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

US Israel Binational Science Foundation

Nanoplasmonics: The Physics behind the Applications

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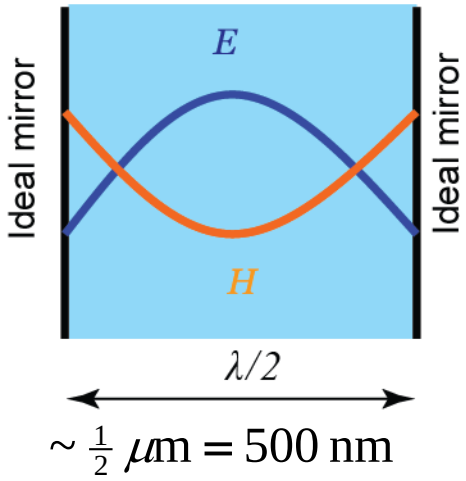
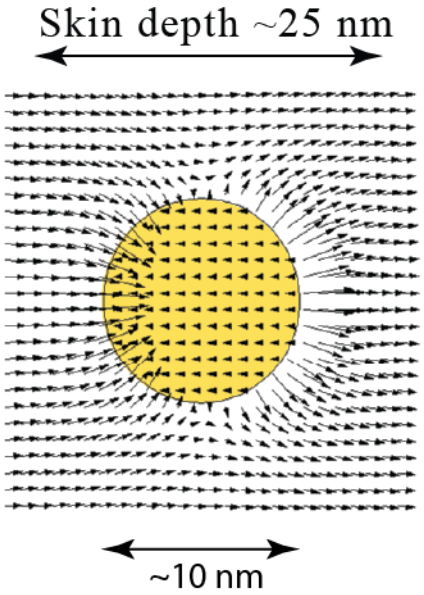
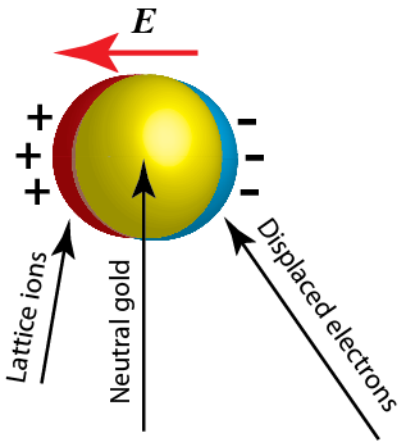
Nanoplasmonics in a nano-nutshell

Concentration of optical energy on the nanoscale







Photon: Quantum of electromagnetic field

Surface Plasmon: Quantum of electromechanical oscillator

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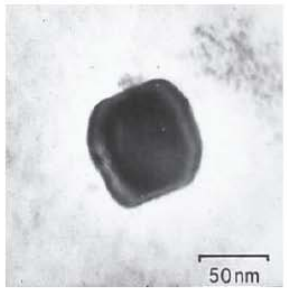
Lycurgus Cup (4th Century AD): Roman Nanotechnology

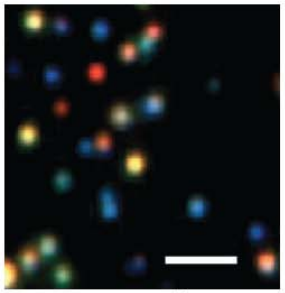


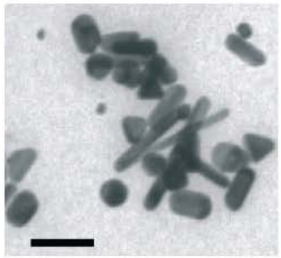
I. Freestone, N. Meeks, M. Sax, and C. Higgitt, *The Lycurgus Cup - a Roman Nanotechnology,* Gold Bull. **40**, 270-277 (2007)

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

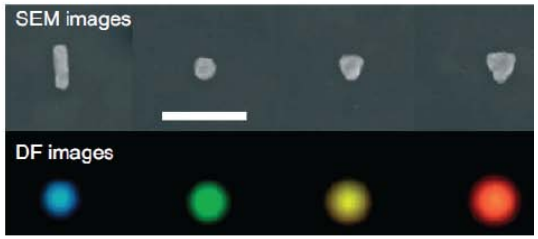
Nanoplasmonic colors are also eternal: metal nanoparticles are stable in glass: they do not bleach and do not blink. Gold is stable under biological conditions and is not toxic *in vivo*

Colors of Silver Nanocrystals and Gold Nanoshapes





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



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

Scanning electron microscopy

Dark field optical microscopy

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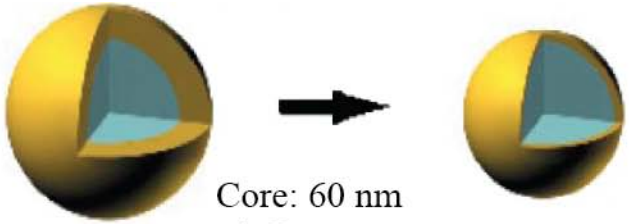
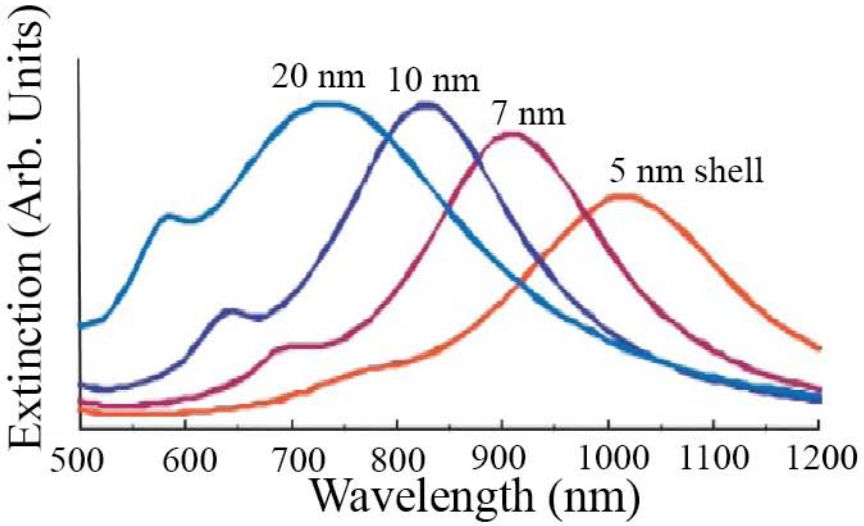
Nanoshell: Dielectric Core and Metal Shell

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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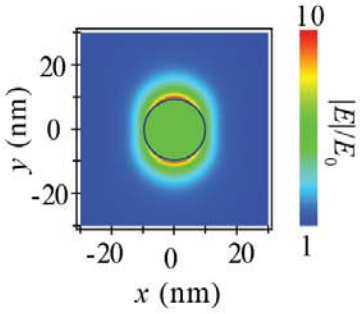
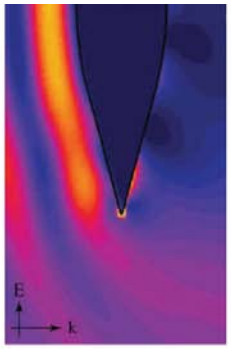
Plasmonic Near-Field **Hot Spots:** Happy 15th Anniversary!

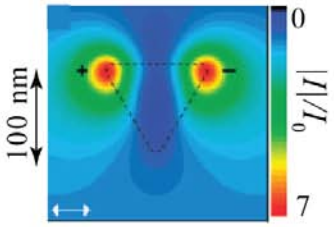
•M. I. Stockman et al., *Phys. Rev. Lett.* **75**, 2450 (1995)



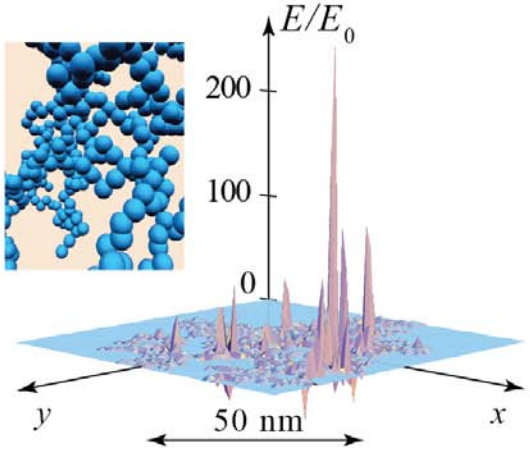
Silver nanosphere



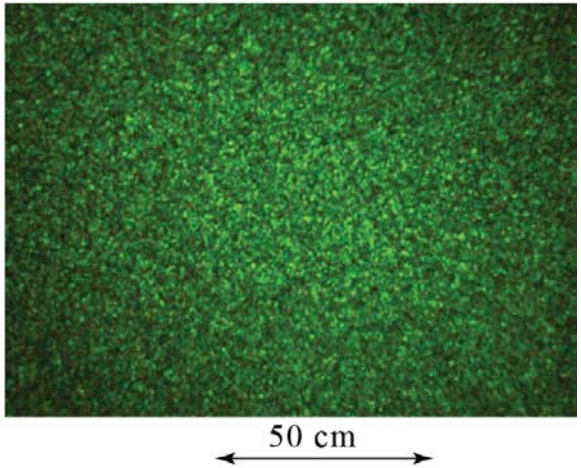
Metal tip: L. Novotny and S. J. Stranick, Annual Rev. Phys. Chem. **57**, 303-331 (2006)



Nano-pyramid: M. Rang et al., Nano Lett. **8**, 3357 (2008)



Fractal cluster of silver: M. I. Stockman, L. N. Pandey, and T. F. George, Phys. Rev. B **53**, 2183-2186 (1996)



Optical counterpart: laser speckles on a screen

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

$R_{Speckle}$ is speckle size

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

A is laser spot size,

L is distance to the screen

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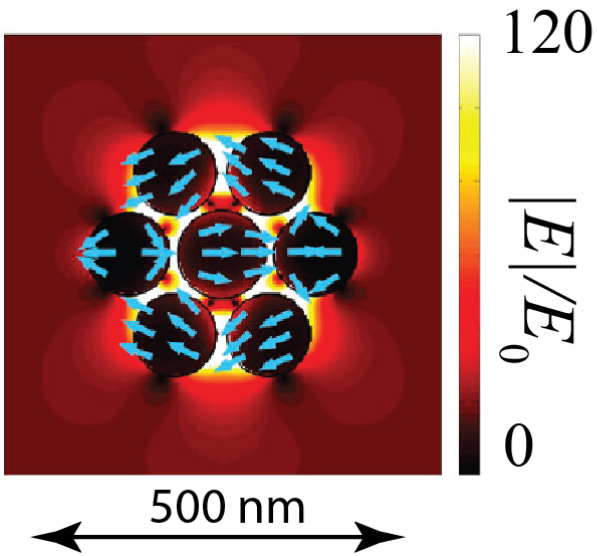
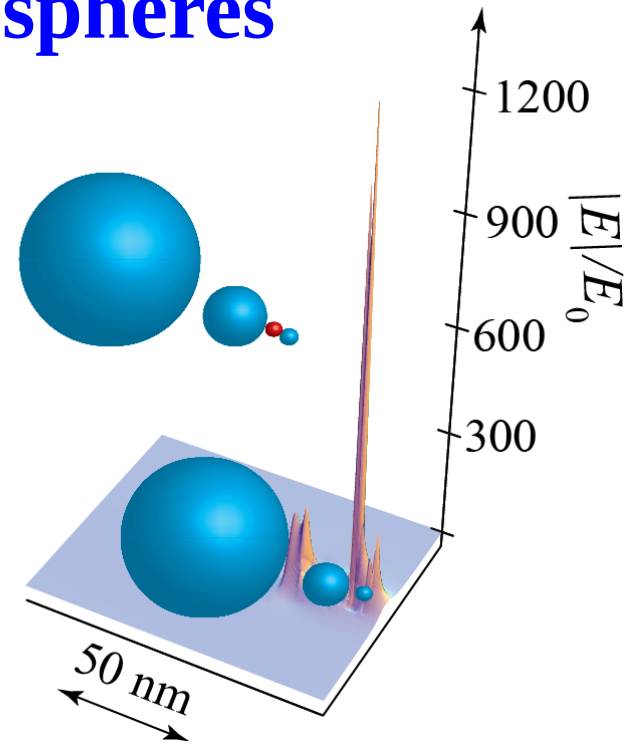
Engineered Nanoplasmonic Hot Spots in Small Clusters of Nanospheres





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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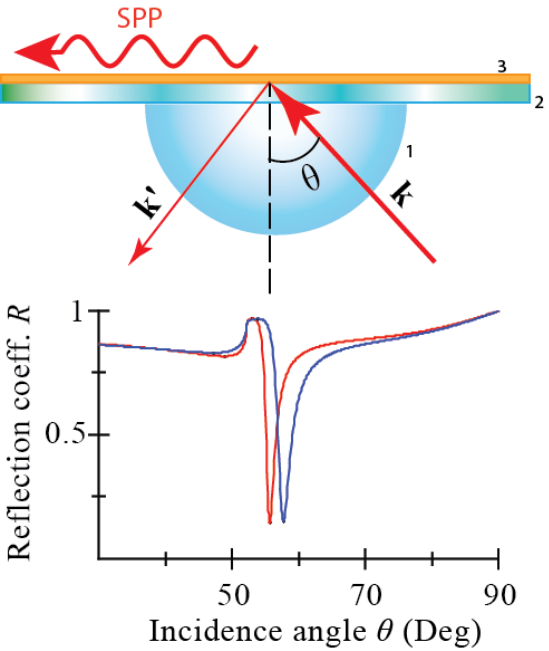
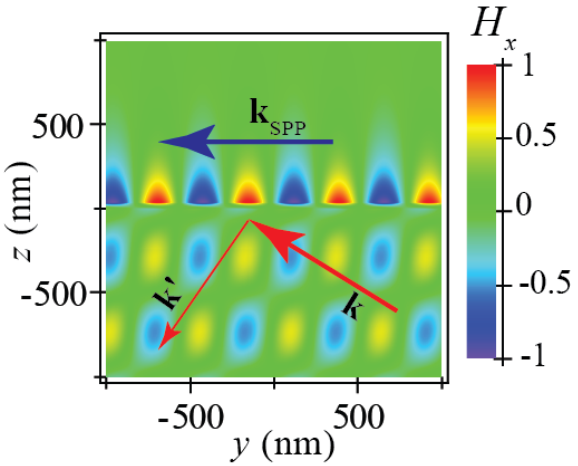
Surface plasmon polaritons (SPPs) and their hot spots: electromagnetic waves at metal-dielectric interfaces

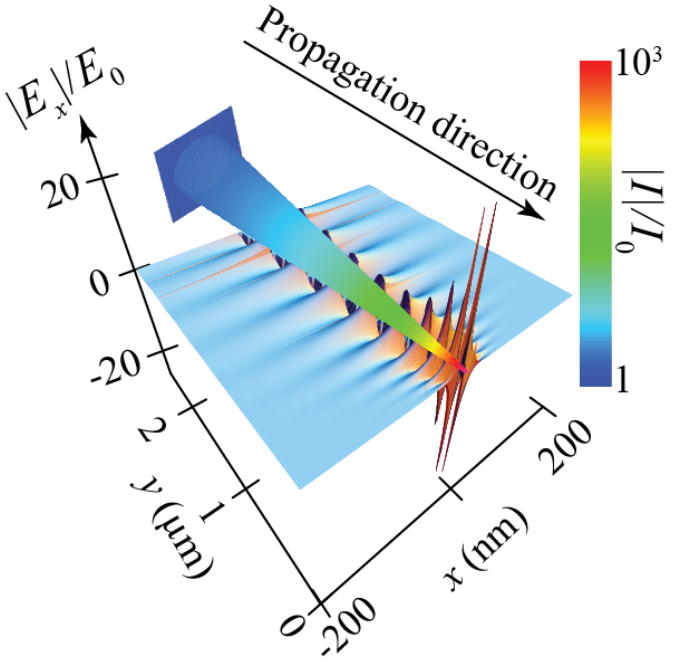


Kretschmann geometry of SPP excitation (top);
Refection coefficient as a function of incidence angle (bottom)



$k_{SPP}=\mathbf{k}\ \mathrm{Cos}\theta$

Local fields (magnetic component) of SPPs



Adiabatic compression of SPPs: M. I. Stockman, Phys. Rev. Lett. **93**, 137404 (2004)

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Enhancement factors for small nanoparticles (size $R < l_s \sim 25\,\text{nm}$)

Plasmonic quality factor : $Q = \dfrac{-\,\text{Re}\,\varepsilon_m}{\text{Im}\,\varepsilon_m} \sim 10 - 100$

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)

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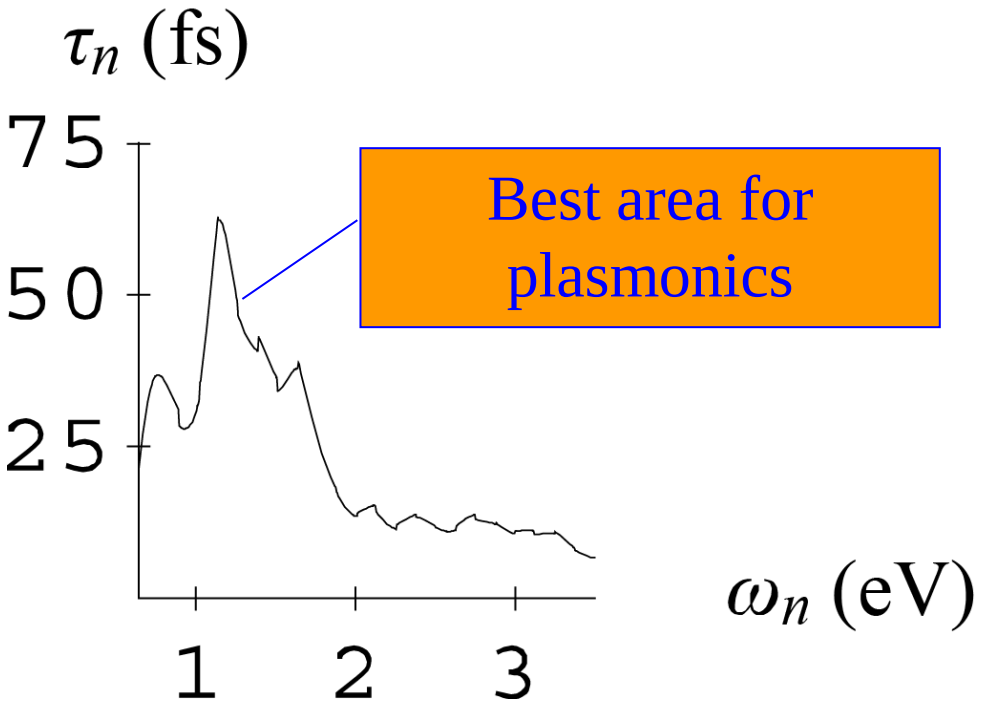
Nanoplasmonics is intrinsically ultrafast:



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

Electron emission: Perturbative two-photon ultrafast intrinsic nonlinearity

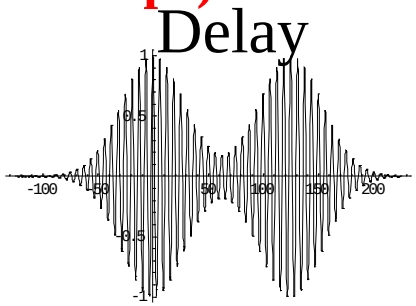
Localized SP hot spots and SPPs coexist in space and time on nanostructured surfaces

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).

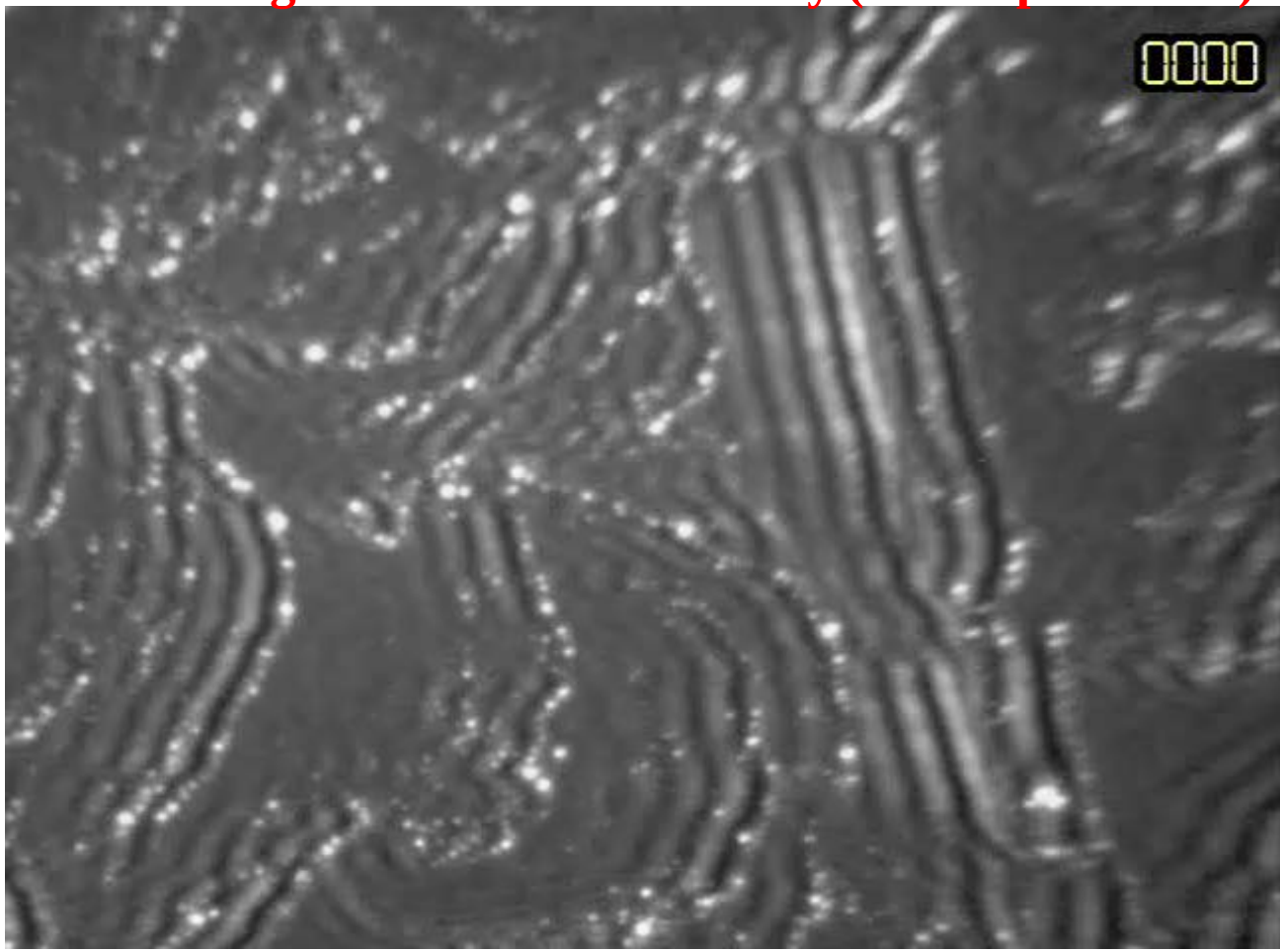
200 nm

30 femtoseconds from life of a nanoplasmonic systems

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



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



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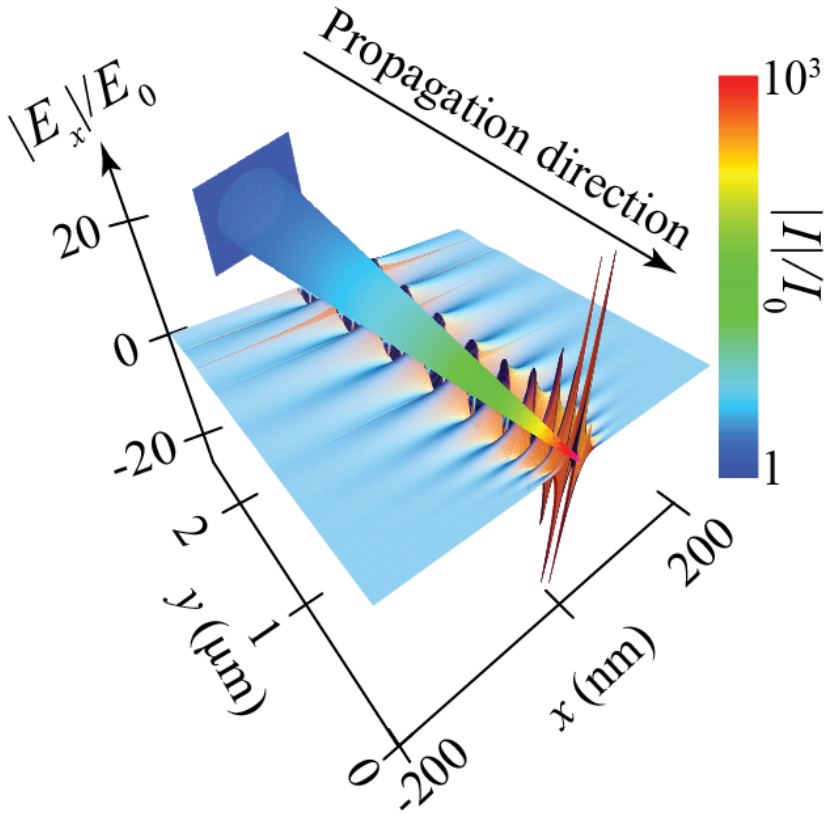
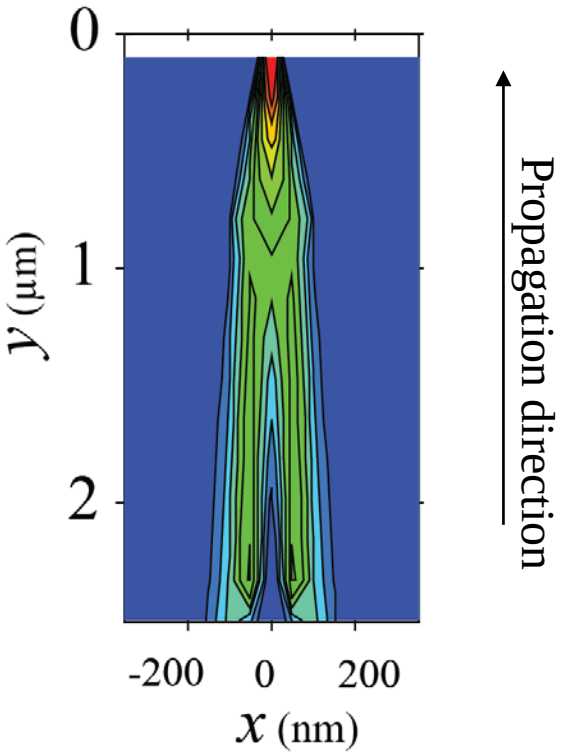
Field enhancement :

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

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

Adiabatic Compression





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

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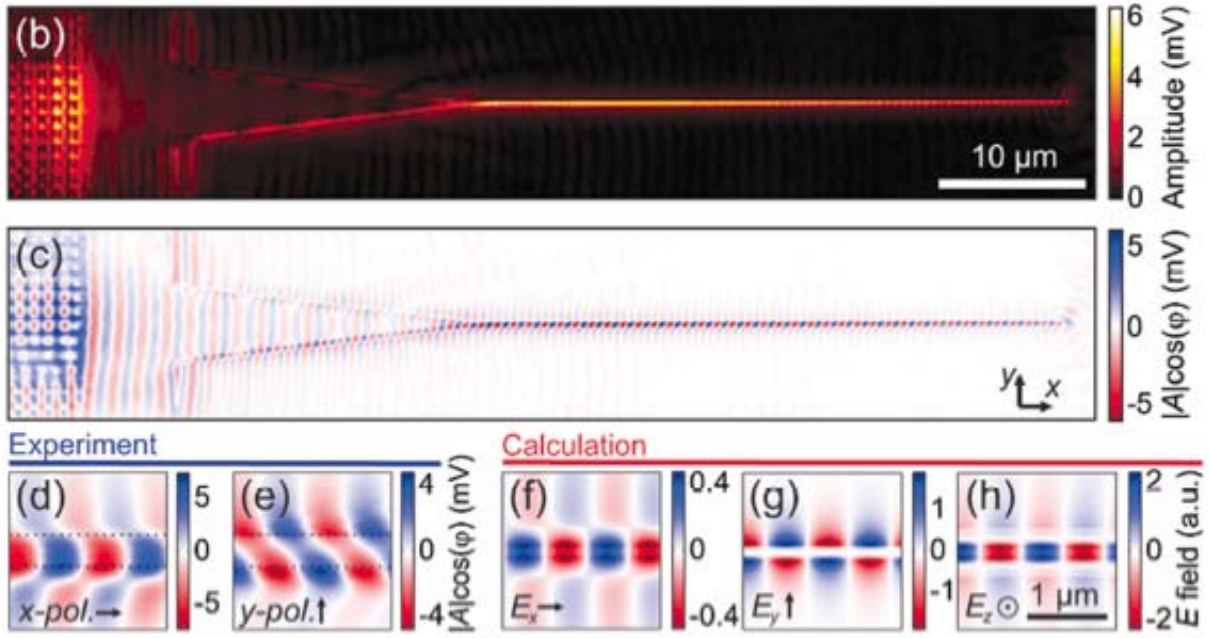
PRL 102, 203904 (2009) PHYSICAL REVIEW LETTERS

Nanowire Plasmon Excitation by Adiabatic Mode Transformation

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



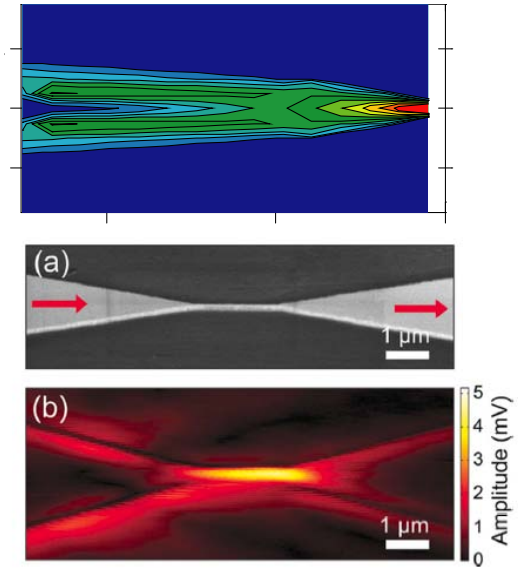


FIG. 4 (color). (a) Secondary electron micrograph of a 2 μm long nanowire connected by tapered waveguide sections for input and output coupling. (b) Near-field amplitude of forward-propagating waves in the structure at $\lambda = 1550$ nm. The intensity transmission of the complete structure is $20 \pm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

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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 98195
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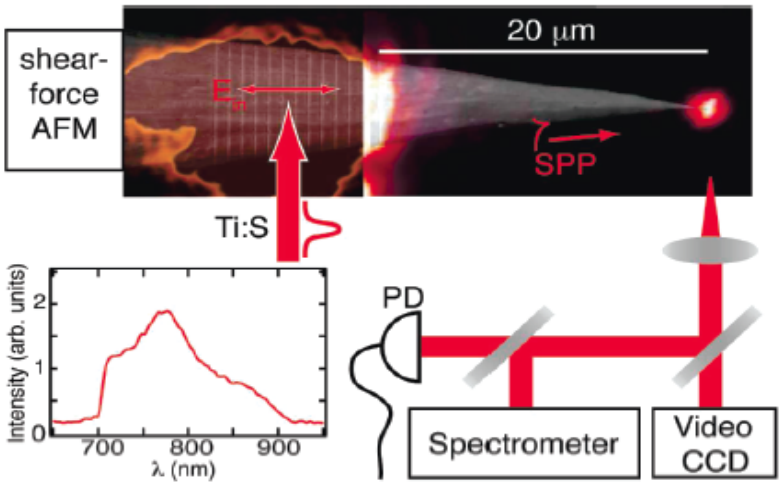

FIGURE 1. Grating coupling of surface plasmons on a tip. Overlay of SEM and optical far-field image of a Au tip with grating written by FIB for surface plasmon coupling of incident near-IR light from a Ti:Sapphire laser (spectrum shown). The grating with period $a_0 \sim$ 770 nm is illuminated with polarization 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 ≲15 nm.

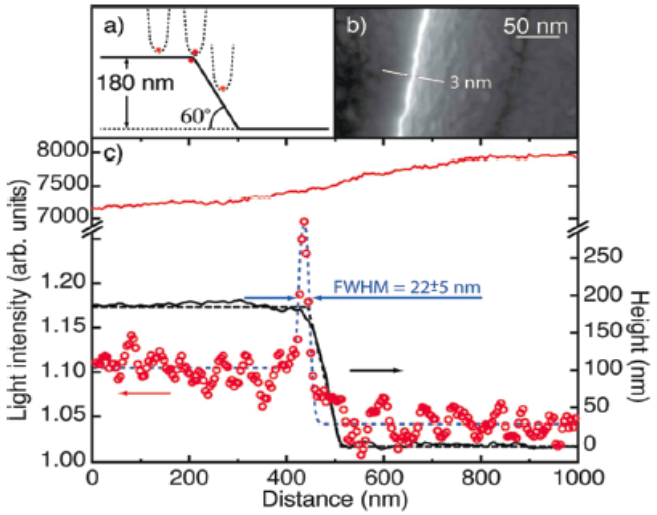

FIGURE 3. Determination of tip emitter size. (a) Schematic of scanning the nanofocusing tip across a silicon step edge with radius 3 ± 1 nm. (b) Top view SEM image of step edge. The wall and lower terrace are on the right-hand side. The edge serves as a local scatterer of the optical near-field of the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

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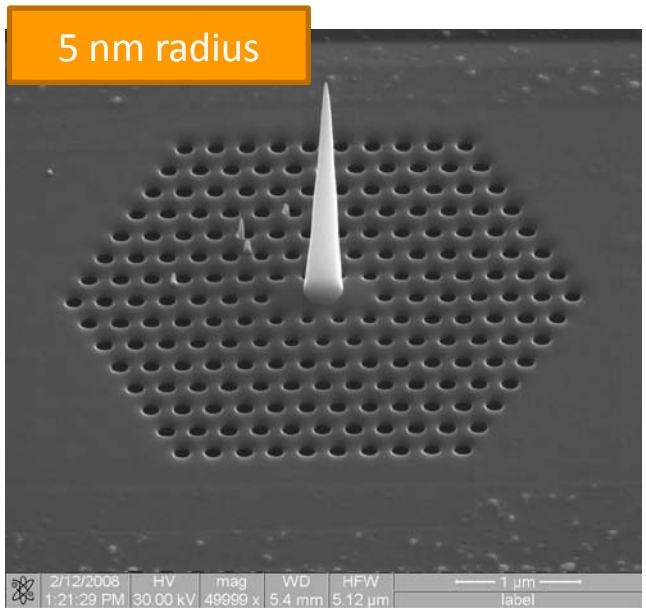
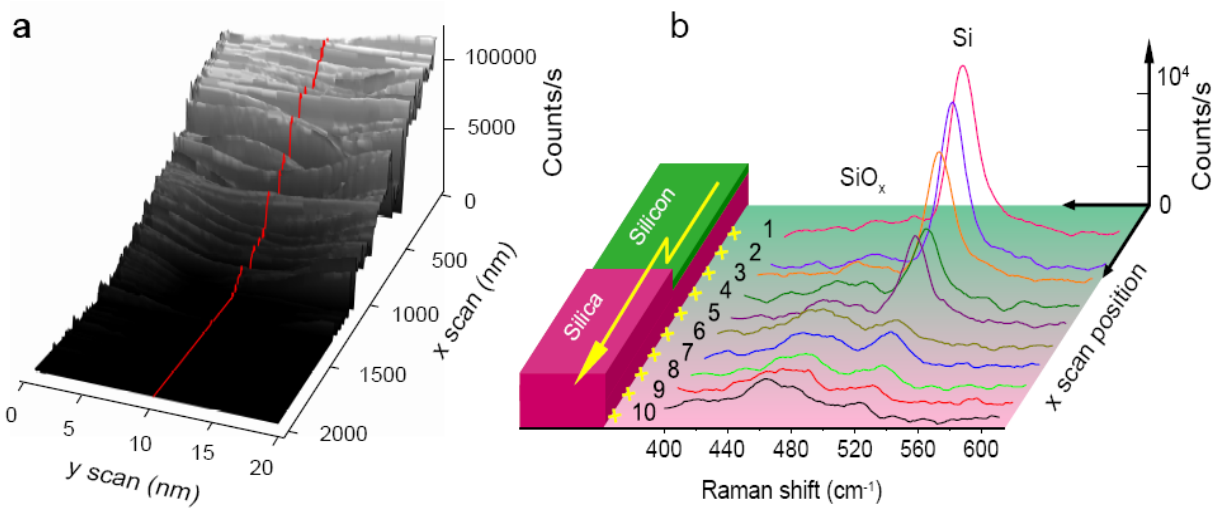
Nanoscale chemical mapping using three-dimensional adiabatic compression of surface plasmon polaritons

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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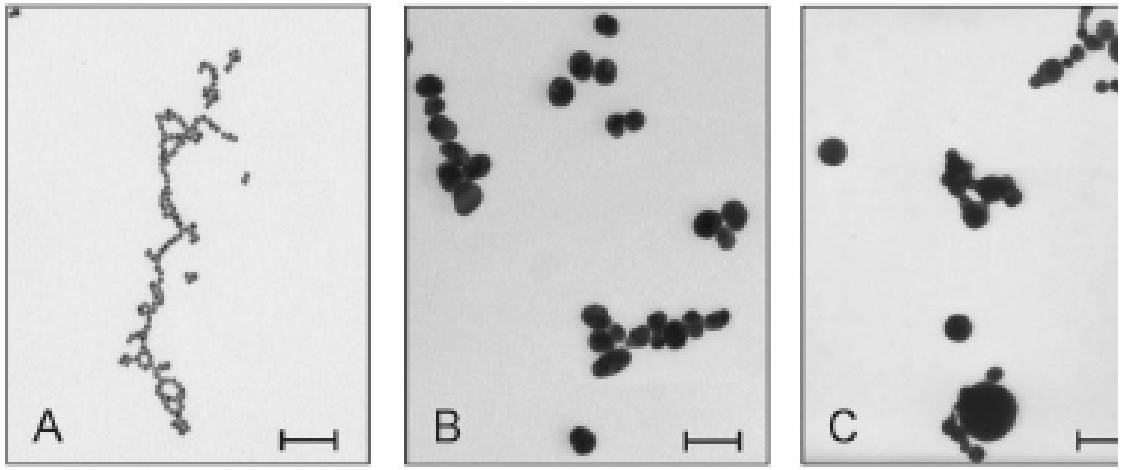
Anal. Chem. 2008, 80, 4247–4251

Correspondence

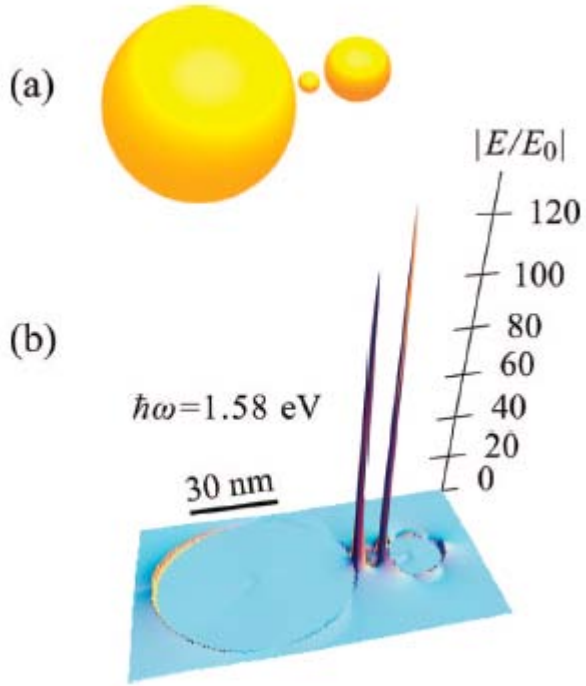
Different types of aggregates of gold nanospheres

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†,||



Scale bar: 100 nm



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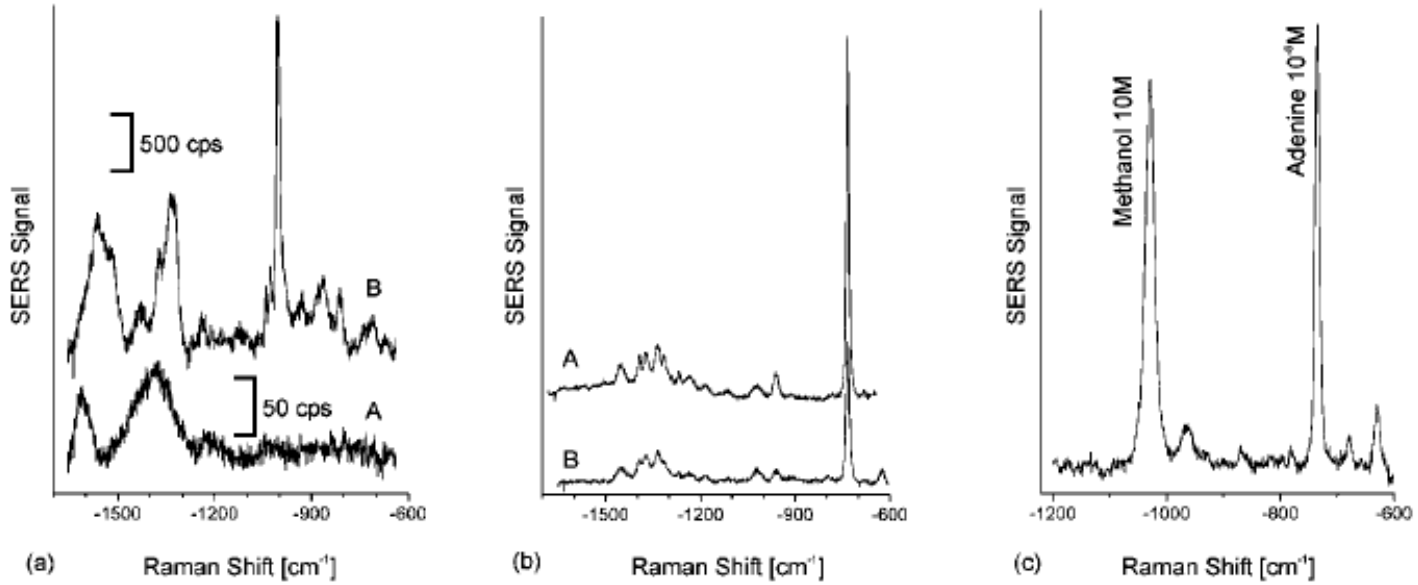

Figure 3. Comparison of SERS using gold nanolenses made by ablation and chemically prepared nanoaggregates as enhancing nanostructures. (a) Raman spectra measured from aqueous solutions of gold nanoaggregates without any analyte to compare background signals. The chemically prepared gold nanoparticles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

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Quantum Nanoplasmonics: Surface Plasmon Amplification by Stimulated Emission of Radiation (SPASER)

1. 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).
2. M. I. Stockman, *Spasers Explained*, Nat. Phot. **2**, 327-329 (2008) .
3. M. I. Stockman and D. J. Bergman, *Surface Plasmon Amplification by Stimulated Emission of Radiation (SPASER)*, USA Patent No. 7,569,188 (August 4, 2009)
4. M. I. Stockman, *Spaser as Nanoscale Quantum Generator and Ultrafast Amplifier*, Journal of Optics (JOPT) **12**, 024004-1-13 (2010).
5. M. A. Noginov, G. Zhu, A. M. Belgrave, R. Bakker, V. M. Shalaev, E. E. Narimanov, S. Stout, E. Herz, T. Suteewong, and U. Wiesner, *Demonstration of a Spaser-Based Nanolaser*, Nature **460**, 1110-1112 (2009).
6. M. T. Hill, M. Marell, E. S. P. Leong, B. Smalbrugge, Y. Zhu, M. Sun, P. J. van Veldhoven, E. J. Geluk, F. Karouta, Y.-S. Oei, R. Nötzel, C.-Z. Ning, and M. K. Smit, *Lasing in Metal-Insulator-Metal Sub-Wavelength Plasmonic Waveguides*, Opt. Express **17**, 11107-11112 (2009).
7. R. F. Oulton, V. J. Sorger, T. Zentgraf, R.-M. Ma, C. Gladden, L. Dai, G. Bartal, and X. Zhang, *Plasmon Lasers at Deep Subwavelength Scale*, Nature **461**, 629-632 (2009).

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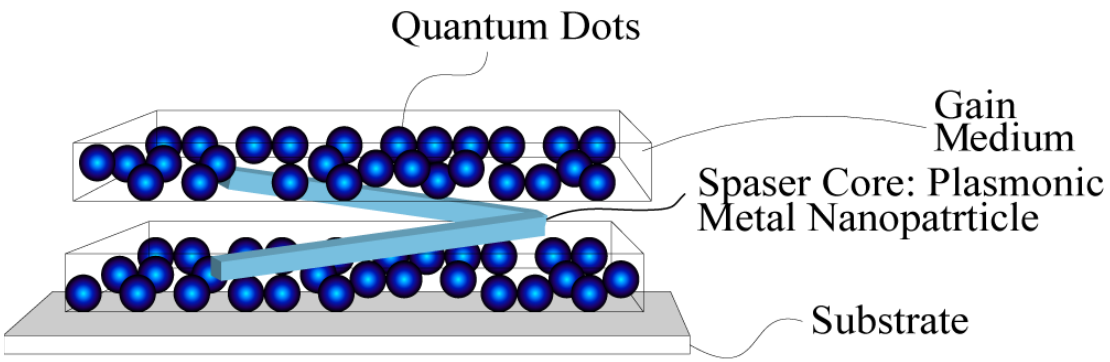
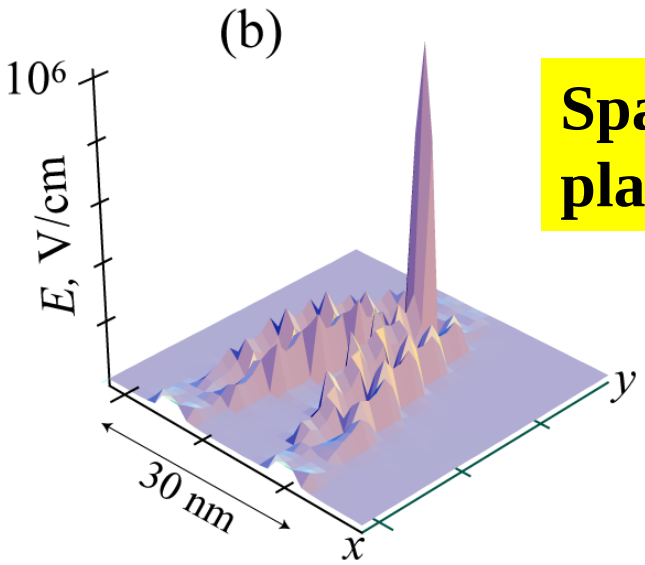
The original spaser geometry





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 an
e-mail: mstockman@gsu.edu

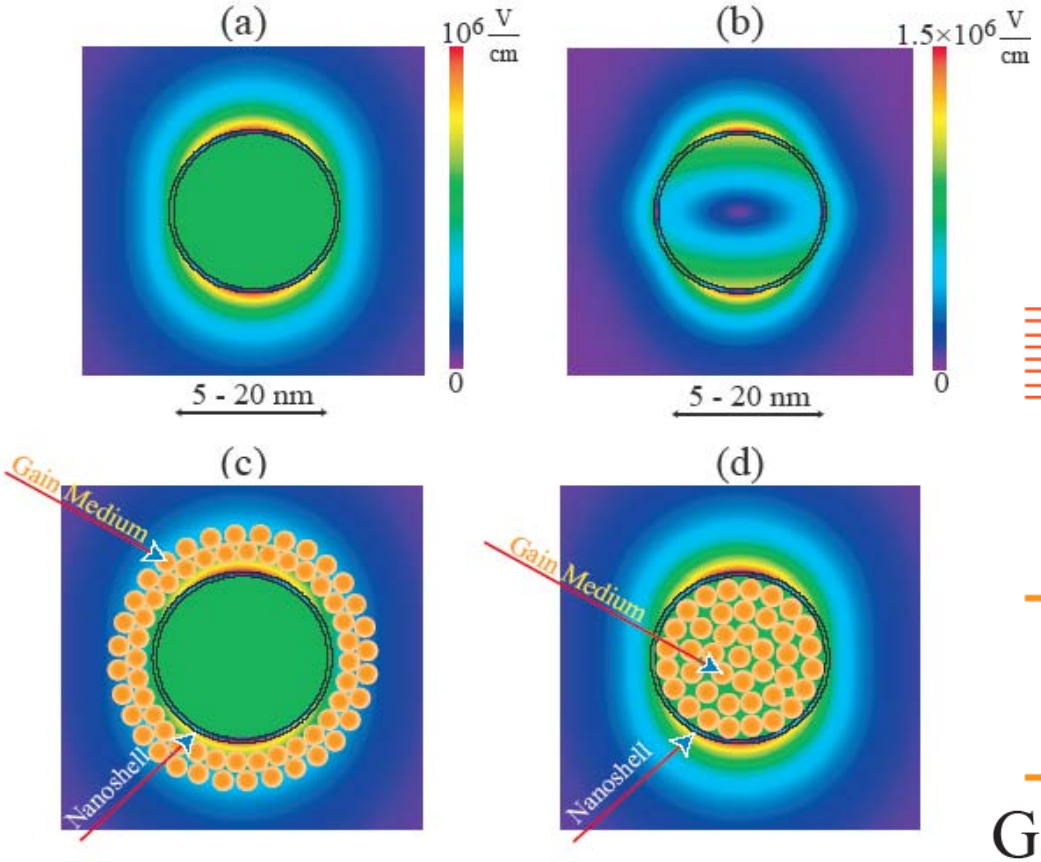
The spaser is a prope
number of leading lab
applications, includin

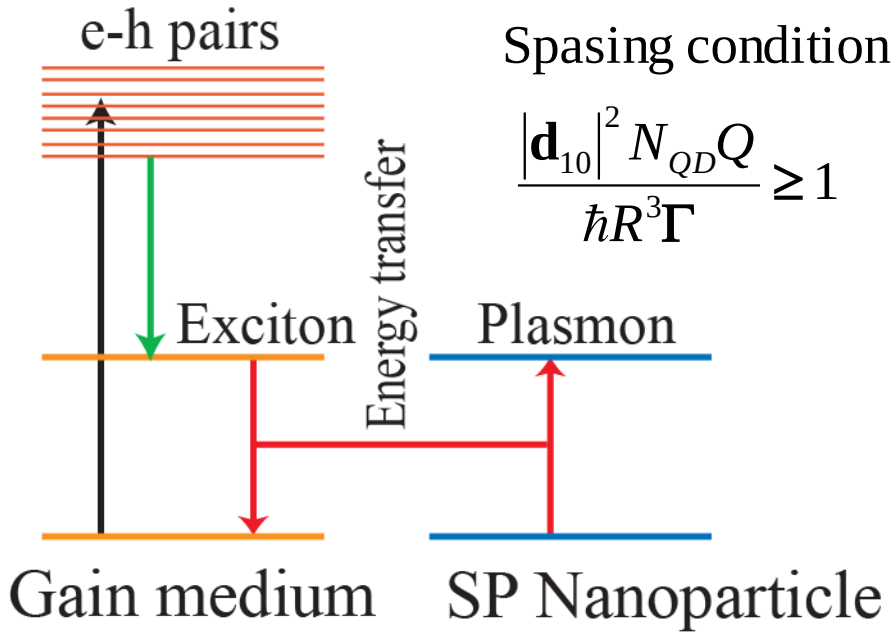
ge of

Spaser is the ultimately smallest quantum nano-generator and nano-amplifier

For small nanoparticles, radiative loss is negligible.

Spaser is quasistatic and fully scalable





Spasing condition :

$$\frac{|\mathbf{d}_{10}|^2 N_{QD} Q}{\hbar R^3 \Gamma} \geq 1$$

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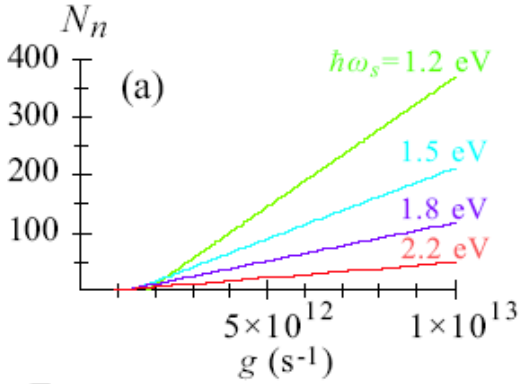
Stationary (CW) spaser regime

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

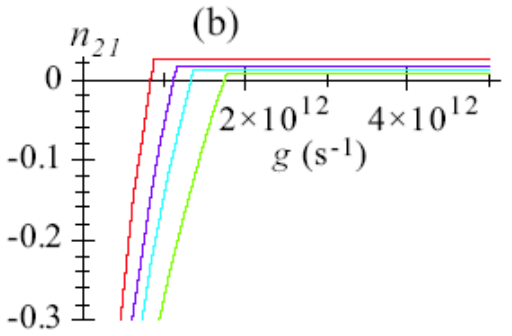
arXiv:0908.3559
Journal of Optics, **12**, 024004-1-13 (2010).

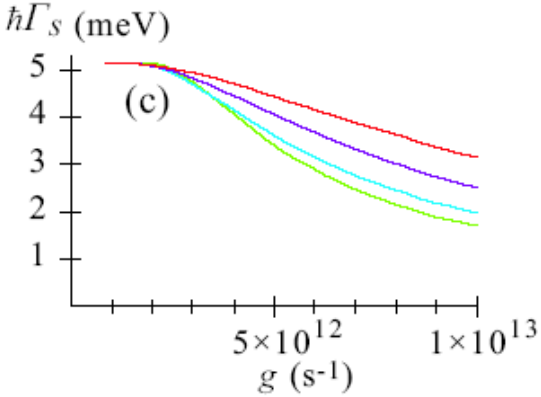
Spaser linewidth $\propto N_{SP}^{-1}$

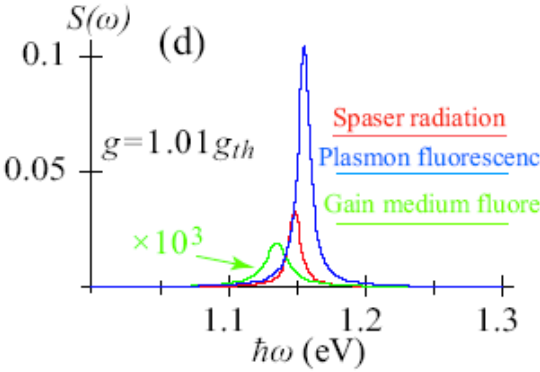
Plasmon number

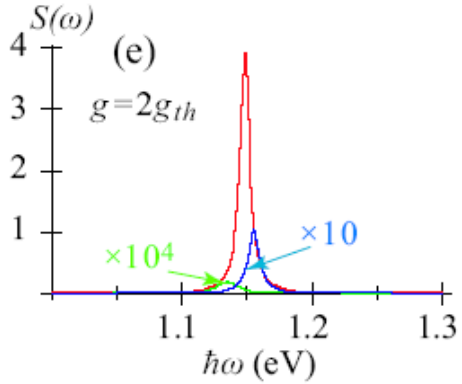


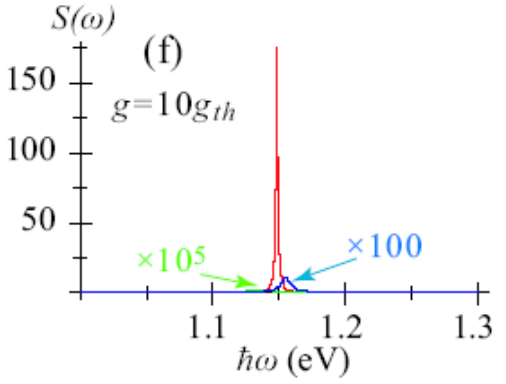
Inversion vs. pumping rate











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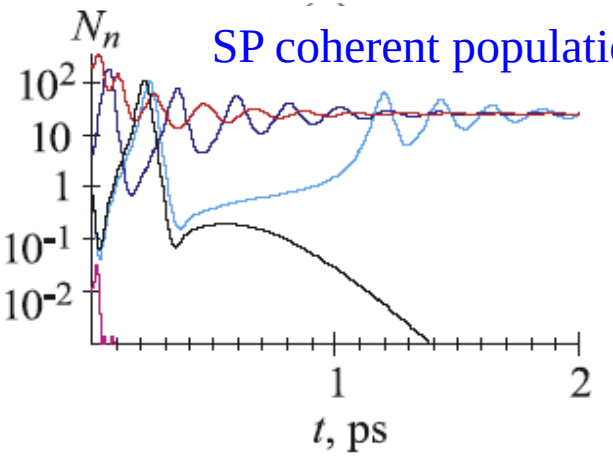
Bandwidth ~ 10-100 THz

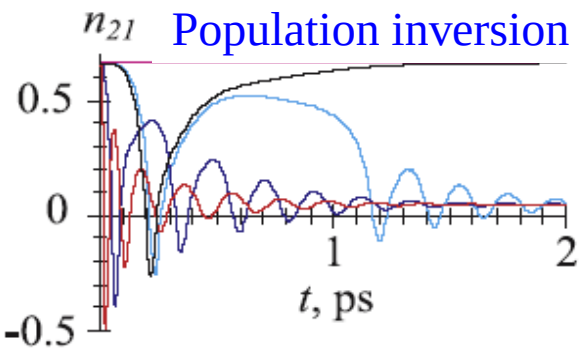
Very high resistance to ionizing radiation

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

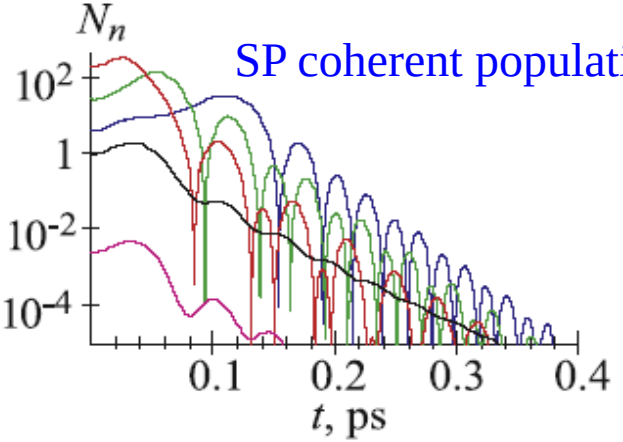
Stationary pumping

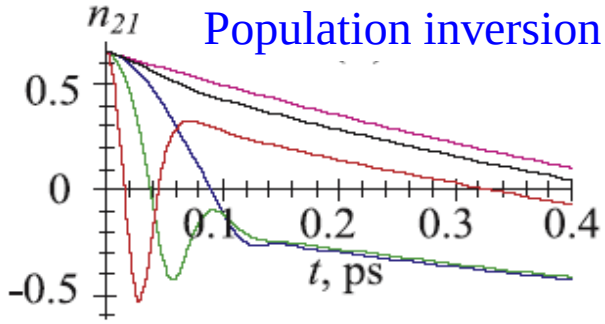
This very high speed of the spaser is due to the small modal volume





Pulse pumping





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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]

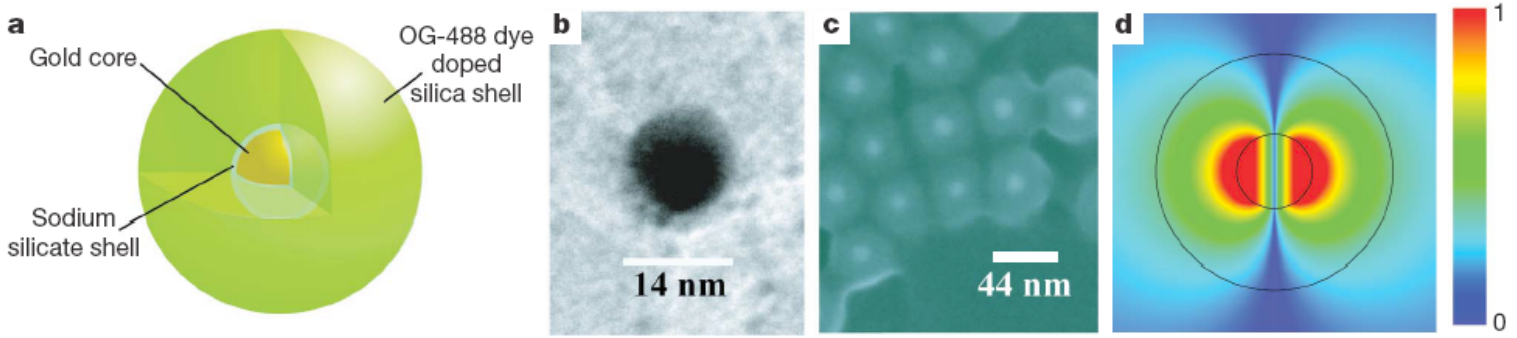

Figure 1 | Spaser design. **a**, Diagram of the hybrid nanoparticle architecture (not to scale), indicating dye molecules throughout the silica shell. **b**, Transmission electron microscope image of Au core. **c**, Scanning electron microscope image of Au/silica/dye core–shell nanoparticles. **d**, Spaser mode (in false colour), with $\lambda = 525$ nm and $Q = 14.8$; the inner and the outer circles represent the 14-nm core and the 44-nm shell, respectively. The field strength colour scheme is shown on the right.

[1]Center for Materials Research, Norfolk State University, Norfolk, Virginia 23504, USA. [2]School of Electrical & Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA. [3]Materials Science and Engineering Department, Cornell University, Ithaca, New York 14850, USA.

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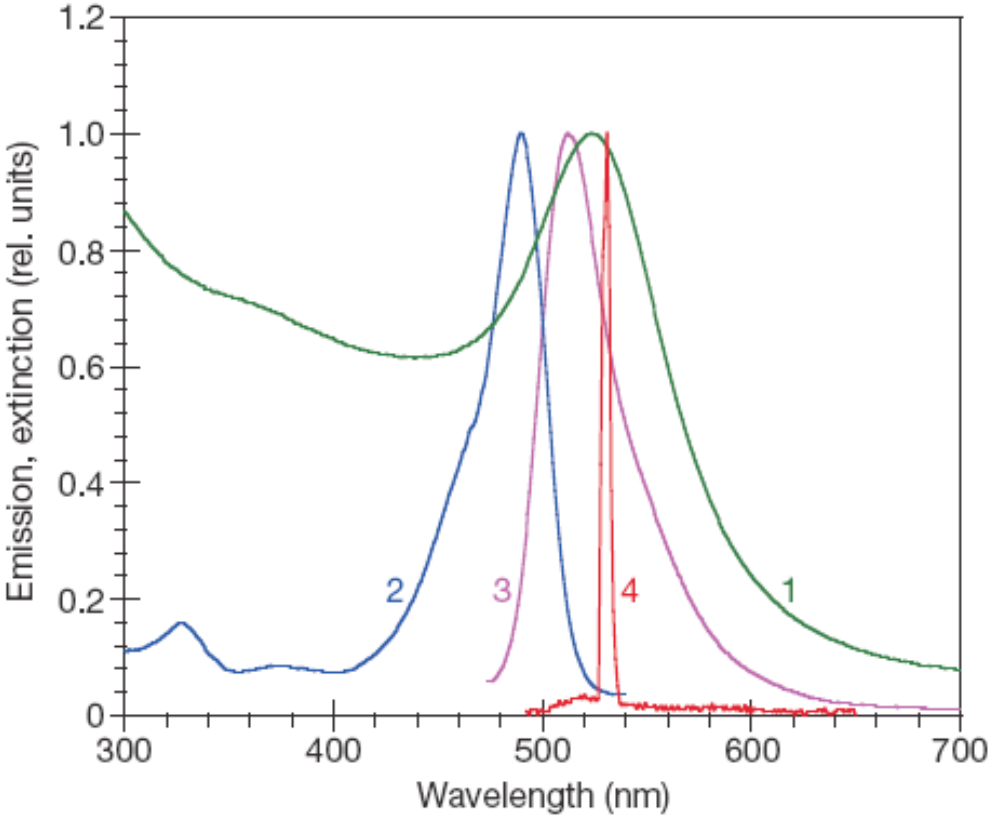

Figure 2 | Spectroscopic results. Normalized extinction (1), excitation (2), spontaneous emission (3), and stimulated emission (4) spectra of Au/silica/dye nanoparticles. The peak extinction cross-section of the nanoparticles is 1.1×10^{-12} cm^2. The emission and excitation spectra were measured in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

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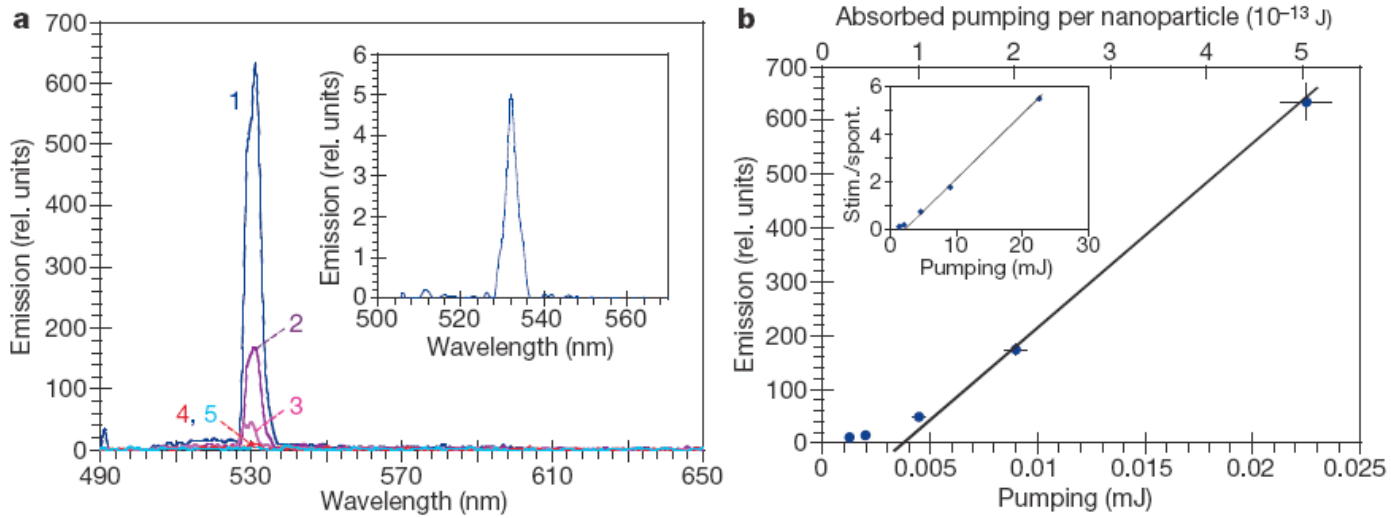

Figure 4 | Stimulated emission. **a**, Main panel, stimulated emission spectra of the nanoparticle sample pumped with 22.5 mJ (1), 9 mJ (2), 4.5 mJ (3), 2 mJ (4) and 1.25 mJ (5) 5-ns optical parametric oscillator pulses at $\lambda = 488$ nm. **b**, Main panel, corresponding input–output curve (lower axis, total launched pumping energy; upper axis, absorbed pumping energy per nanoparticle); for most experimental points, ~5% error bars (determined 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 >537 nm).

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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22 June 2009 / Vol. 17, No. 13 / OPTICS EXPRESS 11107

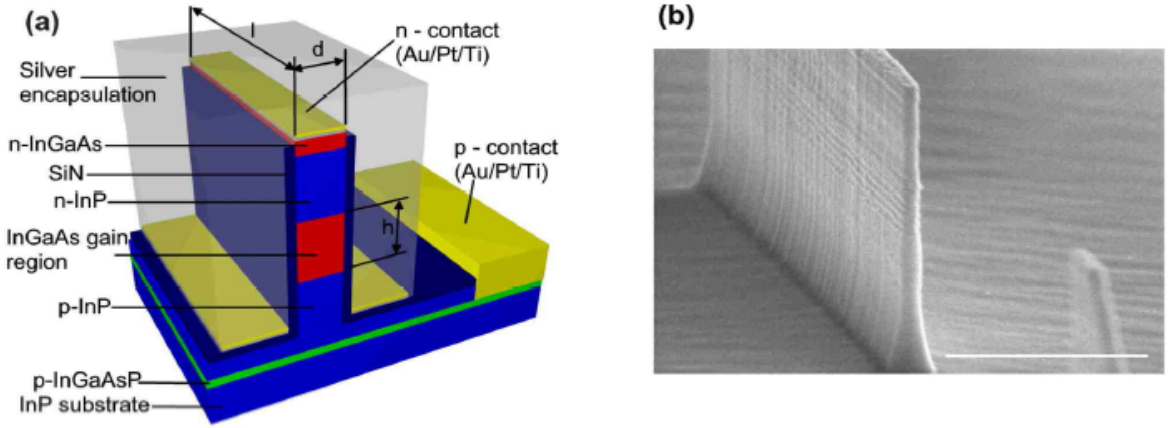

Fig. 1. Structure of cavity formed by a rectangular semiconductor pillar encapsulated in Silver. (a) Schematic showing the device layer structure. (b) Scanning electron microscope image showing the semiconductor core of one of the devices. The scale bar is 1 micron.

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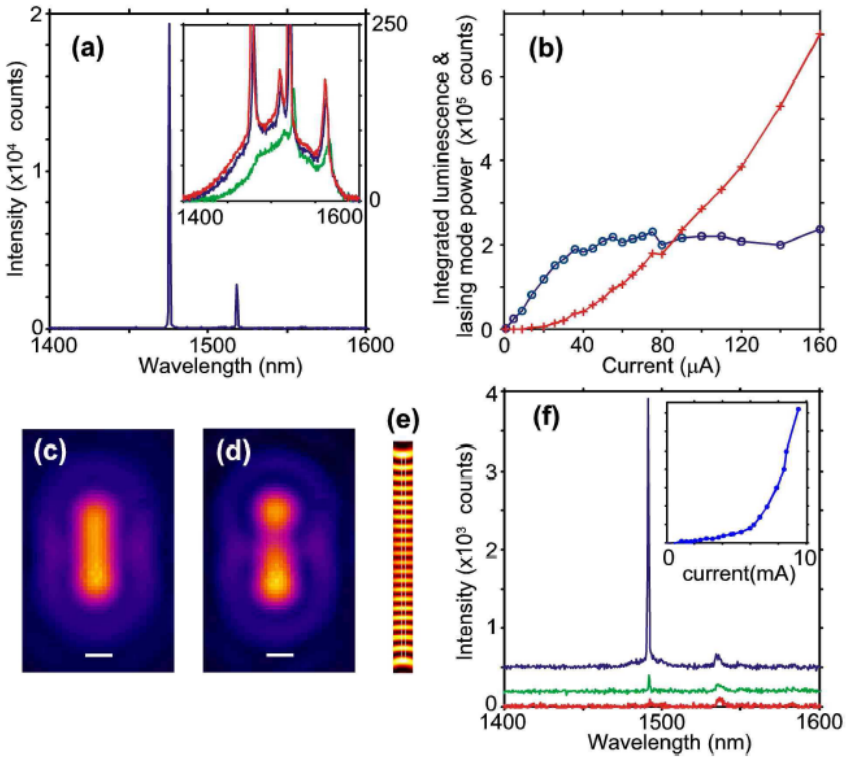

Fig. 2. Spectra and near field patterns showing lasing in devices. (a) Above threshold emission spectrum for 3 micron long device with semiconductor core width d~130nm (± 20nm), with pump current 180 μA at 78K. Inset: emission spectra for 20 (green), 40 (blue) and 60 (red) μA, all at 78K. (b) Lasing 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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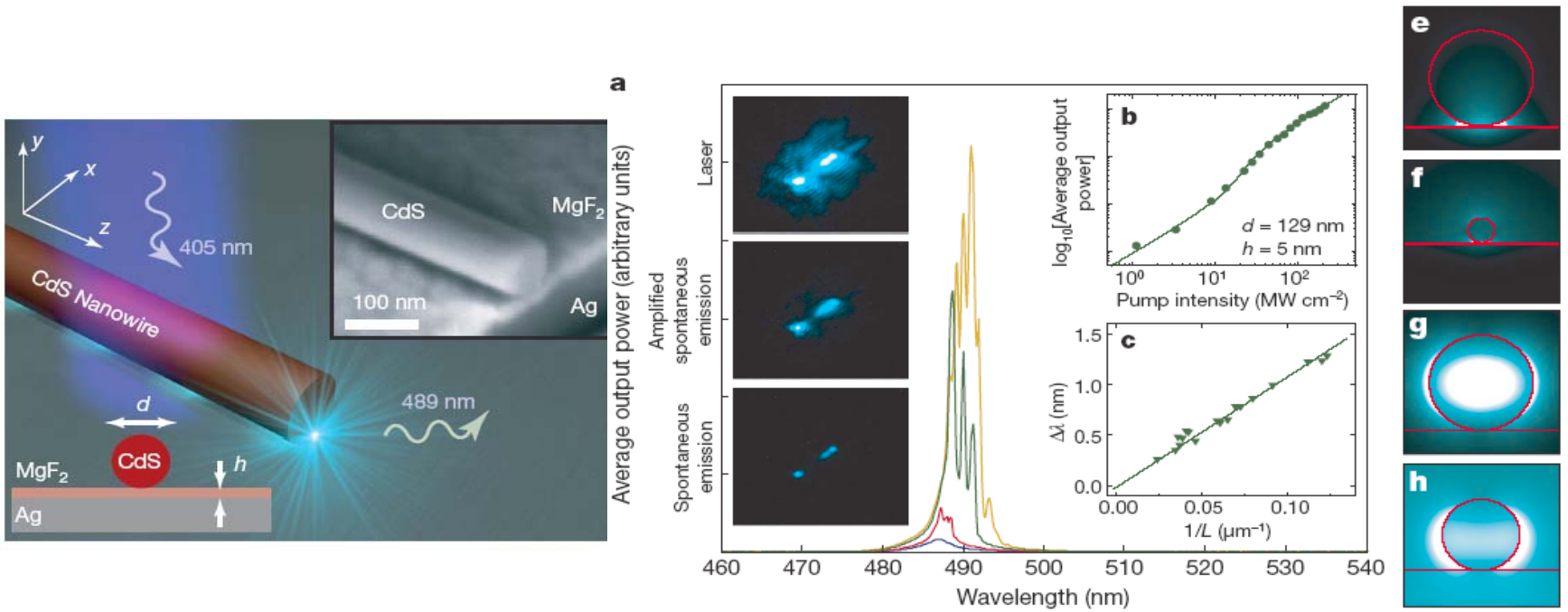
doi:10.1038/nature08364 nature

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]



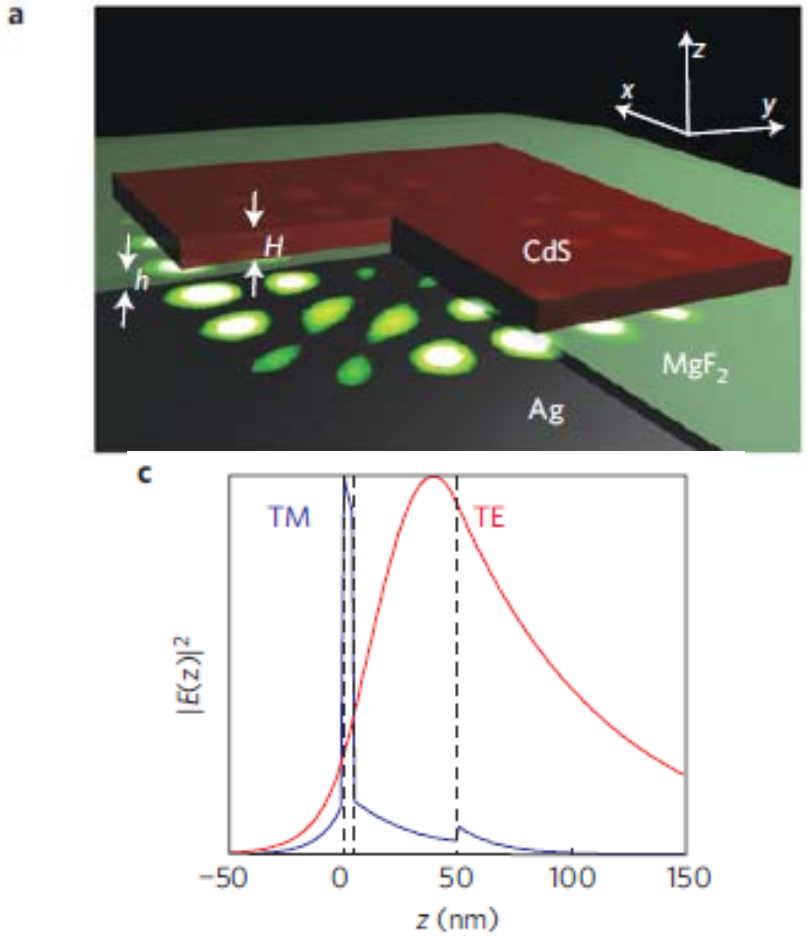
nature materials

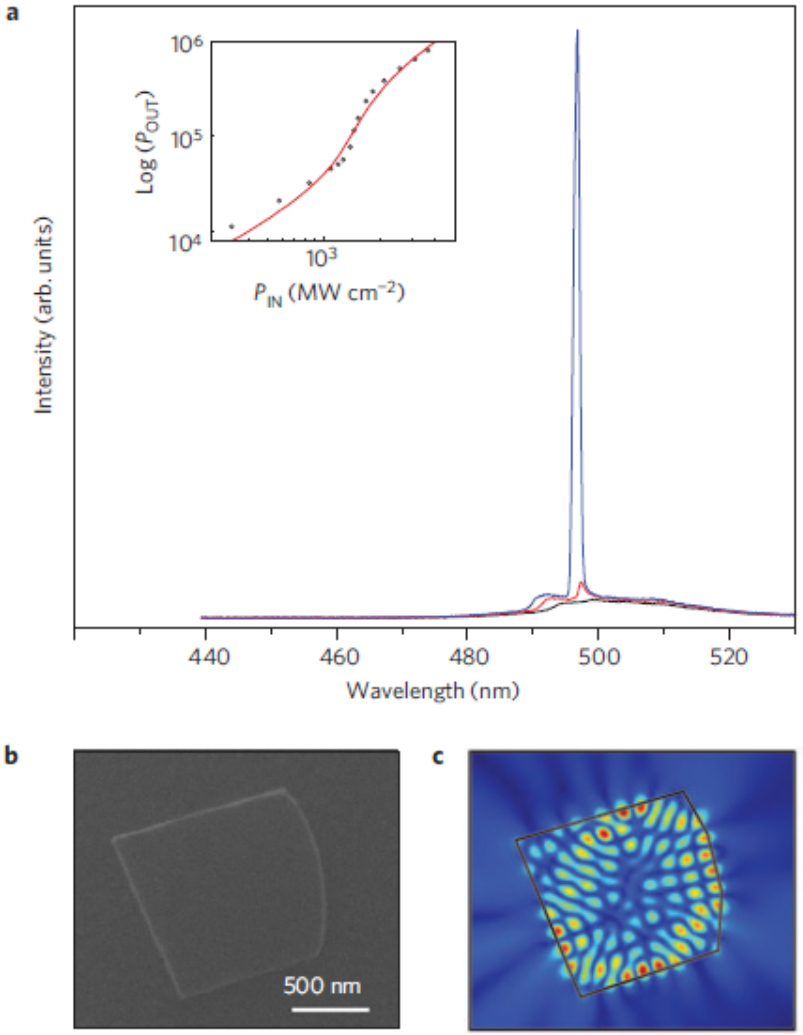
LETTERS

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]





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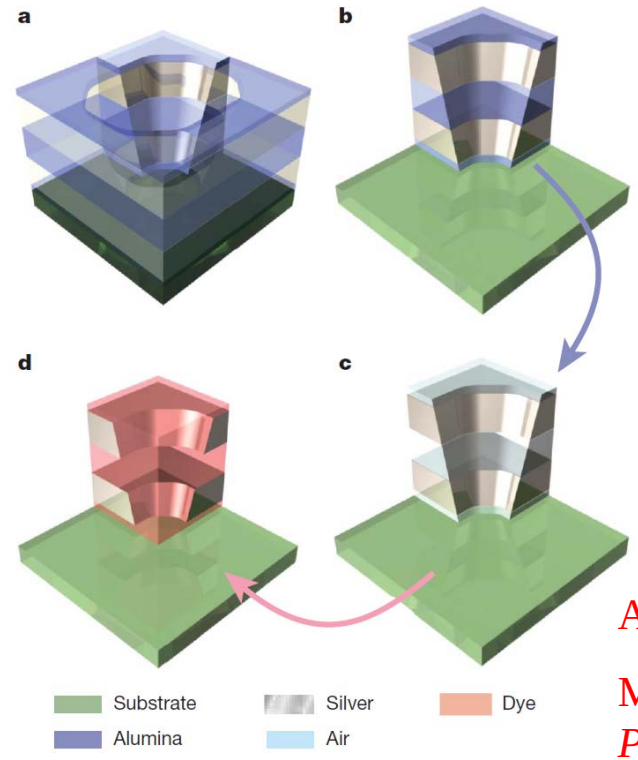
Vol 466|5 August 2010|doi:10.1038/nature09278 nature

LETTERS

Loss-free and active optical negative-index metamaterials

Shumin Xiao[1], Vladimir P. Drachev[1], Alexander V. Kildishev[1], Xingjie Ni[1], Uday K. Chettiar[1]†, Hsiao-Kuan Yuan[1]† & Vladimir M. Shalaev[1]

active optical NIM. The original loss-limited negative refractive index and the figure of merit (FOM) of the device have been drastically improved with loss compensation in the visible wavelength range between 722 and 738 nm. In this range, the NIM becomes active such that the sum of the light intensities in transmission and reflection exceeds the intensity of the incident beam. At a wavelength of 737 nm, the negative refractive index improves from −0.66 to −1.017 and the FOM increases from 1 to 26. At 738 nm, the FOM is expected to become macroscopically large, of the order of 10^6. This study demonstrates the possibility of fabricating an optical negative-index metamaterial that is not limited by the inherent loss in its metal constituent.



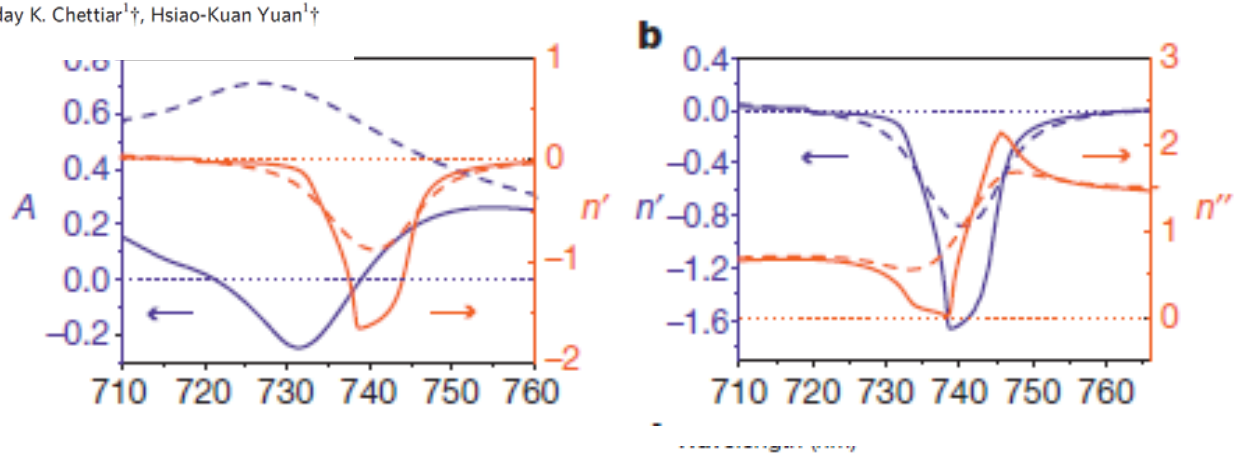


Figure 4 | Simulation and determined parameters. **a**, The simulated refractive index, n' (real part), and absorptance, A (in the forward direction), as functions of wavelength with (solid) and without (dashed) gain. **b**, The effective refractive index, $n = n' + in''$, determined with (solid) and without (dashed) gain. **c**, The effective FOM determined with (solid) and without

A fully-compensated metamaterial should spase:

M. I. Stockman, *Spaser Action, Loss Compensation, and Stability in Plasmonic Systems with Gain*, Phys. Rev. Lett. **106**, 156802-1-4 (2011).

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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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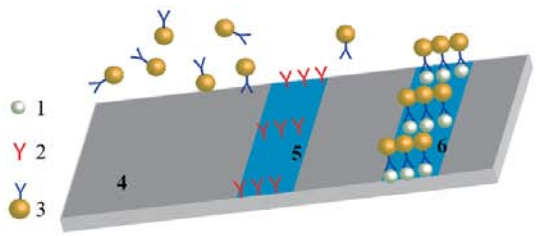
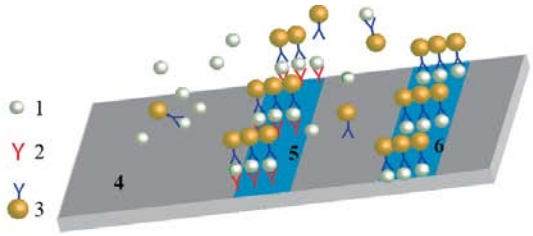
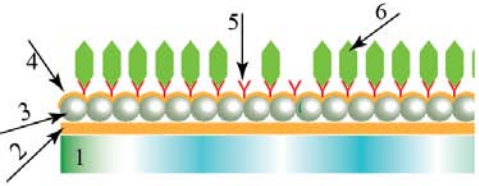
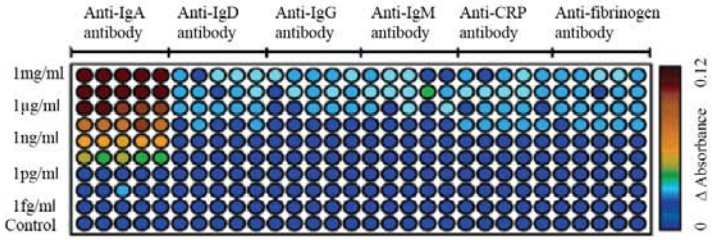
Sensing and Detection with Localized Surface Plasmons



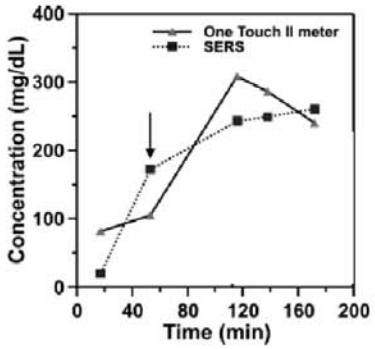


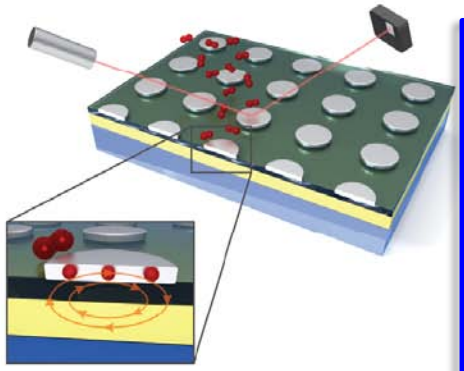
Immunochromatographic assay with immunotargeted gold nanosphere suspension. Detection of: hCG (human chorionic gonadotropin) -- Home pregnancy test; PSA (prostate-specific antigen) -- Prostate cancer ; troponin – heart attack test; HIV/AIDS (trials)





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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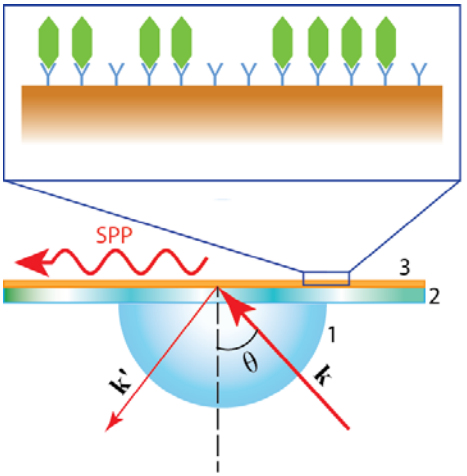
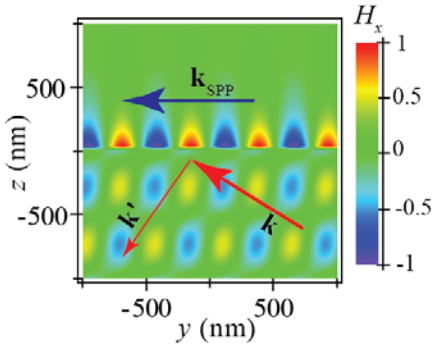
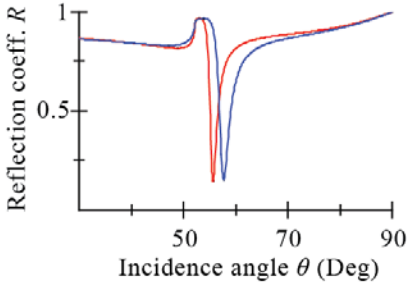
Surface Plasmon Polariton Sensors

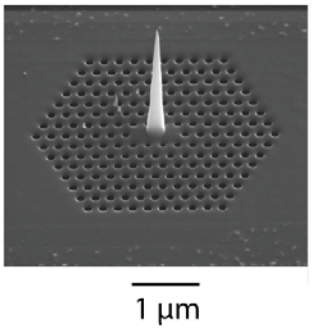
Surface plasmon polariton sensor based on Kretschmann geometry. Sensitivity~ 10^3 - 10^4 large molecules. See, e.g., http://www.biacore.com/

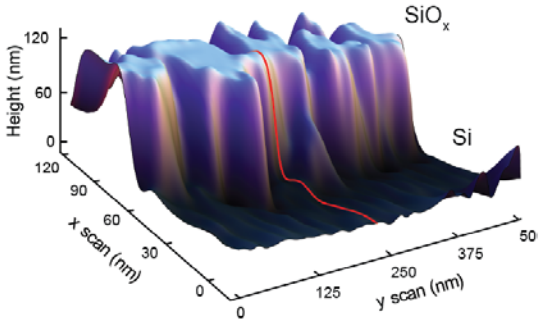
GE Healthcare

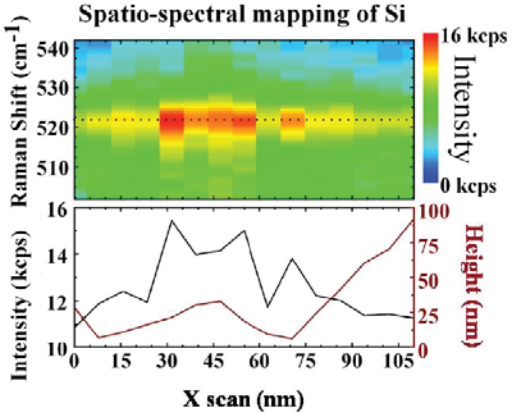












Surface plasmon polariton SERS sensor and NSOM based on adiabatic concentration. Sensitivity~100 molecules

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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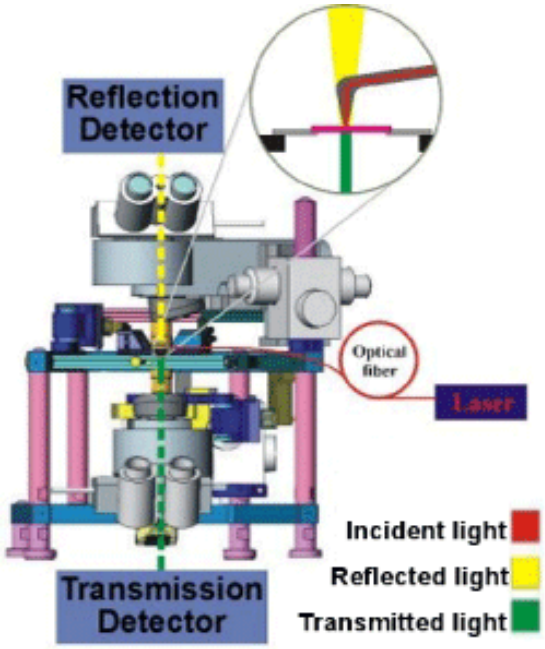
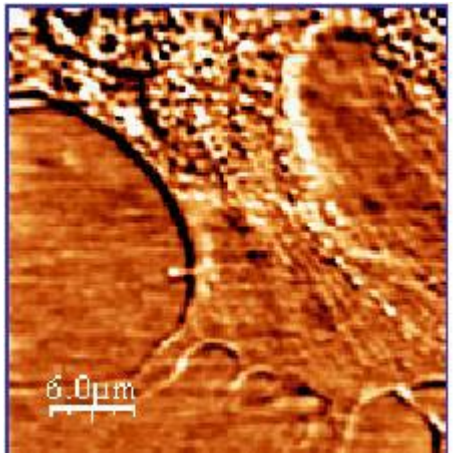
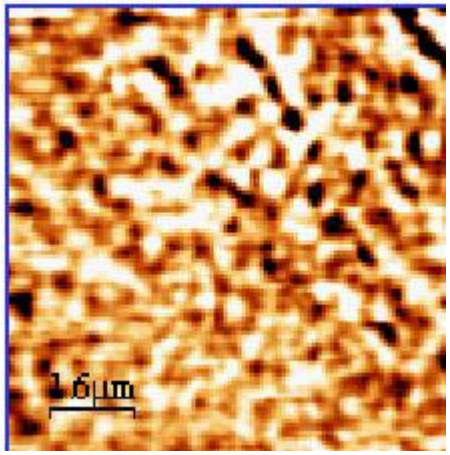
Plasmonic Nanoscopy

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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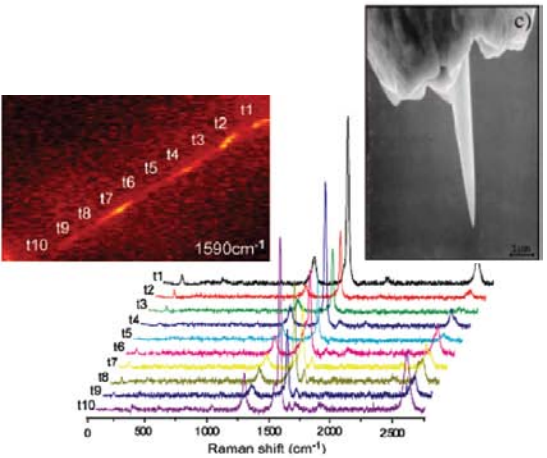
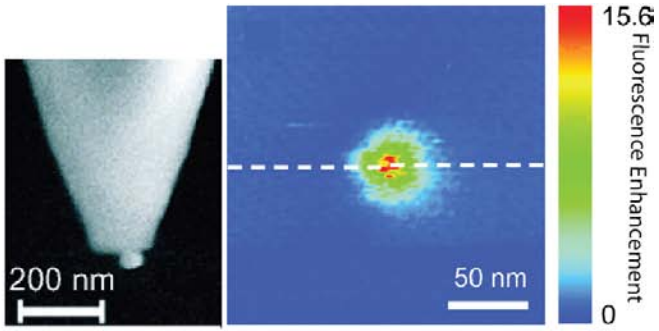
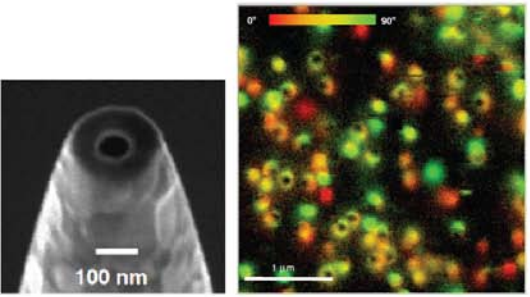
Plasmonic Nanoscopy

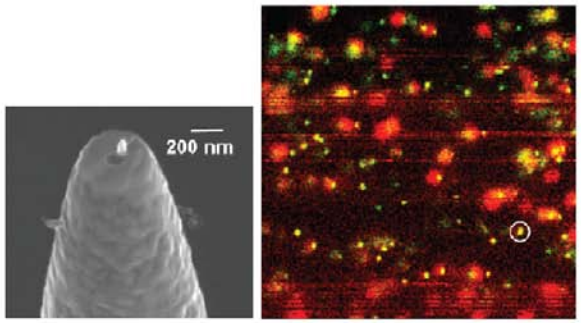




Left: Chemical vision: SERS image and spectra of a single-wall carbon nanotube obtained with a FIB-fabricated silver tip. L. Novotny and S. J. Stranick, Annual Rev. Phys. Chem. **57**, 303-331 (2006)

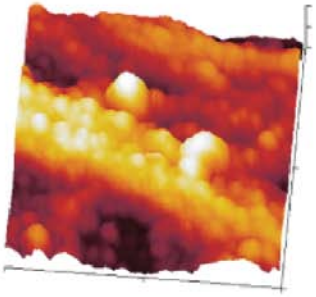
Right: Nanosphere probe and image of fluorescence enhancement of a single dye molecule. H. Eghlidi et al., Nano Lett. **9**, 4007-4011 (2009)

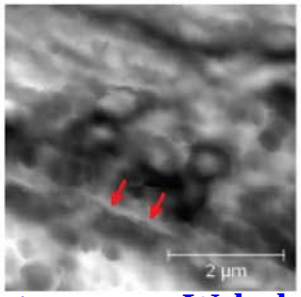


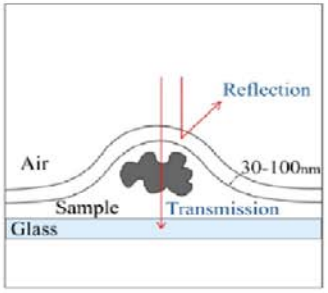


Left: Metallized tapered fiber probe and NSOM image of a single fluorescent molecules with polarization resolution.

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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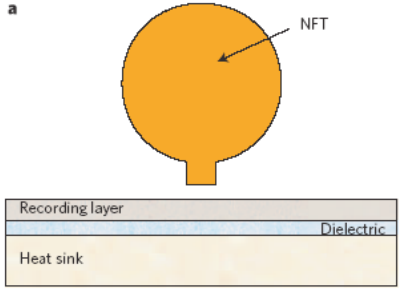
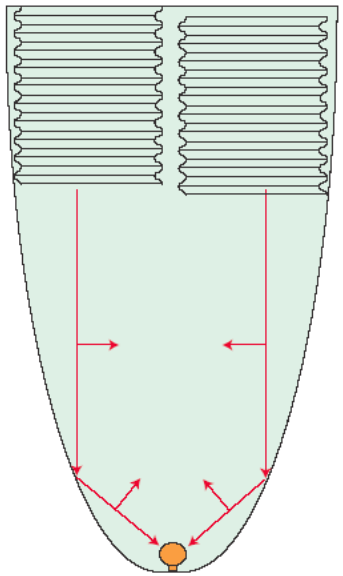
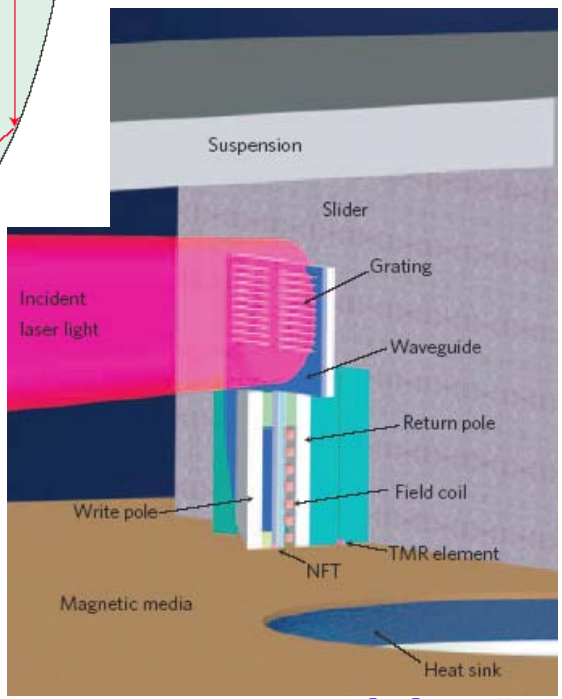


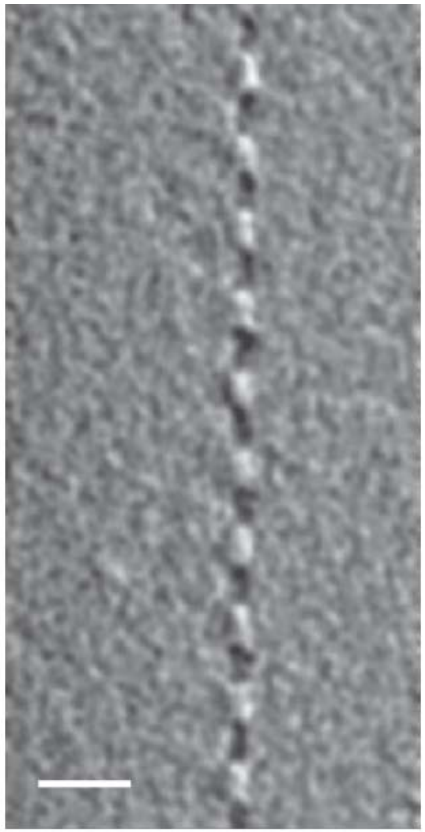
nature photonics
ARTICLES
PUBLISHED ONLINE: 22 MARCH 2009 | DOI: 10.1038/NPHOTON.2009.26

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

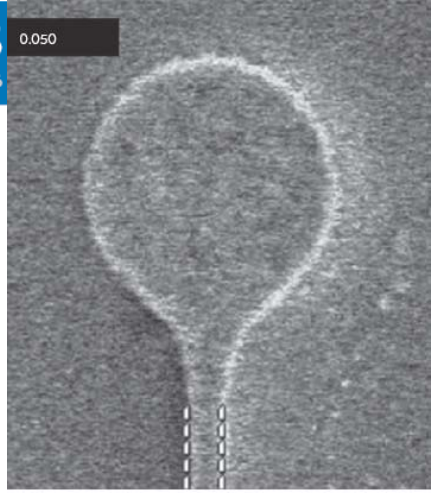
W. A. Challener*, Chubing Peng, A. V. Itagi, D. Karns, Wei Peng, Yingguo Peng, XiaoMin Yang, Xiaobin Zhu, N. J. Gokemeijer, Y.-T. Hsia, G. Ju, Robert E. Rottmayer, Michael A. Seigler and E. C. Gage

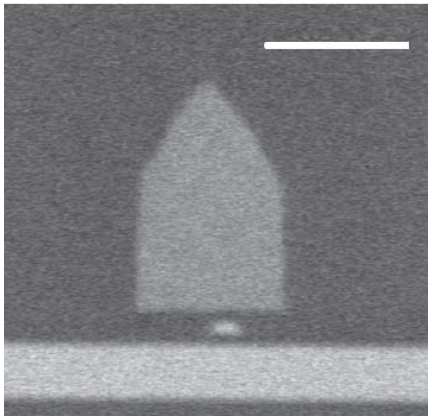






MFM image of a recorded track. The track width is ~70 300 nm.





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

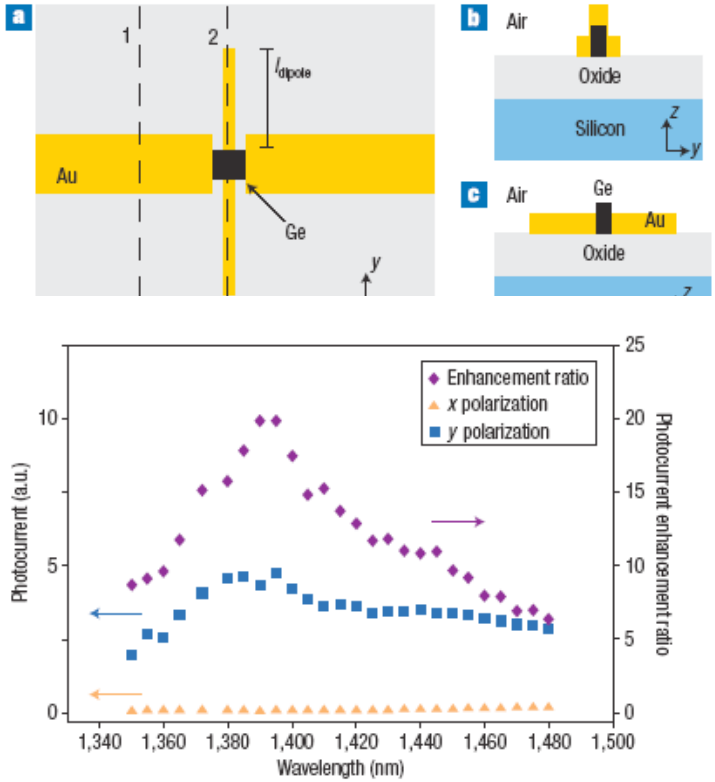


Figure 5 Measured photocurrent responses for light polarization in the *y* and *x* directions. The wavelengths were 1,350–1,480 nm for the detector with $l_{dipole} = 160$ nm.

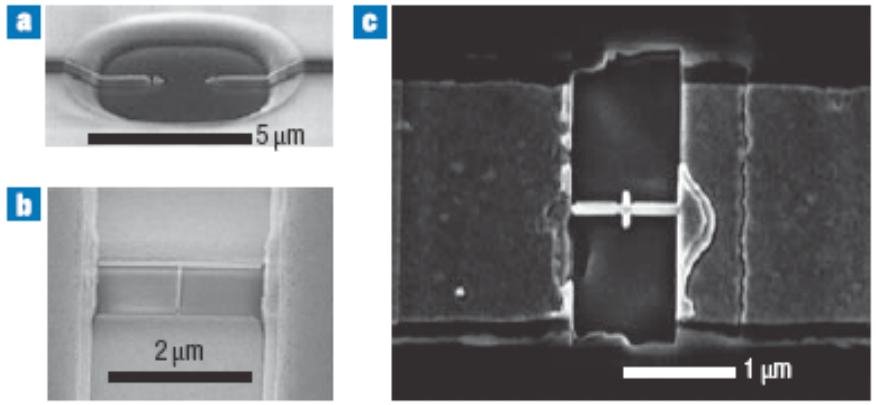


Figure 3 Scanning electron microscopy (SEM) images of the fabricated devices. a, Silicon seeding window with 2-μm-wide germanium crystalline lines. b, 60-nm-wide and 2-μm-long germanium nanowire fabricated by the first FIB step. c, An open-sleeve dipole antenna detector with $l_{dipole} = 155$ nm (this 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.)

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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]*

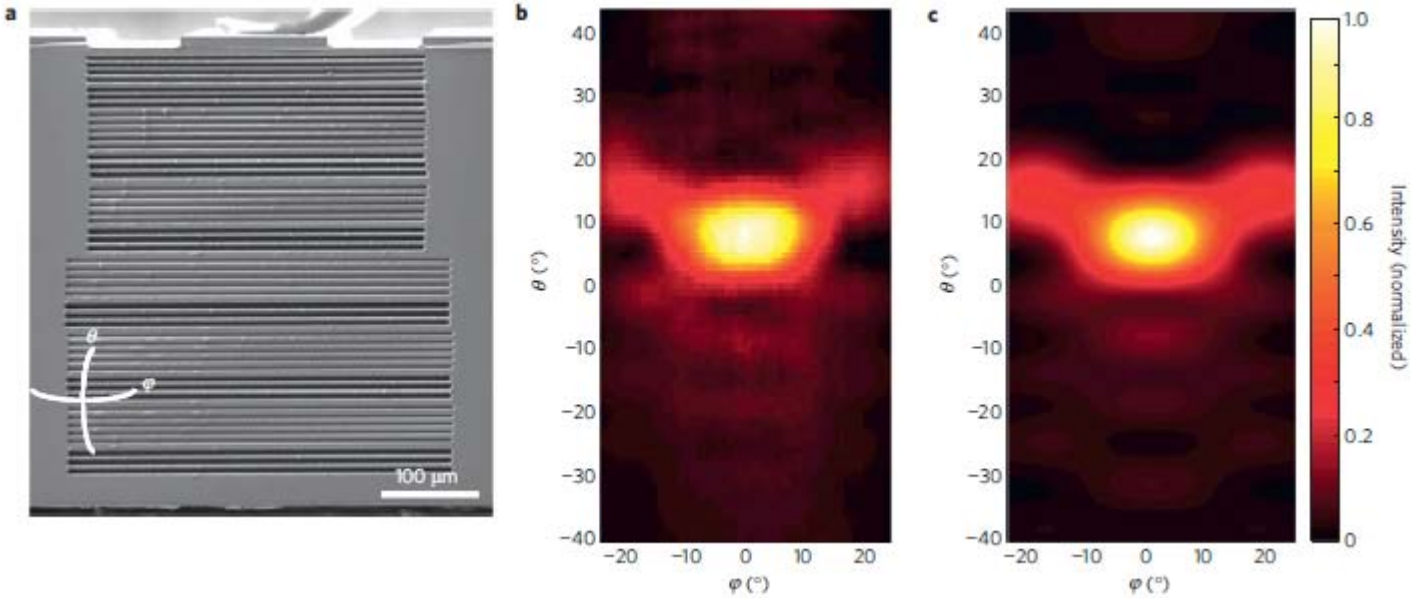

Figure 3 | Experimental results for a device fabricated according to the design in Fig. 1. a, Scanning electron microscope image of the device facet. The device has a 1.2-mm-long, 150-μm-wide and 10-μm-thick waveguide and lases at $\lambda_0 = 100$ μm. The plasmonic pattern is wider at the bottom part 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.
5. Nanolenses are highly efficient enhancers of local field and SERS
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.
7. SPASERs have been observed in a number of experiments
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

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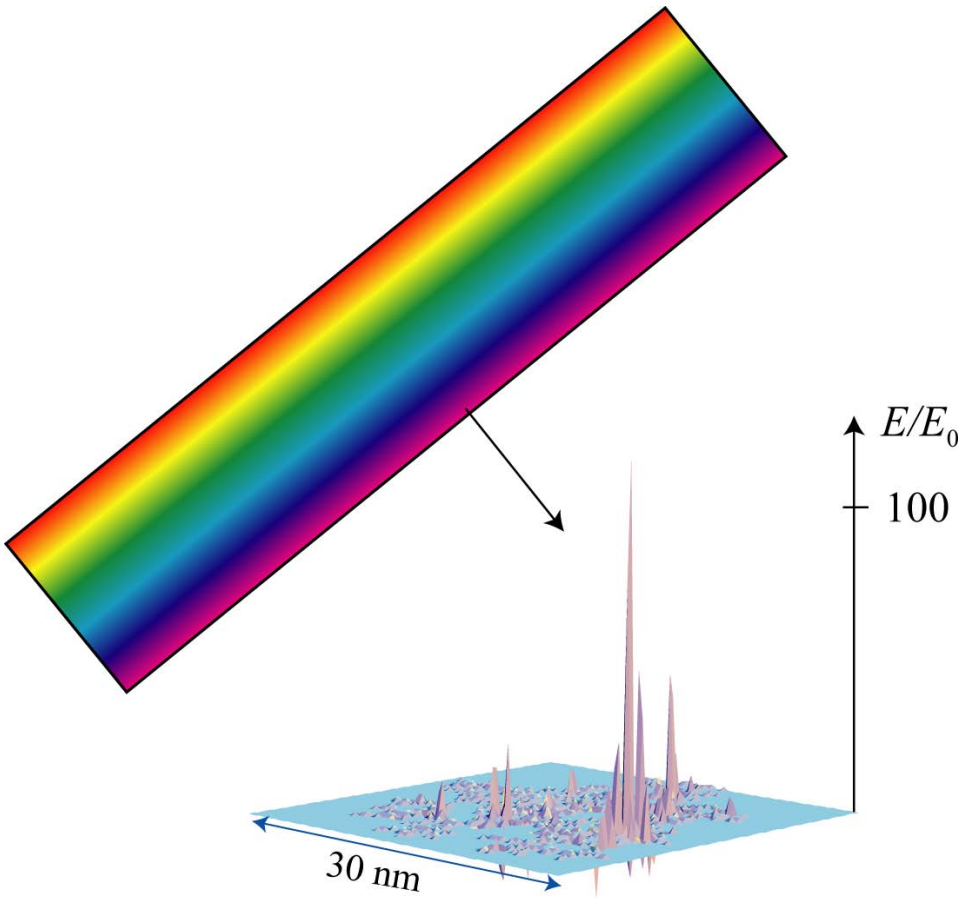
•M. I. Stockman, S. V. Faleev, and D. J. Bergman, *Coherent Control of Femtosecond Energy Localization in Nanosystems*, Phys. Rev. Lett. **88**, 67402-1-4 (2002).
•M. I. Stockman, D. J. Bergman, and T. Kobayashi, *Coherent Control of Nanoscale Localization of Ultrafast Optical Excitation in Nanosystems*, Phys. Rev. B **69**, 054202 (2004)

Schematic of Coherent Control by Phase Modulation

Different spectral components of the excitation pulse excite resonant surface plasmon modes.

These excitations dynamically interfere creating time-dependent hot spots of local fields during their coherence time

This interference can be directed by choosing phases and amplitudes of the different frequency components of the excitation pulse (pulse shaping)



Vol 446|15 March 2007|doi:10.1038/nature05595 nature

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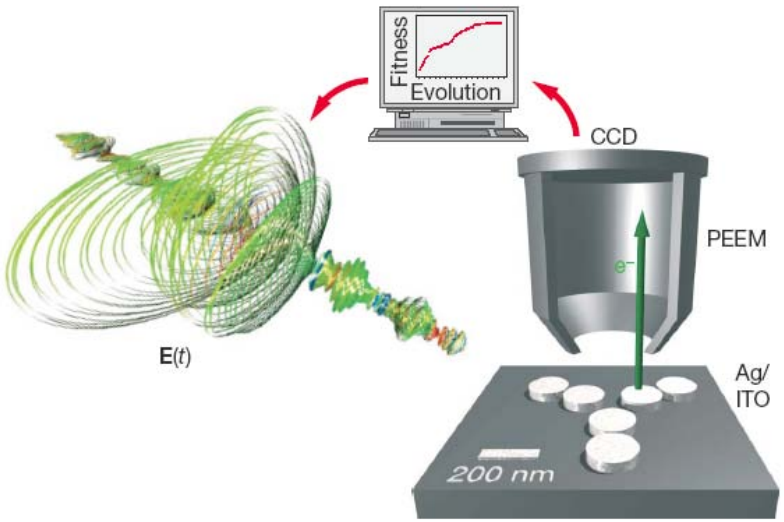
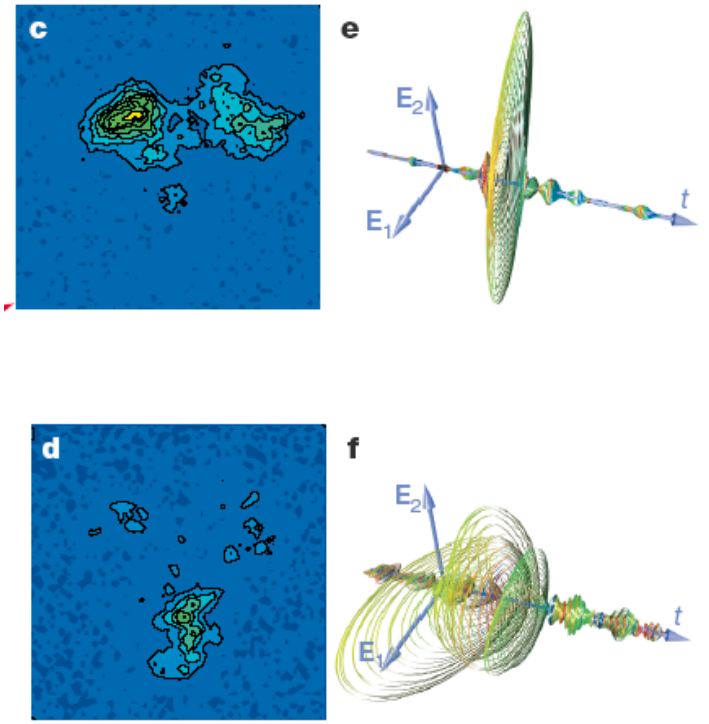
LETTERS

Adaptive subwavelength control of nano-optical fields

Martin Aeschlimann[1], Michael Bauer[2], Daniela Bayer[1], Tobias Brixner[3], F. Javier García de Abajo[4], Walter Pfeiffer[5], Martin Rohmer[1], Christian Spindler[3] & Felix Steeb[1]





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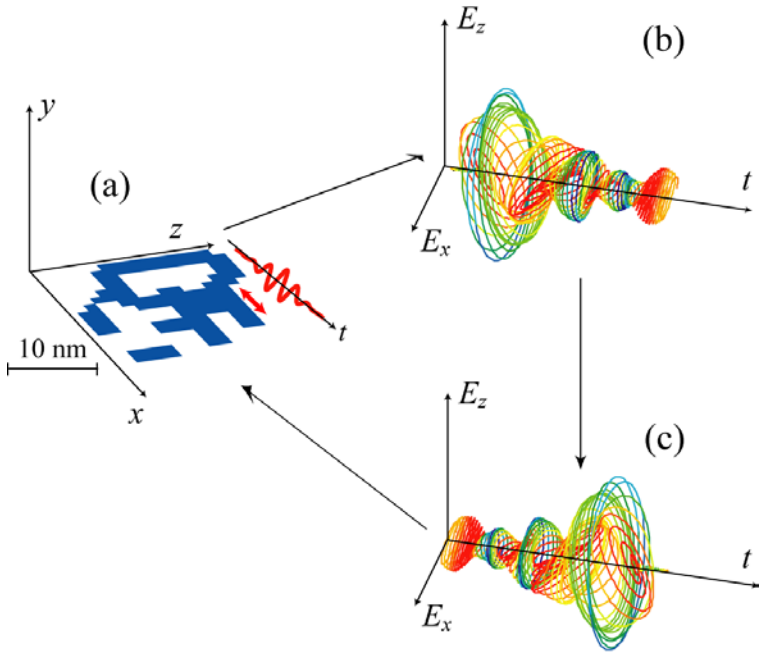
Nanoplasmonic Energy Localization, Time Reversal, and Coherent Control

X. Li and M. I. Stockman, *Highly efficient spatiotemporal coherent control in nanoplasmonics on a nanometer-femtosecond scale by time reversal*, Phys. Rev. B **77**, 195109 (2008)

Idea of time reversal for subwavelength EM-wave localization:

G. Lerosey, J. de Rosny, A. Tourin, and M. Fink, *Focusing Beyond the Diffraction Limit with Far-Field Time Reversal*, Science **315**, 1120-1122 (2007).

A. Derode, A. Tourin, J. de Rosny, M. Tanter, S. Yon, and M. Fink, *Taking Advantage of Multiple Scattering to Communicate with Time-Reversal Antennas*, Phys. Rev. Lett. 90, 014301 (2003).



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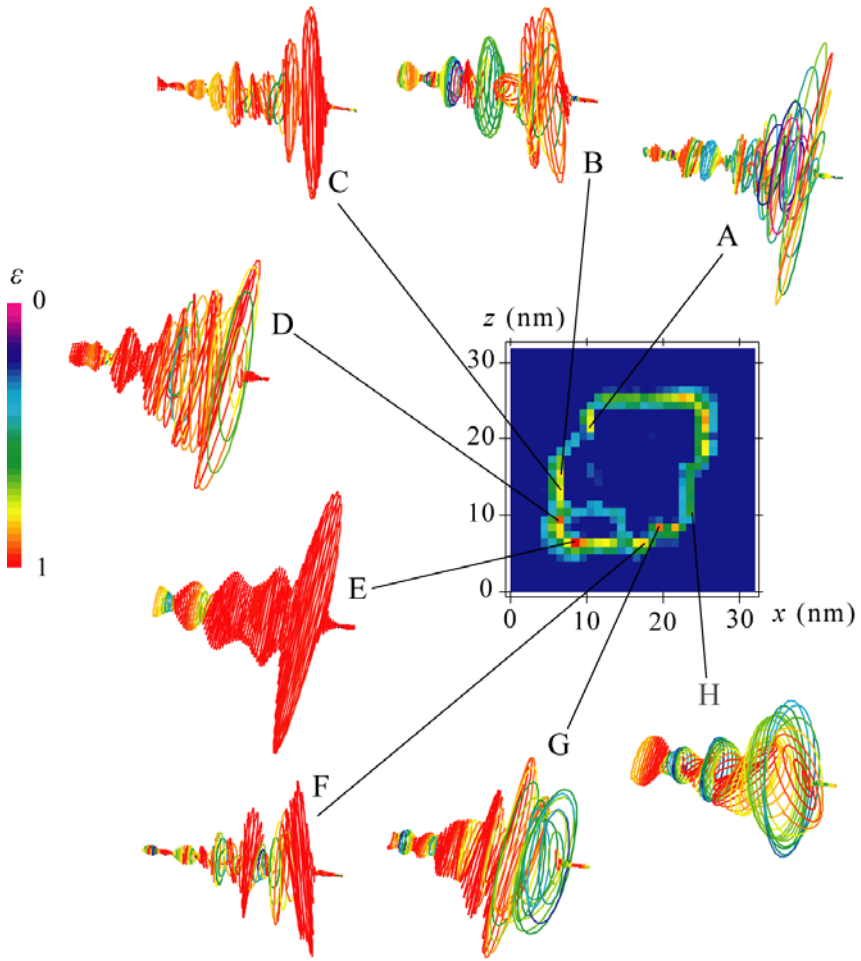
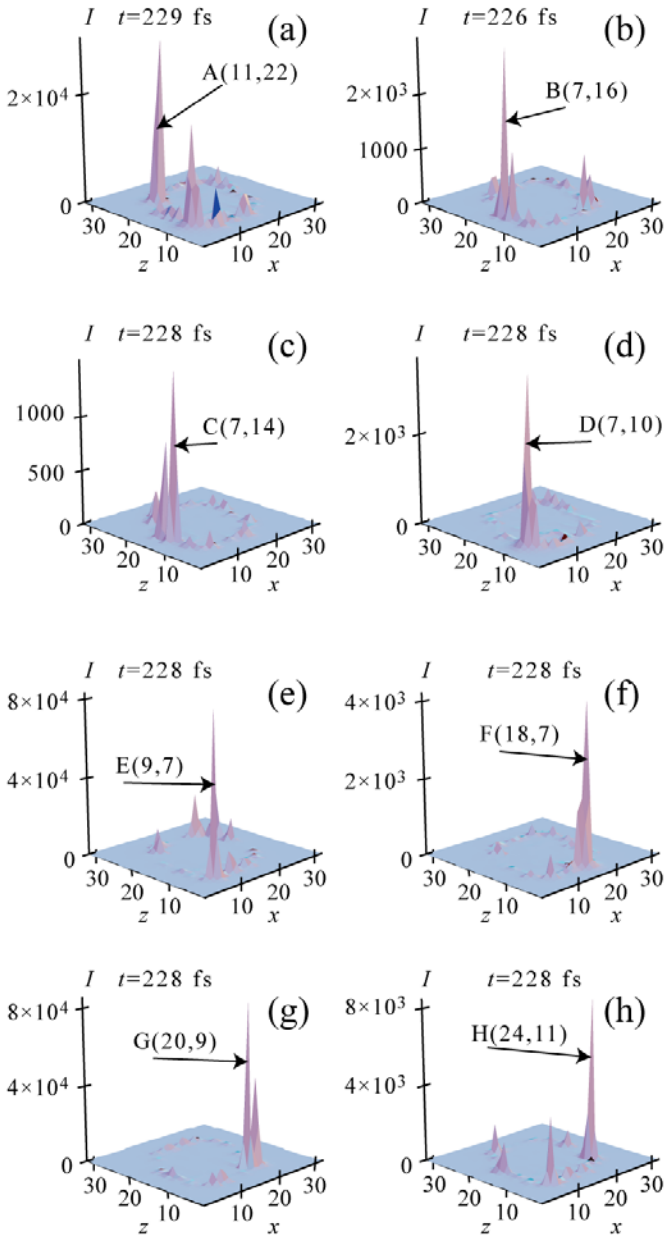




Resonant Metalenses for Breaking the Diffraction Barrier

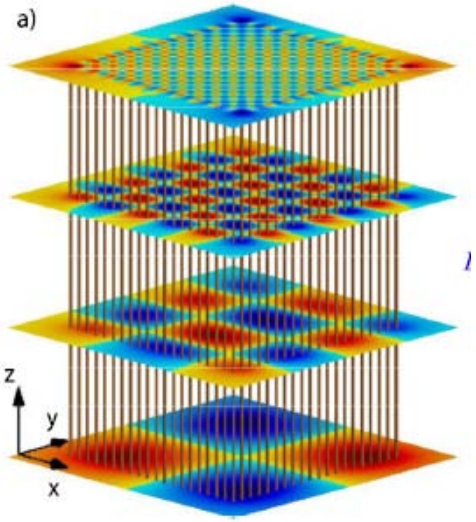
Fabrice Lemoult, Geoffroy Lerosey,* Julien de Rosny, and Mathias Fink

Institut Langevin, ESPCI ParisTech & CNRS, Laboratoire Ondes et Acoustique, 10 rue Vauquelin, 75231 Paris Cedex 05, France

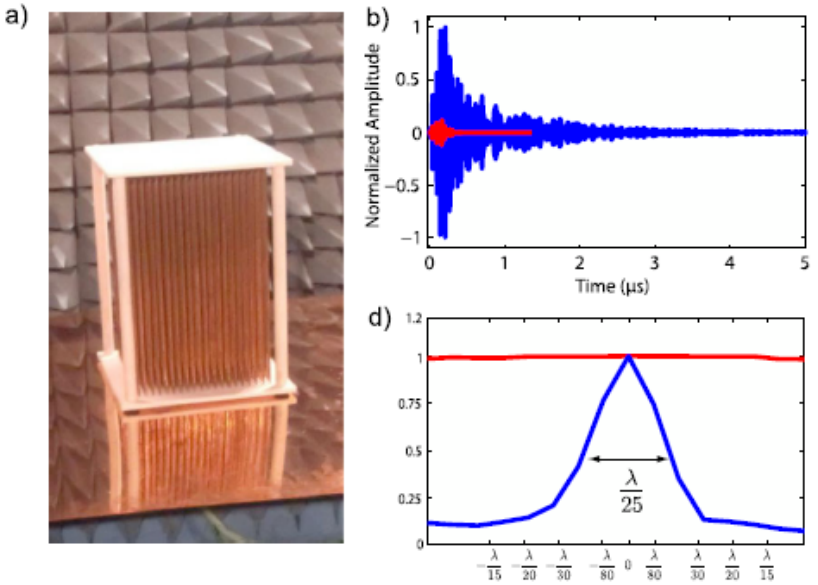
(Received 8 January 2010; revised manuscript received 14 April 2010; published 18 May 2010)

We introduce the resonant metalens, a cluster of coupled subwavelength resonators. Dispersion allows the conversion of subwavelength wave fields into temporal signatures while the Purcell effect permits an efficient radiation of this information in the far field. The study of an array of resonant wires using microwaves provides a physical understanding of the underlying mechanism. We experimentally demonstrate imaging and focusing from the far field with resolutions far below the diffraction limit. This concept is realizable at any frequency where subwavelength resonators can be designed.

DOI: 10.1103/PhysRevLett.104.203901 PACS numbers: 41.20.−q, 78.67.Pt, 81.05.Xj



amplitude of E_x TEM Bloch modes (1,1), (2,3), (5,6), and (19,19).



(d) Focal spot obtained after far field time reversal

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Attosecond nanoplasmonic-field microscope

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[1]Department of Physics and Astronomy, Georgia State University, Atlanta, Georgia 30303, USA
[2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany
[3]Ludwig-Maximilians-Universität München, Department für Physik, Am Coulombwall 1, D-85748 Garching, Germany
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Published online: 3 September 2007; doi:10.1038/nphoton.2007.169

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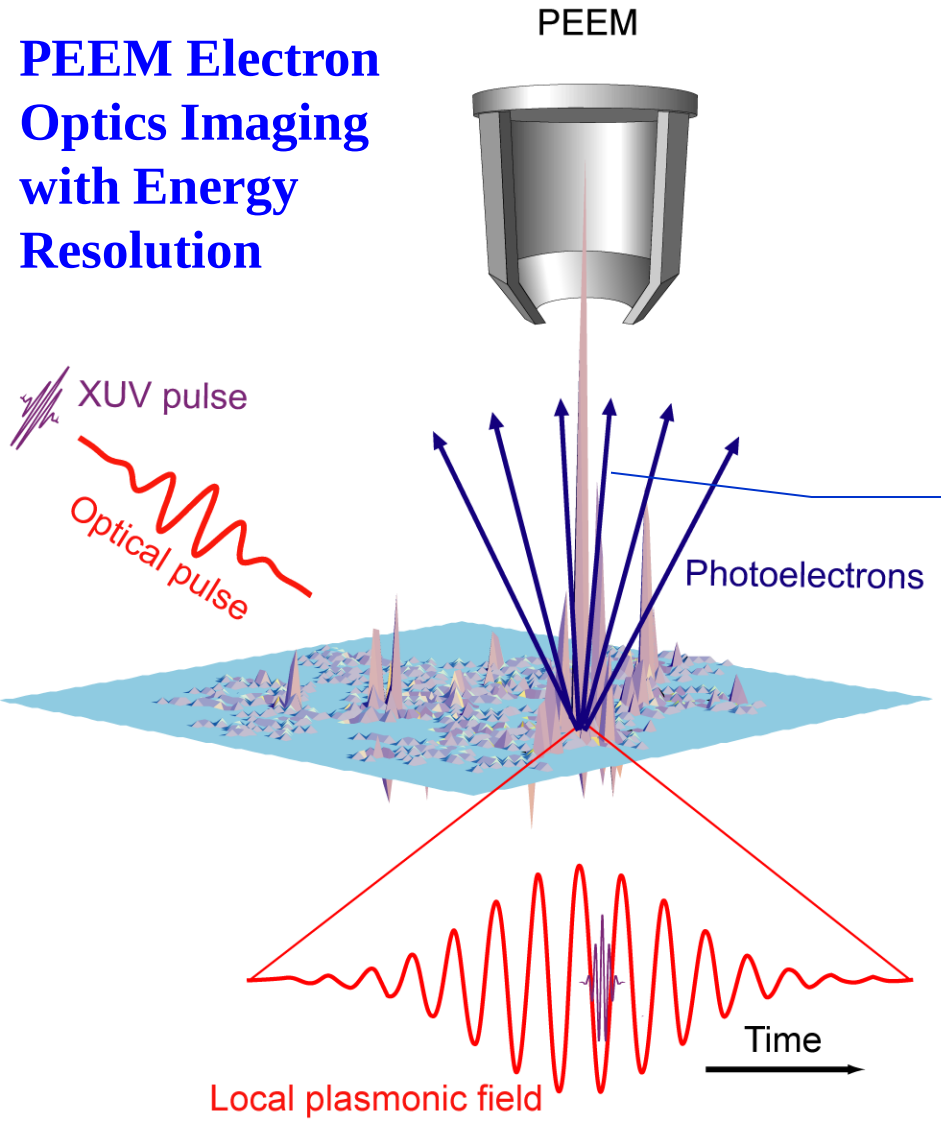
PEEM Electron Optics Imaging with Energy Resolution



Schematic of Attosecond Nanoplasmonic Field Microscope

XUV photoelectrons accelerated by enhanced IR plasmonic local fields

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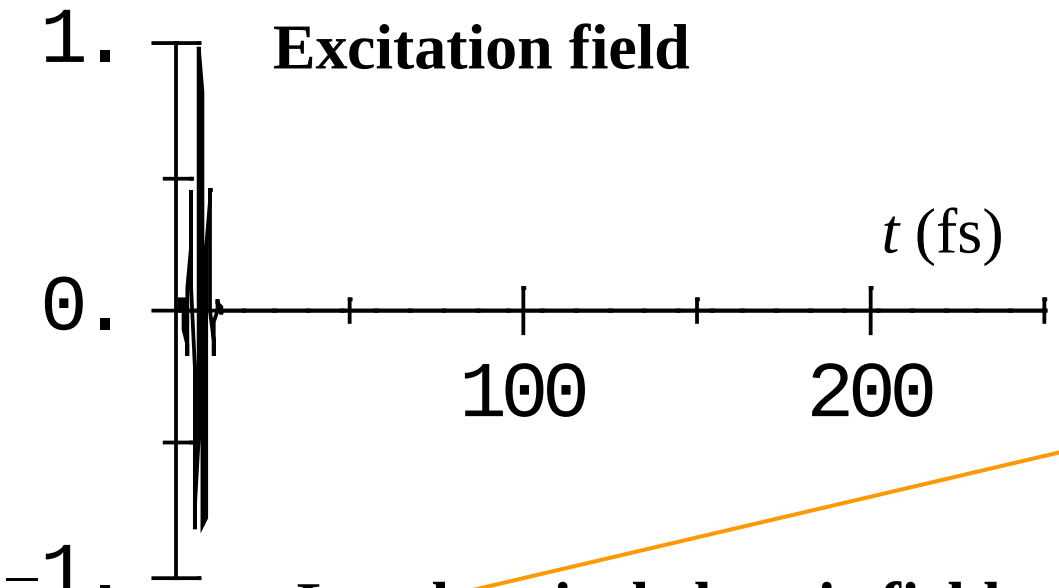
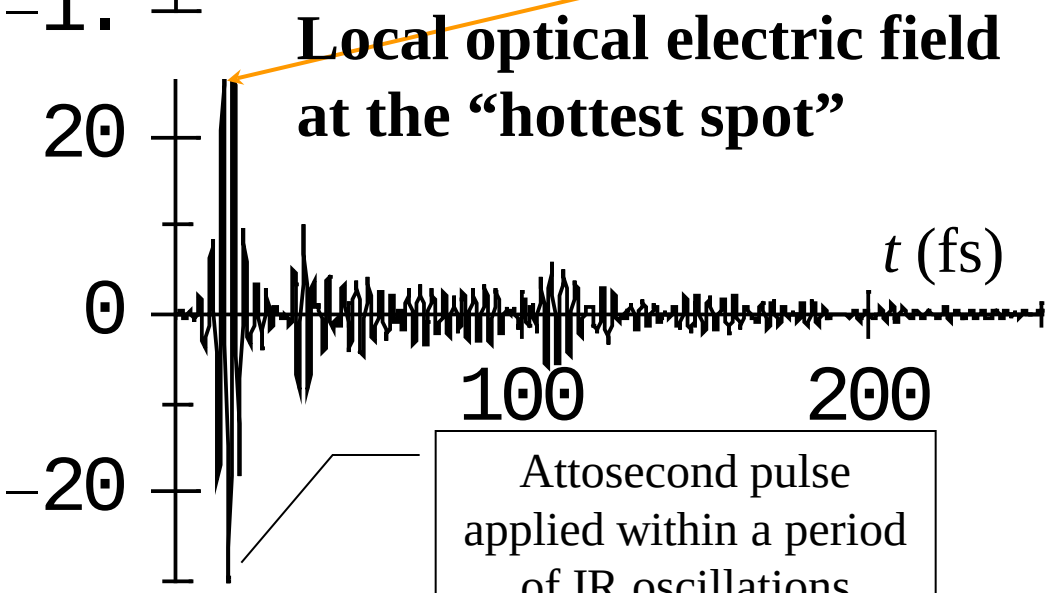
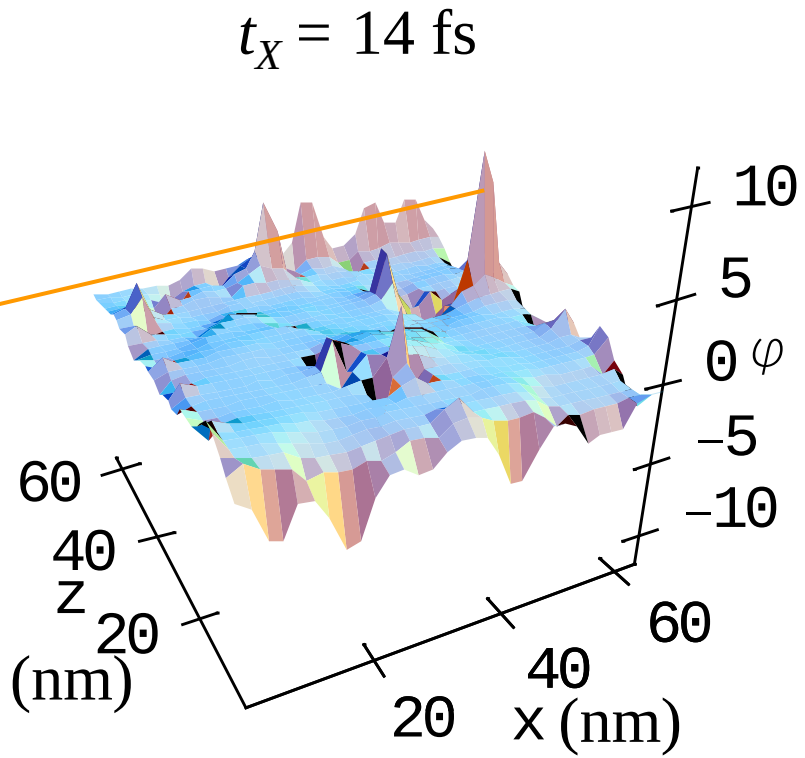




Attosecond pulse applied within a period of IR oscillations



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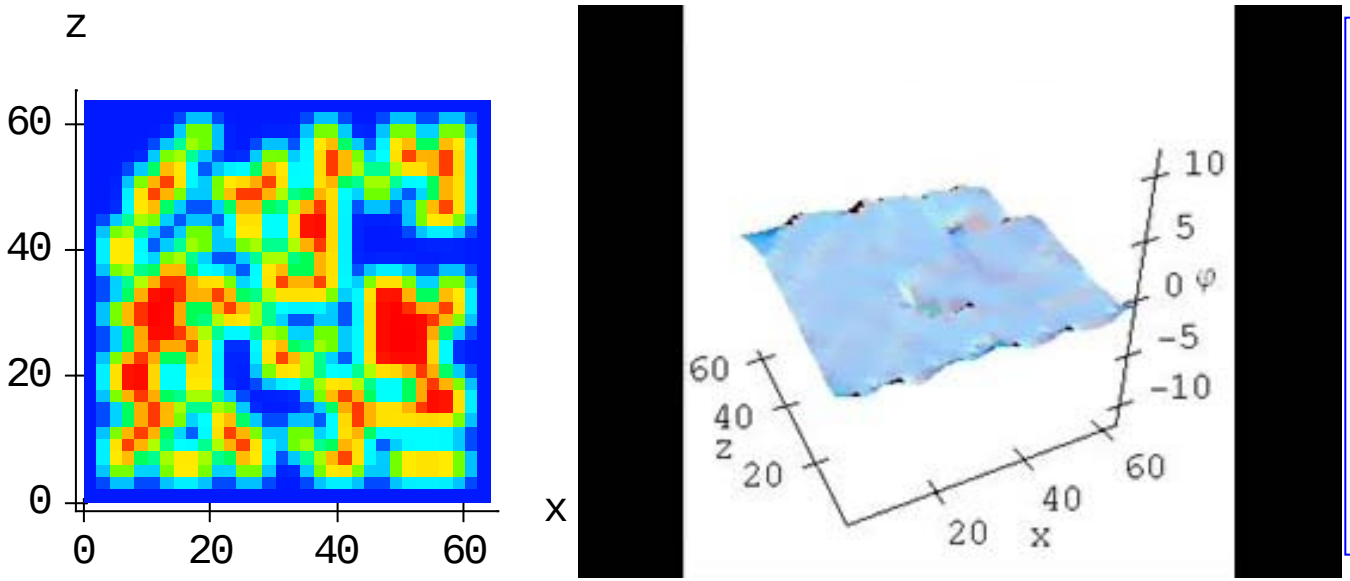
Energy shift (eV) of electrons emitted by a 95 eV XUV attosecond pulse as a function of the as pulse excitation instant with respect to the infrared excitation field (frames are in 200 as) as observed in Photoemission Electron Microscope (PEEM).

Experiment directly measures instantaneous electric potential of nanoplasmonic oscillations with nm spatial and ~200 as temporal resolution



Energy change (eV) of 90 eV XUV photoelectrons from silver nanosystem for 10 GW/cm^2 800 nm IR power; × 10^{15} slowed down

Nanosystem is **60x60 nm** random silver film (50% filling factor)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