表面等离激元导论
Introduction to plasmonics

研究： 金属和介质表面以及纳米金属颗粒的光学性质。

解读： Surface plasmon polariton （SPP)
Surface: 金属和介质的界面
Plasmon: 金属界面自由电子的集体振荡，借用等离子的概念
Polariton: 模式

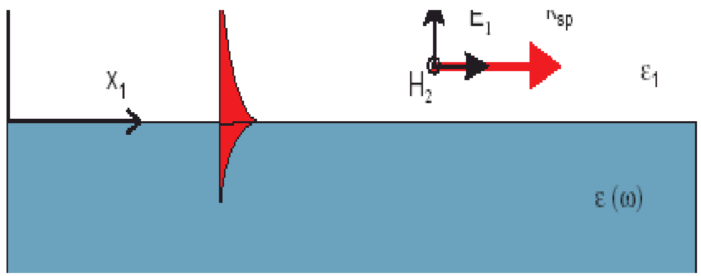
属于： Mesoscopic optics, nano optics, nano photonics, near field optics

古英 ygu@pku.edu.cn 2011年3月

Difference between surface plasmon (SP) and surface plasmon polaritons (SPP)

"a trapped surface mode which has electromagnetic fields decaying into both media but which, tied to the oscillatory surface charge density, propagates along the interface"

R.J. Sambles 1991



"we are dealing with a resonant excitation of a coupled state between the plasma oscillations and the photons, i.e., the plasmon surface polariton"

W. Knoll 1991

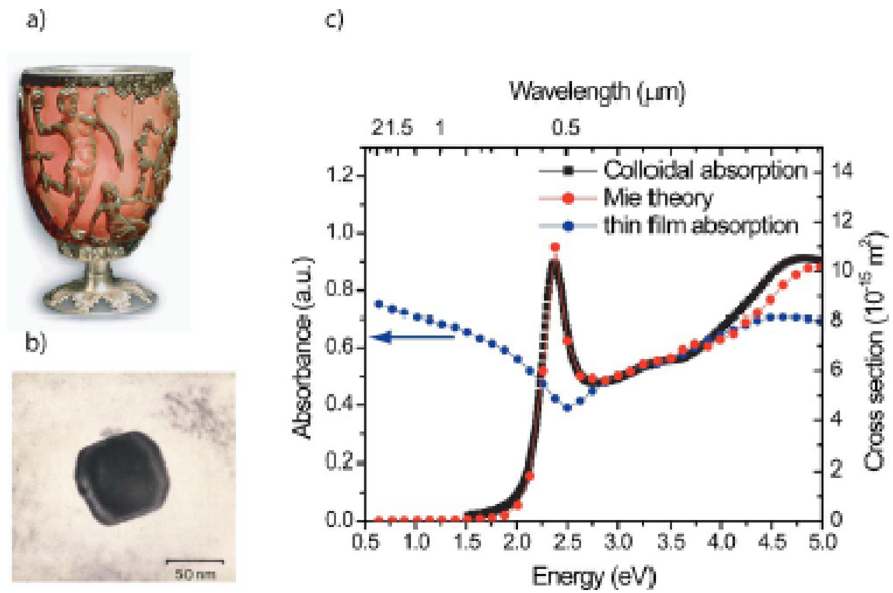


Fig. 1(a) by example of the Lycurgus cup (Byzantine empire, 4th century A. D.). The glass cup, on display in the British Museum, shows a striking red color when viewed in transmitted light, while appearing green in reflection. This peculiar behavior is due to small Au nanoparticles embedded in the glass [Fig. 1(b)], which show a strong optical absorption of light in the green part of the visible spectrum [Fig. 1(c)].

Plasmonics: Localization and guiding of electromagnetic energy in metal/dielectric
Stefan A. Maier and Harry A. Atwater, JOURNAL OF APPLIED PHYSICS 98, 011101 2005

五个部分：

第一章 SPP的发展简史

第二章 SPP的基本概念及物理

第三章 介观光学的理论方法

第四章 SPP的科学前沿和应用

第五章 SPP和量子体系的交叉研究

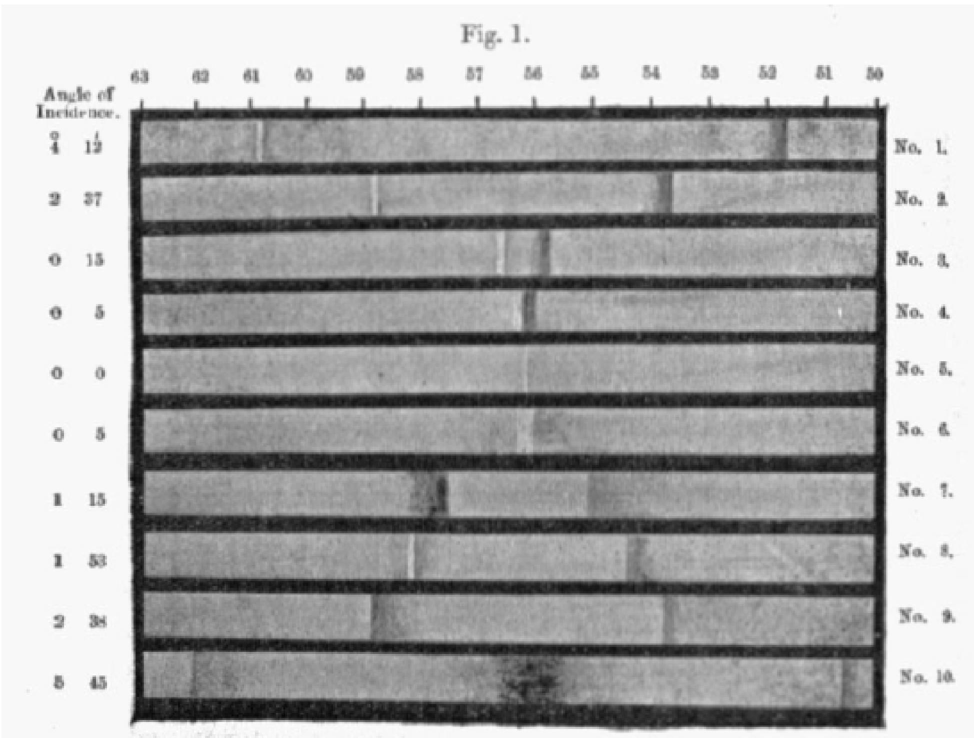
参考文献

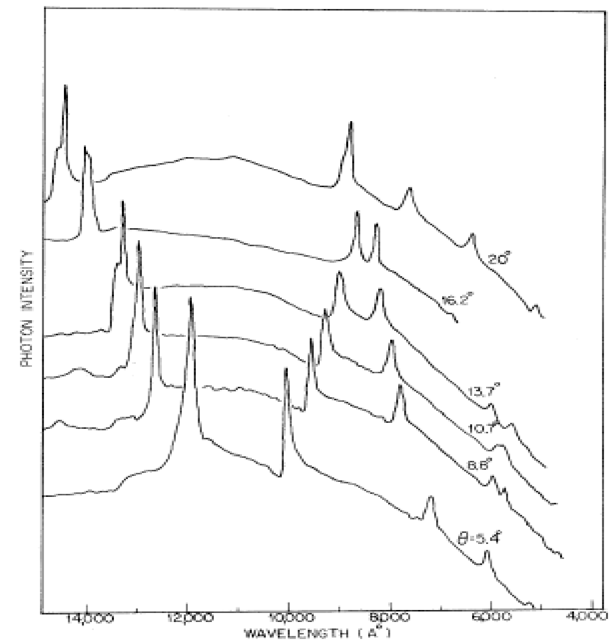
纳米结构制备及实验光路等略讲

作业： report（三到五页）

第一章 SPP的发展简史

Wood's anomalies，1902





On a Remarkable Case of Uneven Distribution of Light in a Diffraction Grating Spectrum
R W Wood 1902 *Proc. Phys. Soc. London* 18 269

SURFACE-PLASMON RESONANCE EFFECT IN GRATING DIFFRACTION
RITCHIE RH, ARAKAWA ET, COWAN JJ, et al （1968） PRL, 21 , 1530.

Mie theory , 1908

Exact solution of sphere, spherical symmetry structure
Absorption, scattering, and extinction

Zenneck (1907) & Sommerfeld (1909)

Demonstrated (theoretically) that radio frequency surface EM waves occur at the boundary of two media when one medium is either a "lossy" dielectric, or a metal, and the other is a loss-free medium.

They also suggested that it is the "lossy" (imaginary) part of the dielectric function that is responsible for binding the EM wave to the interface.

Fano (1939)

Suggested that surface EM waves were responsible for the striking anomalies in the continuous source diffraction spectra of metallic gratings - **'Wood's Anomalies'**

According to Fano : Surface EM wave, at metal-air interfaces, are evanescent waves whose wave vectors are greater than those of the incident and diffracted bulk EM waves, and that the grating augments the wave vector of the incident EM waves enabling them to couple with the surface EM waves.

Fano suggested:

1. surface EM waves at lossy-dielectric-air interfaces at radio frequencies (Zenneck-Sommerfeld waves)
2. surface EM waves at metal-air interfaces in the optical region (Fano modes)
3. loss-free dielectric/air interfaces (Brewster anle EM waves)

"represent for media of different electrical properties the same singular case defined by the same mathematical equation."

Ritchie (1957)

Demonstrated theoretically the existence of Surface plasma excitations (surface plasmons) at a metal surface.

Stern (1958)

Showed (theoretically) that surface EM waves at a metallic surface involved EM radiation coupled to surface plasmons.

Derived, for the first time, the dispersion relations for surface EM waves at metal surfaces.

Powell & Swan (1960)

Observed the excitation of **surface plasmons** at metal interfaces using electrons.

Otto (1968)

Devised the ATR (prism coupling) method for the coupling of bulk EM waves (optical) to surface EM waves.

Kretschmann (1971)

Modified the Otto geometry is now the most widely used device geometry.

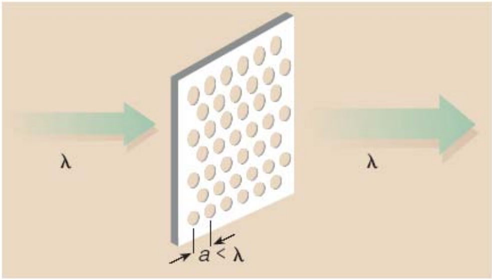
Knoll (1989)

Introduced the technique of Surface Plasmon Microscopy

Extraordinary optical transmission
T.W.Ebbesen group , 1998

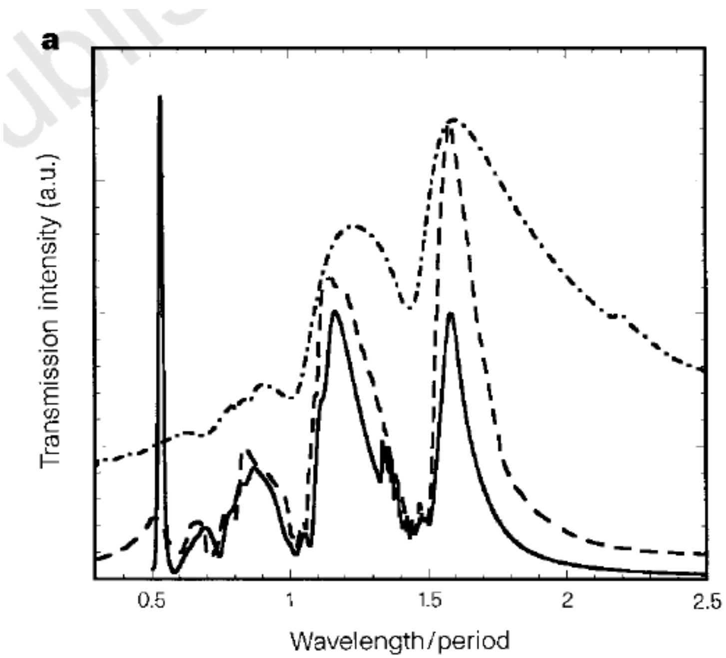
Start point of SPP

Bottleneck: low light transmittivity of apertures smaller than the wavelength of incident photon



Hole arrays in silver film:
metal film thickness **t**
Periodicity of holes **a_0**
Scale of holes **d**

Results:
Extraordinary transmission
Maximum at $\lambda/d \sim 10$
Influence of t (in APL)



Explanation:
Coupling of light and plasmons

Extraordinary optical transmission through subwavelength holes
T.W. Ebbesen et al, NATURE |VOL 391 | 12 FEBRUARY 1998

Beaming light from a bull's eyes structure
T.W.Ebbesen group , 2002

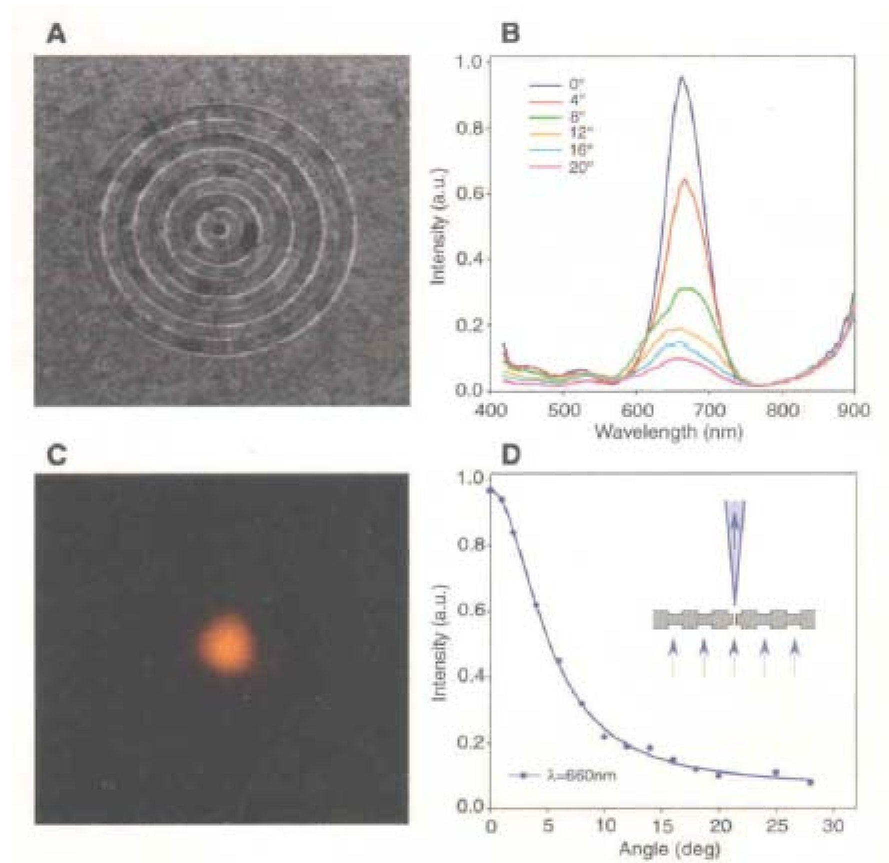
Progress work

To solve: light diffracts in all directions when an aperture is small.

Bull's eye of Ag film:
thickness 300nm
Groove periodicity 500nm
And depth 60nm
Hole diamter 250nm

Results:
Beaming light

Explanation:
Coupling of light and plasmons



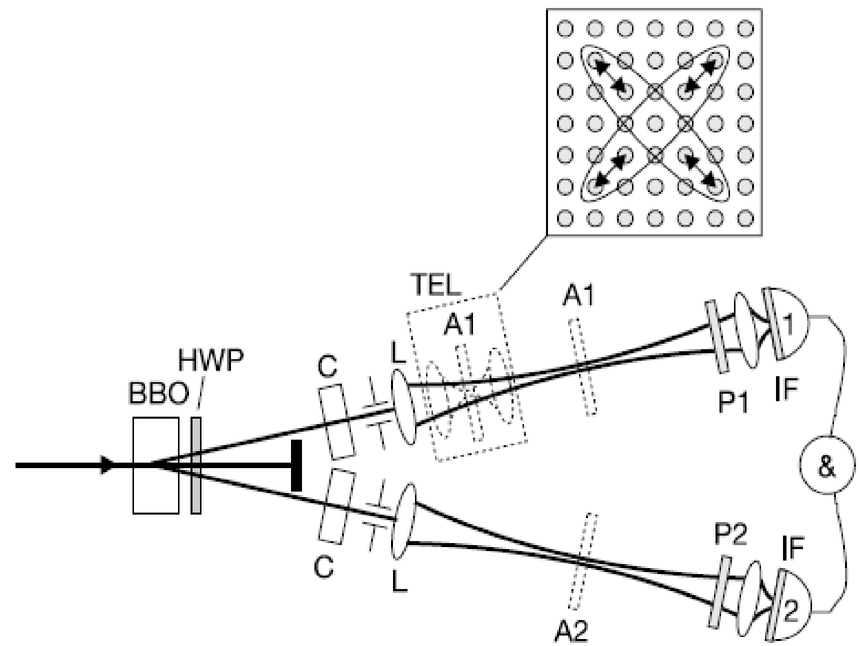
Beaming light from a subwavelength hole, T.W. Ebbesen et al, Science,297,820(2002)

Plasmon-assisted transmission of entangled photons
E. Altewischer el al, 2002

Application work

Aim to: Investigate the effects of nanostructured metal on entangled photons.

Results:
Such arrays convert photons into surface-plasmon —optically excited compressive charge density waves — which tunnel through the holes before reradiating as photons.

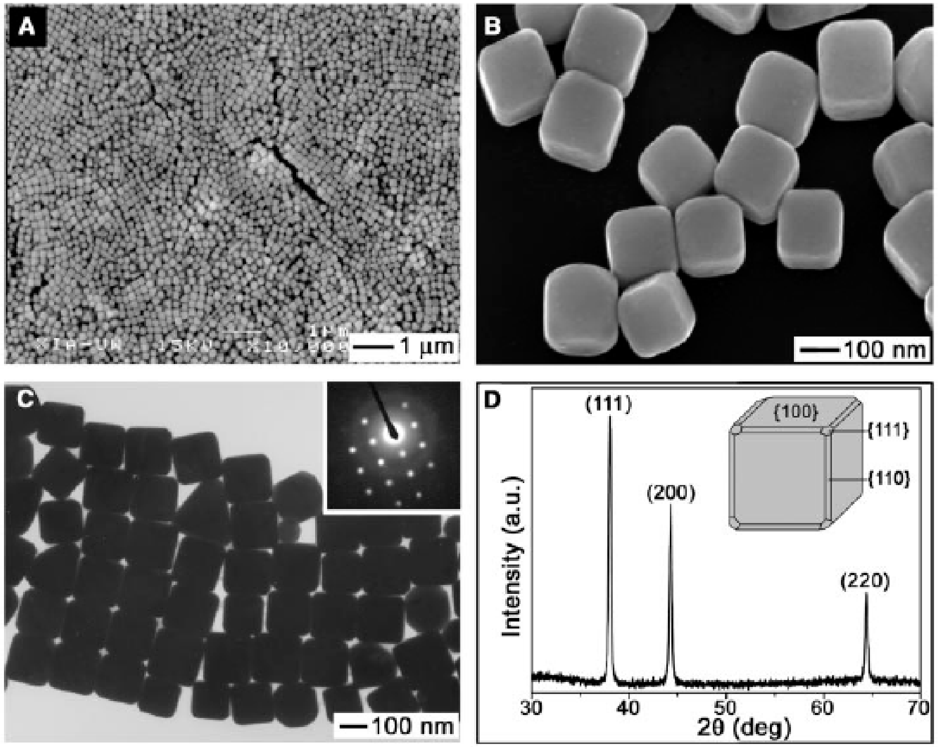


Explanation:
Conversion between photons and plasmons, quantum feature of SPP

Plasmon-assisted transmission of entangled photons,
E. Altewischer, M. P. van Exter & J. P. Woerdman, NATURE |VOL 418 | 304| 2002 |

Synthesis of Ag and Au nanocubes
Xia YN el al, 2002

Progress work



Significience:

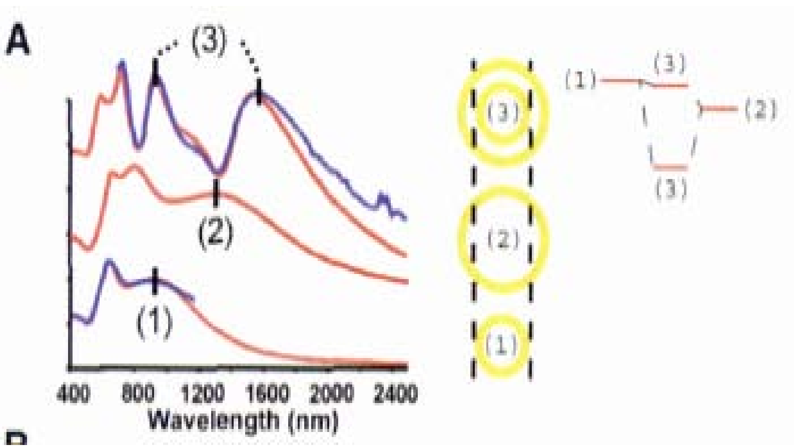
Controlling the size, shape, and structure of metal nanoparticles is technologically important to tailor the plasmonic properties.

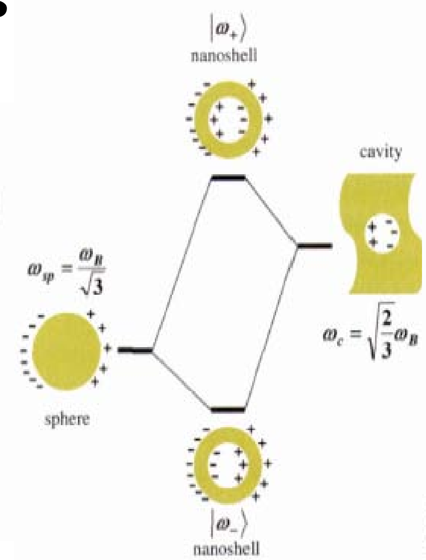
Shape-Controlled Synthesis of Gold and Silver Nanoparticles
Yugang Sun and Younan Xia, science, 76 (2002); 298 Science

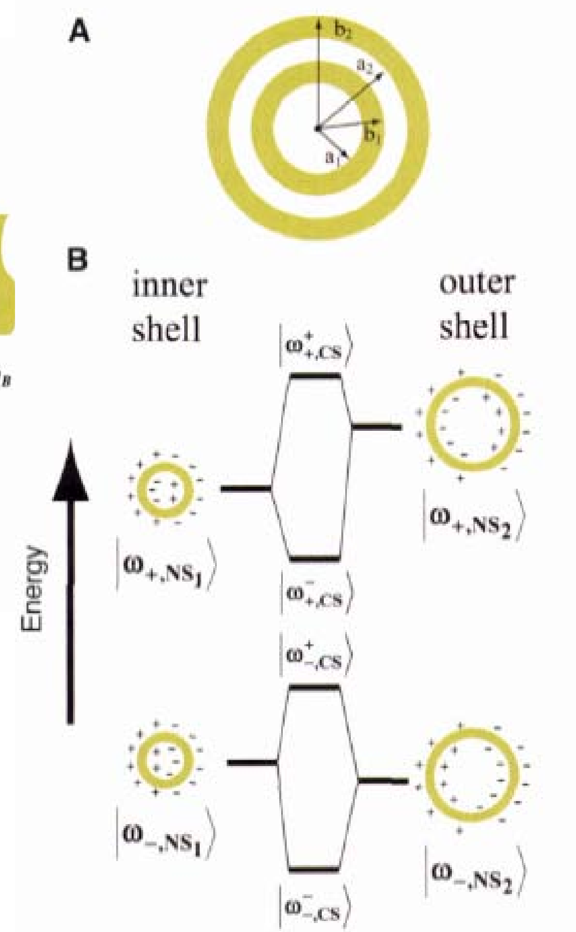
A hybridization model for plasmon response
N J Halas el al, 2003

Progress work

To solve: surface plasmon resonances in nanoshells







A hybridization of sphere and cavity

A hybridization of inner and outer shells

Results:

Several response peaks

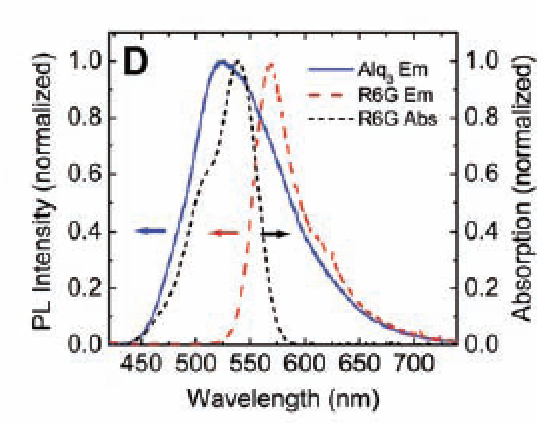
A hybridization model for the plasmon response of complex nanostructures

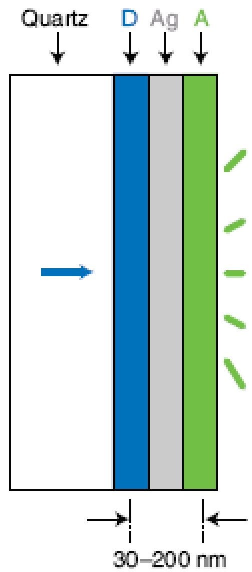
E Prodan; C Radloff; N J Halas; P Nordlander,Science, 302,419, 2003.

Forster Energy Transfer Across a Metal Film
W. L. Barnes et al, 2004

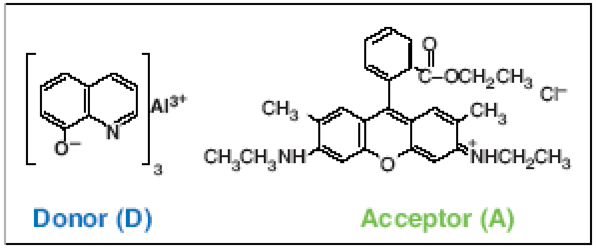
Application work
Molecular plasmonics

Aim to: realize the Forster energy transfer between donor and acceptor across silver film





Significance:
toward the realization of an active plasmonic device by combining thin polymer films with thin silver films

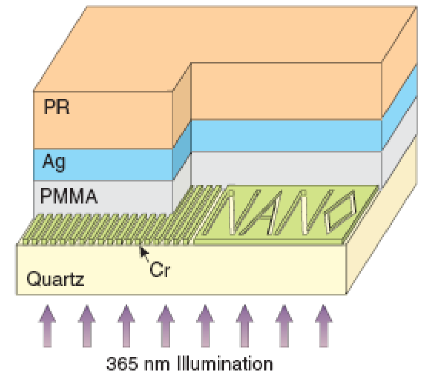


Energy Transfer Across a Metal Film Mediated by Surface Plasmon Polaritons
P. Andrew and W. L. Barnes,science,306,1002(2004).

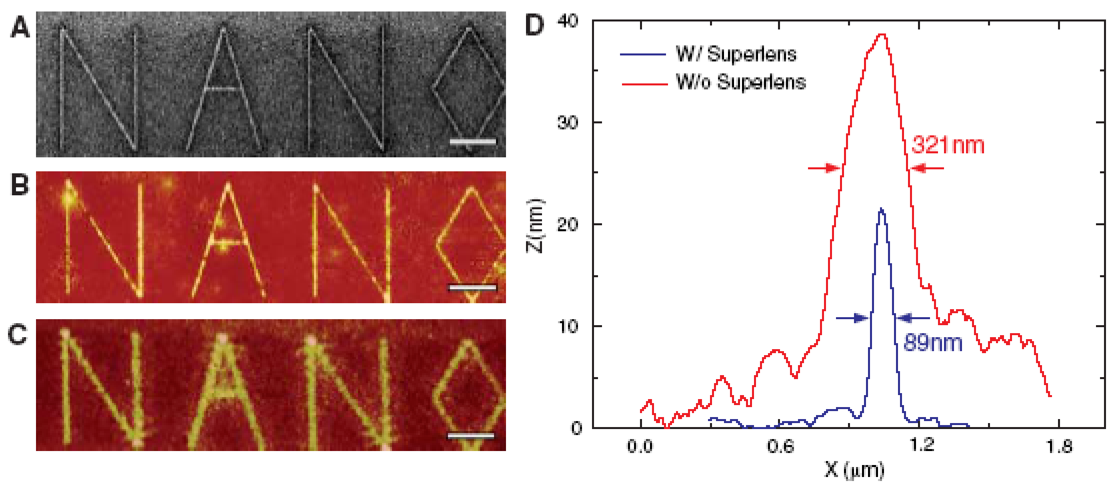
Optical Imaging below the Diffraction Limit
X. Zhang et al, 2005

Progress work

Aim to: realize the image by collecting the of evanescent waves via the excitation of surface plasmons



Results:
60-nanometer resolution,
Or 1/6 of wavelength.



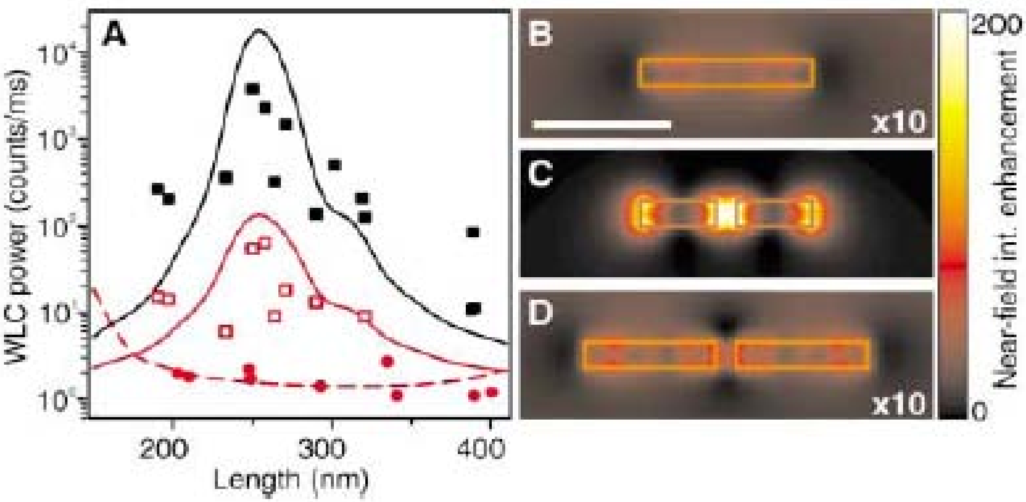
Significance:
breakthrough the diffraction limit

[Sub–Diffraction-Limited Optical Imaging with a Silver Superlens]
Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang, Science,308,534,2005.

Resonant Optical Antennas
O.J.F. Martin et al, 2005

Progress work

Aim to: The antenna length at resonance is considerably shorter than one-half the wavelength of the incident light



Results:
Fields localized in the gap and White light emission

Parameters:
Incident light: 830 nm
Size: 255*40*45 nm^3
Gap: 30 nm

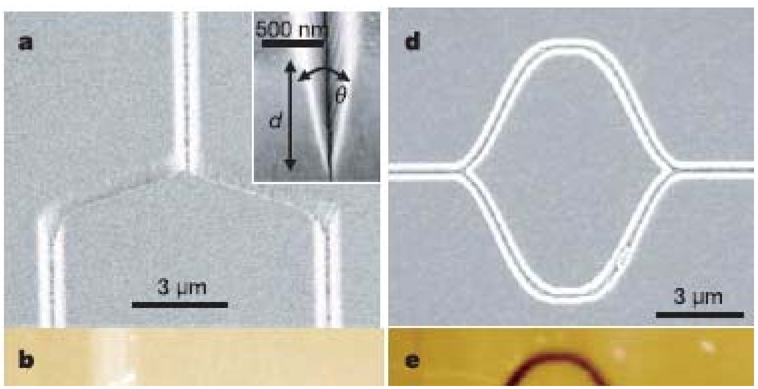
Significance:
Realization of optical nanoantenna

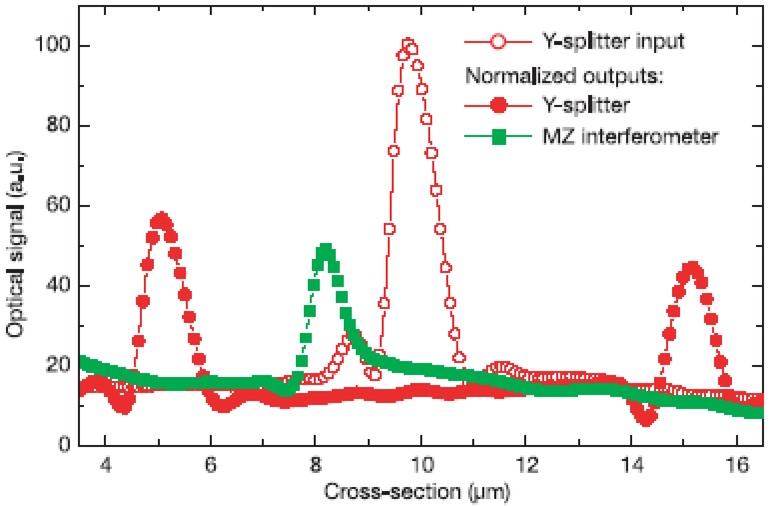
Resonant Optical Antennas, **O. J. F. Martin and B. Hecht et al, Science,308,1607,2005.**

Channel SPP waveguide components including interferometers and ring resonators
T. W. Ebbesen et al, 2006

Application work

challenge to: the miniaturization and high-density integration of optical circuits at telecom. Wavelength





Results:
Grooves in silver, strong light confinement, low propagation loss

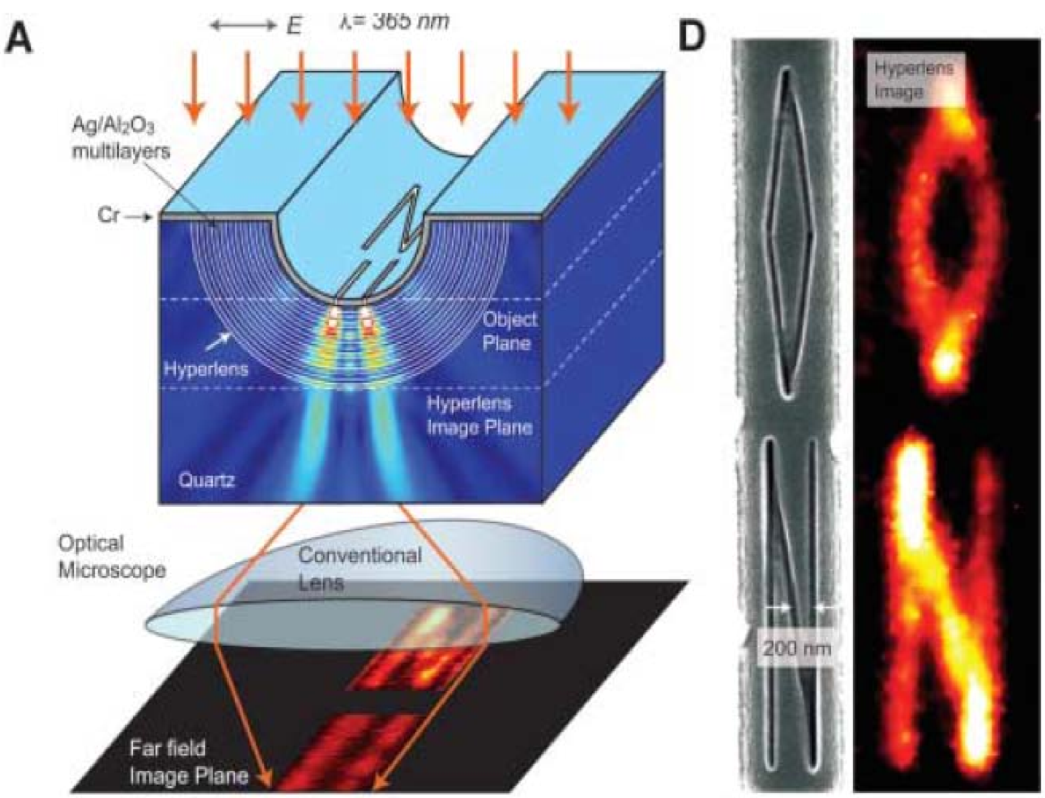
Significance:
nano devices based Channel SPP

Channel plasmon subwavelength waveguide components including interferometers and ring resonators, T.W. Ebbesen et al, NATURE|Vol 440|508| 2006

Hyperlens Magnifying Sub-Diffraction-Limited Objects
X. Zhang et al, 2005

Progress work

Aim to: realize the image magnification by collecting far field



Parameters:

Ag and Al_2O_3 layers: 35 nm

Object: 40 nm

Results:

By transforming evanescent waves into propagating waves, projecting a high-resolution image into the far field.

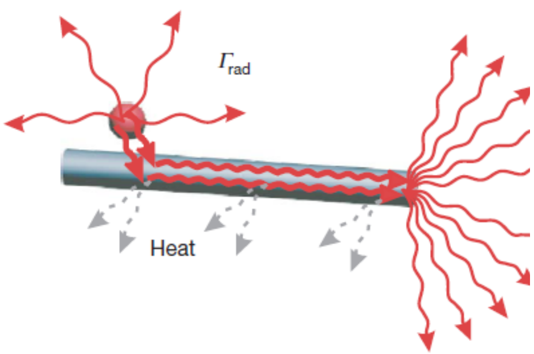
[Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects](#)

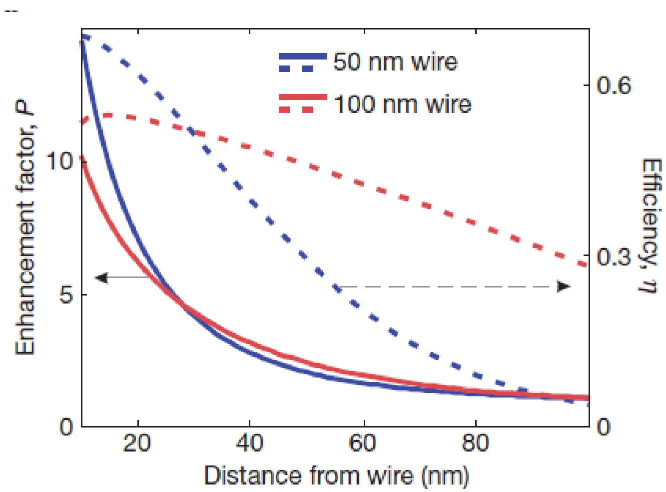
X. Zhang et al, science,315,1686,2007

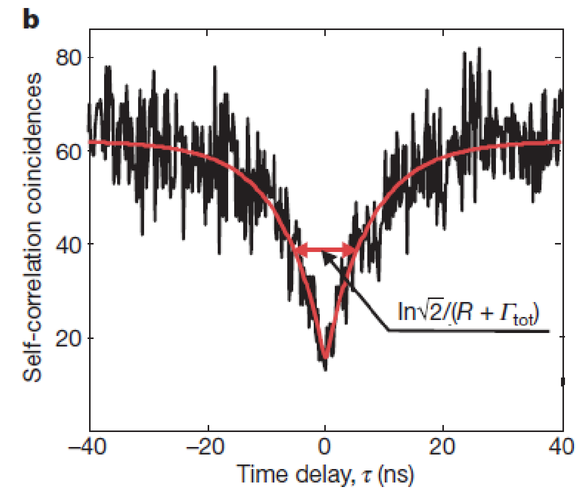
Generation of single optical plasmons in metallic nanowires coupled to quantum dots
M. D. Lukin et al, 2007

Crossing work

Aim to: efficient coupling between quantum dots and SPP, single photon switch and transistor, long range quantum bits.







Results:

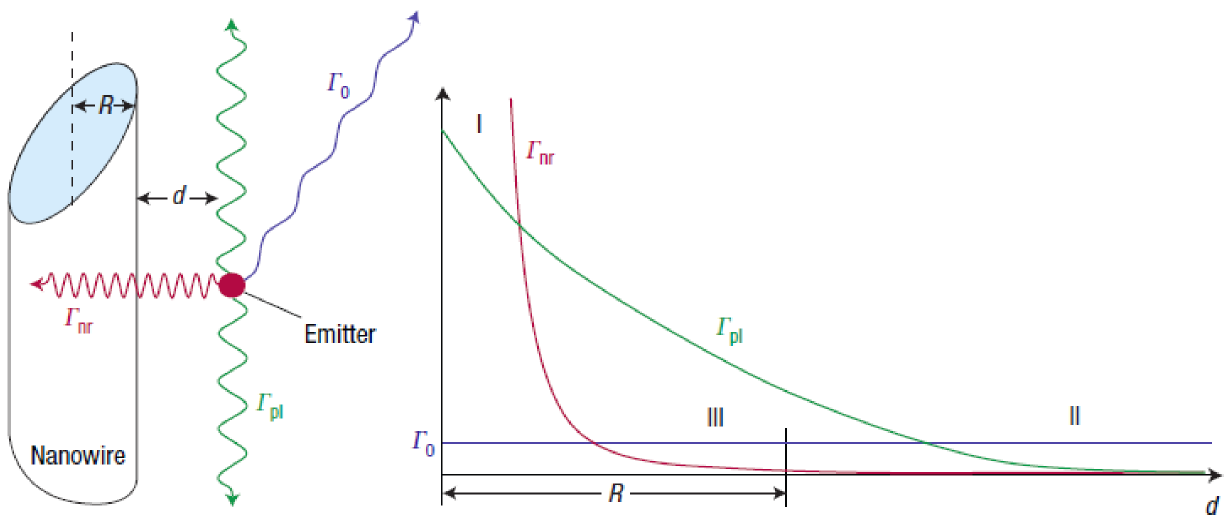
Realizing single quanta of surface plasmon.

[Generation of single optical plasmons in metallic nanowires coupled to quantum dots](#)
A. V. Akimov et al, NATURE|Vol 450|402| 2007

Quantum light switch: A single-photon transistor using nanoscale surface plasmons
M. D. Lukin et al, 2007

Crossing work

在未来的计算机中光子能够代替电子吗？光子回路体积小，易于集成，损耗小，传的快，但是光子间没有相互作用，实现量子操控比较困难。光子与表面等离激元间的交换弥补了这一不足，量子发射体和表面等离激元强耦合的单光子晶体管，实现了单光子间的强相互作用，可在单光子探测，纠缠，可控相位门，量子的非线性效应方面有应用.

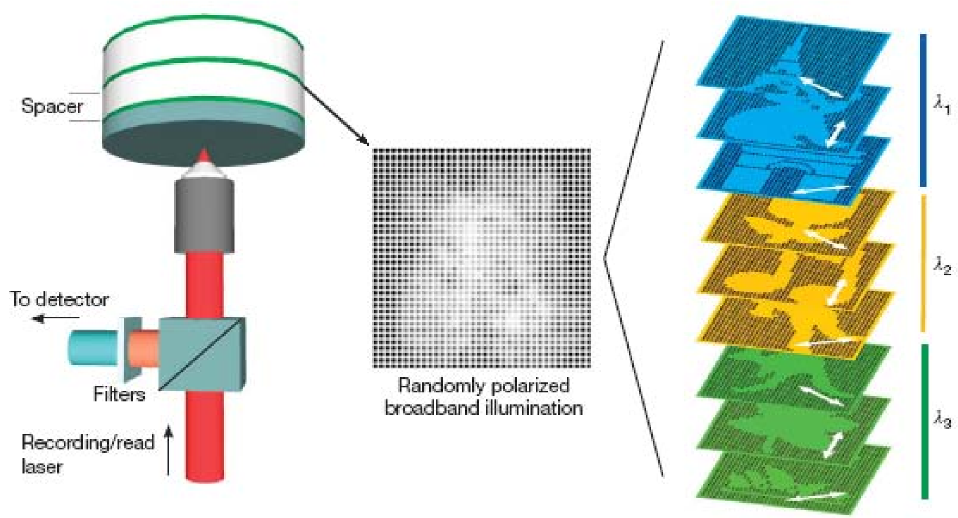


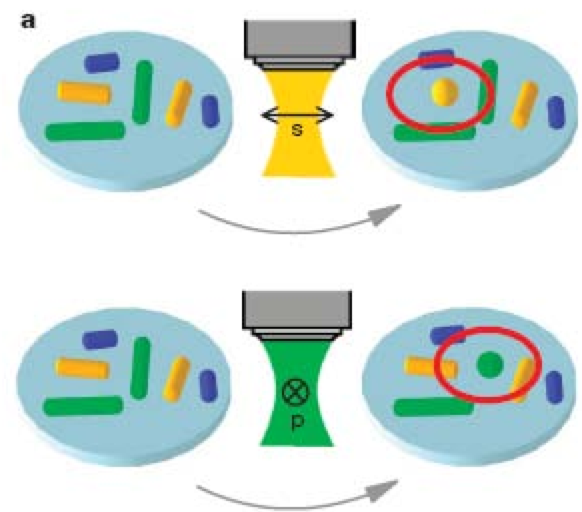
A single-photon transistor using nanoscale surface plasmons, M. D. Lukin et al, NATURE PHYSICS|Vol 3|807| 2007; Quantum light, switch,M.Orrit, NATURE PHYSICS|Vol 3|755| 2007

Optical recording by SPR of gold nanorods
M. Gu et al, 2009

Application work

Aim to: minimize the recording storage by multiplexing: wavelength, polarization, and spatial dimensions





Results:

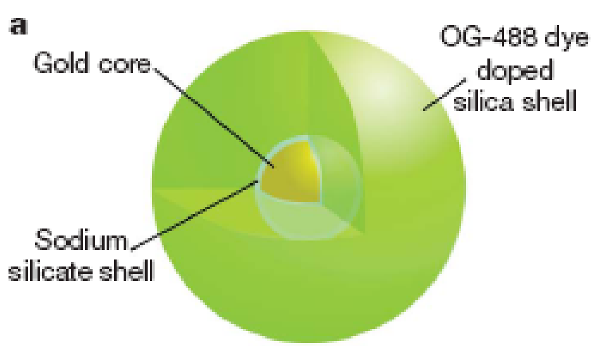
realizing five-dimensional data recording by SPR

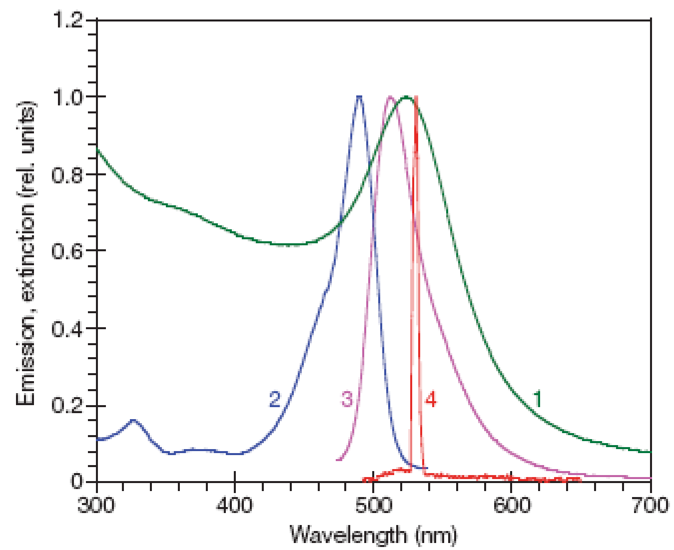
Five-dimensional optical recording mediated by surface plasmons in gold nanorods
M. Gu et al, NATURE|Vol 459|410| 2009

Core-shell nanostructure spaser
M. A. Noginov et al, 2009

Progress work

Aim to: **realize a 'spaser' generating stimulated emission of surface plasmons in resonating metallic nanostructures adjacent to a gain medium.**





Parameters:
gold core : 14 nm
Shell: 44 nm
Wavelength: 525 nm

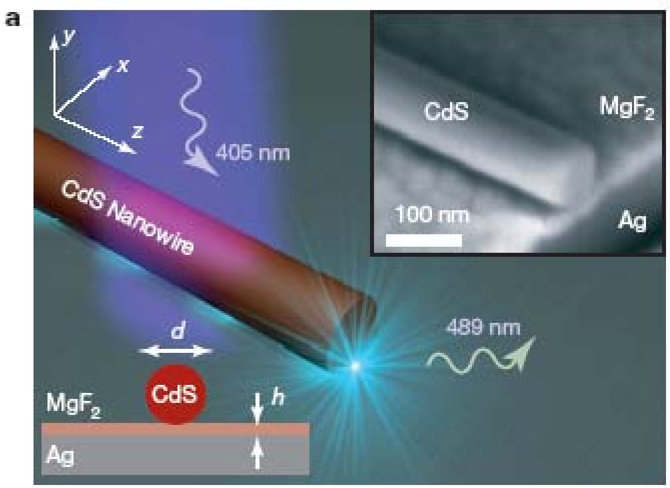
Significance:
the smallest nanolaser
the first operating at visible wavelengths.

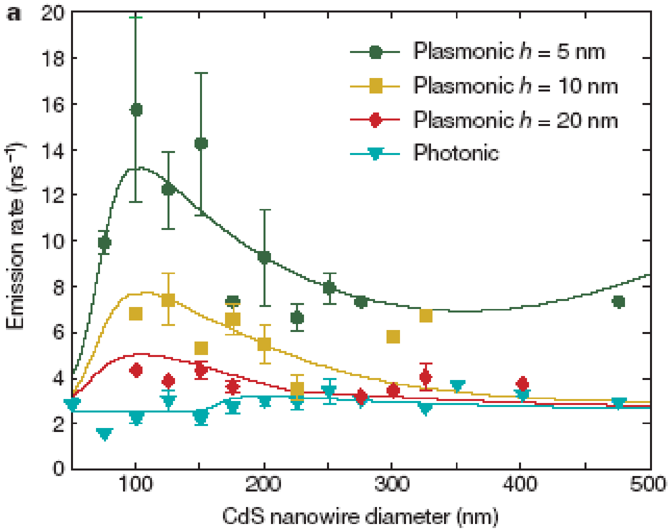
Demonstration of a spaser-based nanolaser, **M. A. Noginov et al, NATURE| Vol 460|1110| 2009**

Nano-spaser based on hybrid waveguide
X. Zhang et al, 2009

Progress work

Challenge to: **realize ultracompact lasers generating coherent optical fields at a nanoscale, far beyond the diffraction limit**





Significance:

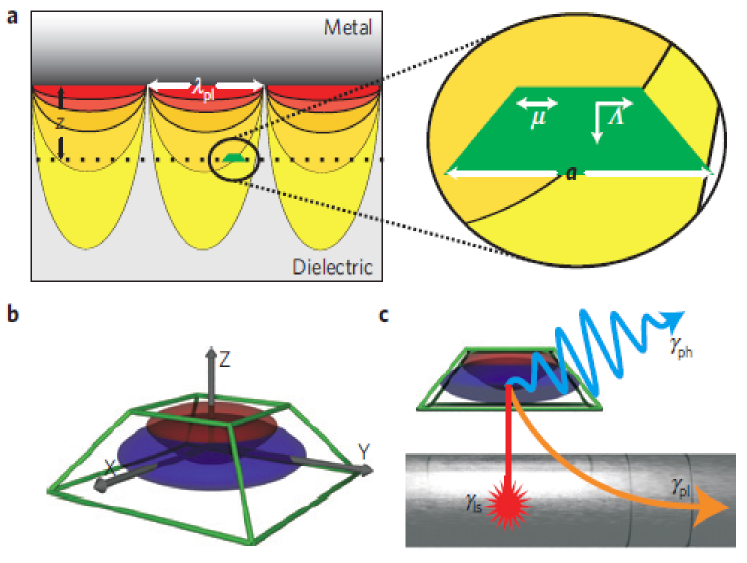
Plasmonic modes have no cutoff, downscaling of the lateral dimensions of both the device and the optical mode is demonstrated.

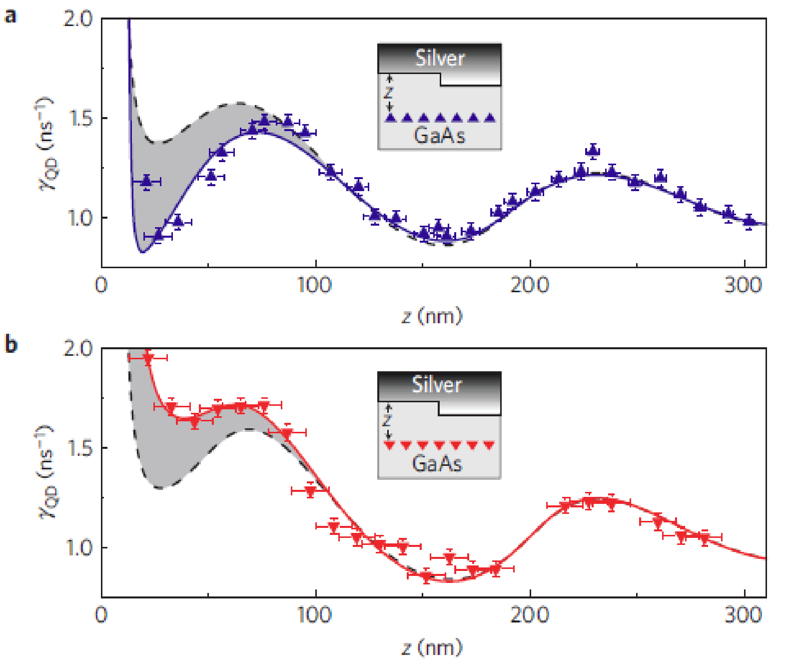
Plasmon lasers at deep subwavelength scale, **X.Zhang et al, NATURE|Vol 461|629| 2009**

modified plasmon–matter interaction with mesoscopic quantum emitters
Mads Lykke Andersen, et al. 2010

Progress work

Aim to: experimentally demonstrate various decay channels with considering the size of quantum emitters.





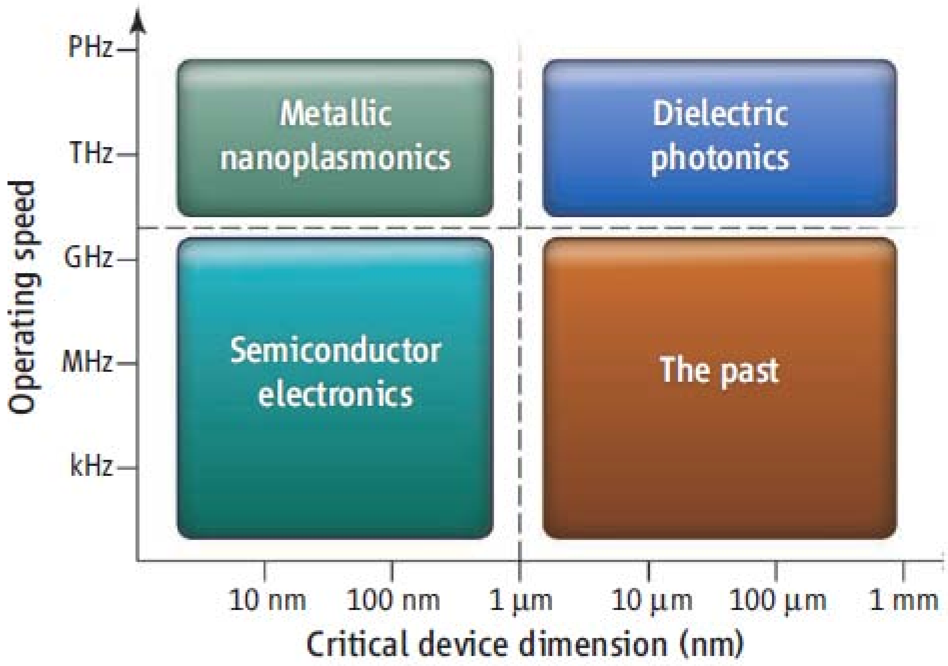
Significance: the effect of the size of nanoscale quantum dot on the coupling between SPP and quantum emitter.

Strongly modified plasmon–matter interaction with mesoscopic quantum emitters

Mads Lykke Andersen, et al. nature physics, DOI: 10.1038/NPHYS1870, 2010

APPLIED PHYSICS: The Case for Plasmonics

Mark L. Brongersma, 1 and Vladimir M. Shalaev, 2010



By squeezing light into nanoscale volumes, plasmonic elements allow for fundamental studies of light-matter interactions at length scales that were otherwise inaccessible

The Case for Plasmonics

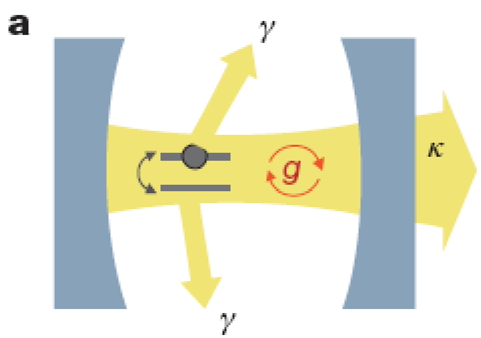
Mark L. Brongersma, et al, VOL 328,440 SCIENCE.

hybrid photonic architectures

The assembly of hybrid nanophotonic devices from different fundamental photonic entities—such as single molecules, nanocrystals, semiconductor quantum dots, nanowires and metal nanoparticles—can yield functionalities that exceed those of the individual subunits.

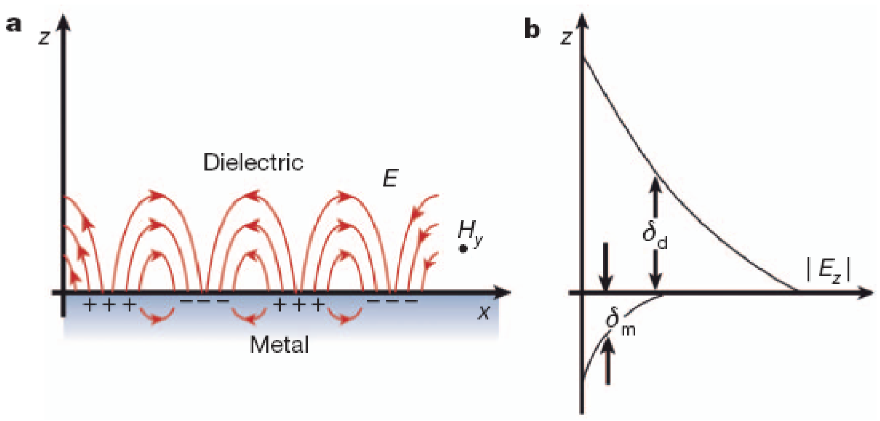
BOX 1

Cavity QED



BOX 2

Plasmonic enhancement



<u>**Oliver Benson, nature, 480, 193 (2011)**</u>

Functionality on the nanoscale

Light guiding and sorting

Enhanced emission and absorption

Nonlinear elements and switches

Nanophotonic–plasmonic hybrid devices

Plasmonically enhanced single-photon sources

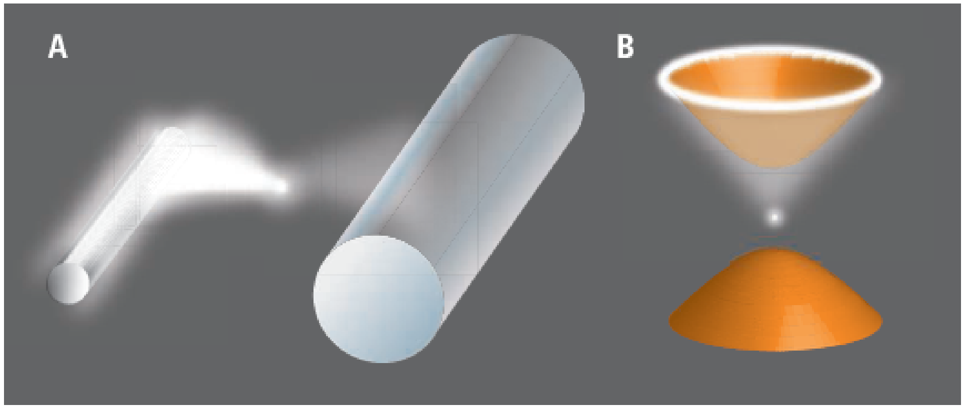
Nanowire photonic elements

Future prospects

plasmons. Also, nonlinear interactions facilitating logical operations are feasible using CQED or plasmonic effects. There is great potential

Oliver Benson, nature, 480, 193 (2011)

Plasmonics Goes Quantum



Make it quantum. Building blocks of an integrated nanoscale quantum information system. (**A**) The nanowire supports a single plasmonic oscillation conceptually similar to a single-mode optical fiber. However, the nanoscale mode volumes of the plasmon lead to strong coupling with the quantum emitter. (**B**) An unorthodox approach of enhancing light-matter interaction is by tailoring the dielectric constant of a medium so that it is dielectric in one direction and metallic in another. The resulting hyperboloidal dispersion relation supports infinitely many electromagnetic states for channeling light into a single-photon resonance cone.

A combined plasmonics and metamaterials approach may allow light-matter interaction to be controlled at the single-photon level.

single plasmon →

antibunching statistics

nanoscale-mode volume →

strong coupling

entangling+squeezing →

quantum information

quantum plasmonics →

Spaser

Cavity QED

QI system

Zubin Jacob and Vladimir M. Shalaev, science, 334, 463 (2011)

Other important affairs

Review articles:

Surface plasmon resonance sensors: review

Jiri Homola, Sinclair S. Yee, Gunter Gauglitz, Sensors and Actuators B 54 (1999) 3–15

Surface plasmon subwavelength optics

T. W. Ebbesen et al, NATURE | VOL 424 | 824| 2003

Photonic structures in biology

J.R. Sambles et al, NATURE | VOL 424 | 852| 2003

Other important affairs

Review articles:

Plasmonics: Merging Photonics and Electronics at Nanoscale Dimensions

Ekmel Ozbay,SCIENCE VOL 311,189, 2006

Nano-optics from sensing to waveguiding

N.J. Halas, nature photonics | VOL 1 |641| 2007

Progresses:

Local detection of electromagnetic energy transport below the diffraction limit in metal nanoparticle plasmon waveguides

S. A.Maier et al, nature materials | VOL 2 |229| 2003

Experimental Verification of Designer Surface Plasmons

Alastair P. Hibbins, Benjamin R. Evans, J. Roy Sambles, SCIENCE,308,670,2005

Nanofabricated media with negative permeability at visible frequencies

A. N. Grigorenko and A. K. Geim el al, NATURE|Vol 438|335| 2005

Progresses:

Magnifying Superlens in the Visible Frequency Range (using metamaterial)

Igor I. Smolyaninov, Yu-Ju Hung, Christopher C. Davis, science, 315, 1699, 2007

Transmission resonances through aperiodic arrays of subwavelength apertures

Tatsunosuke Matsui, NATURE| Vol 446|517| 2007

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本章结束语:

以 Nature 和 Science 上进展、应用和综述文章为主要线索，总结了plasmonics 发展过程中的重要事件，对plasmonics 有全局的了解。Plasmonics 是 nanooptics 的重要组成部分, 目前在应用领域和交叉学科方面有重要发展。