$$

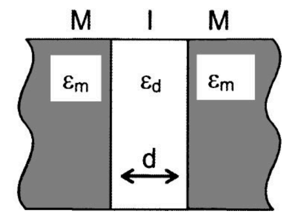
(2) sub-wavelength confinement of light



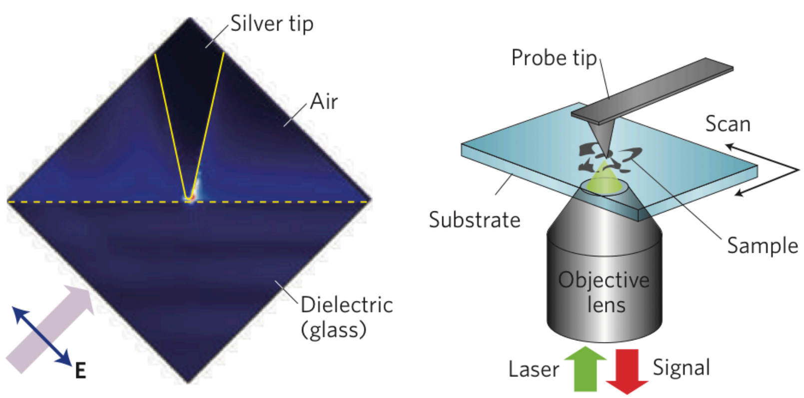
1 Introduction History Applications



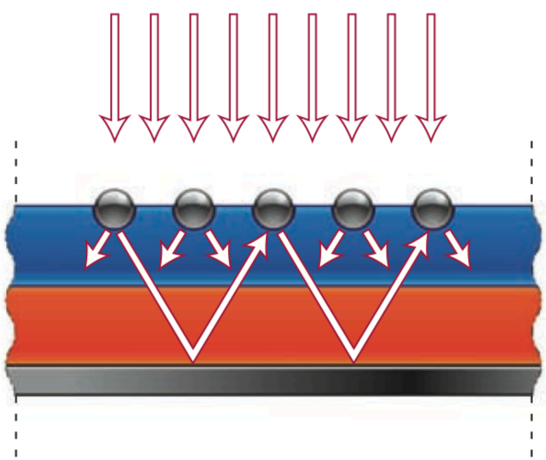
Takahara, Plasmonic Nanoguides and Circuits (2009)



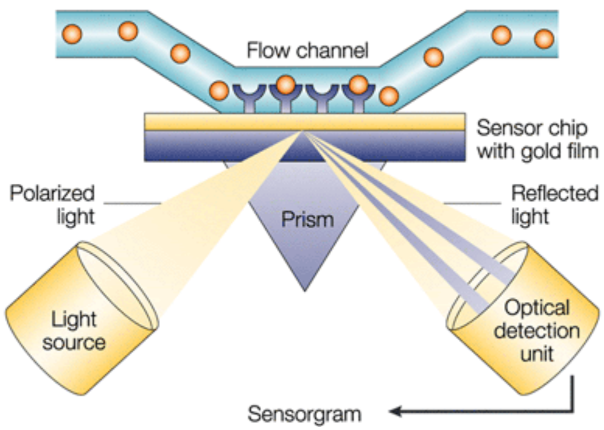
Zia et al., J. Opt. Soc. Am. A 21, 2442 (2004)



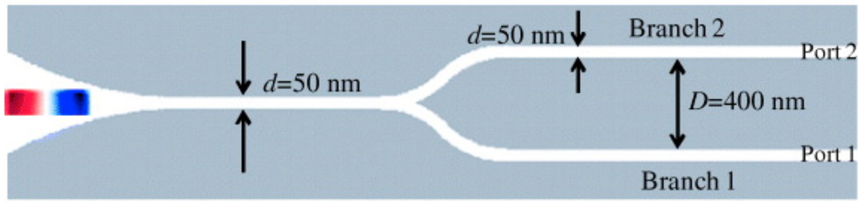
Kawata et al., Nature Phot. 3, 388 (2009)



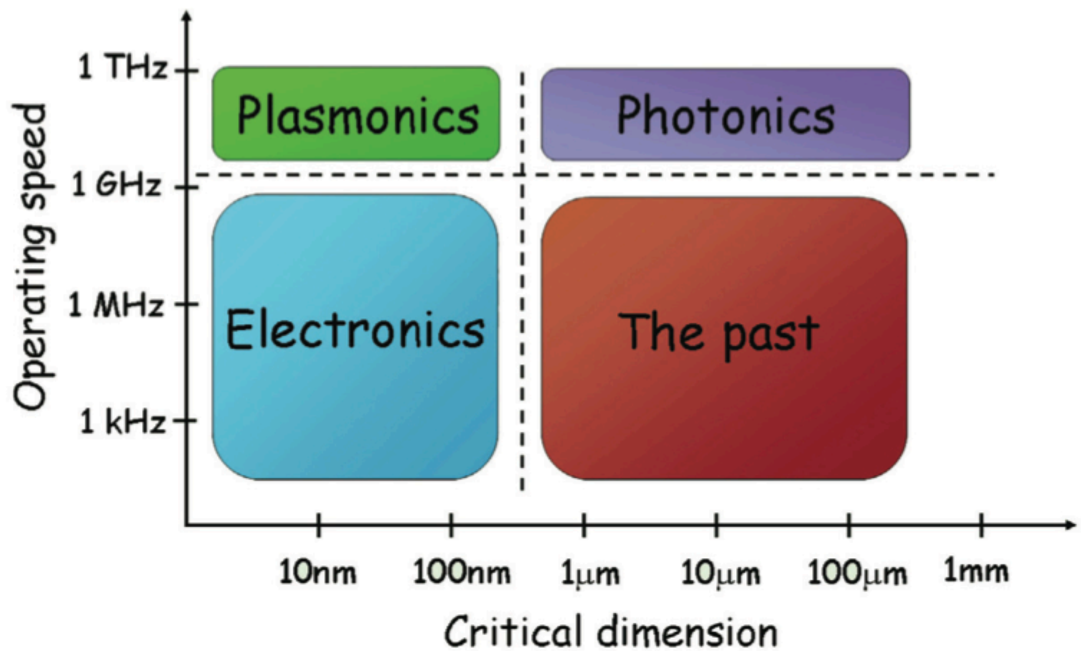
Atwater and Polman, Nature Mat. 9, 205 (2010)



J. N. Anker et al., Nature Mat. 7, 442 (2008)

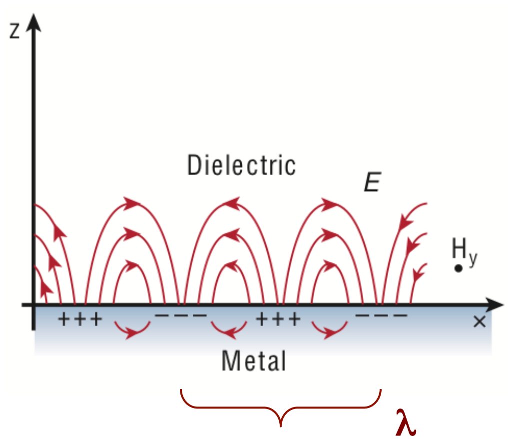


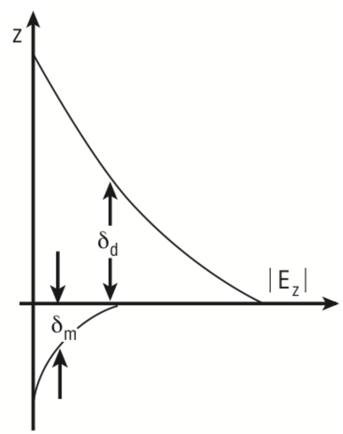
Gramotnev and Bozhevolnyi, Nature Phot. 4, 83 (2010)

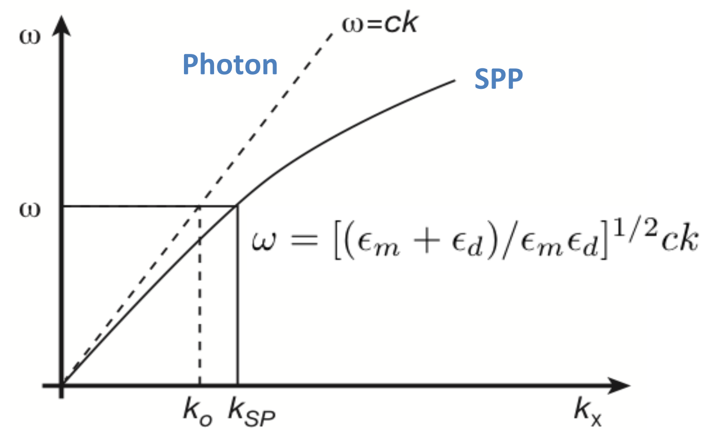


Zia et al., Materials Today 9, 20 (2006)


2
Basics
EM structure
Types of excitations: SPP, LSP



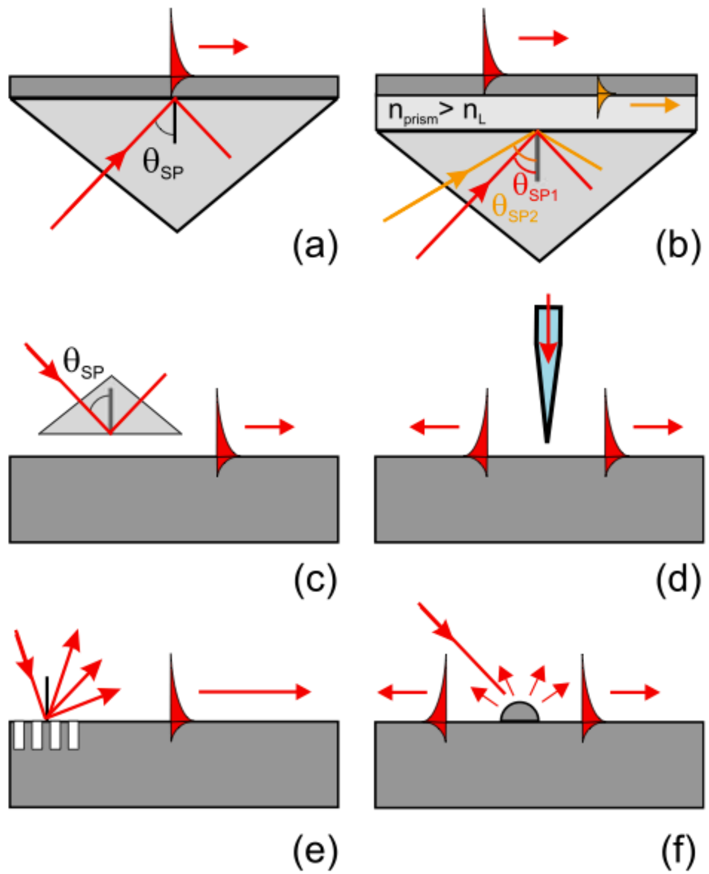


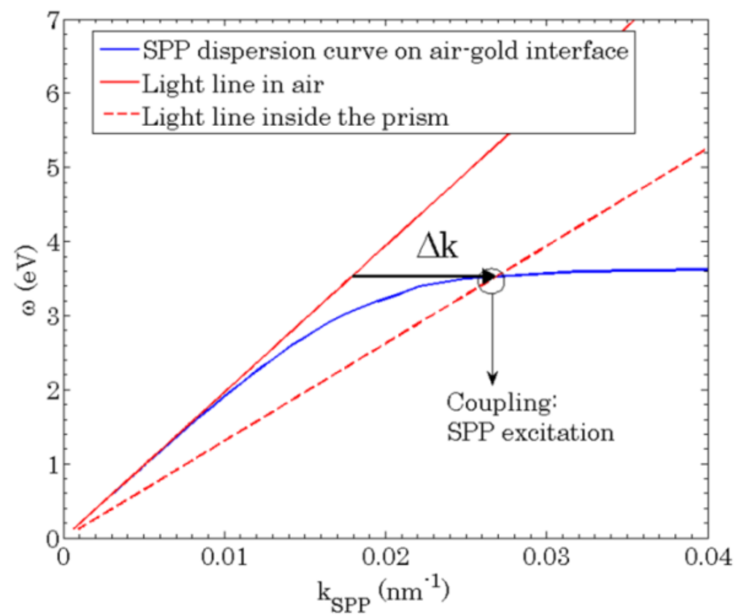


Barnes, Dereux and Ebbesen, Nature 424, 824 (2003)

$$\epsilon_m = 1 - \omega_p^2/(\omega^2 + i\omega\Gamma)$$

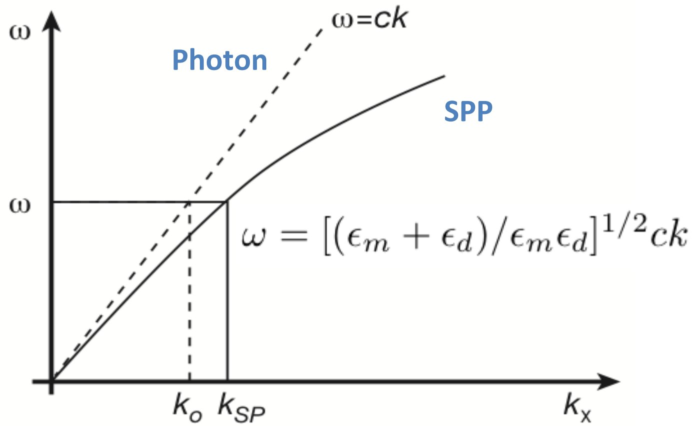
$$\epsilon_{\text{air}} = 1$$

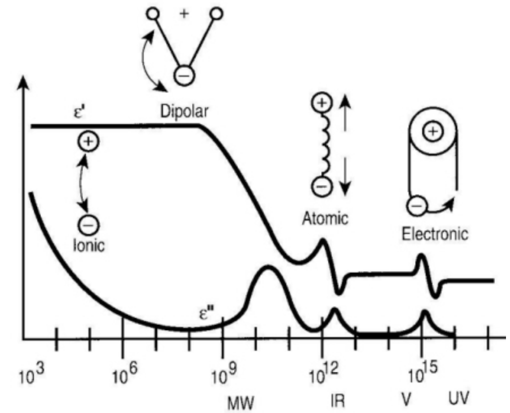


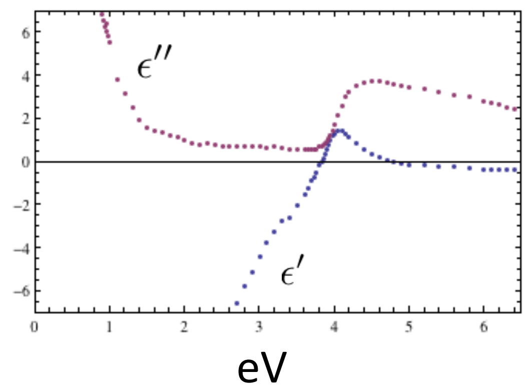


Zayats and Smolyaninov, J. Opt. A: Pure Appl. Opt. 5, S16 (2003)

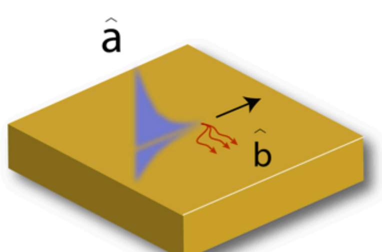
2 Basics | EM structure | Types of excitations: SPP, LSP



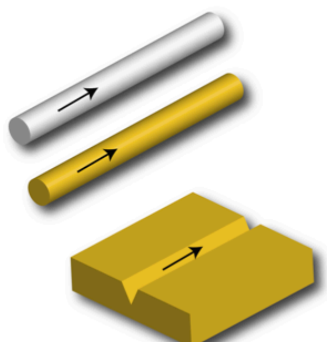




silver



SPP



$$\epsilon_m = 1 - \omega_p^2/(\omega^2 + i\omega\Gamma) = \epsilon' + i\epsilon''$$

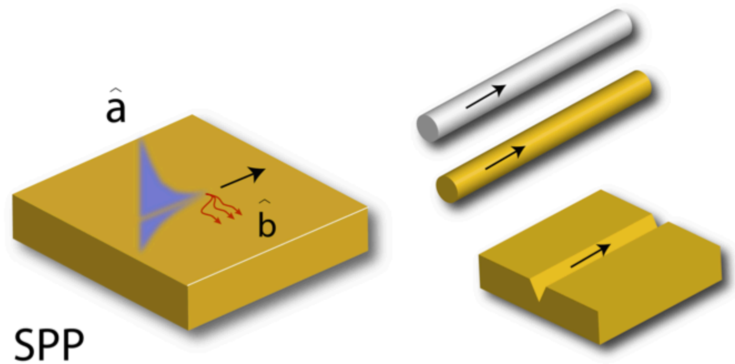
Johnson and Christy, PRB 6, 4370 (1972)

2

Basics

EM structure

Types of excitations: SPP, LSP



Above metal

$$\mathbf{H}^{>}(\mathbf{x};t) = (0, A, 0)e^{ikx_1 - k_3^{(1)}x_3 - i\omega t}$$

$$\mathbf{E}^{>}(\mathbf{x};t) = -A\frac{c}{i\omega\epsilon_1}(k_3^{(1)}, 0, ik)e^{ikx_1 - k_3^{(1)}x_3 - i\omega t}$$

Below metal

$$\mathbf{H}^{<}(\mathbf{x};t) = (0, B, 0)e^{ikx_1 + k_3^{(m)}x_3 - i\omega t}$$

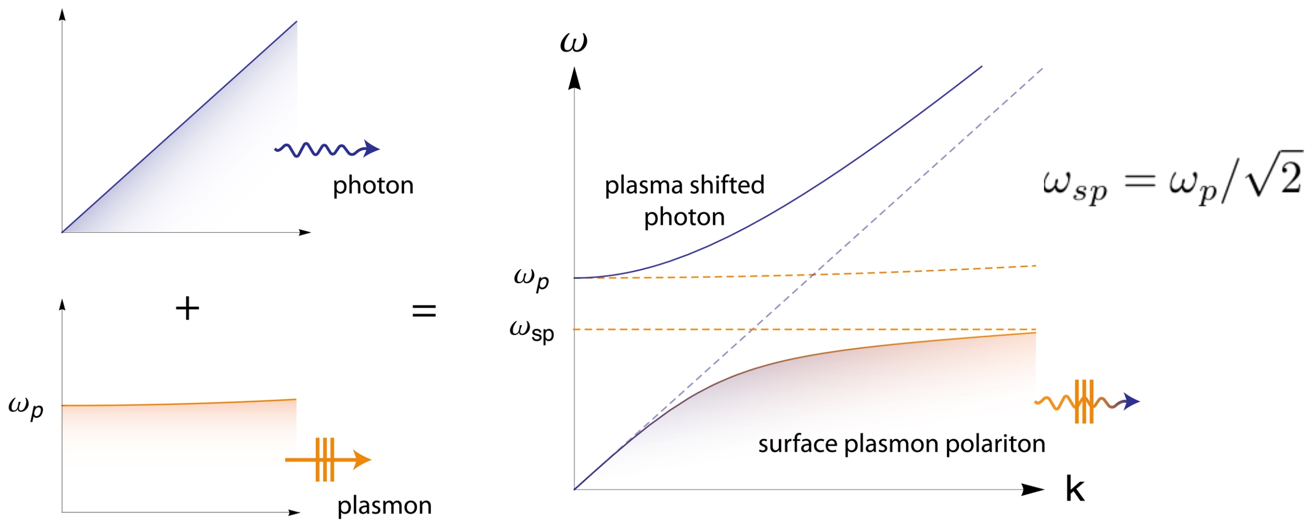
$$\mathbf{E}^{<}(\mathbf{x};t) = -B\frac{c}{i\omega\epsilon(\omega)}(-k_3^{(m)}, 0, ik)e^{ikx_1 + k_3^{(m)}x_3 - i\omega t}$$

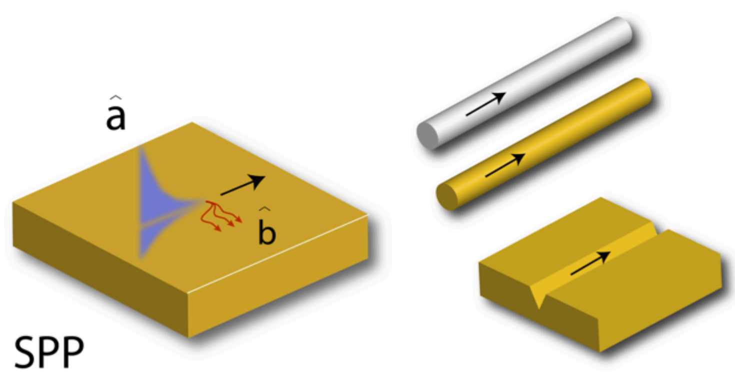
2

Basics

EM structure

Types of excitations: SPP, LSP



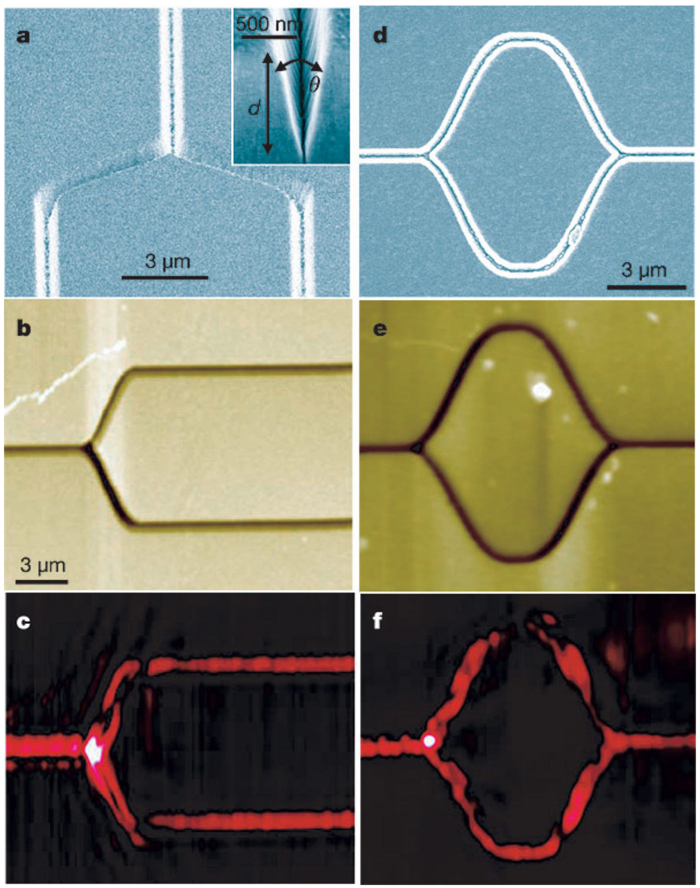


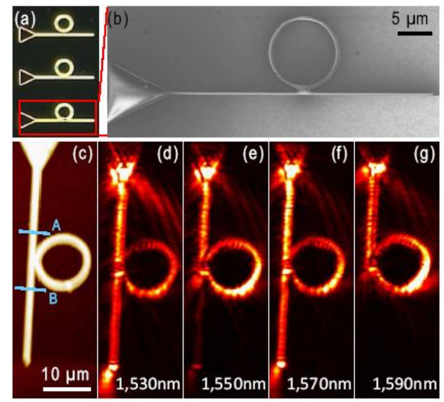
2

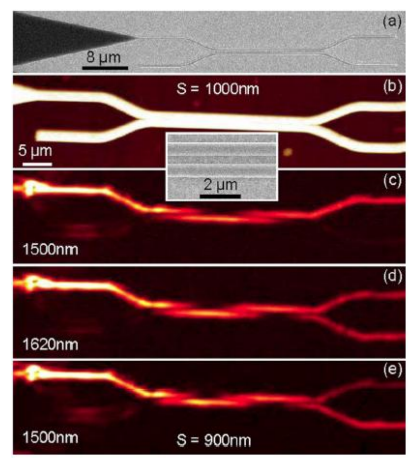
Basics

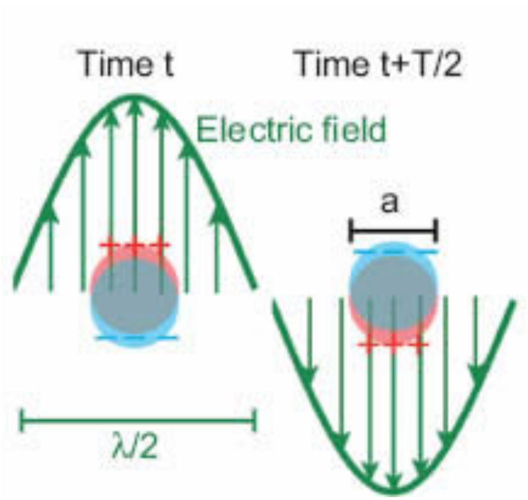
EM structure

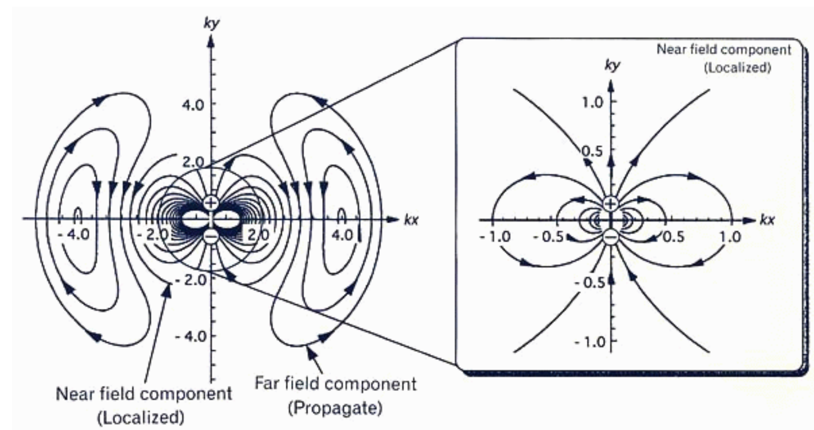
Types of excitations: SPP, LSP







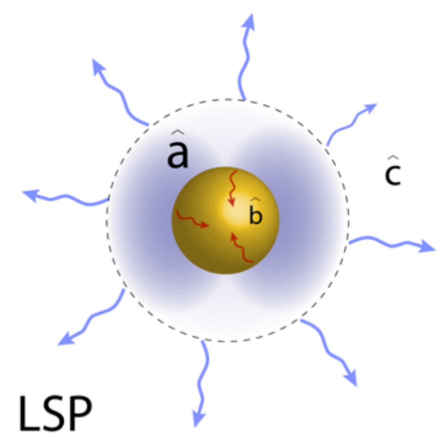




Mie $\left|\epsilon_m + 2\epsilon_d\right|$

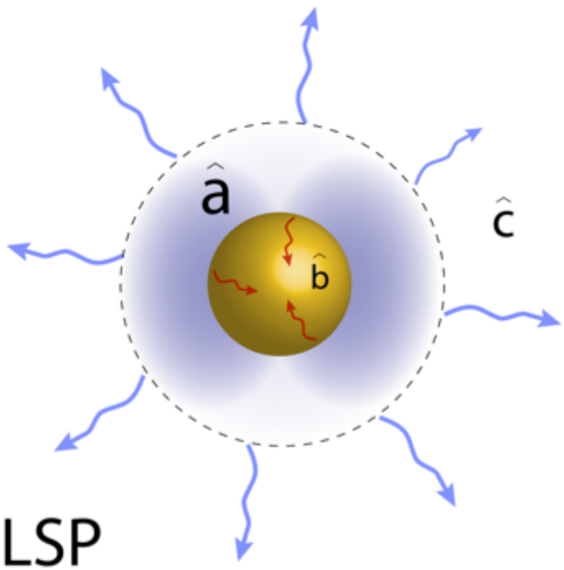
Fröhlich $\mathrm{Re}[\epsilon_m(\omega_i)] = -2\epsilon_d$

$$\omega_i = \omega_0$$



~10nm

localized surface plasmon



localized surface plasmon

$$\mathbf{E} = -\frac{\ddot{\mathbf{p}}}{c^2 r} - \frac{\dot{\mathbf{p}}}{c r^2} + \frac{3(\dot{\mathbf{p}} \cdot \mathbf{r})\mathbf{r}}{c r^4} + \frac{(\ddot{\mathbf{p}} \cdot \mathbf{r})\mathbf{r}}{c^2 r^3} + \underline{\frac{3(\mathbf{r} \cdot \mathbf{p})\mathbf{r}}{r^5} - \frac{\mathbf{p}}{r^3}}$$

$$\mathbf{H} = \frac{\ddot{\mathbf{p}} \times \mathbf{r}}{c^2 r^2} + \underline{\frac{\dot{\mathbf{p}} \times \mathbf{r}}{c r^3}}$$

dipole moment $\mathbf{p} = \mathbf{p}(t)$

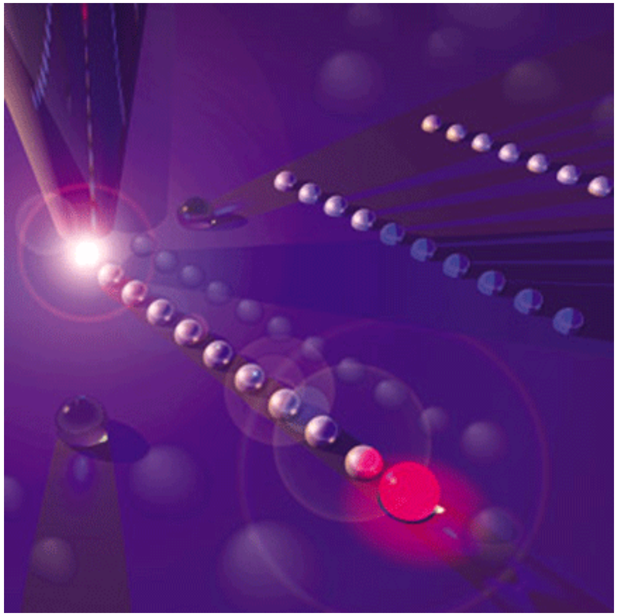
Griener, Classical electrodynamics (1998)

2

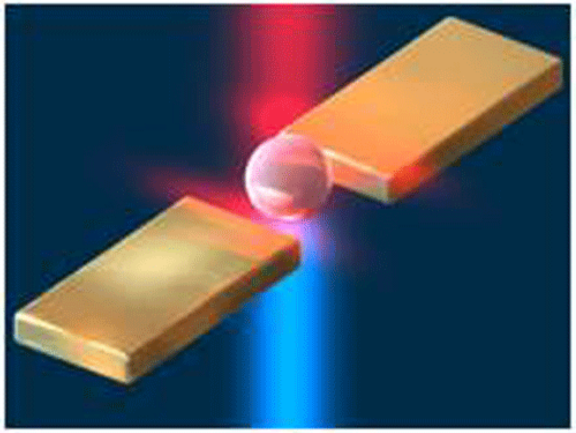
Basics

EM structure

Types of excitations: SPP, LSP



Maier et al., Appl. Phys. Lett. 81, 1714 (2002)
Maier et al., Nature Materials 2, 229 - 232 (2003)

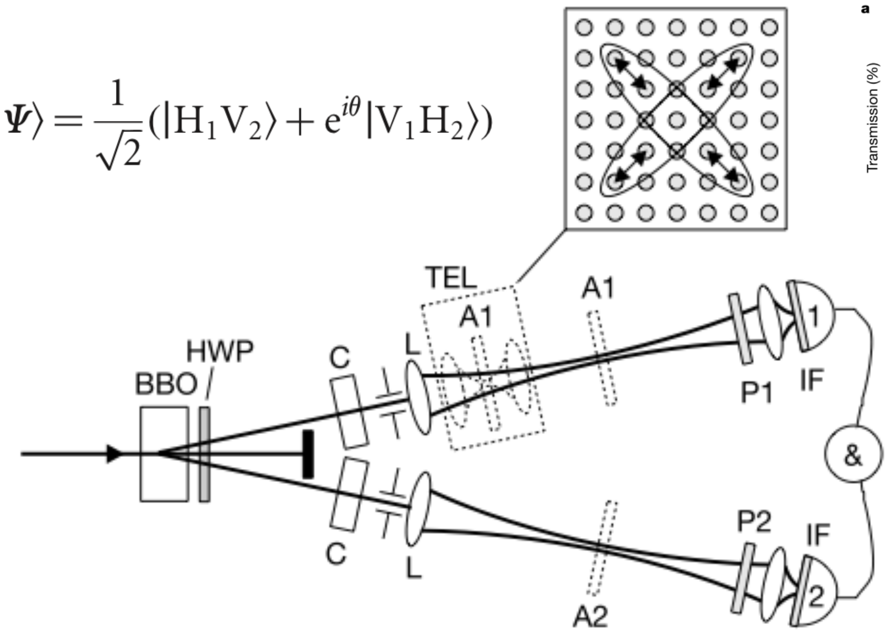


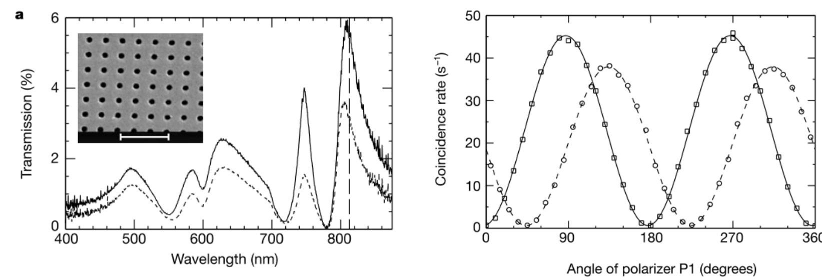
Giannini et al., Chem. Rev. 111, 3888 (2011)


3
Early work
Quantum optics fundamentals
Quantum size effect

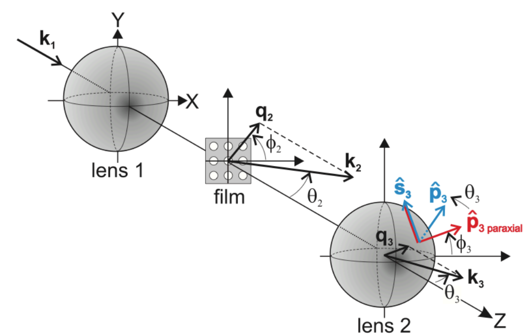
3 Early work | Quantum optics fundamentals | Quantum size effect

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle + e^{i\theta}|V_1H_2\rangle)$$





Altewischer et al., Nature 418, 304 (2002)



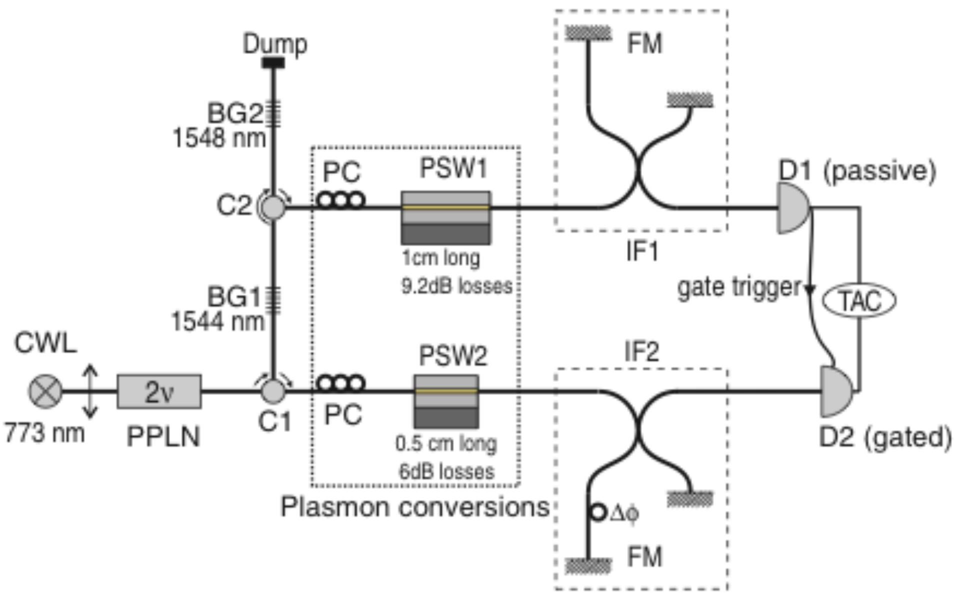
Moreno et al., PRL 92, 236801 (2004)

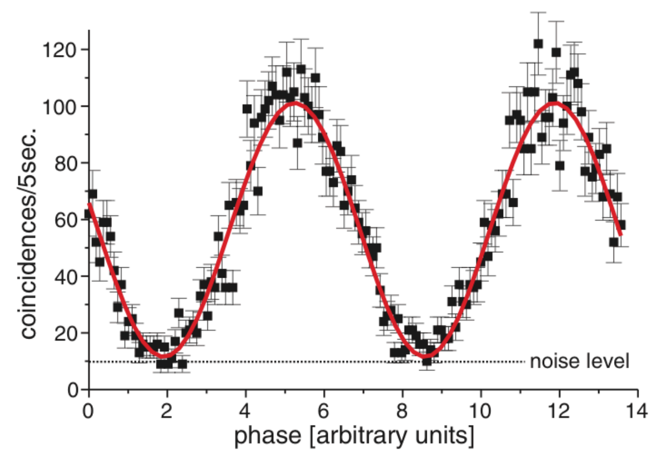
3

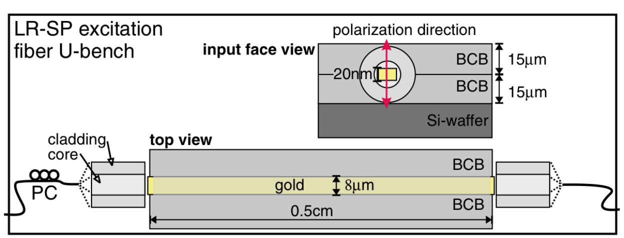
Early work

Quantum optics fundamentals

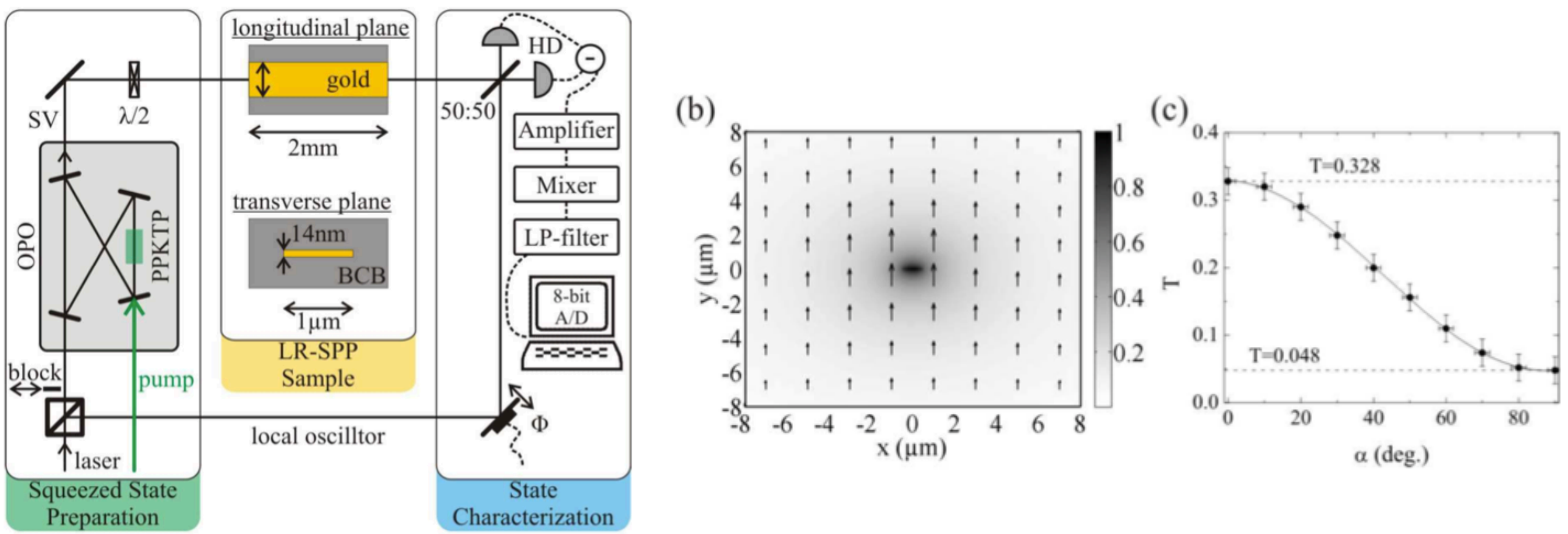
Quantum size effect





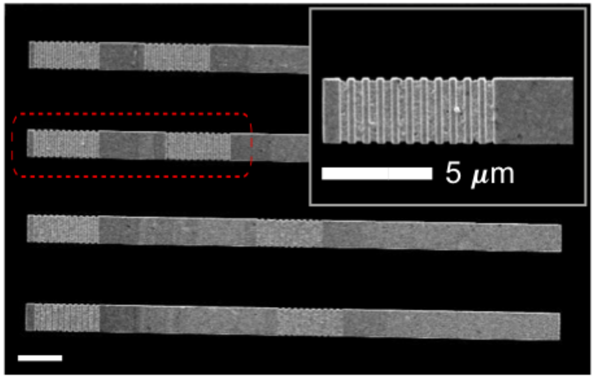


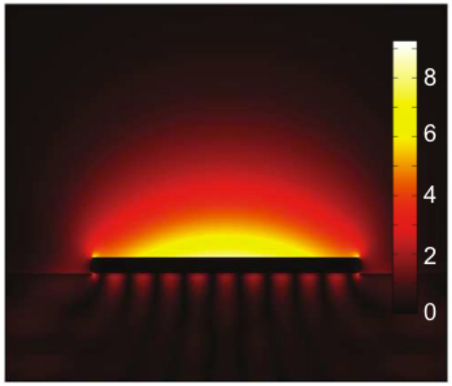
Fasel et al., PRL 94, 110501 (2005)
Fasel et al., NJP 8, 13 (2006)

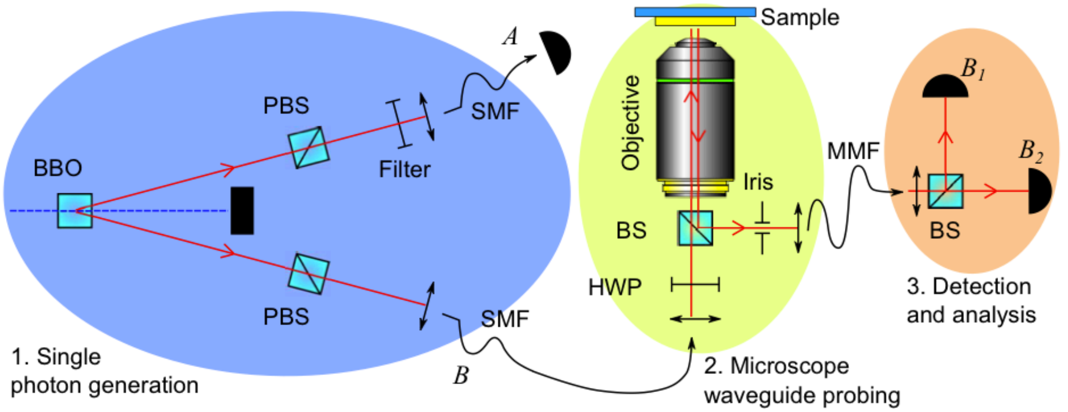


Huck et al., PRL 102, 246802 (2009)

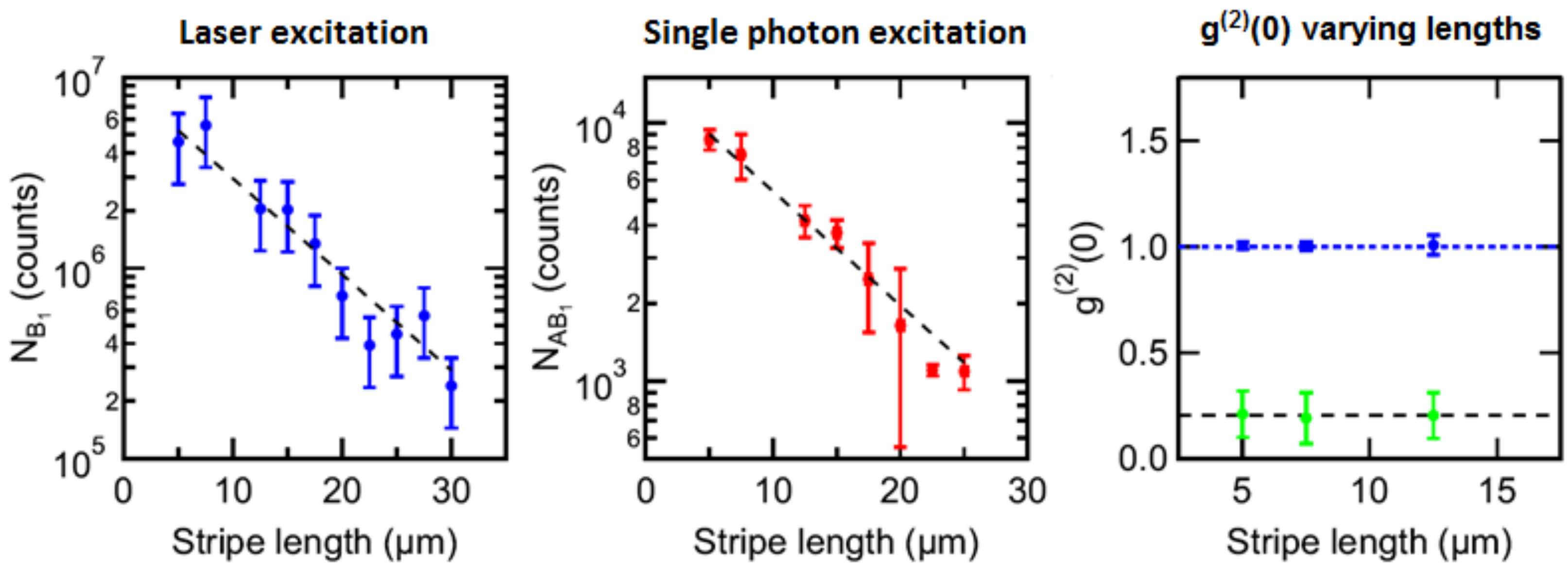
3 Early work | Quantum optics fundamentals | Quantum size effect







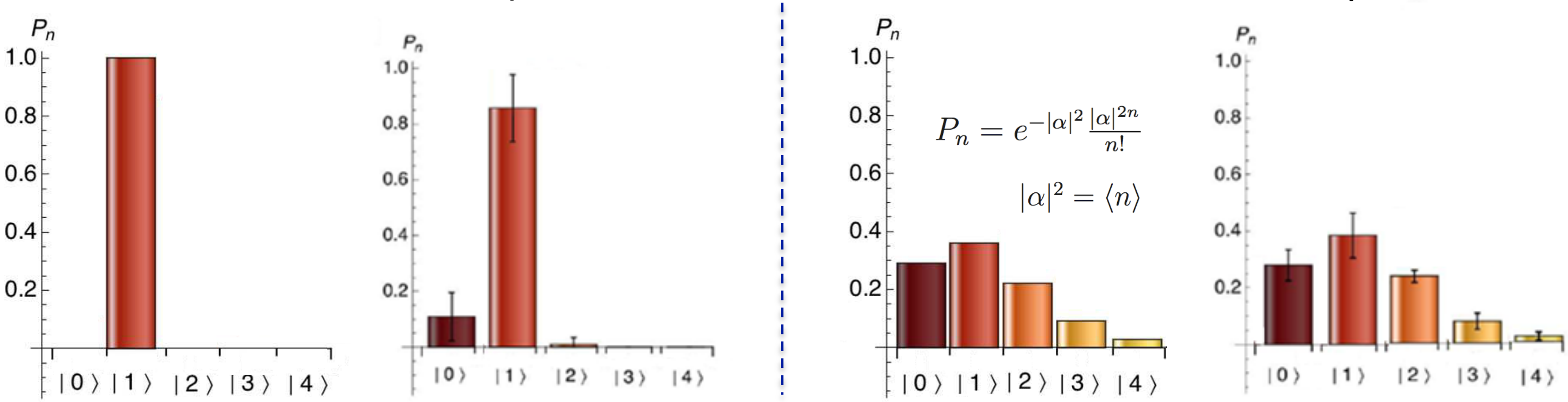
Di Martino et al., NL 12, 2504 (2012)

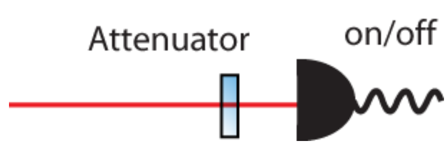

Laser excitation
Single photon excitation
g(2)(0) varying lengths
N_B1 (counts)
N_AB1 (counts)
g(2)(0)
Stripe length (μm)
Stripe length (μm)
Stripe length (μm)

3 | **Early work** | Quantum optics fundamentals | Quantum size effect

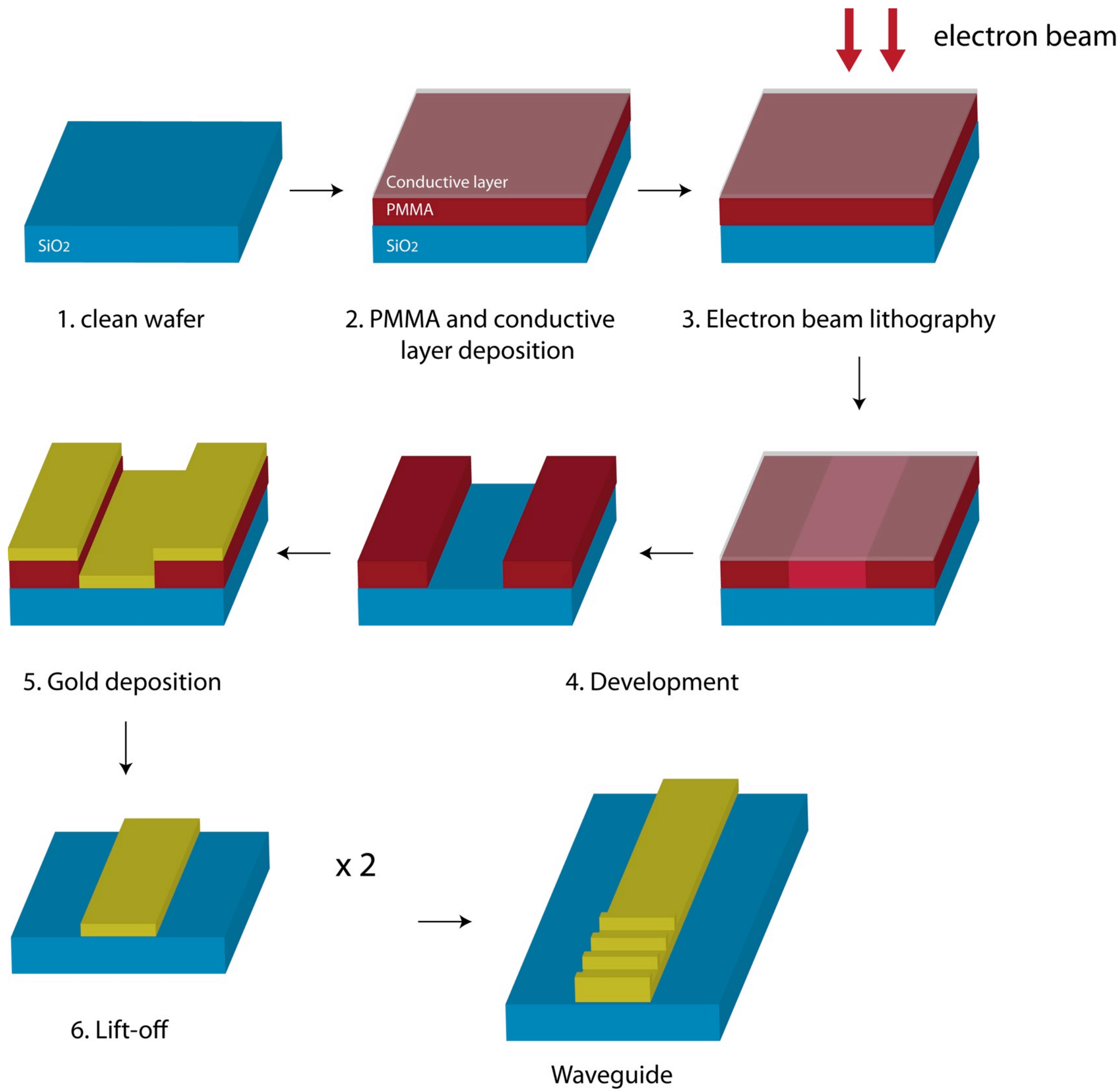
Single-photon source excitation — *ideal* / *experiment*

Attenuated laser excitation — *ideal* / *experiment*





Zambra et al., Phys. Rev. Lett. 2005, 95, 063602.


electron beam
Conductive layer
PMMA
SiO2
SiO2
1. clean wafer
2. PMMA and conductive layer deposition
3. Electron beam lithography
4. Development
5. Gold deposition
6. Lift-off
x 2
Waveguide

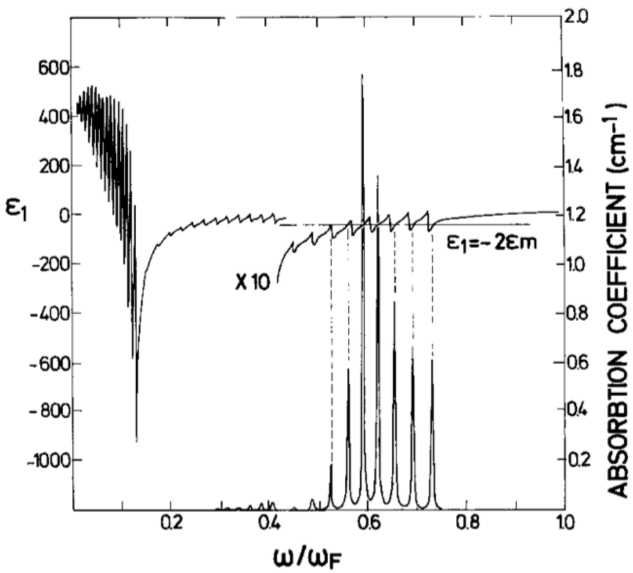
3

Early work

Quantum optics fundamentals

Quantum size effect

16 x 16 x 16 electrons in a box



Genzel et al., Z Physik B 21, 339 (1975)

Frohlich, Physica 6, 406 (1937)

Kubo and Kawabata, JPSJ 17, 975 (1962) and 21, 1765 (1966)

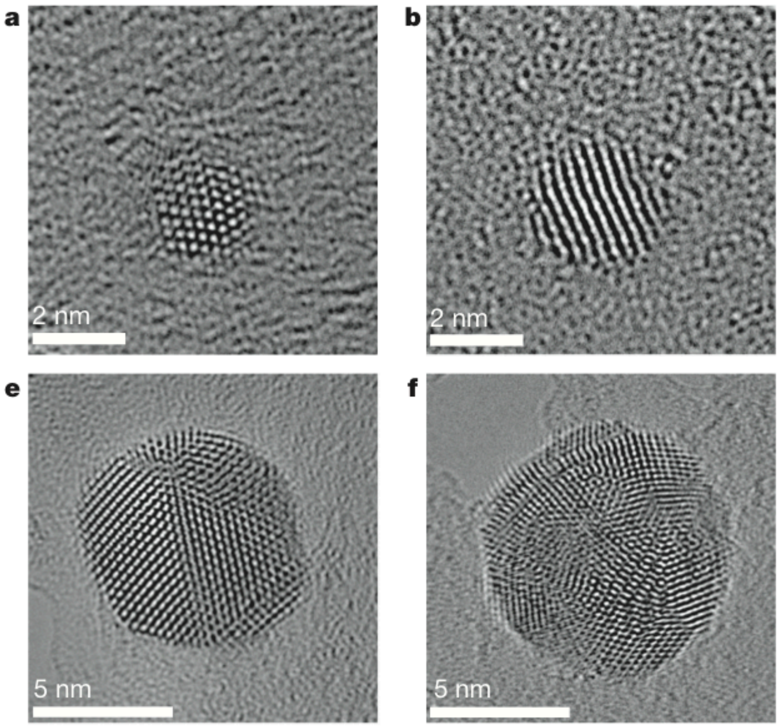
one electron wave functions

$$\psi_{hkl} = \left(\frac{8}{L^3}\right)^{1/2} \sin\left(\frac{h\pi x}{L}\right) \sin\left(\frac{k\pi y}{L}\right) \sin\left(\frac{l\pi z}{L}\right)$$

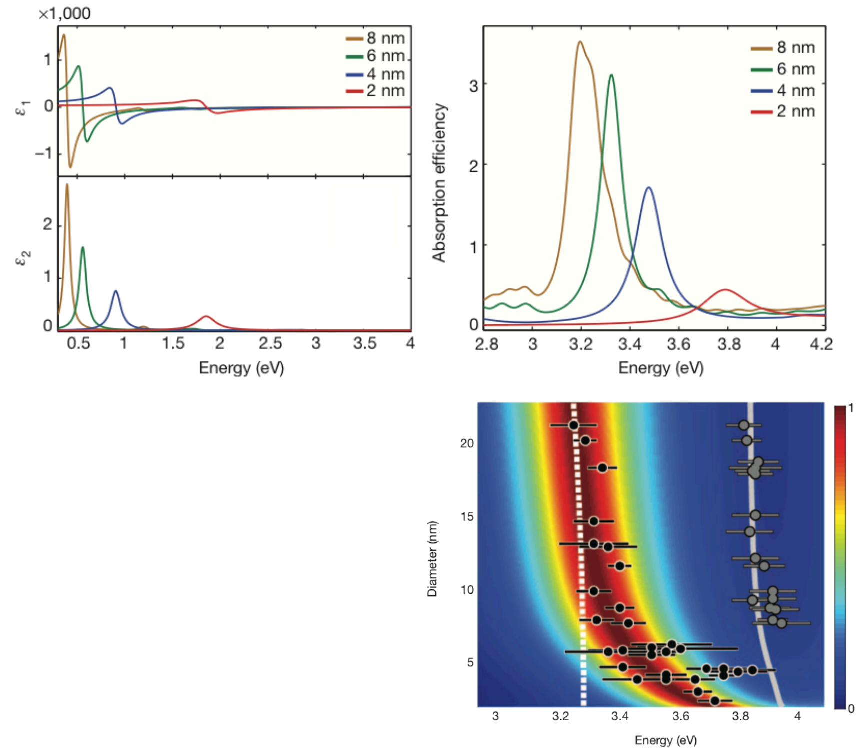
$$\varepsilon(\omega) = \varepsilon_\infty(\omega) + \omega_p^2 \sum_{\Delta l}^{1,3,\ldots} \sum_{l}^{l_F} \frac{S_{l,\Delta l}}{\omega_{l,\Delta l}^2 - \omega^2 - i\omega\gamma_{l,\Delta l}}$$

$$S_{l,\Delta l} = \frac{32}{\pi l_F^3} \frac{l^2 (l+\Delta l)^2}{\Delta l^2 (2l+\Delta l)^2} \simeq \frac{8}{\pi l_F^3} \frac{l^2}{\Delta l^2}$$

$$\sum_{\Delta l} \sum_{l} S_{l,\Delta l} = 1$$



Scholl et al., Nature 483, 421 (2012)



Reviews:

Halperin, RMP 58, 533 (1986)

Kreibig and Genzel, Surf. Sci. 156, 678 (1985)

4 Recent work

Waveguides, sources and switches

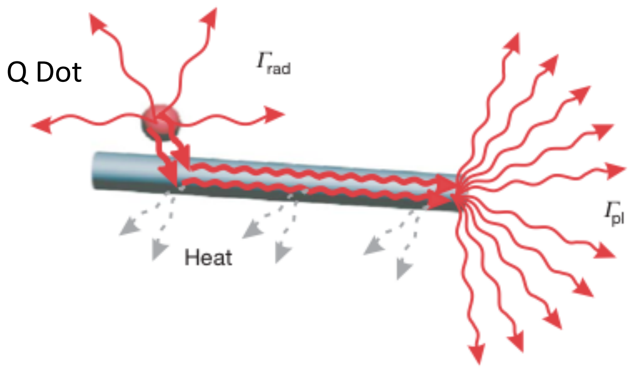
Metamaterials

4 Recent work | Waveguides, sources and switches | Metamaterials

Single-photon sources

Enhancement of light-matter interaction

$$H = \hbar\omega_0 b^\dagger b + \frac{\hbar\omega_a}{2}\sigma_z + \hbar(g b \sigma_+ + g^* b^\dagger \sigma_-)$$



Akimov et al., Nature 450, 402 (2007)

waveguide

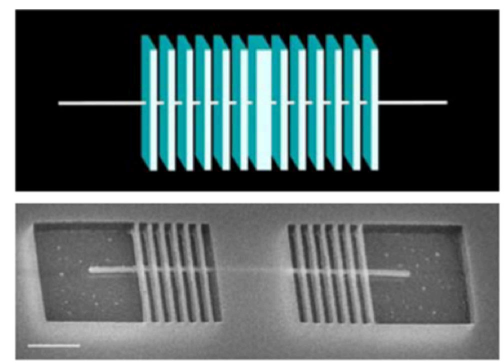
$$g \propto 1/\sqrt{A_{eff}}$$

dielectric: $P \lesssim 1$ metal: $P \gtrsim 100$ theory

$P = 2.5$ exp

Purcell effect

$$P \propto \frac{Q}{V}$$

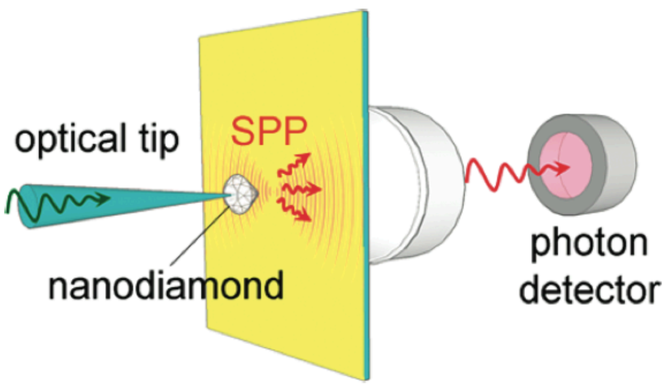


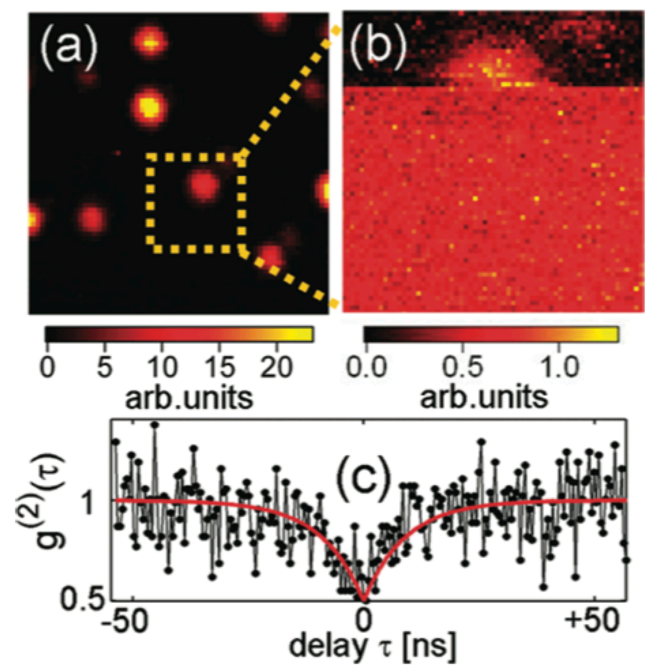
de Leon et al., PRL 108, 226803 (2012)

cavity

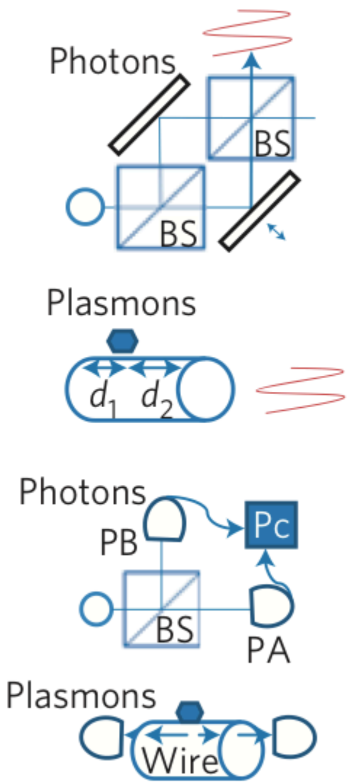
$$g \propto 1/\sqrt{V_{eff}}$$

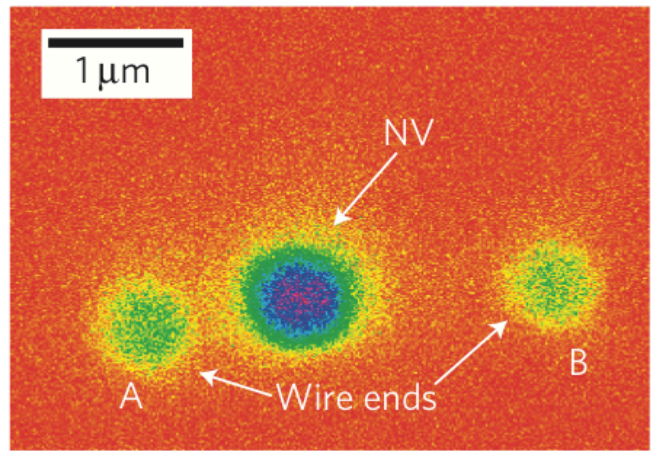
$$P = 75$$





Cuche et al., NL 10, 4566 (2011)

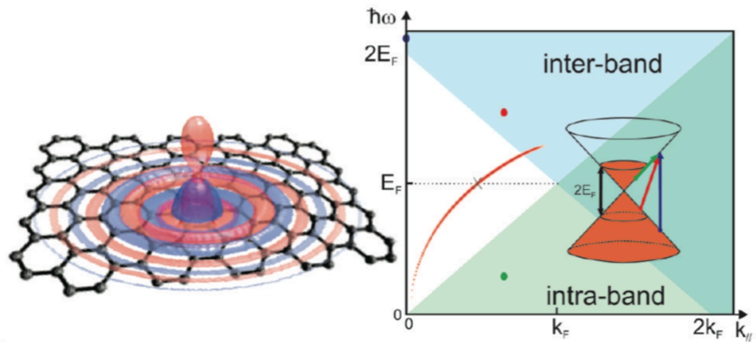


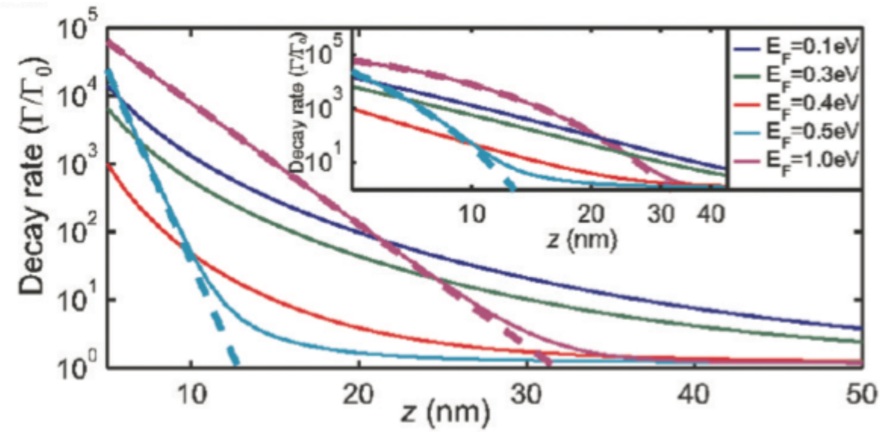


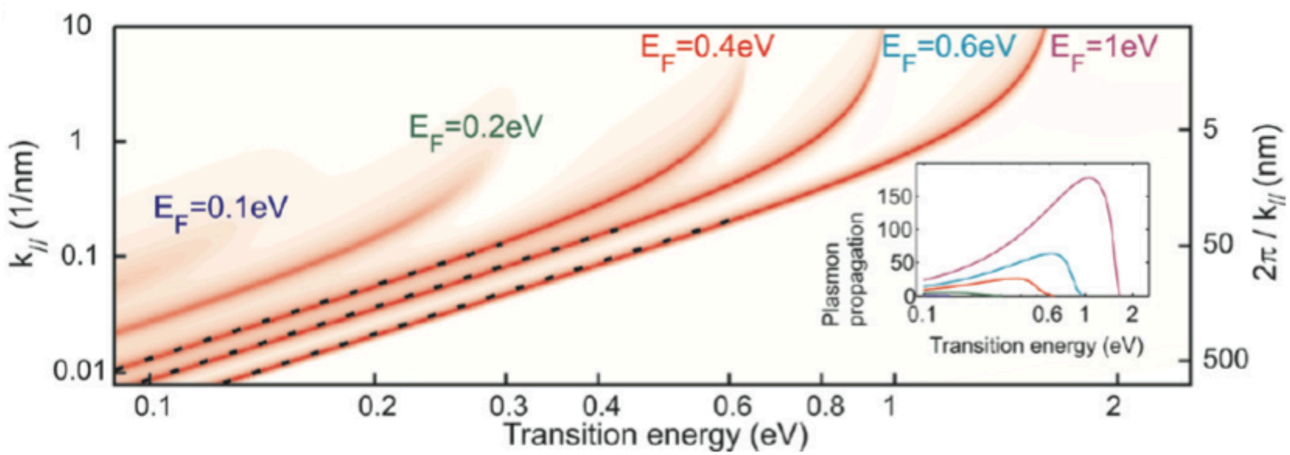
Kolesov et al., Nat. Phys. 5, 470 (2009)

4

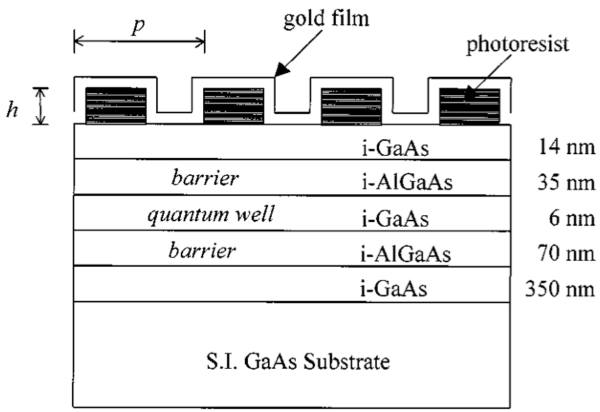
Recent work | Waveguides, sources and switches | Metamaterials

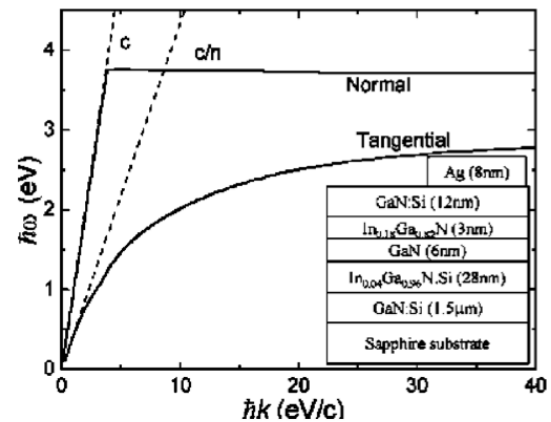


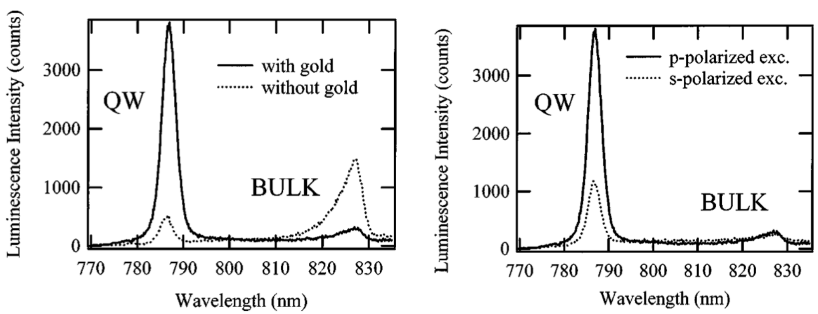


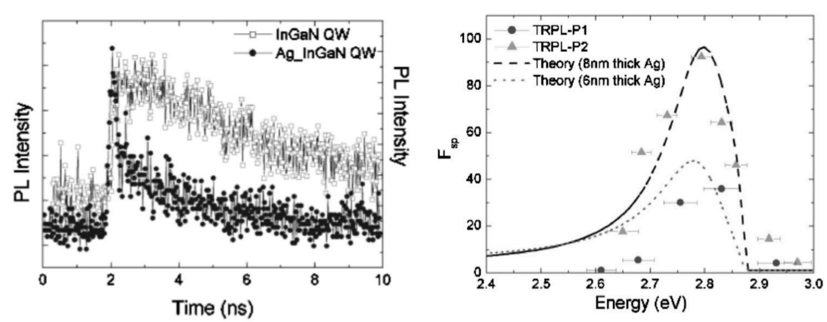


Koppens et al., NL 11, 3370 (2011)







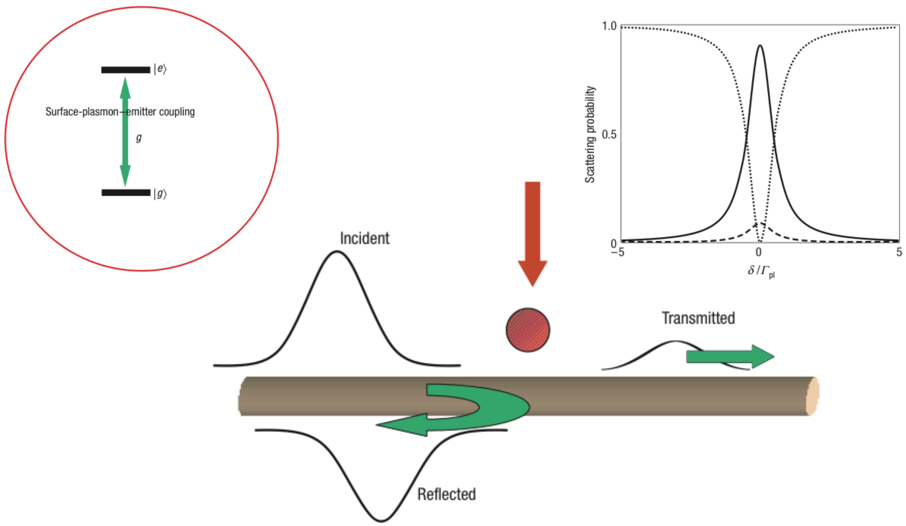


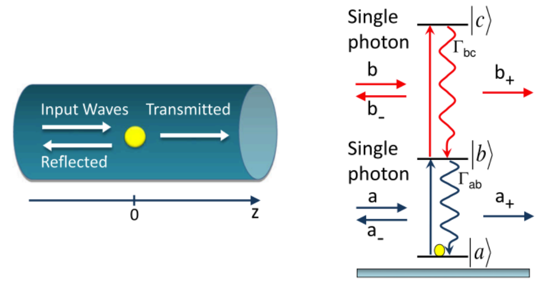
Hecker et al., APL 75, 1577 (1999)

Neogi et al., PRB 66, 153305 (2002)

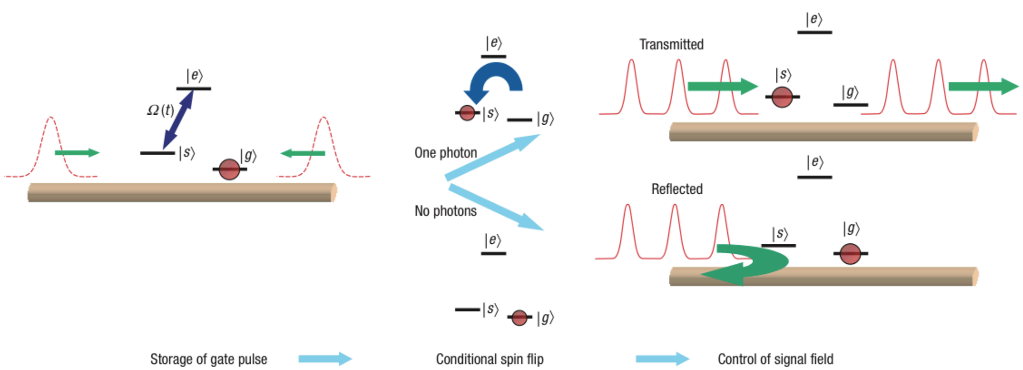
Barnes, JMO 45, 661 (1998)

4 Recent work | Waveguides, sources and switches | Metamaterials

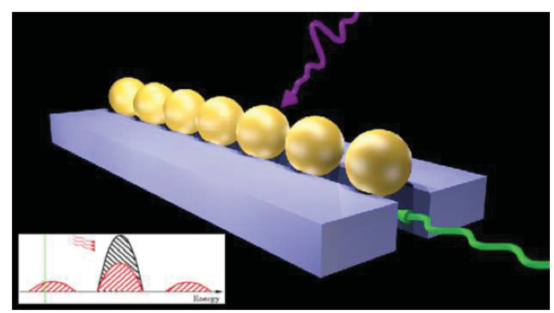




Kolchin et al., PRL 106, 113601 (2011)

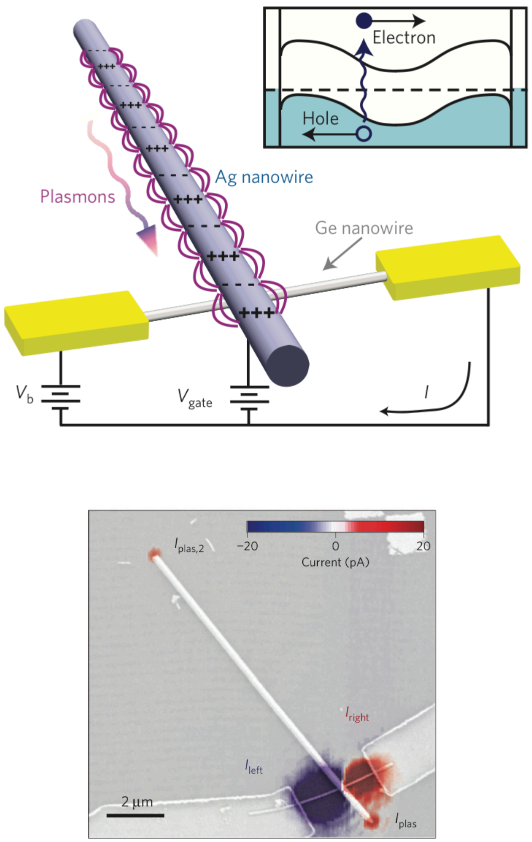


Chang et al., Nat Phys 3, 807 (2007)

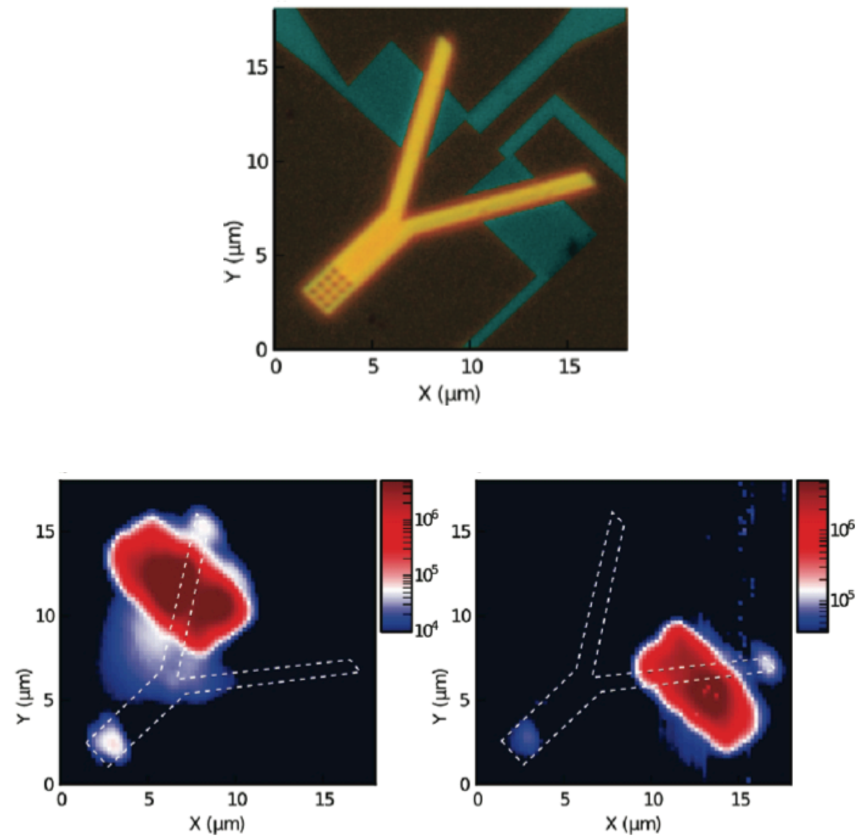


Frank, PRB 85, 195463 (2012)

4 Recent work | Waveguides, sources and switches | Metamaterials

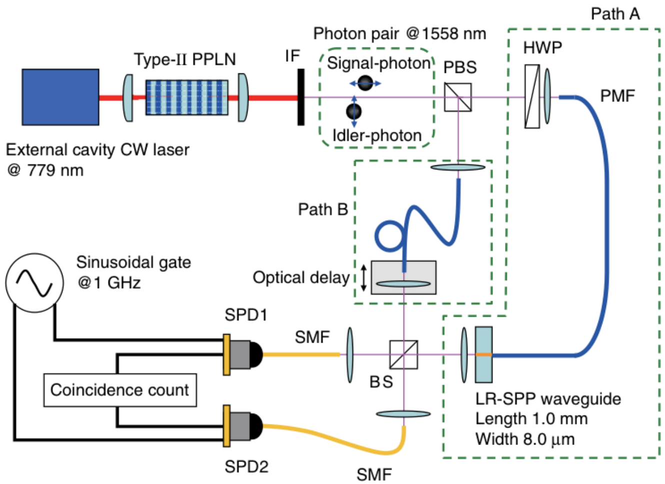


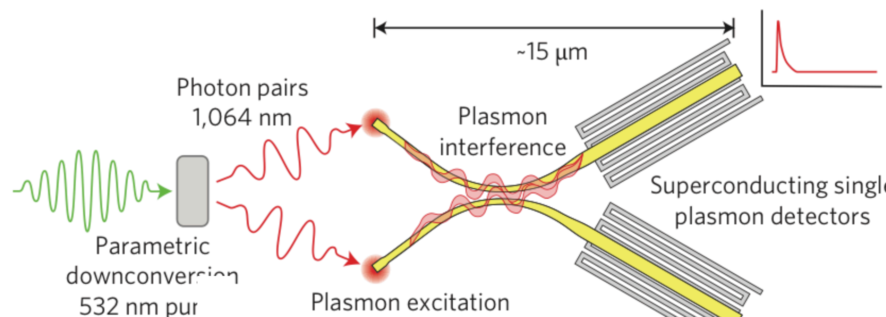
Falk et al., Nat Phys 5, 475 (2009)



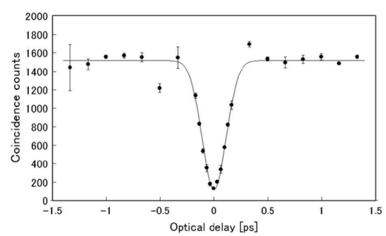
Heeres et al., NL 10, 661 (2010)

4 Recent work → Waveguides, sources and switches → Metamaterials

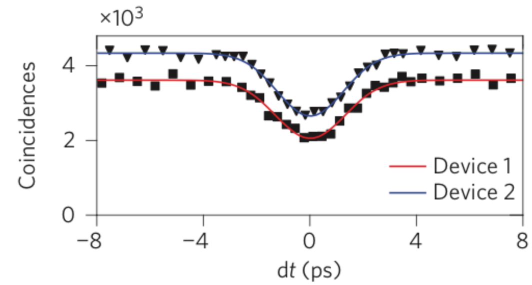




V=92%

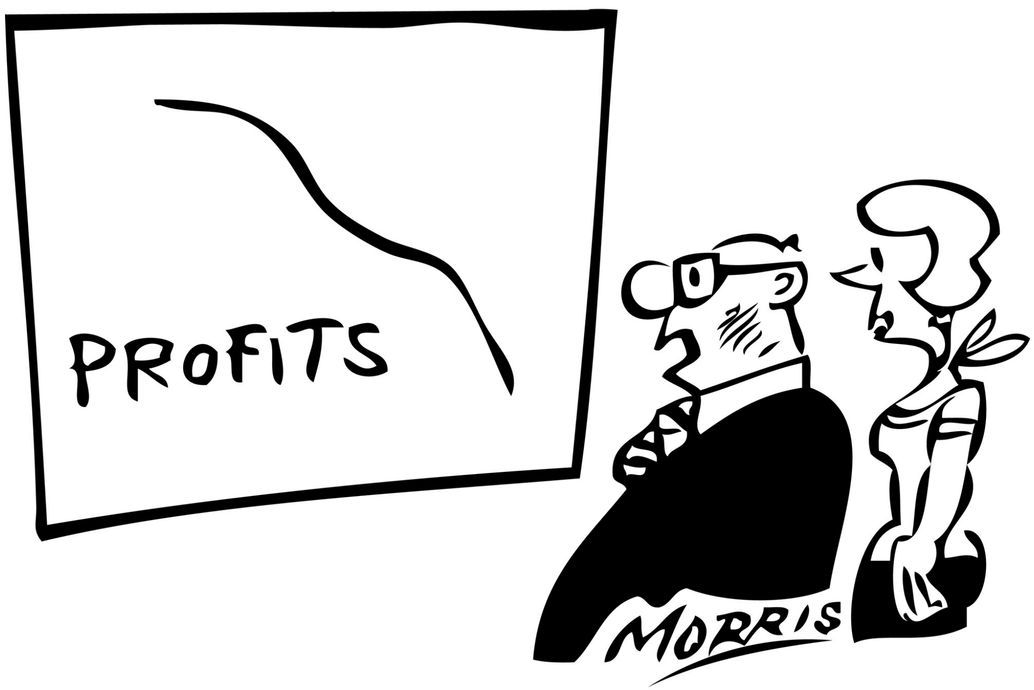


V=43%



Fujii et al., Opt Lett 37, 1535 (2012)

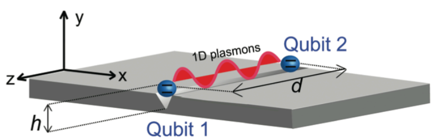
Heeres et al., Nat Nanotech 8, 719 (2013)



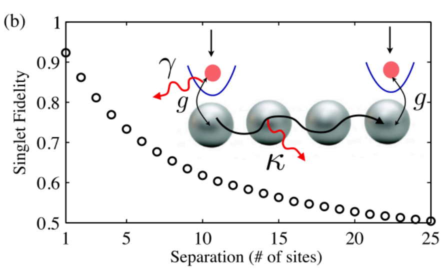
Miss Perkins, send in a scapegoat

Dealing with loss in quantum plasmonics

Dissipative driven



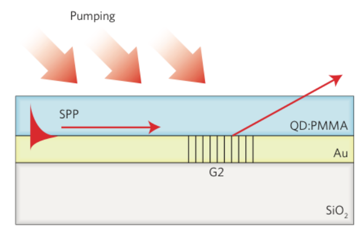
Martín-Cano et al., PRB 84, 235306 (2011)



Gullans et al., PRL 109, 235309 (2012)

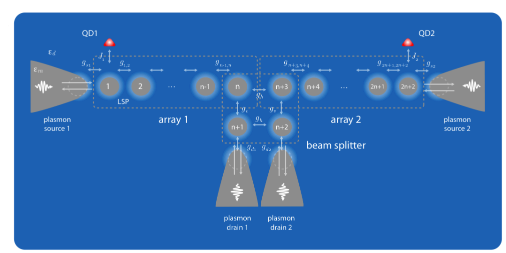
Verstraete et al. Nat Phys 5, 633 (2009)

Loss compensation

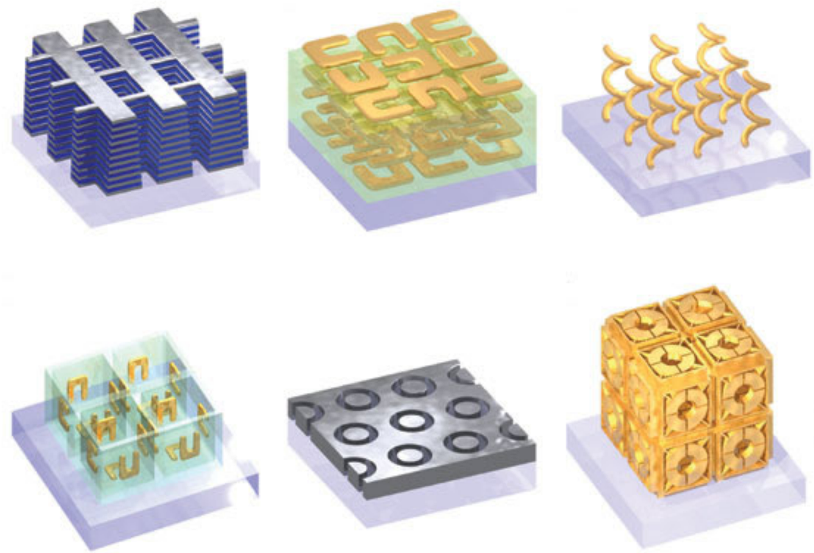


Berini and De Leon, Nat Phot 6, 16-24 (2011)

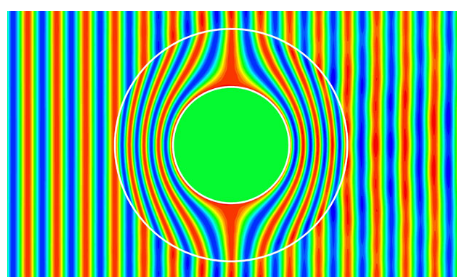
Postselection



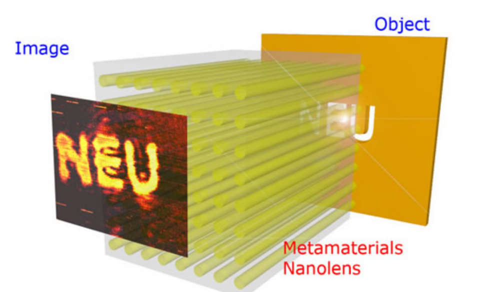
Lee et al., NJP 15, 83017 (2013)



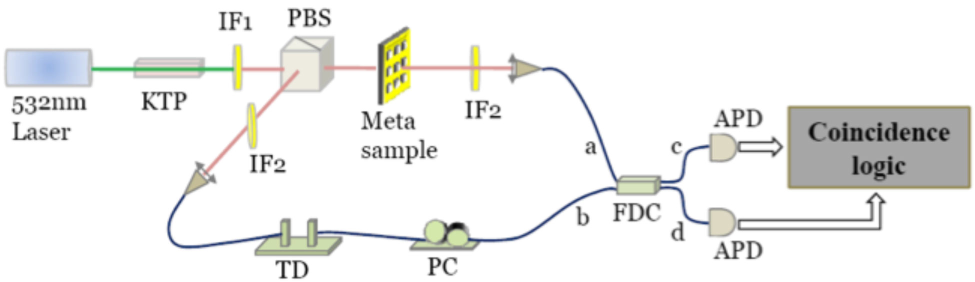
Soukoulis and Wegener, Nat. Phot. 5, 523 (2011)

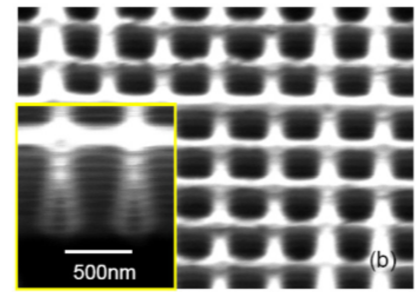


Cai et al., Nat. Phot. 1, 224 - 227 (2007)

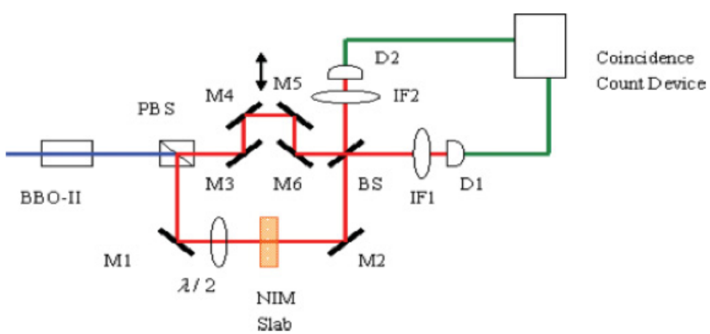


Casse et al., APL 96, 023114 (2010)

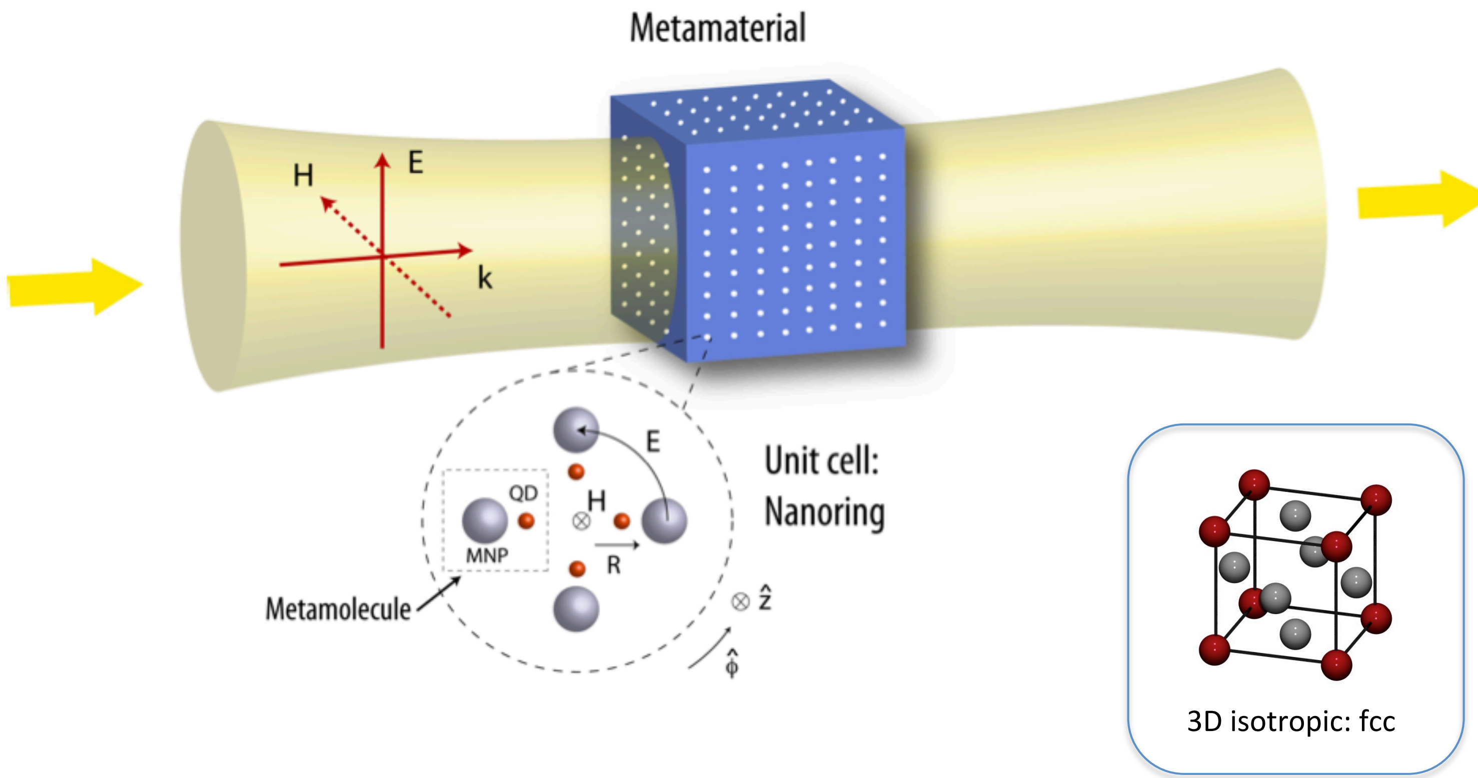




Wang et al., Opt. Exp. 20, 5213 (2012)



Zhou et al., PRA 85, 023841 (2012)



McEnery et al., PRA 89, 013822 (2014)

5

Future directions

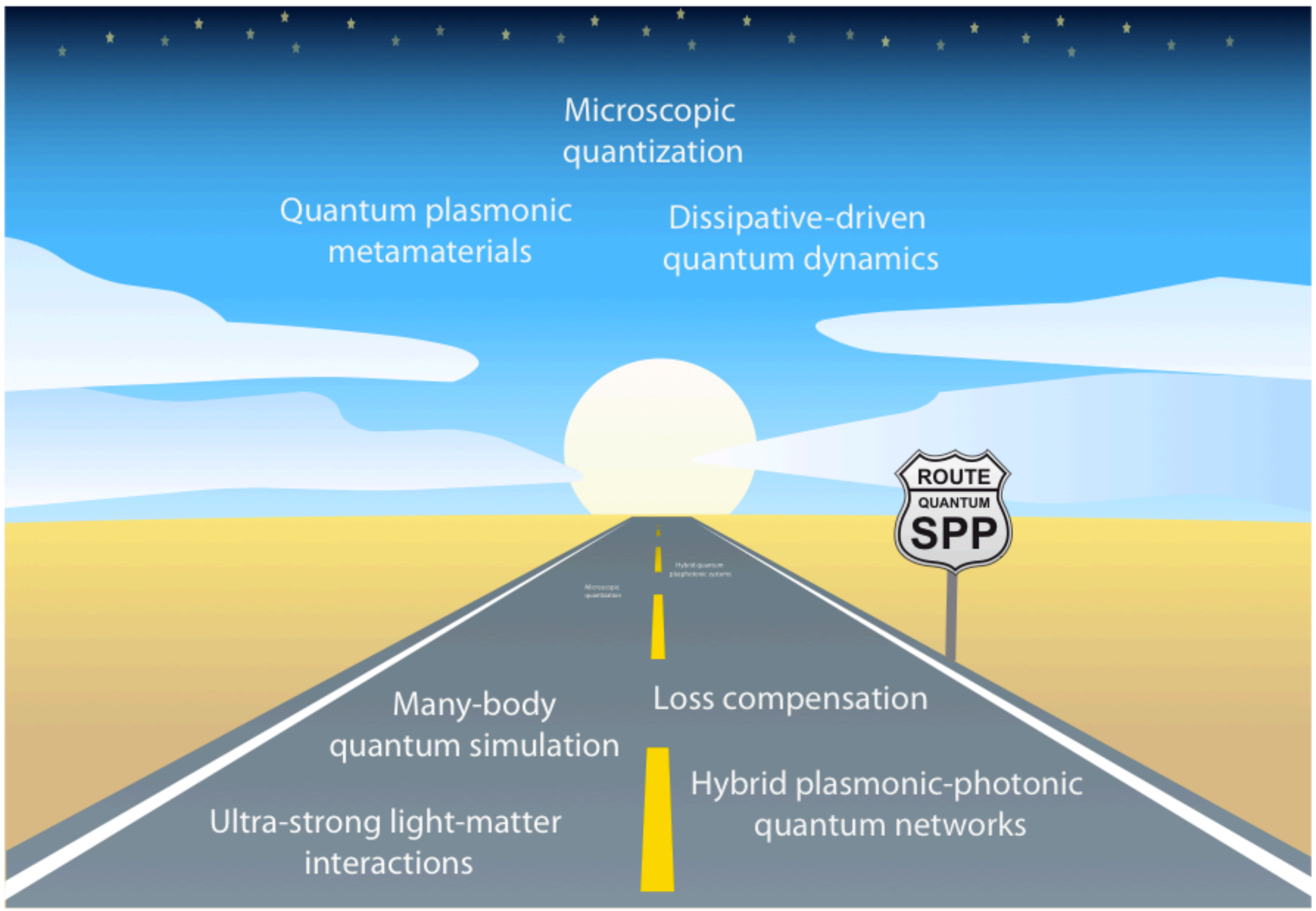
- Media: metals, graphene, superconductors
- Hybridization, quantization

5

Future directions

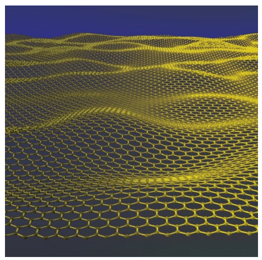
Media: metals, graphene, superconductors

Hybridization, quantization

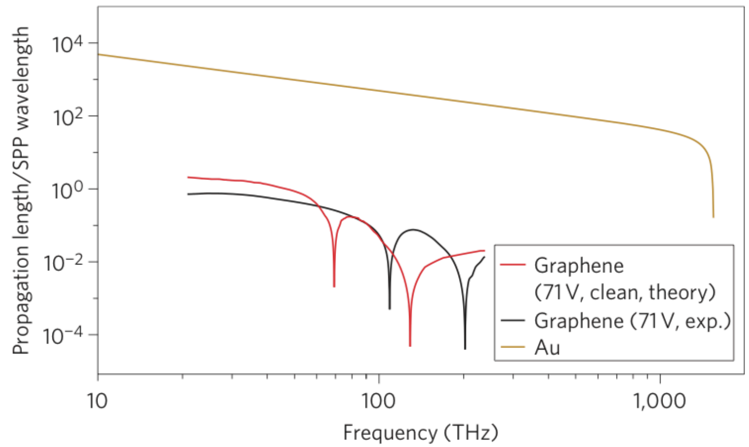


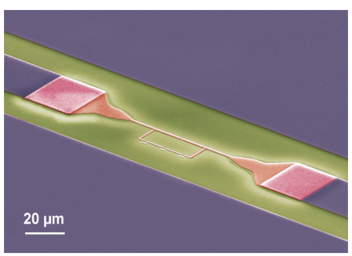
5 Future directions | Media: metals, graphene, superconductors | Hybridization, quantization

Gold vs.

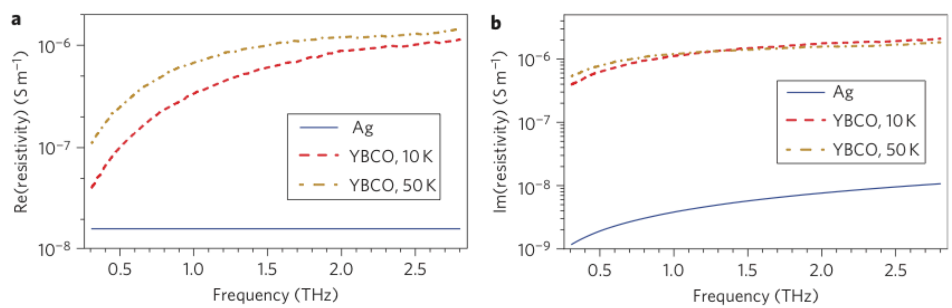


Graphene





Superconductor



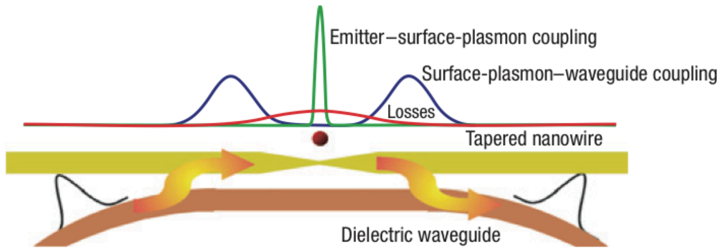
Tassin et al., Nat. Phot. 6, 259 (2012)

5

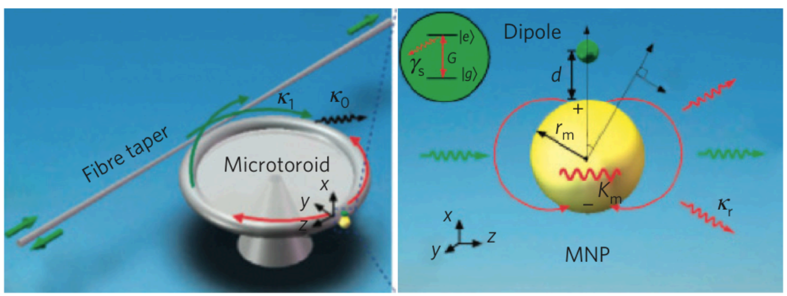
Future directions

Media: metals, graphene, superconductors

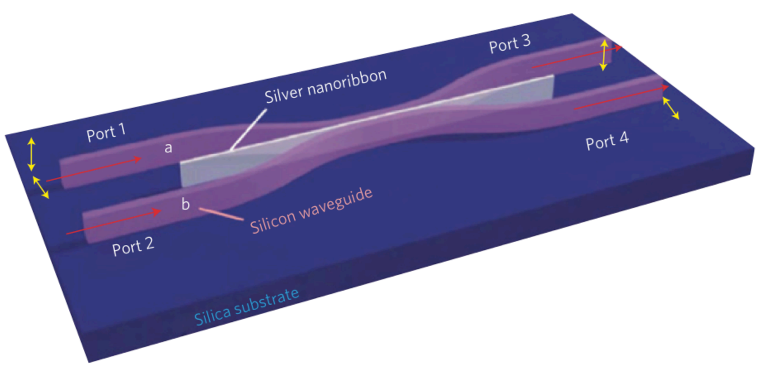
Hybridization, quantization



Chang et al., Nat Phys 3, 807 (2007)



Xiao et al., PRA 85, 031805 (2009)



Zou et al., Opt. Lett. 36, 3630 (2011)

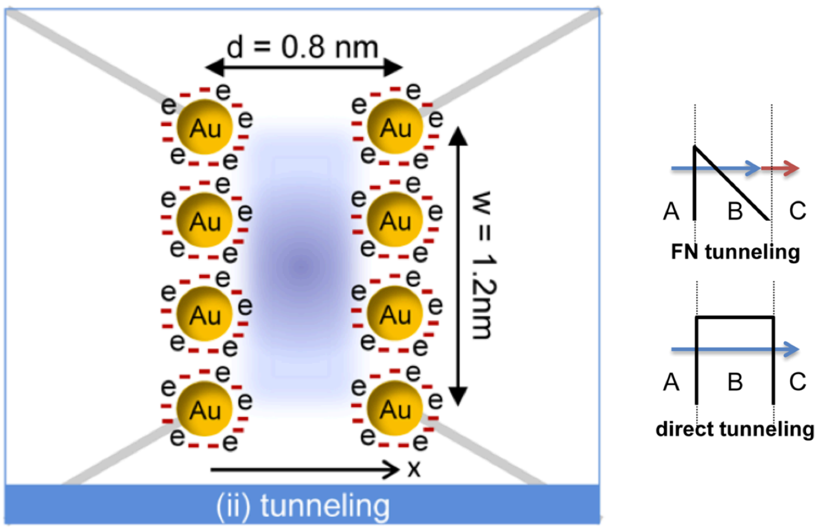
5

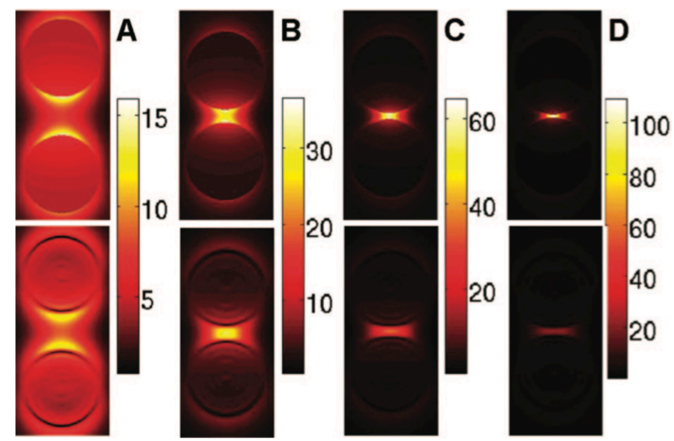
Future directions

Media: metals, graphene, superconductors

Hybridization, quantization

Hybridization of quantum optics and quantum electronics





Wu et al., ACS Nano 7, 707 (2013)

Zuloaga et al., Nano Letters 9, 887 (2009)

Lecture 2 - outline

1	Lecture 1 recap	SPPs, LSPs	Quantum applications
2	Subdiffraction vs subwavelength	Fourier synthesis	K-space
3	Quantization	Macroscopic approach and loss	Other methods
4	Light-matter interactions	Waveguides	Nanoparticles
5	Metamaterials	Refractive index	Quantum effects
6	Open problems	Loss	Hybridization

Quantum Plasmonics

WINTER SCHOOL ON QUANTUM PHYSICS AND QUANTUM INFORMATION
Palacký University, Olomouc, Czech Republic | Jan 2014

MARK TAME

UNIVERSITY OF KWAZULU-NATAL

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