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13. SUPPLEMENTARY NOTES

14. ABSTRACT
We have developed a general methodology to model spontaneous emission enhancements of optical emitters by plasmonic nanoparticles. The results are of importance for the development of Si-based light sources (lasers, LEDs) that operate at visible or infrared frequencies. Novel theory was developed for ellipsoidal particles, that serve as a model system for anisotropic particles in general. We experimentally demonstrated plasmon-enhanced emission from optically active erbium ions (emission at 1.5 μm) and Si quantum dots (emission 600-1000 nm). We demonstrated for the first time control and tuning of the Si quantum dot spontaneous emission spectrum using plasmonic coupling and as well as polarization controlled emission from Si quantum dots. Finally, we demonstrated a Si-based plasmon-enhanced LED based on Si quantum dot emission.

Throughout this MURI program the project was expanded to include the development cathodoluminescence imaging spectroscopy as a novel tool to study the propagation, confinement and damping of surface plasmons and the development of focused ion beam milling as a technique to fabricate photonic nanostructures. We studied dispersion of isolated coaxial plasmonic nanostructures, in which we discovered optical modes with negative refractive index. This then led to the development of the first single-layer wide-angle negative index metamaterial at visible frequencies.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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Final Performance Report
MURI
March 3, 2010

Surface plasmon enhanced Si:Er infrared light emitting diodes

Award No: FA9550-05-1-0450
Start date: 01 AUG 2005

P.I.: Prof. Albert Polman
Investigator: Hans Mertens
Center for Nanophotonics, FOM-Institute AMOLF, Amsterdam, The Netherlands
Collaborators: Julie Biteen, Prof. Harry Atwater (CALTECH)

Budget $ 225.000

Project within granted MURI proposal:
Novel Devices for Plasmonic and Nanophotonic Networks: Exploiting X-ray Wavelengths at Optical Frequencies, submitted to AFOSR/ #21/_ Nanophotonics and Plasmon Optics for Networks, Sources and Sensors
Lead Applicant: Prof. H.A. Atwater (CALTECH)

2. Objectives

Original objective: "*We propose to use surface plasmons to enhance the emission rate and efficiency from optically active erbium ions, embedded in silicon. Final goal is to demonstrate room temperature operation of erbium-doped silicon surface plasmon LEDs with enhanced modulation rate and efficiency.*"

Over the course of the program the project has been expanded to include three other topics:

- developing cathodoluminescence imaging spectroscopy as a novel tool to study the propagation, confinement and dampling of surface plasmons.
- developing focused ion beam milling as a new technique to fabricate photonic nanostructures.
- demonstration of plasmonic negative-index materials

3. Status of effort:

We have developed a general methodology to model spontaneous emission enhancements of optical emitters by plasmonic nanoparticles. The results are of importance for the development of Si-based light sources (lasers, LEDs) that operate at visible or infrared frequencies. Novel theory was developed for ellipsoidal particles, that serve as a model system for anisotropic particles in general. We experimentally demonstrated plasmon-enhanced emission from optically active erbium ions (emission at 1.5 μm) and Si quantum dots (emission 600-1000 nm). We demonstrated for the first time control and tuning of the Si quantum dot spontaneous emission spectrum using plasmonic coupling and as well as polarization controlled emission from Si quantum dots. Finally, we demonstrated a Si-based plasmon-enhanced LED based on Si quantum dot emission.

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4. Accomplishments/New Findings

Plasmons are collective oscillations of the free electrons in a metal or an ionized gas. Plasmons dominate the optical properties of noble-metal nanoparticles, which enables a variety of applications including electromagnetic energy transport at nanoscale dimensions, single-molecule Raman spectroscopy, and photothermal cancer therapy. Plasmons also affect the spontaneous emission dynamics of optical emitters positioned in the vicinity of metal nanoparticles. The luminescence intensity can either be enhanced or quenched, depending on the geometry. Since the associated enhancements can potentially be several orders of magnitude, plasmon-enhanced luminescence is the subject of intense research. This project focused on plasmon-enhanced luminescence of silicon quantum dots (Si QDs) and optically active erbium ions. Both these emitters are compatible with silicon processing technology, and are therefore of great technological interest.

In the first part of the project we developed three fabrication methods of Ag nanoparticles. First, electron beam lithography was developed to fabricate Ag nanoparticles with well defined sizes and shapes on insulating substrates. This technique is later applied in the experiments on plasmon-enhanced luminescence. Subsequently, we present a method, based on a sequential Si/Ag/Si electron-beam evaporation process, to fabricate metal nanoparticles that exhibit plasmon resonances in the infrared. Furthermore, we discuss the fabrication of small Ag nanoparticles by a sequence of $Na^+ \leftrightarrow Ag^+$ ion exchange and ion irradiation of Na^+-containing glass. In particular, we consistently derive the Ag-nanocrystal depth profile and the corresponding refractive index depth profile by combining multiple characterization techniques.

In the second part of the project we showed that the photoluminescence intensity of Si QDs can be enhanced in a spectrally selective way by coupling to Ag nanoparticles. The observed luminescence enhancements range between a factor 2 and a factor 6. In addition, we demonstrate that the luminescence enhancement is polarized for elongated Ag nanoparticles. Based on both the spectral selectivity and the polarization selectivity, we conclude that the observed luminescence enhancement is due to coupling of the Si QD emission dipoles to plasmon modes, rather than due to an enhanced excitation rate. As a consequence, the concept of plasmon-enhanced luminescence could also be applied to enhance the luminescence intensity of electrically driven light sources. This possibility is explored by integrating Ag nanoparticles in prototype Si QD light-emitting devices fabricated using processing facilities at Intel Inc. The Si QD electroluminescence intensity of these devices has been enhanced by up to a factor 2.5. We developed several mechanisms that could explain this enhancement.

By engineering extremely anisotropic Ag nanoparticles, we demonstrated in the third part of the project that the photoluminescence intensity of optically active Er^{3+} ions positioned in close proximity to these nanoparticles is significantly enhanced if the nanoparticles support plasmon modes that are resonant with the erbium emission at 1.5 μm. Also for these systems, the enhancement is polarized corresponding to the plasmon resonances of the nanoparticles. These results indicate the opportunities of Ag nanostructures for the reduction of quench processes of erbium in a wide range of materials. Plasmon-enhanced luminescence of erbium may for example enable the realization of efficient light sources based on erbium-doped silicon. In addition, we describe an experiment in which we study the interaction of Er^3+ ions with Si nanoparticles by cavity ring-down spectroscopy. We demonstrate that the silicon nanoparticles incorporated in Si-rich oxide do not enhance the peak absorption cross section of the Er^{3+} $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition by $1 - 2$ orders of magnitude, contrary to what has been reported in earlier work. This conclusion has implications for the design of compact planar optical amplifiers on silicon.

In the fourth part of the project we did a theoretical investigation of plasmon-enhanced luminescence focusing on the modifications of the radiative and nonradiative decay rates of an optical emitter positioned in close proximity to a noble-metal nanoparticle. First we analyze the influence of a spherical nanoparticle by exact electrodynamical theory. We show that the optimal sphere diameter for luminescence quantum efficiency enhancement associated with resonant coupling to plasmon modes is in the range $30 - 110$ nm, depending on the material properties. The optimal diameter is found to be a trade-off between (1) emitter-plasmon coupling, which is most effective for small spheres, and (2) the outcoupling of plasmons into radiation, which is most efficient for large spheres. In addition, we show that the well-known Gersten and Nitzan model does not describe the existence of a finite optimal diameter unless the model is extended with the correction factor for radiation damping. With this correction and a correction for dynamic depolarization, the Gersten and Nitzan model, which can be generalized to spheroids much more easily than exact electrodynamical theory, is found to provide a reasonably accurate approximation of the decay rate modifications associated with coupling to the dipole plasmon mode. Based on the improved Gersten and Nitzan model, we subsequently analyze how much the intensity emitted by an active layer of a light-emitting device can be enhanced by an array of anisotropic Ag nanoparticles. For this analysis, the radiative decay rate enhancement associated with emitter-plasmon coupling was calculated for emitters positioned in a plane below a two-dimensional array of Ag nanoparticles. The in-plane-averaged radiative decay rate enhancement, which is an upper limit of the enhancement of the intensity emitted by the active layer, is found to be a factor ~10 at a distance of 10 nm from the array for the optimal nanoparticle size of ~100 nm. The distance at which the nanoparticles induce a substantial effect on the radiative decay rate ranges to a few tens of nanometers. We also show that the radiative decay rate enhancement can be up to three orders of magnitude close to a sharp tip of a metal nanostructure.

This results indicates that metal nanostructures can provide even larger improvements to nanoscopic light sources, e.g. based on single nanowires or single quantum dots. Finally, we study the radiative and nonradiative decay processes for emitters close to anisotropic nanoparticles. We find a larger spectral separation between the radiative dipole plasmon mode and the dark higher-order plasmon modes of a Ag nanoparticle for larger anisotropy. In the vicinity of such an anisotropic Ag nanoparticle, the quantum efficiency of a low-quantum-

efficiency emitter (0.1%) can be enhanced by almost a factor 200, instead of a factor 60 for a spherical nanoparticle. These results show that nanoparticle anisotropy does not only influence the plasmon resonance wavelength, but also the ratio at which different plasmon modes are excited by an emitter at short distance.
Altogether, the project provided significant and important insight in the fundamental aspects of plasmon-enhanced luminescence, and correlates these to experiments on light emitters in practical geometries. Specific insights in possible applications have been extensively discussed.

5. Personnel Supported and associated to this project:
PI: Prof. Dr. Albert Polman
PhD student: Hans Mertens

6. Publications
a. Publications directly from MURI project

1. Strong luminescence quantum efficiency enhancement near prolate metal nanoparticles: dipolar versus higher-order modes
   H. Mertens and A. Polman, J. Appl. Phys. **105**, 044302 (2009)
2. Plasmonics applied
   A. Polman, Science **322**, 868 (2008)
3. Plasmon-enhanced photoluminescence of silicon quantum dots: simulation and experiment
   J.S. Biteen, L.A. Sweatlock, H. Mertens, N. Lewis, A. Polman and H.A. Atwater, J. Phys. Chem. C **111**, 13372 (2007)
4. Plasmon-enhanced luminescence near noble-metal nanospheres: Comparison of exact theory and an improved Gersten and Nitzan model
   H. Mertens, A.F. Koenderink, and A. Polman, Phys. Rev. B **75**, 115123 (2007)
5. Polarization-selective plasmon-enhanced Si quantum dot luminescence
   H. Mertens, J.S. Biteen, H.A. Atwater, and A. Polman, Nano Lett. **6**, 2622 (2006)
6. Plasmon-enhanced erbium luminescence
7. H. Mertens and A. Polman, Appl. Phys. Lett. **89** 211107 (2006)
8. Spectral tuning of plasmon-enhanced silicon quantum dot luminescence
   J.S. Biteen, N. Lewis, H.A. Atwater, H. Mertens, and A. Polman, Appl. Phys. Lett. **88**, 131109 (2006)

b. Publications on related topics with Atwater's and Vahala's group within MURI program

1. A single-layer wide-angle negative index metamaterial at visible frequencies
   S.P. Burgos*, R. de Waele*, A. Polman, and H.A. Atwater, Nature Materials **9**, in press (2010)
2. Dispersion of isolated coaxial plasmonic nanostructures: negative index modes
   R. de Waele, S. Burgos, A. Polman and H.A. Atwater, to be submitted to Optics Express
3. Plasmon dispersion in coaxial waveguides from single-cavity optical transmission measurements
   R. de Waele, S. Burgos, A. Polman, and H.A. Atwater, Nano Lett. **9**, 2832 (2009)
4. Purcell factor enhanced scattering from Si nanocrystals in an optical microcavity
   T.J. Kippenberg, A. L. Tchebotareva, J. Kalkman, A. Polman, and K.J. Vahala, Phys. Rev. Lett. **103**, 027406 (2009)
5. Local density of states, spectrum, and far-field interference of surface plasmon polaritons probed by cathodoluminescence
   M. Kuttge, E. J. R. Vesseur, A. F. Koenderink, H. J. Lezec, H. A. Atwater, F. J. García de Abajo, and A. Polman, Phys. Rev. B **79**, **79**, 113405 009)
6. Are negative index materials achievable with surface plasmon waveguides? A case study of three plasmonic geometries

J.A. Dionne, E. Verhagen, A.Polman, and H.A. Atwater, Optics Express **16**, 19001 (2008), also highlighted in Nature Materials **7**, 925 (2008)

7. Loss mechanisms of surface plasmon polaritons on gold probed by cathodoluminescence imaging spectroscopy
M. Kuttge, E. J. R. Vesseur, J. Verhoeven, H. J. Lezec, H. A. Atwater, and A. Polman, Appl. Phys. Lett. **93**, 113110 (2008)
8. Near-field visualization of strongly confined surface plasmon polaritons in metal -insulator-metal waveguides
E. Verhagen, J. Dionne, L. Kuipers, H.A. Atwater, and A. Polman, Nano Lett. **8**, 2925 (2008)
9. Optical cavity modes in gold shell colloids
J.J. Penninkhof, L.A. Sweatlock, A. Moroz, H.A. Atwater, A. van Blaaderen, and A. Polman, J. Appl. Phys. **103**, **123105** (2008)
10. Surface plasmon polariton modes in a single-crystal Au nanoresonator fabricated using focussed ion beam milling
E.J.R. Vesseur, R. de Waele, H.J. Lezec, H.A. Atwater, J. Garcia de Abajo, and A. Polman, Appl. Phys. Lett. **92**, 83110 (2008)
11. Plasmonic modes in annular nanoresonators studied by spectrally resolved cathodoluminescence
Carrie E. Hofmann, F.J.R. Vesseur, L.A. Sweatlock, H. Lezec, J. Garcia de Abajo, A. Polman, and H.A. Atwater, Nano Lett. **7**, **3612** (2007)
12. Direct imaging of propagation and damping of near-resonance surface plasmon polaritons using cathodoluminescence spectroscopy
J.T. van Wijngaarden, E. Verhagen, A. Polman, C.E. Ross, H.J. Lezec, and H.A. Atwater, Appl. Phys. Lett. **88**, 221111 (2006), also featured in Science **312**, 1719 (2006).
13. Photoluminescence quantum efficiency of dense silicon nanocrystal ensembles in SiO_2
14. R. J. Walters, J. Kalkman, A. Polman, H. A. Atwater, and M. J. A. de Dood, Phys. Rev. B **73**, 132302 (2006)
15. Plasmon slot waveguides: towards chip-scale propagation with subwavelength-scale localization
J.A. Dionne, L. Sweatlock, H.A. Atwater, and A. Polman, Phys. Rev. B **73**, 035407 (2006)
16. Planar plasmon metal waveguides: frequency-dependent dispersion, propagation, localization, and loss beyond the free electron model
J.A. Dionne, L. Sweatlock, H.A. Atwater, and A. Polman, Phys. Rev. B **72**, 075405 (2005)
17. Quenching of Si nanocrystal photoluminescence by doping with gold or phosphorous
A.L. Tchebotareva, M.J.A. de Dood, J.S. Biteen, H.A. Atwater, and A. Polman, J. Lumin. **114,** 137 (2005)
18. Highly confined electromagnetic fields in arrays of strongly coupled Ag nanoparticles
L.A. Sweatlock, S.A. Maier, H.A. Atwater, J.J. Penninkhof, and A. Polman, Phys. Rev. B **71**, 235408 (2005)
19. Plasmonics enables photonic access to the nanoworld
H.A. Atwater, S. Maier, A. Polman, J.A. Dionne, and L.A. Sweatlock, MRS Bulletin **30**, 385 (2005)
20. Plasmonics: optics at the nanoscale
A. Polman and H.A. Atwater, Materials Today, January 2005, p. 56.

7. Interactions/Transitions:

a. Participation/presentations at meetings, conferences, seminars, etc.

We have held regular meetings and teleconferences with our collaborators at CALTECH and presented our work at MURI progress meetings. We have given large number of invited talks at international conferences on the topic of this MURI proposal.

1. Optical metamaterials (invited), 2nd International Conference on Metamaterials, Photonic Crystals and Plasmonics, Cairo, Egypt, February 22-25, 2009
2. Plasmonics: from metamaterials to photovoltaics (invited), Summerschool Advances on Nanophotonics, Erice, July 11-18, 2010
3. Plasmonics: from metamaterials to photovoltaics (invited), iNANO summerschool, Aarhus, September 3-7, 2010
4. Plasmonic metamaterials: from negative index materials to photovoltaics (invited), MRS Fall Meeting, Boston, November 29 - December 3, 2010
5. Probing the nanoplasmonic density of states by cathodoluminescence imaging spectroscopy (invited), NanoMeta conference, Seefeld, Austria, January 5-8, 2009
6. Plasmonics: optics at the nanoscale (invited), CMOS Photonics Winter School, Trento, March 14-21, 2009
7. Nanofocusing in plasmonic nanowaveguides, nanotapers and nanocavities (invited), MRS Spring Meeting, April 2009, San Francisco, CA
8. Plasmonics: optics at the nanoscale (invited keynote presentation), QELS-CLEO Europe, June 16-19, 2009, Munich
9. Plasmonics applications (invited), International Workshop on Current Topics in Electron Microscopy, Ringberg, July 22-25, 2009
10. True nano-plasmonics: from nanoscale integrated circuits to nano-photovoltaics (invited keynote presentation), SPIE Conference, San Diego, August 2-6, 2009
11. Plasmonics: optics at the nanoscale (invited keynote presentation), Euromat, Glasgow, September 7-10, 2009
12. Plasmonics: optics at the nanoscale (invited), Nanotech 2009, Berlin, September 2009
13. Plasmonic negative-index metamaterials (invited), IEEE Photonics Society Annual Meeting, Antalya, Turkey, October 4-8, 2009.
14. Plasmonics – optics at the nanoscale (invited plenary presentation), CLEO/QELS Conference, May 6-9, 2008, San Jose, CA
15. Plasmonics-integrated silicon photonics (invited), E-MRS Strasbourg, May 26-30, 2008
16. Probing the nanoplasmonic density of states (invited), Workshop on Ultrafast Nanooptics, Bad Honnef, June 2-4, 2008
17. Solving the emission bottleneck of rare earth emitters (invited), E-MRS Strasbourg, May 28-31, 2007
18. Surface plasmon generation, propagation and detection (invited), SPIE Meeting, August 26-30, 2007, San Diego, CA
19. Surface plasmon generation, propagation and detection (invited), International workshop on plasmonics and applications in nanotechnologies, Singapore, December 5-7, 2006
20. Ion beam synthesis of photonic nanomaterials (invited), International Conference on ion beam modification of materials, Taormina, Italy, September 18-21, 2006
21. Silicon-based photonics (invited), European MRS Conference, Nice, May 29 – June 1, 2006
22. Silicon-based lasers and light sources (invited), MRS Spring Meeting, San Francisco, CA, April 17-21, 2006
23. Silicon-based lasers and light sources, Surface plasmon nanophotonics (invited), Opto-electronics winterschool, Pontresina, March 13-16, 2006
24. Scattering and sensitizing in erbium and silicon nanocrystal-doped toroidal microcavities (invited), International Conference on Group-IV materials, Antwerp, September 2005
25. Ion beam shaping of nanomaterials (invited), Sixth international symposium on swift heavy ions in matter, Aschaffenburg, Germany, May 28-31, 2005
26. Microcavity controlled emission from rare earth ions (invited), MRS Spring Meeting, San Francisco, March 31, 2005

b. Consultative and advisory functions to other laboratories and agencies, especially Air

Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates, and name(s) of principal individuals involved.

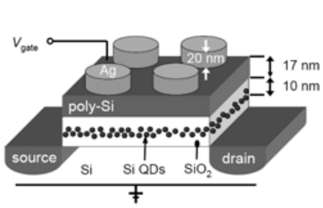
- All through CALTECH (see Report Atwater)

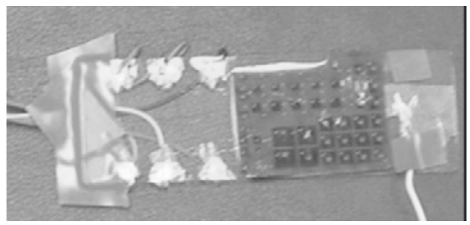
c. Transitions.

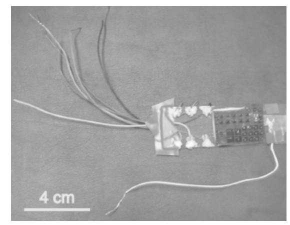
- A computer code has been developed that calculates plasmon enhanced luminescence effects for a range of metals, particle size, particle anisotropy, distance and polarization. A script has been made available on the web: www.erbium.nl, and output files from the calculations can be downloaded.
- Other transitions through CALTECH (see report Atwater)

d. Device demonstrations

We demonstrated a plasmon-enhanced silicon quantum dots LED operating at room temperature. A schematic and photographs of the device are shown below.







8. New discoveries, inventions, or patent disclosures.

- None

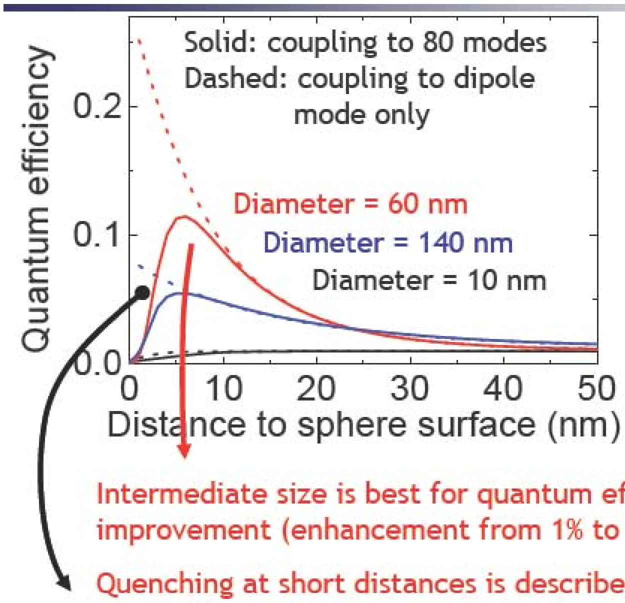
9. Honors/Awards: List honors and awards received during the grant/contract period.

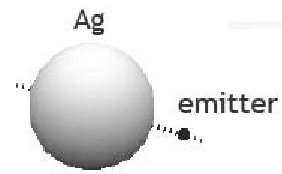
- Albert Polman: Appointed member, Royal Dutch Academy of Sciences (2009)

Appendix:

We list several graphs illustrating the outcome from this project

Analytical modeling of plasmon-enhanced luminescence



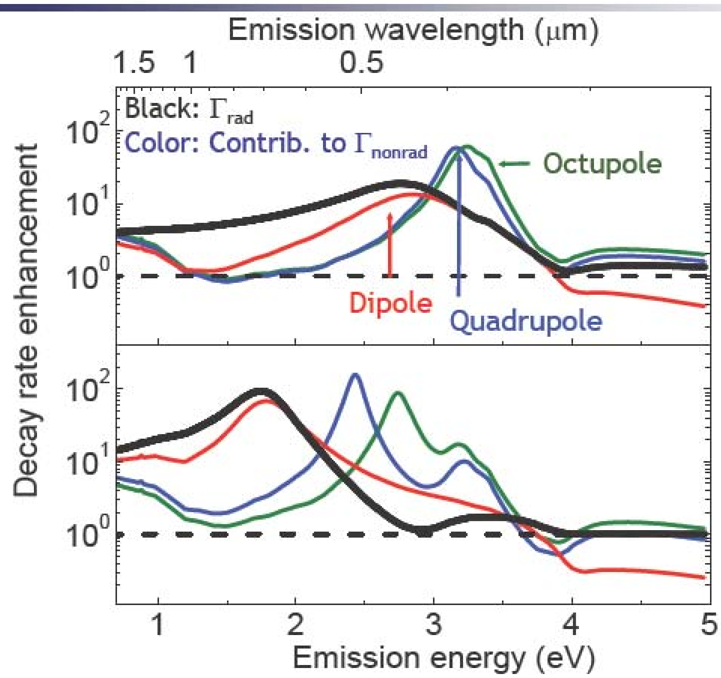


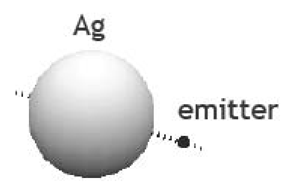
- Quantum efficiency in absence of sphere = 1%
- Emission wavelength = dipole resonance wavelength
- Calc. method: exact electrodynamical theory based on Green's function

Intermediate size is best for quantum efficiency improvement (enhancement from 1% to 11%)

Quenching at short distances is described by coupling to *dark* higher-order plasmon modes (nonlocal effects not essential)

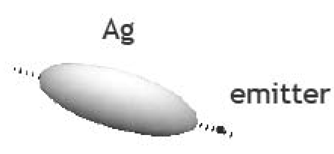
Emission enhancement in anisotropic particles





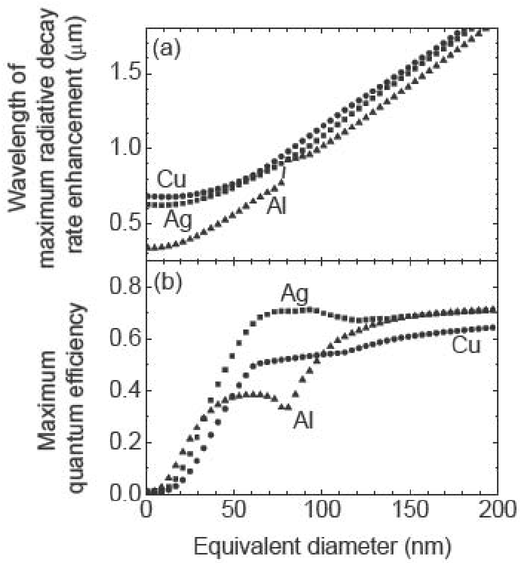
Aspect ratio = 1

Diameter = 80 nm
Distance = 10 nm



Aspect ratio = 3

Cu and Al are good plasmonic materials



Largest effect on quantum efficiency radiative rate:

- Large particle size (albedo → 1)

- Anisotropy causes spectral separation of radiative dipolar modes and dark higher-order modes

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On-chip green silica upconversion microlaser

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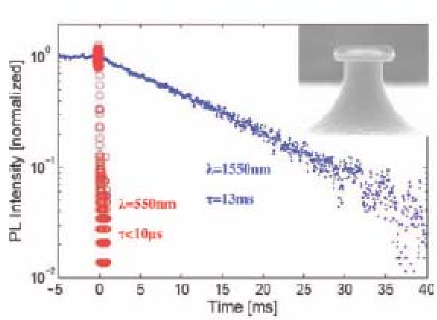
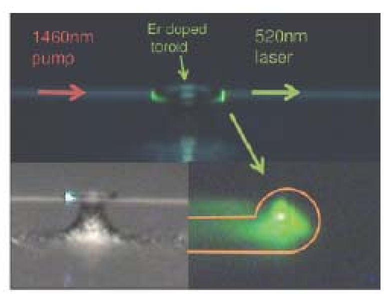
[2]*Center for Nanophotonics, Foundation for Fundamental Research on Matter Institute for Atomic and Molecular Physics, Kruislaan 407, 1098 SJ Amsterdam, The Netherlands*

[3]*Present address: Department of Electrical and System Engineering, Washington University in St. Louis, St. Louis, Missouri 63130, USA*

Corresponding author: vahala@caltech.edu





Plasmonics Applied

Surface plasmons, light-induced excitations of electrons on metal surfaces, may provide integration of electronics and optics on the nanoscale.

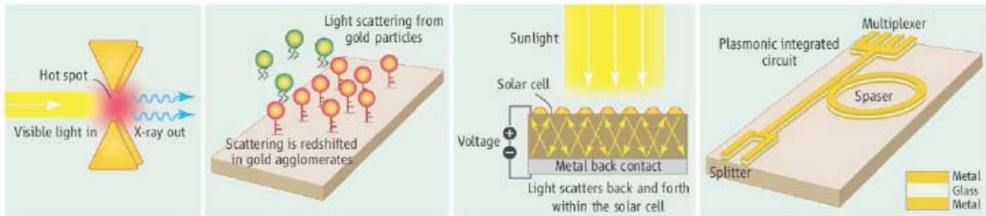
Albert Polman

The ability to engineer metal surfaces and particles at the nanoscale has led to the rapid development of the field of "plasmonics," the optical properties of metal structures at the nanoscale. Surface plasmons are optically induced oscillations of the free

tion of extreme-ultraviolet light by pulsed-laser high harmonic generation (1). This opens a wealth of prospects in lithography or imaging at the nanoscale through the use of soft x-rays (see the figure, left panel).

Because the plasmonic interaction be-

trol over the color, directionality, and polarization of light-emitting diodes. This concept may find large-scale applications in the areas of solid-state lighting and photovoltaics (see the figure, middle right panel). Calculations and experiments (6) show that light scattering



Applied plasmonics. (Left) A plasmonic hot spot between metal nanoparticles creates soft x-rays. **(Middle left)** Measuring the resonance shift in coupled metal nanoparticles leads to efficient sensing. **(Middle right)** Scattering from metal nanoparticles enhances light trapping in a solar cell. **(Right)** Plasmonic integrated circuit with subwavelength dimensions. A plasmonic ring laser is integrated with 50-nm-wide waveguides.

than four orders of magnitude. This leads to a large improvement in sensing techniques that use optical radiation, such as Raman spectroscopy, with potential applications in medical diagnostics. The effect of light concentration via plasmons is most apparent in phenomena that are nonlinear in light intensity, as demonstrated recently by the on-chip genera-

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thereby destroy the cells. Clinical studies are showing promising results (4).

Suitably engineered metal nanostructures can also act as antennas in which the resonant coupling between the particles concentrates light into well-defined hot spots (5), enabling ultrasmall, wavelength-sensitive directional sensors or detectors. The same metal particle arrays, when coupled to optical emitters, can also act as directional emitters. Indeed, the enhanced optical density of states near the surface of metal nanoparticles can provide con-

metal-insulator interfaces. By further tailoring plasmonic waveguide structures, the propagation speed of plasmons can be reduced well below the speed of light (8). More complex geometries, in which arrays of nanoholes are integrated in a metal film, act as efficient color filters (9). Interestingly, in some geometries, plasmon waveguides exhibit a negative refractive index for the guided plasmon, and indeed two-dimensional negative refraction has been observed in these plasmonic waveguides (10).

Are negative index materials achievable with surface plasmon waveguides? A case study of three plasmonic geometries

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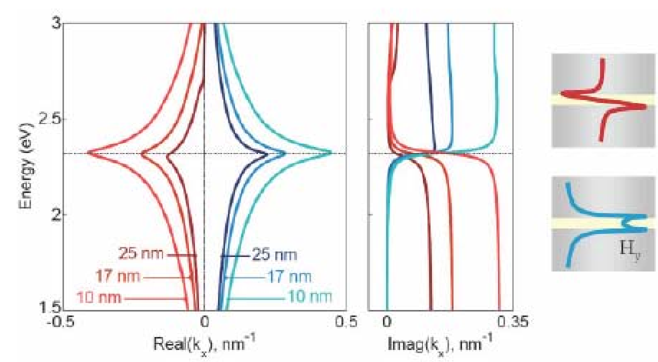

Fig. 2. Lossy dispersion for MIM waveguides consisting of GaP clad by Ag. Three GaP thicknesses are included (d = 25 nm, 17 nm, and 10 nm), and dispersion relations for both H_y-field symmetric (blue hues) and antisymmetric (red hues) modes are shown. Including losses, the necessary condition for negative index modes is: sign(Real{k_x}) ≠ sign(Imag{k_x}). This condition is clearly satisfied for the H_y-field antisymmetric mode, which can exhibit negative indices with very low loss above the surface plasmon resonance (shown as a dotted line).

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Near-Field Visualization of Strongly Confined Surface Plasmon Polaritons in Metal–Insulator–Metal Waveguides

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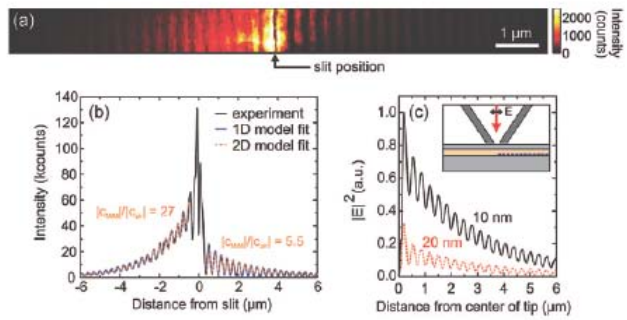
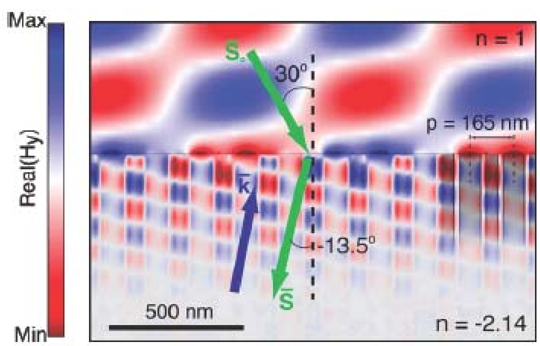


Figure 2. (a) Near-field image obtained by scanning the excitation tip position over the sample containing a single output slit. The excitation wavelength is 638 nm. (b) Collected intensity in panel a as a function of tip–slit distance (black curve), and a fit to the data of the one- and two-dimensional models described in the text (blue and orange curves, respectively). The ratio of the amplitudes of both modes in the two-dimensional model is indicated. (c) Simulated electric field intensity in the Si_3N_4 film as a function of distance from the center of the tip. The inset shows a schematic of the simulated two-dimensional geometry. The dashed blue line indicates the position at which the calculated intensity is plotted. The tip–sample separation is 10 nm (black) or 20 nm (red).

Negative refraction in coaxial plasmonic waveguide metamaterial

83 nm p-polarized excitation, 30°

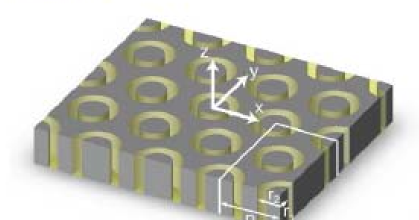


k – phase velocity
Monitor phase-front propagation

S – Effective Poynting vector

n – Effective refractive index
Snell's Law

n = -2.14
η = 25% in-coupling efficiency
FOM = 8.2 figure-of-merit



A single-layer wide-angle negative index metamaterial at visible frequencies
S.P. Burgos*, R. de Waele*, A. Polman, and H.A. Atwater, Nature Materials **9**, in press (2010)