Wave-front Engineering of Light Sources using Metamaterials

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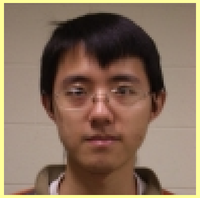
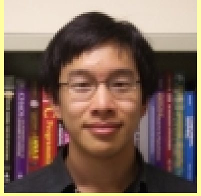


Nanfang Yu



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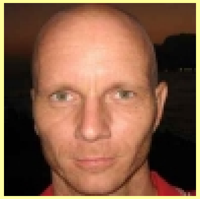

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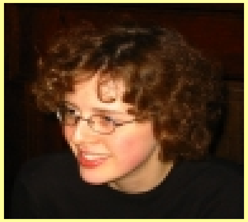

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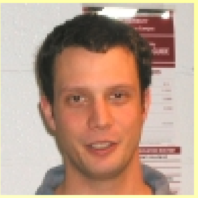
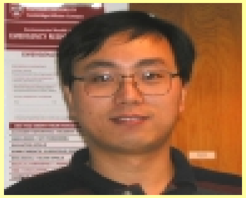


Laurent Diehl



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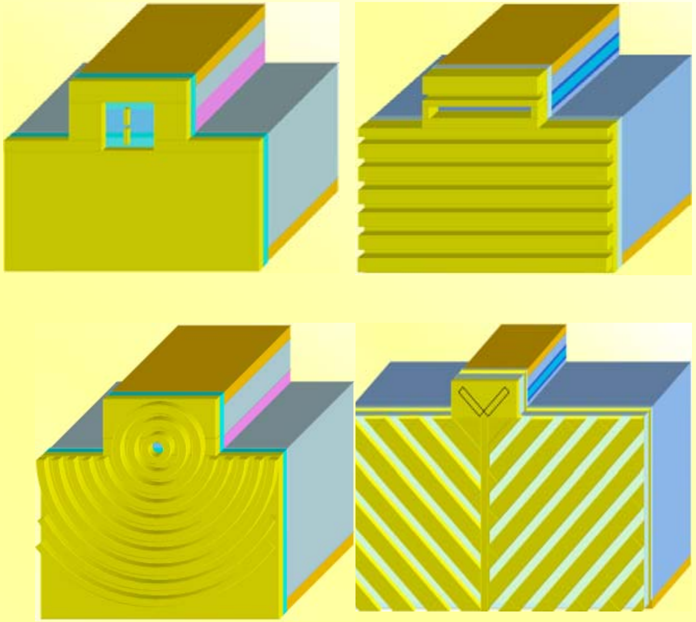
Near-field and far-field Engineering

The Challenge

Facet engineering of lasers and other light sources to achieve enhanced performance or new functionalities in the near-field and in the far-field: "wavefront engineering"



Semiconductor lasers with "arbitrary" wavefront?

- High collimation
- Control of polarization
- Super focusing in the near-field and far-field
- Beam steering using a single device
- Bessel beams (no divergence)
- Beams with orbital angular momentum, etc.

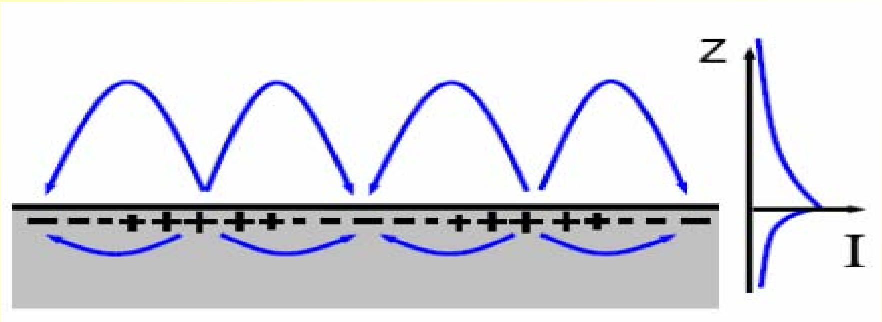
The Approach

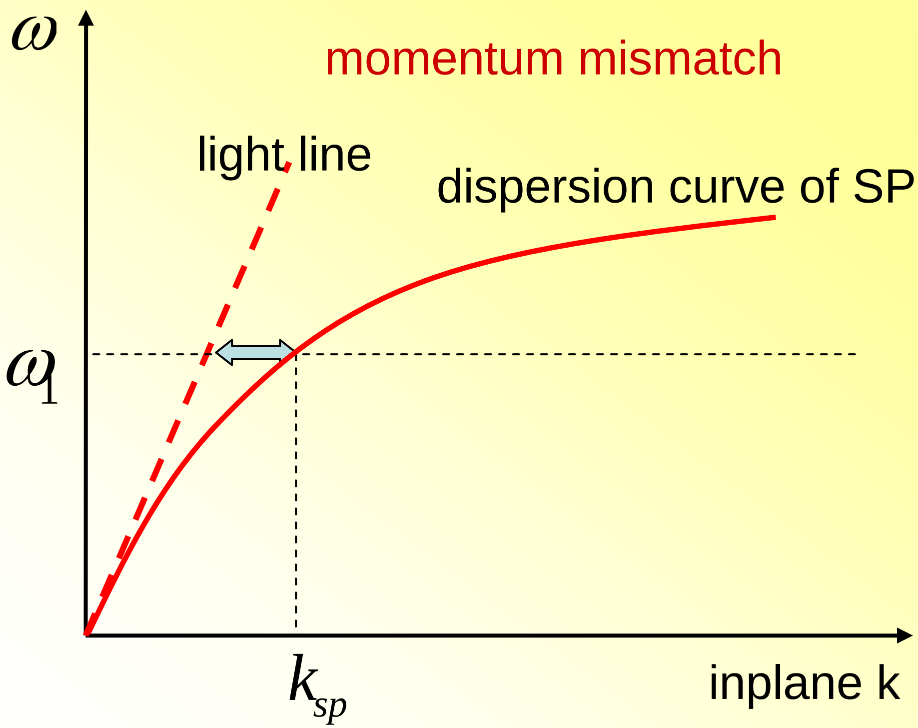
- Pattern plasmonic structures (metallic antennas, apertures, gratings, etc.) on the facet of semiconductor lasers and other optical components
- Plasmonics: Sub-wavelength control of the amplitude and phase of the optical near-field → the amplitude and phase of the far-field
- Development of new patterning techniques based on soft lithography

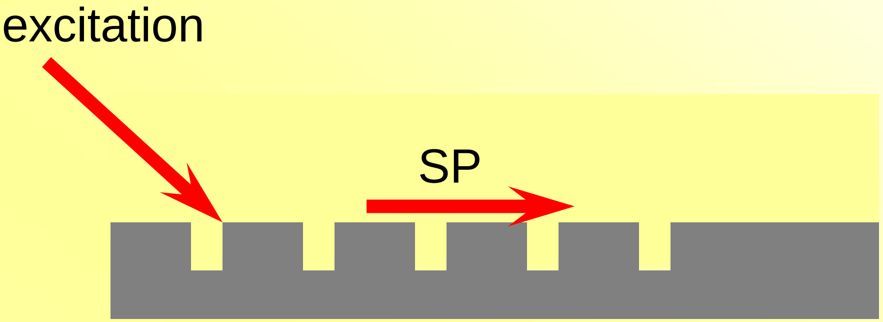
Surface plasmons

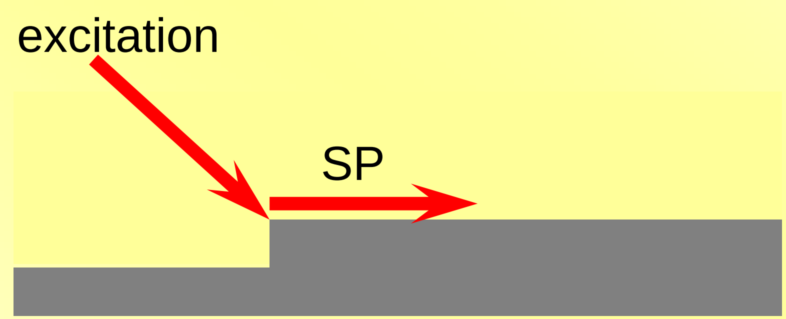
> Surface electromagnetic waves coupled with surface charge oscillations

> Bounded at and propagating along surface

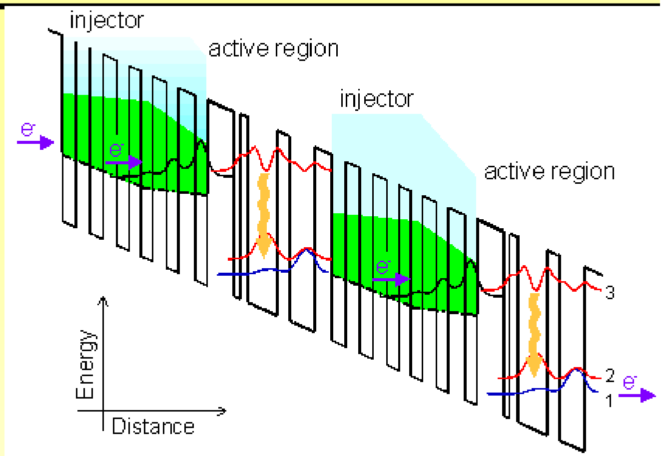


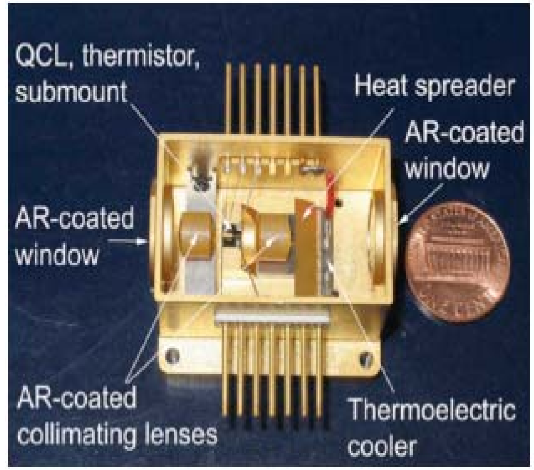


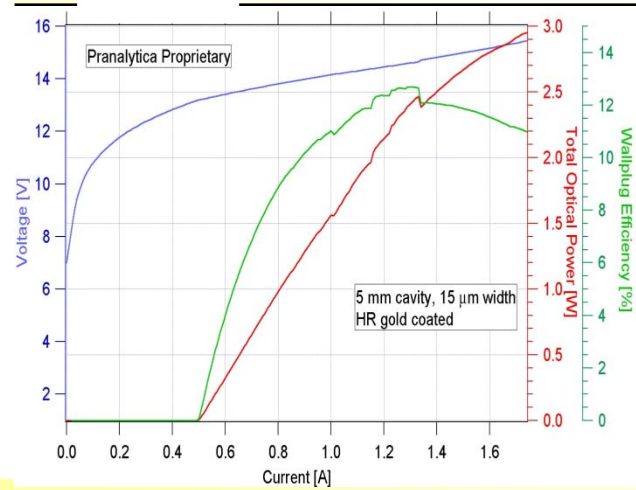




Quantum Cascade Lasers: platform to demonstrate beam engineering







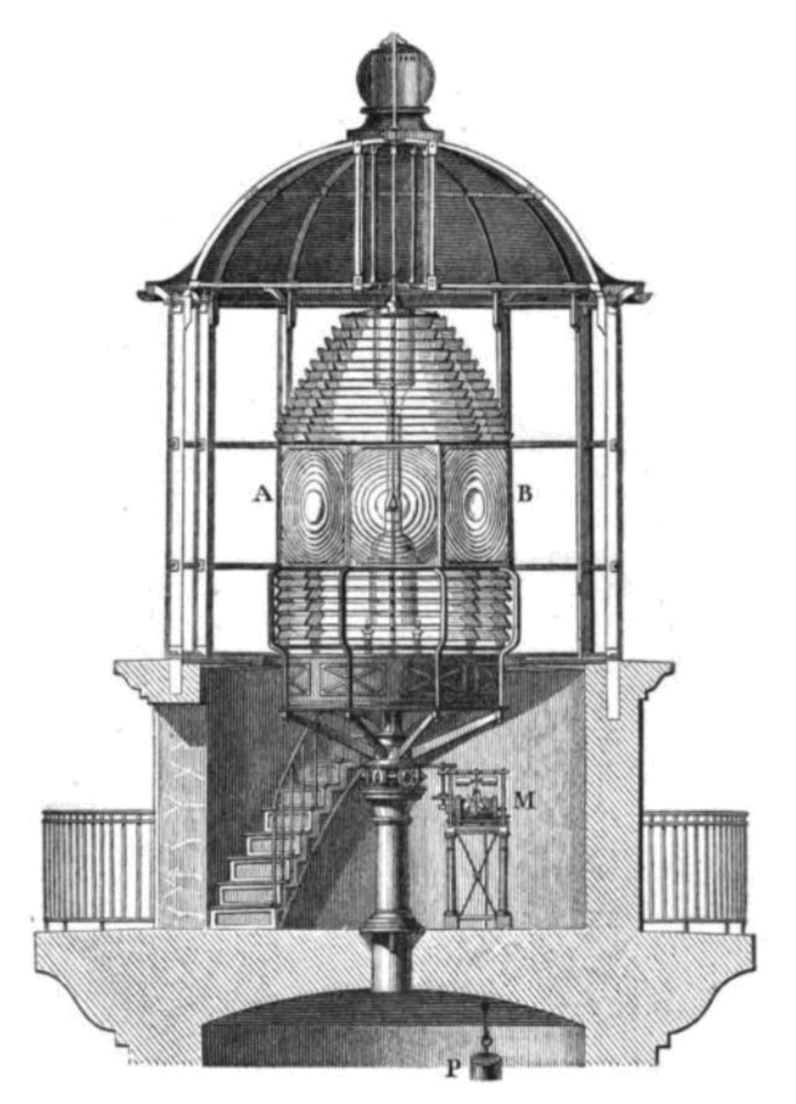
Main features:

- Huge wavelength coverage (mid-ir through far-ir: 3.0-300 μm) using same materials by controlling layer thickness: **wavelength by design**
- Very narrow emission linewidth (for DFB QCLs), 10^{-4}-10^{-5} cm^{-1}
- Gain spectrum by design: Broadband (e.g. 1000-1300 cm^{-1})
- High power, high temperature operation in the mid-ir (4.5 -12 μm)

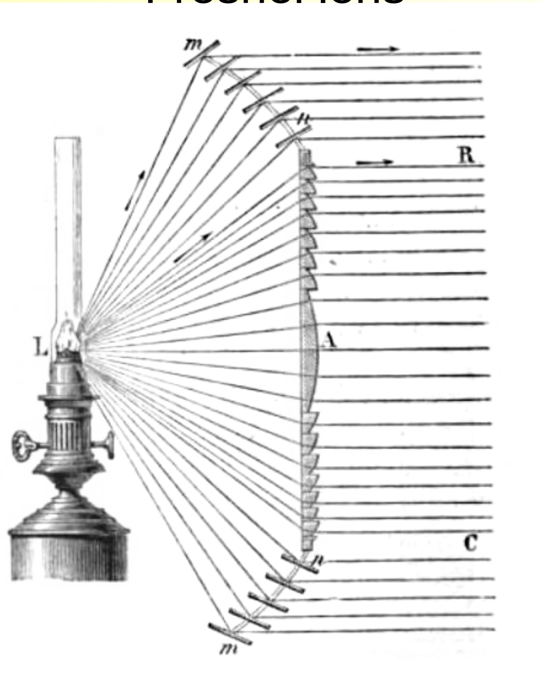
Maturing technology

- High reliability and robustness
- QCL can be grown by MOVPE: standard semiconductor laser platform
- Hundreds of milliwatts of CW output at room temperature in mid-IR
- Increasing number of semiconductor foundries / companies growing QCLs

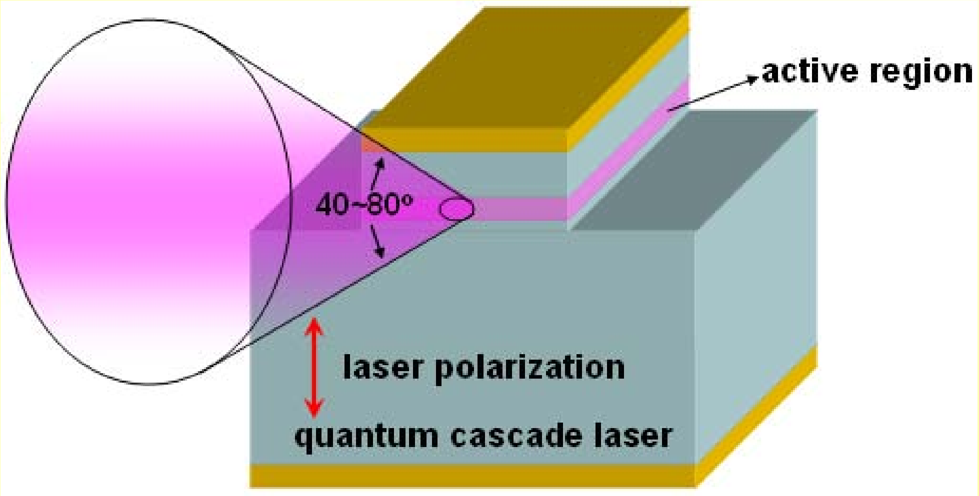
Beam Engineering in a Lighthouse

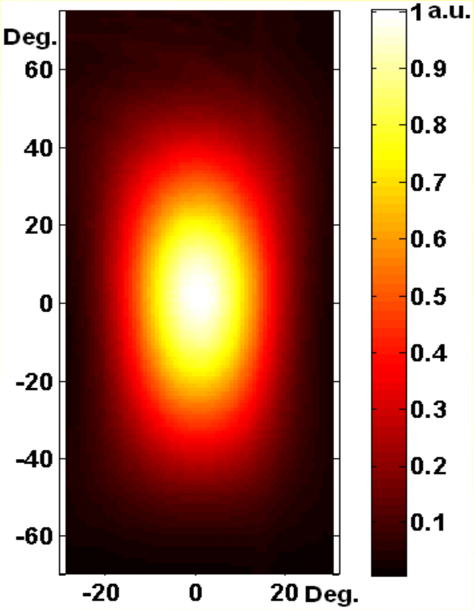


Fresnel lens



The divergence problem in semiconductor lasers

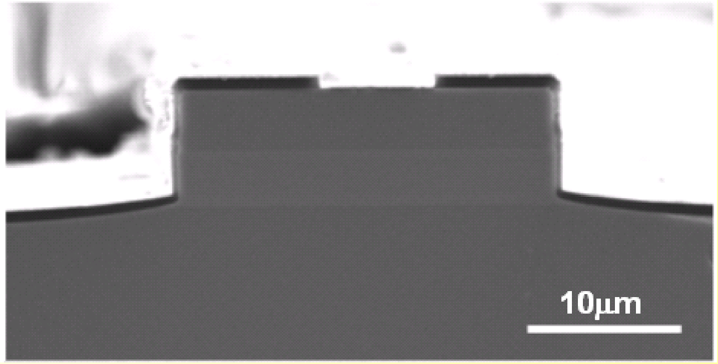




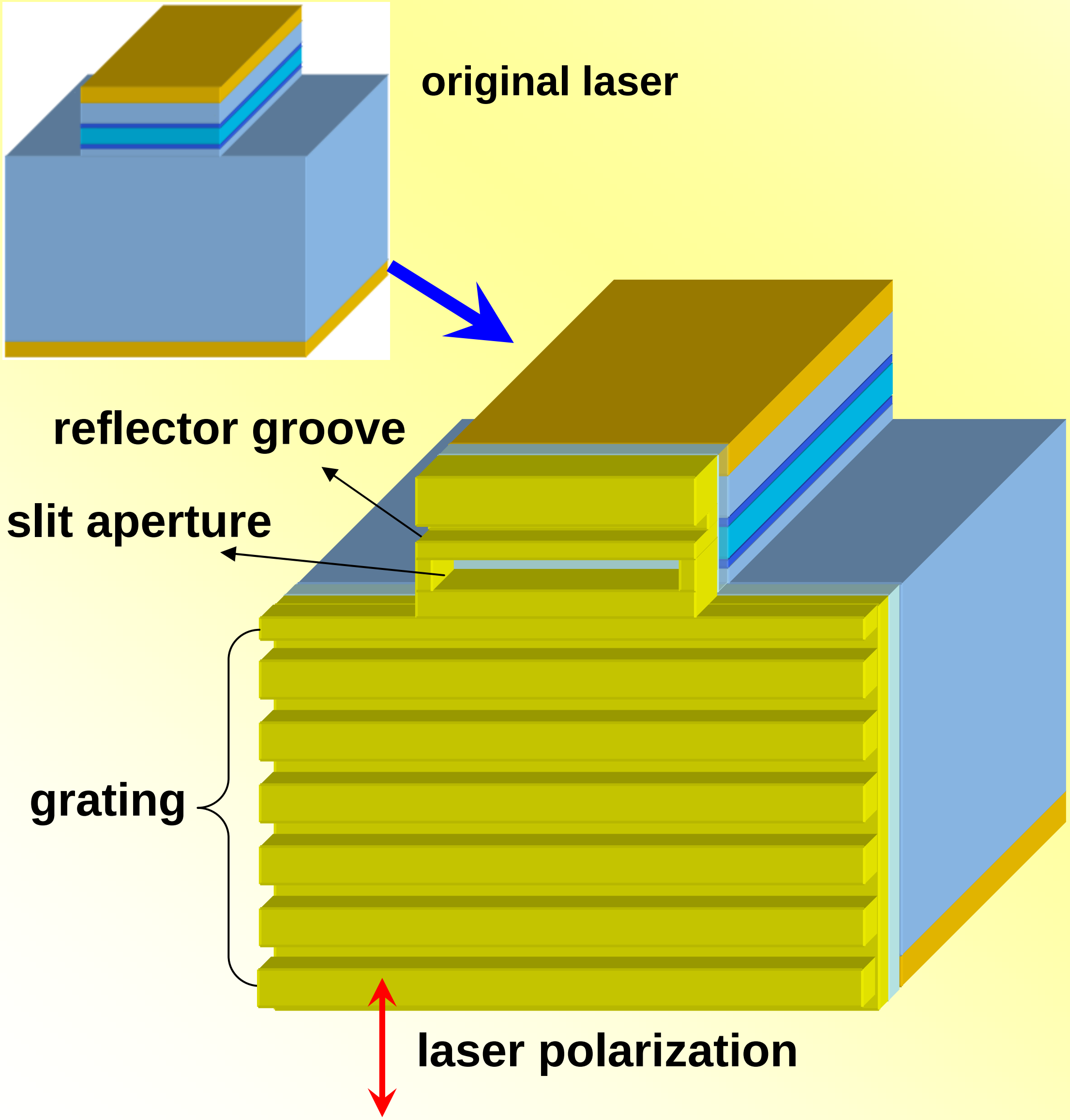
- **Beam divergence of semiconductor lasers: $\theta \approx \lambda_w / L$**

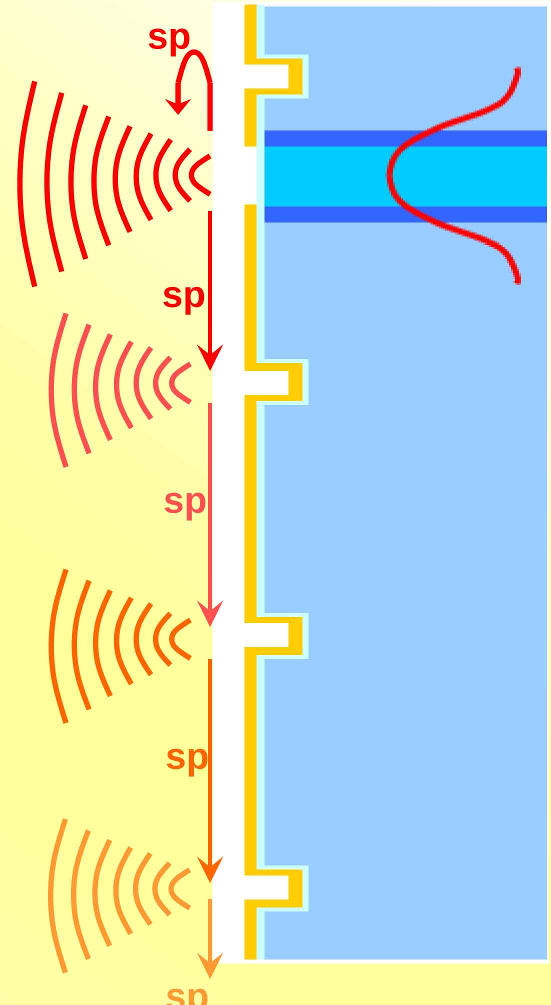
  λ_w laser wavelength in the waveguide material

  L dimension of the waveguide core

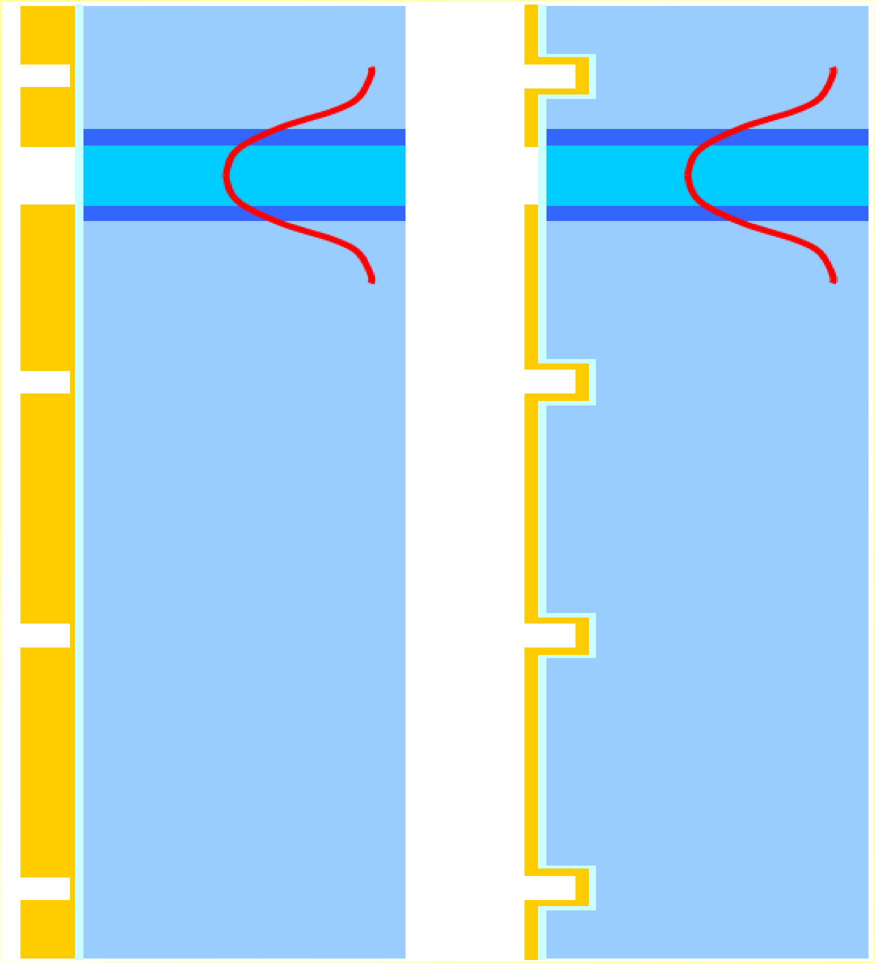


1D Collimation in the Vertical Direction





Two ways of fabrication



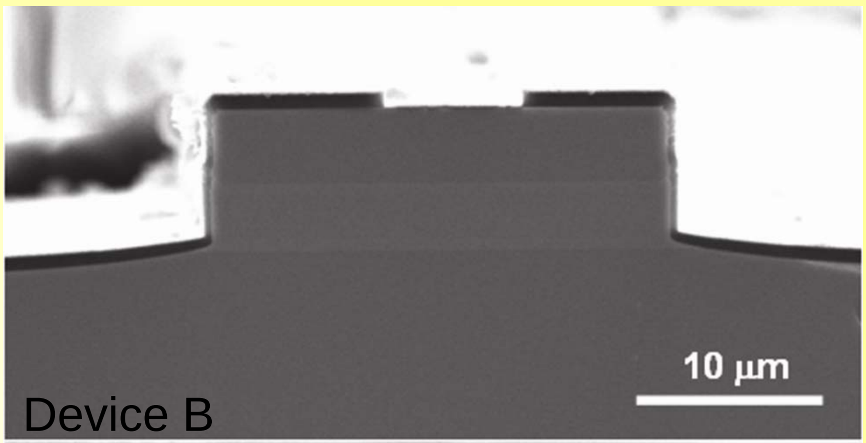
Use focused ion beam milling to define grating grooves and apertures

Two designs equivalent in beam collimation and power throughput

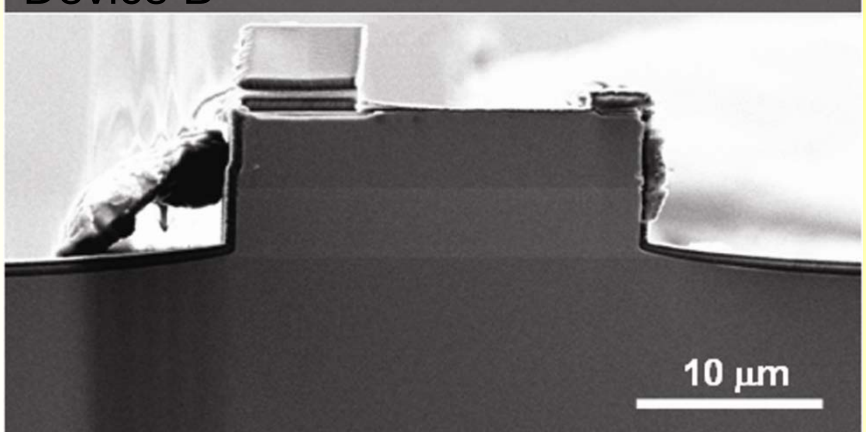
Experiments: Original Devices

SEM images of the device facets

Device A λ=9.9 μm

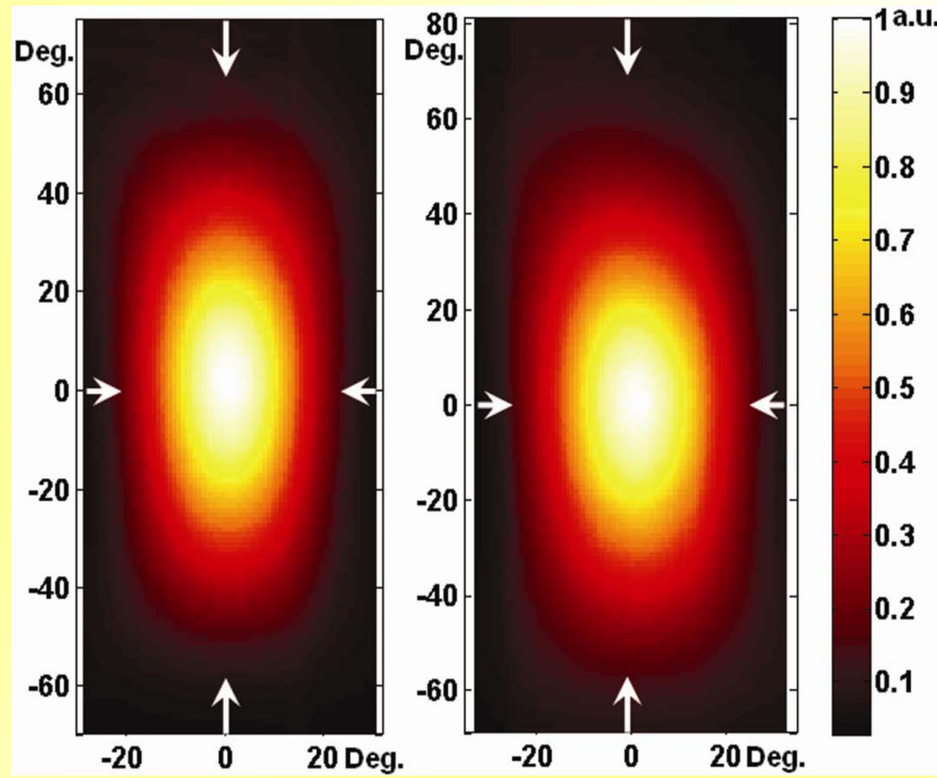


Device B



Measured far-field mode profiles

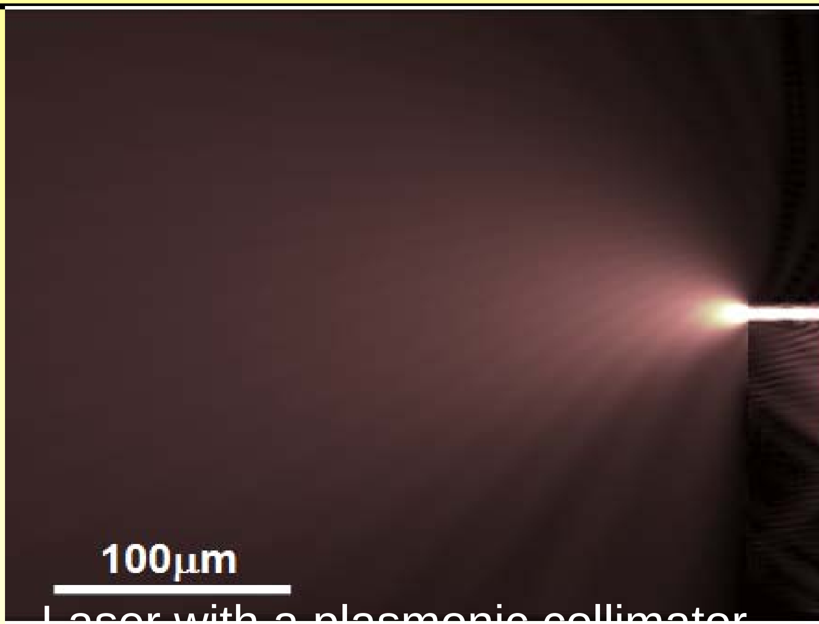
Device A Device B



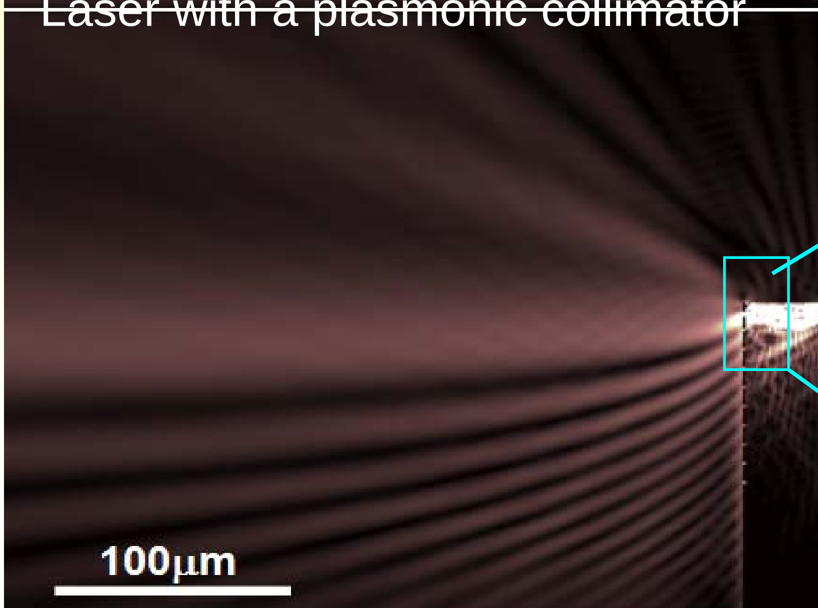
Vertical beam divergence: ~60 deg

Simulations

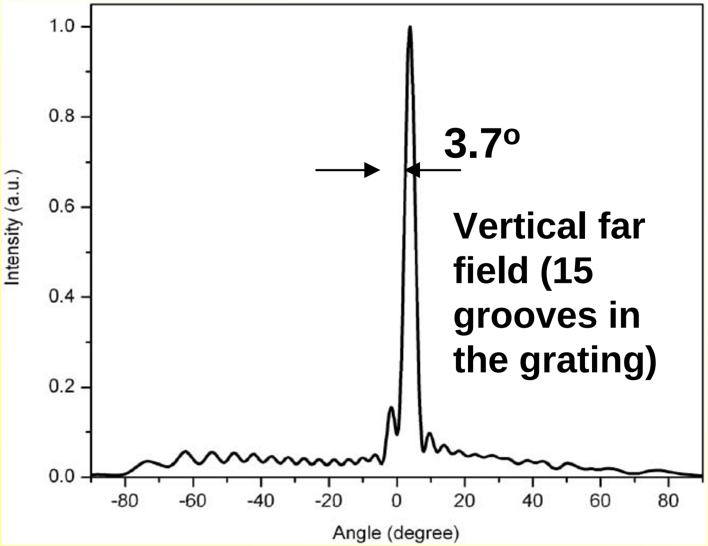
Original laser

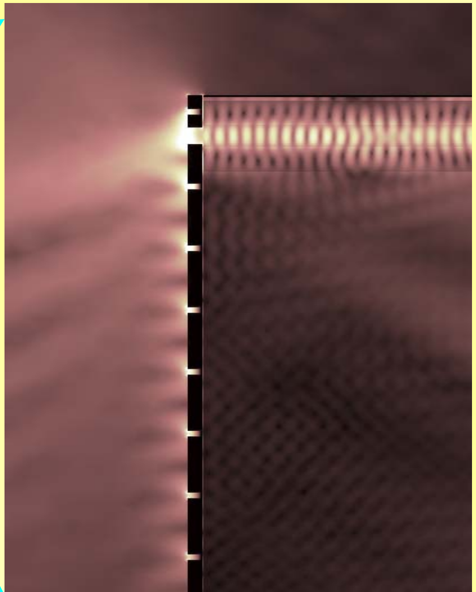


Laser with a plasmonic collimator



λ=9.9 µm



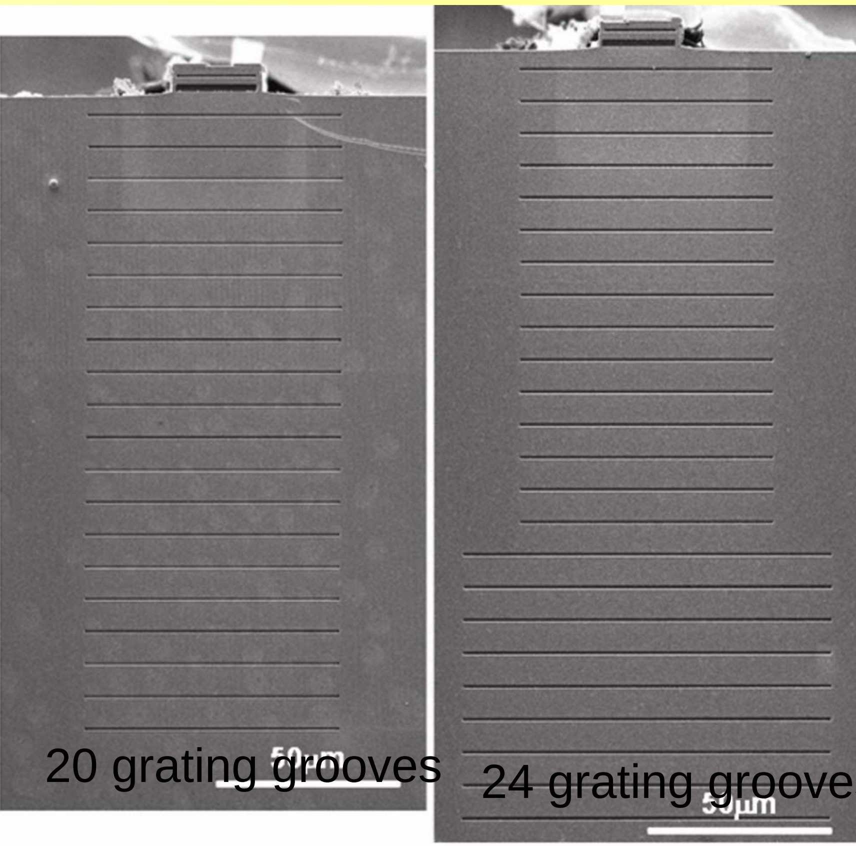


Experiments: Devices with 1D Plasmonic Collimators

SEM images of the device facets

Device A

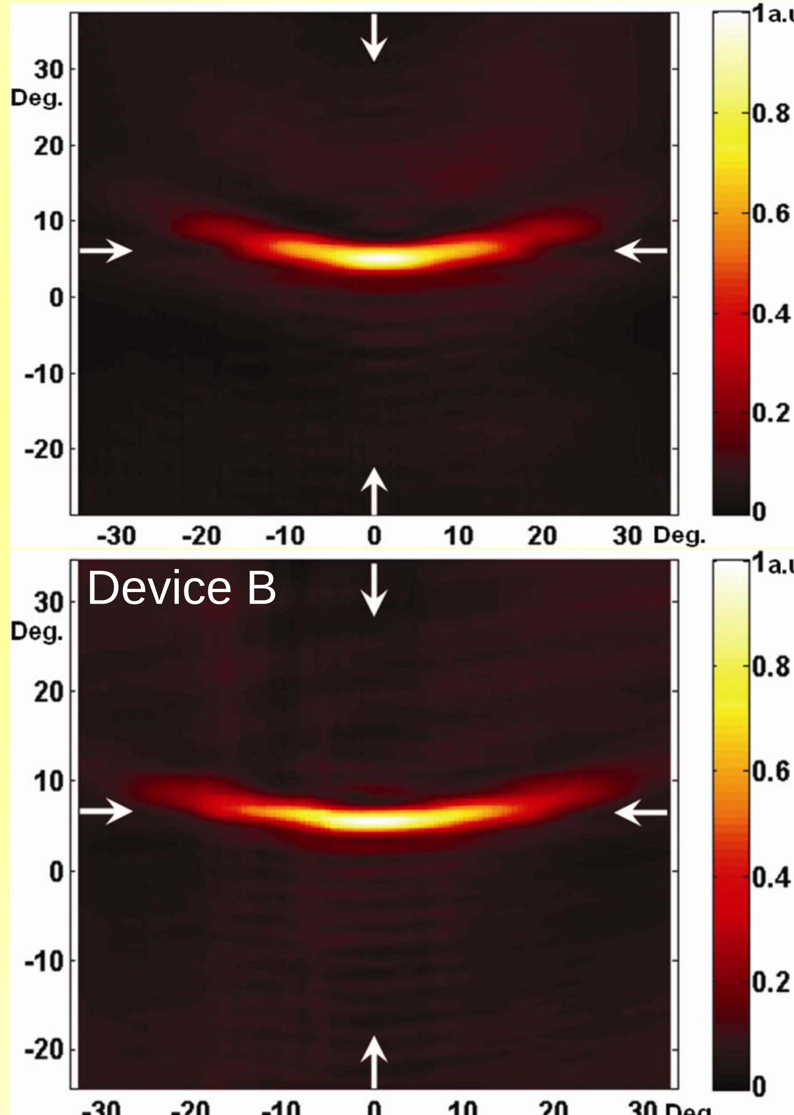
Device B



20 grating grooves

24 grating grooves

Measured far-field mode profiles



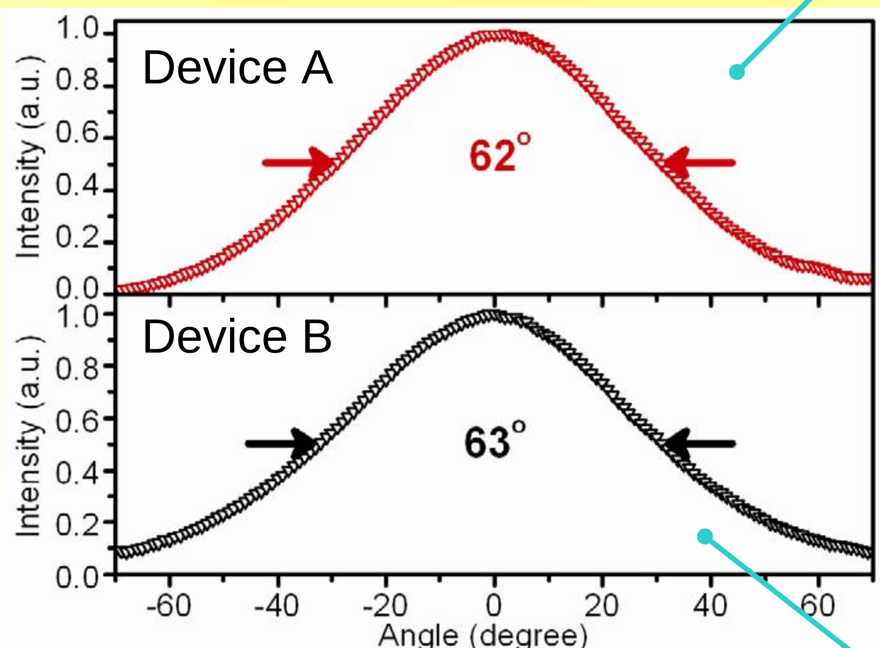
2.9 deg

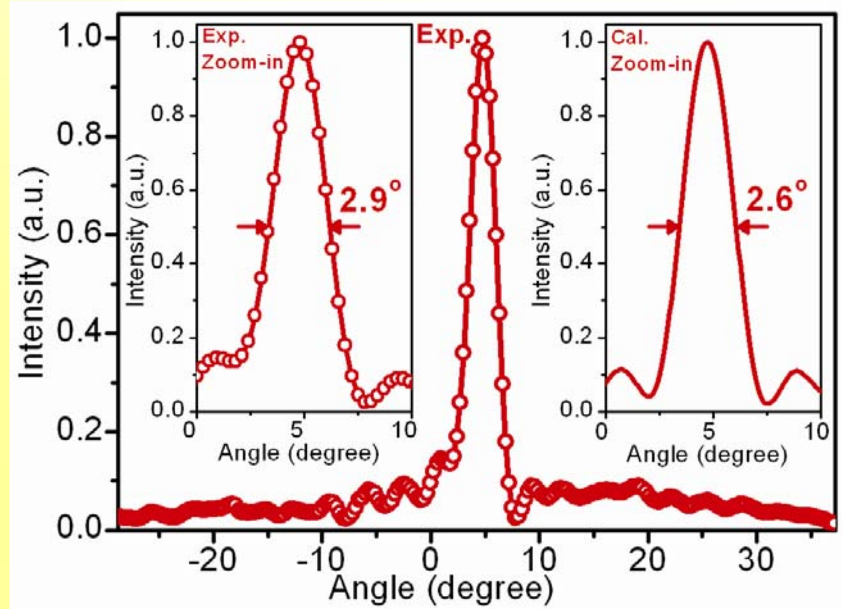
2.4 deg

Experiments: Line Scans of the Far-field Mode Profiles

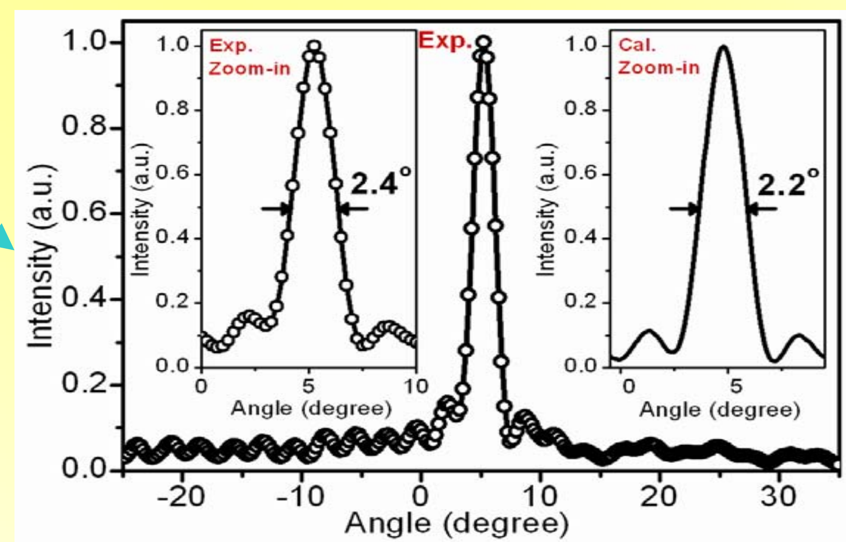
20 grooves

Original devices

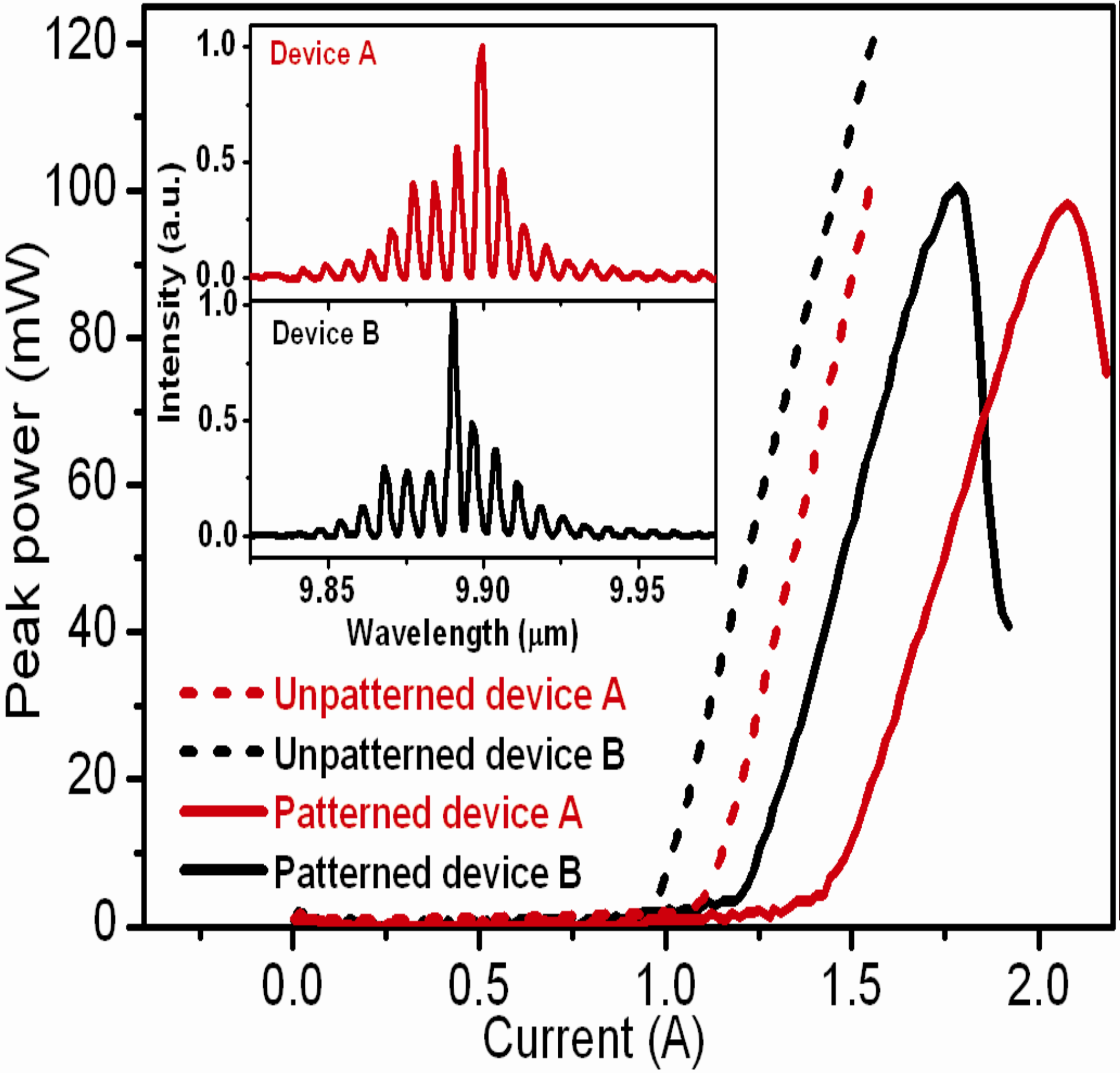


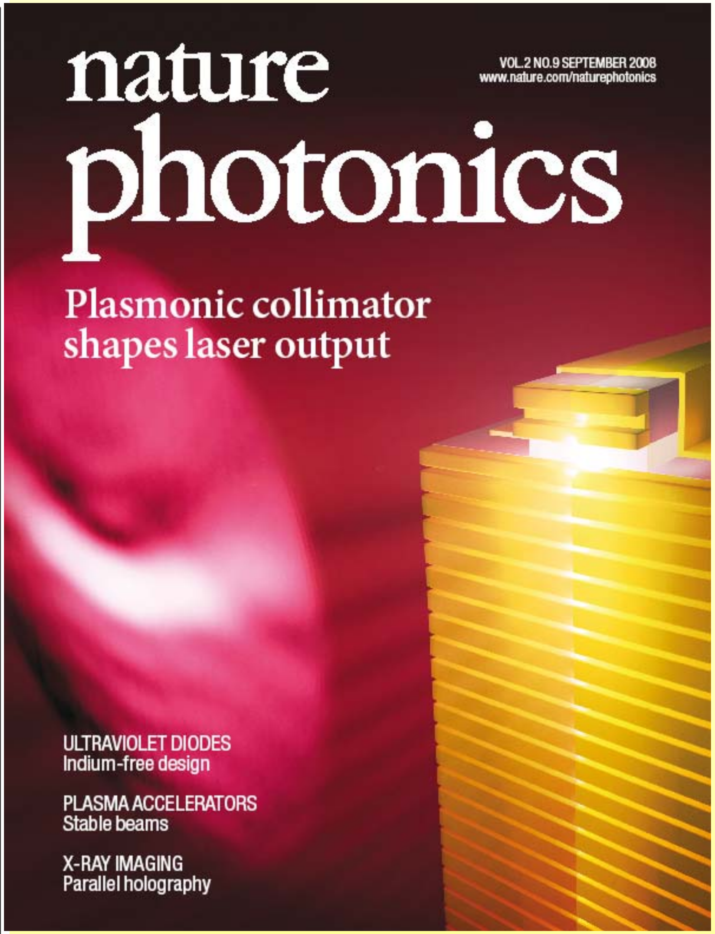


24 grooves



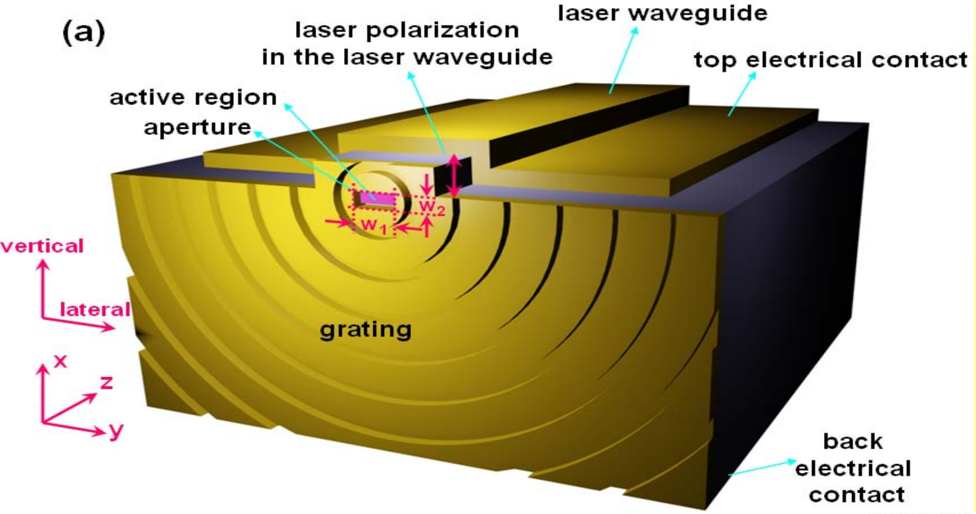
1D Plasmonic collimators



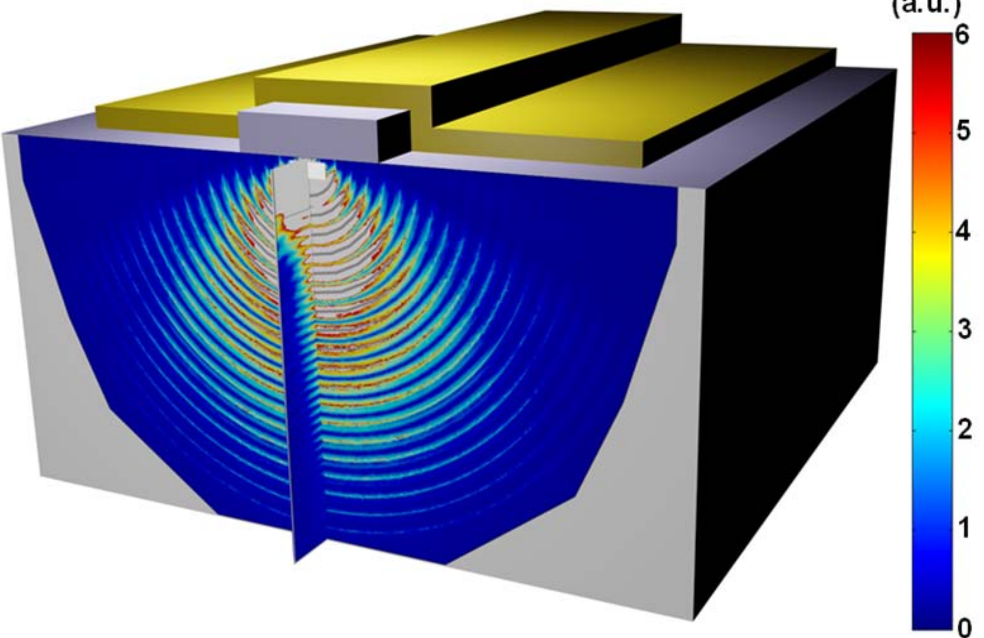


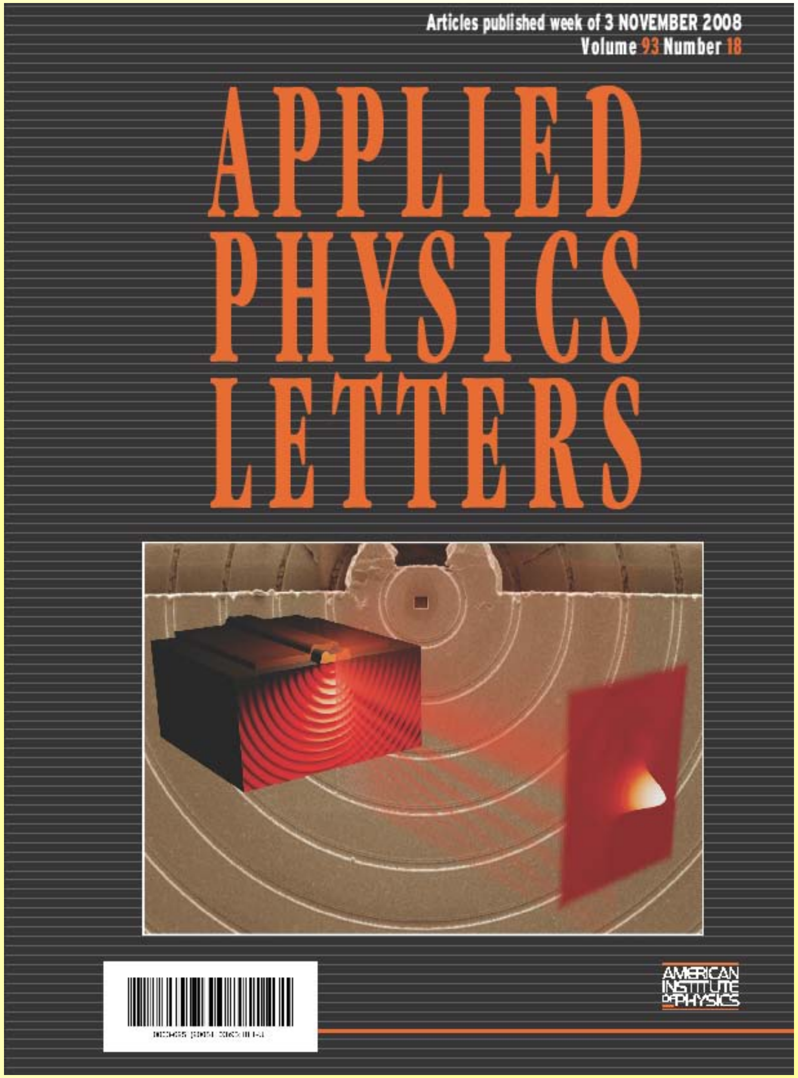
Nanfang Yu, et al.
Nature Photonics vol. **2**, pp. 564-570 (2008)

2D Collimation: Design



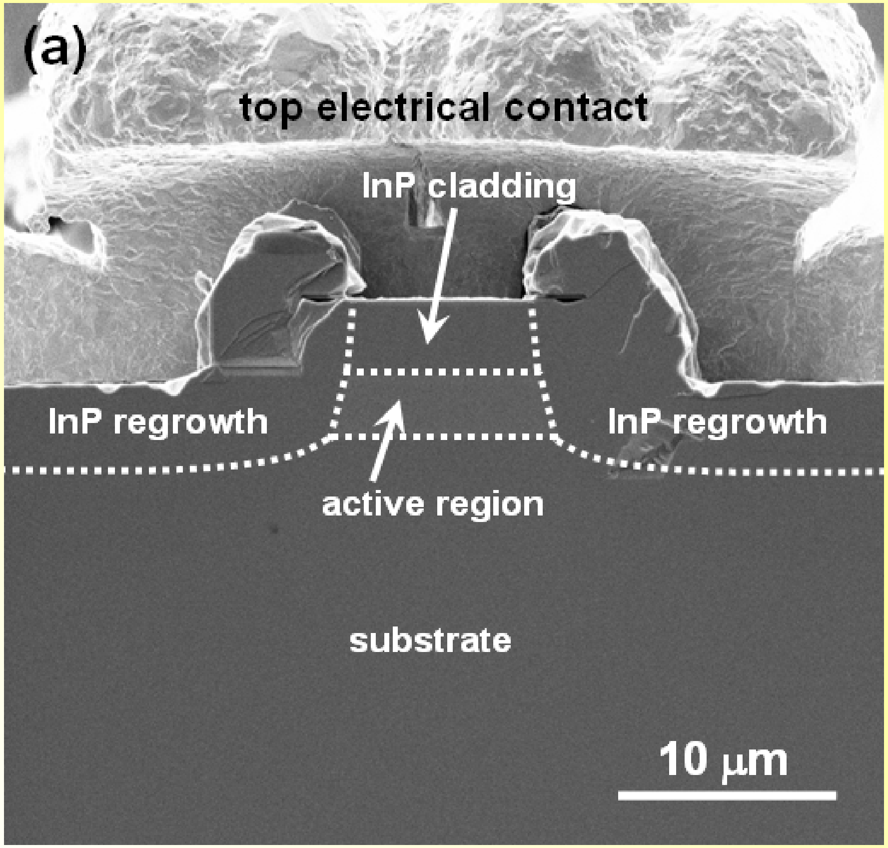
Simulation: $|E|^2$ at 100 nm above surface



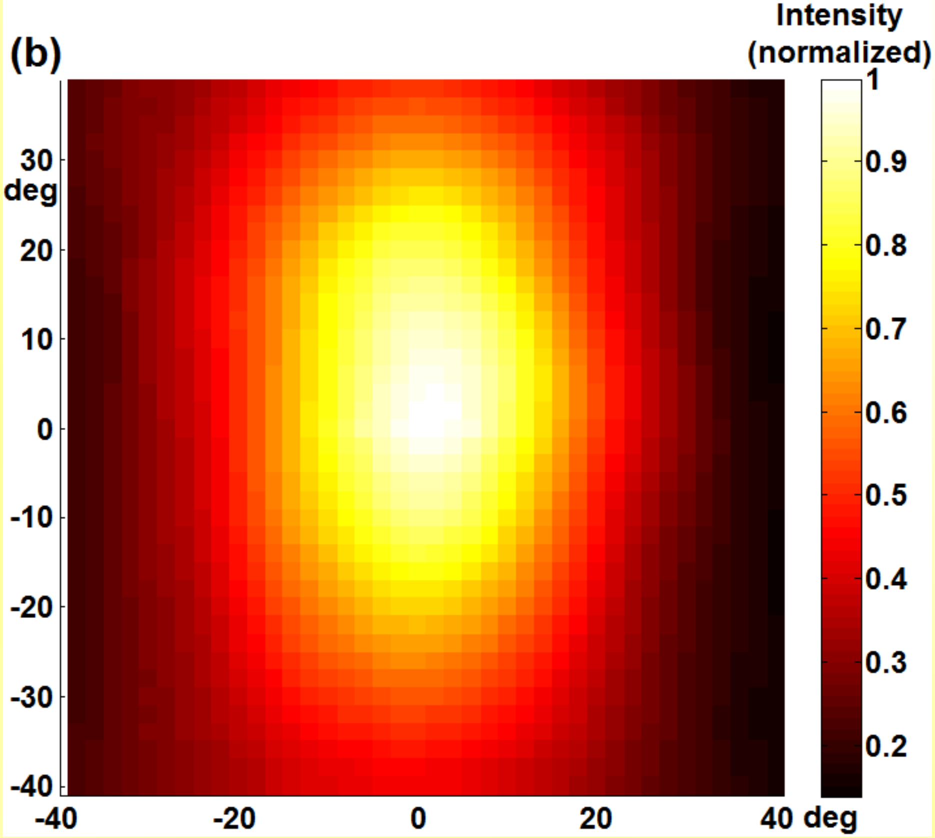


2D Plasmonic Collimation: Original Device

SEM image of the laser facet



Measured far-field mode profile



Hamamatsu MOCVD-grown buried heterostructure device: λ=8.06 μm

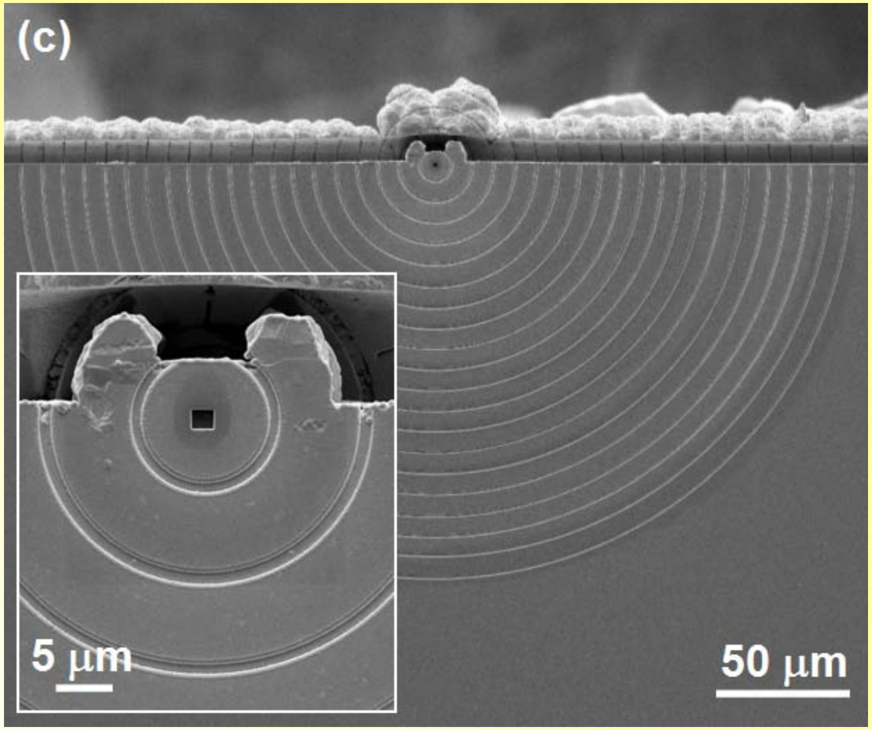
FWHM divergence angles:

$\theta_{\perp}=74^{o}$

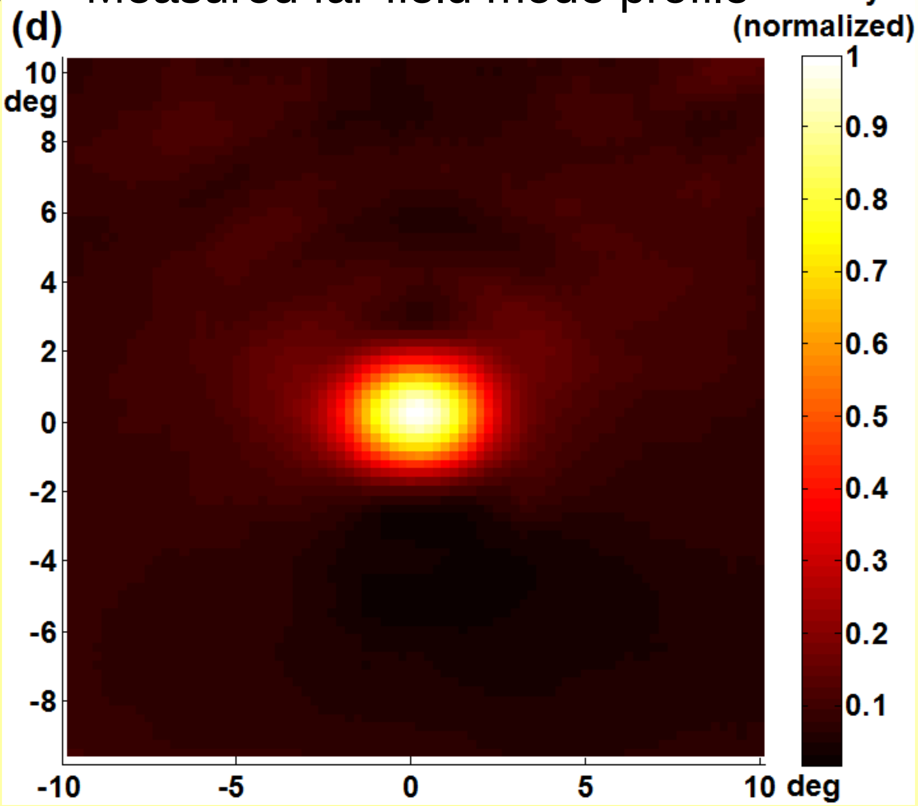
$\theta_{||}=42^{o}$

Experiment: far-field mode profile (20 rings)

SEM image of a fabricated device (λ=8.06 μm)



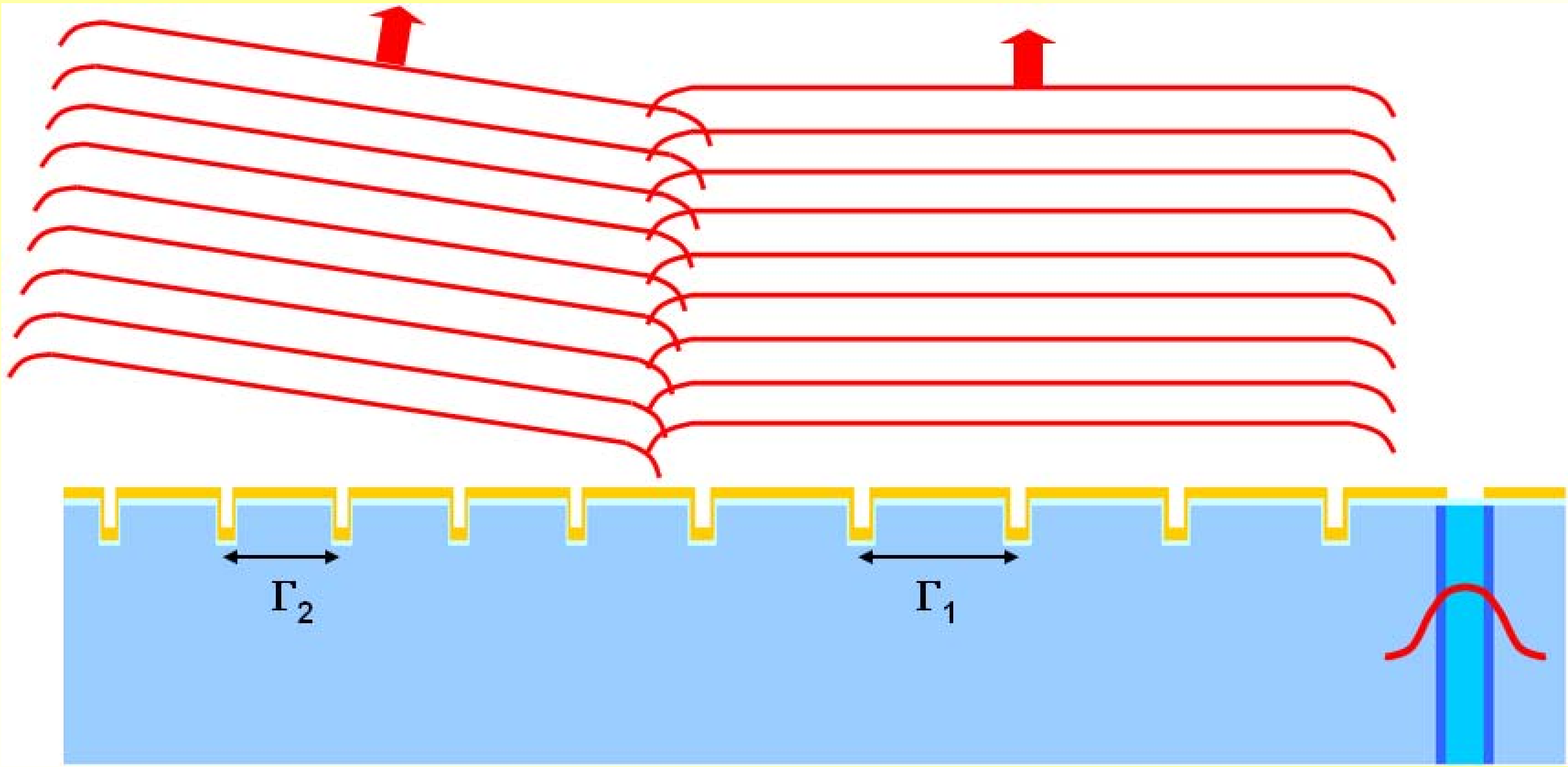
Measured far-field mode profile



Aperture size $w_1 \times w_2$ (μm^2)	grating period Λ (μm)	groove width w (μm)	groove depth d (μm)	radius of the first groove r_1 (μm)
2.1×1.9	7.8	0.6	1.0	6.0

FWHM divergence angles:
$\theta_\perp = 2.7^o$ (reduction by a factor of ~30)
$\theta_{||} = 3.7^o$ (reduction by a factor of ~10)

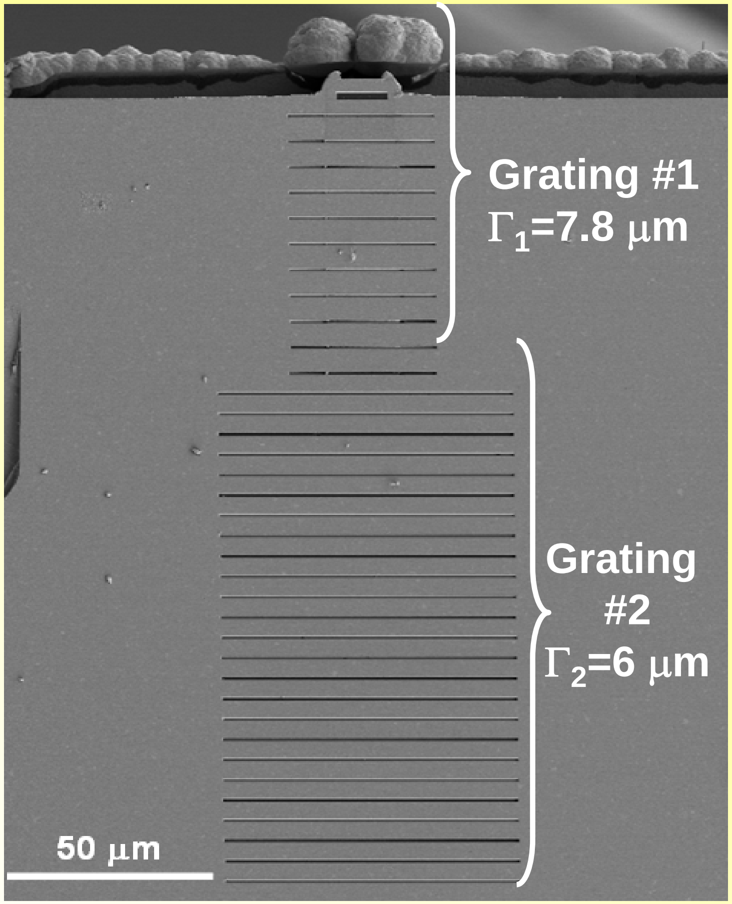
Semiconductor lasers producing small divergence beams in multiple directions

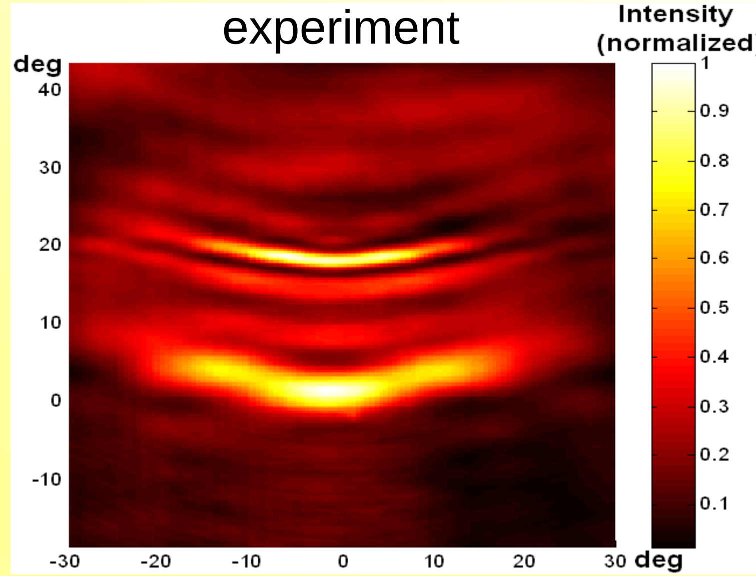


$k_{sp}\Gamma_1 = 2\pi$ gives constructive interference and reduced divergence normal to the facet
$k_{sp}\Gamma_2 + k_{air}\Gamma_2 \sin\theta = 2\pi$ gives constructive interference and reduced divergence in a direction θ with respect to the normal

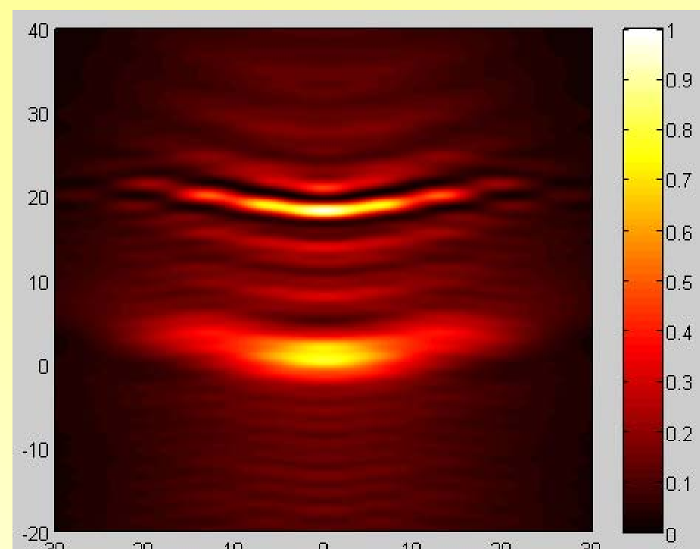
Single-wavelength device emitting dual beams

λ=8.06 μm





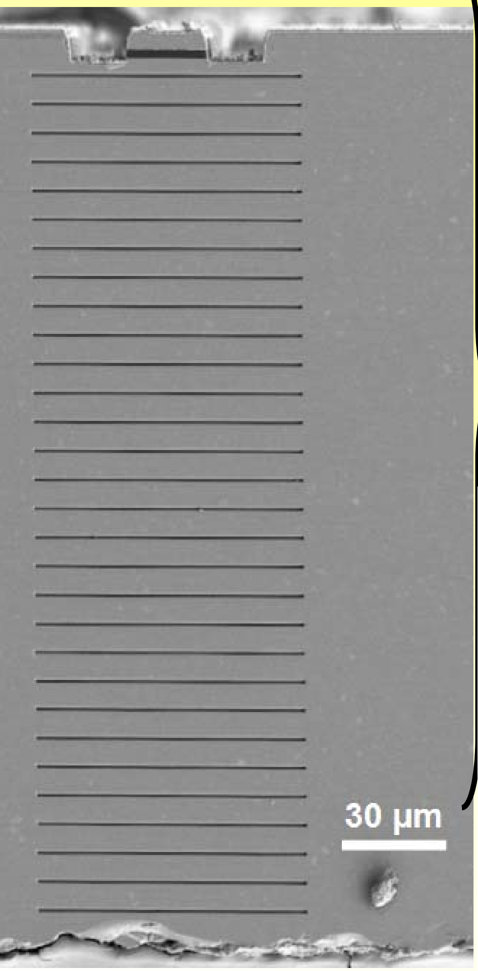
simulation



The design can essential control the intensity and direction of the two beams coming from the two gratings by tuning grating periods and groove numbers.

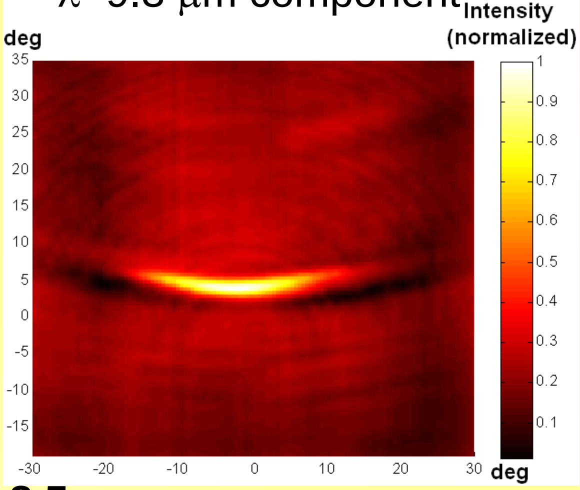
Dual-wavelength device emitting dual beams

QCL emitting at λ=10.5 μm and 9.3 μm

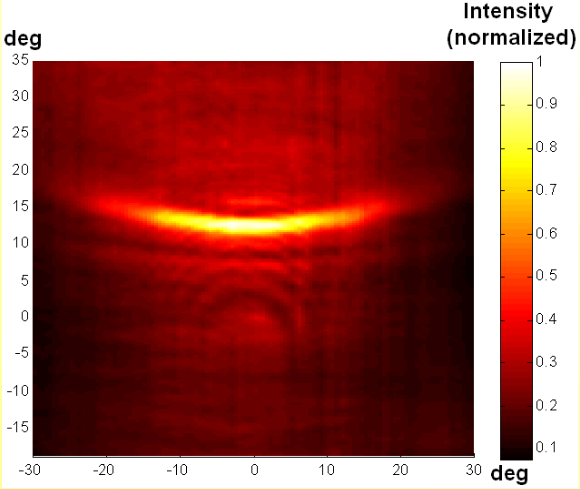


Γ=8.5 μm

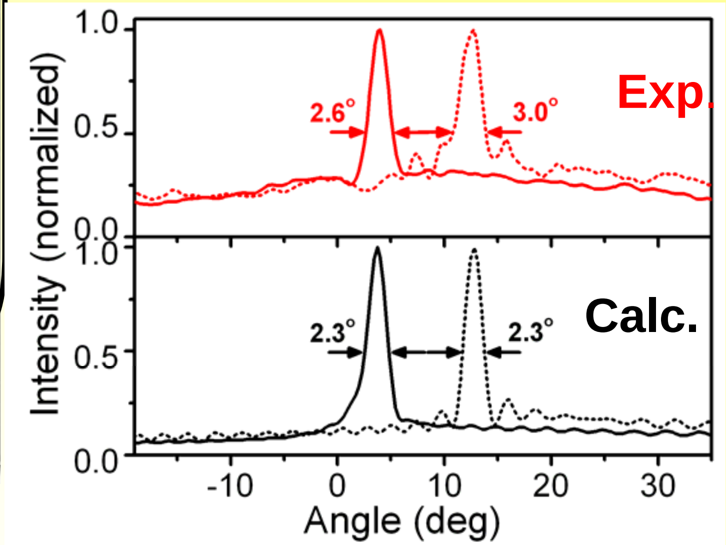
Measured far-field of the λ=9.3 μm component



Measured far-field of the λ=10.5 μm component



Vertical line scans



$$k_{sp,\lambda_1} L_p + k_{1air} L_p \sin\theta_1 = 2\pi$$

$$k_{sp,\lambda_2} L_p + k_{2air} L_p \sin\theta_2 = 2\pi$$

Solid lines: 9.3 μm
Dotted lines: 10.5 μm

Plasmonic Polarizers: Motivation

Semiconductor lasers: linearly polarized

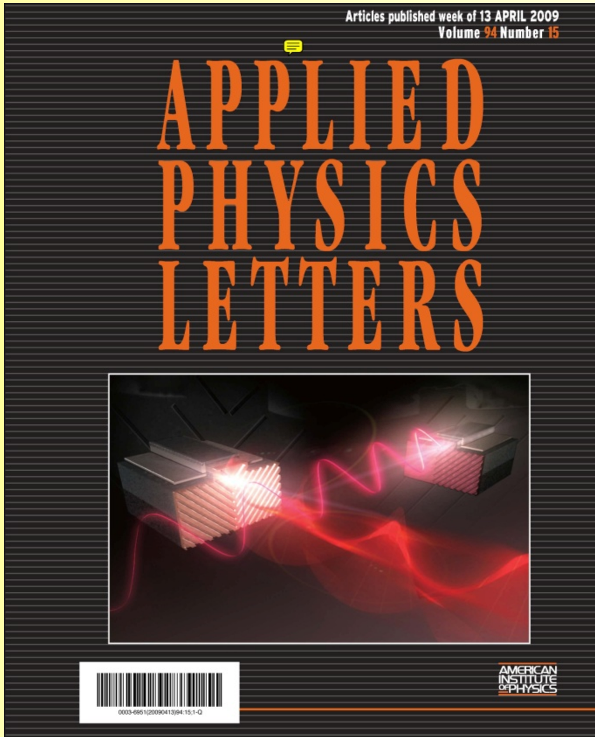
Conventional approaches of selecting and manipulating polarization:
- **absorptive or beam-splitting polarizers**
- **wave plates**

Light sources of a desired polarization are important for many applications:
- **satellite communication (dual-polarization)**
- **chemistry (detection of chiral molecules: protein, DNA, etc.)**
- **quantum cryptography (multiple polarization state)**

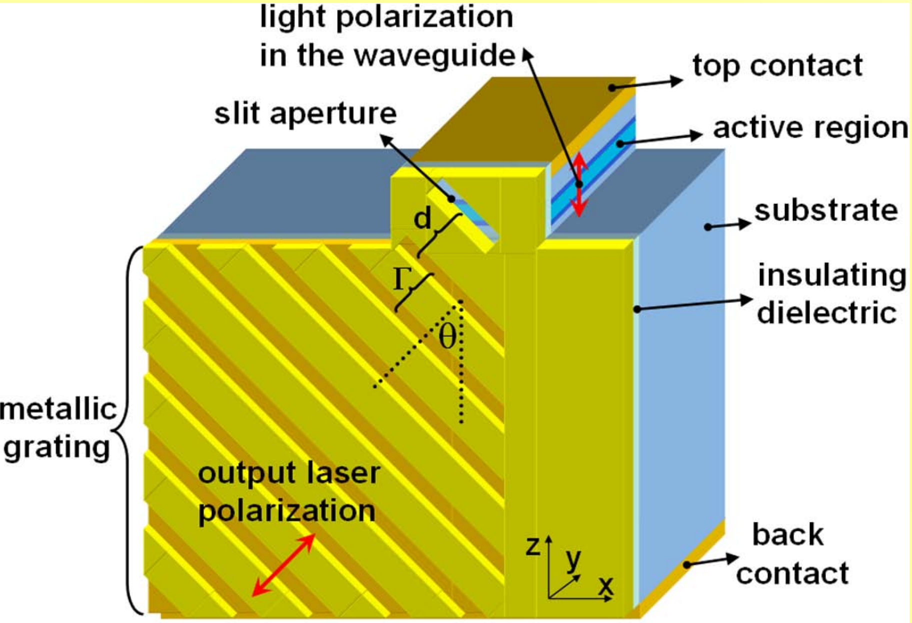
Circularly-polarized light sources: very difficult to achieve
Spin-based semiconductor lasers

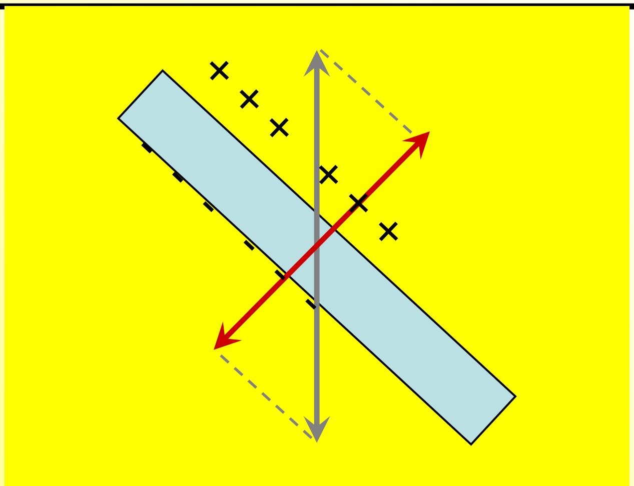
Plasmonics: a compact and technologically simpler approach for controlling the polarization state of light sources

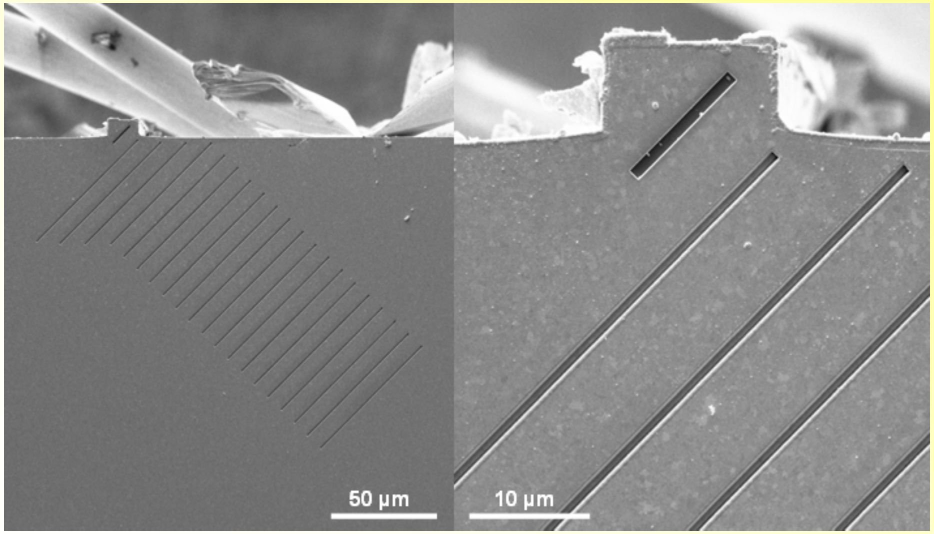
N. Yu et al. *Applied Phys. Lett.* April 13, 2009

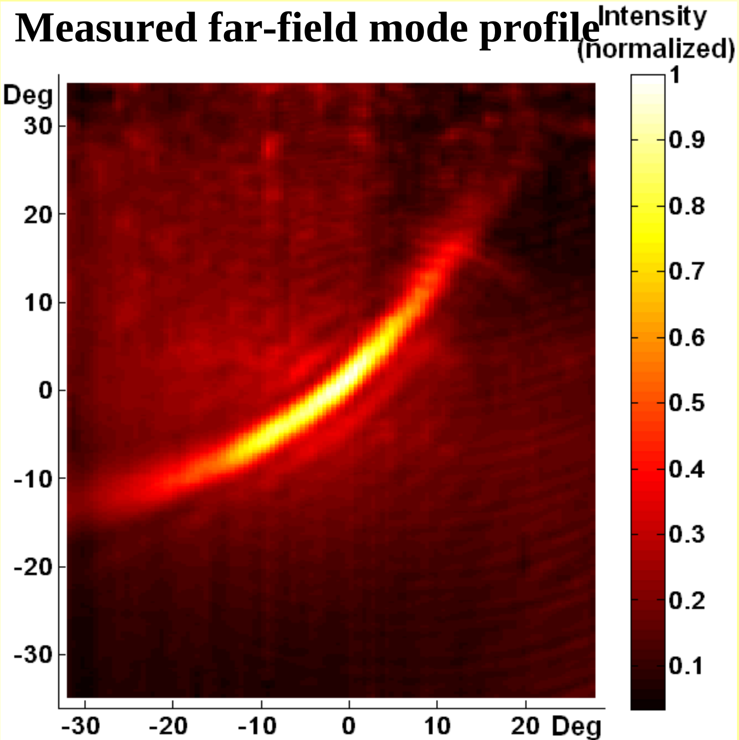


Polarization along θ Direction: Design, Fabrication, Imaging

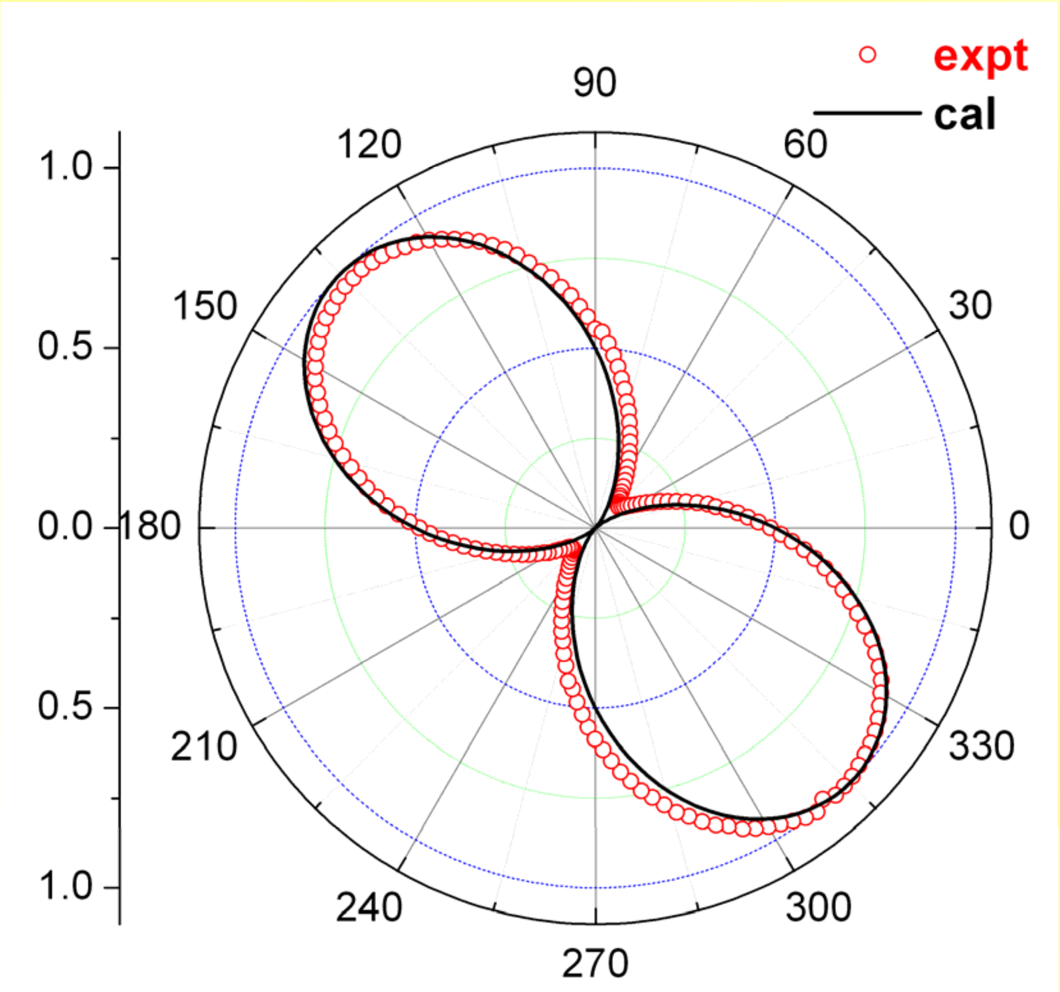


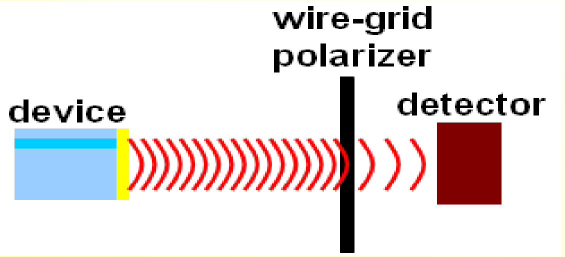


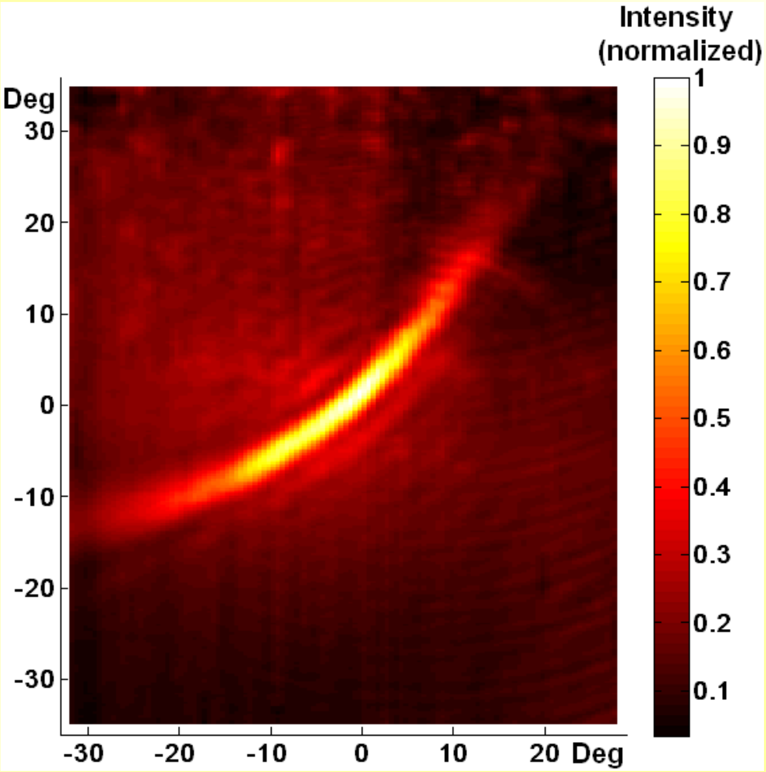




Experiments: Linear-Polarization Direction along 45^{o} Direction

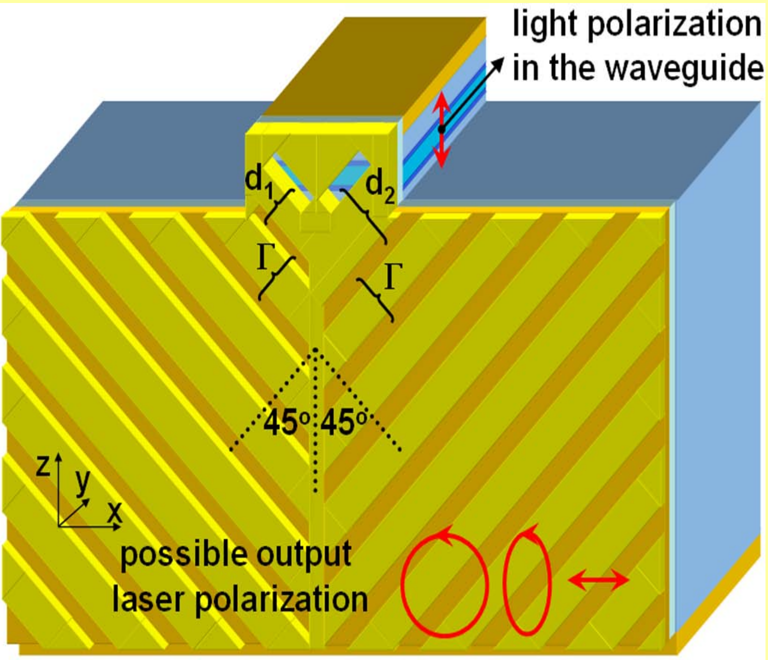


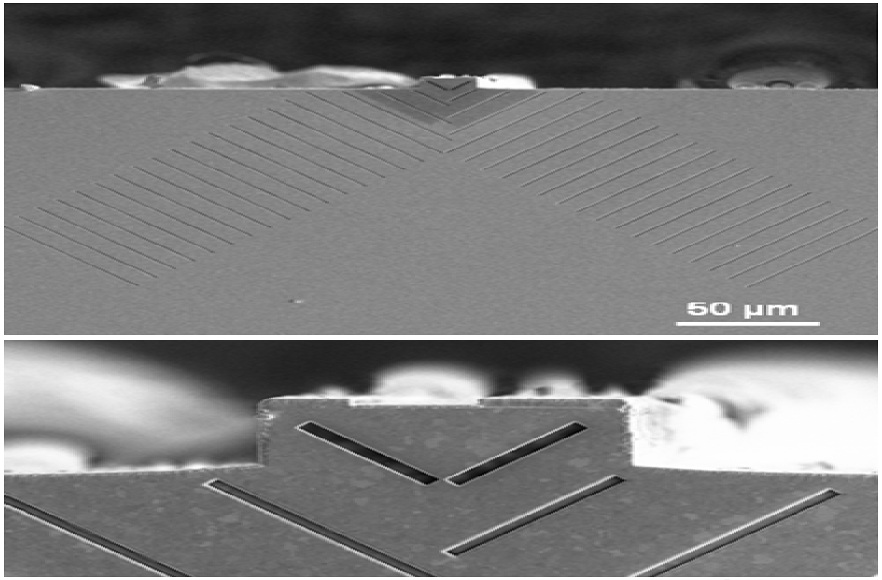




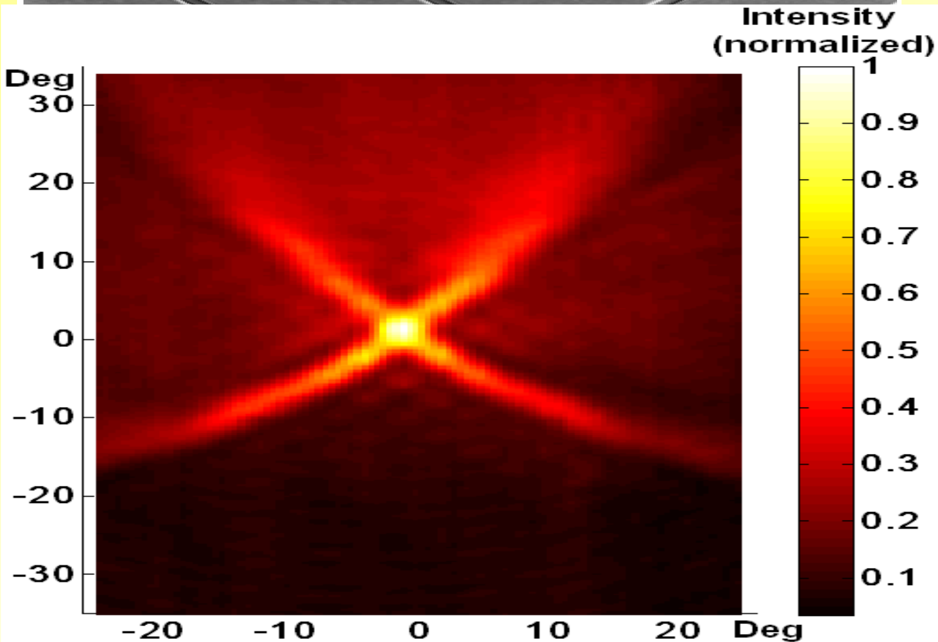
Nanfang Yu, et al., Appl. Phys. Lett., 94, 151101 (2009)

Plasmonic polarizer for circular polarization

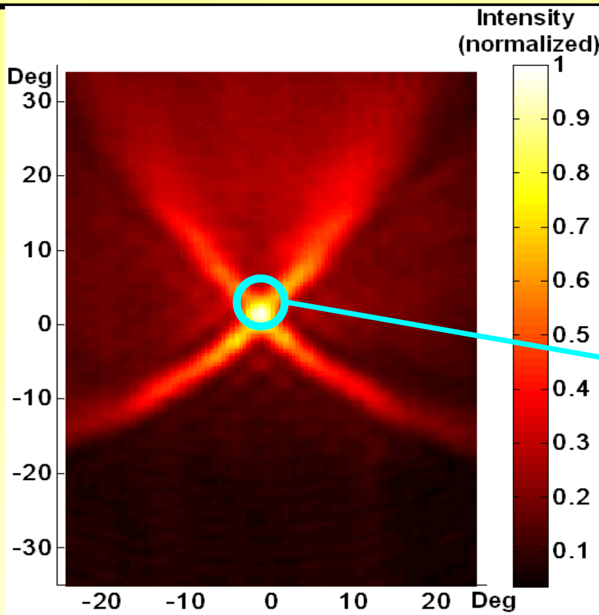


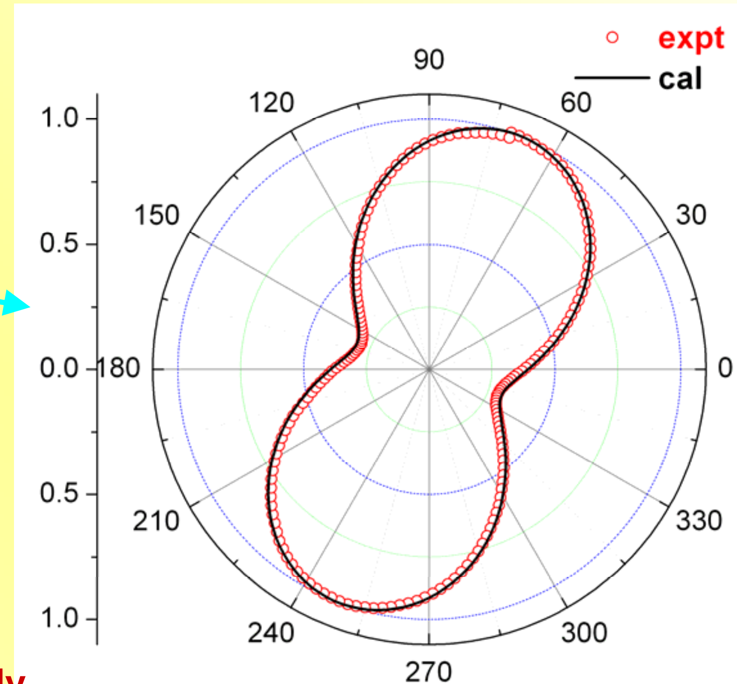


- d_1-d_2=$\lambda_{sp}/4$ → circular polarization
- d_1-d_2=$\lambda_{sp}/2$ → polarization in the horizontal direction

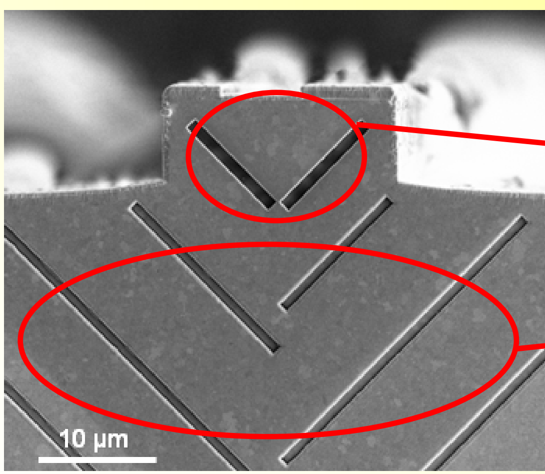


Experiments





$E_{circular}/E_{linear}$ =1.5



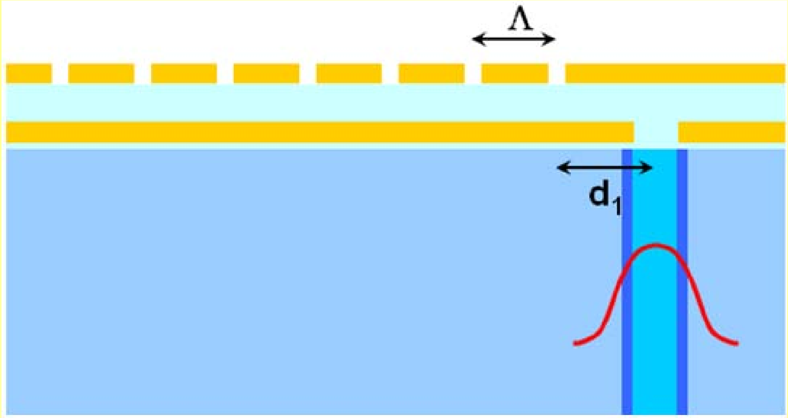
linearly-polarized component

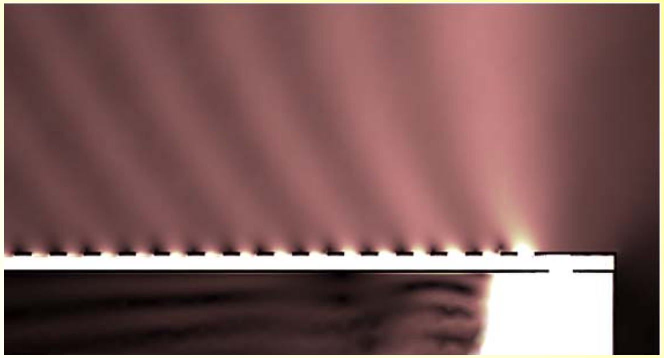
circularly-polarized component

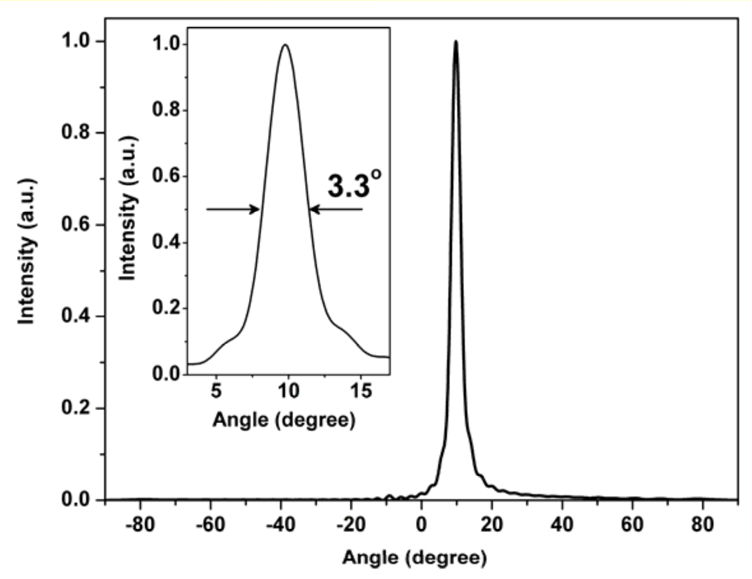
Nanfang Yu, et al., Appl. Phys. Lett., 94, 151101 (2009)

Future directions: improved designs

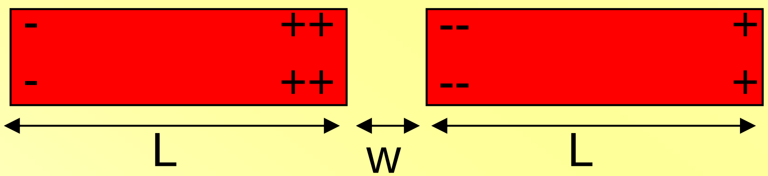
double-metal waveguide

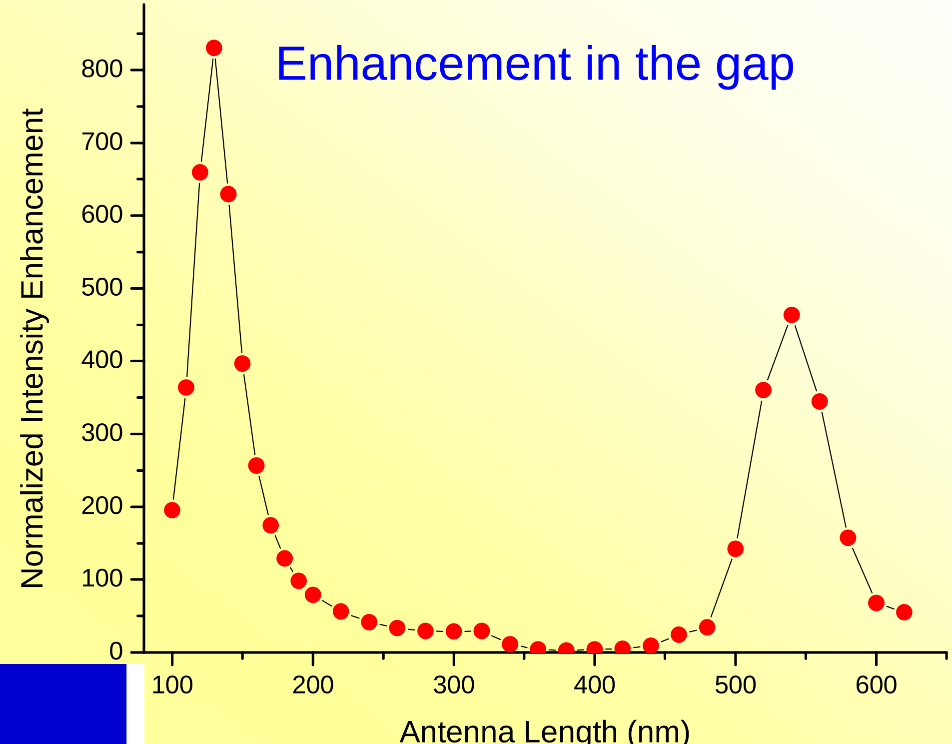




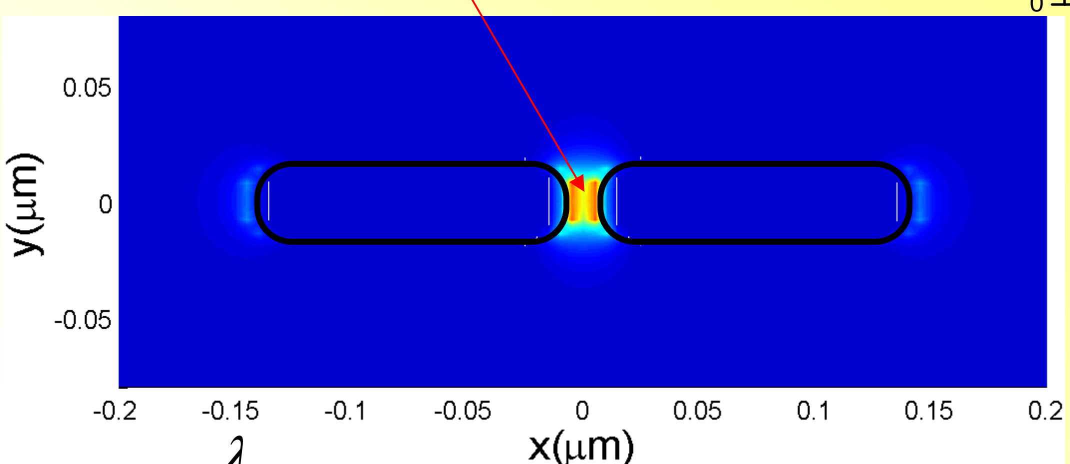


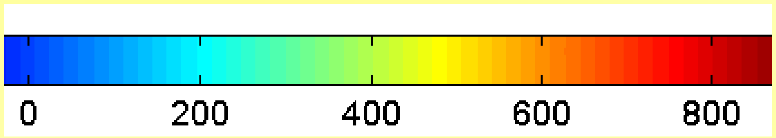
Resonant optical antenna for ultra-intense nanospots





~800 times the incident intensity!

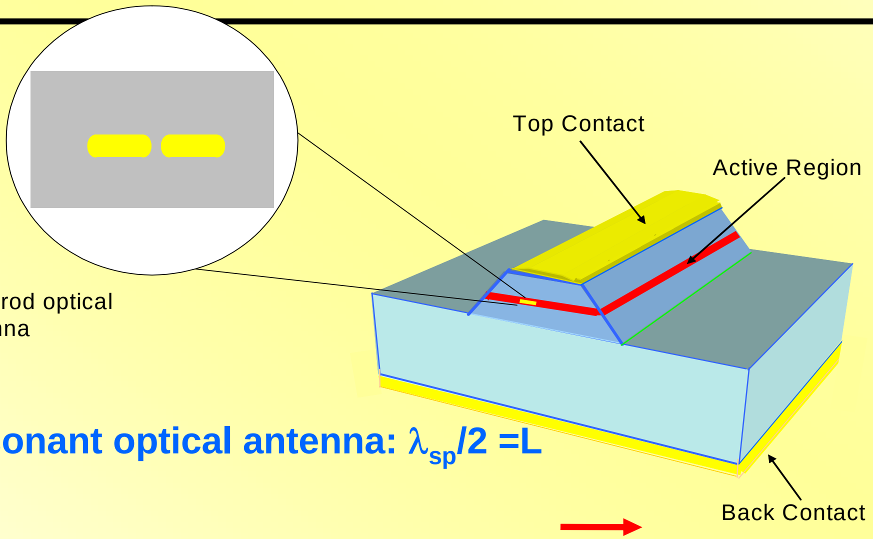




$$L = \frac{\lambda_{eff}}{2}$$

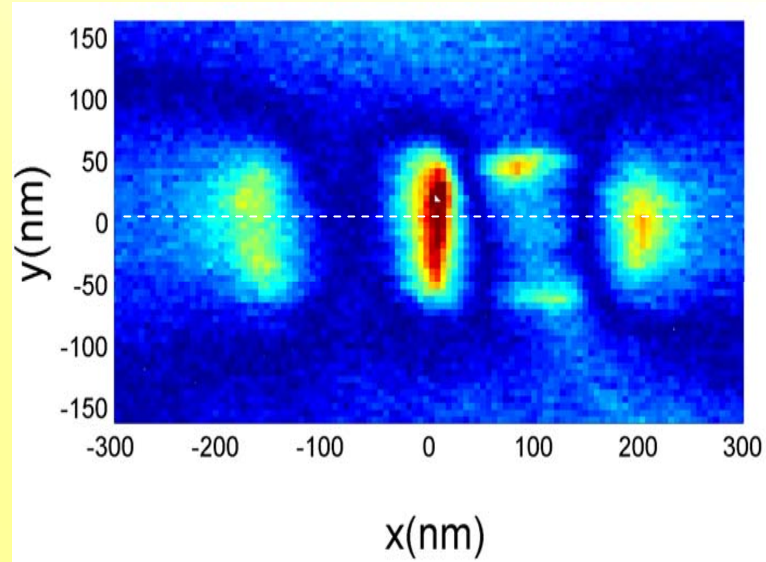
Plasmonic laser antennas: control of near field

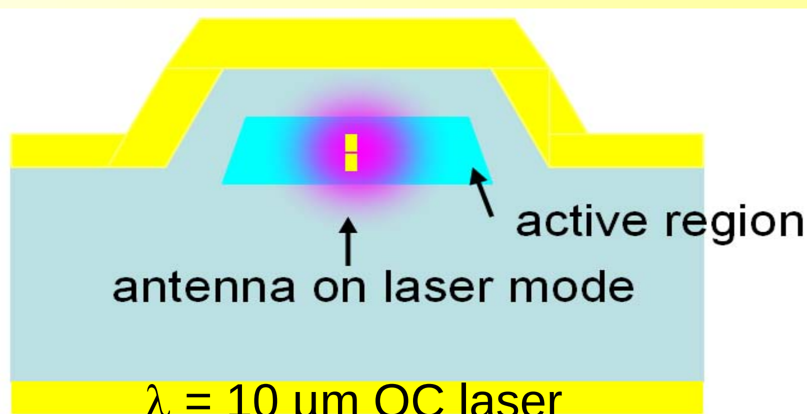
Creation of intense (0.1 – 1 GW/cm^2) nanoscale spots in the near field

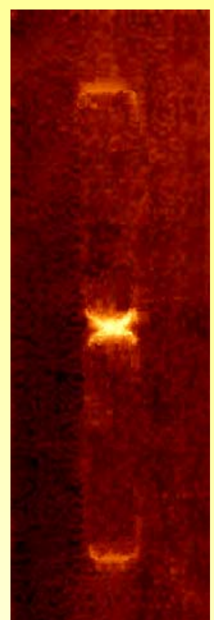


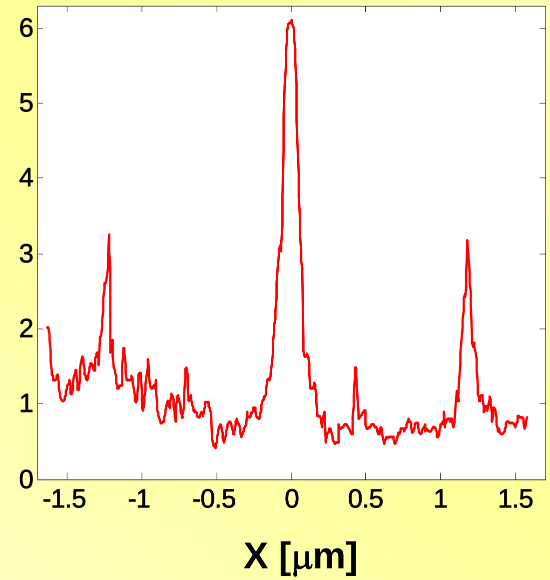
Resonant optical antenna: $\lambda_{sp}/2$ =L

λ = 0.8 μm laser diode









E. Cubukcu et al *Appl. Phys. Lett.* **89**, 093120 (2006)

N. Yu et al. *Appl.Phys. Lett.* **91**, 173113 (2007)

Applications

- Possible applications include
  - high-density optical data storage (up to 1 TB/inch^2)
  - high-resolution spatially resolved imaging and spectroscopy
  - nano-optical tweezers
  - SERS based sensors

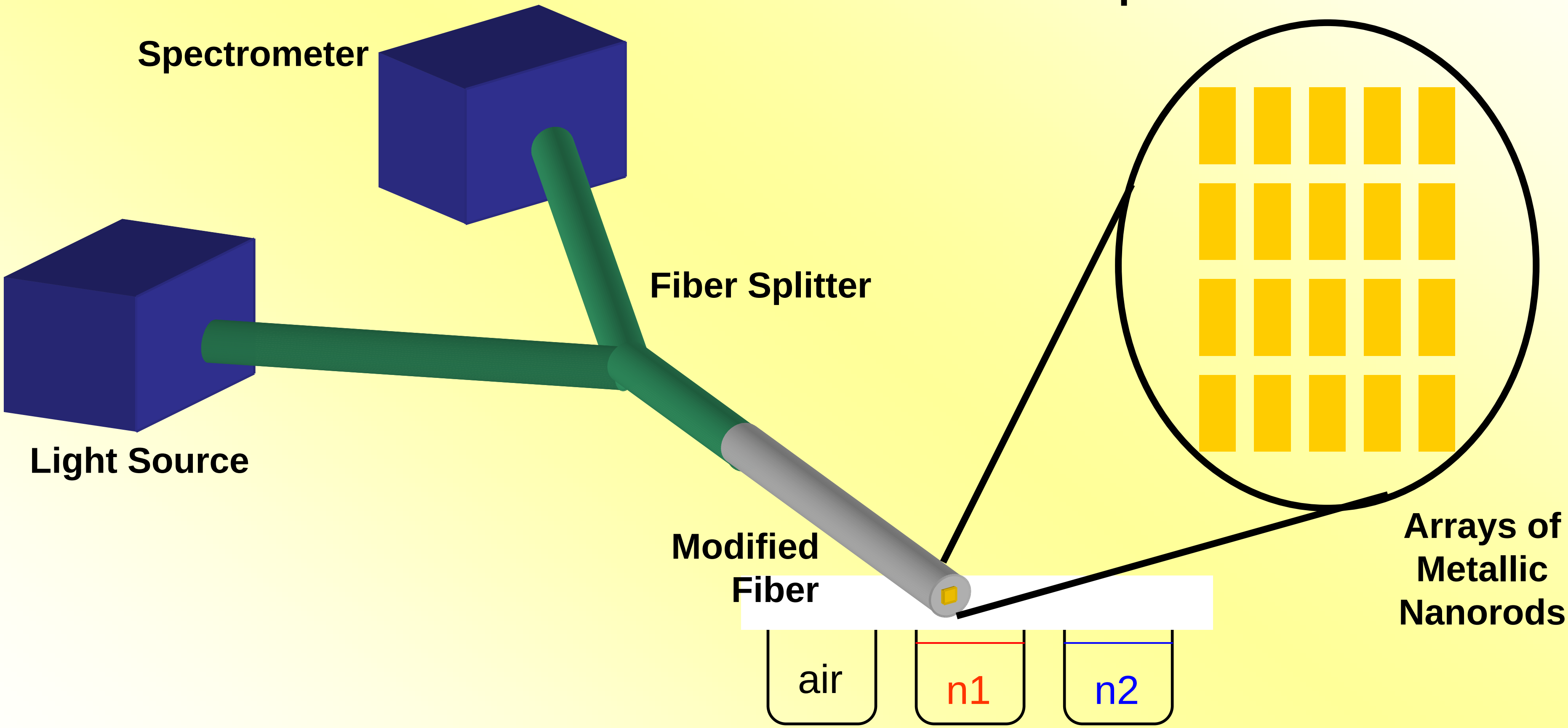
- Potential for circumventing the limitations of current near-field scanning optical microscopes and probes (e.g. low throughput)

- Applications such as manipulating and probing sub-cellular structures can take advantage of this nanoscale resolution to probe and quantify specific aspects of cell behavior and response to their environment

Plasmonic Optical Antenna Fiber Probe

E. Smythe et al. *Optics Express* **15**, 7439 (2007)

A new type of device consisting of arrays of coupled metallic optical antennas fabricated onto the facet of an optical fiber

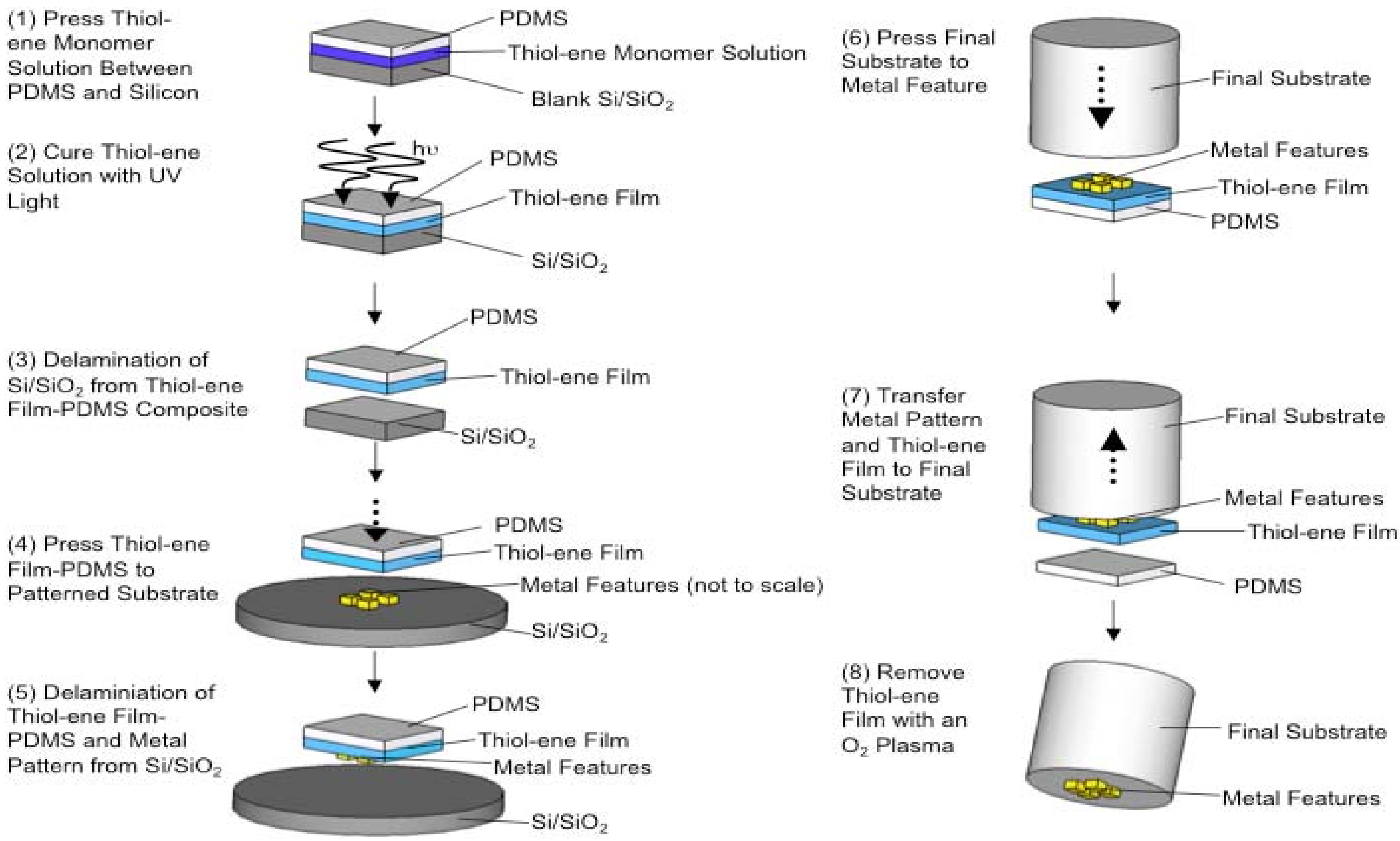


•detection/sensing of analytes in media By Surface Enhanced Raman Scattering

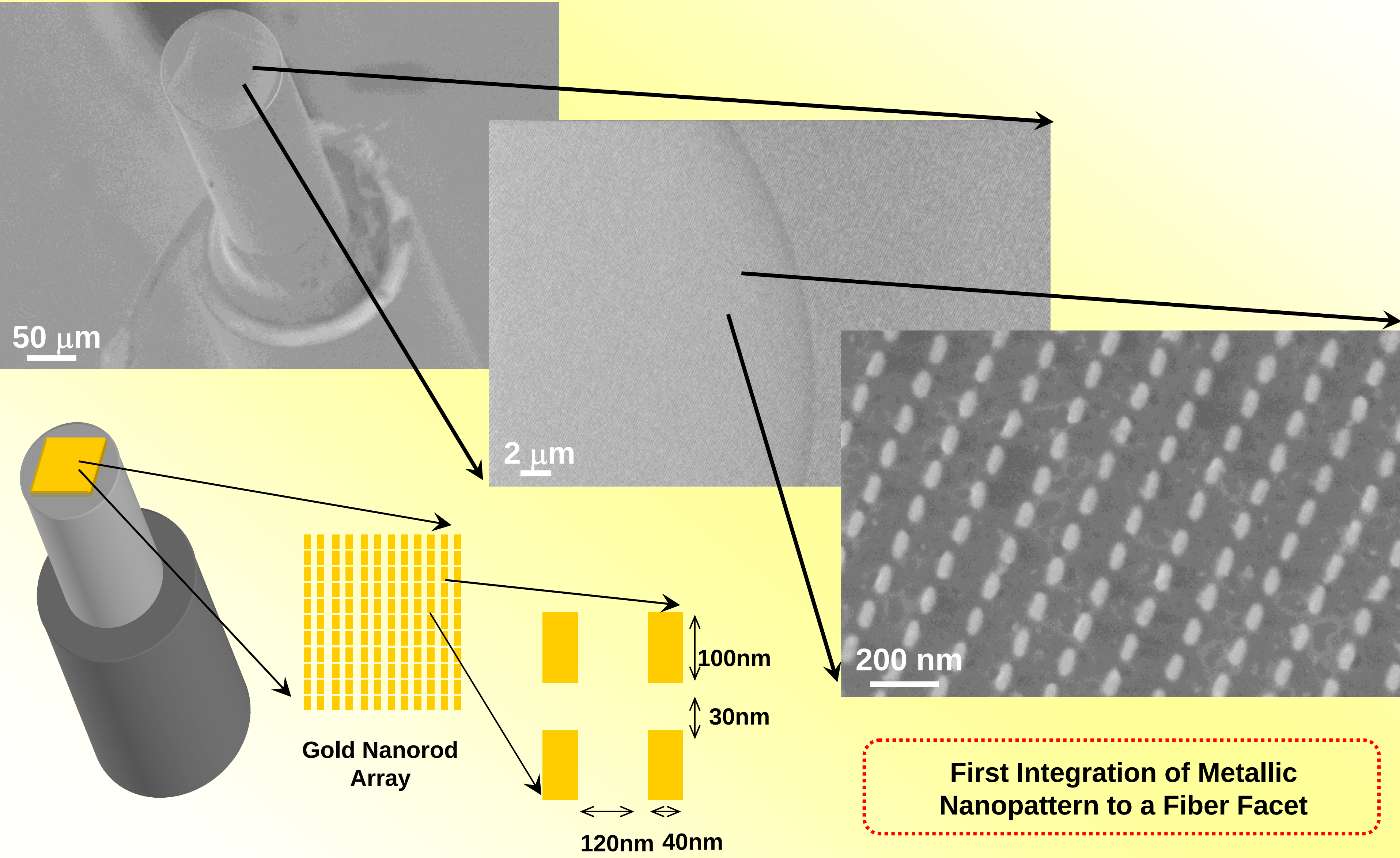
•array geometry allows for tuning of the surface plasmon resonance

Metallic Structure Transfer Technique (Decal Tranfer)

. J. Smythe et al. *ACS Nano* **3**, 59 (2009)



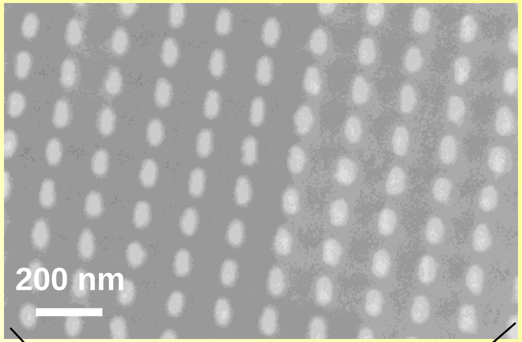
Gold Nanorod Arrays on Fiber Facets

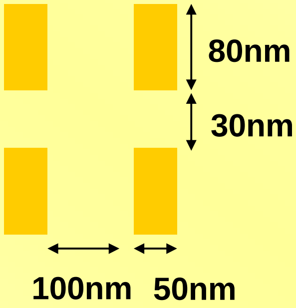


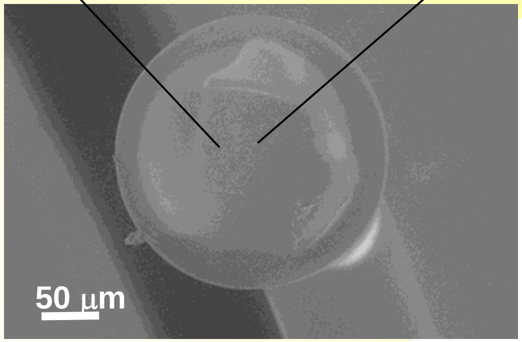
First Integration of Metallic Nanopattern to a Fiber Facet

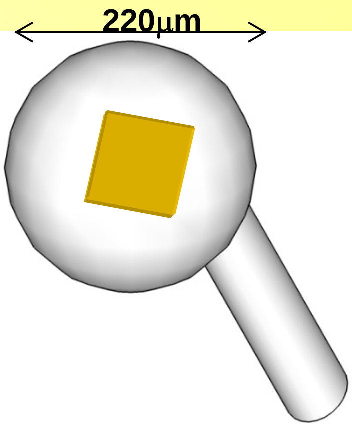
Unconventional Substrates and Arbitrary Patterns

Transfer of Gold Nanorod Arrays To Silica Microspheres







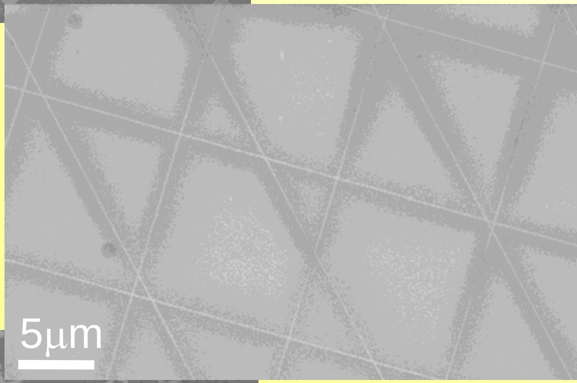


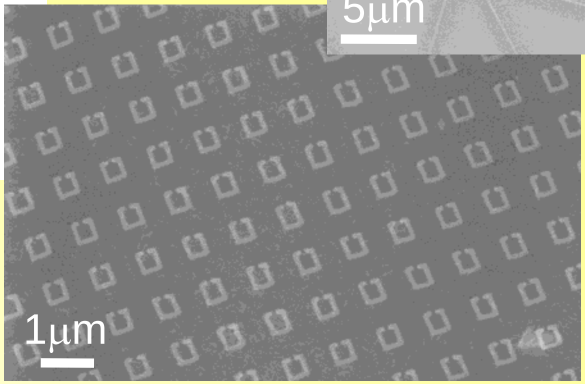
First Patterning of Silica Microspheres

Transfer of Arbitrary Metallic Patterns to Fiber

- 1μm x 1μm gold squares, 40nm tall, separated by 9μm and 1μm

- Lines: 100nm wide, 40nm tall lines, 100μm long.
- Written and transferred as a continuous pattern

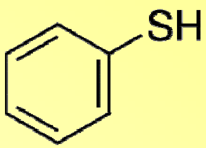


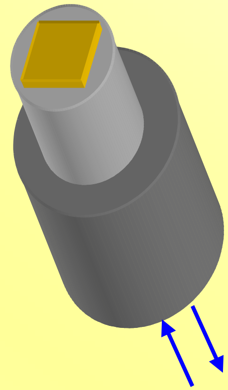


- Split-ring resonators: Sides 420nm, 40nm tall, line widths of 80nm, 60nm gap. Spaced by 480nm.

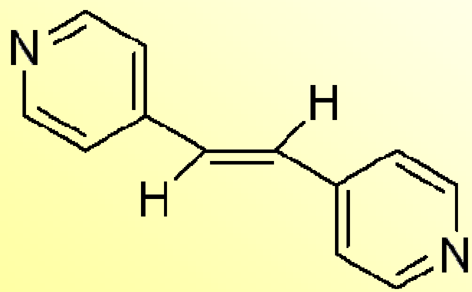
SERS Measurements with Fiber Antenna Arrays

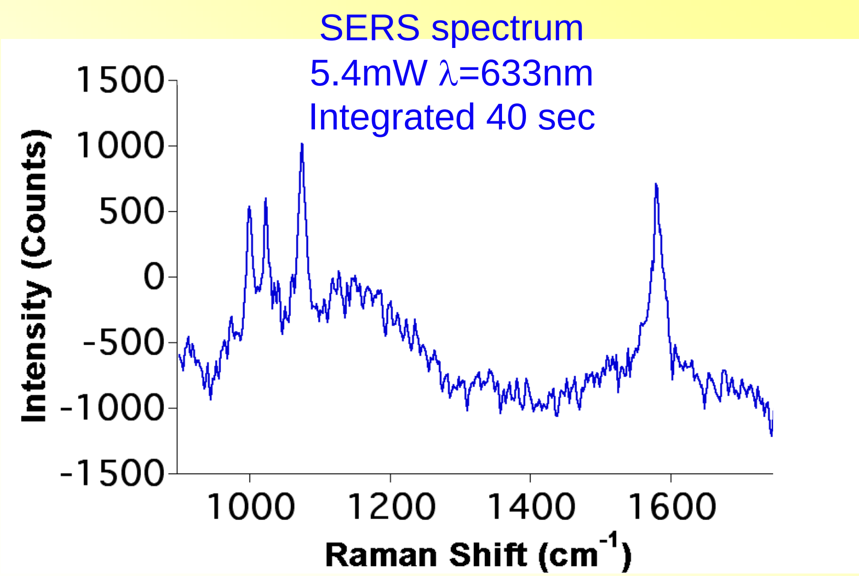
Benzenethiol (BT) solution

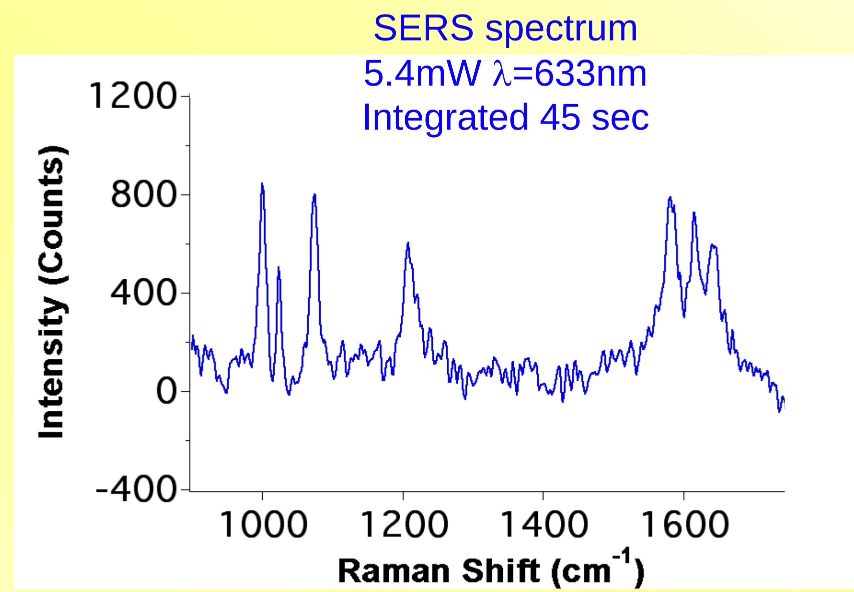




1,2-Bis(4-pyridyl)ethylene in methanol



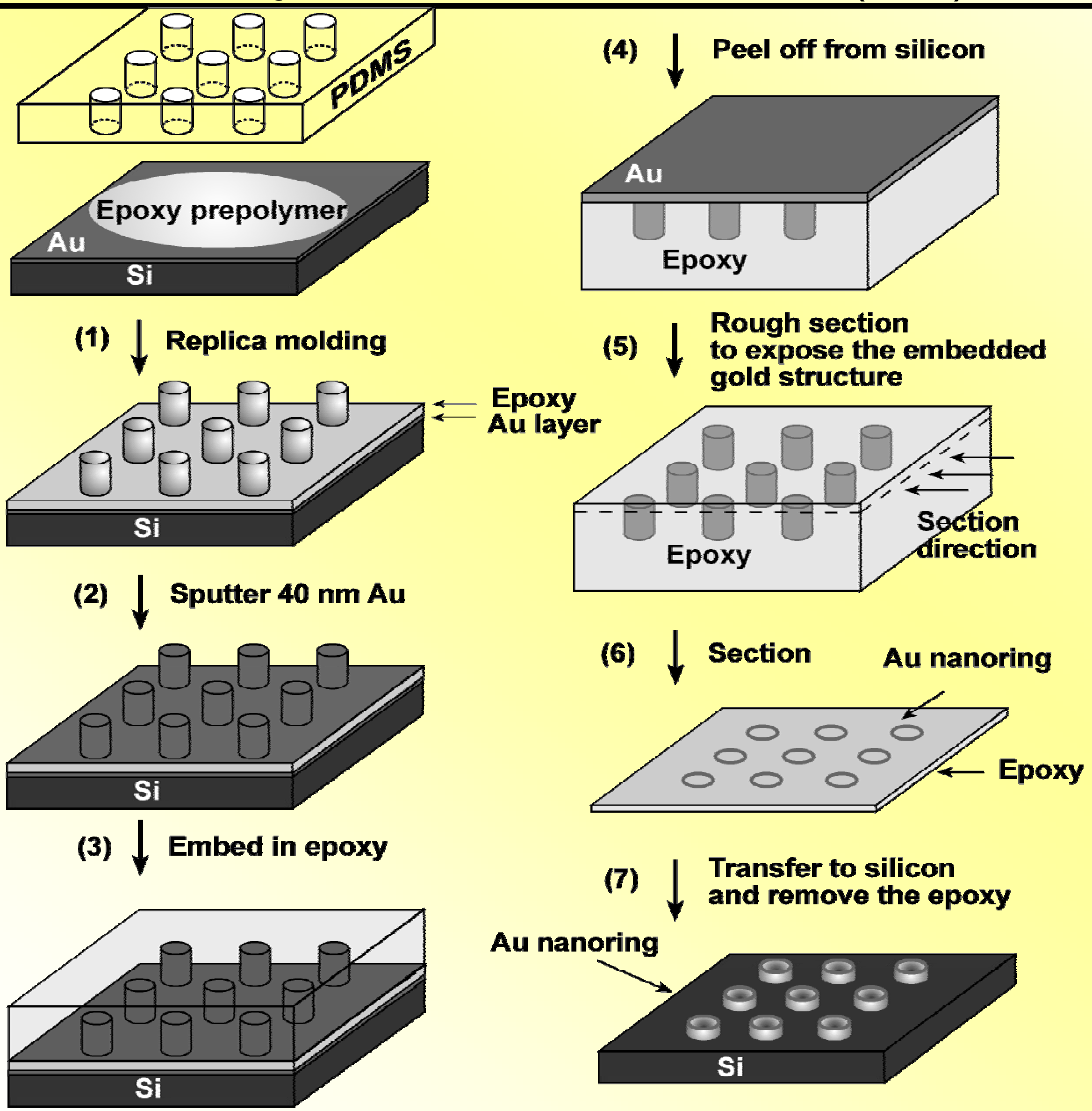




E. J. Smythe, et al., Nano Lett. 9, 1132 (2009)

Nanoskiving of Plasmonic Nanostructures

Q. Xu et al. *Nano Letters* **7**, 2800 (2007)

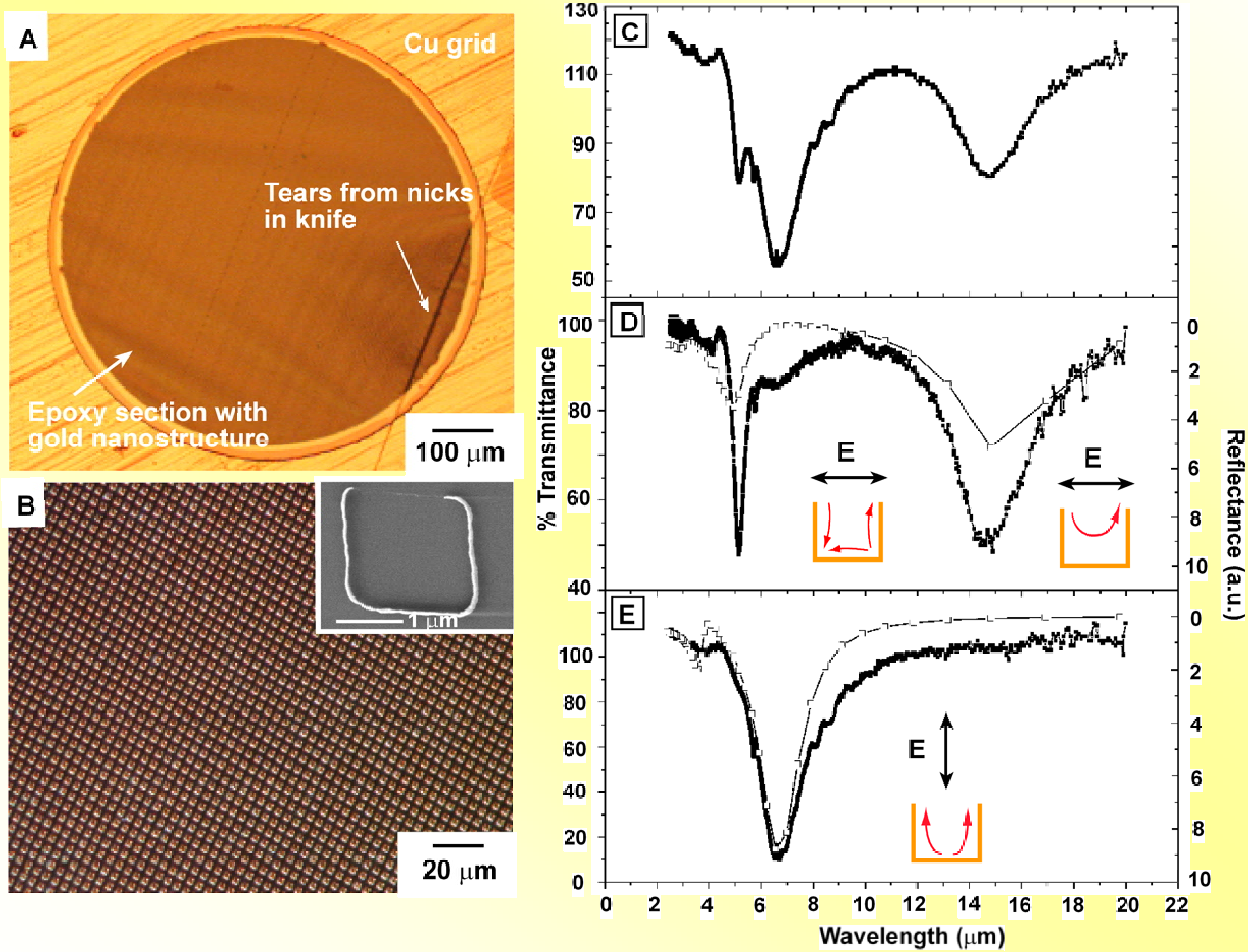


Jiming Bao
Qiaobing Xu
G. Whitesides
FC

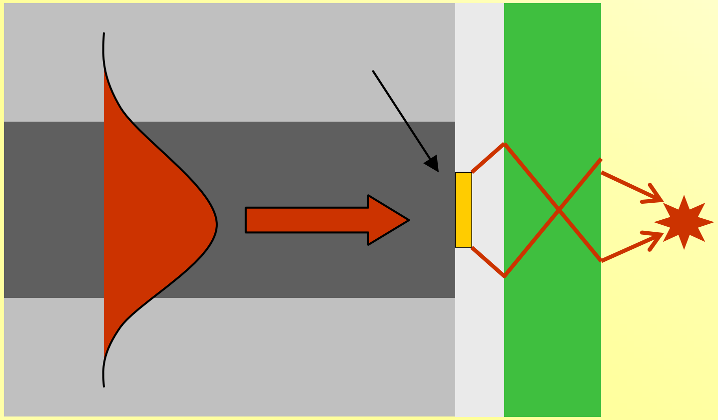
Large Area Patterning!

Transmission of Frequency Selective Surface

Q. Xu et al. *Nano Letters* **7**, 2800 (2007)



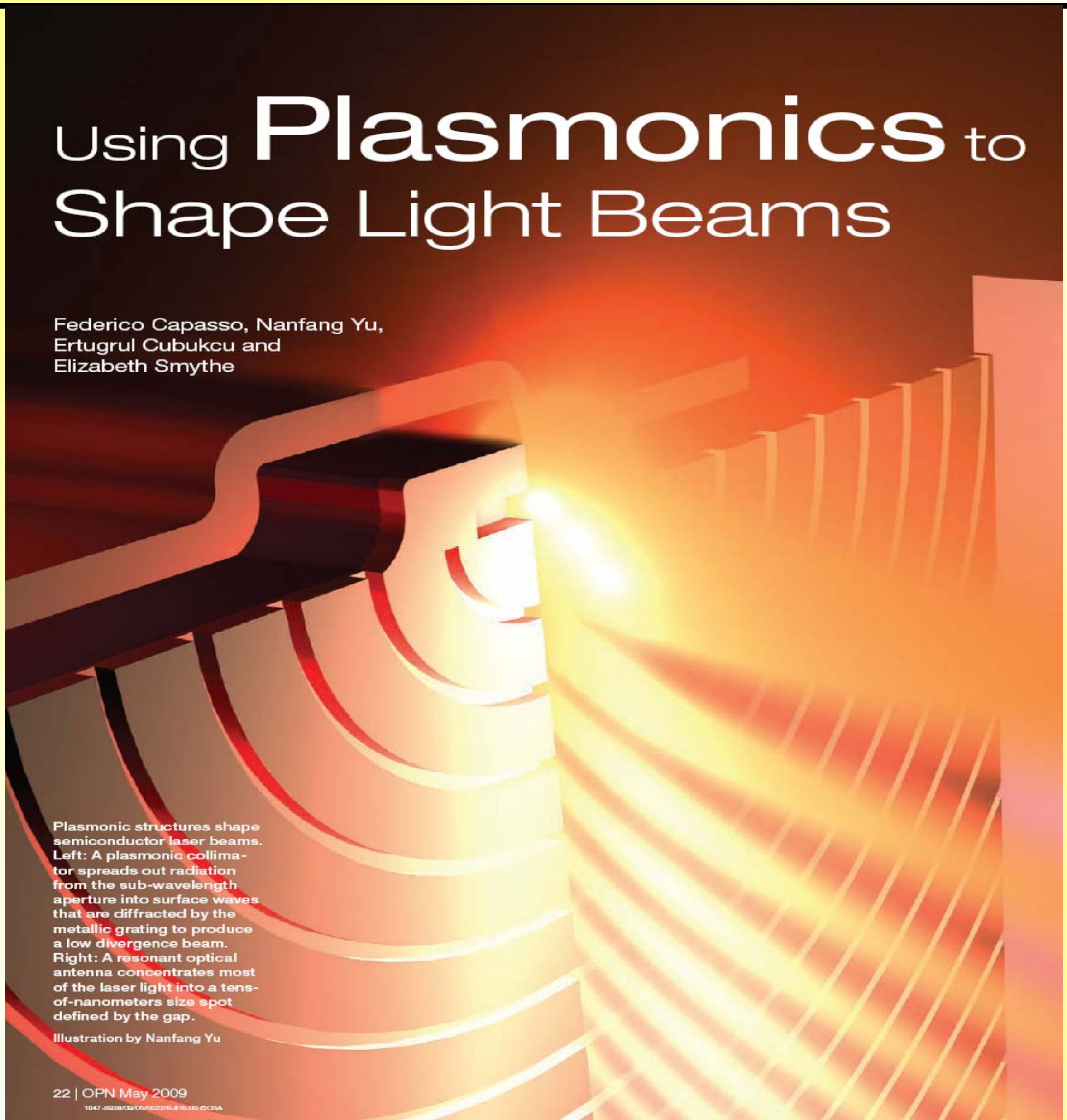
Design of laser facets with negative index metamaterials



Negative index metal-dielectric materials may be directly applied to a laser and fiber facets to get super-focusing of output light

New patterning techniques needed to create “Smart Surfaces”

Recent review: Optics and Photonic News (May 2009)



Using Plasmonics to Shape Light Beams

Federico Capasso, Nanfang Yu,
Ertugrul Cubukcu and
Elizabeth Smythe

Plasmonic structures shape semiconductor laser beams. Left: A plasmonic collimator spreads out radiation from the sub-wavelength aperture into surface waves that are diffracted by the metallic grating to produce a low divergence beam. Right: A resonant optical antenna concentrates most of the laser light into a tens-of-nanometers size spot defined by the gap.

Illustration by Nanfang Yu