BERKELEY LAB

Lawrence Berkeley National Laboratory

Plasmon lasers

---Science and technology of a nanoscale coherent light source

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凝聚态物理-北京大学论坛 2013/03/28

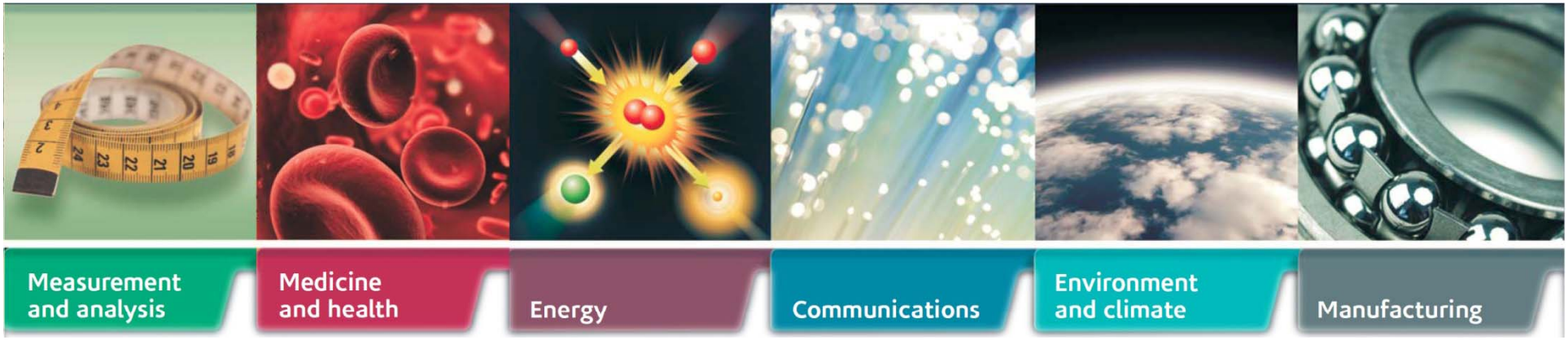
Laser Innovation: It Makes Our Life Even Brighter

1964 Construction of Lasers

1971 holographic

1981 laser spectroscopy

1997 laser cooling



1999 Monitoring chemical reactions using fs spectroscopy

2000 information and communication technology

2001 BEC

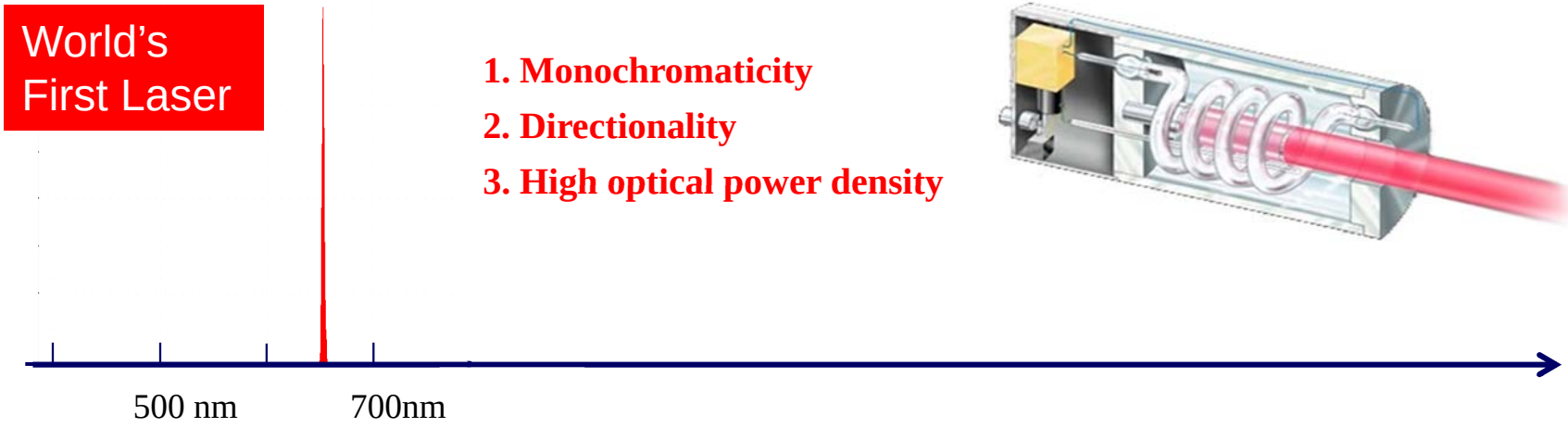
2005 laser-based precision spectroscopy

2009 fibers for optical communication

2012 measuring individual quantum systems

Why lasers are so special?

World's First Laser



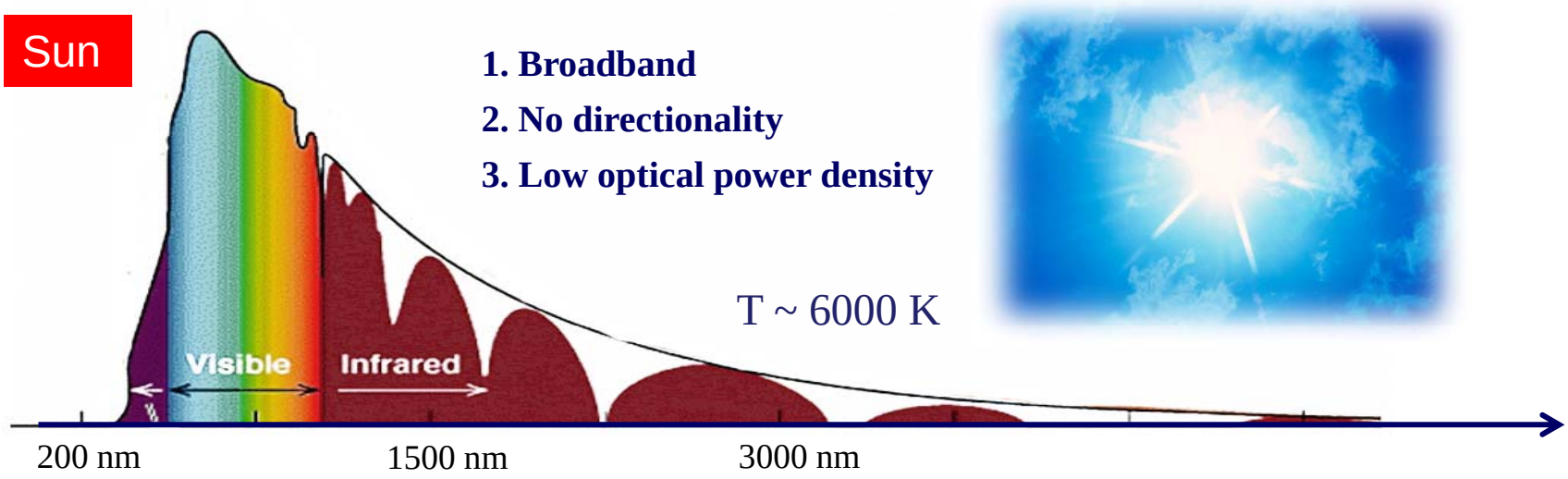
1. Monochromaticity

2. Directionality

3. High optical power density

To reach the same power level of a **1mW laser** with a linewidth of **GHz**
A thermal light need to be **heated to 10^{11} K**!

Sun



1. Broadband

2. No directionality

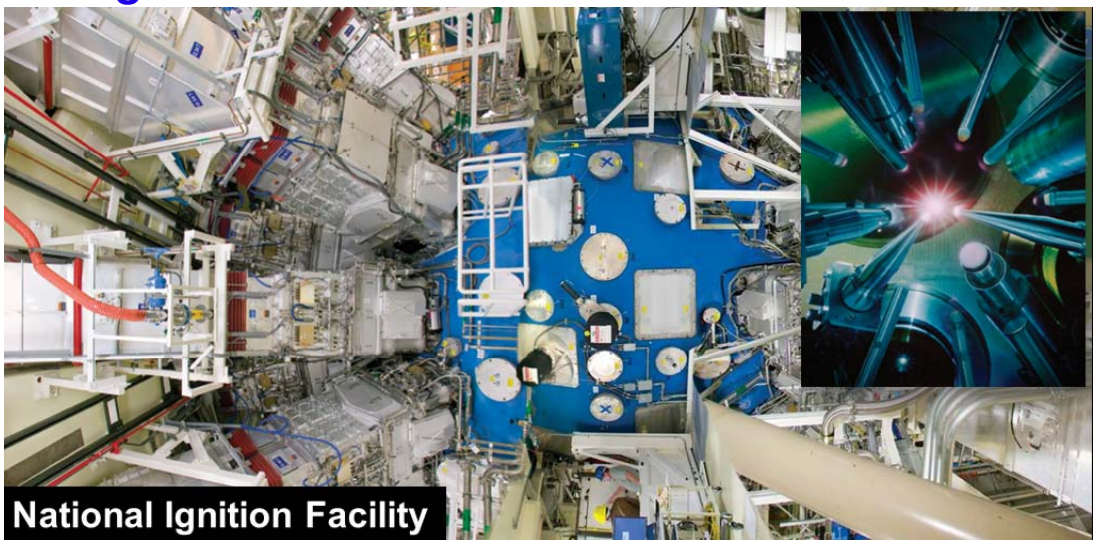
3. Low optical power density

T ~ 6000 K

The scale of a laser

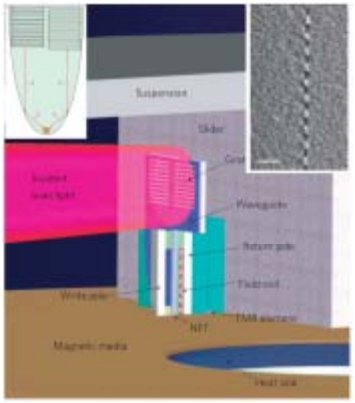
How Big a Laser can be?

Bring Star Power To Earth

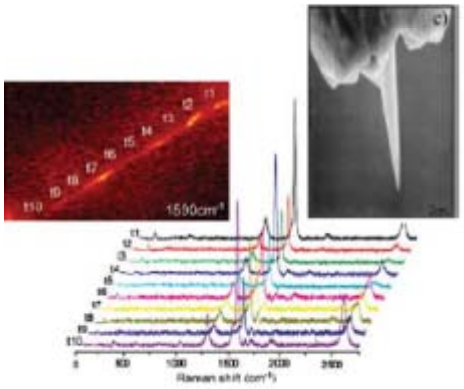


How Small a Laser can be?

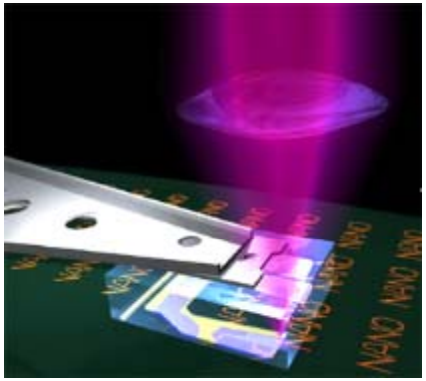
Ultra-dense Data storage



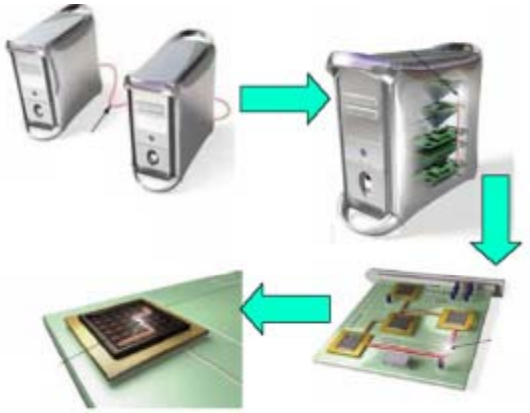
Nanoscopy, Sensing



Nanolithography

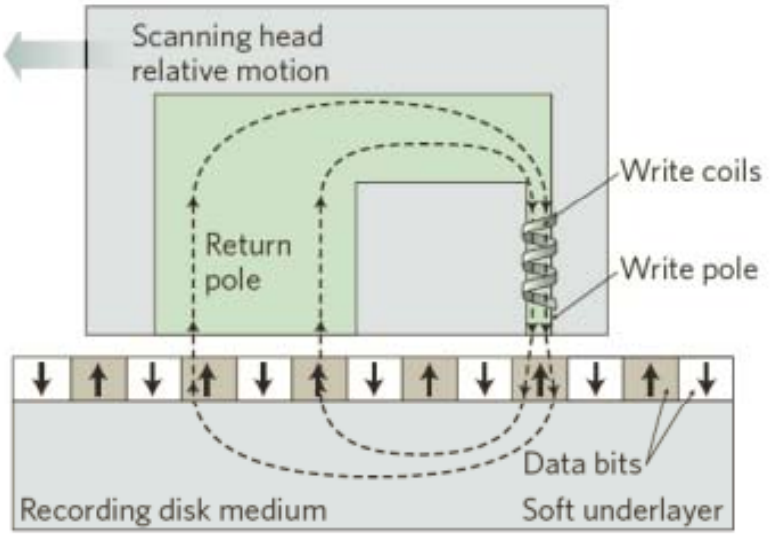


On-chip optical interconnector



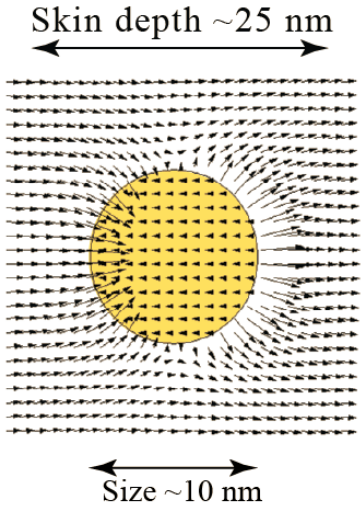
HAMR, A technology for the era of ‘big data’

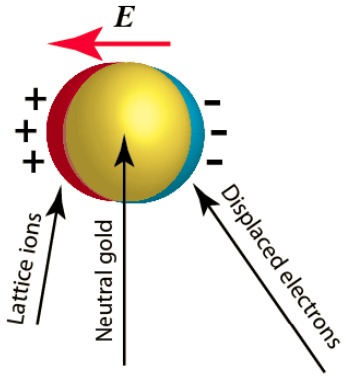
An example: HAMR, A technology for the era of 'big data'



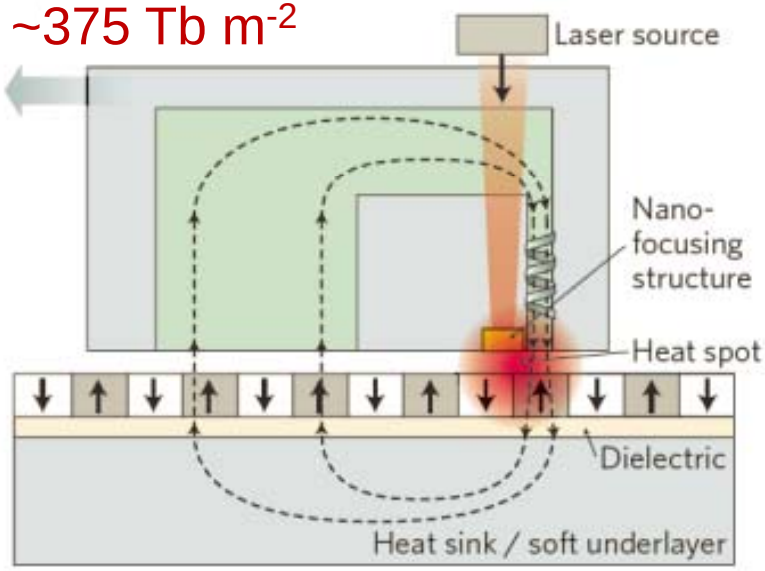
HAMR: Heat-Assisted Magnetic Recording

Storage density ~375 Tb m^{-2}



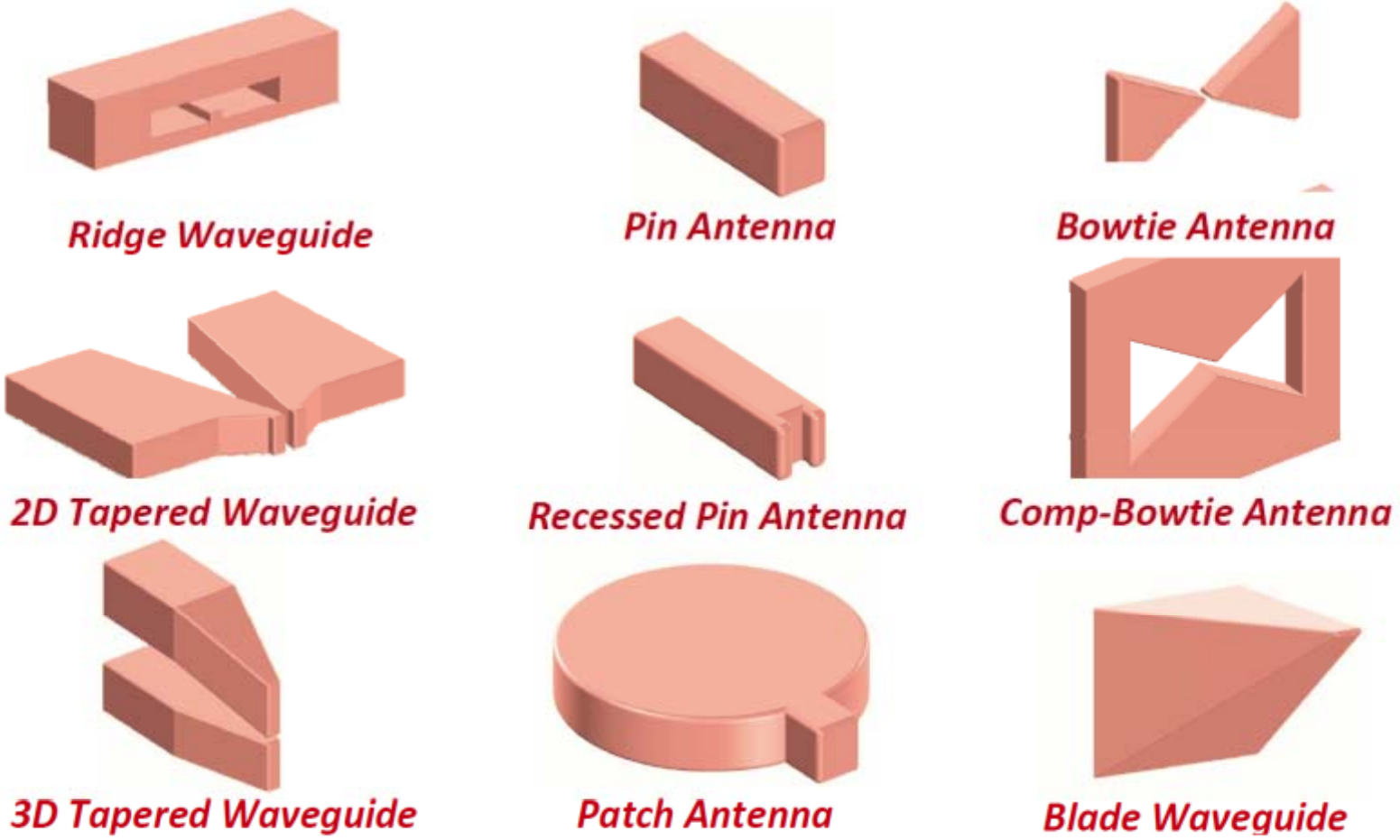


Surface Plasmons



Plasmonic structure for nanofocusing

- Typical Energy Efficiency 1~2%



Scaling down of lasers, diffraction and loss limits

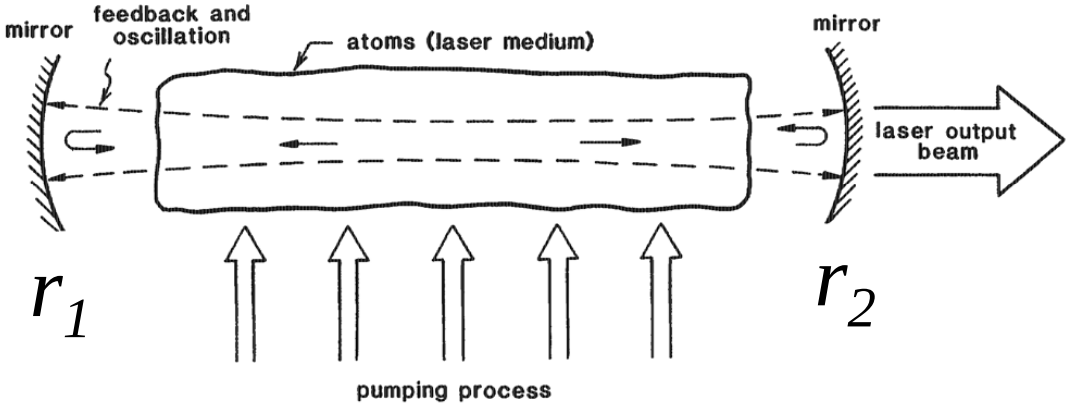


FIGURE 1.1
Elements of a typical laser oscillator.

Essential Elements of a Laser

- a gain medium
- a pump process
- a cavity

Anthony E. Siegman, *Lasers*

Lasing condition: $r_1 r_2 \exp\{2ikL\} E_0 = E_0$

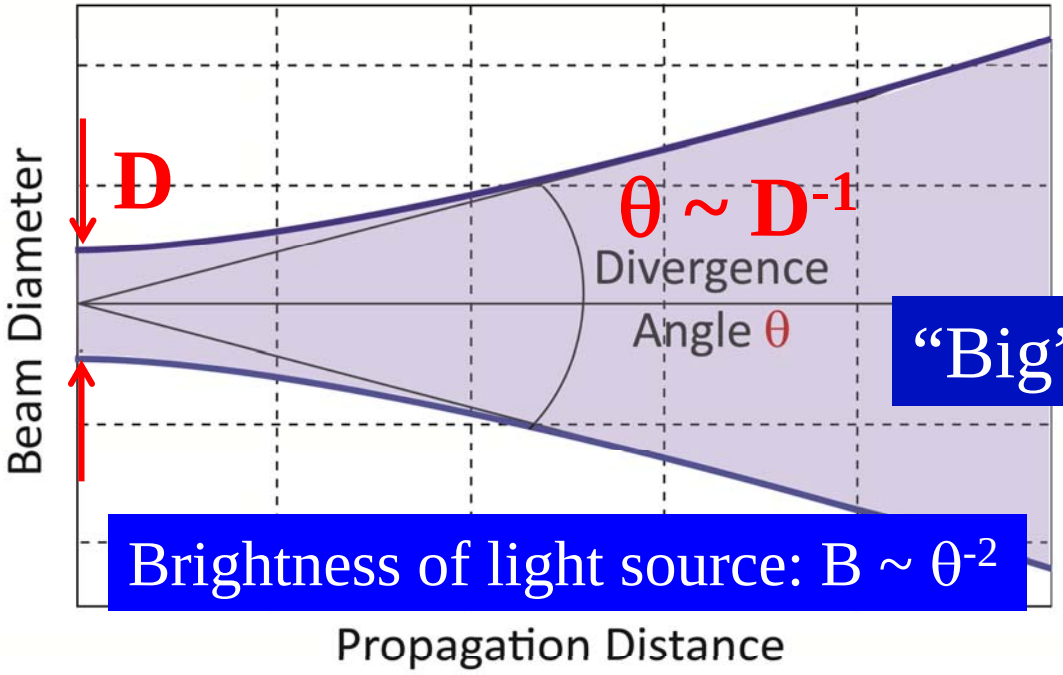
$$L = \frac{\lambda}{2n_{\text{eff}}} m, \quad m = 1, 2, \ldots,$$ Diffraction limit

$$L = \frac{-\ln(r_1 r_2)}{G_{\text{m}}}$$ Loss limit

Mirror loss $\alpha_e = \frac{1}{L} \ln \frac{1}{R_e}$ L=1μm, R_e=20%, α_e ~1.6 ×10^4/cm

The smaller, the higher loss

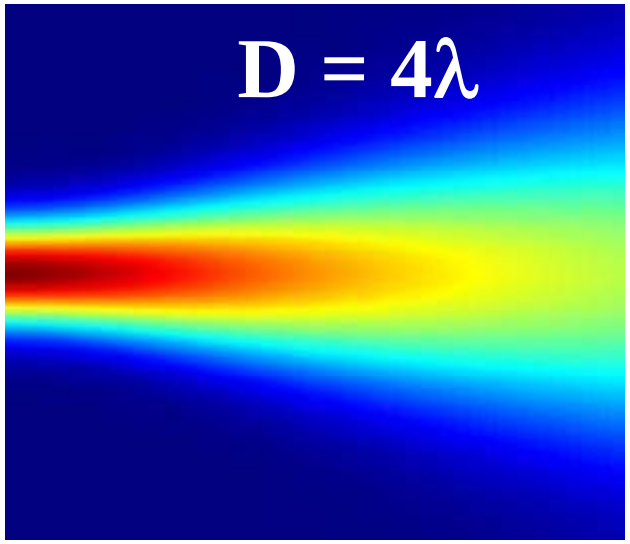
Beam divergence, collection efficiency limits



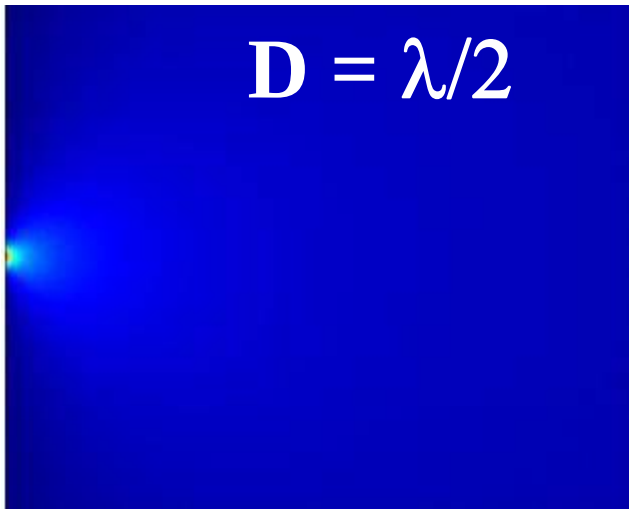
Brightness of light source: $B \sim \theta^{-2}$

Smaller, stronger divergence
Smaller, less brightness

"Big" laser



Nanolaser



1. Monochromaticity

2. Directionality ✗

3. High optical power density ✗

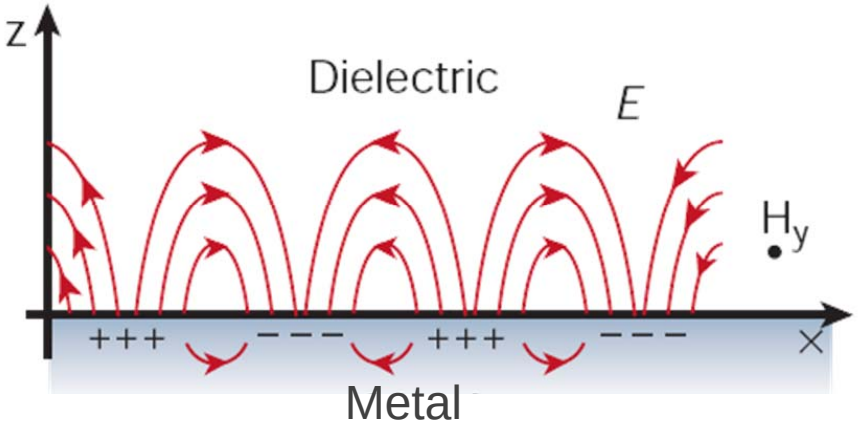
Plasmon lasers

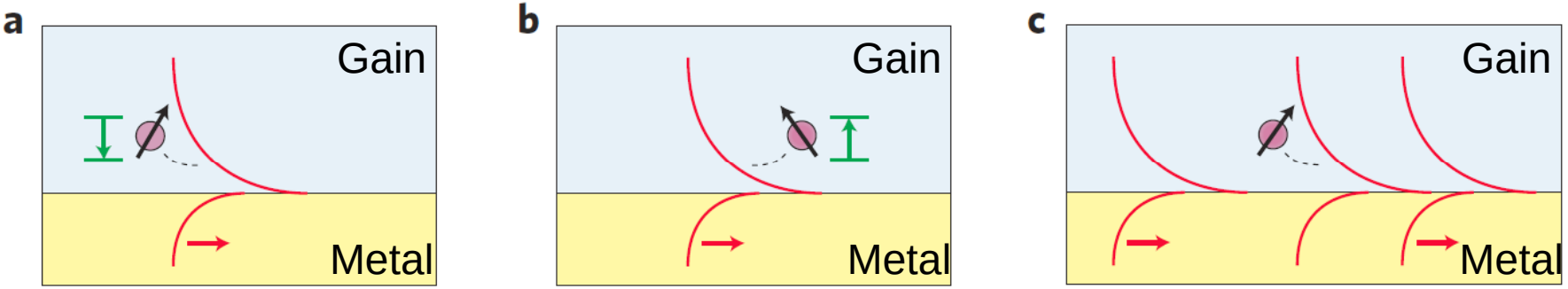
Laser: **L**ightwave **A**mplification by **S**timulated **E**mission of **R**adiation

Plasmon Laser: Surface **P**lasmon **A**mplification by **S**timulated **E**mission of **R**adiation

--- Amplify surface plasmons instead of light

- ☆ Ultra-Small Physical Size & Mode Volume
- ☆ Ultra-Fast Modulation Speed
- ☆ Strong light-matter interaction

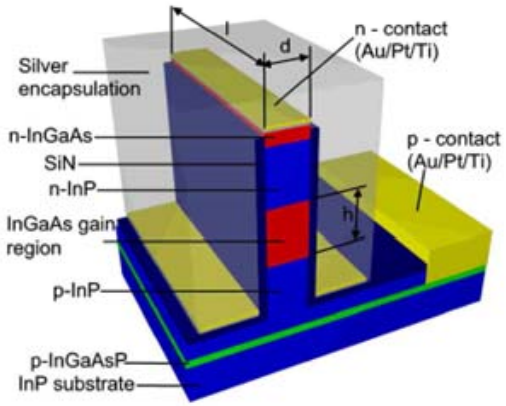




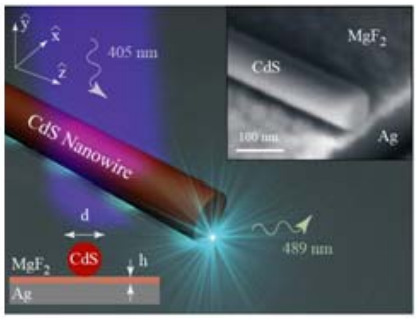
Spontaneous emission **Absorption** **Stimulated emission**

D. Bergerman & M. Stockman *Physical Review Letters* **90** 027402 (2003)
R. M. Ma et al. *Laser & Photonics Reviews* 7 (2013) 1

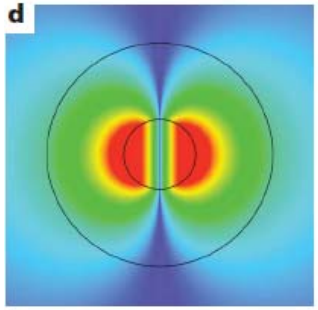
Plasmon lasers



Optical Express
17 (2009) 11107

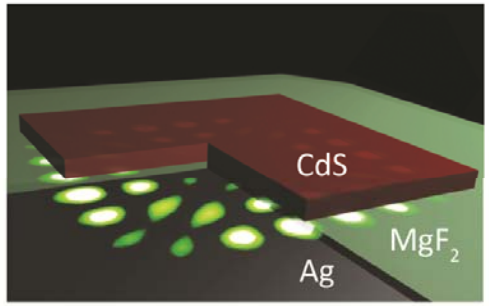


Nature
461 (2009) 629

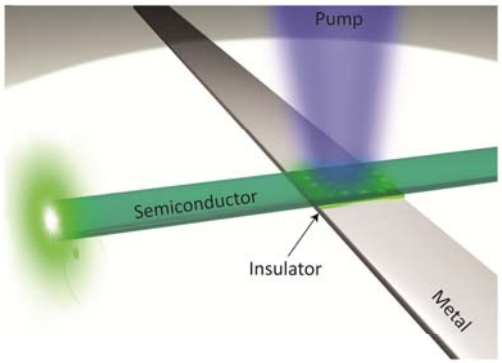


Nature
460 (2009) 1110

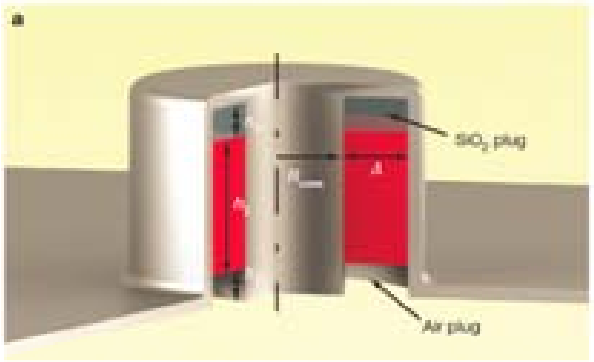
Solid state RT



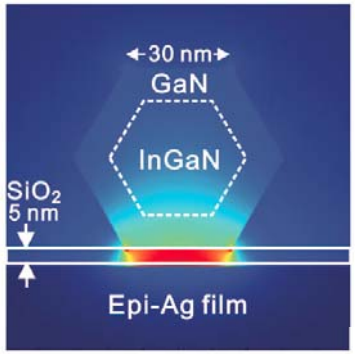
Nature Materials
10 (2011) 110



Nano Letters 12 (2012) 5396



Nature 482 (2012) 204



Science 337 (2012) 450

Outline

- 1. Nanowire plasmon laser
- 2. Room temperature square plasmon lasers
- 3. Directionally emitted WEB plasmon laser
- 4. WEB plasmon laser circuit
- 5. Conclusions

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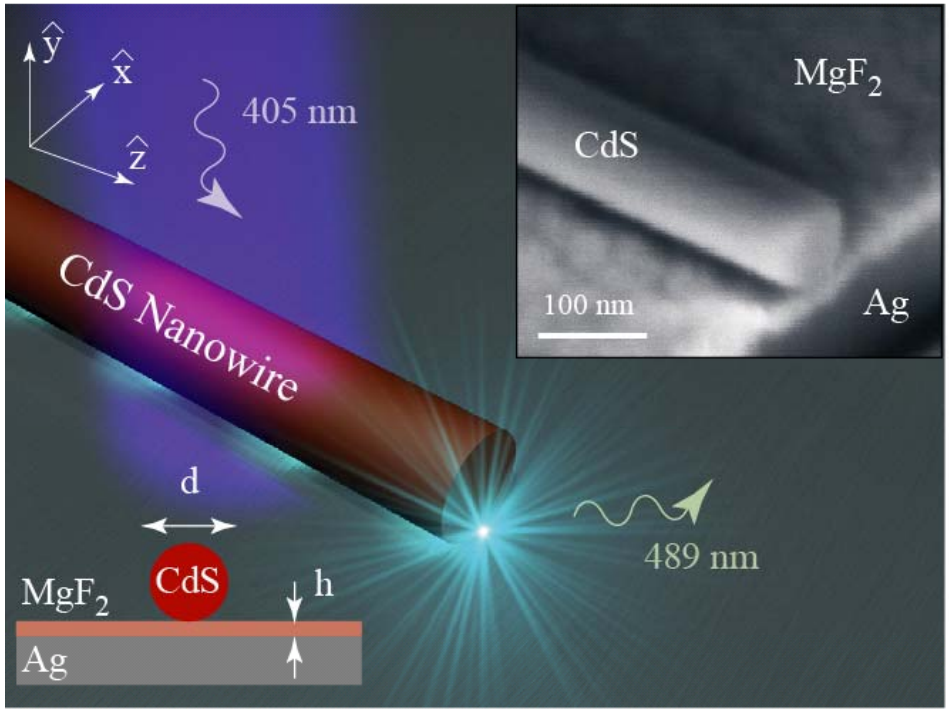
Nanowire plasmon laser

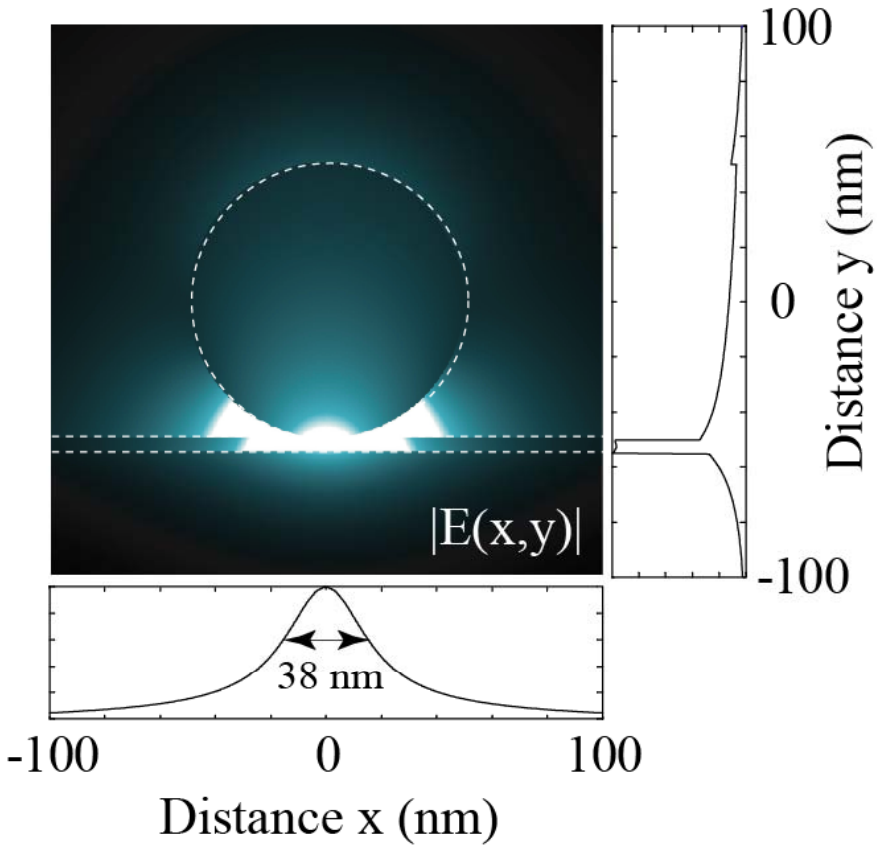
Key Features

- **First plasmon laser**
- **$\lambda^2/400$ optical confinement**

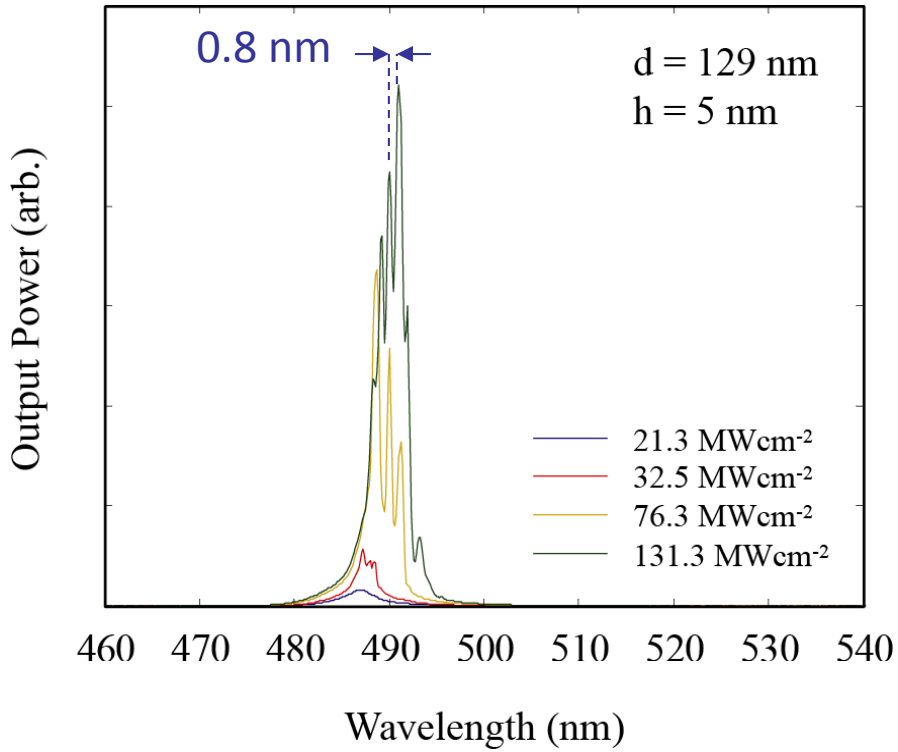
Oulton, Sorger, Zentgraf, **Ma**, *et al. Nature 461 (2009) 629*

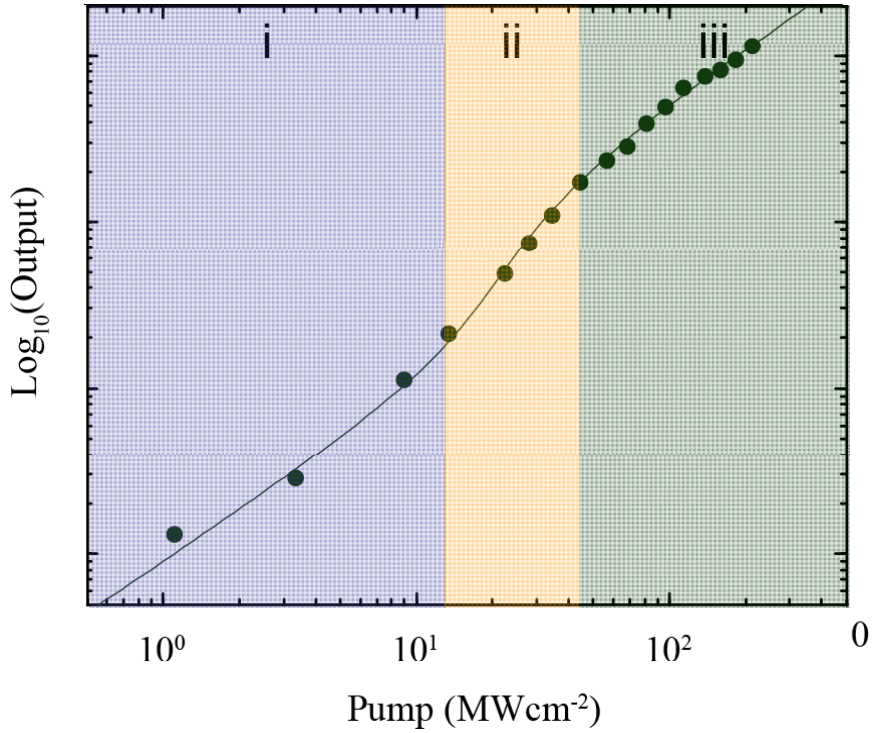
Configuration of nanowire plasmon laser





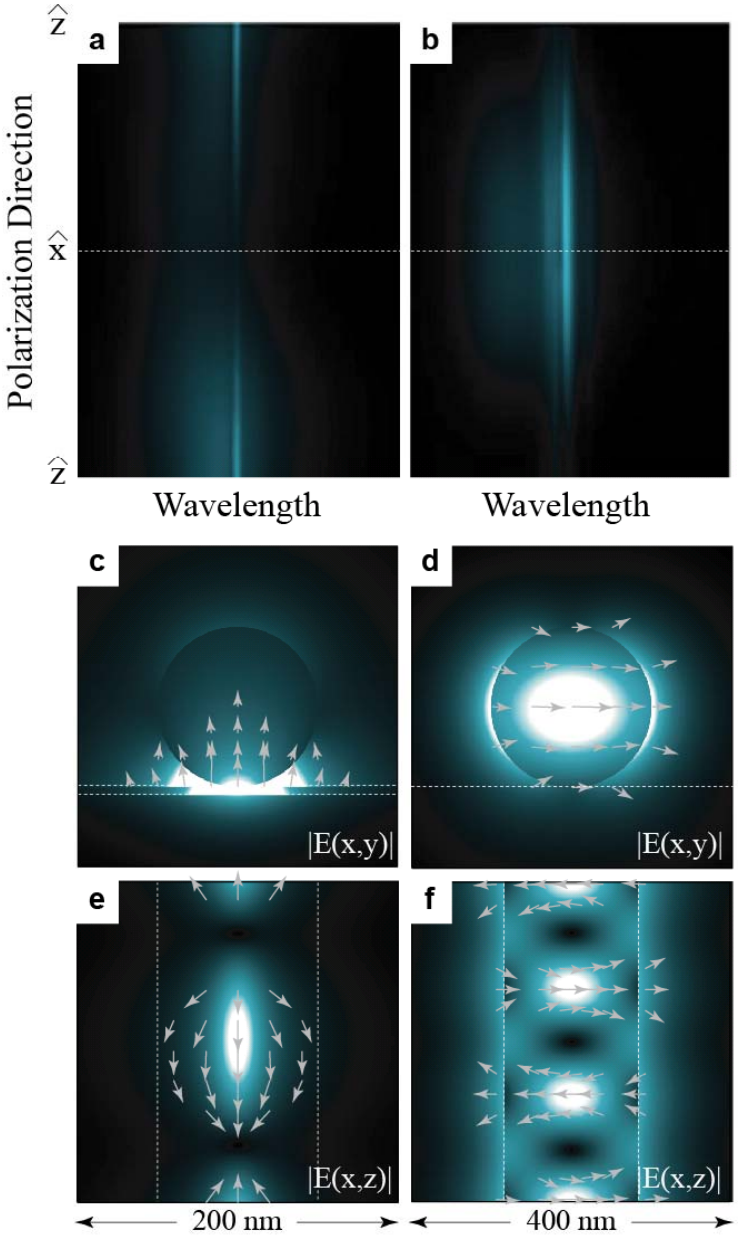
Nanowire plasmon laser

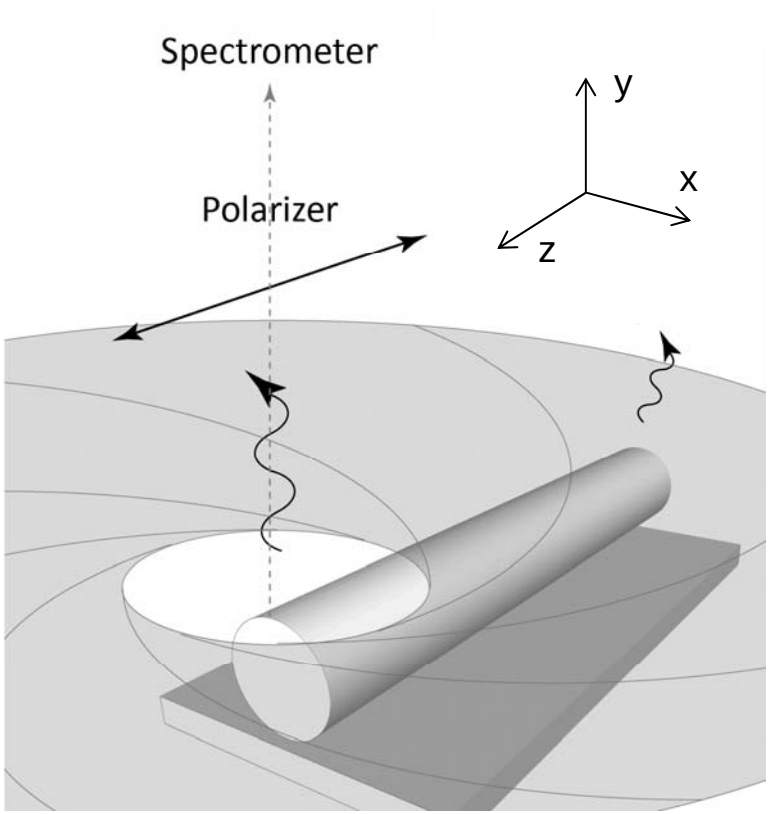




16

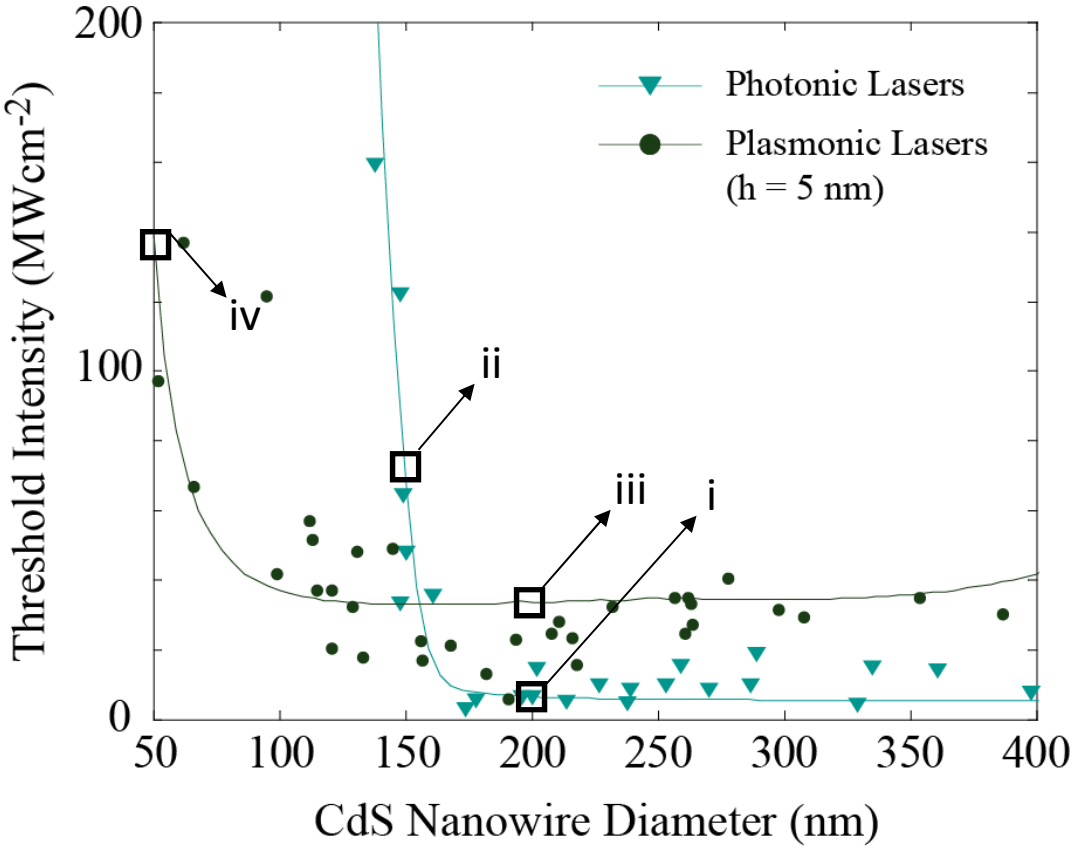
Plasmonic and photonic laser mode polarization

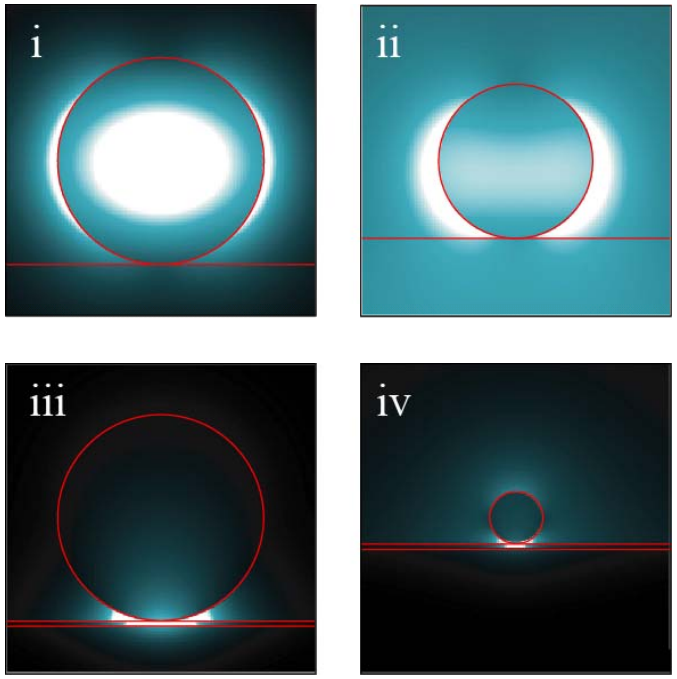




- Plasmonic lasers: scattered light polarized along z-direction (|| wire axis).
- Photonic lasers: scattered light polarized along x-direction (⊥ wire axis).

Laser threshold of plasmonic and photonic lasers





Outline

- 1. Nanowire plasmon laser
- 2. Room temperature square plasmon lasers
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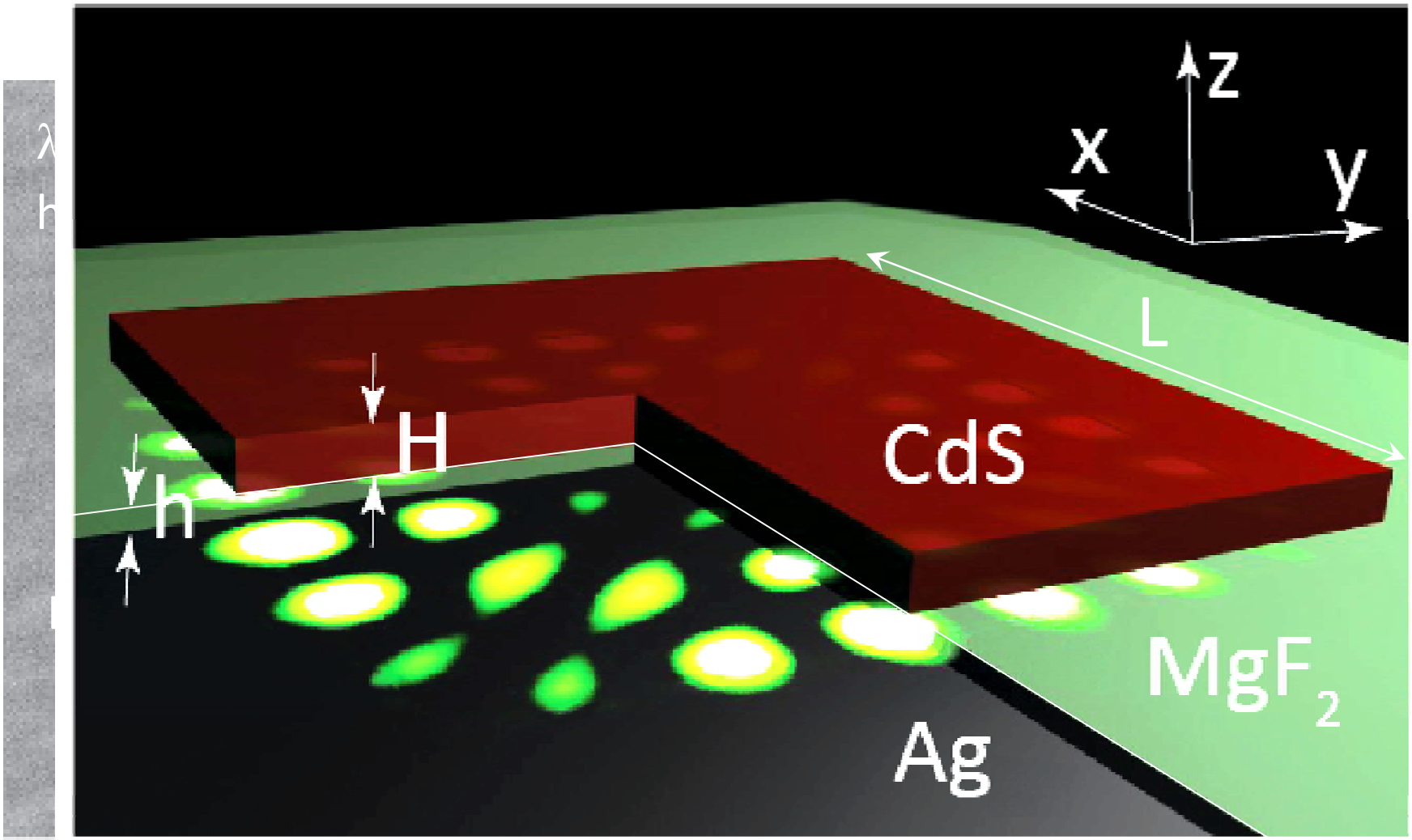
Room temperature square plasmon laser

Key Features

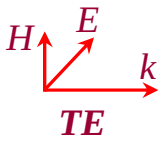
- **First room temperature operated plasmon laser**
- **Single mode**
- **Strong light-matter interaction**
- **Ultrafast speed**

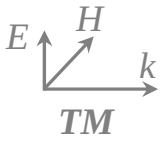
R. M. Ma et al. ***Nature Materials***, 10 (2011) 110

Square plasmon laser

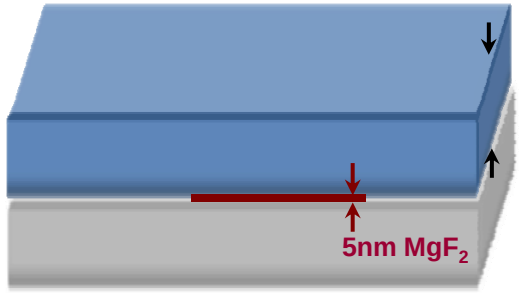


Metal-Insulator-Semiconductor Surface Plasmon Mode



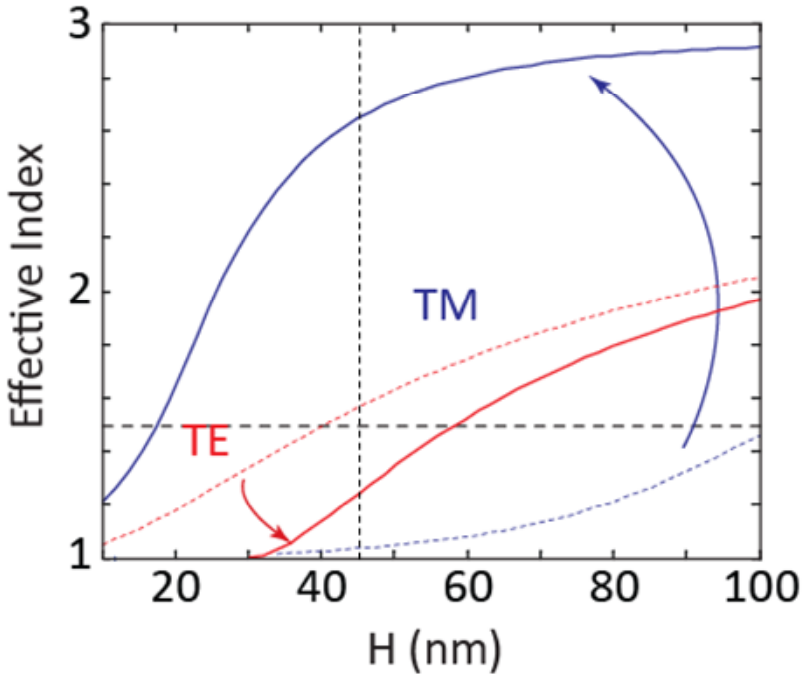


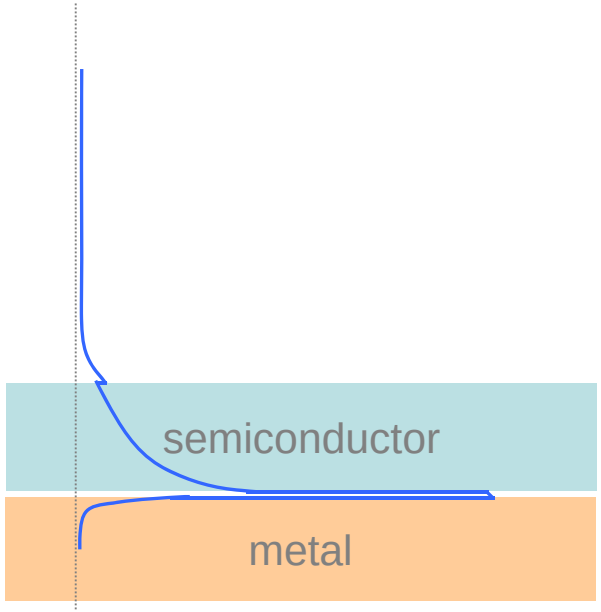
CdS



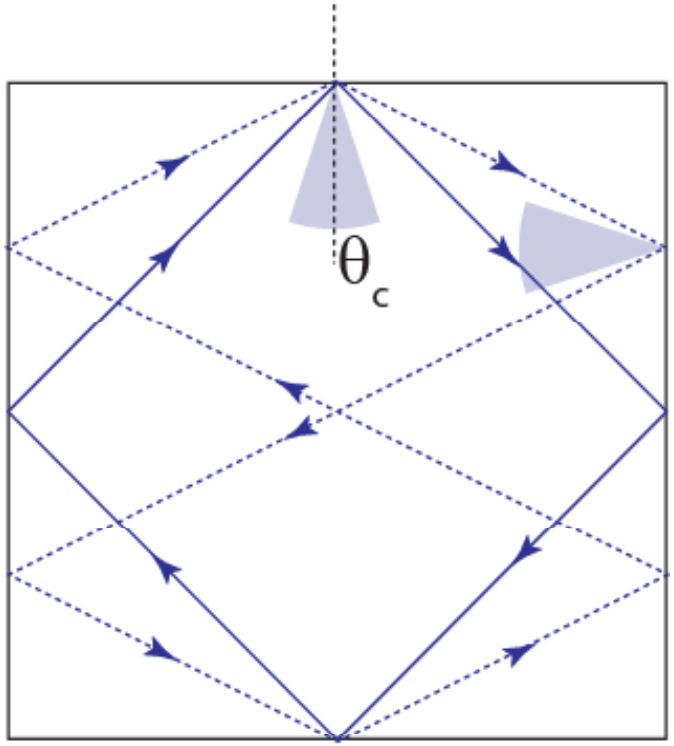
Nanosquare thickness

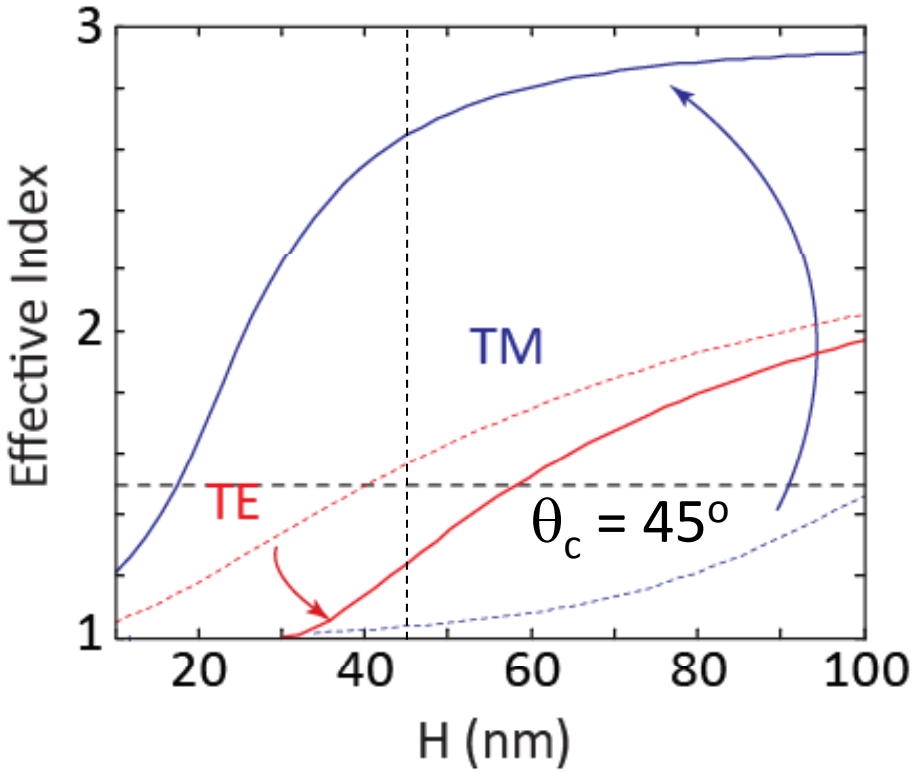
metal





Total internal reflection of surface plasmons

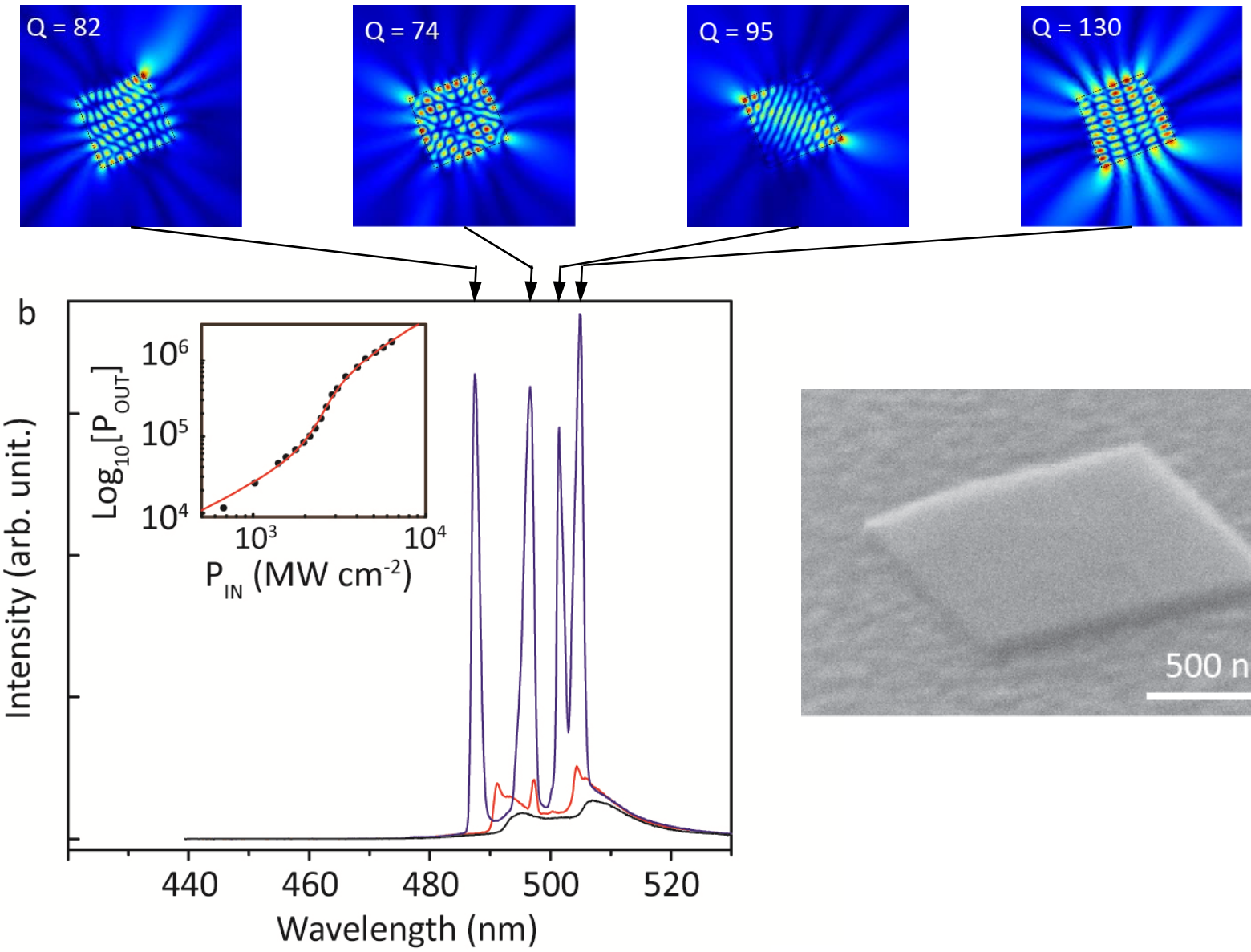




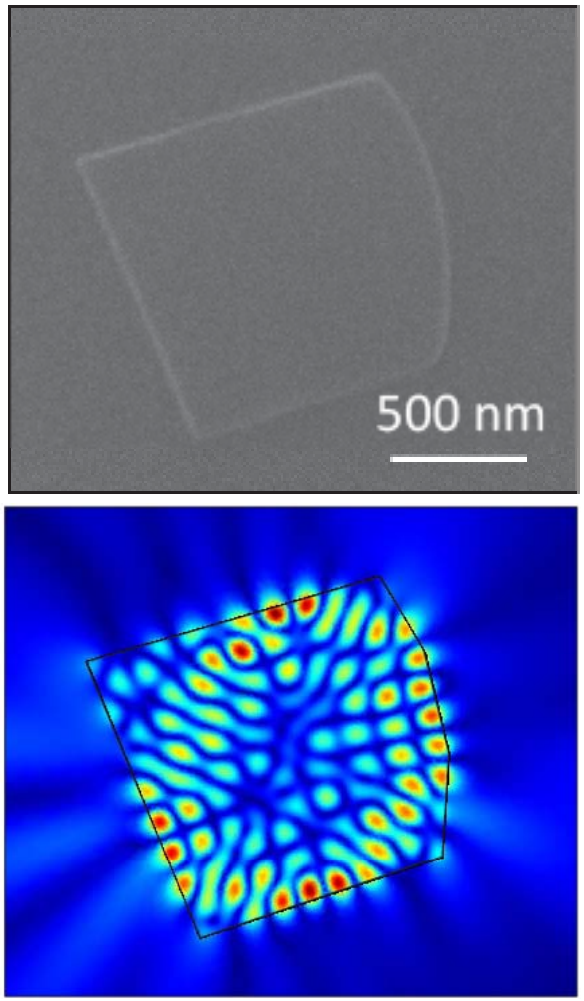
Photonic mode can NOT lase

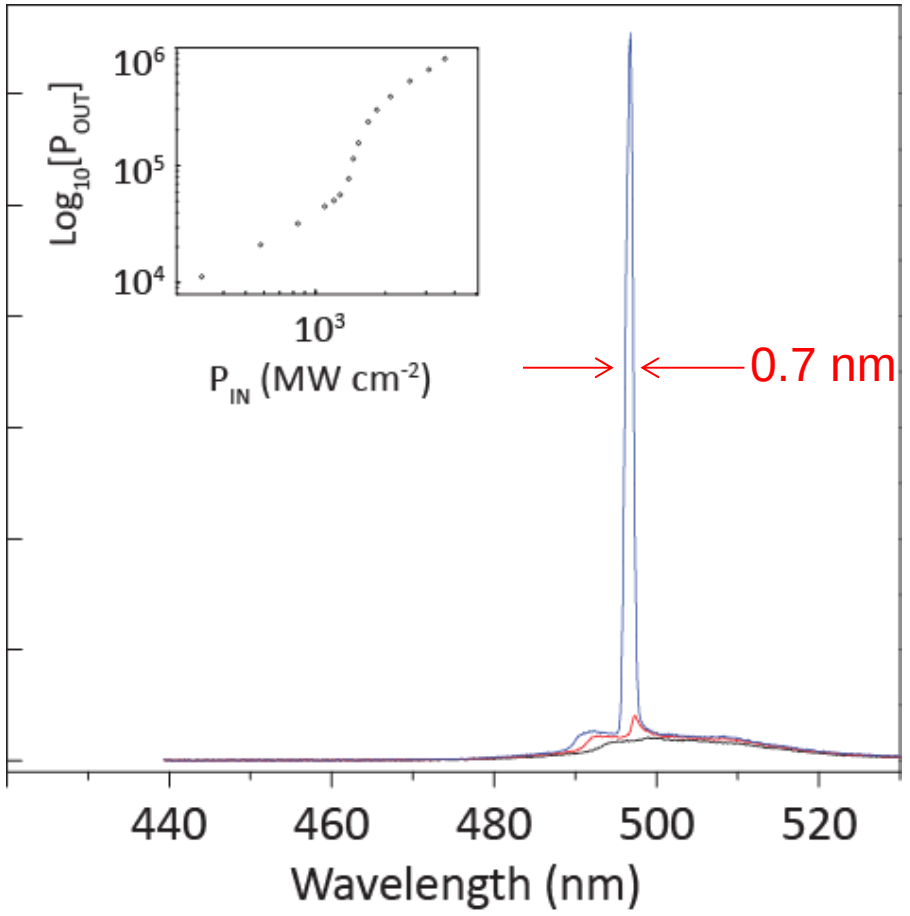
Plasmon mode has lower loss than photonic mode

Multi-mode plasmon laser



Single mode plasmon laser



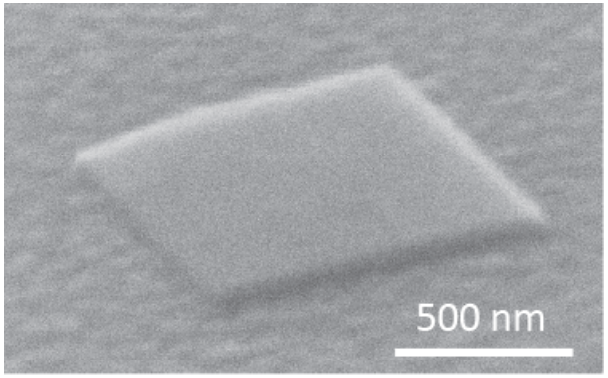


Room temperature, single mode

Plasmon mode has lower loss than photonic mode

Caution note: the direction limit is only broken in z direction in this work

Purcell effect in plasmon cavities



- How does strongly confined light interact with matter?
  - It substantially modifies the rate of spontaneous emission

Fermi's Golden Rule:

$$\frac{1}{\tau_{sp}} = \frac{2\pi}{\hbar^2}\left\langle f \left| d \cdot E \right| i \right\rangle^2 \rho(\omega)$$

Field Enhancement

Modified PDOS

Outline

- 1. Nanowire plasmon laser
- 2. Room temperature square plasmon lasers
- 3. Directionally emitted WEB plasmon laser
- 4. WEB plasmon laser circuit
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New configuration: Waveguide Embedded (WEB) Plasmon Laser

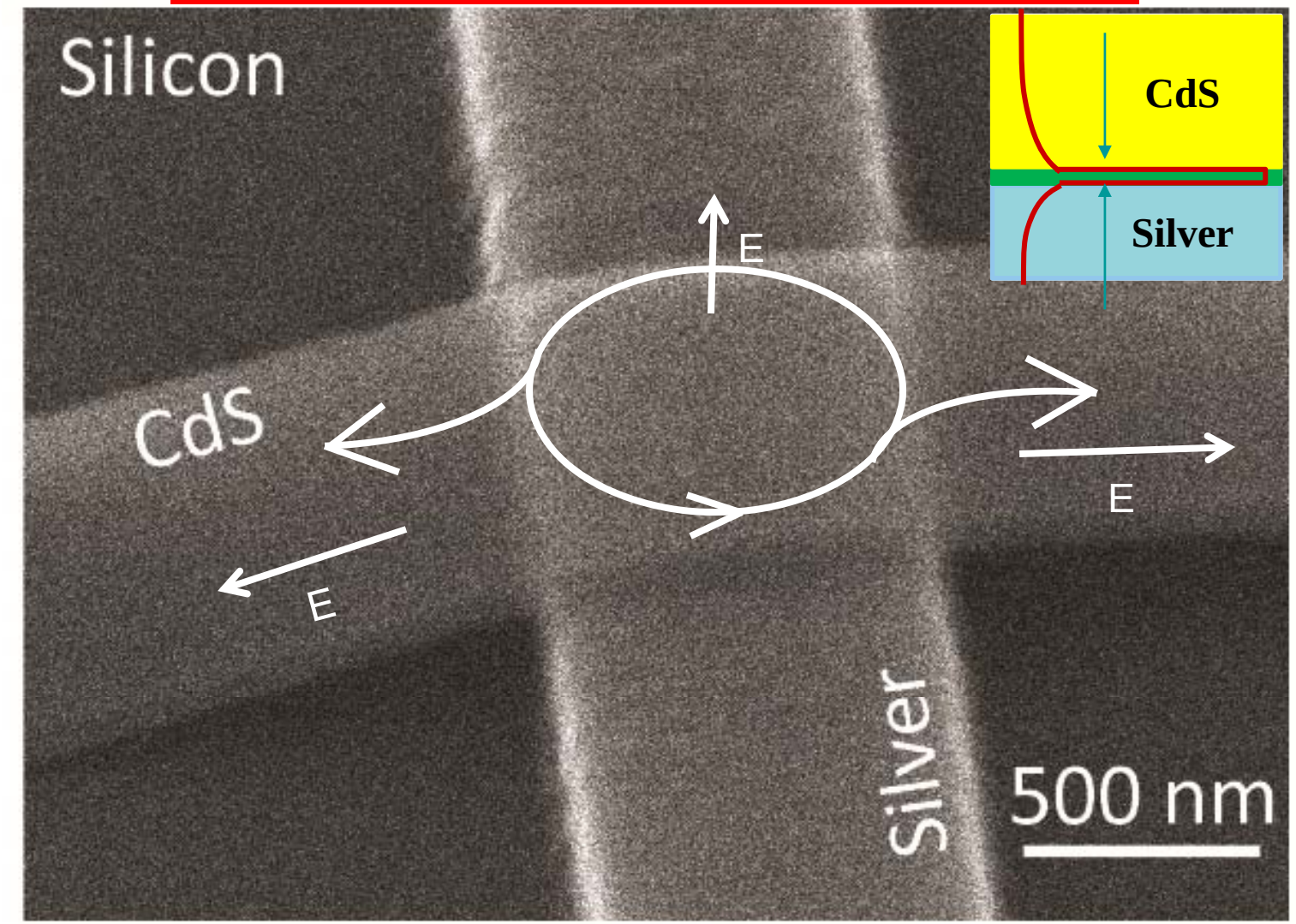
Key Features

- **First directionally emitted plasmon laser**
- **High extrinsic efficiency**
- **Break parasitic loss limitation**

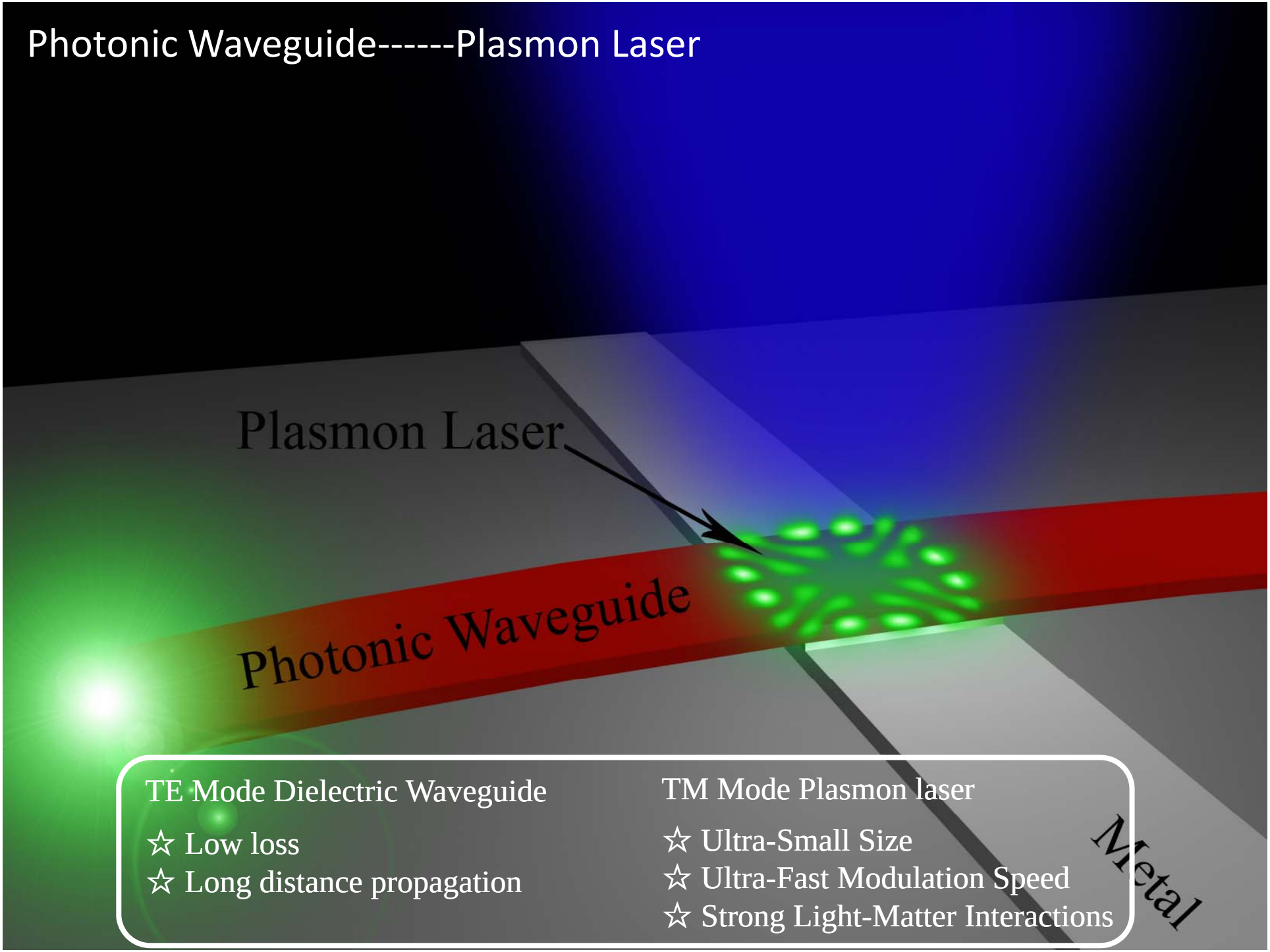
R. M. Ma et al. ***Nano Letters*** **12 (2012) 5396.**

Directionally emitting WEB Plasmon laser

Plasmon TM mode cavity ➔ photonic TE mode waveguide?



Photonic Waveguide------Plasmon Laser



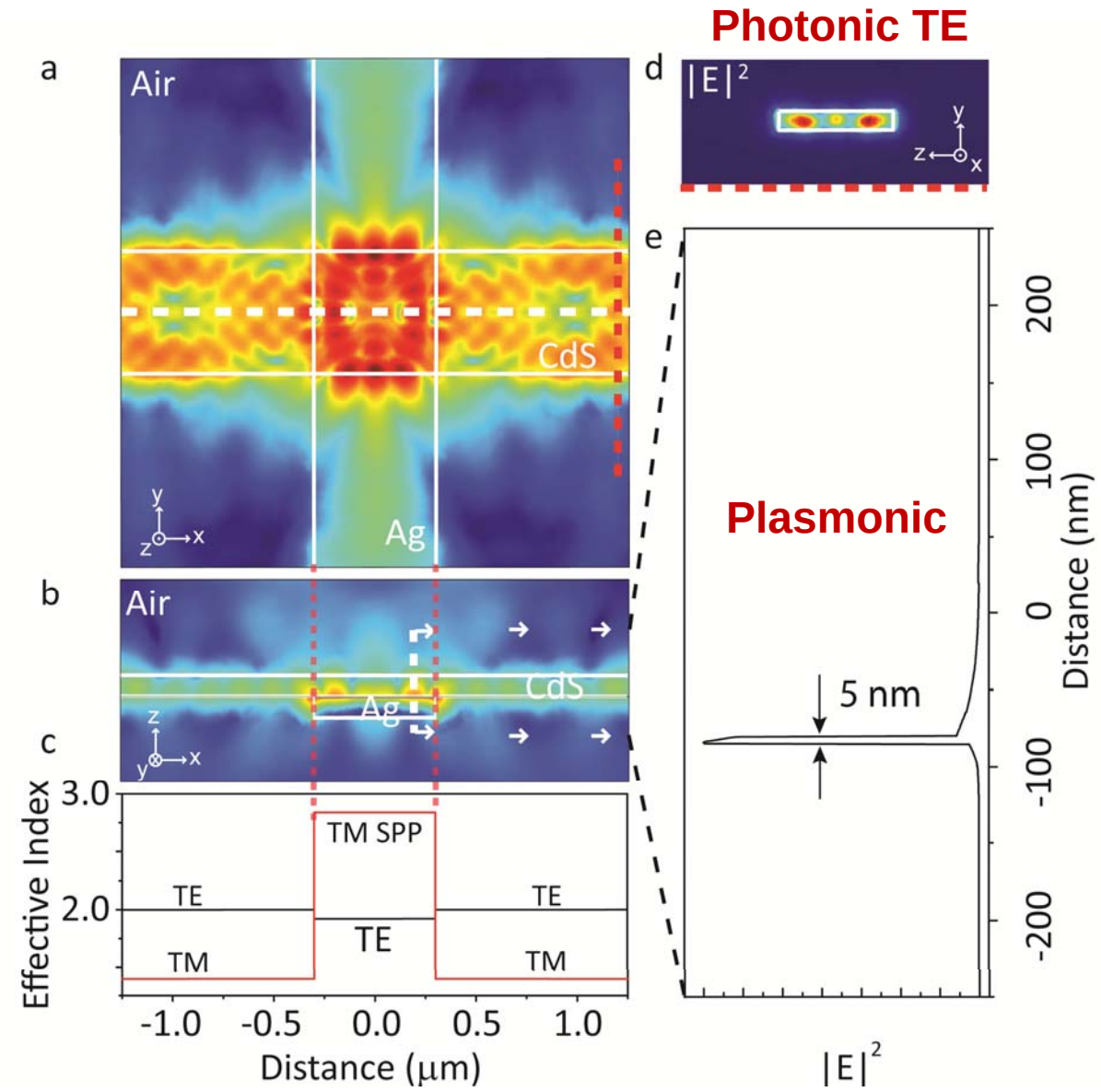
TE Mode Dielectric Waveguide

☆ Low loss
☆ Long distance propagation

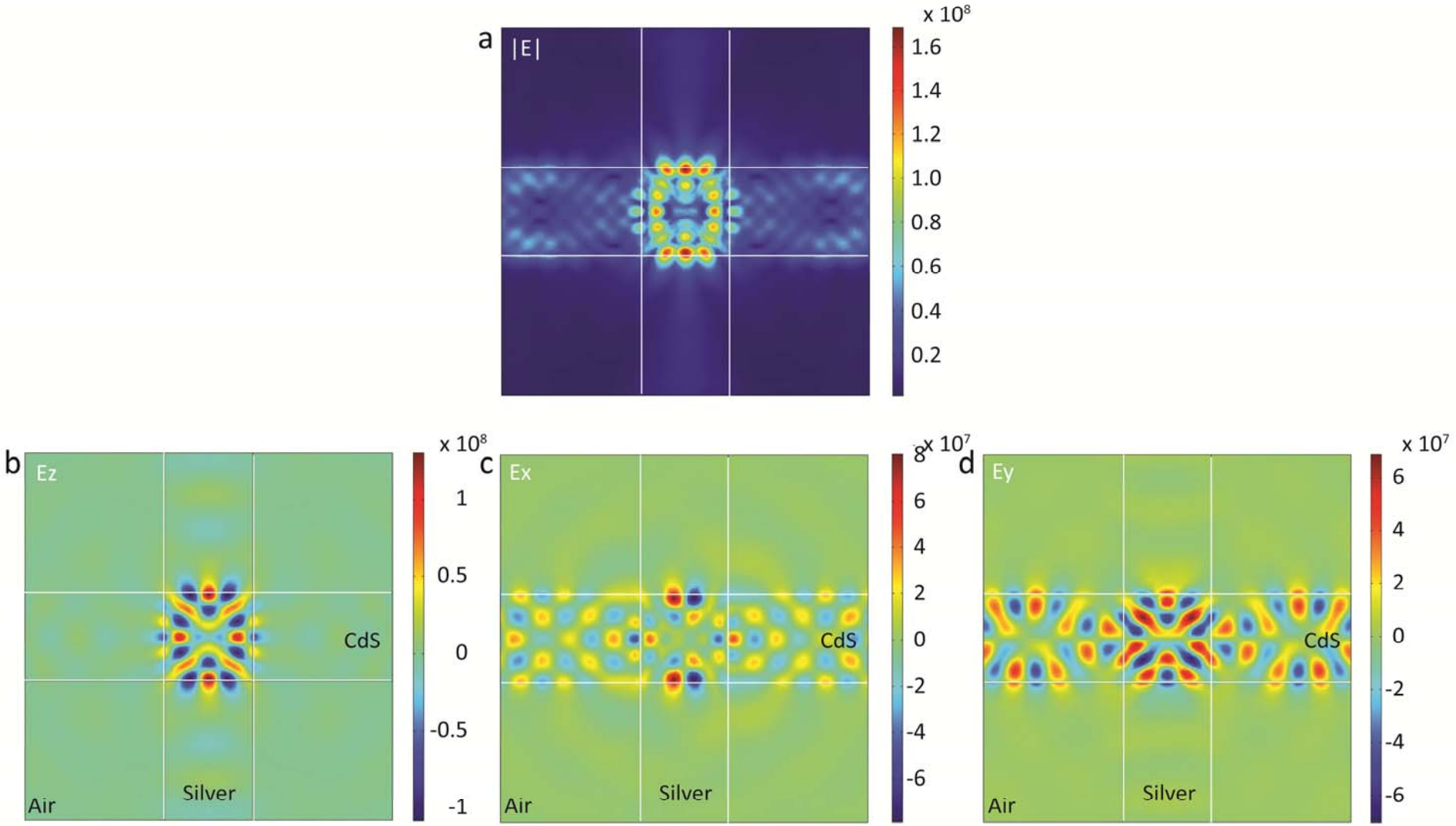
TM Mode Plasmon laser

☆ Ultra-Small Size
☆ Ultra-Fast Modulation Speed
☆ Strong Light-Matter Interactions

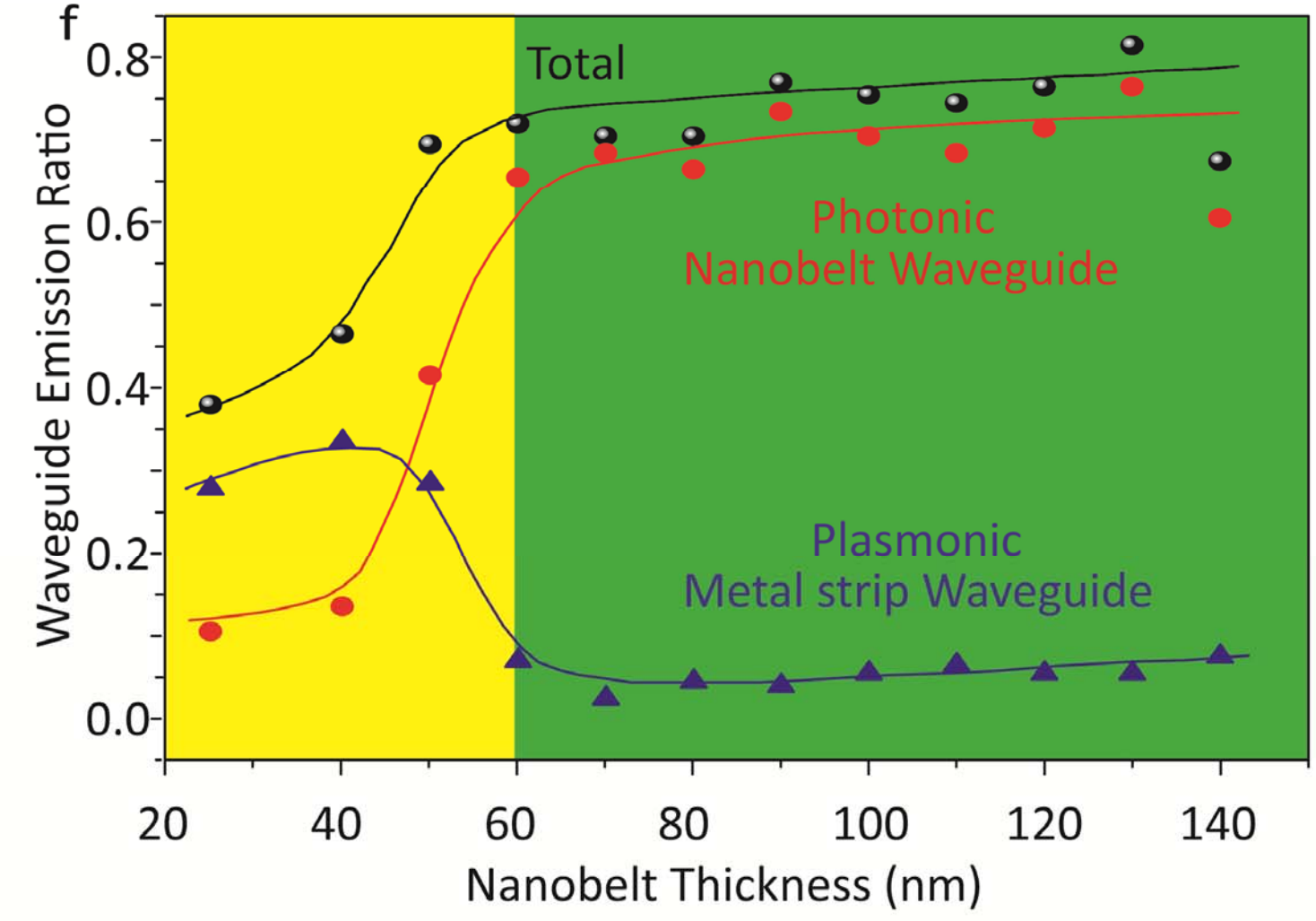
Directionally emitting Plasmon laser 3D simulation results



Directionally emitting Plasmon laser 3D simulation results

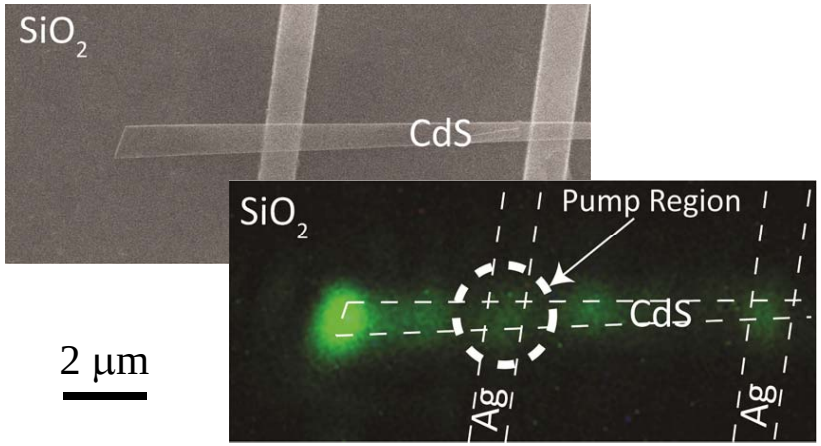


Laser-to-waveguide coupling efficiency



>70% radiation of **Plasmon laser** launched to **Photonic waveguide**

Directionally emitting Plasmon laser

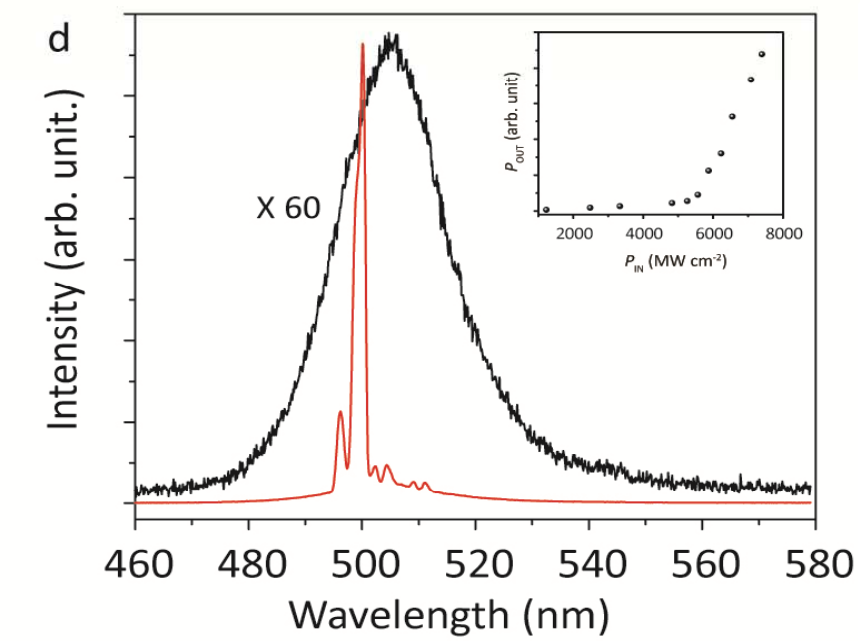


- Extrinsic Efficiency

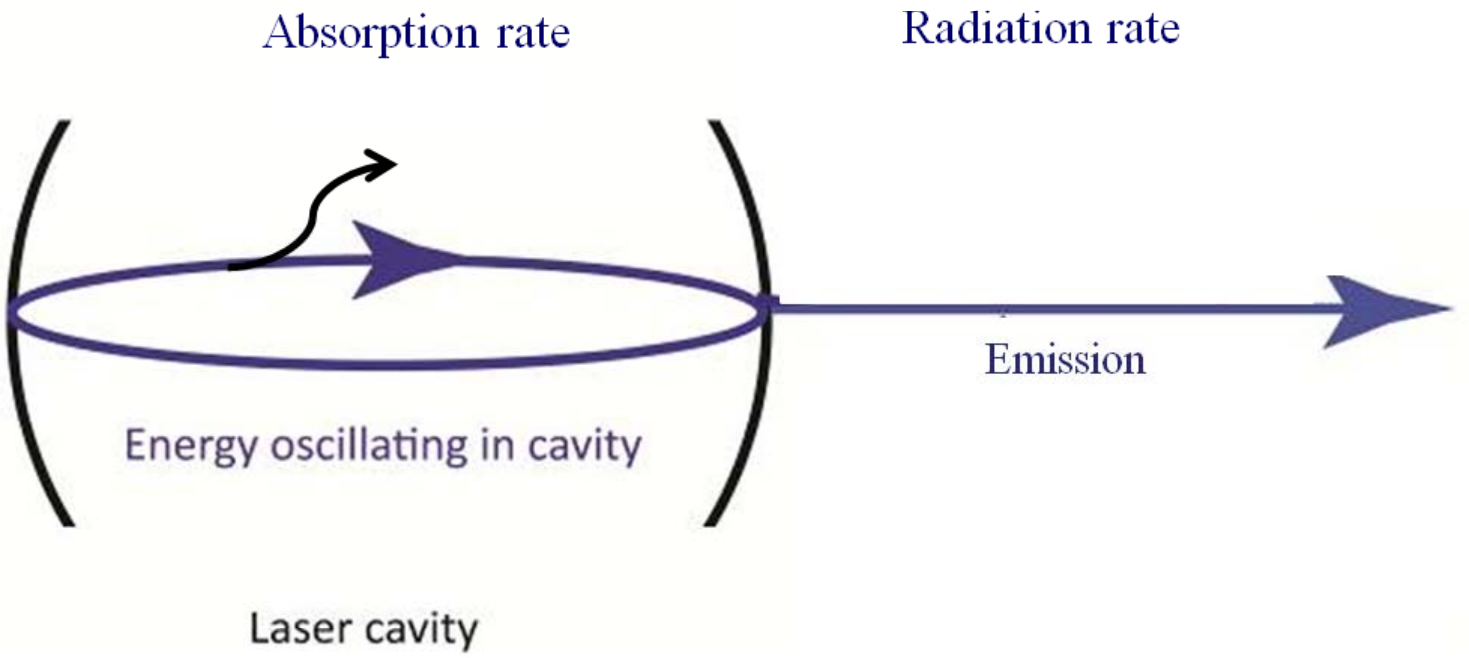
  (β-factor/extraction efficiency)

$$\beta = \frac{\gamma_{\text{mode}}}{\gamma_{\text{mode}} + \gamma_{\text{spp}} + \gamma_{\text{free space}}} \sim 80\%$$

~ 80% emission is directly coupled



Radiation efficiency, parasitic loss limitation

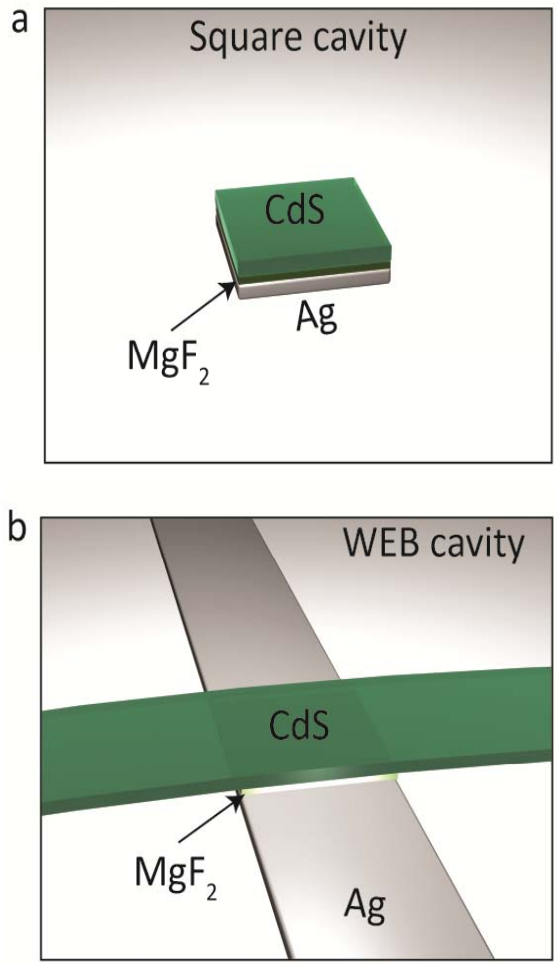


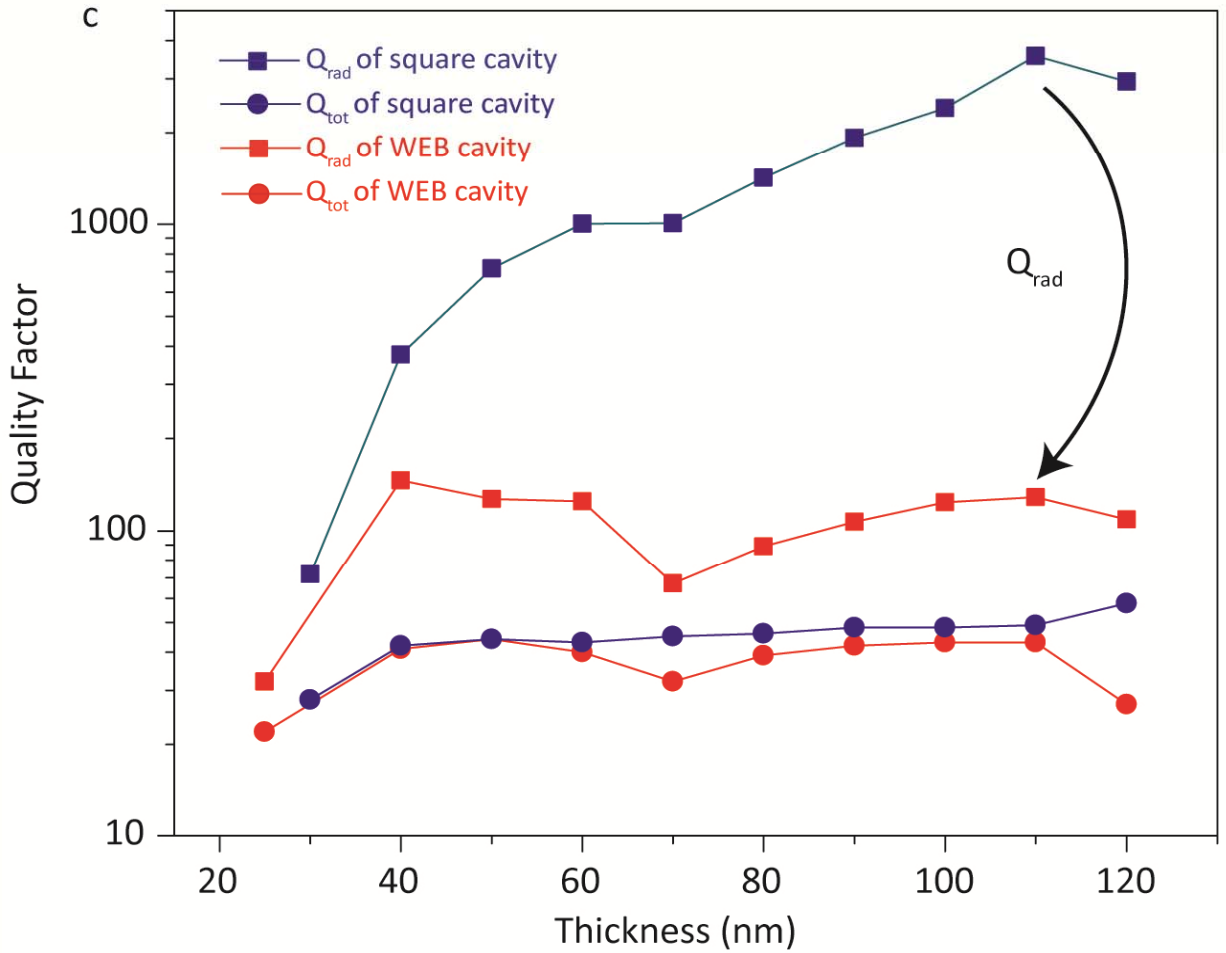
Radiative efficiency = Q / Q_{rad} $(Q=w/\gamma)$

$$\frac{1}{Q} = \frac{1}{Q_{rad}} + \frac{1}{Q_{abs}}$$

We need to lower the radiation Q!

Radiation efficiency enhancement of WEB plasmon laser





Radiative efficiency 2 % ➔ 40 %

Outline

- 1. Nanowire plasmon laser
- 2. Room temperature square plasmon lasers
- 3. Directionally emitted WEB plasmon laser
- 4. WEB plasmon laser circuit
- 5. Conclusions

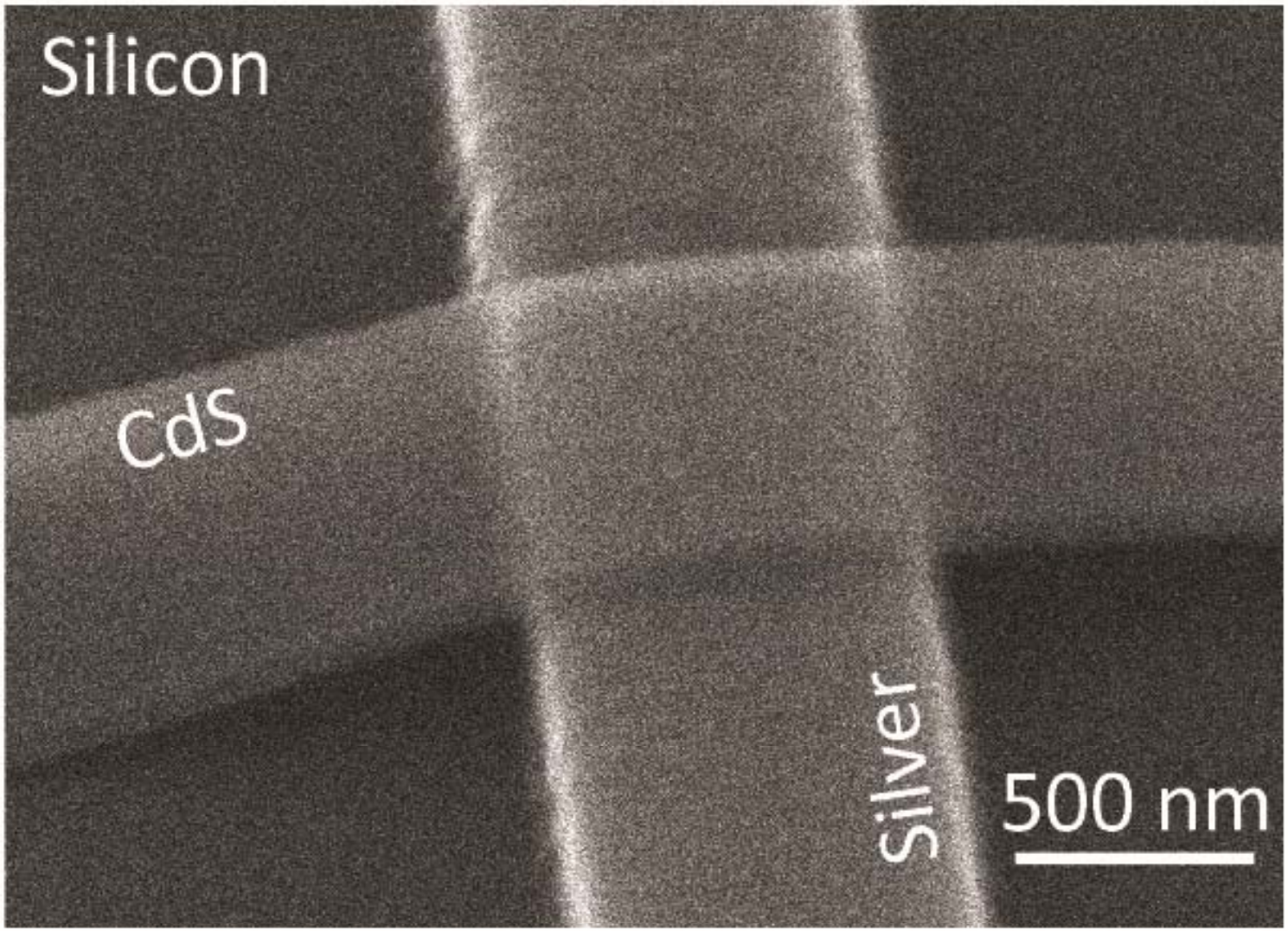
WEB plasmon laser circuits

Key Features

- **New architecture for ultra-compact circuits**
- **Four key elements for a transmitter integrated on single waveguide**
- **Direct electrical modulation**
- **Wavelength multiplexing**

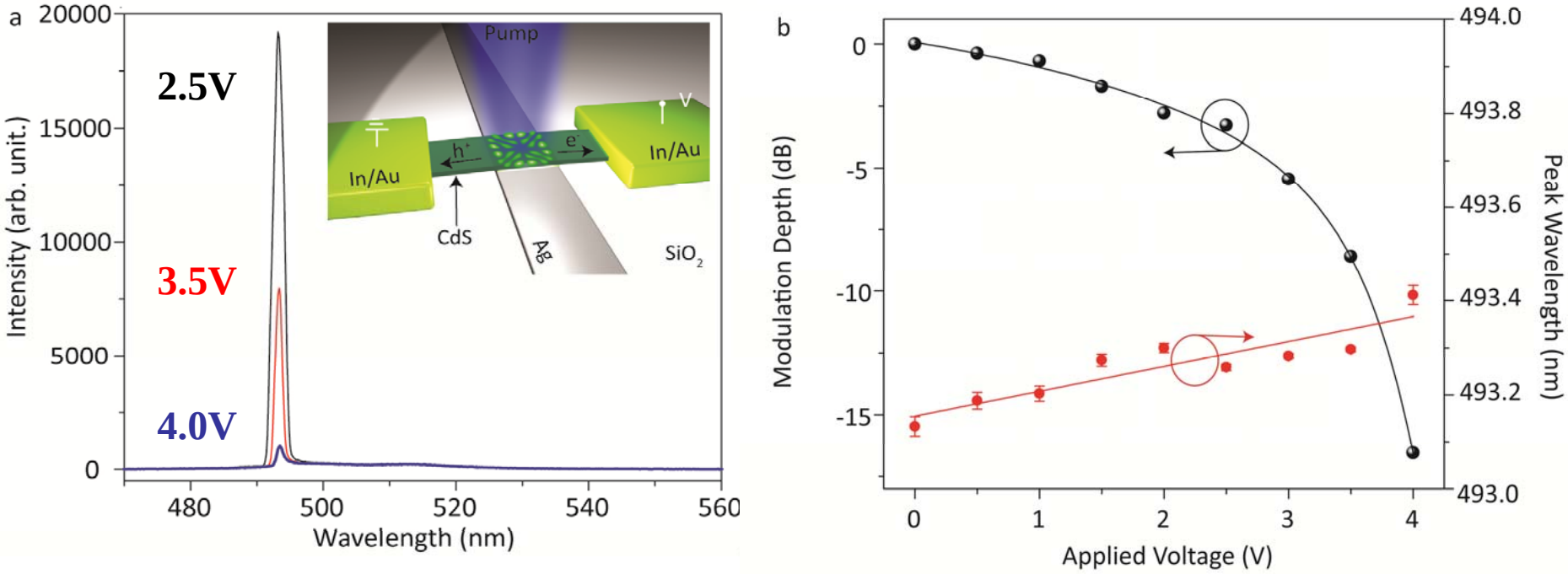
R. M. Ma et al. ***Nano Letters*** **12 (2012) 5396.**

Electrically modulated Plasmon laser



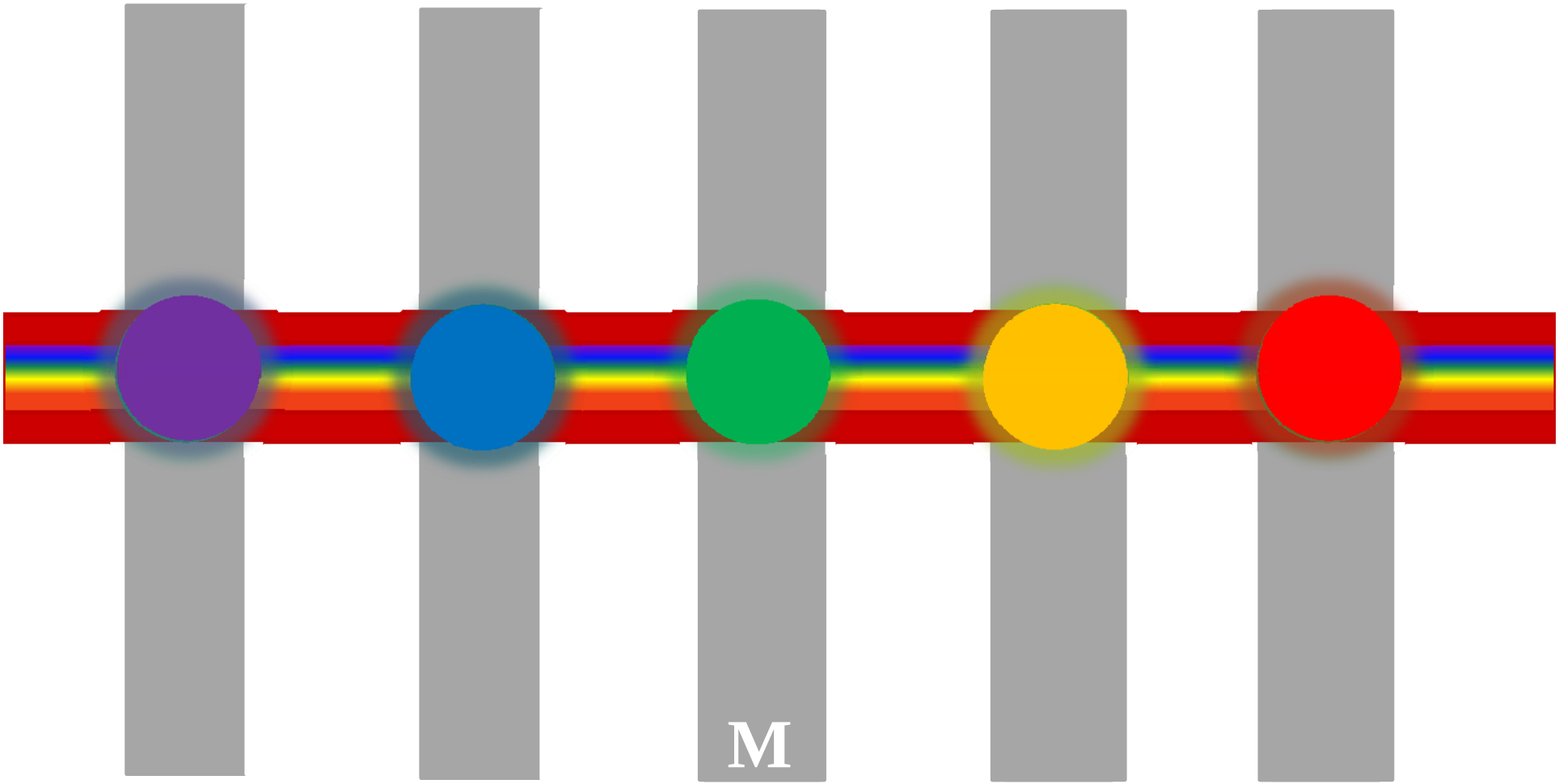
Electrical interface without jeopardizing the plasmon modes

Electrically modulated Plasmon laser



Modulation depth: 16 dB for a peak bias of 4 V

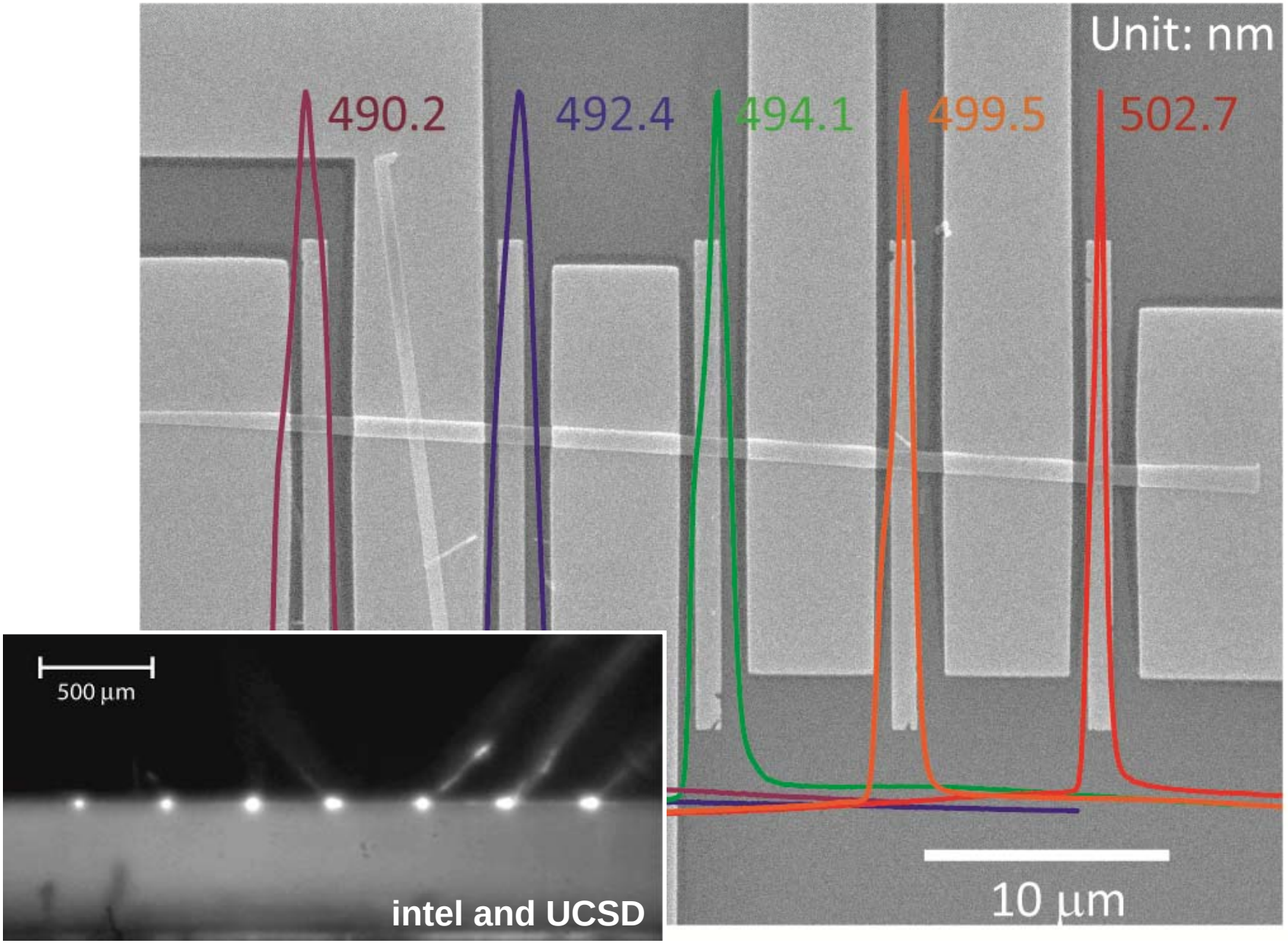
Multi-color plasmon laser array, Multiplexing



Multi-Color Plasmon Laser Array

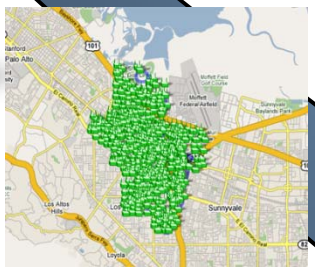
Wavelength Multiplexing

Multi-color plasmon laser array



Global Data Hunger

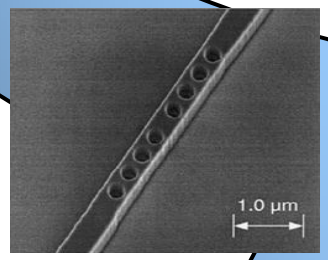
1,000 *km*



1 *km*

1 *m*

1 *mm* (intel 2011)



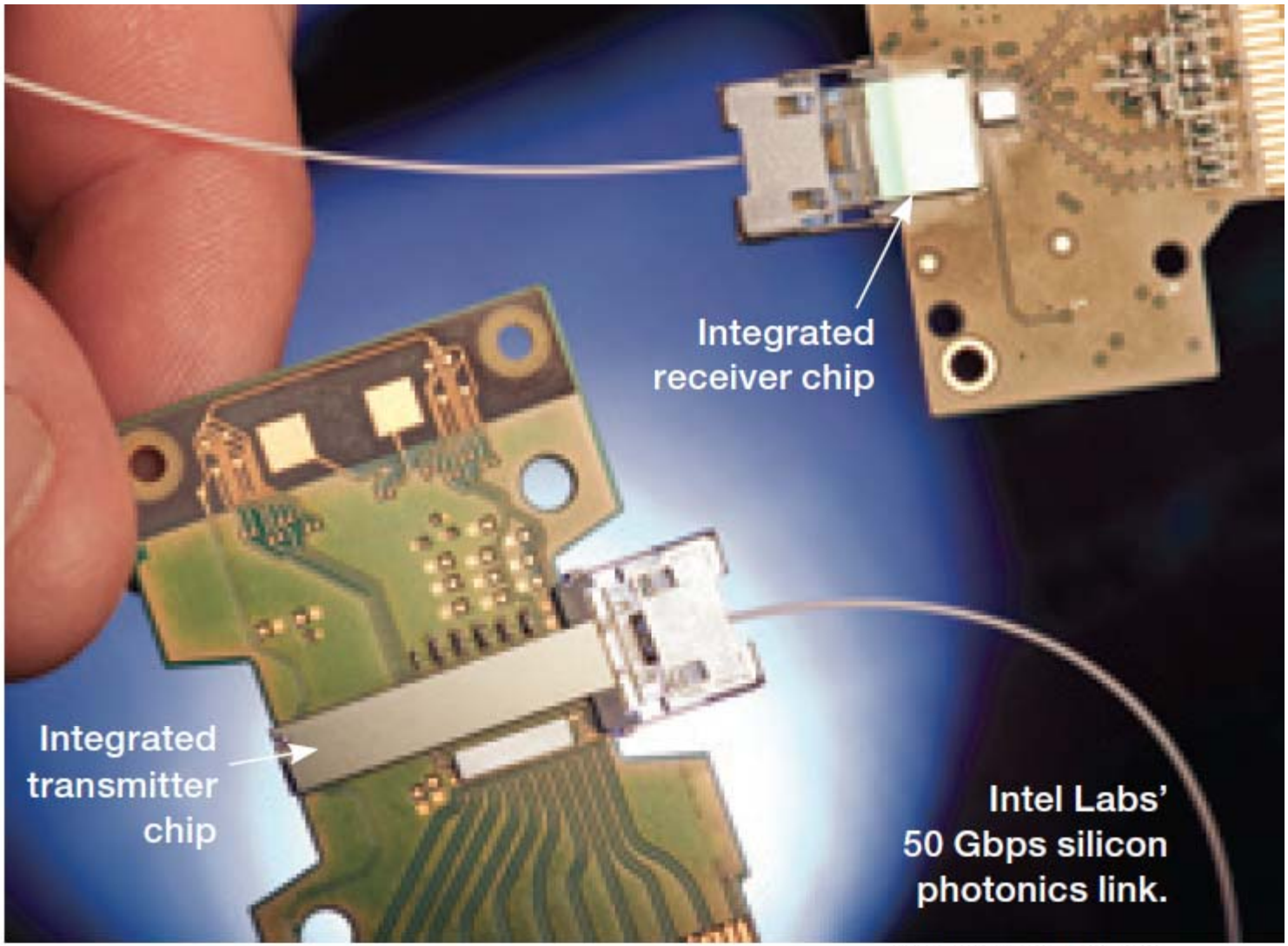
1 *µm*

The call for nanoscopic optical interconnector:

To meet the ever increasing global bandwidth demands, optical interconnect is now moving to shorter and shorter distance applications, and eventually will take over interconnects inside a chip.

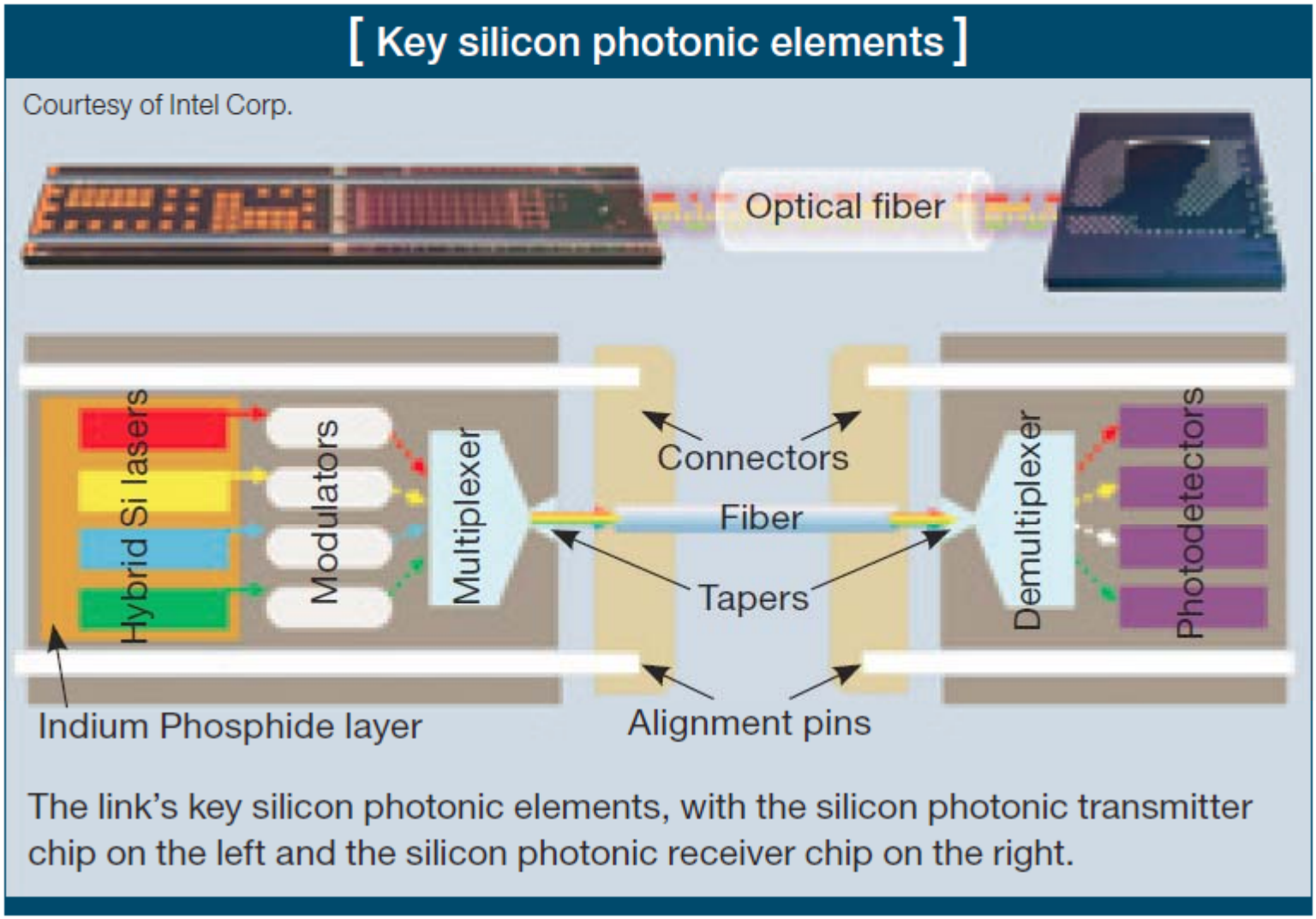
A science and technology that spans more 15 orders of magnitudes!

A prototype optical connector made by Intel 2011

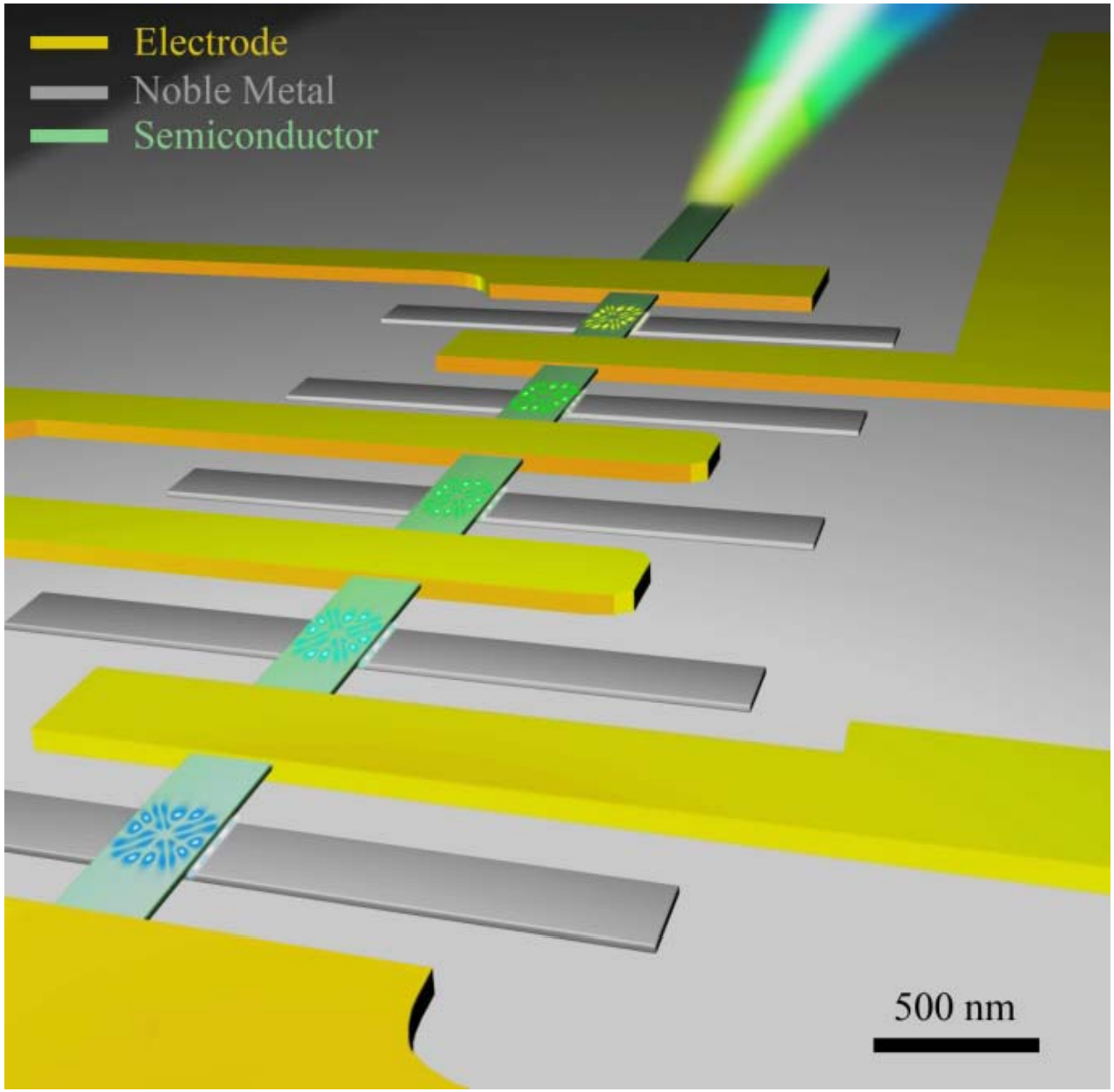


Courtesy of Intel Corp.

A prototype optical connector made by Intel 2011



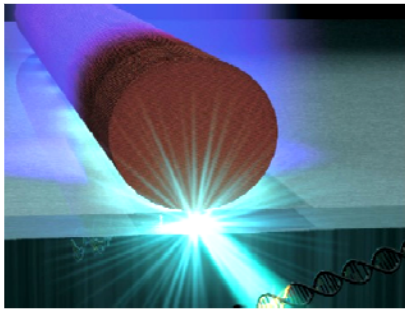
A possible nanoscale version



Conclusions

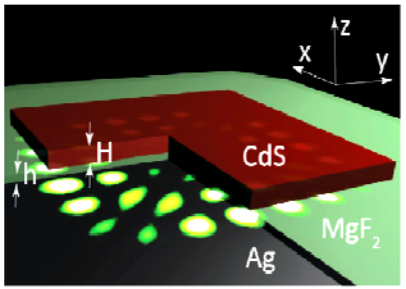
Nanowire plasmon laser

- First plasmon laser
- $\lambda^2/400$ optical confinement



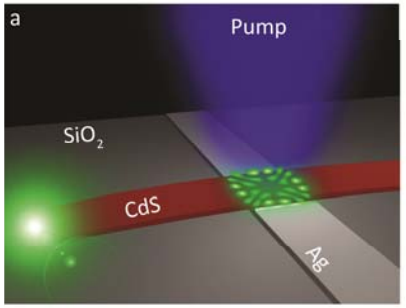
Room temperature square plasmon laser

- First room temperature operated plasmon laser
- Single mode
- Strong light-matter interaction
- Ultrafast speed



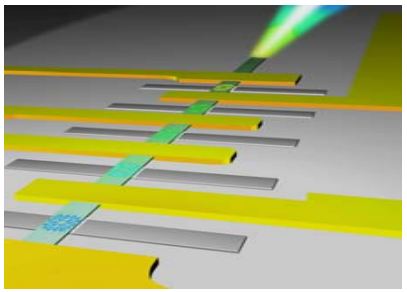
WEB plasmon laser

- First directionally emitted plasmon laser
- High extrinsic efficiency
- Break parasitic loss limitation



WEB plasmon laser circuit

- **New architecture for ultra-compact circuits**
- **Four key elements for a transmitter integrated on single waveguide**
- **Direct electrical modulation**
- **Wavelength multiplexing**



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Dr. Peicai Wu

…

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Thanks for your attention!