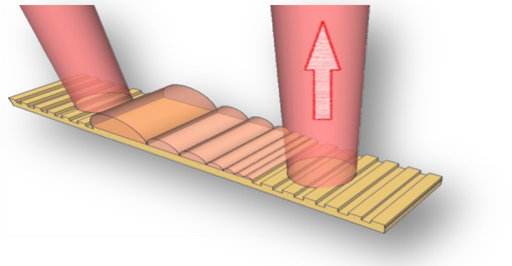


QUANTUM PLASMONICS

Mark Tame

Imperial College London

The Leverhulme Trust

EUROPEAN OFFICE OF AEROSPACE R&D

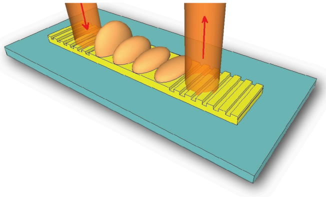
EPSRC
Pioneering research and skills

?

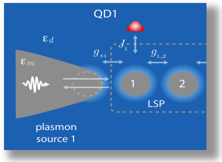
Overview of talk

1. *Introduction* – What is ‘Quantum Plasmonics’?

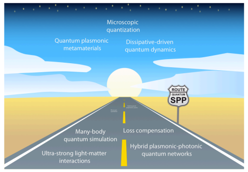
2. *Experimental work*



3. *Theory work*

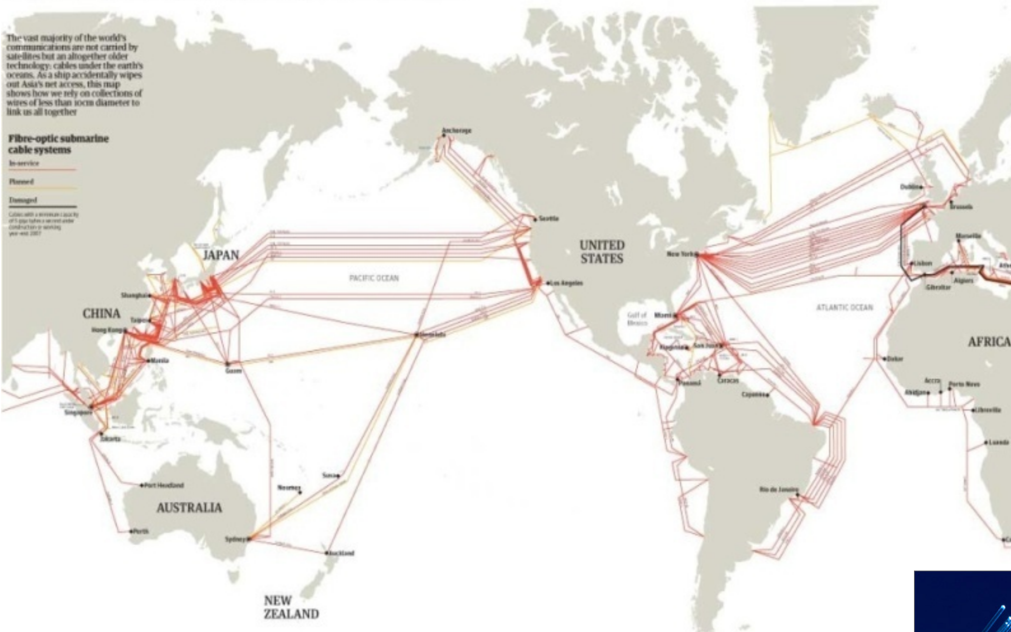


4. *Future directions*



Introduction

The internet's undersea world

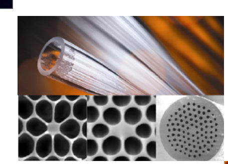


10^3
macroscale

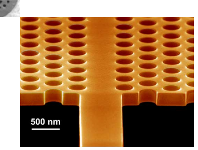
UK

US

10^{-3} m
mesoscale

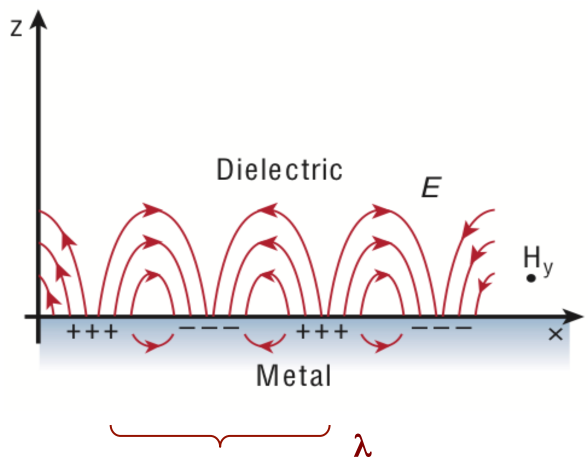


10^{-6} m
microscale



10^{-9} m
nanoscale

Introduction



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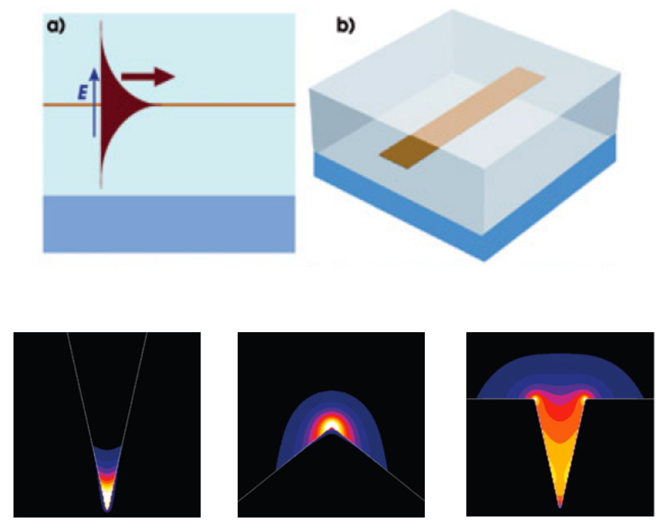

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Introduction

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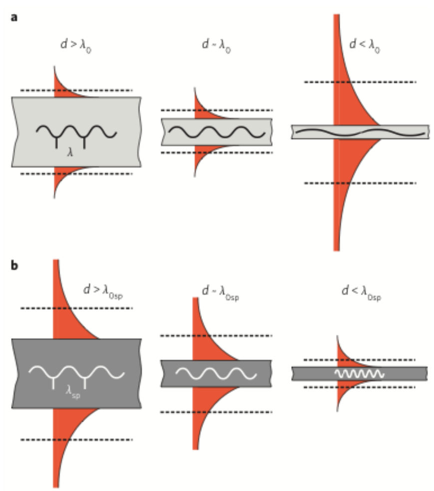
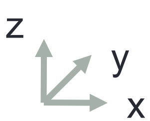
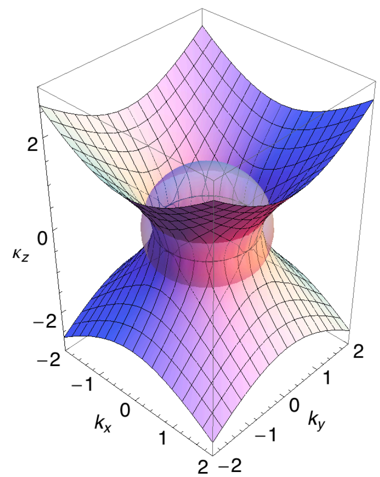




Dielectric optical fibre



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

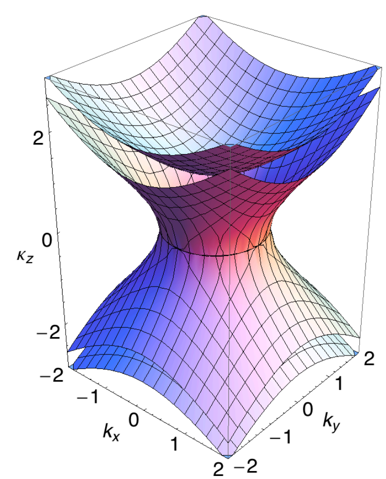
$$k_x^2 + k_y^2 - \kappa_z^2 = \epsilon\mu(\frac{\omega}{c})^2$$

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



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

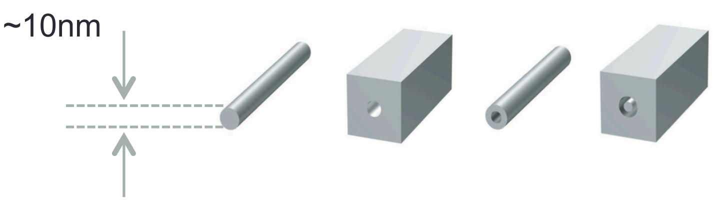
$$\Delta x, \Delta y \geq \frac{\lambda_0}{2n}\sqrt{1 - \frac{\epsilon}{|\epsilon_{ND}|}}$$

(1) sub-diffraction confinement of light

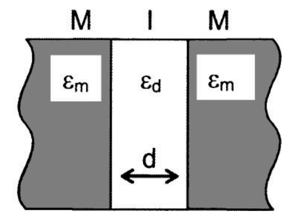
$$\delta_{SPP} < \frac{\lambda_0}{2\pi n} < \frac{\lambda_0}{2n}$$

(2) sub-wavelength confinement of light

Introduction



Takahara, Plasmonic Nanoguides and Circuits (2009)



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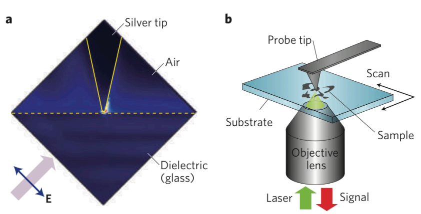
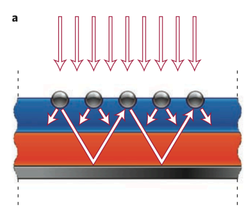
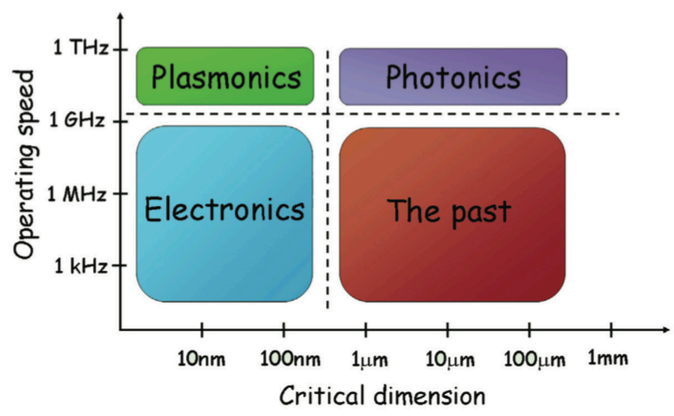


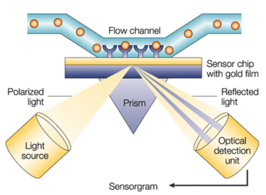
Kawata, Inouye and Verma,
Nature Phot. 3, 388 (2009)



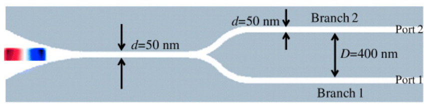
Atwater and Polman,
Nature Mat. 9, 205 (2010)



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



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



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

Introduction

Enhancement of light-matter interaction

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

cavity

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

waveguide

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

Purcell effect

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

waveguides

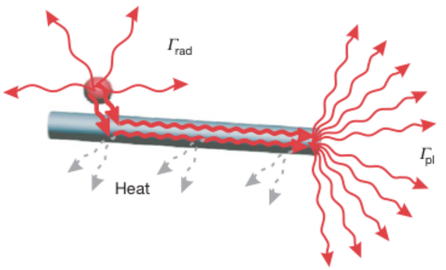
dielectric

$$P \lesssim 1$$

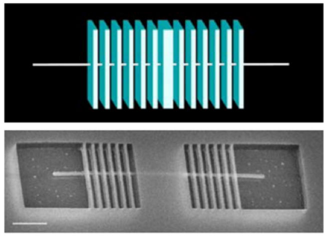
metal

$$P \gtrsim 100$$

Single-photon sources

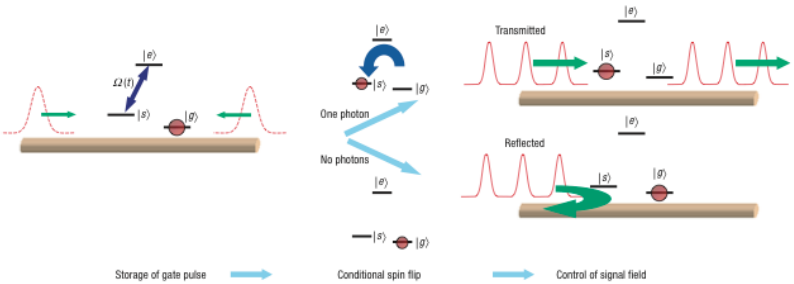


Akimov et al., Nature 450, 402 (2007)



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

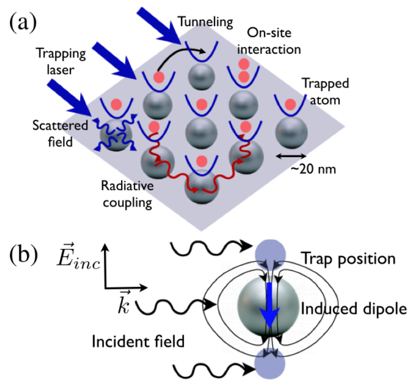
Single-photon transistors



Chang et al., Nature Physics 3, 807 (2007)

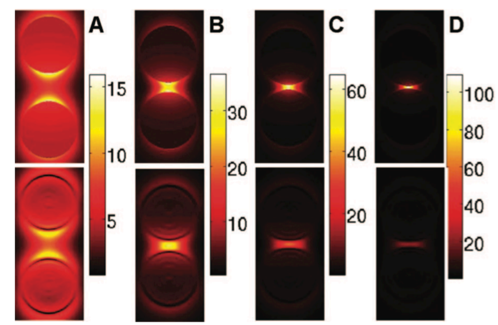
Introduction

Simulation of many-body interacting quantum systems



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

Exploring new kinds of light-matter quantum systems



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

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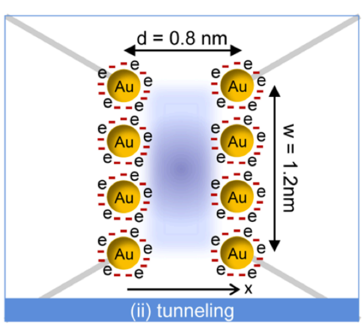
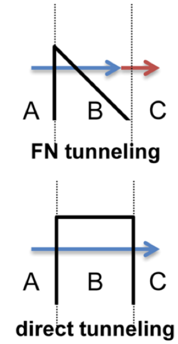
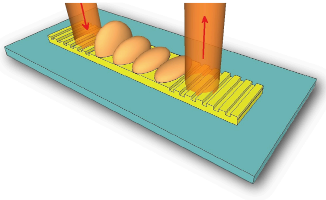
Wu et al., ACS Nano 7, 707 (2013)



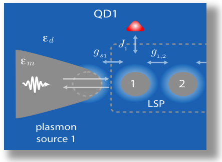


Overview of talk

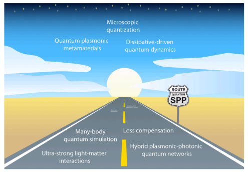
1. *Introduction* – What is 'Quantum Plasmonics'?
2. *Experimental work*



3. *Theory work*



4. *Future directions*



Experiment

Demonstrations of quantum properties of SPPs

- Transmission entangled photons
  Altewischer et al., Nature 2002

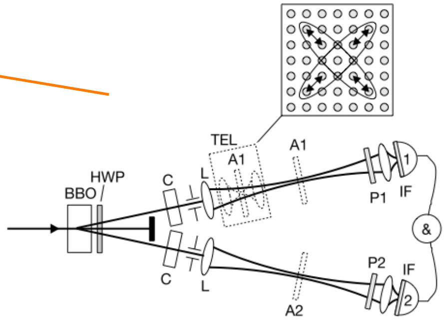
- Energy-time entanglement
  Fasel et al., PRL 2005

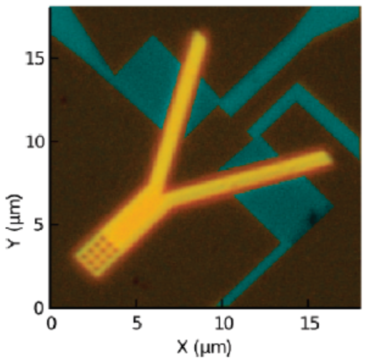
- Quantum superposition
  Fasel et al., New J. Phys 2006

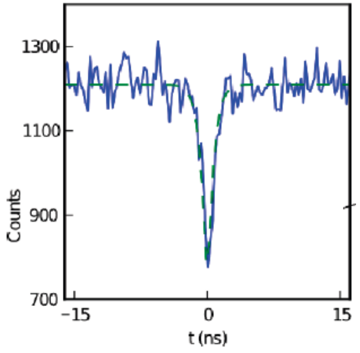
- Wave-particle duality
  Kolesov et al., Nature Phys. 2009

- On-chip single plasmon detection
  Heeres et al., Nano Lett. 2010

- etc…

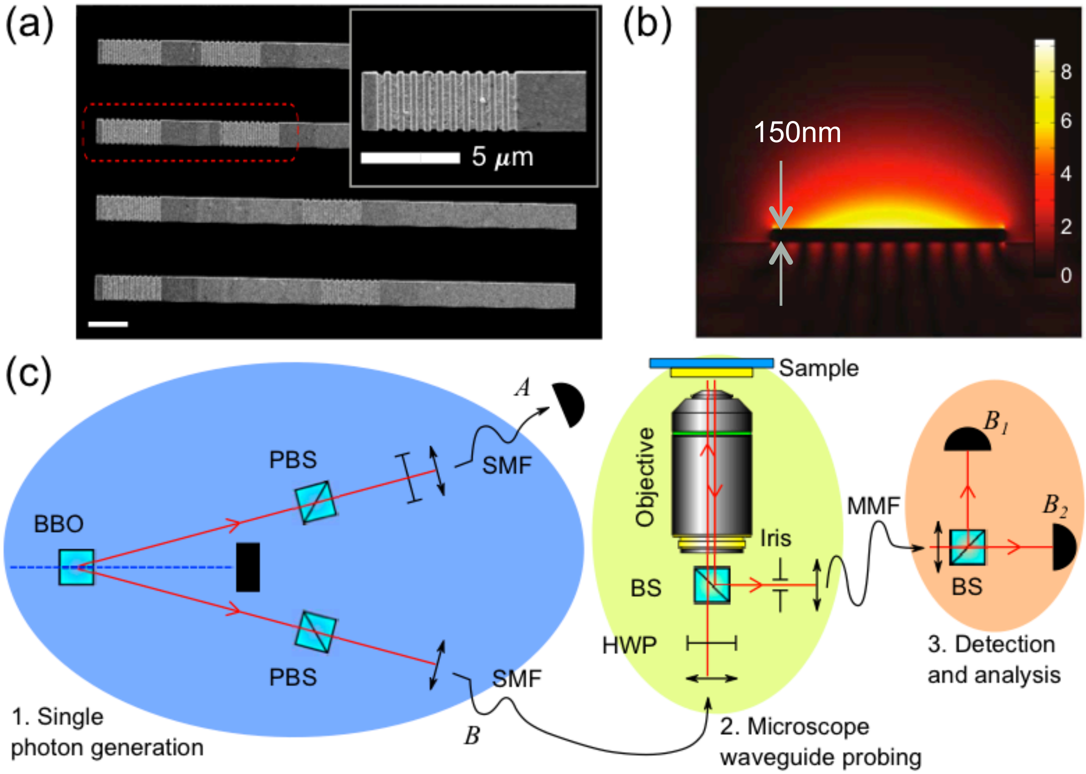






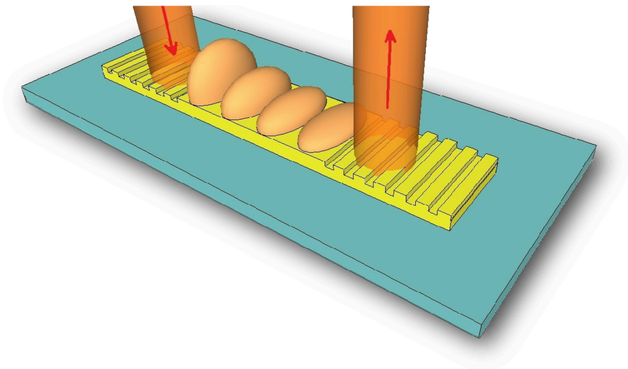
- **Number state degree of freedom**
  Di Martino et al., Nano Lett. 2012

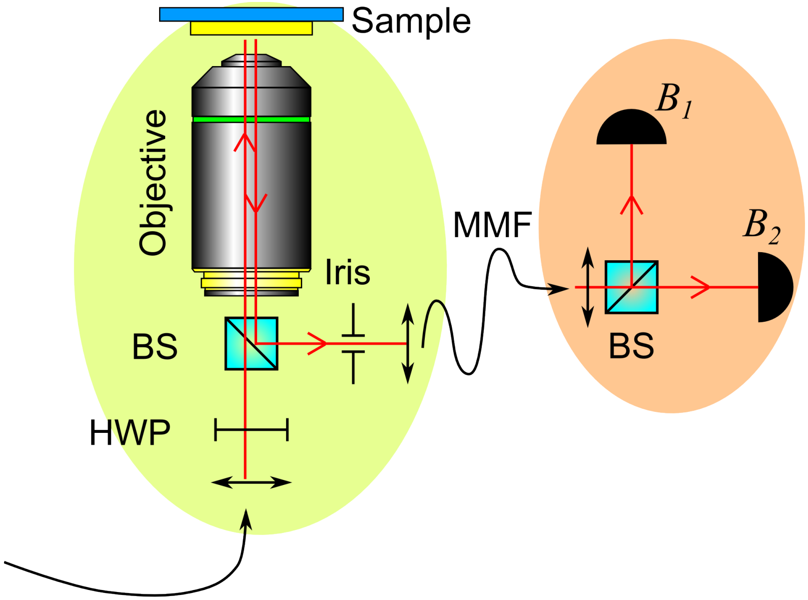
Experiment



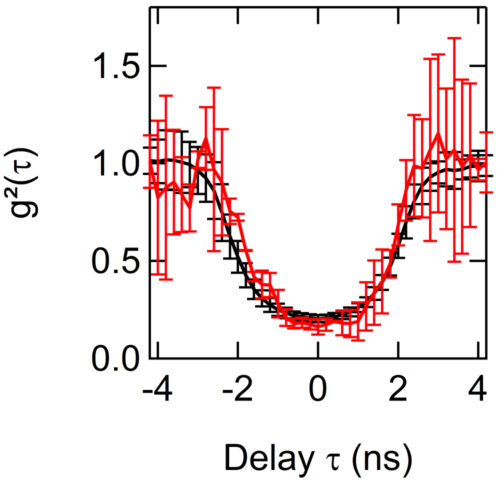
Di Martino et al., Nano Lett. 12, 2504 (2012)

Experiment

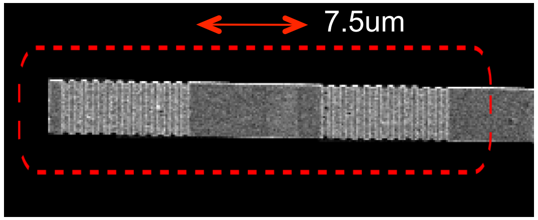




Sample
Objective
Iris
BS
HWP
MMF
B_1
B_2
BS

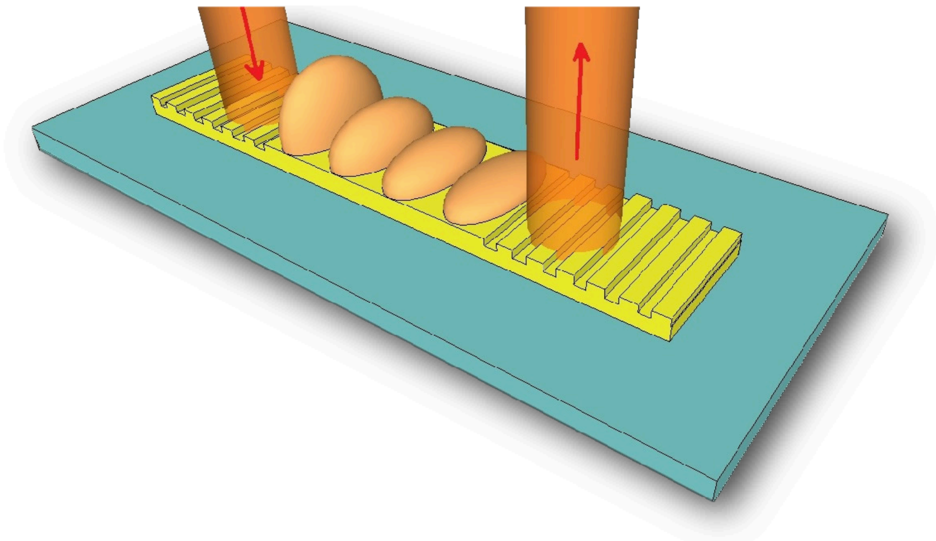


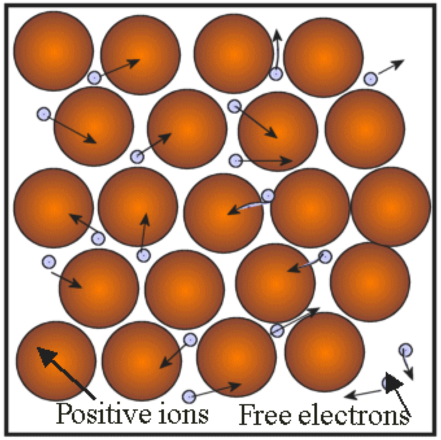
1.5
1.0
0.5
0.0
-4
-2
0
2
4
$g^2(\tau)$
Delay τ (ns)

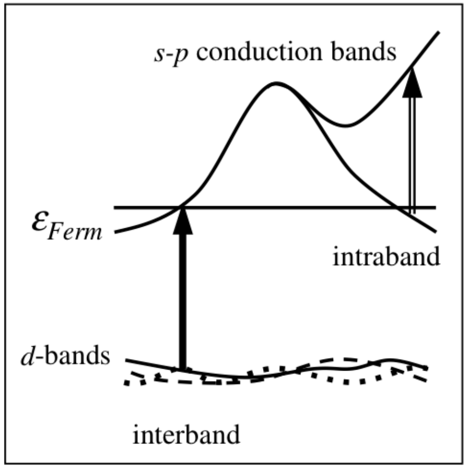


7.5um

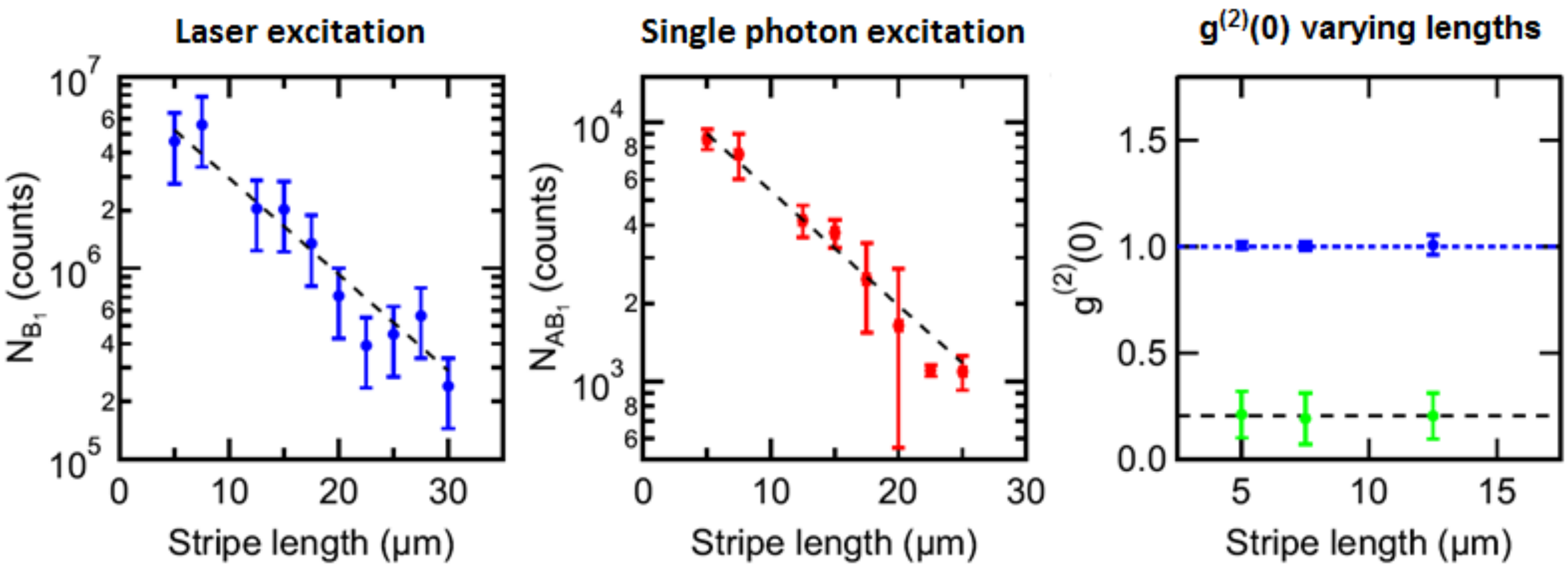
Experiment




Positive ions
Free electrons


s-p conduction bands
ε_{Ferm}
intraband
d-bands
interband

Experiment



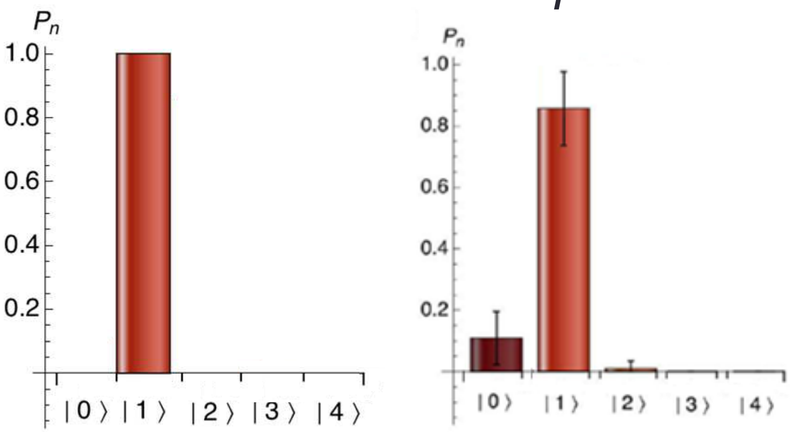
- $g^{(2)}(0)$ remains unchanged for different lengths $g^{(2)}(0) = \langle m(m-1)\rangle / \langle m\rangle^2$
- Consistent with a linear loss model:

$$\text{loss coefficient } \eta^{1/2} \qquad \langle m\rangle \to \eta\langle m\rangle \qquad \langle m(m-1)\rangle \to \eta^2\langle m(m-1)\rangle$$

Experiment

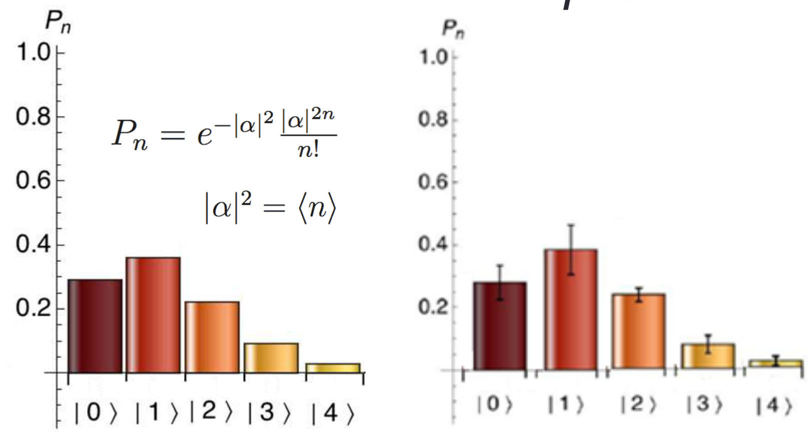
Single-photon source excitation

ideal *experiment*



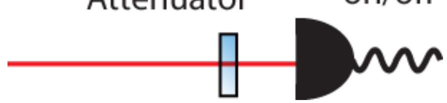
Attenuated laser excitation

ideal *experiment*



The outcoupled field is found to be close to a number state |1>

Consistent with a weak coherent state |α> with mean excitation number of 1.



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

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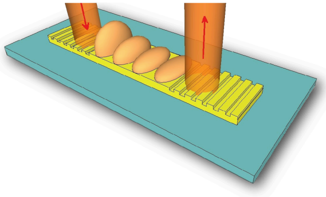

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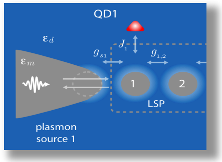

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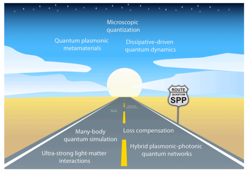
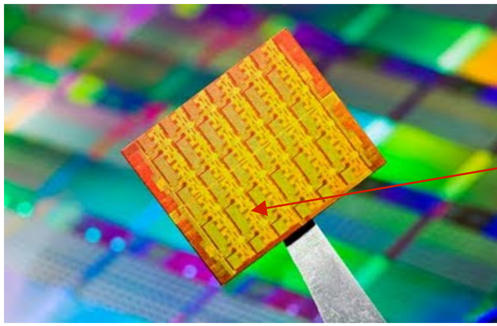
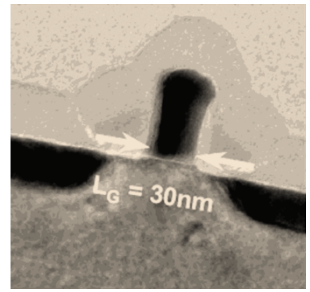
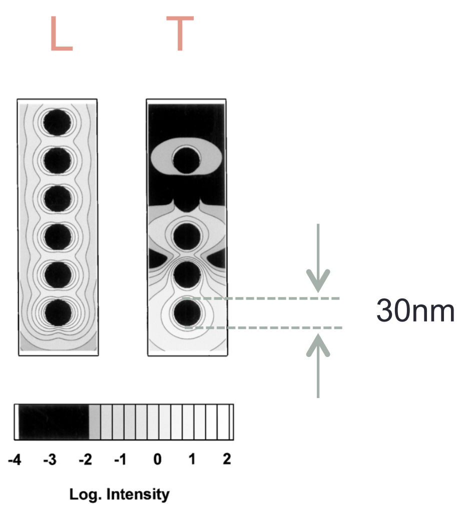


Theory





Intel Labs ‘Single-chip Cloud Computer’ (2013)



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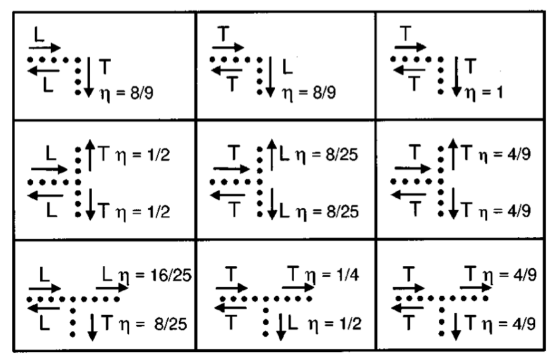

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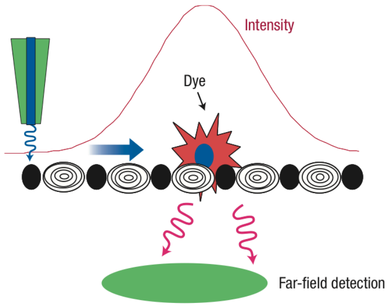
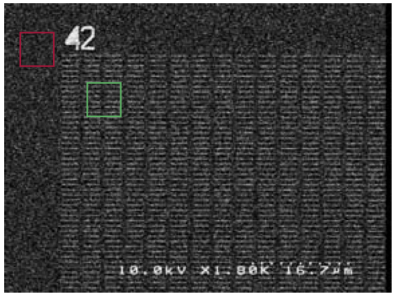
Theory





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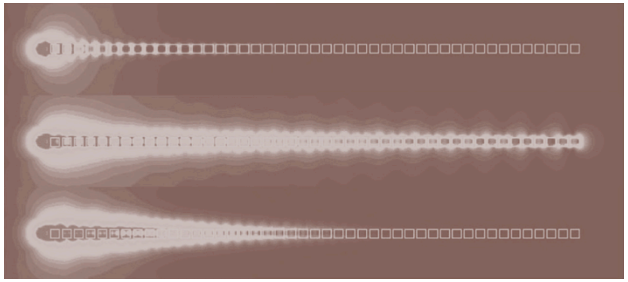
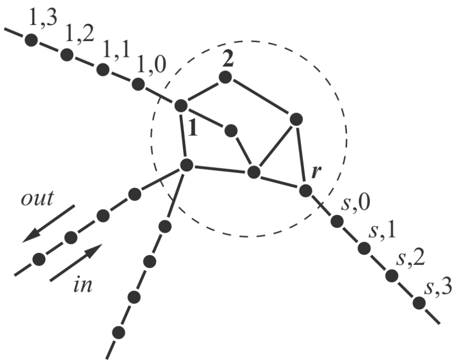


Maier, IEEE J. Sel. Top. Quant. Elec. 12, 1214 & 1671 (2006)

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



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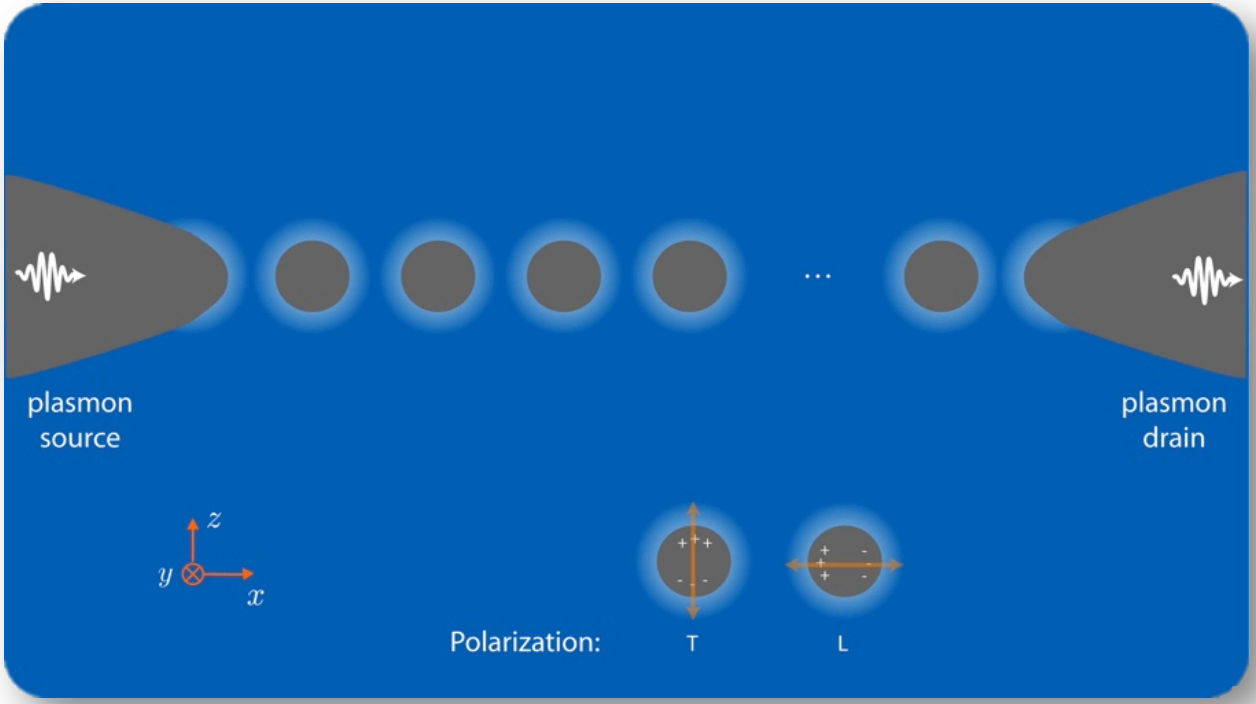
Theory



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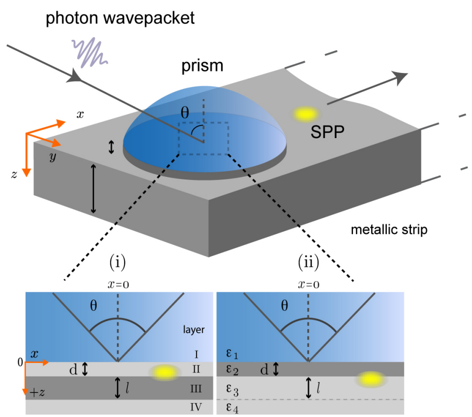
Theory



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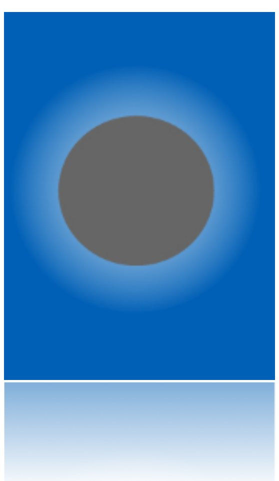
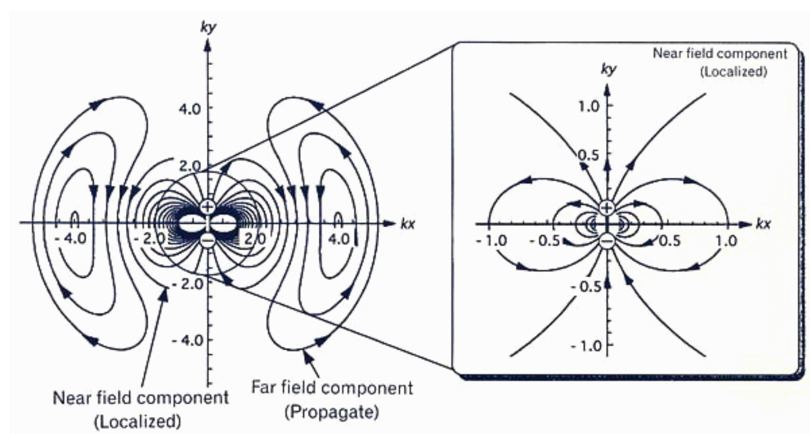
M. S. Tame et al., Phys. Rev. Lett. 101, 190504 (2008)

A. Archambault et al., Phys. Rev. B 82, 035411 (2010)



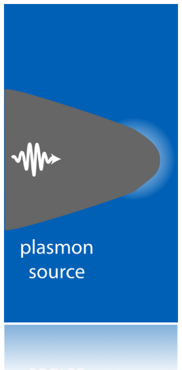


$$\hbar\omega_i \hat{a}_i^\dagger \hat{a}_i$$

W. Greiner, Classical Electrodynamics, (Springer-Verlag, New York, 1996)

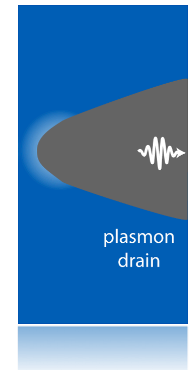
E. Waks and D. Sridharan, Phys. Rev. A 82, 043845 (2010)

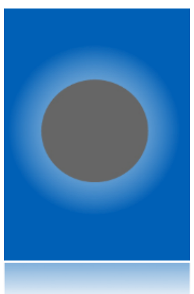
Theory



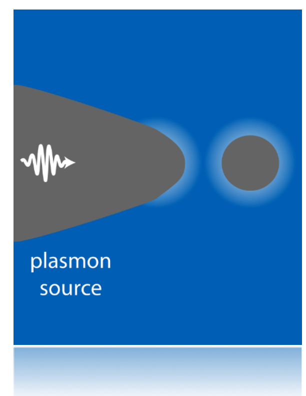
$$\hat{H}_s = \int_{-\infty}^{\infty} d\omega \hbar\omega \hat{s}^{\dagger}(\omega)\hat{s}(\omega)$$

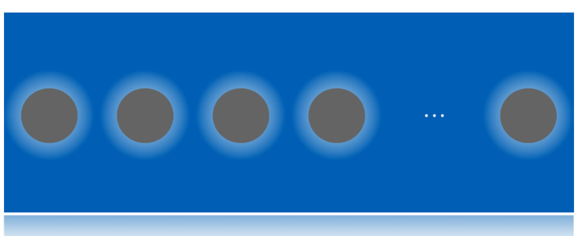
$$\hat{H}_d = \int_{-\infty}^{\infty} d\omega \hbar\omega \hat{d}^{\dagger}(\omega)\hat{d}(\omega)$$





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

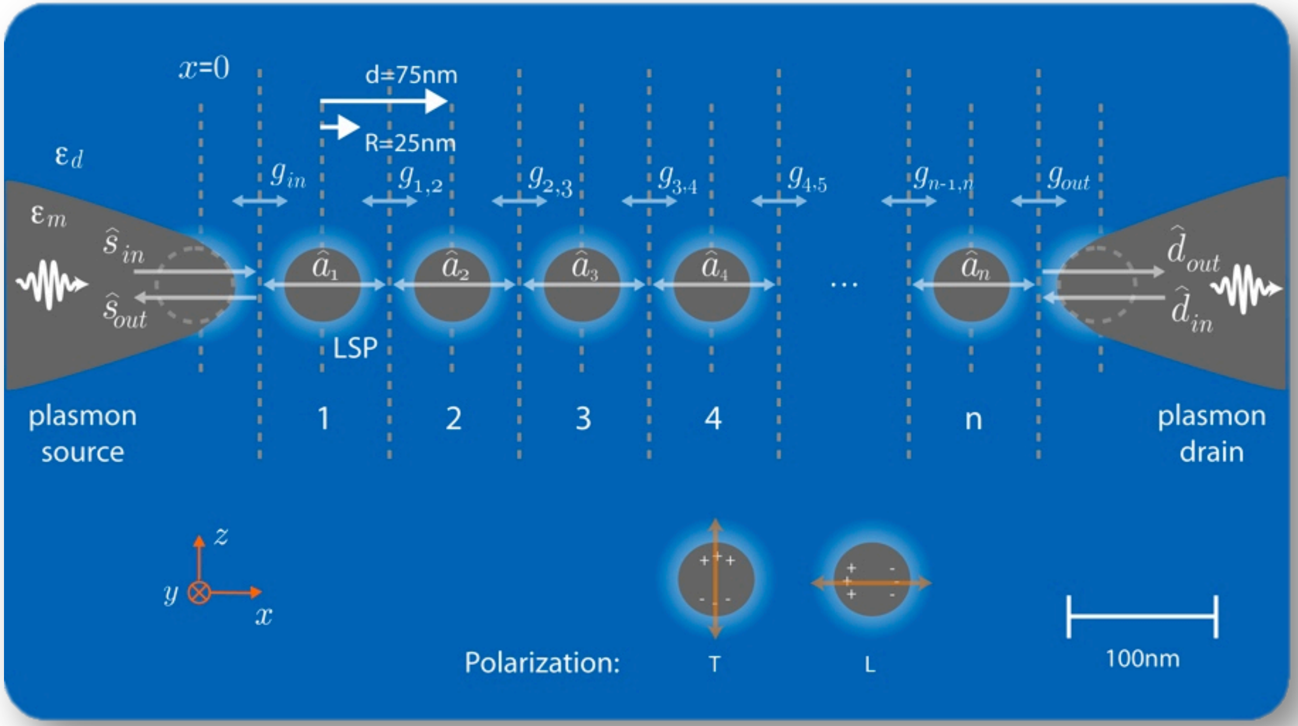




$$\sum_{[i,j]} \hbar g_{i,j}\left(\hat{a}_i^{\dagger}\hat{a}_j + \hat{a}_j^{\dagger}\hat{a}_i\right)$$

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

Theory

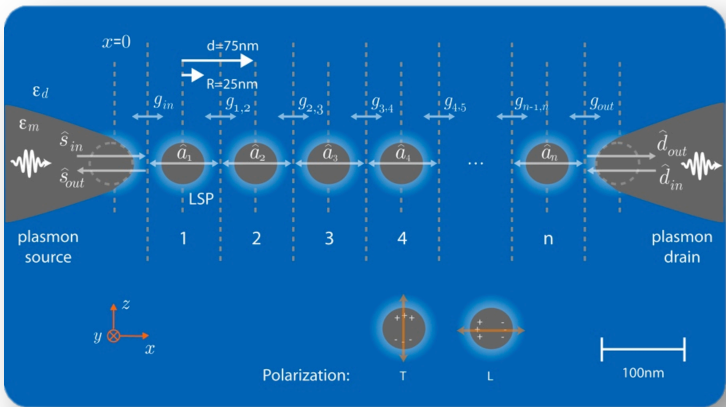


$$\hat{H} = \hat{H}_{np} + \hat{H}_s + \hat{H}_d + \hat{H}_{np,s} + \hat{H}_{np,d}$$

↓

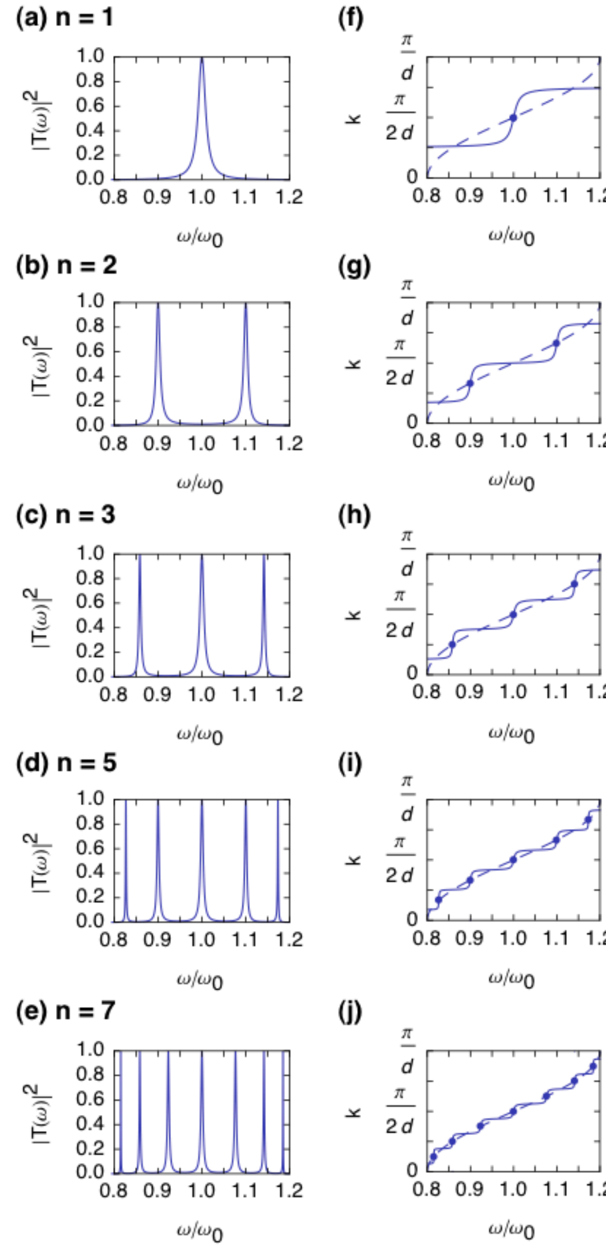
$$\hat{s}^{\dagger}_{\text{in}}(\omega) = \mathcal{R}(\omega)\hat{s}^{\dagger}_{\text{out}}(\omega) + \mathcal{T}(\omega)\hat{d}^{\dagger}_{\text{out}}(\omega)$$

Theory



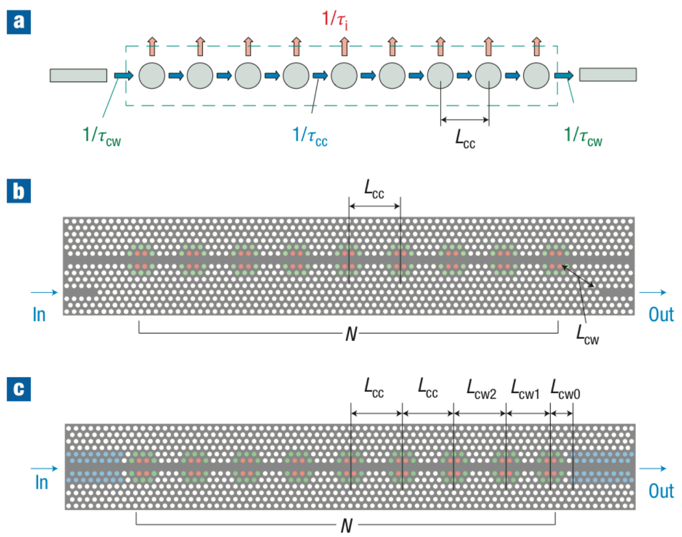
$$\left|1_{\xi}\right\rangle_{s} = \int_{-\infty}^{\infty} \mathrm{d}\omega\, \xi(\omega)\, \hat{s}^{\dagger}_{\mathrm{in}}(\omega) \left|0\right\rangle_{s}$$

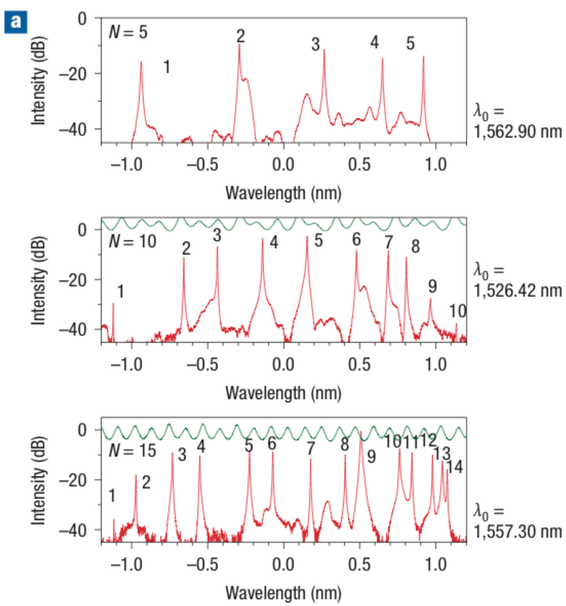
$$\int_{-\infty}^{\infty} \mathrm{d}\omega \left|\xi(\omega)\right|^{2} = 1$$



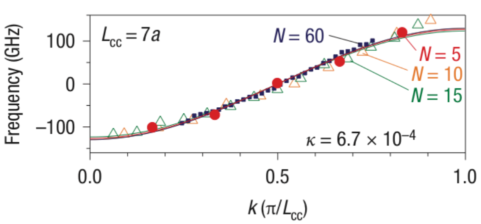
Theory

Photonic crystals





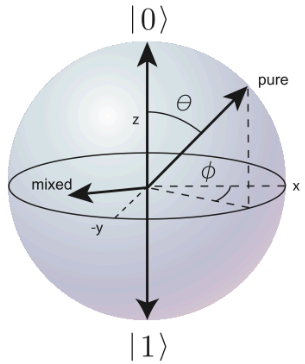
equivalent plasmonic array size: ⊢⊣



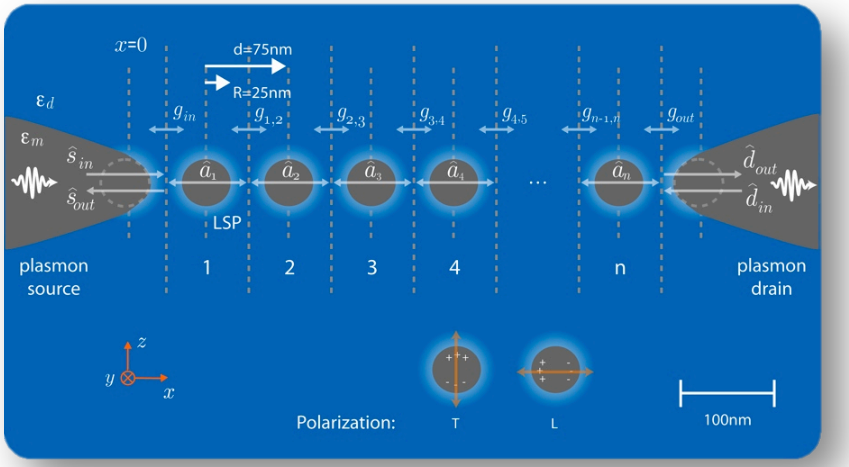
A. Yariv et al., Opt. Lett. 24, 711 (1999)
M. Bayindir et al., Phys. Rev. Lett. 84, 2140 (2000)
M. Notomi et al., Nature Photonics 2, 741 (2008)

Theory

Classical bit



Quantum bit

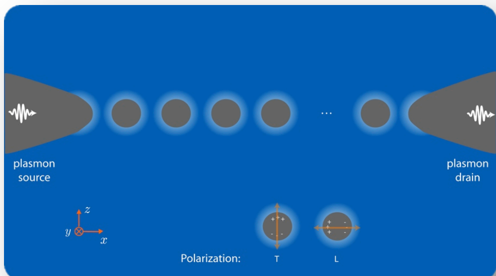


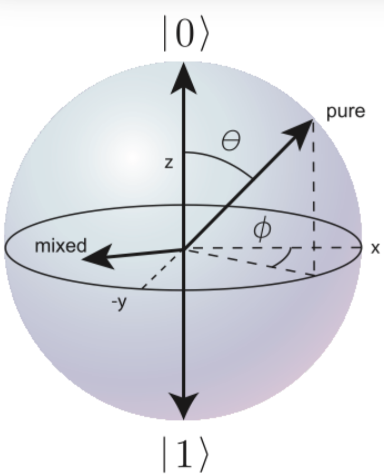
$$|\psi\rangle_s = a\,|0\rangle_s + b\,|1_\xi\rangle_s$$

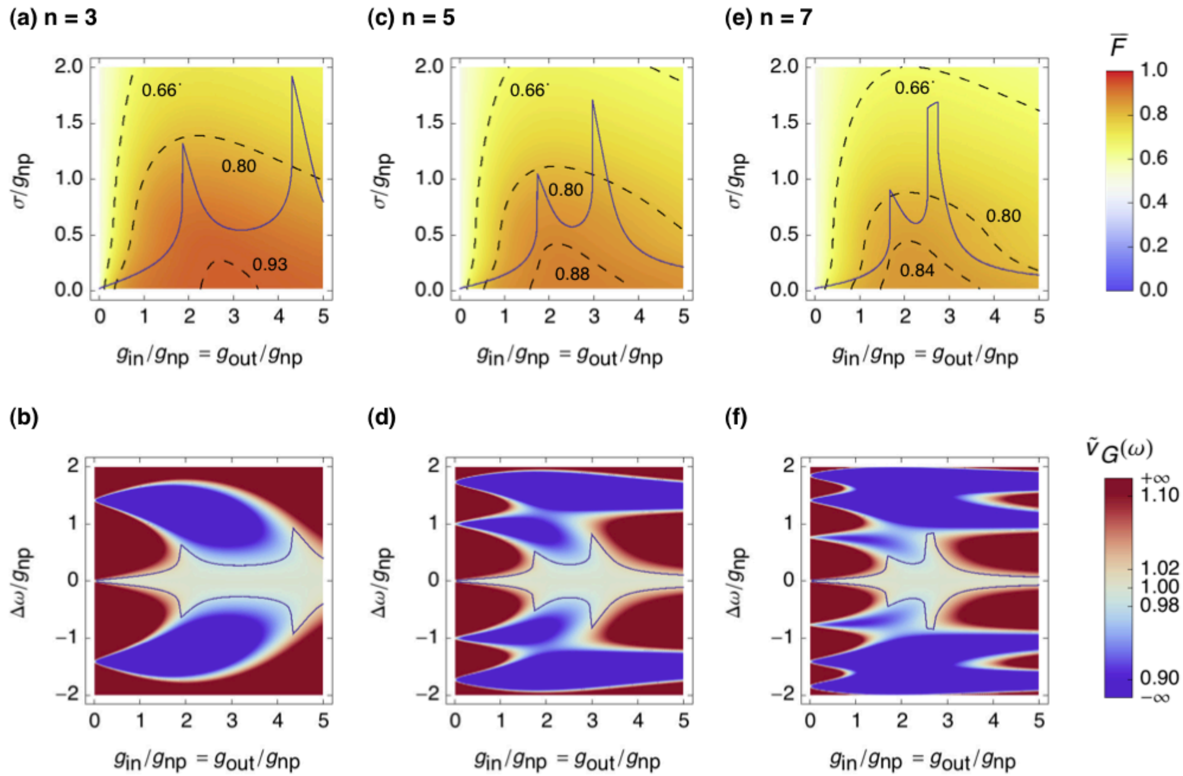
D. T. Pegg et al., Phys. Rev. Lett. 81, 1604 (1998)
K. J. Resch et al., Phys. Rev. Lett. 88, 113601 (2002)

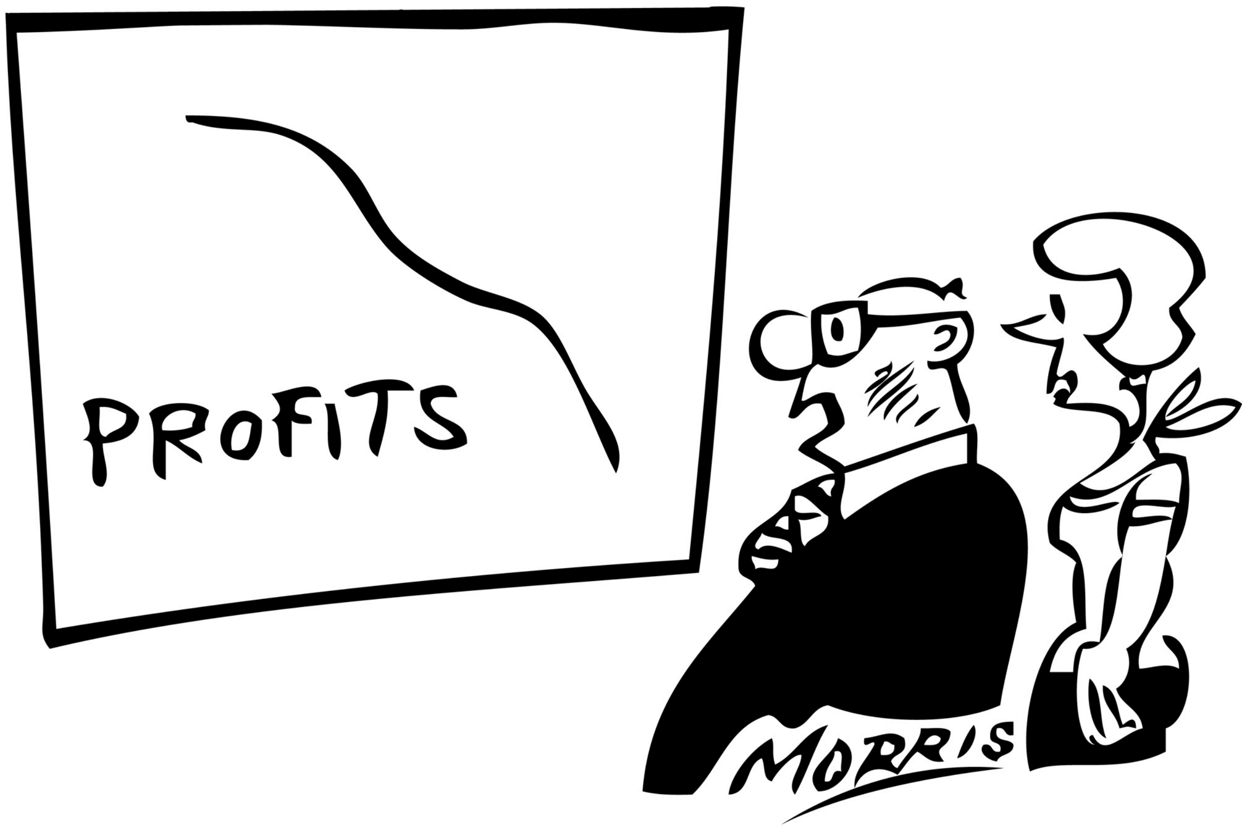
$$|\psi\rangle_s = a\,|0\rangle_s + b\int_{-\infty}^{\infty} \mathrm{d}\omega\,\xi(\omega)\,\hat{s}^{\dagger}_{\mathrm{in}}(\omega)\,|0\rangle_s$$

Theory


plasmon source
plasmon drain
Polarization:
T
L


$|0\rangle$
pure
z
θ
ϕ
mixed
x
-y
$|1\rangle$


(a) n = 3
(c) n = 5
(e) n = 7
σ/g_{np}
0.66
0.80
0.93
0.88
0.84
$g_{in}/g_{np} = g_{out}/g_{np}$
$\bar{F}$
1.0
0.8
0.6
0.4
0.2
0.0
(b)
(d)
(f)
$\Delta\omega/g_{np}$
$\tilde{v}_G(\omega)$
$+\infty$
1.10
1.02
1.00
0.98
0.90
$-\infty$



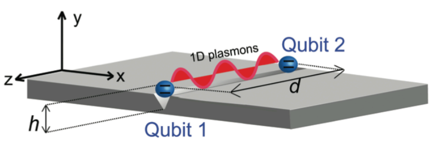
Miss Perkins, send in a scapegoat

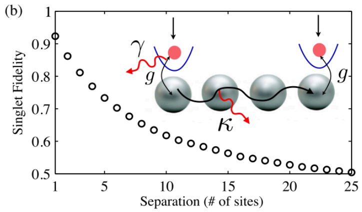
Theory

Dealing with loss in quantum plasmonics

- Dissipative-driven

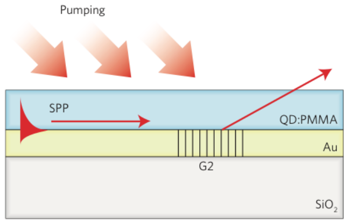
Martín-Cano et al., PRB 84, 235306 (2011)





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

- Loss compensation



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

- Postselection

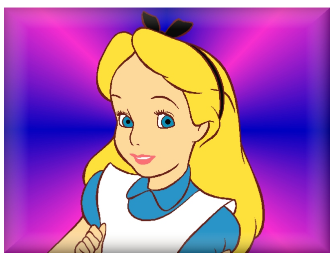
Theory

Postselection

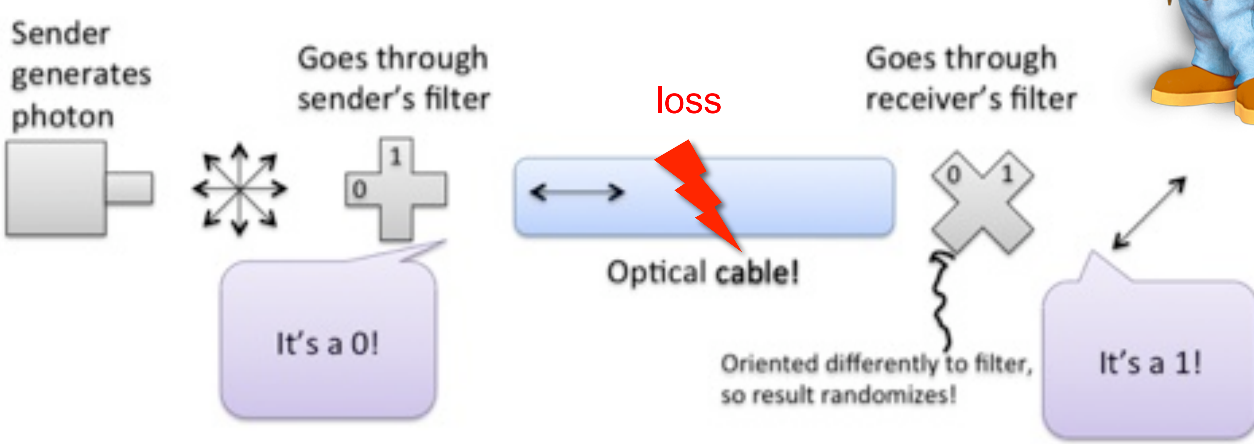
Example: Quantum Cryptography

Alice's bit	0	1	1	0	1	0	0	1
Alice's basis	+	+	X	+	X	X	X	+
Alice's polarization	↑	→	↖	↑	↖	↗	↗	→
Bob's basis	+	X	X	X	+	X	+	+
Bob's measurement	↑	↗	↖	↗	→	↗	→	→
Public discussion								
Shared Secret key	0		1			0		1

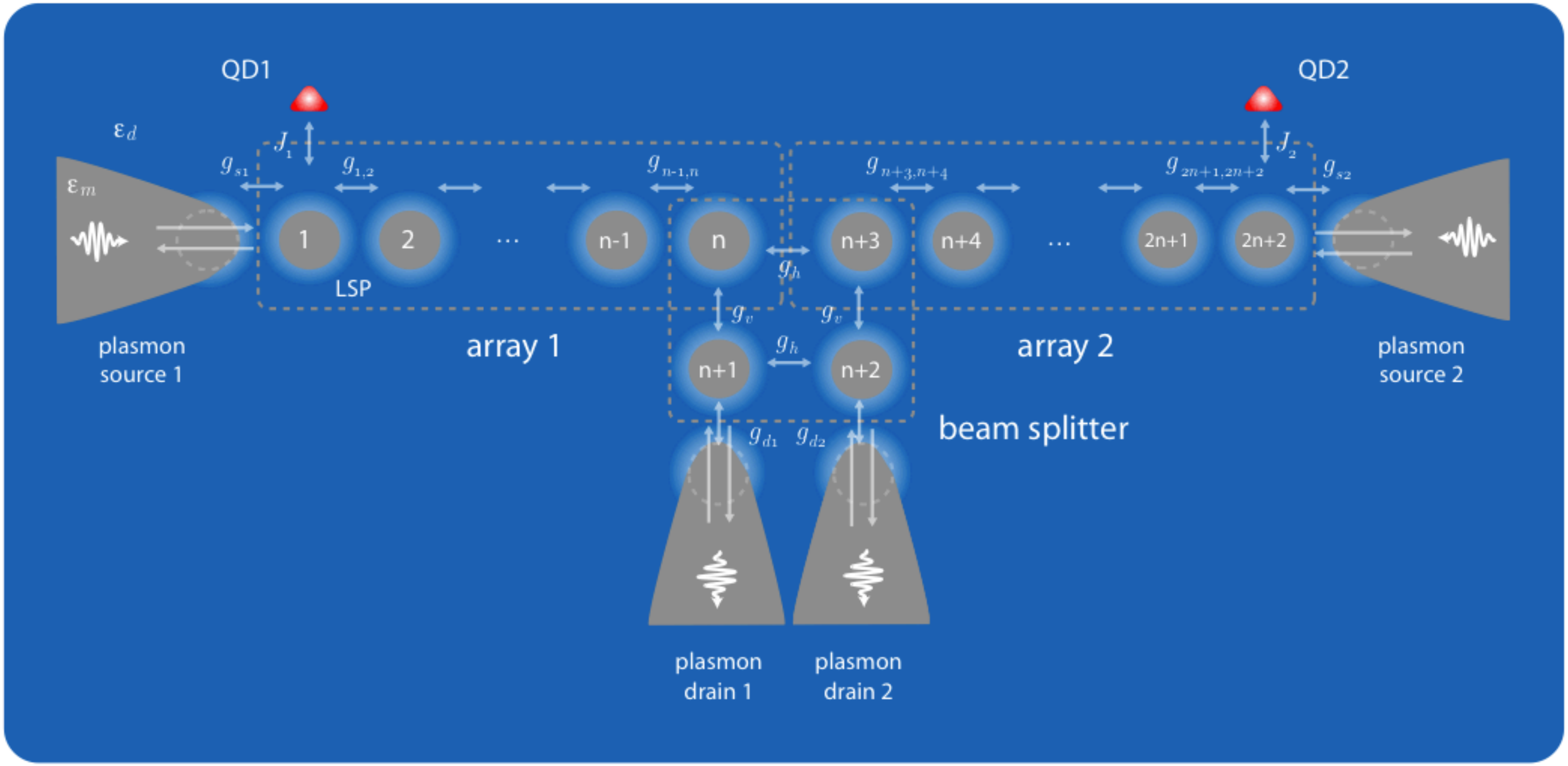
Gisin et al., RMP 74, 145 (2002)



Loss – affects efficiency
Eavesdropping/noise – affects quality

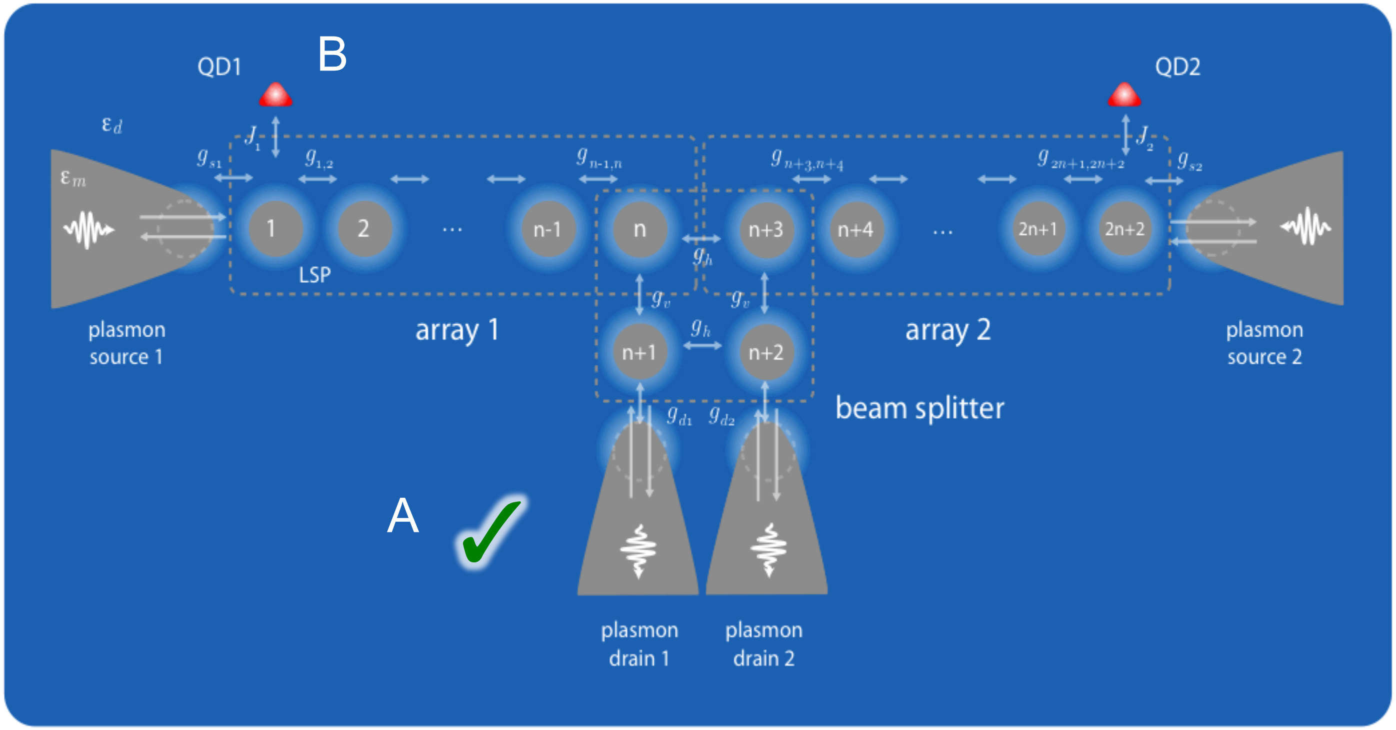


Theory



C. Lee, MST, C. Noh, J. Lim, S. A. Maier, J. Lee and D. G. Angelakis, arXiv:1303.5092 (2013).

Theory

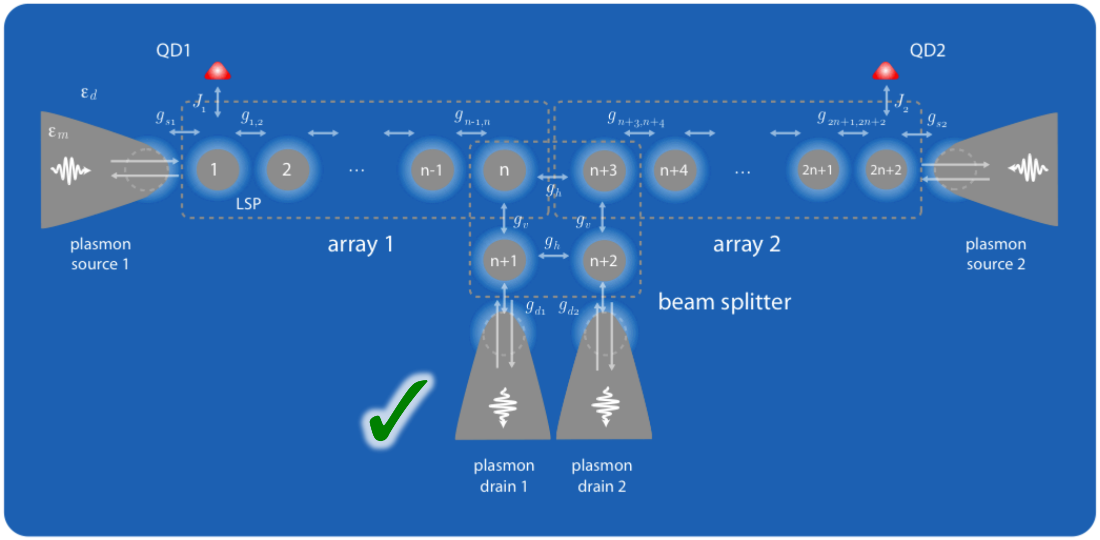


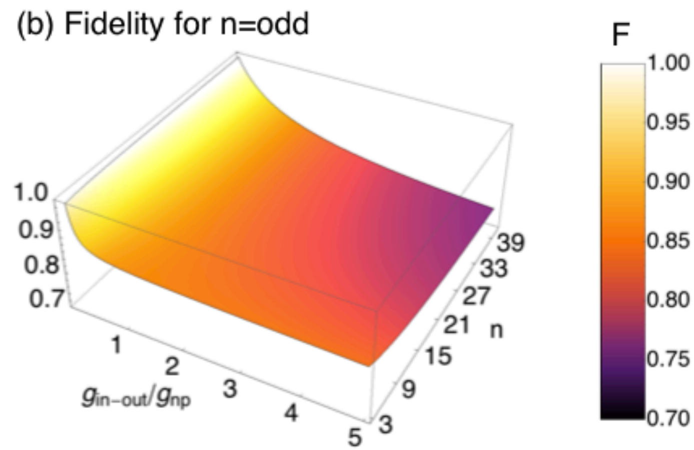
1 $$\frac{1}{\sqrt{2}}(|g\rangle_1 + |m\rangle_1) \otimes \frac{1}{\sqrt{2}}(|g\rangle_2 + |m\rangle_2)$$

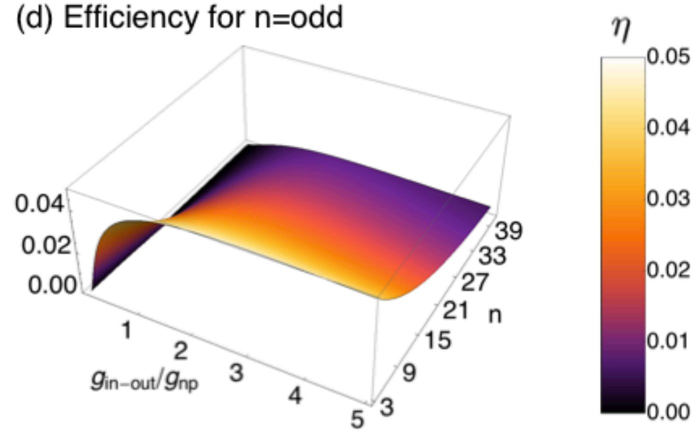
2 $$~~|gg\rangle~~ \quad |gm\rangle \quad |mg\rangle \quad ~~|mm\rangle~~$$

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

Theory







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

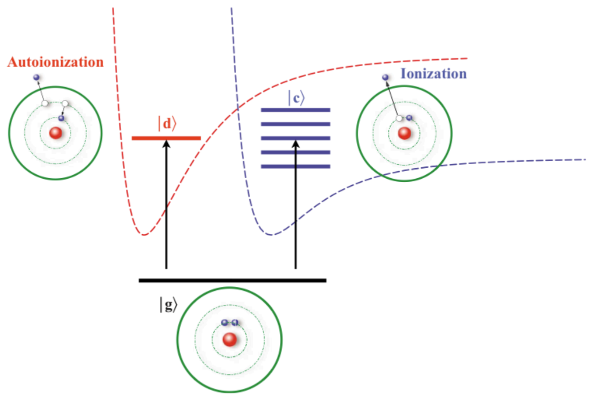
2 ~~$|gg\rangle$~~ $|gm\rangle$ $|mg\rangle$ ~~$|mm\rangle$~~

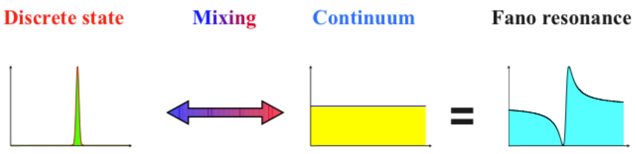
3 $|\Psi\rangle_{\text{QDs}} = \frac{1}{\sqrt{2}}(|mg\rangle - |gm\rangle)$

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

Theory

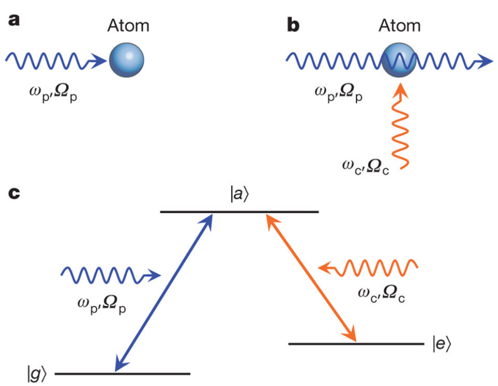
Fano interference:

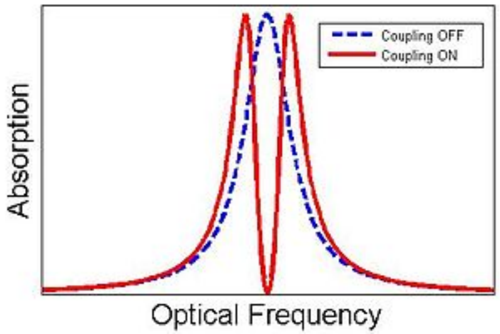




Miroshnichenko et al. RMP 82, 2257 (2010)

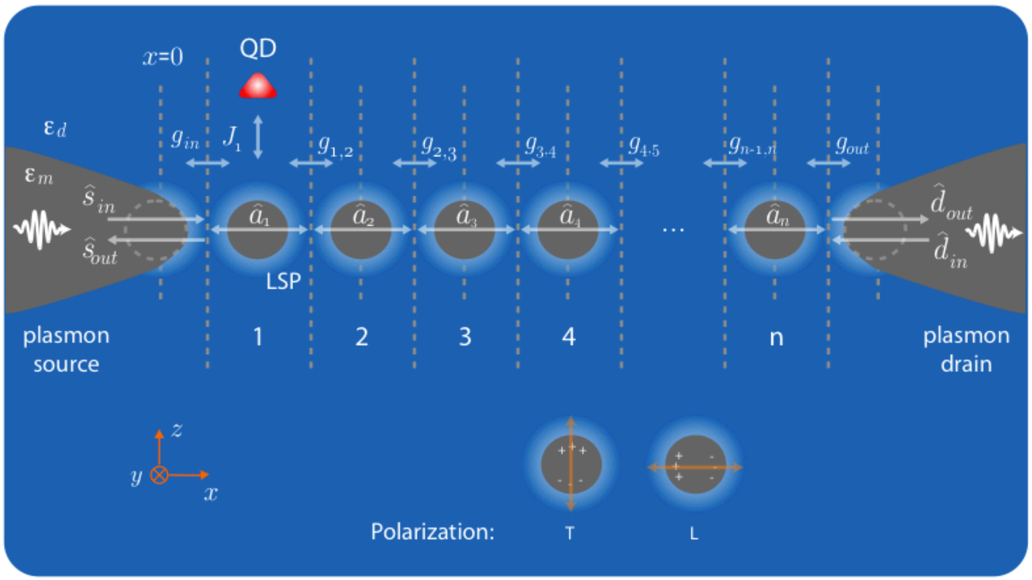
Electromagnetic-induced transparency:

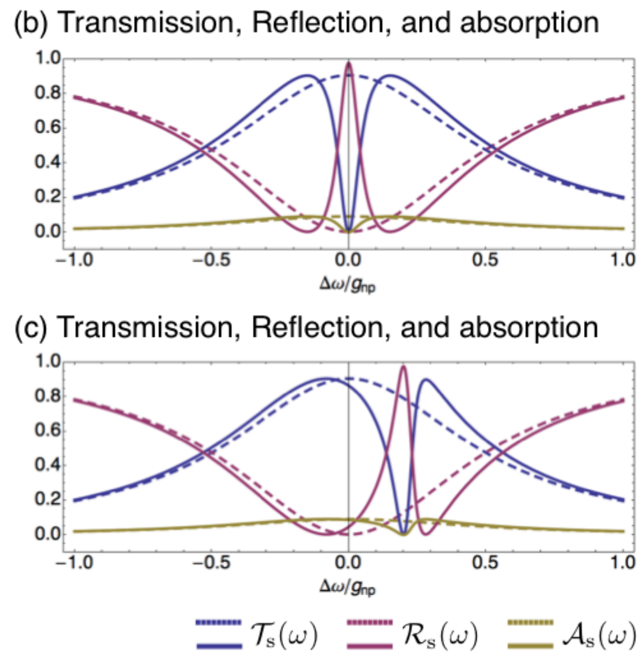


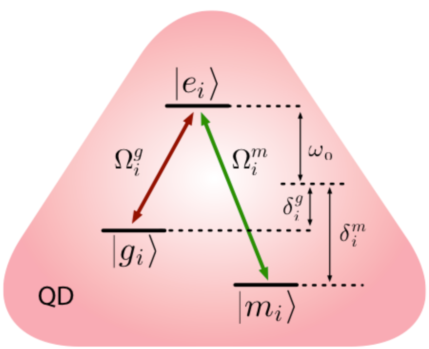


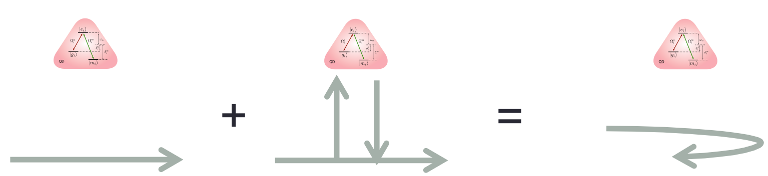
Fleischhauer et al., RMP 77, 633 (2005)

Theory









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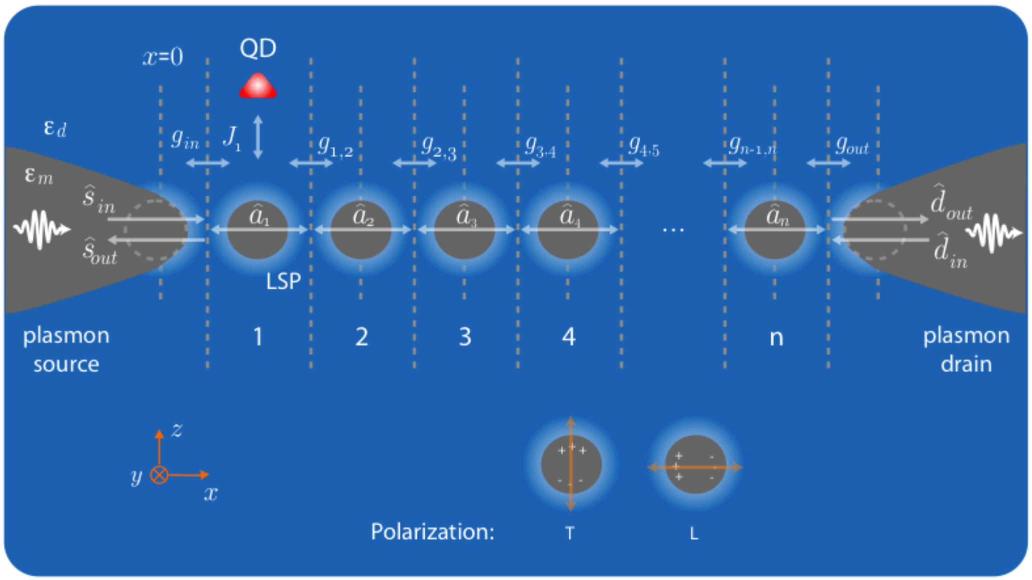
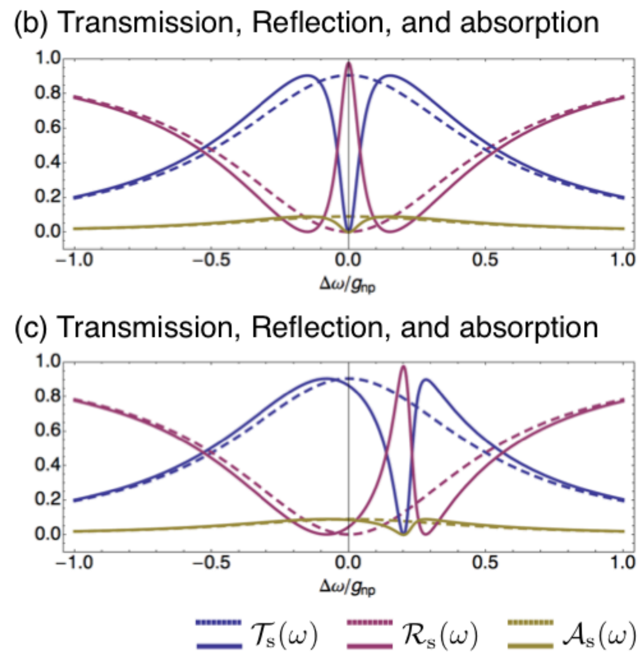
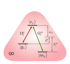
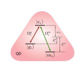
Waks and Vuckovic, PRL 96, 153601 (2006)

Theory





m 

g 

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

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

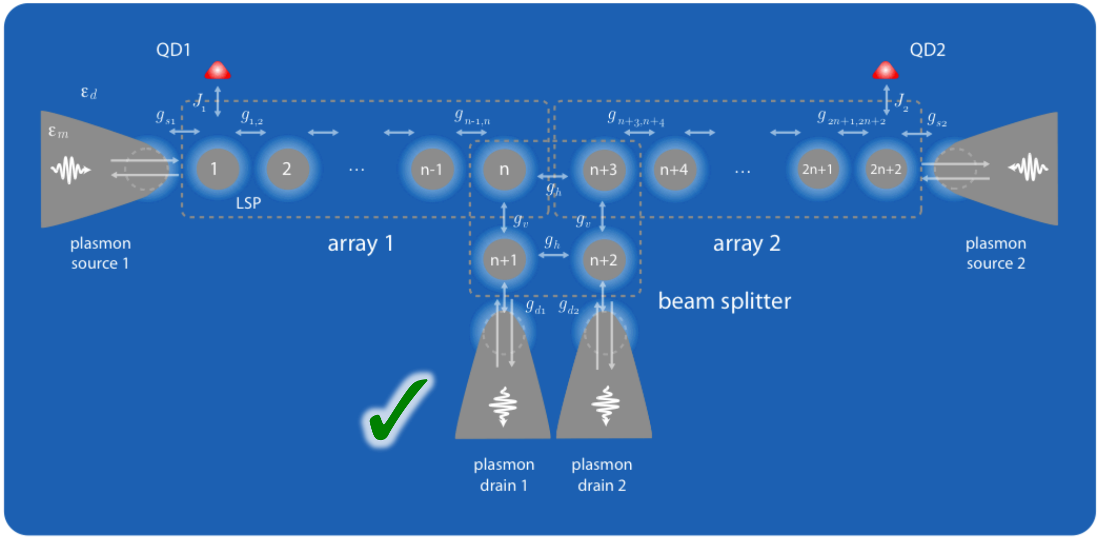
$$t_s = t_0/(F_p + 1)$$

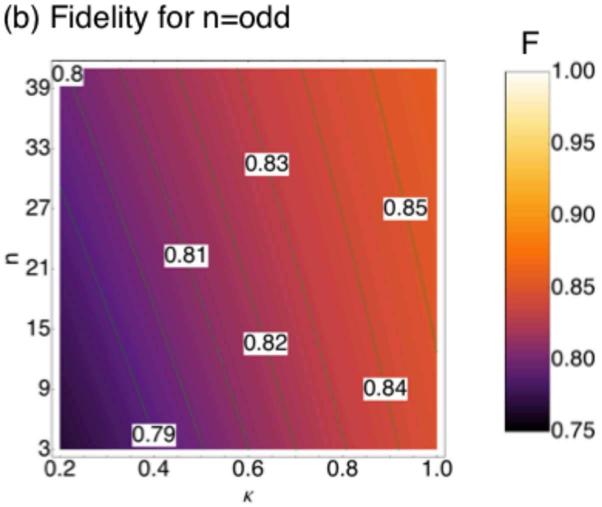
$$F_p \gg 1$$

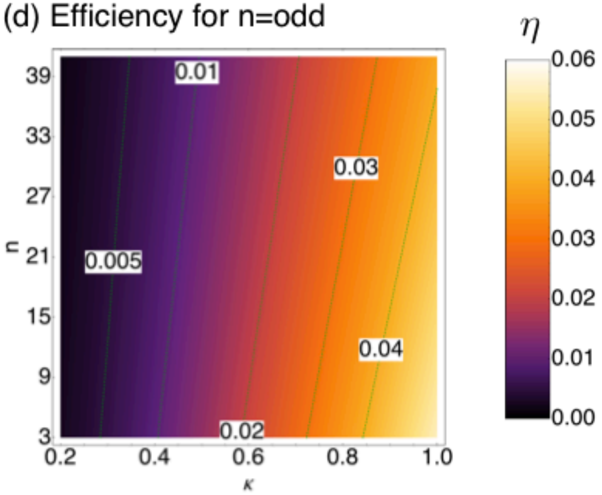
Bad-cavity: $\gamma \ll g_{\text{in-out}} + \Gamma_0/2$

$J \ll g_{\text{in-out}} + \Gamma_0/2$

Theory





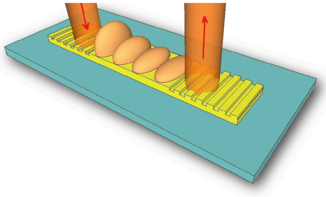


$$|\Psi\rangle_{\mathrm{QDs}} = \frac{1}{\sqrt{2}}(|mg\rangle - |gm\rangle)$$

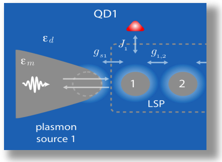
Overview of talk

1. *Introduction* – What is ‘Quantum Plasmonics’?

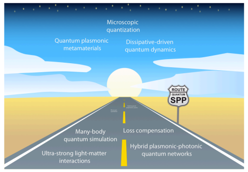
2. *Experimental work*



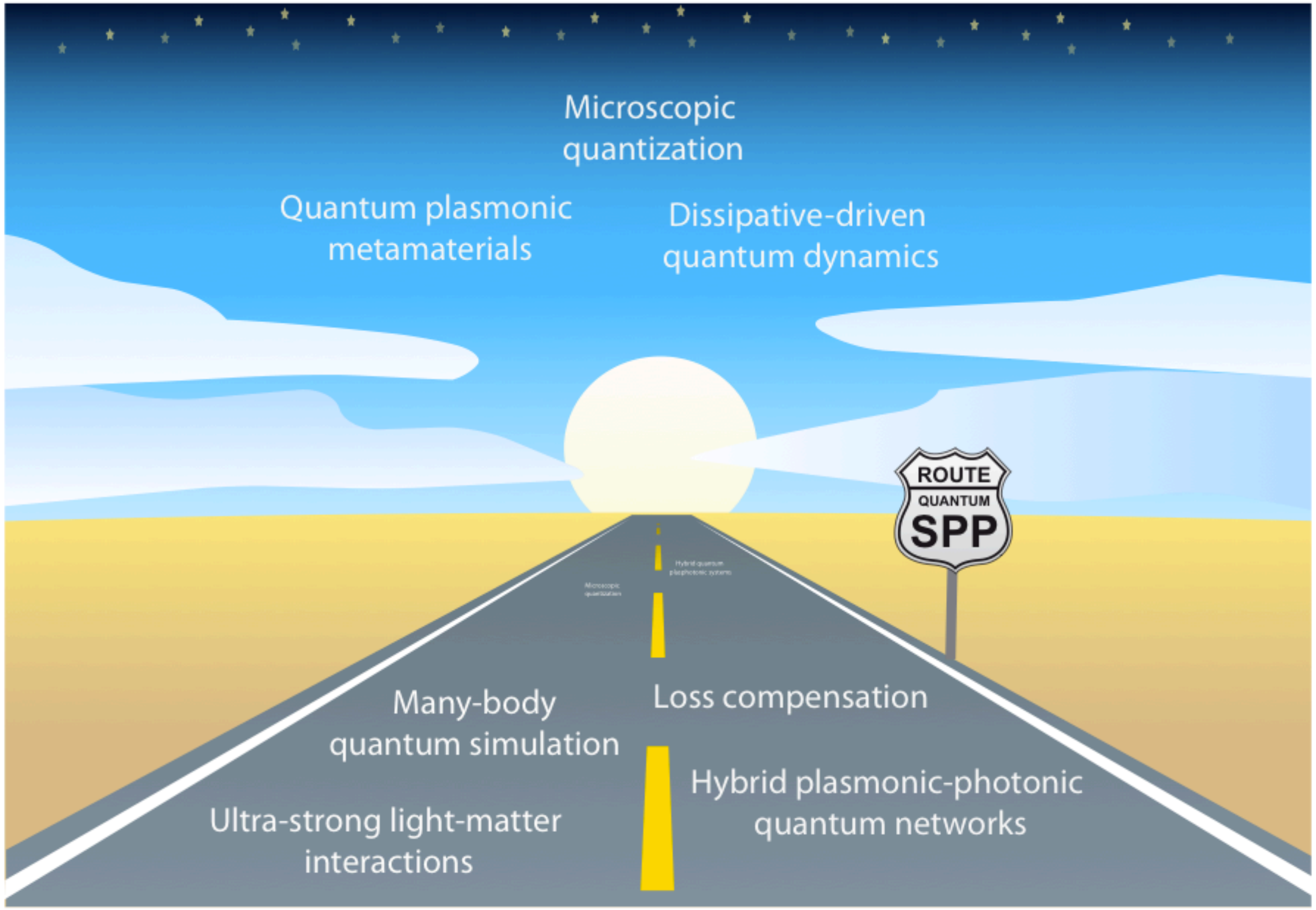
3. *Theory work*



4. *Future directions*



Future directions



Review article

nature physics

REVIEW ARTICLE

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Quantum plasmonics

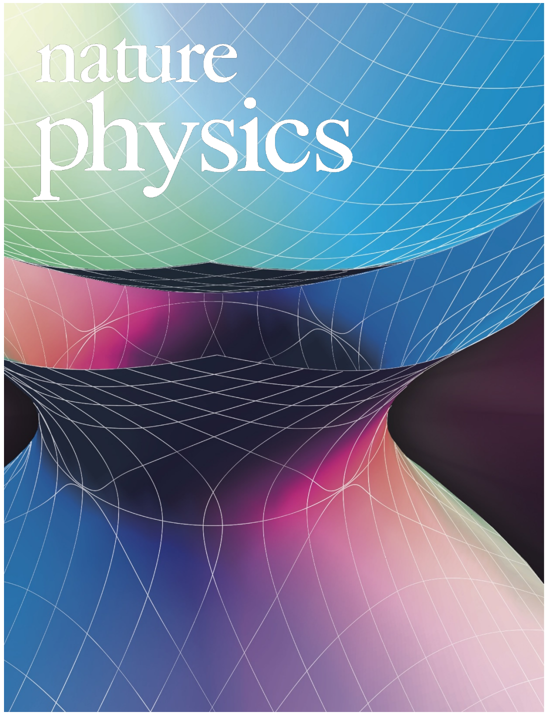
M. S. Tame[1]*, K. R. McEnery[1,2], Ş. K. Özdemir[3], J. Lee[4], S. A. Maier[1]* and M. S. Kim[2]

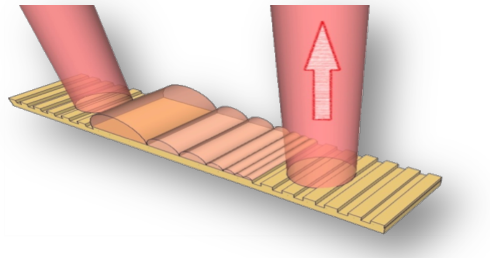
Quantum plasmonics is a rapidly growing field of research that involves the study of the quantum properties of light and its interaction with matter at the nanoscale. Here, surface plasmons—electromagnetic excitations coupled to electron charge density waves on metal-dielectric interfaces or localized 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.

M. S. Tame et al., Nature Physics, June (2013)





QUANTUM PLASMONICS

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