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

Nanoplasmonics and Spaser

Mark I. Stockman

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

- **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
- Applications of Nanoplasmonics
- Sensing and Detection
- Plasmonic Nanoscopy
- Spaser as an Ultrafast Quantum Generator and Nanoamplifier

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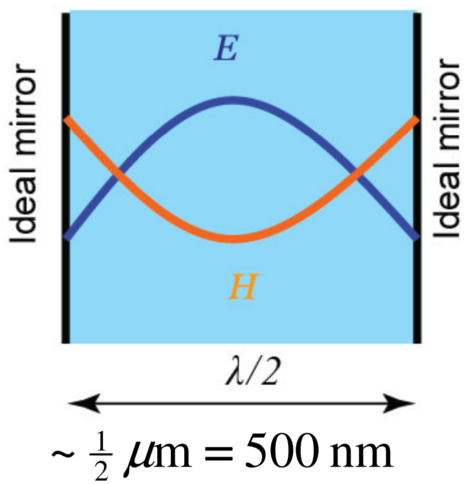
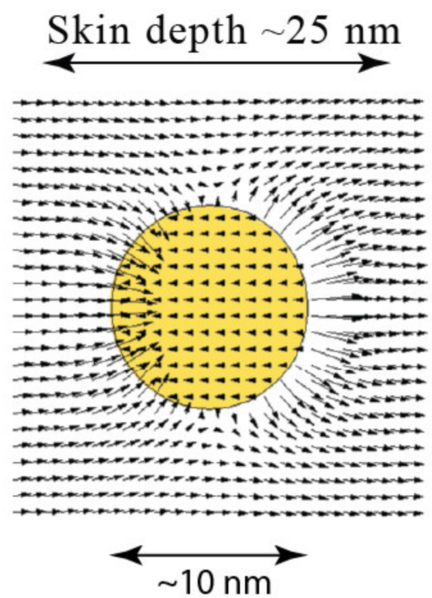
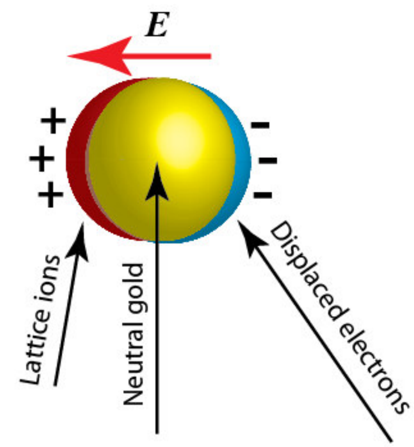
M. I. Stockman, *Nanoplasmonics: The Physics Behind the Applications*, Phys. Today **64**, 39-44 (2011).

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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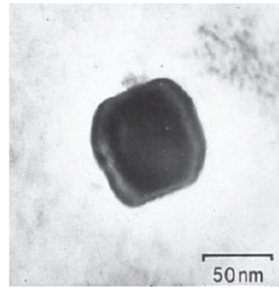
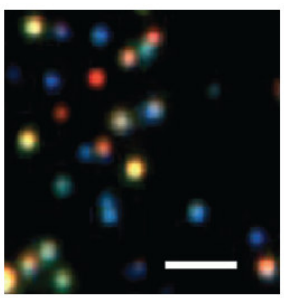
Lycurgus Cup (4th Century AD): Roman Nanotechnology



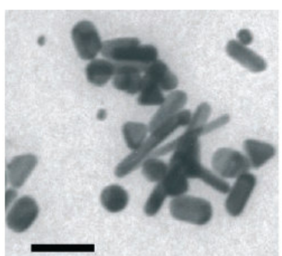
I. Freestone, N. Meeks, M. Sax, and C. Higgitt, *The Lycurgus Cup - a Roman Nanotechnology,* Gold Bull. **40**, 270-277 (2007

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

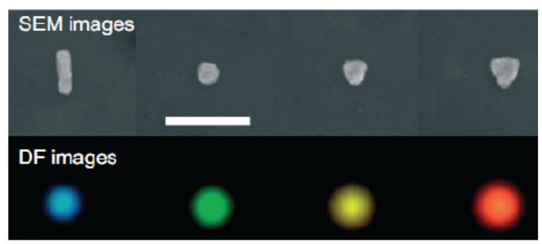


2 µm



100 nm

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

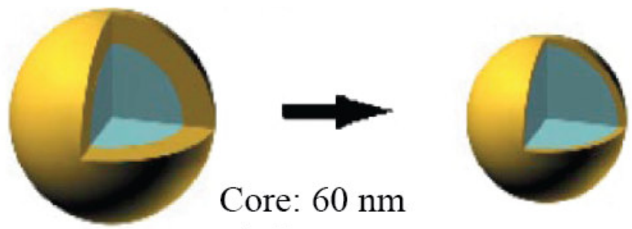


Scanning electron microscopy

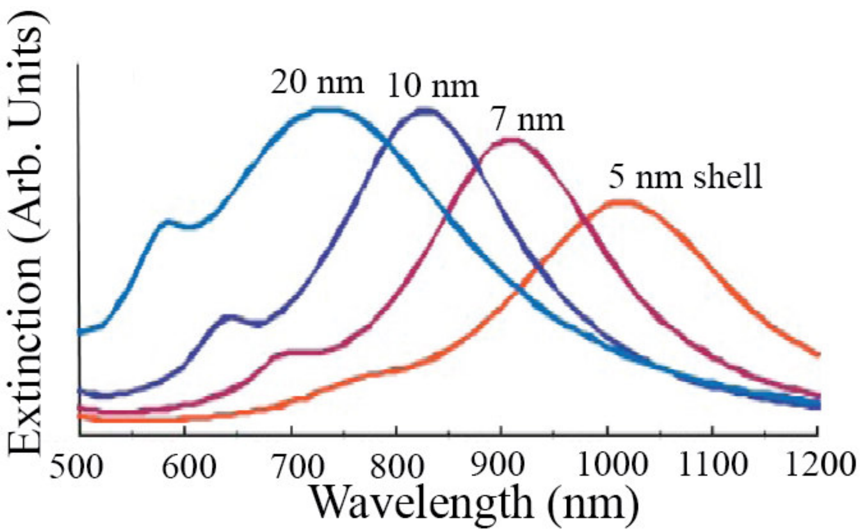
Dark field optical microscopy

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

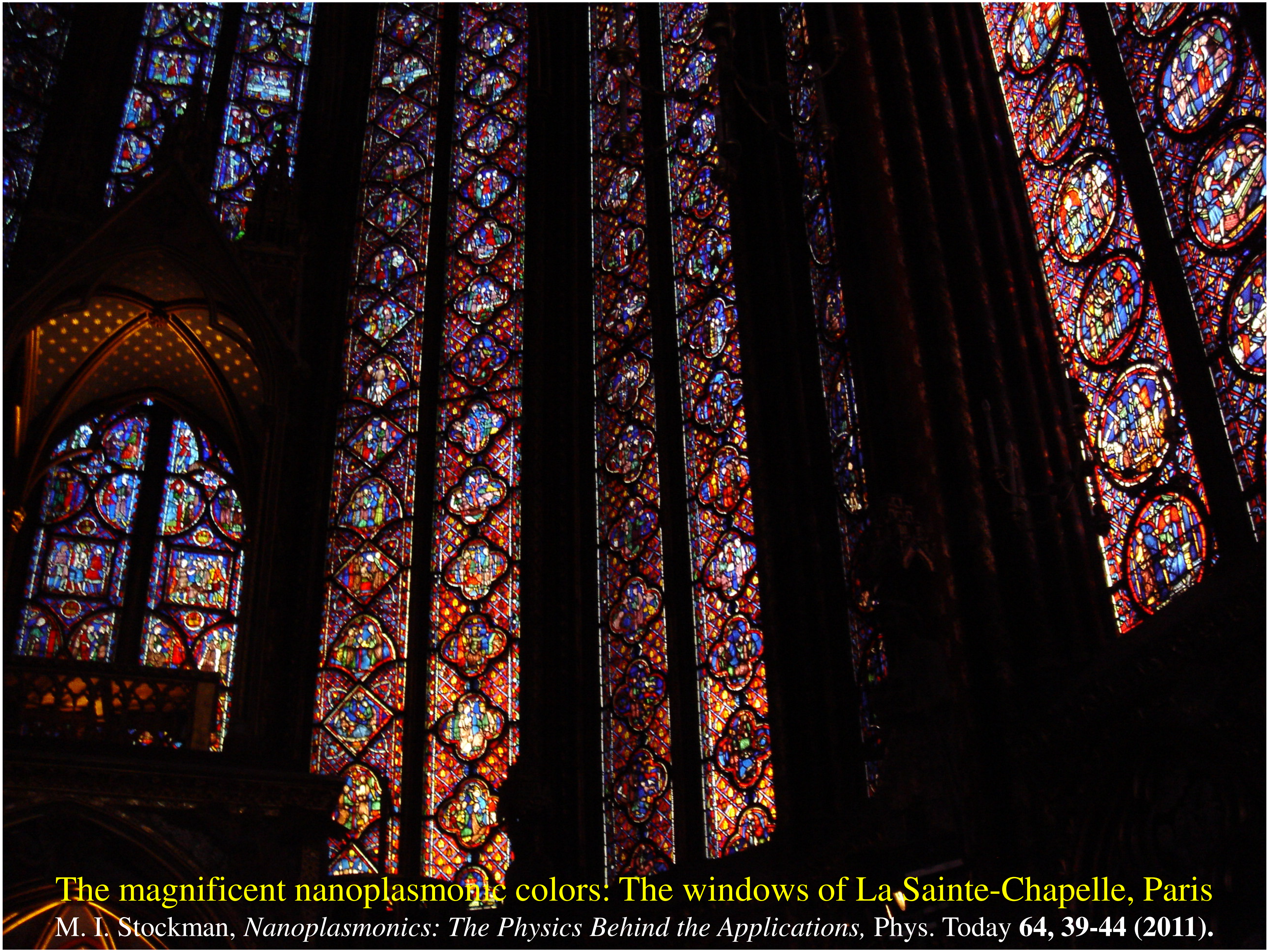
When shell becomes progressively thinner comparing to the core, the spectrum of the nanoshell shifts to the red and then to the near-infrared where biological tissues do not absorb



Core: 60 nm
Shell 20→5 nm



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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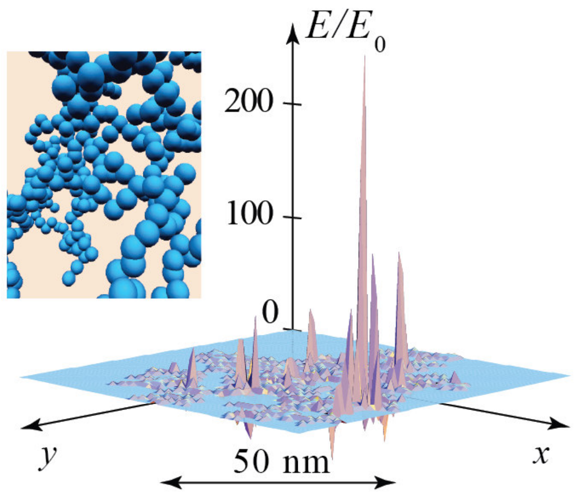
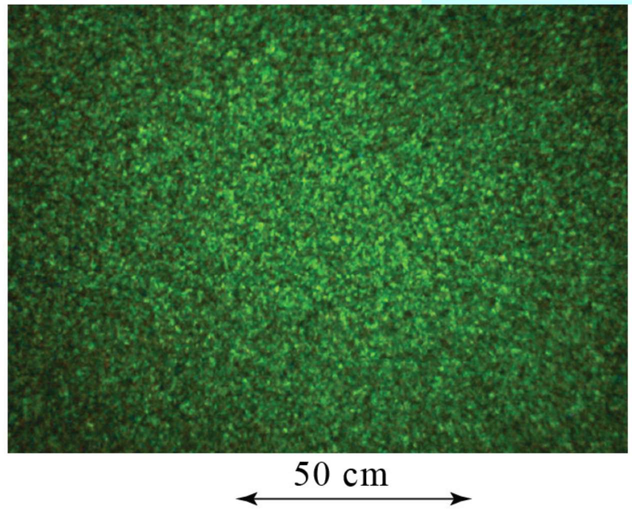
Plasmonic Near-Field **Hot Spots:** Happy 20th Anniversary!

- 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

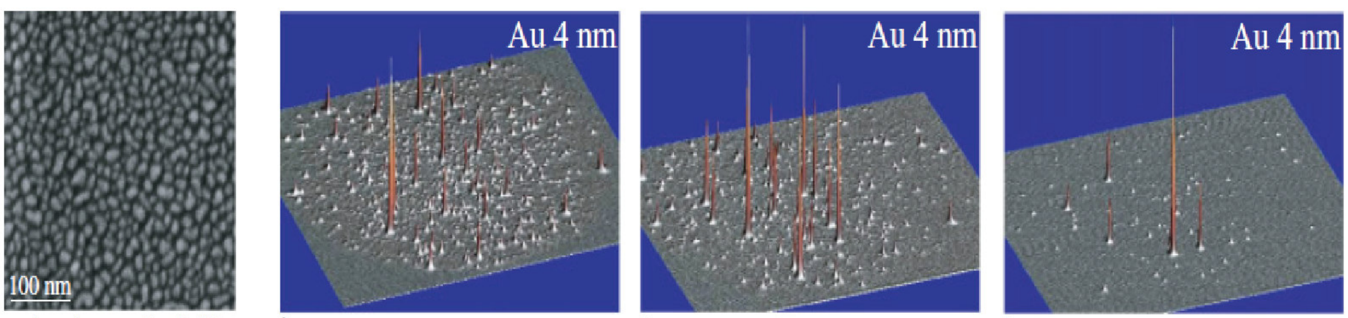
$$R_{Speckle} \sim \frac{\lambdabar}{A} L$$

$R_{Speckle}$ is speckle size

$\lambdabar \sim 100$ 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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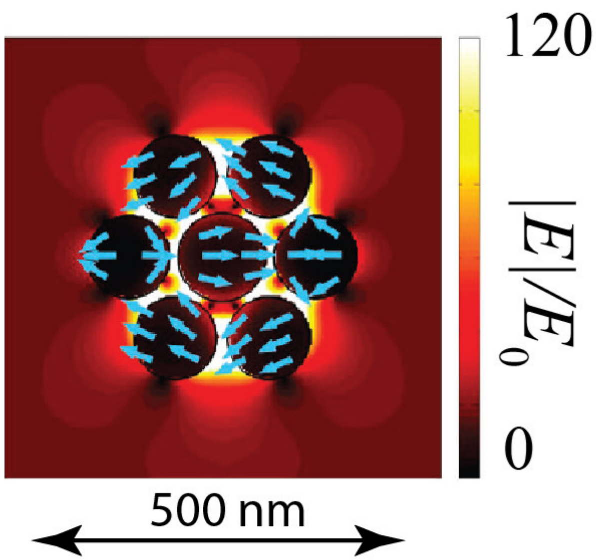
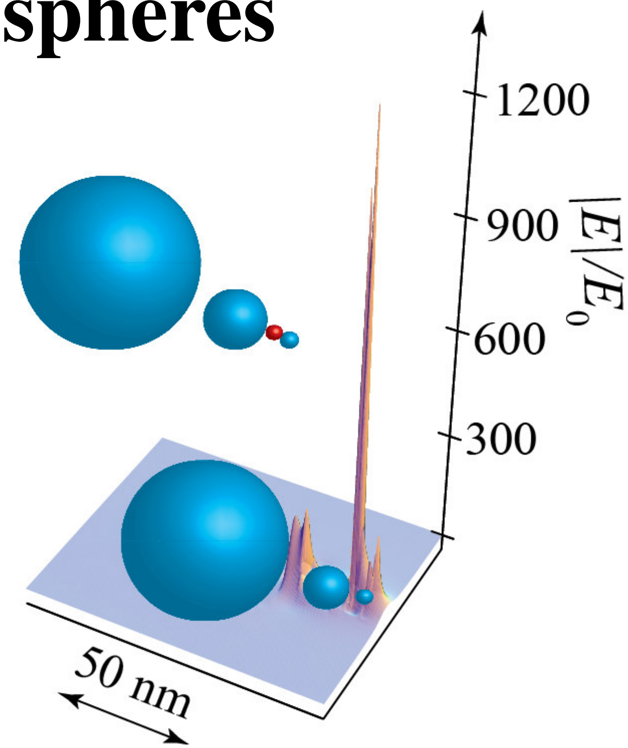
Engineered Nanoplasmonic Hot Spots in Small Clusters of Nanospheres



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

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

Excitation rate enhancement : $\sim Q^2$

SERS enhancement: $\sim Q^4$

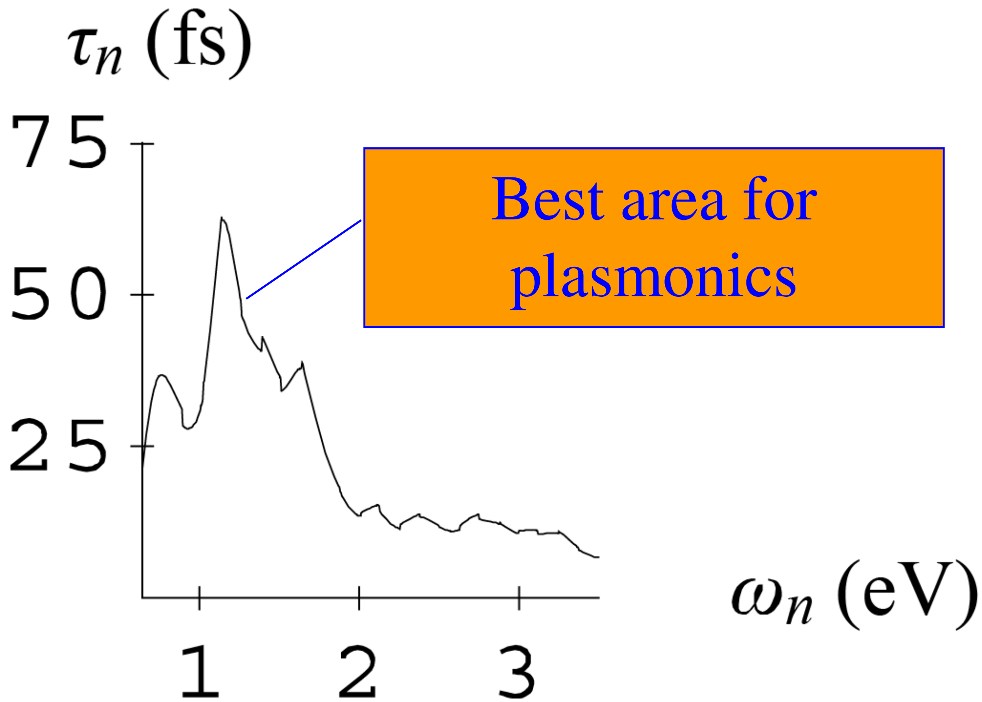
The above-listed enhancement factors do not depend on size *R*

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

This with respect to free photons: $\sim \dfrac{\lambda^3 Q}{R^3}$ (Purcell factor)

This enhancement factor is *inversely* proportional to R^3
This is of fundamental importance for spasers (plasmonic nanolasers)

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

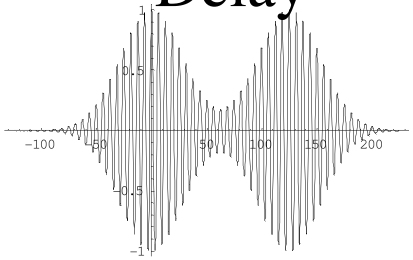
A. Kubo, K. Onda, H. Petek, Z. Sun, Y. S. Jung, and H. K. Kim, *Femtosecond Imaging of Surface Plasmon Dynamics in a Nanostructured Silver Film*, Nano Lett. 5, 1123 (2005).

200 nm

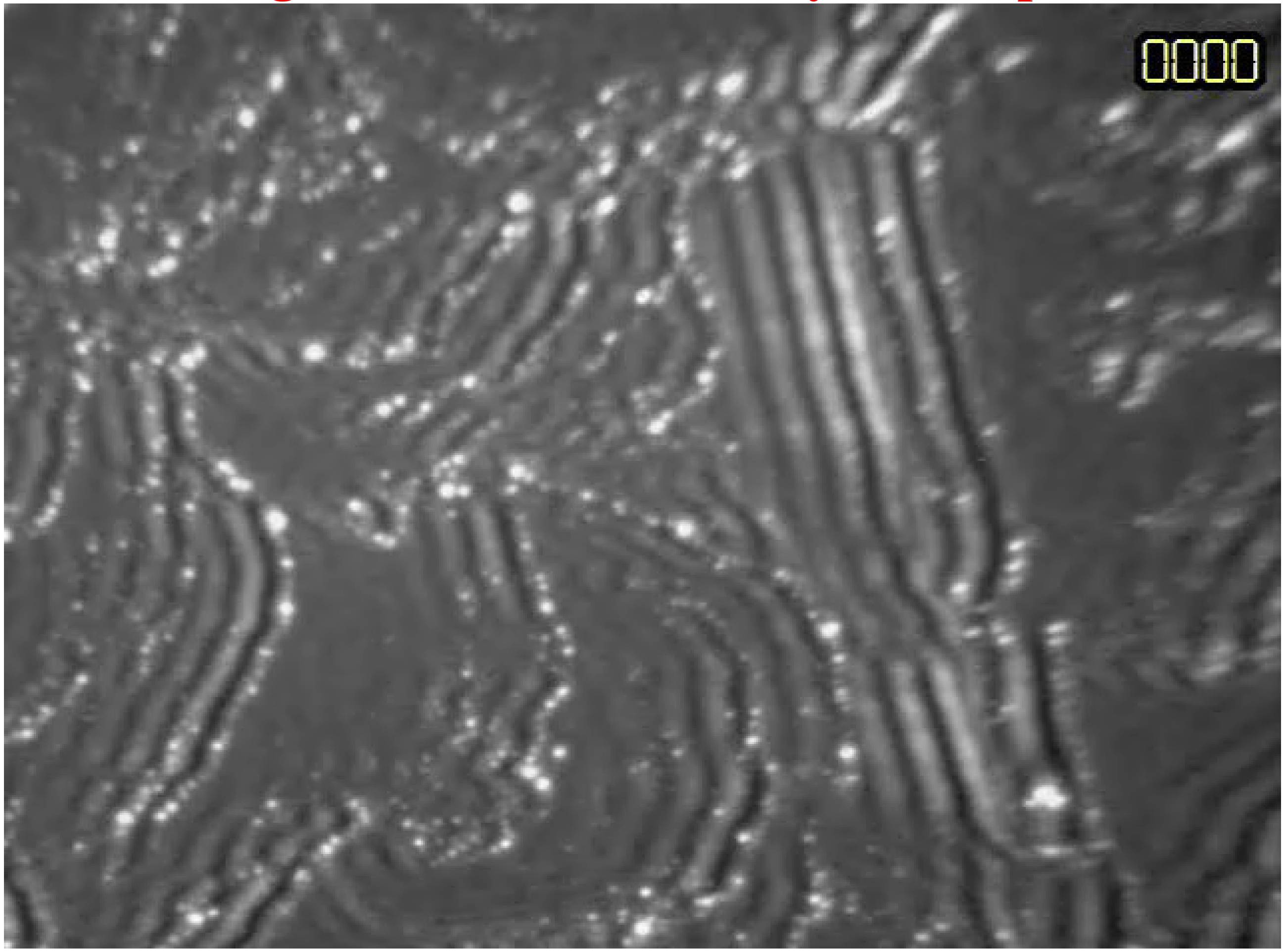
30 femtoseconds from life of a nanoplasmonic systems

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)



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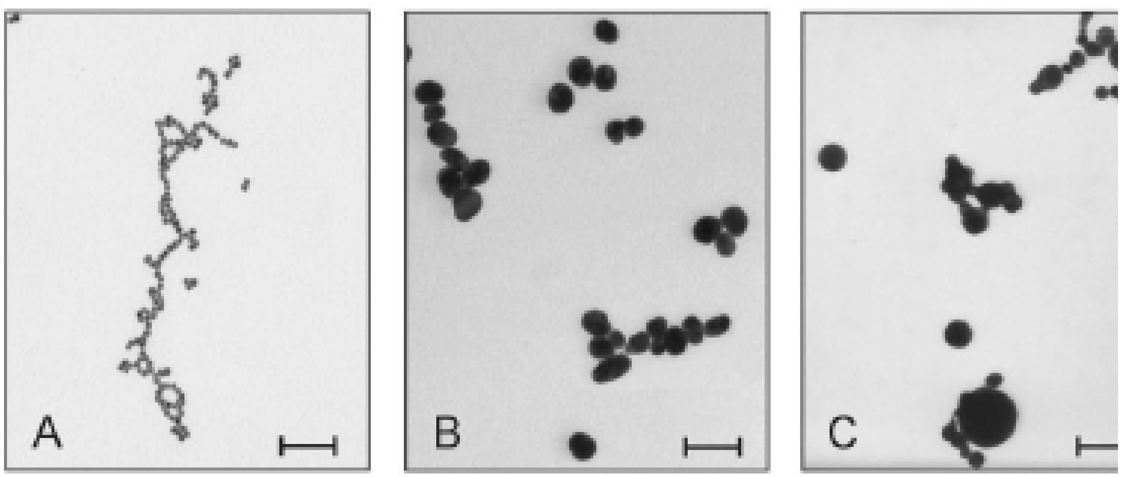
Anal. Chem. **2008**, *80*, 4247–4251

Correspondence

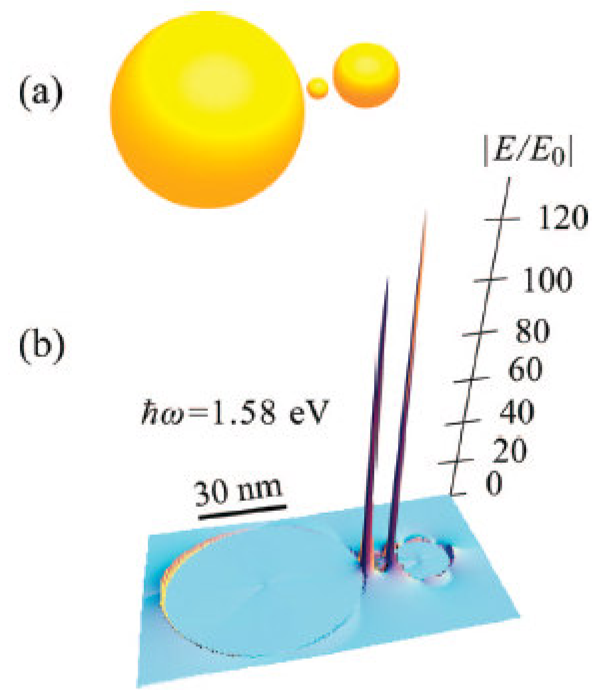
Gold Nanolenses Generated by Laser Ablation-Efficient Enhancing Structure for Surface Enhanced Raman Scattering Analytics and Sensing

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



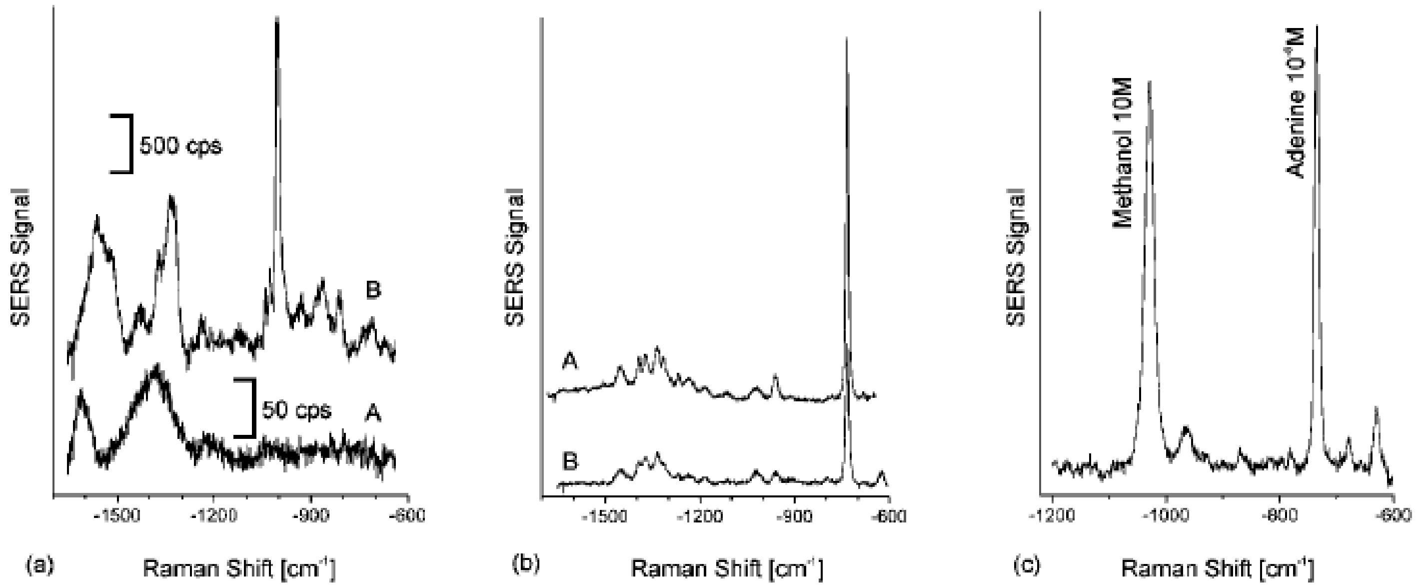
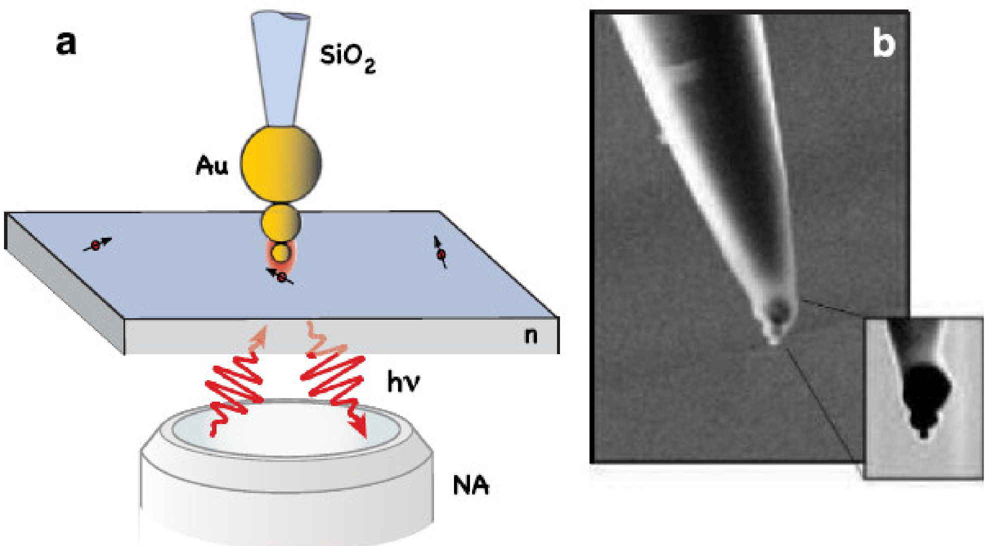


Figure 3. Comparison of SERS using gold nanolenses made by ablation and chemically prepared nanoaggregates as enhancing nanostructures. (a) Raman spectra measured from aqueous solutions of gold nanoaggregates without any analyte to compare background signals. The chemically prepared gold nanoparticles (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 $\sim$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.

PRL **109,** 017402 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

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*



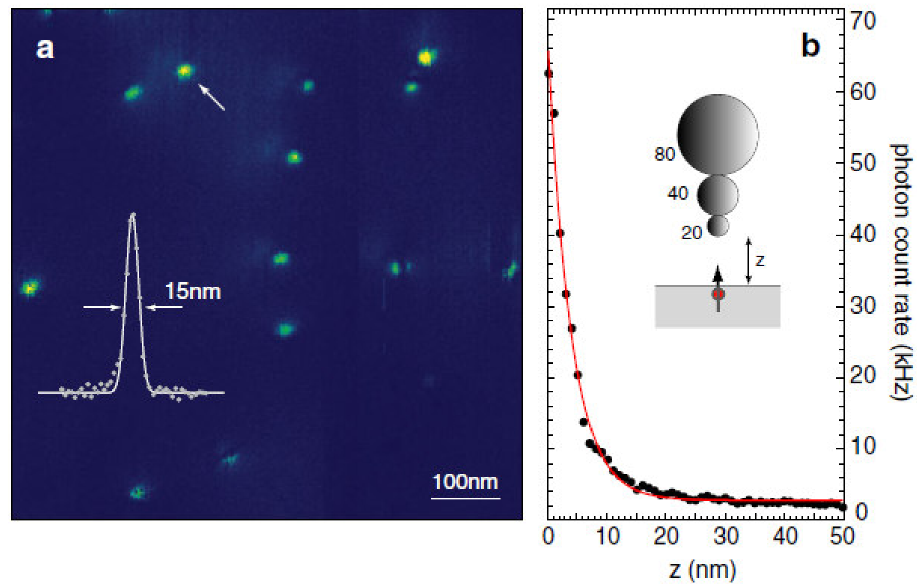


FIG. 4 (color online). Excitation of single-molecule fluorescence with a trimer antenna consisting of 80, 40, and 20 nm gold nanoparticles. (a) Fluorescence image of the single-molecule sample. Inset: Line cut through the single fluorescence spot marked by the arrow. (b) Fluorescence from a single z-oriented 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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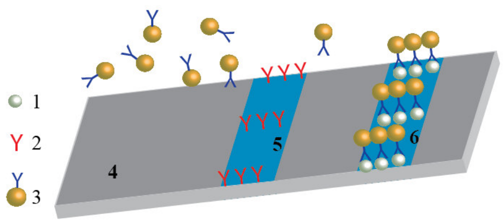
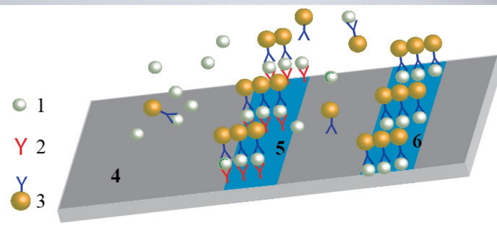
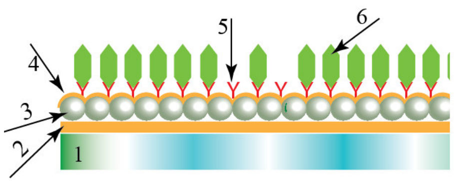
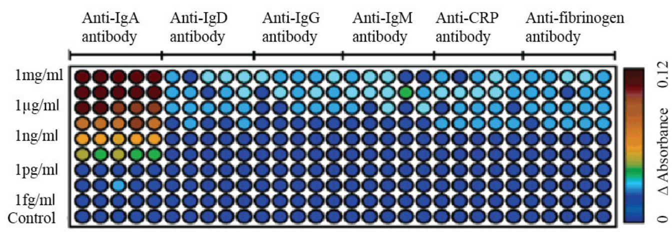
Sensing and Detection with Localized Surface Plasmons

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)

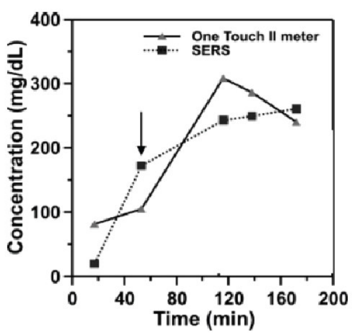


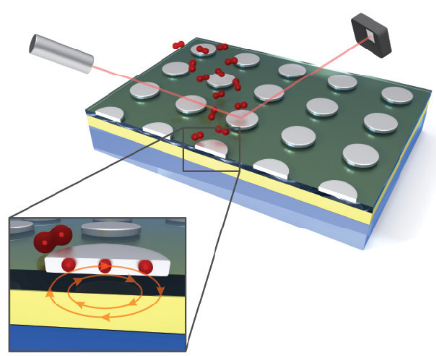






Immunoassay with immobilized immunotargeted gold nanospheres. T. Endo et al., *Multiple Label-Free Detection of Antigen-Antibody Reaction Using Localized Surface Plasmon* ... Anal. Chem. **78**, 6465-6475 (2006)





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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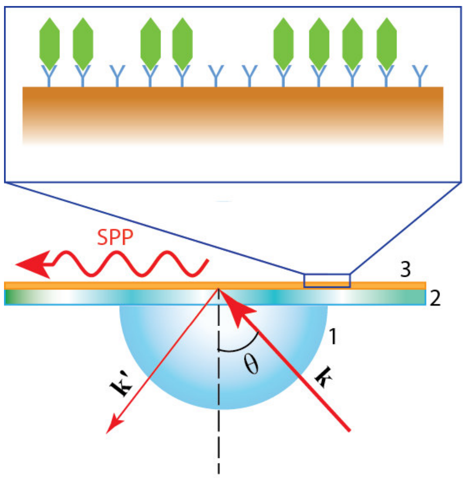
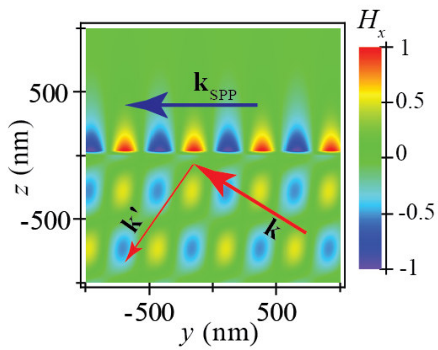
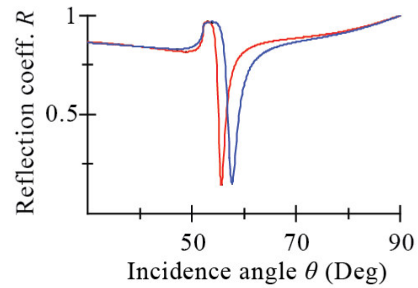
Surface Plasmon Polariton Sensors

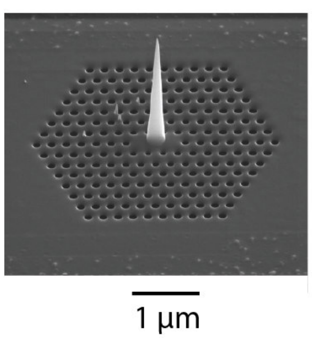


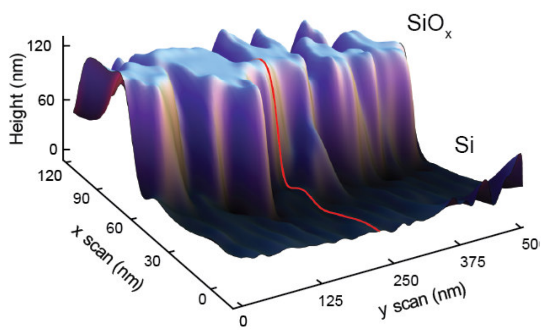


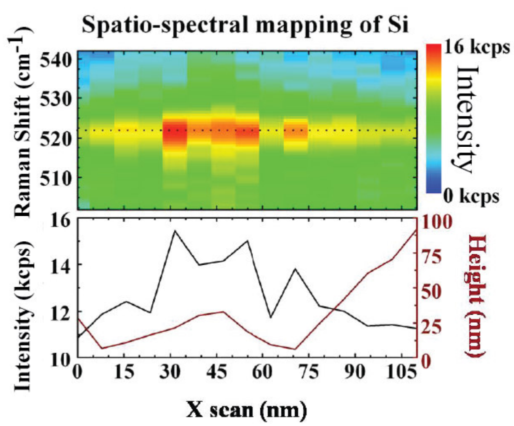


Surface plasmon polariton sensor based on Kretschmann geometry. Sensitivity~ 10^3 - 10^4 large molecules. See, e.g., http://www.biacore.com/

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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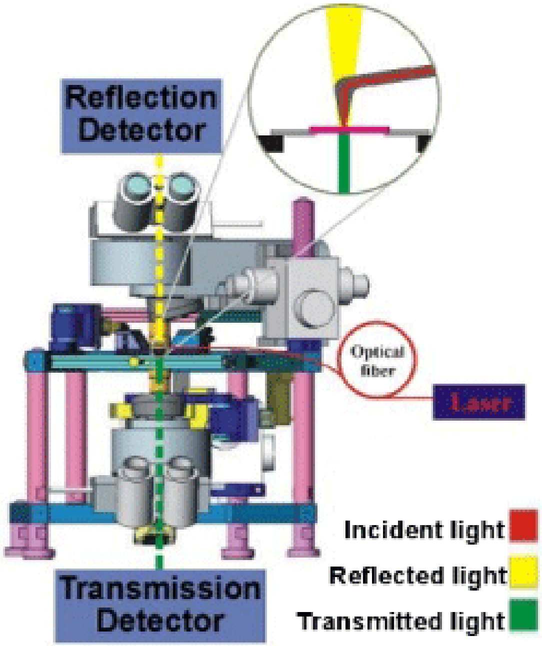
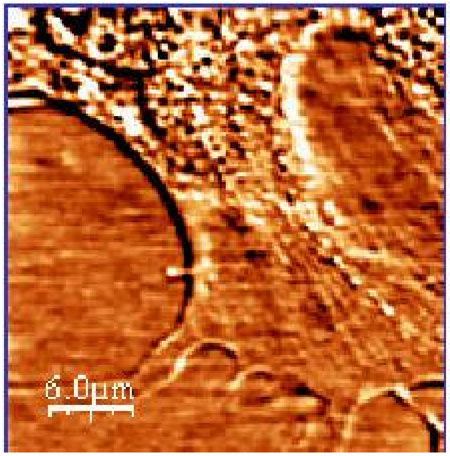
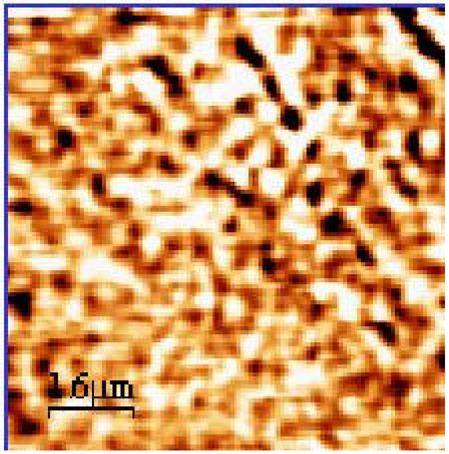
Plasmonic Nanoscopy

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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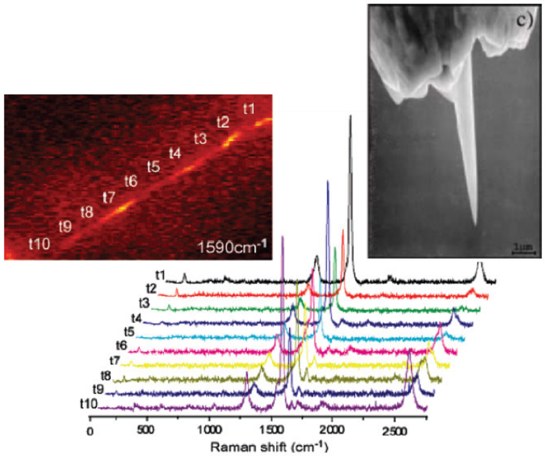
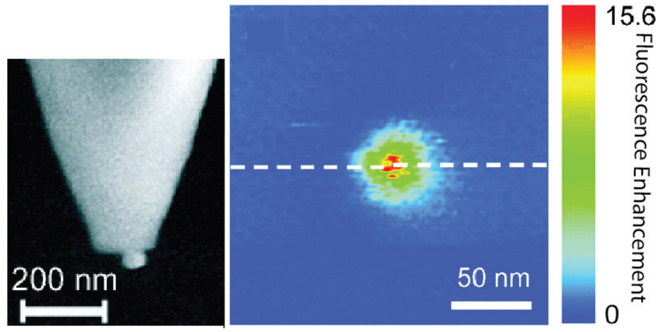
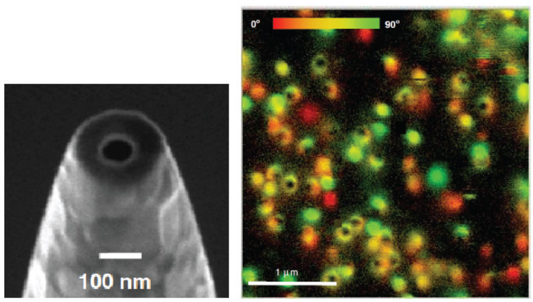
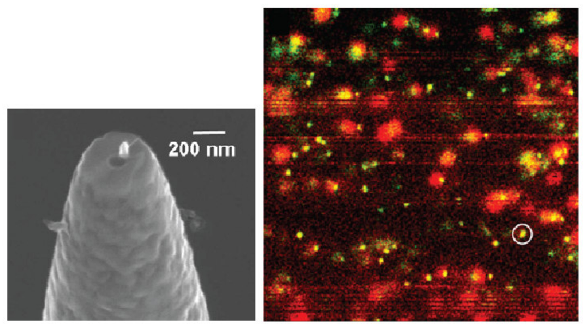
Plasmonic Nanoscopy



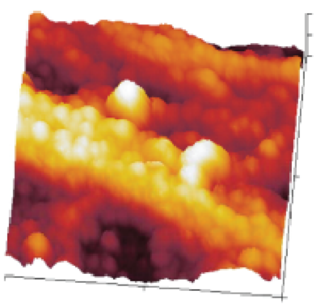


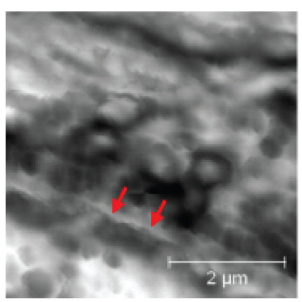
Left: Chemical vision: SERS image and spectra of a single-wall carbon nanotube obtained with a FIB-fabricated silver tip. L. Novotny and S. J. Stranick, Annual Rev. Phys. Chem. **57**, 303-331 (2006)
Right: Nanosphere probe and image of fluorescence enhancement of a single dye molecule. H. Eghlidi et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

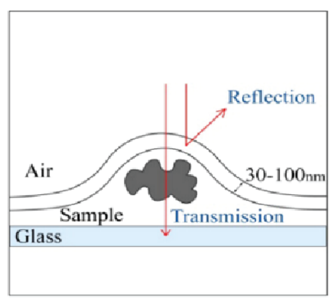




Left: Metallized tapered fiber probe and NSOM image of a single fluorescent molecules with polarization resolution.
Right: Nanoantenna-on-fiber probe and NSOM image of a single fluorescent molecules with polarization resolution. T. H. Taminiau, F. B. Segerink, R. J. Moerland, L. Kuipers, and N. F. van 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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- Introduction: Plasmonics and Nano-confinement of Optical Energy
- Nanoplasmonic Resonances and their Frequencies (Colors)
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- Plasmonic Enhancement and Ultrafast Nature of Plasmonics
- Nanolenses
- Applications of Nanoplasmonics
- Sensing and Detection
- Plasmonic Nanoscopy
- **Spaser as an Ultrafast Quantum Generator and Nanoamplifier (Theory)**
- Spaser (Experiment)

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Spasers explained

nature photonics | VOL 2 | JUNE 2008 |

MARK I. STOCKMAN
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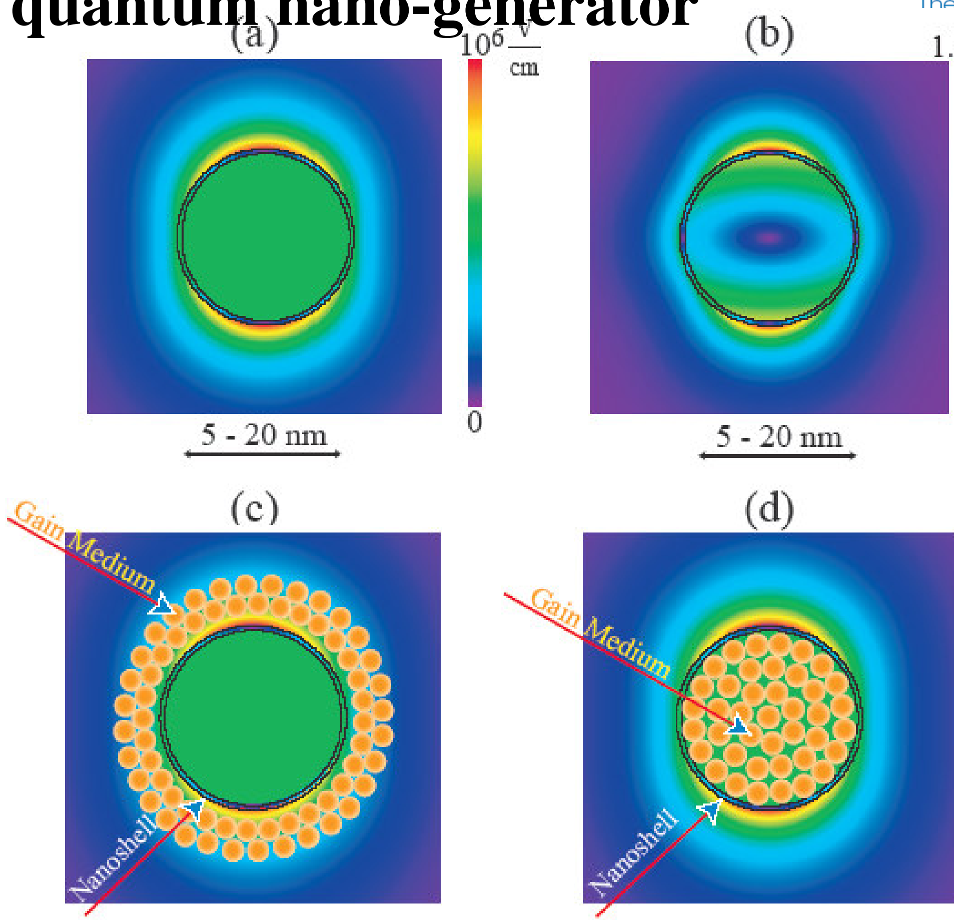
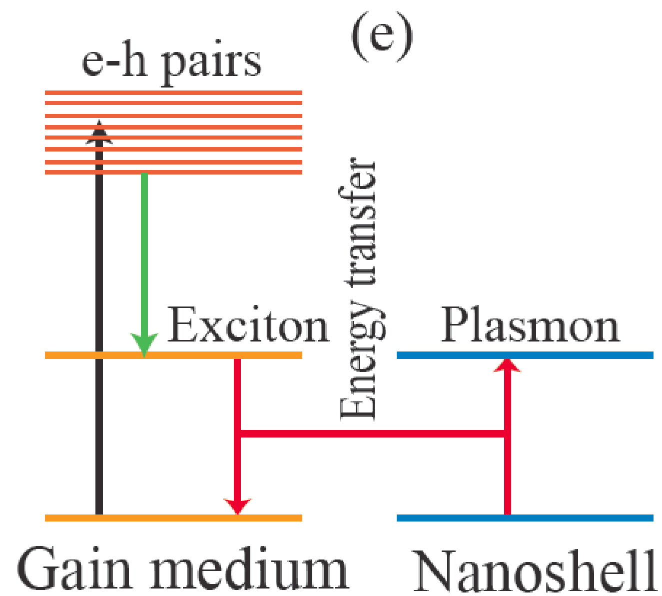
e-mail: mstockman@gsu.edu

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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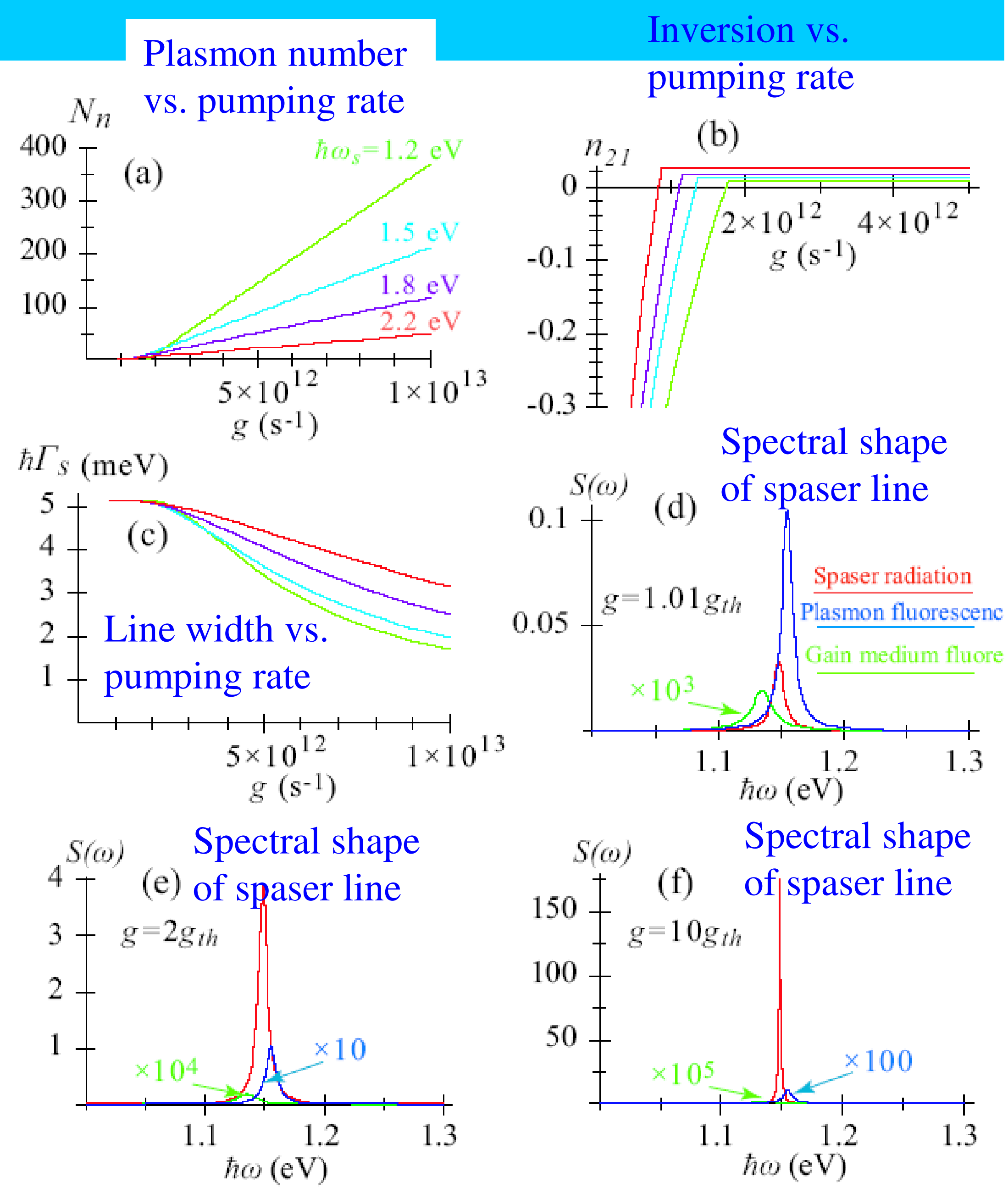
Stationary (CW) spaser regime

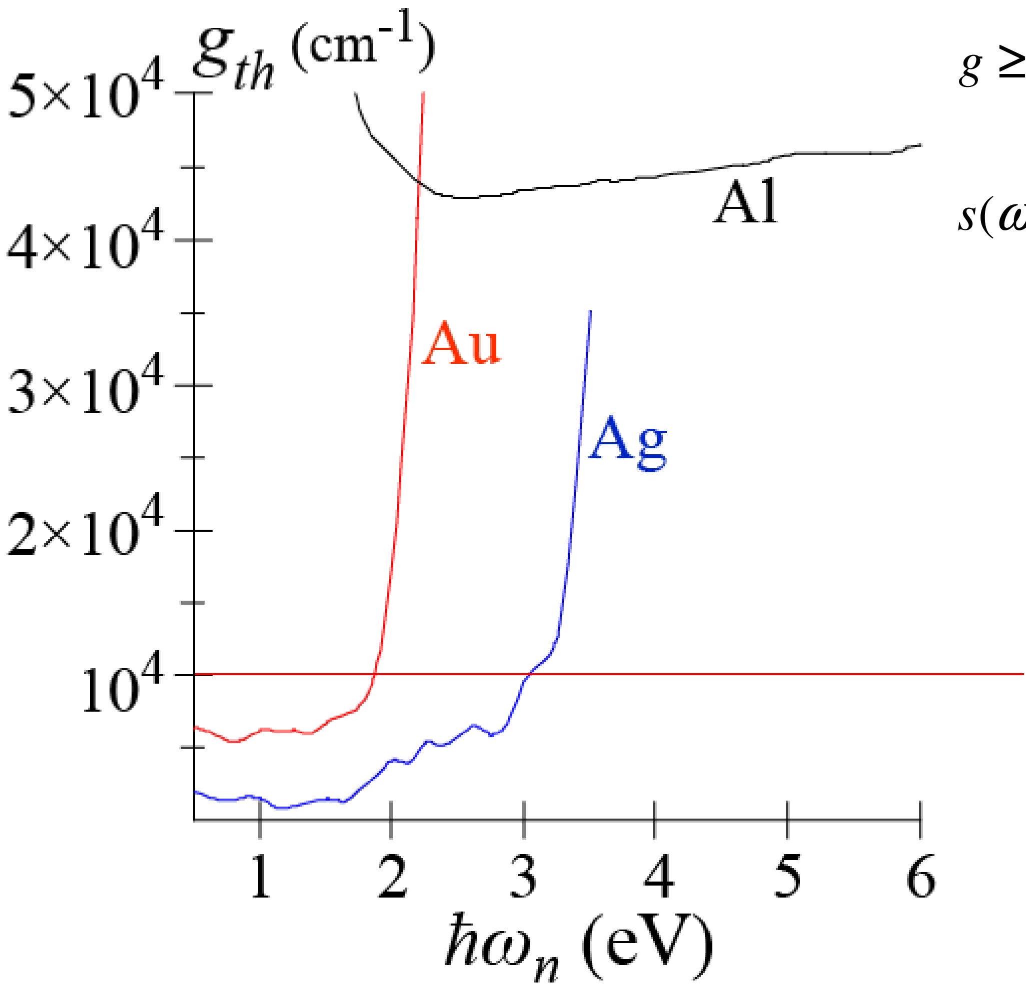
This quasilinear dependence of the number of plasmons per mode $N_n(g)$ is a result of the very strong feedback in spaser due to the small modal volume

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



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

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).



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

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

Realistic gain for direct band-gap semiconductors

Scaling of Spaser

Local optical field: $E \sim \frac{\sqrt{\hbar\omega}}{R^{3/2}}\sqrt{N_p} \sim \left(\frac{R}{10\ \text{nm}}\right)^{-3/2}\sqrt{N_p}\ \frac{\text{MV}}{\text{cm}}$

Heat per flop: $H = \hbar\omega N_p$

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

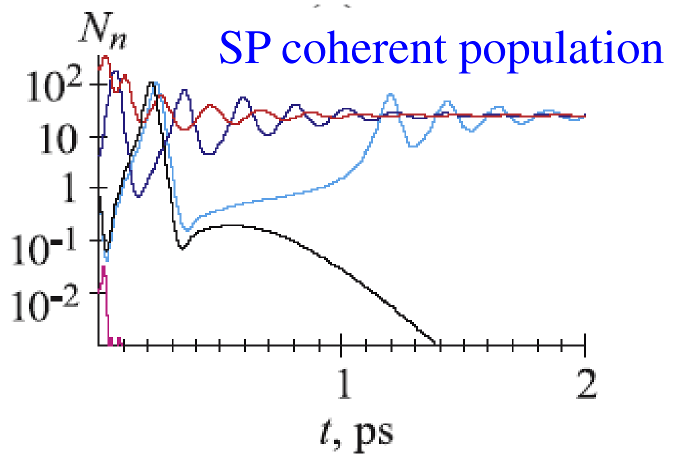
Switching time: $\tau \sim \frac{1}{\omega_R} \sim \left(\frac{R}{10\ \text{nm}}\right)^{3/2}\frac{100}{\sqrt{N_p}}\ \text{fs}$

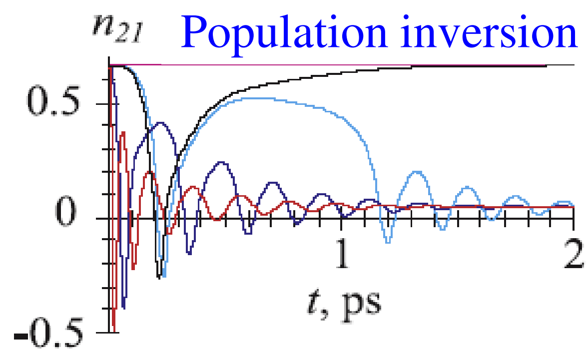
Conclusion: Spaser is orders of magnitude more efficient (less heat per flop) and much faster than transistor. It can operate close to the quantum limit ($\omega_R \sim \omega$).

Bandwidth ~ 10-100 THz
Very high resistance to ionizing radiation

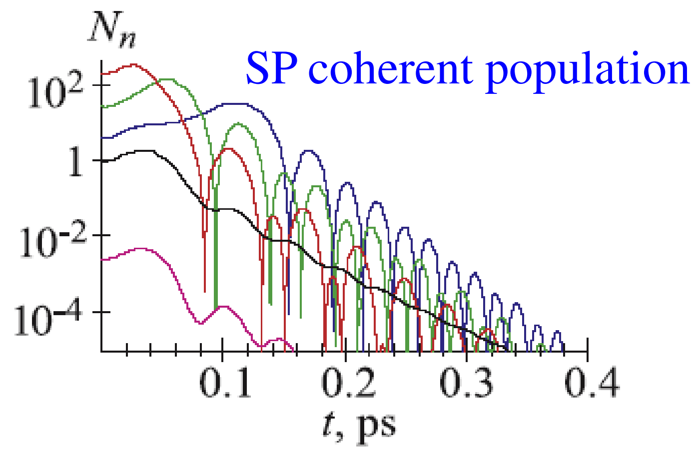
Amplification in Spaser with a Saturable Absorber (1/3 of the gain chromophores)

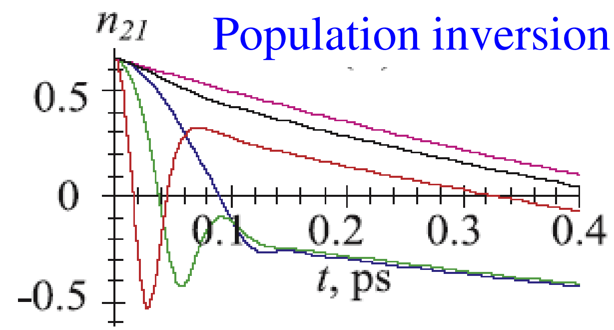
Stationary pumping





Pulse pumping





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- **Spaser (Experiment)**

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]

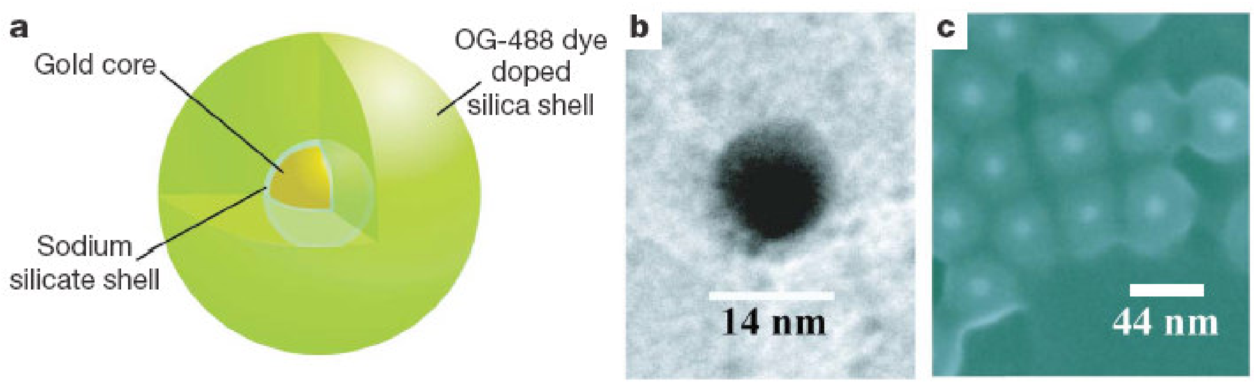

Figure 1 | Spaser design. a, Diagram of the hybrid nanoparticle architecture (not to scale), indicating dye molecules throughout the silica shell. **b**, Transmission electron microscope image of Au core. **c**, Scanning electron microscope image of Au/silica/dye core–shell nanoparticles. **d**, Spaser 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

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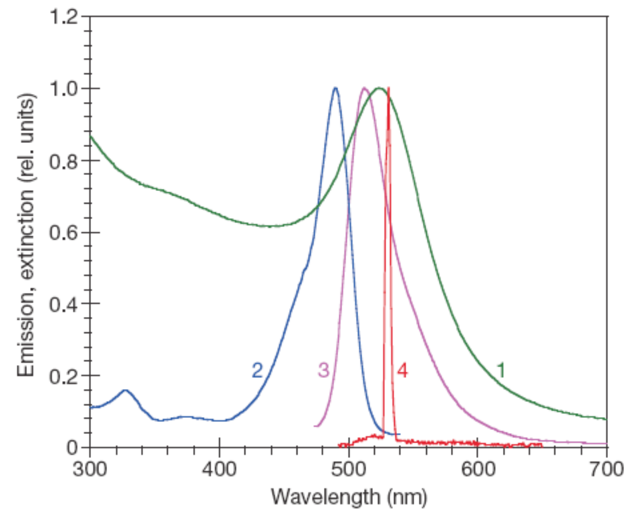

Figure 2 | Spectroscopic results. Normalized extinction (1), excitation (2), spontaneous emission (3), and stimulated emission (4) spectra of Au/silica/dye nanoparticles. The peak extinction cross-section of the nanoparticles is $1.1 \times 10^{-12}\ \mathrm{cm}^2$. The emission and excitation spectra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

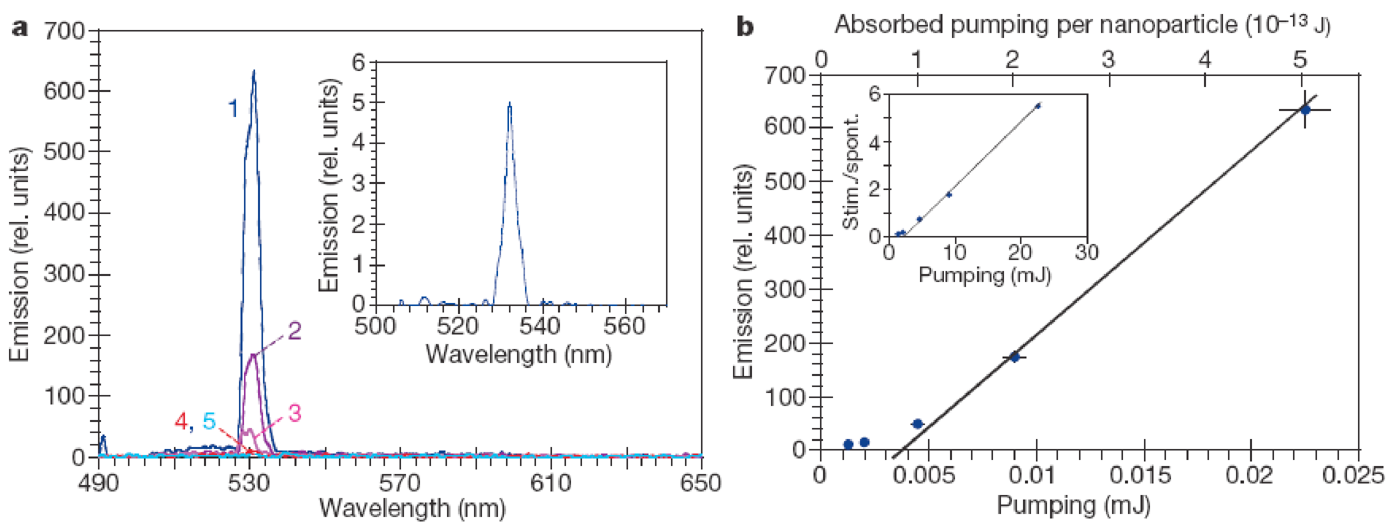

Figure 4 | Stimulated emission. a, Main panel, stimulated emission spectra of the nanoparticle sample pumped with 22.5 mJ (1), 9 mJ (2), 4.5 mJ (3), 2 mJ (4) and 1.25 mJ (5) 5-ns optical parametric oscillator pulses at $\lambda = 488$ nm. **b**, Main panel, corresponding input–output curve (lower axis,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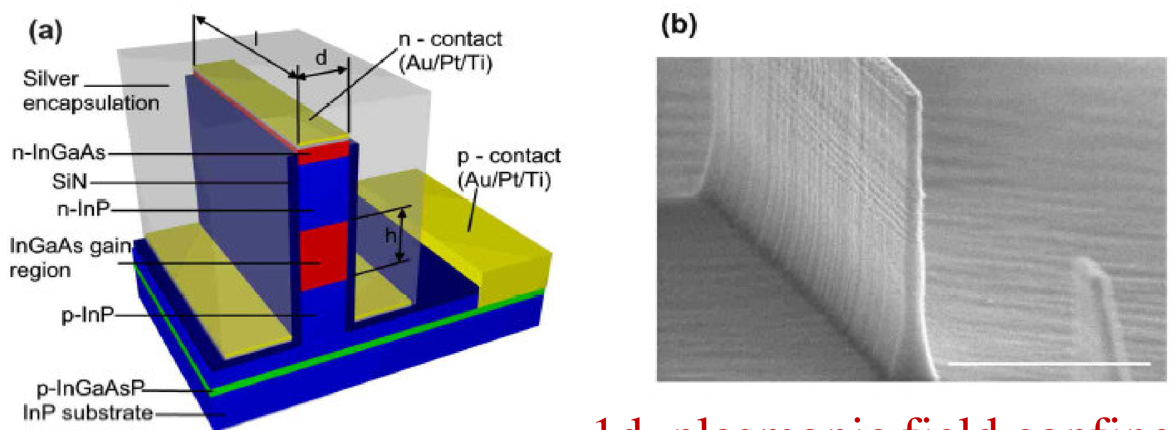


1d plasmonic field confinement

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.

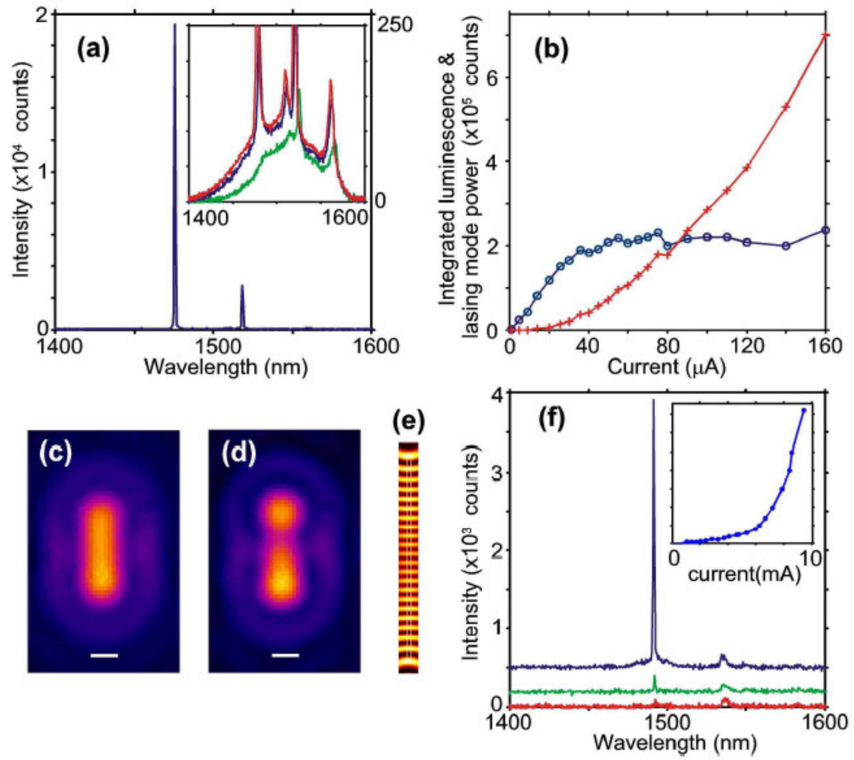


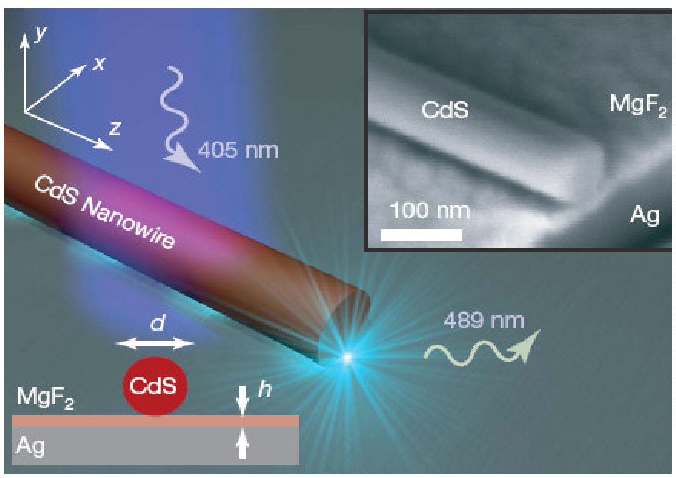
Fig. 2. Spectra and near field patterns showing lasing in devices. (a) Above threshold emission spectrum for 3 micron long device with semiconductor core width d~130nm (± 20nm), with pump current 180 μA at 78K. Inset: emission spectra for 20 (green), 40 (blue) and 60 (red) μA, all at 78K. (b) Lasing 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.

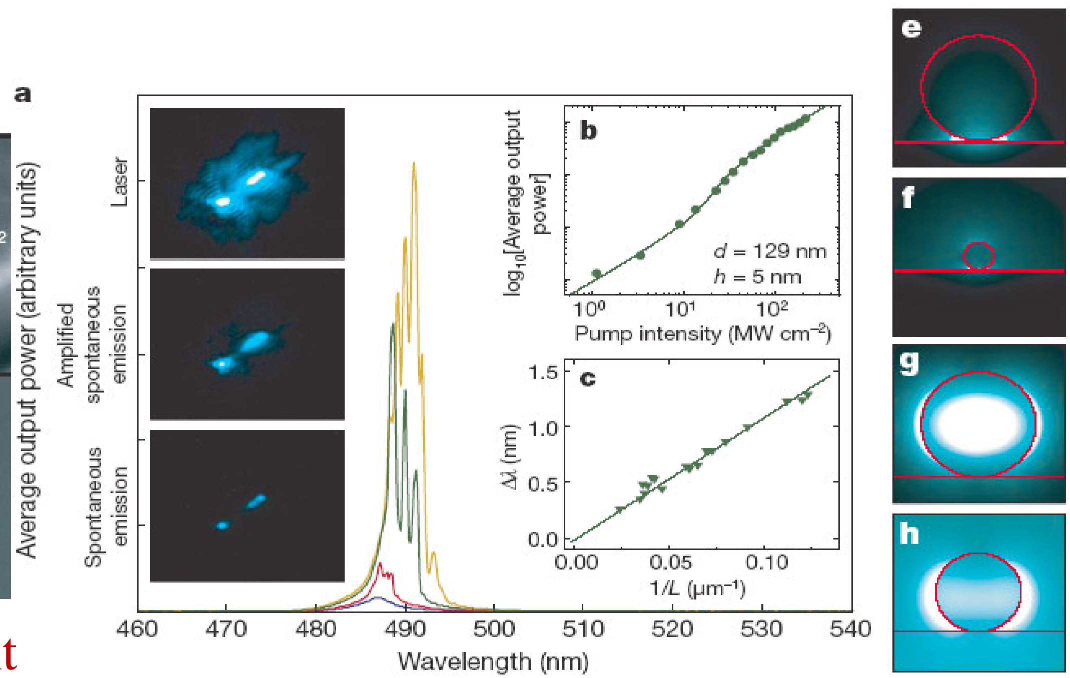
doi:10.1038/nature08364 nature

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]





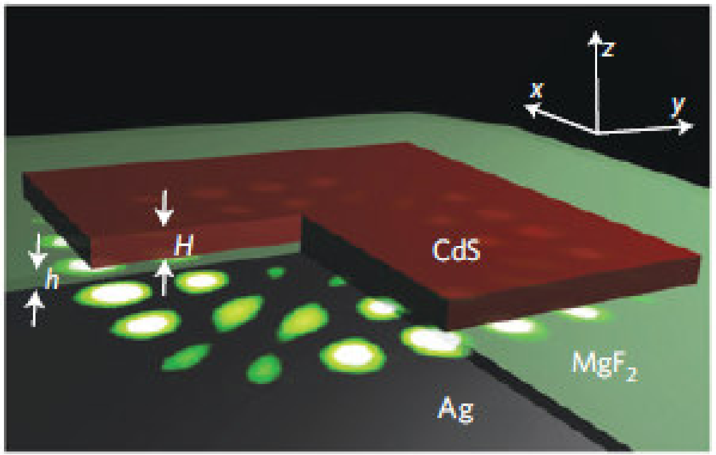
2d plasmonic field confinement

nature materials
LETTERS
PUBLISHED ONLINE: 19 DECEMBER 2010 | DOI: 10.1038/NMAT2919

Room-temperature sub-diffraction-limited plasmon laser by total internal reflection

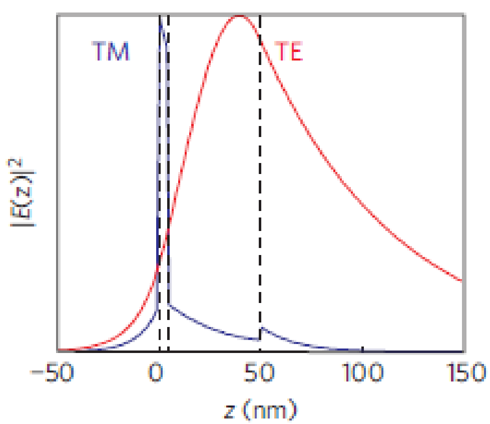
Ren-Min Ma[1†], Rupert F. Oulton[1†], Volker J. Sorger[1], Guy Bartal[1] and Xiang Zhang[1,2]*

a



1d +2d plasmonic field confinement

c



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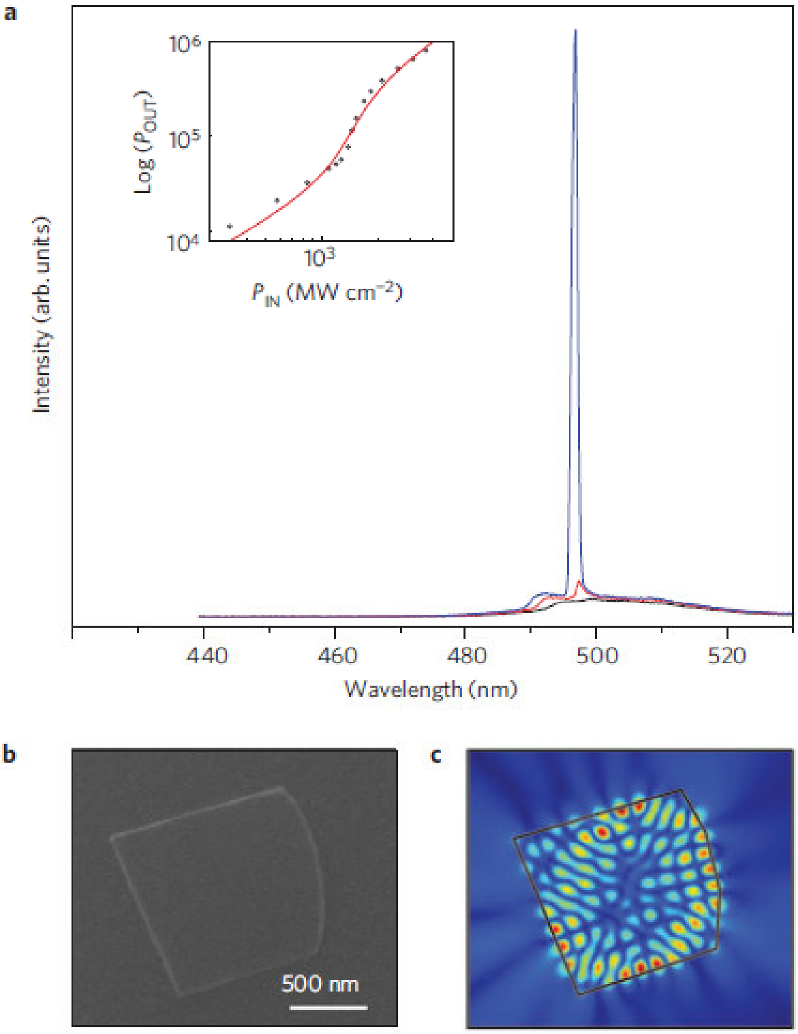

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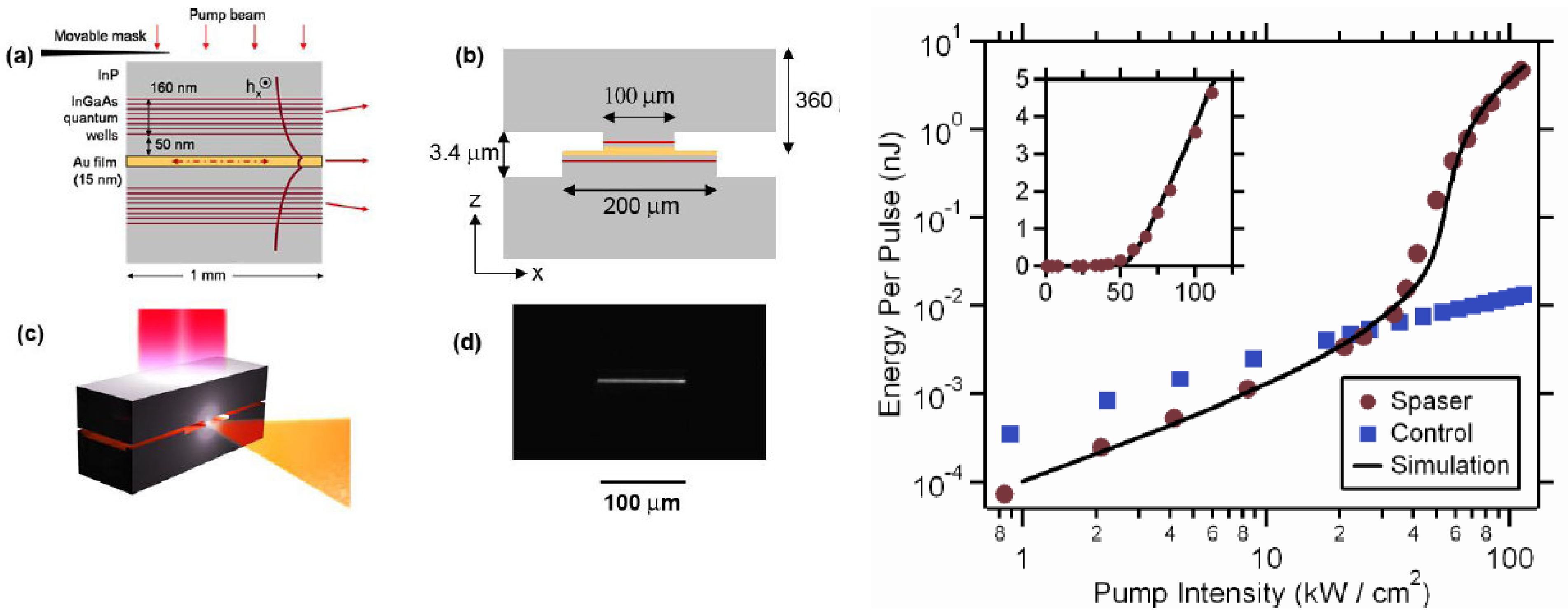
A room-temperature semiconductor spaser operating near 1.5 μm

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



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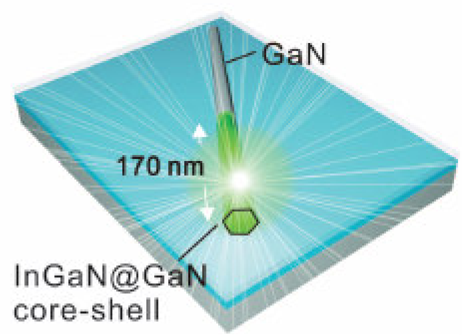
Atlanta, GA 3(

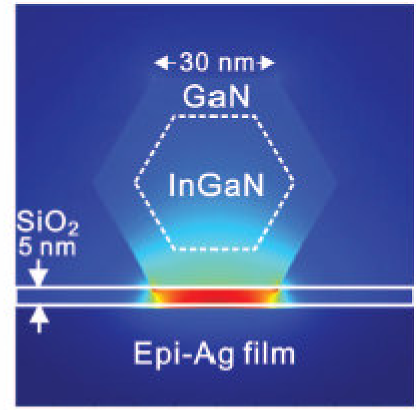
Plasmonic Nanolaser Using Epitaxially Grown Silver Film

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 AAAS

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





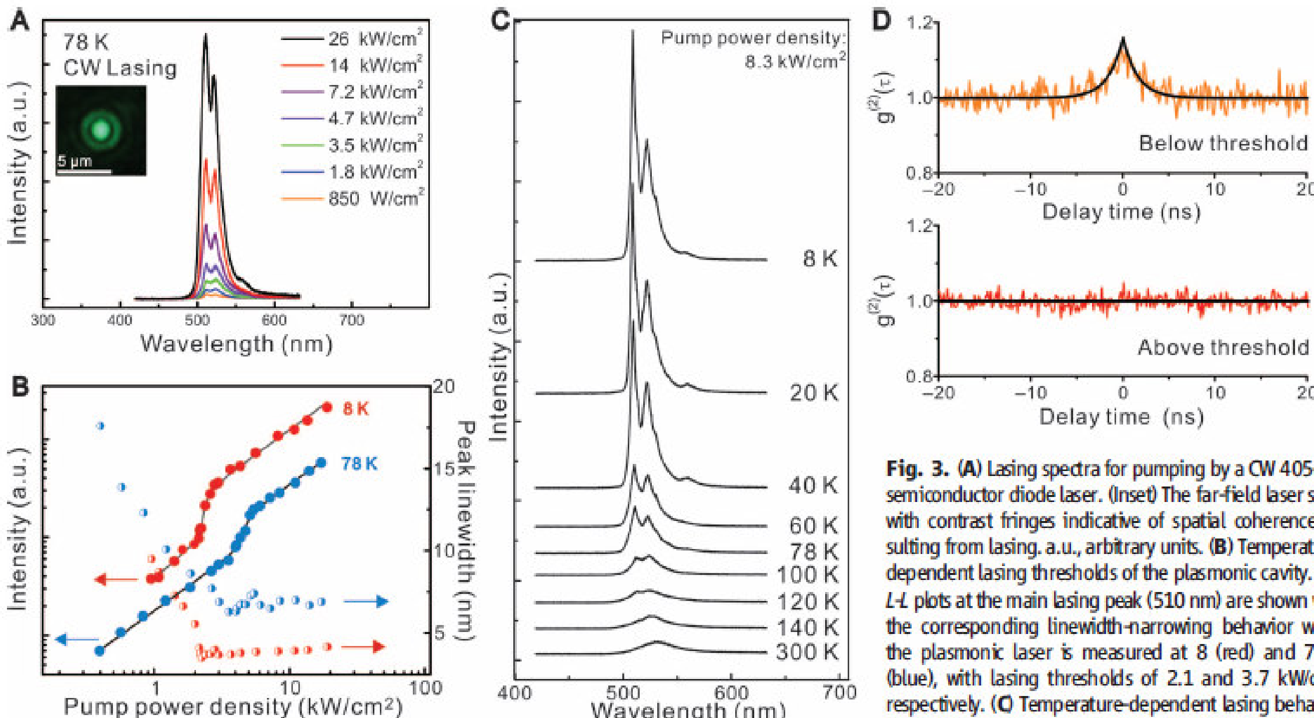
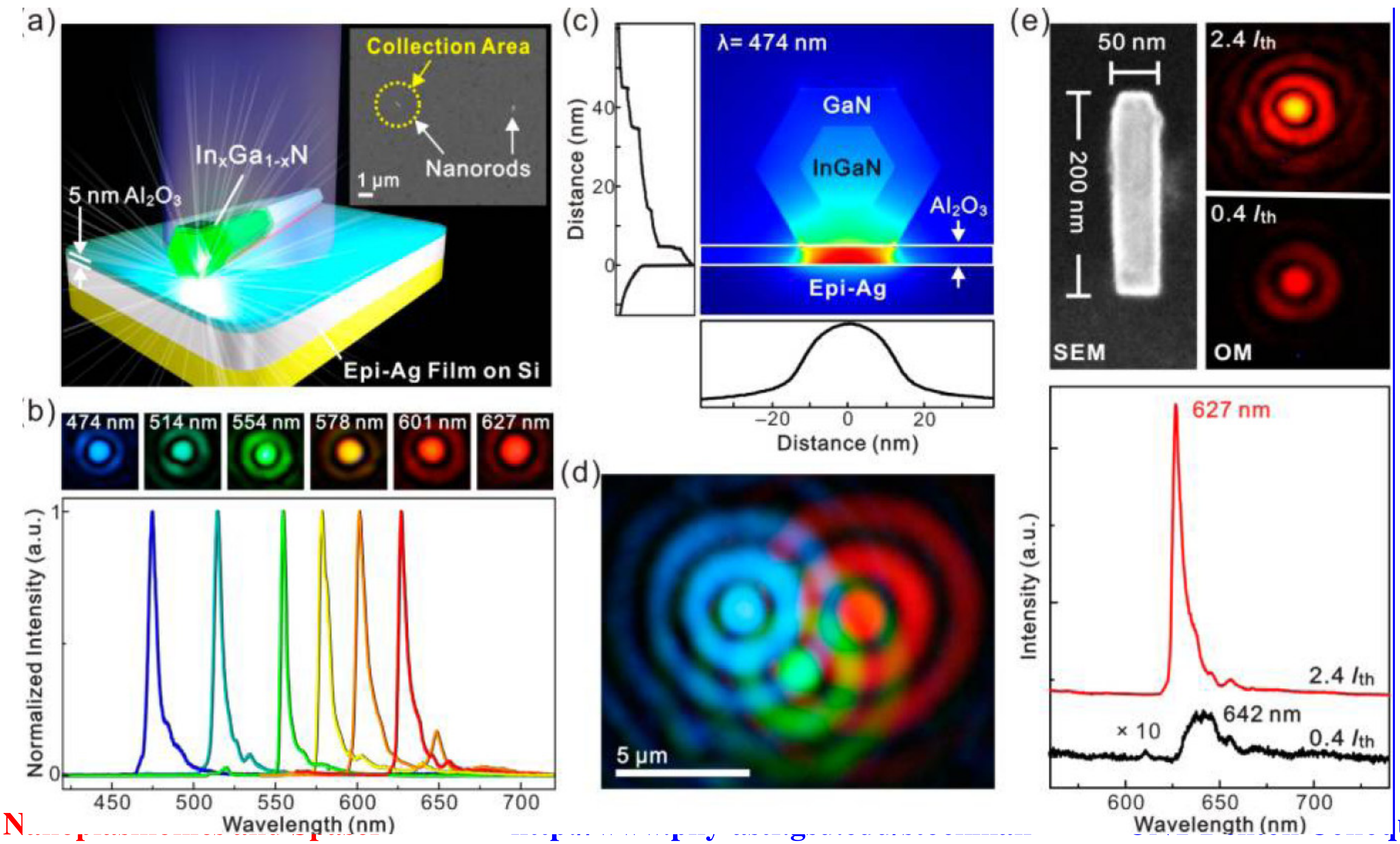


Fig. 3. (A) Lasing spectra for pumping by a CW 405-nm semiconductor diode laser. (Inset) The far-field laser spot, with contrast fringes indicative of spatial coherence resulting from lasing. a.u., arbitrary units. **(B)** Temperature-dependent lasing thresholds of the plasmonic cavity. The *L-L* plots 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.

NANO LETTERS
Letter
pubs.acs.org/NanoLett
dx.doi.org/10.1021/nl501273u
Y.-J. Lu *et al.*, Nano Lett. **14**, 4381 (2014)

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

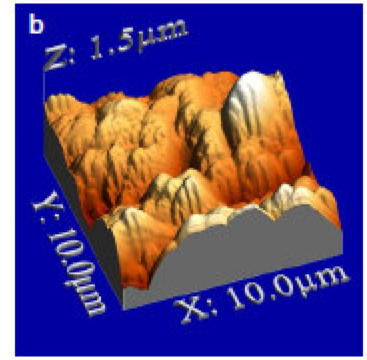
Yu-Jung Lu,[†] Chun-Yuan Wang,[†] Jisun Kim,[‡] Hung-Ying Chen,[†] Ming-Yen Lu,[‖] Yen-Chun Chen,[⊥] Wen-Hao Chang,[⊥] Lih-Juann Chen,[‖] Mark I. Stockman,[§,#,¶] Chih-Kang Shih,[*,‡] and Shangjr Gwo[*,†]



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

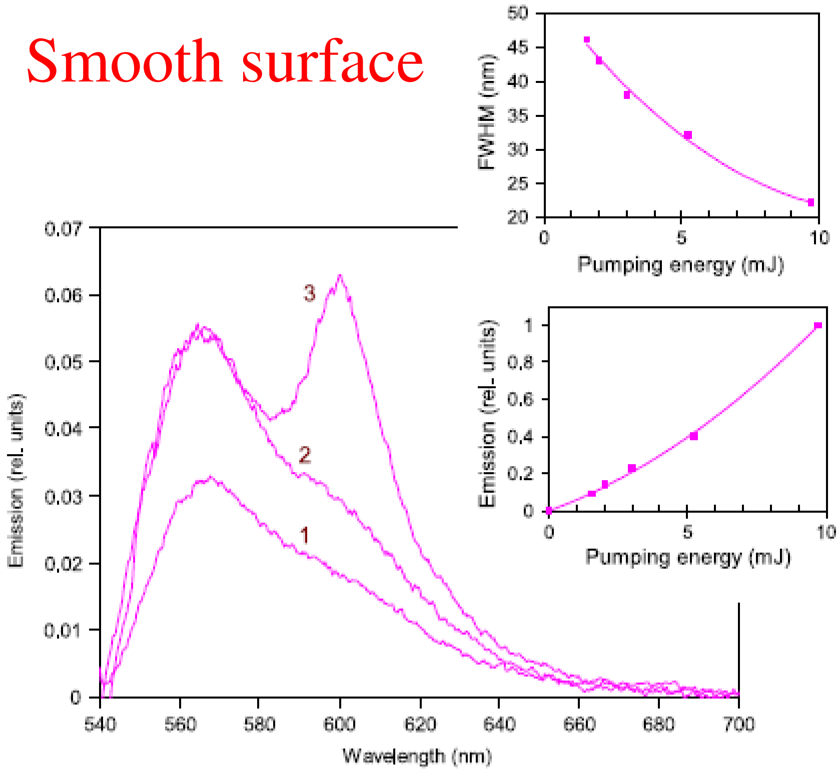
Stimulated emission of surface plasmon polaritons on smooth and corrugated silver surfaces

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



Random Spaser

Smooth surface



Rough surface

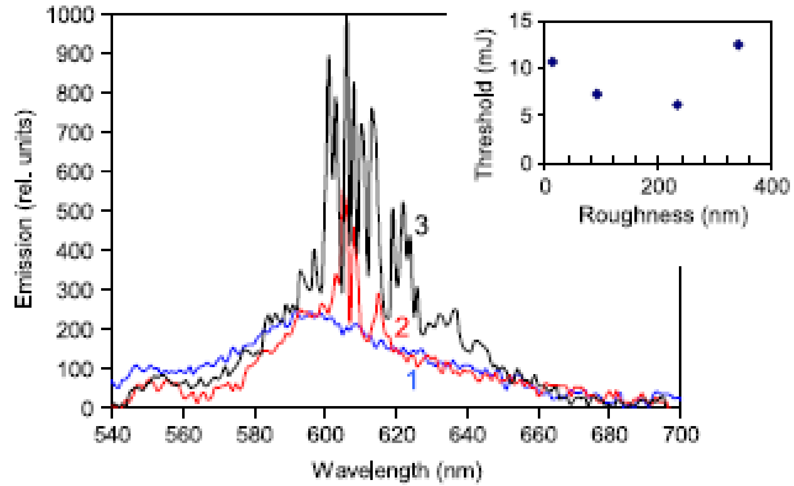


Figure 5. Emission spectra in the RB:PMMA film deposited on a roughened silver with surface roughness equal to 234 nm, pumped with 7 mJ (1), 13 mJ (2) and 20 mJ (3) laser pulses. Inset: stimulated emission threshold as a function of the surface roughness.

Surface plasmon lasing observed in metal hole arrays

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

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*
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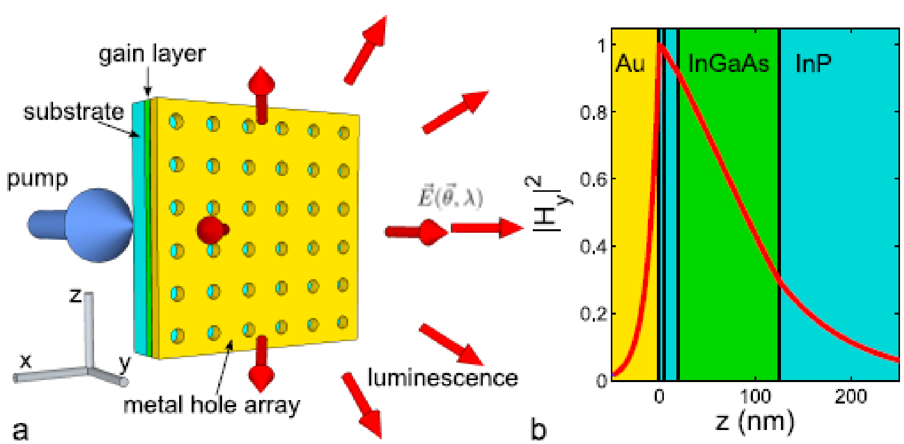
[3] *Philips Research Laboratories, Prof. Holstlaan 4, 5656 AA Eindhoven, Netherlands*

See also: W. Zhou, M. Dridi, J. Y. Suh, C. H. Kim, D. T. Co, M. R. Wasielewski, G. C. Schatz, and T. W. Odom, *Lasing Action in Strongly Coupled Plasmonic Nanocavity Arrays,* Nature Nanotechnology **8**, 506-511 (2013)



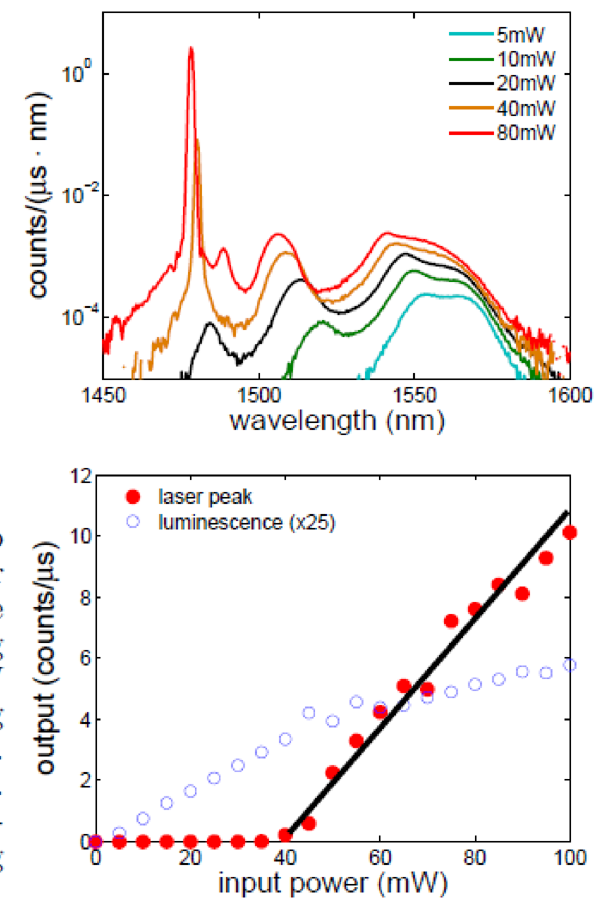
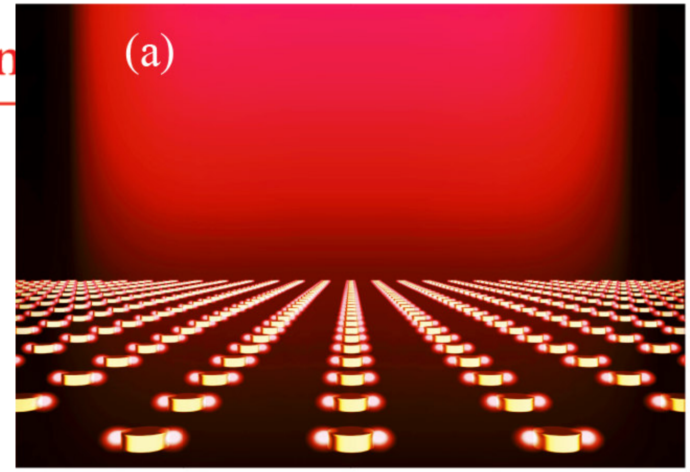


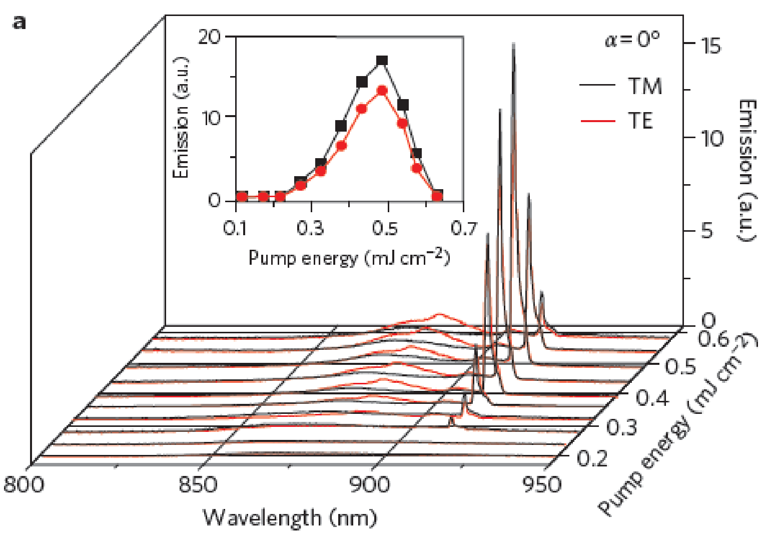
FIG. 2. (a) Luminescence spectra as a function of pump power, plotted on a semilog scale. For increasing pump power the bandwidth of the luminescence increases until the device starts lasing. Above threshold, the emission of the non-lasing resonances starts to saturate at a maximum intensity. 80 mW corresponds 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).

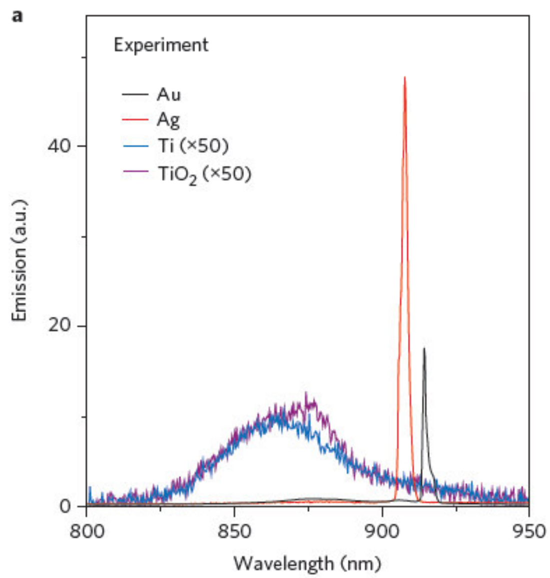
LETTERS
PUBLISHED ONLINE: 16 JUNE 2013 | DOI: 10.1038/NNANO.2013.99
nature nanotechn

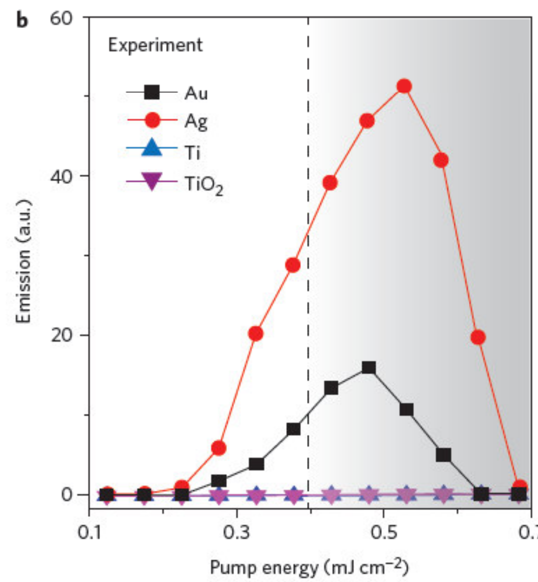
Lasing action in strongly coupled plasmonic nanocavity arrays

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]*









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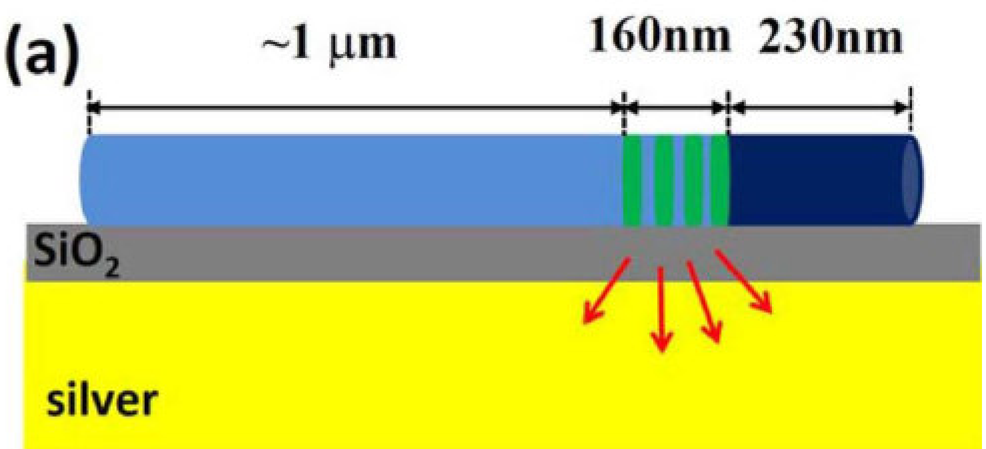
Room temperature plasmonic lasing in a continuous wave operation mode from an InGaN/GaN single nanorod with a low threshold

Y. Hou, P. Renwick, B. Liu, J. Bai & T. Wang

SCIENTIFIC REPORTS | 4 : 5014 | DOI: 10.1038/srep0501



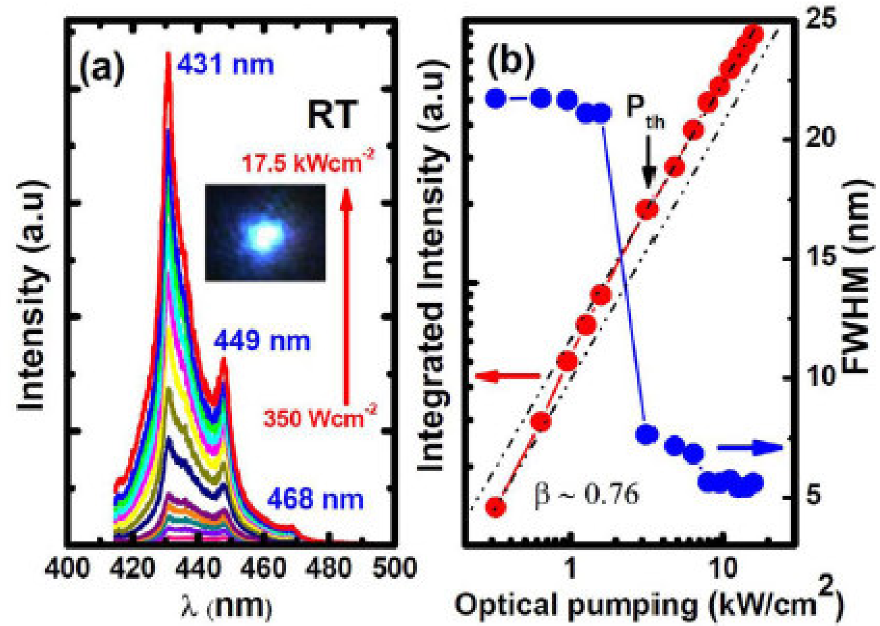


Figure 2 | (a) Lasing spectra from our nano-SPASER recorded as a function of optical pumping at room temperature. Inset showing the far-field laser spot; (b) L-L curve plotted in a log-log scale and FWHM as a function of optical pumping, respectively. The dash-lines are guides to eyes.

Graphene spaser

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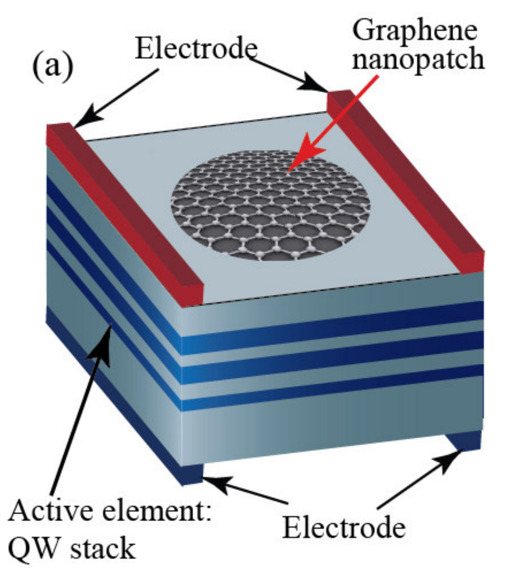
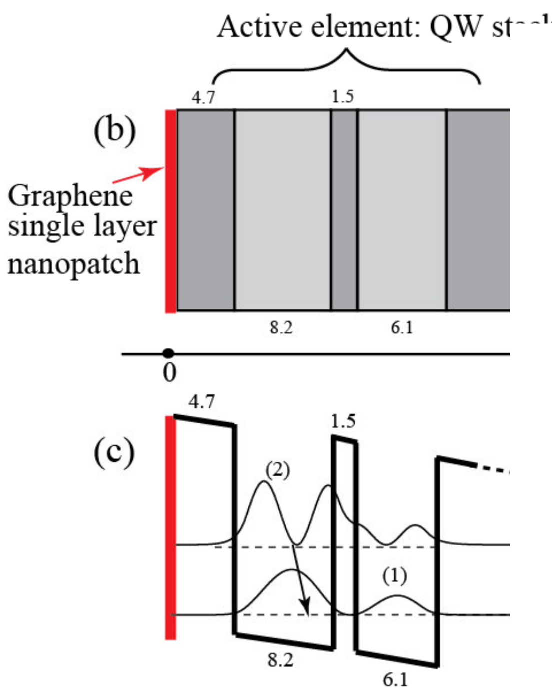
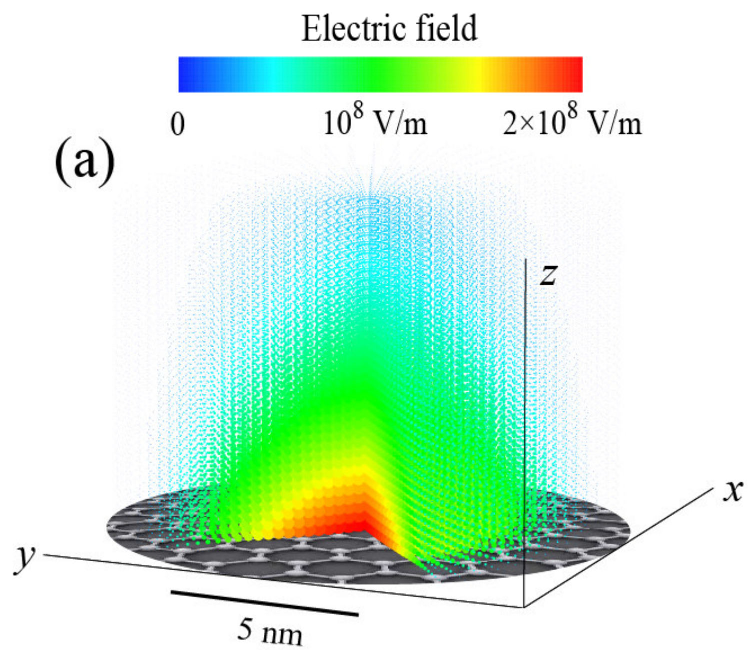
[2]*Fakultät für Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, D-80539 München, Germany*
[3]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*
(Dated: May 10, 2013)

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).







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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*]

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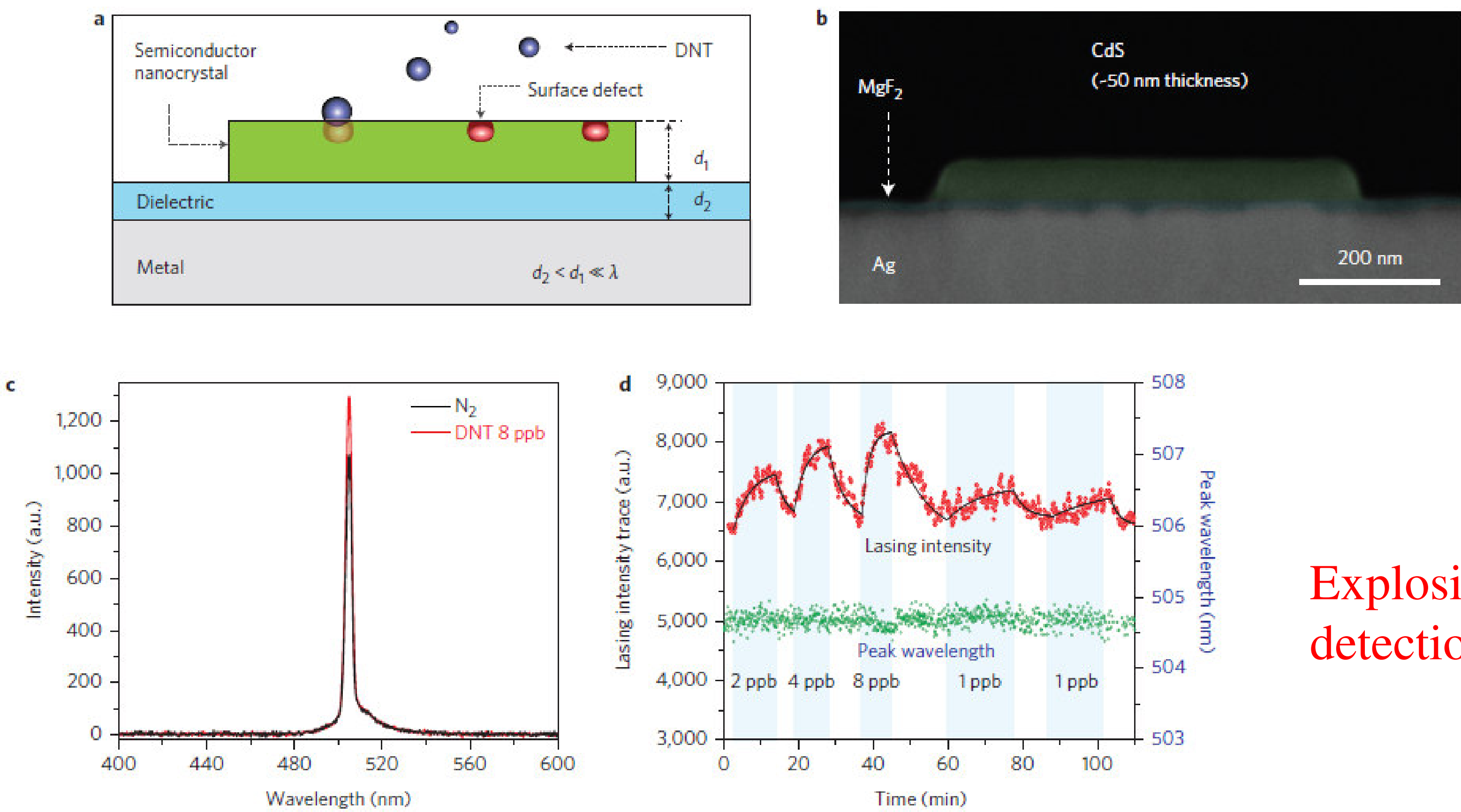

Explosive (DNT) detection

NATURE PHYSICS | **ARTICLE**

Ultrafast plasmonic nanowire lasers near the surface plasmon frequency

Themistoklis P. H. Sidiropoulos, Robert Röder, Sebastian Geburt, Ortwin Hess, Stefan A. Maier, Carsten Ronning & Rupert F. Oulton

Nature Physics (2014) doi:10.1038/nphys3103
Received 14 April 2014 Accepted 19 August 2014 Published online 28 September 2014

Abstract

Light–matter interactions are inherently slow as the wavelengths of optical and electronic states differ greatly. Surface plasmon polaritons — electromagnetic excitations at metal–dielectric interfaces — have generated significant interest because their spatial scale is decoupled from the vacuum wavelength, promising accelerated light–matter interactions. Although recent reports suggest the possibility of accelerated dynamics in surface plasmon lasers, this remains to be verified. Here, we report the observation of pulses shorter than 800 fs from hybrid plasmonic zinc oxide (ZnO) nanowire lasers. Operating at room temperature, ZnO excitons lie near the surface plasmon frequency in such silver-based plasmonic lasers, leading to accelerated spontaneous recombination, gain switching and gain recovery compared with conventional ZnO nanowire lasers. Surprisingly, the laser dynamics can be as fast as gain thermalization in ZnO, which precludes lasing in the thinnest nanowires (diameter less than 120 nm). The capability to combine surface plasmon localization with ultrafast amplification provides the means for generating extremely intense optical fields, with applications in sensing, nonlinear optical switching, as well as in the physics of strong-field phenomena.

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3. Lu, Y-J. *et al*. Plasmonic nanolaser using epitaxially grown silver film. *Science* **337**, 450–453 (2012).
4. Oulton, R. F. Surface plasmon lasers: Sources of nanoscopic light. *Mater. Today* **15**, 592–600 (2012).

Spaser as Versatile Biomedical Tool

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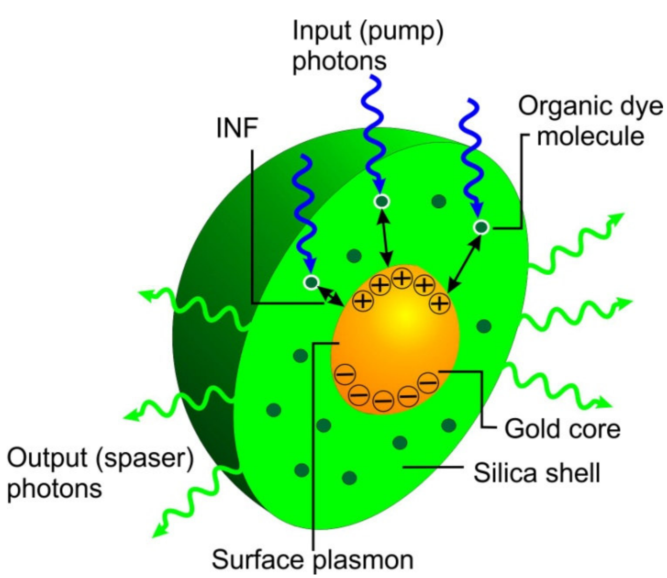
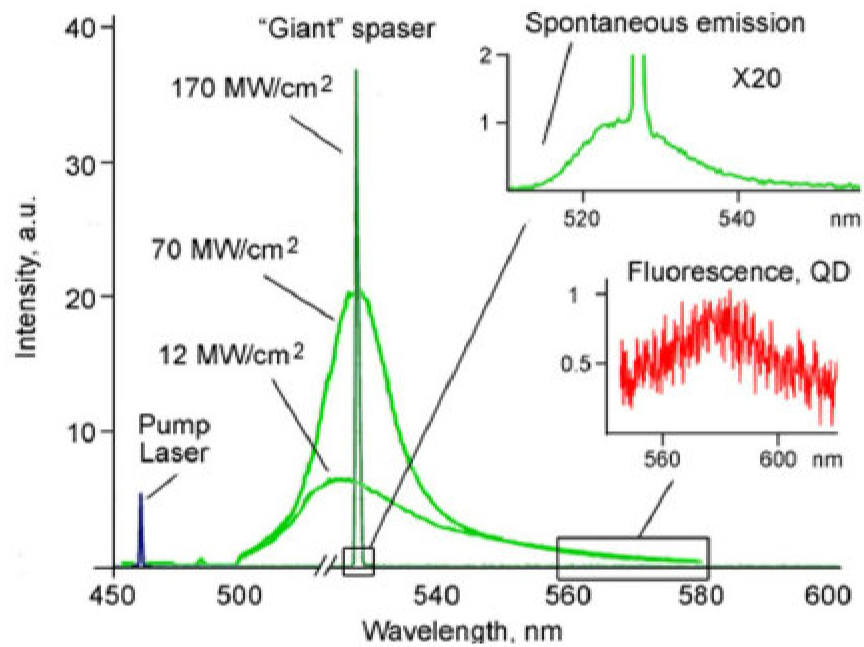
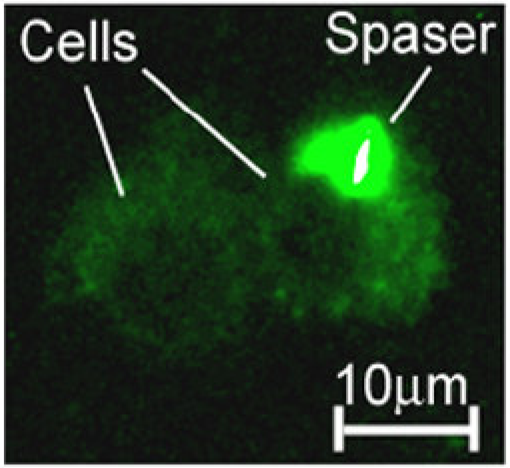
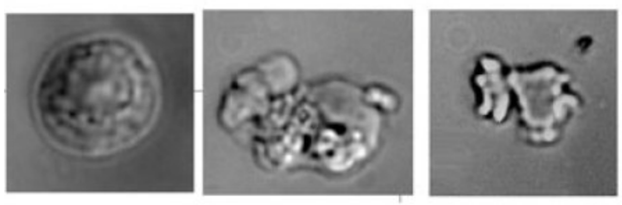
Science (Submitted)

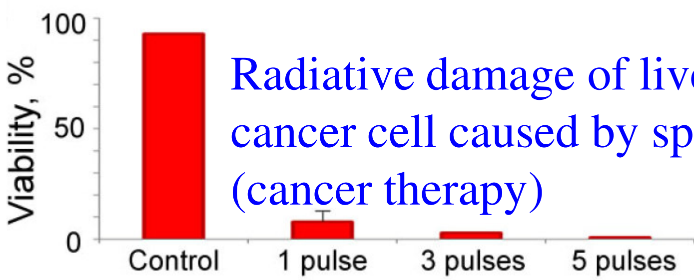




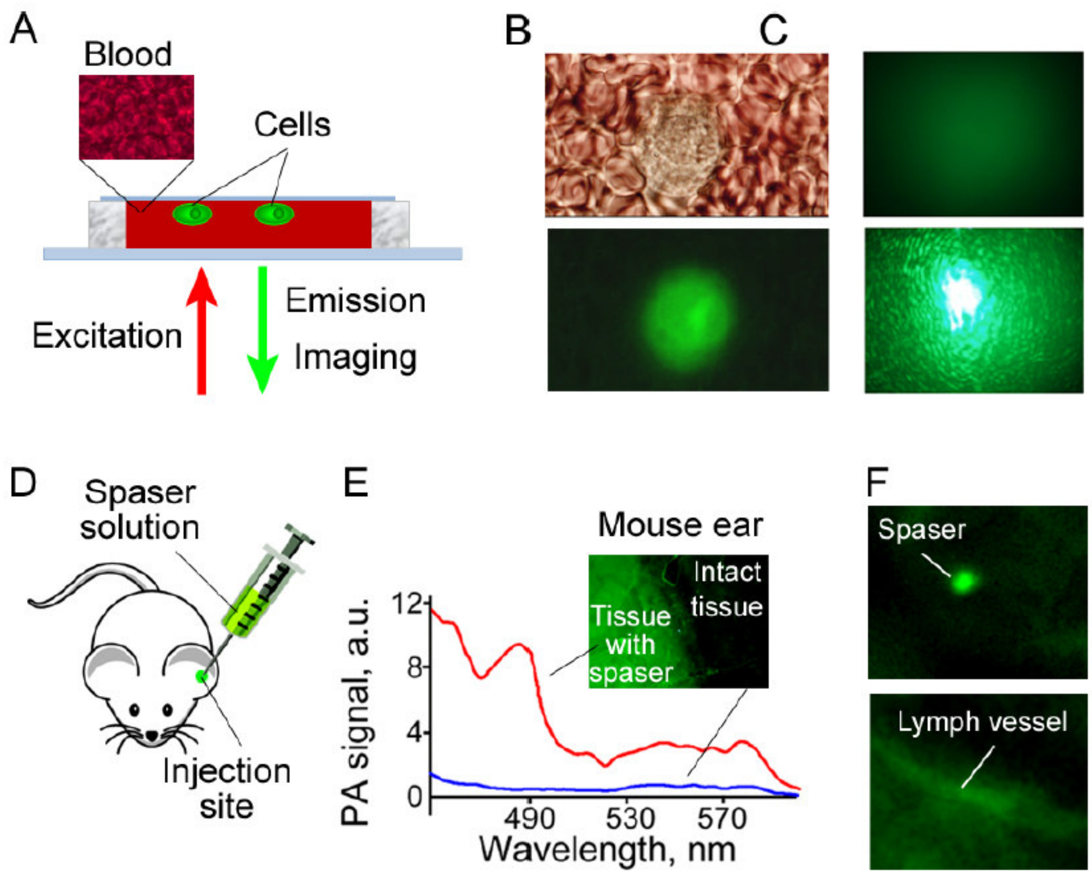


Radiation of spaser inside live cancer cell





Radiative damage of live cancer cell caused by spasers (cancer therapy)



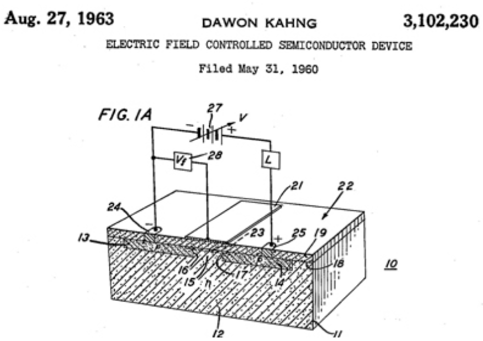
Radiation of spaser in a blood vessel model and *in vivo*

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*

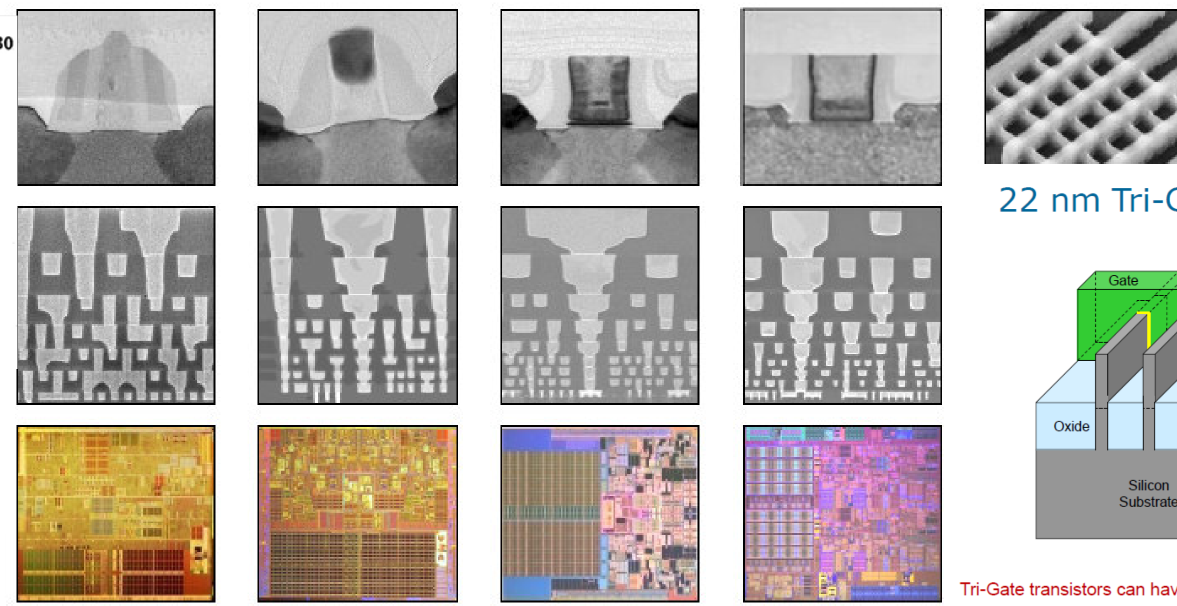
Abstract:
A 32nm logic technology for high performance microprocessors is described. 2nd generation high-k + metal gate transistors provide record drive currents at the tightest gate pitch reported for any 32 nm or 28nm logic technology. NMOS drive currents are 1.62mA/um Idsat and 0.231mA/um Idlin at 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

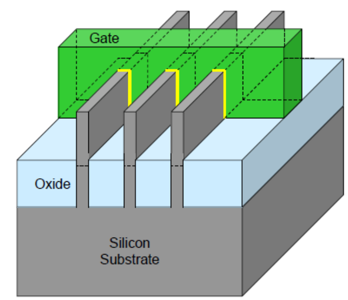


Speed ~ 100-300 GHz
Low resistance to ionizing radiation

90 nm	65 nm	45 nm	32 nm	22 nm
2003	2005	2007	2009	2011



22 nm Tri-Gate Transistor

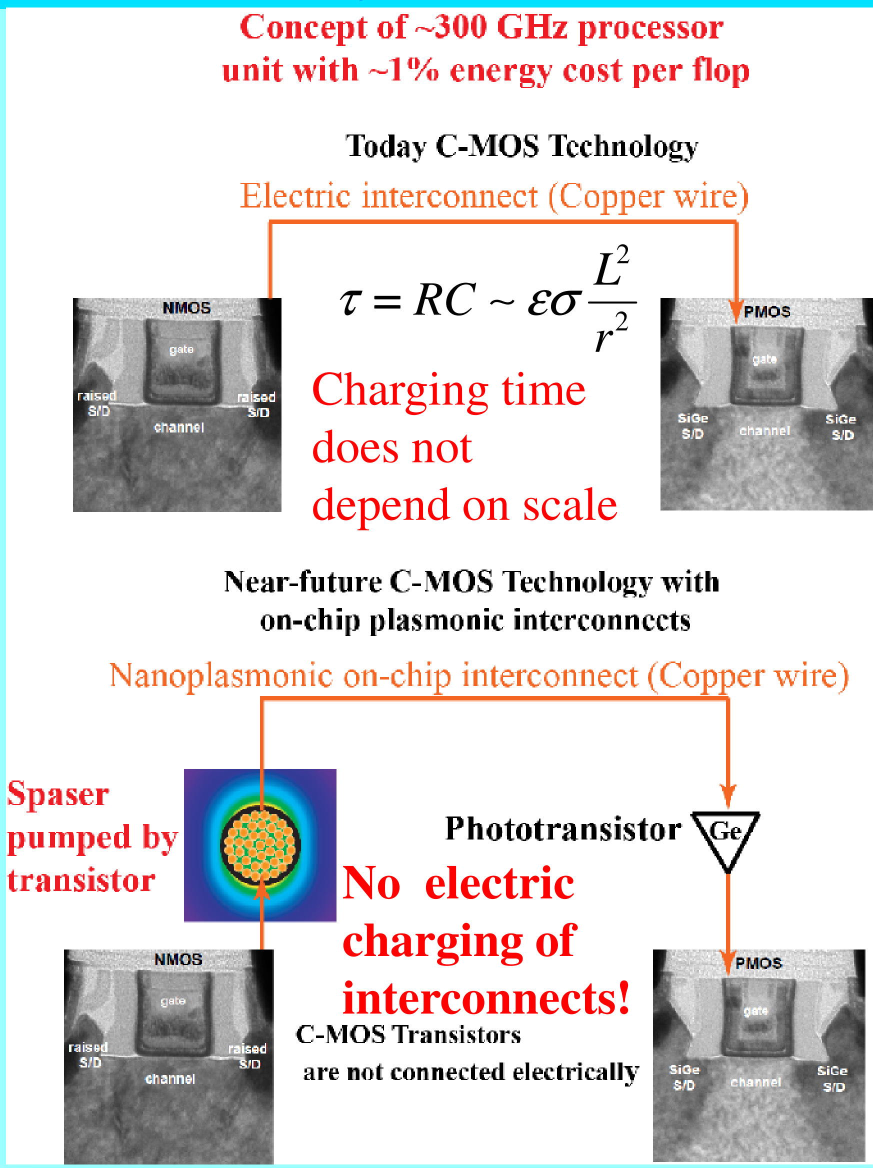


Tri-Gate transistors can have multiple fins connected together to increase total drive strength for higher performance

Processor speed :

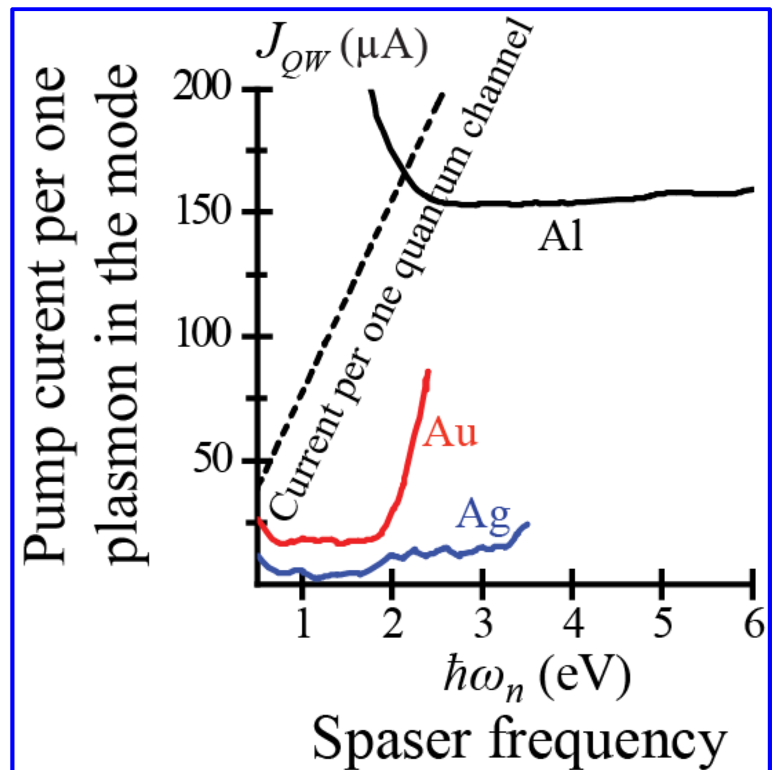
$$f_{\max} = I_{\text{drive}} / \left(C_{\text{Intercon}} \Delta U \right) \sim 3 \text{ GHz}$$

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



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

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




The End

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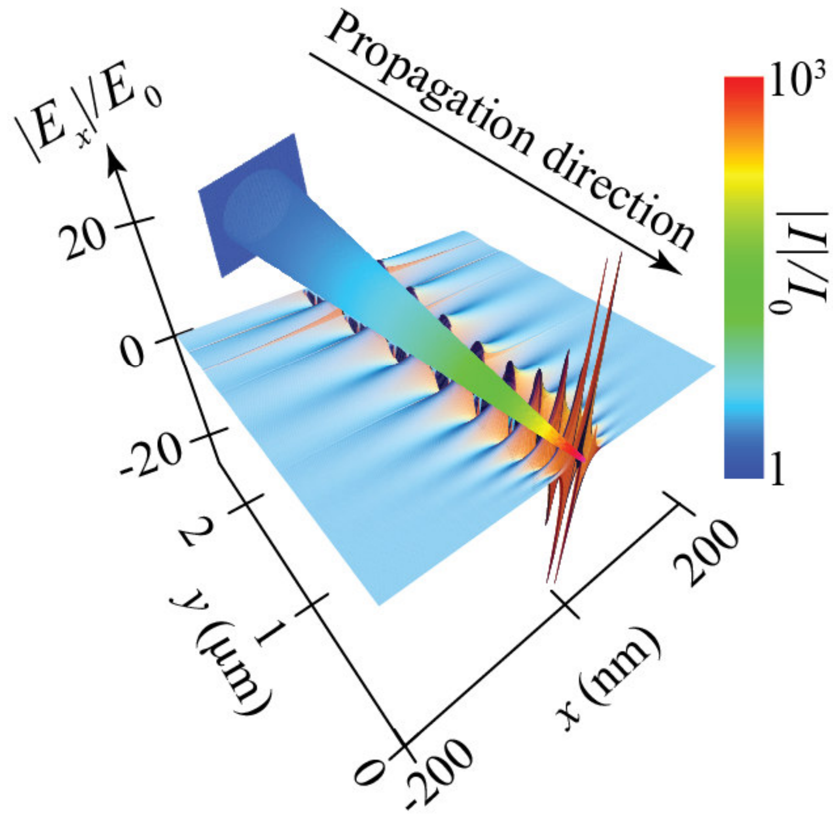
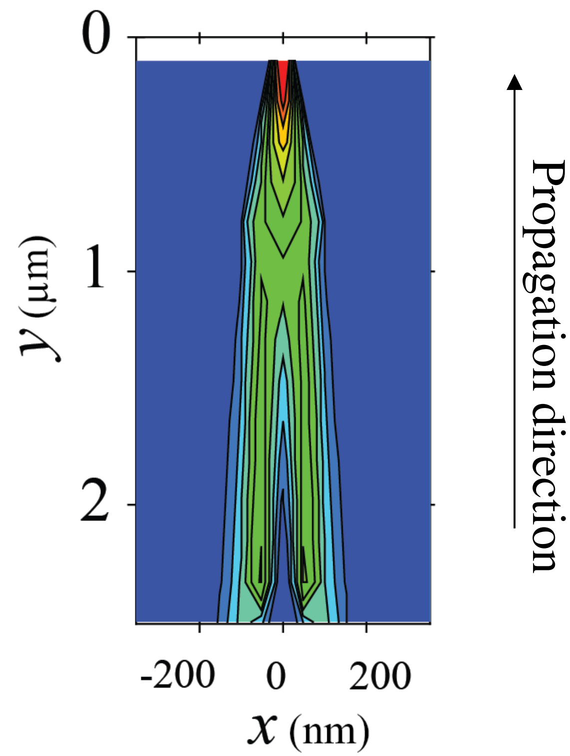
Georgia State University
Atlanta, GA 30303-3083

Field enhancement :

$$\sim \frac{L_s}{R} \text{ (for 2d compression), } L_s \approx 25 \text{ nm}$$

$$\sim \left(\frac{L_s}{R}\right)^{3/2} \text{ (for 3d compression)}$$



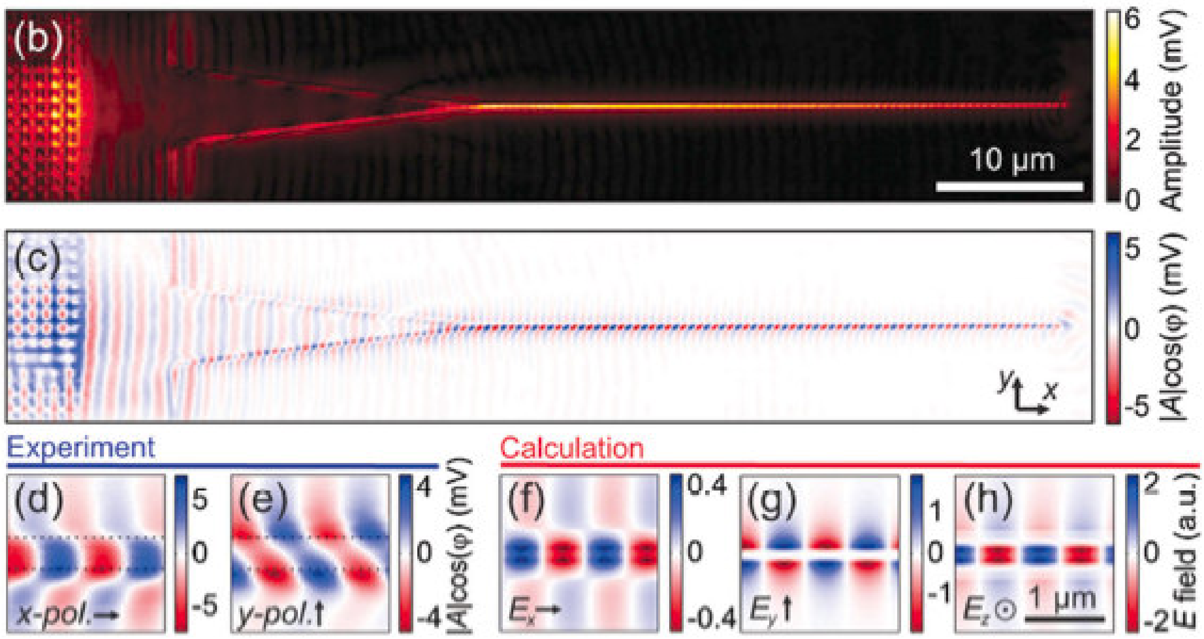


M. I. Stockman, *Nanofocusing of Optical Energy in Tapered Plasmonic Waveguides*, Phys. Rev. Lett. **93**, 137404-1-4 (2004).

PRL **102,** 203904 (2009) PHYSICAL REVIEW LETTERS

Nanowire Plasmon Excitation by Adiabatic Mode Transformation

Ewold Verhagen,* Marko Spasenović, Albert Polman, and L. (Kobus) Kuipers



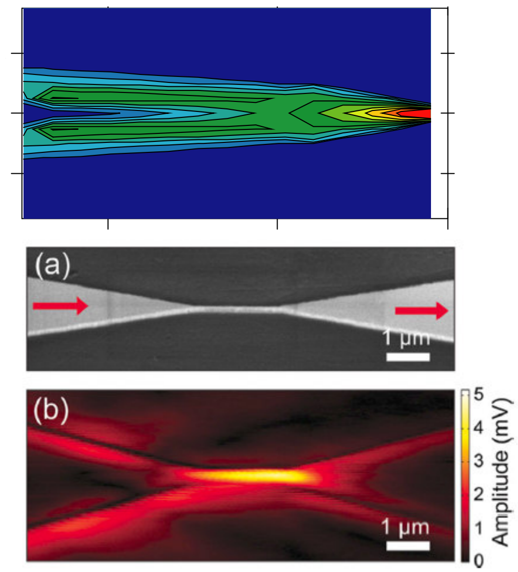


FIG. 4 (color). (a) Secondary electron micrograph of a 2 μm long nanowire connected by tapered waveguide sections for input and output coupling. (b) Near-field amplitude of forward-propagating waves in the structure at $\lambda = 1550$ nm. The intensity transmission of the complete structure is $20 \pm 6\%$.

NANO LETTERS

pubs.acs.org/NanoLett

DOI: 10.1021/nl903574a | *Nano Lett.* **2010,** *10,* 592-596

Near-Field Localization in Plasmonic Superfocusing: A Nanoemitter on a Tip

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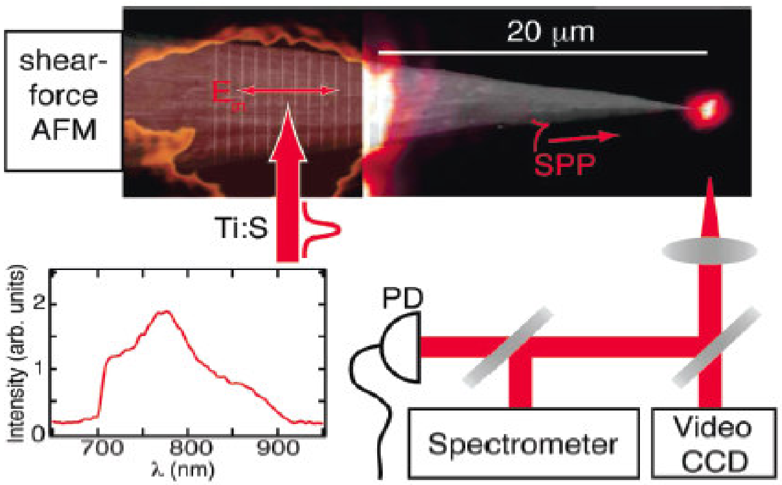

FIGURE 1. Grating coupling of surface plasmons on a tip. Overlay of SEM and optical far-field image of a Au tip with grating written by FIB for surface plasmon coupling of incident near-IR light from a Ti:Sapphire laser (spectrum shown). The grating with period $a_0 \sim 770$ nm is illuminated with polarization parallel with respect to the tip axis and an incident focus size of ~8 μm. The nonradiative SPP propagation leads to energy transfer and focusing and finally reemission near the tip apex with radius $\lesssim$15 nm.

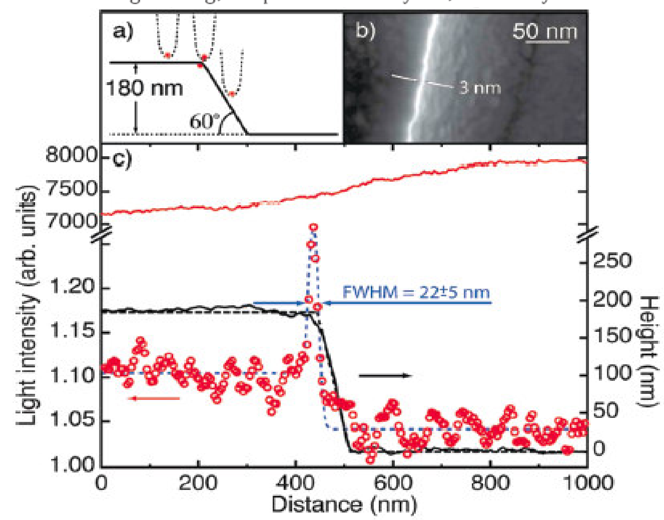

FIGURE 3. Determination of tip emitter size. (a) Schematic of scanning the nanofocusing tip across a silicon step edge with radius 3 ± 1 nm. (b) Top view SEM image of step edge. The wall and lower terrace are on the right-hand side. The edge serves as a local scatterer of the optical near-field of the apex. (c) The optical signal of a lateral scan across the step edge provides a measure of the spatial field confinement and thus the emitter size at the apex. Solid black line: AFM topography of the step. Red circles: plasmonic edge-scattered light intensity of the apex. The optical intensity peaks at the step edge and displays a width of 22 ± 5 nm, demonstrating the near-field localization at the apex. Solid red: Signal obtained under direct illumination of the apex under otherwise identical conditions.

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Femtosecond Nanofocusing with Full Optical Waveform Control

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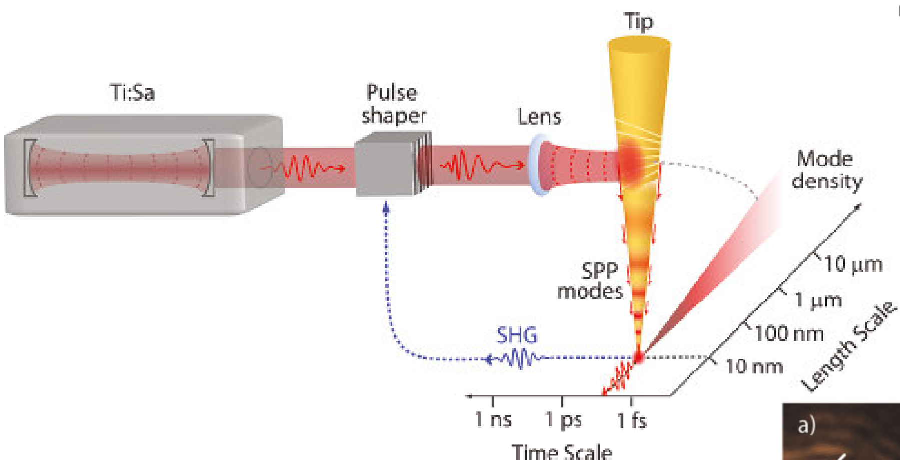

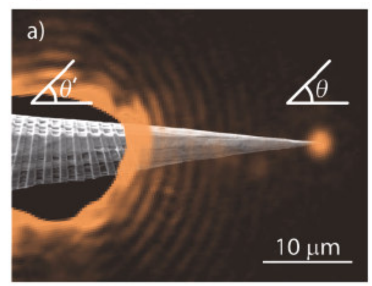

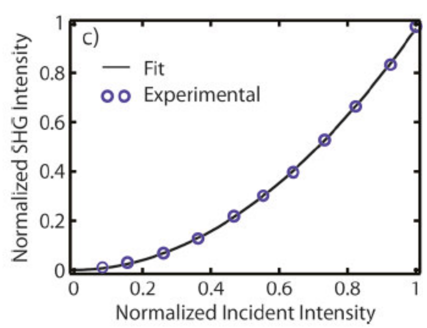

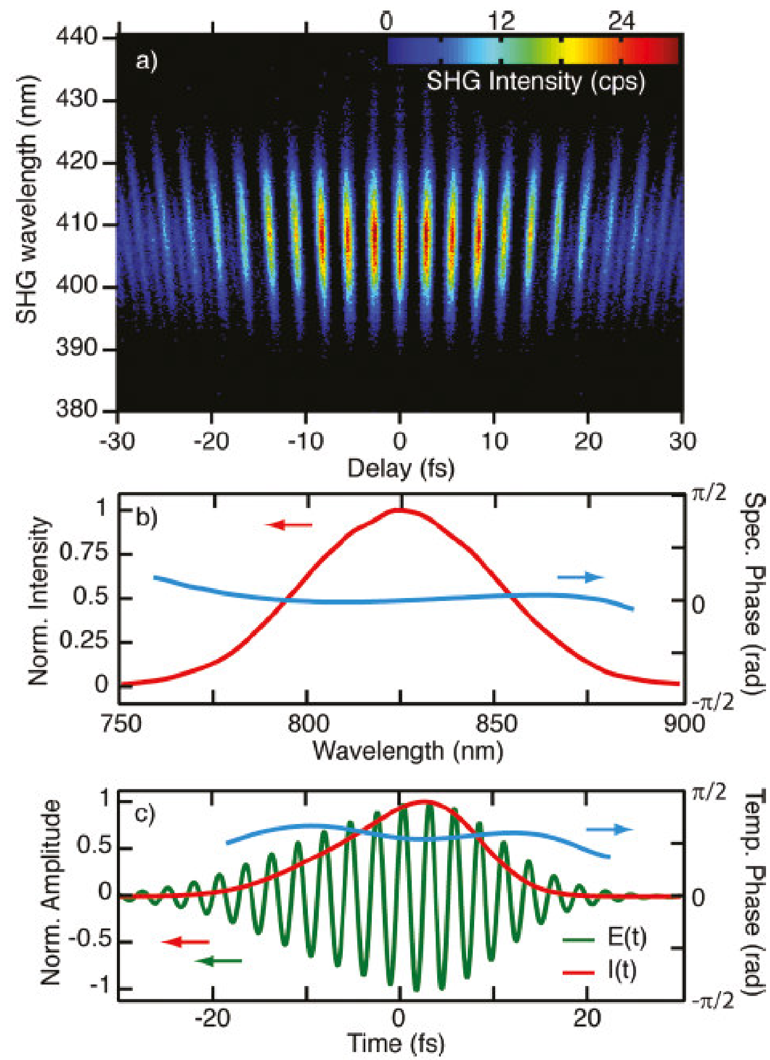

Nanoplasmonics and Spaser

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