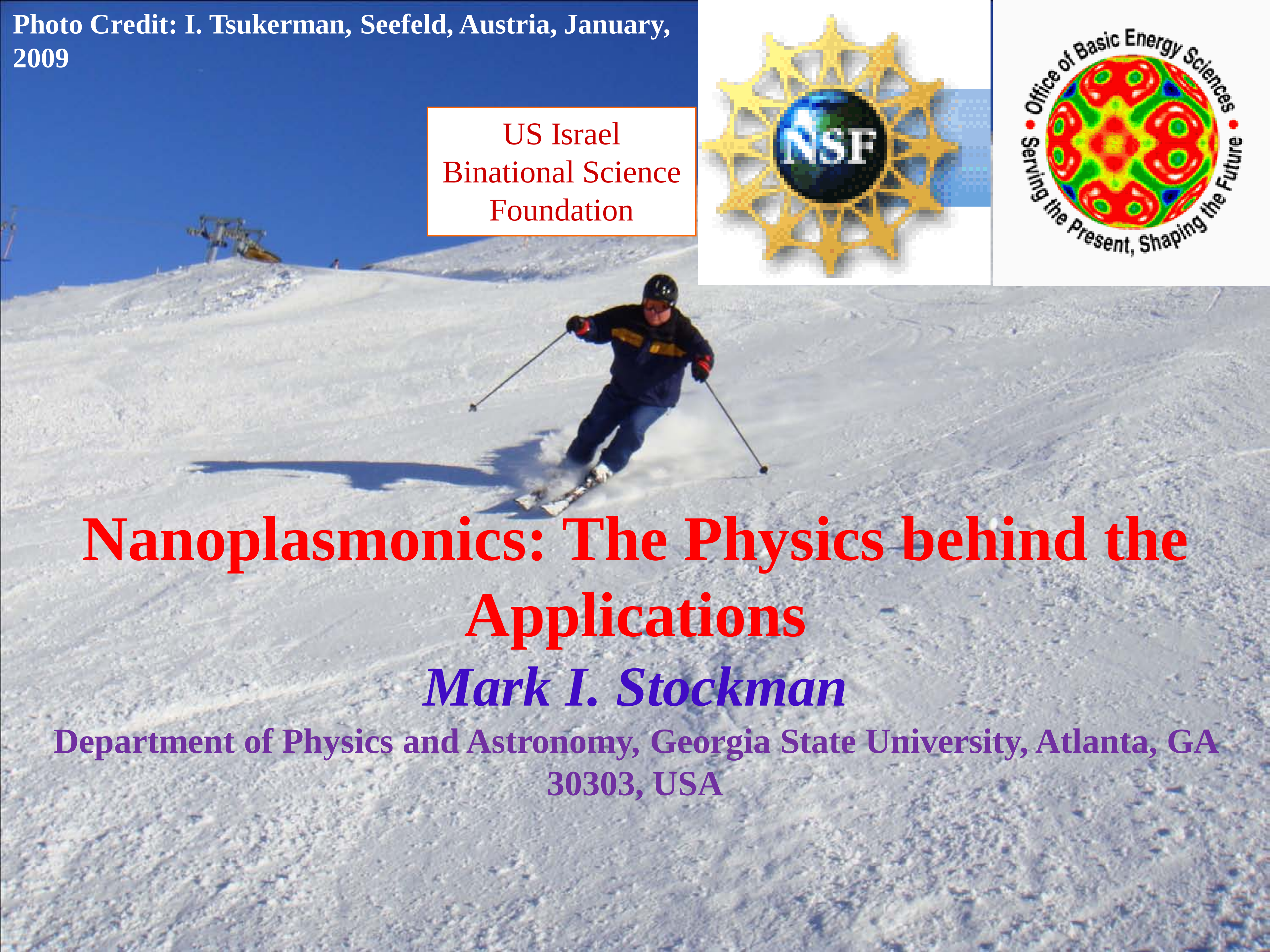

Photo Credit: I. Tsukerman, Seefeld, Austria, January, 2009

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Nanoplasmonics: The Physics behind the Applications

Mark I. Stockman

Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, 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
- Adiabatic Nanofocusing
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- Conclusions

Importance of fundamentals for applications

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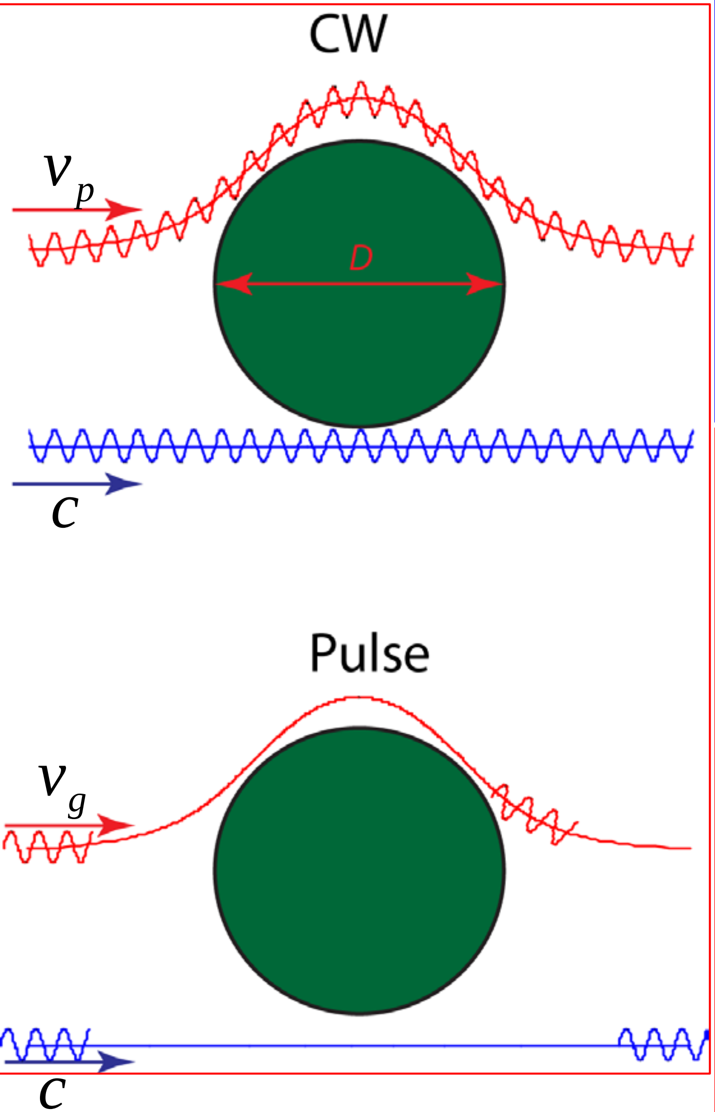

Breaking the Cloak: Relativistic Causality

For CW radiation, the ray that bends around the cloak carries radiation with higher than *c* phase velocity, ~~which is possible~~

$$v_p = \frac{\pi}{2}c > \frac{3}{2}c$$

For pulse radiation, the ray that bends around the cloak carries radiation with *group* velocity than *must* be less than *c* *(relativistic causality)*. Thus, it arrives with a delay,

$$\Delta t = \left(\frac{\pi}{2v_g} - \frac{1}{c}\right)D > \left(\frac{\pi}{2} - 1\right)\frac{D}{c} = \left(\frac{\pi}{2} - 1\right)\frac{D}{\lambda}T >> T$$

which for a *macroscopic* cloak is much larger than the period *T* (typically, $> 10^6 T$)

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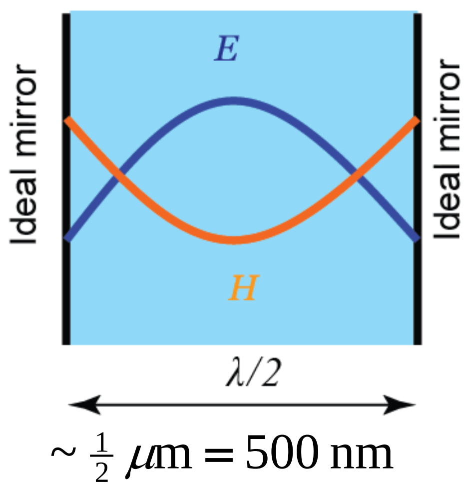
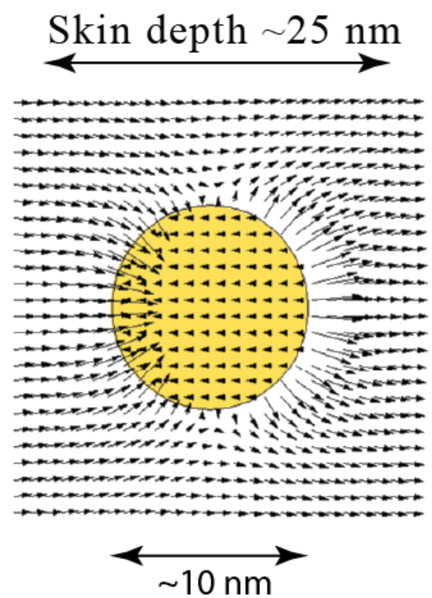
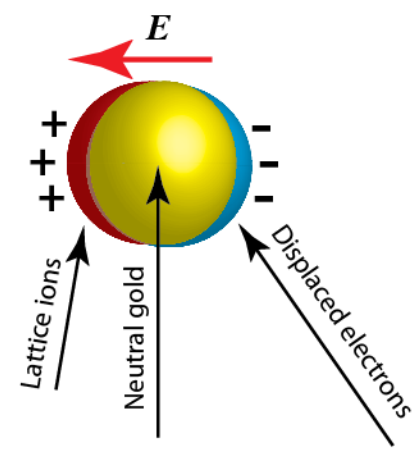
Nanoplasmonics in a nano-nutshell

Concentration of optical energy on the nanoscale



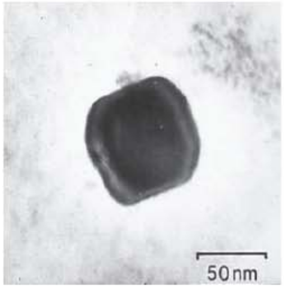




Photon: Quantum of electromagnetic field

Surface Plasmon: Quantum of electromechanical oscillator

Lycurgus Cup (4th Century AD): Roman Nanotechnology

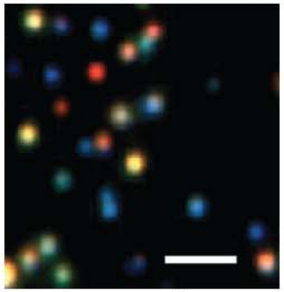


I. Freestone, N. Meeks, M. Sax, and C. Higgitt, *The Lycurgus Cup - a Roman Nanotechnology*, Gold Bull. **40**, 270-277 (2007

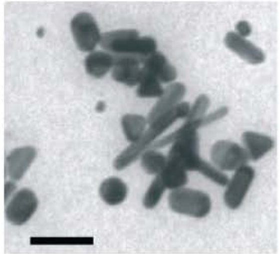
Nanoplasmonic colors are very bright. Scattering and absorption of light by them are very strong. This is due to the fact that all of the millions of electrons move in unison in plasmonic oscillations

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

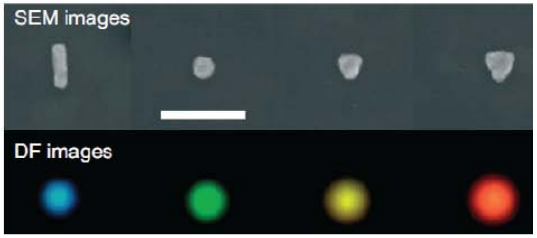


2 μm



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]

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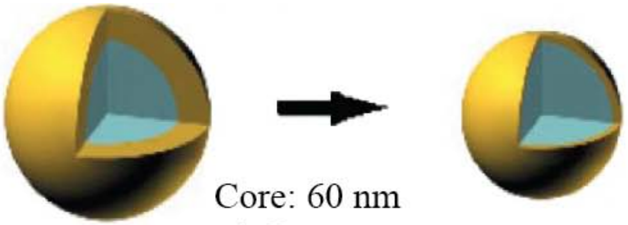
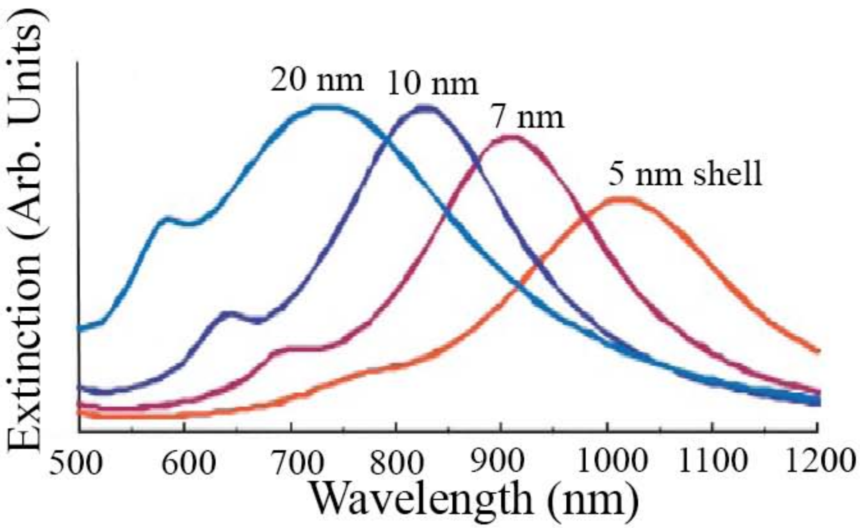
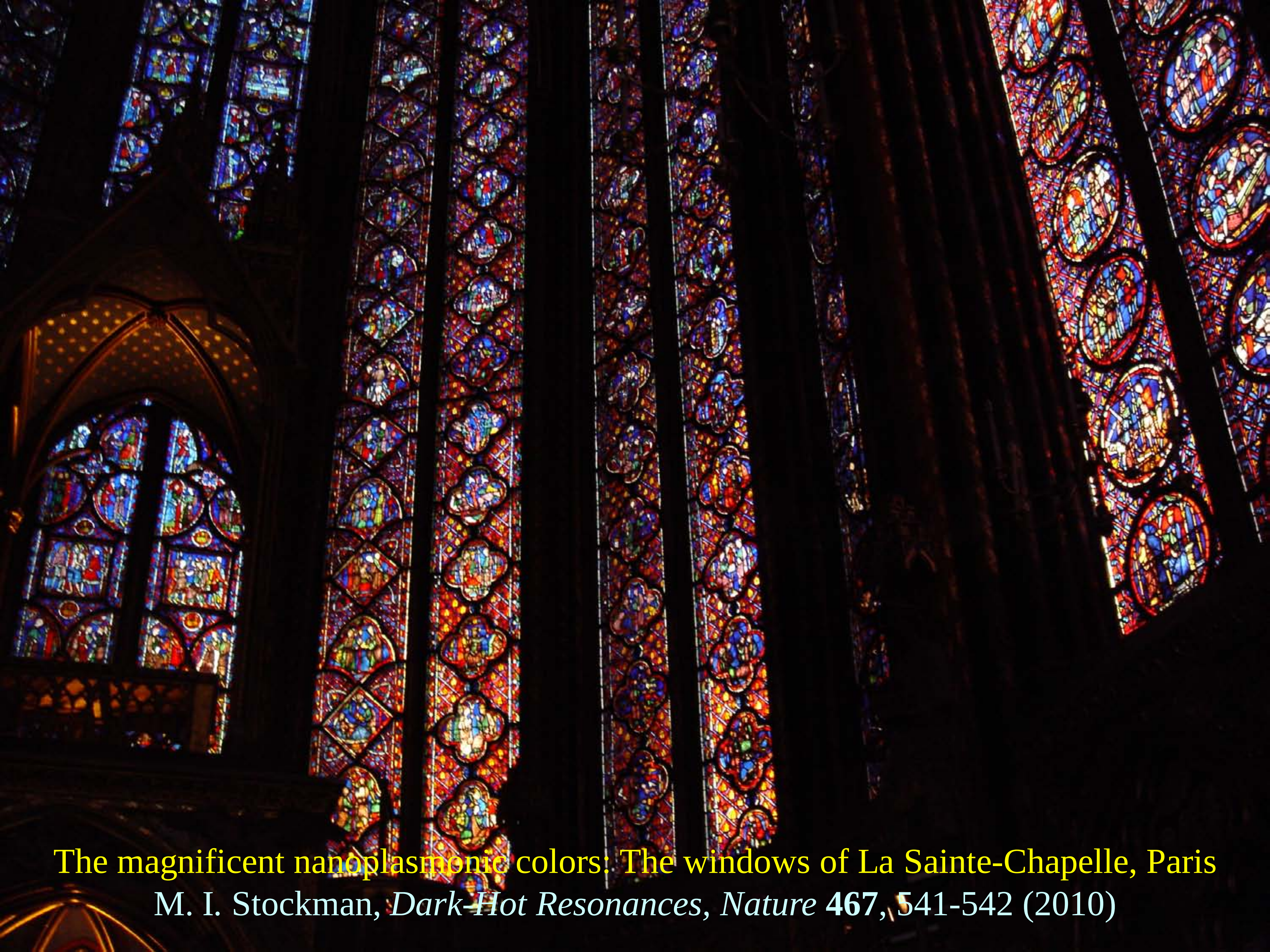
When shell becomes progressively thinner comparing to the core, the spectrum of the nanoshell shifts to the red and then to the near-infrared where biological tissues do not absorb





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, *Dark-Hot Resonances*, *Nature* **467**, 541-542 (2010)

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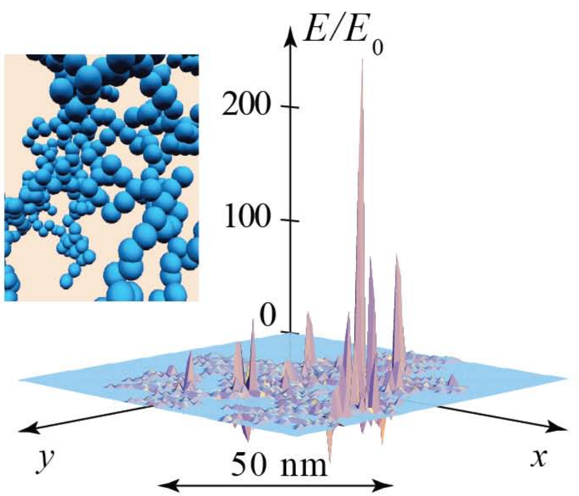
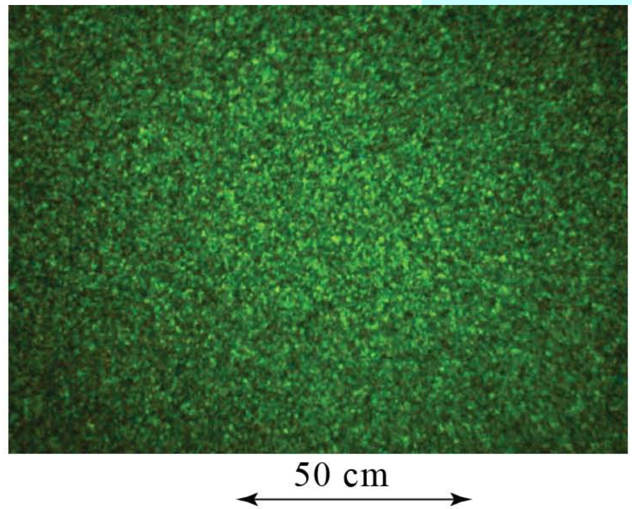
Plasmonic Near-Field **Hot Spots:** Happy 19th Anniversary!

- 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

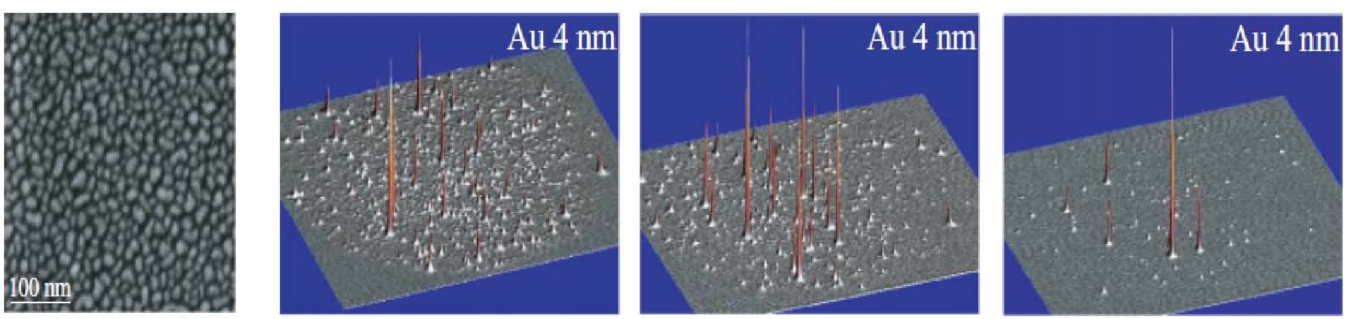
$$R_{Speckle} \sim \frac{\lambdabar}{A} L$$

$R_{Speckle}$ is speckle size

$\lambdabar \sim 100$ nm is reduced wave length

A is laser spot size,

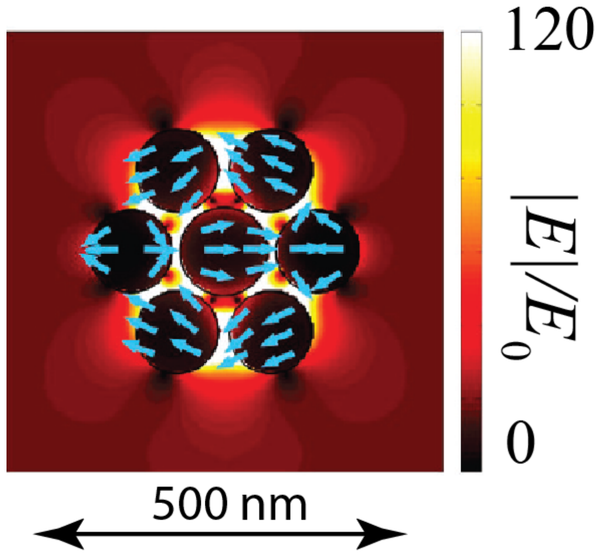
L is distance to the screen

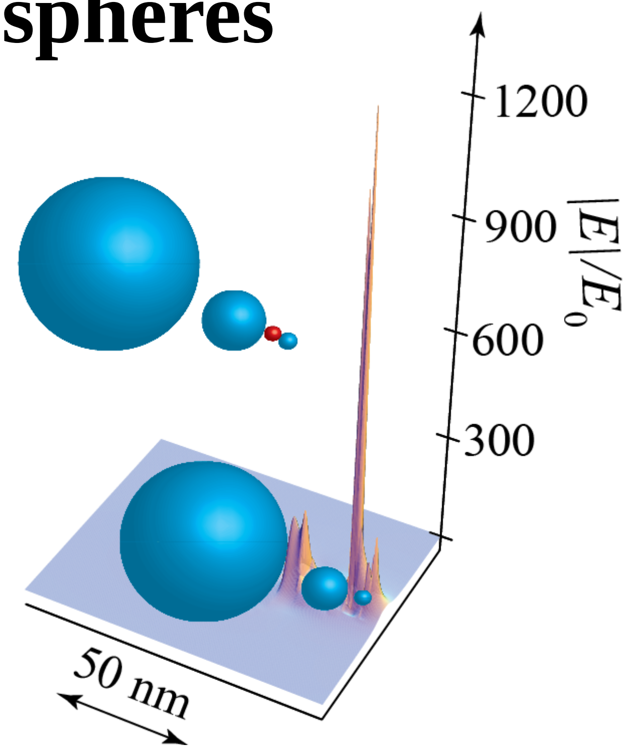


Au 4 nm, f = 0.53 | λ = 800 nm, Hot Spots Nb = 617 | λ = 930 nm, Hot Spots Nb = 453 | λ = 970 nm, Hot Spots Nb = 402

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

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*

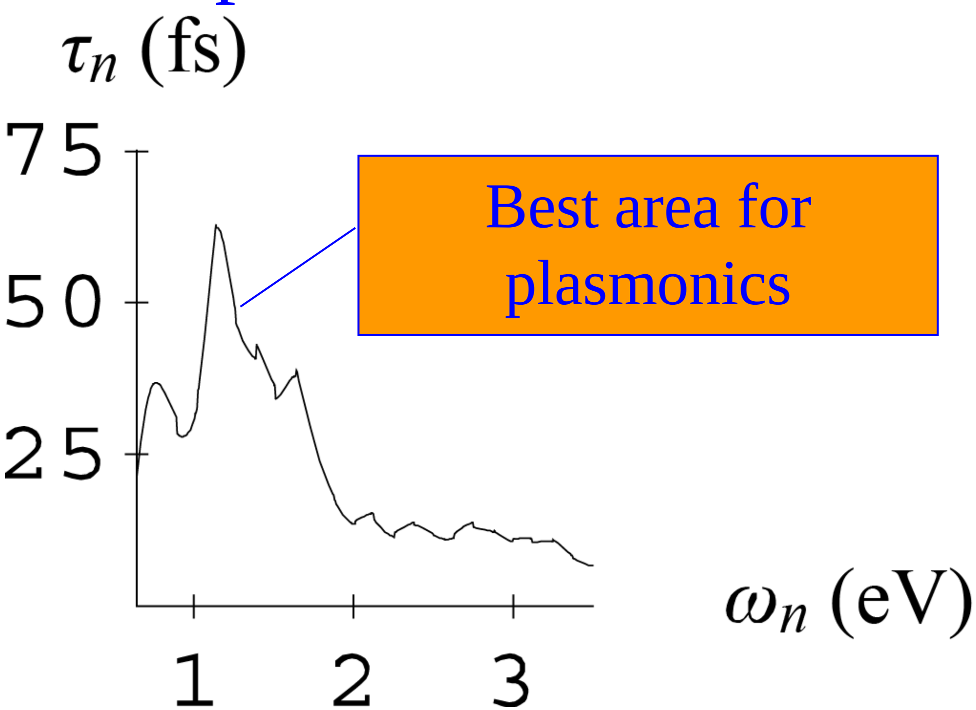
Emission rate of SPs into a mode: $\propto \frac{Q}{R^3}$

This with respect 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)

Nanoplasmonics is intrinsically ultrafast:



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

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

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

Corresponding rise time of plasmonic responses ~ 100 as

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

Electron emission: Perturbative two-photon ultrafast intrinsic nonlinearity

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

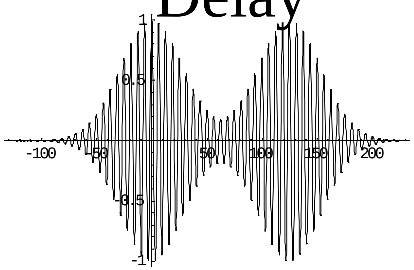
A. Kubo, K. Onda, H. Petek, Z. Sun, Y. S. Jung, and H. K. Kim, *Femtosecond Imaging of Surface Plasmon Dynamics in a Nanostructured Silver Film*, Nano Lett. 5, 1123 (2005).

200 nm

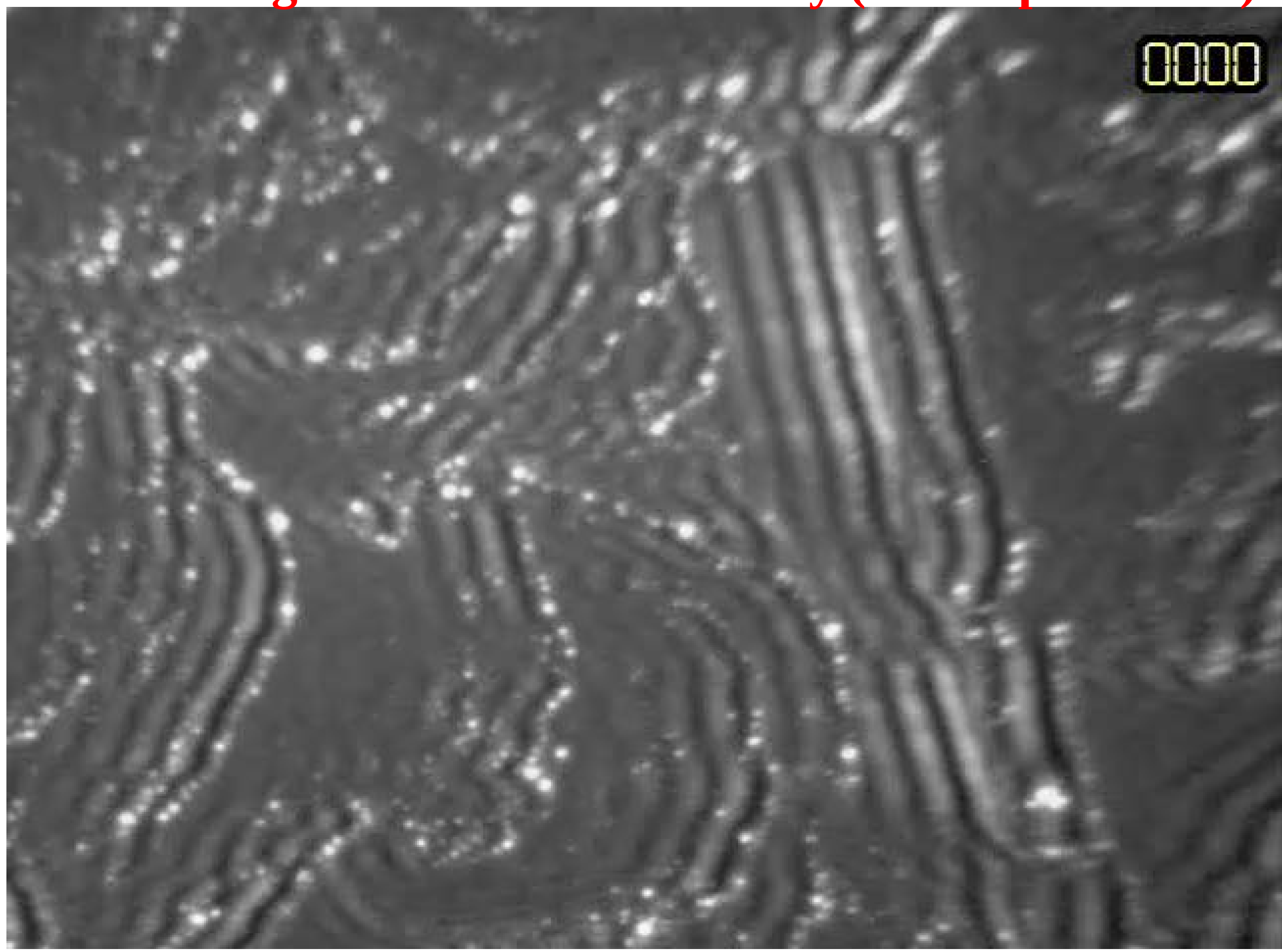
30 femtoseconds from life of a nanoplasmonic systems

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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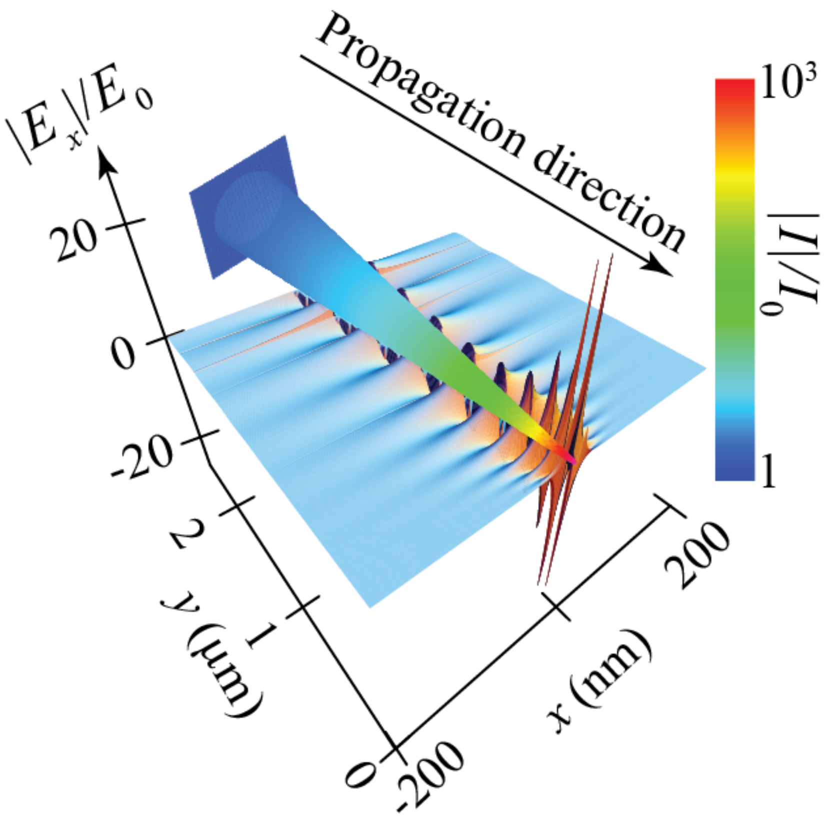
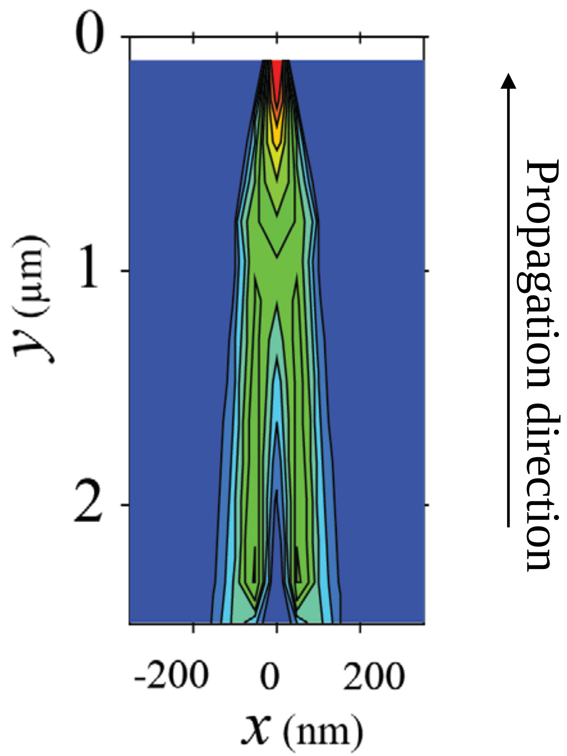
Field enhancement :

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

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



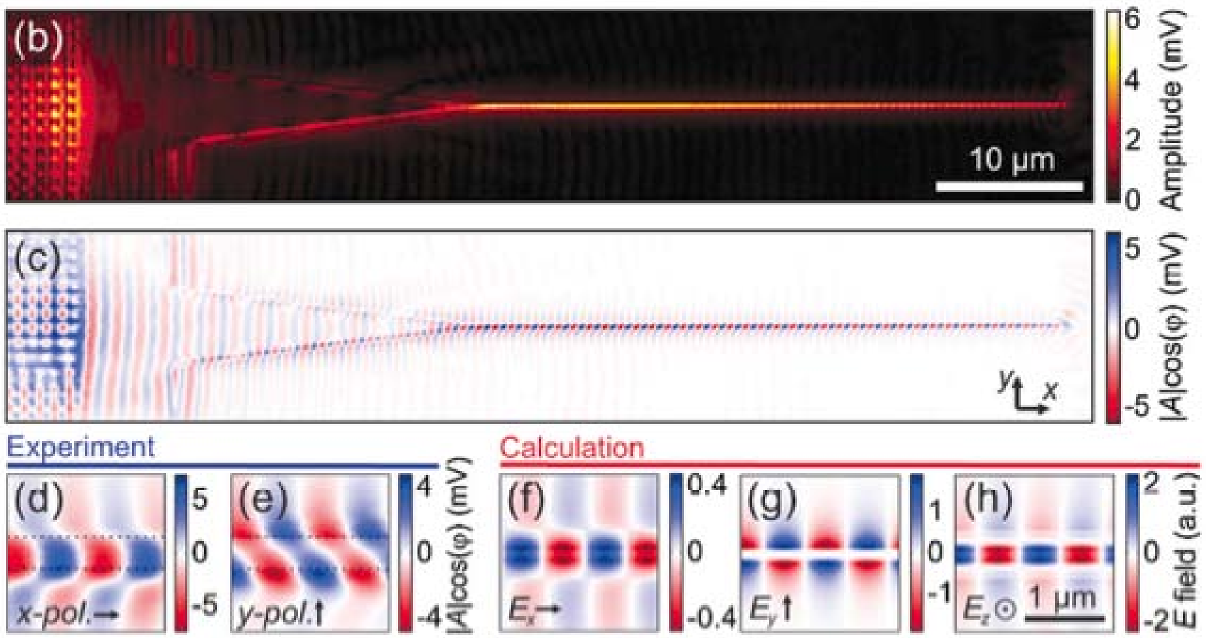


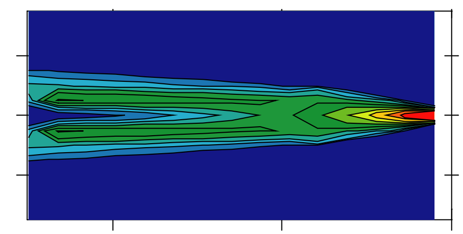
M. I. Stockman, *Nanofocusing of Optical Energy in Tapered Plasmonic Waveguides*, Phys. Rev. Lett. **93**, 137404-1-4 (2004).

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

Nanowire Plasmon Excitation by Adiabatic Mode Transformation

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





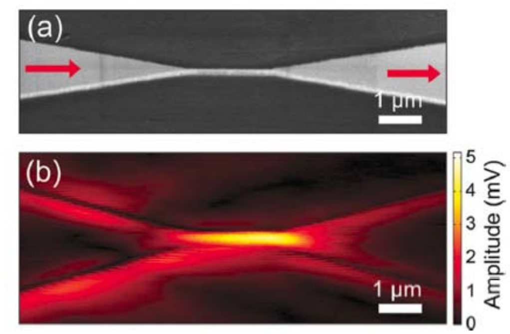


FIG. 4 (color). (a) Secondary electron micrograph of a 2 μm long nanowire connected by tapered waveguide sections for input and output coupling. (b) Near-field amplitude of forward-propagating waves in the structure at $\lambda = 1550$ nm. The intensity transmission of the complete structure is $20 \pm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

NANO LETTERS

pubs.acs.org/NanoLett

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

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

Catalin C. Neacsu,[†,#] Samuel Berweger,[†,#] Robert L. Olmon,[†,‡,#] Laxmikant V. Saraf,[‖] Claus Ropers,[⊥] and Markus B. Raschke*[,†,§]

[†]Department of Chemistry, [‡]Department of Electrical Engineering, [§]Department of Physics, University of Washington, Seattle, Washington 9819
Laboratory, Richland, Washington 9935
University of Göttingen, Germany

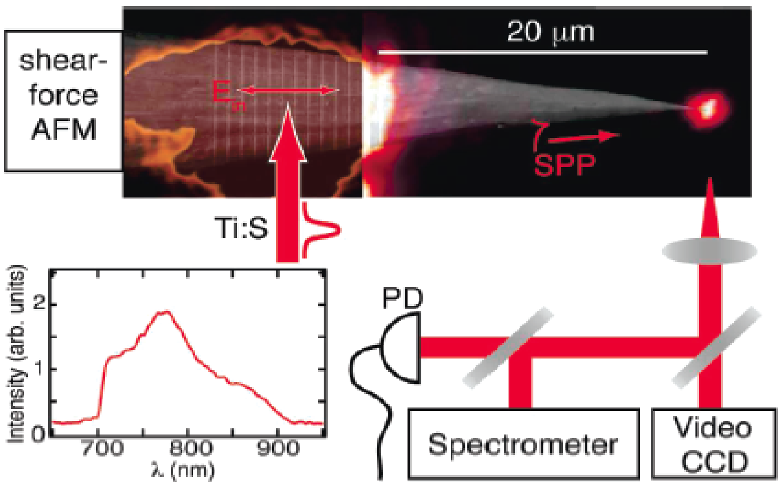


FIGURE 1. Grating coupling of surface plasmons on a tip. Overlay of SEM and optical far-field image of a Au tip with grating written by FIB for surface plasmon coupling of incident near-IR light from a Ti:Sapphire laser (spectrum shown). The grating with period $a_0 \sim$ 770 nm is illuminated with polarization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

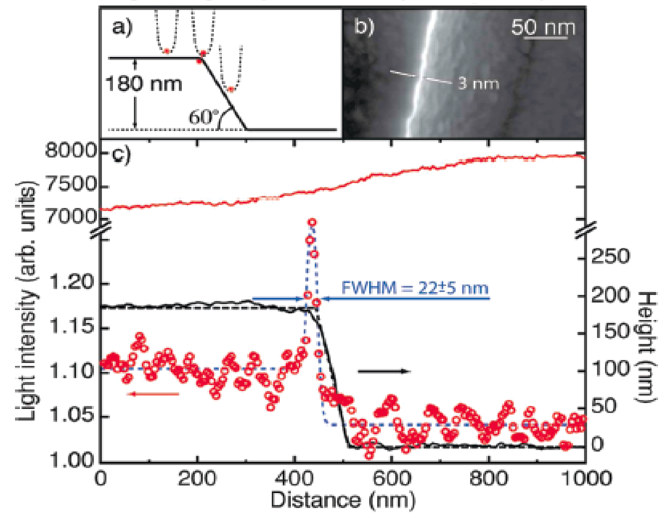


FIGURE 3. Determination of tip emitter size. (a) Schematic of scanning the nanofocusing tip across a silicon step edge with radius 3 ± 1 nm. (b) Top view SEM image of step edge. The wall and lower terrace are on the right-hand side. The edge serves as a local scatterer of the optical near-field of the 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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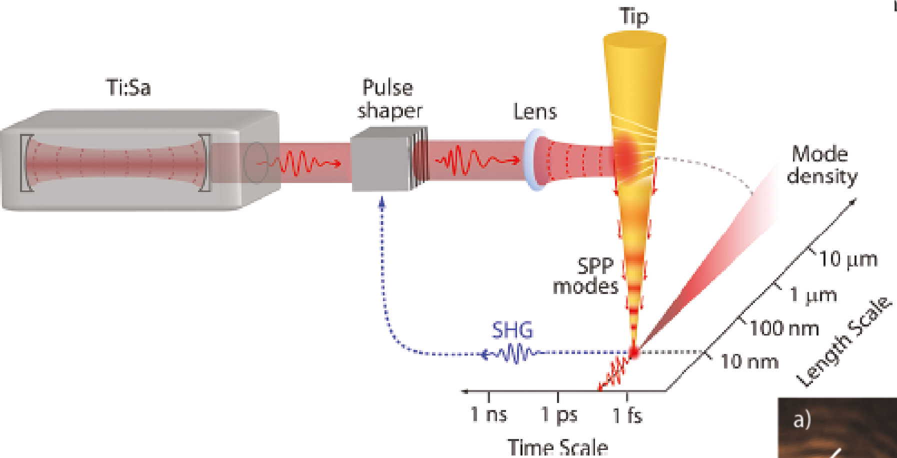
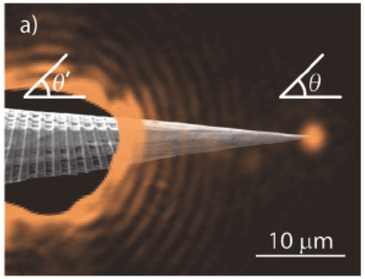
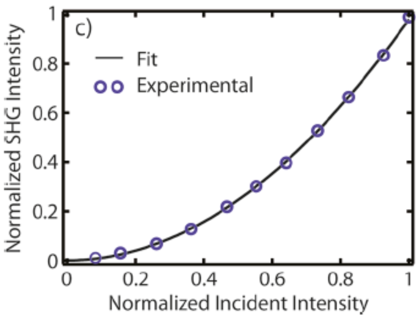
Femtosecond Nanofocusing with Full Optical Waveform Control

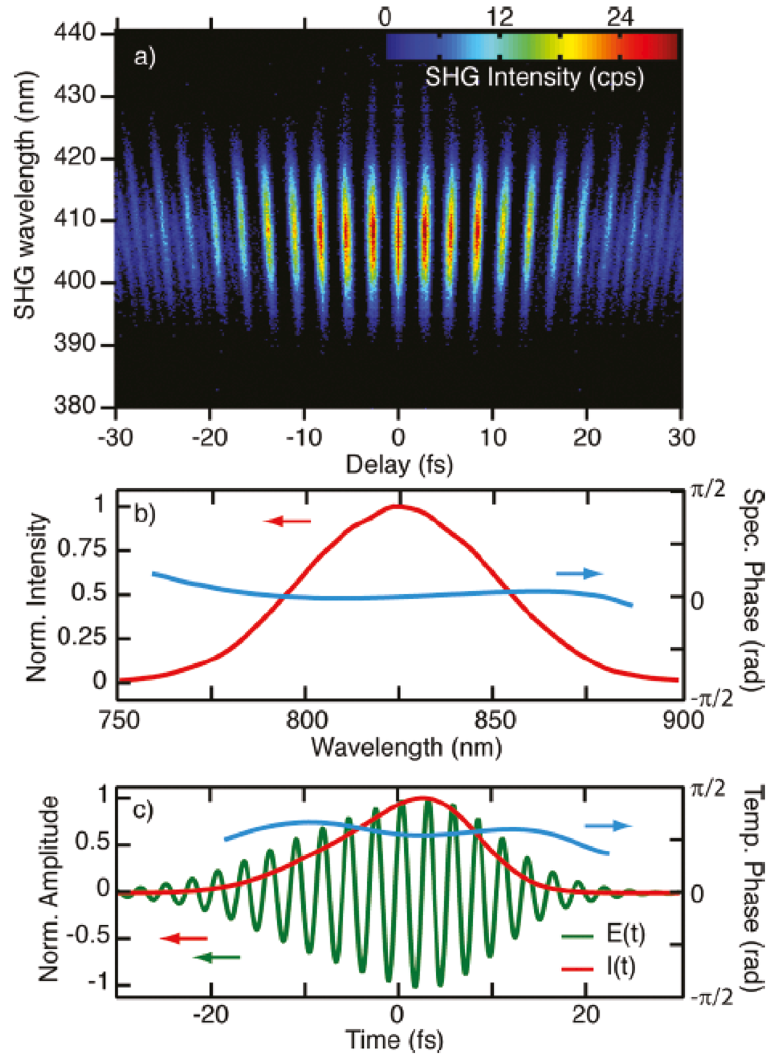
Samuel Berweger,[†] Joanna M. Atkin,[†] Xiaoji G. Xu, Robert L. Olmon, and Markus B. Raschke*

ıt of Chemistry, and JILA, University of Colorado at Boulder, Boulder, Colorado 80309, United States









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Anal. Chem. 2008, 80, 4247–4251

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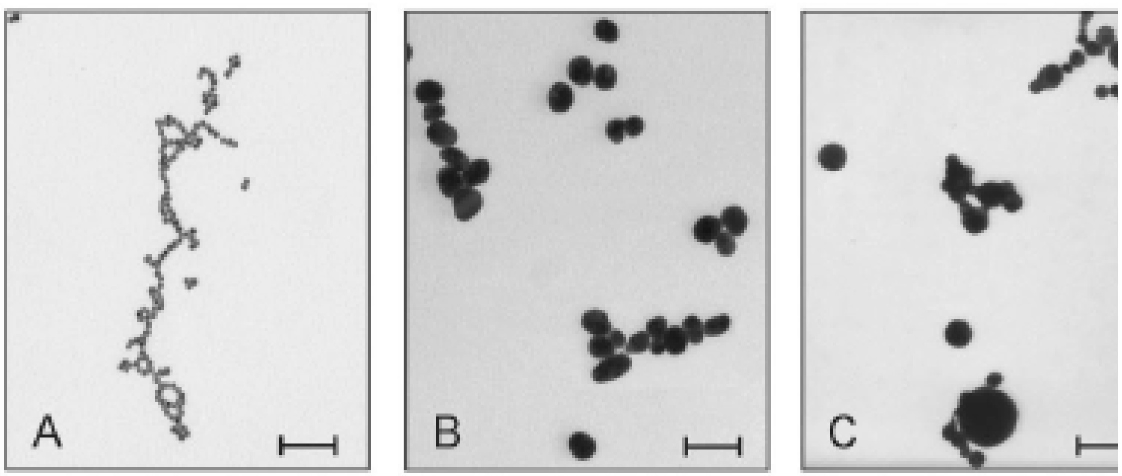
Gold Nanolenses Generated by Laser Ablation-Efficient Enhancing Structure for Surface Enhanced Raman Scattering Analytics and Sensing

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

Different types of aggregates of gold nanospheres



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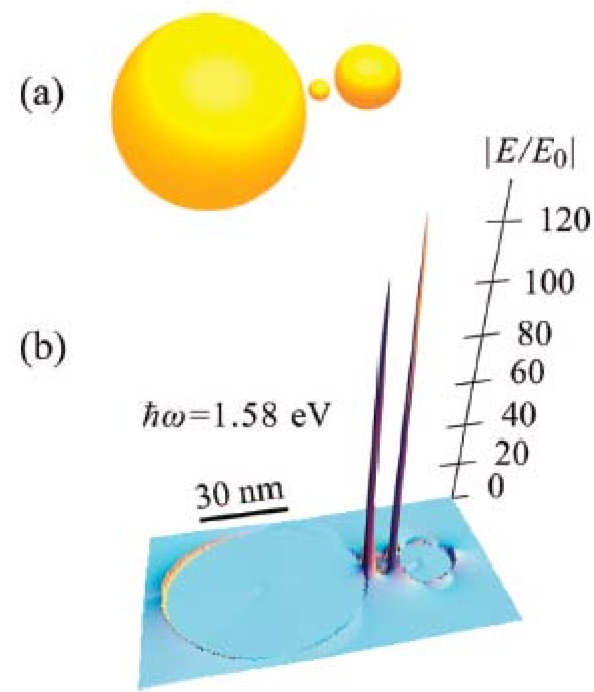

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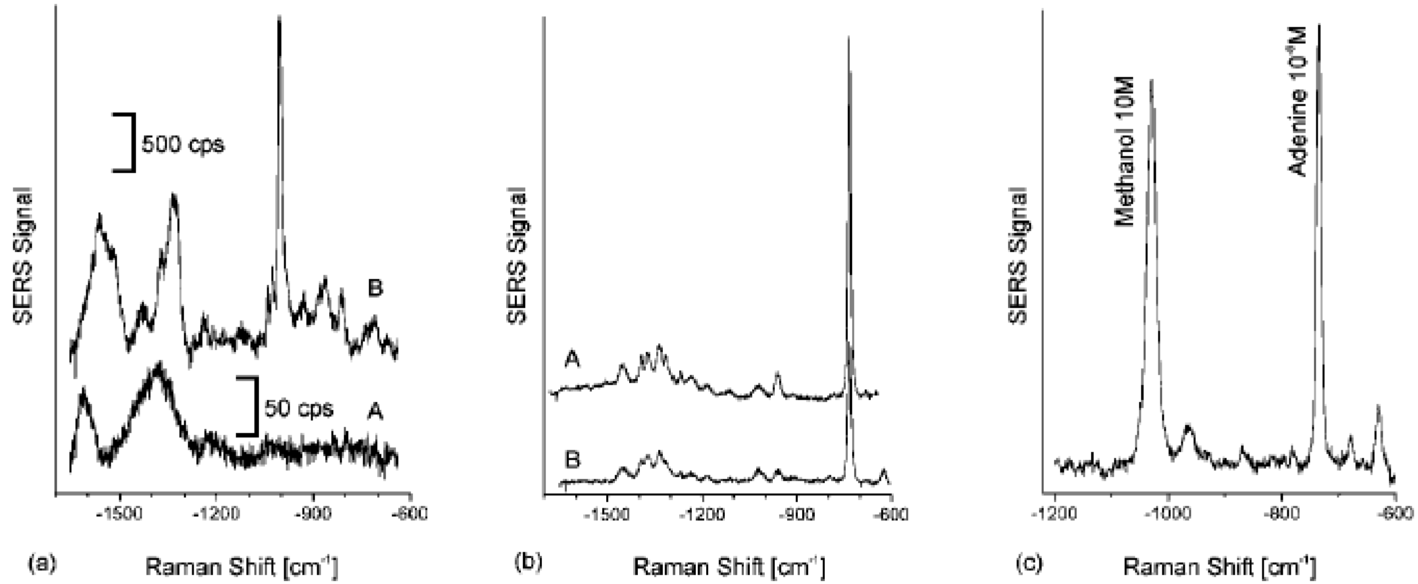
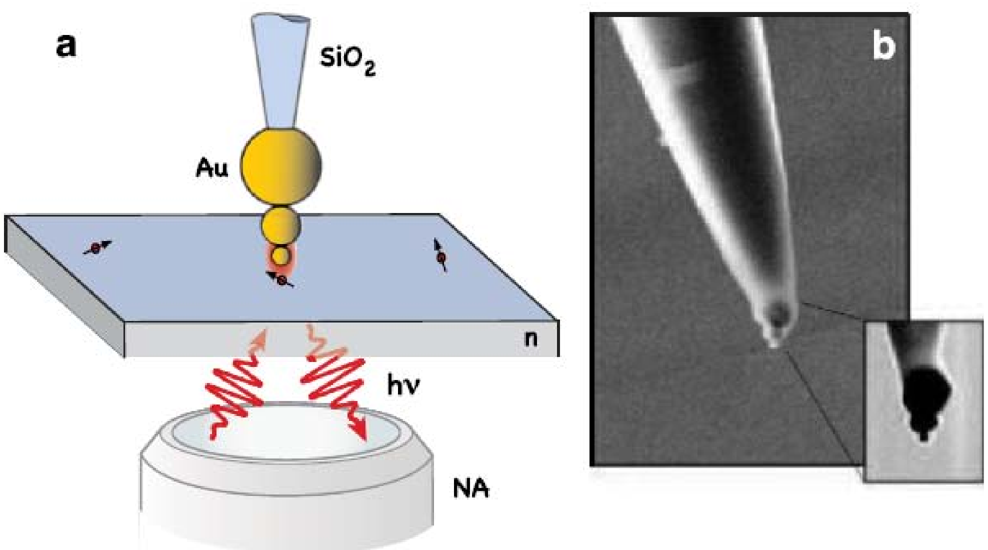


Figure 3. Comparison of SERS using gold nanolenses made by ablation and chemically prepared nanoaggregates as enhancing nanostructures. (a) Raman spectra measured from aqueous solutions of gold nanoaggregates without any analyte to compare background signals. The chemically prepared gold nanoparticles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

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*



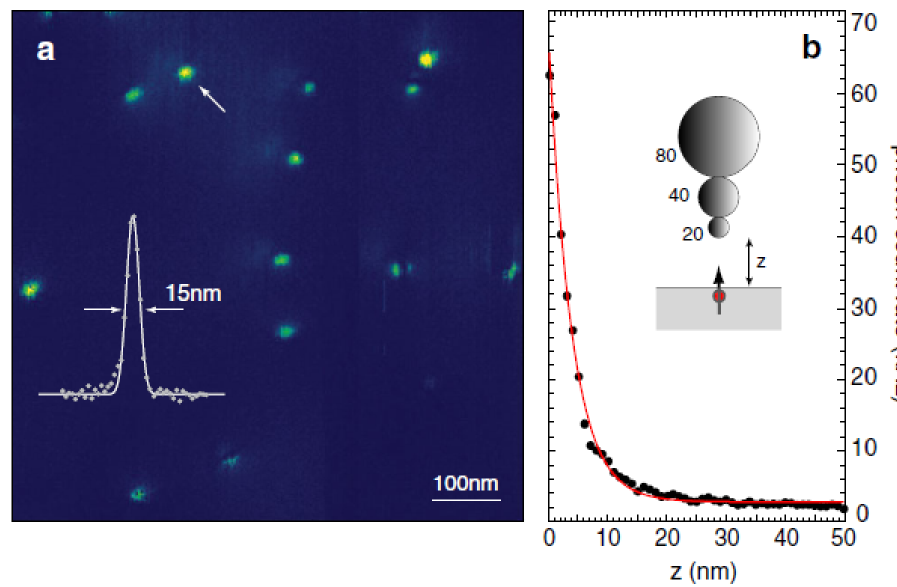


FIG. 4 (color online). Excitation of single-molecule fluorescence with a trimer antenna consisting of 80, 40, and 20 nm gold nanoparticles. (a) Fluorescence image of the single-molecule sample. Inset: Line cut through the single fluorescence spot marked by the arrow. (b) Fluorescence from a single z-oriented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

nature photonics | VOL 2 | JUNE 2008 |

MARK I. STOCKMAN

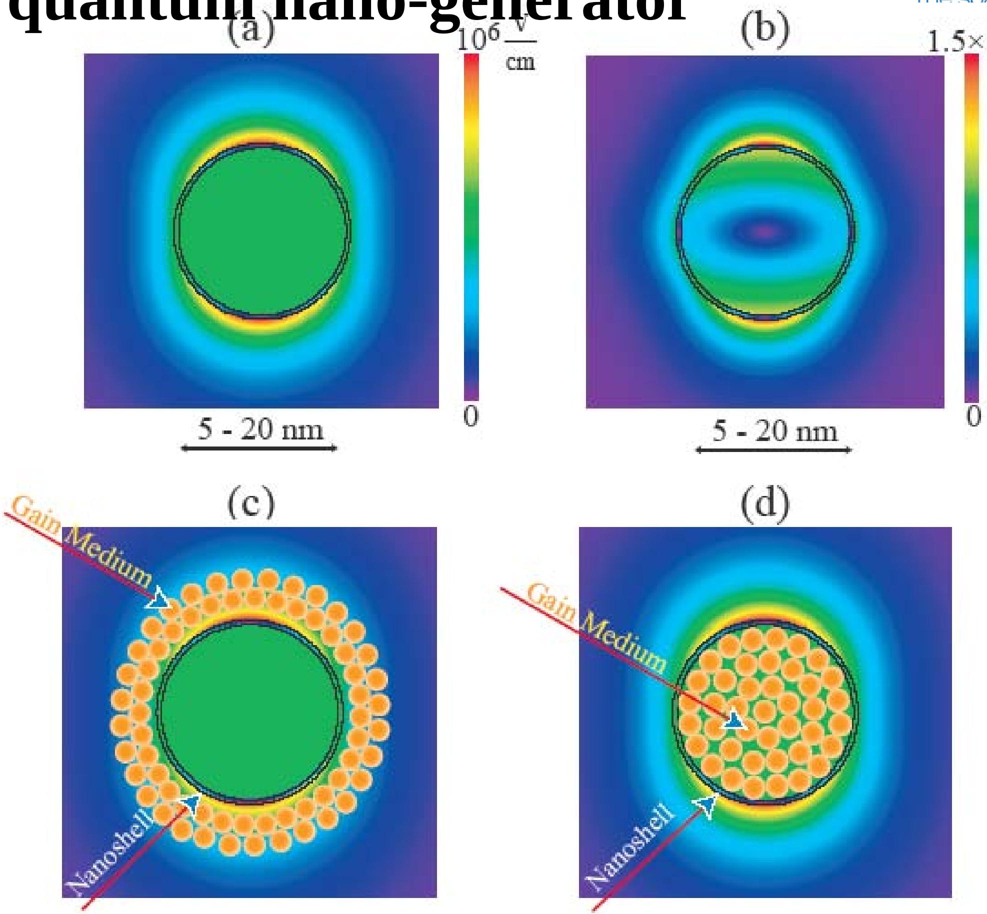
is in the Department of Physics and
e-mail: mstockman@gsu.edu

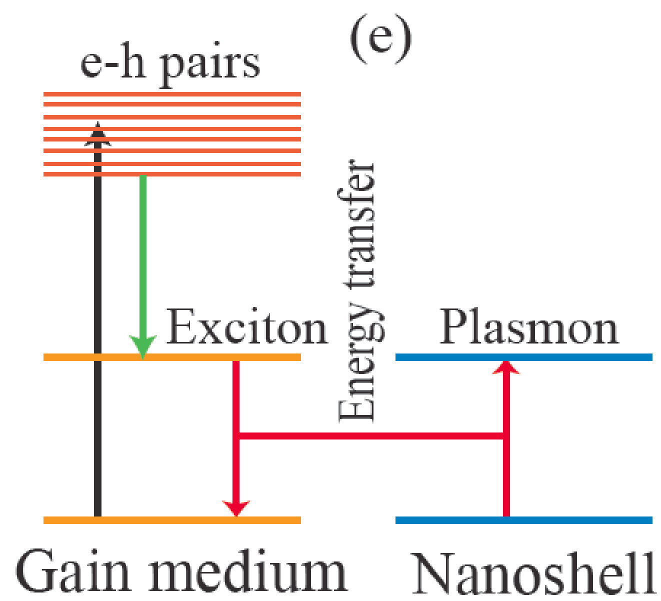
The spaser is a propos

Spaser is the ultimately smallest quantum nano-generator

For small nanoparticles, radiative loss is negligible.

Spaser is fully scalable





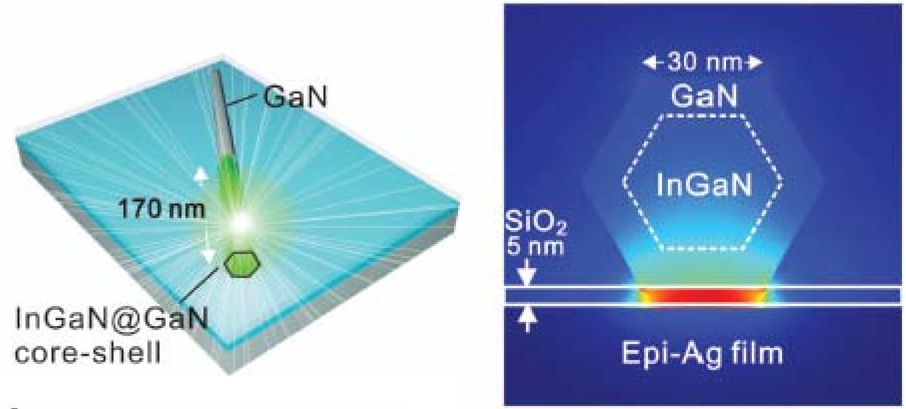
D. J. Bergman and M. I. Stockman, *Surface Plasmon Amplification by Stimulated Emission of Radiation: Quantum Generation of Coherent Surface Plasmons in Nanosystems*, Phys. Rev. Lett. **90**, 027402-1-4 (2003).

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



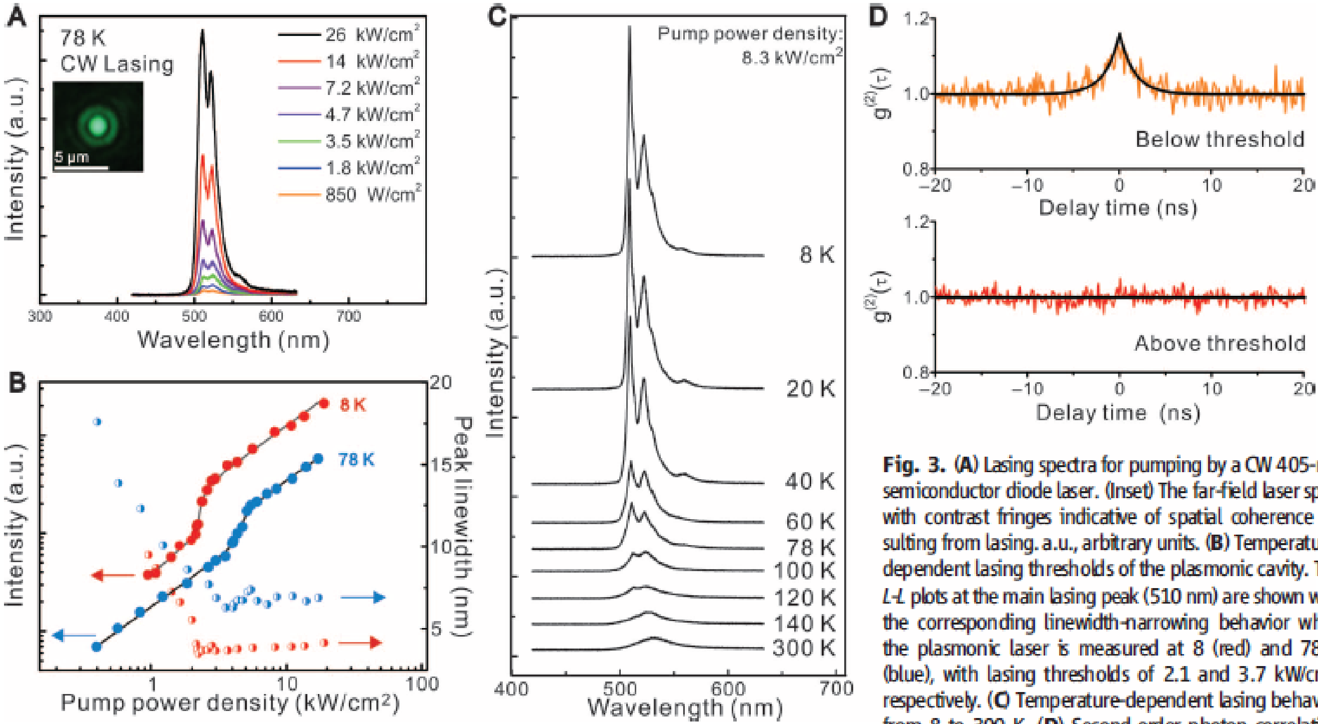


Fig. 3. **(A)** Lasing spectra for pumping by a CW 405-nm semiconductor diode laser. (Inset) The far-field laser spot, with contrast fringes indicative of spatial coherence resulting from lasing. a.u., arbitrary units. **(B)** Temperature-dependent lasing thresholds of the plasmonic cavity. The *L-L*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

Speed of computations: Transistor speed is not a limiting factor

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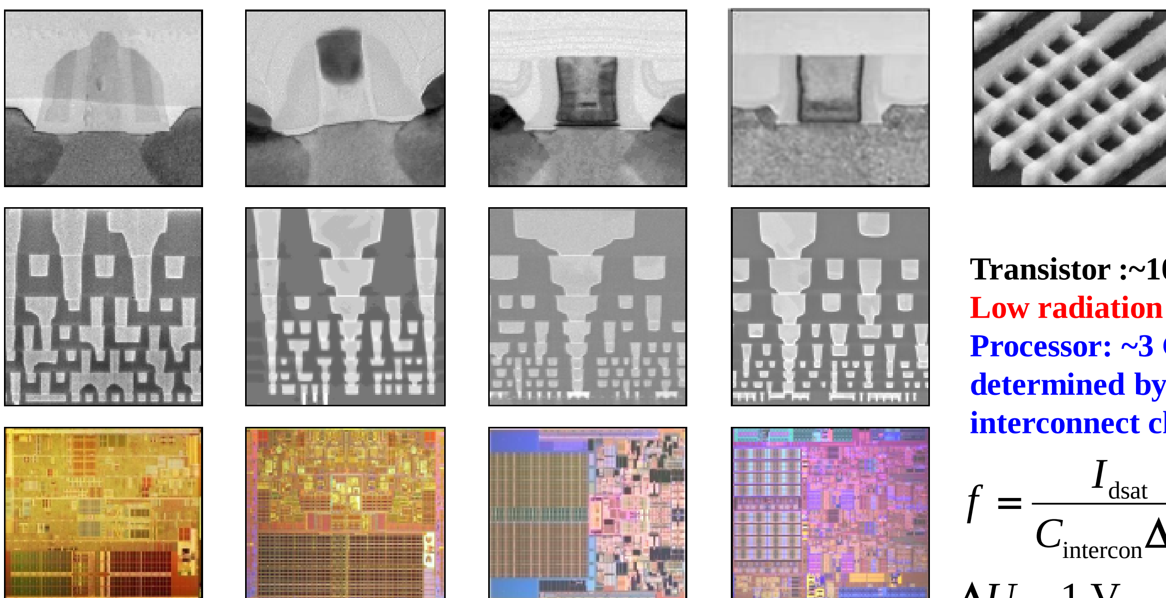
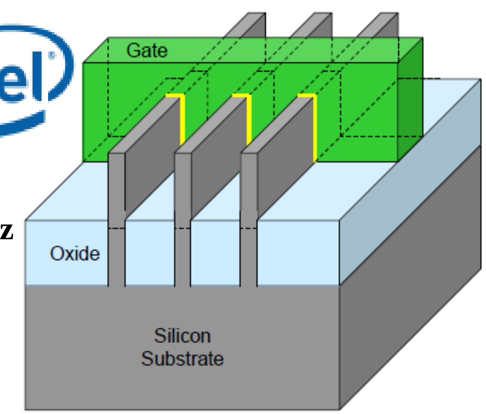
P. Packan et al., in 2009 IEEE International Electron Devices Meeting (IEDM), *High Performance 32nm Logic Technology Featuring Second Generation High-K + Metal Gate Transistors (Baltimore, MD, 2009), Vol. IEDM09-662, p. 28.4.1-28.4.4*

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.

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



22 nm Tri-Gate Transistor



Transistor :~100-300 GHz
Low radiation resistance
Processor: ~3 GHz, determined by interconnect charging

$$f = \frac{I_{\mathrm{dsat}}}{C_{\mathrm{intercon}} \Delta U},$$

$$\Delta U \sim 1\ \mathrm{V}$$

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

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- Plasmonic Nanoantennas
- Conclusions

Applications of Nanoplasmonics:

1. Ultrasensitive and express sensing and detection using both SPPs and SPs (LSPRs): see, e.g., J. N. Anker, W. P. Hall, O. Lyandres, N. C. Shah, J. Zhao, and R. P. Van Duyne, *Biosensing with Plasmonic Nanosensors*, Nature Materials 7, 442-453 (2008);
2. Near-filed scanning microscopy (or, nanoscopy): NSOM (SNOM)
3. Nanoantennas: Coupling of light to nanosystems. Extraction of light from LEDs and lasers [N. F. Yu, J. Fan, Q. J. Wang, C. Pflugl, L. Diehl, T. Edamura, M. Yamanishi, H. Kan, and F. Capasso, *Small-Divergence Semiconductor Lasers by Plasmonic Collimation*, Nat. Phot. 2, 564-570 (2008)]; nanostructured antennas for photodetectors and solar cells; heat-assisted magnetic memory [W. A. Challener *et al.*, Nat. Photon. 3, 220 (2009)]
4. Photo- and chemically stable labels and probes for biomedical research and medicine
5. Nanoplasmonic-based immunoassays and tests. Home pregnancy test (dominating the market), PSA test (clinic), troponin heart-attack test, and HIV tests (in trials)
6. Near perspective: Generation of EUV and XUV pulses
7. Thermal cancer therapy: L. R. Hirsch, R. J. Stafford, J. A. Bankson, S. R. Sershen, B. Rivera, R. E. Price, J. D. Hazle, N. J. Halas, and J. L. West, *Nanoshell-Mediated Near-Infrared Thermal Therapy of Tumors under Magnetic Resonance Guidance*, Proc. Natl. Acad. Sci. USA 100, 13549-13554 (2003). C. Loo, A. Lowery, N. Halas, J. West, and R. Drezek, *Immunotargeted Nanoshells for Integrated Cancer Imaging and Therapy*, Nano Lett. 5, 709-711 (2005)

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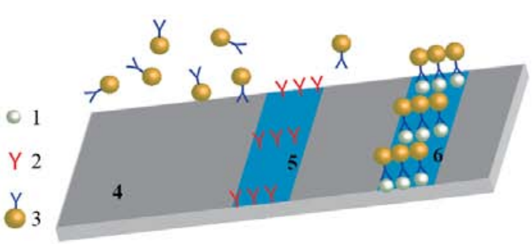
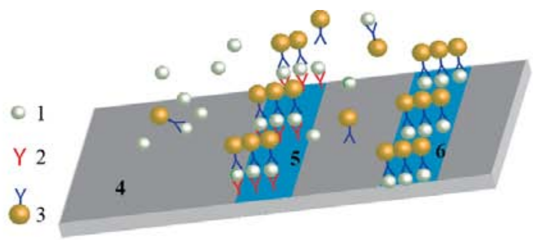
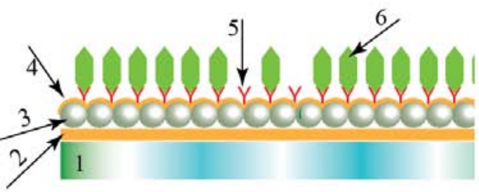
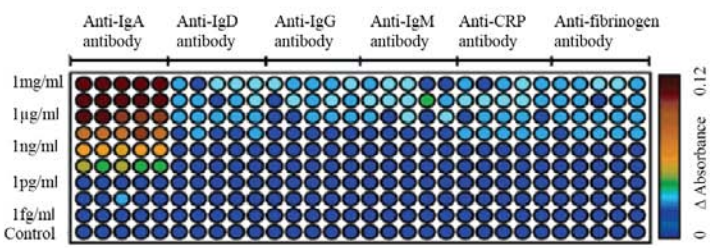
Sensing and Detection with Localized Surface Plasmons



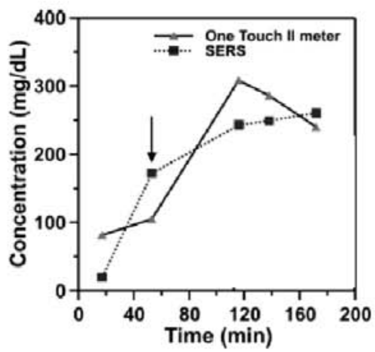


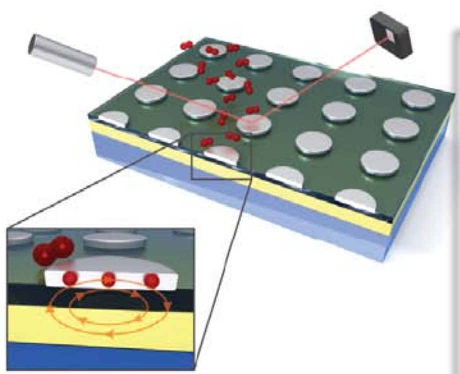
Immunochromatographic assay with immunotargeted gold nanosphere suspension. Detection of: hCG (human chorionic gonadotropin) -- Home pregnancy test; PSA (prostate-specific antigen) -- Prostate cancer ; troponin – heart attack test; HIV/AIDS (trials)





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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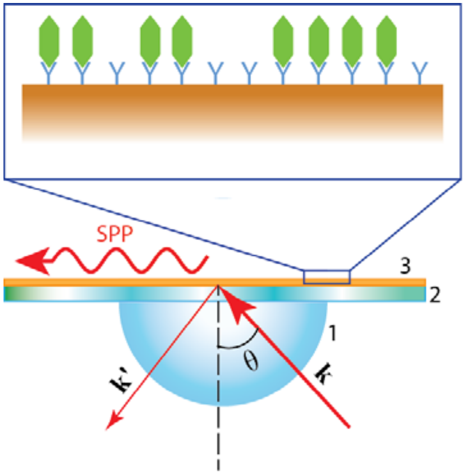
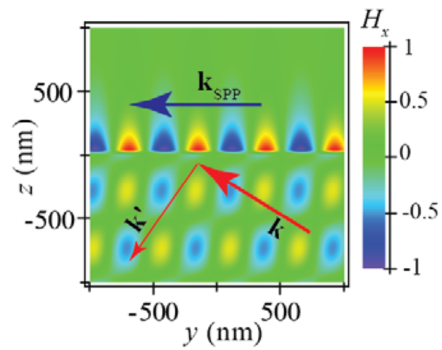
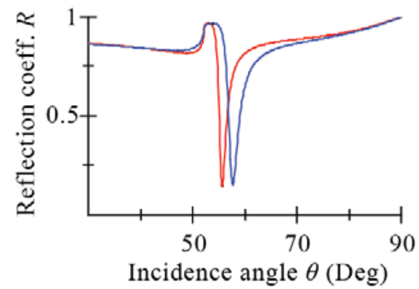
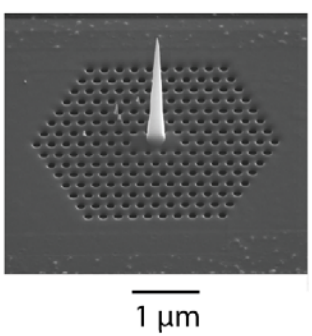
Surface Plasmon Polariton Sensors

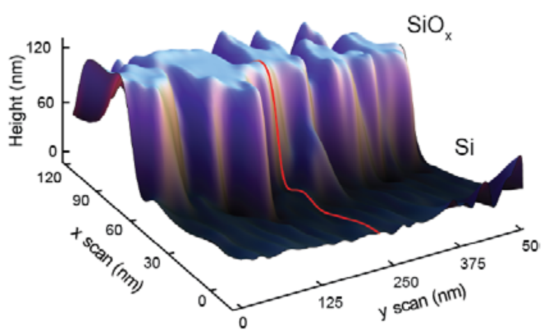


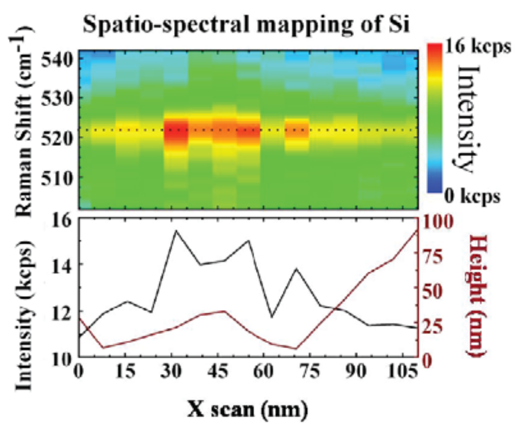




Surface plasmon polariton sensor based on Kretschmann geometry. Sensitivity~ 10^3 - 10^4 large molecules. See, e.g., http://www.biacore.com/







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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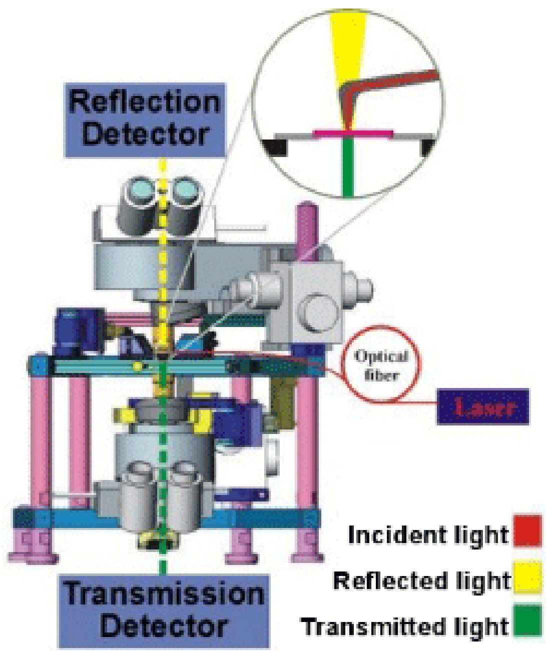
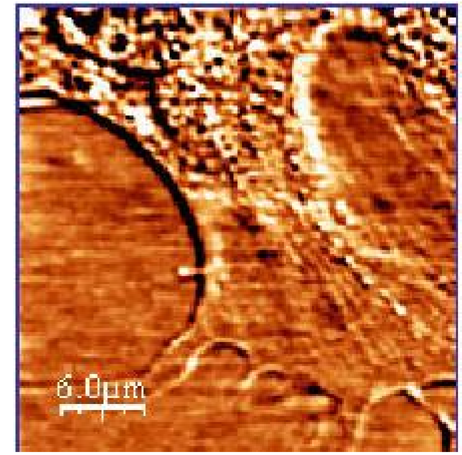
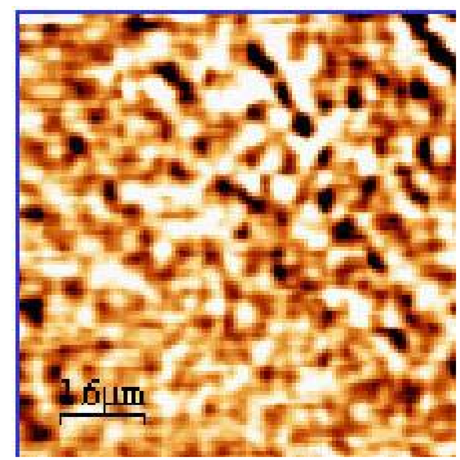
Plasmonic Nanoscopy

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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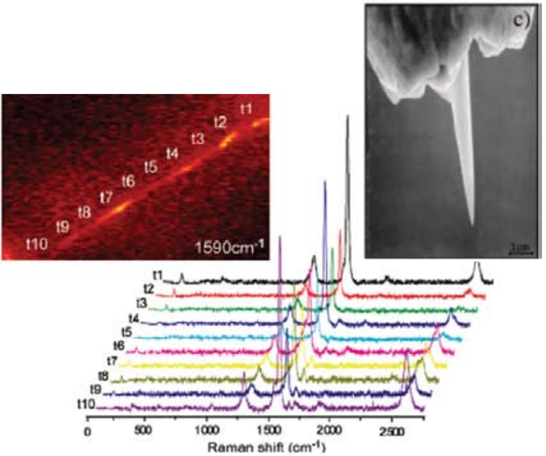
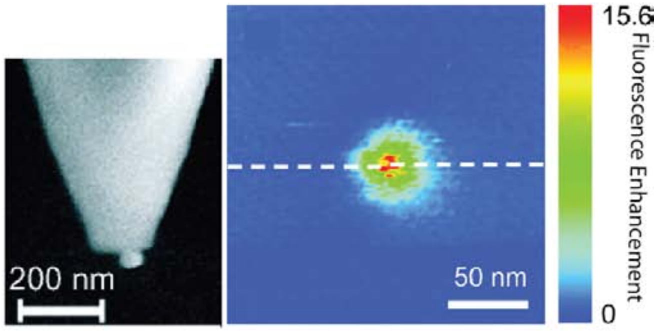
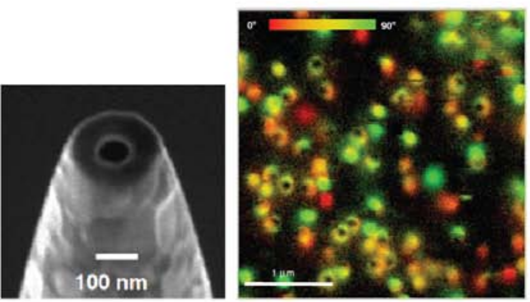
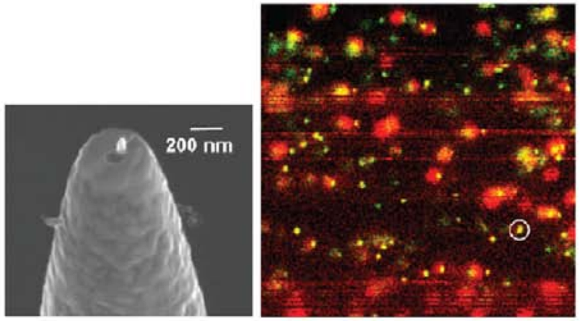
Plasmonic Nanoscopy



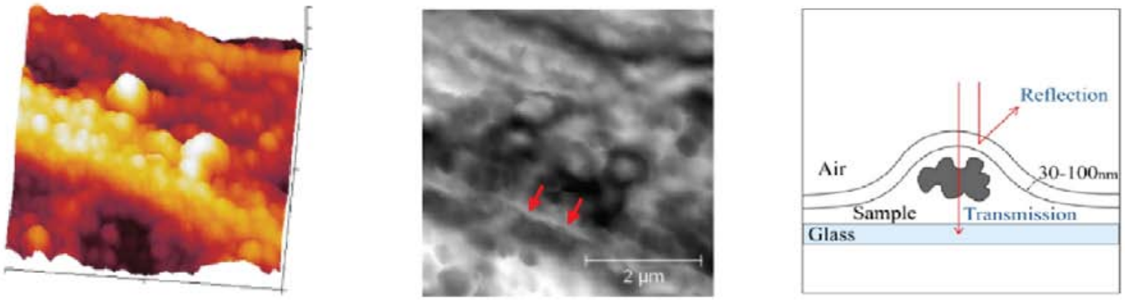


Left: Chemical vision: SERS image and spectra of a single-wall carbon nanotube obtained with a FIB-fabricated silver tip. L. Novotny and S. J. Stranick, Annual Rev. Phys. Chem. **57**, 303-331 (2006)
Right: Nanosphere probe and image of fluorescence enhancement of a single dye molecule. H. Eghlidi et 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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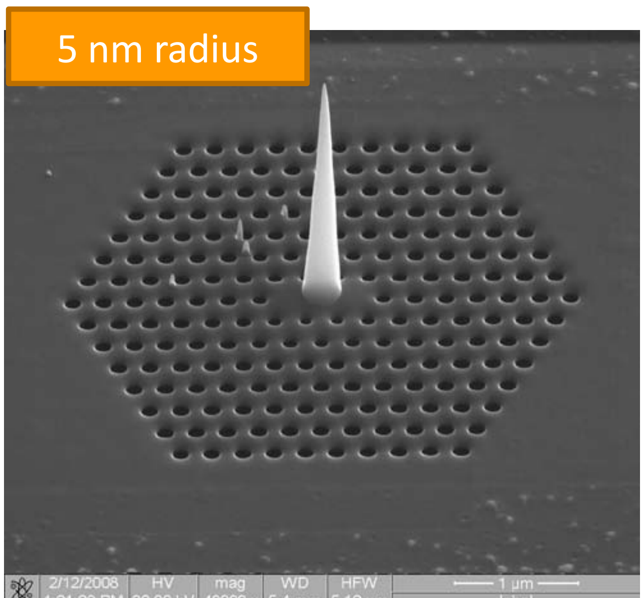
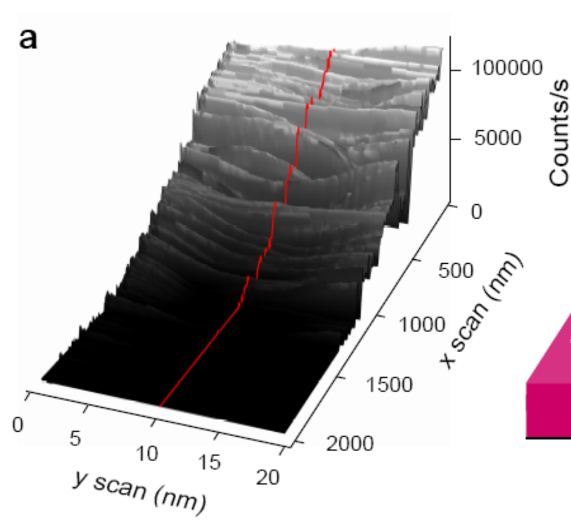
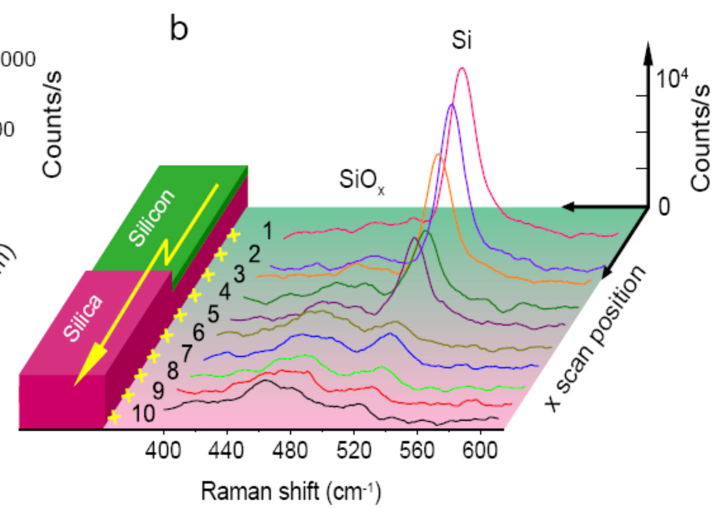
nature nanotechnology | ARTICLES
PUBLISHED ONLINE: 22 NOVEMBER 2009 | DOI: 10.1038/NNANO.2009.348

Nanoscale chemical mapping using three-dimensional adiabatic compression of surface plasmon polaritons

Francesco De Angelis[1,2], Gobind Das[1], Patrizio Candeloro[2], Maddalena Patrini[3], Matteo Galli[3], Alpan Bek[4], Marco Lazzarino[4,5], Ivan Maksymov[3], Carlo Liberale[2], Lucio Claudio Andreani[3] and Enzo Di Fabrizio[1,2]*







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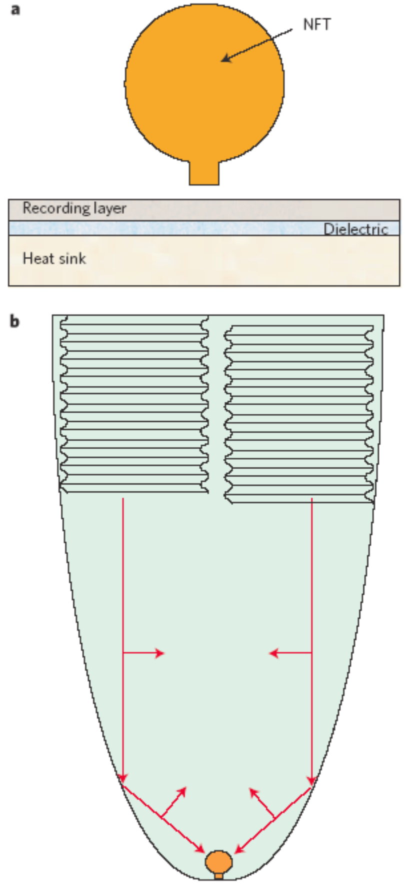
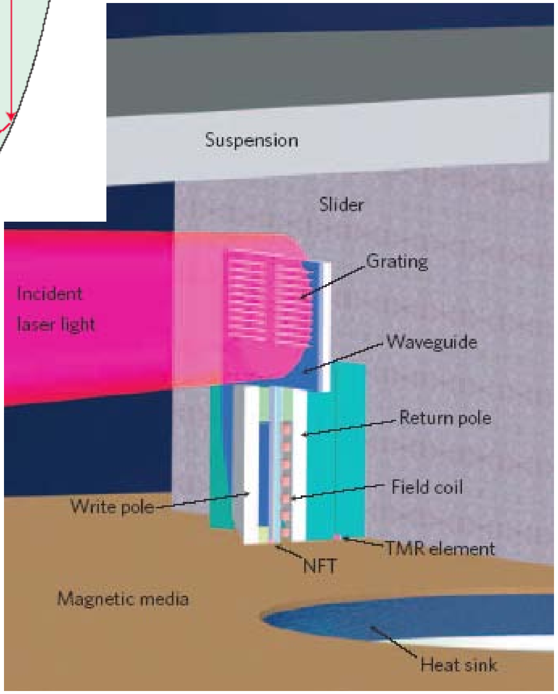
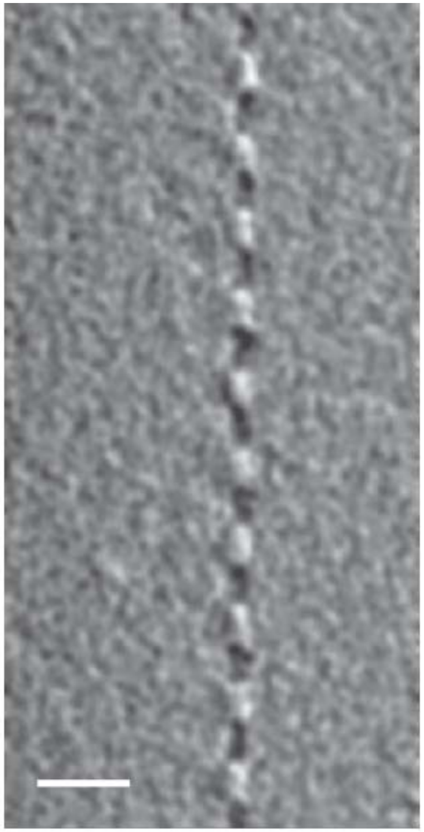


nature photonics
ARTICLES
PUBLISHED ONLINE: 22 MARCH 2009 | DOI: 10.1038/NPHOTON.2009.26

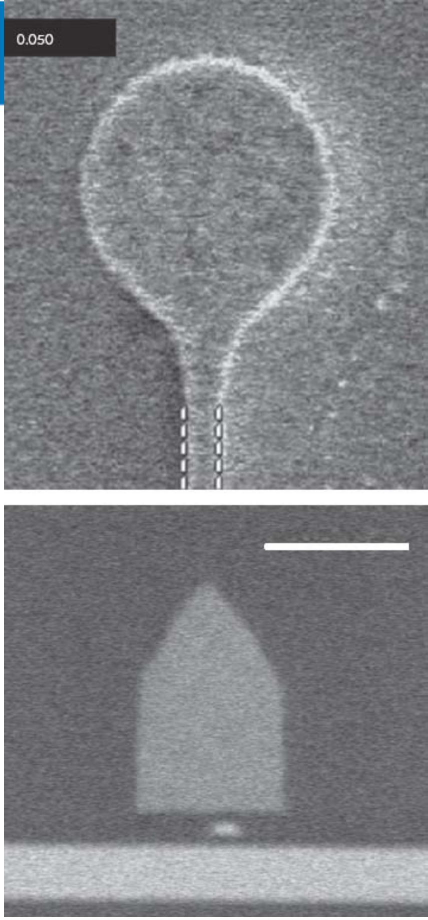
Heat-assisted magnetic recording by a near-field transducer with efficient optical energy transfer

W. A. Challener*, Chubing Peng, A. V. Itagi, D. Karns, Wei Peng, Yingguo Peng, XiaoMin Yang, Xiaobin Zhu, N. J. Gokemeijer, Y.-T. Hsia, G. Ju, Robert E. Rottmayer, Michael A. Seigler and E. C. Gage





MFM image of a recorded track. The track width is ~70
300 nm.



Nanometre-scale germanium photodetector enhanced by a near-infrared dipole antenna

nature photonics | VOL 2 | APRIL 2008 | www.nature.com/naturephotonics

LIANG TANG[1]*, SUKRU EKIN KOCABAS[1], SALMAN LATIF[1], ALI K. OKYAY[2], DANY-SEBASTIEN LY-GAGNON[1], KRISHNA C. SARASWAT[2] AND DAVID A. B. MILLER[1]

[1]Ginzton Laboratory, Stanford University, Stanford, California 94305, USA

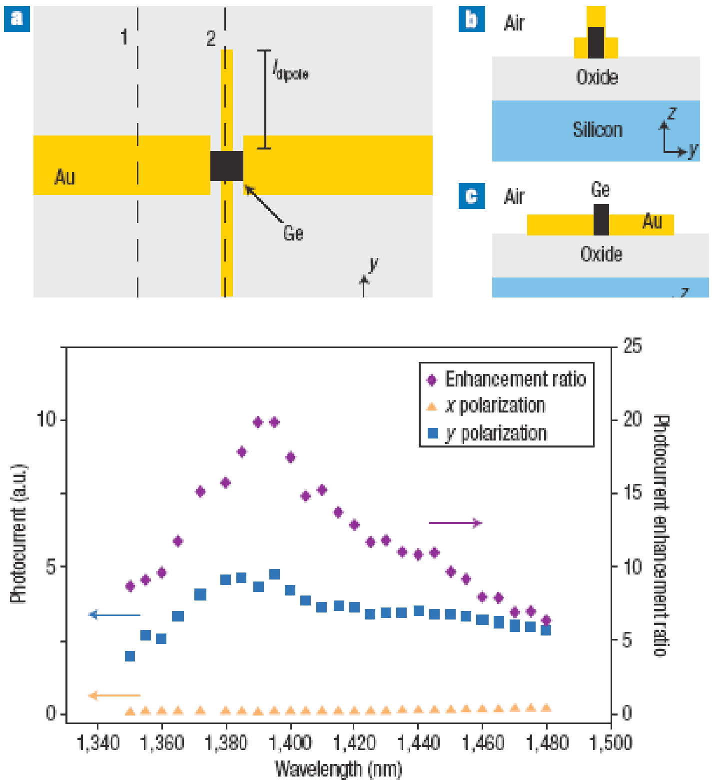


Figure 5 **Measured photocurrent responses for light polarization in the *y* and *x* directions.** The wavelengths were 1,350–1,480 nm for the detector with l_{dipole} = 160 nm.

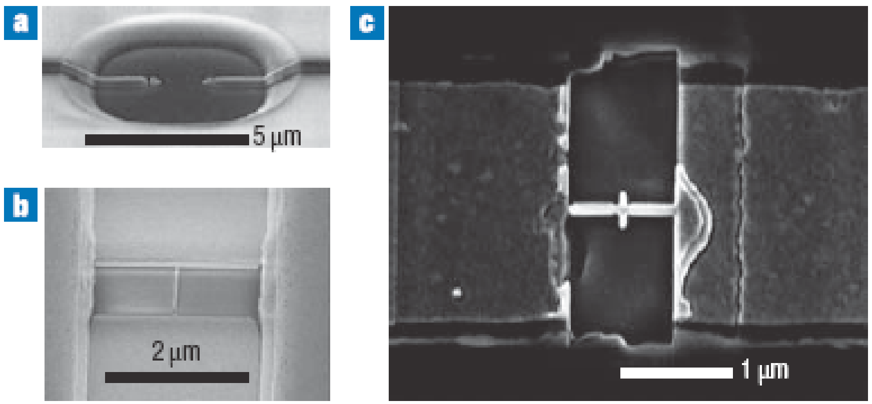


Figure 3 **Scanning electron microscopy (SEM) images of the fabricated devices.** **a**, Silicon seeding window with 2-µm-wide germanium crystalline lines. **b**, 60-nm-wide and 2-µm-long germanium nanowire fabricated by the first FIB step. **c**, An open-sleeve dipole antenna detector with l_{dipole} = 155 nm (this image is rotated by 90° in relation to that in **b**). (Charging due to a thick oxide layer limits the resolution in this SEM image.)

nature materials
LETTERS
PUBLISHED ONLINE: 8 AUGUST 2010 | DOI:10.1038/NMAT2822

Designer spoof surface plasmon structures collimate terahertz laser beams

Nanfang Yu[1]*, Qi Jie Wang[1†], Mikhail A. Kats[1], Jonathan A. Fan[1], Suraj P. Khanna[2], Lianhe Li[2], A. Giles Davies[2], Edmund H. Linfield[2] and Federico Capasso[1]*

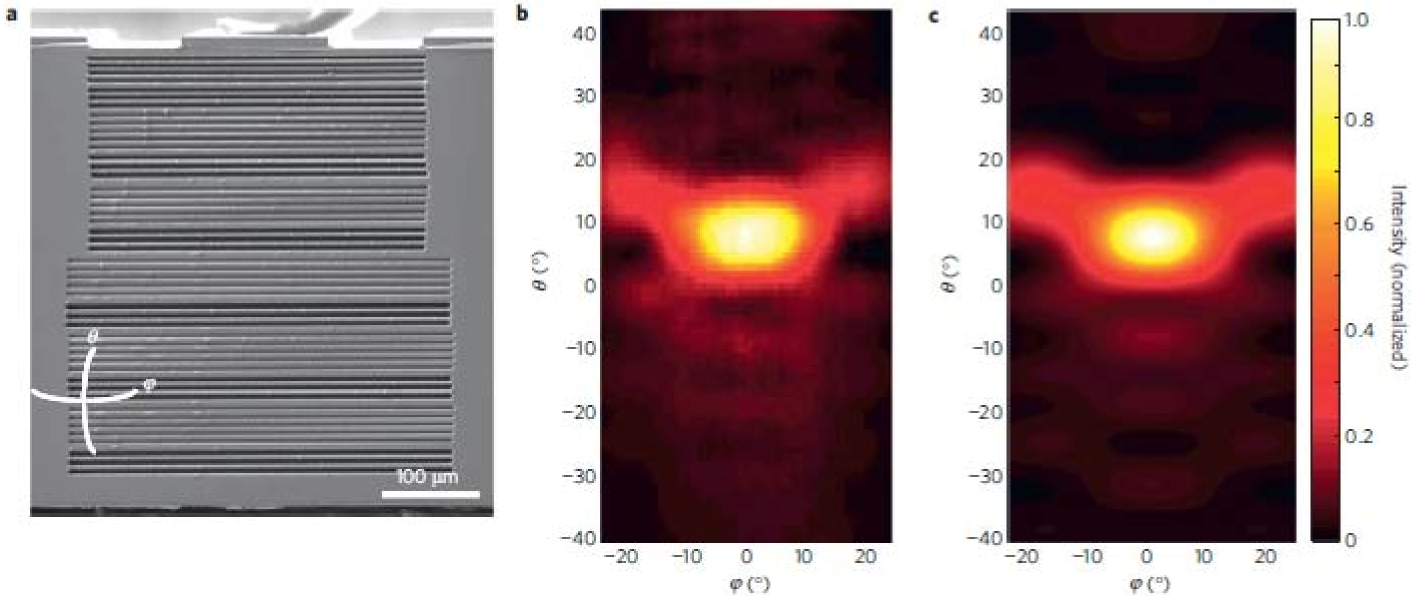


Figure 3 | Experimental results for a device fabricated according to the design in Fig. 1. a, Scanning electron microscope image of the device facet. The device has a 1.2-mm-long, 150-μm-wide and 10-μm-thick waveguide and lases at $\lambda_0 = 100$ μm. The plasmonic pattern is wider at the bottom part to further expand the wavefront of SPs. **b**,**c**, Measured (**b**) and simulated (**c**) 2D far-field intensity profiles of the device. **d**, Line-scans of **b** (red circles) and

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BRIEF CONCLUSIONS

1. Nanoplasmonics is based on nanolocalization of optical fields due to SPs
2. Enhancement in nanoplasmonics is due to quality factor of SP modes and geometric concentration
3. Plasmonic hot spots is universal phenomena due to the scale-invariance of the nanoplasmonic phenomena
4. Adiabatic concentration is a non-resonant, wide-band, and non-radiative root to nanofocusing with extremely high throughput. There are demonstrated applications to nanoscopy and chemical nano-imaging.

6. SPASER is an efficient nanoscale generator and ultrafast quantum amplifier with a switch time ~100 fs for silver and ~10 fs for gold. It has the same size as MOSFET and can perform the same functions but is ~1000 times faster.

8. The most developed applications of nanoplasmonics are: biomedical sensing, immunoassays, nanoscopy, chemical vision nanoscopy, cancer therapy, THz lasers
9. The emerging applications of nanoplasmonics are: nanoantennas for photodetectors and solar cells, ultrafast computations, new optical elements (circular-polarization filters, etc.), metamaterials, generation of EUV and XUV with plasmonic enhancement, etc.


The End