Plasmon Empowered Single-Photon Sources

Sergey I. Bozhevolnyi

[1]Centre for Nano Optics, University of Southern Denmark

- **Introduction:**
  - two faces of plasmons
- **Single-photon sources in cavities**
  - photonic vs plasmonic cavities
  - plasmonic cavities: theory and experiments
- **Single-photon sources in waveguides**
  - photonic vs plasmonic waveguides
  - plasmonic waveguides: experiments
- **Outlook**

Plasmon Empowered Single-Photon Sources

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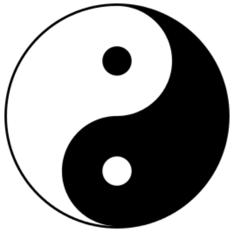
Letter | Vol. 3, No. 12 / December 2016 / *Optica* 1418

optica

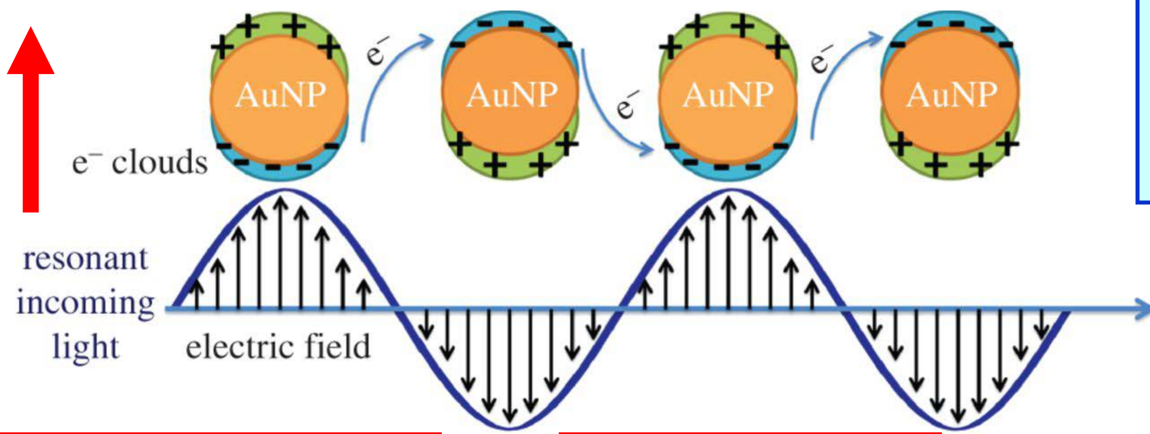
Fundamental limitations in spontaneous emission rate of single-photon sources

Sergey I. Bozhevolnyi[1,*] and Jacob B. Khurgin[2]

Plasmons have two faces …

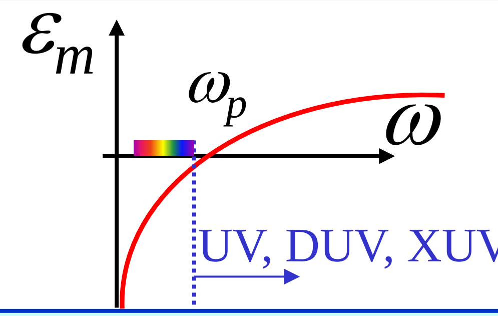


Localized surface plasmons (LSPs)
- Plasmonic resonators/antennas



Polarizability of a nanosphere:

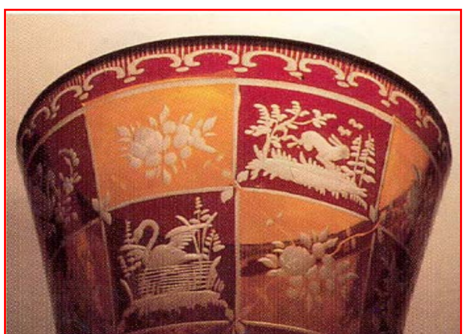
$$\alpha = 4\pi a^3 \frac{\varepsilon_m(\omega) - \varepsilon_d}{\varepsilon_m(\omega) + 2\varepsilon_d}$$

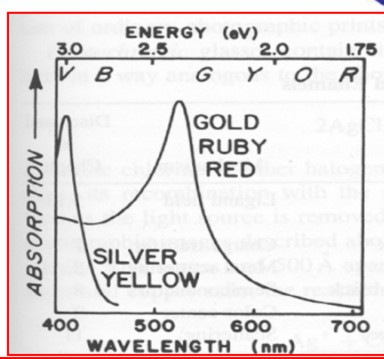


Resonance condition:

$$\mathrm{Re}\left[\varepsilon_m(\omega)\right] = -2\varepsilon_d$$

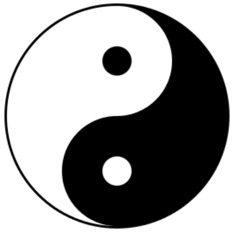
Localized surface plasmon (LSP)



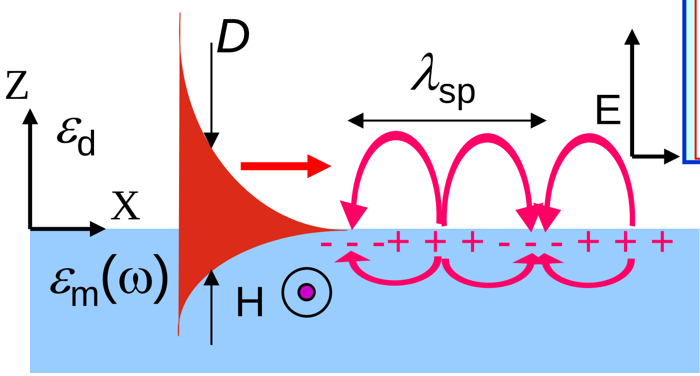


The **scattering** and **absorption** cross sections and the **EM field** inside and near a metal particle are **strongly enhanced at** the **LSP resonance !**

Plasmons have two faces …

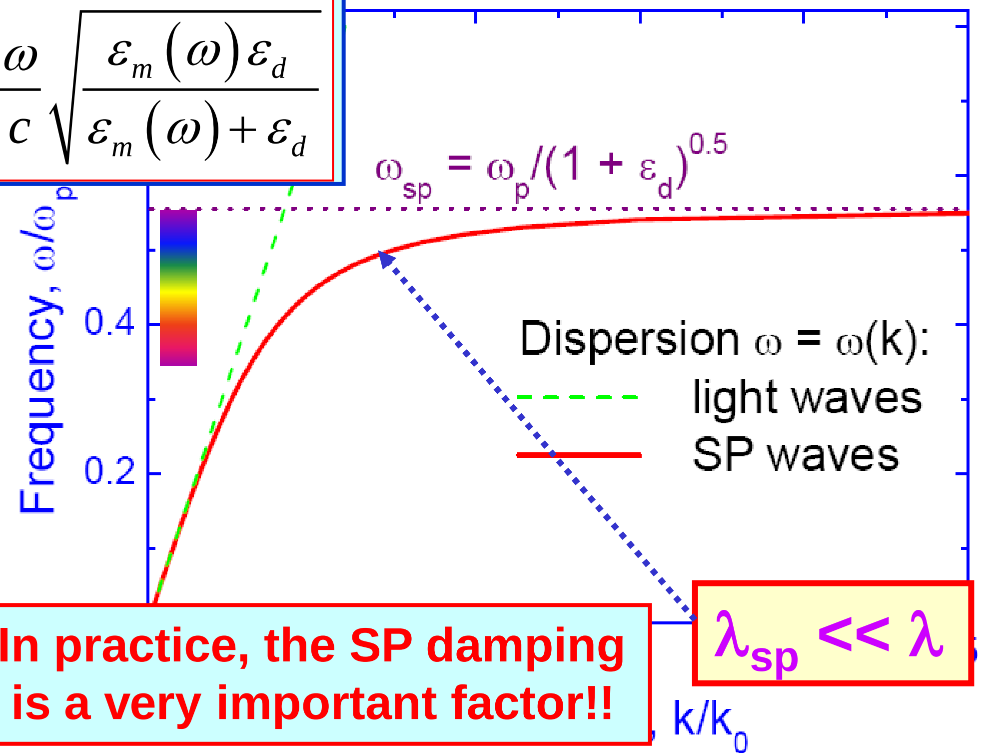


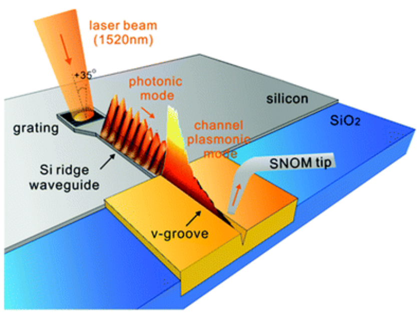
Propagating surface plasmons (SPs) - Plasmonic waveguides

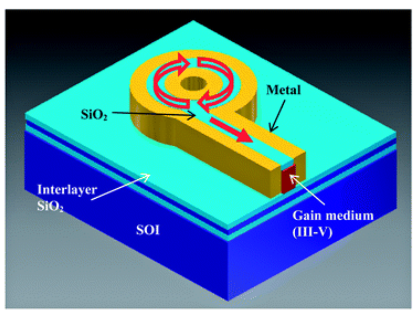


Propagation constant:

$$k_{SPP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m(\omega)\varepsilon_d}{\varepsilon_m(\omega)+\varepsilon_d}}$$







In practice, the SP damping is a very important factor!!

Fundamentally, SP wavelengths can reach nanoscale!

erc European Research Council

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Plasmons have two faces …

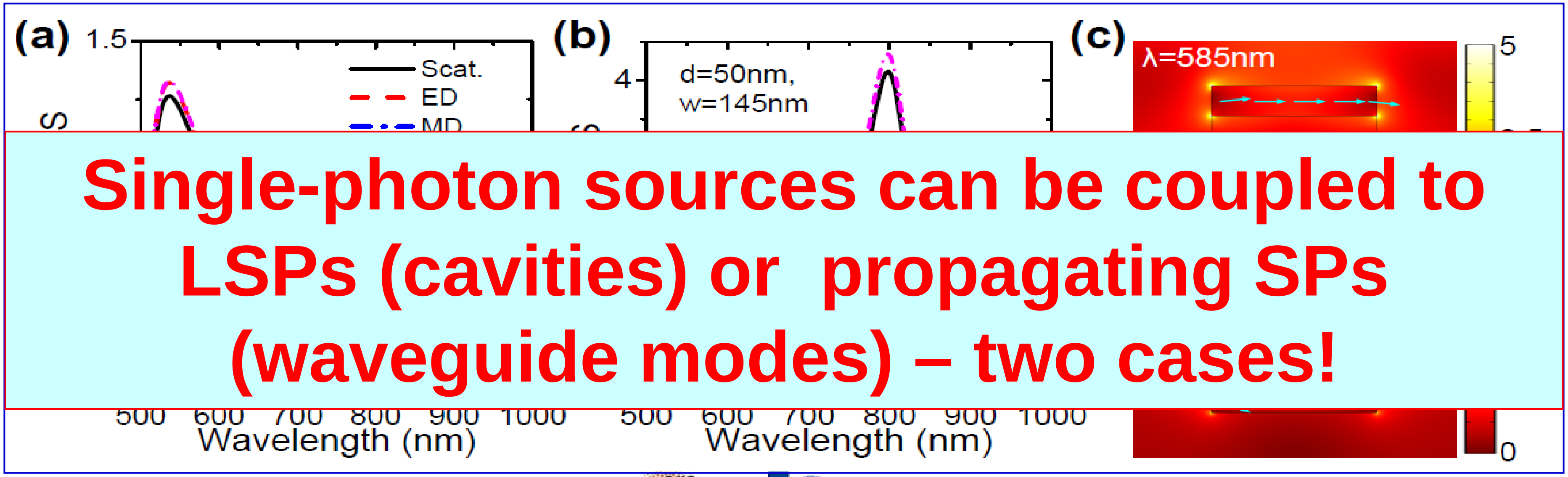
Localized surface plasmons (LSPs)

- Plasmonic resonators/antennas

Propagating surface plasmons (SPs)

- Plasmonic waveguides

LSPs can be viewed as modes of a Fabry-Pérot cavity made by terminating an SP-based waveguide **!**

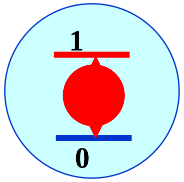


Single-photon sources can be coupled to LSPs (cavities) or propagating SPs (waveguide modes) – two cases!

Single-photon sources

Quantum dipole emitter: two-level atom (QD, NV center,…)

$$\text{Emission: } \sim \exp(-\gamma_0 t) \;\Rightarrow\; \text{emission time: } \tau_0 = \frac{1}{\gamma_0}, \quad \gamma_0 = \frac{\omega^3 n d^2}{3\pi\varepsilon_0 \hbar c^3}$$



Quantum circuitry

Fundamentally, lifetime is ~ 10 ns → the rate of photons is not large enough!

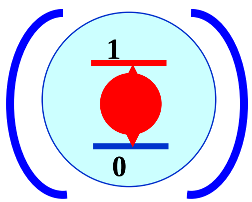
Two relevant configurations: cavities and waveguides

Increase LDOS near QDE - Purcell factor!

Single-photon sources in cavities

Quantum dipole emitter inside a cavity:

Emission time: $\tau = \dfrac{\tau_0}{F}$, with Purcell factor: $F = \dfrac{3}{4\pi^2}\left(\dfrac{\lambda}{n}\right)^3 \dfrac{Q}{V} \Rightarrow \gamma = F\gamma_0$



Quantum circuitry

For conventional (dielectric-based) cavities, fundamentally, the volume can be as small $(\lambda/2n)^3$ whereas the quality factor Q can be as large as 10^5!

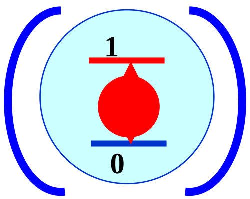
Does this mean that the rate can be 10 Tbit/s?

No way!

Single-photon sources in cavities

Quantum dipole emitter inside a very good cavity:

Emission-out-of-cavity time: $\tau_{cav} = \frac{1}{\gamma_{cav}} = \frac{Q}{\omega}, \quad \Rightarrow \tau_{emit} = \max\left\{\tau_{cav}, \frac{\tau_0}{F}\right\}$



Quantum circuitry

Optimum case: $\tau_{cav} = \frac{\tau_0}{F}, \Rightarrow \frac{1}{\tau_{cav}} = \gamma_0 F, \Rightarrow \frac{\omega}{Q_{opt}} = \gamma_0 \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q_{opt}}{V}$

$$\Rightarrow Q_{opt} = \pi\sqrt{\frac{\omega V_{norm}}{6\gamma_0}}, V_{norm} = V\left(\frac{2n}{\lambda}\right)^3 \Rightarrow \gamma_{SE}^{\max} \le \frac{\sqrt{6\omega\gamma_0}}{\pi}$$

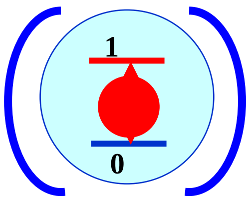
Out-of-cavity emission rate is diffraction-limited!

Single-photon sources in cavities

Quantum dipole emitter inside a cavity (QM analysis):

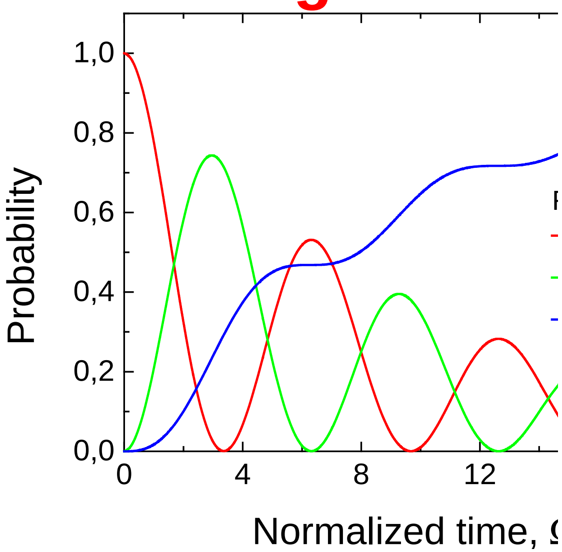
$$\Omega = \frac{\sqrt{6\gamma_0\omega}}{\pi}$$

$$R = \gamma_{cav}/\Omega$$

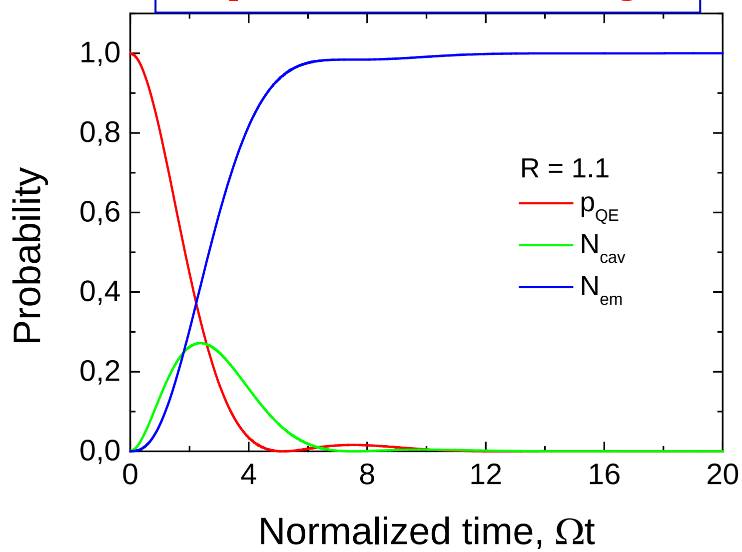


Quantum circuitry

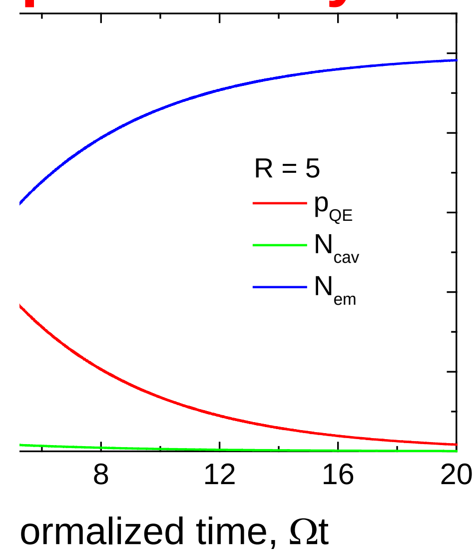
Too good cav



Optimum cavity:



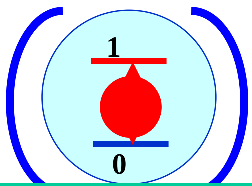
poor cavity:



Optimum cavity does make a difference!

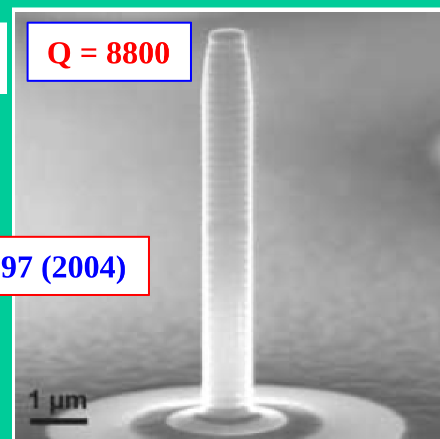
Single-photon sources in cavities

Quantum dipole emitter inside a cavity (QM analysis):

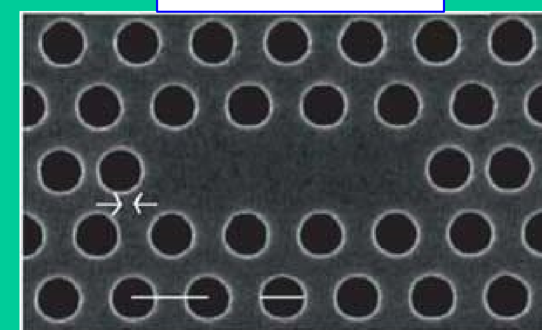


Quantum circuitry

First strong coupling experiments:

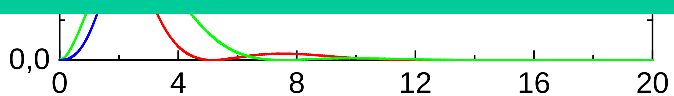


Nature 432, 197 (2004)



Q = 16000 - 20000

Nature 432, 200 (2004)



Normalized time, Ωt

Diffraction limited performance:

$Q_{opt} \geq 5100;\ B_{rate}^{\max} \cong 54\,\text{Gbit/s}$

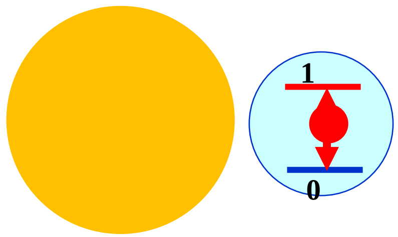
Not much!

Let us seek the help from plasmonics!

Single-photon sources in cavities

Quantum dipole emitter inside a plasmonic cavity:

$$\text{Emission rate: } \gamma_{emit} = F\frac{\gamma_{rad}}{\gamma_{abs}+\gamma_{rad}}\gamma_0 = \left\| Q = \frac{\omega}{\gamma_m+\gamma_{rad}} \sim 100 \right\| = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{\omega\gamma_{rad}}{V_{SP}\left(\gamma_m+\gamma_{rad}\right)^2}\gamma_0$$



Quantum circuitry

$$\text{Emission rate: } \gamma_{emit} = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{\omega\gamma_{rad}}{V_{SP}\left(\gamma_m+\gamma_{rad}\right)^2}\gamma_0 = \left\| \begin{array}{l} V_{SP} \to 0 \text{ , but} \\ \gamma_{rad} = \frac{4}{3}\pi^2\omega\frac{V_{SP}}{\lambda\lambda_p^2} \end{array} \right\| \le \frac{1}{n^3}\cdot\frac{\omega_p^2}{\gamma_m^2}\gamma_0 = \gamma_{emit}^{\max}$$

The emission rate in plasmonics is loss-limited!

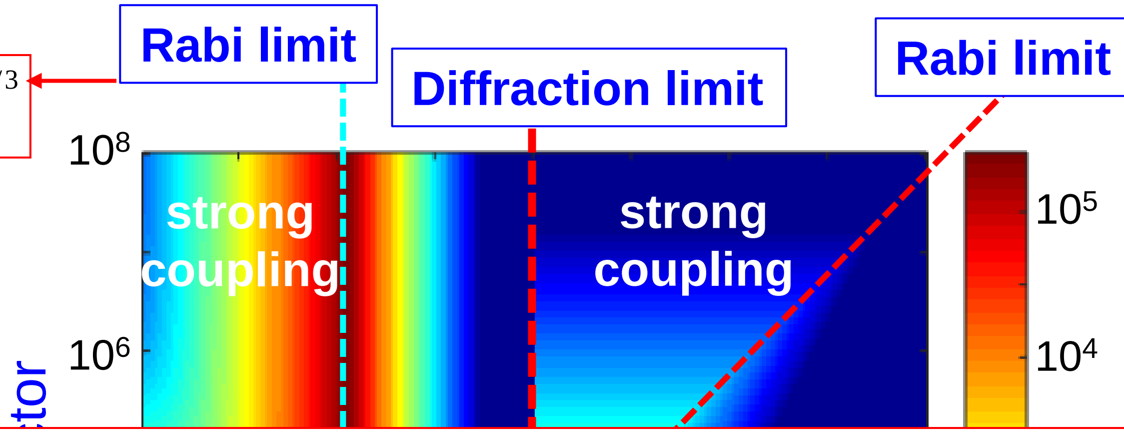
Numerical example for gold $\Rightarrow$ loss-limited performance: $B_{rate}^{\max} \cong 5.4\,T\text{bit/s}$

100 times better!

Single-photon sources in cavities

Cavity-enhanced single-photon emission rate:

$$\Gamma_{\text{plas}}^{\text{lim}} = \left(\omega_{\text{p}} / \gamma_0 \right)^{2/3}$$



commentary

NATURE PHOTONICS | VOL 11 | JULY 2017 | www.nature.com/naturephotonics

The case for quantum plasmonics

Sergey I. Bozhevolnyi and Jacob B. Khurgin

The rate enhancement by plasmonics is larger by 100!

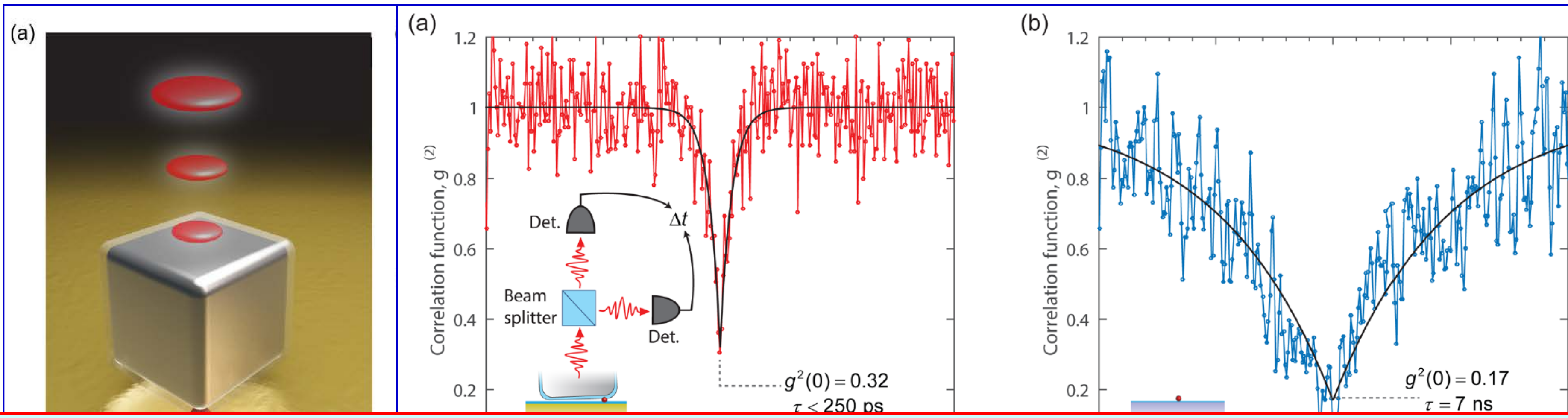
Plasmonic single-photon sources

NANO LETTERS
Letter
pubs.acs.org/NanoLett
DOI: 10.1021/acs.nanolett.5b03724
Nano Lett. 2016, 16, 270–275

Ultrafast Room-Temperature Single Photon Emission from Quantum Dots Coupled to Plasmonic Nanocavities

Thang B. Hoang,[†,‡] Gleb M. Akselrod,[‡,§] and Maiken H. Mikkelsen*[,†,‡,§]

[†]Department of Physics, [‡]Center for Metamaterials and Integrated Plasmonics, and [§]Department of Electrical and Computer Engineering, Duke University, Durham, North Carolina 27708, United States



Plasmonics can deliver ultimate emission rates!

Lifetime of 13 ps and ~1900 times SE enhancement are achieved!

Plasmonic single-photon sources

ACS Photonics
Article
pubs.acs.org/journal/apchd5

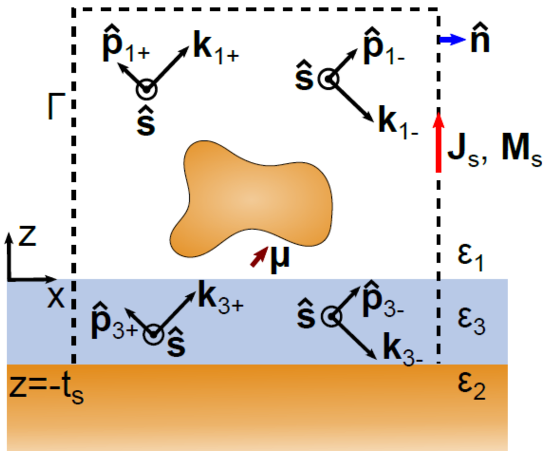
**Quantum Emitters near Layered Plasmonic Nanostructures: Dec
Rate Contributions**

DOI: 10.1021/ph500
ACS Photonics 2015, 2, 228-

Anders Pors* and Sergey I. Bozhevolnyi

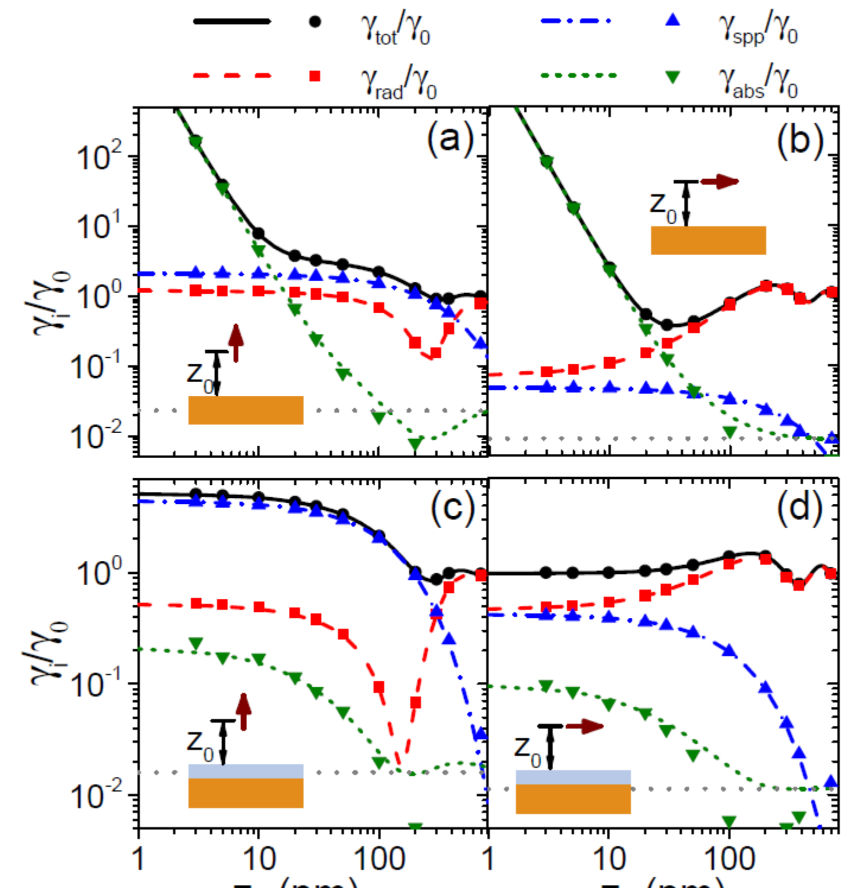
Anders L. Pors

General configuration:



$$\mathbf{J}_s = \hat{\mathbf{n}} \times \mathbf{H}, \quad \mathbf{M}_s = -\hat{\mathbf{n}} \times \mathbf{E}$$

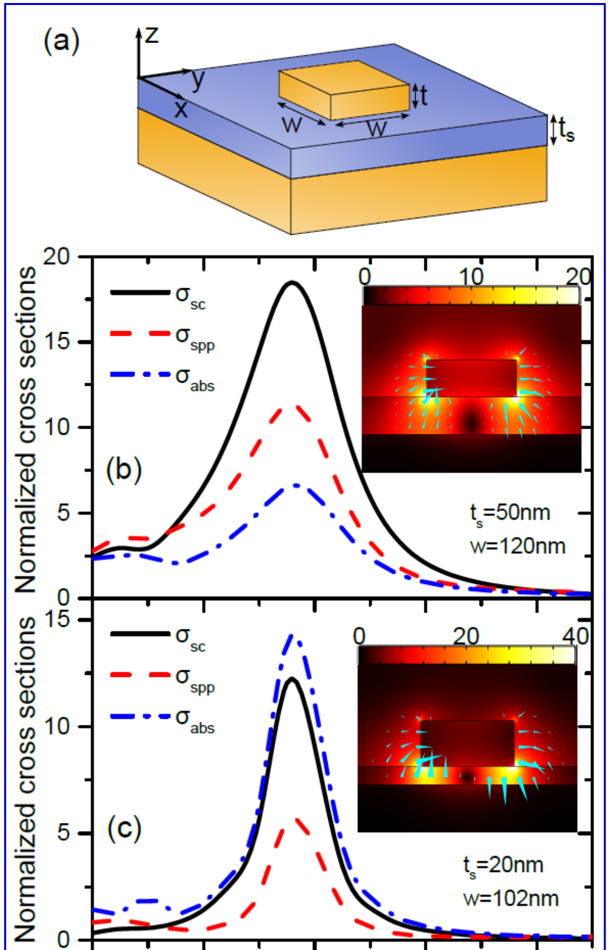
Comparison of analytical and numerical results:



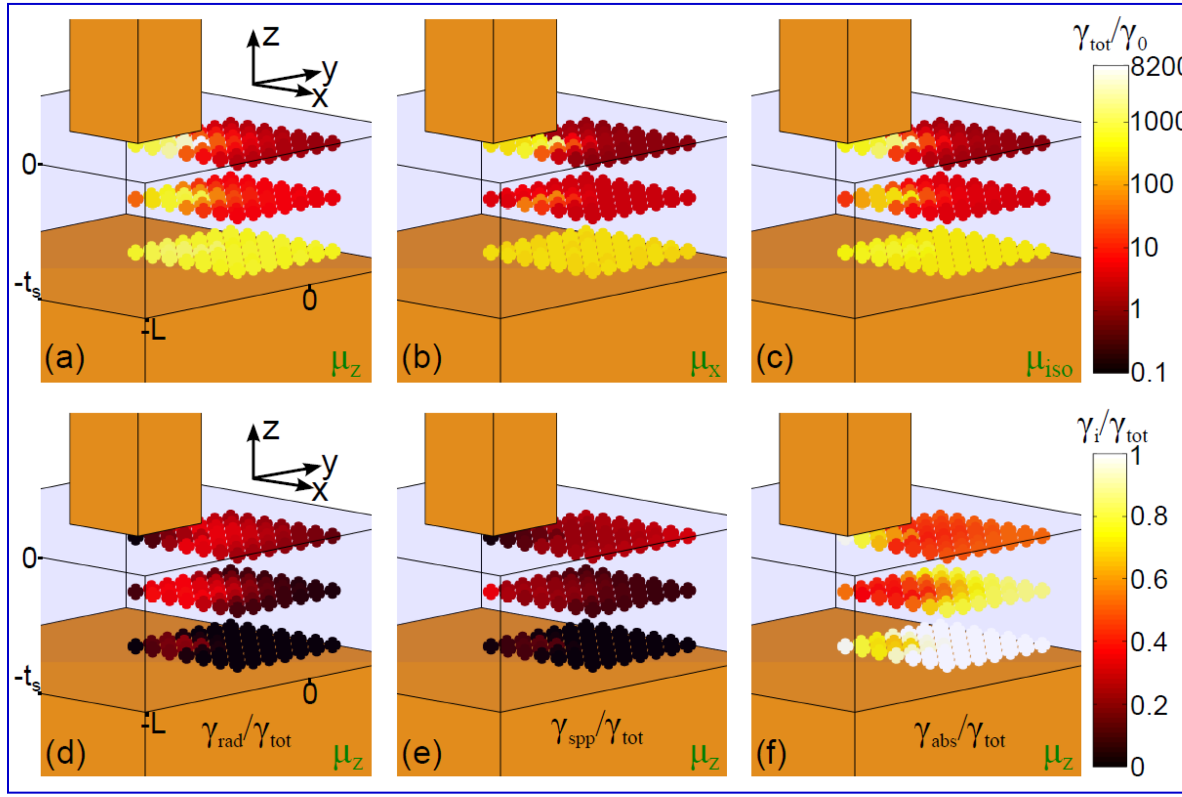
Comparison confirmed the validity of the approach developed!

Plasmonic single-photon sources

Main configuration:



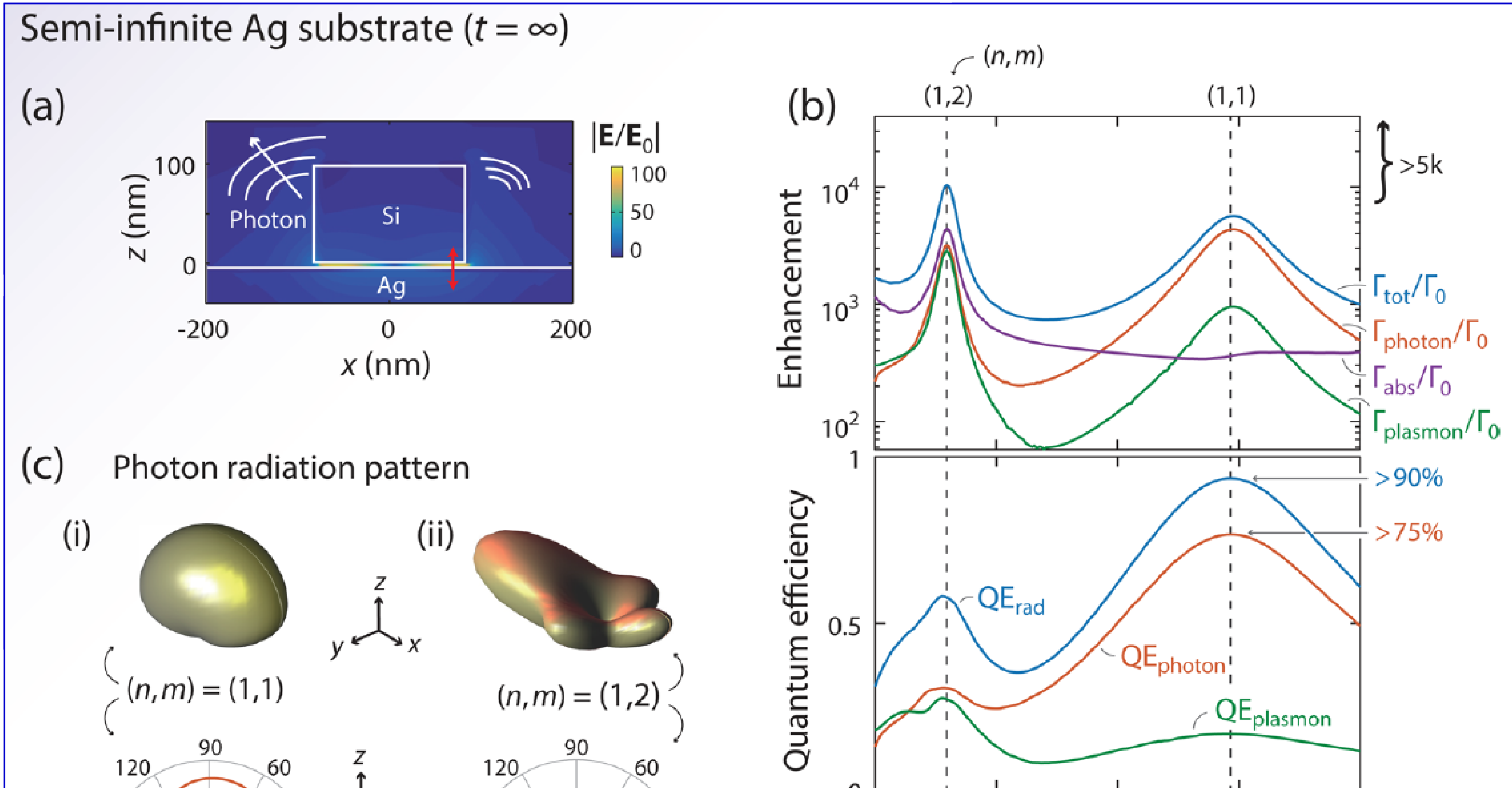
Total decay rates and its contributors (t_s = 20 nm):



Total decay rate modification for (a) z-directed, (b) x-directed, and (c) isotropically

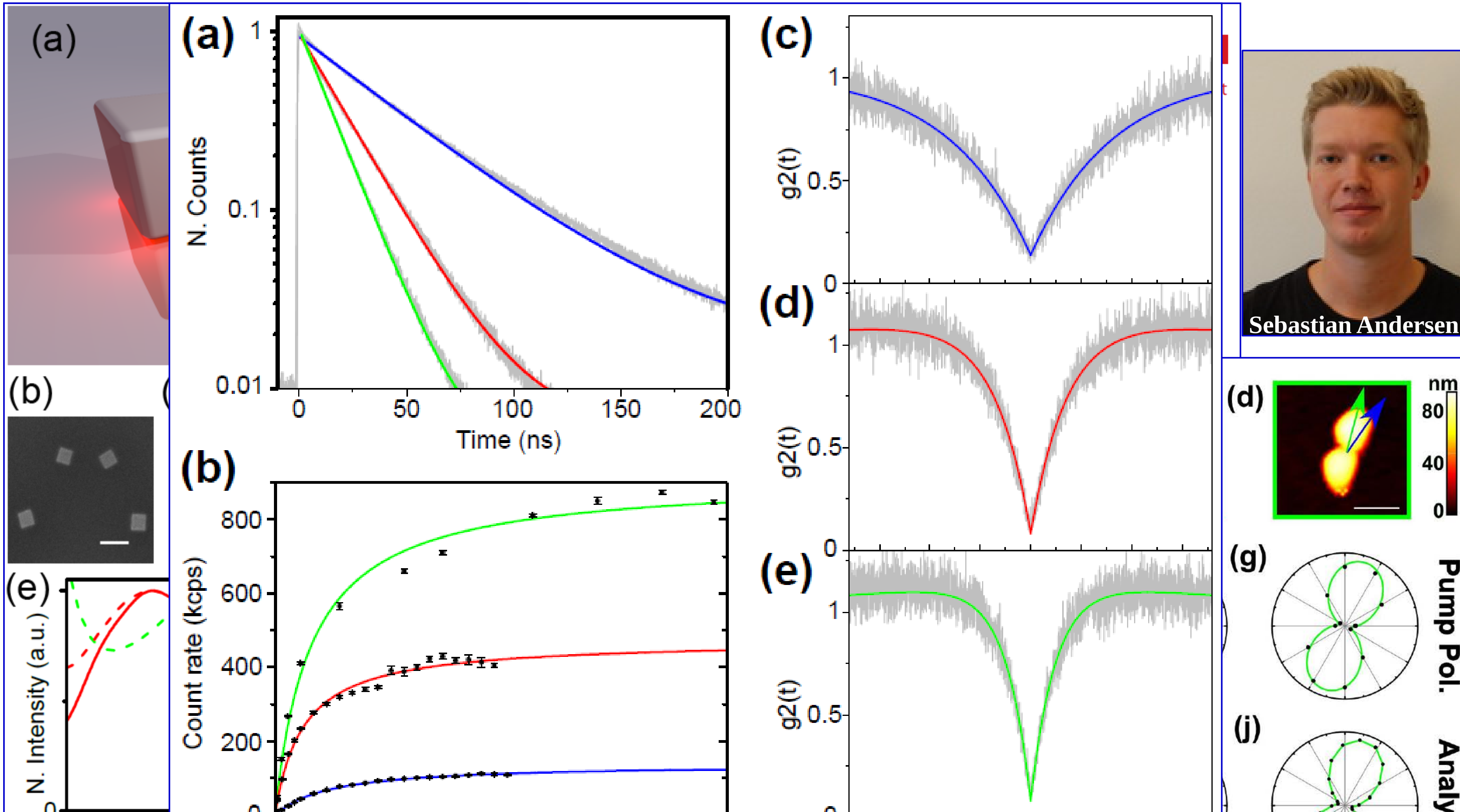
GSP-based resonators enhance not only free-space SE emission, but, depending on the QE position/orientation, also result in strong SP emission and SE absorption/quenching!

Plasmonic single-photon sources



The cavity length is diffraction-limited – careful comparison with GSP configurations is yet to be carried out!

Plasmonic single-photon sources

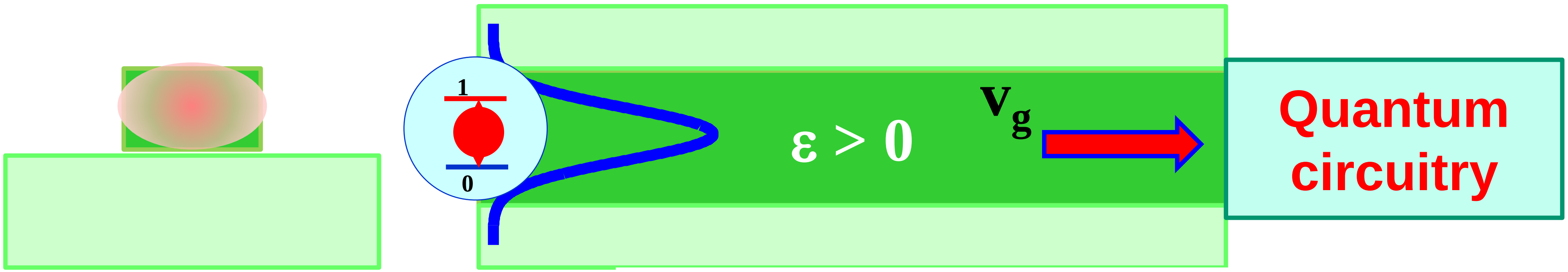


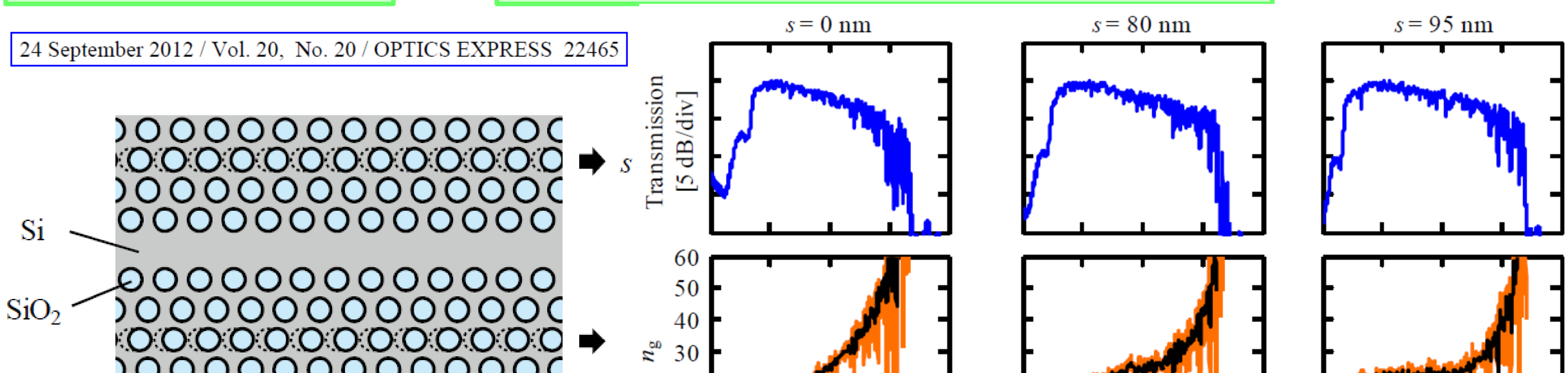
Bright (850 kcps) pure single-photon ($g^{(2)}$ ~ 0.08) linearly-polarized sources are demonstrated!

Single-photon sources in waveguides

Quantum dipole emitter inside a dielectric waveguide

Emission rate: $\gamma_{emi} = \gamma_0(\beta)F, \;\; F \cong \frac{1}{\pi}\frac{n_g}{n^2}\frac{(\lambda/2)^2}{A_{wm}} = \left\| A_{wm} \geq \left(\frac{\lambda}{2n}\right)^2 \right\| \leq \frac{n_g}{\pi}$



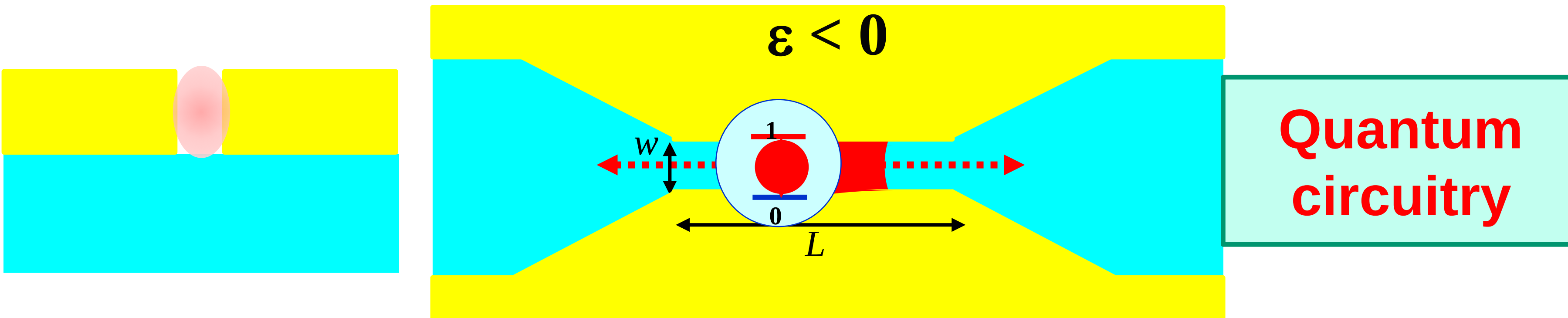


In PC waveguides near band-gap edge $n_g \to \infty$, but the effect is of narrow bandwidth and with high insertion losses (!), so realistically $F < 50$.

Single-photon sources in waveguides

Quantum dipole emitter inside a plasmonic waveguide

Emission rate: $\gamma_{emi} = \gamma_0(\beta) F \exp\left(-L/L_{SPP}\right)$, $F \cong \left\| n_g = \frac{2\lambda\varepsilon_d}{\pi|\varepsilon_m'| w}; A_{GSP} = \frac{\lambda_{GSP}}{2} w \right\| = \frac{\varepsilon_d}{\pi^3}\frac{\lambda_p}{\lambda}\left(\frac{\lambda_p}{w}\right)^3$



Example:

Gold: $\gamma_m \cong 6.46\cdot 10^{12}$ Hz, $\omega_p \cong 2.183\cdot 10^{15}$ Hz, $\lambda = 1\,\mu\text{m}$, $\lambda_p \cong 130$ nm, $w \cong 4$ nm $\Rightarrow F(n=1) \cong 150$

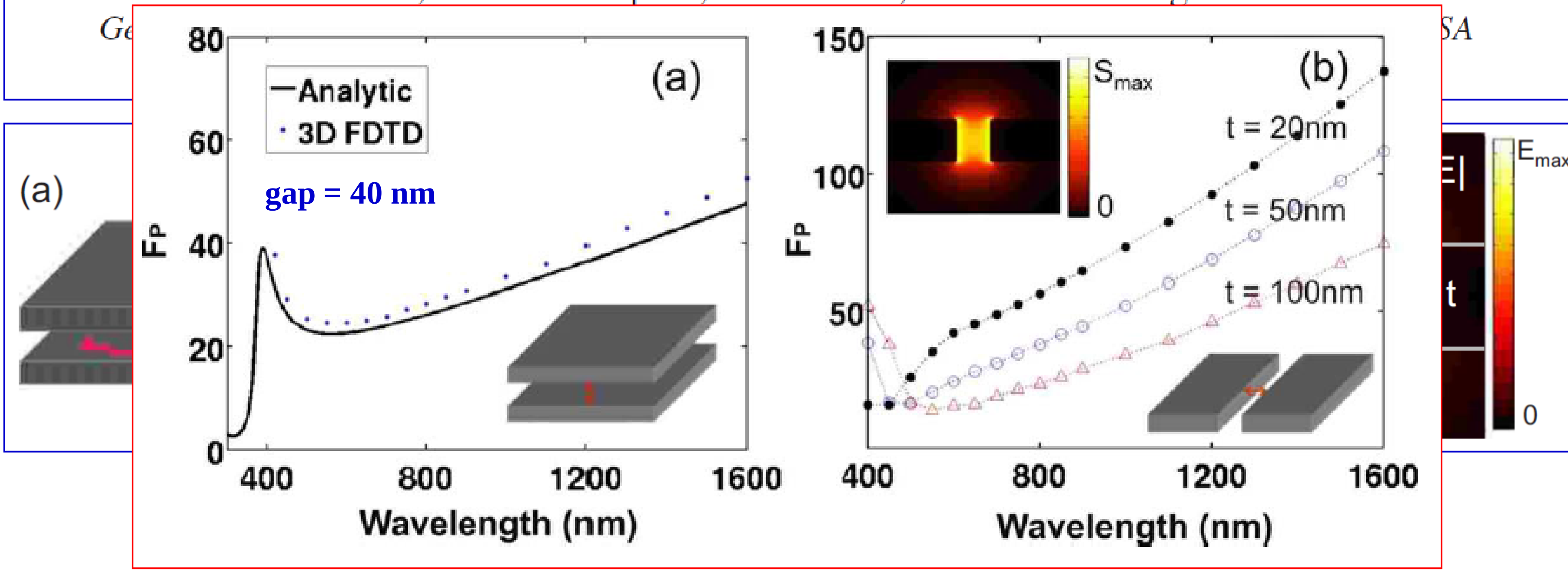
Purcell enhancement in GSP-based waveguides can be enormous, while preserving its broadband (nonresonant) nature, but the usage of tapers is strictly required!

Plasmonic single-photon sources

PHYSICAL REVIEW B **78**, 153111 (2008)

Nonresonant enhancement of spontaneous emission in metal-dielectric-metal plasmon waveguide structures

Y. C. Jun, R. D. Kekatpure, J. S. White, and M. L. Brongersma*



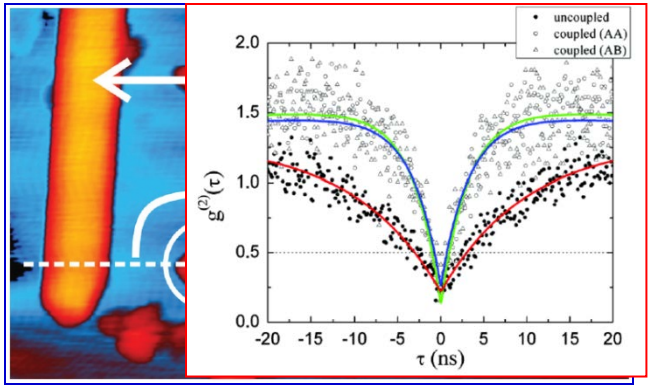
Purcell factor of 100 in GSP-based waveguides has been predicted already in the first simulations for 20-nm gaps!

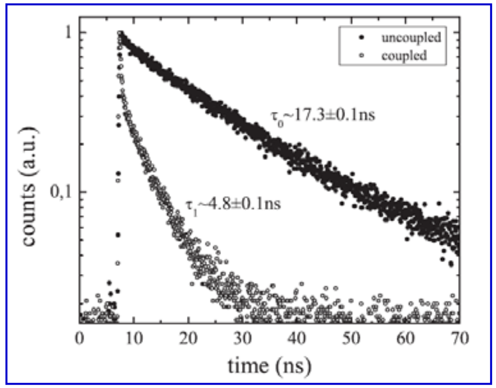
Plasmonic single-photon sources

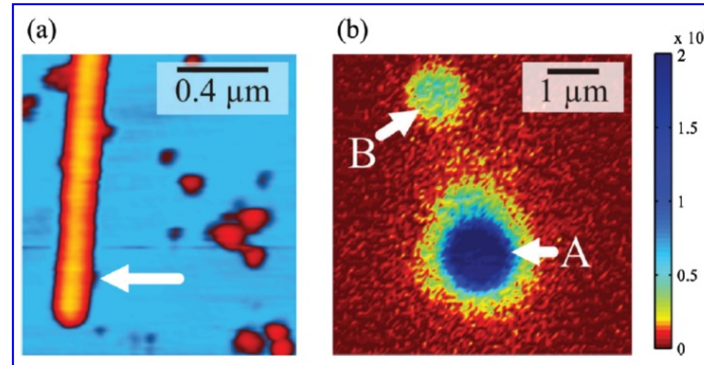
PRL 106, 096801 (2011) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2011

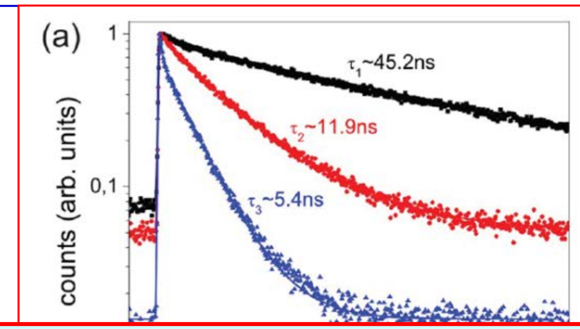
Controlled Coupling of a Single Nitrogen-Vacancy Center to a Silver Nanowire

Alexander Huck,[1,*] Shailesh Kumar,[1] Abdul Shakoor,[1,†] and Ulrik L. Andersen[1]

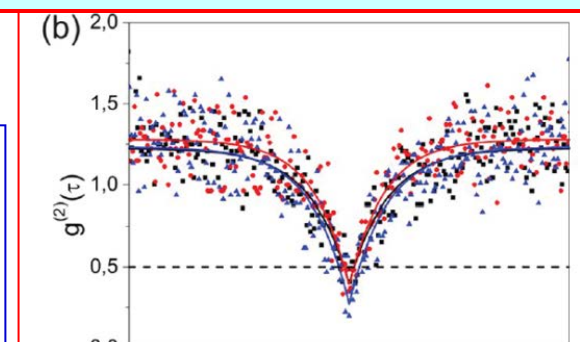








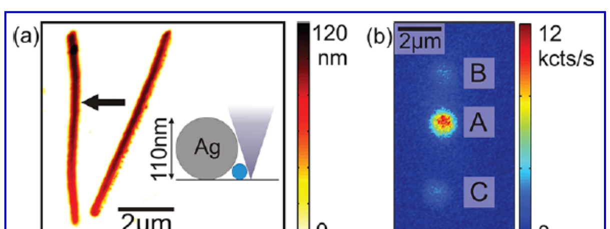
Purcell factor ~ 9

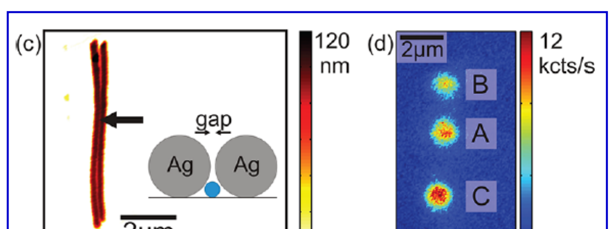


NANO LETTERS *Nano Lett.* 2013, 13, 1221−1225 Letter pubs.acs.org/NanoLett

Efficient Coupling of a Single Diamond Color Center to Propagating Plasmonic Gap Modes

Shailesh Kumar,* Alexander Huck, and Ulrik L. Andersen





Plasmonic waveguides can increase emission rates!

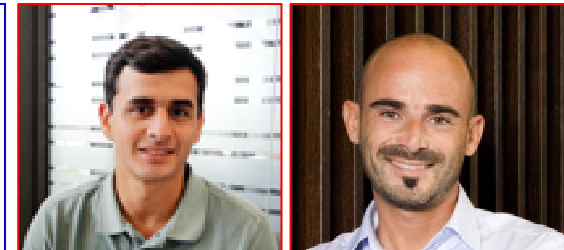
Plasmonic single-photon sources

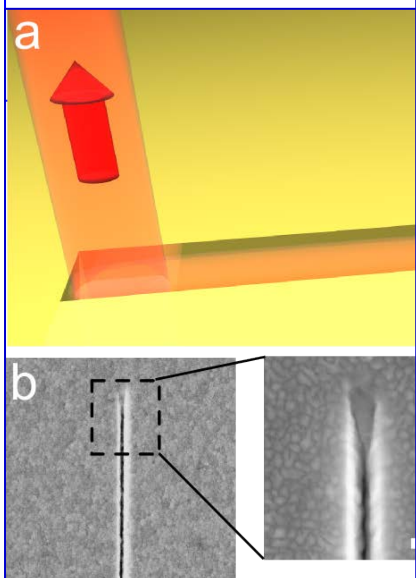
ARTICLE
Received 2 Oct 2014 | Accepted 23 Jun 2015 | Published 7 Aug 2015
DOI: 10

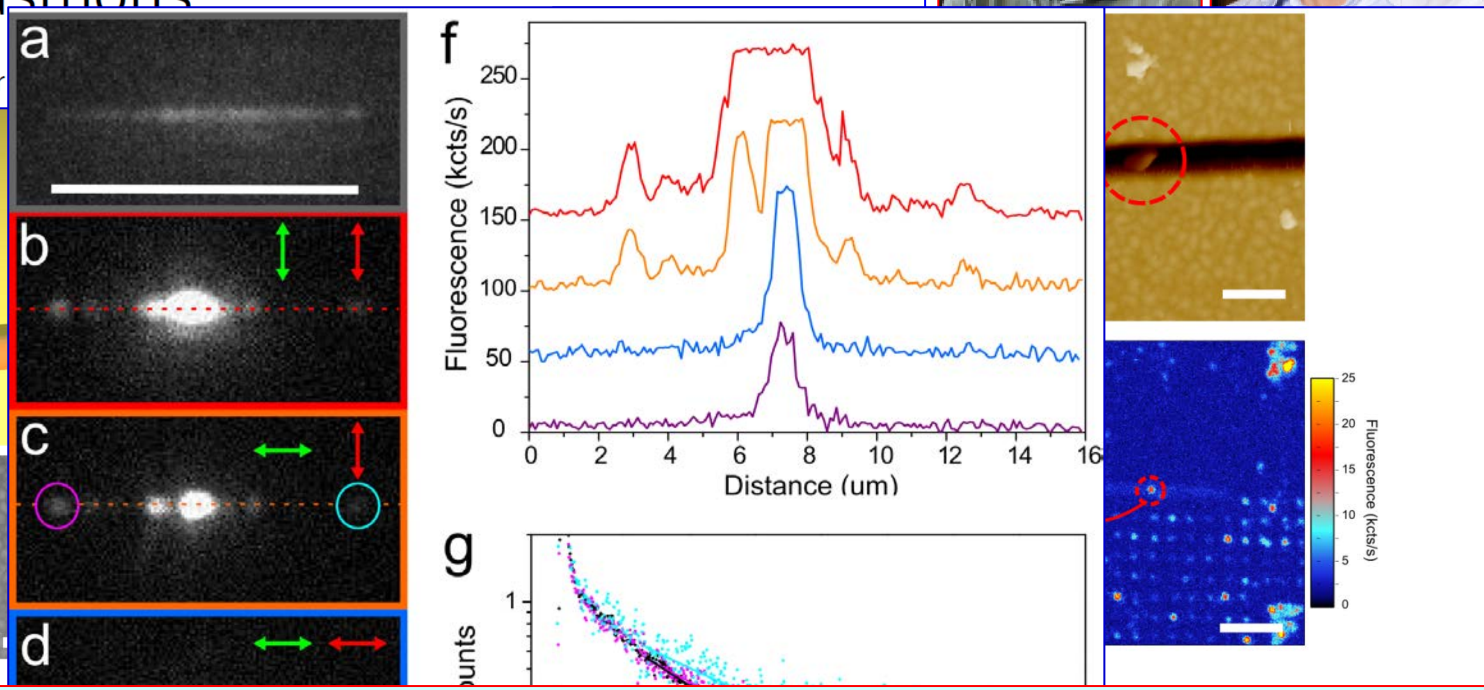
nature COMMUNICATIONS

Coupling of individual quantum emitters to channel plasmons

Esteban Bermúdez-Ureña[1], Car







The combination of the *β*-factor of 0.42, Purcell factor of 2.3 along with propagation length of 4.65 *μ*m normalized by the operating wavelength of 0.68 *μ*m, makes the demonstrated configuration one of the best in terms of FOM (6.6 ± 1.5).

Plasmonic single-photon sources

ACS Photonics

Letter

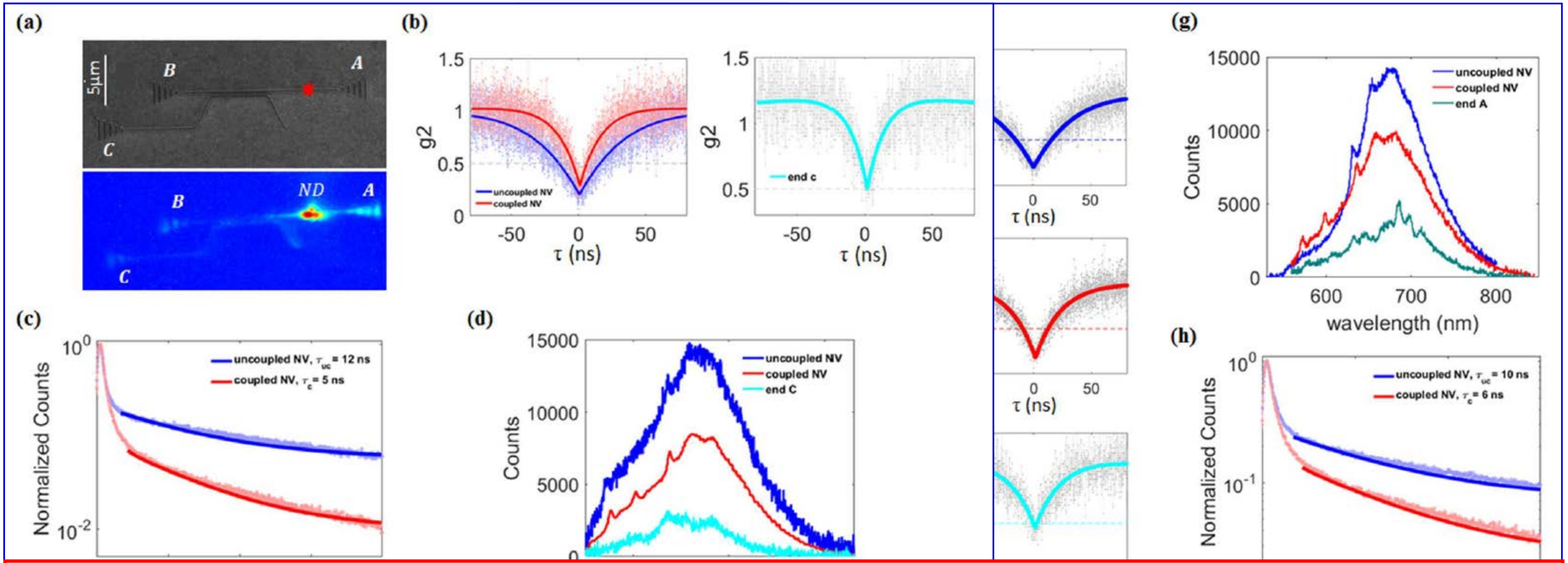
DOI: 10.1021/acsphotonics.7b00374
ACS Photonics 2017, 4, 1879–1884

pubs.acs.org/journal/apchd5

Nanofabrication of Plasmonic Circuits Containing Single Photon Sources

Hamidreza Siampour,* Shailesh Kumar, and Sergey I. Bozhevolnyi*

Hamidreza Siampour



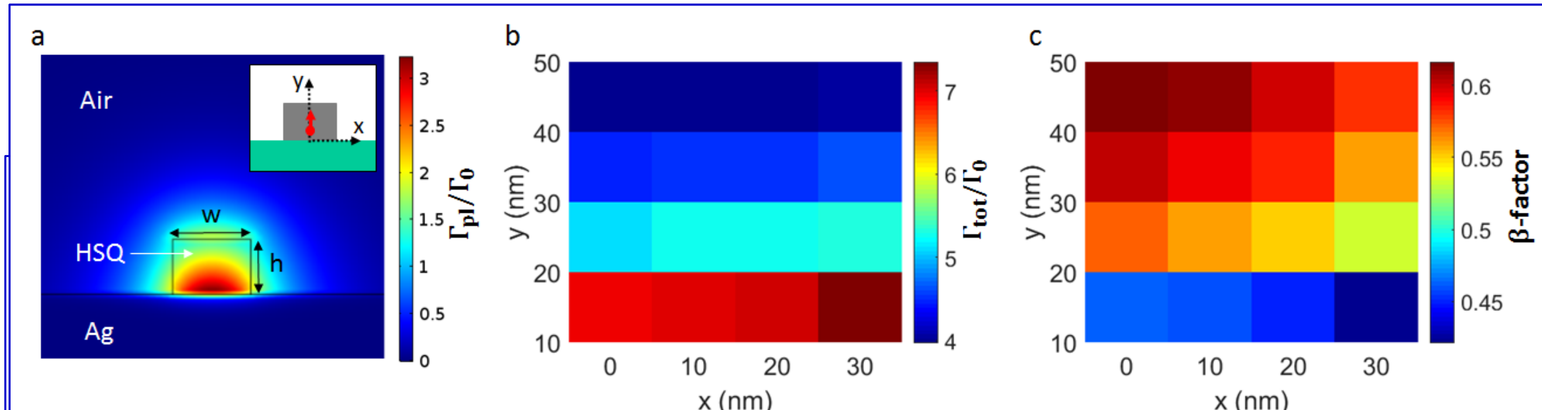
Quantum plasmonic circuitry is indeed realistic!

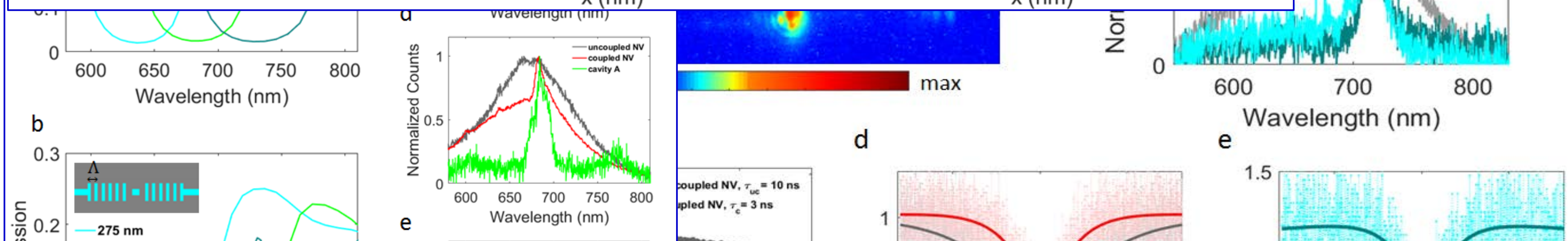
Plasmonic single-photon sources

Chip-integrated plasmonic cavity-enhanced single nitrogen-vacancy center emission

Hamidreza Siampour, Shailesh Kumar and Sergey I. Bozhevolnyi

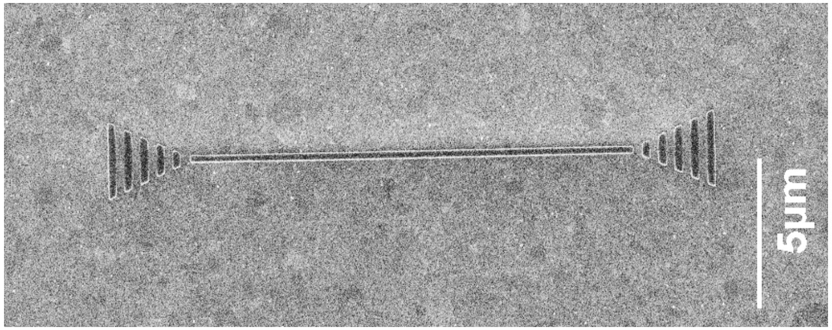
submitted

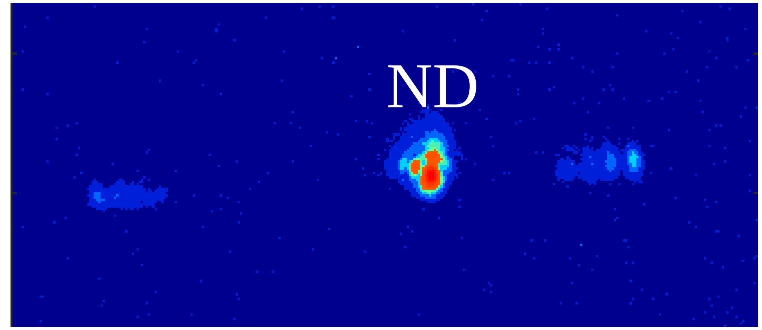


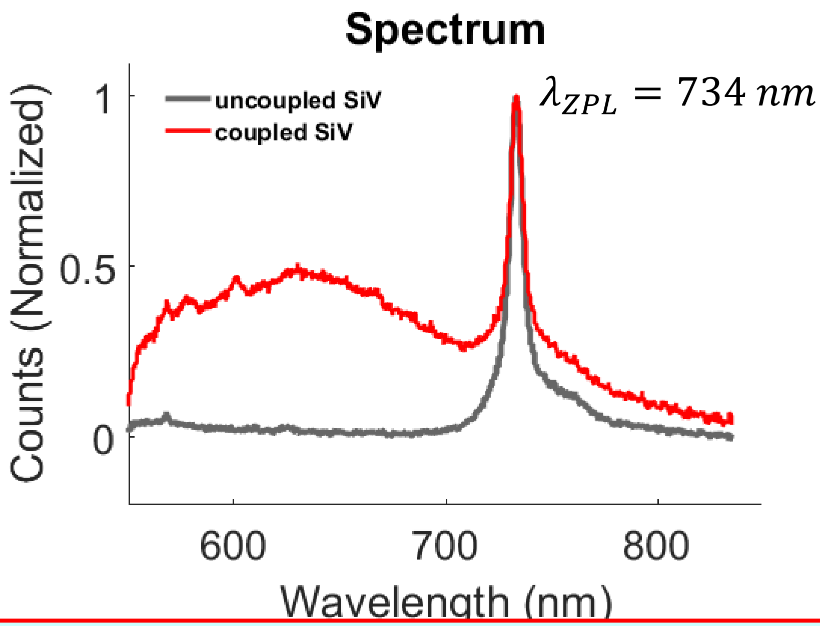


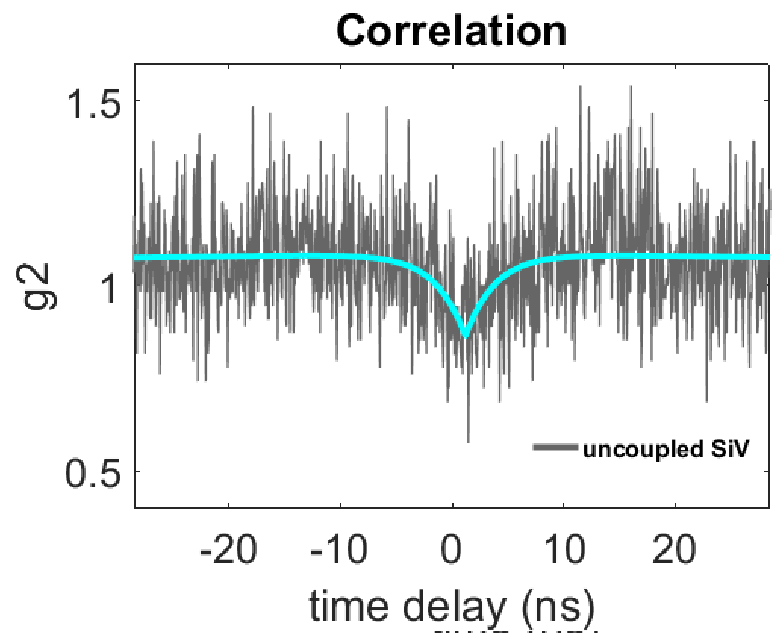
This configuration features the *β*-factor of 0.58, Purcell factor of 5 and propagation length of 20 *μ*m, resulting together in the (so far) best FOM of 83 (!).

Next: experiments with SiV centers









No need for NDs containing only single SiV centers for single-photon nonlinear (low-temperature) experiments!

Feasibility of X-confined GSPs

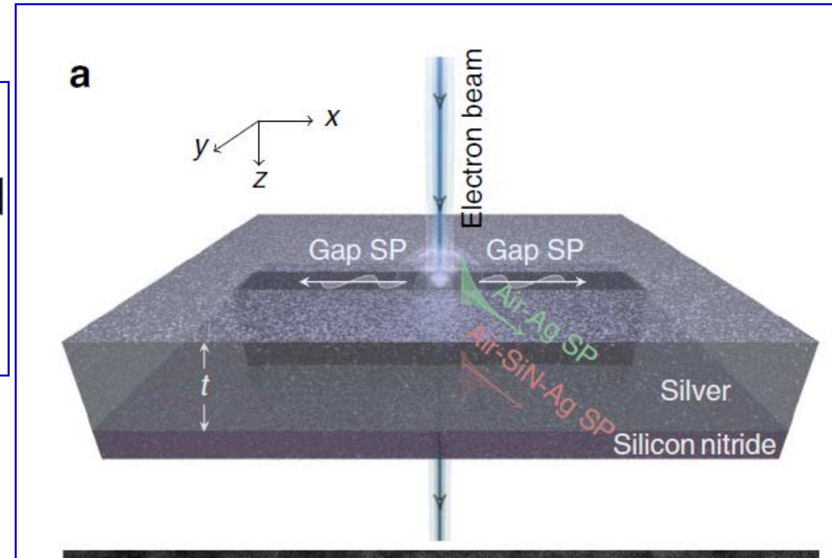
nature COMMUNICATIONS

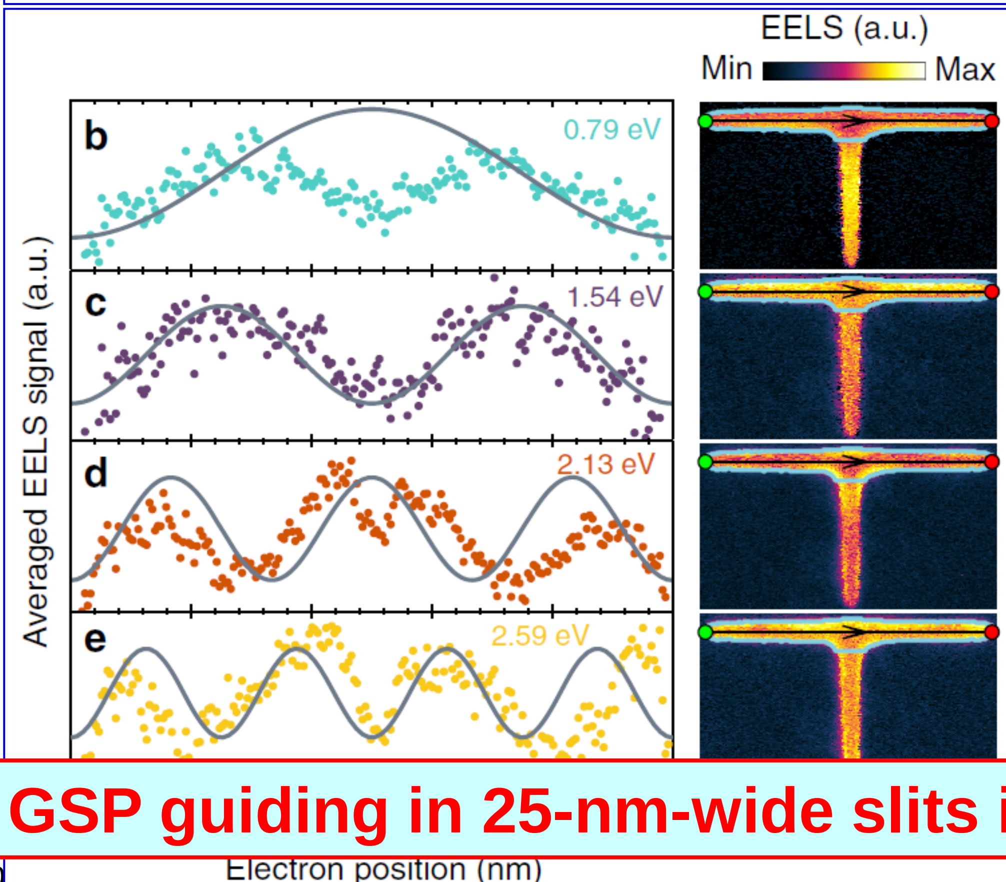
ARTICLE

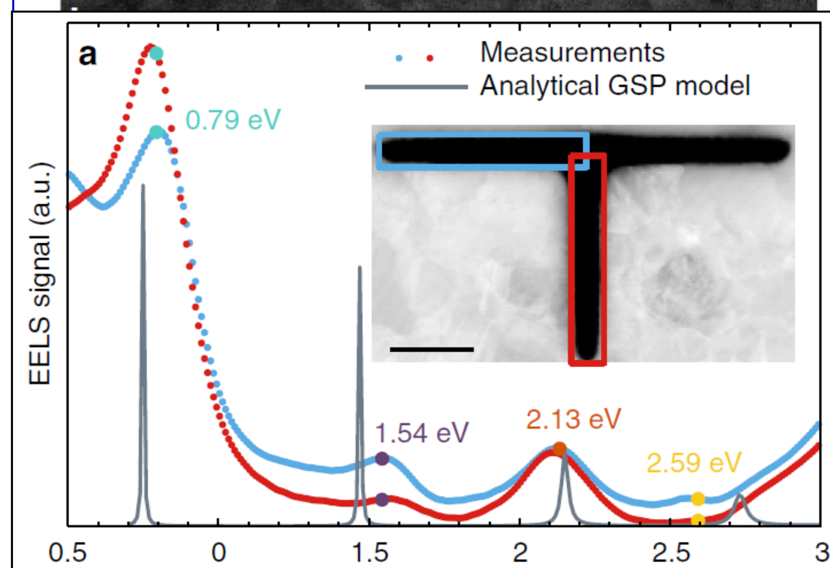
Received 4 Feb 2016 | Accepted 2 Nov 2016 | Published 16 Dec 2016 DOI: 10.1038/ncomms13790 OPEN

Electron energy-loss spectroscopy of branched gap plasmon resonators

Søren Raza[1,2], Majid Esfandyarpour[2], Ai Leen Koh[3], N. Asger Mortensen[4,5], Mark L. Brongersma[2] & Sergey I. Bozhevolnyi[1]







GSP guiding in 25-nm-wide slits is feasible in optical range!

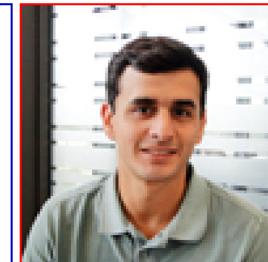
Feasibility of CPP-coupled lasers

NANO LETTERS

Letter

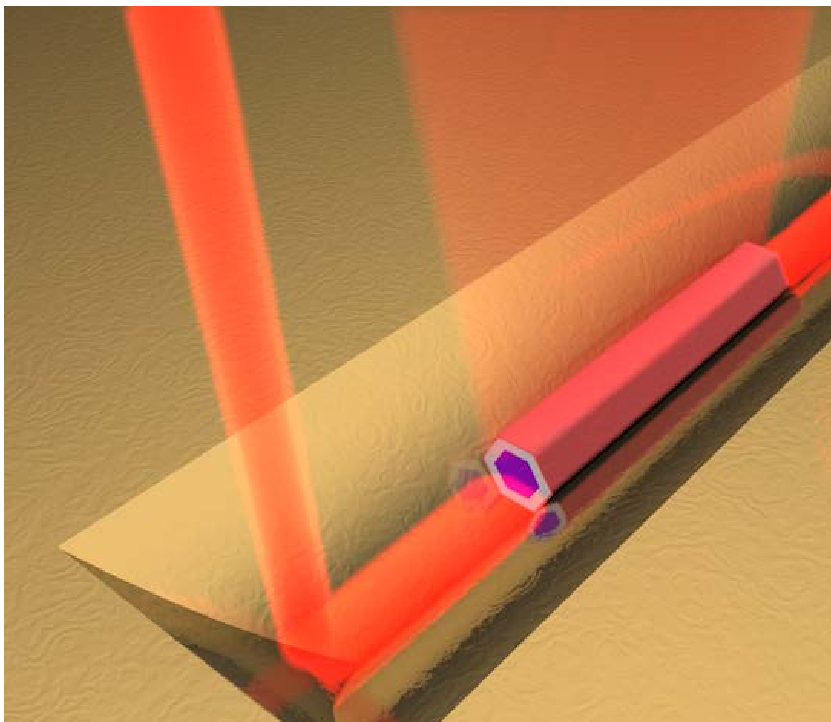
DOI: 10.1021/acs.nanolett.6b03879
Nano Lett. 2017, 17, 747–754

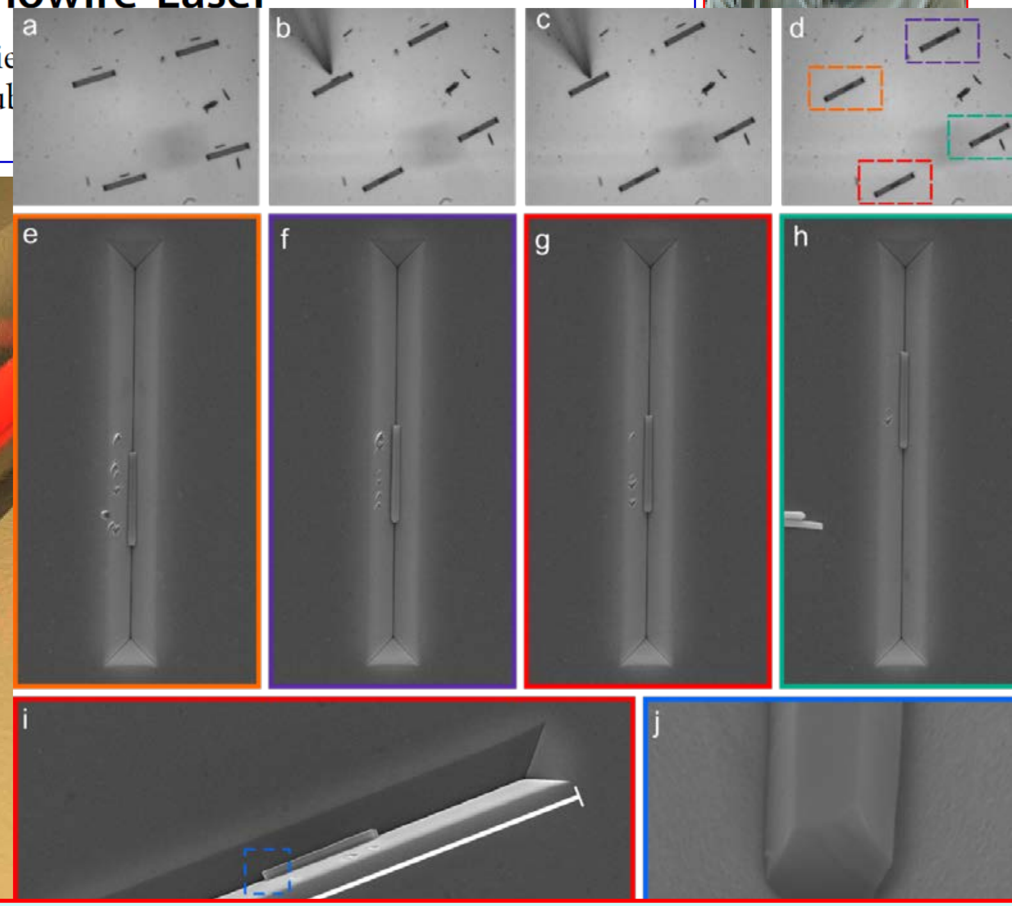
pubs.acs.org/NanoLett



Plasmonic Waveguide-Integrated Nanowire Laser

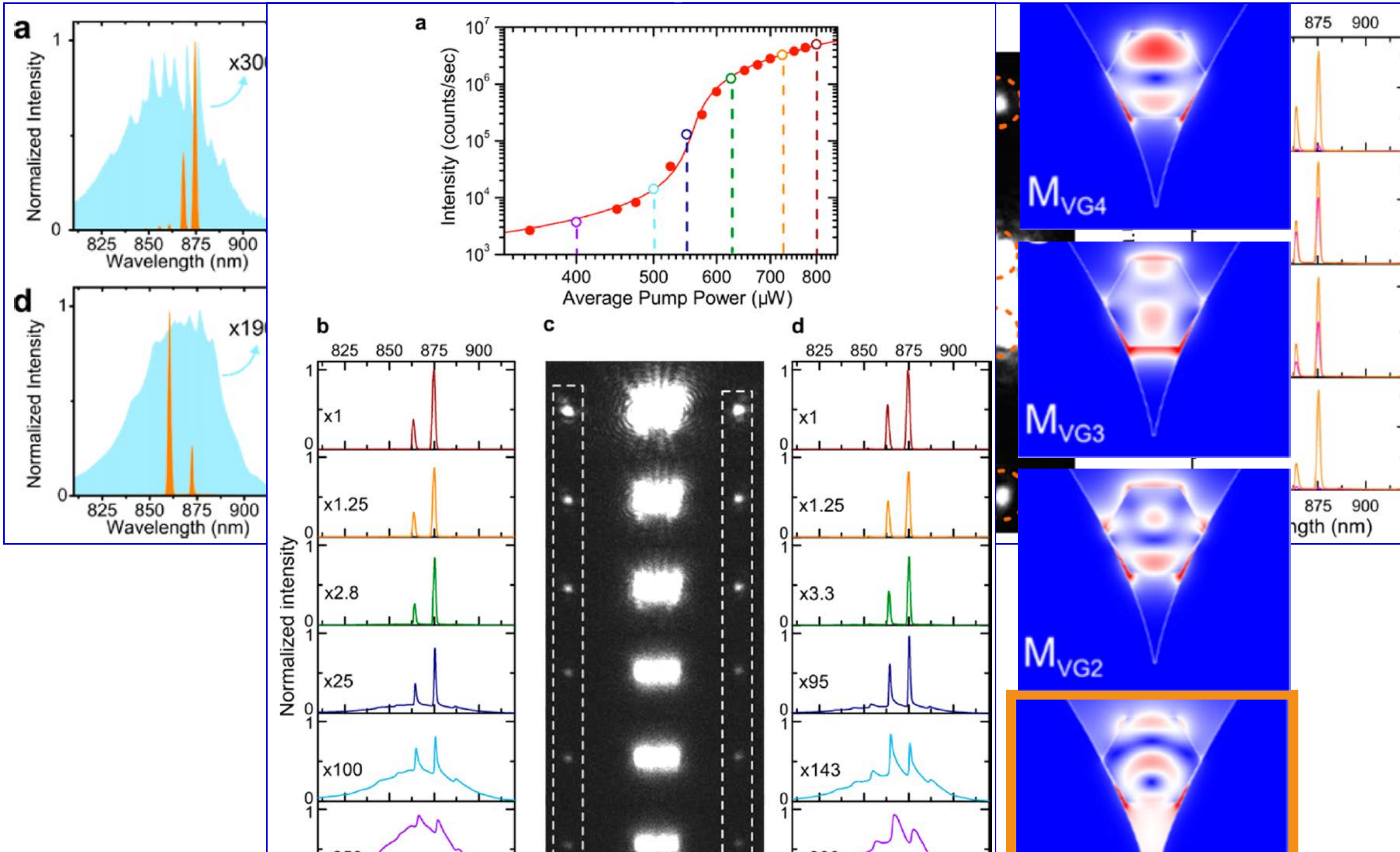
Esteban Bermúdez-Ureña,*,† Gozde Tutuncuoglu,‡ Javie
Jorge Bravo-Abad,§ Sergey I. Bozhevolnyi,⊥ Anna Fontcu
and Romain Quidant*,†,∇





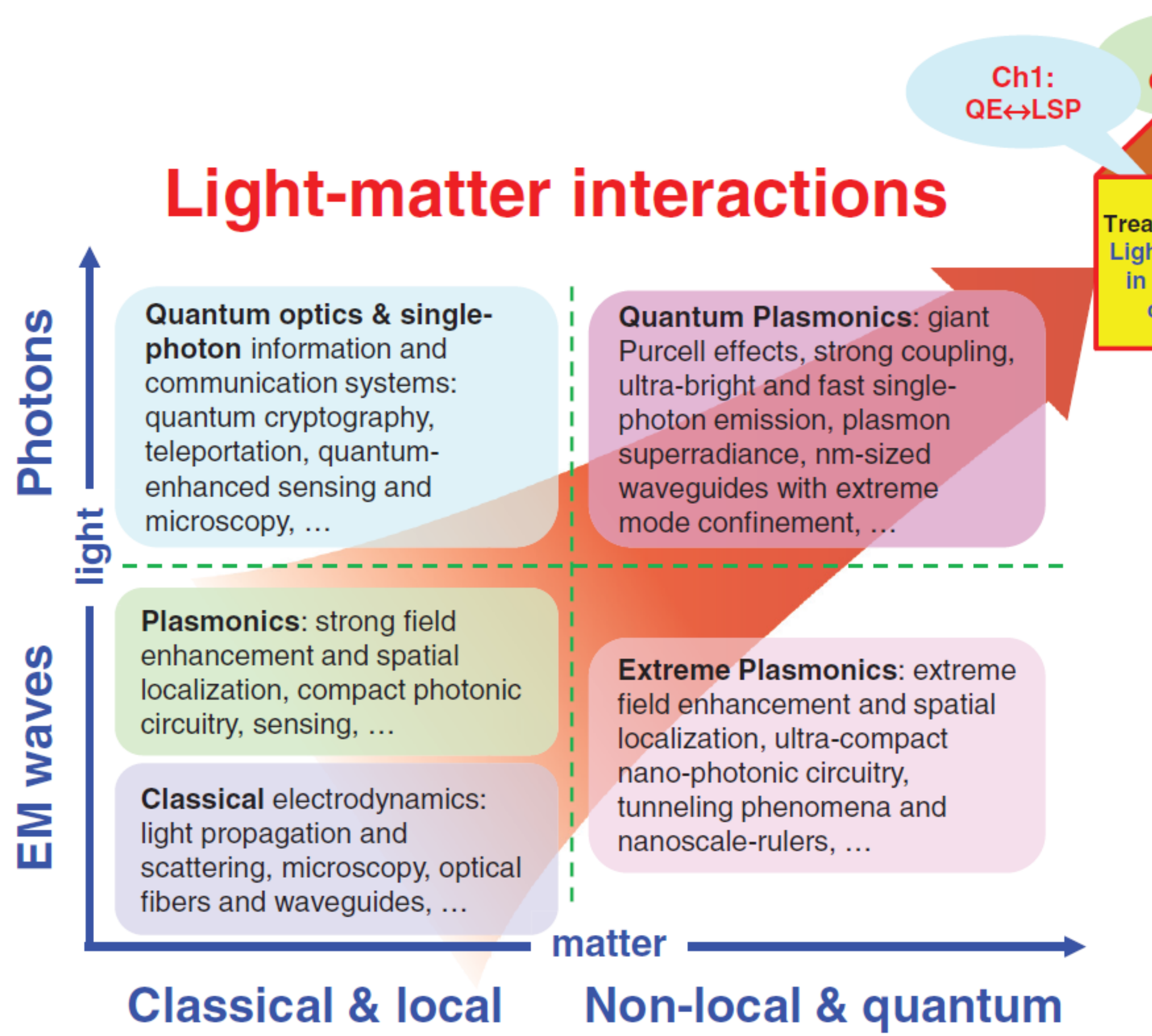
Accurate AFM-based assembly of hybrid NW-VG devices!

Feasibility of CPP-coupled lasers



Room temperature lasing into tightly confined CPP modes!

Outlook



Bozhevolnyi & Mortensen, “Plasmonics for emerging quantum technologies”, Nanophotonics **6**, (2017).

Acknowledgements

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