Photo Credit: I. Tsukerman, Seefeld, Austria, January, 2009

Latest Progress in Nanoplasmonics and Spaser

Mark I. Stockman

Center for Nano-Optics (CeNO) and Department of Physics and Astronomy, Georgia State University, Atlanta, GA, USA

Department of Physics and Astronomy
Georgia State University
Atlanta, GA 30303-3083

- **Introduction: Plasmonics and Nano-confinement of Optical Energy**
- Nanoplasmonic Resonances and their Frequencies (Colors)
- Localized Surface Plasmons and Plasmonic Hot Spots
- Plasmonic Enhancement and Ultrafast Nature of Plasmonics
- Nanolenses
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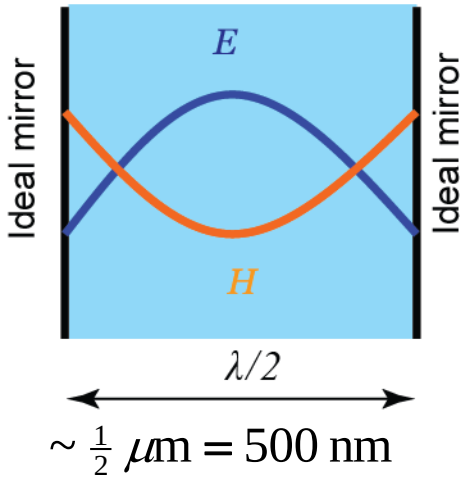
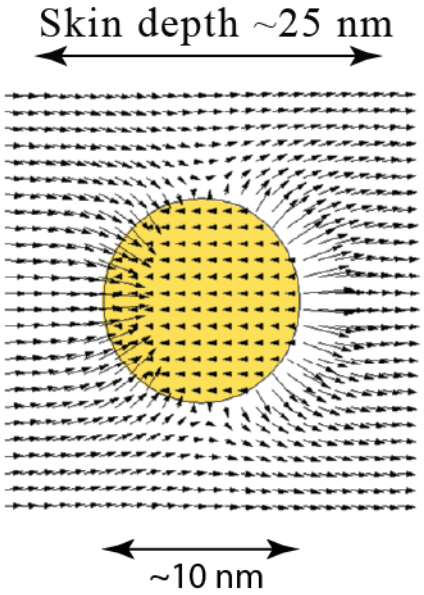
Georgia State University
Atlanta, GA 30303-3083

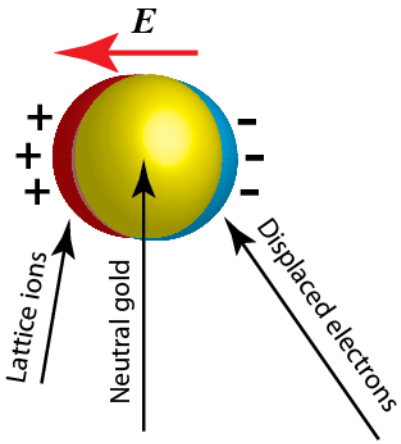
M. I. Stockman, *Nanoplasmonics: The Physics Behind the Applications*, Phys. Today **64**, 39-44 (2011).

Nanoplasmonics in a nano-nutshell

Concentration of optical energy on the nanoscale







Photon: Quantum of electromagnetic field

Surface Plasmon: Quantum of electromechanical oscillator

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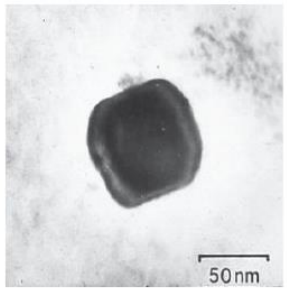
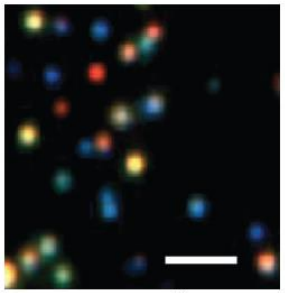
Lycurgus Cup (4th Century AD): Roman Nanotechnology

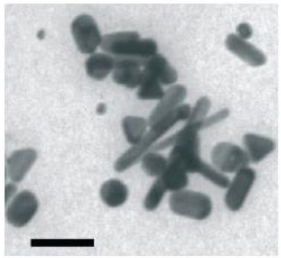


I. Freestone, N. Meeks, M. Sax, and C. Higgitt, *The Lycurgus Cup - a Roman Nanotechnology,* Gold Bull. **40**, 270-277 (2007

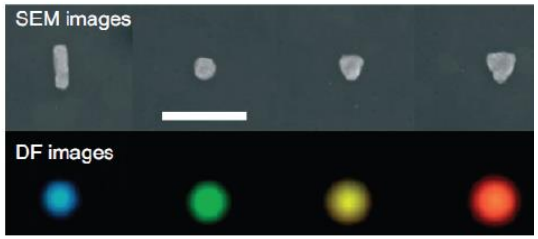
Nanoplasmonic colors are very bright. Scattering and absorption of light by them are very strong. This is due to the fact that all of the millions of electrons move in unison in plasmonic oscillations Nanoplasmonic colors are also eternal: metal nanoparticles are stable in glass: they do not bleach and do not blink. Gold is stable under biological conditions and is not toxic *in vivo*

Colors of Silver Nanocrystals and Gold Nanoshapes





C. Orendorff, T. Sau, and C. Murphy, *Shape-Dependent …*, Small **2**, 636-639 (2006)

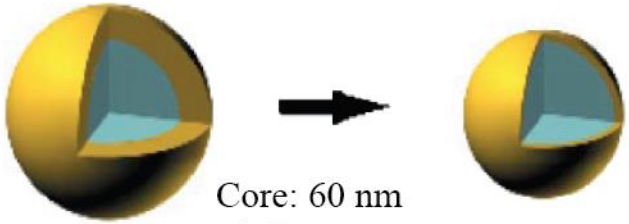


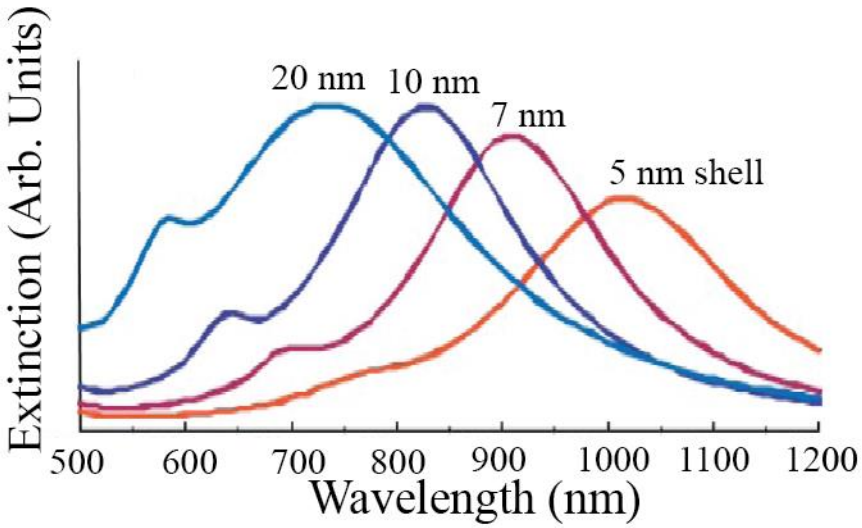
Scanning electron microscopy

Dark field optical microscopy

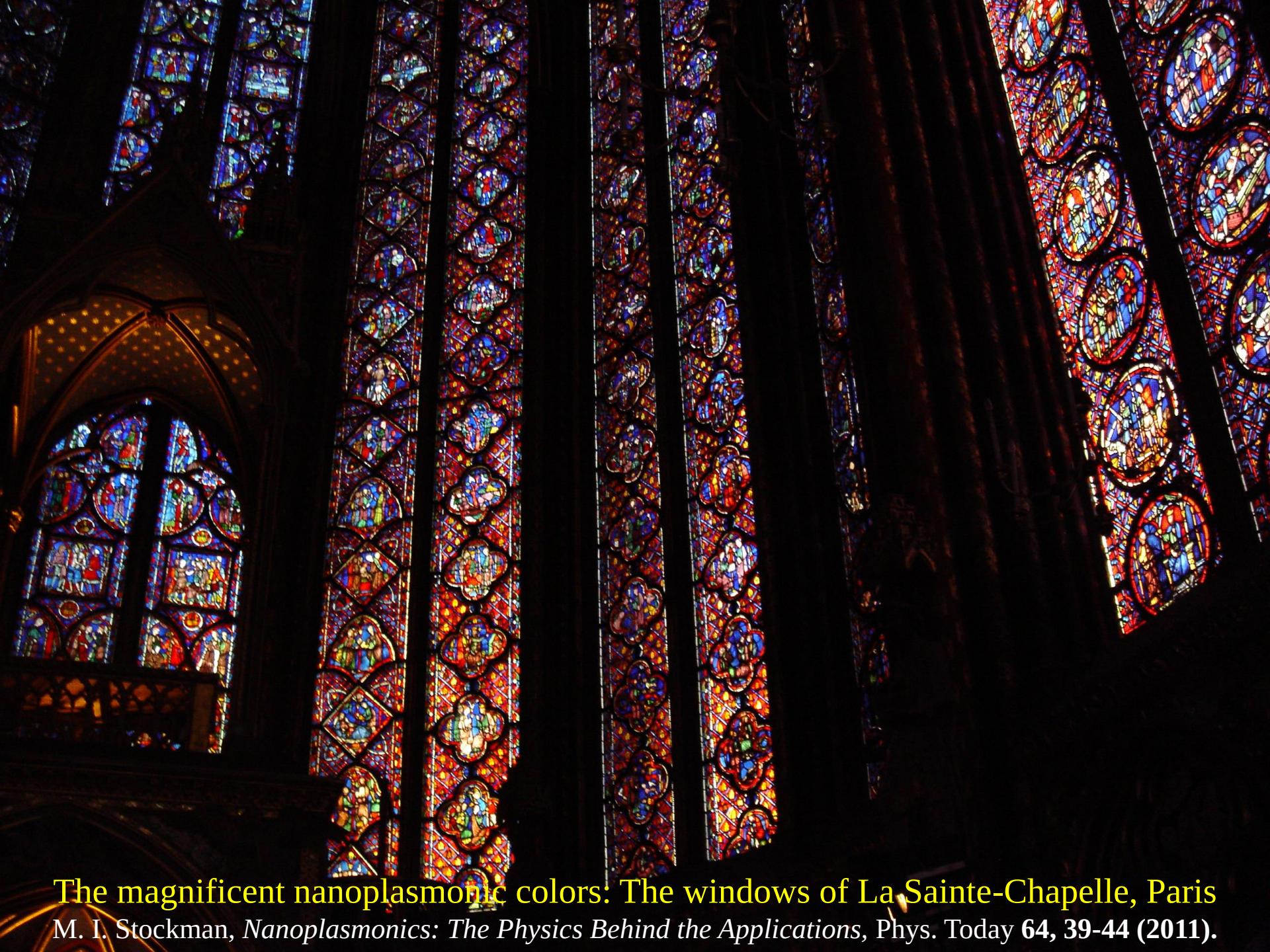
W. A. Murray and W. L. Barnes, *Plasmonic Materials*, Adv. Mater. **19**, 3771-3782 (2007) [Scale bar: 300 nm]

When shell becomes progressively thinner comparing to the core, the spectrum of the nanoshell shifts to the red and then to the near-infrared where biological tissues do not absorb





J. L. West and N. J. Halas, *Engineered Nanomaterials for Biophotonics Applications: Improving Sensing, Imaging, and Therapeutics*, Annu. Rev. Biomed. Eng. **5**, 285-292 (2003).



The magnificent nanoplasmonic colors: The windows of La Sainte-Chapelle, Paris

M. I. Stockman, *Nanoplasmonics: The Physics Behind the Applications*, Phys. Today **64, 39-44 (2011).**

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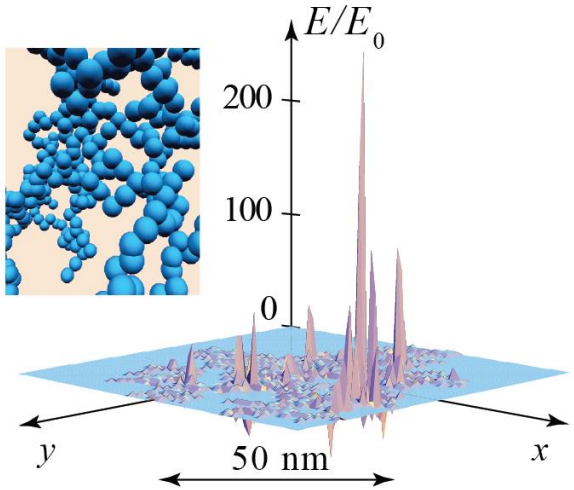
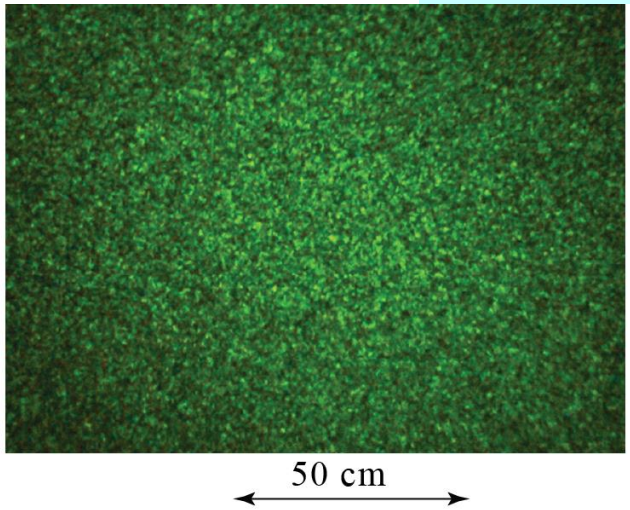
Georgia State University
Atlanta, GA 30303-3083

Plasmonic Near-Field **Hot Spots:** Happy 22nd Anniversary!

•D. P. Tsai et al., Phys. Rev. Lett. **72**, 4149 (1994).
•M. I. Stockman et al., *Phys. Rev. Lett.* **75**, 2450 (1995)
•M. I. Stockman, L. N. Pandey, and T. F. George, Phys. Rev. B **53**, 2183 (1996)



M. I. Stockman, L. N. Pandey, and T. F. George, Phys. Rev. B 53, 2183 (1996).



Random scattering speckles

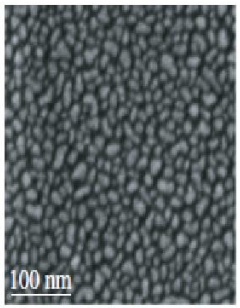
$$R_{Speckle} \sim \frac{\lambda\!\!\!^{-}}{A} L$$

$R_{Speckle}$ is speckle size

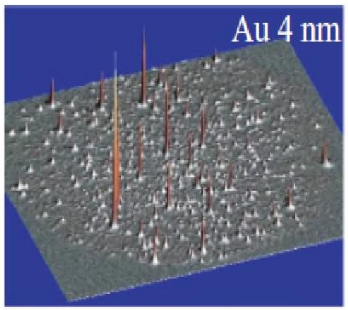
$\lambda\!\!\!^{-} \sim 100$ nm is reduced wave length

A is laser spot size,

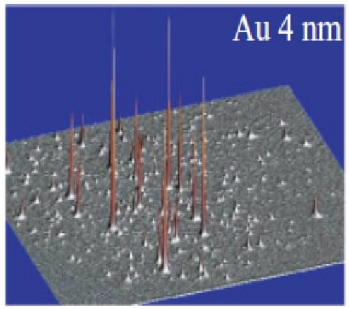
L is distance to the screen



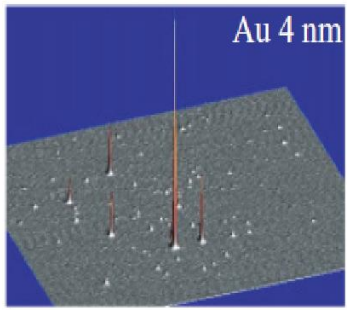
Au 4 nm, f = 0.53



λ = 800 nm, Hot Spots Nb = 617



λ = 930 nm, Hot Spots Nb = 453



λ = 970 nm, Hot Spots Nb = 402

C. Awada, G. Barbillon, F. Charra, L. Douillard, and J. J. Greffet, Phys. Rev. B **85**, 045438 (2012).

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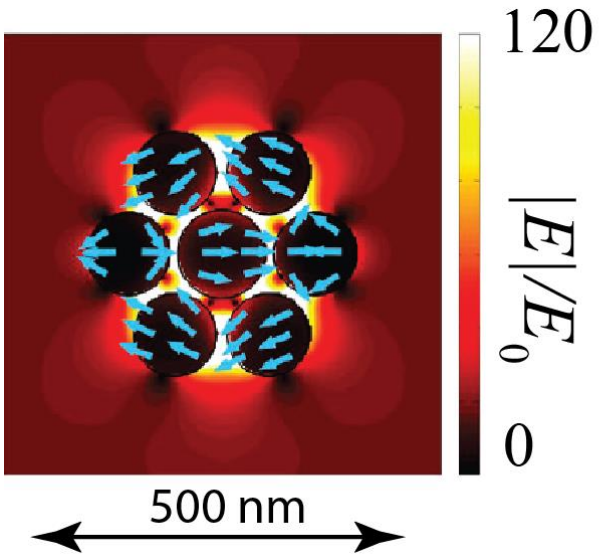
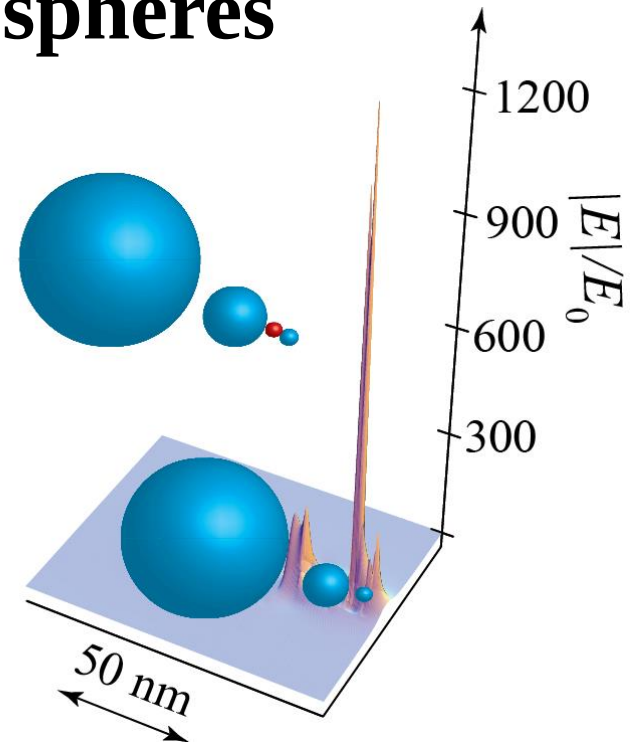
Engineered Nanoplasmonic Hot Spots in Small Clusters of Nanospheres





Fano resonance in a nanosphere cluster:
•J. A. Fan et al., Science **328**, 1135 (2010)
•M. Hentschel et al., Nano Lett. **10**, 2721 (2010)

Self-similar nanosphere nanolens: K. Li, M. I. Stockman, and D. J. Bergman, Phys. Rev. Lett. **91**, 227402 (2003)

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Enhancement factors for small nanoparticles (size $R < l_s$ ~25 nm)

Plasmonic quality factor: $Q = \frac{\omega}{2\gamma} \approx \frac{-\mathrm{Re}\,\varepsilon_m}{\mathrm{Im}\,\varepsilon_m} \sim 10-100$

Radiative rate enhancement for dipole mode frequency: $\sim Q^2$

Excitation rate enhancement : $\sim Q^2$

SERS enhancement: $\sim Q^4$

The above-listed enhancement factors do not depend on size *R*

Emission rate of SPs into a mode: $\propto \frac{Q}{R^3}$

This relative to free photons: $\sim \frac{\lambda\!\!\!^{-3} Q}{R^3}$ (Purcell factor)

This enhancement factor is *inversely* proportional to R^3

This is of fundamental importance for spasers (plasmonic nanolasers)

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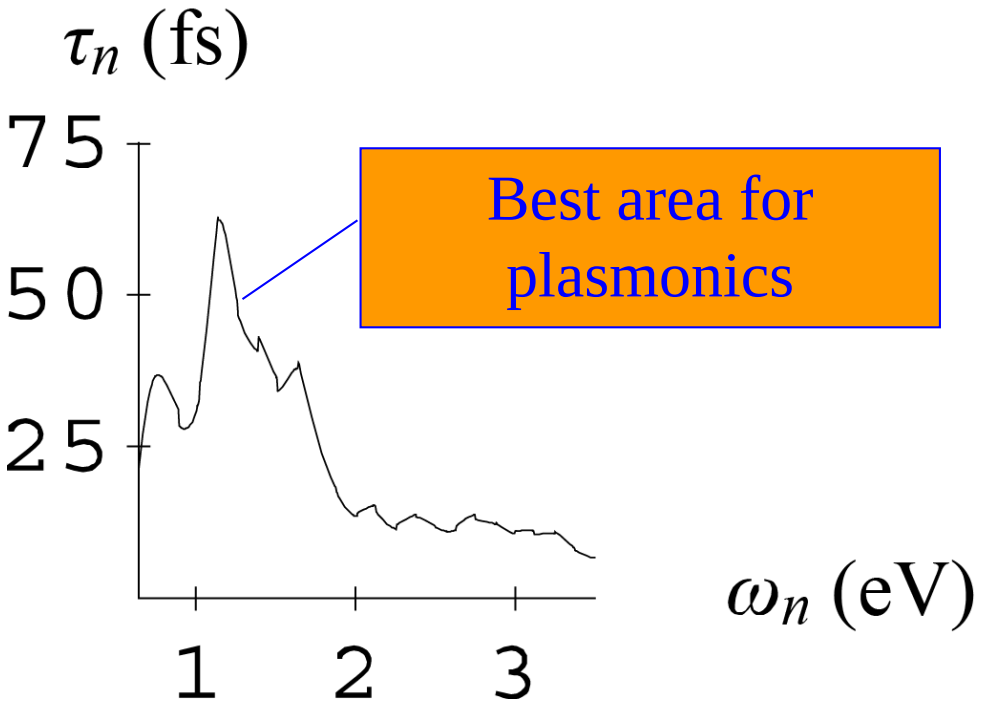
Nanoplasmonics is intrinsically ultrafast:



Surface plasmon relaxation times are in ~10-100 fs range

Spectrally, surface plasmon resonances in complex systems occupy a very wide frequency band; for gold and silver:

$$\Delta\omega \approx \omega_p / \sqrt{2} \approx 4\,\text{eV}$$

Including aluminum with plasmon responses in the ultraviolet, this spectral width increases to ~10 eV.

Corresponding rise time of plasmonic responses ~ 100 as

Localized SP hot spots and SPPs coexist in space and time on nanostructured surfaces

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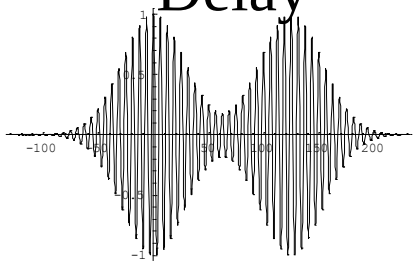
A. Kubo, K. Onda, H. Petek, Z. Sun, Y. S. Jung, and H. K. Kim, *Femtosecond Imaging of Surface Plasmon Dynamics in a Nanostructured Silver Film*, Nano Lett. 5, 1123 (2005).

200 nm

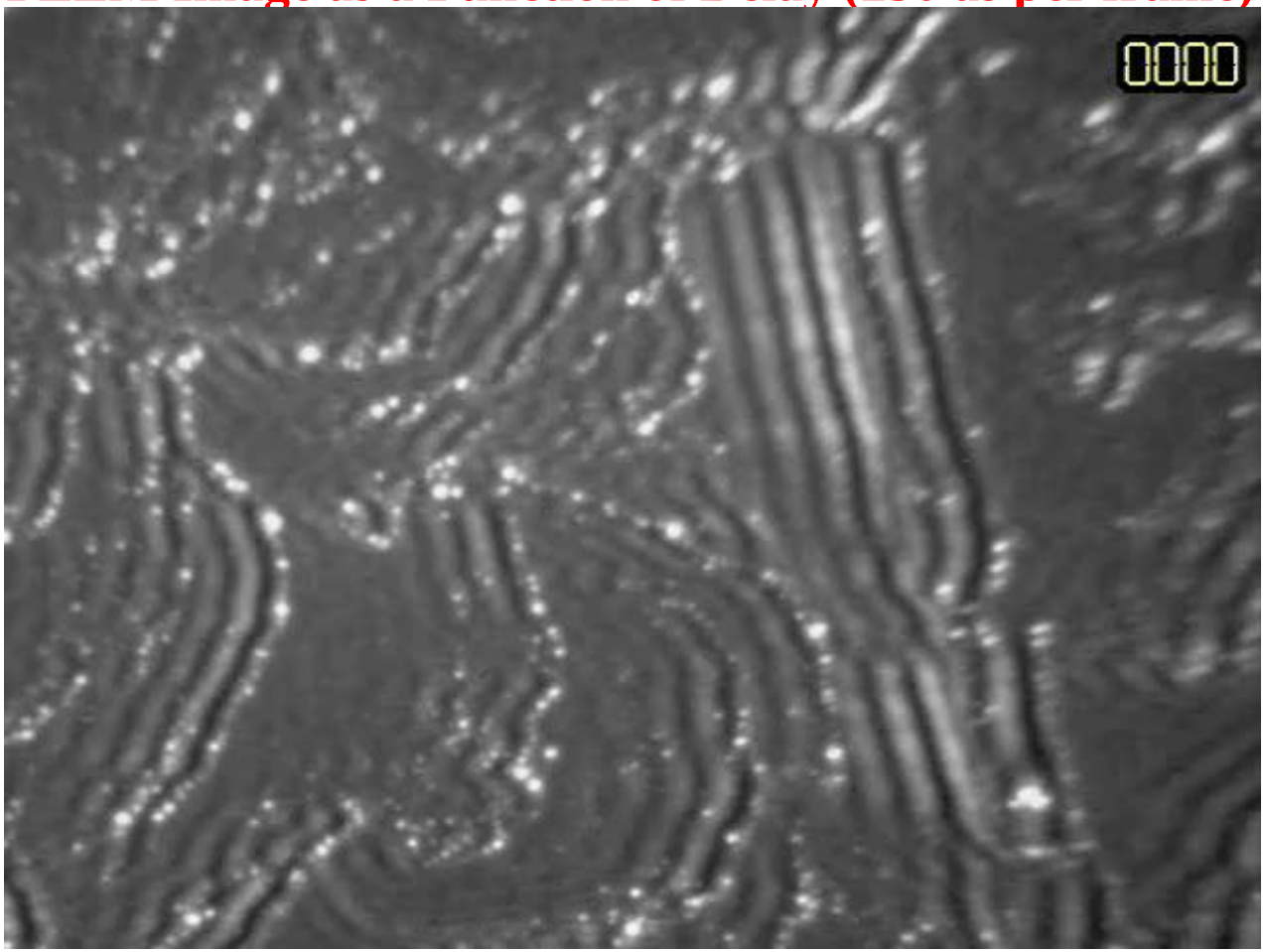
30 femtoseconds from life of a nanoplasmonic systems

Localized SP hot spots are deeply subwavelength as seen in PEEM (photoemission electron microscope)

Delay



PEEM Image as a Function of Delay (250 as per frame)



Department of Phy
Georgia State Uni
Atlanta, GA 30303

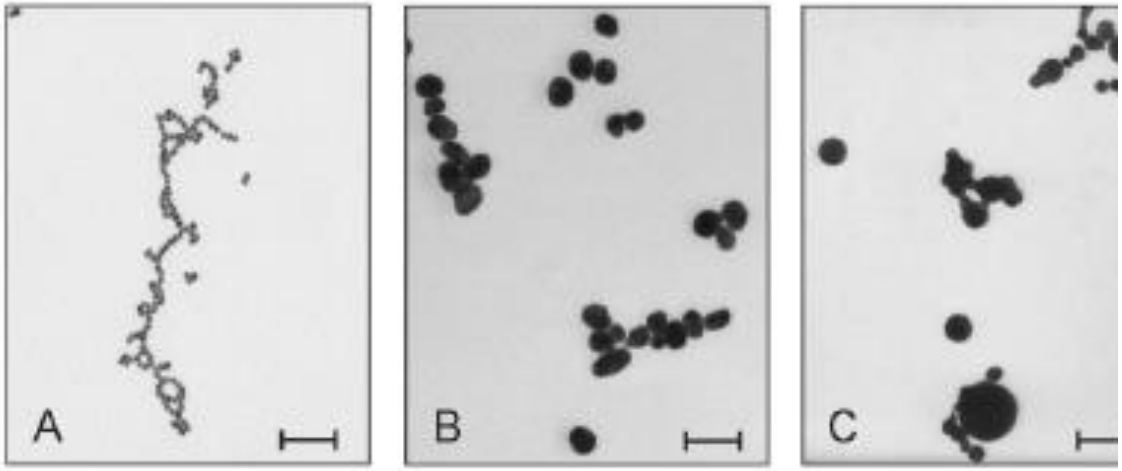
Anal. Chem. 2008, 80, 4247–4251

Correspondence

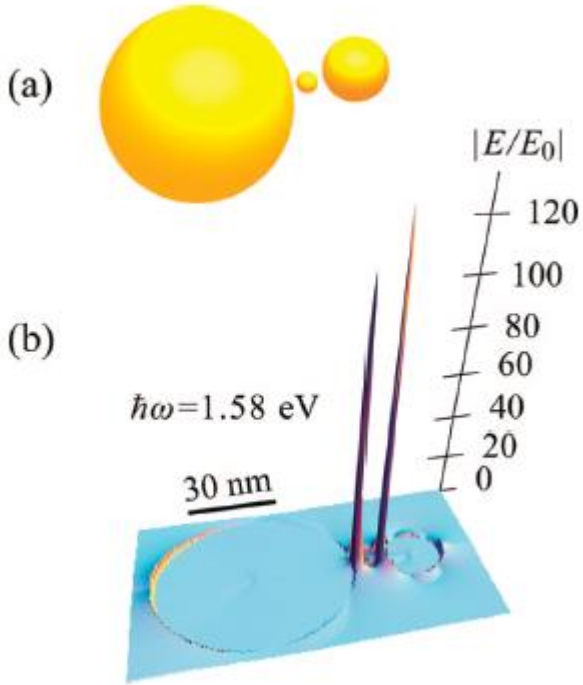
Gold Nanolenses Generated by Laser Ablation-Efficient Enhancing Structure for Surface Enhanced Raman Scattering Analytics and Sensing

Janina Kneipp,*,†,‡ Xiangting Li,§ Margaret Sherwood,† Ulrich Panne,‡ Harald Kneipp,† Mark I. Stockman,§ and Katrin Kneipp†,||

Different types of aggregates of gold nanospheres



Scale bar: 100 nm



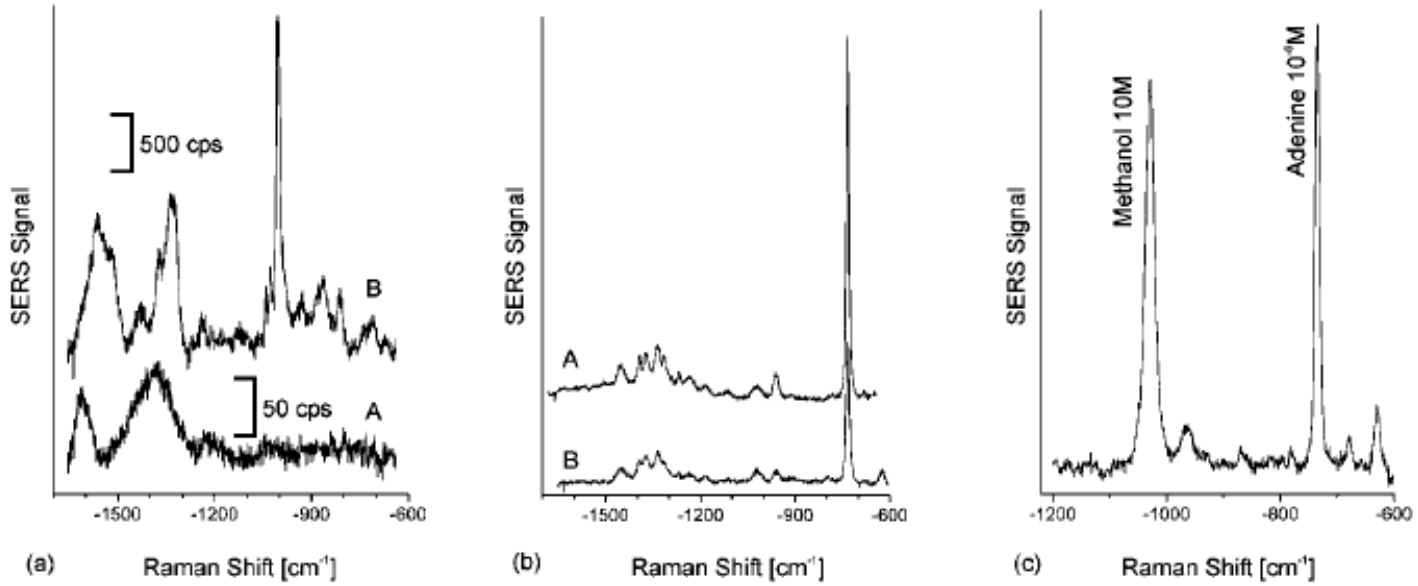


Figure 3. Comparison of SERS using gold nanolenses made by ablation and chemically prepared nanoaggregates as enhancing nanostructures. (a) Raman spectra measured from aqueous solutions of gold nanoaggregates without any analyte to compare background signals. The chemically prepared gold nanoparticles (spectrum B) display surface enhanced Raman lines, resulting from impurities introduced during the preparation process of this particular batch of colloids, such as the line at ~1000 cm^{-1}. The bands around 1500 cm^{-1} in the spectrum of the ablation nanoaggregates can be assigned to carbonate complexes.[18] Spectra were measured at 50 mW at 785 nm excitation in 10 s (spectrum A) and 1 s (spectrum B) collection times. Abbreviation: cps, counts per second. (b) SERS signals of adenine measured in solutions of ablation aggregates (spectrum A) and chemically prepared nanoaggregates (spectrum B) using 10 mW at 785 nm excitation. (c) Comparison of the Raman signal of 10^{-8} M adenine and 10 M methanol measured in aqueous solutions of nanoaggregates.

Self-Similar Gold-Nanoparticle Antennas for a Cascaded Enhancement of the Optical Field

Christiane Höppener,[1,2] Zachary J. Lapin,[1] Palash Bharadwaj,[1] and Lukas Novotny[1,*]
[1]*Institute of Optics, University of Rochester, Rochester, New York 14627, USA*
[2]*Institute of Physics, University of Münster, 48149 Münster, Germany*

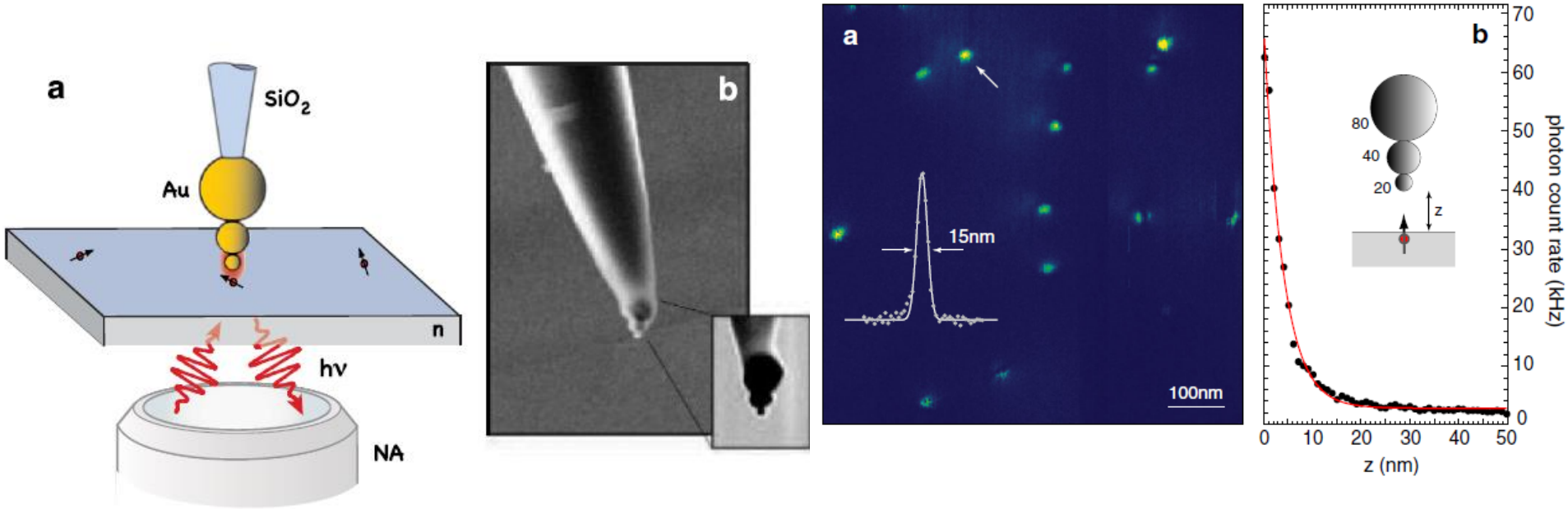


FIG. 4 (color online). Excitation of single-molecule fluorescence with a trimer antenna consisting of 80, 40, and 20 nm gold nanoparticles. (a) Fluorescence image of the single-molecule sample. Inset: Line cut through the single fluorescence spot marked by the arrow. (b) Fluorescence from a single z-oriented molecule recorded as a function of distance from a trimer antenna. The steep rise of fluorescence counts for separations smaller than 15 nm is due to strong field localization along the z axis at the apex of the trimer antenna.

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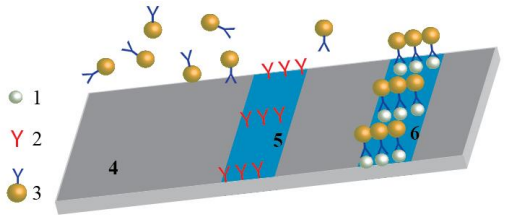
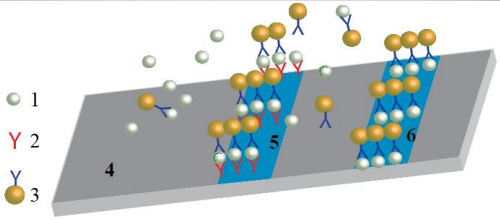
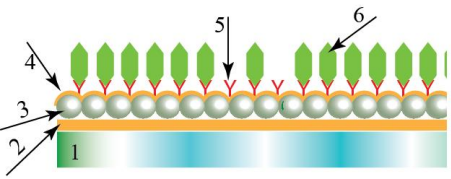
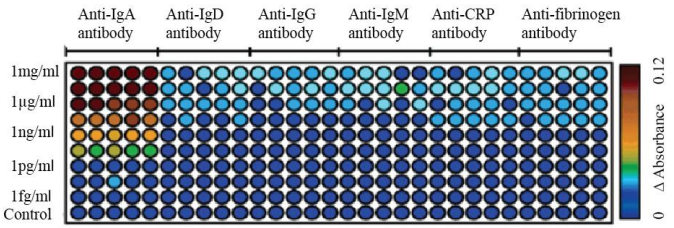
Sensing and Detection with Localized Surface Plasmons

Immunochromatographic assay with immunotargeted gold nanosphere suspension. Detection of: hCG (human chorionic gonadotropin) -- Home pregnancy test; PSA (prostate-specific antigen) -- Prostate cancer ; troponin – heart attack test; HIV/AIDS (trials)

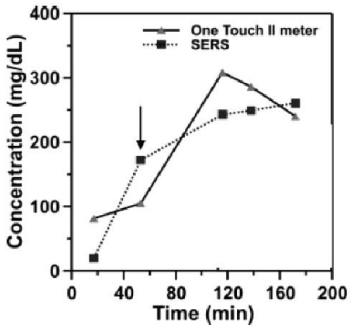


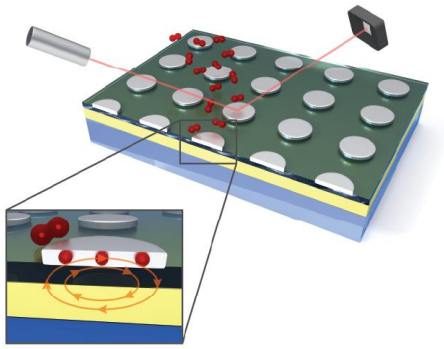






Immunoassay with immobilized immunotargeted gold nanospheres. T. Endo et al., *Multiple Label-Free Detection of Antigen-Antibody Reaction Using Localized Surface Plasmon* ... Anal. Chem. **78**, 6465-6475 (2006)





Left: Glucose in vivo monitoring using SERS from immobilized functionalized gold nanospheres. J. N. Anker, et al., *Biosensing with Plasmonic Nanosensors*, Nat. Mater. **7**, 442-453 (2008).
Right: Palladium-nanocylinder hydrogen sensor for hydrogen energy applications. H. Giessen at al.

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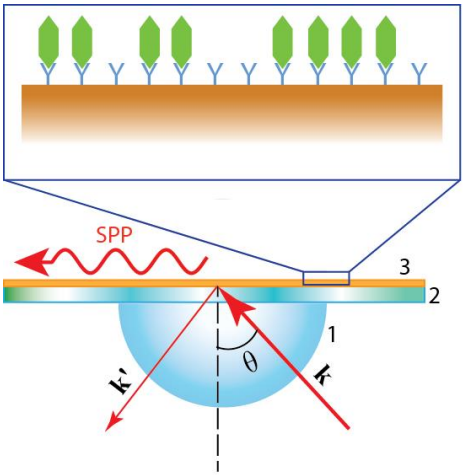
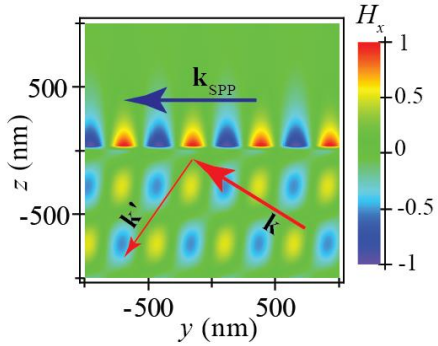
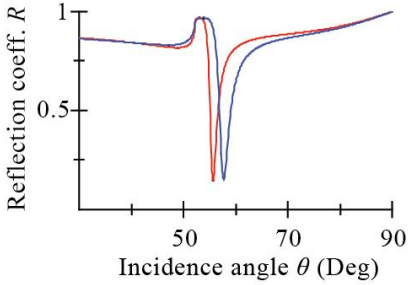
Georgia State University
Atlanta, GA 30303-3083

Surface Plasmon Polariton Sensors

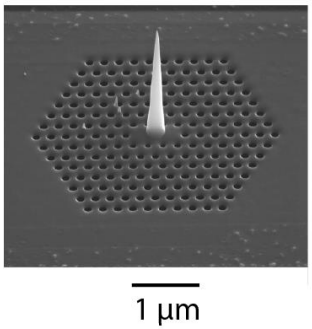


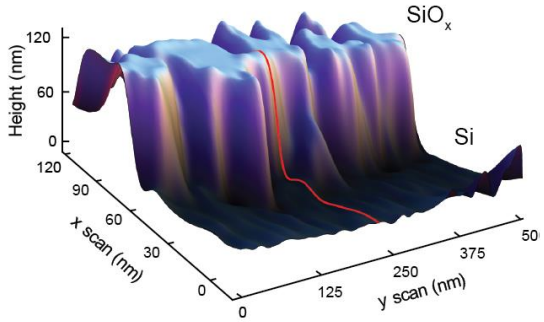


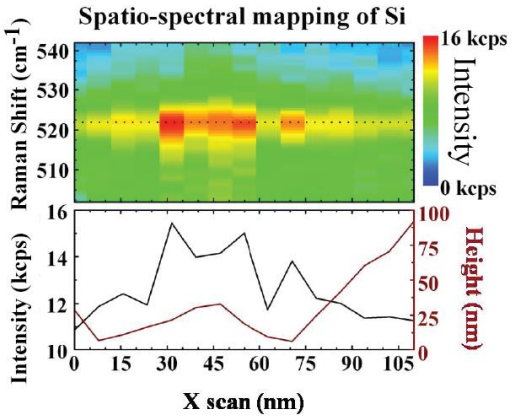


Surface plasmon polariton sensor based on Kretschmann geometry. Sensitivity~ 10^3 - 10^4 large molecules. See, e.g., http://www.biacore.com/

GE Healthcare







Surface plasmon polariton SERS sensor and NSOM based on adiabatic concentration. Sensitivity~100 molecules F. De Angelis et al, *Nanoscale Chemical Mapping Using Three-Dimensional Adiabatic Compression of SPPs.* Nature Nanotechnology **5,** 67-72 (2009).

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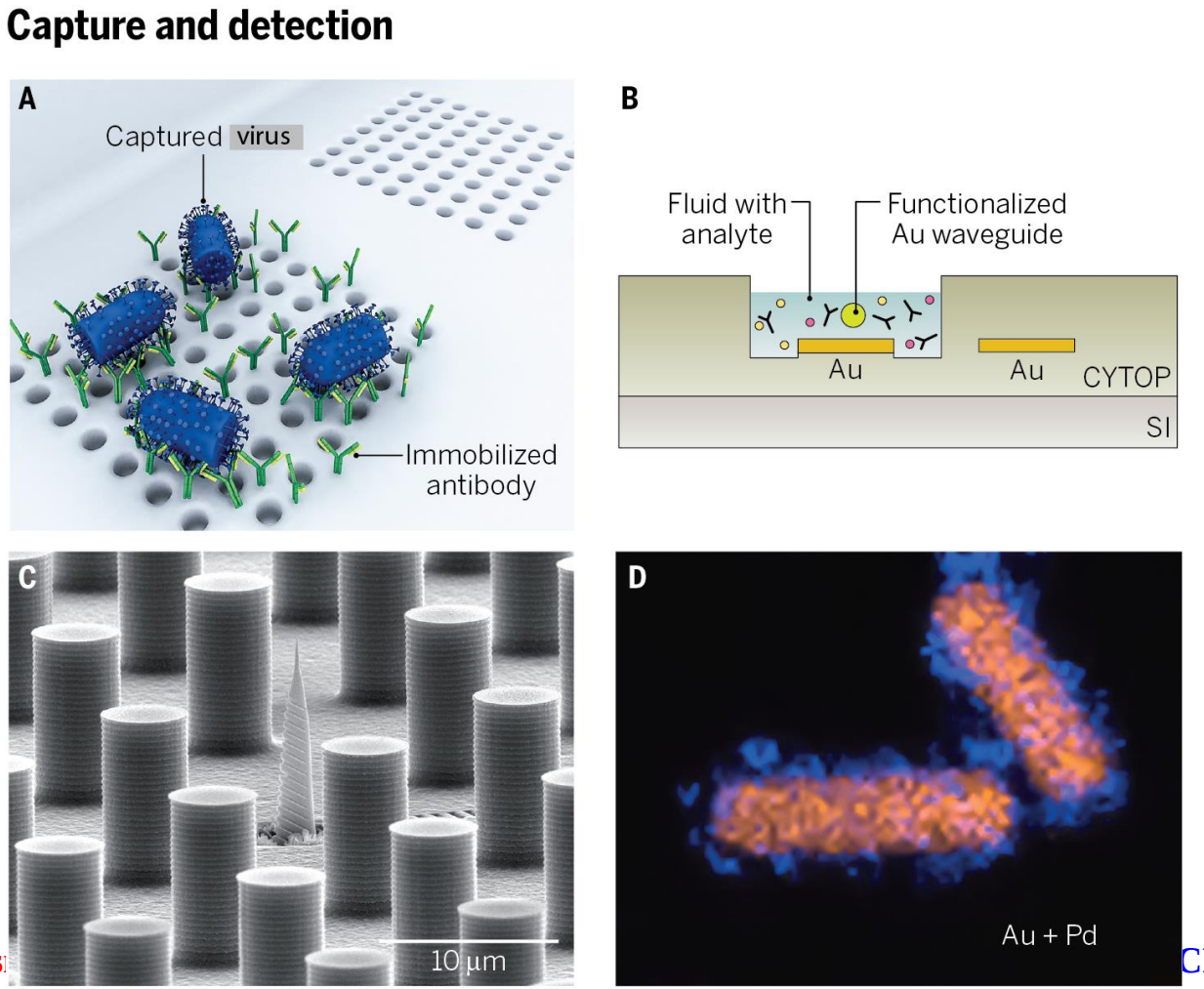
M. I. Stockman, *Nanoplasmonic Sensing and Detection*, Science **348,** 287-288 (2015).



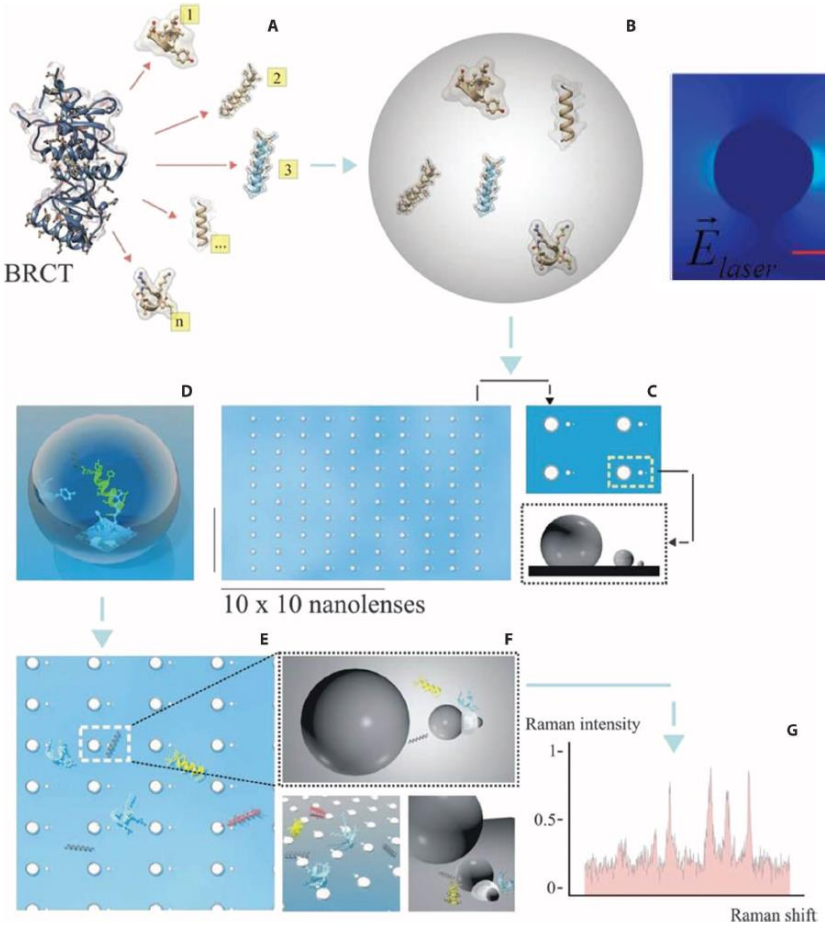
RESEARCH ARTICLE

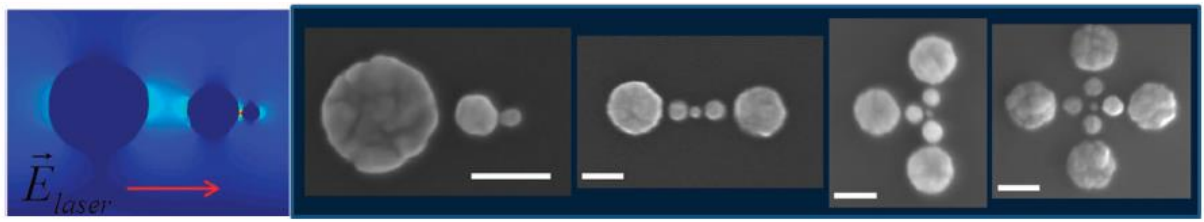
OPTICS

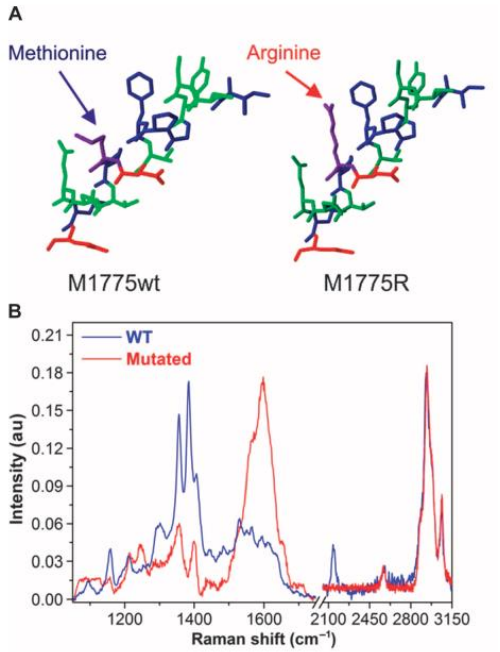
Detection of single amino acid mutation in human breast cancer by disordered plasmonic self-similar chain

10.1126/sciadv.1500487

Maria Laura Coluccio,[1] Francesco Gentile,[1,2] Gobind Das,[3] Annalisa Nicastri,[1] Angela Mena Perri,[1] Patrizio Candeloro,[1] Gerardo Perozziello,[1] Remo Proietti Zaccaria,[4] Juan Sebastian Totero Gongora,[5] Salma Alrasheed,[3] Andrea Fratalocchi,[5] Tania Limongi,[3] Giovanni Cuda,[1] Enzo Di Fabrizio[1,3]*







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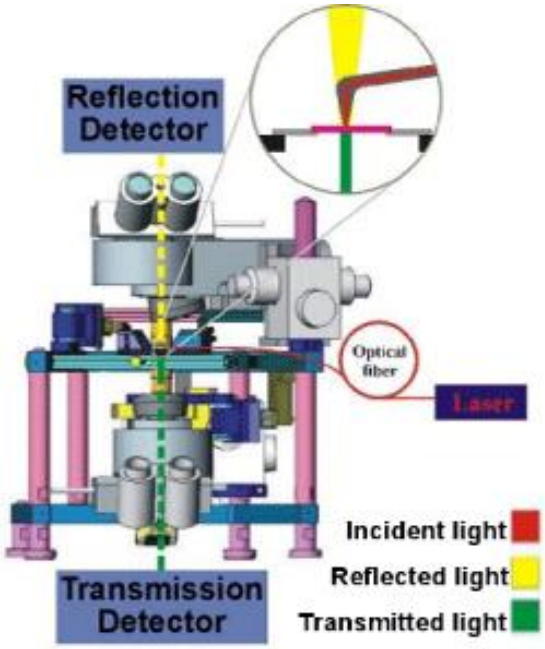
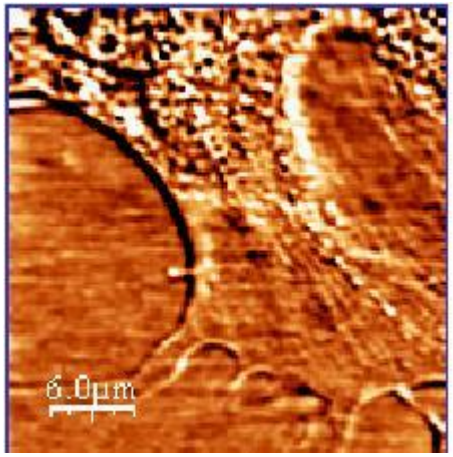
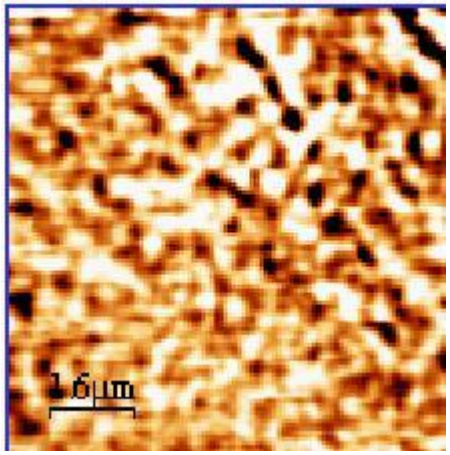
Plasmonic Nanoscopy

NANONICS IMAGING Ltd.

NSOM images of healthy human dermal fibroblasts in liquid obtained in transmission mode with a Nanonics cantilevered tip with a gold nanosphere (A. Lewis et al.)







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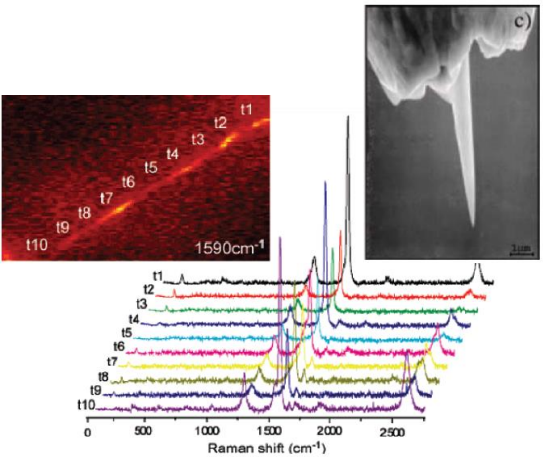
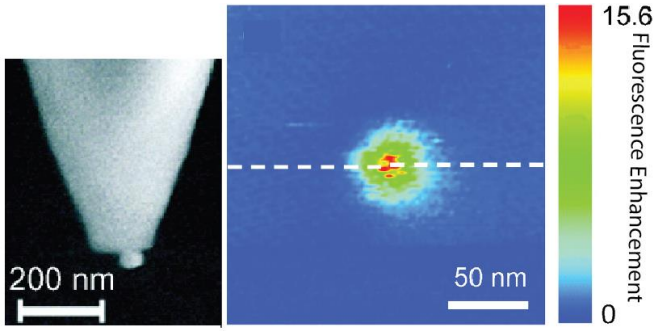
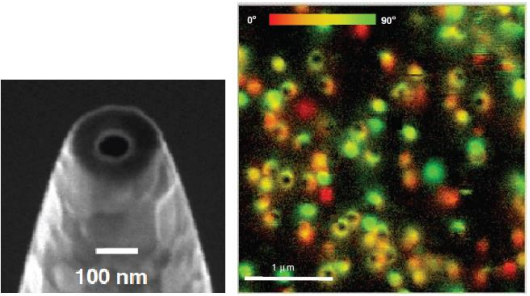
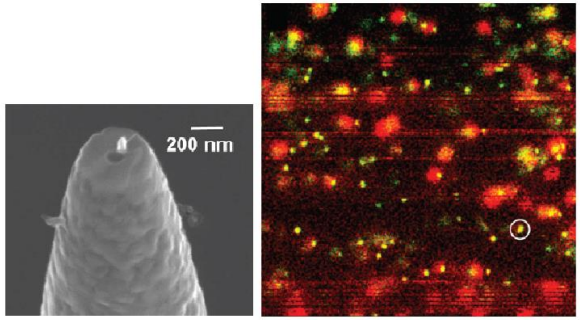
Plasmonic Nanoscopy



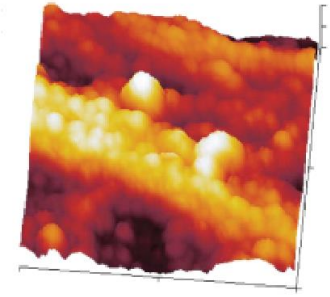


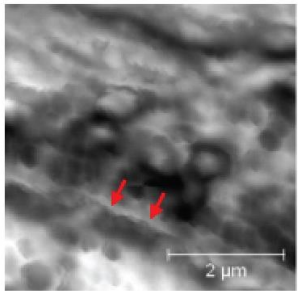
Left: Chemical vision: SERS image and spectra of a single-wall carbon nanotube obtained with a FIB-fabricated silver tip. L. Novotny and S. J. Stranick, Annual Rev. Phys. Chem. **57**, 303-331 (2006)
Right: Nanosphere probe and image of fluorescence enhancement of a single dye molecule. H. Eghlidi et al., Nano Lett. **9**, 4007-4011 (2009)

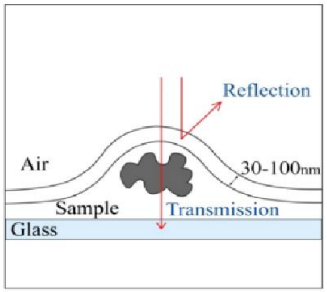




Left: Metallized tapered fiber probe and NSOM image of a single fluorescent molecules with polarization resolution.
Right: Nanoantenna-on-fiber probe and NSOM image of a single fluorescent molecules with polarization resolution. T. H. Taminiau, F. B. Segerink, R. J. Moerland, L. Kuipers, and N. F. van Hulst, Journal of Optics a-Pure and Applied Optics **9**, S315-S321 (2007)







Imaging of living cells in culture with a tapered fiber NSOM. Left: Topology, Center: NSOM image, Right: Schematic. E. Trevisan, E. Fabbretti, N. Medic, B. Troian, S. Prato, F. Vita, G. Zabucchi, and M. Zweyer, *Novel Approaches for Scanning near-Field Optical Microscopy Imaging of Oligodendrocytes in Culture*, Neuroimage **49**, 517-524 (2010)

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Dawn of the new bold era: seminal first paper on laser (originally "optical maser" then laser)

letters to nature

Nature 187, 493 - 494 (06 August 1960); doi:10.1038/187493a0

Stimulated Optical Radiation in Ruby

T. H. MAIMAN

Hughes Research Laboratories, A Division of Hughes Aircraft Co., Malibu, California.

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å. ; the active material used was ruby (chromium in corundum).

1. Schawlow, A. L. , and Townes, C. H. , *Phys. Rev.*, **112**, 1940 (1958). | Article | ISI | ChemPort |
2. Javan, A. , *Phys. Rev. Letters*, **3**, 87 (1959). | Article | ISI |
3. Sanders, J. H. , *Phys. Rev. Letters*, **3**, 86 (1959). | Article | ISI | ChemPort |
4. Maiman, T. H. , *Phys. Rev. Letters*, **4**, 564 (1960). | Article | ISI |

VOLUME 90, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2003

Surface Plasmon Amplification by Stimulated Emission of Radiation: Quantum Generation of Coherent Surface Plasmons in Nanosystems

David J. Bergman[1,*] and Mark I. Stockman[2,†]

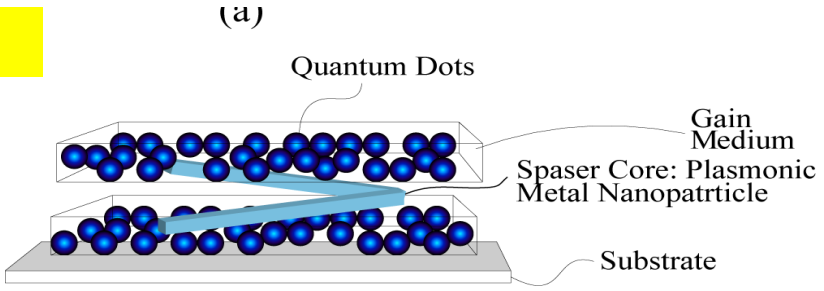
[1]*School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, 69978, Israel*

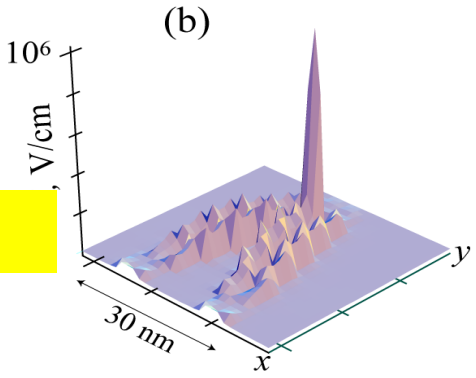
[2]*Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia 30303*

(Received 15 September 2002; published 14 January 2003)

We make a step towards quantum nanoplasmonics: surface plasmon fields of a nanosystem are quantized and their stimulated emission is considered. We introduce a quantum generator for surface plasmon quanta and consider the phenomenon of surface plasmon amplification by stimulated emission of radiation (spaser). Spaser generates temporally coherent high-intensity fields of selected surface plasmon modes that can be strongly localized on the nanoscale, including dark modes that do not couple to far-zone electromagnetic fields. Applications and related phenomena are discussed.

The original spaser proposal





Spaser field per one plasmon in the core

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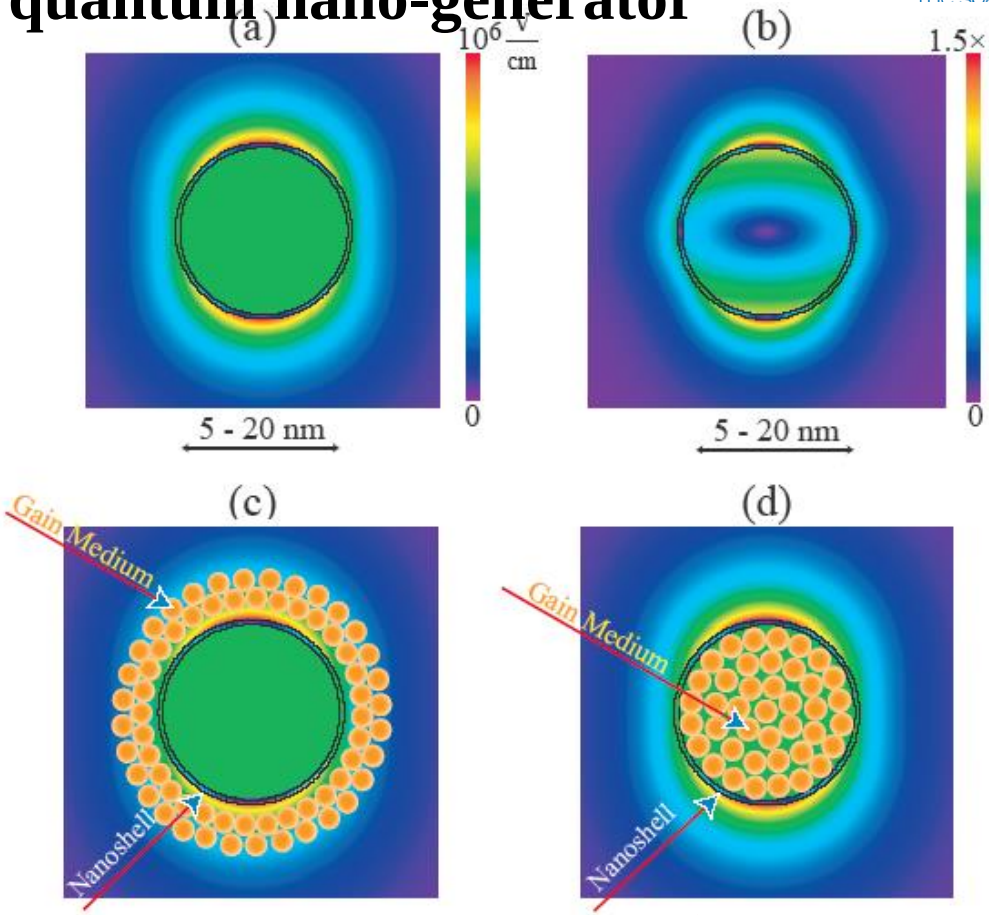
Spasers explained

nature photonics | VOL 2 | JUNE 2008 |

MARK I. STOCKMAN
is in the Department of Physics and
e-mail: mstockman@gsu.edu

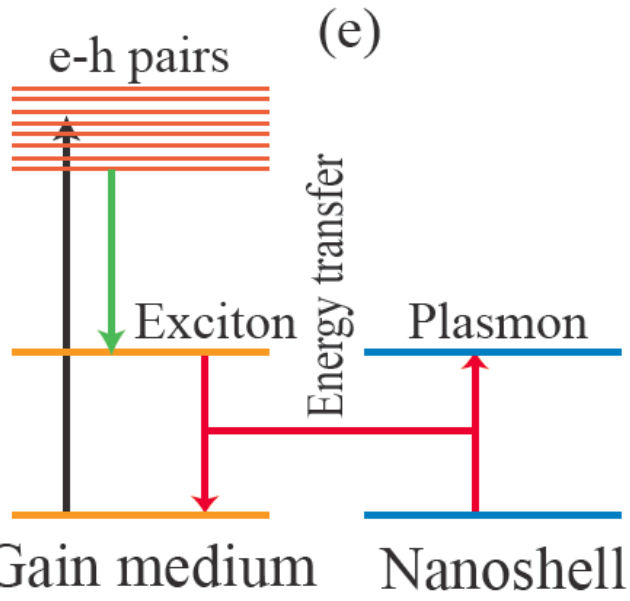
The spaser is a propos ling labo cluding e of

Spaser is the ultimately smallest quantum nano-generator



For small nanoparticles, radiative loss is negligible.

Spaser is fully scalable



D. J. Bergman and M. I. Stockman, *Surface Plasmon Amplification by Stimulated Emission of Radiation: Quantum Generation of Coherent Surface Plasmons in Nanosystems*, Phys. Rev. Lett. **90**, 027402-1-4 (2003).

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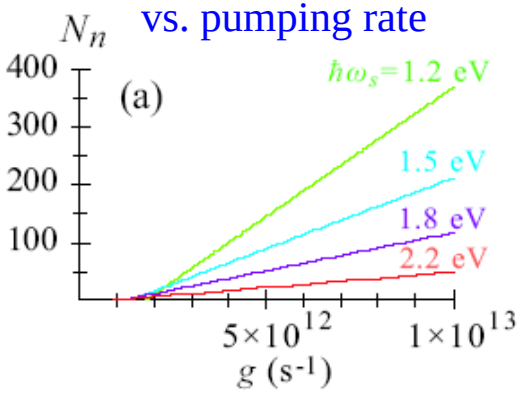
Stationary (CW) spaser regime

This quasilinear dependence of the number of plasmons per mode $N_n(g)$ is a result of the very strong feedback in spaser due to the small modal volume

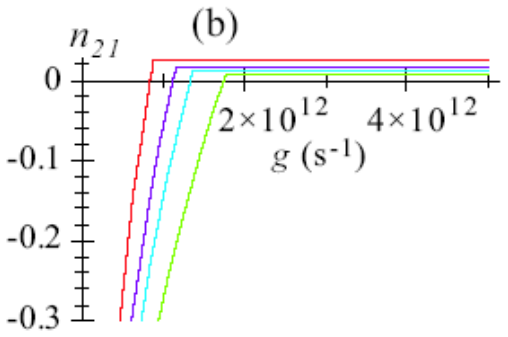
$$\Gamma_s \propto g^{-1}$$

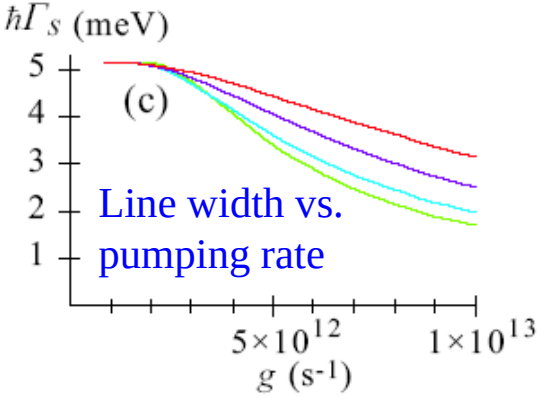
arXiv:0908.3559
Journal of Optics, **12**, 024004-1-13 (2010).

Plasmon number vs. pumping rate



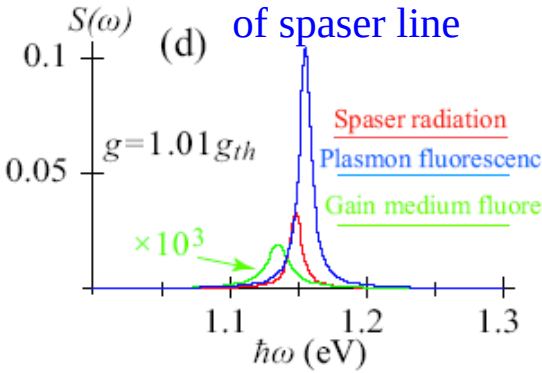
Inversion vs. pumping rate



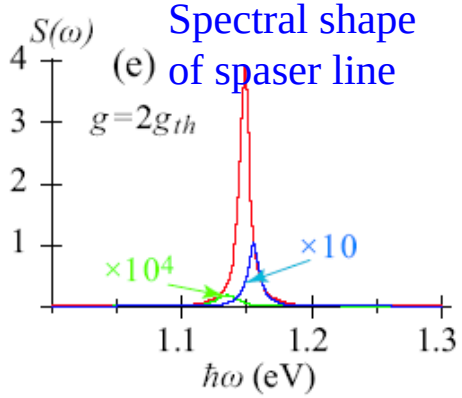


Line width vs. pumping rate

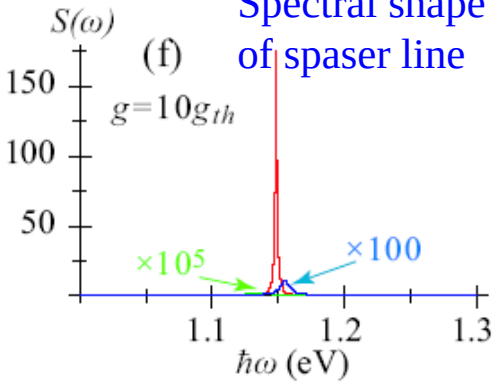
Spectral shape of spaser line



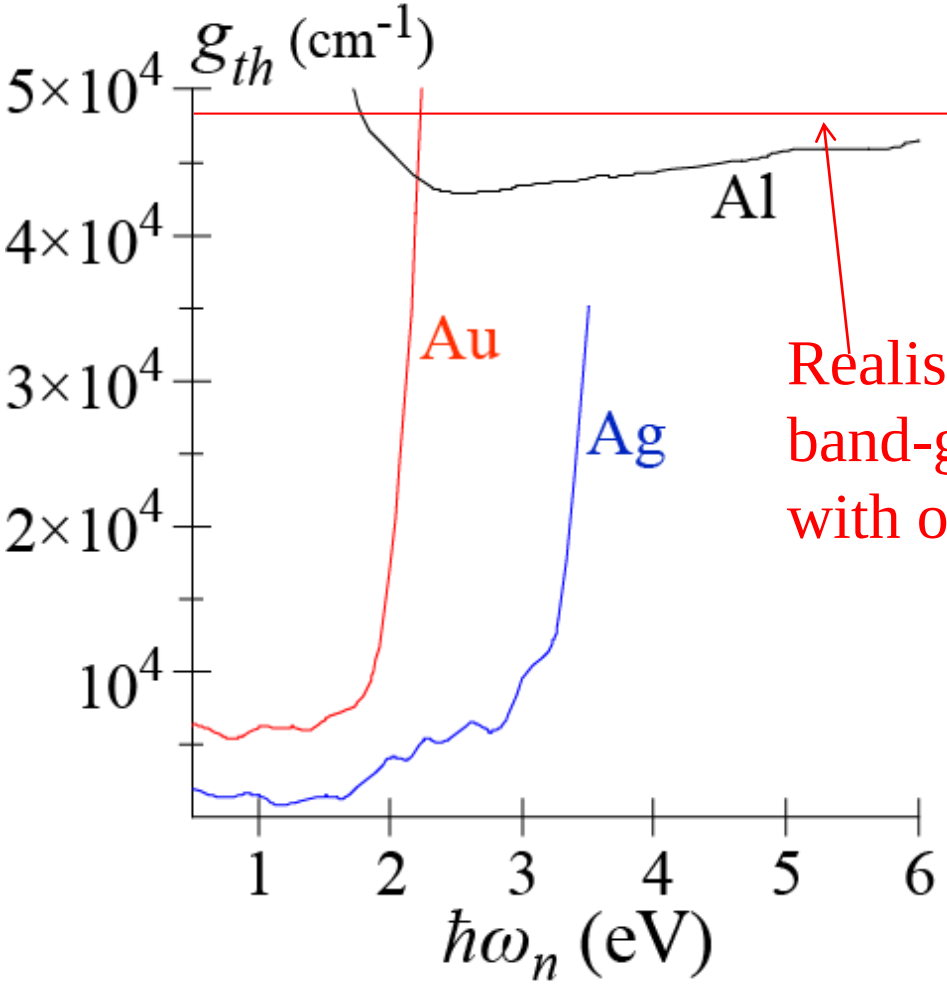
Spectral shape of spaser line



Spectral shape of spaser line



Gain of bulk medium required for spasing and for loss compensation by gain: M. I. Stockman, *Spaser Action, Loss Compensation, and Stability in Plasmonic Systems with Gain*, Phys. Rev. Lett. **106**, 156802-1-4 (2011); Phil. Trans. R. Soc. A **369**, 3510 (2011).



$$g \geq g_{th},\ g_{th} = \frac{\omega}{c\sqrt{\varepsilon_d}} \frac{\mathrm{Re}\, s(\omega)\, \mathrm{Im}\, \varepsilon_m(\omega)}{1 - \mathrm{Re}\, s(\omega)}$$

$$s(\omega) = \frac{\varepsilon_d}{\varepsilon_d - \varepsilon_m(\omega)};\quad 1 > \mathrm{Re}\, s(\omega) > 0$$

Realistic gain for direct band-gap semiconductors with optical pumpimg

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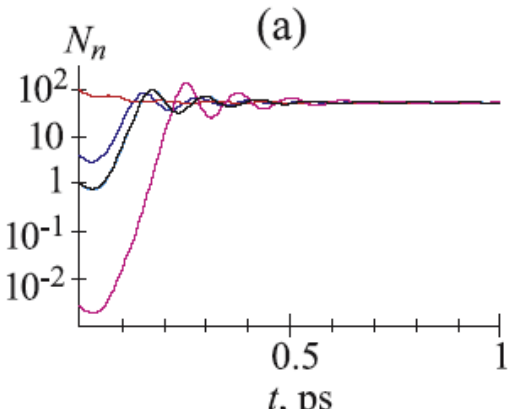
Georgia State University
Atlanta, GA 30303-3083

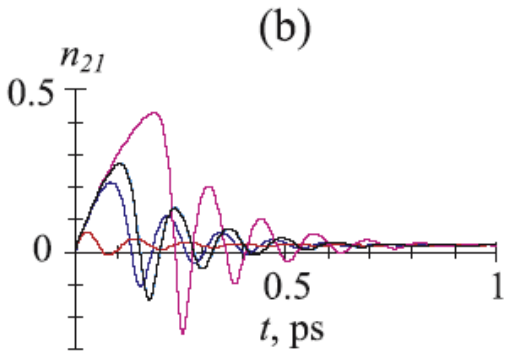
Amplification in Spaser without a Saturable Absorber

Stationary pumping

SP coherent population

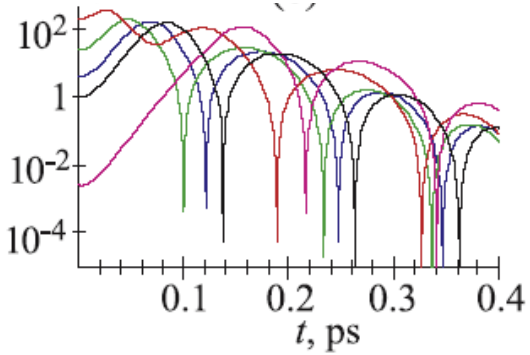


Population inversion

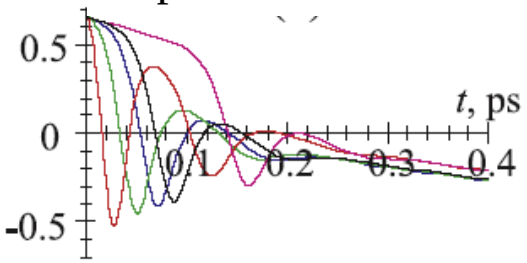


Pulse pumping

SP coherent population



n Population inversion



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Georgia State Unive
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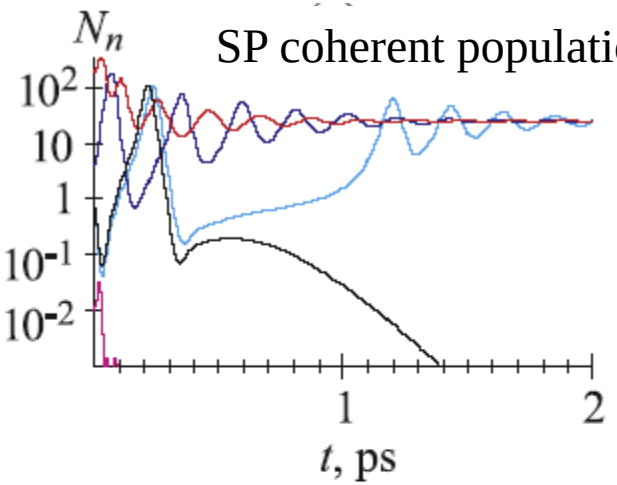
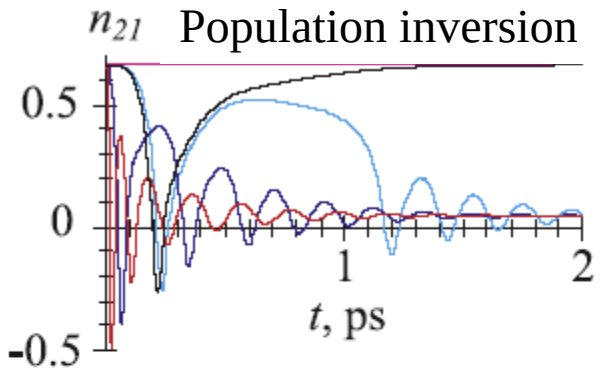
Bandwidth ~ 10-100 THz

Very high resistance to ionizing radiation

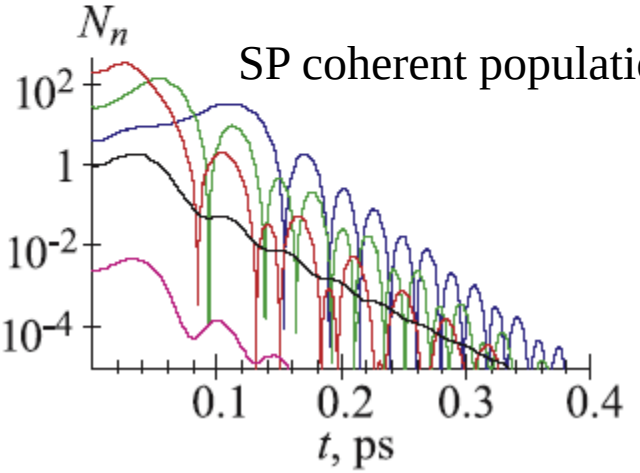
Amplification in Spaser with a Saturable Absorber (1/3 of the gain chromophores)

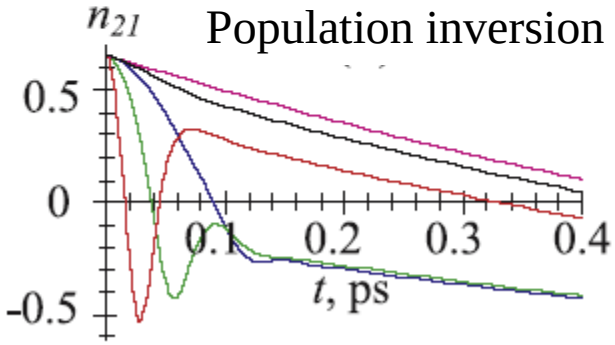
Stationary pumping





Pulse pumping





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Experimental Observations of Spaser

doi:10.1038/nature08318 nature

LETTERS

Demonstration of a spaser-based nanolaser

M. A. Noginov[1], G. Zhu[1], A. M. Belgrave[1], R. Bakker[2], V. M. Shalaev[2], E. E. Narimanov[2], S. Stout[1,3], E. Herz[3], T. Suteewong[3] & U. Wiesner[3]

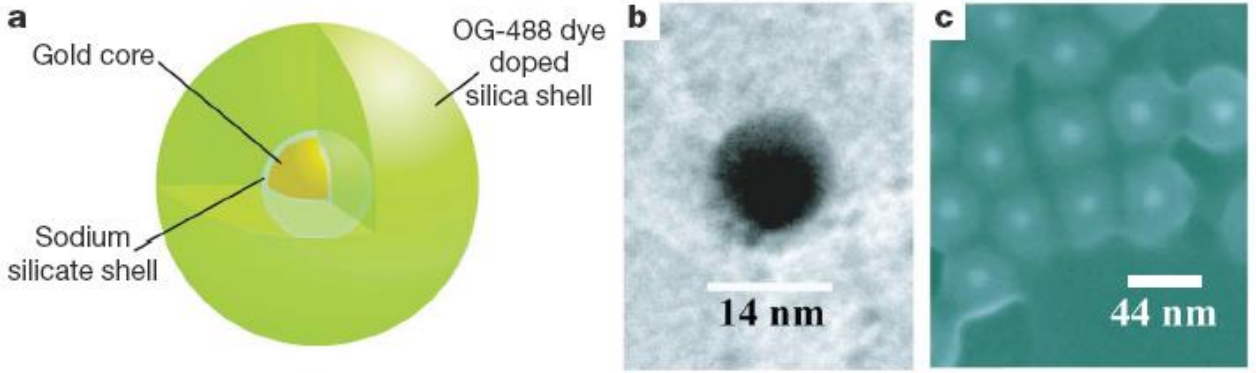

Figure 1 | Spaser design. **a**, Diagram of the hybrid nanoparticle architecture (not to scale), indicating dye molecules throughout the silica shell. **b**, Transmission electron microscope image of Au core. **c**, Scanning electron microscope image of Au/silica/dye core–shell nanoparticles. **d**, Spaser mode (in false colour), with $\lambda = 5$ circles represent the 14-nm strength colour scheme is sl

[1]Center for Materials Research, Norfolk State University, Norfolk, Virginia 23504, USA. [2]School of Electrical & Computer Eng University, West Lafayette, Indiana 47907, USA. [3]Materials Science and Engineering Department, Cornell University, Ithaca

Department of Physics and Astronom
Georgia State University
Atlanta, GA 30303-3083

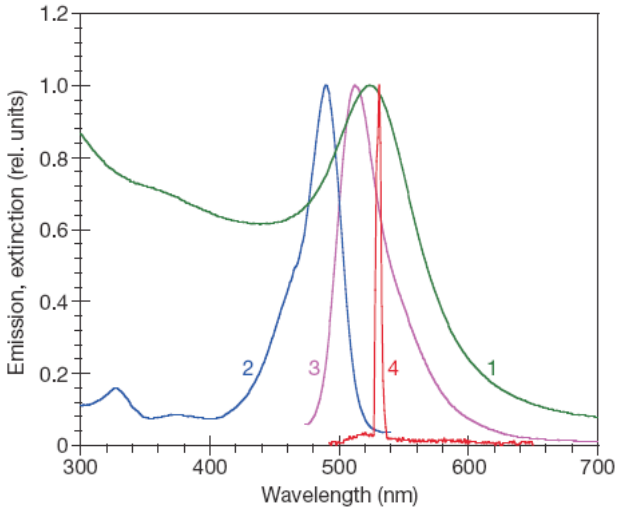

Figure 2 | Spectroscopic results. Normalized extinction (1), excitation (2), spontaneous emission (3), and stimulated emission (4) spectra of Au/silica/dye nanoparticles. The peak extinction cross-section of the nanoparticles is 1.1×10^{-12} cm^2. The emission and excitation spectra were measured in a spectrofluorometer at low fluence.

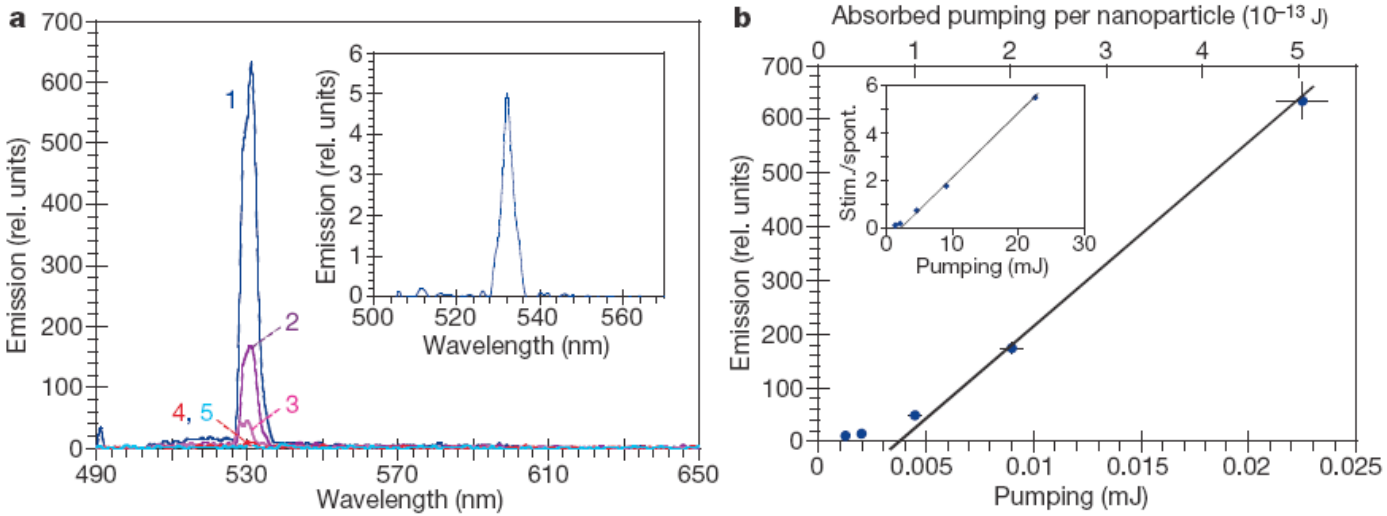

Figure 4 | Stimulated emission. **a**, Main panel, stimulated emission spectra of the nanoparticle sample pumped with 22.5 mJ (1), 9 mJ (2), 4.5 mJ (3), 2 mJ (4) and 1.25 mJ (5) 5-ns optical parametric oscillator pulses at $\lambda = 488$ nm. **b**, Main panel, corresponding input–output curve (lower axis, total launched pumping energy; upper axis, absorbed pumping energy per

by the noise of the photodetector and the instability of the pumping laser) do not exceed the size of the symbol. Inset of **a**, stimulated emission spectrum at more than 100-fold dilution of the sample. Inset of **b**, the ratio of the stimulated emission intensity (integrated between 526 nm and 537 nm) to the spontaneous emission background (integrated at <526 nm and

Lasing in metal-insulator-metal sub-wavelength plasmonic waveguides

Martin T. Hill[1*], Milan Marell[1], Eunice S. P. Leong[2], Barry Smalbrugge[1], Youcai Zhu[1], Minghua Sun[2], Peter J. van Veldhoven[1], Erik Jan Geluk[1], Fouad Karouta[1], Yok-Siang Oei[1], Richard Nötzel[1], Cun-Zheng Ning[2], and Meint K. Smit[1]

[1]COBRA Research Institute, Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, The Netherlands
[2] Department of Electrical Engineering, Arizona State University, Tempe AZ 85287, USA
**m.t.hill@ieee.org*

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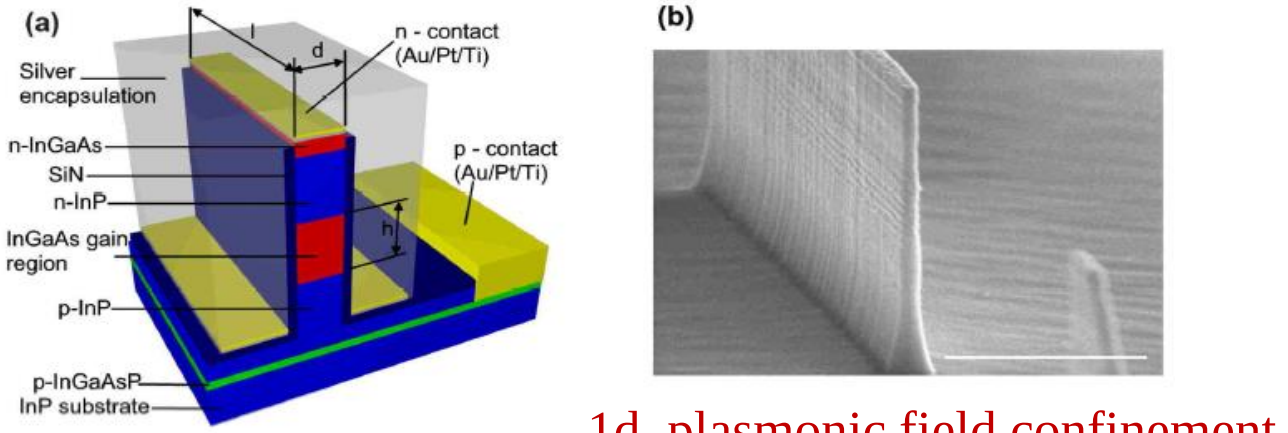

1d plasmonic field confinement

Fig. 1. Structure of cavity formed by a rectangular semiconductor pillar encapsulated in Silver. (a) Schematic showing the device layer structure. (b) Scanning electron microscope image showing the semiconductor core of one of the devices. The scale bar is 1 micron.

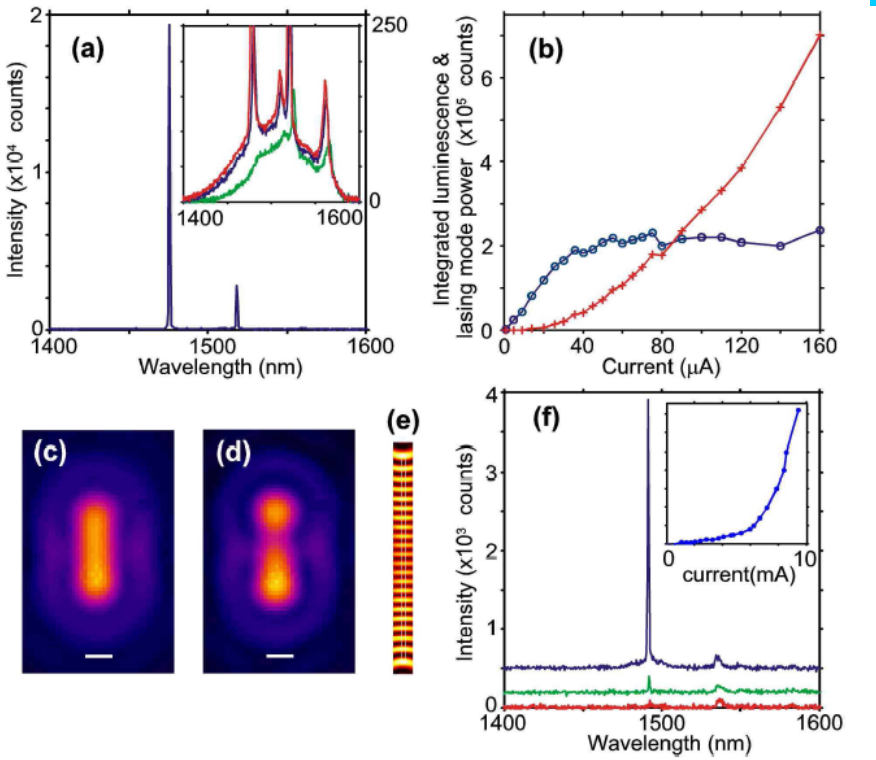

Fig. 2. Spectra and near field patterns showing lasing in devices. (a) Above threshold emission spectrum for 3 micron long device with semiconductor core width d~130nm (± 20nm), with pump current 180 μA at 78K. Inset: emission spectra for 20 (green), 40 (blue) and 60 (red) μA, all at 78K. (b) Lasing mode light output (red crosses), integrated luminescence (blue circles), versus pump current for 78K. (c) Actual near field pattern (in x-y plane) for 6 micron (d = 130nm) device captured with 100x, 0.7 NA long working distance microscope objective and infrared camera, the scale bar is 2 micron, for below threshold 30 μA, and (d) above threshold 320 μA. (e) Simulated vertical (z) component of the Poynting vector taken at 0.7 microns below the pillar base, shows most emitted light at ends of device. (f) Spectra for a 6 micron long device with d~310nm at 298K, pulsed operation (28 ns wide pulses, 1MHz repetition). Spectra for peak currents of 5.2mA (red), 5.9mA (green) and 7.4mA (blue), (currents were estimated from the applied voltage pulse amplitude). The spectra for 5.9 and 7.4 mA are offset from 0 for clarity. Inset shows the total light collected by the spectrometer from the device for currents ranging from 0 to 10mA.

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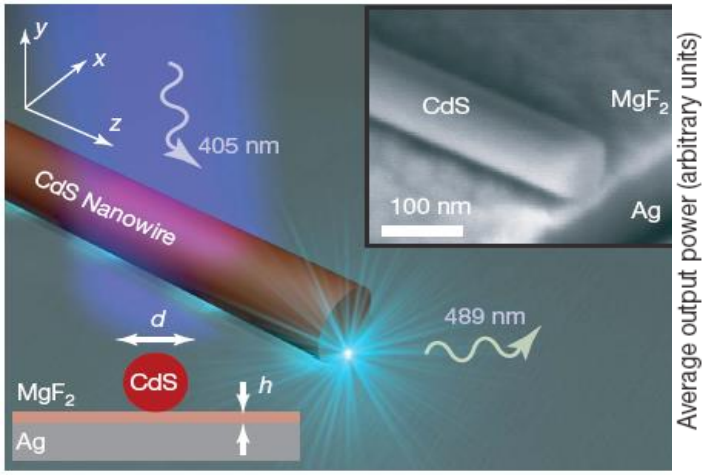
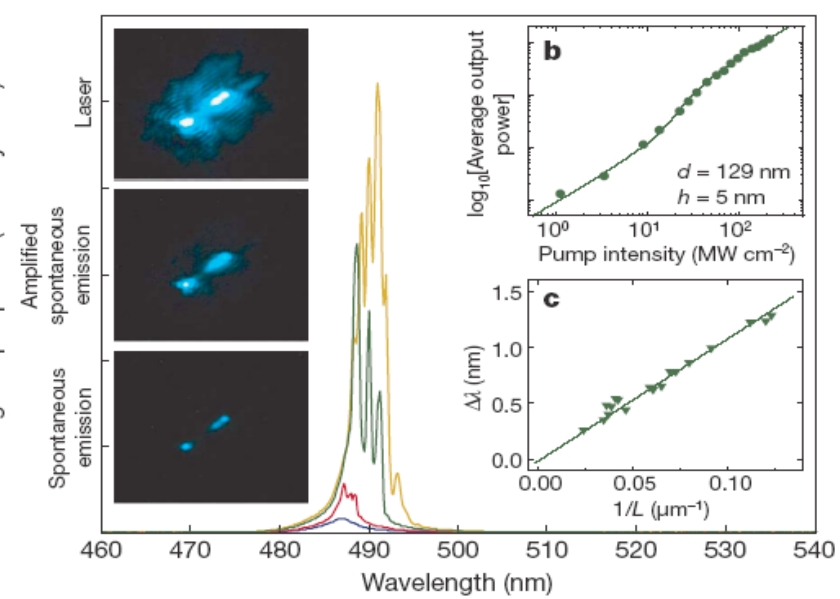
LETTERS

Plasmon lasers at deep subwavelength scale

Rupert F. Oulton[1]*, Volker J. Sorger[1]*, Thomas Zentgraf[1]*, Ren-Min Ma[3], Christopher Gladden[1], Lun Dai[3], Guy Bartal[1] & Xiang Zhang[1,2]





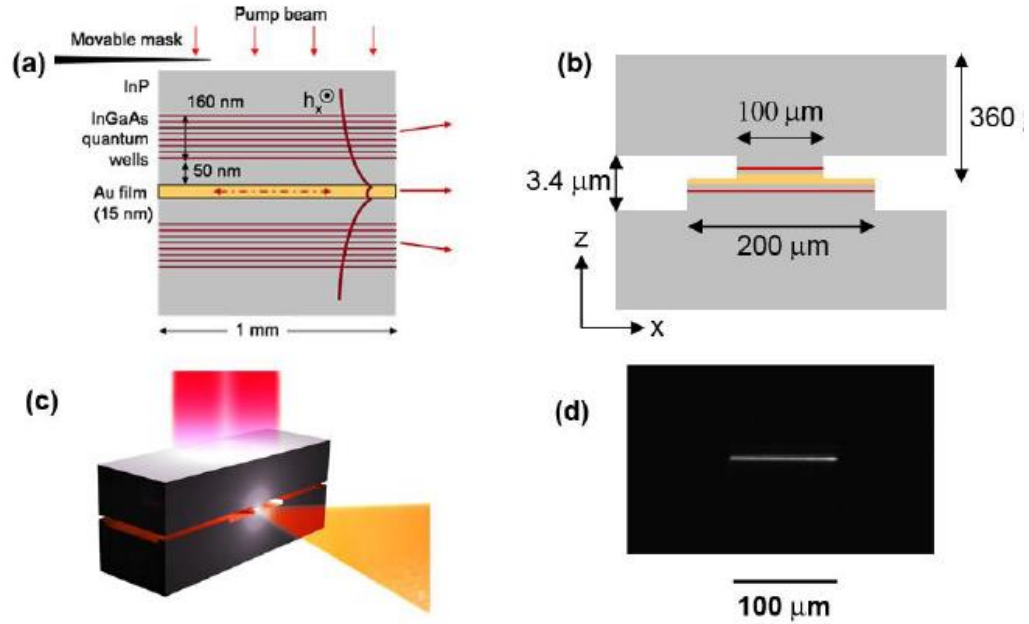
2d plasmonic field confinement

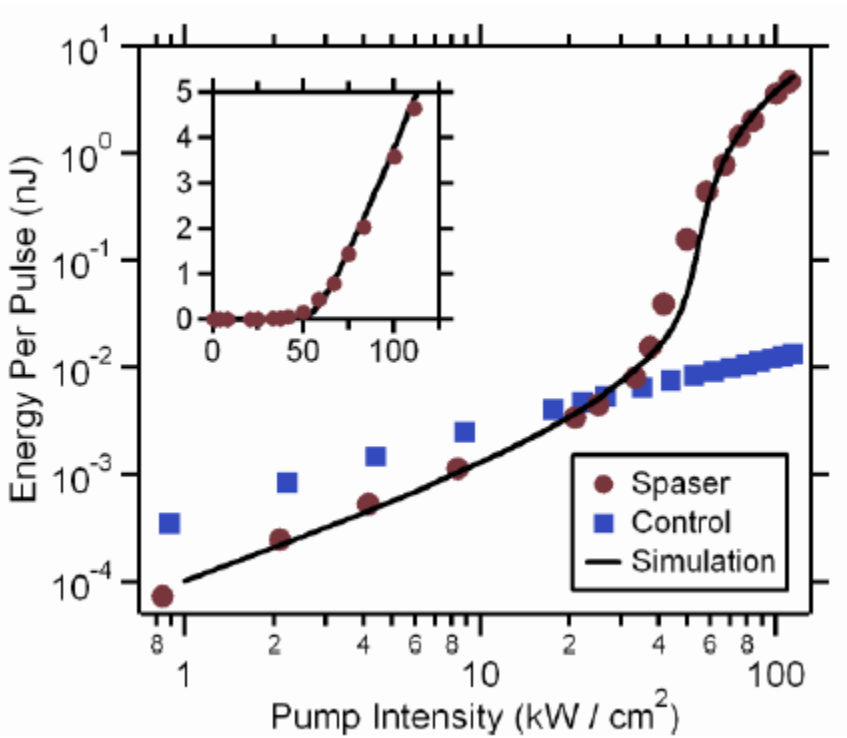
Department of Physics and Astronomy
Georgia State University
Atlanta, GA 30303-3083

A room-temperature semiconductor spaser operating near 1.5 μm

R. A. Flynn,[1] C. S. Kim,[1] I. Vurgaftman,[1] M. Kim,[1] J. R. Meyer,[1] A. J. Mäkinen,[1]
K. Bussmann,[2] L. Cheng,[3] F.-S. Choa,[3] and J. P. Long[4,*]

25 April 2011 / Vol. 19, No. 9 / OPTICS EXPRESS 8954





Department o
Georgia State
Atlanta, GA 3

Plasmonic Nanolaser Using Epitaxially Grown Silver Film

Yu-Jung Lu,[1]* Jisun Kim,[2]* Hung-Ying Chen,[1] Chihhui Wu,[2] Nima Dabidian,[2] Charlotte E. Sanders,[2] Chun-Yuan Wang,[1] Ming-Yen Lu,[3] Bo-Hong Li,[4] Xianggang Qiu,[4] Wen-Hao Chang,[5] Lih-Juann Chen,[3] Gennady Shvets,[2] Chih-Kang Shih,[2]† Shangjr Gwo[1]†

Science
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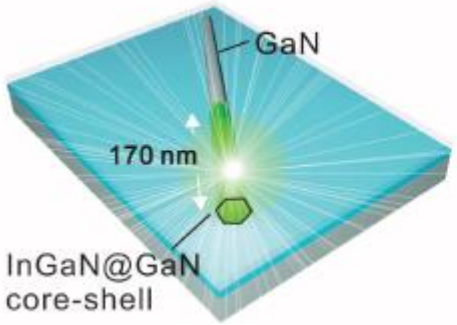
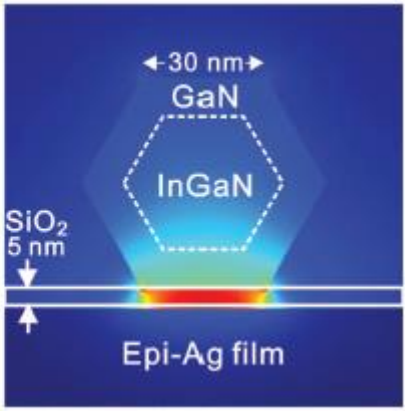
Having developed epitaxially grown, atomically smooth Ag films as a scalable plasmonic platform, we report a SPASER under CW operation with an ultralow lasing threshold at liquid nitrogen temperature and a mode volume well below the 3D diffraction limit. The device has





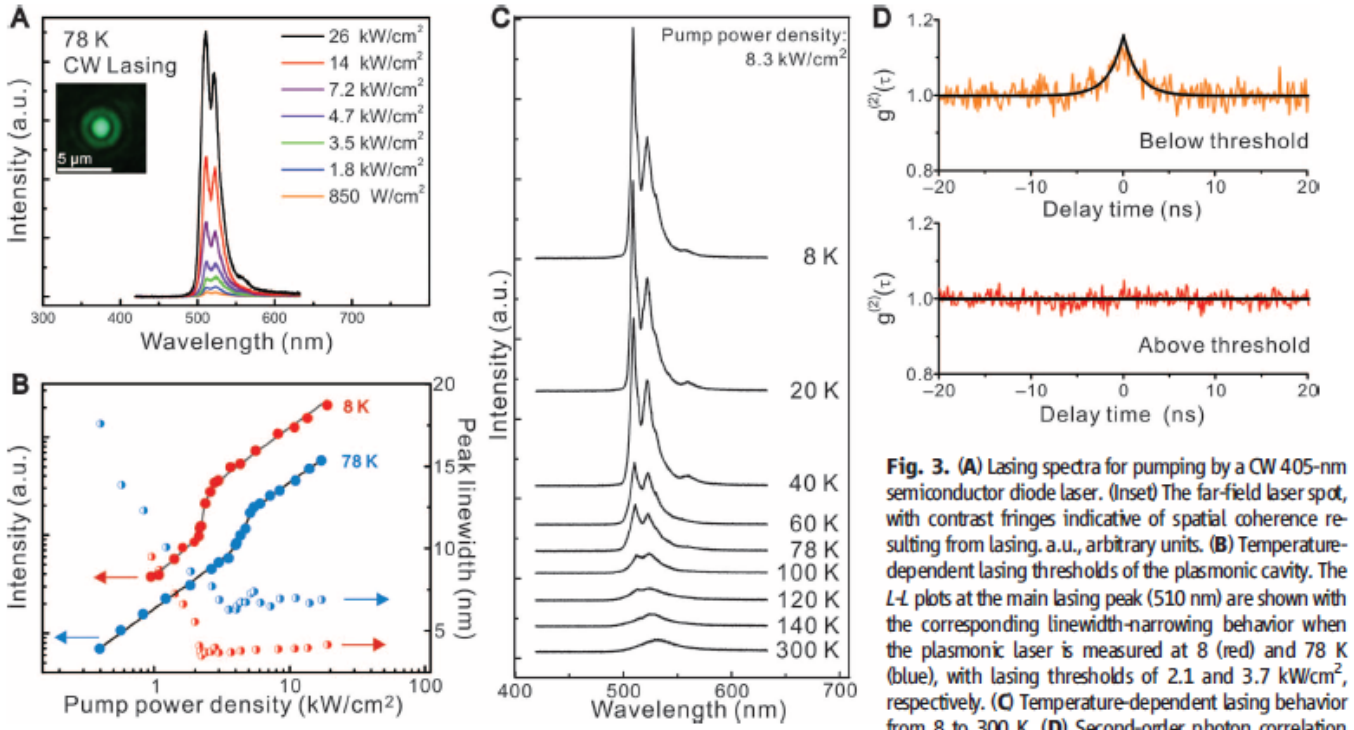


Fig. 3. (**A**) Lasing spectra for pumping by a CW 405-nm semiconductor diode laser. (Inset) The far-field laser spot, with contrast fringes indicative of spatial coherence resulting from lasing. a.u., arbitrary units. (**B**) Temperature-dependent lasing thresholds of the plasmonic cavity. The *L-L* plots at the main lasing peak (510 nm) are shown with the corresponding linewidth-narrowing behavior when the plasmonic laser is measured at 8 (red) and 78 K (blue), with lasing thresholds of 2.1 and 3.7 kW/cm^2, respectively. (**C**) Temperature-dependent lasing behavior from 8 to 300 K. (**D**) Second-order photon correlation function measurements at 8 K.

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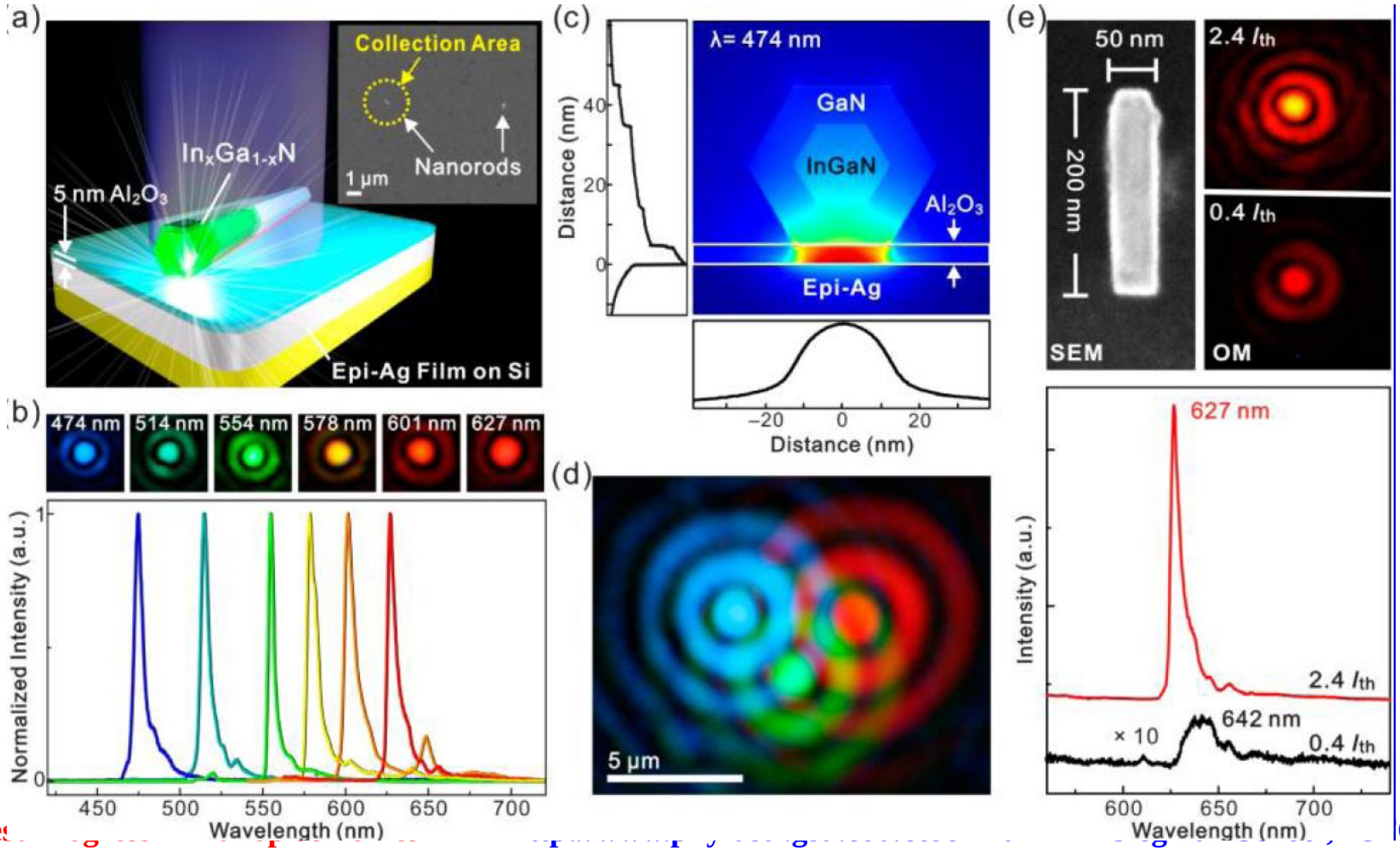
pubs.acs.org/NanoLett
Y.-J. Lu *et al.*, Nano Lett. **14**, 4381 (2014)

All-Color Plasmonic Nanolasers with Ultralow Thresholds: Autotuning Mechanism for Single-Mode Lasing

Yu-Jung Lu,[†] Chun-Yuan Wang,[†] Jisun Kim,[‡] Hung-Ying Chen,[†] Ming-Yen Lu,[∥] Yen-Chun Chen,[⊥] Wen-Hao Chang,[⊥] Lih-Juann Chen,[∥] Mark I. Stockman,[§,#,¶] Chih-Kang Shih,[*,‡] and Shangjr Gwo[*,†]



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ARTICLE

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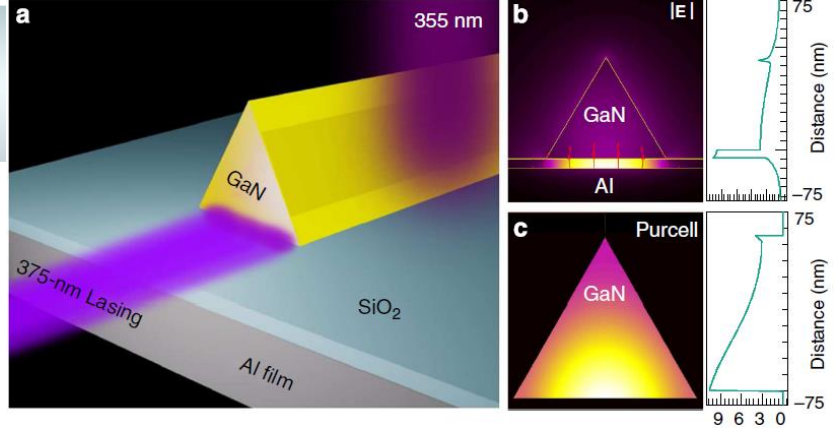
A room temperature low-threshold ultraviolet plasmonic nanolaser

Qing Zhang[1], Guangyuan Li[1], Xinfeng Liu[1], Fang Qian[2], Yat Li[3], Tze Chien Sum[1,4], Charles M. Lieber[5] & Qihua Xiong[1,6]



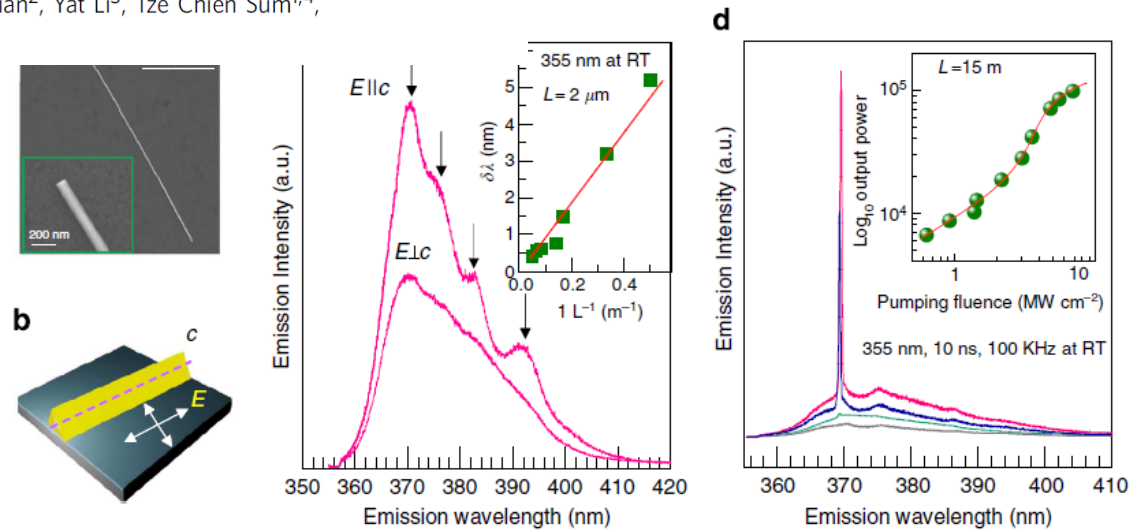


Figure 2 | Room temperature ultraviolet plasmonic lasing characterization. (**a**) Scanning electron microscopy (SEM) image of a GaN nanowire sitting on SiO_2/Al film. Inset: magnified scanning electron microscopy image of one end of the GaN nanowire. The nanowire length and diameter is 15 μm and 100 nm, respectively. (**b**) Schematic of optical measurement and polarization detection setup. *c* is defined as the orientation of nanowire. The incidence excitation laser is circular polarized and the focused laser beam can cover the whole nanowire. The emission scattered out from two ends is collected and the polarization property along and perpendicular to nanowire axis *c* is analysed. (**c**) Spontaneous emission of as-fabricated plasmonic device below lasing threshold at room temperature under a power fluence of 0.5 MW cm^{-2}. Arrows highlight the Fabry–Pérot peaks. The nanowire length is 2 μm. Inset: cavity mode spacing $\delta\lambda$ variation with nanowire length L (green dots). $\delta\lambda$ versus $1/L$ can be well fitted with a linear function (red curve), suggesting a high group index n_g ($n_g = \lambda^2/2L$) of 7.61 due to the high gain requirement of the plasmonic laser device. (**d**) Power-dependent emission spectra of the plasmonic devices. One sharp peak with a maximum full width at half maximum (FWHM) ~0.8 nm appears above the spontaneous emission background. The nanowire length is 15 μm. Inset: integrated emission versus pumping intensity. The *S*-shaped plot suggests the evolution from a spontaneous emission, amplified spontaneous emission to lasing process.

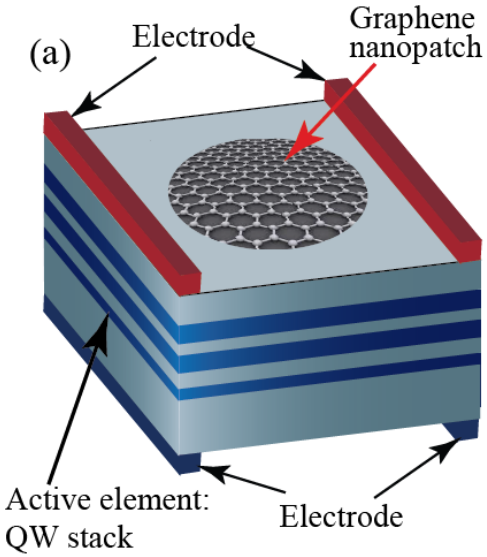
Latest Progress in N and Spa

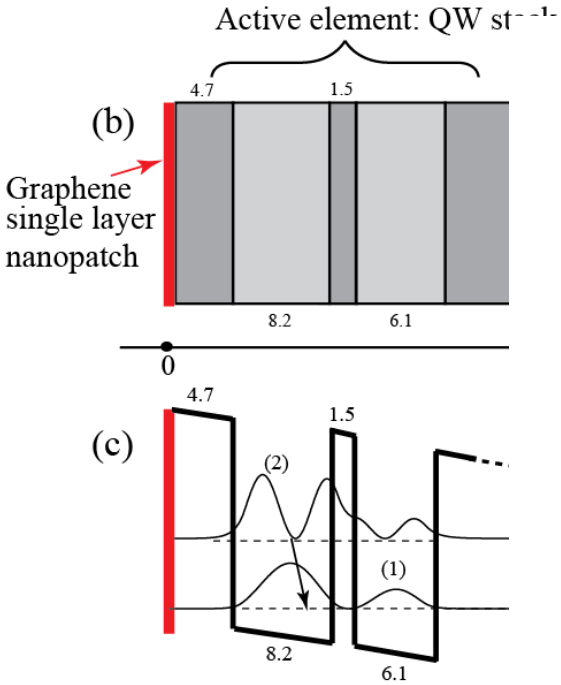
Graphene spaser

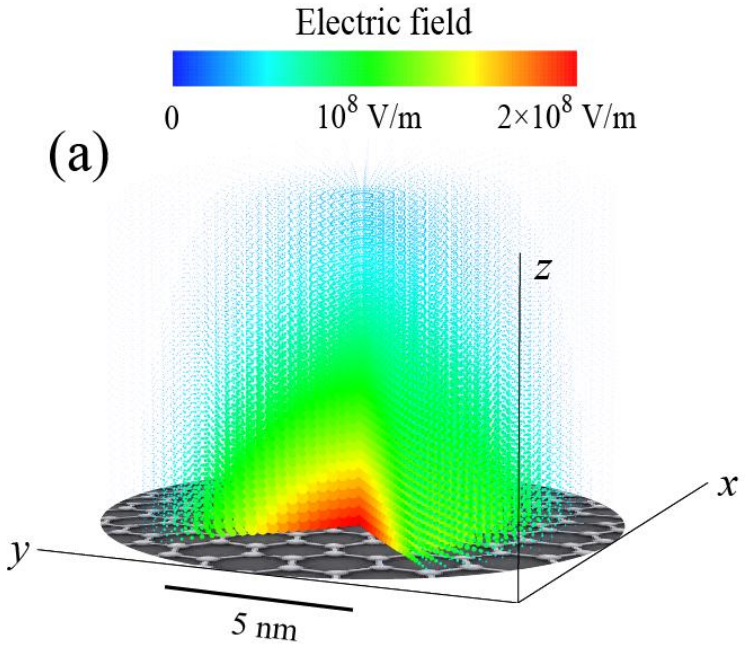
Vadym Apalkov[1] and Mark I. Stockman[1,2,3]
[1] *Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia 30303, USA*
[2] *Fakultät für Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, D-80539 München, Germany*
[3] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*
(Dated: May 10, 2013)

We propose a graphene spaser, which is a coherent quantum generator of surface plasmons in nanostructured graphene. The plasmonic core of this spaser is a graphene monolayer nanopatch and its active (gain) element is a multi-quantum well system with a design similar to the design of an active element of quantum cascade laser. For realistic parameters of the multi-quantum well system, the spasing in graphene monolayer can be achieved at a finite doping of graphene and at a plasmon frequency, ≈ 0.15 eV, close to the typical frequency of intersubband transitions in multi-quantum well systems. The proposed graphene spaser will be an efficient source of intense and coherent nanolocalized fields in the mid-infrared spectral region with wide perspective applications in mid-infrared nanoscopy, nano-spectroscopy, and nano-lithography.

V. Apalkov and M. I. Stockman, *Proposed Graphene Nanospaser,* NPG: Light Sci. Appl. **3,** e191 (2014).



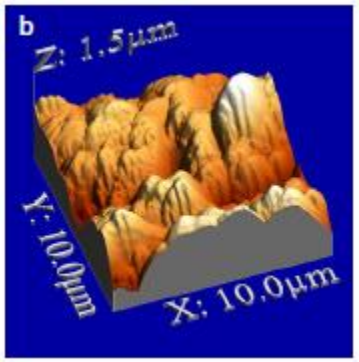




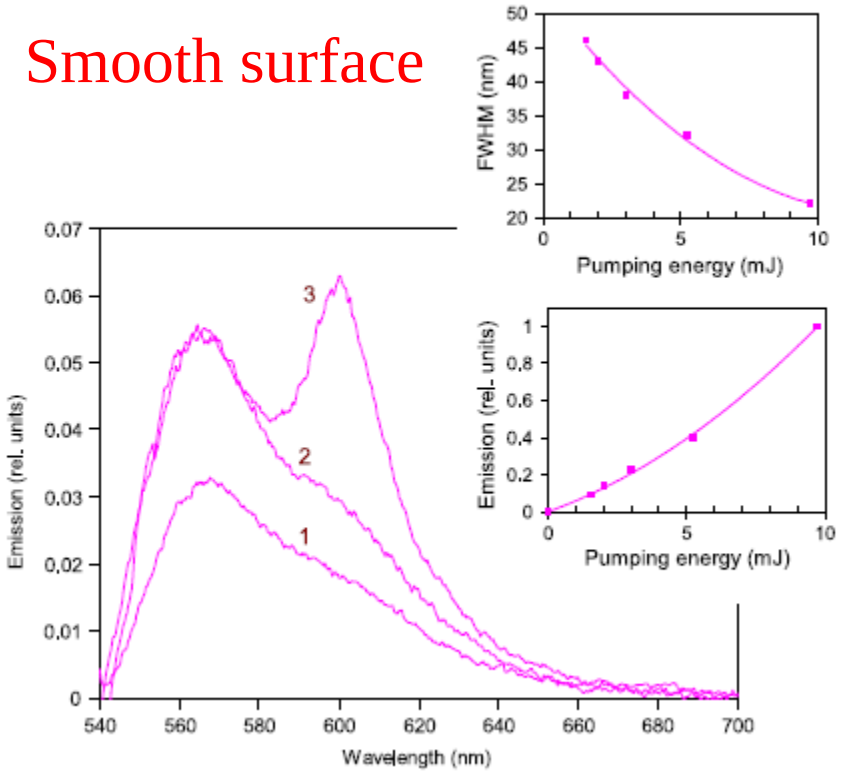
IOP PUBLISHING JOURNAL OF OPTICS
J. Opt. **14** (2012) 114015 (7pp) doi:10.1088/2040-8978/14/11/114015

Stimulated emission of surface plasmon polaritons on smooth and corrugated silver surfaces

J K Kitur, G Zhu, Yu A Barnakov and M A Noginov



Smooth surface



Random Spaser

Rough surface

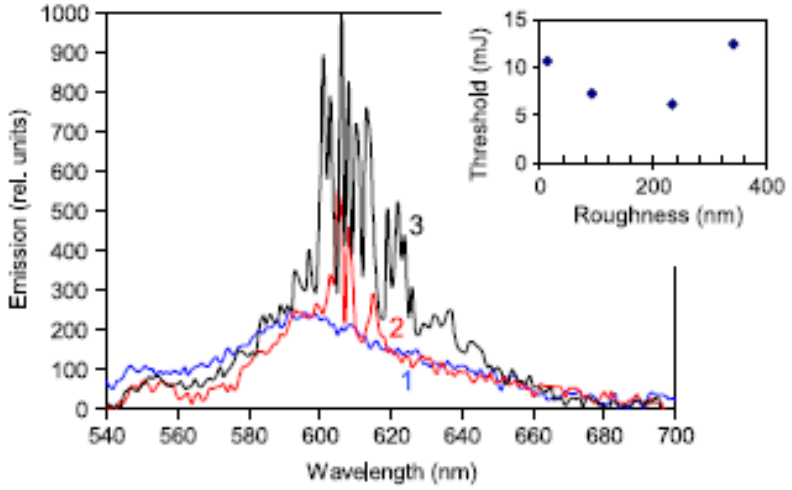


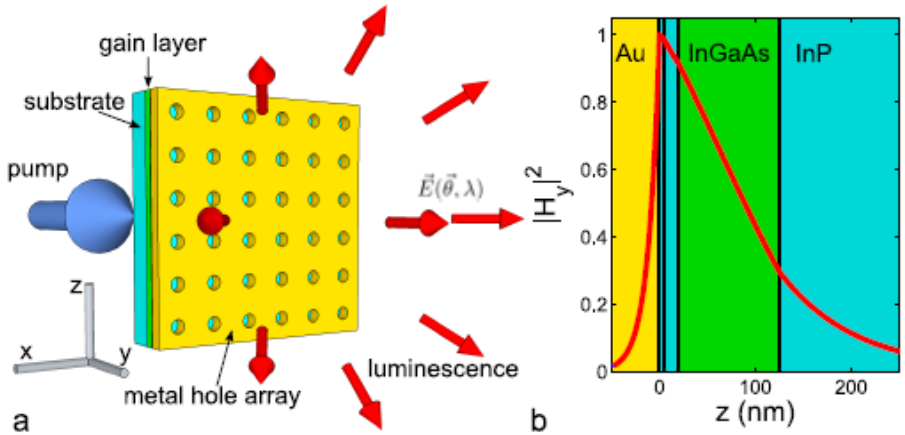
Figure 5. Emission spectra in the RB:PMMA film deposited on a roughened silver with surface roughness equal to 234 nm, pumped with 7 mJ (1), 13 mJ (2) and 20 mJ (3) laser pulses. Inset: stimulated emission threshold as a function of the surface roughness.

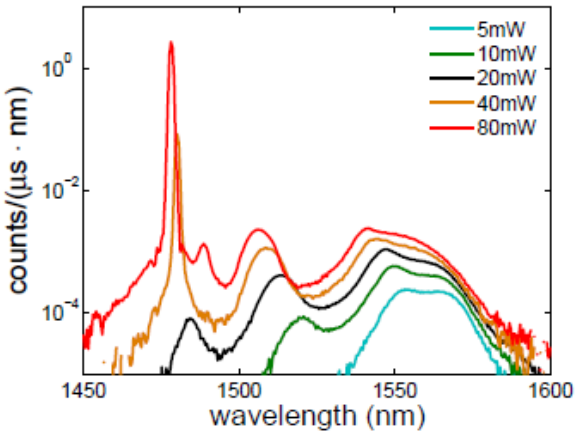
Surface plasmon lasing observed in metal hole arrays

Frerik van Beijnum,[1] Peter J. van Veldhoven,[2] Erik Jan Geluk,[2]
Michiel J.A. de Dood,[1] Gert W. 't Hooft,[1,3] and Martin P. van Exter[1]

[1] *Leiden University, Huygens Laboratory, P.O. Box 9504, 2300 RA Leiden, The Netherlands*
[2] *COBRA Research Institute, Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, The Netherlands*
[3] *Philips Research Laboratories, Prof. Holstlaan 4, 5656 AA Eindhoven, Netherlands*

Phys. Rev. Lett. **110, 206802-1-5 (2013)**





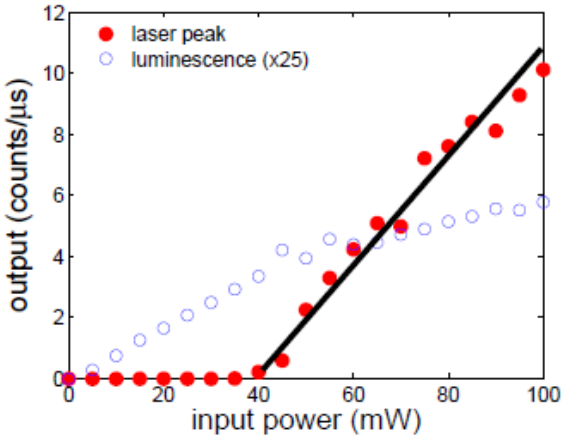


FIG. 2. (a) Luminescence spectra as a function of pump power, plotted on a semilog scale. For increasing pump power the bandwidth of the luminescence increases until the device starts lasing. Above threshold, the emission of the non-lasing resonances starts to saturate at a maximum intensity. 80 mW corresponds to $\sim$ 11 kW/cm^2 (b) The output in the lasing peak and in the luminescence in the range of 1485 – 1600 nm. The power in the lasing peak shows a clear threshold (red). The black line is a guide to the eye. The luminescence outside the lasing peak starts to level off, as expected for lasing in semiconductor devices (blue).

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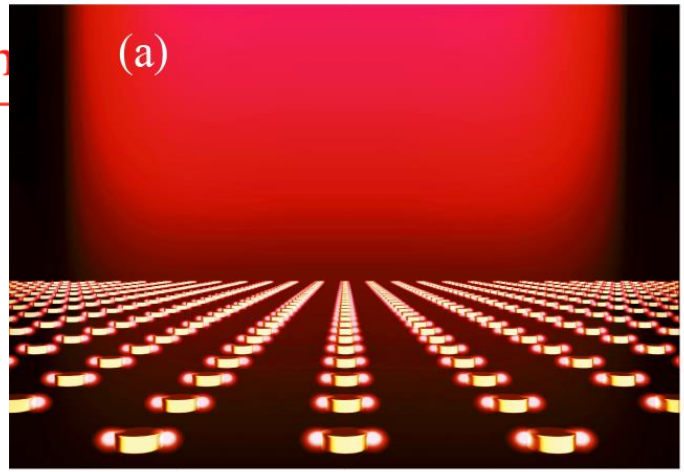
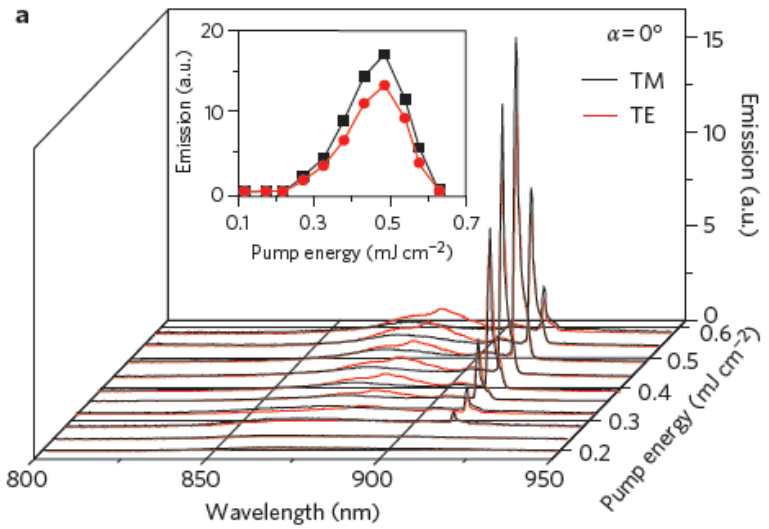
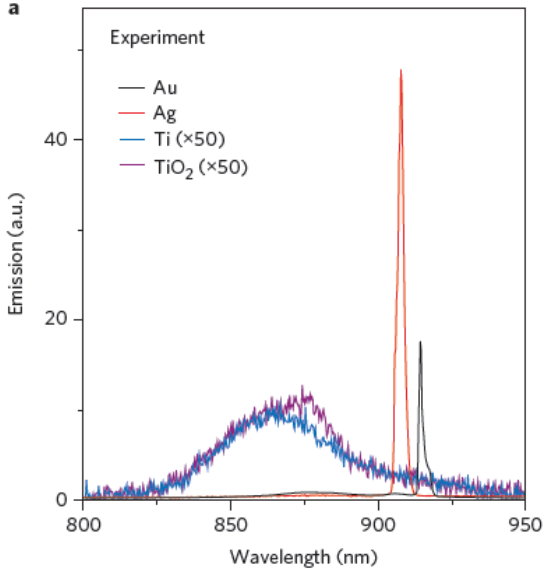
nature nanotechn

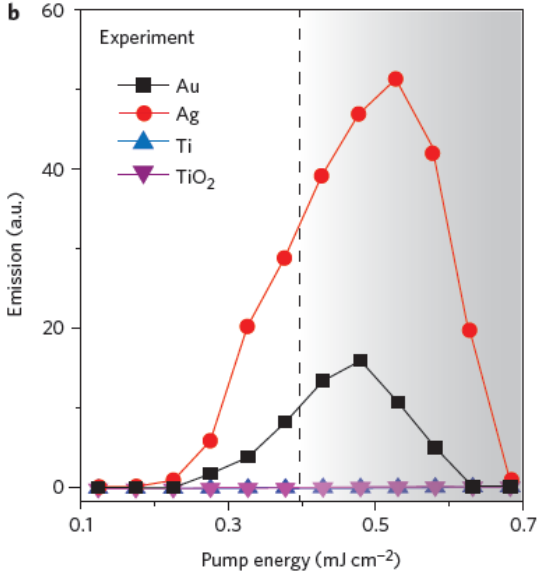
Lasing action in strongly coupled plasmonic nanocavity arrays

Wei Zhou[1†], Montacer Dridi[2], Jae Yong Suh[2], Chul Hoon Kim[2,3†], Dick T. Co[2,3], Michael R. Wasielewski[2,3], George C. Schatz[2] and Teri W. Odom[1,2,3*]









ARTICLES
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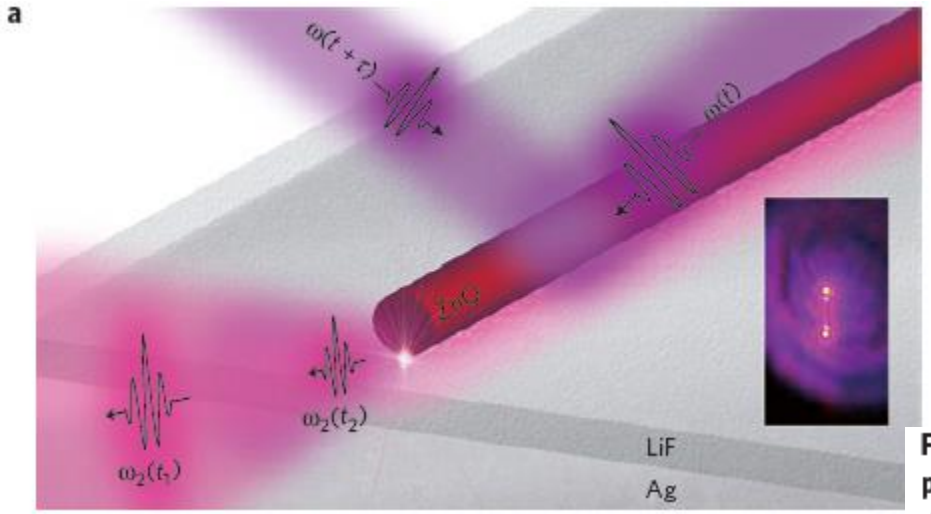
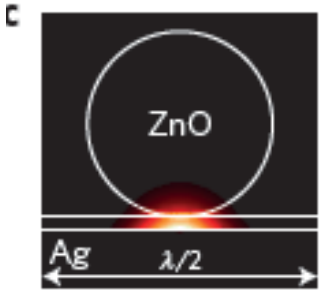
nature physics

Ultrafast plasmonic nanowire lasers near the surface plasmon frequency

Themistoklis P. H. Sidiropoulos[1]*, Robert Röder[2], Sebastian Geburt[2], Ortwin Hess[1], Stefan A. Maier[1], Carsten Ronning[2] and Rupert F. Oulton[1]*





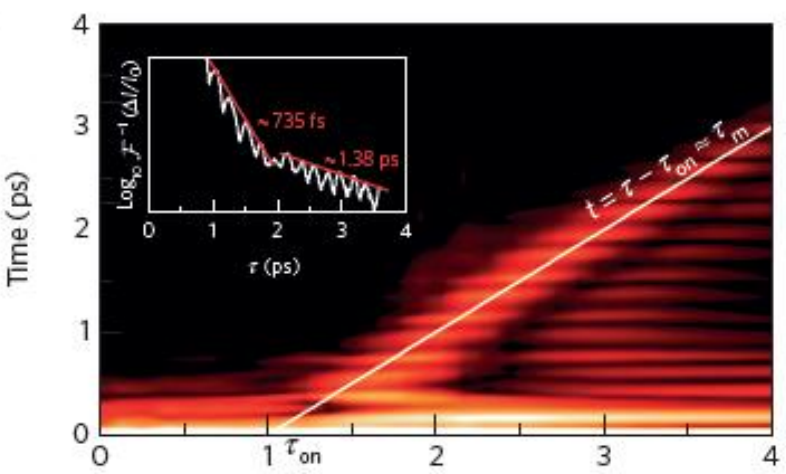


Figure 5 | Measured spectra versus double-pump pulse delay for the plasmonic nanowire laser and its Fourier transform. a, Normalized difference spectrum, $\Delta I(\lambda,\tau)/I_0(\lambda) - I(\lambda,\tau)/I_0(\lambda) - 1$, of the plasmonic nanowire laser for $\tau \geq 0$, where $I(\lambda,\tau)$ is the spectrum under double-pump excitation and $I_0(\lambda)$ is the single strong pump pulse spectrum. The two upper panels show the $\Delta I/I_0$ spectra for the pulse delays, $\tau = 2.0$ ps and $\tau = 3.1$ ps, indicating the increasing spectral modulation frequency with pulse delay. **b**, Fourier transform of each spectrum shown in **a** versus pulse delay. The white trend line follows $t = \tau - \tau_{on} \approx \tau_m$, indicating a turn-on time of $\tau_{on} = 1.1$ ps. The inset shows the amplitude decay of the Fourier transform along the white trend line, with linear fits (red lines) to the modulation peaks. The presented data in this figure correspond to measurements at the highest pump power (situation i) shown in Fig. 4a.

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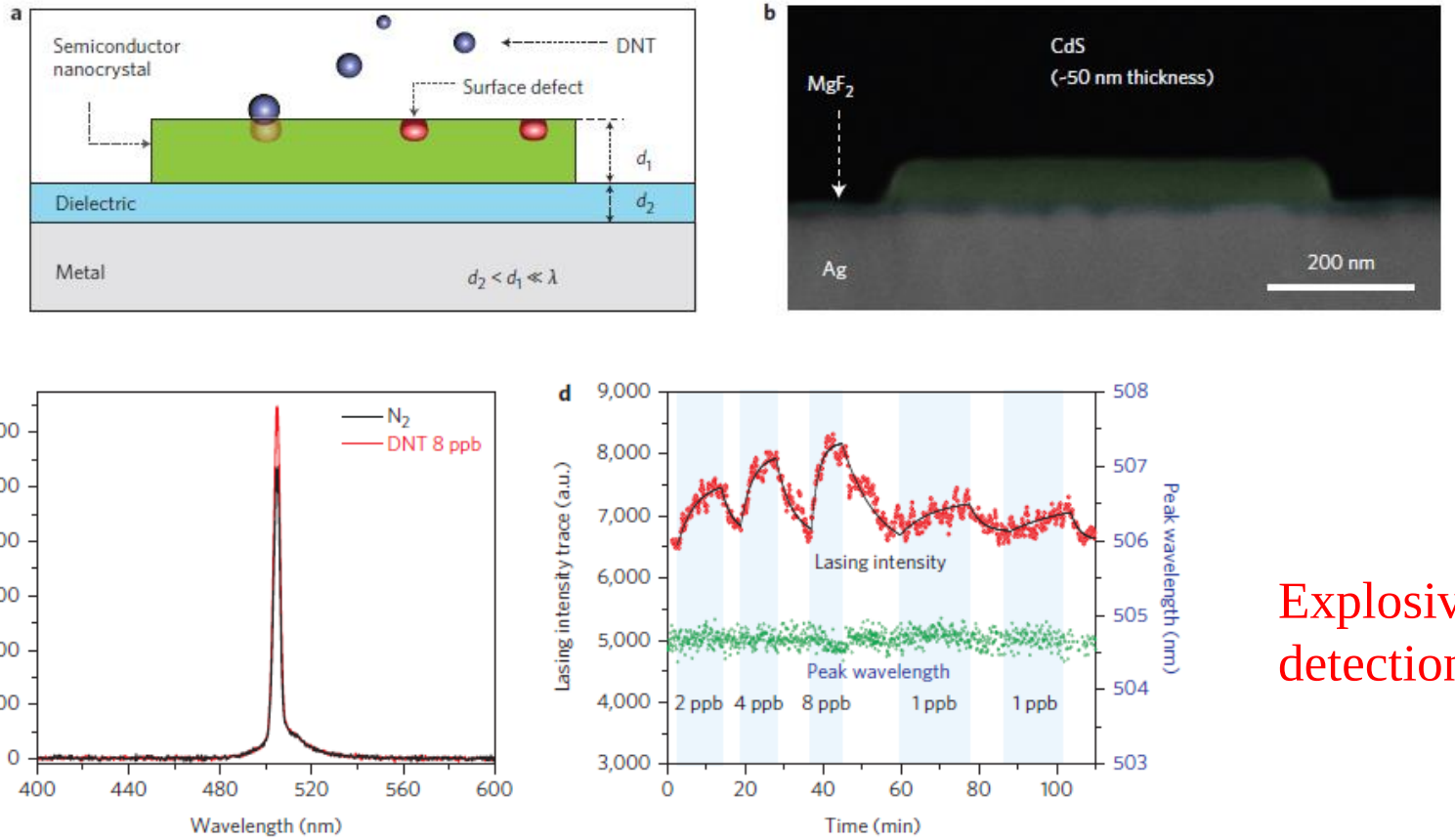
Explosives detection in a lasing plasmon nanocavity

Ren-Min Ma[1†], Sadao Ota[1†], Yimin Li[1], Sui Yang[1] and Xiang Zhang[1,2*]

[1]NSF Nanoscale Science and Engineering Centre, 3112 Etcheverry Hall, University of California, Berkeley, California 94720, USA, [2]Materials Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA,

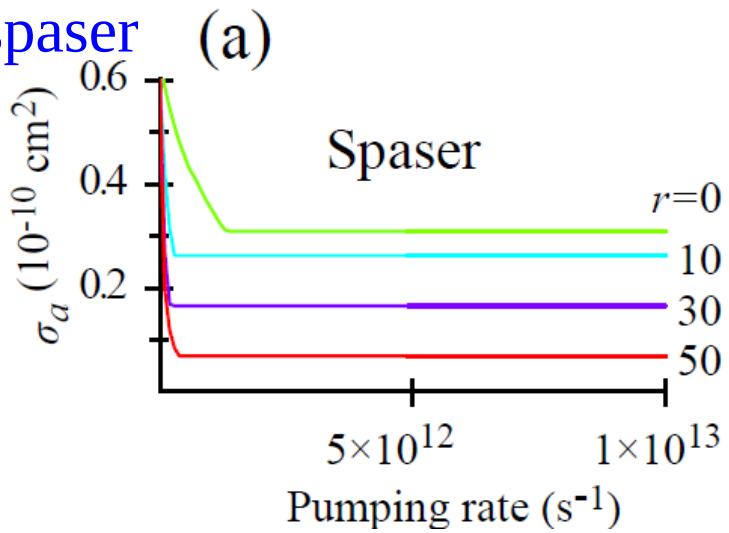


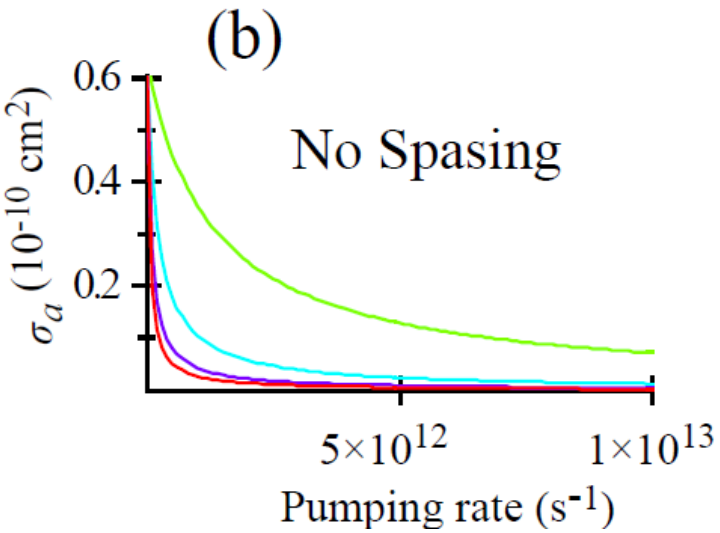
Explosive (DNT) detection

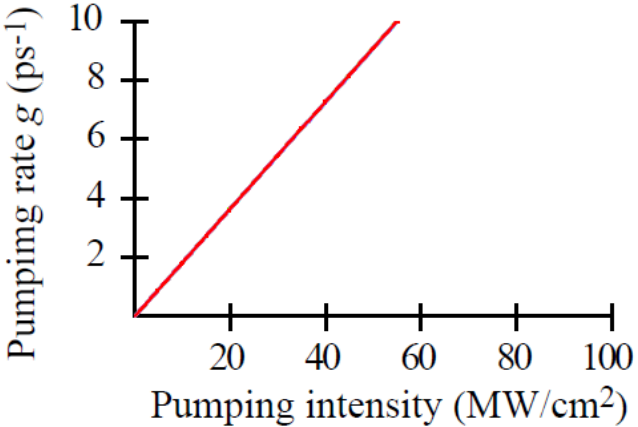
Department of Physics and Astronomy
Georgia State University
Atlanta, GA 30303-3083

Applications in Biomedicine: Why spaser is efficient as fluorescent, photothermal and photoacoustic agent? It does not saturate!

Absorption cross section as a function of the pumping rate for different loads *r* of spaser







H. Koochaki and M. Stockman (In preparation)

http://www.phy-astr.gsu.edu/stockman
E-mail: mstockman@gsu.edu

Spaser as Versatile Biomedical Tool

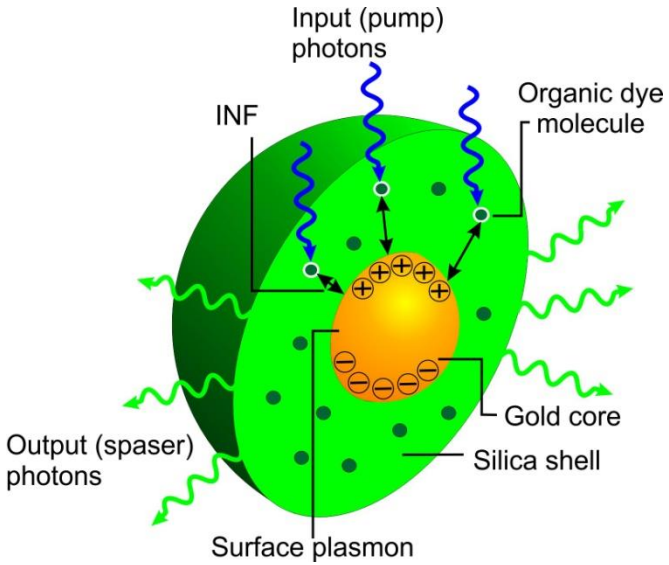
Ekaterina I. Galanzha,[1] Robert Weingold,[1] Dmitry A. Nedosekin[1], Mustafa Sarimollaoglu,[1] Alexander S. Kuchyanov[2], Roman G. Parkhomenko[3], Alexander I. Plekhanov[2], Mark I. Stockman[4], Vladimir P. Zharov[1]

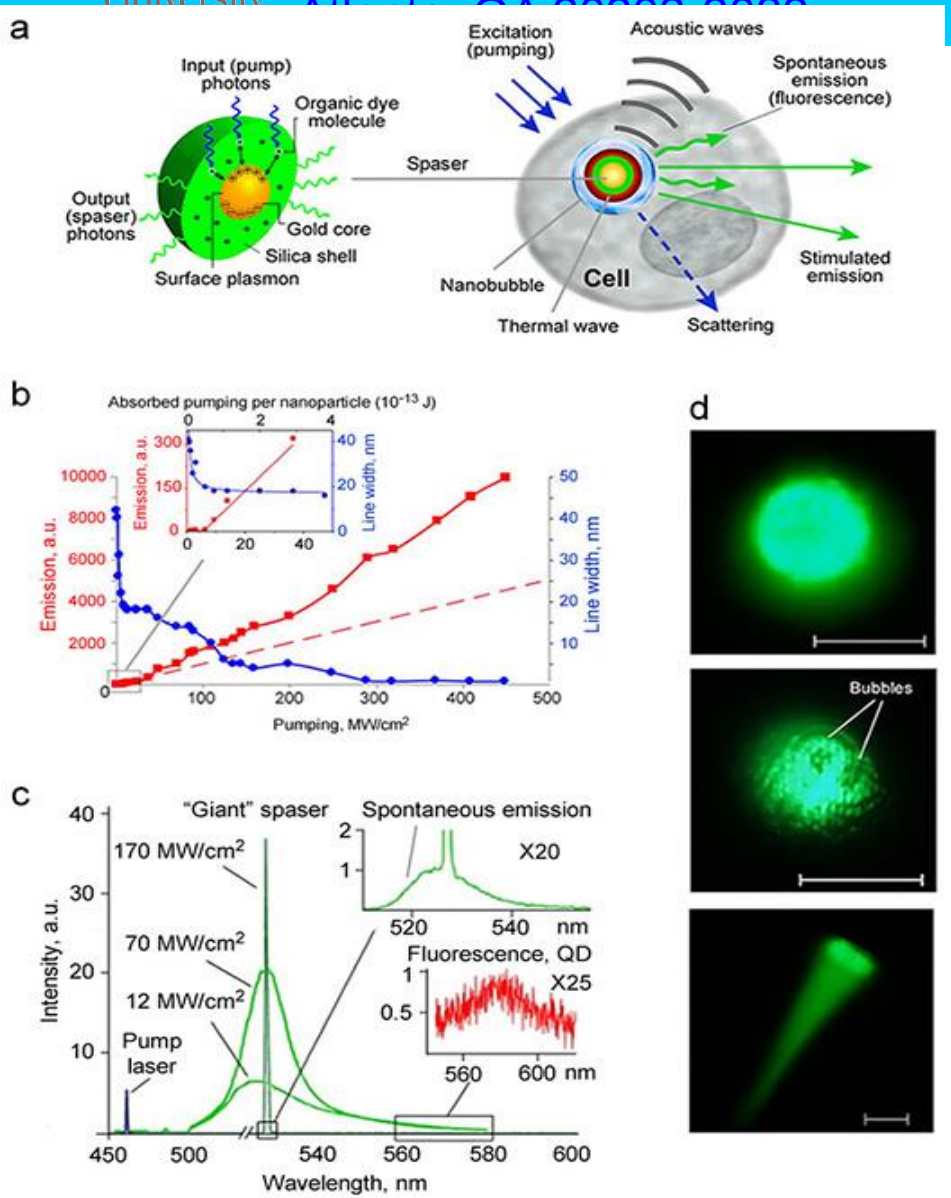
[1]Winthrop P. Rockefeller Cancer Institute, Arkansas Nanomedicine Center, University of Arkansas for Medical Sciences, Little Rock, Arkansas 72205

[2]Institute of Automation and Electrometry of the Siberian Branch of the Russian Academy of Science, Koptyug Ave. 1, 630090 Novosibirsk, Russia

[3]Nikolaev Institute of Inorganic Chemistry of the Siberian Branch of the Russian Academy of Science, Lavrentiev Ave. 3, 630090 Novosibirsk, Russia

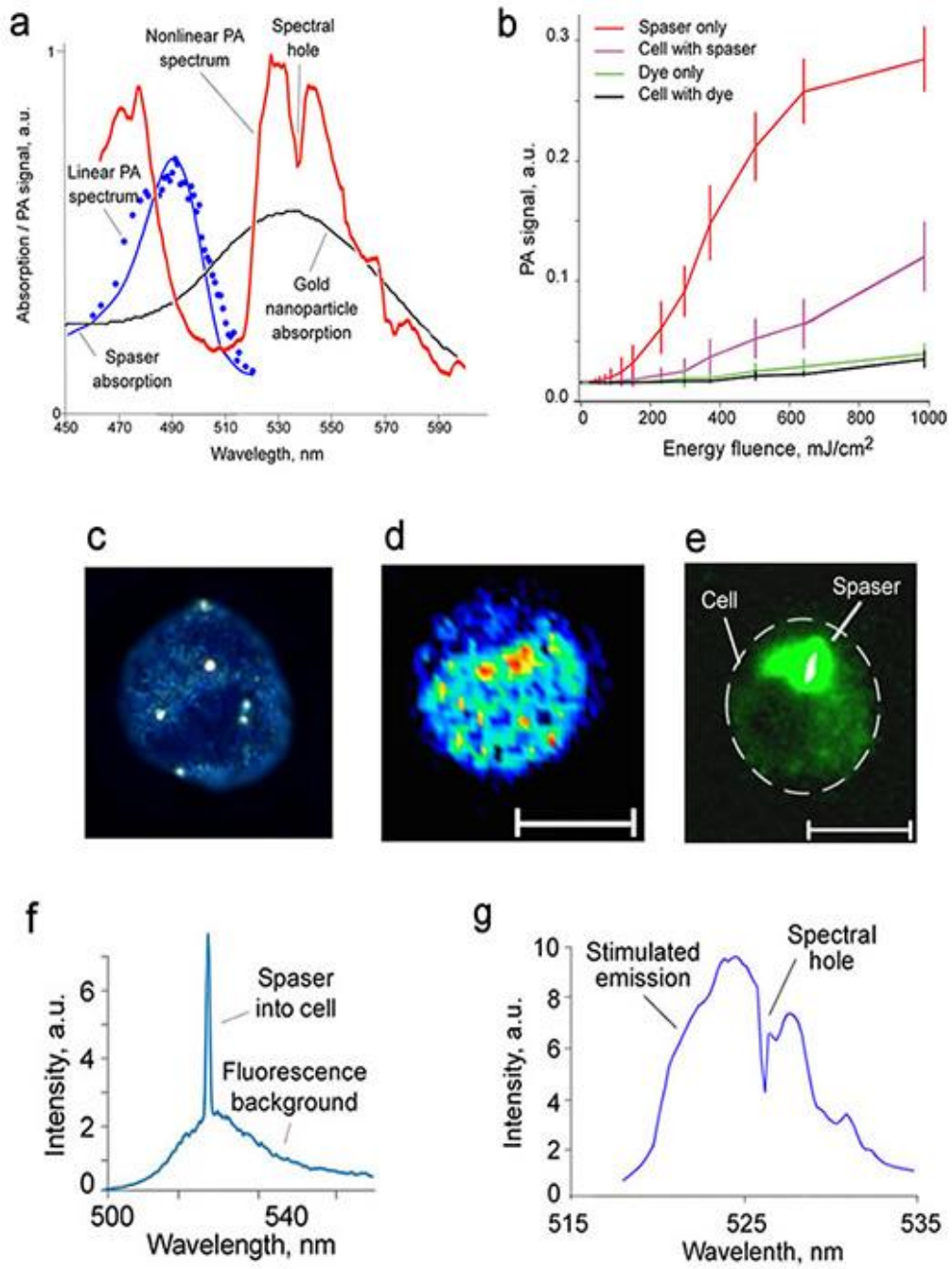
[4]Center for Nano-Optics and Department of Physics and Astronomy, Georgia State University, 29 Peachtree Center Ave., Atlanta, GA 30302, USA



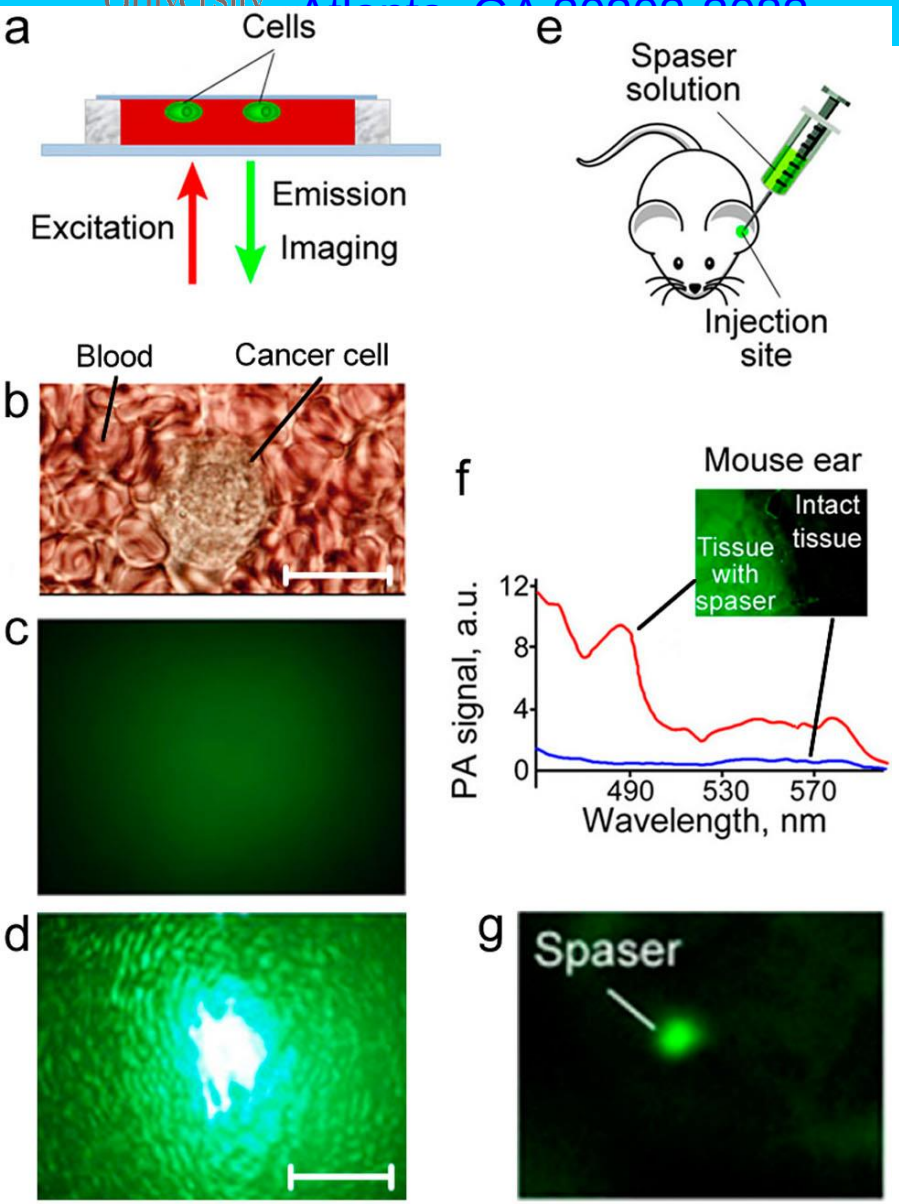


Spaser for biological applications

a, Schematic of spaser as multifunctional intracellular nanoprobe. **b,** Stimulated emission in spaser suspension. **c,** Radiation spectrum of spaser in suspension at 528 nm at different pump intensities. **d,** Spatially homogenous spaser's emission at a relatively low pump intensity (30 MW/cm^2, 120-μm thick spaser's suspension)**; Middle**: emission during the bubble formation around overheated spasers (150 MW/cm^2); **Bottom:** "directional" spaser emission in the presence of two large bubbles (200 MW/cm^2). Scale bars, 10 μm.

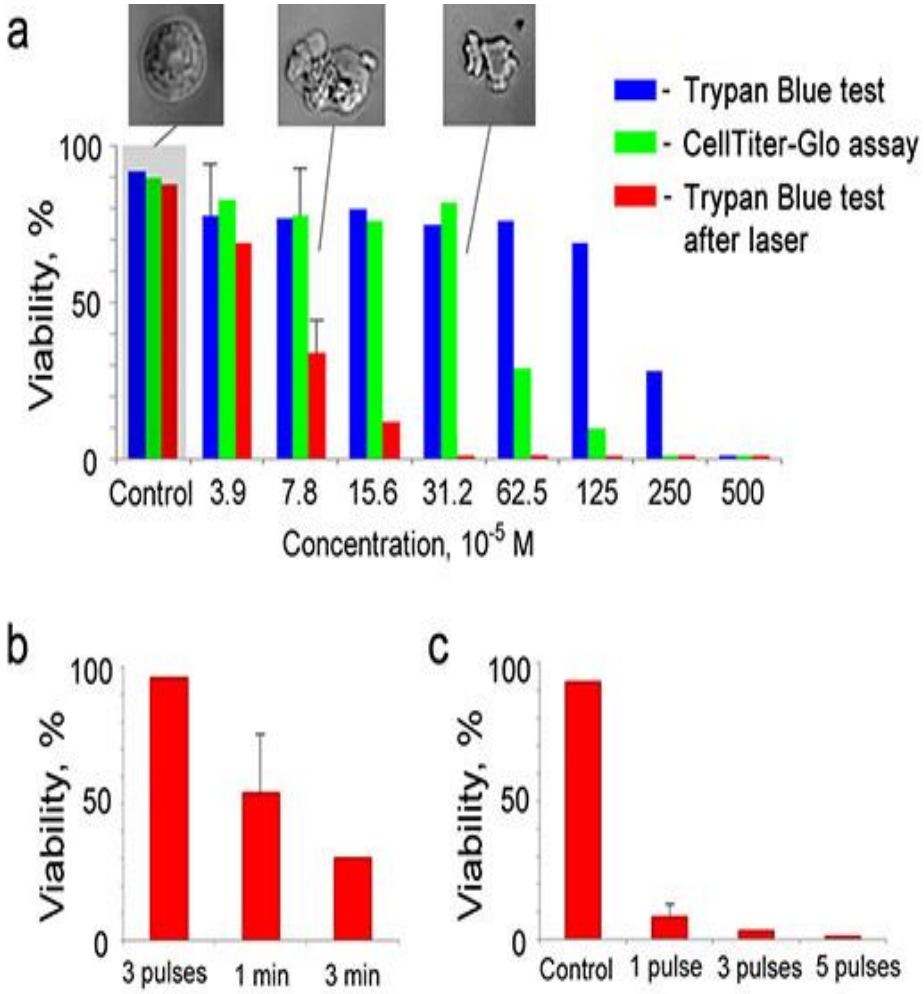


Photoacoustic (PA) and photothermal (PT) spectral microscopy of spasers. a, Absorption spectra, and linear and nonlinear PA spectra of spaser in suspension at laser energy fluence of 20 mJ/cm^2 and 150 mJ/cm^2, respectively. **b,** PA signal dependence on laser pump energy fluence for dye and spaser in suspension and into cells. **c-e,** Images of single cancer cell with spasers loaded through endocytosis . (**c**)-scattering (dark field), (**d**) –photothermal (PT) ; (**e**)- stimulated emission for local irradiated cell zone in background of conventional fluorescence image. **f,** Spectral peak from single cancer cell with spasers at relatively low energy fluence (80 mJ/cm^2). Scale bars, 10 μm. **g,** Spectral peak single cancer cell with spasers showing spectral hole burning in stimulated emission spectra at moderate energy fluence (135 mJ/cm^2).



Imaging of spasers in viable cells *in vitro* and in biotissue *in vivo*. a, Schematic *in vitro*. **b,** Optical transmission image. **c, d,** Fluorescence imaging using conventional optical source (lamp) of blood with cancer cells at depth of ~1 mm **(top)** and spaser emission from single cancer cell at depth of 1 mm **(bottom). e,** Schematic of intradermal injection of spaser suspension into top layer of mouse ear tissue. **f,** PA identification of spasers in ear tissue using laser spectral scanning **(top).** Laser parameters: beam diameter 15 μm, fluence 20 mJ/cm^2. **g,** Spaser emission through ~250 μm ear tissue. Pump parameters: beam diameter: 10 μm**;** intensity, 30 MW/cm^2.

Department of Physics and Astronomy
Georgia State University
Atlanta, GA 30303-3083



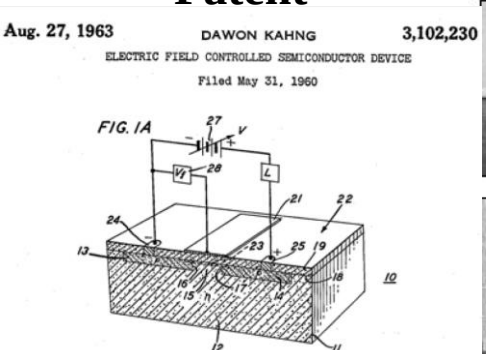
Demonstration of spaser as theranostic agent. **a,** Cell viability tests for different spaser concentration using two various kits without (blue, green) and after (red) laser irradiation (100 mJ/cm^2 , 1 Hz, 3min). Inset: intact cell **(left)** and cells labeled with spasers at different concentration (middle and right) after laser irradiation. **b,** Viability test for concentration 15.6 x 10^{-5} M as a function of laser exposure time (3s [3 pulses], 1 min, and 3 min); **c,** Viability test for concentration 15.6 x 10^{-5} M as a function of laser pulse number (1, 3 and 5) showing that even single laser pulse at fluence of 500 mJ/cm^2 is sufficient for significant damage of cancer cells labeled by spasers. The average SD for each column is 15-20%.

The most important technological application: Information processing

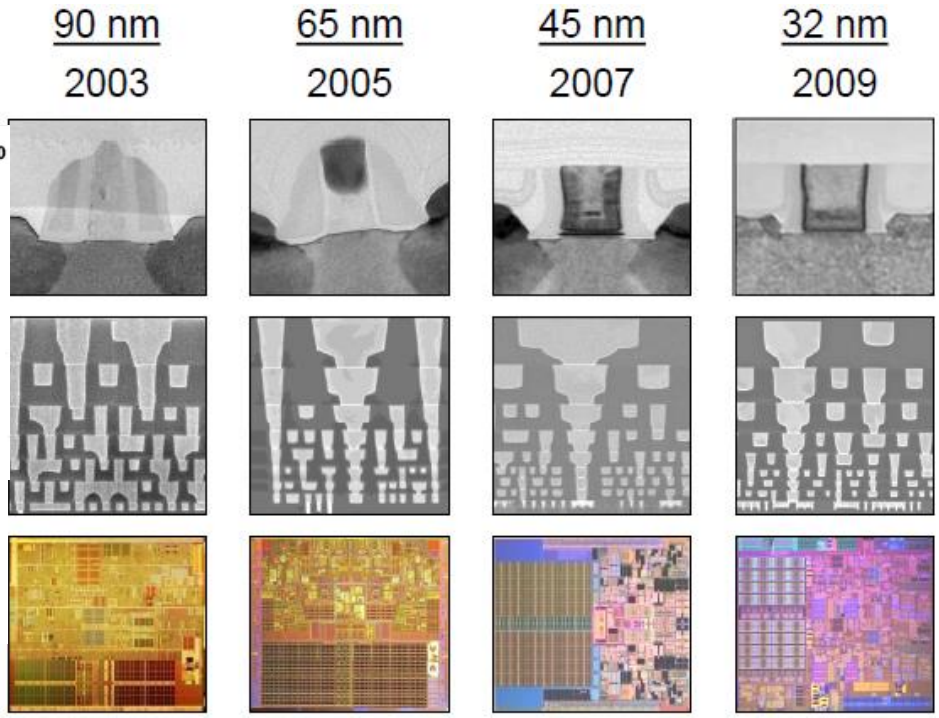
P. Packan et al., in 2009 IEEE International Electron Devices Meeting (IEDM), *High Performance 32nm Logic Technology Featuring Second Generation High-K + Metal Gate Transistors (Baltimore, MD, 2009), Vol. IEDM09-662, p. 28.4.1-28.4.4*

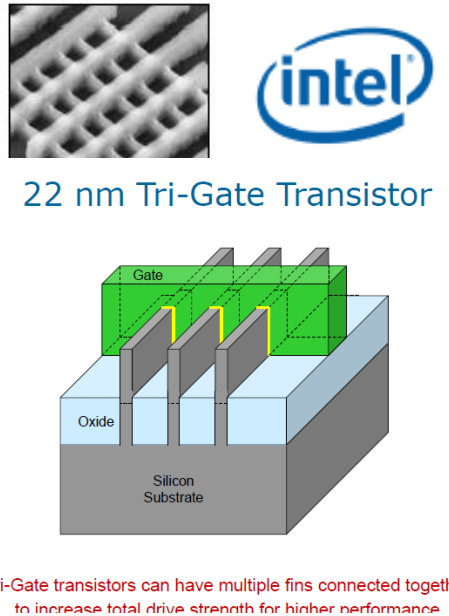
Abstract:
A 32nm logic technology for high performance microprocessors is described. 2nd generation high-k + metal gate transistors provide record drive currents at the tightest gate pitch reported for any 32 nm or 28nm logic technology. NMOS drive currents are 1.62mA/um Idsat and 0.231mA/um Idlin at 1.0V and 100nA/um Ioff. PMOS drive currents are 1.37mA/um Idsat and 0.240mA/um Idlin at 1.0V and 100nA/um Ioff. The impact of SRAM cell and array size on Vccmin is reported.

MOSFET US Patent



Speed ~ 100-300 GHz
Low resistance to ionizing radiation





Processor speed :

$$f_{\max} = I_{\text{drive}} / \left(C_{\text{Intercon}} \Delta U \right) \sim 3 \text{ GHz}$$

Transistor speed is not a limiting factor!
Charging the interconnects is.

Department of Physics and Astronomy
Georgia State University
Atlanta, GA 30303-3083

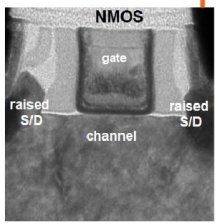
Nanospaser with electric excitation ("pumping") does not exist as of today *yet*, but fundamentally it is entirely possible

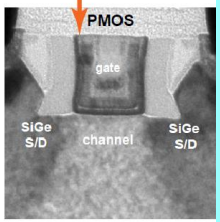
Concept of ~300 GHz processor unit with ~1% energy cost per flop

Today C-MOS Technology

Electric interconnect (Copper wire)

$$\tau = RC \sim \varepsilon\sigma \frac{L^2}{r^2}$$



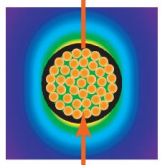


Charging time does not depend on scale

Near-future C-MOS Technology with on-chip plasmonic interconnects

Nanoplasmonic on-chip interconnect (Copper wire)

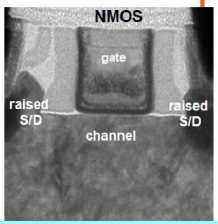
Spaser pumped by transistor

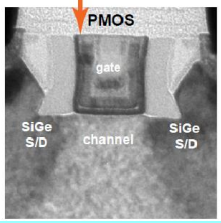


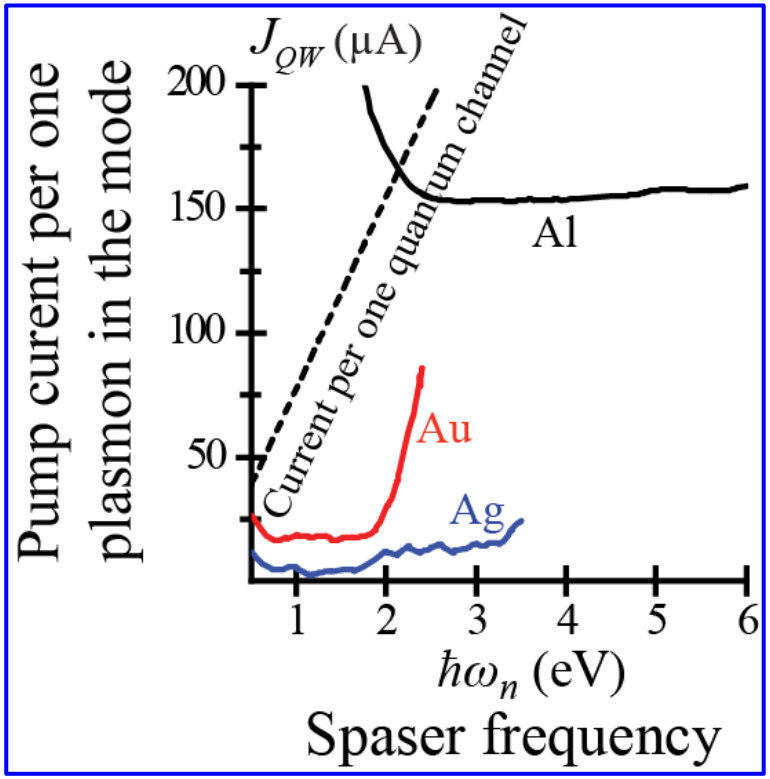
Phototransistor Ge

No electric charging of interconnects!

C-MOS Transistors are not connected electrically







D. Li and M. I. Stockman, *Electric Spaser in the Extreme Quantum Limit*, Phys. Rev. Lett. **110**, 106803-1-5 (2013)

Department of Physics and Astronomy
Georgia State University
Atlanta, GA 30303-3083

CONCLUSIONS

- **Spasers are plasmonic nanolasers that have been demonstrated to generate in a wide range of optical frequencies: from near-UV to near-IR**
- **Various designs of spasers have been implemented:**
  - **metal core/gain shell**
  - **gain semiconductor nanorod over continuous metal nanofilm**
  - **Rough metal nanofilm/gain dye nanolayer**
  - **metal/gain semiconductor/metal**
  - **lasing spaser of periodic array of nanoholes in a metal nanofilm with a semiconductor gain nanofilm over it**
  - **lasing spaser of a periodic array of metal nanoparticles on a gain dye nanolayer**
- **Mid IR nanospaser on graphene has been proposed**
- **First applications of spasers in explosives detection and cancer diagnostics and treatment have been introduced**


The End