Quantum Plasmonics

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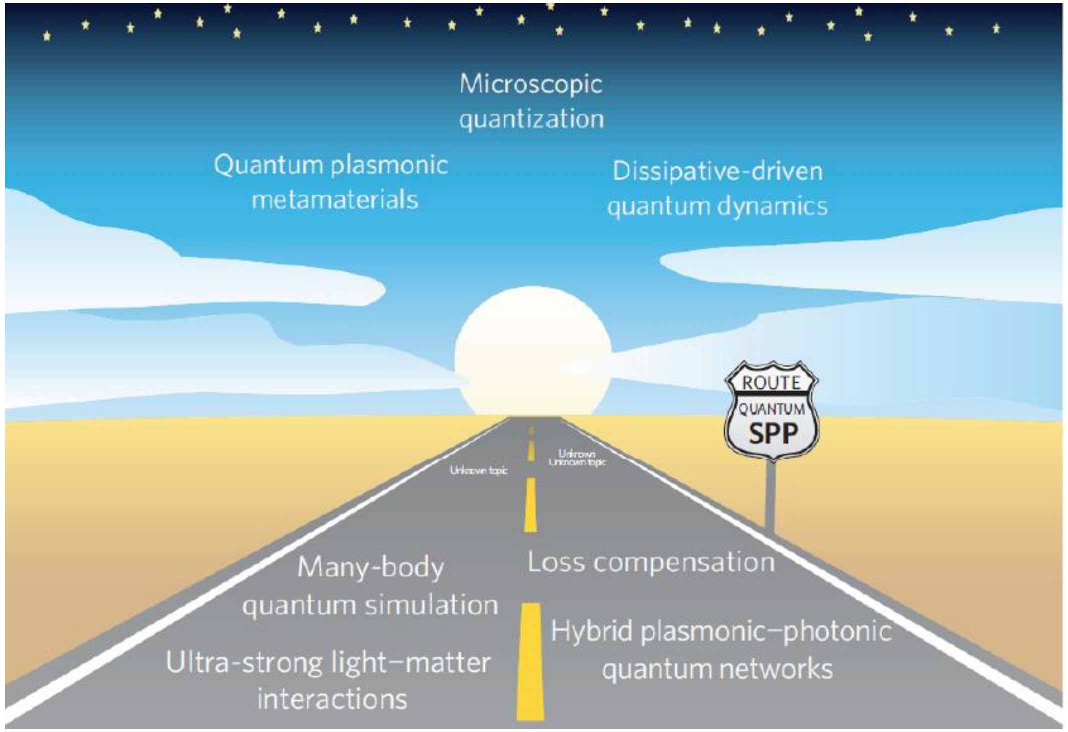


QUANTUM PLASMONICS represents one of the most promising and fundamental research directions enabling:

the ultimate miniaturization of photonic components for quantum optics when being taken to extreme limits in light-matter interactions.

Expanding the frontiers of **information processing technologies**,

+ computing with ever-increasing speed and capacity

+ calling for the development of the next generation of quantum technologies

Quantum computing opens up possibilities to carry out calculations that ordinary computers could not finish in the lifetime of the universe,

Whereas optical communications based on **quantum cryptography** become completely secure

Interactions between light and matter can be greatly modified by concentrating light into a small volume + for a long period of time.

Controlling such interaction is critical for realizing many schemes for classical and quantum information processing, including

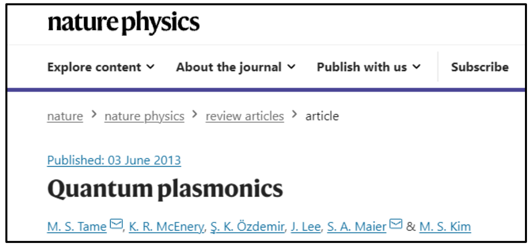
- ✓ **optical and quantum computing**
- ✓ **quantum cryptography**
- ✓ **sensing**
- ✓ **metrology**

Plasmonic structures are capable of confining light to nanometer scales far below the diffraction limit,

→ providing a promising route for strong coupling between:

light and matter + miniaturization of photonic circuits.

Nathalie P. de Leon, Mikhail D. Lukin, and Hongkun Park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Quantum plasmonics

M. S. Tame, K. R. McEnery, Ş. K. Özdemir, J. Lee, S. A. Maier & M. S. Kim

The performance of plasmonic circuits is limited by

- losses
- poor collection efficiency

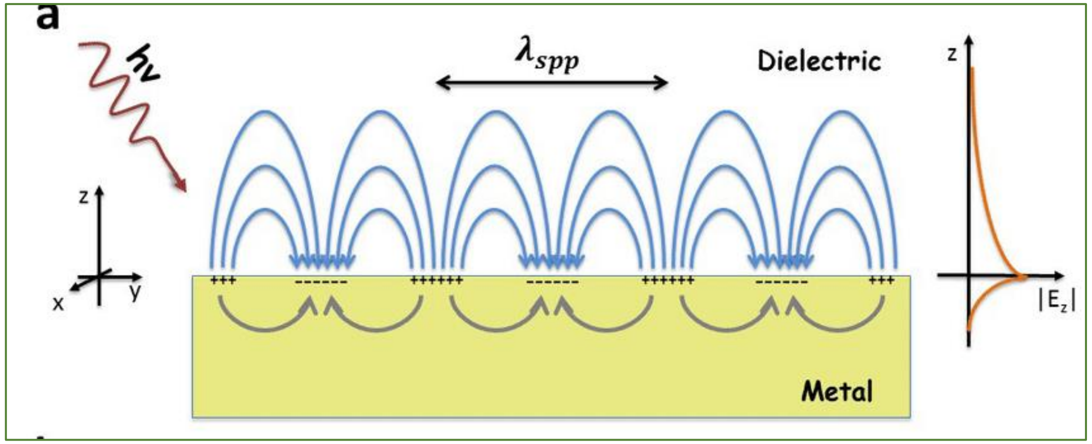
Presenting unique challenges that need to be overcome for quantum plasmonic circuits to become a reality

Surface plasmon polaritons = combined excitations of light + free electrons of a metal

SPPs have emerged as an alternative information carrier for nanoscale circuitry due to their ability to confine light far below the size of the wavelength.

→ They hold the potential to act as a revolutionary bridge between:

❖ current diffraction-limited microphotonics
❖ bandwidth limited nanoelectronics.



Plasmonics Goes Quantum ?

Light in a silica fiber + electrons in silicon = the backbones of current communication and computation systems.

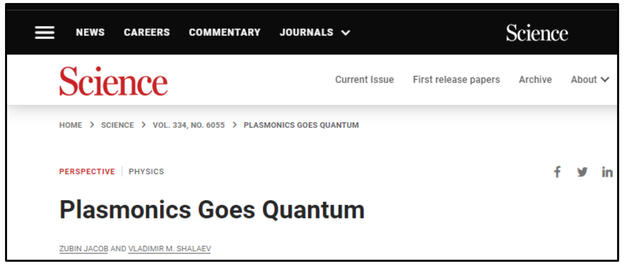
Fundamental incompatibility arises between **photonics** and **nanometer-scale electronics** because **light breaks free** when confined to sizes below its wavelength.

Instead, coupling light to the free electrons of metals can lead to a quasiparticle called a plasmon, **with nanometer-scale mode volumes**.

→ efficient interfacing **((photonics + nanoelectronics))** has been the impetus for the field of plasmonics → **nanoscale plasmons**

SPs can be generally divided into two categories:

- **localized SP**
- **propagating SP**



Light emitters like quantum dots and molecules interact:

✅ **well with low–mode-volume plasmons**

❌ **but not with the photonic modes of a conventional optical fiber**

The goal = exploring **quantum properties of surface plasmons** and building plasmonic devices that operate faithfully at the quantum level.

In addition:

Their potential for providing strong coupling of light to emitter systems, such as quantum dots and nitrogen–vacancy (NV) centers, via highly confined fields → new opportunities for the quantum control of light, enabling devices such as efficient single-photon sources to be realized.

Quantum Plasmonics →

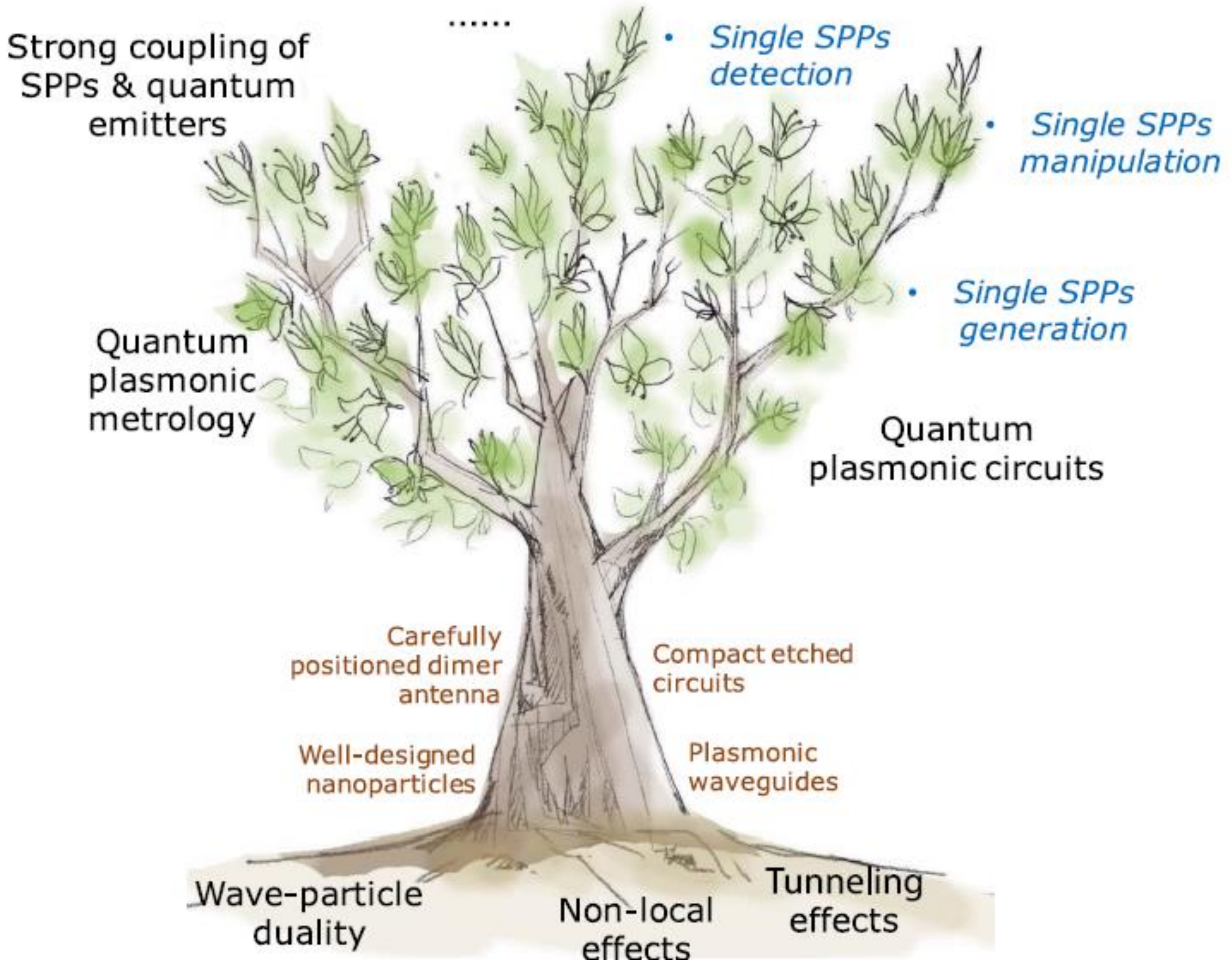
This new field of research combining:
- ✓ **Modern plasmonics**
- ✓ **Quantum optics**

Tree map of quantum plasmonics:

Roots: Fundamentals in quantum plasmonics including the wave–particle duality of plasmon-polaritons, and the non-local and tunneling effects due to screening electrons.

Central trunk:
Basic functioning plasmonic structures composed of NPs, antennas, waveguides, etc.

Branches:
Various quantum plasmonics applications, such as the strong interaction with quantum emitters, quantum plasmonic circuits, and quantum metrology.



Advances in Optics and Photonics Vol. 10, Issue 4, pp. 703-756 (2018) • https://doi.org/10.1364/AOP.10.000703

Quantum plasmonics: new opportunity in fundamental and applied photonics

Da Xu, Xiao Xiong, Lin Wu, Xi-Feng Ren, Ching Eng Png, Guang-Can Guo, Qihuang Gong, and Yun-Feng Xiao

Quantum Plasmonics

↓

For example, plasmons were proven to:

- ✓ **have the capability to preserve the entanglement and the bosonic features of photons during photon–SPP–photon**
- ✓ **demonstrations that the bosonic features of photons were still preserved even after propagating through plasmonic waveguides**

↓

Building up quantum photonic integrated circuits with propagating SPPs → The most fundamental aspects of quantum plasmonics lie in the quantization of plasmon- polaritons and their basic quantum properties

Quantum properties of SPPs

Wave-particle duality

Antibunching

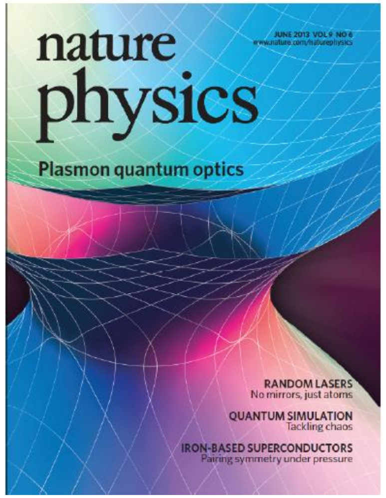
Nonlocality

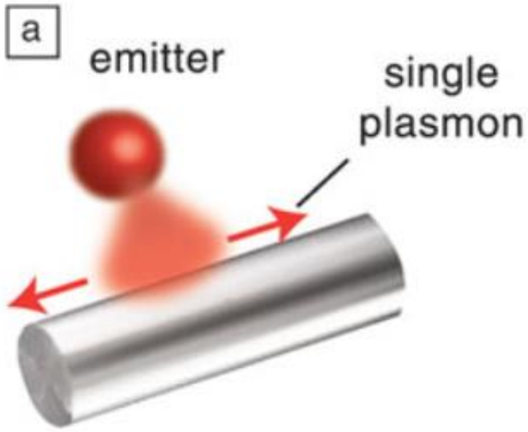
Survival of entanglement

Quantum size effect

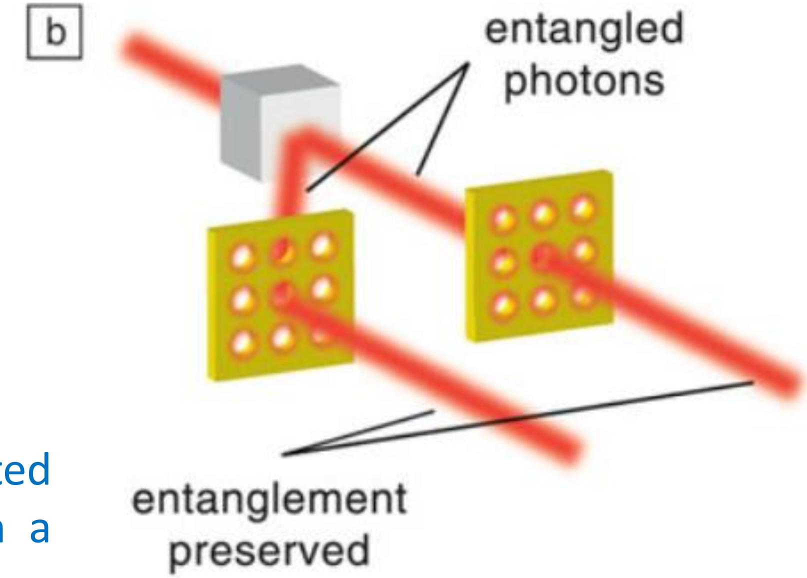
Tunneling

Decoherence and loss

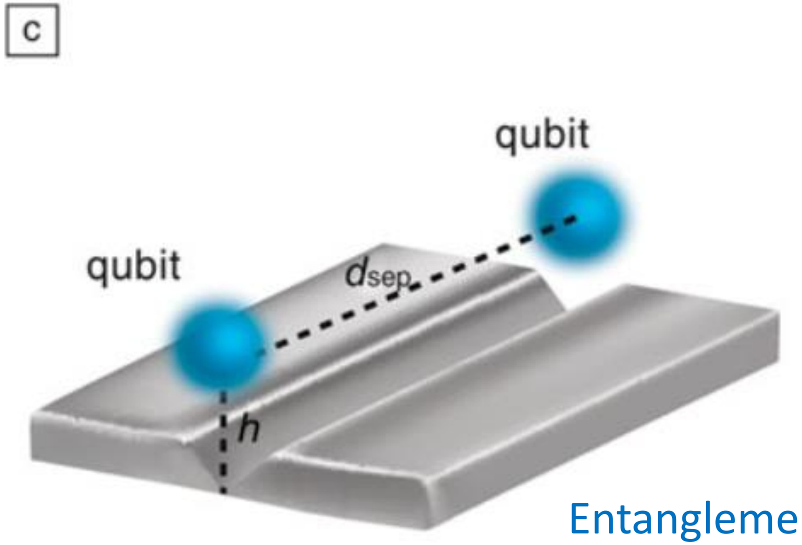




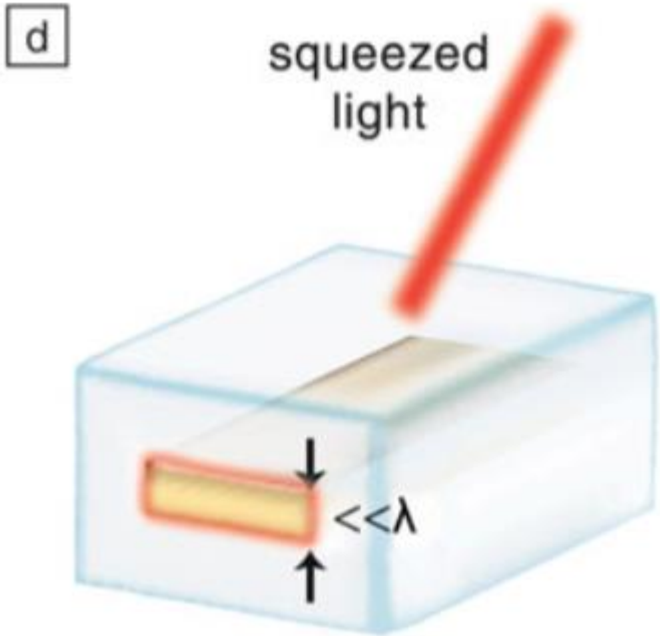
Broadband coupling of an isolated quantum emitter to a plasmon on a metal nanowire.



Conventional enhanced transmission experiment through metallic nanohole arrays repeated with entangled photons showed that entanglement is preserved by excited surface plasmons

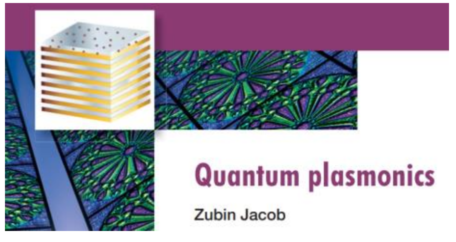


Entanglement between qubits mediated by V-groove plasmon waveguides.



Long range surface plasmon polaritons of a gold metal stripe excited using “squeezed” vacuum

DOI: 10.1557/mrs.2012.175



Applications

Quantum plasmonic circuits

- **Single – photon sources**
- **Single – photon detectors**

✓ Quantum key distribution

✓ Long distance quantum repeater protocols

✓ Optical quantum computing.

NOW

Weak coherent laser pulses

Disadvantage: using vacuum + the signal pulses +faint pulses with a mean photon number per pulse = 0.5 .

→ **Quantum Plasmonic Integrated Circuits** →

- Generation
- Manipulation
- Detection

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Evaluation of nitrogen- and silicon-vacancy defect centres as single photon sources in quantum key distribution

Matthias Leifgen[5,1], Tim Schröder[6,1], Friedemann Gädeke[1], Robert Riemann[1], Valentin Métillon[2], Elke Neu[7,3], Christian Hepp[3], Carsten Arend[3], Christoph Becher[3], Kristian Lauritsen[4] + Show full author list

Published 13 February 2014 • © 2014 IOP Publishing and Deutsche Physikalische Gesellschaft

Single – photon sources

A true single photon source is favourable in quantum information protocols compared to weak coherent pulses:

- emitting a single photon into a well-defined spectral and spatial mode
- with a probability near unity each time a trigger is applied
- a practical single photon source should also have a stable emission rate
- easy-to-use
- should operate at room temperature
- and at high repetition frequencies.

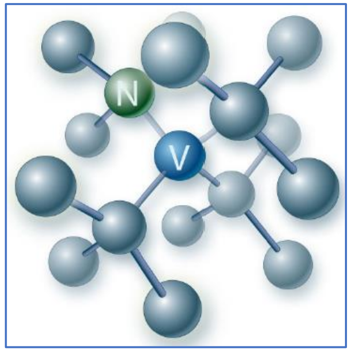
Quantum dots → Tiny semiconductor particles a few nanometres in size, having optical and electronic properties that differ from larger particles due to quantum mechanics.

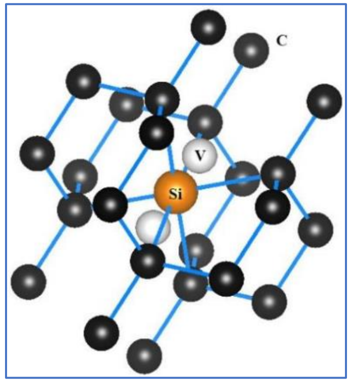
,

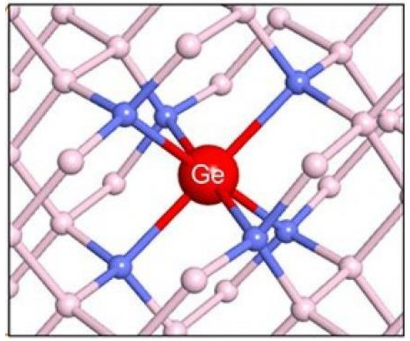
When the quantum dots are illuminated by UV light →

- An electron in the quantum dot can be excited to a state of higher energy.
- In the case of a semiconducting quantum dot, this process corresponds to the transition of an electron from the valence band to the conductance band.
- The excited electron can drop back into the valence band releasing its energy by the emission of light.
- The colour of that light depends on the energy difference between the conductance band and the valence band.

Vacancy centers in diamond

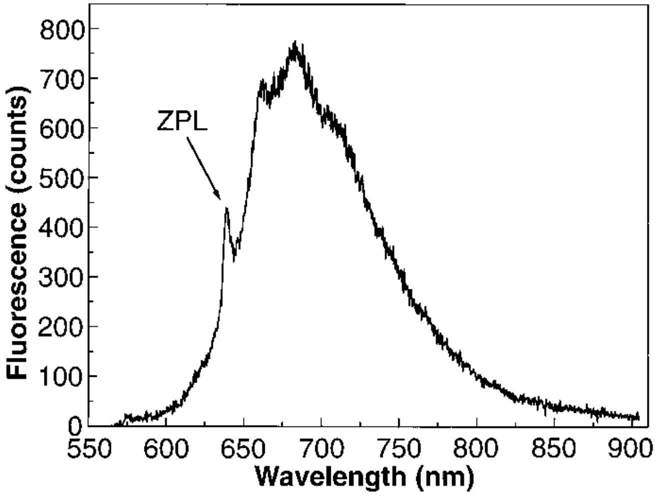


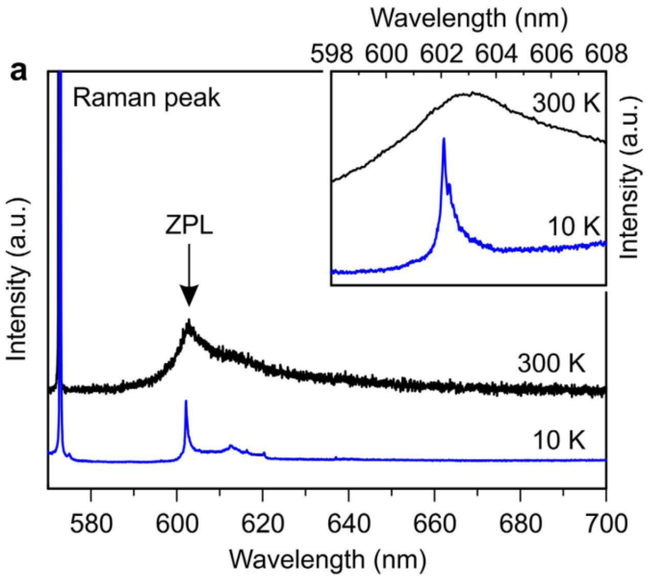


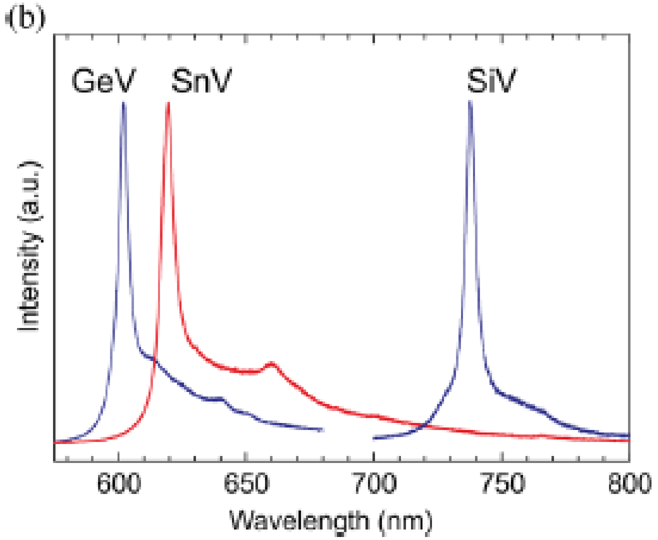


Color centers are crystal defects that absorb light in a spectral region where the crystal itself has no absorption.
It has later been confirmed both experimentally and theoretically that the F-center is a crystalline vacancy with captured unpaired electron(s) that absorbs light in the visible region, thus giving various colors to the crystals.

Color centers can be found in diamond , their formation occurs under extreme conditions due to the chemical inertness and mechanical rigidity of the material.



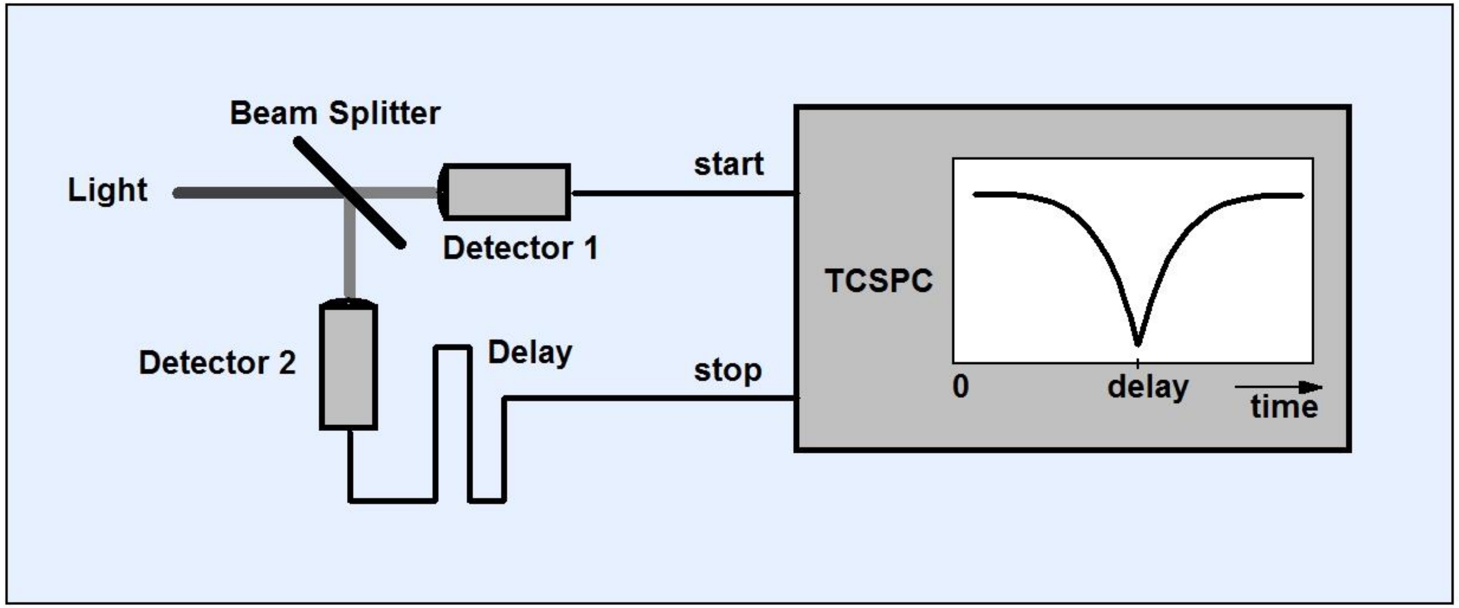




Characterization of a single photon sources

➢ **Hanbury Brown and Twiss, 1956**

The second-order correlation function $g^{(2)}(\tau)$ can be employed to verify the single-photon emission of a source.

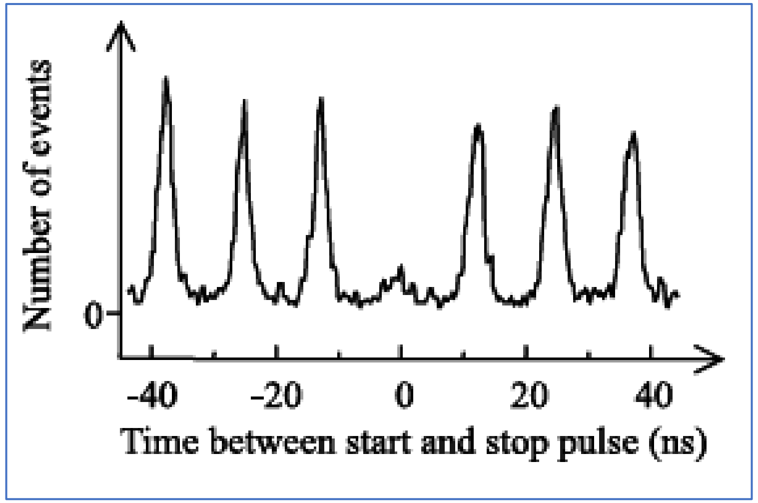


$$g^{(2)}(\tau) = \frac{\langle n_1(t)n_2(t+\tau)\rangle}{\langle n_1(t)\rangle\langle n_2(t+\tau)\rangle},$$

$$g^{(2)}(0) < g^{(2)}(\tau),$$

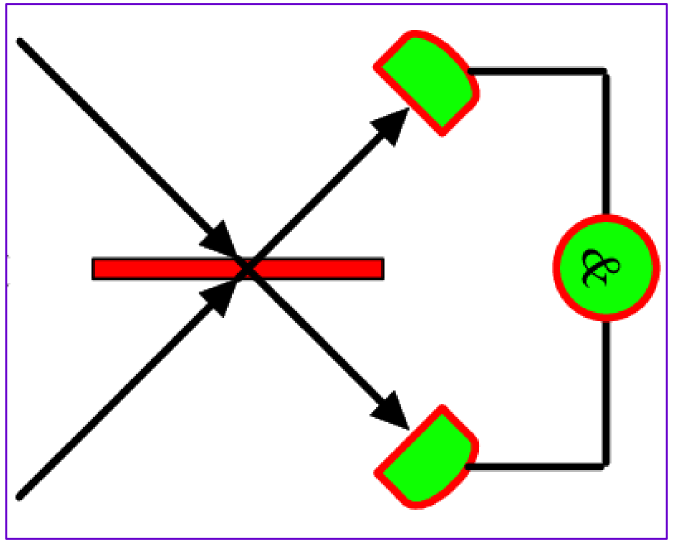
$$g^{(2)}(0) < 1.$$

Classical description	Photon stream	$g^{(2)}(0)$
Chaotic	Bunched	>1
Coherent	Random	1
None	Antibunched	<1



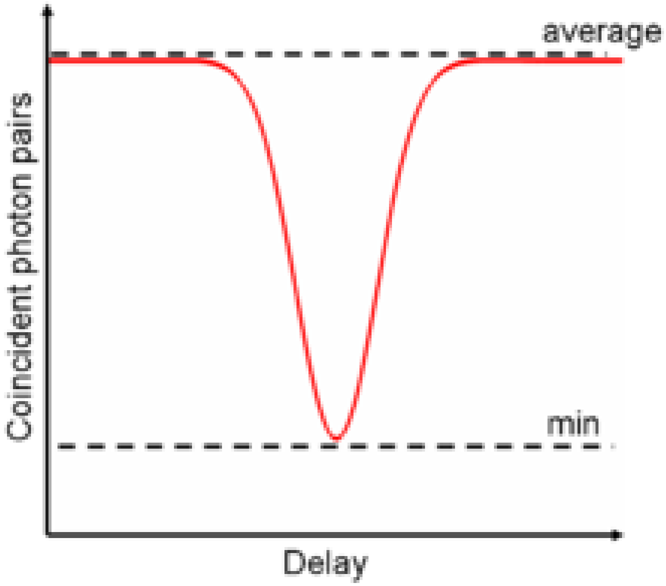
Hong–Ou–Mandel , 1987

The effect occurs when two identical single-photon waves enter a 1:1 beam splitter, one in each input port.



When the photons are → identical, they will extinguish each other. If they become more distinguishable, the probability of detection will increase.

$$|1,1\rangle_{ab} = \frac{|2,0\rangle_{cd} - |0,2\rangle_{cd}}{\sqrt{2}}$$



Single-photon sources *FOM*:

$$FOM = F_p \times L_{spp} \times \frac{\beta}{\lambda}$$

The coupling between a **quantum emitter and a waveguide** depends on:

- the properties of the waveguide
- the properties of the emitter.

The total decay rate depends on:

- the dipole moment of the emitter,
- the position and orientation of the emitter in the waveguide
- the confinement of the waveguide mode.

Purcell factor

$$F_p = {}^{\gamma}/_{\gamma_0}$$

Coupling efficiency

$$\beta = {}^{\gamma_{CPP}}/_{\gamma}$$

γ: the decay rate of the quantum emitter

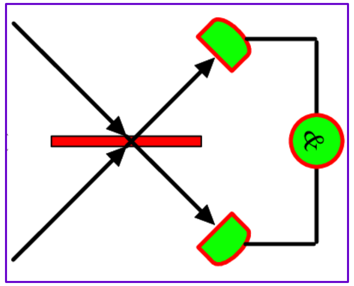
γ_0: the decay rate of the quantum emitter in vacuum

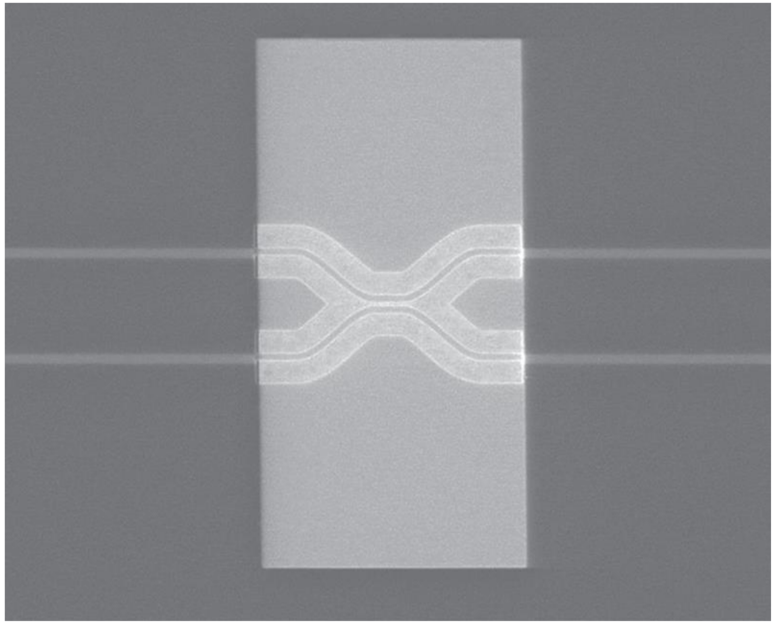
γ_{CPP}: the decay rate into the guided plasmonic modes

Examples

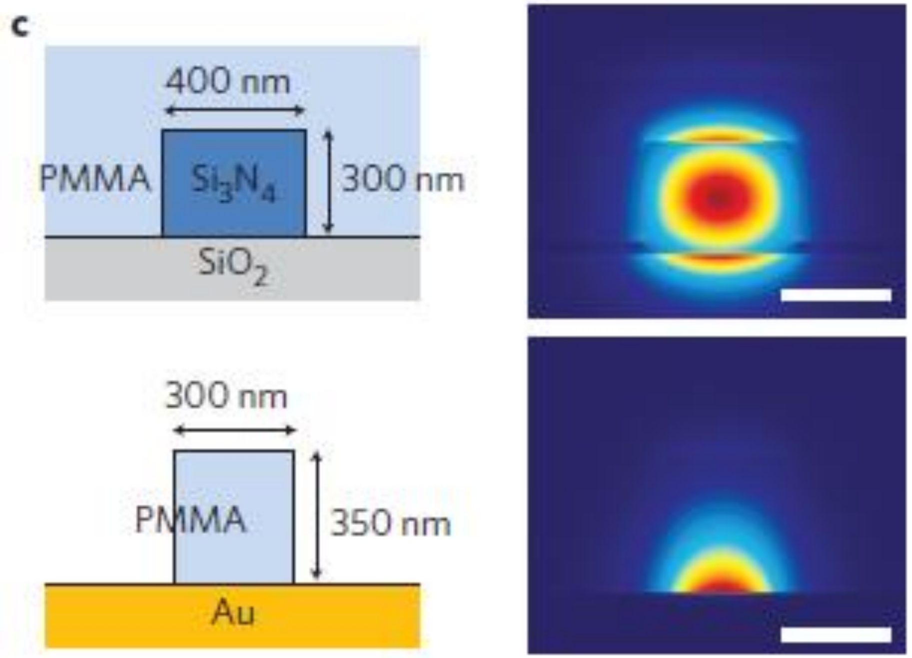
Two-plasmon quantum interference

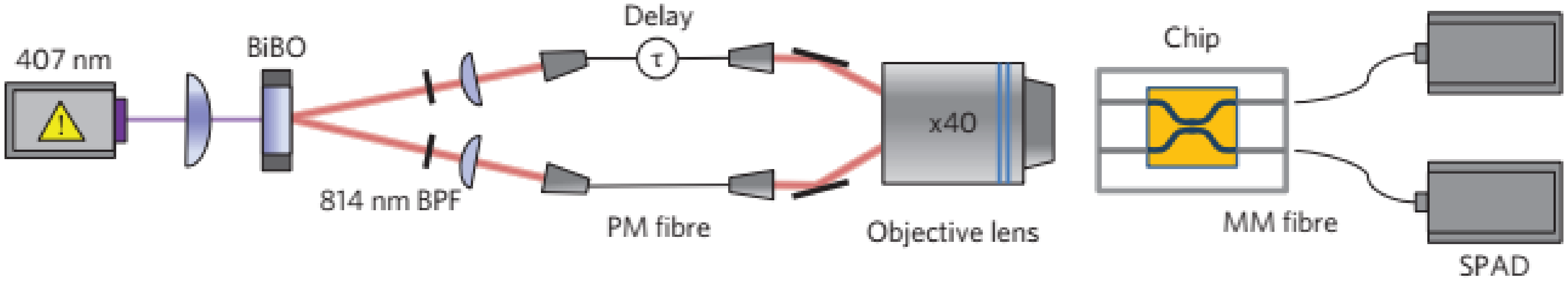
Surface plasmons should exhibit all the same quantum phenomena that photons do → plasmonic version of the Hong–Ou–Mandel experiment, in which unambiguous two-photon quantum interference between plasmons is observed

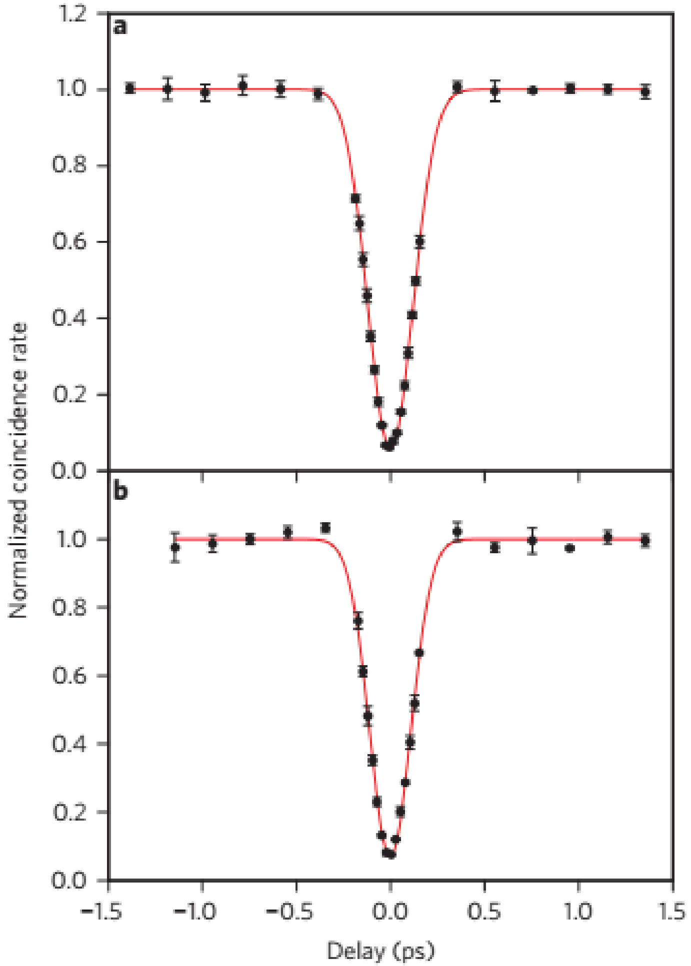




These properties are important if plasmonic devices are to be employed in quantum information applications, which typically require indistinguishable particles







nature photonics 2 MARCH 2014

Two-plasmon quantum interference

James S. Fakonas[1,2], Hyunseok Lee[2], Yousif A. Kelaita[2] and Harry A. Atwater

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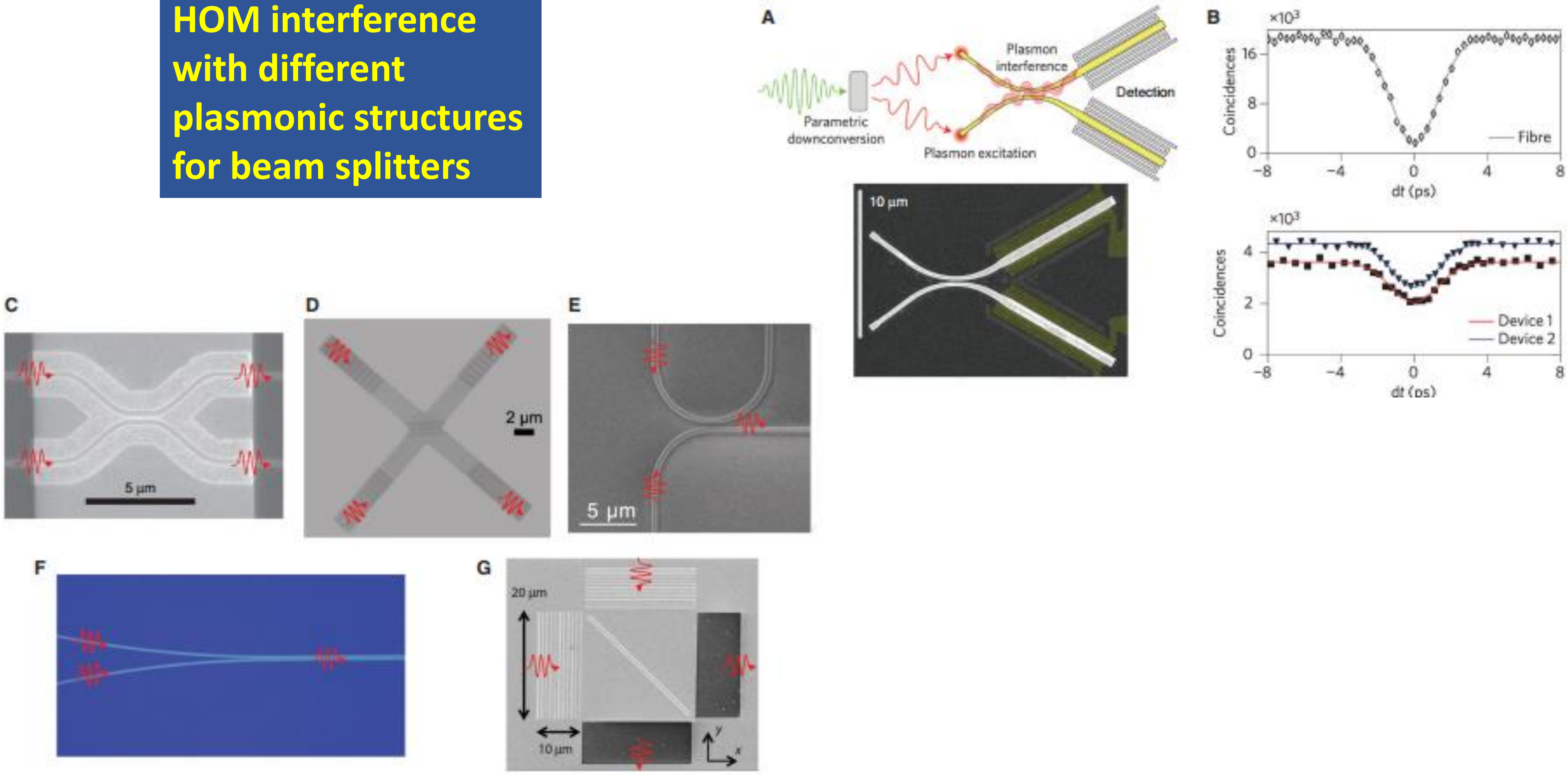
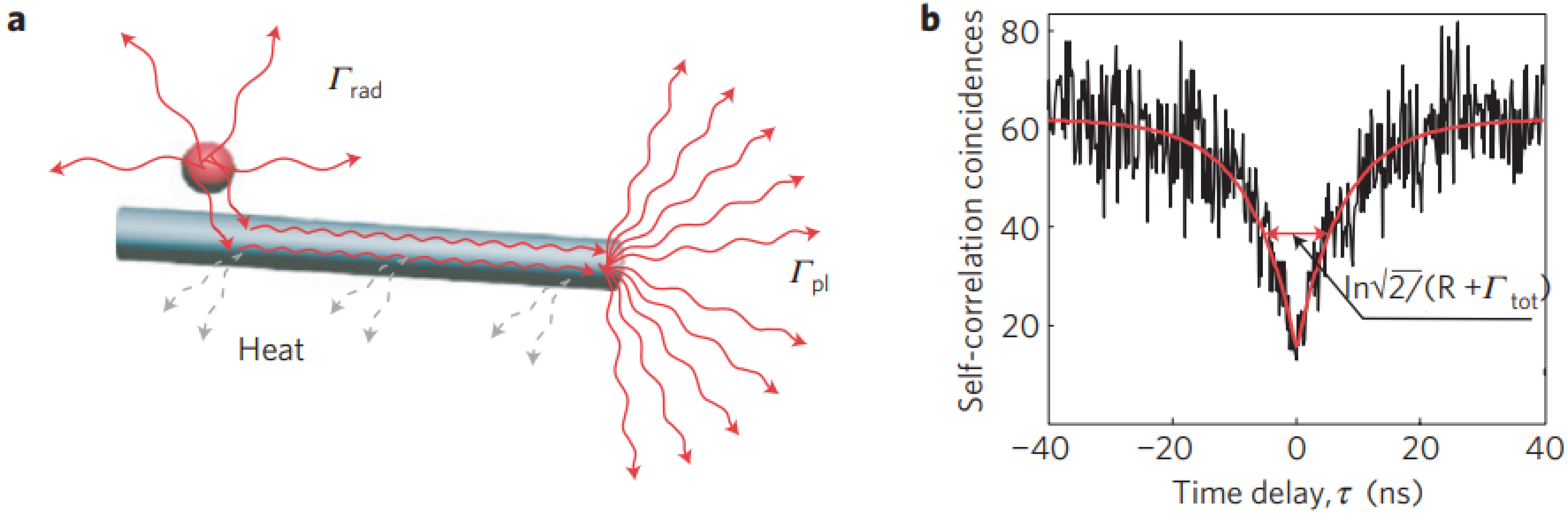
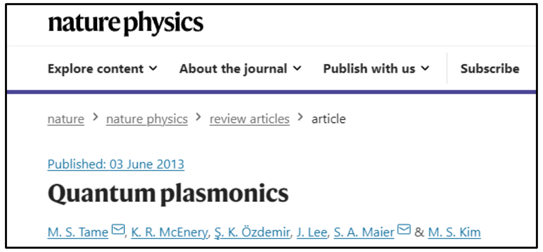
HOM interference with different plasmonic structures for beam splitters



Quantum dot emission into SPP modes of a silver nanowire



- ✓ **2.5-fold enhancement in the emission of a single quantum dot into an SPP mode of a silver nanowire**
- ✓ **The light scattered from the end of the nanowire was antibunched, confirming that the SPP mode could collect and radiate single photons from the quantum dot**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Quantum plasmonics

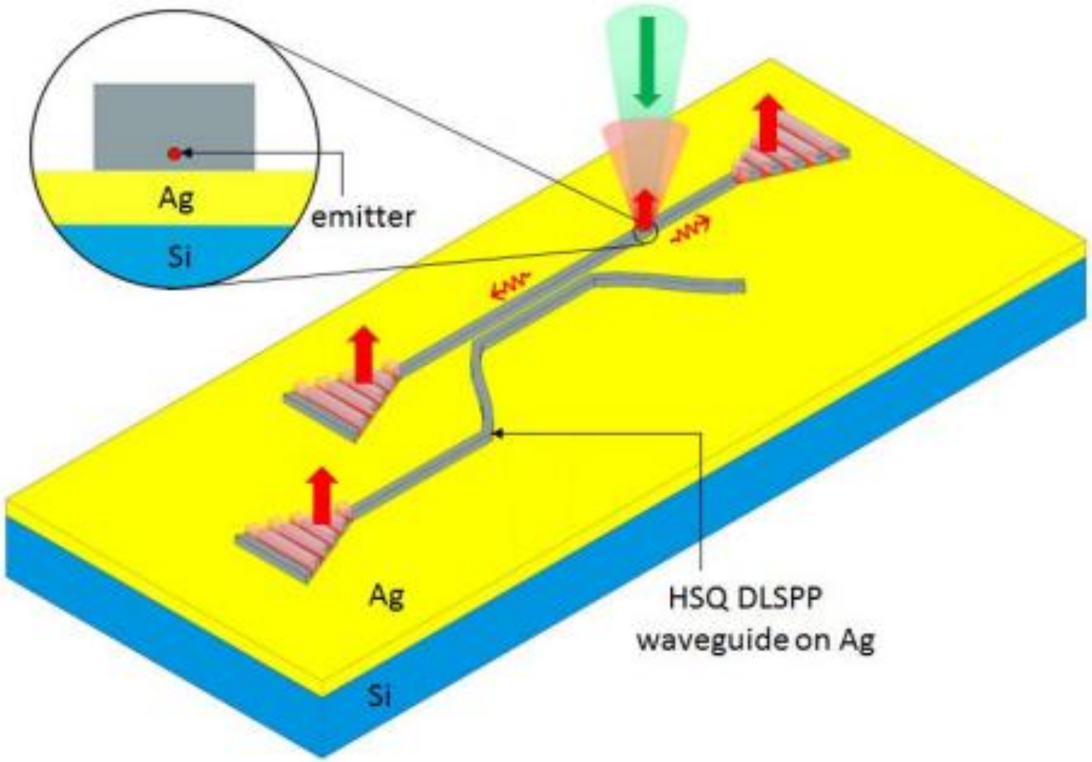
M. S. Tame, K. R. McEnery, Ş. K. Özdemir, J. Lee, S. A. Maier & M. S. Kim

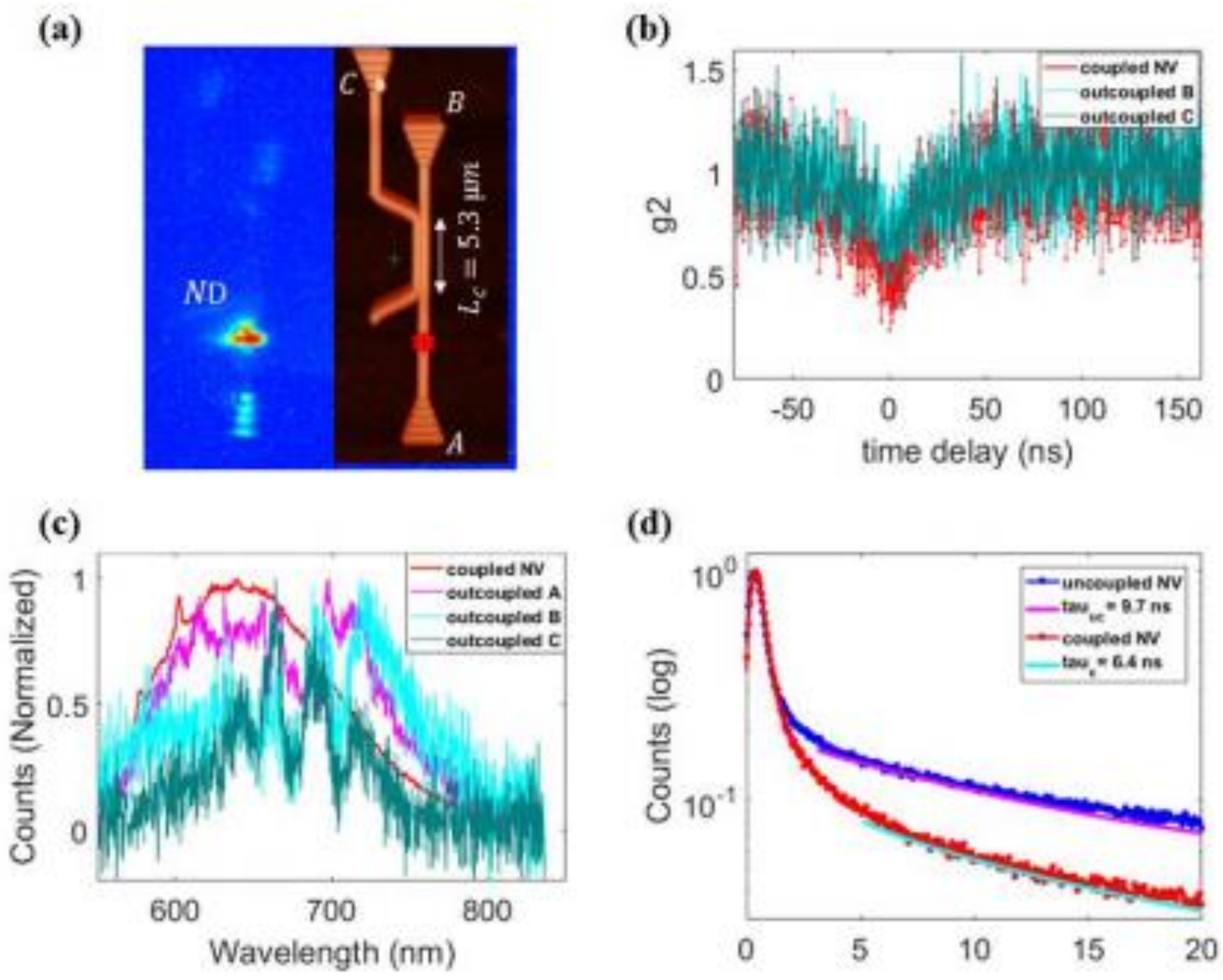
Nanofabrication of Plasmonic Circuits Containing Single Photon Sources

DLSPP waveguides is demonstrated to incorporate nanodiamonds that are certified to contain a single nitrogen vacancy (NV) center → to be single-photon sources.

NV centers are known to be stable and bright single-photon sources, that also have an optically accessible electron and nuclear spin that can be used as qubits.

DLSPP waveguides are built with nanometer precision around pre-characterized nanodiamonds.





ACS Photonics Aug. 2017

Nanofabrication of Plasmonic Circuits Containing Single Photon Sources

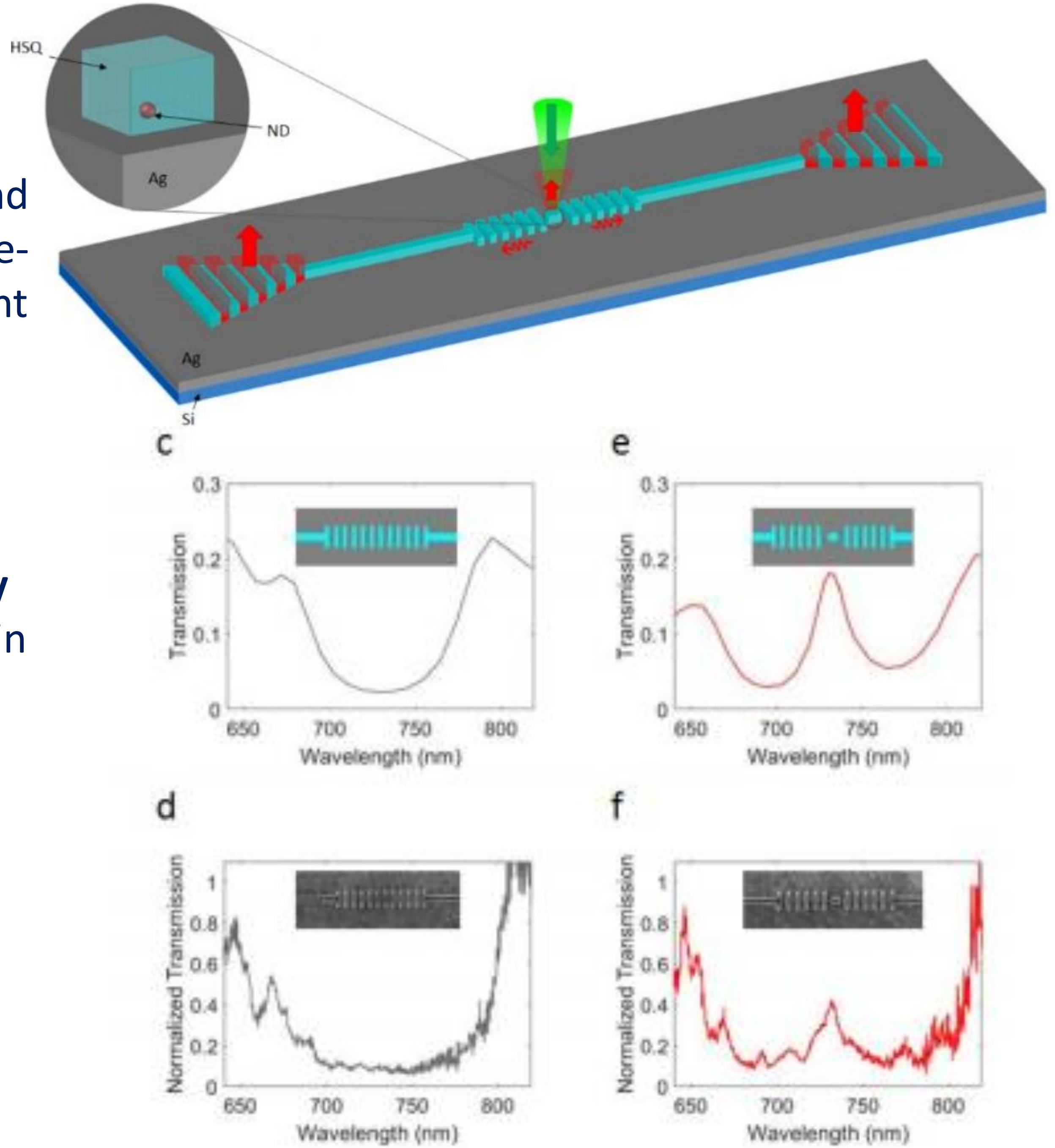
Hamidreza Siampour,* Shailesh Kumar, and Sergey I. Bozhevolnyi*

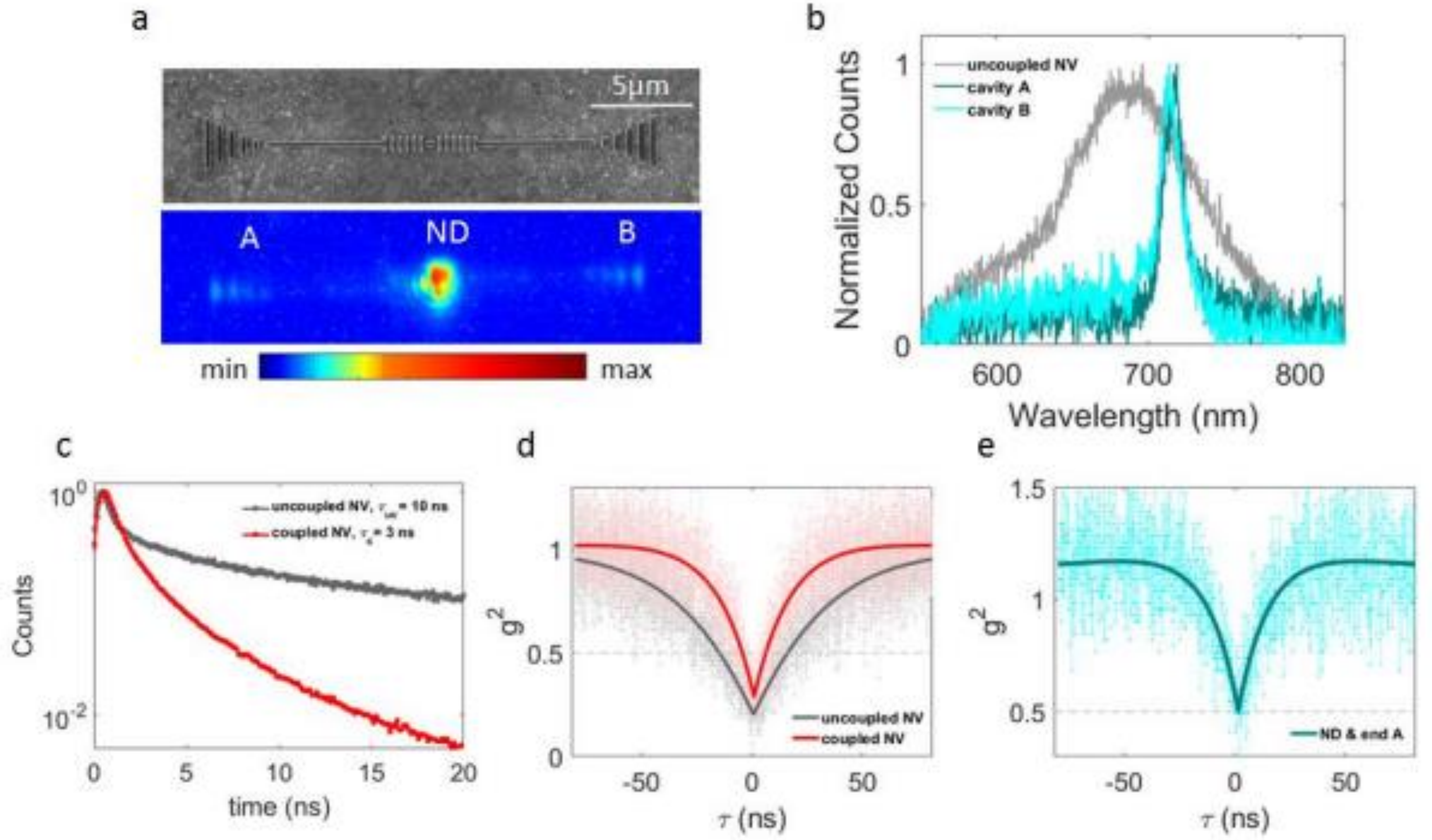
Chip-integrated plasmonic cavity-enhanced single nitrogen-vacancy center emission

A compact plasmonic configuration based on a broadband NV quantum emitter resulting in a narrow-band single-photon source with colour selective emission enhancement

The idea is to → **combine the surface plasmon polariton (SPP) confinement + relatively low insertion loss** by employing a **hybrid plasmonic-photonic waveguide-cavity design** and to achieve thereby a significant enhancement in the decay rate of NV spontaneous emission at the cavity resonance.

The cavity resonator consists of **two distributed Bragg mirrors** that are built at opposite sides of the coupled NV emitter and are integrated with a dielectric-loaded SPP waveguide (DLSPPW)



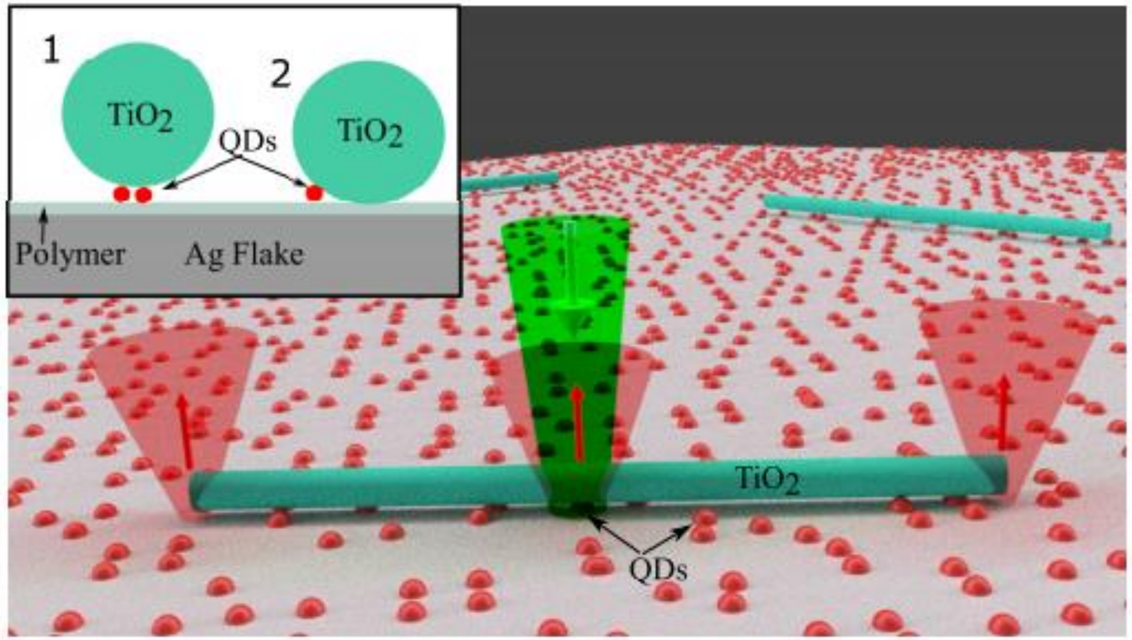


Nanoscale 20 Oct 2017

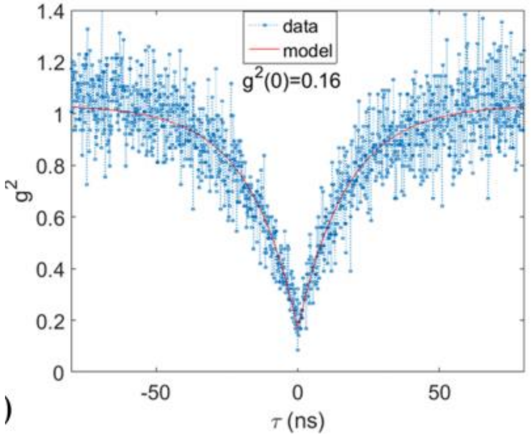
Chip-integrated plasmonic cavity-enhanced single nitrogen-vacancy center emission

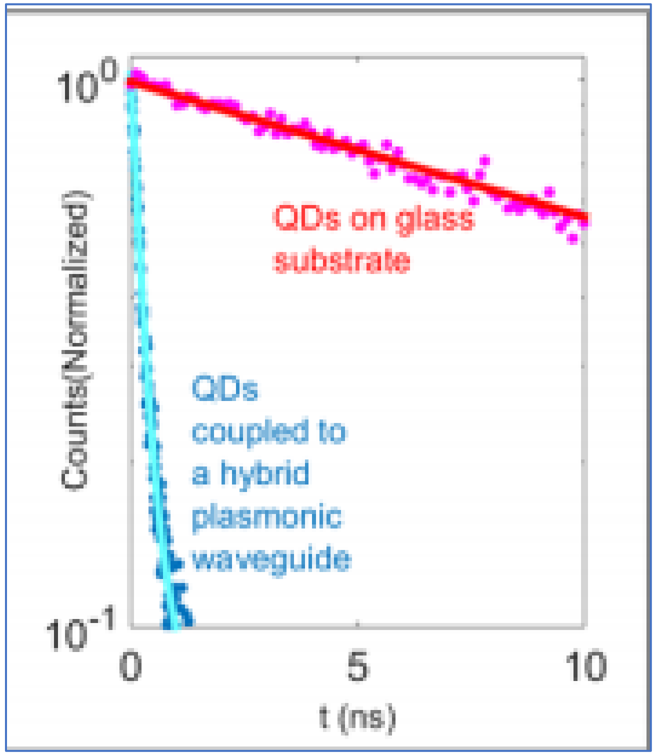
Hamidreza Siampour,* Shailesh Kumar and Sergey I. Bozhevolnyi

Excitation of Hybrid Plasmonic Waveguide Modes by Colloidal Quantum Dots



Hybrid plasmonic waveguide modes are relatively low-loss confined modes, which provide an opportunity for coupling to quantum emitters with the rate of emission being significantly enhanced and channeled into the waveguide.





The excitation of hybrid plasmonic is achieved by waveguide modes supported by **titanium dioxide nanowires placed** on monocrystalline silver flakes with a low-index polymer gap.

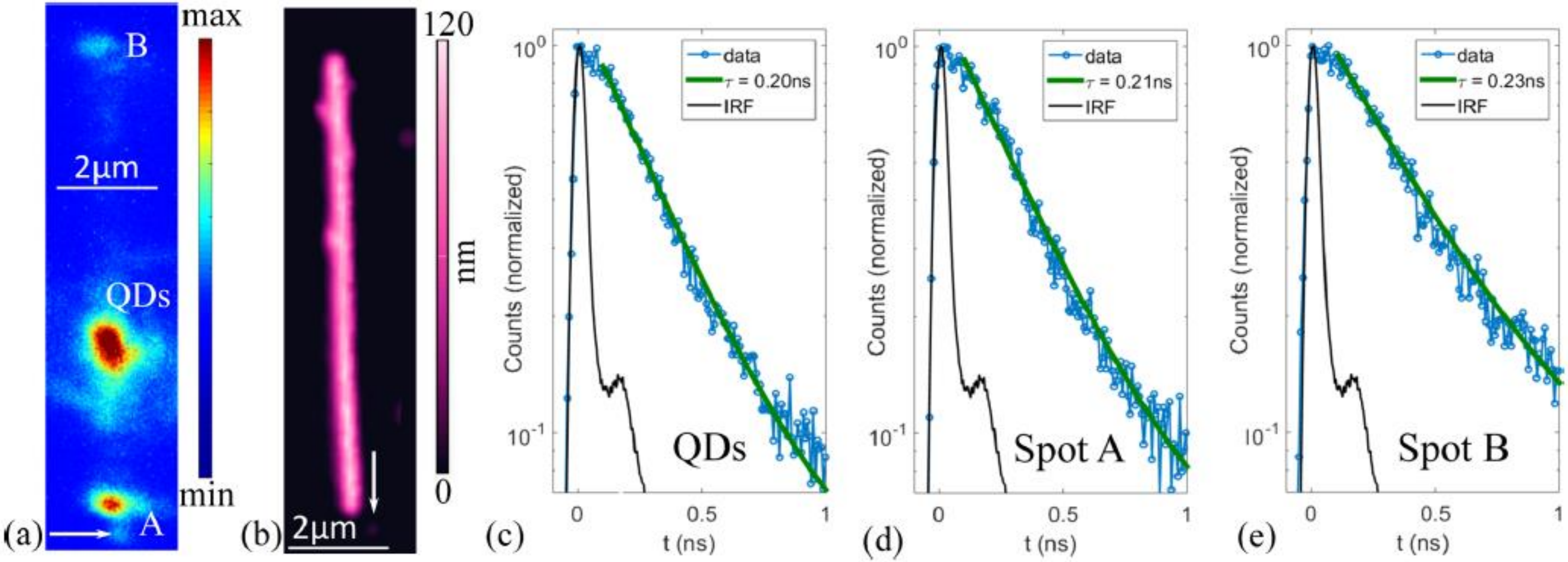


Figure 5. (a) Fluorescence image of coupled system captured with QDs excited continuously by a 532 nm CW laser. (b) AFM image of the coupled system. (c, d, and e) Lifetime measurement data and a single-exponential fit for spots QDs, A, and B in (a), respectively.

ACS Photonics July 2, 2019

Excitation of Hybrid Plasmonic Waveguide Modes by Colloidal Quantum Dots

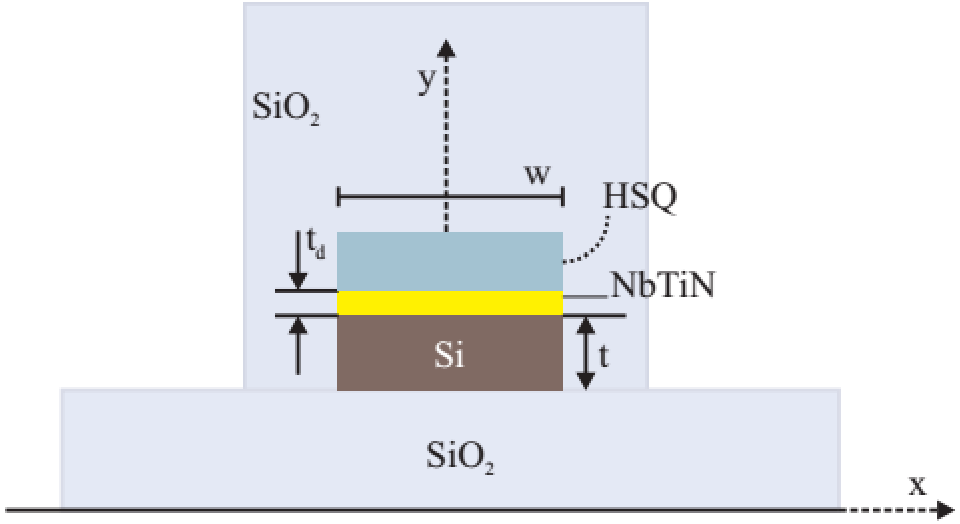
Shailesh Kumar* and Sergey I. Bozhevolnyi

Excitation of Hybrid plasmonic waveguide modes by colloidal quantum dots.pdf

Single – photon detectors

Plasmonic structure's integration into photo-detectors: → **enhancement of absorptance due to the giant electromagnetic field enhancement accompanying excitation of propagating and localized plasmonic modes.**

of enhancing quantum efficiency of through plasmonic excitation



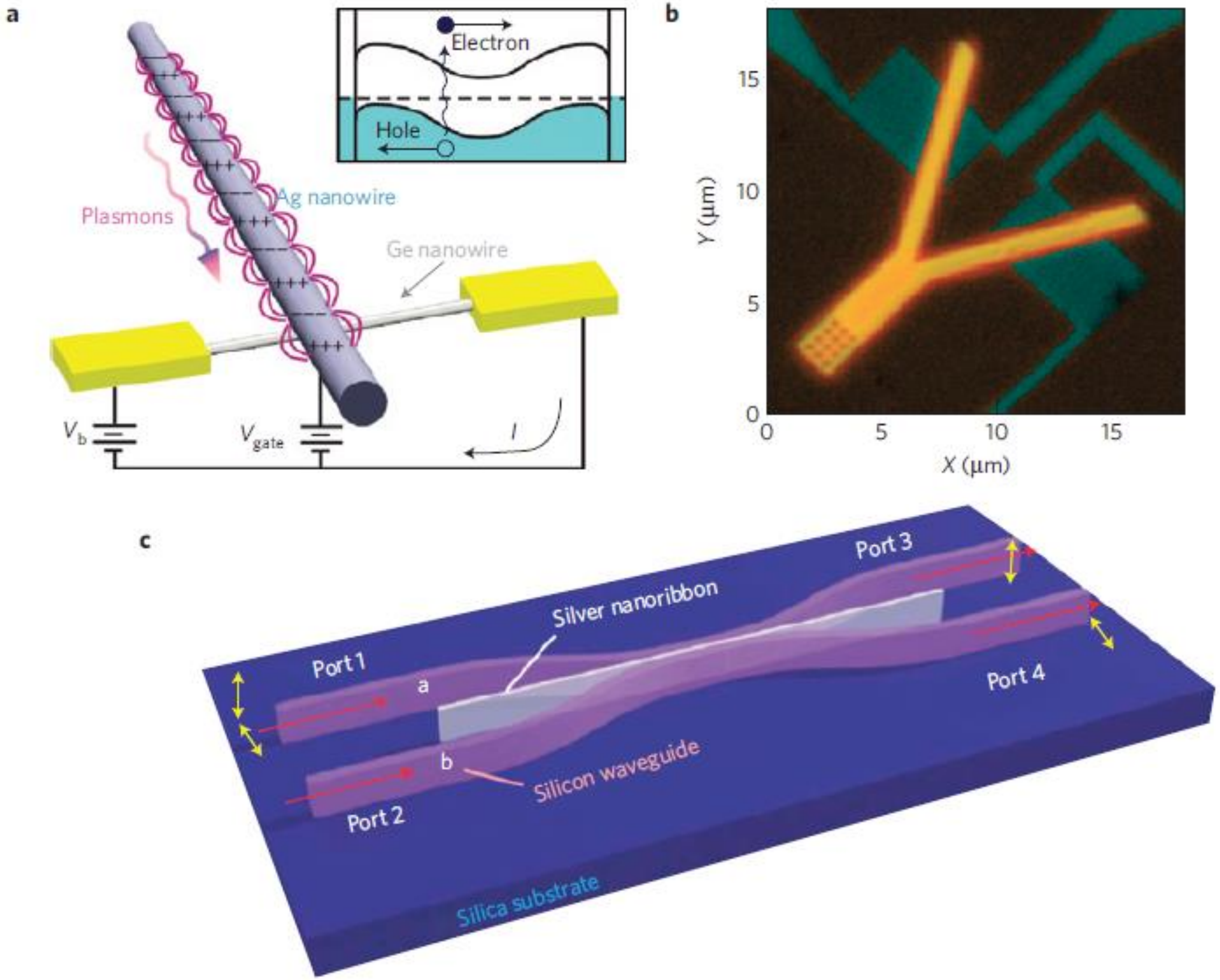
Important advantages of appropriately designed complex plasmonic structures are:

- the possibility to achieve resonant absorption enhancement.
- polarization sensitivity, which allows to select specific polarization states

Among the large number of plasmonic structure integrated photodetectors the **SNSPDs** offer unique possibility to realize single plasmon detection

Quantum Plasmonic Circuits

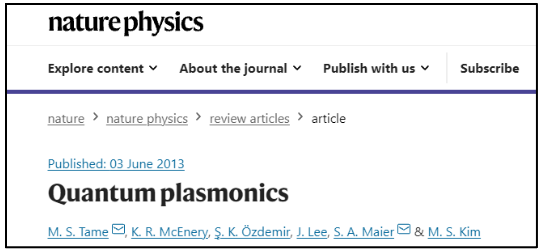
Quantum plasmonic circuitry



a) electron–hole pair production in a germanium nanowire ,from the light field of SPPs on the silver nanowire, generates a current that can be used for detection.

b) superconducting nanowire detectors are placed on top of gold stripe waveguides to achieve single-SPP detection.

c) Hybrid metal–dielectric beamsplitter, where the excitation of SPPs enables an integrated polarization sensitive BS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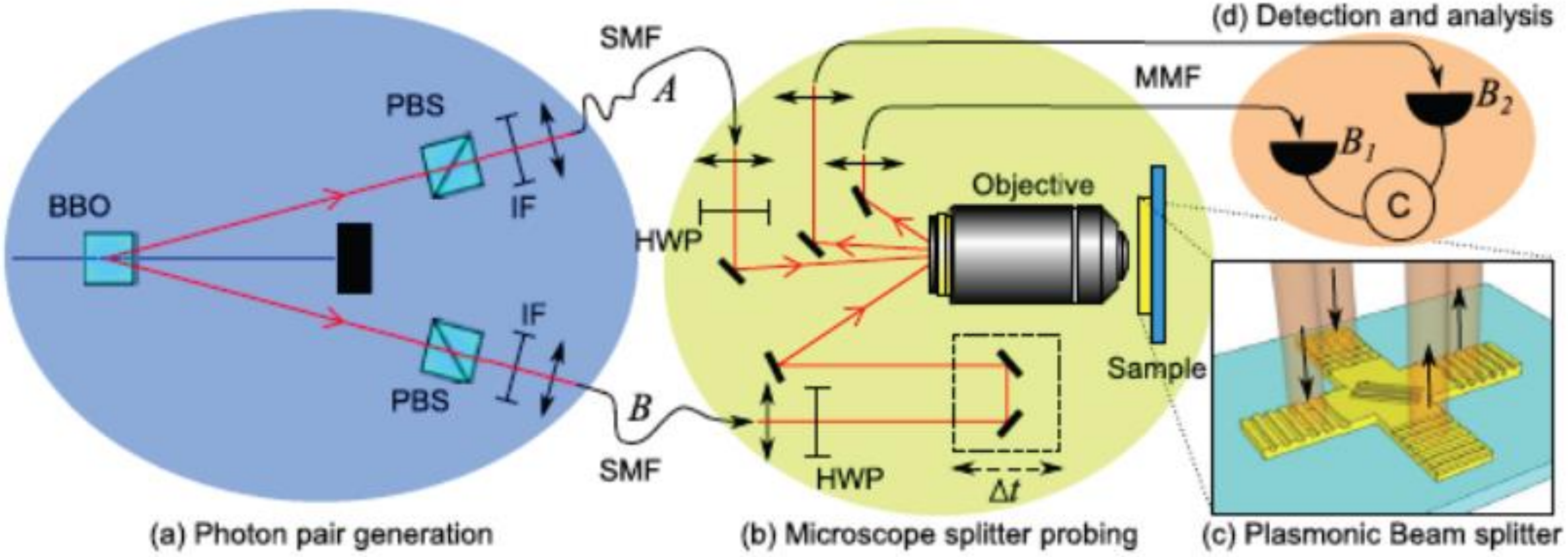
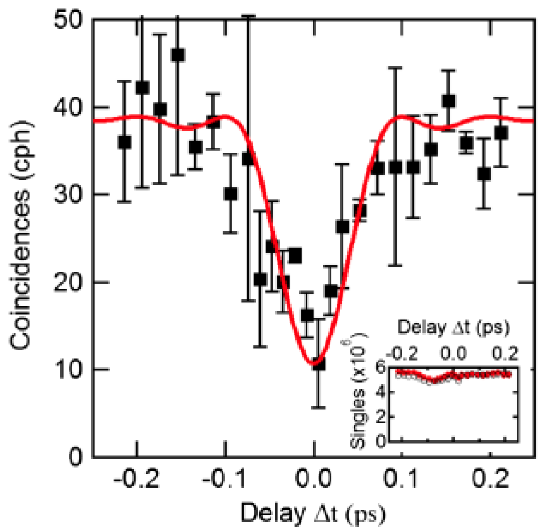
Published: 03 June 2013

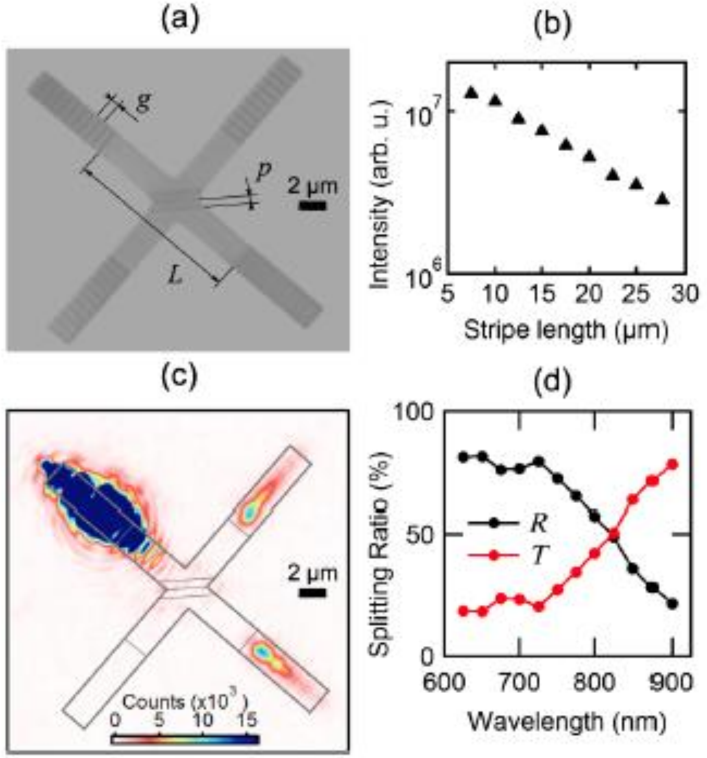
Quantum plasmonics

M. S. Tame, K. R. McEnery, Ş. K. Özdemir, J. Lee, S. A. Maier & M. S. Kim

Plasmonic Hong-Ou-Mandel interference experiments utilizing a 4-port plasmonic beam splitter







Quantum plasmonics: quantum information at the nanoscale 122054

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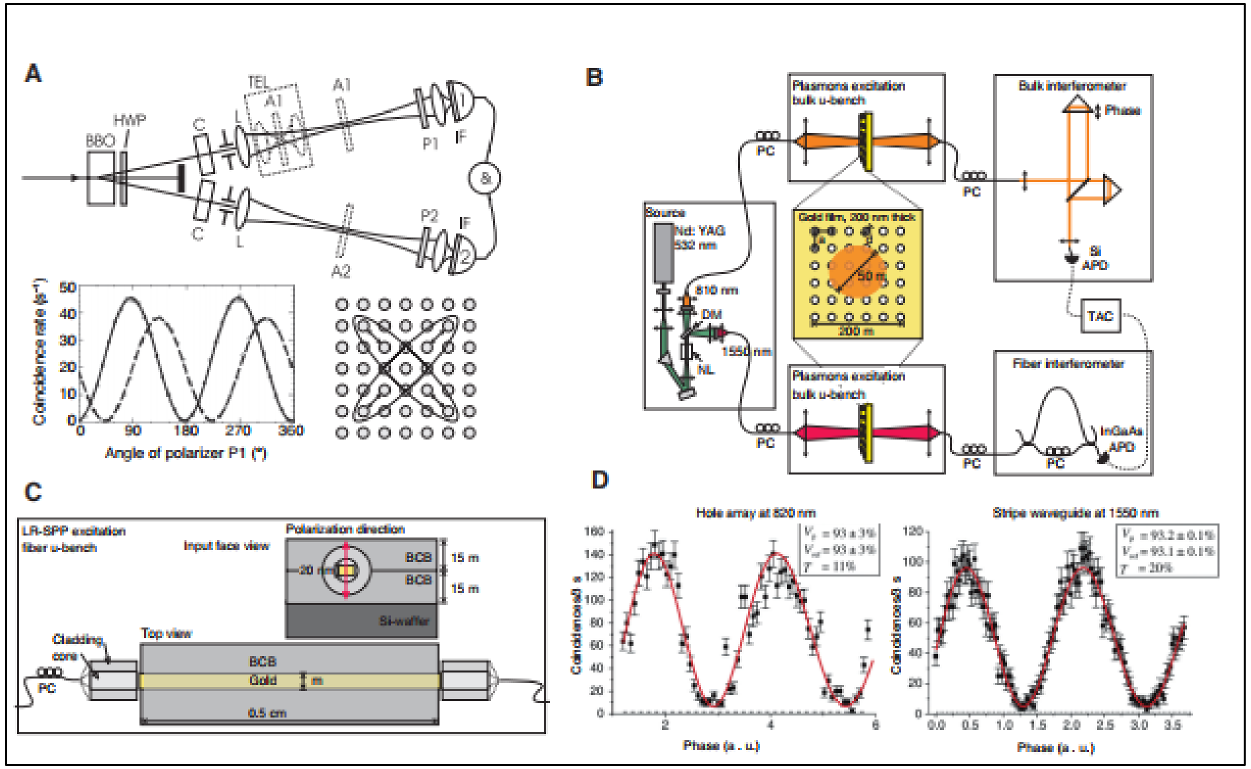
Final Report

Plasmonic beam splitter

Experiments demonstrating entanglement preservation in plasmonic systems

First experiment that demonstrated **plasmon-assisted transmission of entangled photons.** This was confirmed through the measurement of two-photon quantum interference after **photon-plasmon-photon conversion**, which demonstrated the preservation of entanglement



Multiparticle quantum plasmonics

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THANK YOU