Quantum applications using plasmonics

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www.quantumnanophotonics.org

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NRF National Research Foundation

NITheP National Institute for Theoretical Physics

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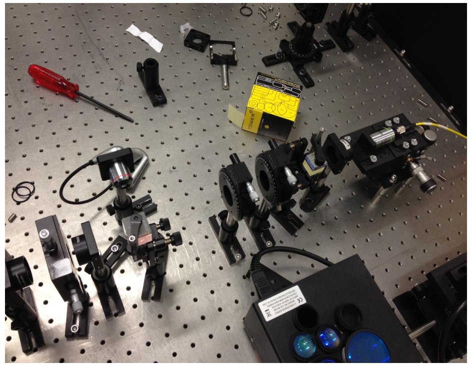
Quantum Nanophotonics Group

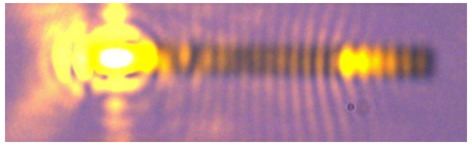
Solomon Uriri (PhD)

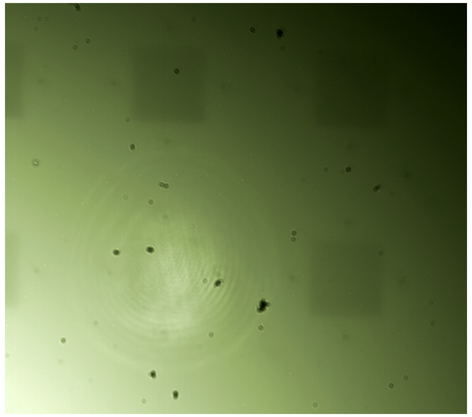
Sanele Dlamini (PhD)

Jason Francis (PhD)

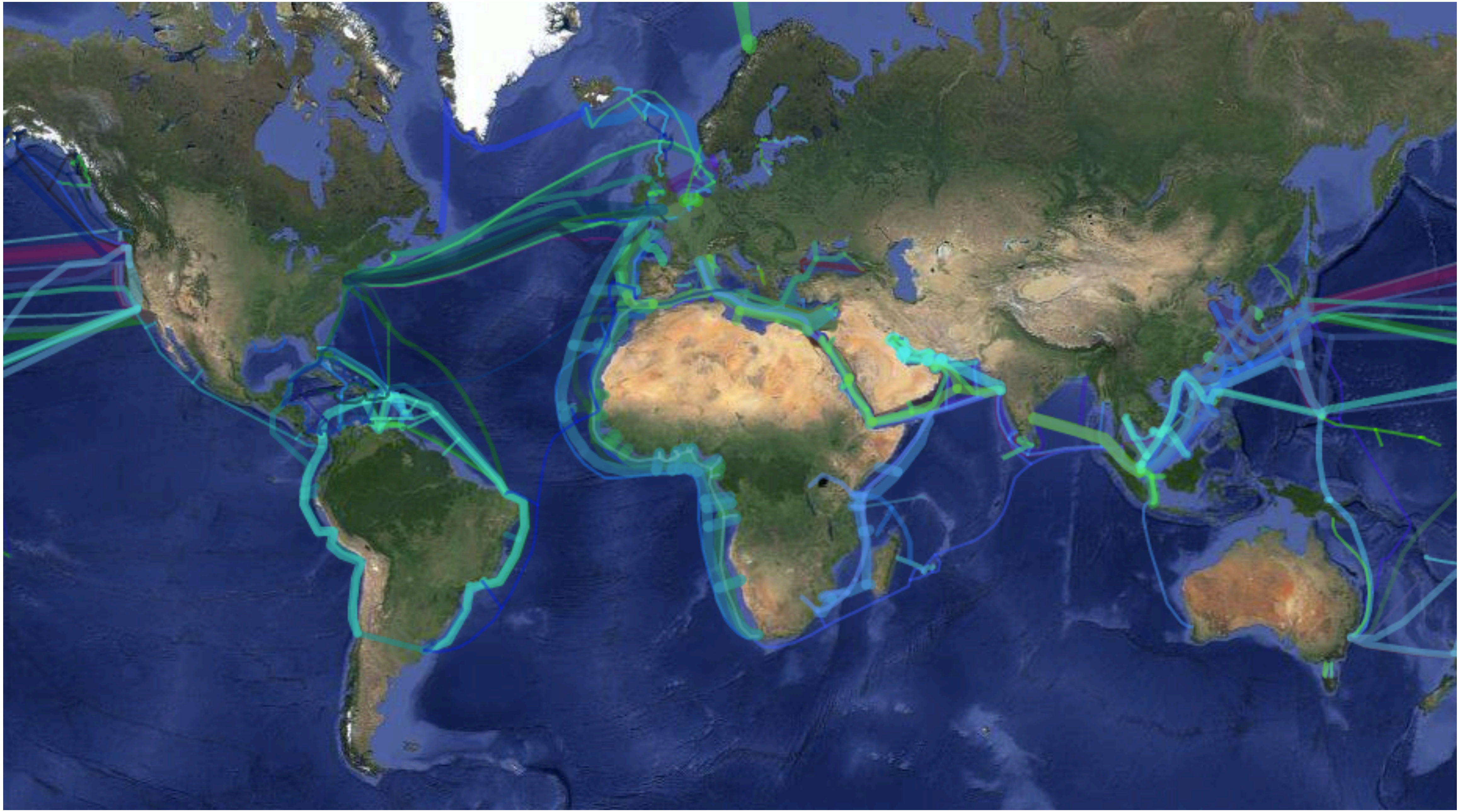
Kelvin Mpofu (MSc)



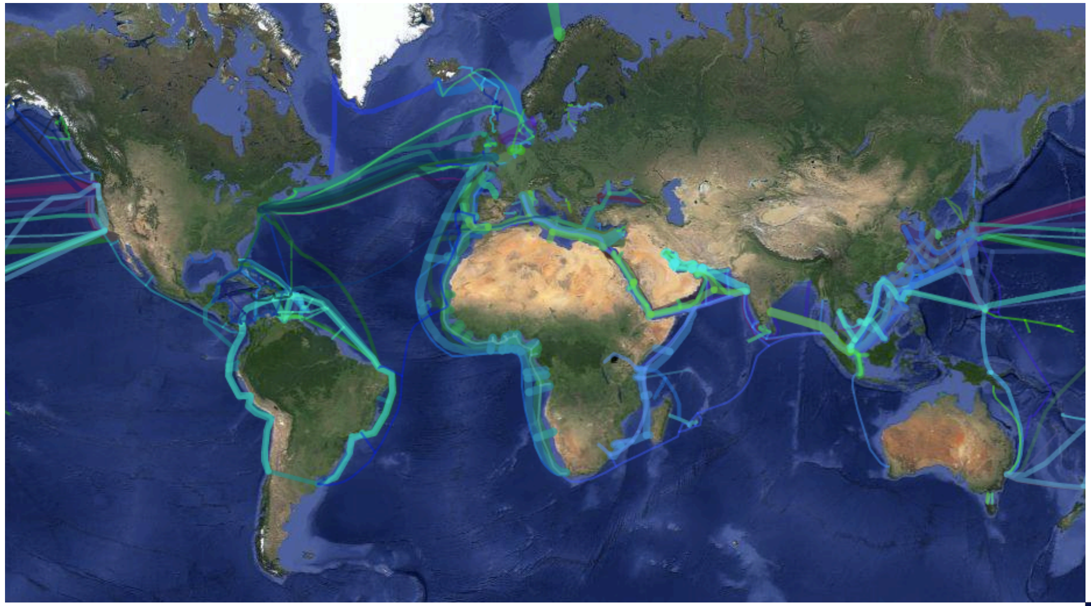




Introduction

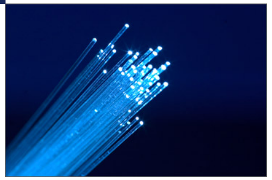


The shrinking scale of optics

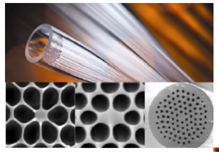


10^3
macroscale

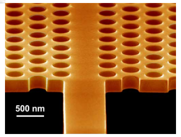
South Africa - fibre optic network



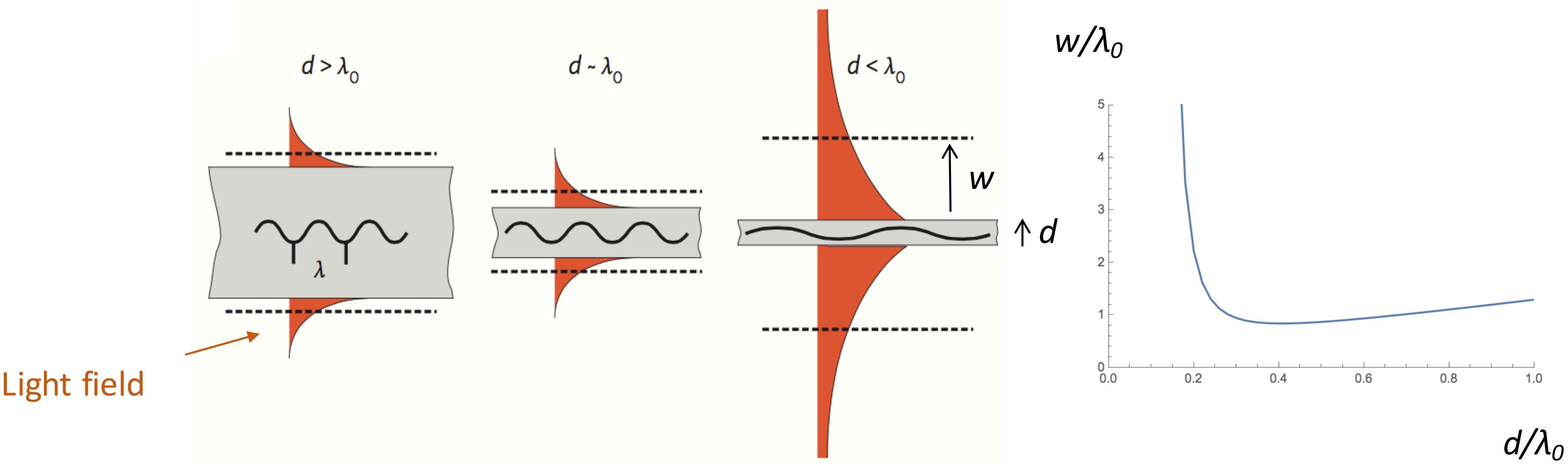
10^{-3} m
mesoscale



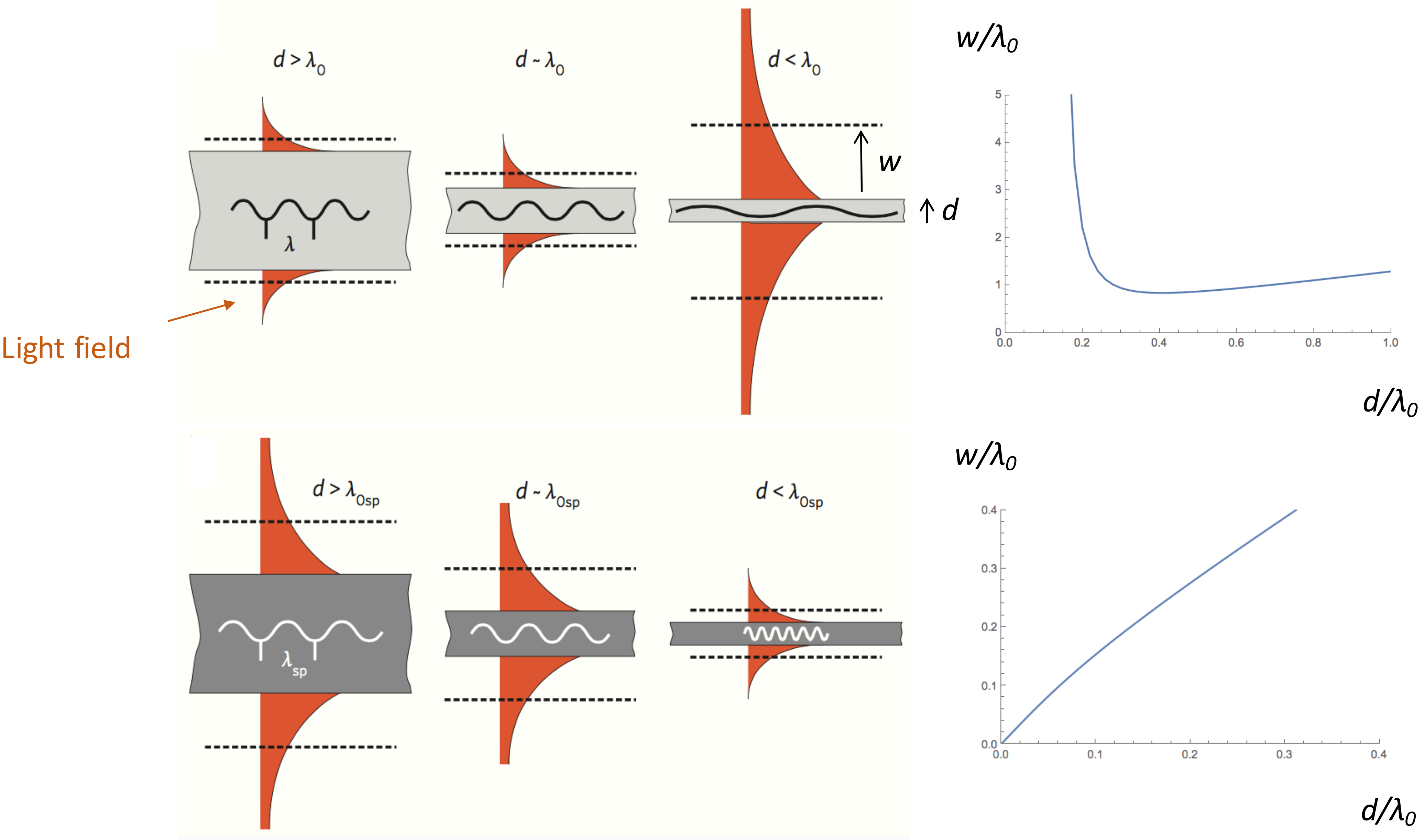
10^{-6} m
microscale



10^{-9} m
nanoscale



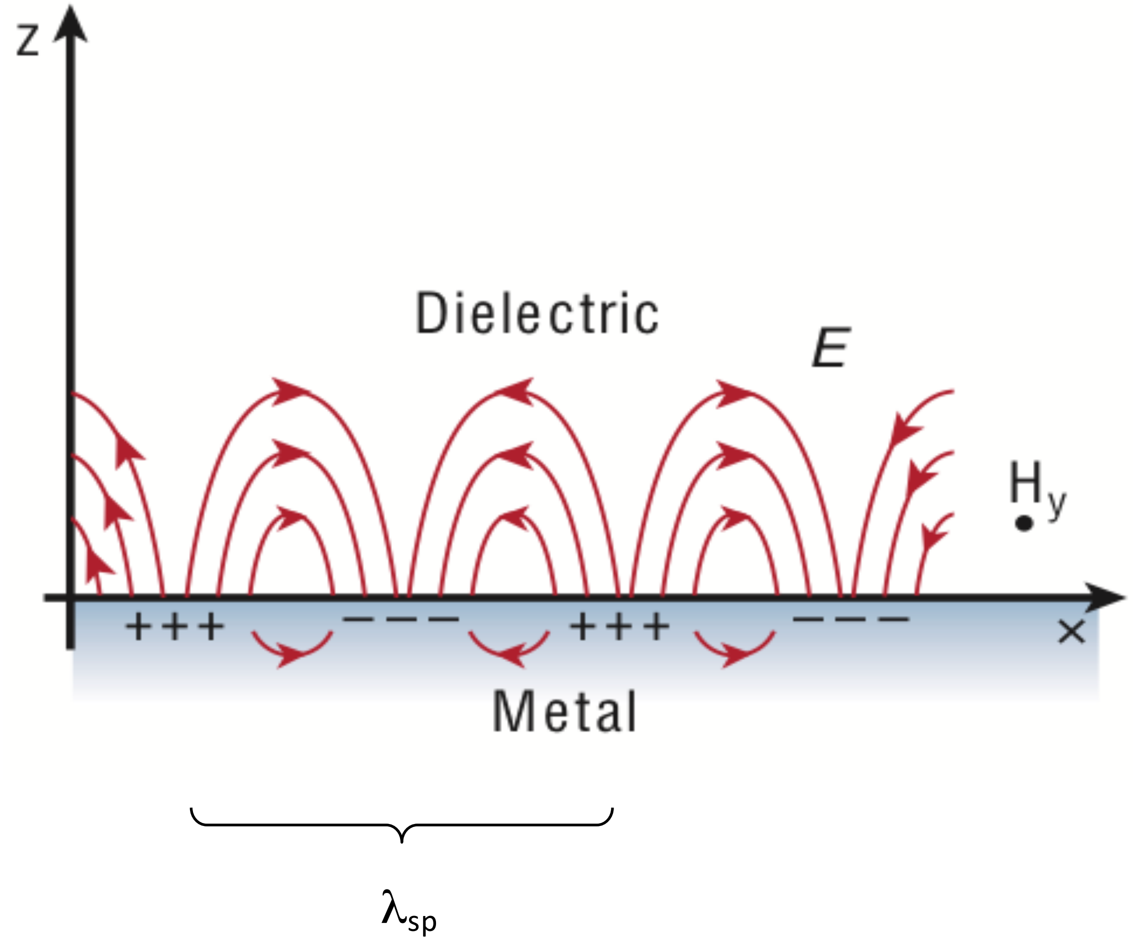
$d > \lambda_0$
$d \sim \lambda_0$
$d < \lambda_0$
λ
w
d
Light field
w/λ_0
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
d/λ_0



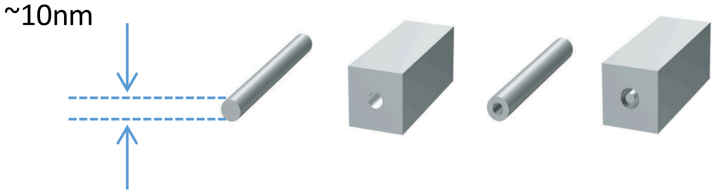
Gramotnev and Bozhevolnyi, Nat. Phot. 4, 83 (2010)

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

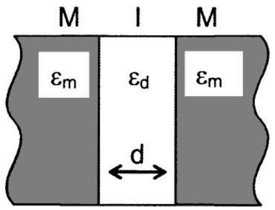
Surface plasmon polariton



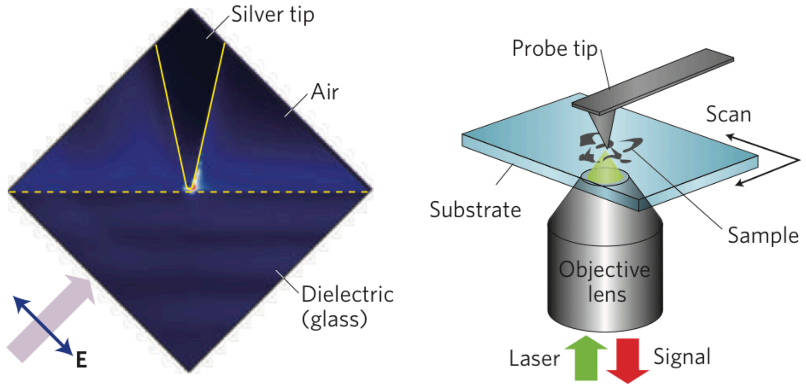
Barnes, Dereux and Ebbesen, Nature 424, 824 (2003)



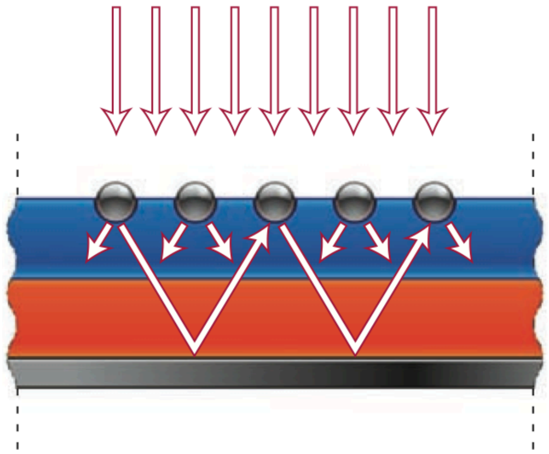
Takahara, Plasmonic Nanoguides and Circuits (2009)



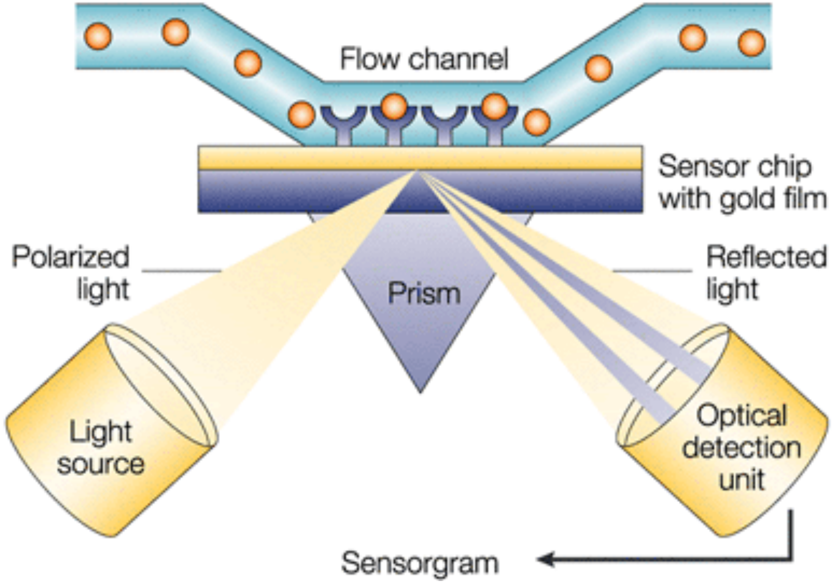
Zia et al., J. Opt. Soc. Am. A 21, 2442 (2004)



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

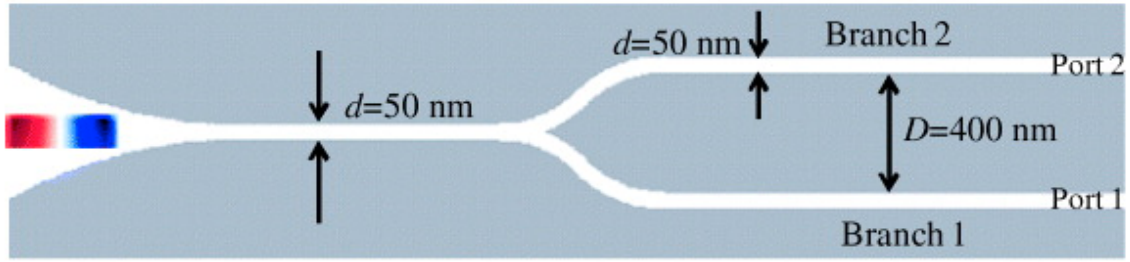


Atwater and Polman, Nature Mat. 9, 205 (2010)

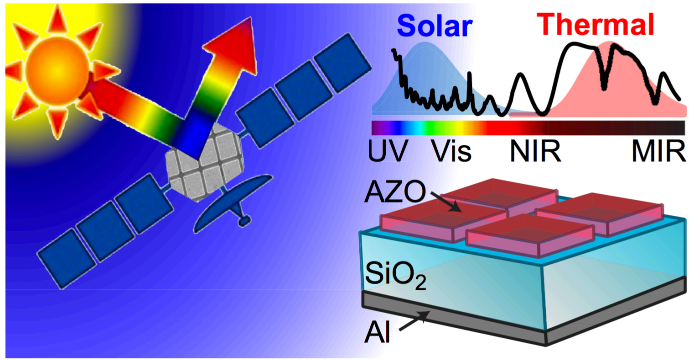


Anker et al., Nature Mat. 7, 442 (2008)

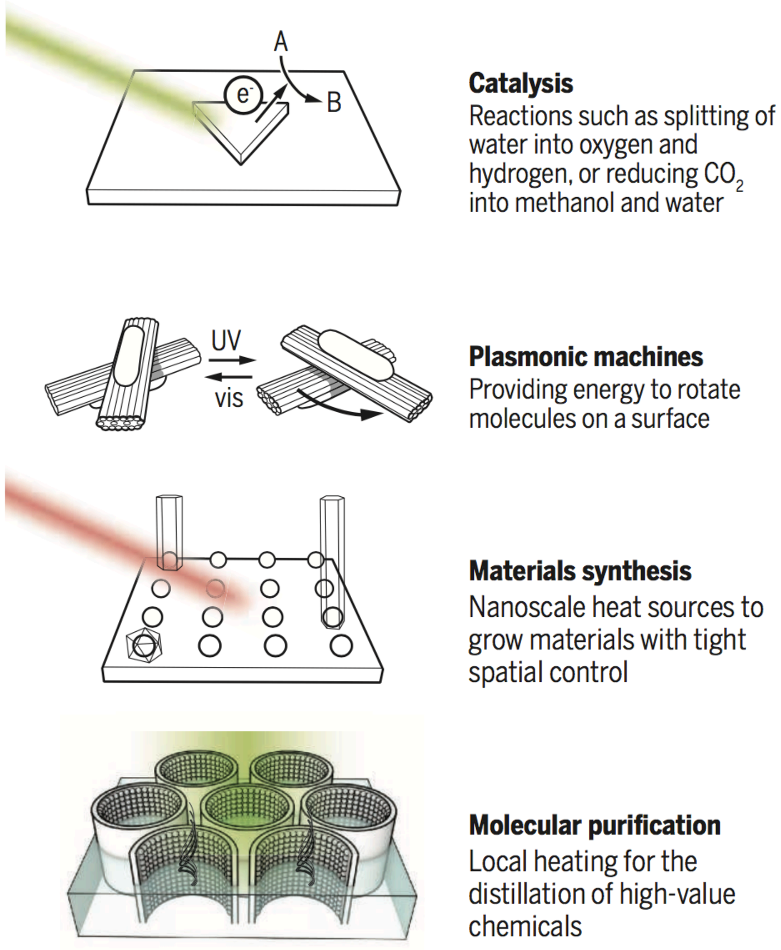
e.g. BIACORE, Dynamic Biosensors, Attana AB etc.



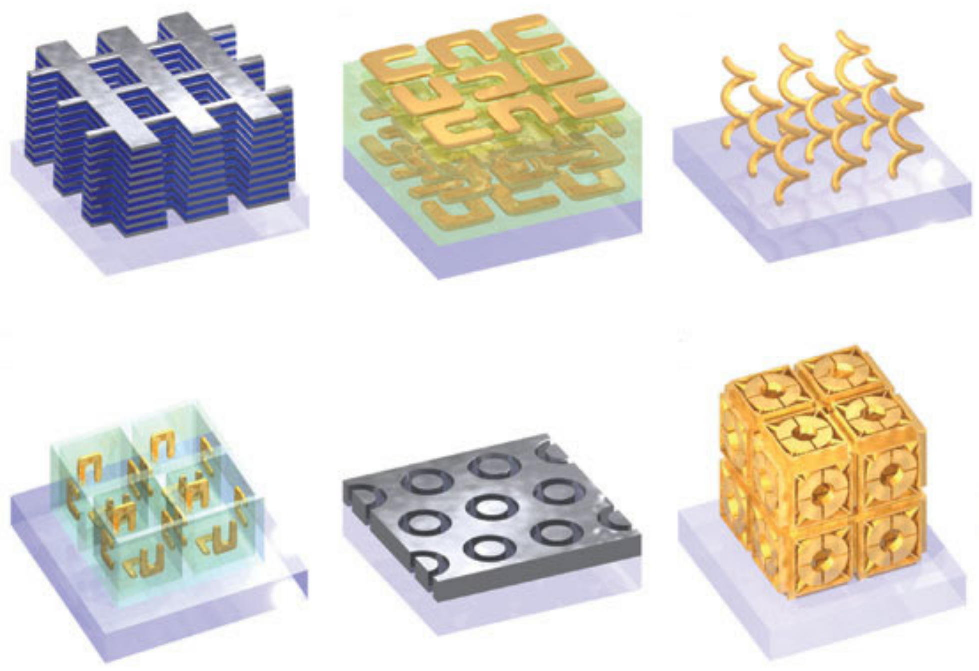
Gramotnev and Bozhevolnyi, Nature Phot. 4, 83 (2010)



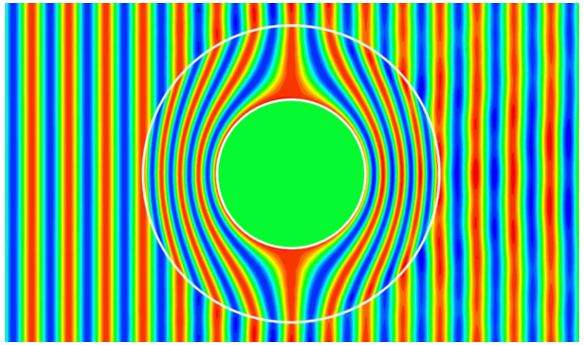
Sun et al., ASAP, ACS Photonics (2018)



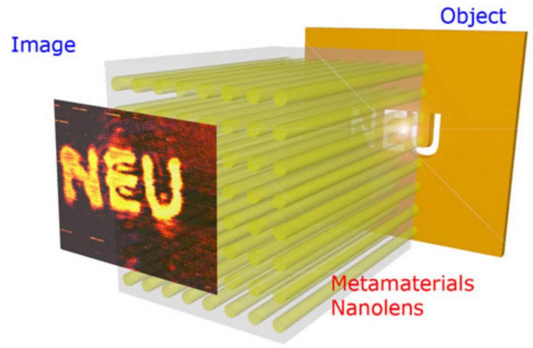
Naldoni et al., Science 356, 908 (2017)



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

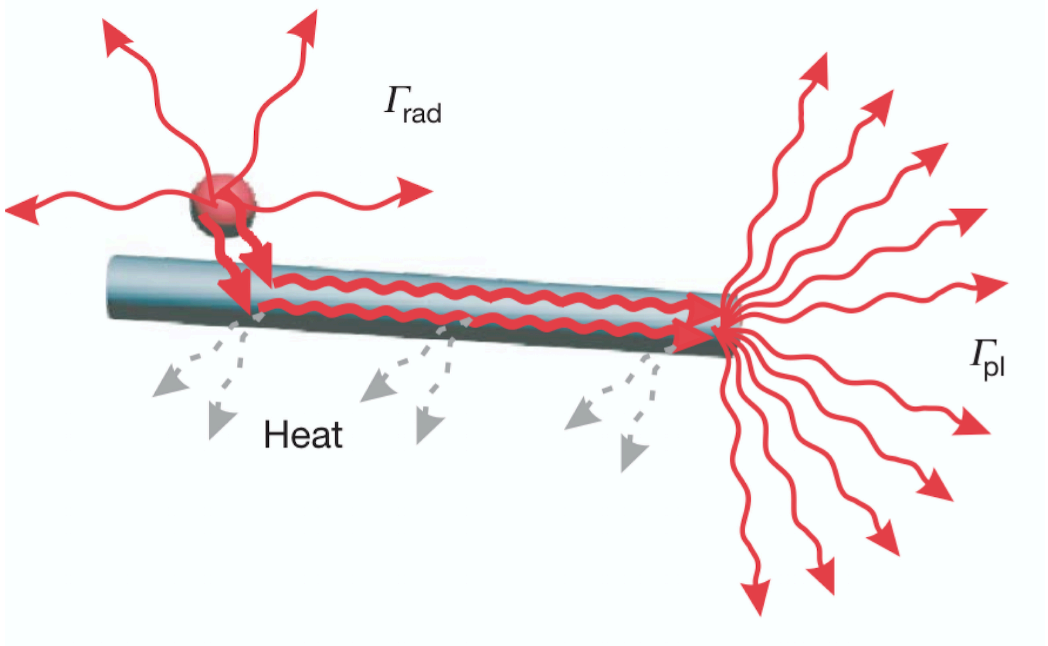


Cai et al., Nat. Phot. 1, 224 (2007)

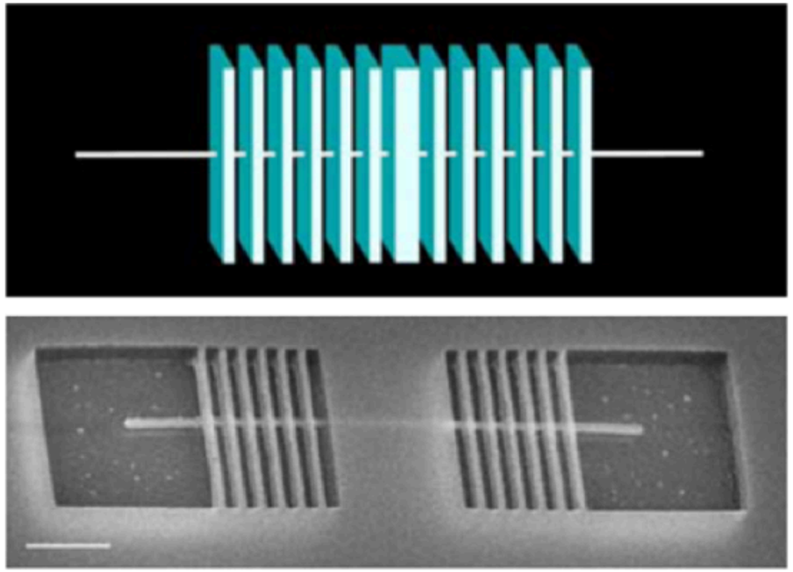


Casse et al., APL 96, 023114 (2010)

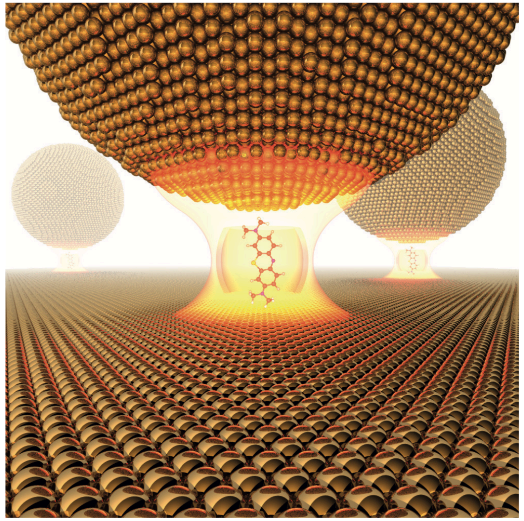
What about quantum?

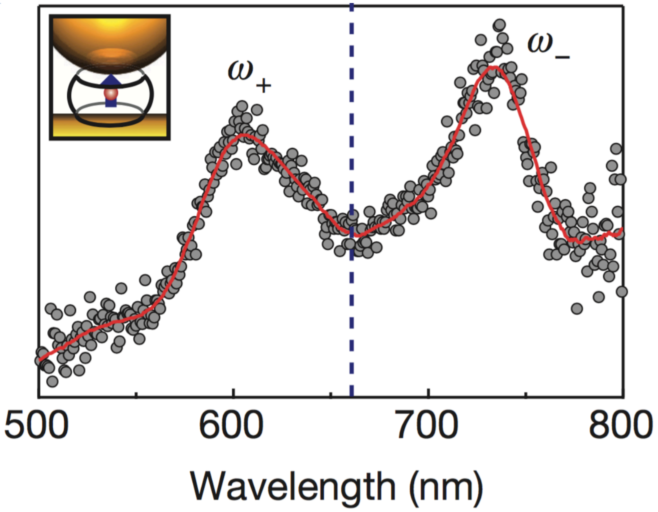


Akimov et al., Nature 450, 402 (2007)

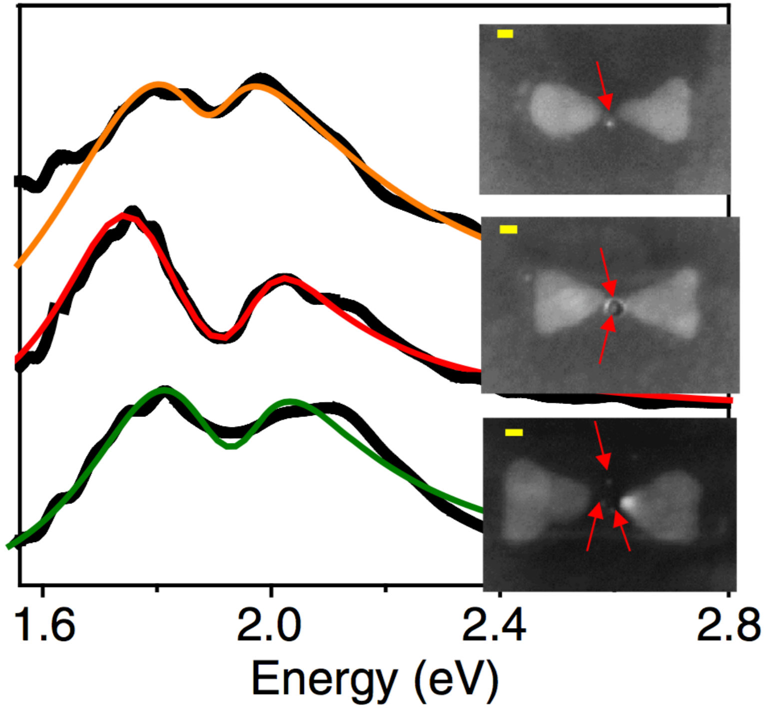


de Leon et al., PRL 108, 226803 (2012)

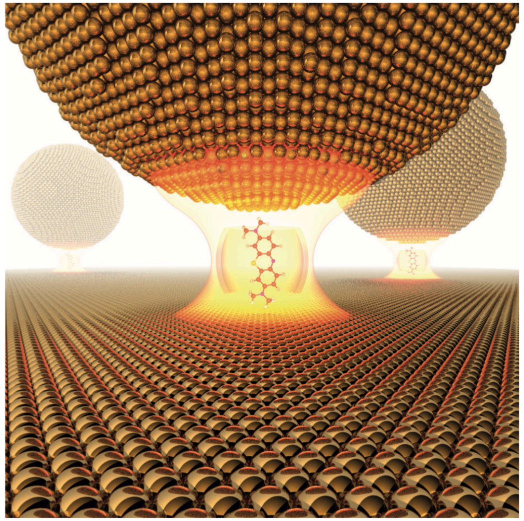


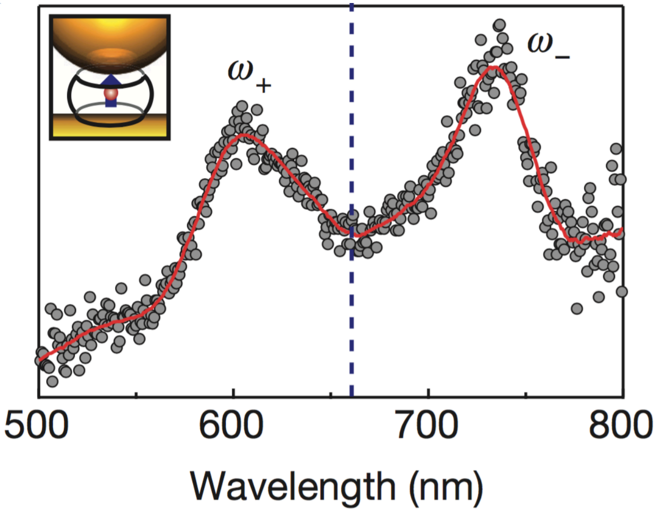


Chikkaraddy et al., Nature 535, 127 (2016)

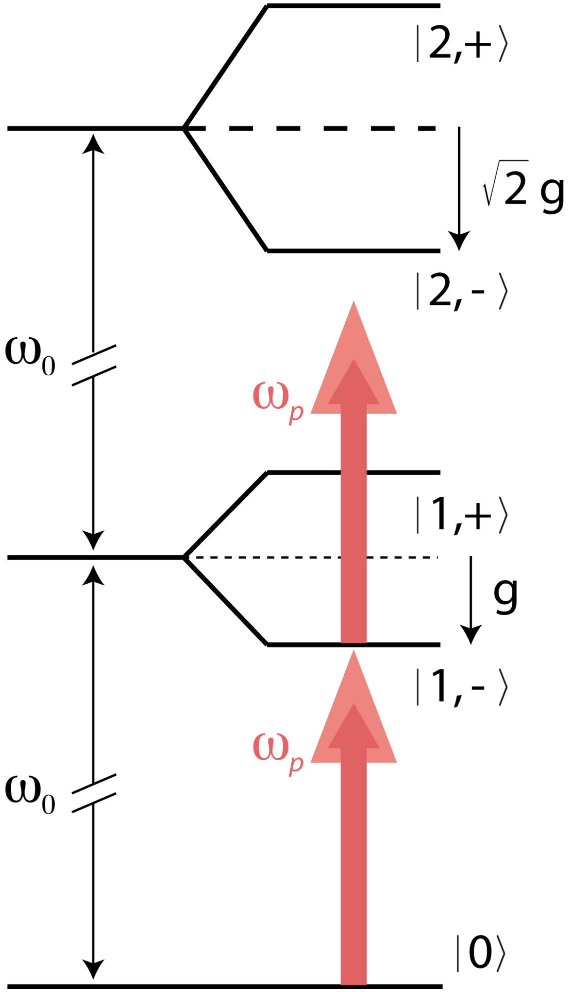


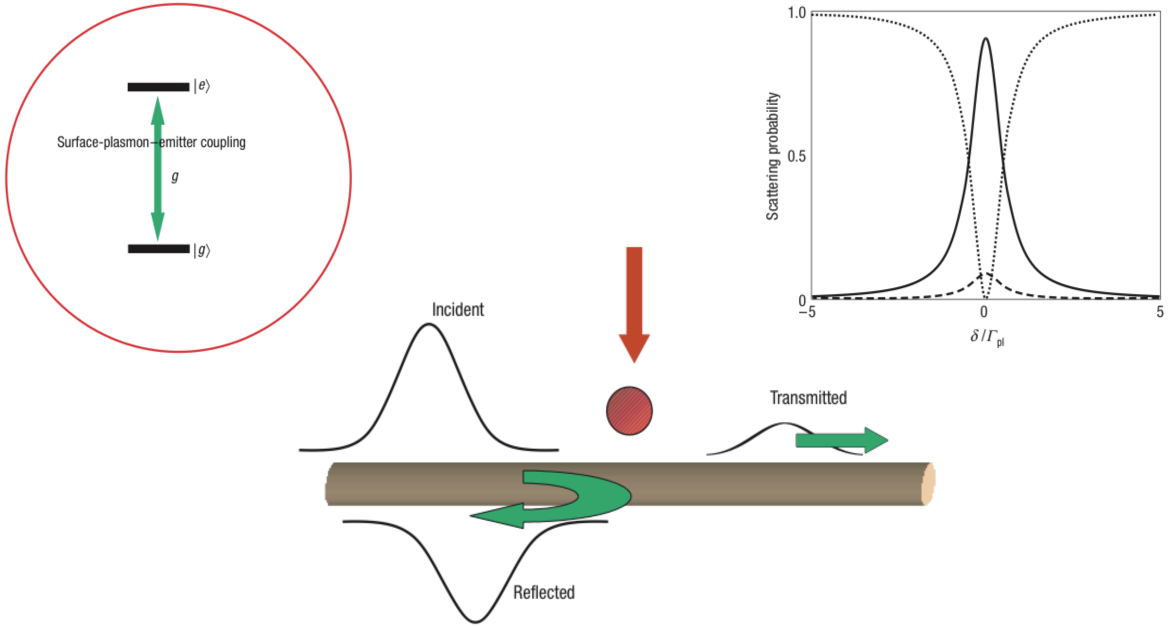
Santhosh et al. Nature Comm. 7, 11823 (2016)



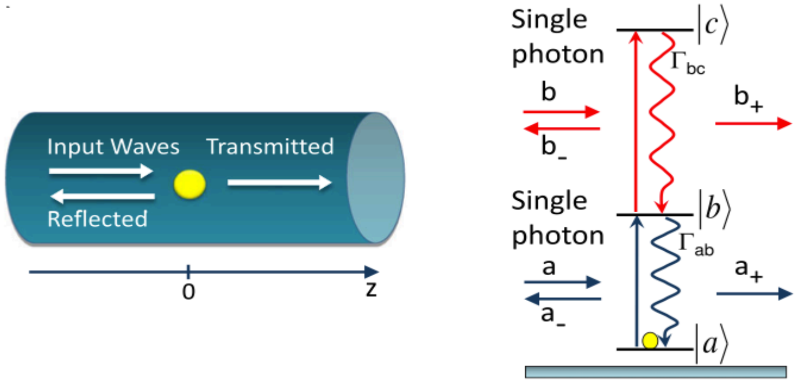


Chikkaraddy et al., Nature 535, 127 (2016)

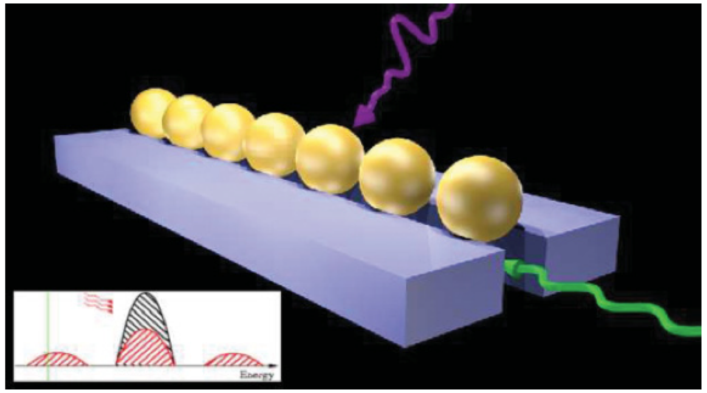




Chang et al., Nature Phys. 3, 807 (2007)

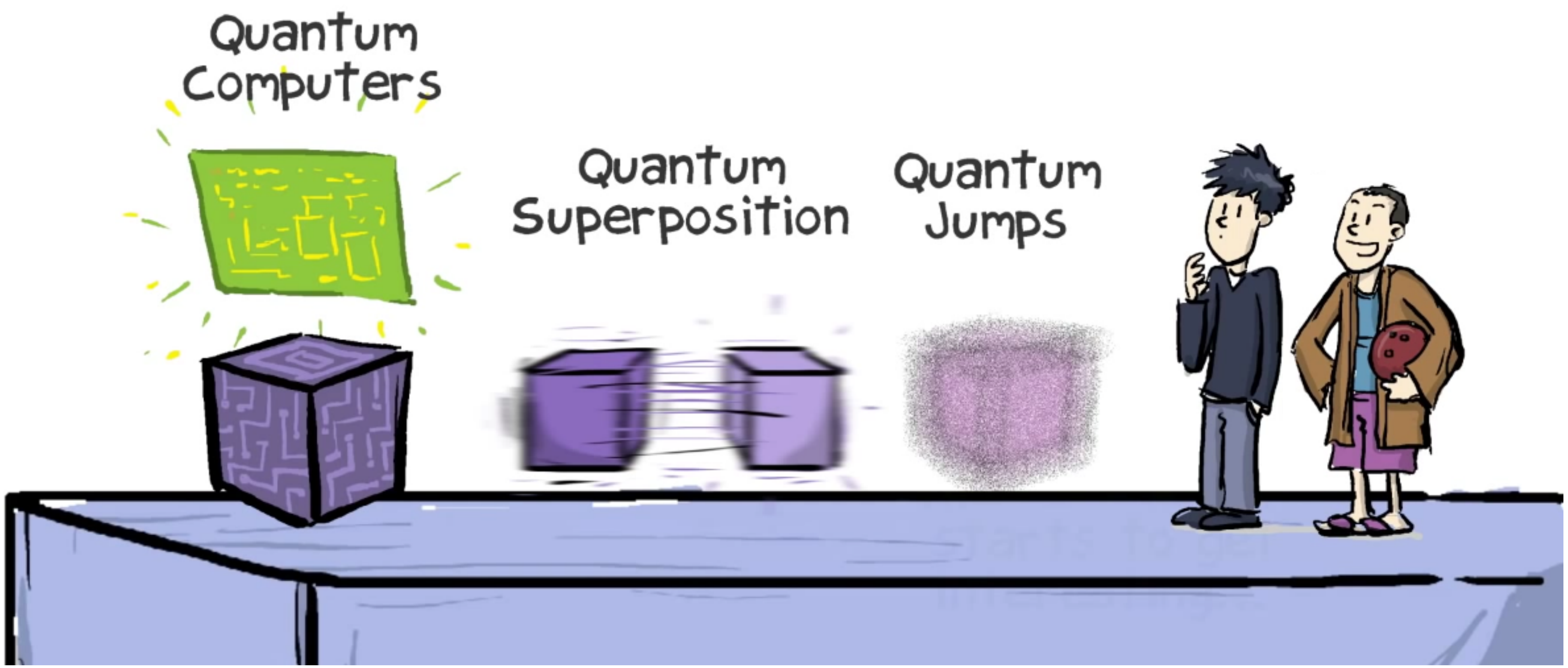


Kolchin et al., PRL 106, 113601 (2011)



Frank, PRB 85, 195463 (2012)

PhD comics

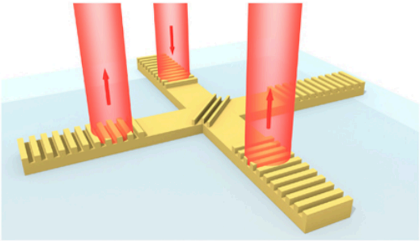


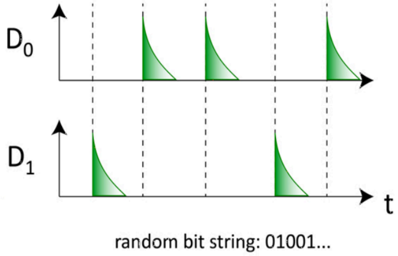
Quantum Communication   Quantum Sensing

Quantum Simulation   Quantum Networks

Quantum applications

1. Quantum random number generation



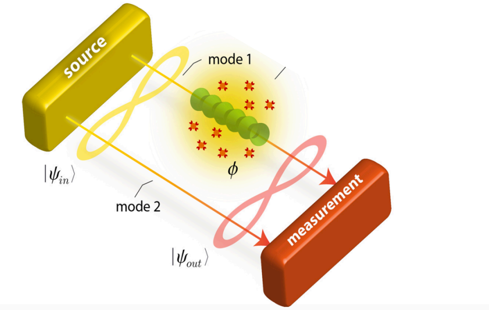


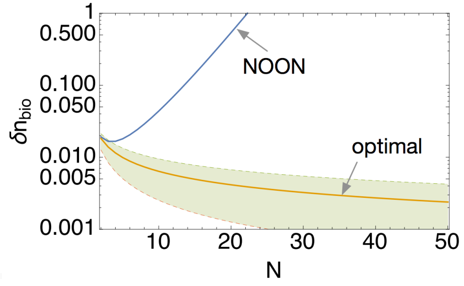
J. Francis et al. Quant. Sci. Tech. 2, 035004 (2017)

exp

the

2. Quantum sensing



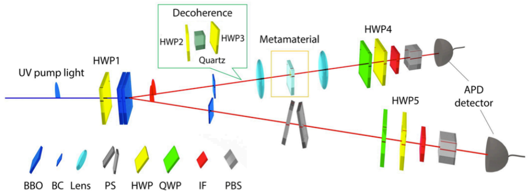


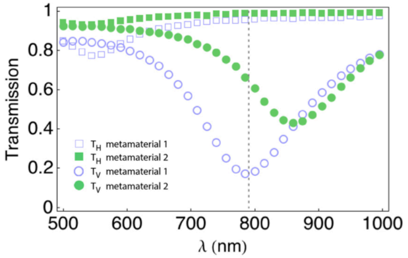
C. Lee et al. ACS Photonics 3, 992 (2016)

exp

exp

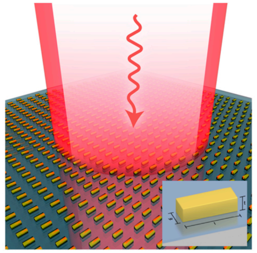
3. Metamaterial entanglement distillation

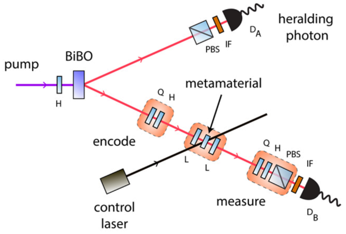




M. Asano et al. *Sci. Rep. 5, 18313* (2015)

4. Active quantum metamaterials





S. Uriri et al. *under review, Phys. Rev. A* (2018)

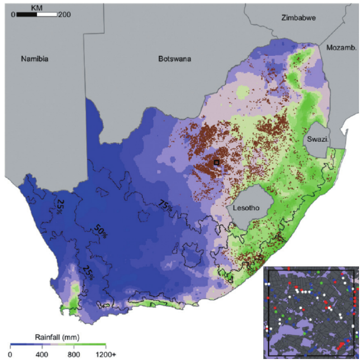
1. Random number generation

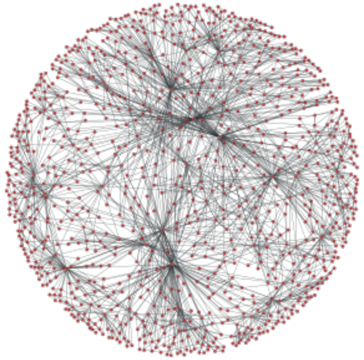
Random numbers are useful in many areas of science and technology:

Cryptography

Online gaming and casinos

Simulation of economic and agricultural models



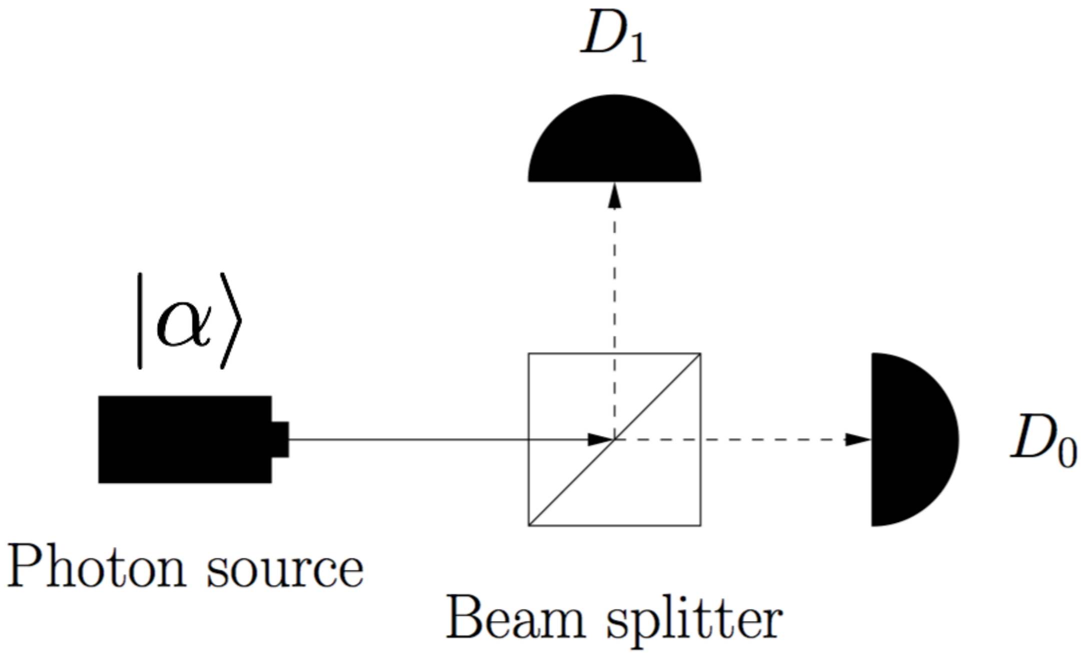


Coordination in computer networks

Herrero-Collantes and Garcia-Escartin,
Rev. Mod. Phys. 89, 015004 (2017)

‘True’ random numbers are hard to generate

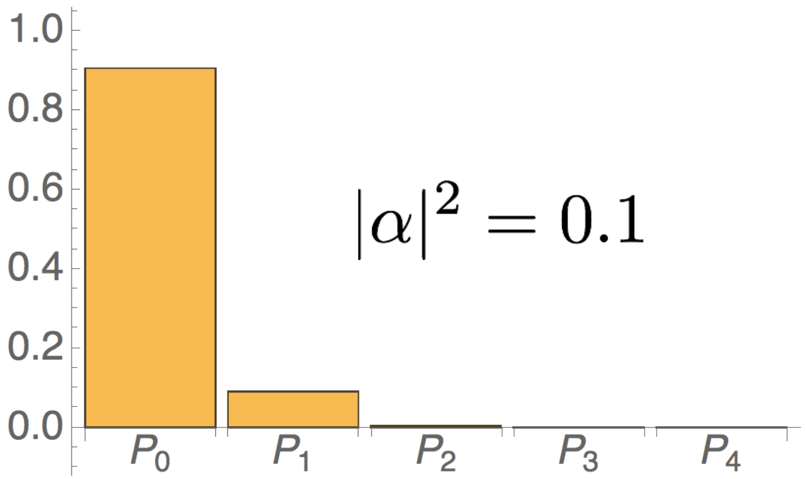
Quantum random number generation



$$|\alpha\rangle = \sum_n \alpha_n |n\rangle$$

$$|\alpha_n|^2 = P_n = e^{-|\alpha|^2} \frac{|\alpha|^{2n}}{n!}$$

$$|\alpha|^2 = \langle \hat{n} \rangle \ll 1$$



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USB
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ComScire, Picoquant, MPD, Qutools…

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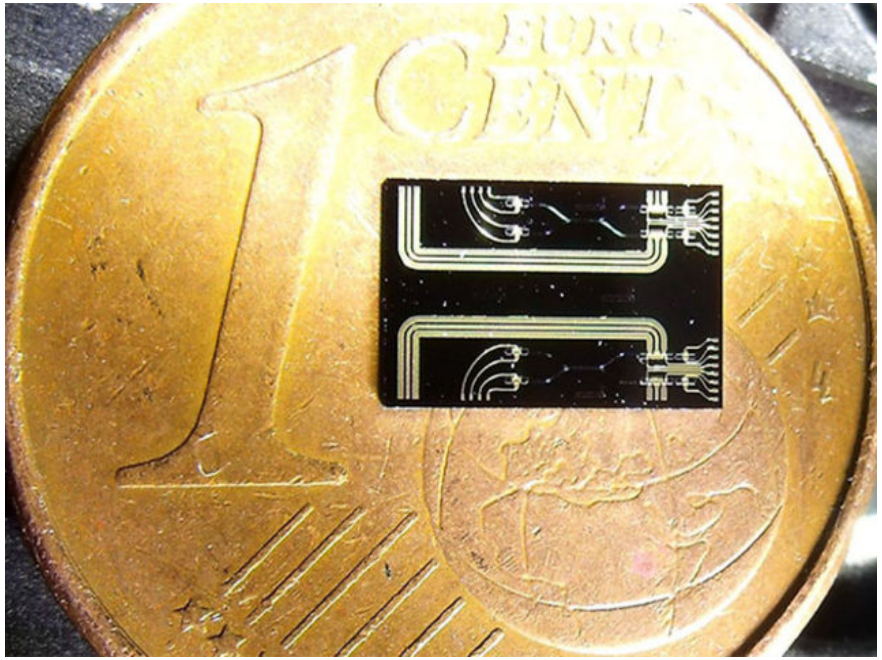
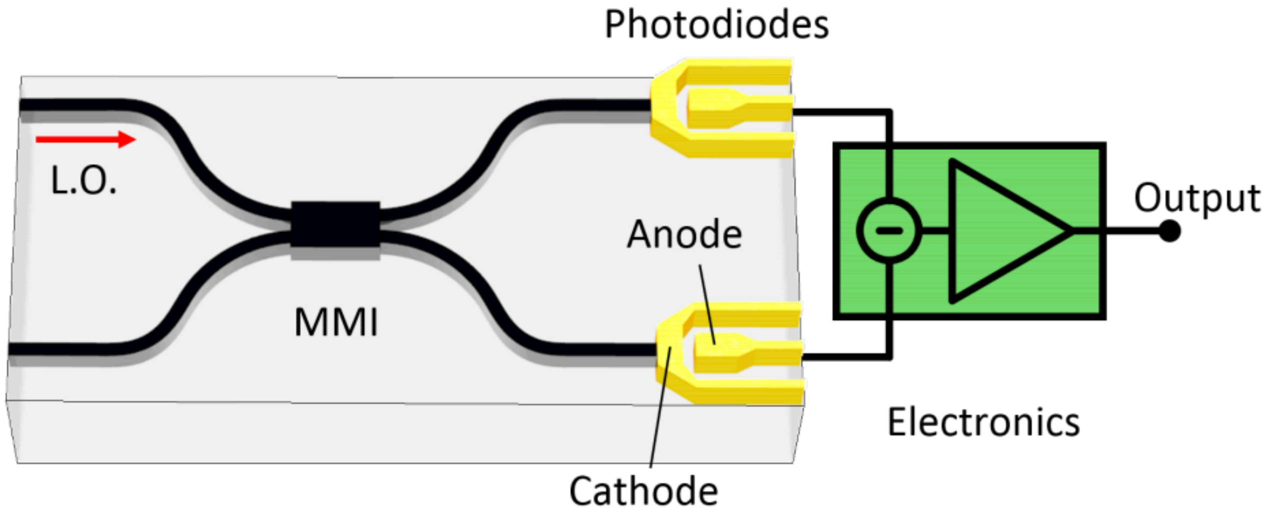
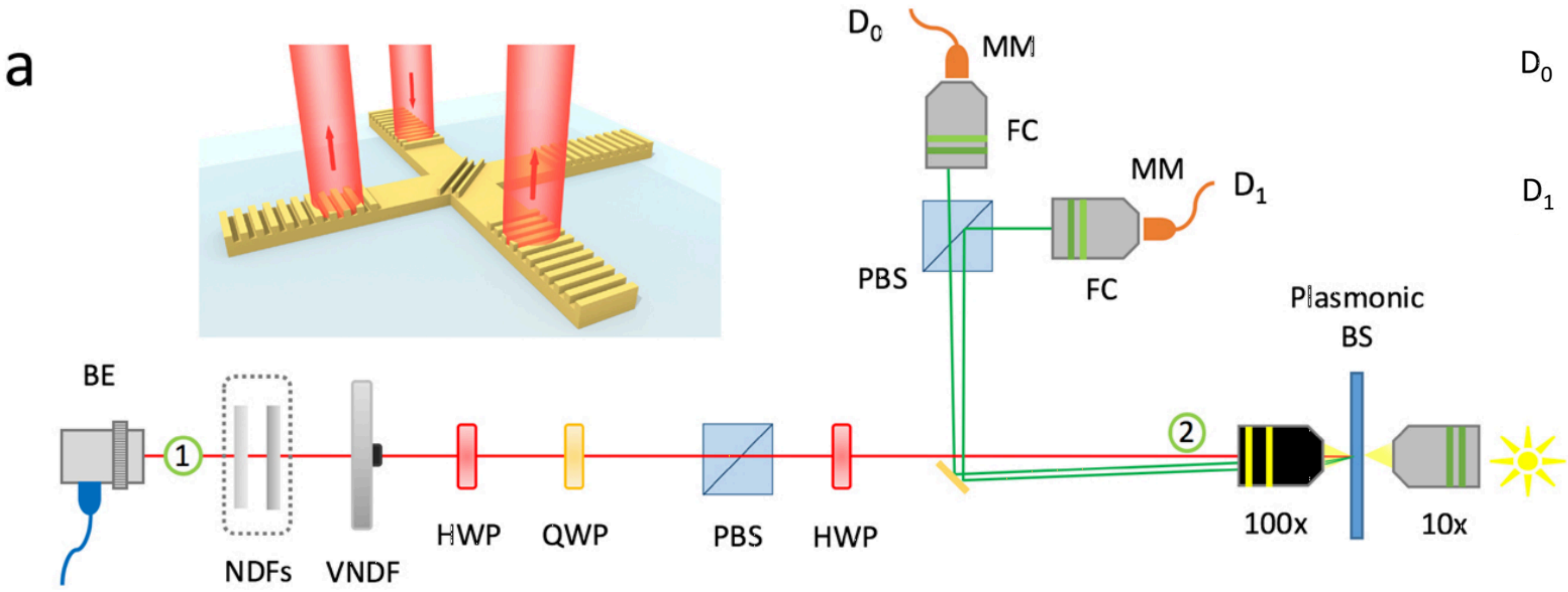
qrng.anu.edu.au

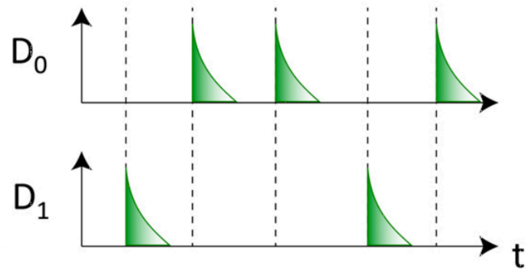


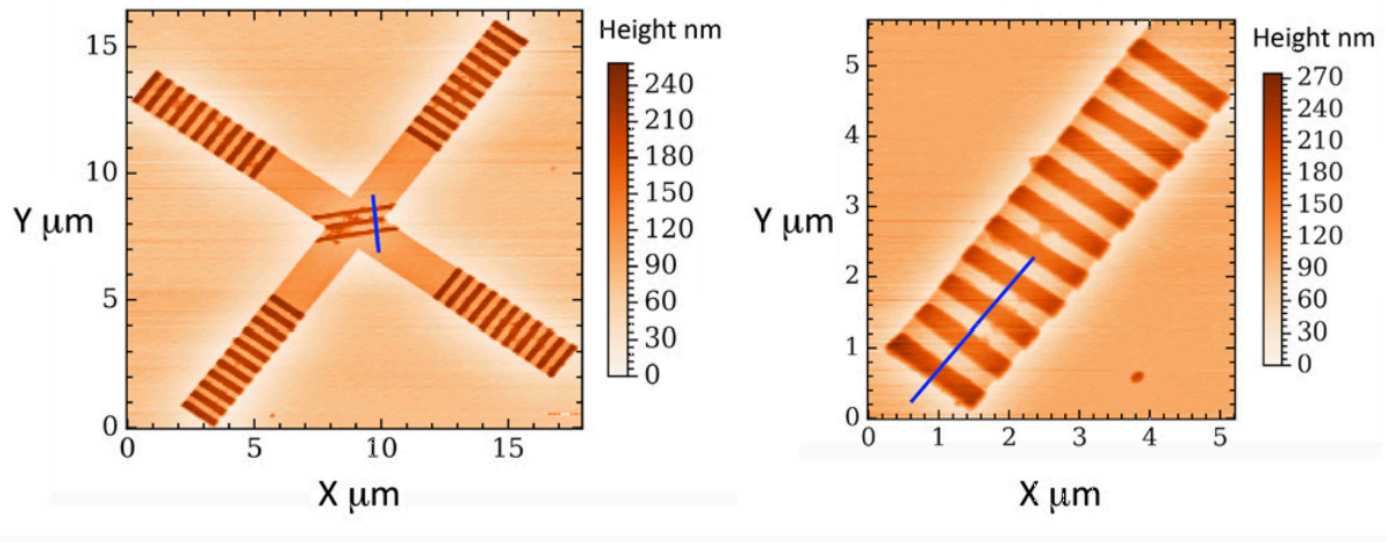
Abellan et al., Optica 3, 989 (2016)



Raffaelli et al., arXiv: 1612.04676 (2016)



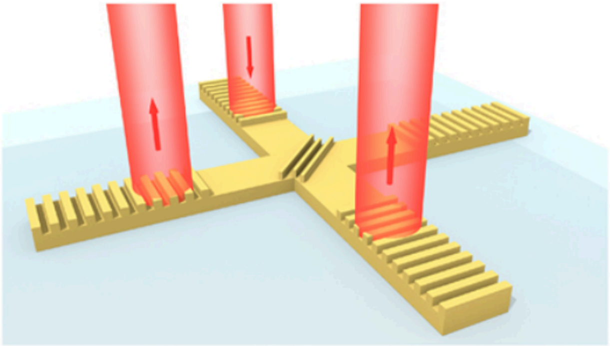


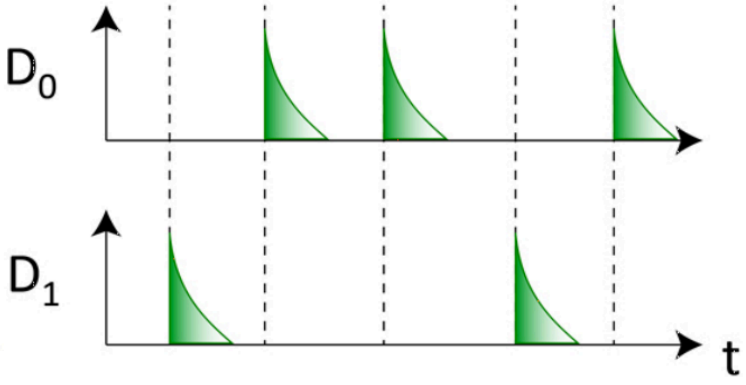


Jason Francis

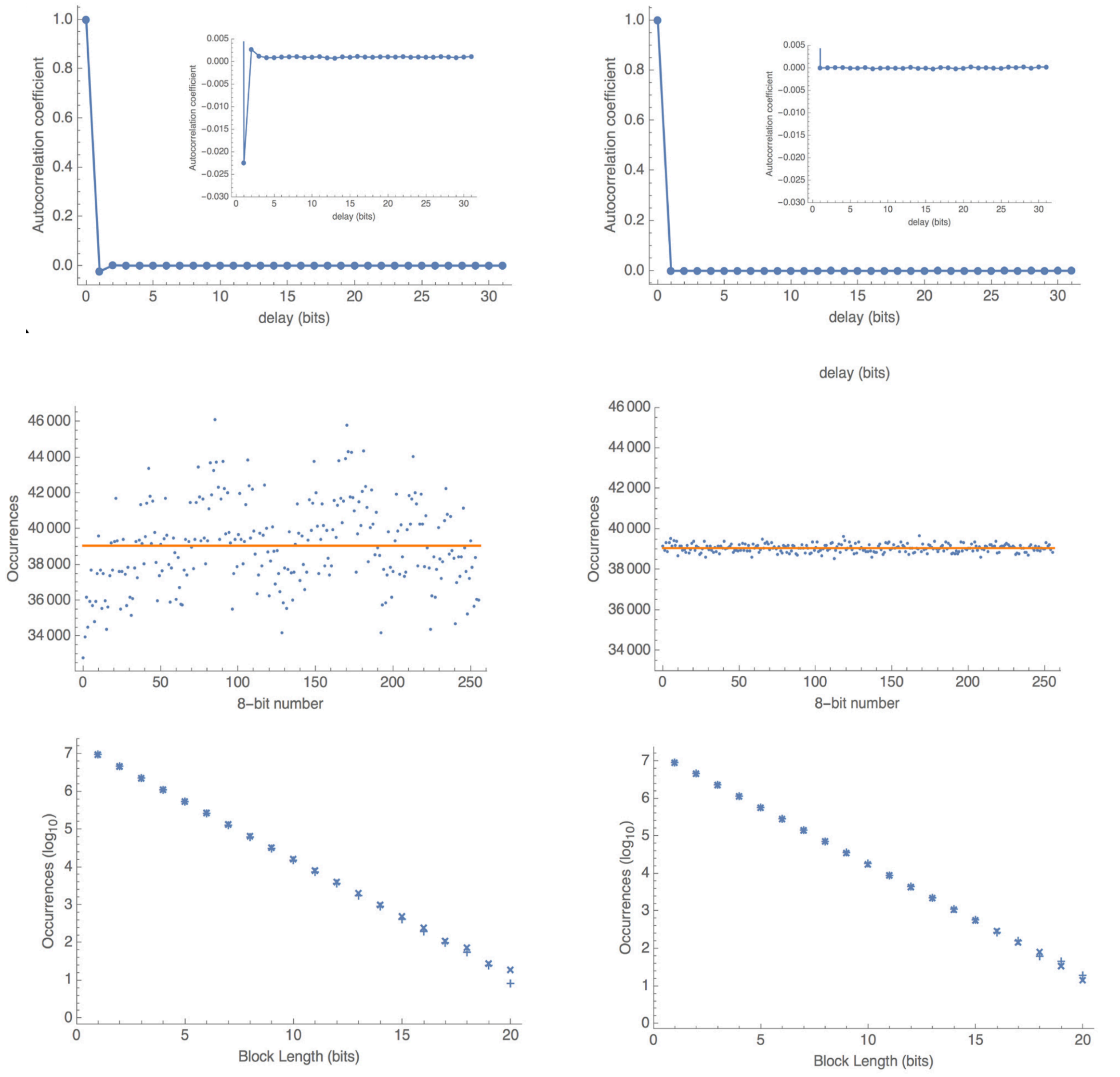
Francis et al., Quant. Sci. Tech. 2, 035004 (2017)

in principle we can go smaller, unlike
the previous examples





random bit string: 01001...

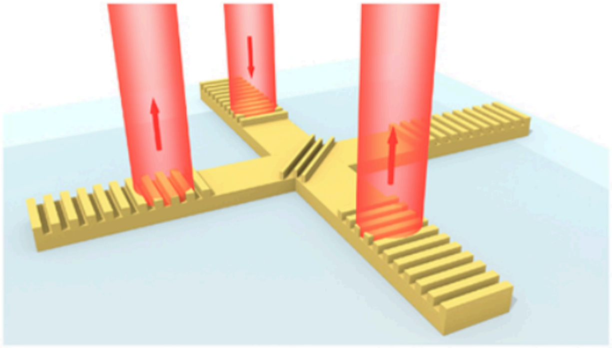


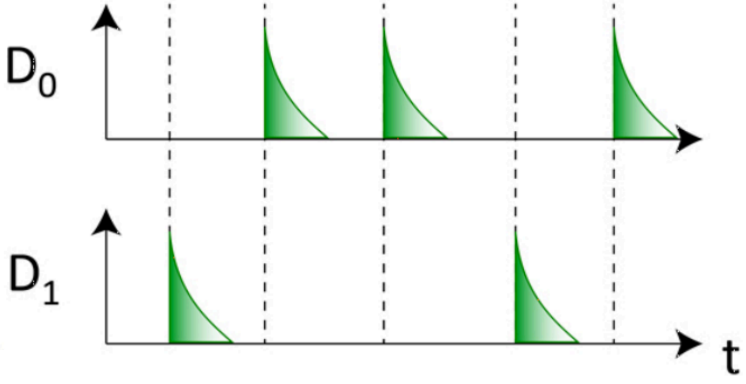
raw

2.43 Mbits/s

postprocessed
(recursive von Neumann)

2.37 Mbits/s



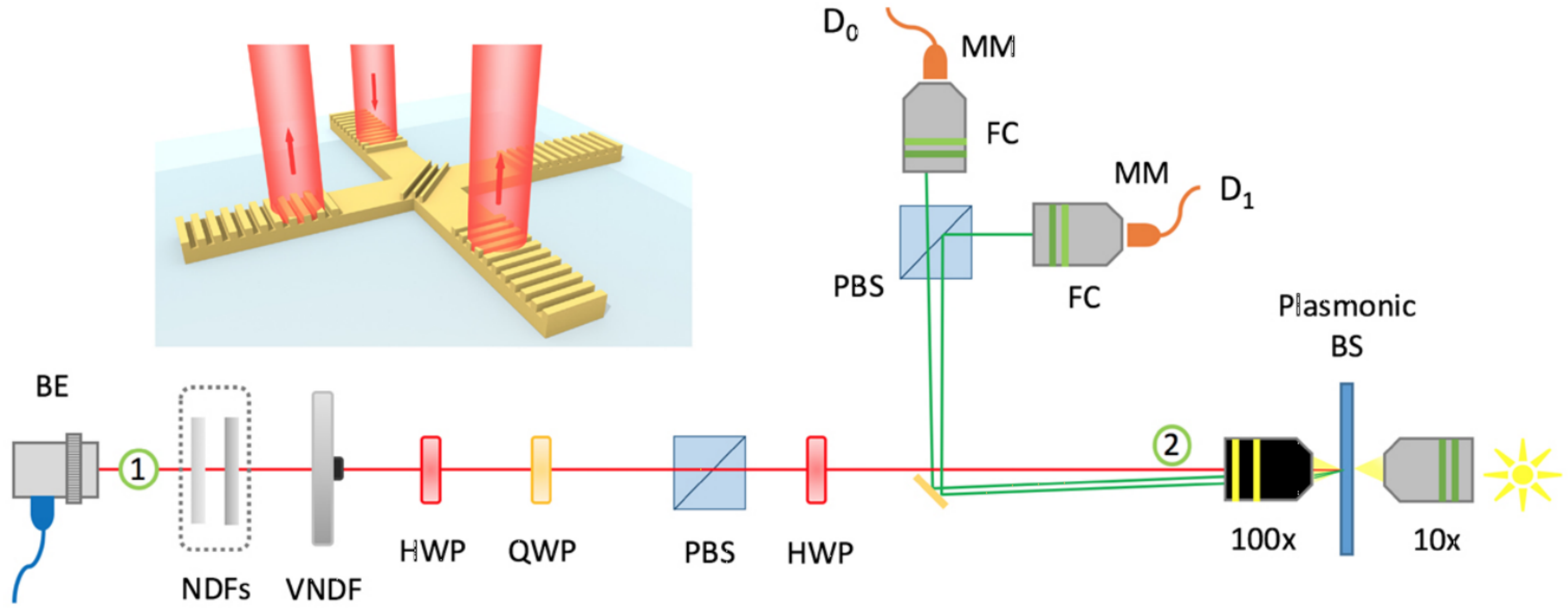


random bit string: 01001...

Statistical Test	p-value	Proportion/Threshold	Pass
Frequency	0.546791	156/154	Yes
Block Frequency	0.624107	159/154	Yes
Cumulative sums	0.606531	158/154	Yes
Runs	0.371101	159/154	Yes
Longest Run	0.284375	159/154	Yes
Rank	0.162606	158/154	Yes
FFT	0.947557	157/154	Yes
Non Overlapping Template	0.723759	158/154	Yes
Overlapping Template	0.559523	79/76	Yes
Universal	0.330628	159/154	Yes
Approximate Entropy	0.350485	157/154	Yes
Random Excursions	0.516893	44/42	Yes
Random Excursions Variant	0.054933	45/42	Yes
Serial	0.606531	160/154	Yes
Linear Complexity	0.392456	79/76	Yes

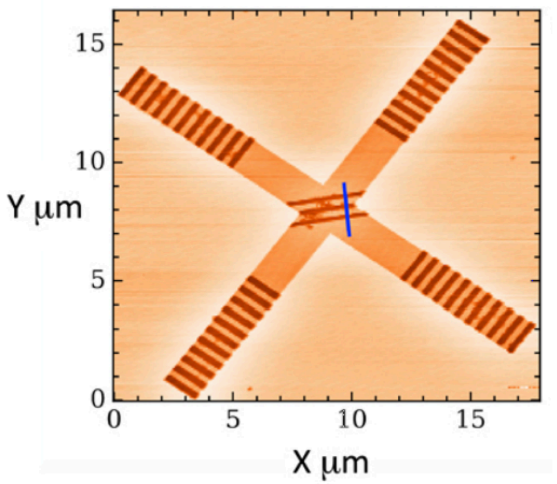
NIST test suite

Impact of losses

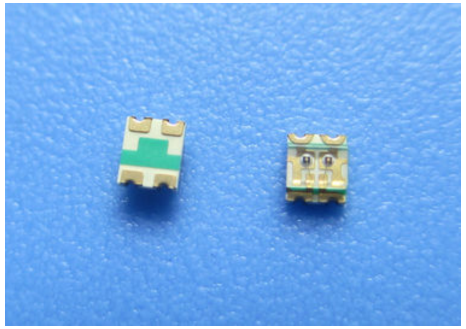


Rate of single SPPs entering beamsplitter region $1.47 \times 10^{10}\ \mathrm{s}^{-1}$ << $1/\tau = 2.60 \times 10^{13}\ \mathrm{s}^{-1}$

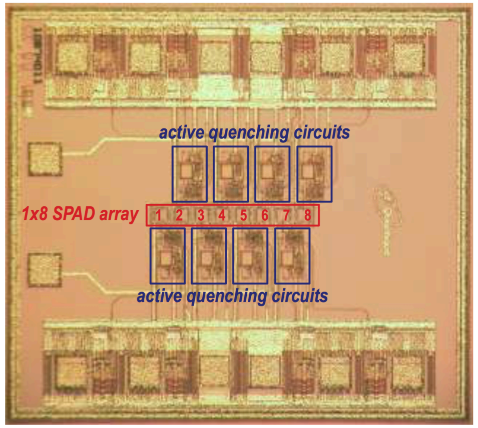
Photon detection rate $1.2 \times 10^{6}\ \mathrm{s}^{-1} \ll 1/\tau_d = 4.2 \times 10^{7}\ \mathrm{s}^{-1}$



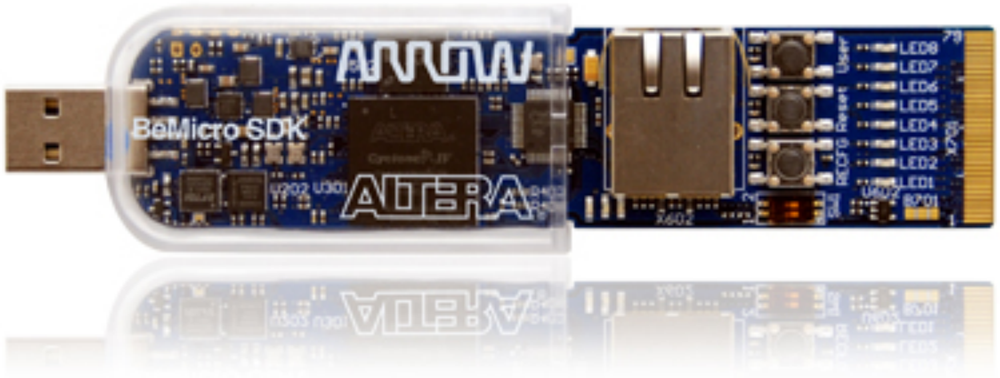
compact



LED source



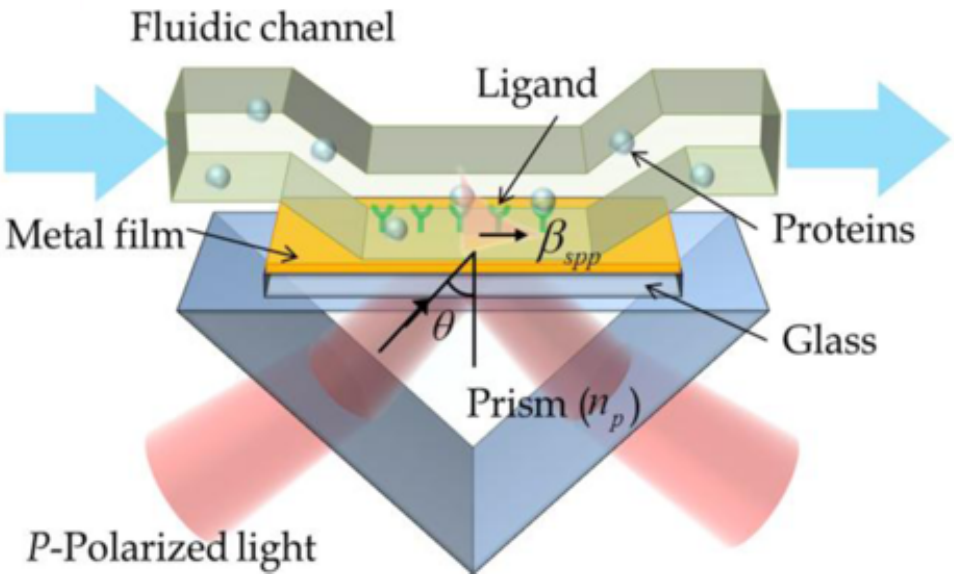
Chip detection

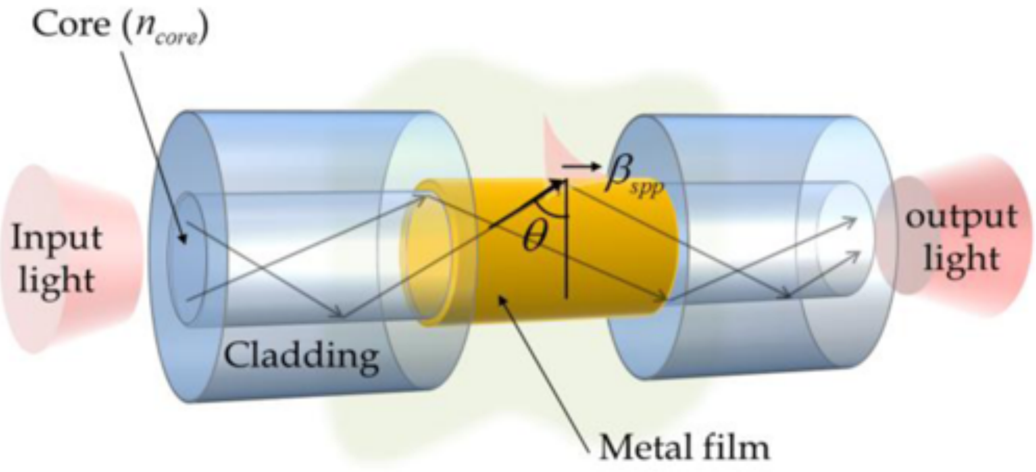


technology innovation AGENCY

And eventually NV centre source and on-chip detection

2. Quantum sensing





J. N. Anker et al., Nature Mat. 7, 442 (2008)
S. Roh et al. Sensors 11, 1565 (2011)

BIACORE

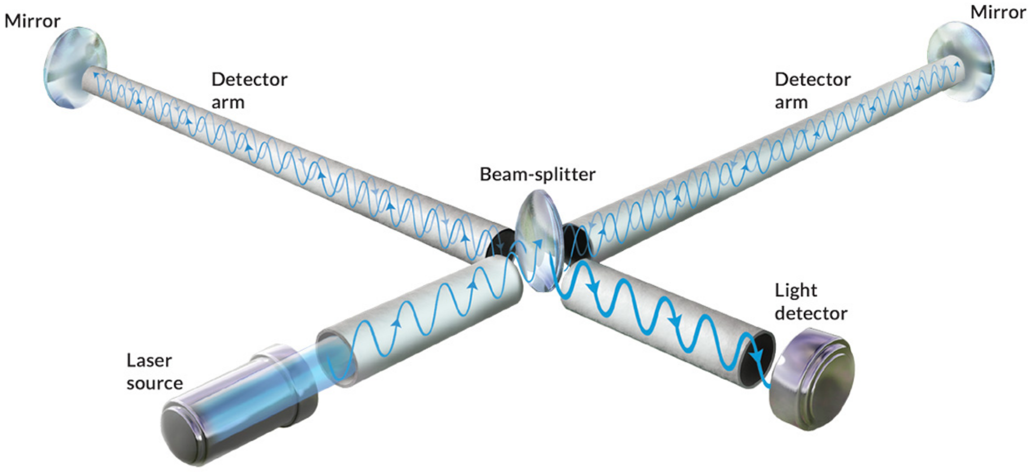
www.biacore.com

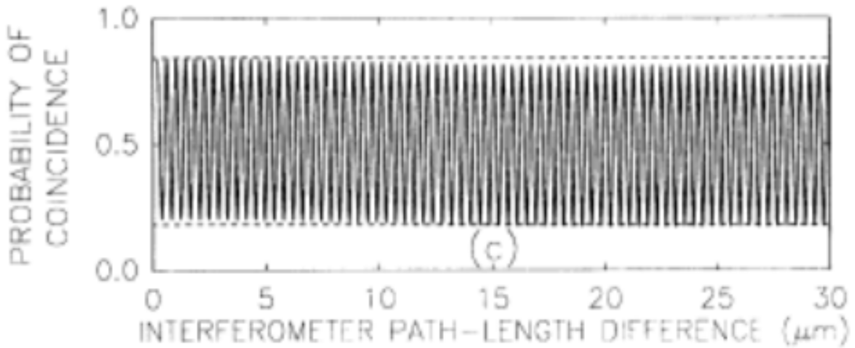
dynamic BIOSENSORS

www.dynamic-biosensors.com

Biacore 2000: 325,000 euros

$$|\psi_{\rm in}\rangle = \frac{1}{\sqrt{2}}(|N0\rangle + |0N\rangle)_{12}$$

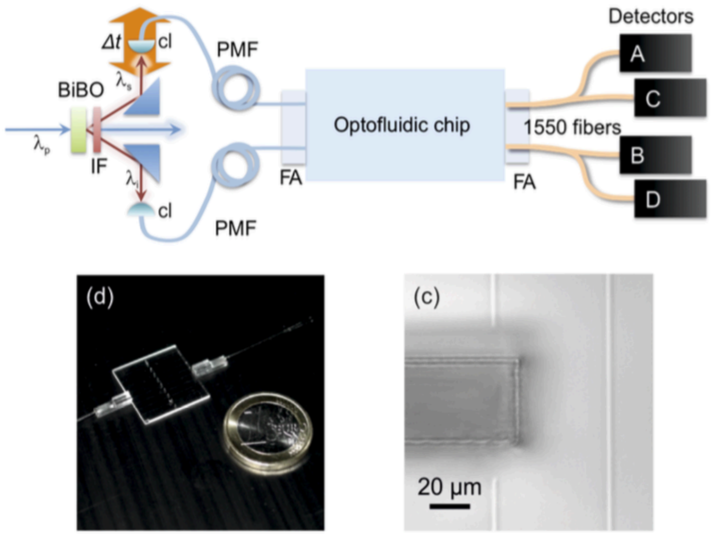




N=2

Rarity et al., PRL 65, 1348 (1990)

Caves, PRD 23, 1693 (1981)



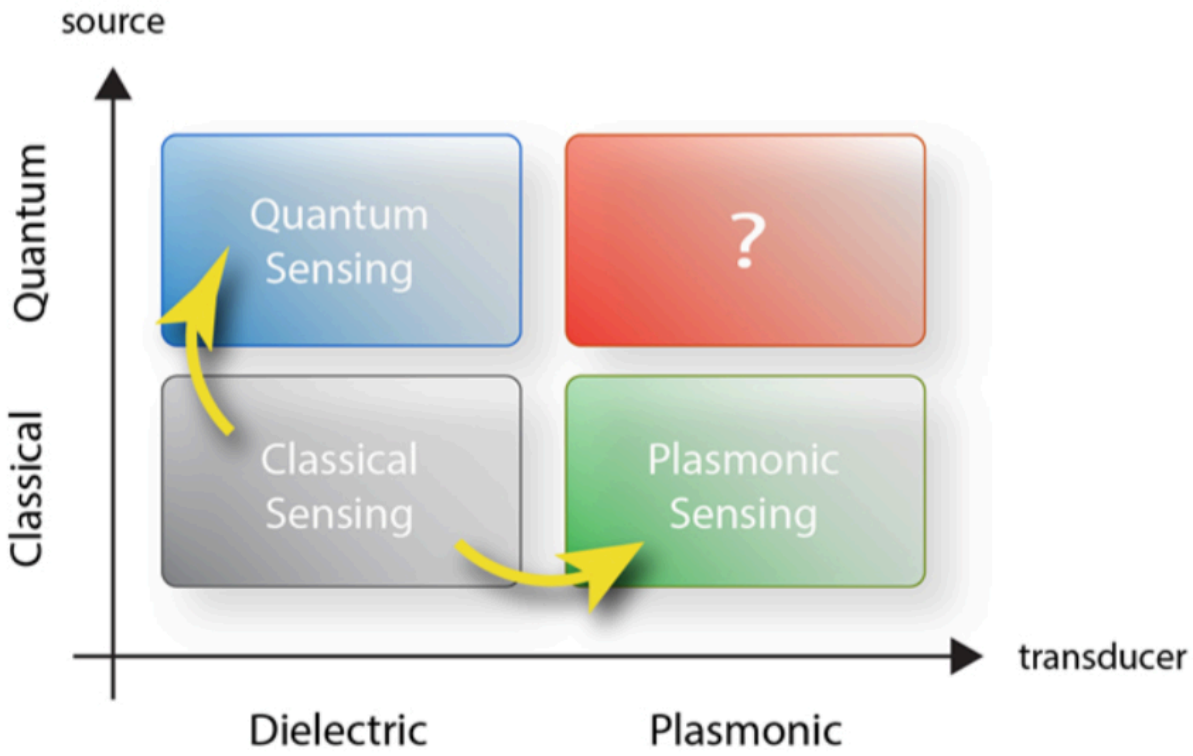
Lee et al., J. Mod. Opt. 49, 2325 (2002)

Giovannetti et al., Science 306, 1330 (2004)

Nagata et al., Science 316, 5825 (2007) N=4

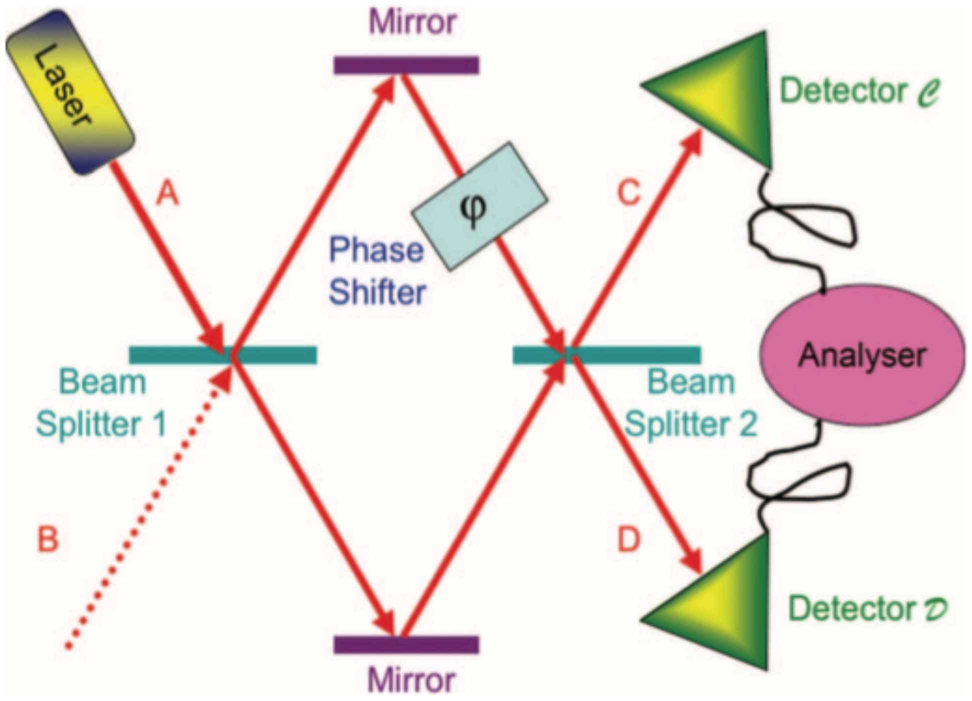
Demkowicz-Dobrzanski et al., Prog. Opt. 60, 345 (2015)

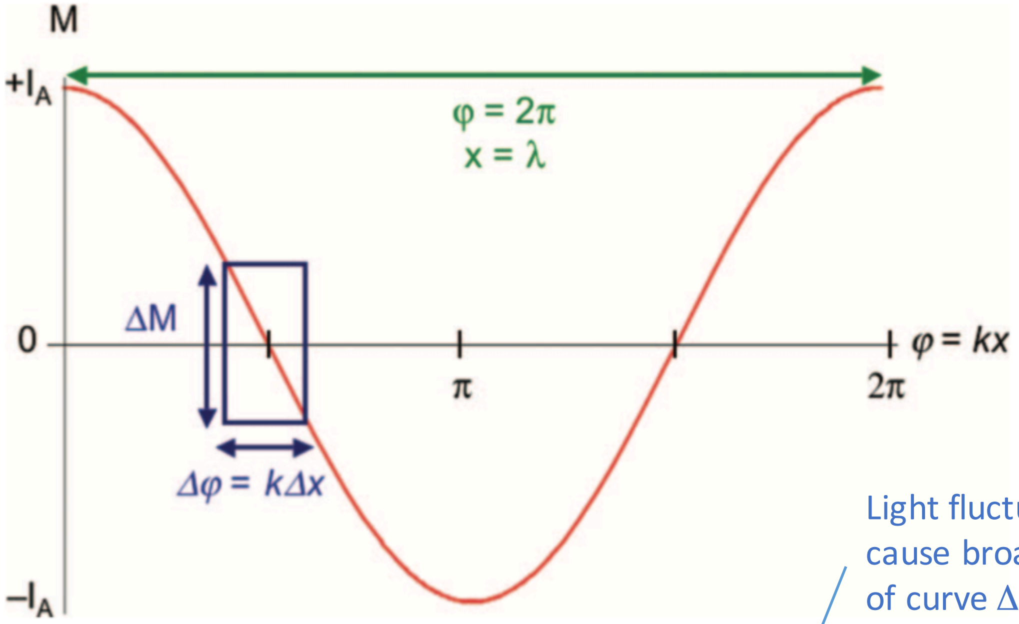
Crespi et al., APL 100, 233704 (2012)



C. Lee et al. ACS Photonics 3, 992 (2016)

$$M(\varphi) \equiv I_D - I_C = I_A \cos(\varphi)$$





Light fluctuations cause broadening of curve ΔM=0 not possible

$$\frac{\Delta M}{\Delta\varphi} = \frac{\partial M}{\partial\varphi} \qquad \Delta\varphi = \frac{\Delta M}{\partial M/\partial\varphi}$$

Dowling, Contem. Phys. 49, 125 (2008)

Dowling and Seshadreesan, J. Light. Tech. 33, 2359 (2015)

→ minimum precision

$$\Delta\varphi = \delta\phi^{(\mathrm{SNL})} = 1/\sqrt{N}$$

'shot noise' limit

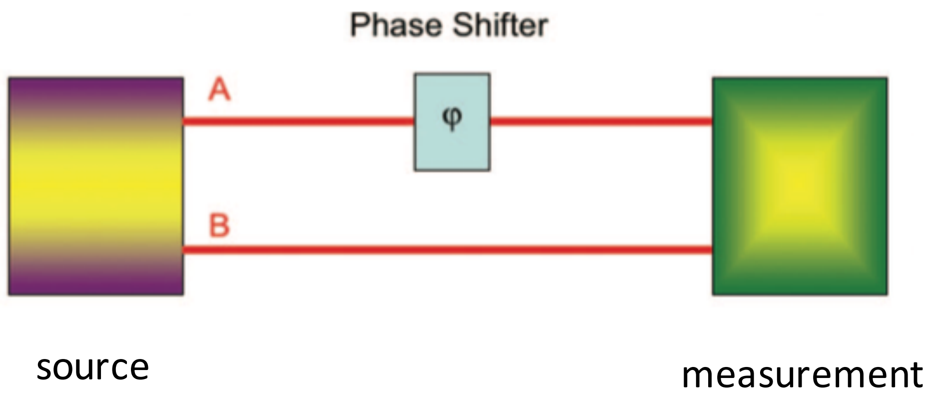
1. Source (fixed number of photons N)

(i) Classical:

$$|\alpha\rangle_A |0\rangle_B \rightarrow \left|\frac{\alpha}{\sqrt{2}}\right\rangle_A \left|\frac{\alpha}{\sqrt{2}}\right\rangle_B \quad , \; |\alpha|^2 = N$$

(ii) Quantum:

$$|\mathrm{N00N}\rangle = \frac{1}{\sqrt{2}}(|N\rangle_A |0\rangle_B + |0\rangle_A |N\rangle_B)$$



1. Source (fixed number of photons N)

(i) Classical:

$$|\alpha\rangle_A |0\rangle_B \rightarrow \left|\frac{\alpha}{\sqrt{2}}\right\rangle_A \left|\frac{\alpha}{\sqrt{2}}\right\rangle_B \quad , \; |\alpha|^2 = N$$

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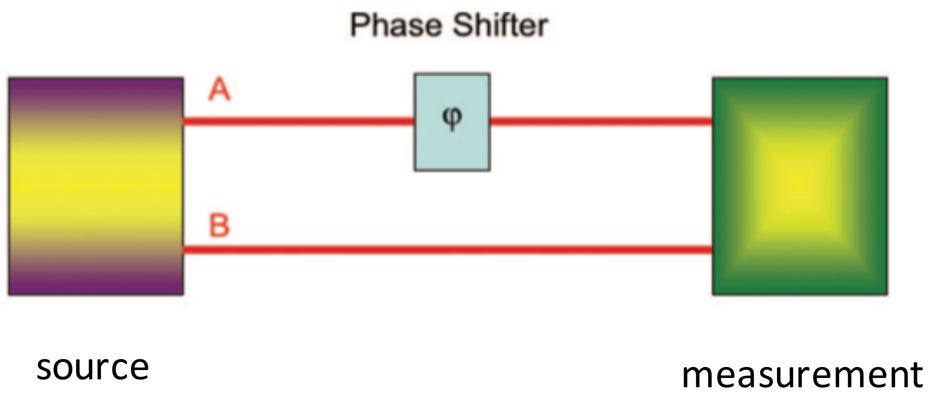


2. Phase ϕ picked up in mode A

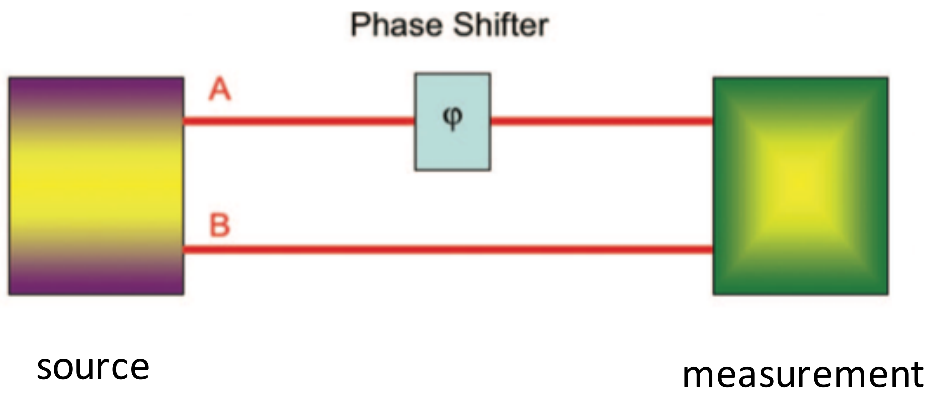
1. Source (fixed number of photons N)

(i) Classical:

$$|\alpha\rangle_A\,|0\rangle_B \rightarrow \left|\frac{\alpha}{\sqrt{2}}\right\rangle_A \left|\frac{\alpha}{\sqrt{2}}\right\rangle_B \quad , \ |\alpha|^2 = N$$

(ii) Quantum:

$$|\mathrm{N00N}\rangle = \frac{1}{\sqrt{2}}\left(|N\rangle_A\,|0\rangle_B + |0\rangle_A\,|N\rangle_B\right)$$



2. Phase ϕ picked up in mode A

3. Measurement

(i) Classical: beamsplitter (BS) on modes, then measurement of intensity difference (optimal)

$$M = I_B - I_A \rightarrow$$

→ minimum precision $\delta\phi^{(\mathrm{SNL})} = 1/\sqrt{N}$

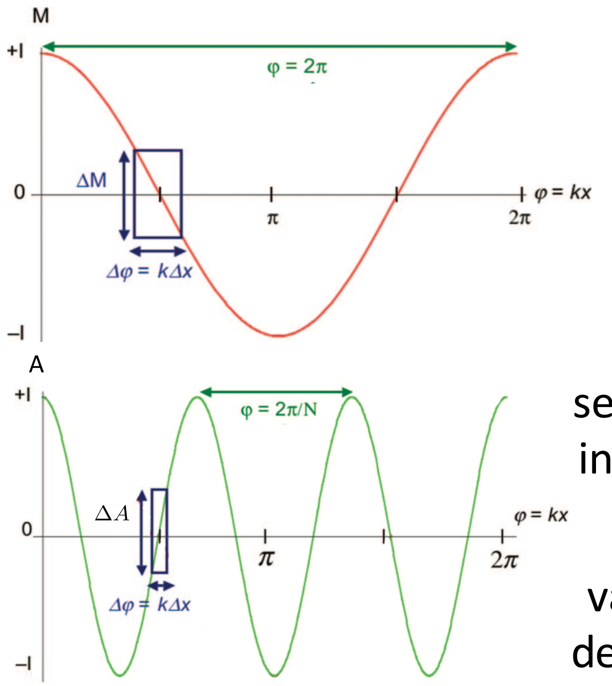
'shot noise' limit

(ii) Quantum: measurement of operator (optimal)

$$\hat{A} = |0,N\rangle\,\langle N,0| + |N,0\rangle\,\langle 0,N| \rightarrow$$

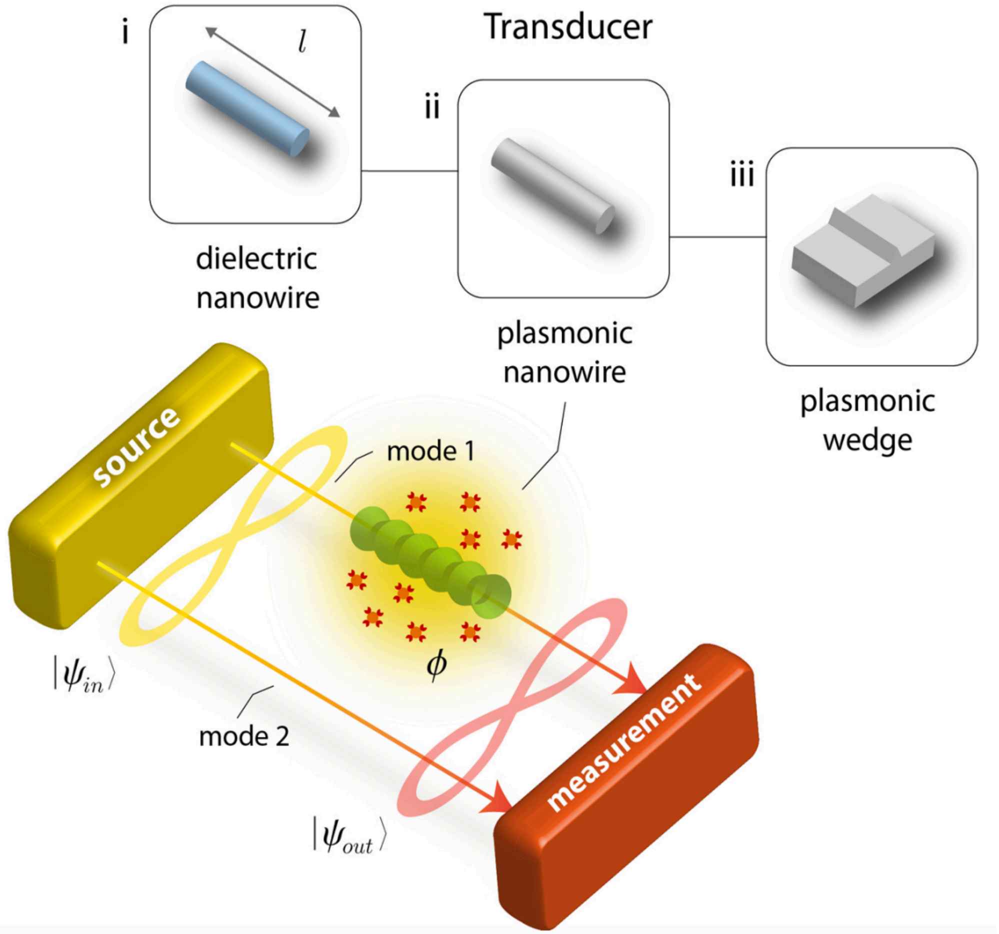
→ minimum precision $\delta\phi^{(\mathrm{HL})} = 1/N$

'Heisenberg' limit



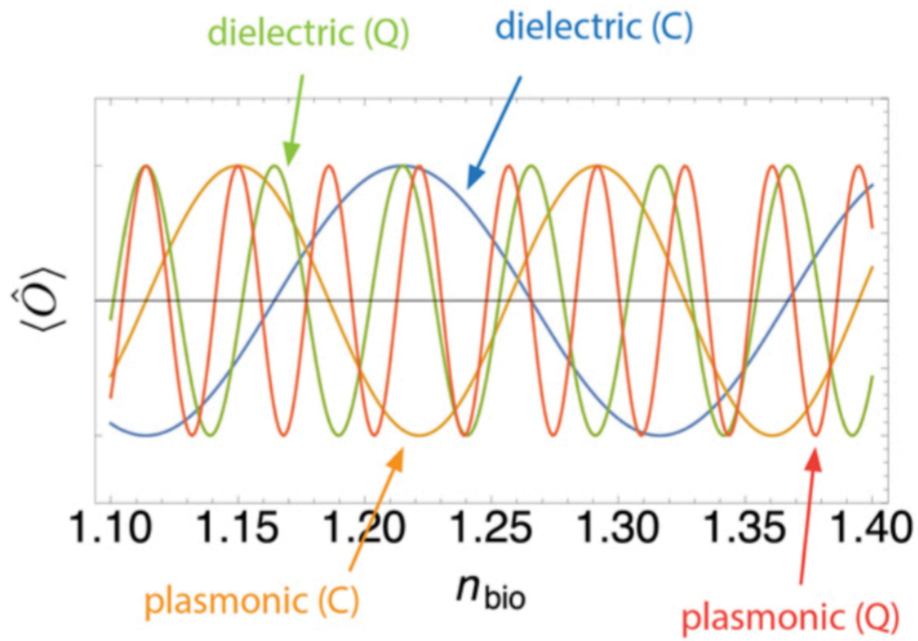
sensitivity increases $\dfrac{\partial\langle\hat{O}\rangle}{\partial\phi}$

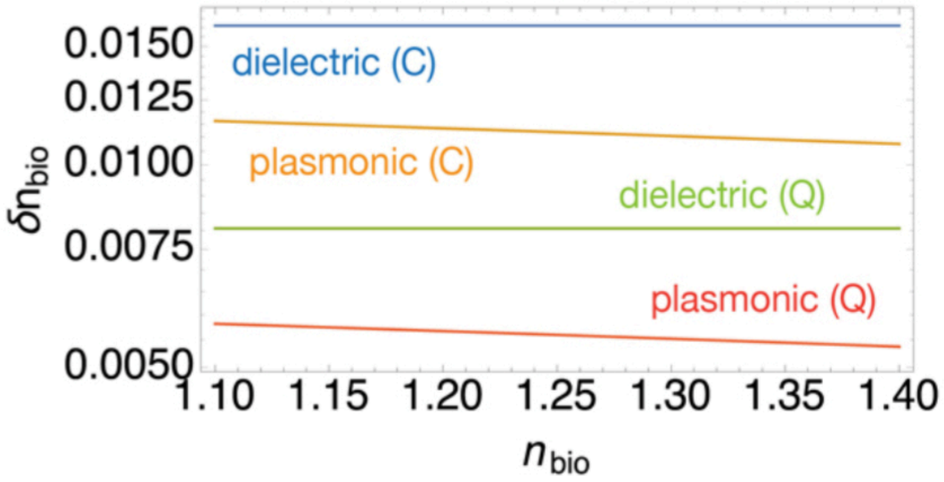
variance decreases $\Delta\hat{O}$



nanowire
l = 4um
λ_0 = 810 nm
r = 50 nm

N=4



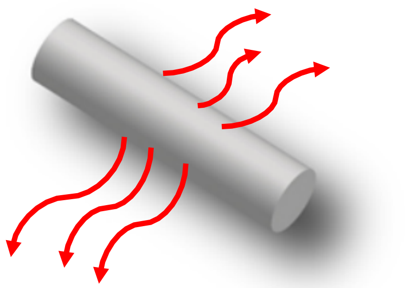


Minimum precision: $$\delta n_{\text{bio}} = \frac{\Delta \hat{O}}{|\partial \langle \hat{O} \rangle / \partial n_{\text{bio}}|}$$

$$\Delta \hat{O} = (\langle \hat{O}^2 \rangle - \langle \hat{O} \rangle^2)^{1/2}$$

When loss is included the NOON state is no longer optimal
Neither is the measurement operator A

Optimal states



$$|\psi_{\rm in}\rangle = \sum_{n=0}^{N} c_n |n, N-n\rangle$$

for some set of coefficients c_n depending on loss

Dorner et al., PRL 102, 040403 (2009)

$$|\psi_{\rm in}\rangle = c_0 |0,4\rangle + c_1 |1,3\rangle + c_2 |2,2\rangle + c_3 |3,1\rangle + c_4 |4,0\rangle$$

Optimal measurement

Hard to find but we can use the following relation:

$$\delta\phi = F_Q^{-1/2}$$

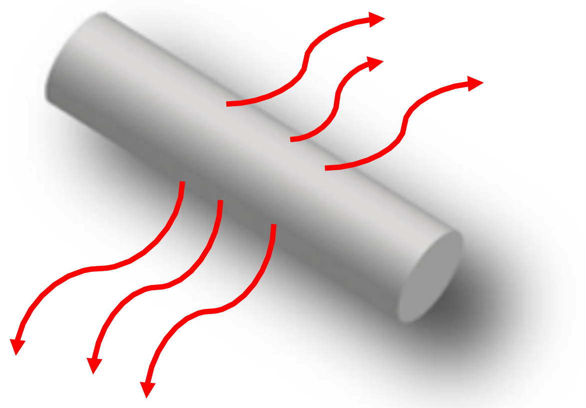
F_Q – Fisher information
(amount of info about ϕ that state contains)

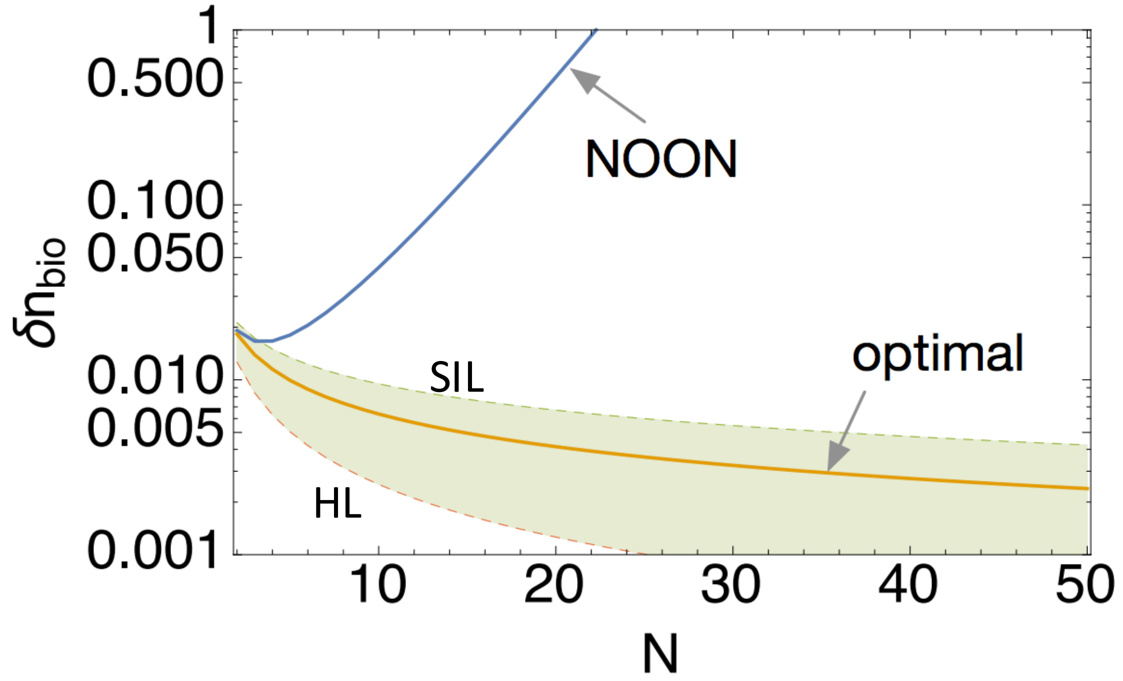
and use $$\delta n_{\rm bio} = \delta\phi \left| \frac{\partial\phi}{\partial n_{\rm bio}} \right|^{-1}$$

depends on medium (dielectric or plasmonic)

depends on state and measurement

$\partial\phi/\partial n_{\rm bio}$ $(= l \times \partial\beta/\partial n_{\rm bio})$

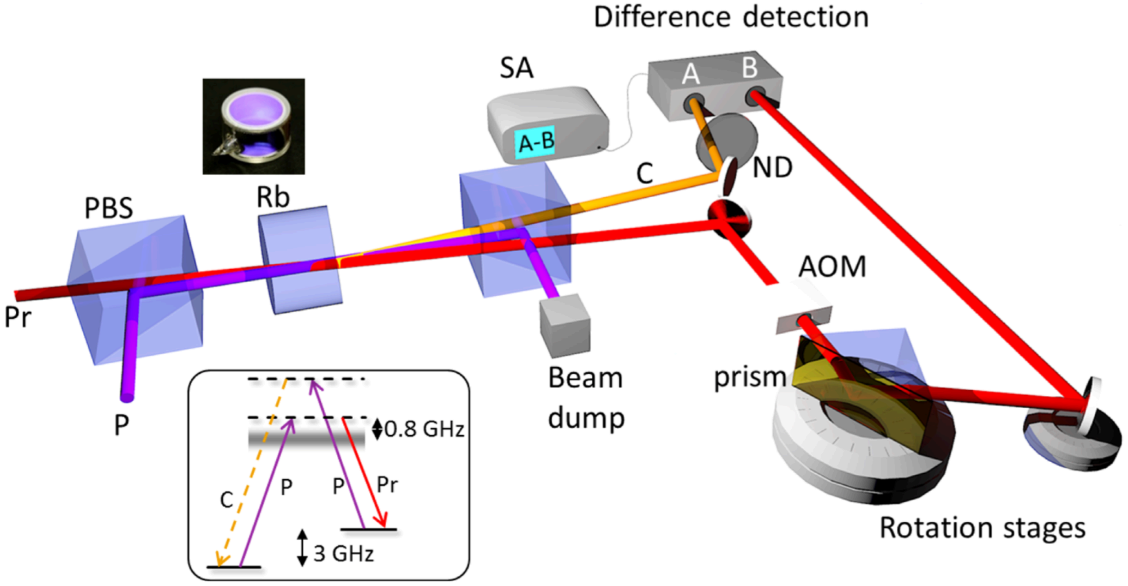




Quantum plasmonic sensing with definite photon states is useful for highly photosensitive material of which only a small quantity is available

Taylor and Bowen, Phys. Rep. 615, 1 (2016)

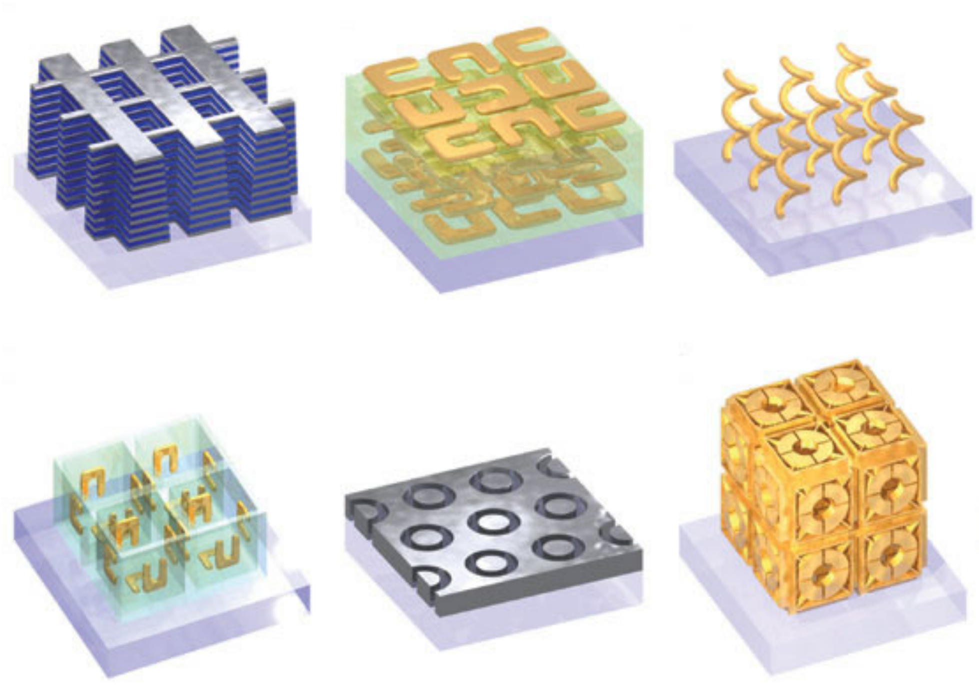
Continuous variable states for quantum plasmonic sensing



Pooser and Lawrie, ACS Photonics 3, 8 (2016)

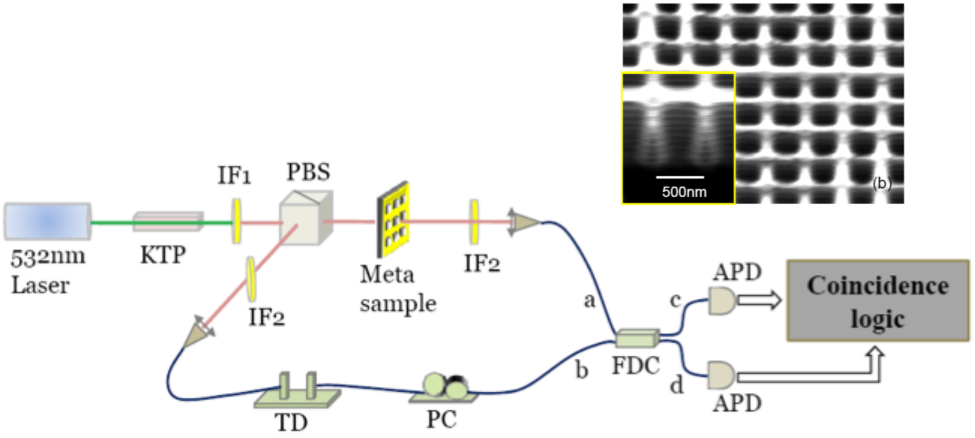
Fan et al., Phys. Rev. A 92, 053812 (2015)

3. Quantum Metamaterials

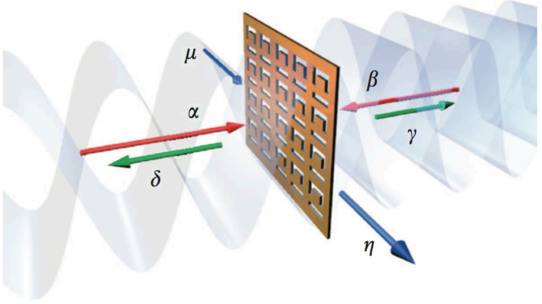


Soukoulis and Wegener, Nat. Phot. 5, 523 (2011)

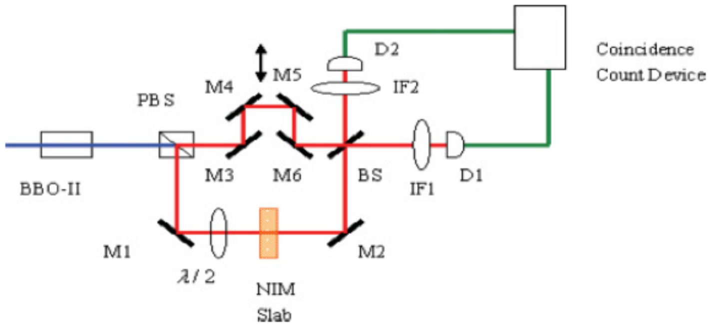
Quantum optical metamaterials



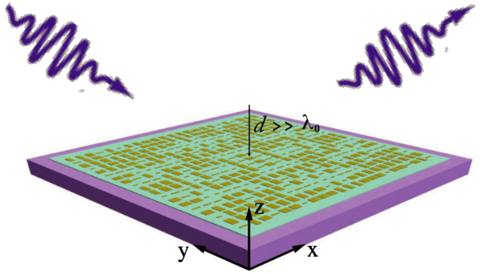
Wang et al., Opt. Exp. 20, 5213 (2012)



Roger et al., Nat. Comm. 6, 7031 (2015)

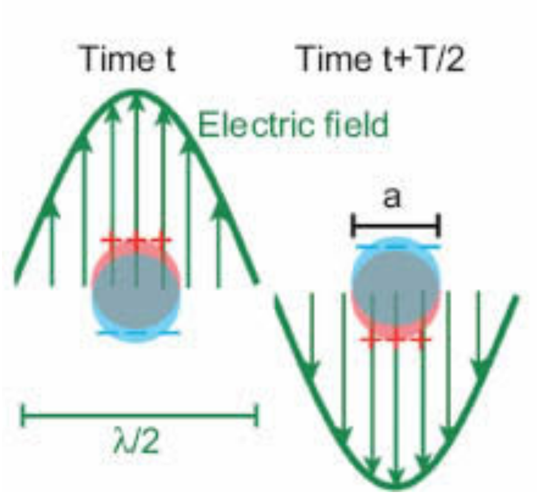


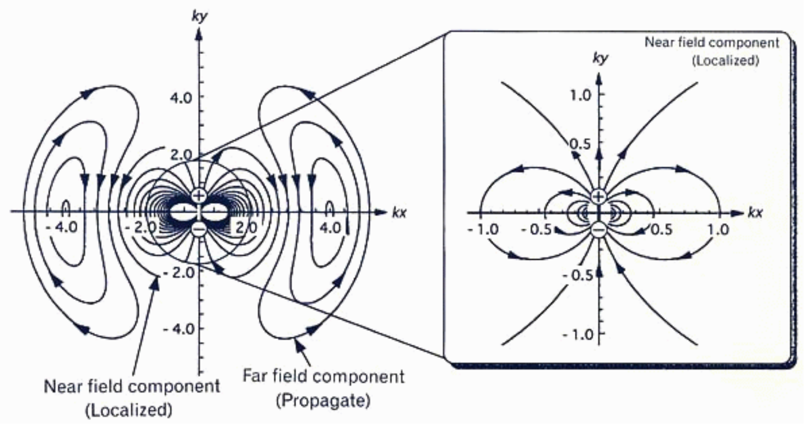
Zhou et al., PRA 85, 023841 (2012)

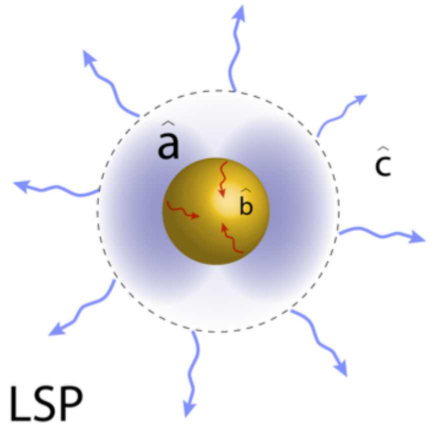


Jha et al., PRL 115, 025501 (2015)

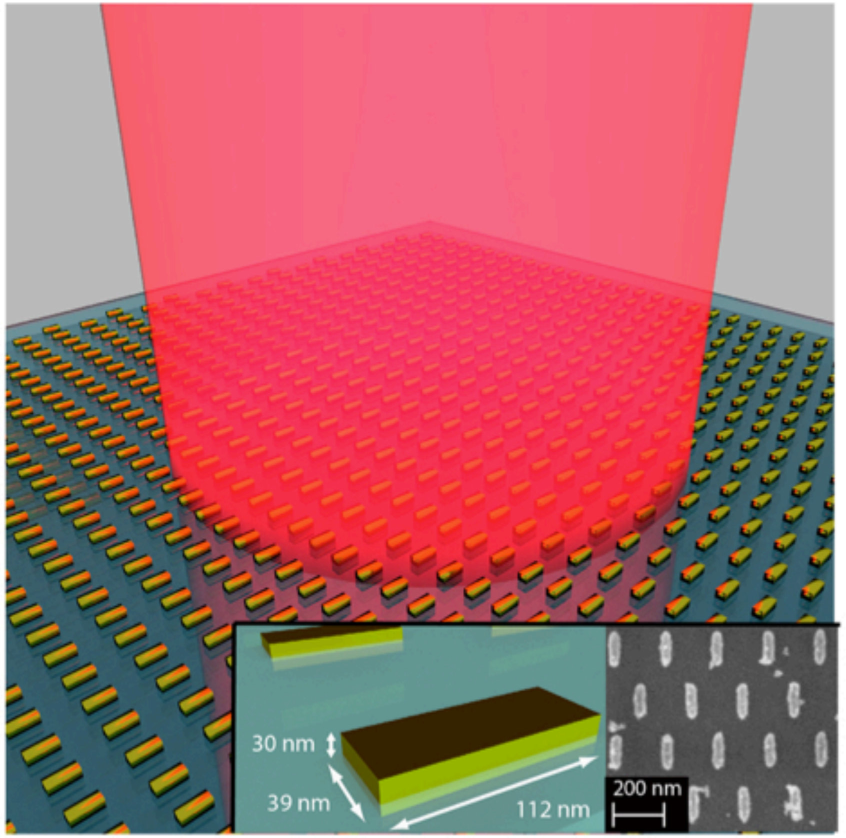
Nanoparticles in quantum regime





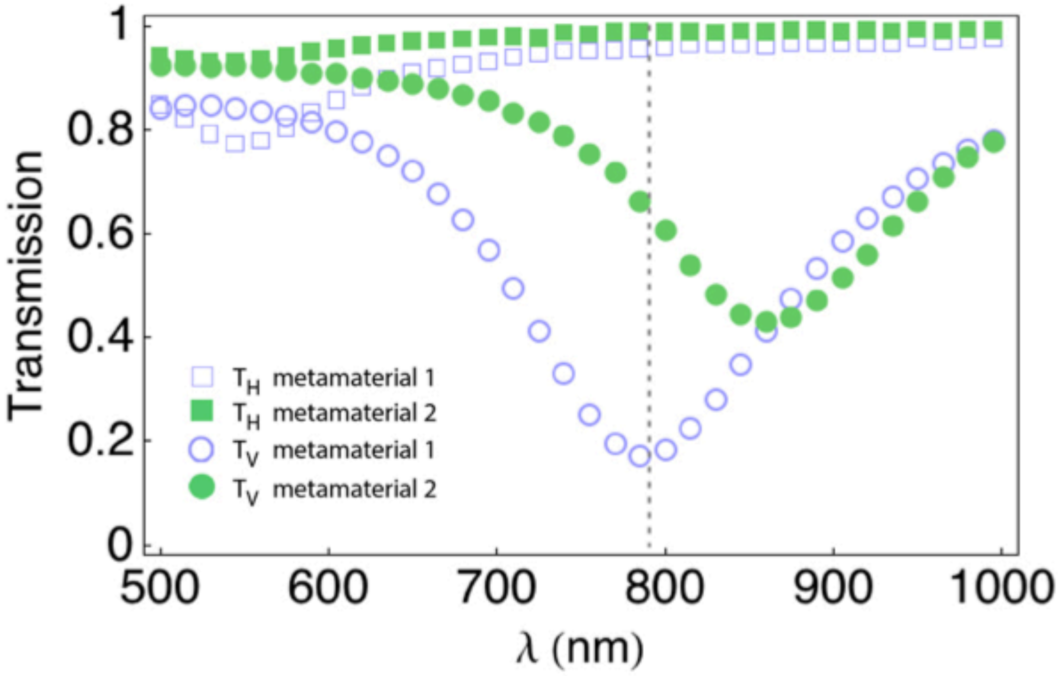


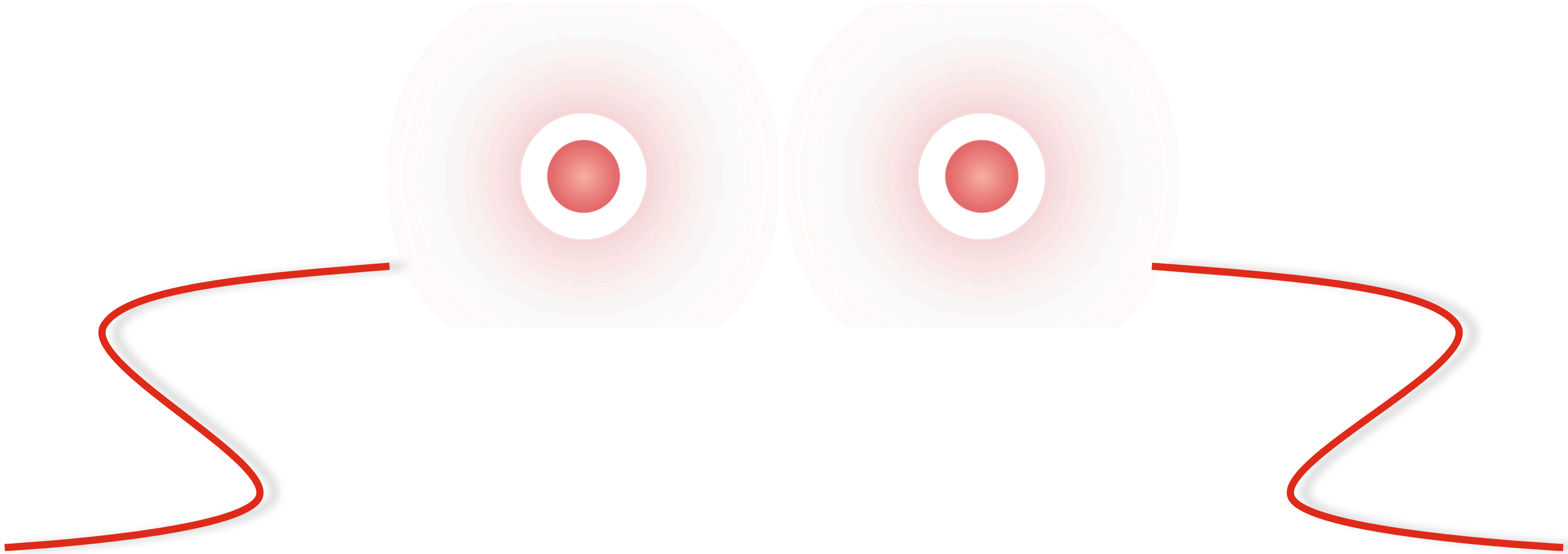
(localized surface plasmon)

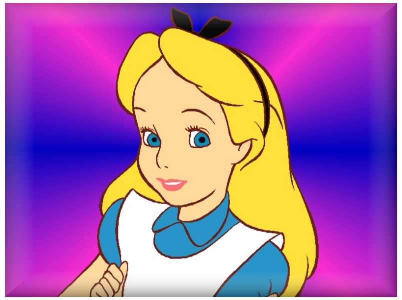


Asano et al., Sci. Rep. 5, 18313 (2015)

beam size 90 μm





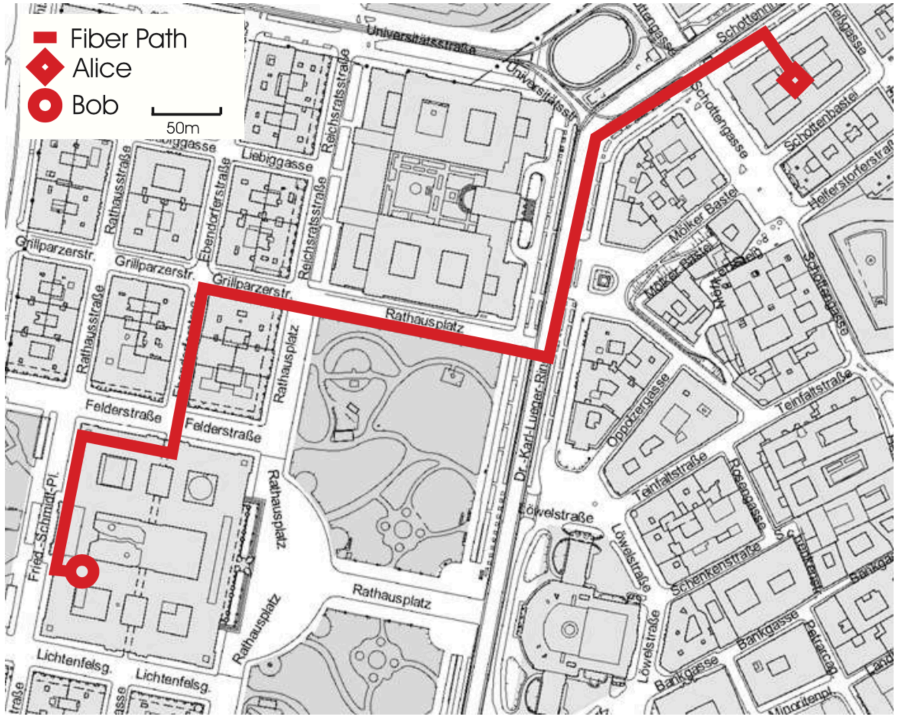


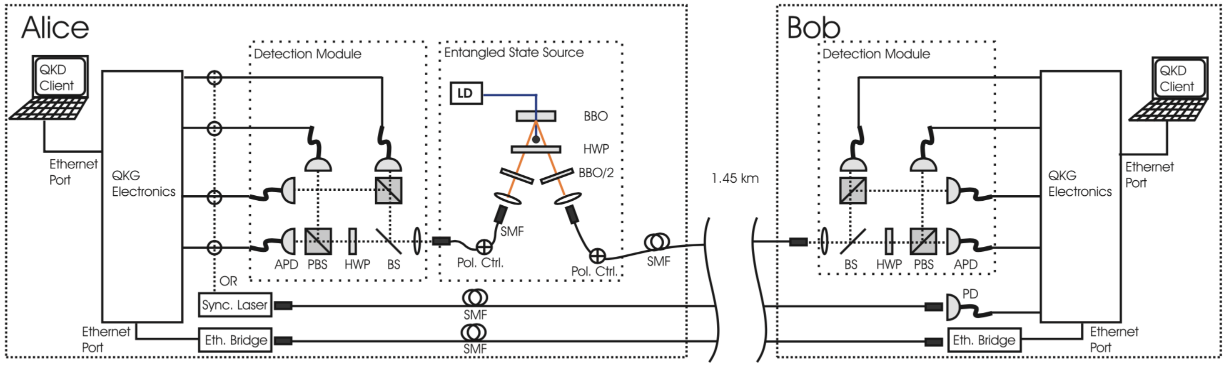
$$\frac{1}{\sqrt{1+\epsilon^2}}\left(\epsilon\,|H\rangle_A\,|H\rangle_B + |V\rangle_A\,|V\rangle_B\right)$$

Alice

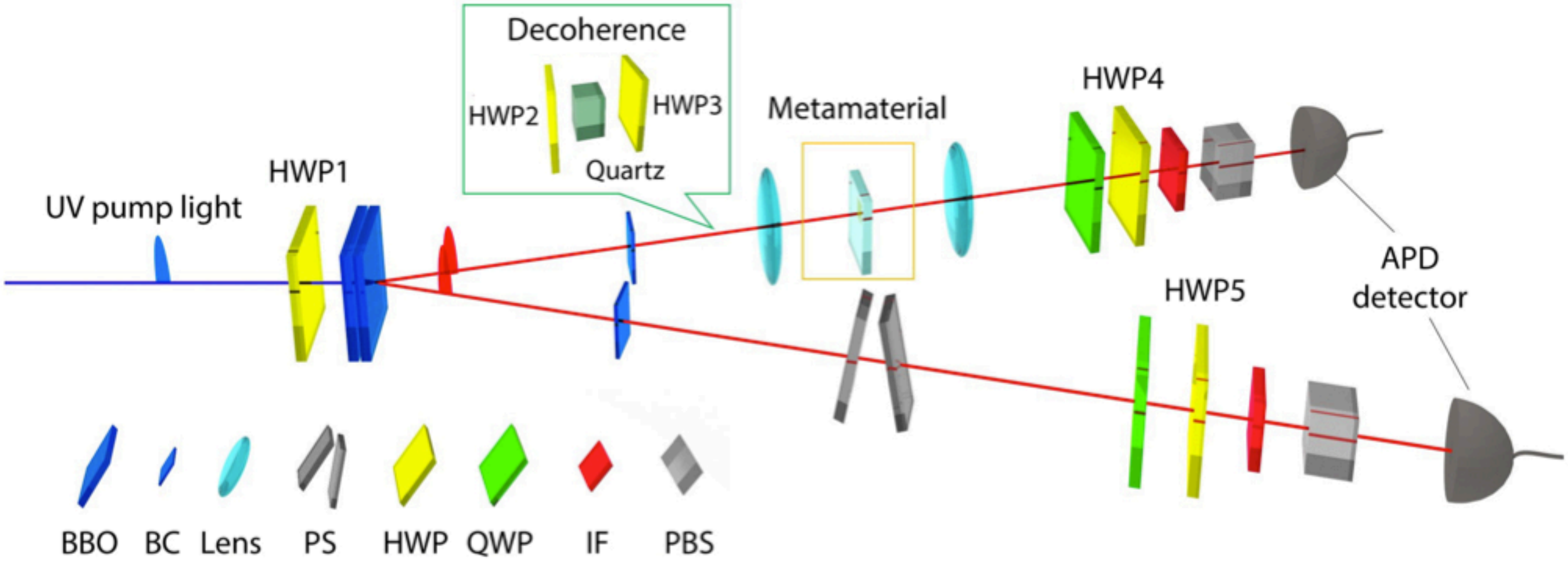
Ekert PRL 67, 661 (1991)

Bob





Poppe et al., Opt. Express 12, 3865 (2004)



Decoherence
HWP2
HWP3
Quartz
Metamaterial
HWP4
UV pump light
HWP1
APD
detector
HWP5
BBO
BC
Lens
PS
HWP
QWP
IF
PBS

Real Imaginary

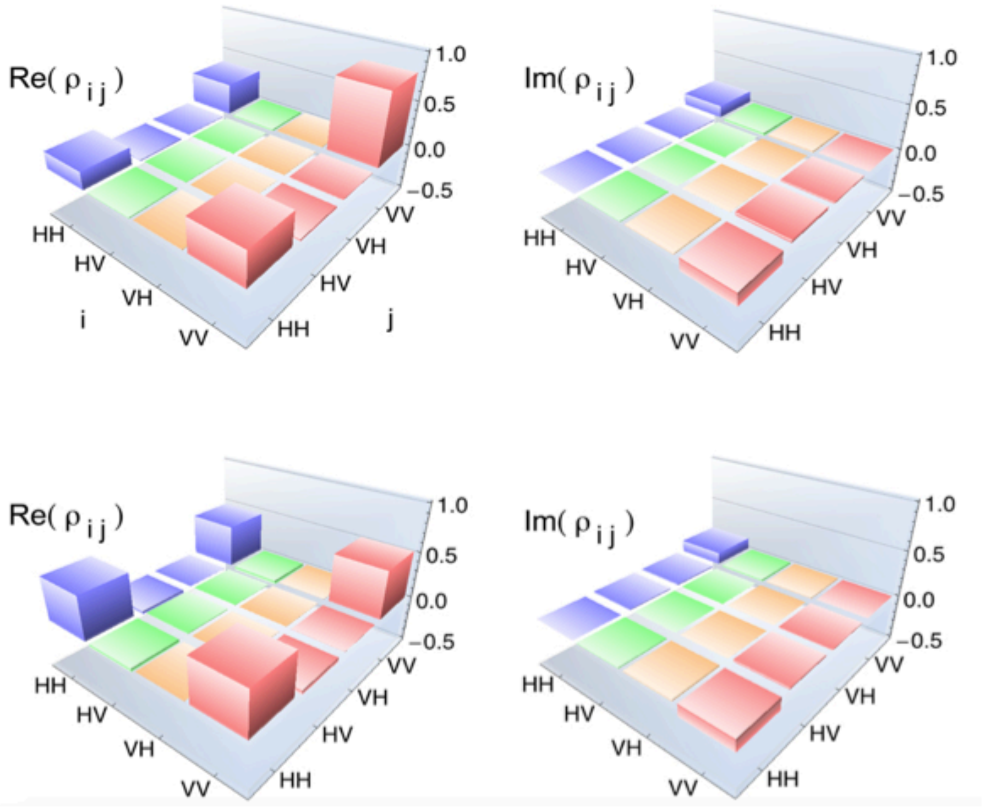
$$\frac{1}{\sqrt{1+\epsilon^2}}(\epsilon \left|H\right\rangle_A \left|H\right\rangle_B + \left|V\right\rangle_A \left|V\right\rangle_B)$$

$$\epsilon = 0.49$$

before

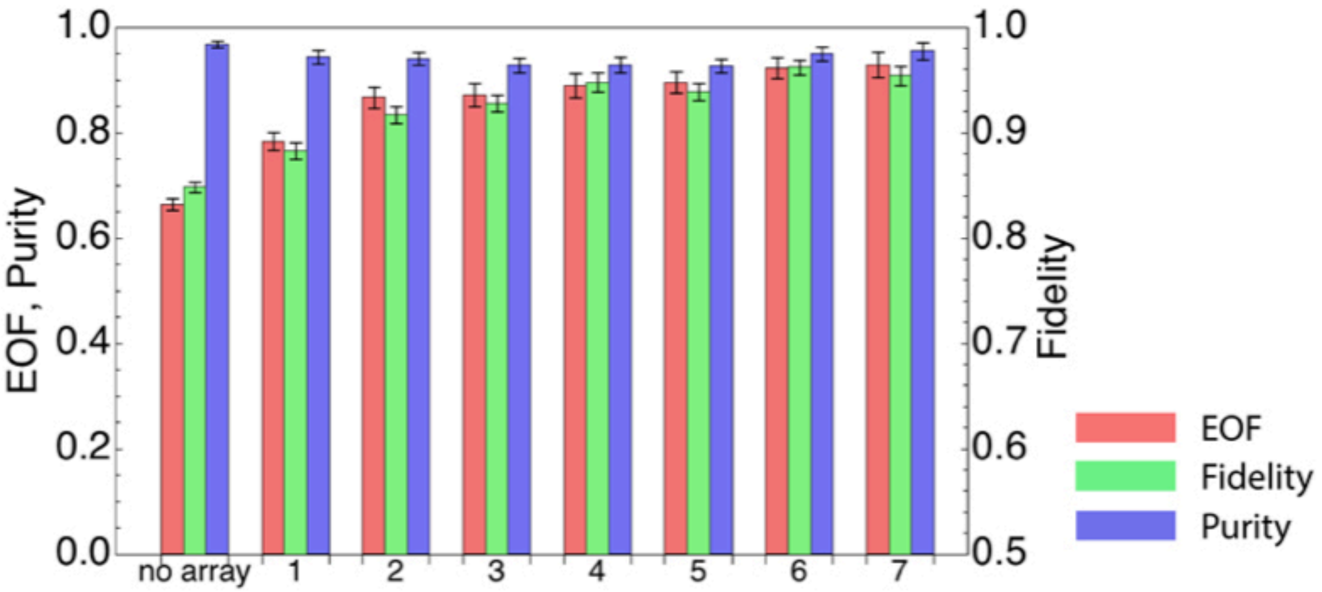
$$\frac{1}{\sqrt{2}}(\left|H\right\rangle_A \left|H\right\rangle_B + \left|V\right\rangle_A \left|V\right\rangle_B)$$

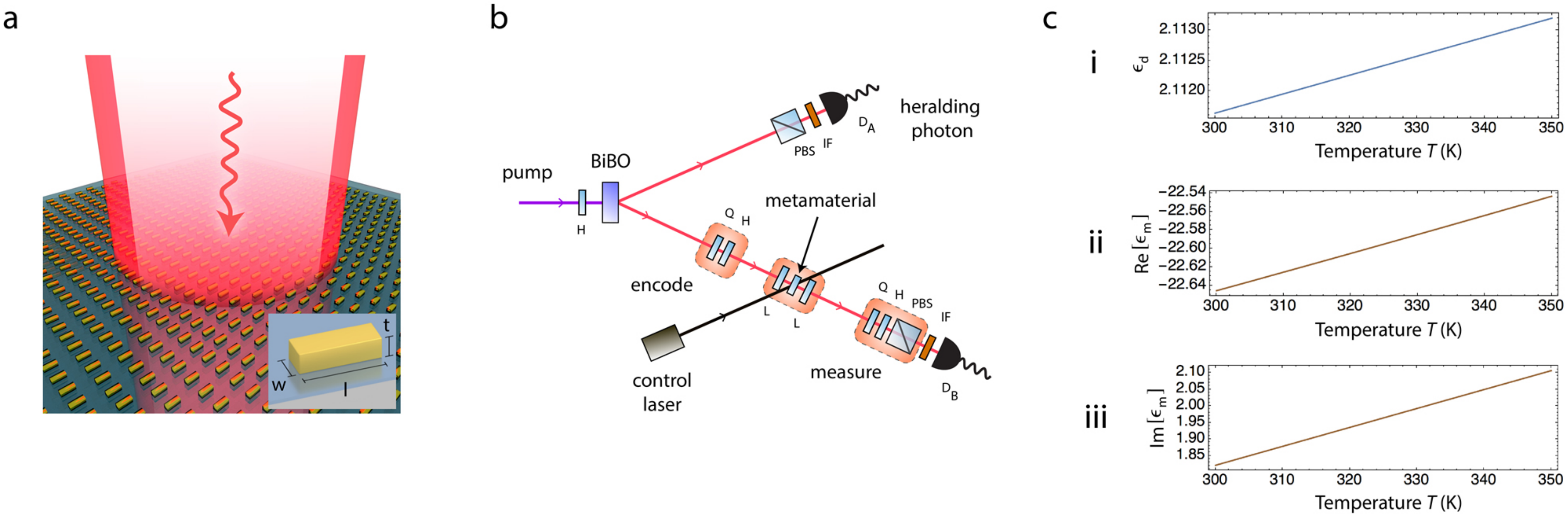
after



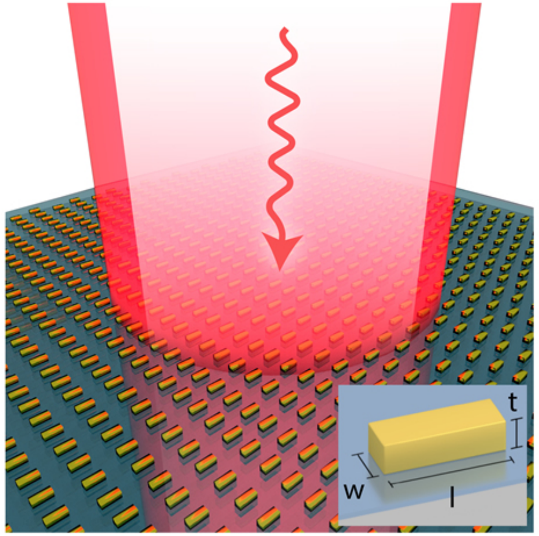
$$\frac{1}{\sqrt{1+\epsilon^2}}\left(\epsilon\left|H\right\rangle_A\left|H\right\rangle_B+\left|V\right\rangle_A\left|V\right\rangle_B\right)$$

$$\epsilon = 0.49$$





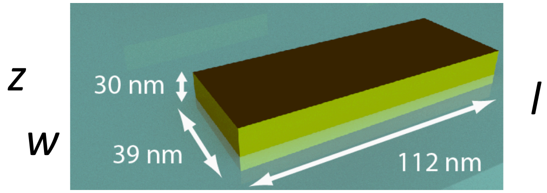
S. Uriri et al. *under review, Phys. Rev. A* (2018)



Polarizability of individual nanorod

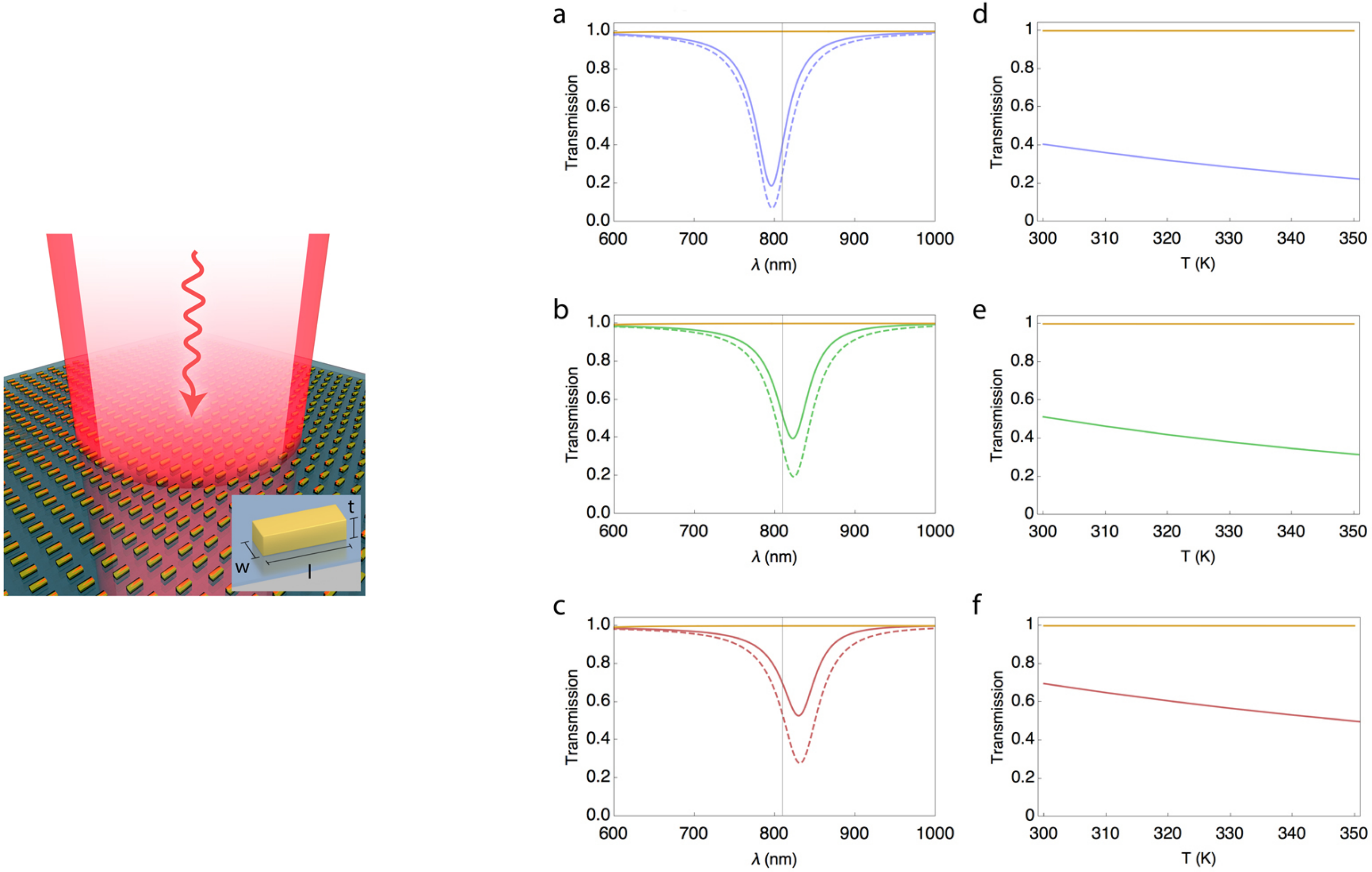
$$\alpha_{ii} = \frac{\pi}{8} w z \ell \frac{\epsilon_m - \epsilon_d}{3\epsilon_d + 3L_{ii}(\epsilon_m - \epsilon_d)}$$

Bohren and Huffman,
'Absorption and scattering of light by small particles' (1983)

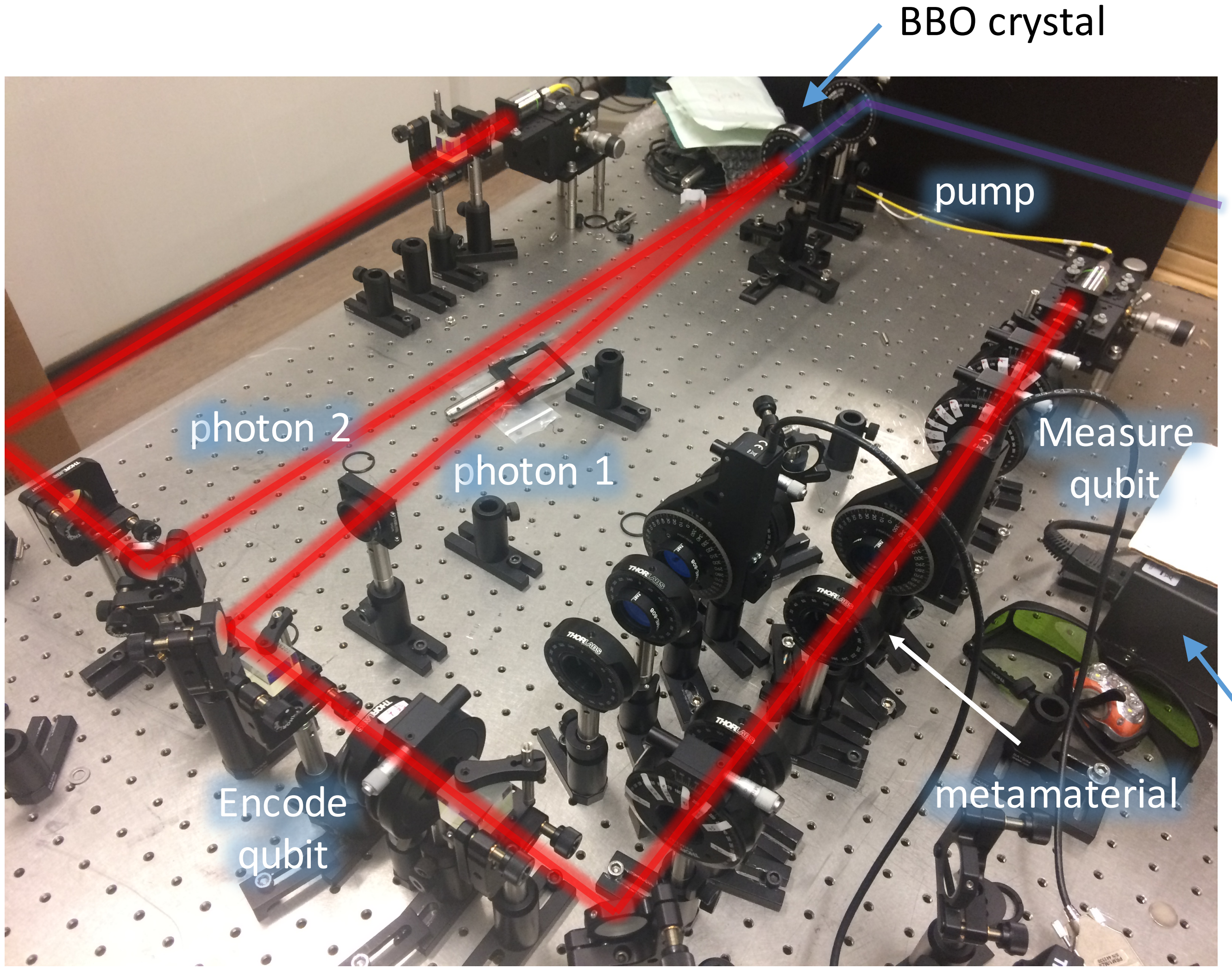


$$\mathbf{T} = \begin{pmatrix} T_{xx} & 0 \\ 0 & T_{yy} \end{pmatrix} = \begin{pmatrix} 1 - \dfrac{j\mu_0 \pi f c}{d_x d_y} \dfrac{\alpha_{xx}}{1 - C_{xx}\alpha_{xx}} & 0 \\ 0 & 1 - \dfrac{j\mu_0 \pi f c}{d_x d_y} \dfrac{\alpha_{yy}}{1 - C_{yy}\alpha_{yy}} \end{pmatrix}$$

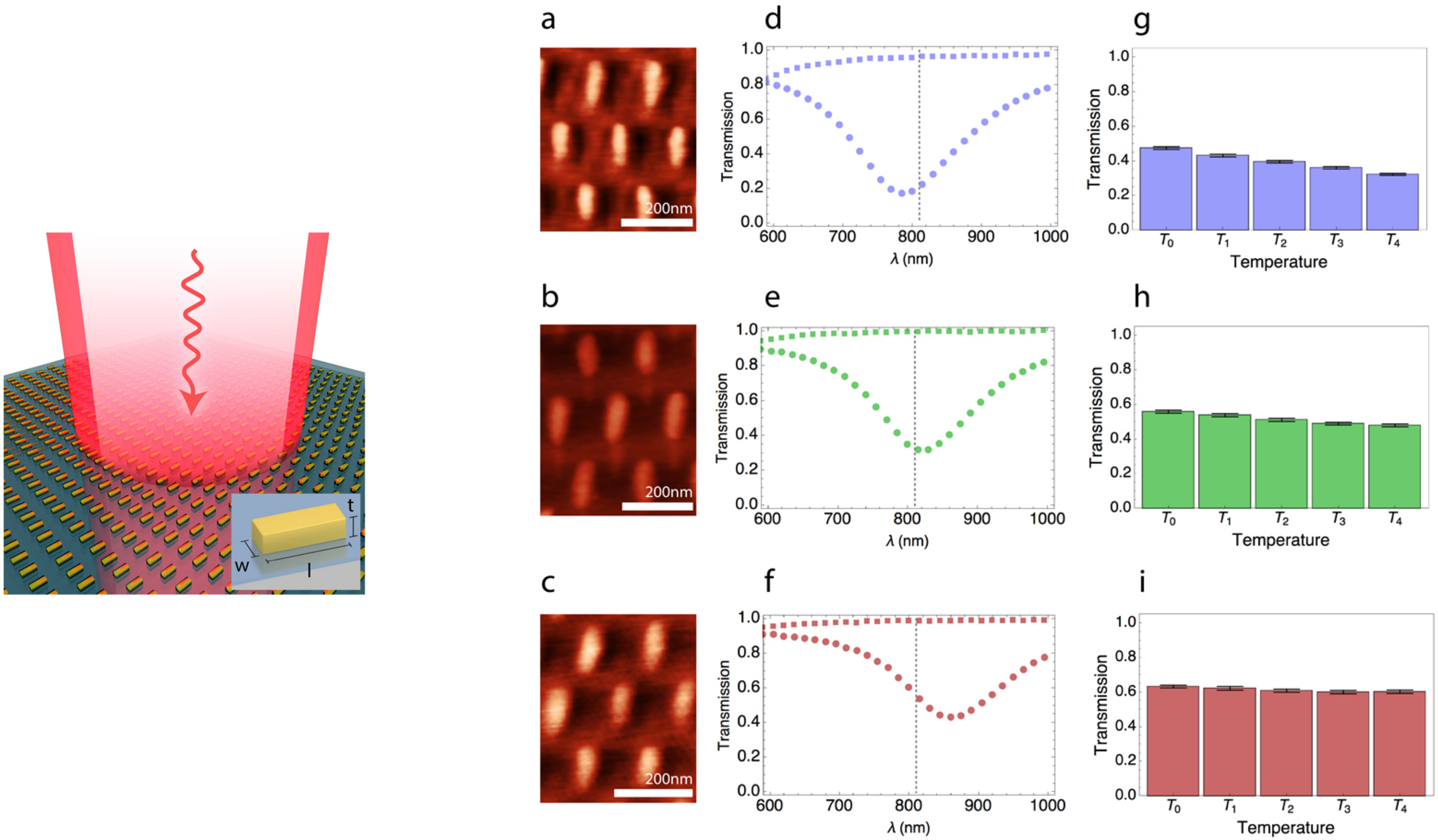
Alu and Engheta,
in 'Structured surfaces as optical metamaterials' (2011)



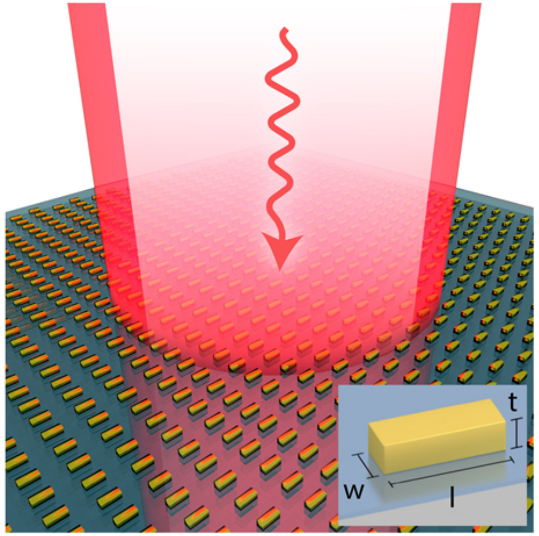
t
w
l
a
b
c
d
e
f
Transmission
λ (nm)
T (K)
1.0
0.8
0.6
0.4
0.2
0.0
600
700
800
900
1000
1
0
300
310
320
330
340
350



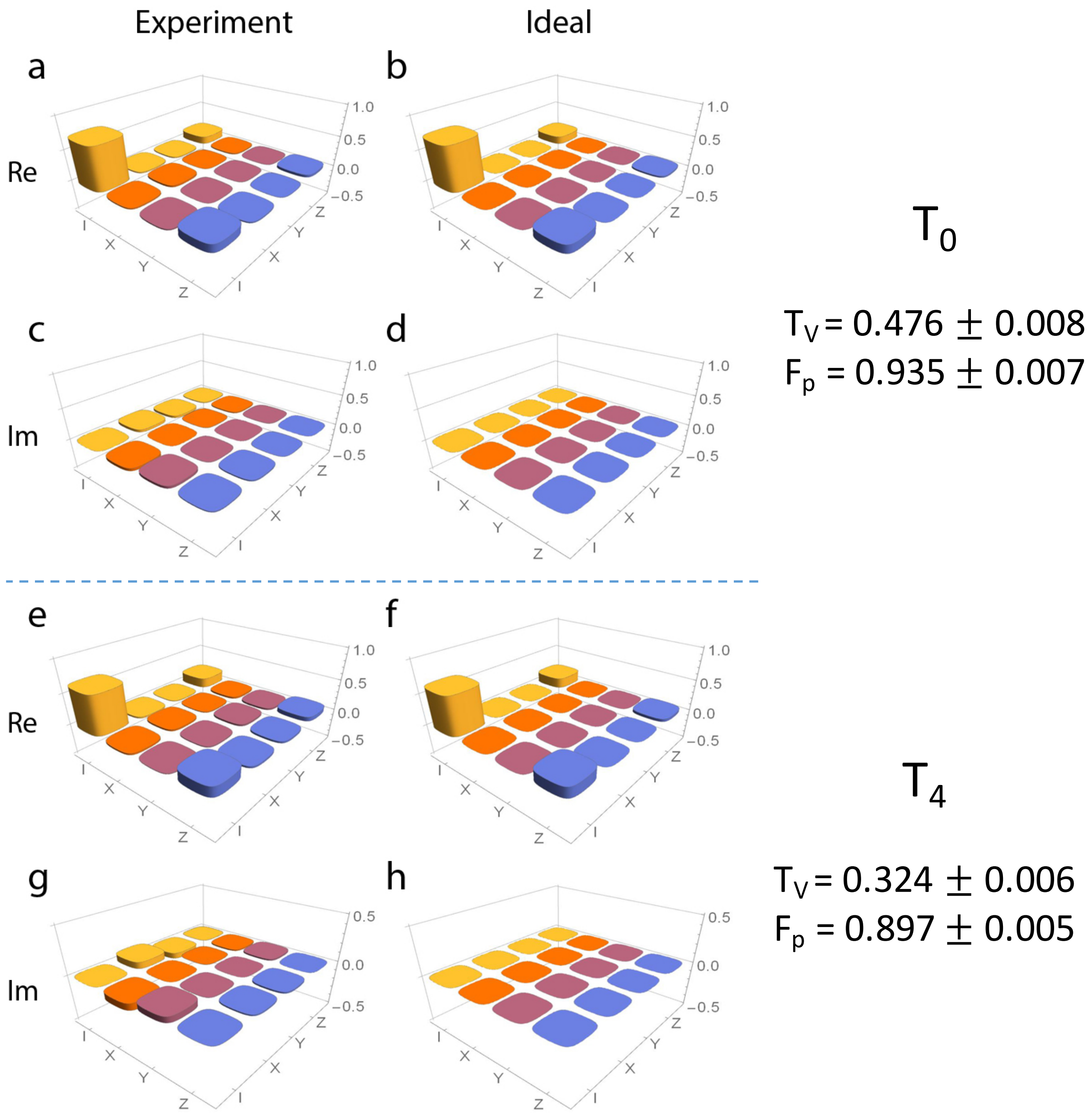
Solomon Uriri



t
w
l
a
200nm
b
200nm
c
200nm
d
e
f
Transmission
λ (nm)
600
700
800
900
1000
0.0
0.2
0.4
0.6
0.8
1.0
g
h
i
Temperature
T_0
T_1
T_2
T_3
T_4

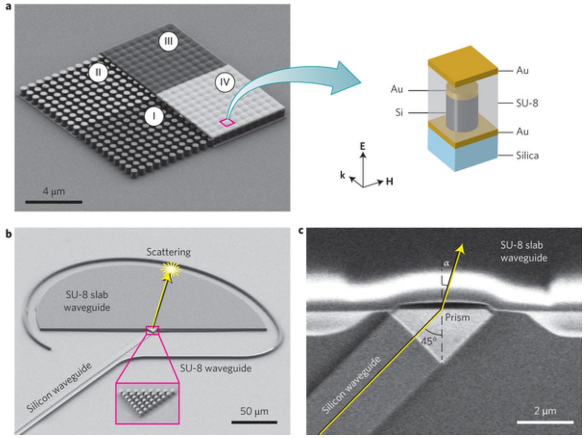


$$K_0 = |H\rangle\langle H| + \sqrt{T_V}\,|V\rangle\langle V|$$

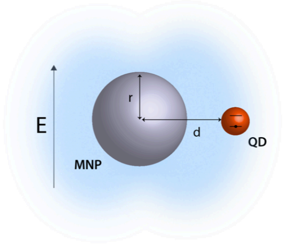


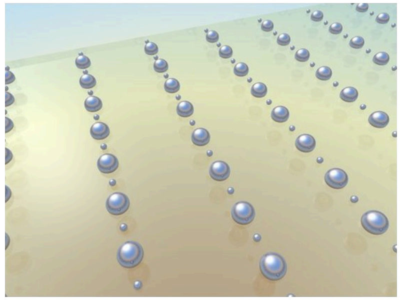
Future work

Metamaterials



Embed in waveguides

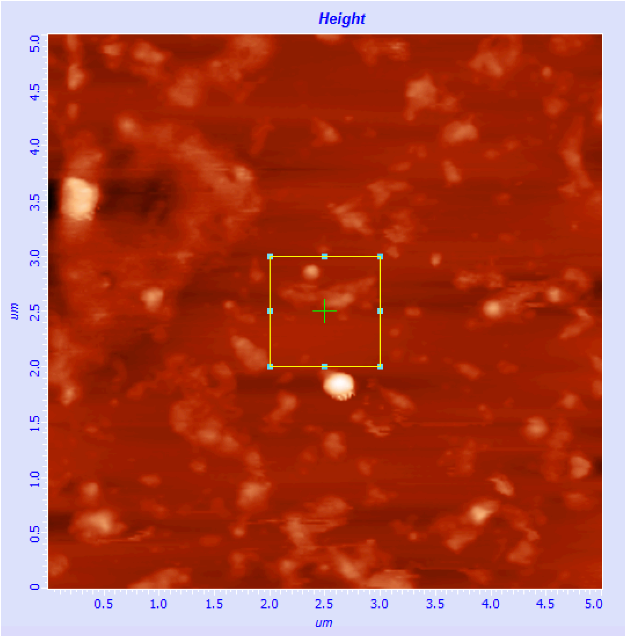


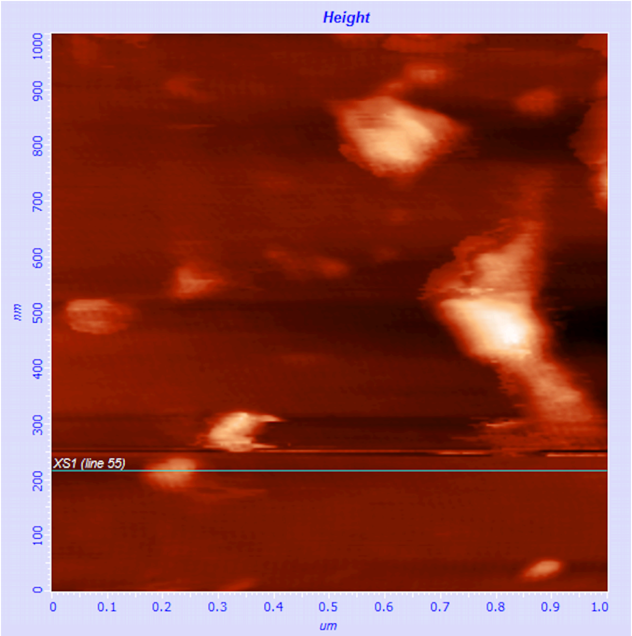


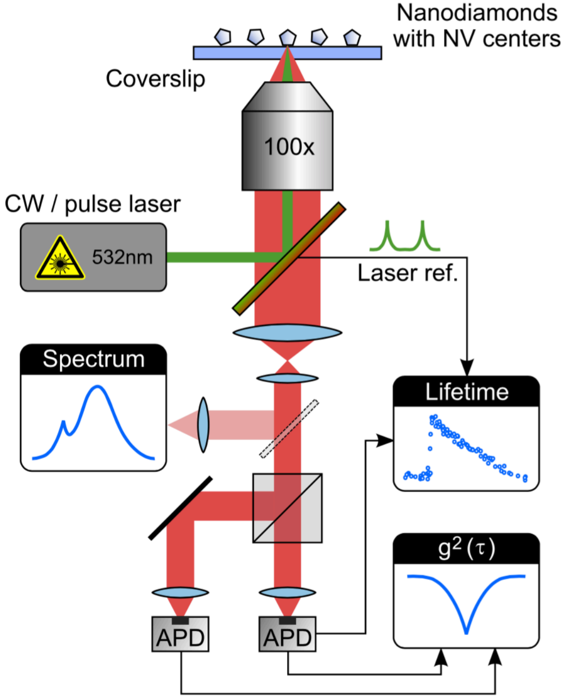
‘Active’ quantum optical metamaterials

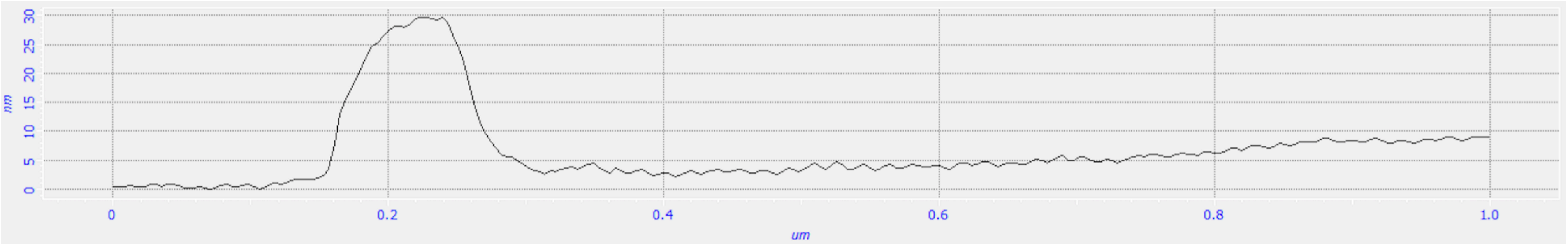
Atomic Force Microscope
manipulation of NV centres

Waveguides


Height
um
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

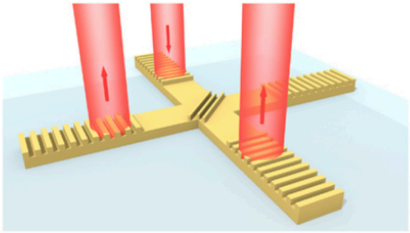

Height
XS1 (line 55)
nm
0 100 200 300 400 500 600 700 800 900 1000
um
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

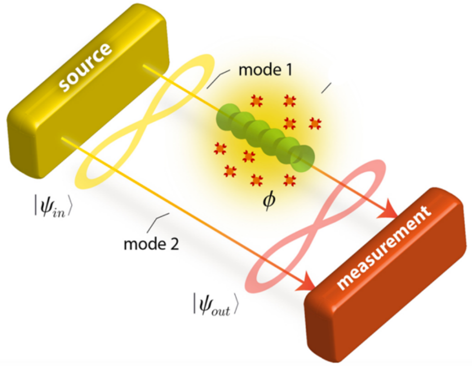

Nanodiamonds
with NV centers
Coverslip
100x
CW / pulse laser
532nm
Laser ref.
Spectrum
Lifetime
g2(τ)
APD
APD

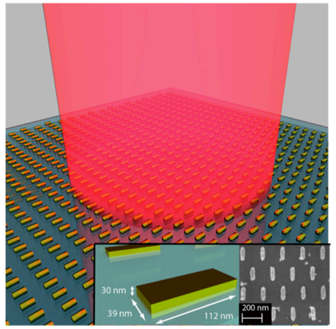

nm
0 5 10 15 20 25 30
0 0.2 0.4 0.6 0.8 1.0
um

Summary

- Introduction
  - Classical and quantum plasmonics
- Recent studies in quantum plasmonics
  - Quantum random number generation
  - Quantum sensing
  - Quantum metamaterials
- Future work







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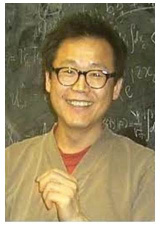

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NRF National Research Foundation

NITheP National Institute for Theoretical Physics

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