

QUANTUM PLASMONICS II

WINTER SCHOOL ON QUANTUM PHYSICS AND QUANTUM INFORMATION

Palacký University, Olomouc, Czech Republic | Jan 2014

MARK TAME



european
social fund in the
czech republic



EUROPEAN UNION



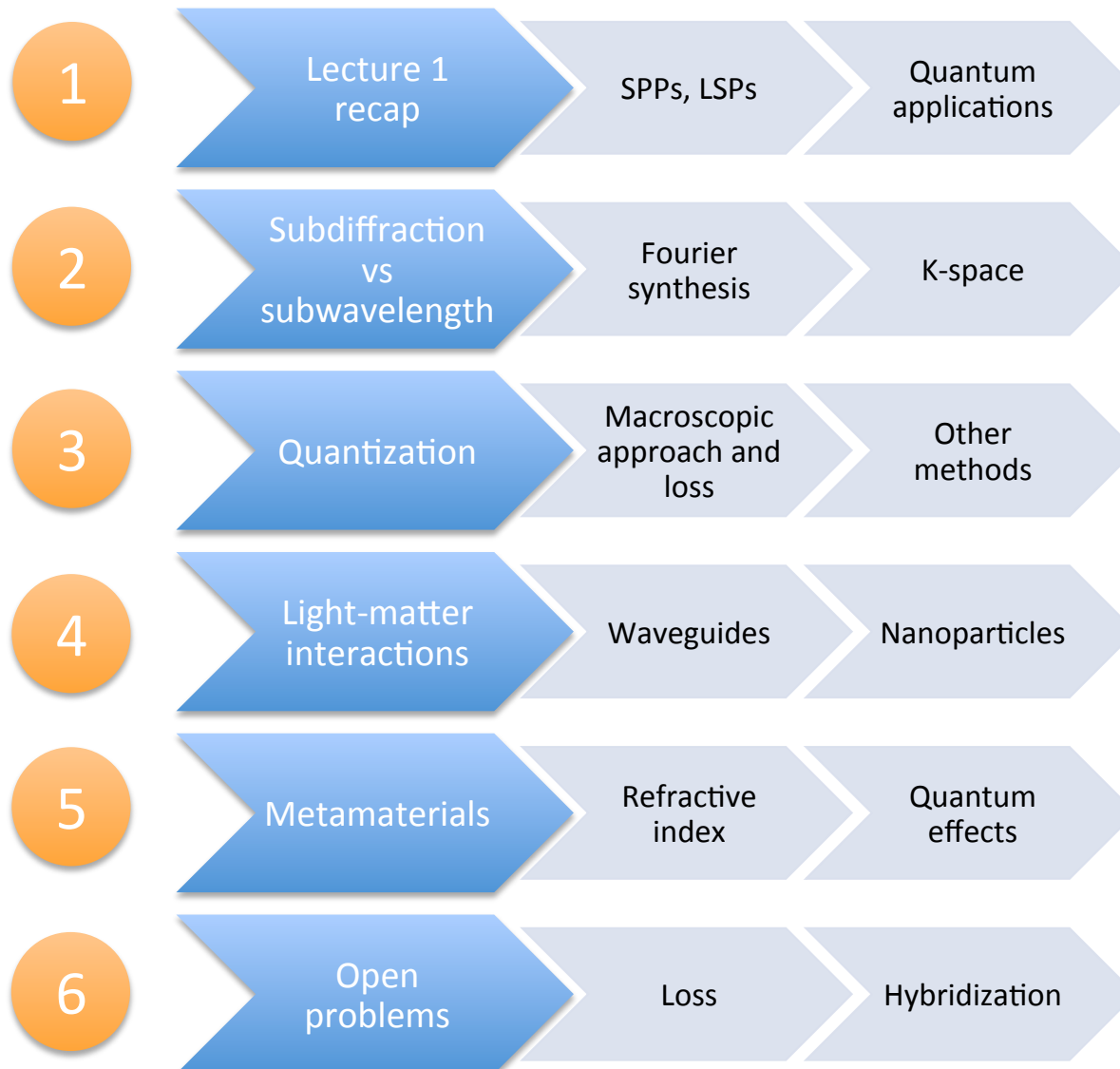
MINISTRY OF EDUCATION,
YOUTH AND SPORTS



OP Education
for Competitiveness

INVESTMENTS IN EDUCATION DEVELOPMENT

Lecture 2 - outline



1

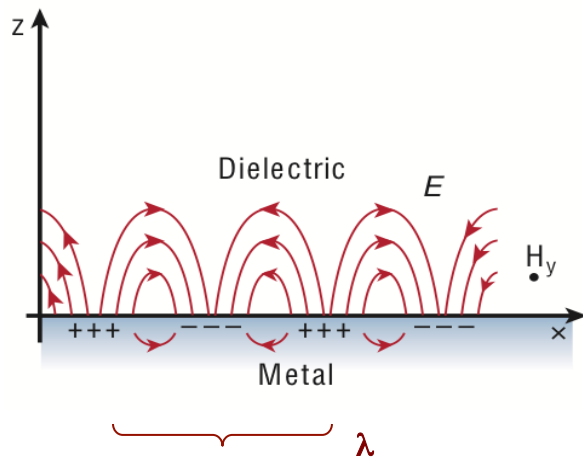
Lecture 1
recap

SPPs, LSPs

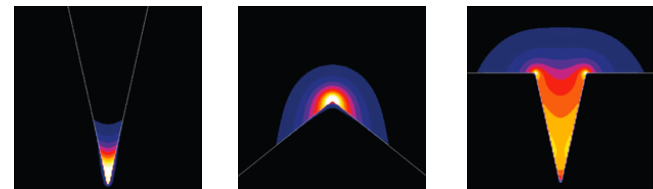
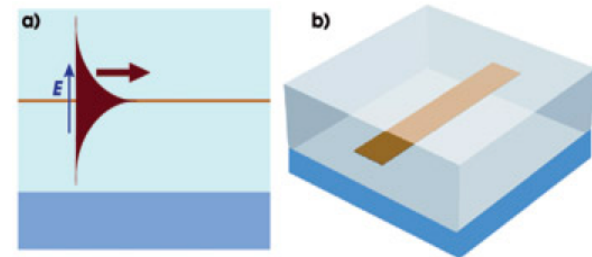
Quantum
applications



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graph LR; A((1)) --> B[Lecture 1 recap]; B --> C[SPPs, LSPs]; C --> D[Quantum applications]
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Barnes, Dereux and Ebbesen, Nature 424, 824 (2003)



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

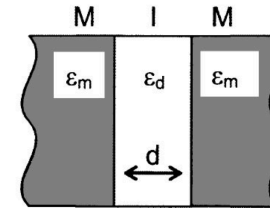
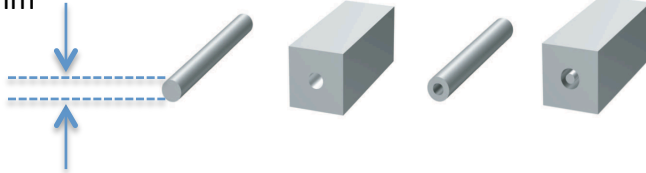
1

Lecture 1 recap

SPPs, LSPs

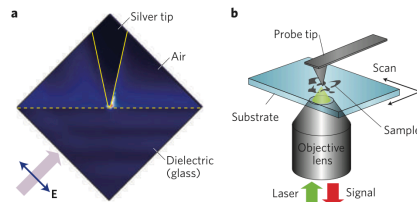
Quantum
applications

~10nm

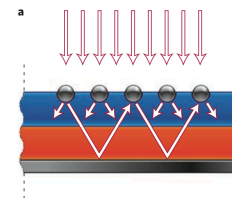


Takahara, Plasmonic Nanoguides and Circuits (2009)

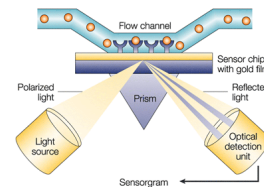
Zia et al., J. Opt. Soc. Am. A 21, 2442 (2004)



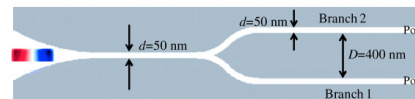
Kawata, Inouye and Verma,
Nature Phot. 3, 388 (2009)



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



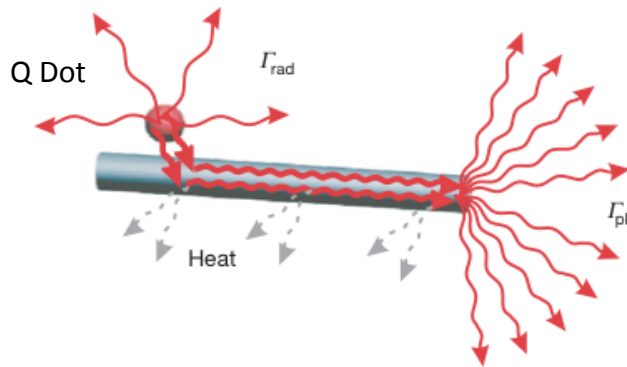
J. N. Anker et al.,
Nature Mat. 7, 442 (2008)



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

Enhancement of light-matter interaction

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



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

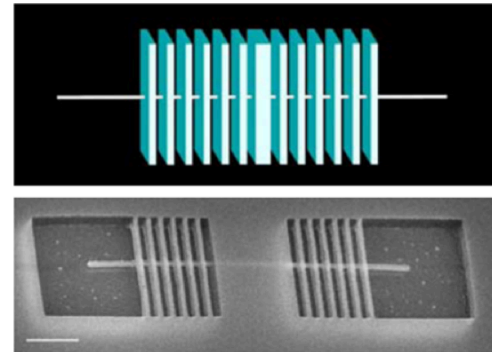
waveguide

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

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

Purcell effect

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



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

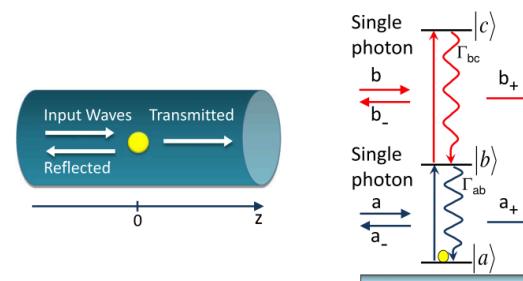
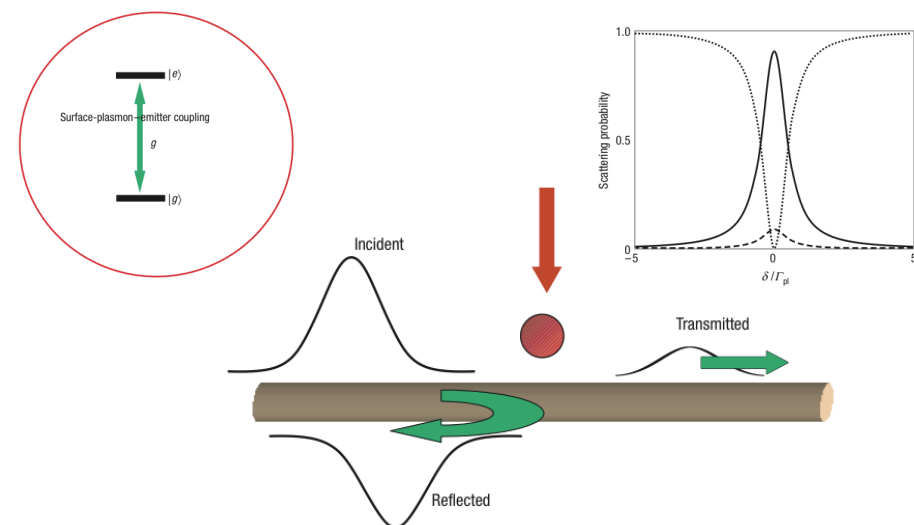
cavity

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

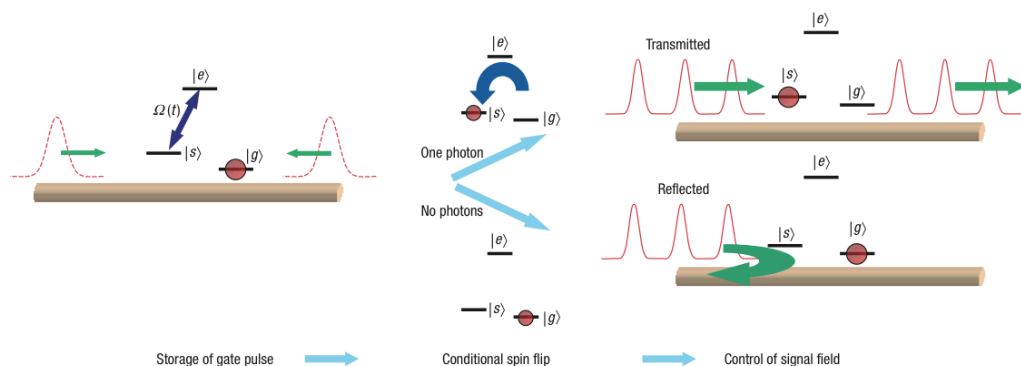
1

Lecture 1
recap

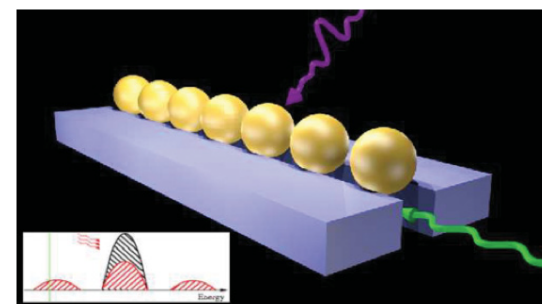
SPPs, LSPs

Quantum
applications

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

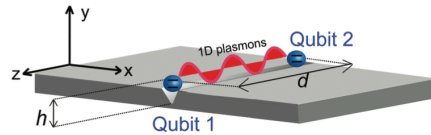


Chang et al., Nat Phys 3, 807 (2007)

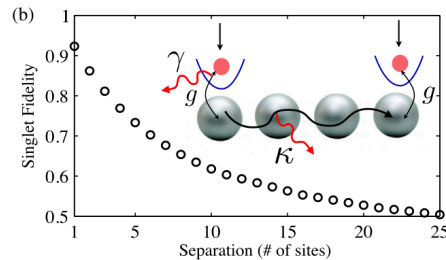


Frank, PRB 85, 195463 (2012)

Dissipative driven



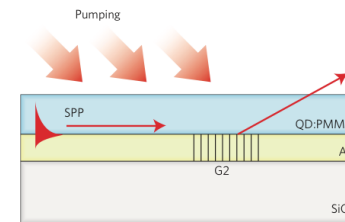
Martín-Cano et al., PRB 84, 235306 (2011)



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

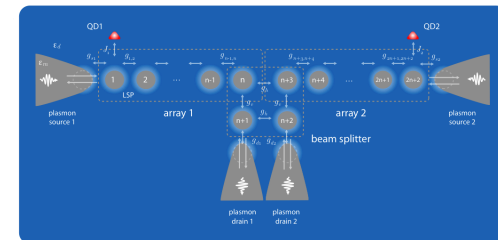
Verstraete et al. Nat Phys 5, 633 (2009)

Loss compensation



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

Postselection



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

2

Subdiffraction
vs
subwavelength

Fourier
synthesis

K-space







2

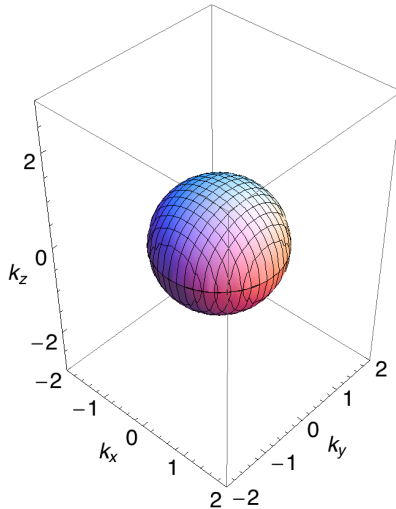
Subdiffraction
vs
subwavelength

Fourier
synthesis

K-space

J. Takahara, in Plasmonic Nanoguides and Circuits (2009)

3D:



$$\mathbf{k} = (k_x, k_y, k_z) \quad |\mathbf{k}|^2 = n^2 \frac{\omega^2}{c^2}$$

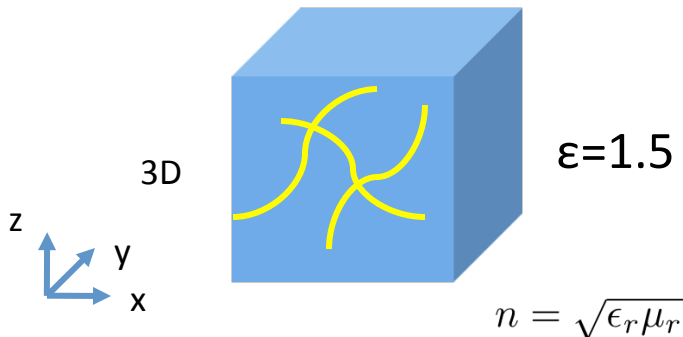
$$k_x^2 + k_y^2 + k_z^2 = (nk_0)^2 = \epsilon\mu\left(\frac{\omega}{c}\right)^2 \quad k_0 = 2\pi/\lambda_0$$

$$-k \leq k_j \leq k$$

$$\Delta k_x = 2nk_0$$

$$\Delta x \Delta k_x \geq 2\pi \quad \text{Fourier reciprocity relation}$$

$$\Delta x \geq \frac{2\pi}{\Delta k_x} = \frac{\lambda_0}{2n} \quad \text{3D Diffraction limit}$$



2

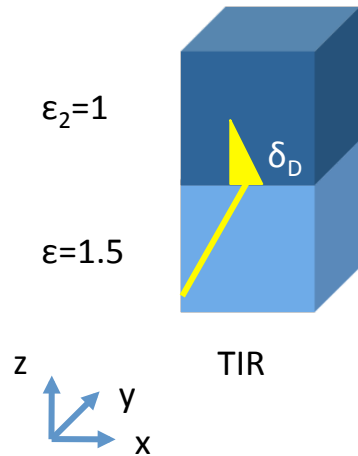
Subdiffraction
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2D:

i) 2D-D (Dielectric)



2D

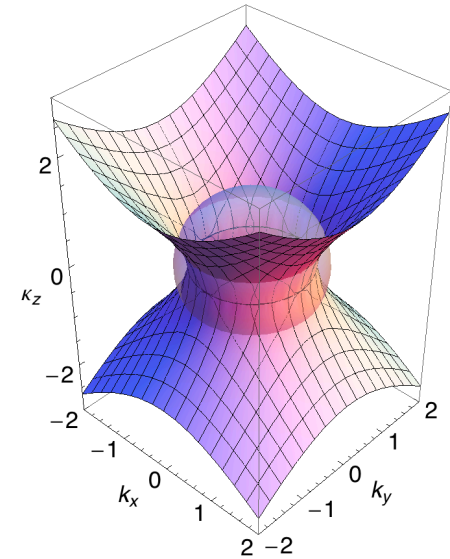
$$\mathbf{k} = (k_x, k_y, i\kappa_z)$$

$$k_x^2 + k_y^2 - \kappa_z^2 = \epsilon_2 \mu \left(\frac{\omega}{c} \right)^2$$

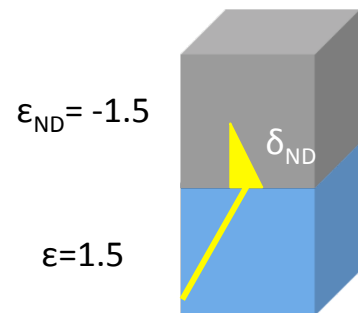
3D

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

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



ii) 2D-ND (Negative Dielectric)



2D

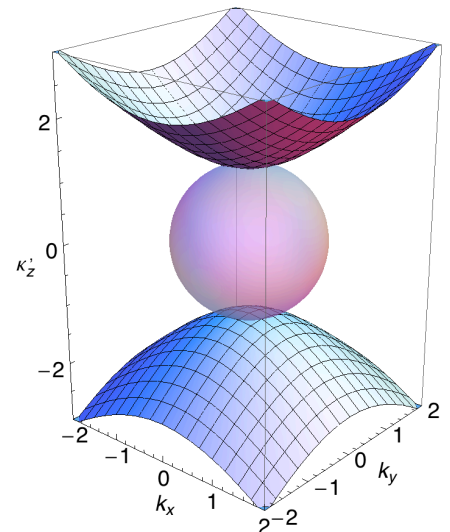
$$\mathbf{k} = (k_x, k_y, i\kappa'_z)$$

$$k_x^2 + k_y^2 - \kappa'_z{}^2 = \epsilon_{ND} \mu \left(\frac{\omega}{c} \right)^2$$

3D

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

$$\delta_{ND} \geq \frac{\lambda_0}{2\pi(n^2 - \epsilon_{ND})^{1/2}}$$

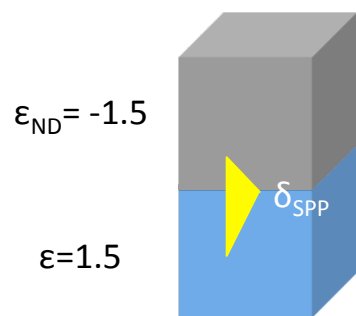


2

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synthesis

K-space

2D SPP:



2D

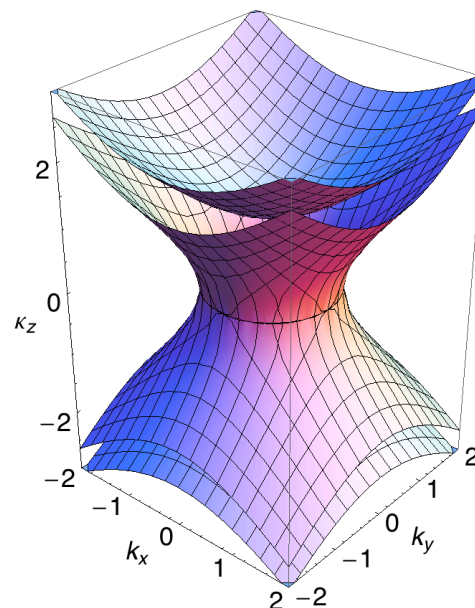
$$\mathbf{k} = (k_x, k_y, i\kappa'_z)$$

$$\mathbf{k} = (k_x, k_y, i\kappa_z)$$

2D

$$k_x^2 + k_y^2 - \kappa_z'^2 = \epsilon_{ND} \mu \left(\frac{\omega}{c} \right)^2$$

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



$$k_x^2 + k_y^2 = \sqrt{\frac{\epsilon \epsilon_{ND}}{\epsilon + \epsilon_{ND}}}$$

$$\delta_{SPP} = \frac{\lambda_0}{2\pi n} \left[\sqrt{\frac{|\epsilon_{ND}| - \epsilon}{\epsilon}} + \frac{\sqrt{\epsilon(|\epsilon_{ND}| - \epsilon)}}{\epsilon_{ND}} \right]$$

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

2D diffraction limit

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

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

3D Diffraction limit

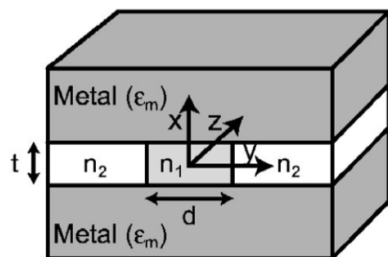
2

Subdiffraction
vs
subwavelength

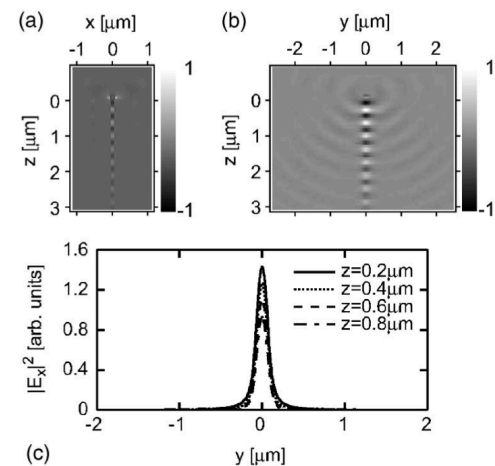
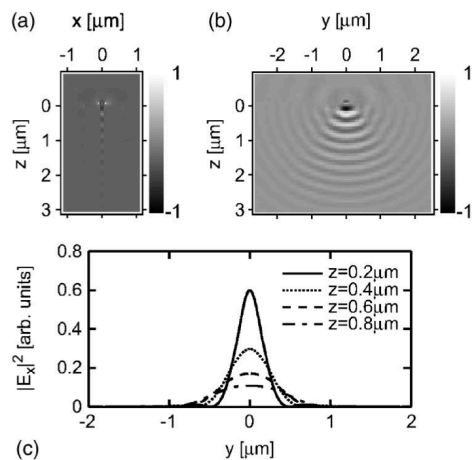
Fourier
synthesis

K-space

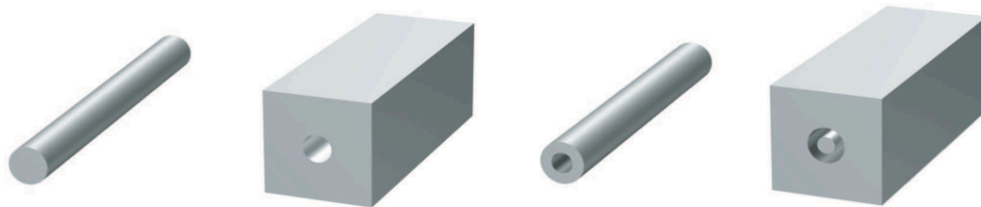
2D



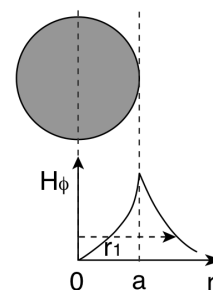
Kusunoki et al, APL 86, 211101 (2005)



1D



J. Takahara, in Plasmonic Nanoguides and Circuits (2009)

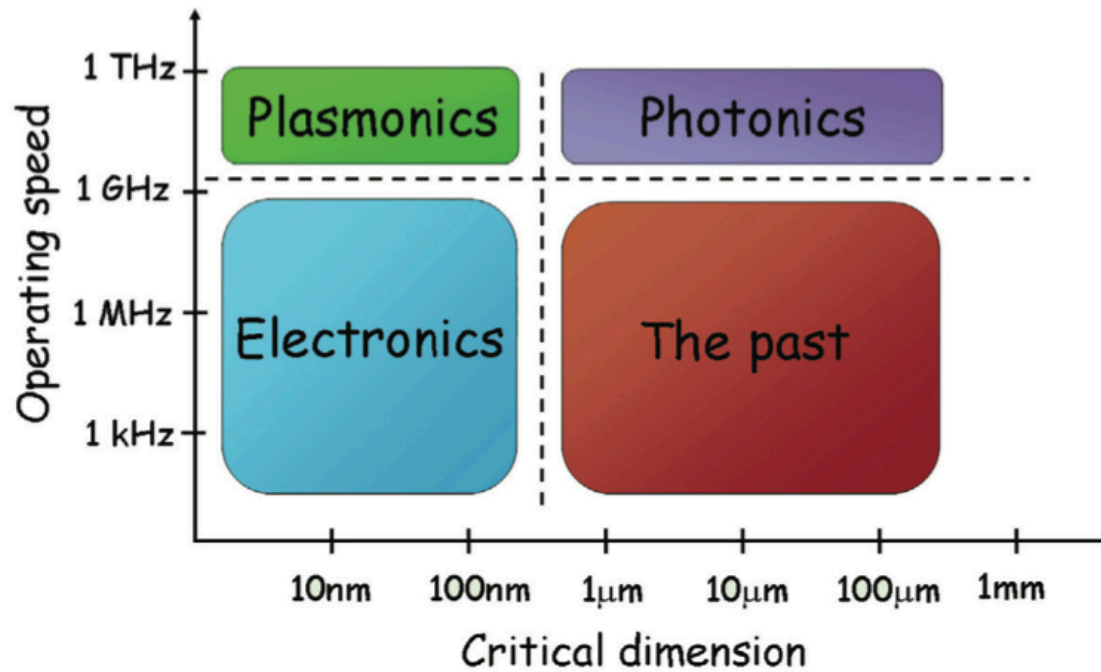


2

Subdiffraction
vs
subwavelength

Fourier
synthesis

K-space

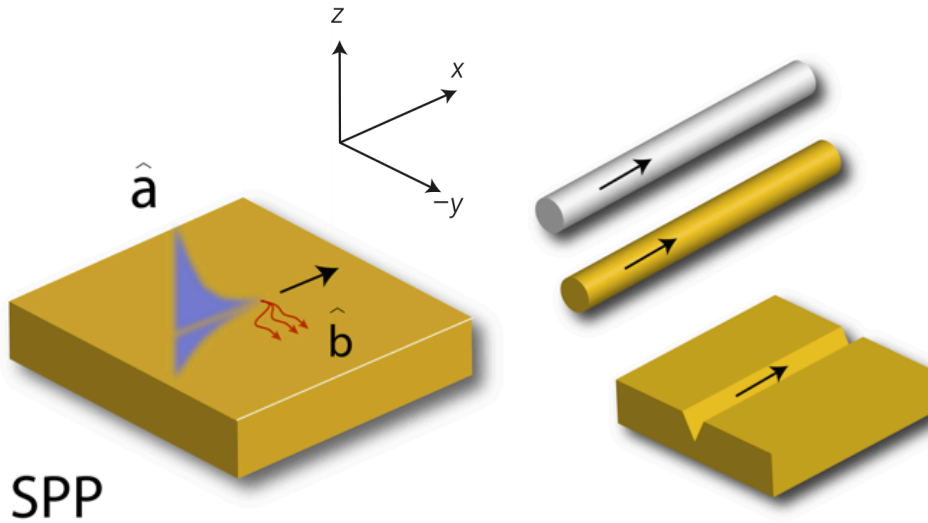


Zia et al., Materials Today 9, 20 (2006)



3

Quantization

Macroscopic
approach
and lossOther
methods

Tame et al., Nat. Phys. 9, 329 (2013)

Archambault et al., PRB 82, 035411 (2010)

1. Classical mode description:

$$\mathbf{A}(\mathbf{r}, t) = \frac{1}{(2\pi)^2} \int d^2\mathbf{K} \alpha_{\mathbf{K}} \mathbf{u}_{\mathbf{K}}(\mathbf{r}) \exp(-i\omega t) + \text{c.c.}$$

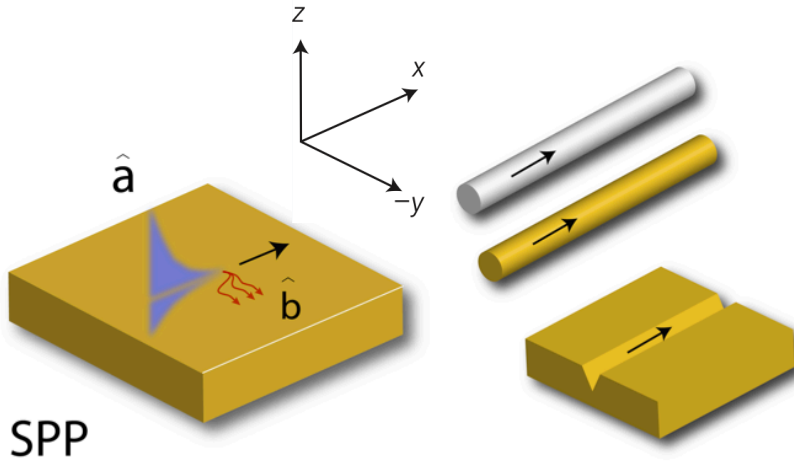
$$\mathbf{u}_{\mathbf{K}}(\mathbf{r}) = \frac{1}{\sqrt{L(\omega)}} \exp(-\kappa_j z) (\hat{\mathbf{K}} - i \frac{K}{\kappa_j} \hat{\mathbf{z}}) \exp(i\mathbf{K} \cdot \mathbf{r})$$

$$K = \frac{\omega}{c} \sqrt{\frac{\varepsilon(\omega)}{\varepsilon(\omega)+1}} \quad \kappa_j^2 = K^2 - \varepsilon_j \omega^2 / c^2$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \quad \mathbf{B} = \nabla \times \mathbf{A}$$

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$$A(\mathbf{r}, t) = \frac{1}{(2\pi)^2} \int d^2\mathbf{K} \alpha_{\mathbf{K}} \mathbf{u}_{\mathbf{K}}(\mathbf{r}) \exp(-i\omega t) + \text{c.c.}$$

$$\mathbf{u}_{\mathbf{K}}(\mathbf{r}) = \frac{1}{\sqrt{L(\omega)}} \exp(-\kappa_j z) (\hat{\mathbf{K}} - i \frac{\kappa_j}{K} \hat{\mathbf{z}}) \exp(i\mathbf{K} \cdot \mathbf{r})$$

2. Discretization of classical modes:

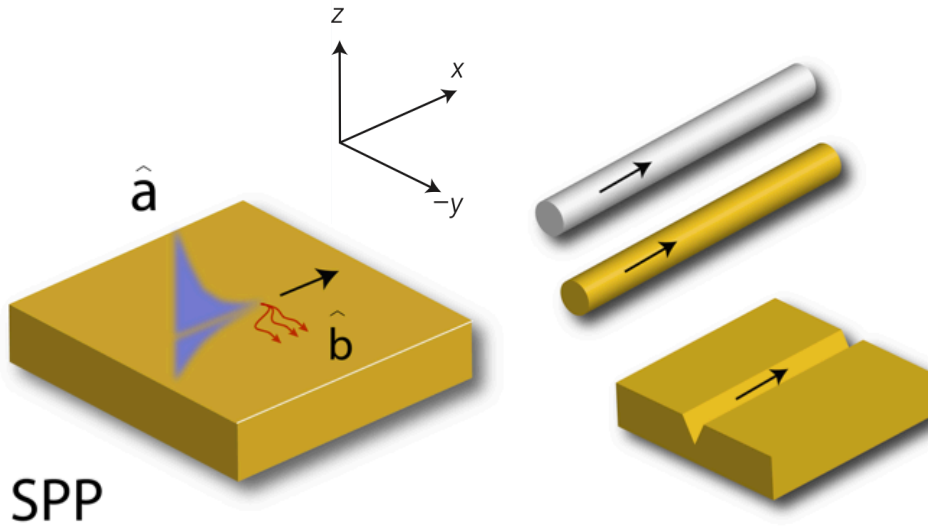
$$S = L_x \times L_y \quad K_x = n_x 2\pi / L_x \quad \frac{1}{(2\pi)^2} \int d^2\mathbf{K} \rightarrow \frac{1}{S} \sum_{\mathbf{K}}$$

$$\alpha_{\mathbf{K}} \rightarrow S A_{\mathbf{K}} \quad K_y = n_y 2\pi / L_y$$

$$U = \int dt \int d\mathbf{r} \left(\mathbf{E} \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \frac{\partial \mathbf{B}}{\partial t} \right) = \sum_{\mathbf{K}} \epsilon_0 \omega^2 S [A_{\mathbf{K}} A_{\mathbf{K}}^* + A_{\mathbf{K}}^* A_{\mathbf{K}}]$$

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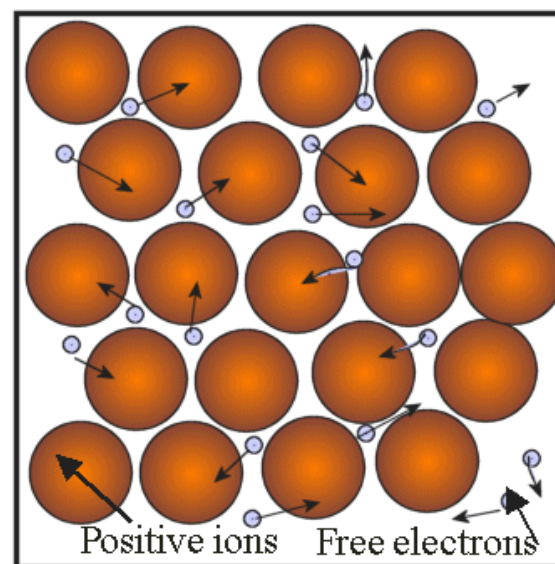
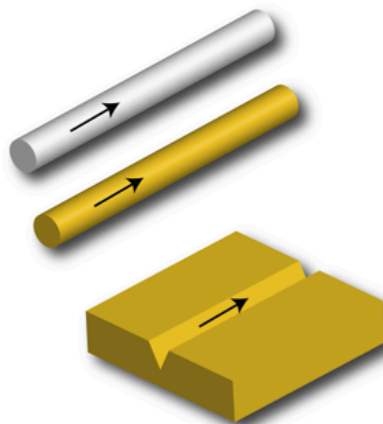
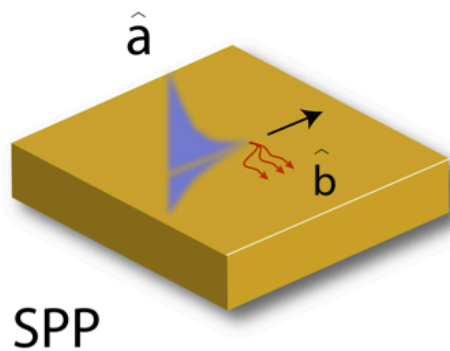
$$U = \int dt \int d\mathbf{r} \left(\mathbf{E} \frac{\partial \mathbf{D}}{\partial t} + \mathbf{H} \frac{\partial \mathbf{B}}{\partial t} \right) = \sum_K \varepsilon_0 \omega^2 S [A_K A_K^* + A_K^* A_K]$$

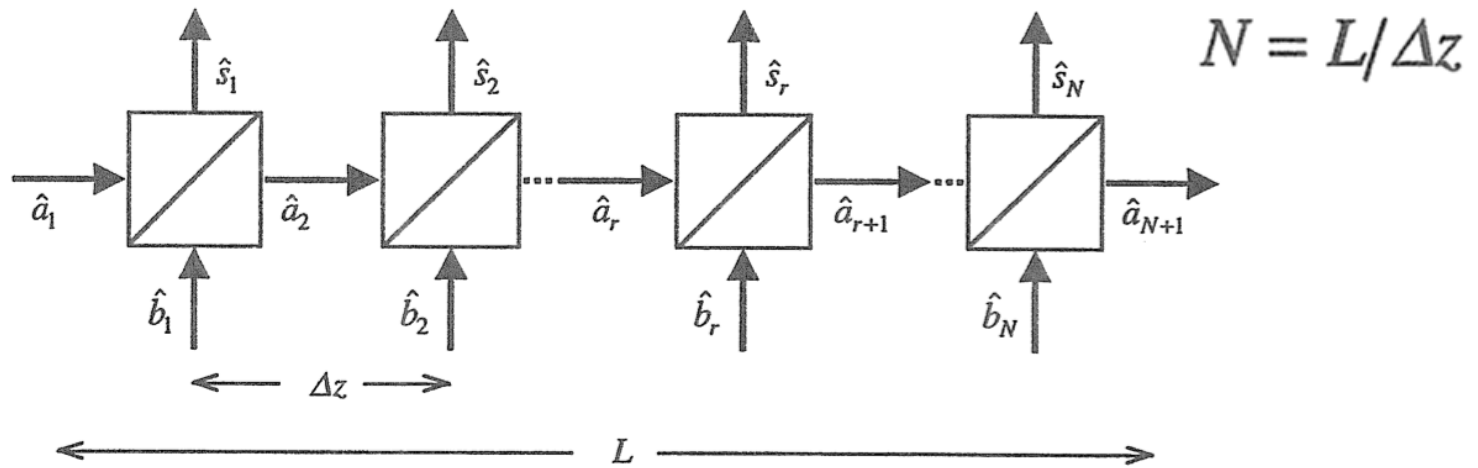
3. Quantization via correspondence principle:

$$\hat{H} = \sum_K \frac{\hbar \omega_K}{2} [\hat{a}_K \hat{a}_K^\dagger + \hat{a}_K^\dagger \hat{a}_K] \quad A_K \rightarrow \sqrt{\frac{\hbar}{2\varepsilon_0 \omega S}} \hat{a}_K \quad [\hat{a}_K, \hat{a}_{K'}^\dagger] = \delta_{K,K'} \quad |1_K\rangle = \hat{a}_K^\dagger |\text{vac}\rangle$$

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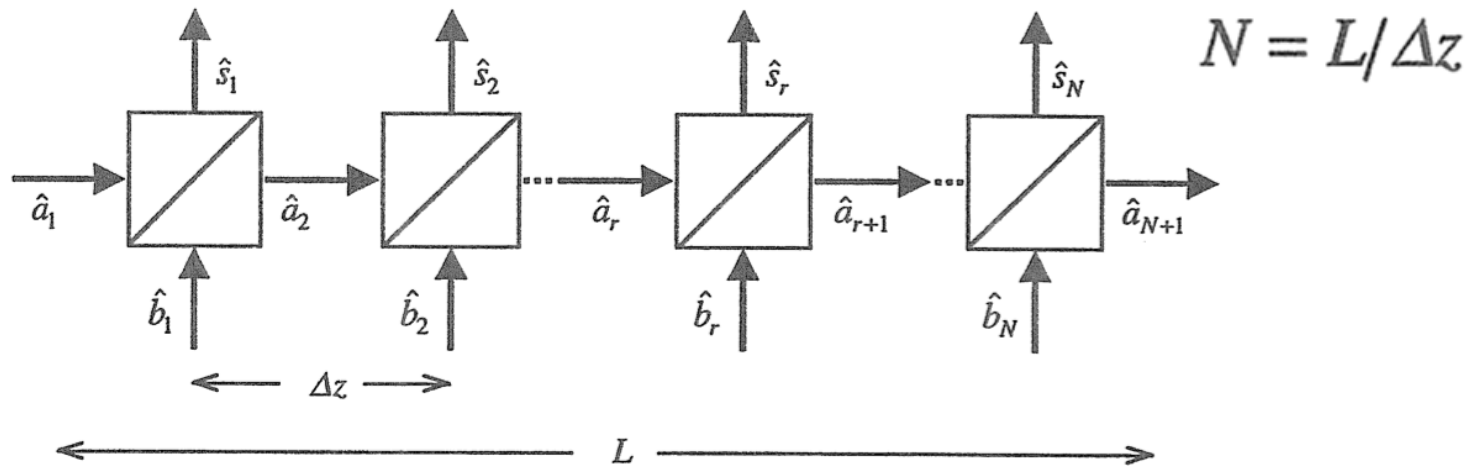
Loudon, Quantum Theory of Light (2000)

$$\hat{s}_r(\omega) = \mathcal{R}(\omega)\hat{a}_r(\omega) + \mathcal{T}(\omega)\hat{b}_r(\omega)$$

$$\hat{a}_{r+1}(\omega) = \mathcal{T}(\omega)\hat{a}_r(\omega) + \mathcal{R}(\omega)\hat{b}_r(\omega)$$

$$[\hat{a}_r(\omega), \hat{a}_r^\dagger(\omega')] = [\hat{a}_{r+1}(\omega), \hat{a}_{r+1}^\dagger(\omega')] = [\hat{s}_r(\omega), \hat{s}_r^\dagger(\omega')] = \delta(\omega - \omega') \quad [\hat{b}_q(\omega), \hat{b}_r^\dagger(\omega')] = \delta_{qr}\delta(\omega - \omega')$$

$$\hat{a}_{N+1}(\omega) = [\mathcal{T}(\omega)]^N \hat{a}_1(\omega) + \mathcal{R}(\omega) \sum_{r=1}^N [\mathcal{T}(\omega)]^{N-r} \hat{b}_r(\omega)$$

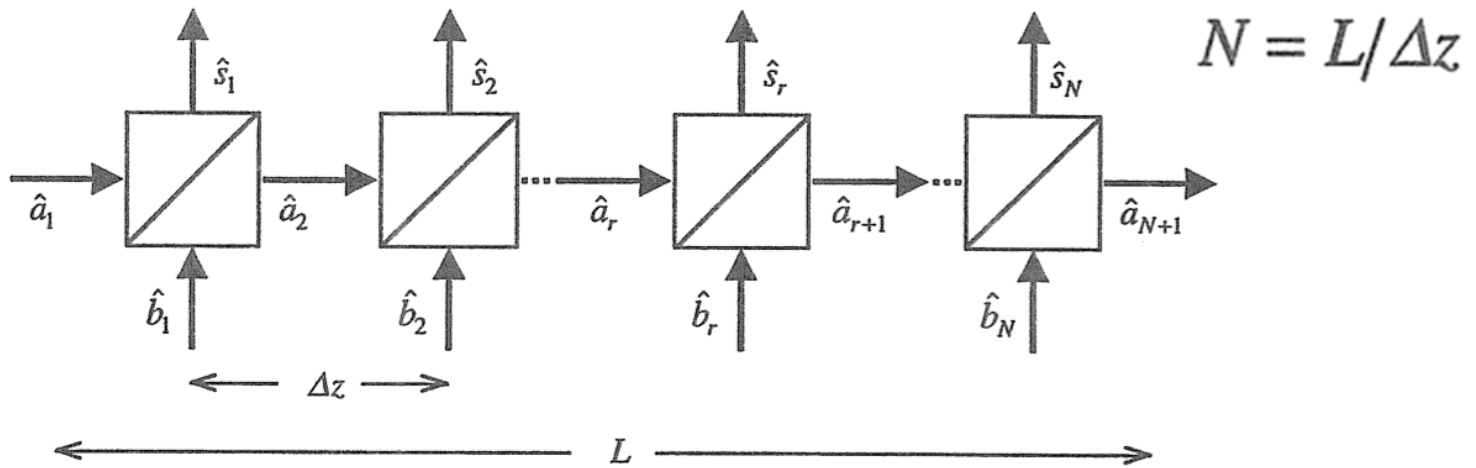


$$\hat{a}_{N+1}(\omega) = [\mathcal{T}(\omega)]^N \hat{a}_1(\omega) + \mathcal{R}(\omega) \sum_{r=1}^N [\mathcal{T}(\omega)]^{N-r} \hat{b}_r(\omega)$$

$$\boxed{\varepsilon(\omega) \rightarrow \eta(\omega) K(\omega)} \quad \text{medium}$$

$$N \rightarrow \infty, \quad \Delta z \rightarrow 0 \quad \text{and} \quad |\mathcal{R}(\omega)|^2 \rightarrow 0 \quad K(\omega) = |\mathcal{R}(\omega)|^2 / \Delta z$$

$$[\mathcal{T}(\omega)]^N = \exp\left\{\left[i\eta(\omega)(\omega/c) - \frac{1}{2}K(\omega)\right]L\right\} \quad \hat{b}_r(\omega) \rightarrow (\Delta z)^{1/2} \hat{b}(z, \omega)$$



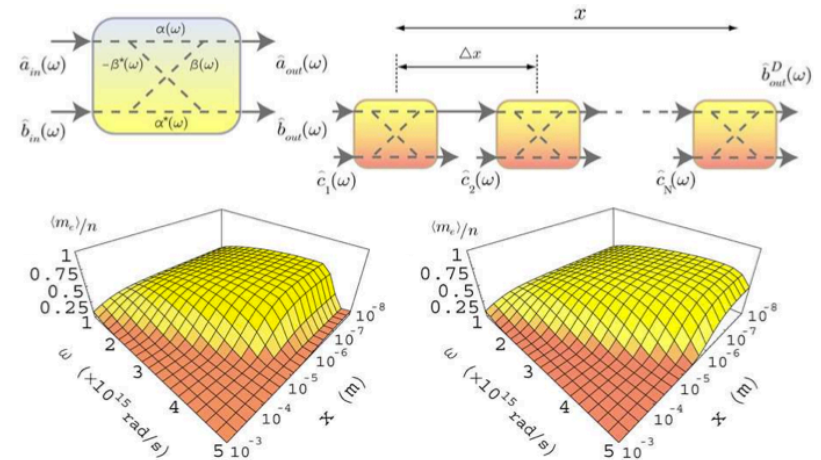
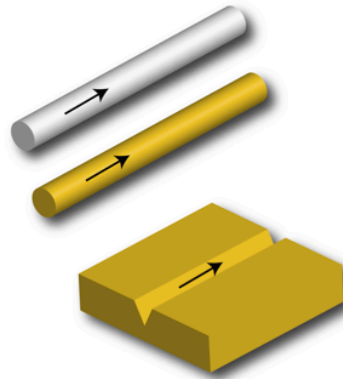
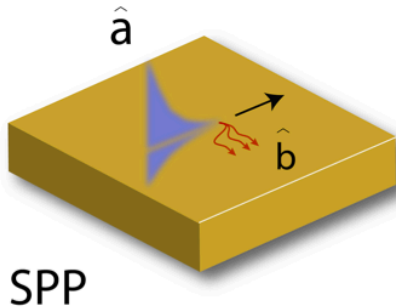
$$\sum_{r=1}^N \rightarrow \frac{1}{\Delta z} \int_0^L dz$$

$$\hat{a}_L(\omega) = \exp\left\{\left[i\eta(\omega)(\omega/c) - \frac{1}{2}K(\omega)\right]L\right\}\hat{a}_0(\omega)$$

$$+ i\sqrt{K(\omega)} \int_0^L dz \exp\left\{\left[i\eta(\omega)(\omega/c) - \frac{1}{2}K(\omega)\right](L-z)\right\}\hat{b}(z, \omega)$$

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Tame et al., Phys. Rev. Lett. 101, 190504 (2008)

$$\hat{a}_L(\omega) = \exp\left\{\left[i\eta(\omega)(\omega/c) - \frac{1}{2}K(\omega)\right]L\right\}\hat{a}_0(\omega) + i\sqrt{K(\omega)}\int_0^L dz \exp\left\{\left[i\eta(\omega)(\omega/c) - \frac{1}{2}K(\omega)\right](L-z)\right\}\hat{b}(z,\omega)$$

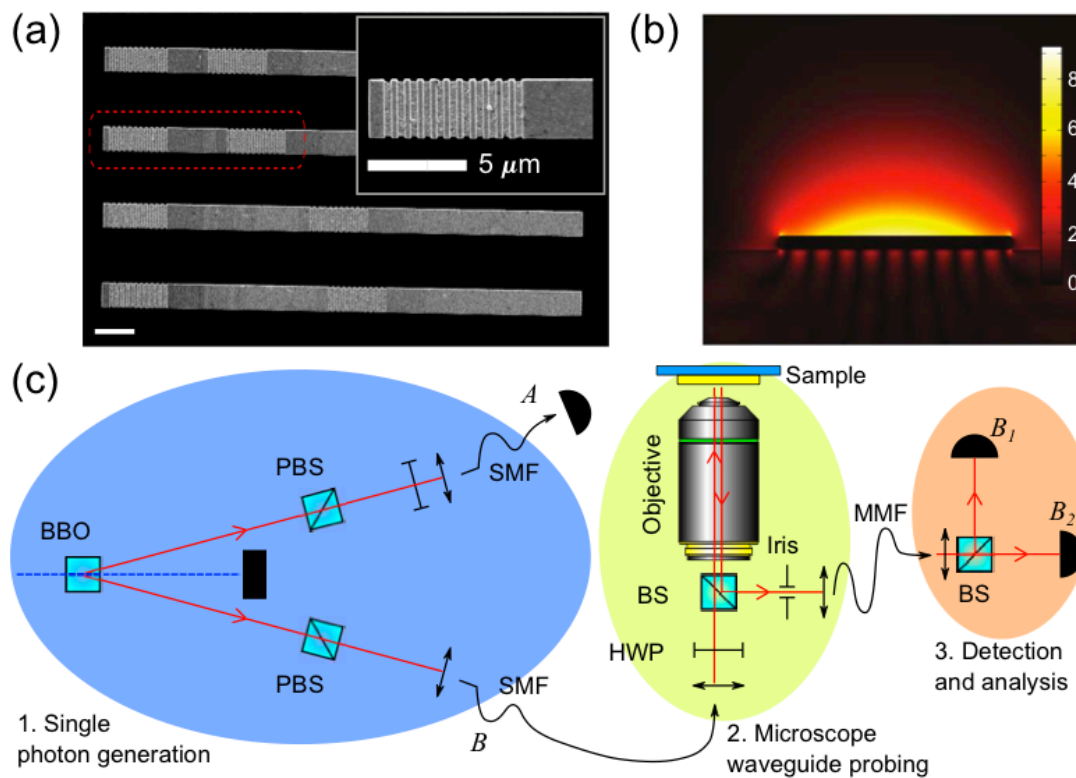
$$\langle m \rangle = ne^{-2K(\omega_0)z}$$

3

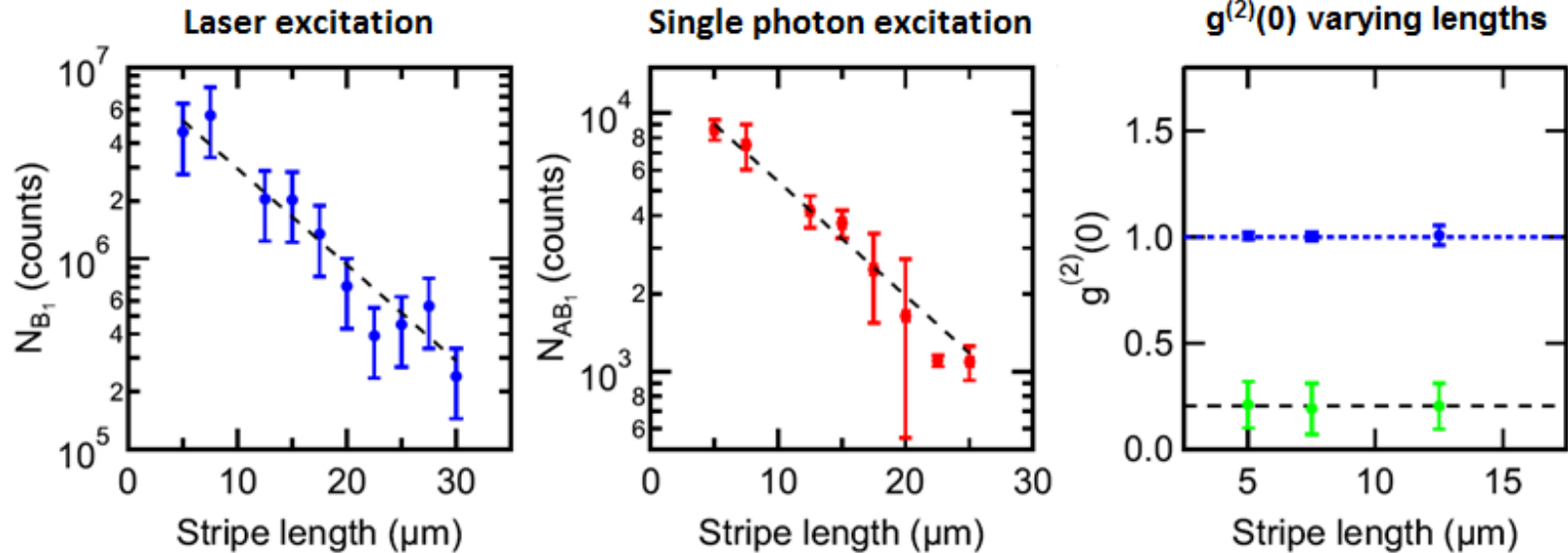
Quantization

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Metal stripe



Di Martino et al., Nano Lett. 12, 2504 (2012)



- $g^{(2)}(0)$ remains unchanged for different lengths

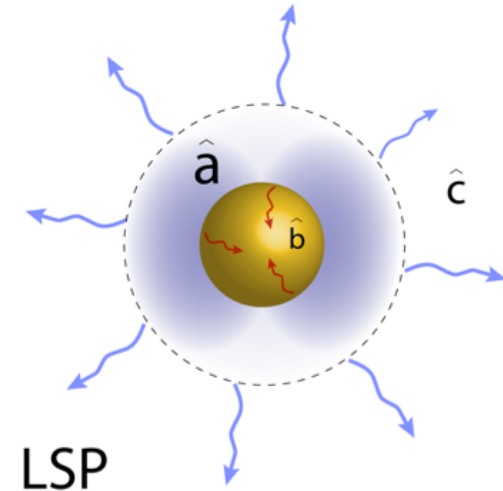
$$g^{(2)}(0) = \langle m(m-1) \rangle / \langle m \rangle^2$$

- Consistent with a linear loss model:

$$\text{loss coefficient } \eta^{1/2} = e^{-K(\omega_0)z} \quad \langle m \rangle \rightarrow \eta \langle m \rangle \quad \langle m(m-1) \rangle \rightarrow \eta^2 \langle m(m-1) \rangle$$

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Quantization

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$$\mathbf{A}(\mathbf{r}, t) = \sum_i \alpha_i \mathbf{u}_i(\mathbf{r}) \sin(\omega_0 t)$$

$$\mathbf{u}_i(\mathbf{r}) = \hat{\mathbf{i}} \quad r < R$$

$$\mathbf{u}_i(\mathbf{r}) = -\frac{R^3}{r^3} [3(\hat{\mathbf{i}} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \hat{\mathbf{i}}] \quad r > R$$

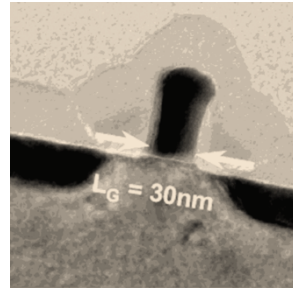
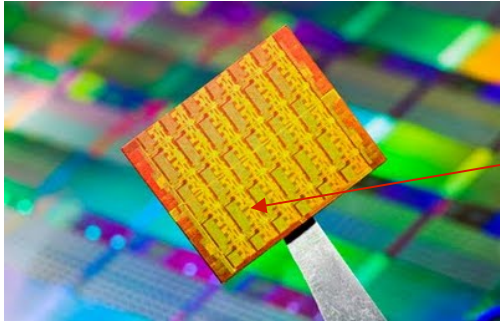
$$(i = x, y, z)$$

Waks and Sridharan, Phys. Rev. A 82, 043845 (2010)

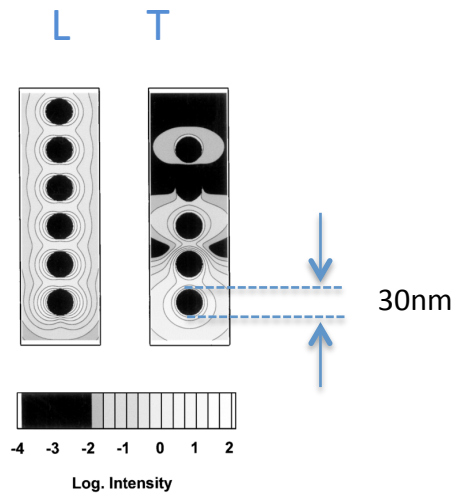
$$|1\rangle = \hat{a}^\dagger |\text{vac}\rangle$$

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Intel Labs 'Single-chip Cloud Computer' (2013)



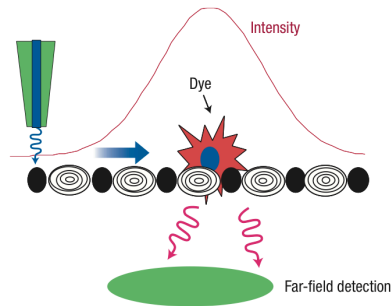
$\begin{array}{c} \leftarrow L \\ \rightarrow L \\ \vdots \\ \downarrow T \\ \uparrow T \end{array} \quad \eta = 8/9$	$\begin{array}{c} \leftarrow T \\ \rightarrow T \\ \vdots \\ \downarrow L \\ \uparrow L \end{array} \quad \eta = 8/9$	$\begin{array}{c} \leftarrow T \\ \rightarrow T \\ \vdots \\ \downarrow T \\ \uparrow T \end{array} \quad \eta = 1$
$\begin{array}{c} \leftarrow L \\ \rightarrow L \\ \vdots \\ \downarrow T \\ \uparrow T \end{array} \quad \eta = 1/2$	$\begin{array}{c} \leftarrow T \\ \rightarrow T \\ \vdots \\ \downarrow L \\ \uparrow L \end{array} \quad \eta = 8/25$	$\begin{array}{c} \leftarrow T \\ \rightarrow T \\ \vdots \\ \downarrow T \\ \uparrow T \end{array} \quad \eta = 4/9$
$\begin{array}{c} \leftarrow L \\ \rightarrow L \\ \vdots \\ \downarrow T \\ \uparrow T \end{array} \quad \eta = 16/25$	$\begin{array}{c} \leftarrow T \\ \rightarrow T \\ \vdots \\ \downarrow L \\ \uparrow L \end{array} \quad \eta = 1/4$	$\begin{array}{c} \leftarrow T \\ \rightarrow T \\ \vdots \\ \downarrow T \\ \uparrow T \end{array} \quad \eta = 4/9$

Brongersma et al., Phys. Rev. B 62, R16356 (2000)

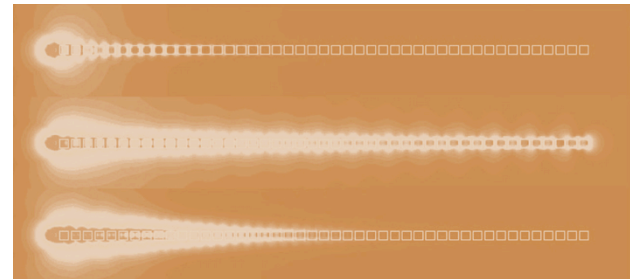
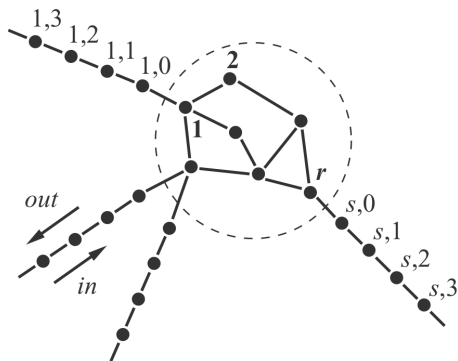
Quinten et al., Opt. Lett. 23, 1331 (1998)

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



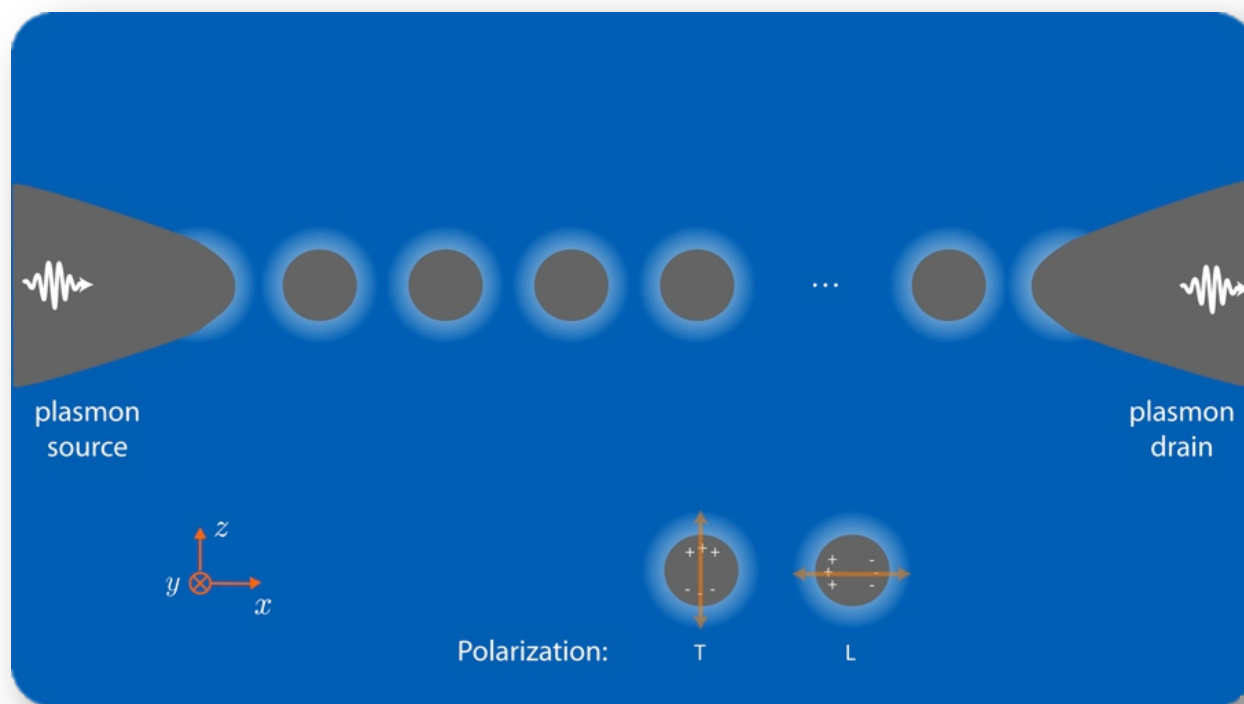
Maier, IEEE J. Sel. Top. Quant. Elec. 12, 1214 & 1671 (2006)

Alù and Engheta, Phys. Rev. B 74, 205436 (2006)

Yurke and Kuang, Phys. Rev. A 81, 033814 (2010)

3

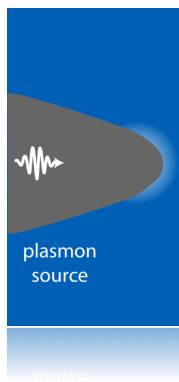
Quantization

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Lee, Tame, Lim and Lee, Phys. Rev. A 85, 063823 (2012)

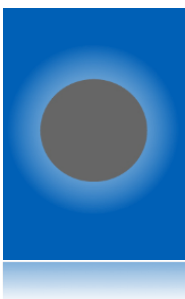
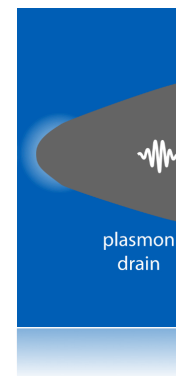
3

Quantization

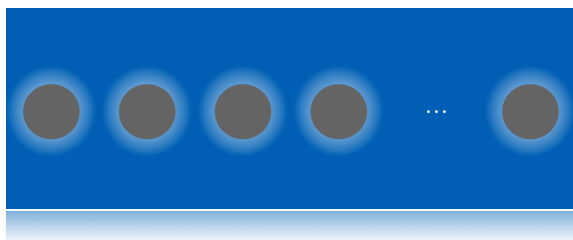
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$$\hat{H}_s = \int_{-\infty}^{\infty} d\omega \hbar \omega \hat{s}^\dagger(\omega) \hat{s}(\omega)$$

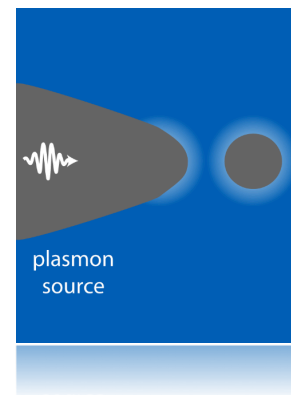
$$\hat{H}_d = \int_{-\infty}^{\infty} d\omega \hbar \omega \hat{d}^\dagger(\omega) \hat{d}(\omega)$$



$$\sum_{i=1}^n \hbar \omega_i \hat{a}_i^\dagger \hat{a}_i$$



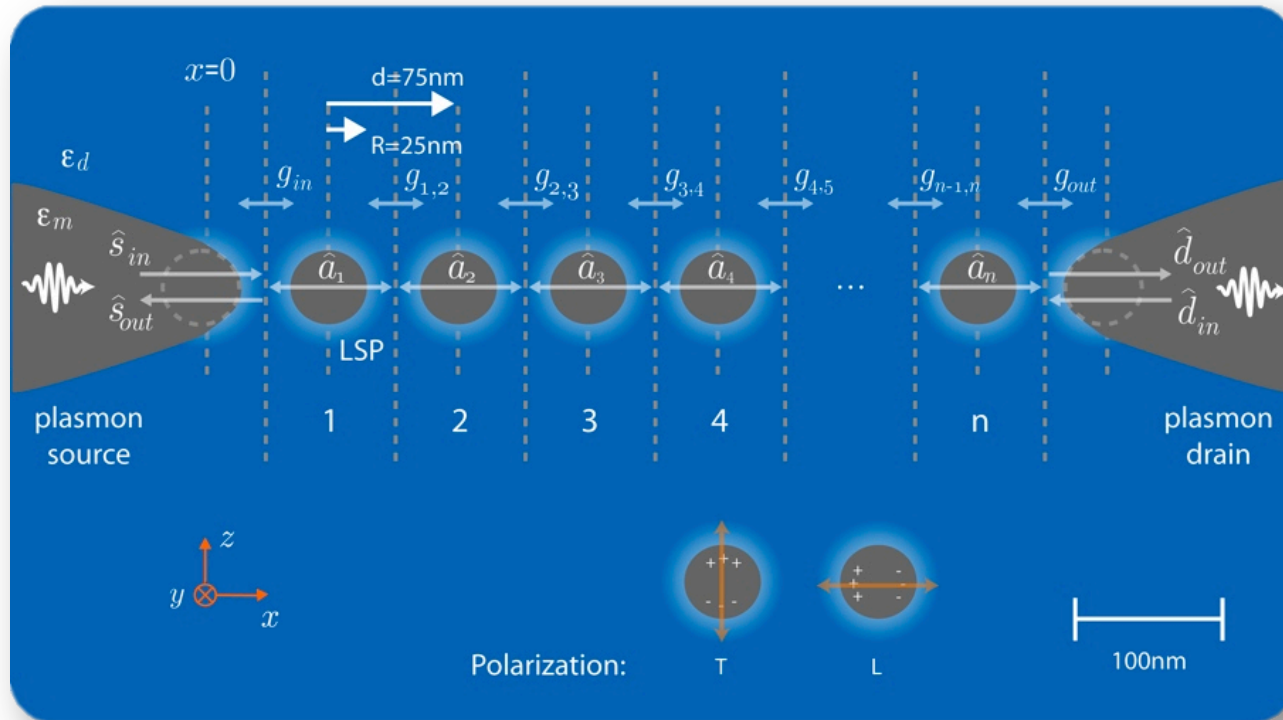
$$\sum_{[i,j]} \hbar g_{i,j} (\hat{a}_i^\dagger \hat{a}_j + \hat{a}_j^\dagger \hat{a}_i)$$



$$\hat{H}_{np,s} = i\hbar \int_{-\infty}^{\infty} d\omega g_{\text{in}}(\omega) [\hat{a}_1 \hat{s}^\dagger(\omega) - \hat{s}(\omega) \hat{a}_1^\dagger]$$

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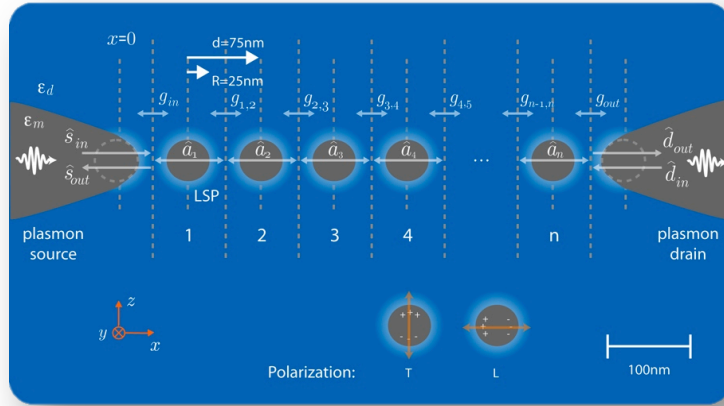
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$$\hat{H} = \hat{H}_{np} + \hat{H}_s + \hat{H}_d + \hat{H}_{np,s} + \hat{H}_{np,d}$$

$$\hat{s}_{in}^\dagger(\omega) = \mathcal{R}(\omega)\hat{s}_{out}^\dagger(\omega) + \mathcal{T}(\omega)\hat{d}_{out}^\dagger(\omega)$$

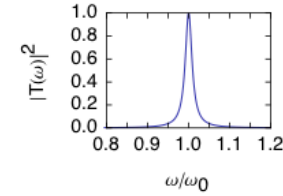
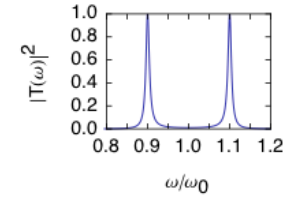
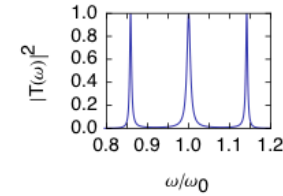
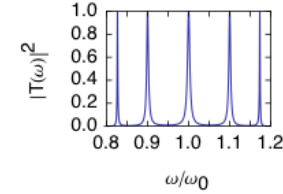
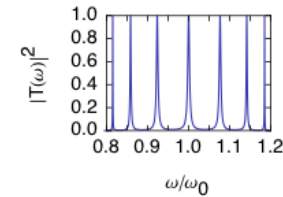
3

Quantization

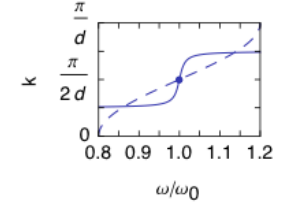
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$$|1_\xi\rangle_s = \int_{-\infty}^{\infty} d\omega \xi(\omega) \hat{s}_{in}^\dagger(\omega) |0\rangle_s$$

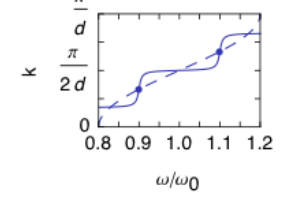
$$\int_{-\infty}^{\infty} d\omega |\xi(\omega)|^2 = 1$$

(a) $n = 1$ (b) $n = 2$ (c) $n = 3$ (d) $n = 5$ (e) $n = 7$ 

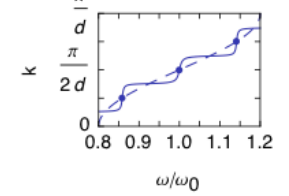
(f)



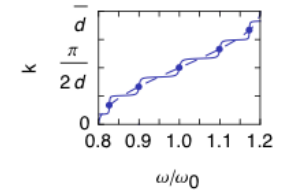
(g)



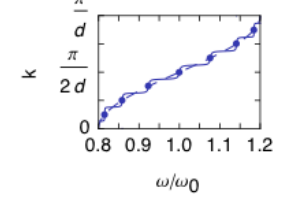
(h)



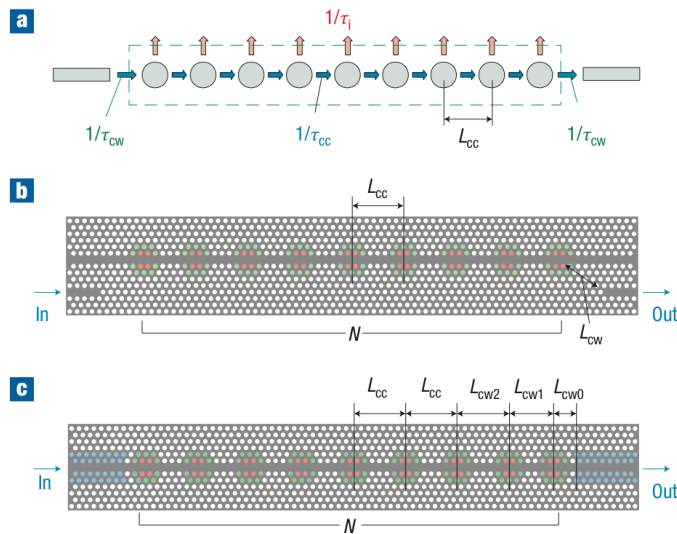
(i)



(j)

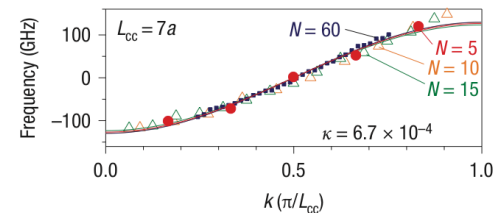
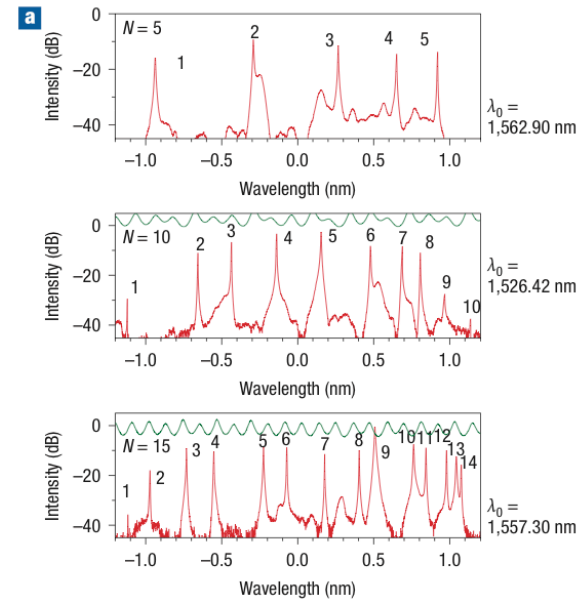


Photonic crystals



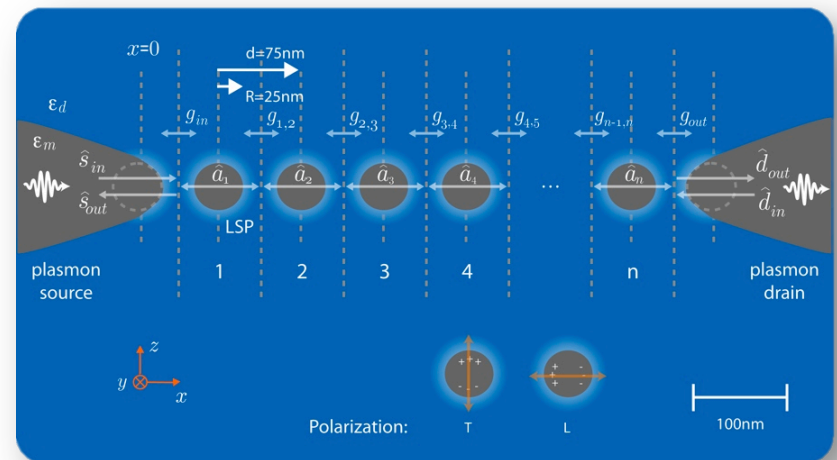
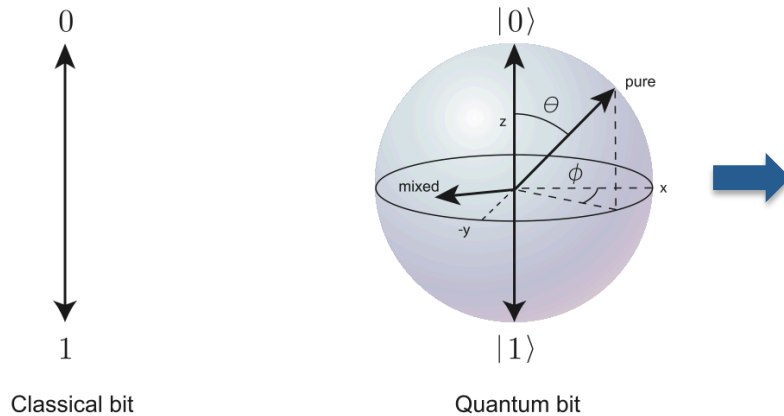
equivalent plasmonic array size: Γ

Yariv et al., Opt. Lett. 24, 711 (1999)
 Bayindir et al., Phys. Rev. Lett. 84, 2140 (2000)
 Notomi et al., Nature Photonics 2, 741 (2008)



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$$|\psi\rangle_s = a |0\rangle_s + b |1_\xi\rangle_s$$

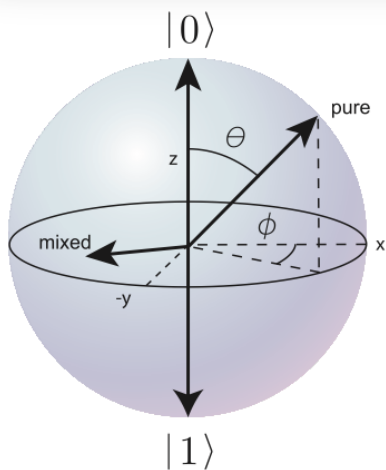
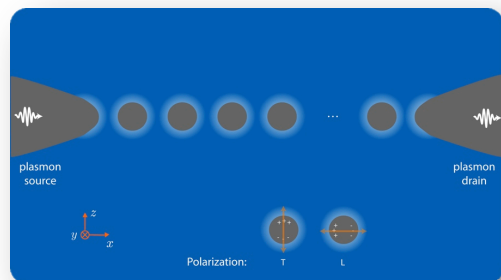
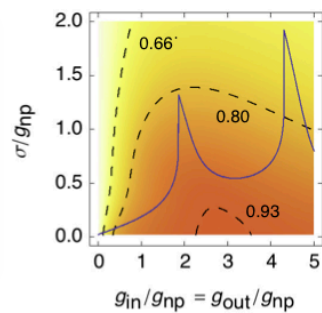
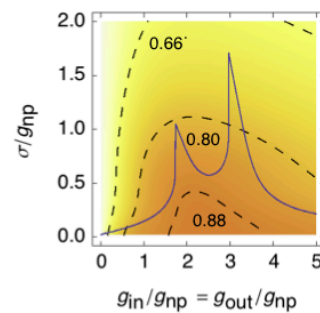
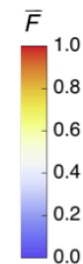
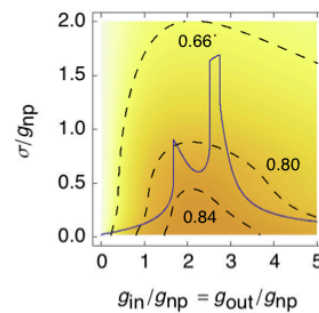
Pegg et al., Phys. Rev. Lett. 81, 1604 (1998)

Resch et al., Phys. Rev. Lett. 88, 113601 (2002)

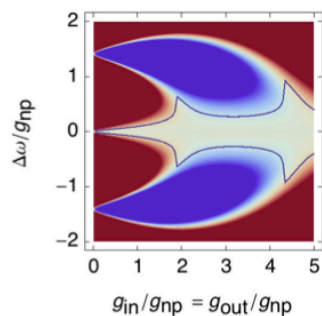
$$|\psi\rangle_s = a |0\rangle_s + b \int_{-\infty}^{\infty} d\omega \xi(\omega) \hat{s}_{in}^\dagger(\omega) |0\rangle_s$$

3

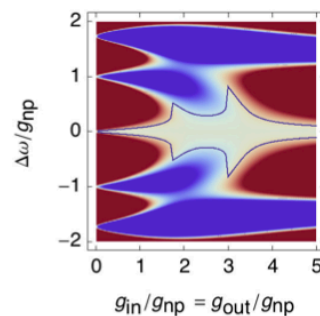
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methods(a) $n = 3$ (c) $n = 5$ (e) $n = 7$ 

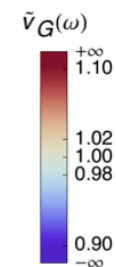
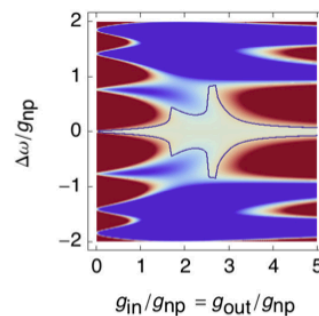
(b)



(d)



(f)

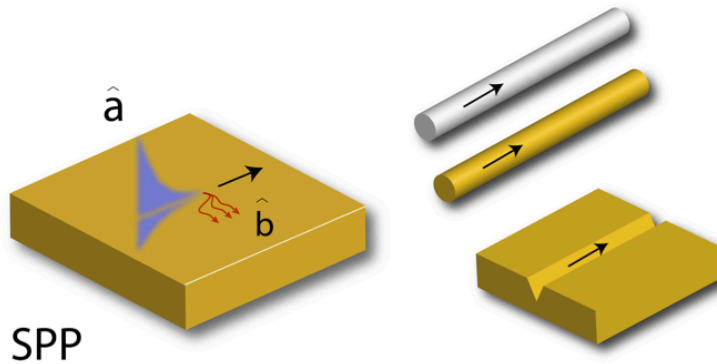


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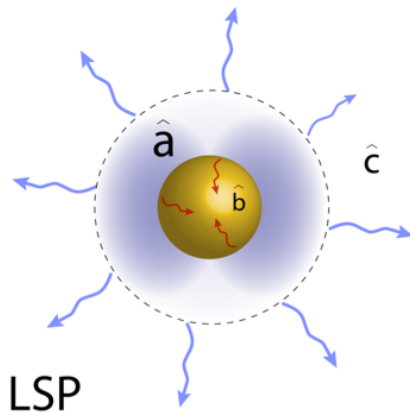


microscopic

Huttner and Barnett, PRA 46, 4306 (1992)

macroscopic

Philbin, NJP 12, 123008 (2010)



Dung et al., PRA 57, 3931 (1998)

Trugler and Hohenester, PRB 77, 115403 (2008)

4

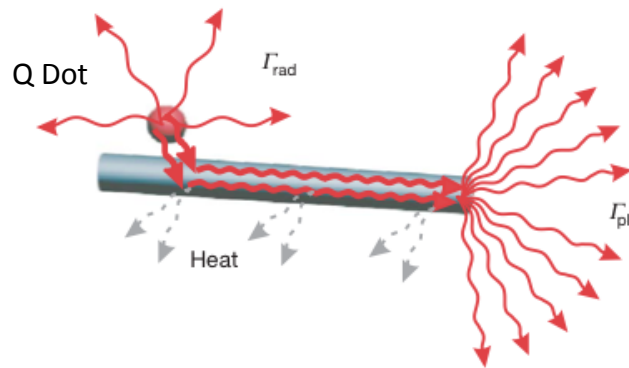
Light-matter
interactions

Waveguides

Nanoparticles

Enhancement of light-matter interaction

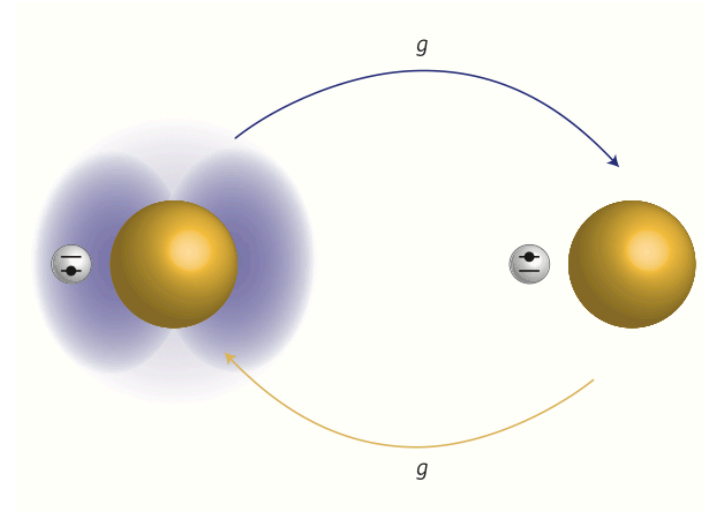
$$H = \hbar\omega_0 b^\dagger b + \frac{\hbar\omega_a}{2} \sigma_z + \hbar(gb\sigma_+ + g^*b^\dagger\sigma_-)$$



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

waveguide

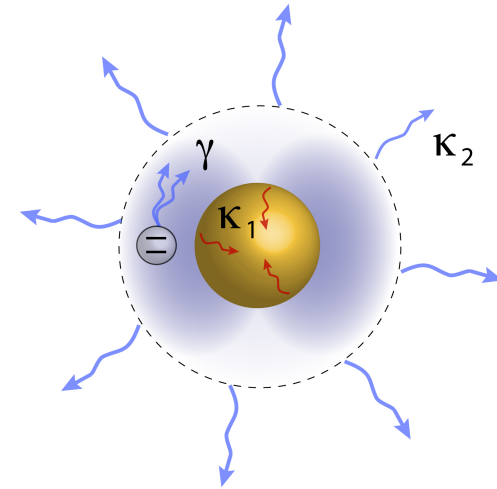
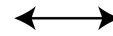
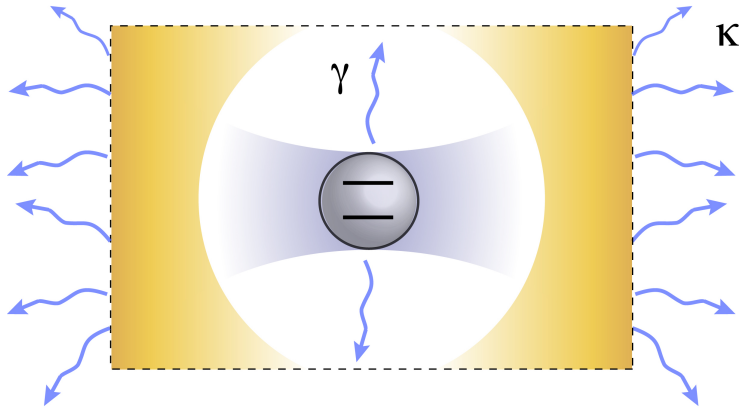
$$g \propto 1/\sqrt{A_{\text{eff}}} \propto 1/d$$



Waks and Sridharan, PRA 82, 043845 (2010)

nanoparticle

$$g \propto 1/d^3$$



$$\hat{H} = \hat{H}_0 + \hat{H}_{\text{int}} + \hat{H}_{\text{drive}}$$

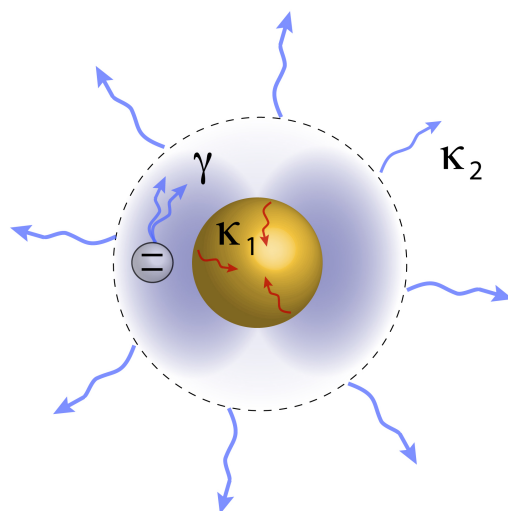
$$\hat{H}_0 = \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar\omega_x \hat{\sigma}^\dagger \hat{\sigma}$$

$$\hat{H}_{\text{int}} = i\hbar g(\hat{\sigma} \hat{a}^\dagger - \hat{\sigma}^\dagger \hat{a})$$

$$\begin{aligned} \hat{H}_{\text{drive}} = & -E_0\mu(\hat{\sigma} e^{-i\omega t} + \hat{\sigma}^\dagger e^{i\omega t}) \\ & - E_0(\chi^* \hat{a} e^{-i\omega t} + \chi \hat{a}^\dagger e^{i\omega t}) \end{aligned}$$

$$g = \frac{S\mu}{d^3} \sqrt{\frac{3\eta r^3}{4\pi\epsilon_0\hbar}}$$

$$\chi = -i\epsilon_b \sqrt{12\eta\epsilon_0\pi\hbar r^3}$$



$$\dot{\hat{\rho}} = \hat{\mathcal{L}}(\hat{\rho})$$

$$\hat{\mathcal{L}}(\hat{\rho}) = \frac{i}{\hbar}[\hat{\rho}, \hat{H}] + \hat{L}_0 + \hat{L}_x$$

$$\hat{L}_j = \frac{\gamma_j}{2}(2\hat{c}_j \hat{\rho} \hat{c}_j^\dagger - [\hat{c}_j^\dagger \hat{c}_j, \hat{\rho}]_+) \quad j = \{0, x\}$$

$\hat{c}_0$ ($\hat{c}_x$) represents $\hat{a}$ ($\hat{\sigma}$)

γ

κ_1

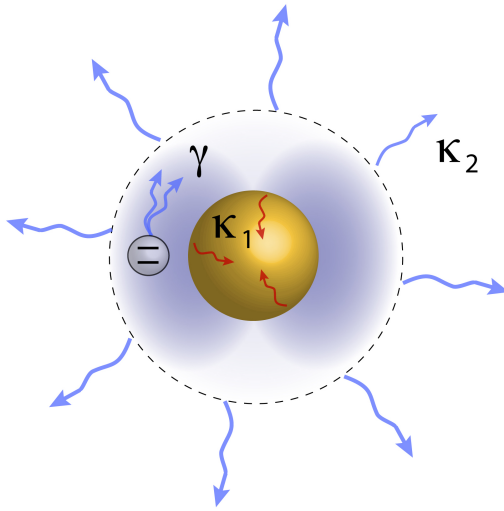
κ_2

γ_x

$$\gamma_0 = \gamma_{nr} + \gamma_r$$

$$\gamma_{nr} = \gamma + \frac{\gamma^3(2\epsilon_b + \epsilon_\infty)}{\omega_p}$$

$$\gamma_r = \frac{2k^3 \omega_0 r^3}{\epsilon_\infty + 2\epsilon_b}$$



$$\langle \dot{\hat{a}} \rangle = - \left(i \Delta_0 + \frac{\gamma_0}{2} \right) \langle \hat{a} \rangle + g \langle \hat{\sigma} \rangle + \frac{i \chi E_0}{\hbar}$$

$$\begin{aligned} \langle \dot{\hat{\sigma}} \rangle = & - \left(i \Delta_x + \frac{\gamma_x}{2} \right) \langle \hat{\sigma} \rangle - g \langle \hat{a} \rangle + 2g \langle \hat{a} \hat{\sigma}^\dagger \hat{\sigma} \rangle \\ & + \frac{i \mu E_0}{\hbar} (1 - 2 \langle \hat{\sigma}^\dagger \hat{\sigma} \rangle), \end{aligned}$$

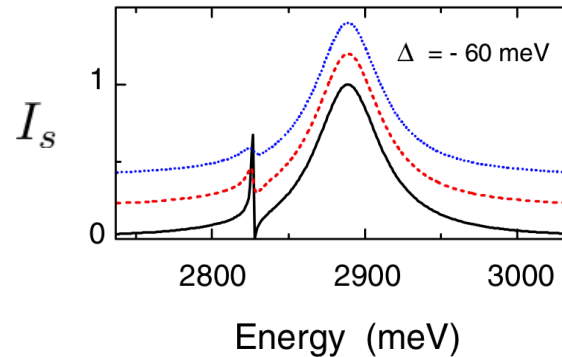
$$\Delta_{0(x)} = (\omega_{0(x)} - \omega)$$

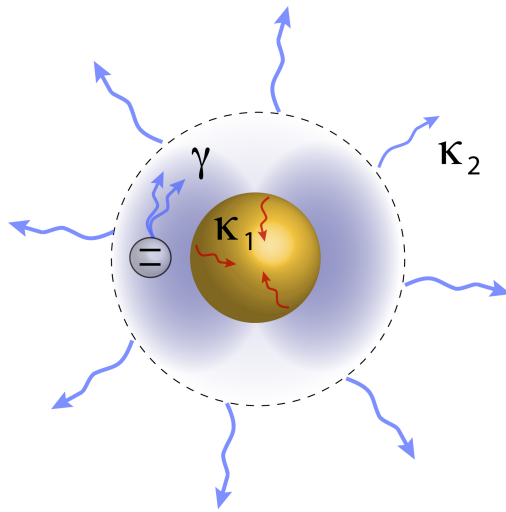
$$I_s = \langle \hat{P}^- \hat{P}^+ \rangle$$

$$\hat{P}^+ = \chi \hat{a} + \mu \hat{\sigma}$$

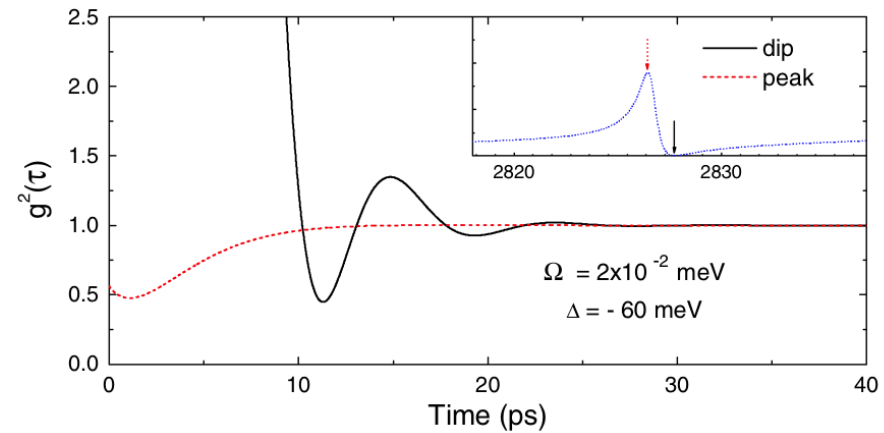
$$\hat{P}^- = (\hat{P}^+)^\dagger$$

Ridolfo et al., PRL 105, 263601 (2010)

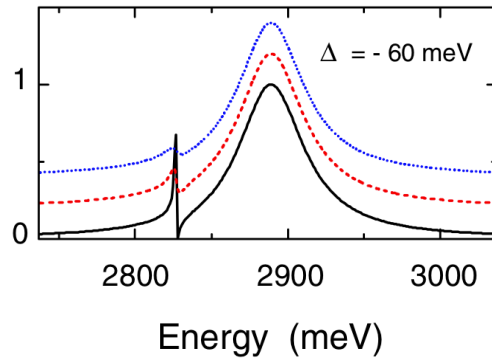




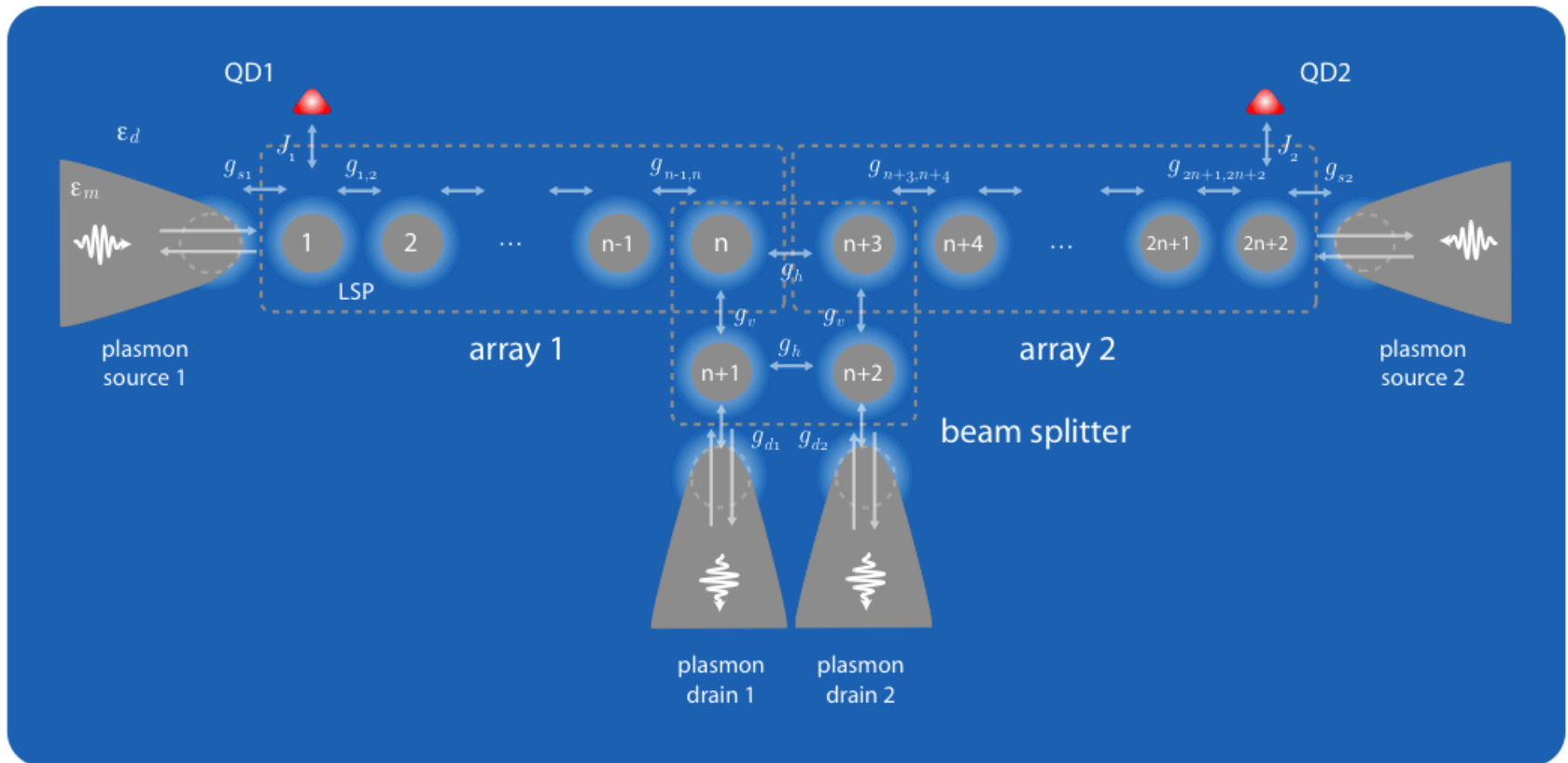
Ridolfo et al., PRL 105, 263601 (2010)



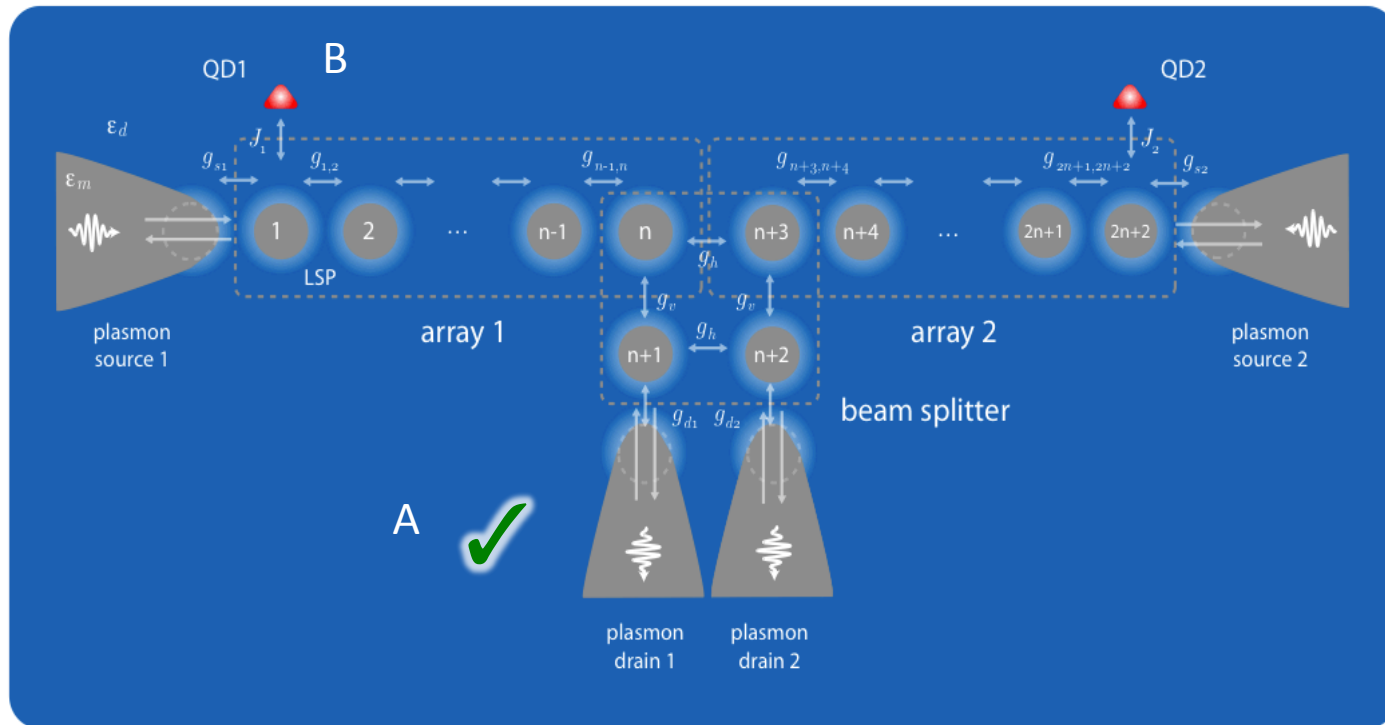
$$g^{(2)}(\tau) = \langle \hat{P}^-(t) \hat{P}^-(t+\tau) \hat{P}^+(t+\tau) \hat{P}^+(t) \rangle / |\langle \hat{P}^- \hat{P}^+ \rangle|^2$$



Entanglement generation



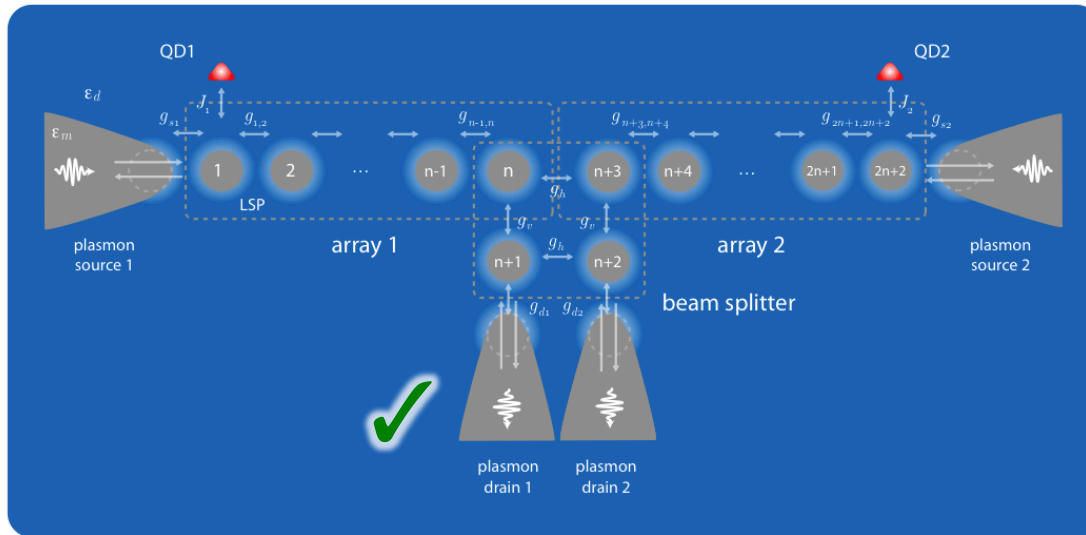
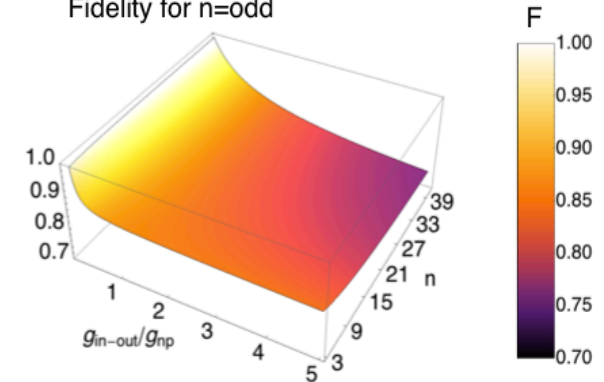
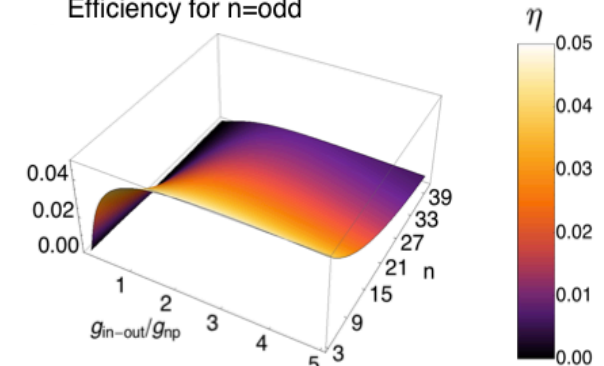
Lee et al., NJP 15, 83017 (2013)



$$1 \quad \frac{1}{\sqrt{2}}(|g\rangle_1 + |m\rangle_1) \otimes \frac{1}{\sqrt{2}}(|g\rangle_2 + |m\rangle_2)$$

$$2 \quad \cancel{|gg\rangle} \quad |gm\rangle \quad |mg\rangle \quad \cancel{|mm\rangle}$$

$$3 \quad |\Psi\rangle_{\text{QDs}} = \frac{1}{\sqrt{2}}(|mg\rangle - |gm\rangle)$$

Fidelity for $n=\text{odd}$ Efficiency for $n=\text{odd}$ 

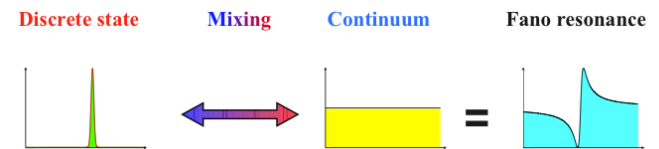
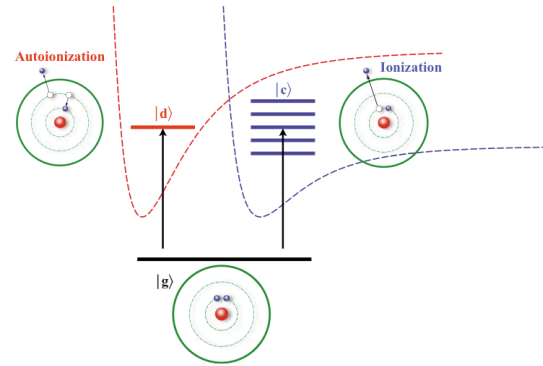
$$1 \quad \frac{1}{\sqrt{2}}(|g\rangle_1 + |m\rangle_1) \otimes \frac{1}{\sqrt{2}}(|g\rangle_2 + |m\rangle_2)$$

$$2 \quad \cancel{|gg\rangle} \quad |gm\rangle \quad |mg\rangle \quad \cancel{|mm\rangle}$$

$$3 \quad |\Psi\rangle_{\text{QDs}} = \frac{1}{\sqrt{2}}(|mg\rangle - |gm\rangle)$$

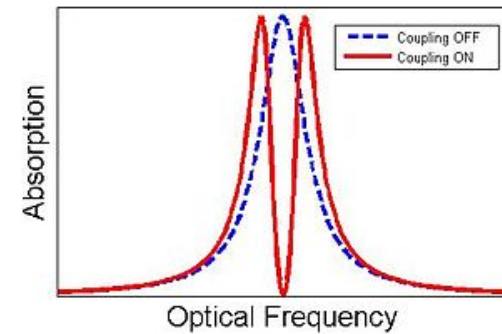
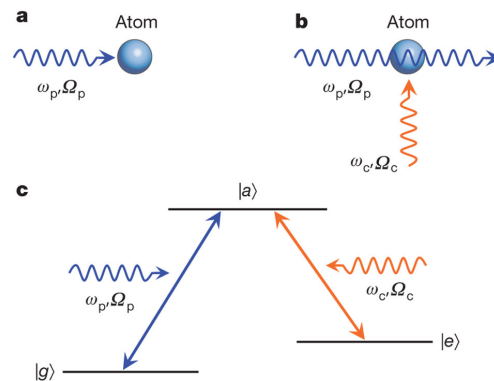
$$F = \langle \psi^- | \rho_{\text{QDs}} | \psi^- \rangle \quad C \geq \max(0, 2F - 1)$$

Fano interference:

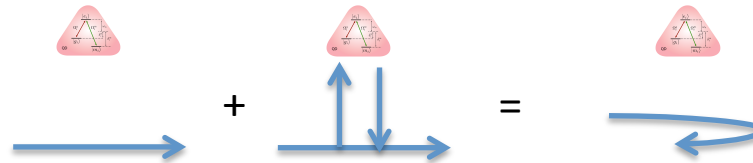
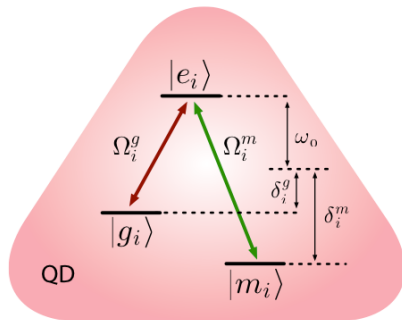
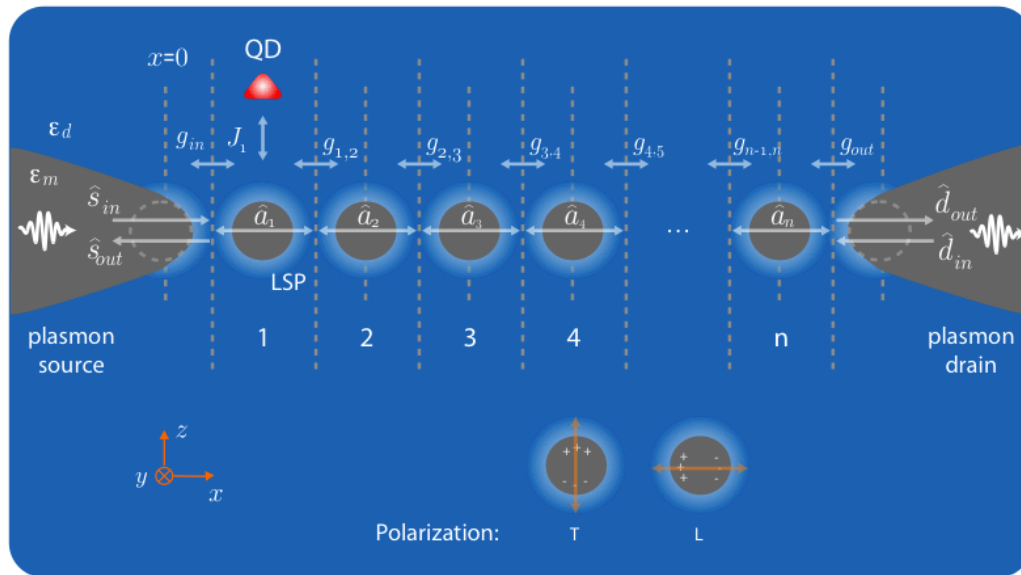


Miroshnichenko et al. RMP 82, 2257 (2010)

Electromagnetic-induced transparency:



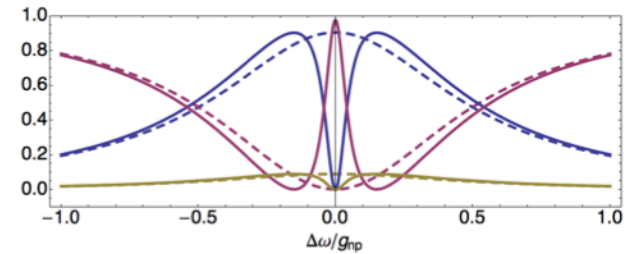
Fleischhauer et al., RMP 77, 633 (2005)



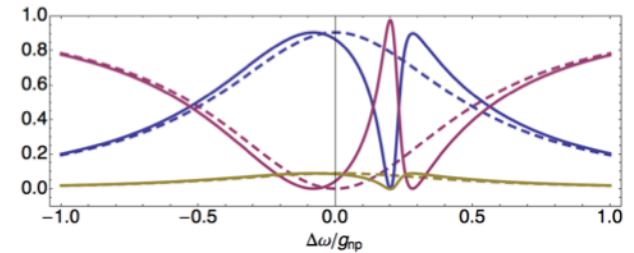
DIR

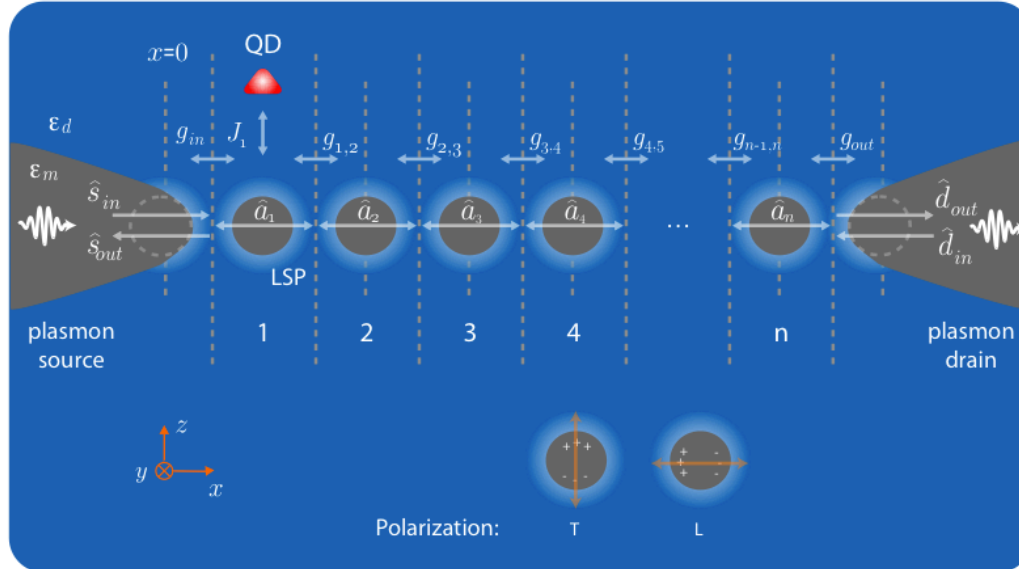
Waks and Vuckovic, PRL 96, 153601 (2006)

Transmission, Reflection, and absorption

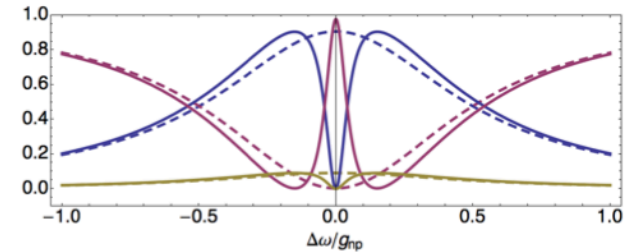


Transmission, Reflection, and absorption

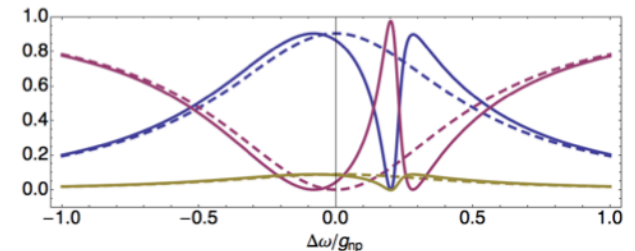

 $T_s(\omega)$ $R_s(\omega)$ $A_s(\omega)$



Transmission, Reflection, and absorption



Transmission, Reflection, and absorption



— $T_s(\omega)$ — $R_s(\omega)$ — $A_s(\omega)$

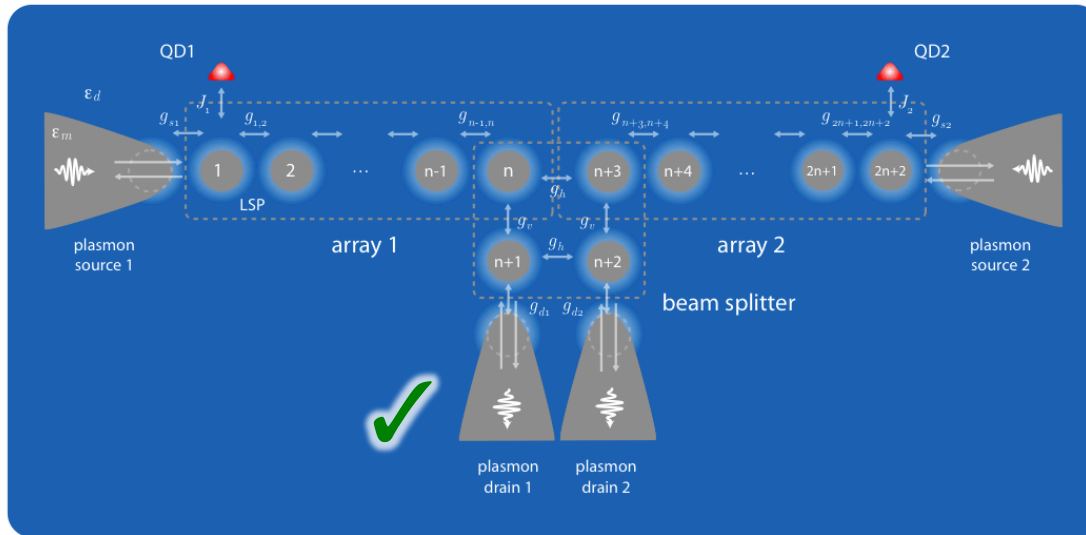
$$F_p = \frac{2J^2}{\gamma} \frac{1}{g_{in-out} + \Gamma_0/2}$$

Bad-cavity: $\gamma \ll g_{in-out} + \Gamma_0/2$
 $J \ll g_{in-out} + \Gamma_0/2$

$$t_0 = \frac{g_{in-out}}{g_{in-out} + \Gamma_0/2}$$

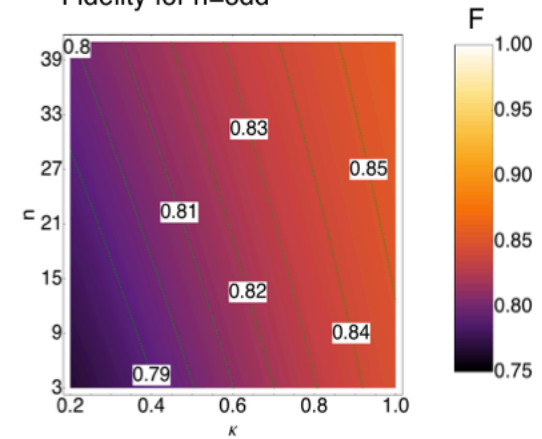
$$t_s = t_0 / (F_p + 1)$$

$$F_p \gg 1$$

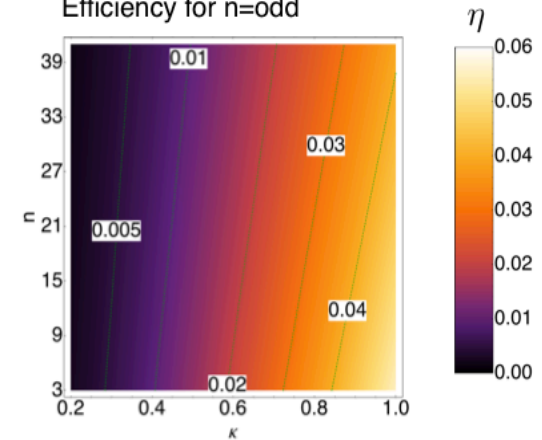


$$|\Psi\rangle_{\text{QDs}} = \frac{1}{\sqrt{2}}(|mg\rangle - |gm\rangle)$$

Fidelity for n=odd



Efficiency for n=odd



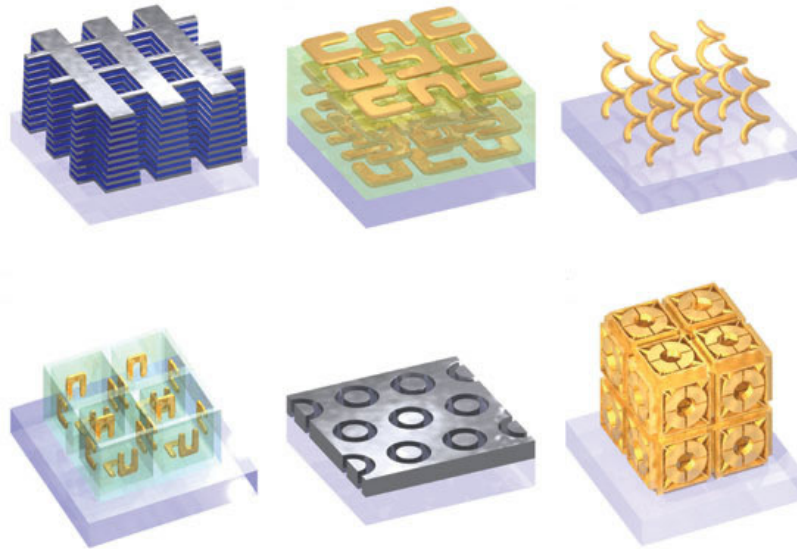


5

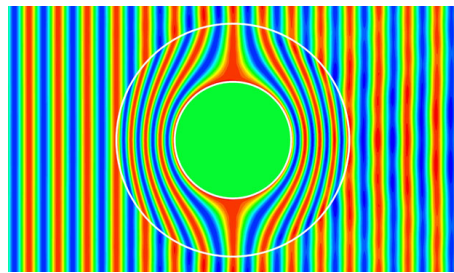
Metamaterials

Refractive
index

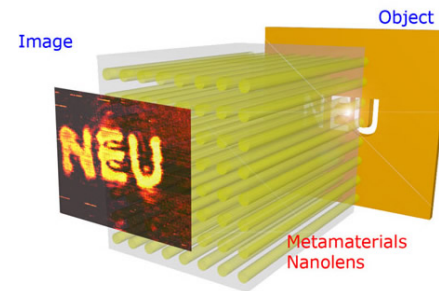
Quantum
effects



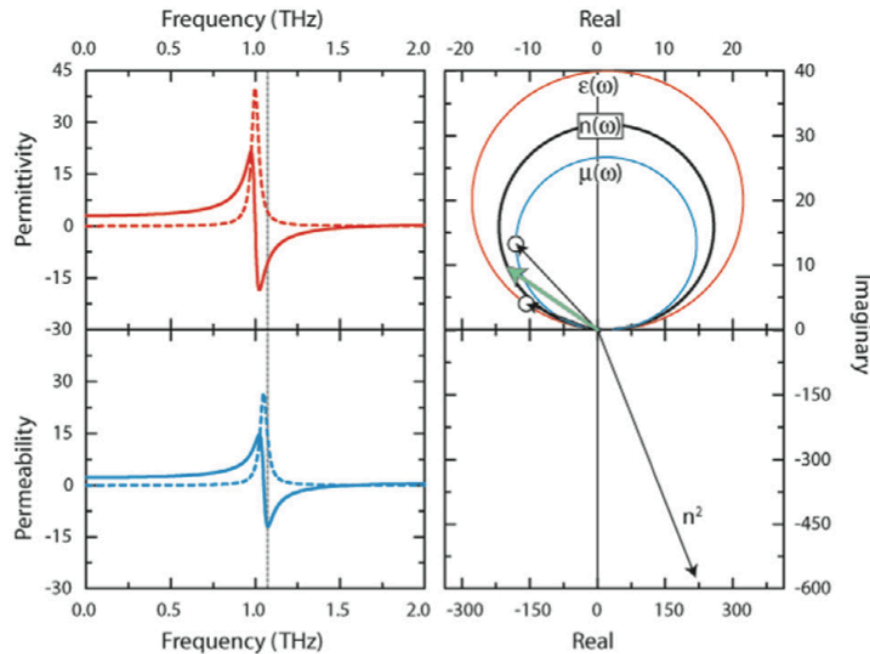
Soukoulis and Wegener, Nat. Phot. 5, 523 (2011)



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



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



$$\epsilon(\omega) = 1 - (\omega_p^2)/(\omega^2 - \omega_0^2 + i\omega\Gamma)$$

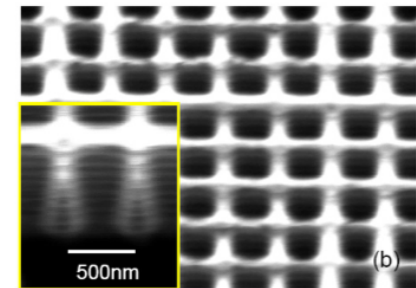
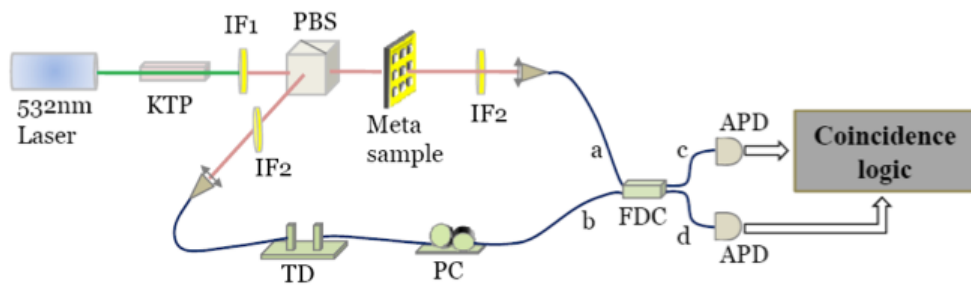
$$\mu_{eff}(\omega) = 1 + (F\omega^2)/(\omega_0^2 - \omega^2 - i\Gamma\omega)$$

$$n_{\pm} = \pm n_0 \exp i\phi_n$$

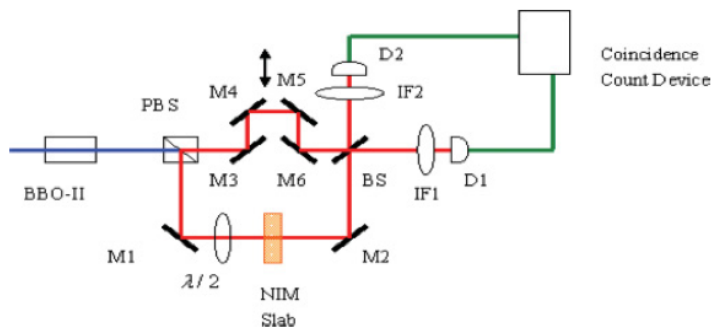
$$n_0 = +\sqrt{|\epsilon_r| |\mu_r|}$$

$$\phi_n = \frac{\phi_{\epsilon} + \phi_{\mu}}{2}$$

Padilla et al., Materials Today 9, 28 (2006)



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



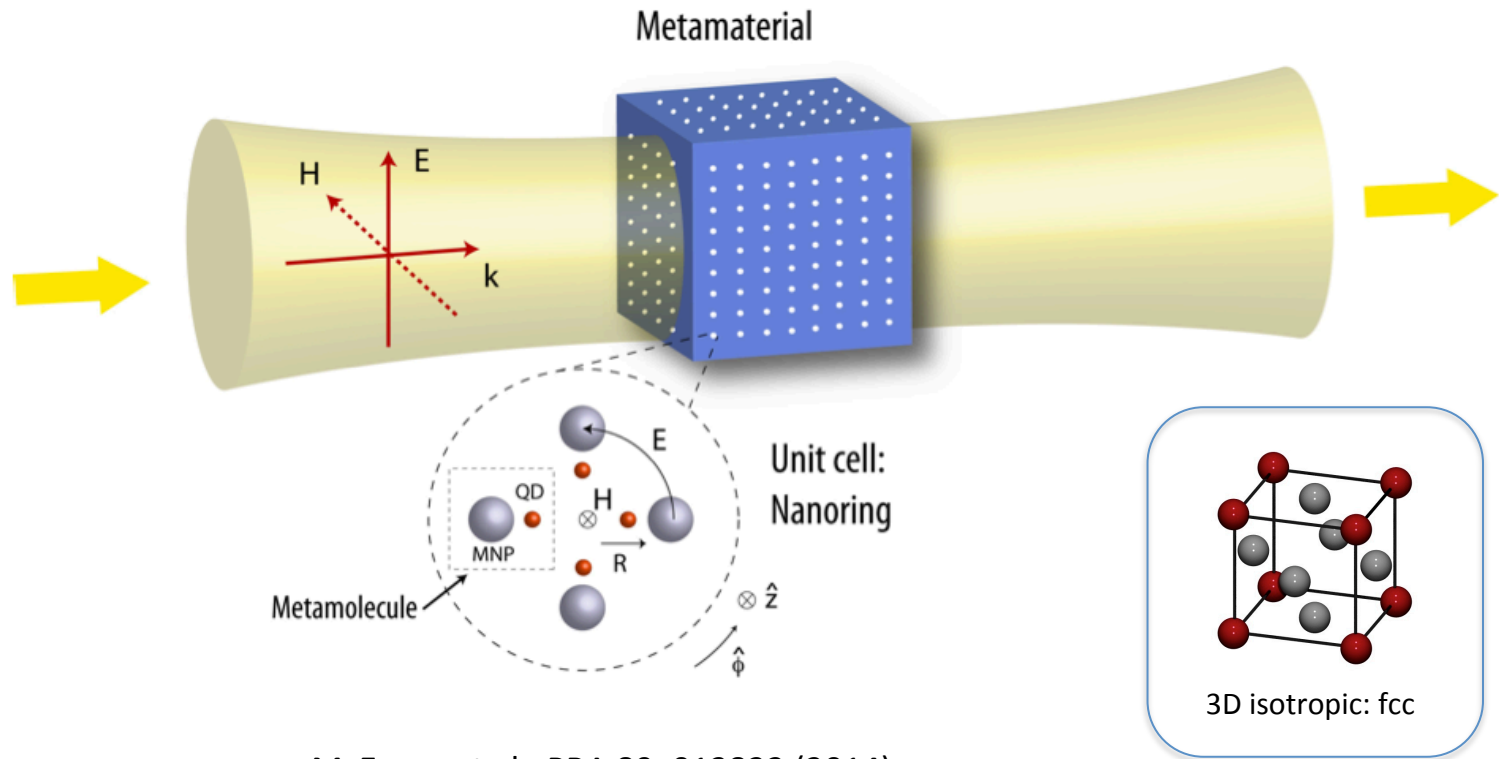
Zhou et al., PRA 85, 023841 (2012)

5

Metamaterials

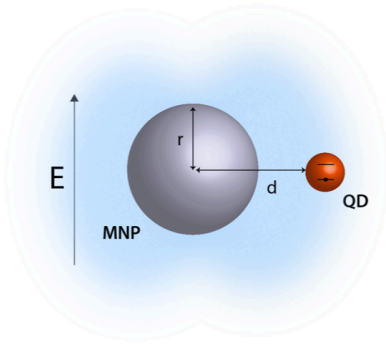
Refractive index

Quantum effects



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

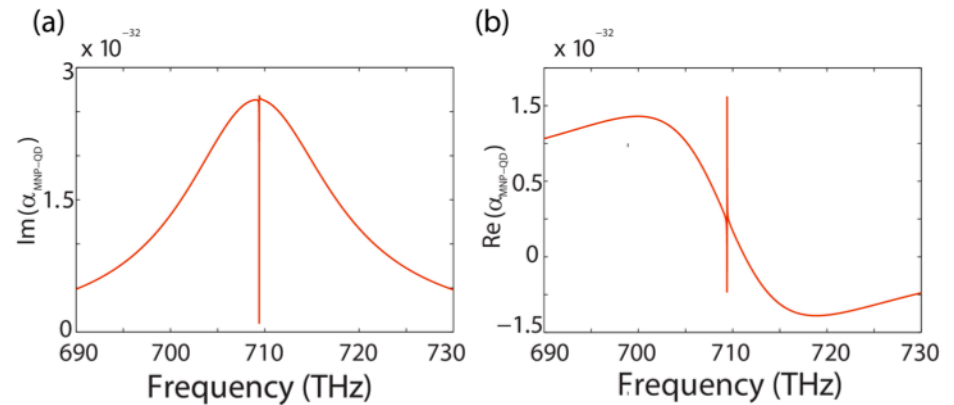
Alu, Salandrino and Engheta, Opt. Exp. 14, 1557 (2006)



Zhang, Govorov and Bryant, PRL 97, 146804 (2006)

Ridolfo et al., PRL 105, 263601 (2010)

Waks and Sridharan, PRA 82, 043845 (2010)

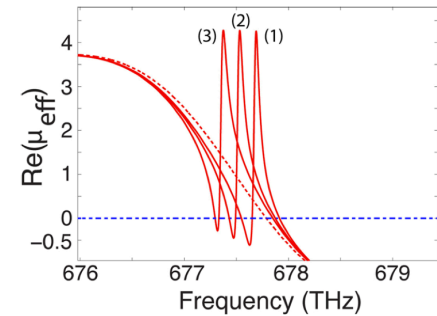
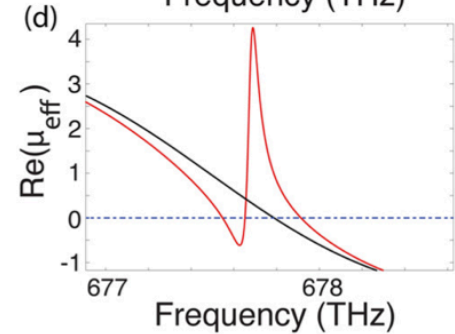
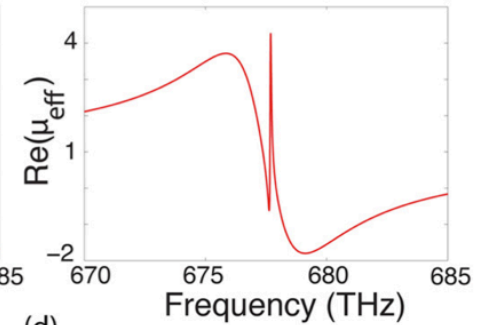
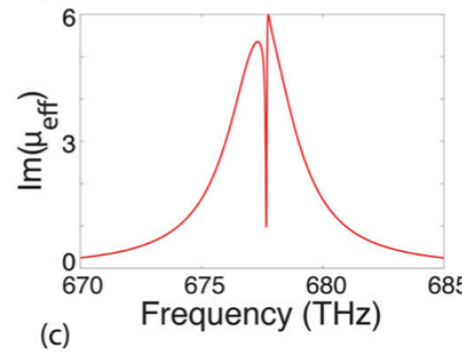
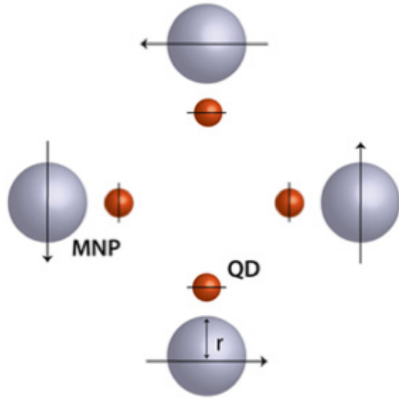


$$\hat{H} = \hat{H}_0 + \hat{H}_{int} + \hat{H}_{drive}$$

$$\hat{H}_0 = \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar\omega_x \hat{\sigma}^\dagger \hat{\sigma},$$

$$\hat{H}_{int} = i\hbar g(\hat{\sigma}^\dagger \hat{a} + \hat{\sigma} \hat{a}^\dagger),$$

$$\begin{aligned} \hat{H}_{drive} = & -E_0 \mu (\hat{\sigma} e^{-i\omega t} + \hat{\sigma}^\dagger e^{i\omega t}) \\ & - E_0 (\chi^* \hat{a} e^{-i\omega t} + \chi \hat{a}^\dagger e^{i\omega t}) \end{aligned}$$



$$\hat{H}_0 = \sum_{n=0}^{N-1} \hbar \omega_0 \hat{a}_n^\dagger \hat{a}_n,$$

$$\hat{H}_{int} = \sum_{n,m=0}^{N-1} \hbar J_{nm} (\hat{a}_n^\dagger \hat{a}_m + \hat{a}_m^\dagger \hat{a}_n) \quad n \neq m$$

$$\hat{H}_{drive} = -E_0 \sum_{n=0}^{N-1} (\chi^* \hat{a}_n e^{-i\omega t} + \chi \hat{a}_n^\dagger e^{i\omega t}).$$

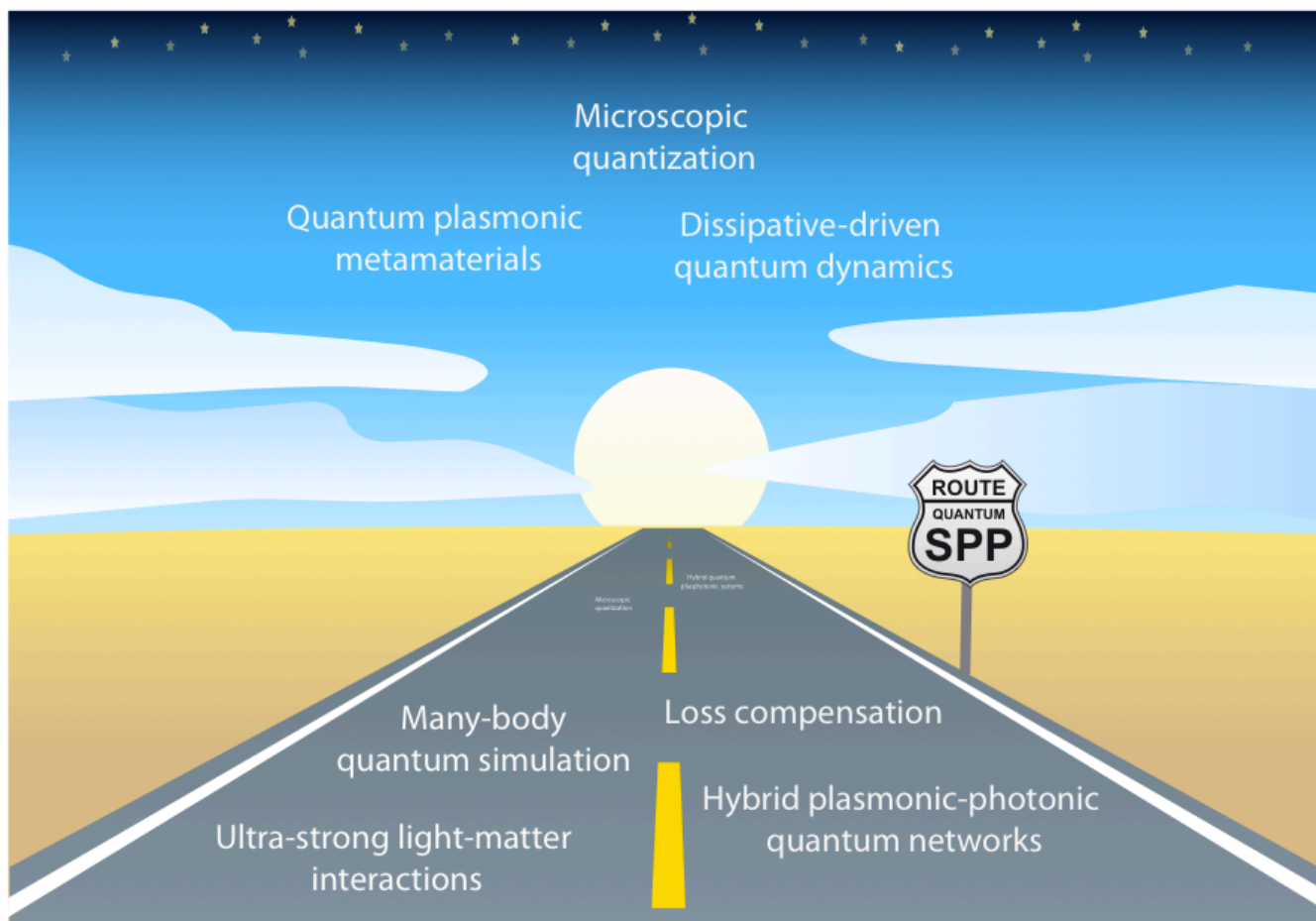


6

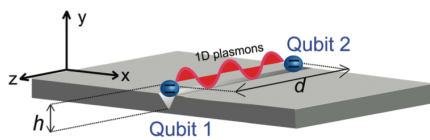
Open
problems

Loss

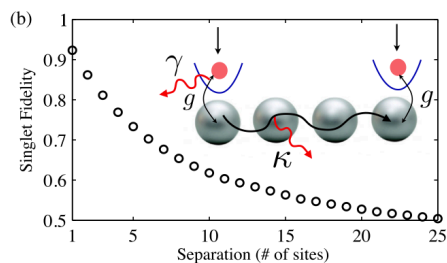
Hybridization



Dissipative driven



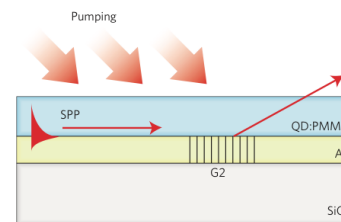
Martín-Cano et al., PRB 84, 235306 (2011)



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

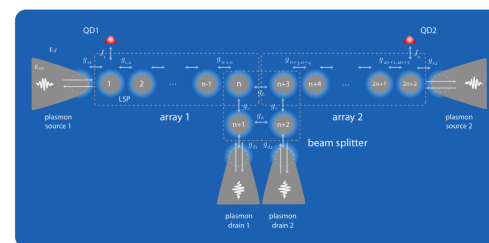
Verstraete et al. Nat Phys 5, 633 (2009)

Loss compensation



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

Postselection



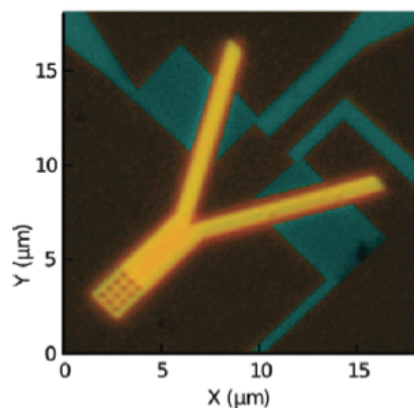
Lee et al., NJP 15, 83017 (2013)

6

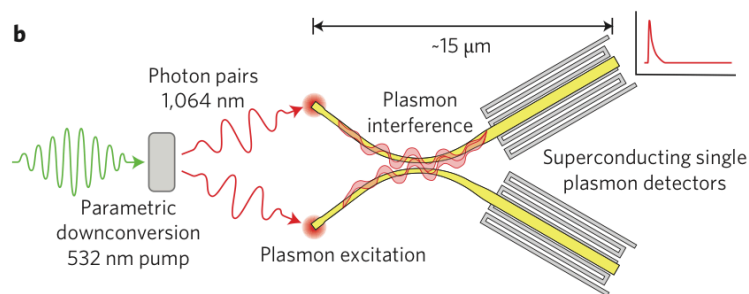
Open
problems

Loss

Hybridization

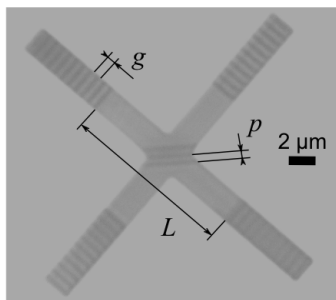


Heeres et al., NL 10, 661 (2010)



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

Knill et al., Nature 409, 46 (2001)



Di Martino et al., submitted (2014)

Knill, PRA 71, 042322 (2005)

Varnava et al., PRL 97, 120501 (2006)

Barrett and Stace, PRL 105, 200502 (2010)

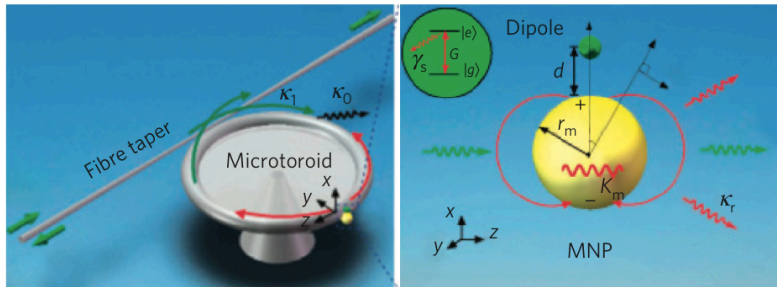
50% loss

6

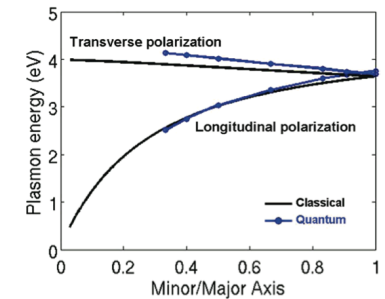
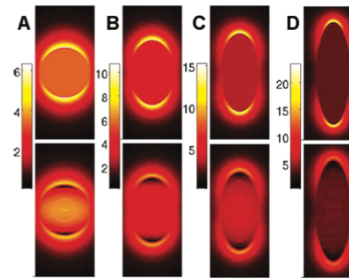
Open
problems

Loss

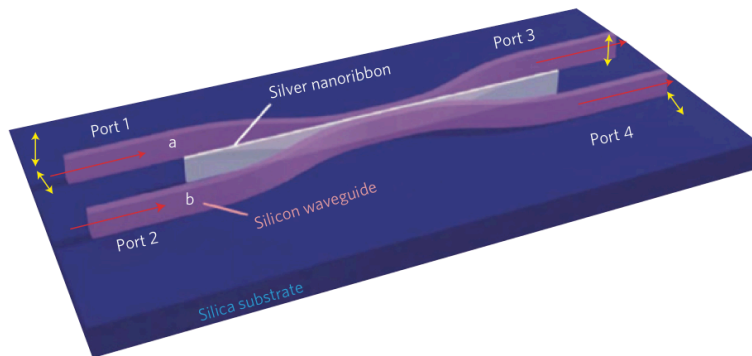
Hybridization



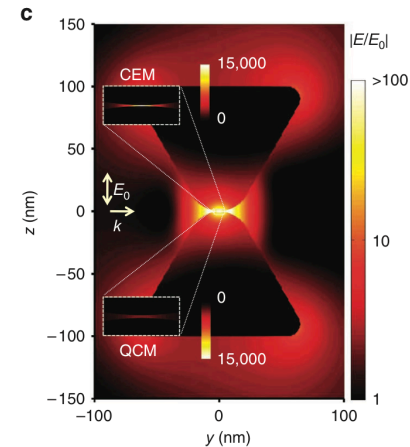
Xiao et al., PRA 85, 031805 (2009)



Zuloaga et al., ACS Nano 4, 5269 (2010)



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



Esteban et al., Nature Comm. 3 825 (2012)

Quantum plasmonics

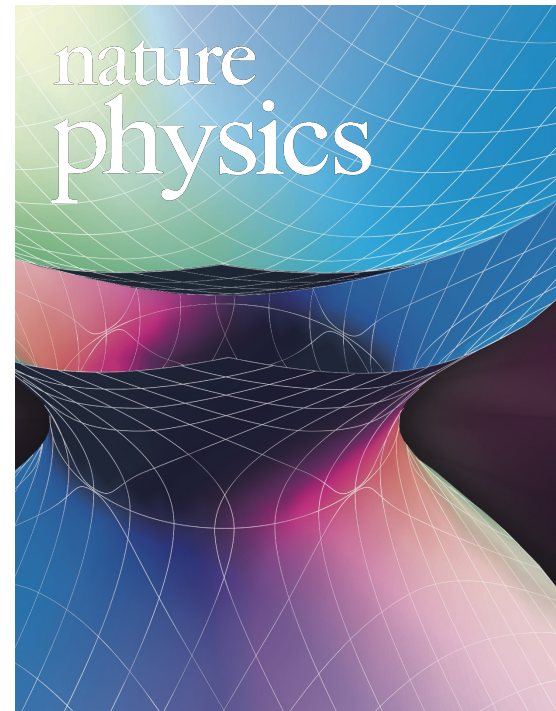
M. S. Tame^{1*}, K. R. McEnery^{1,2}, Ş. K. Özdemir³, J. Lee⁴, S. A. Maier^{1*} and M. S. Kim²

Quantum plasmonics is a rapidly growing field of research that involves the study of the quantum properties of light and its interaction with matter at the nanoscale. Here, surface plasmons—electromagnetic excitations coupled to electron charge density waves on metal-dielectric interfaces or localized on metallic nanostructures—enable the confinement of light to scales far below that of conventional optics. We review recent progress in the experimental and theoretical investigation of the quantum properties of surface plasmons, their role in controlling light-matter interactions at the quantum level and potential applications. Quantum plasmonics opens up a new frontier in the study of the fundamental physics of surface plasmons and the realization of quantum-controlled devices, including single-photon sources, transistors and ultra-compact circuitry at the nanoscale.

Plasmonics provides a unique setting for the manipulation of light via the confinement of the electromagnetic field to regions well below the diffraction limit^{1,2}. This has

outlook on some of the important challenges that remain to be addressed and new directions for the field.

Tame et al., Nature Phys. 9, 329 (2013)



QUANTUM PLASMONICS II

WINTER SCHOOL ON QUANTUM PHYSICS AND QUANTUM INFORMATION

Palacký University, Olomouc, Czech Republic | Jan 2014

MARK TAME



european
social fund in the
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INVESTMENTS IN EDUCATION DEVELOPMENT