BERKELEY LAB

Lawrence Berkeley National Laboratory

Plasmon lasers

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

NSF Nano-scale Science and Engineering Center

UC Berkeley, Berkeley CA, USA

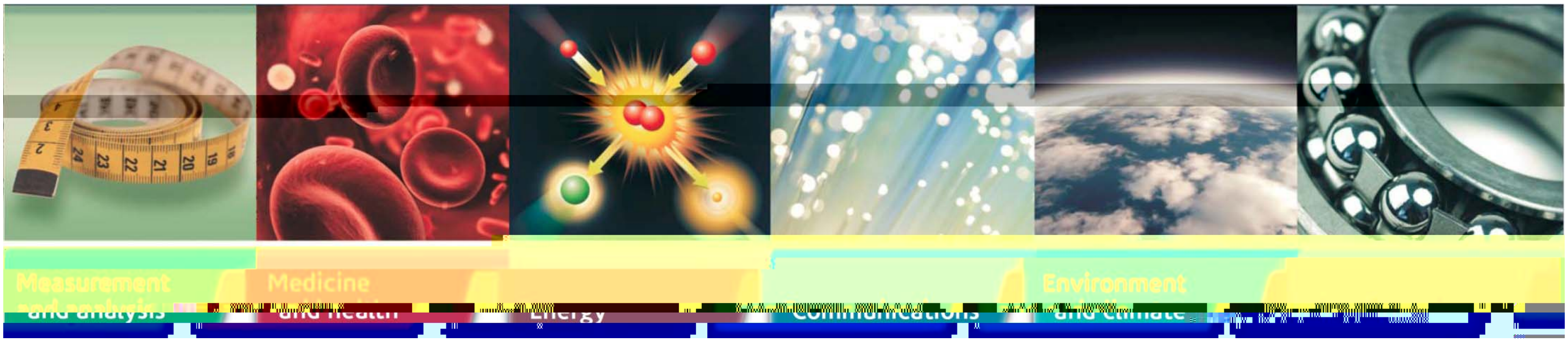
- 2013/03/28

1964 Construction of Lasers

1971 holographic

1981 laser spectroscopy

1997 laser cooling



1999 Monitoring chemical reactions using fs spectroscopy

2000 information and communication technology

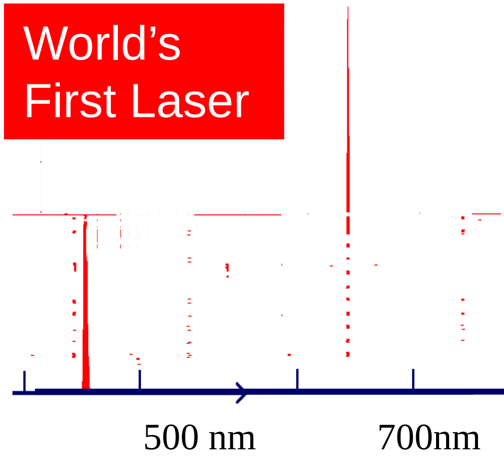
2001 BEC

2005 laser-based precision spectroscopy

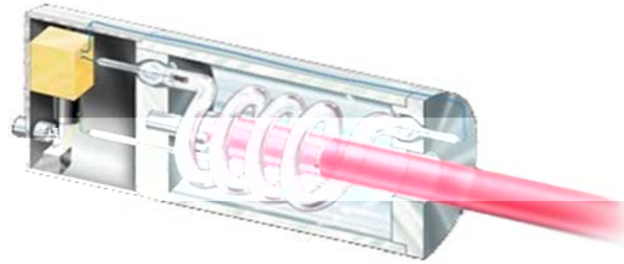
2009 fibers for optical communication

2012 measuring individual quantum systems

World’s
First Laser

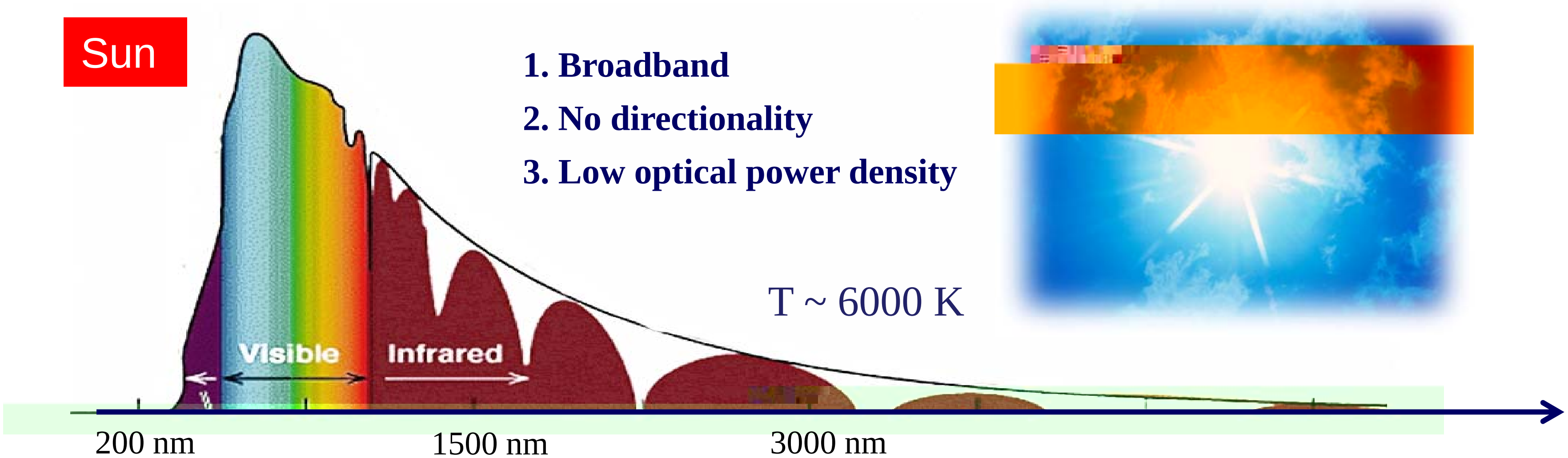


1. **Monochromaticity**
2. **Directionality**
3. **High optical power density**



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



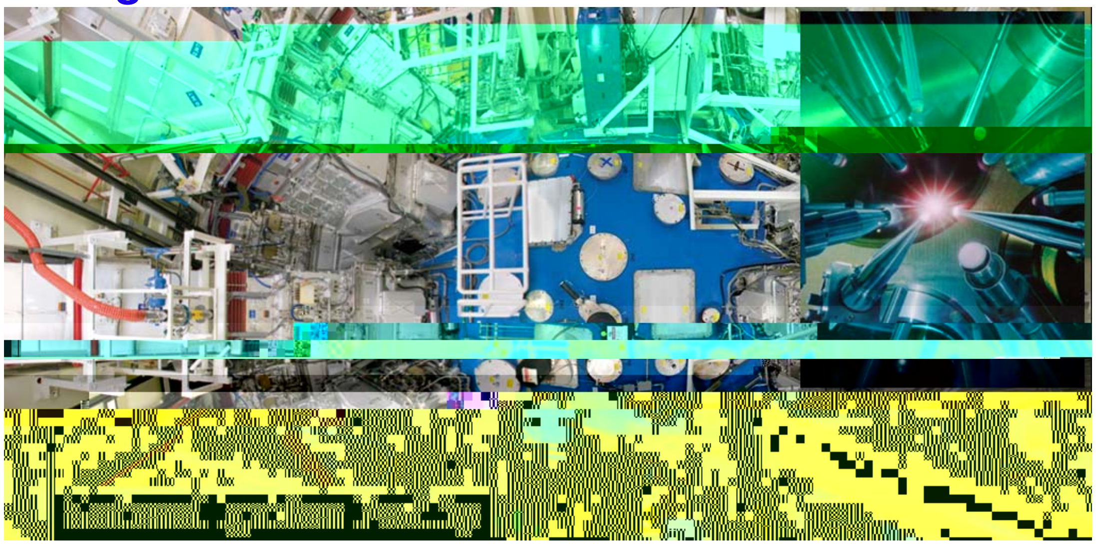
1. **Broadband**
2. **No directionality**
3. **Low optical power density**

T ~ 6000 K

How Big a Laser can be?

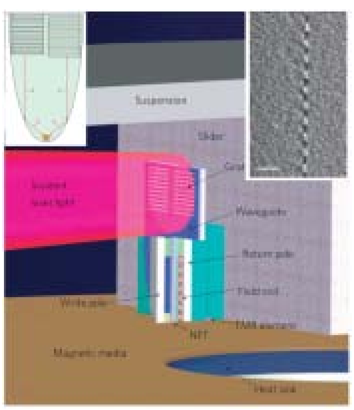
How Small a Laser can be?

Bring Star Power To Earth

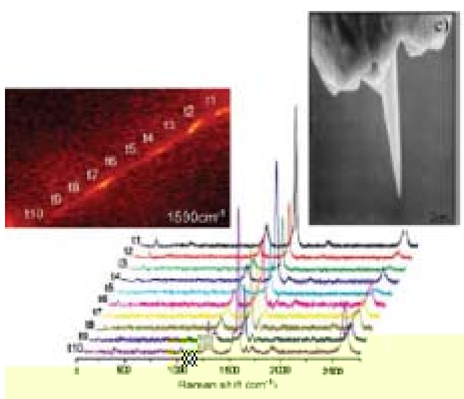


?

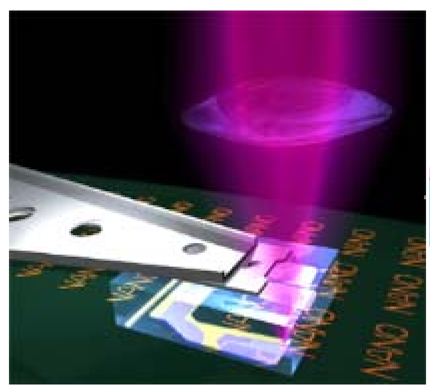
Ultra-dense Data storage



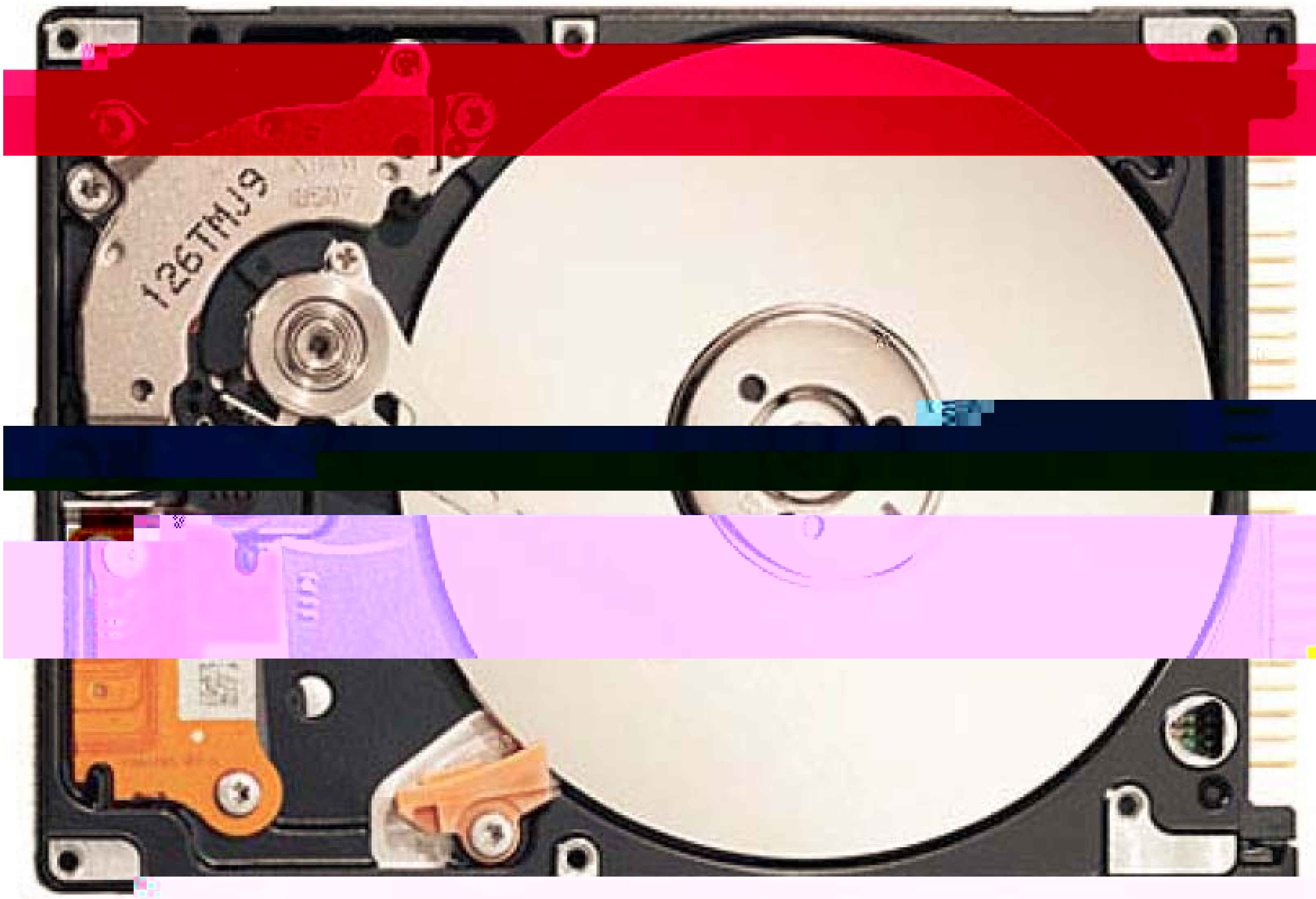
Nanoscopy, Sensing

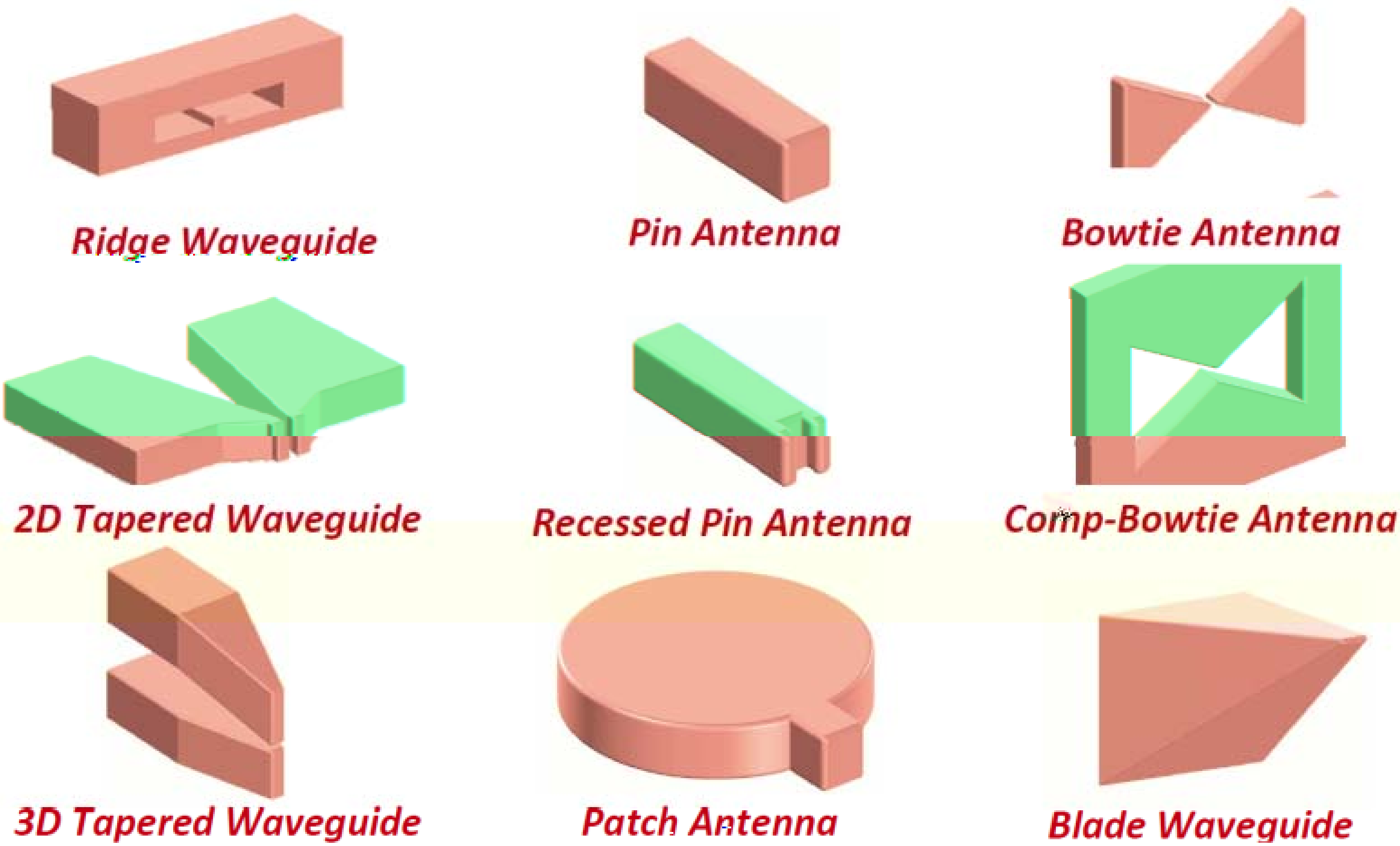


Nanolithography



On-chip optical interconnector




Ridge Waveguide
Pin Antenna
Bowtie Antenna
2D Tapered Waveguide
Recessed Pin Antenna
Comp-Bowtie Antenna
3D Tapered Waveguide
Patch Antenna
Blade Waveguide

Essential Elements of a Laser

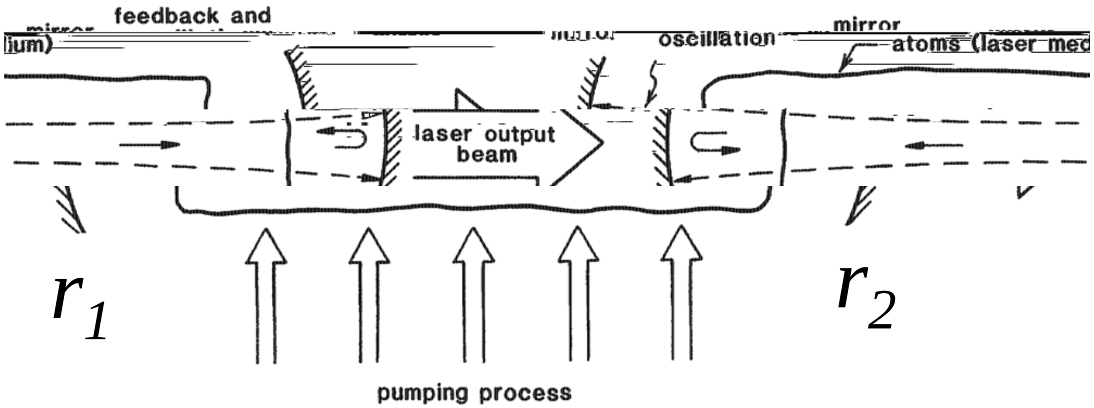


FIGURE 1.1
Elements of a typical laser oscillator.

Anthony E. Siegman, *Lasers*

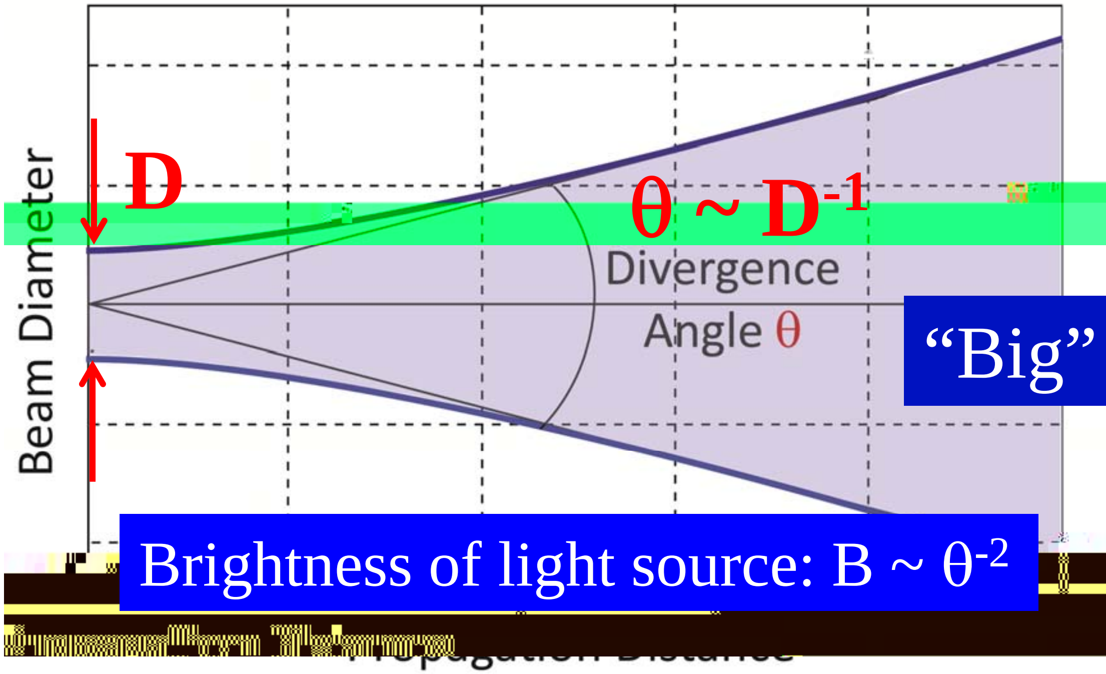
Lasing condition: $r_1 r_2 \exp\{2ikL\} E_0 = E_0$

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



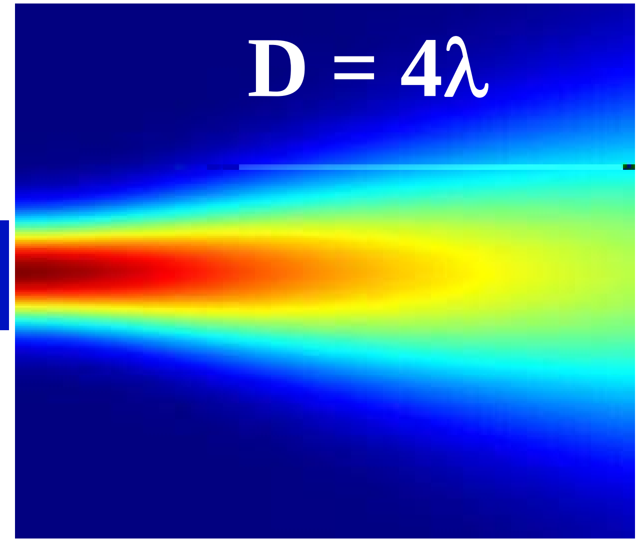
Smaller, stronger divergence
Smaller, less brightness

1. Monochromaticity

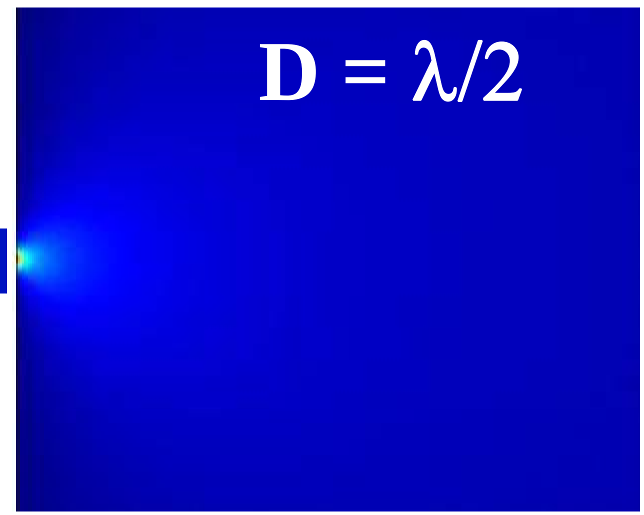
2. Directionality ✗

3. High optical power density ✗

“Big” laser



Nanolaser



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

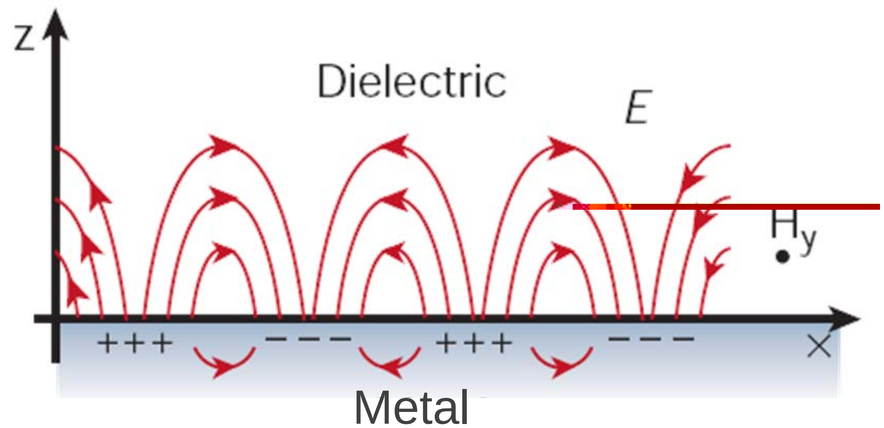
Plasmon Laser: Surface **P**lasmon **A**mplification by **S**timulated **E**mission of **R**adiation

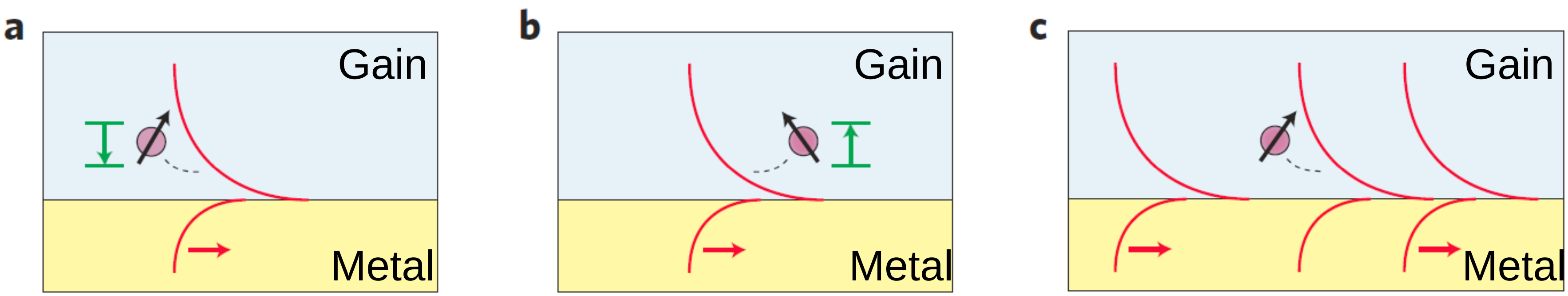
--- Amplify surface plasmons instead of light

Ultra-Small Physical Size & Mode Volume

Ultra-Fast Modulation Speed

Strong light-matter interaction

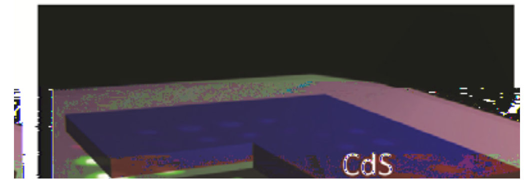




Spontaneous emission **Absorption** **Stimulated emission**

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

Solid state PT

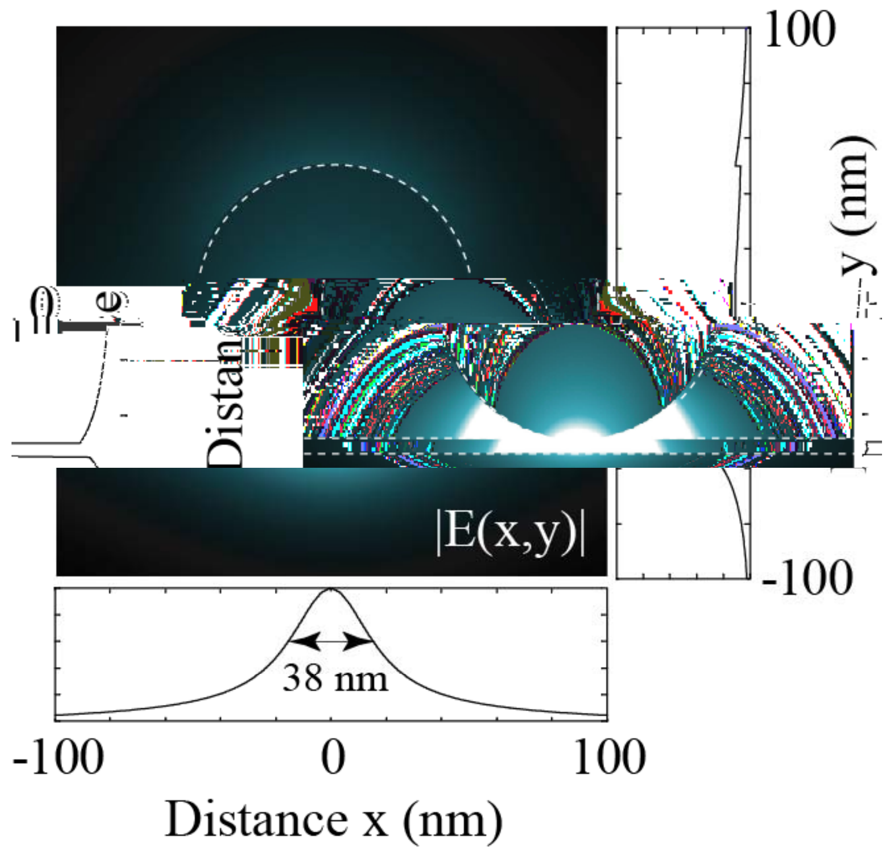


Nanowire plasmon laser

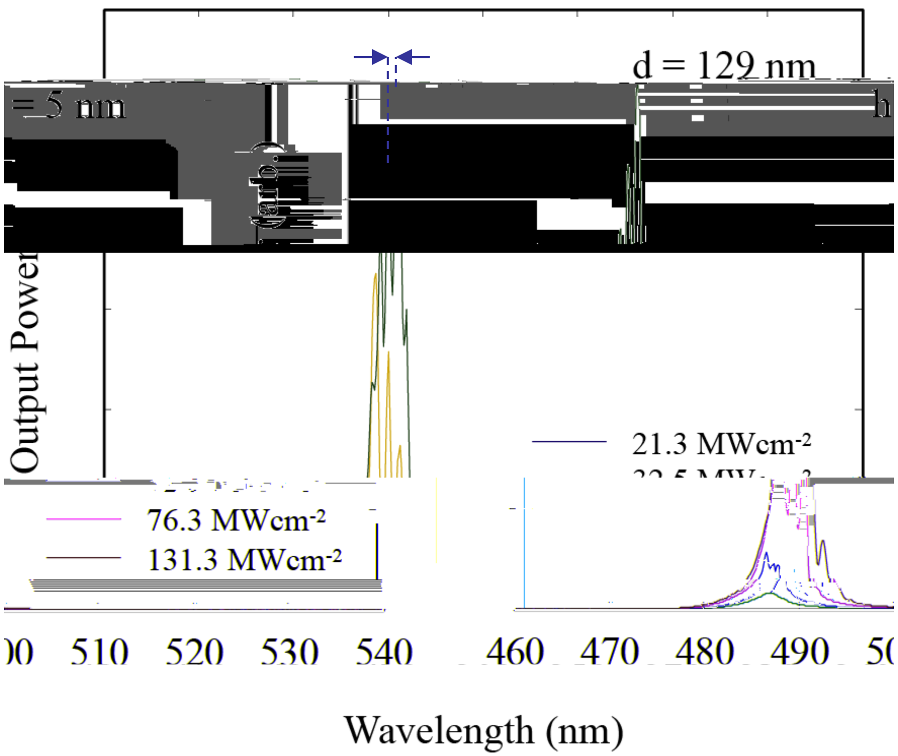
Key Features

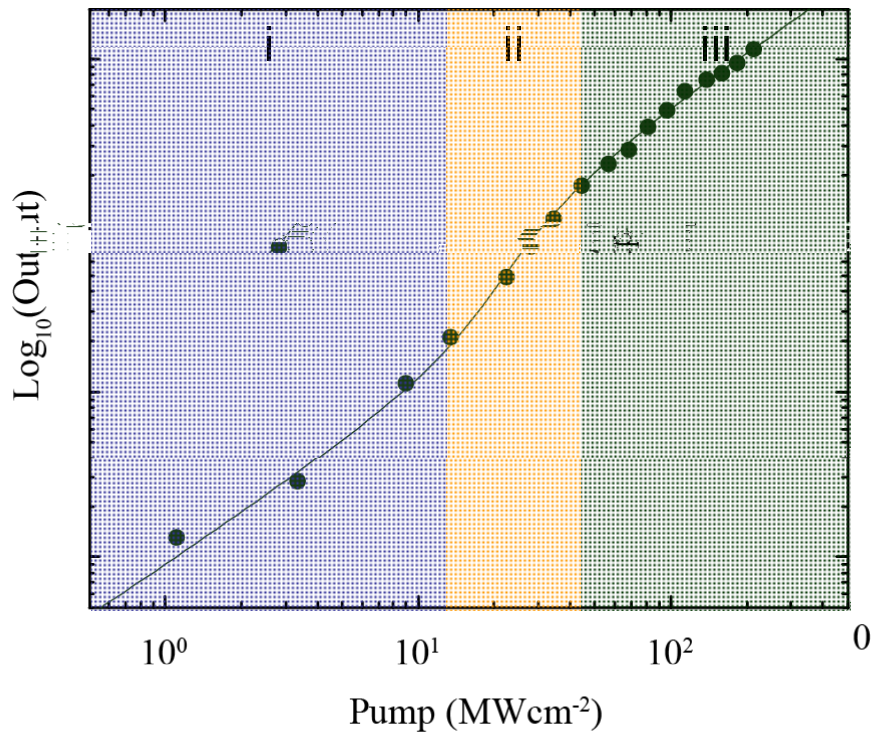
- **First plasmon laser**
- **λ^2/400 optical confinement**

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

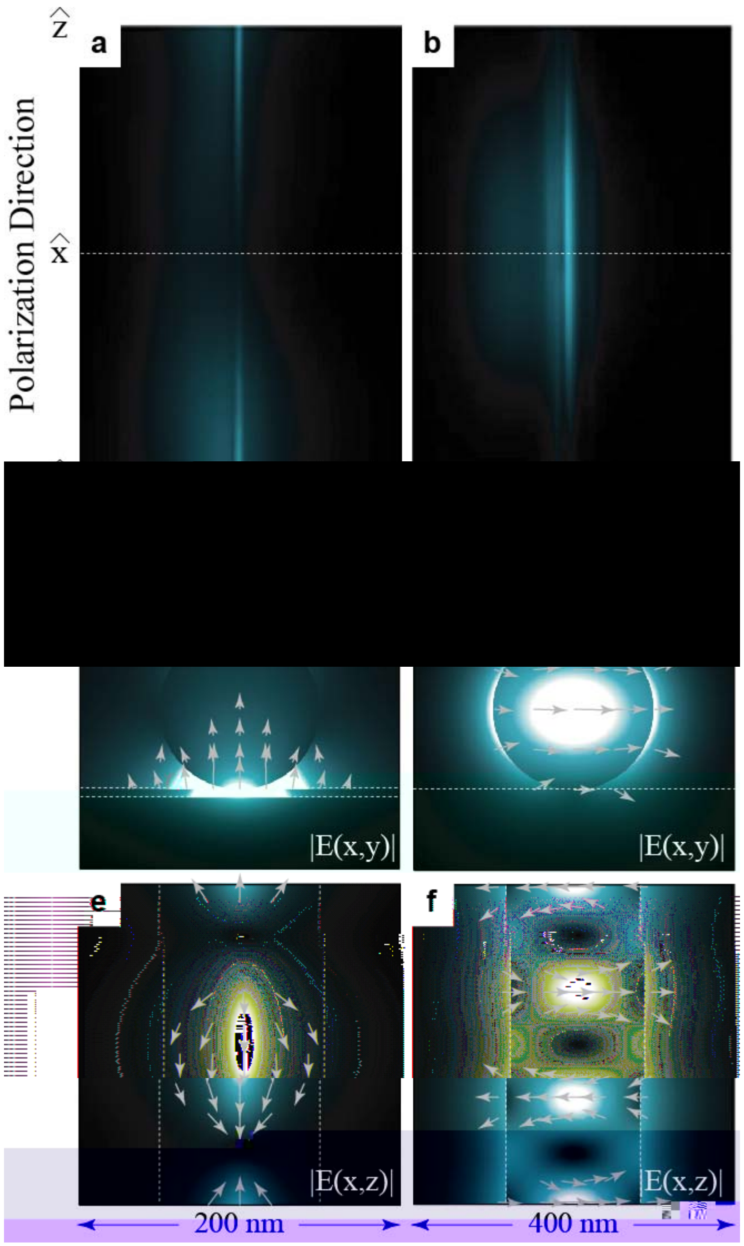


100
y (nm)
-100
|E(x,y)|
38 nm
-100
0
100
Distance x (nm)

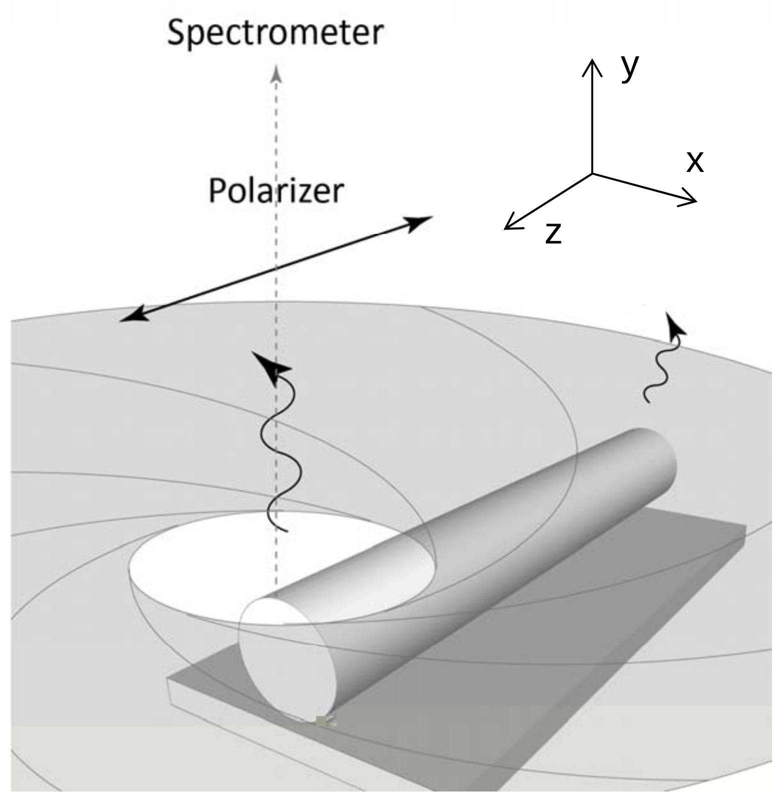

d = 129 nm
Output Power
21.3 MWcm-2
76.3 MWcm-2
131.3 MWcm-2
510 520 530 540
460 470 480 490
Wavelength (nm)


i
ii
iii
10^0 10^1 10^2
Pump (MWcm-2)

16



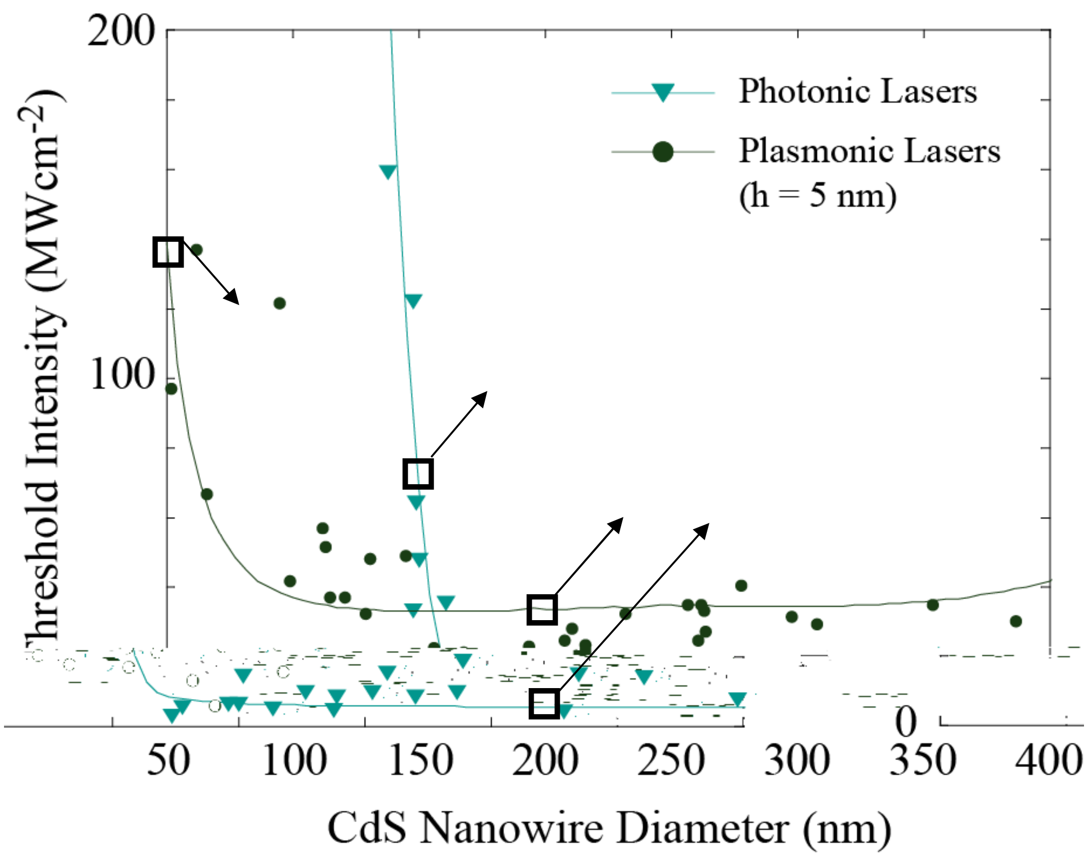
z
a
b
Polarization Direction
x
|E(x,y)|
|E(x,y)|
e
f
|E(x,z)|
|E(x,z)|
200 nm
400 nm



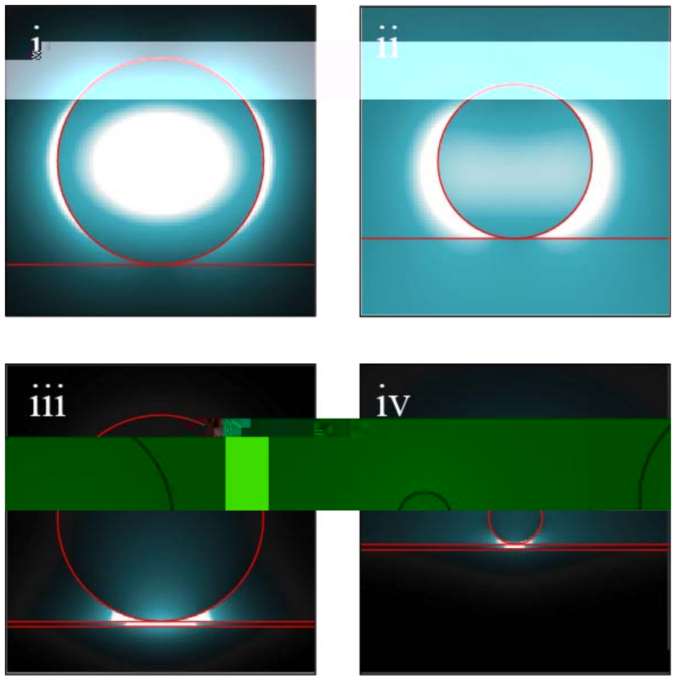
Spectrometer
Polarizer
y
x
z

∥

⊥



200
100
0
50
100
150
200
250
300
350
400
CdS Nanowire Diameter (nm)
Threshold Intensity (MWcm-2)
Photonic Lasers
Plasmonic Lasers
(h = 5 nm)



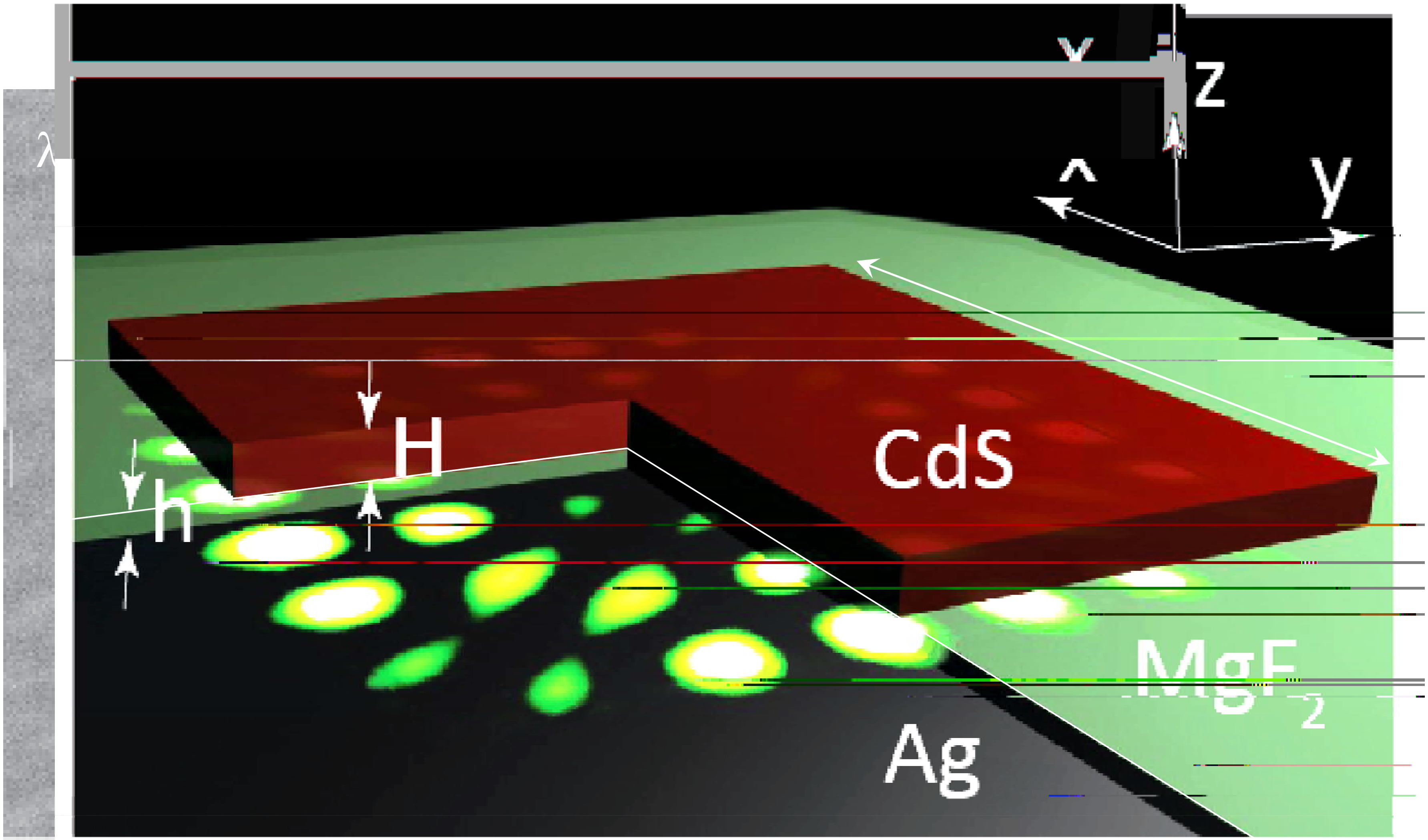
i
ii
iii
iv

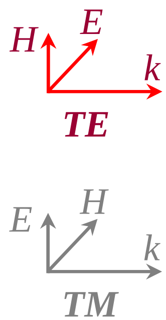
Room temperature square plasmon laser

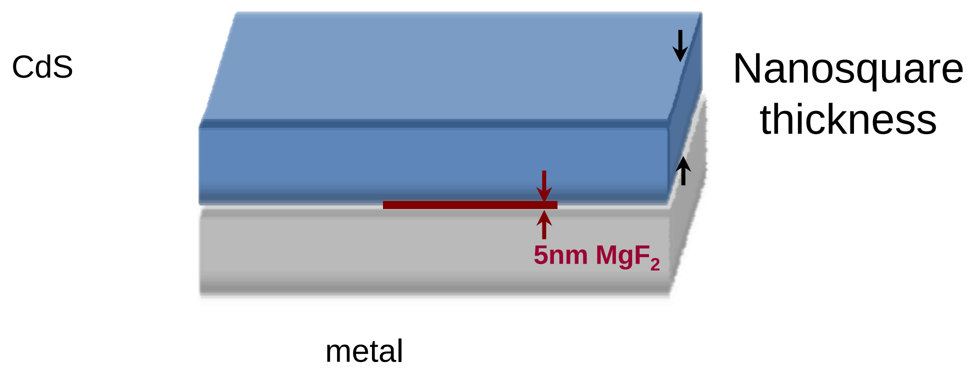
Key Features

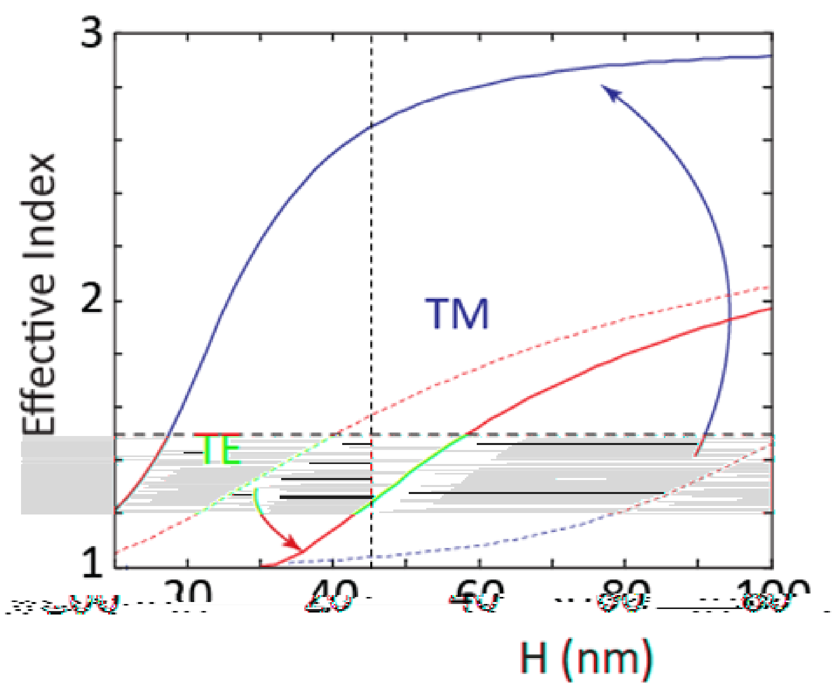
- **First room temperature operated plasmon laser**
- **Single mode**
- **Strong light-matter interaction**
- **Ultrafast speed**

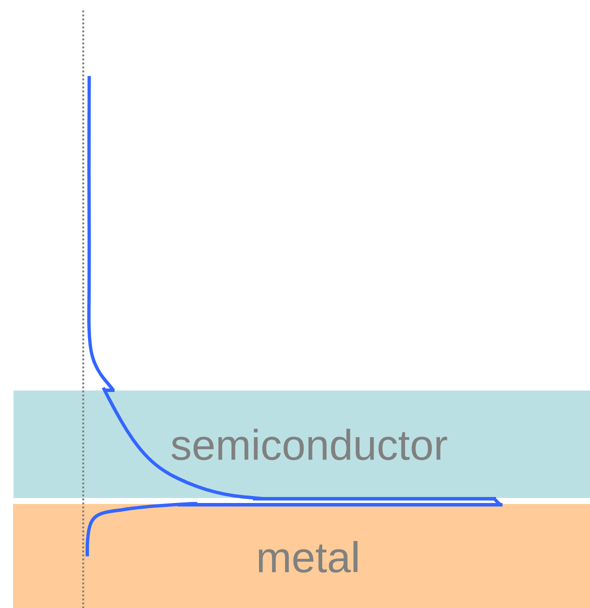
R. M. Ma et al. ***Nature Materials***, 10 (2011) 110

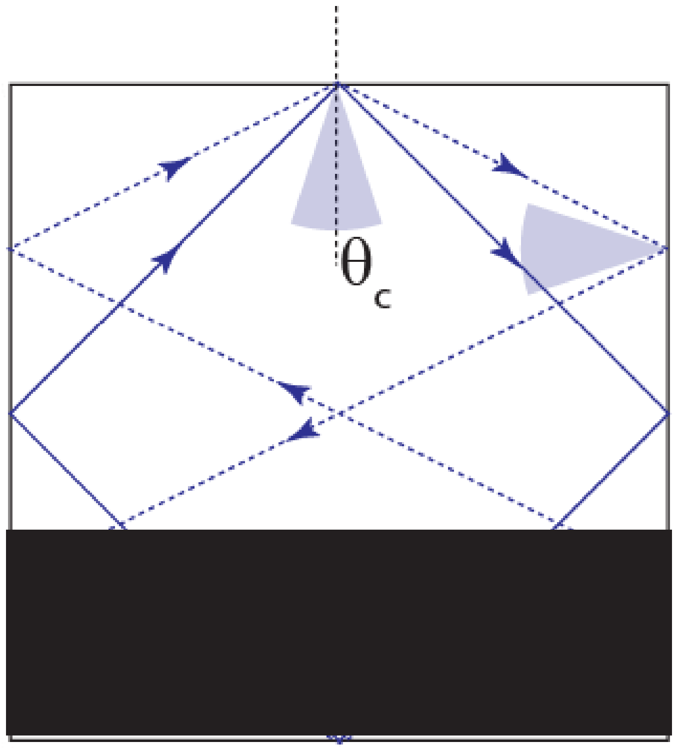

z
y
H
h
CdS
MgF2
Ag
λ

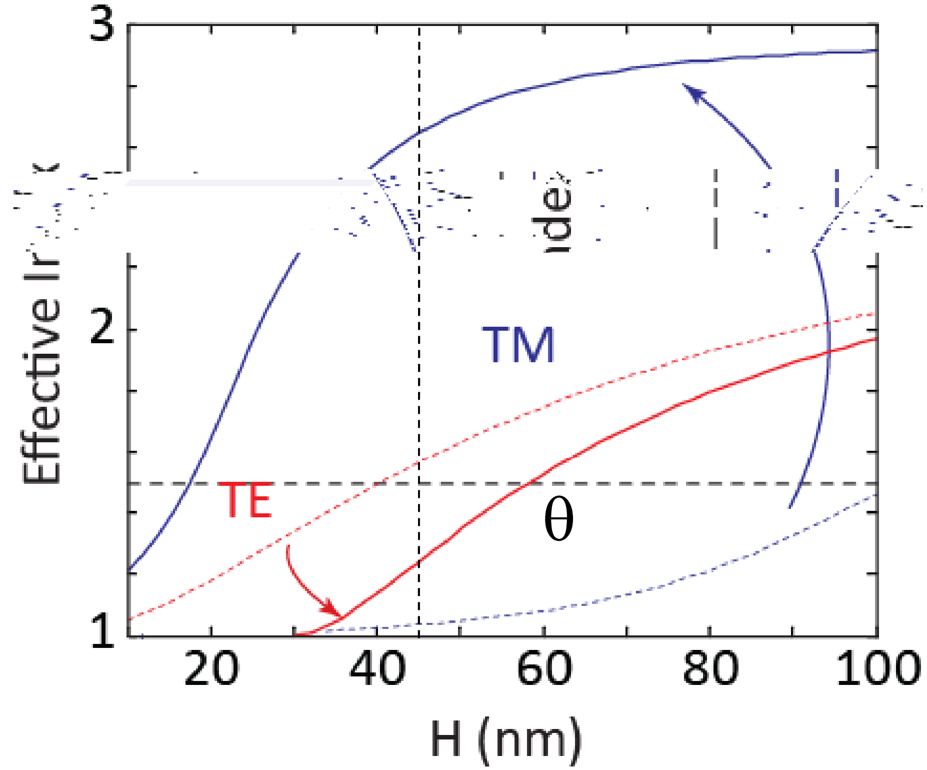

H
E
k
TE
E
H
k
TM


CdS
Nanosquare thickness
5nm MgF_2
metal


Effective Index
3
2
1
TM
TE
H (nm)

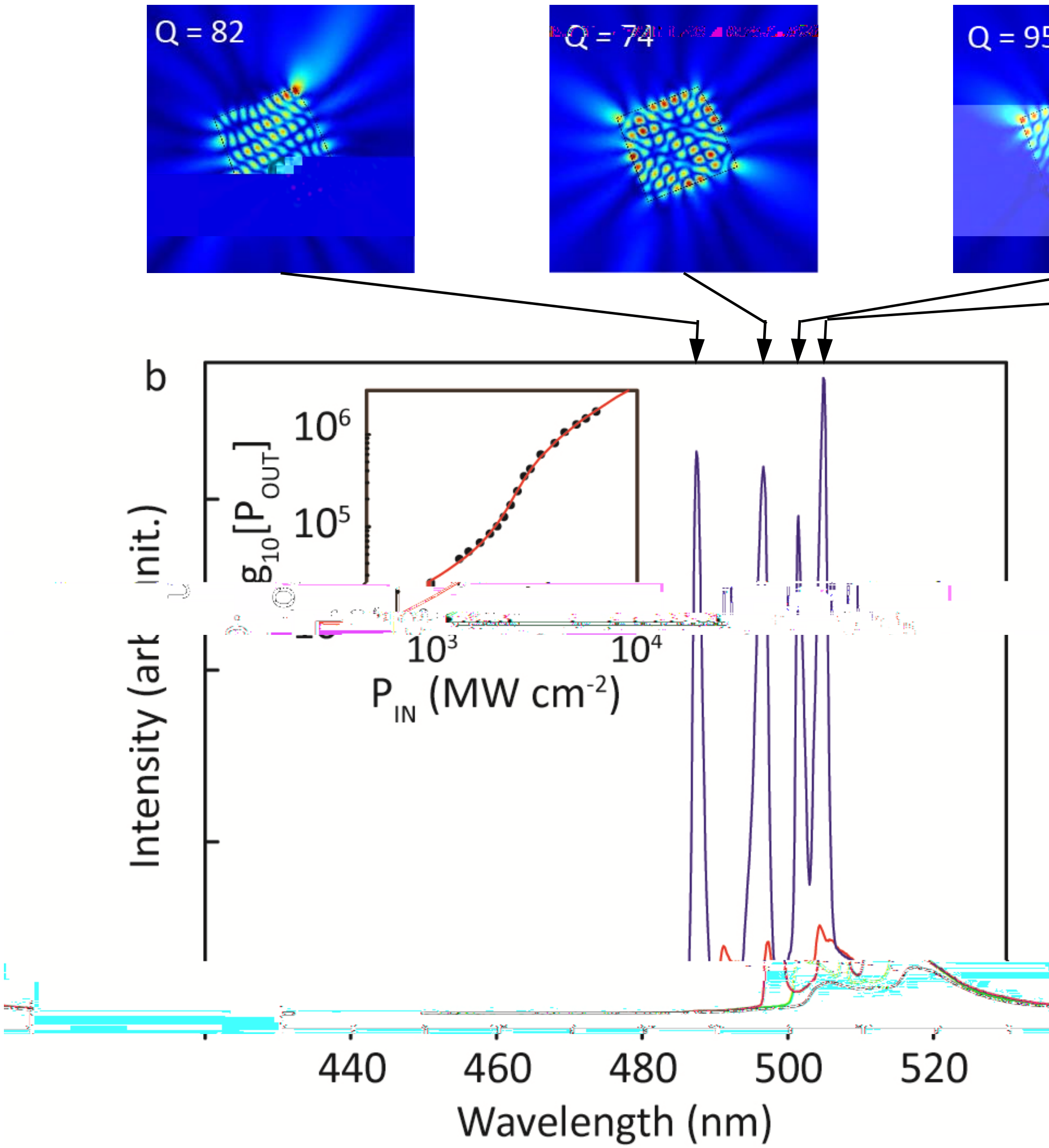

semiconductor
metal

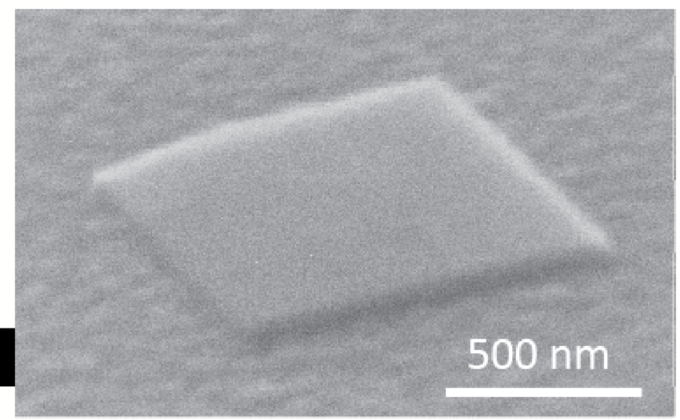


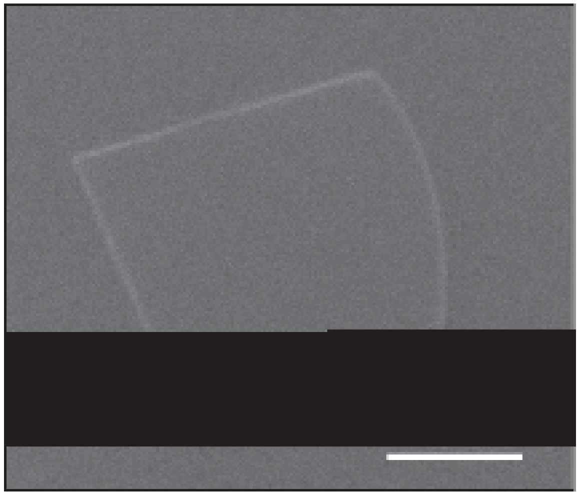


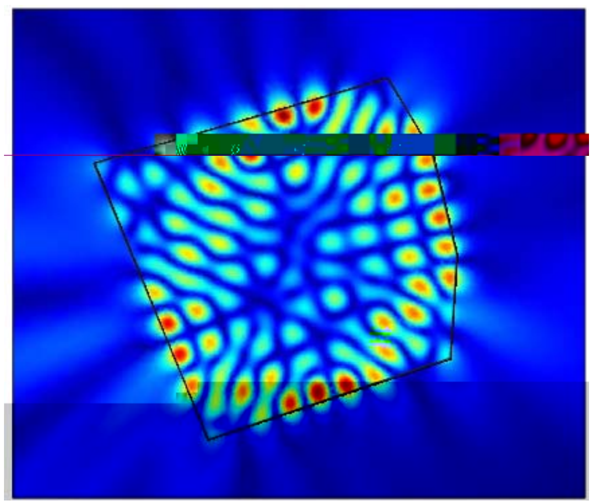
Photonic mode can NOT lase

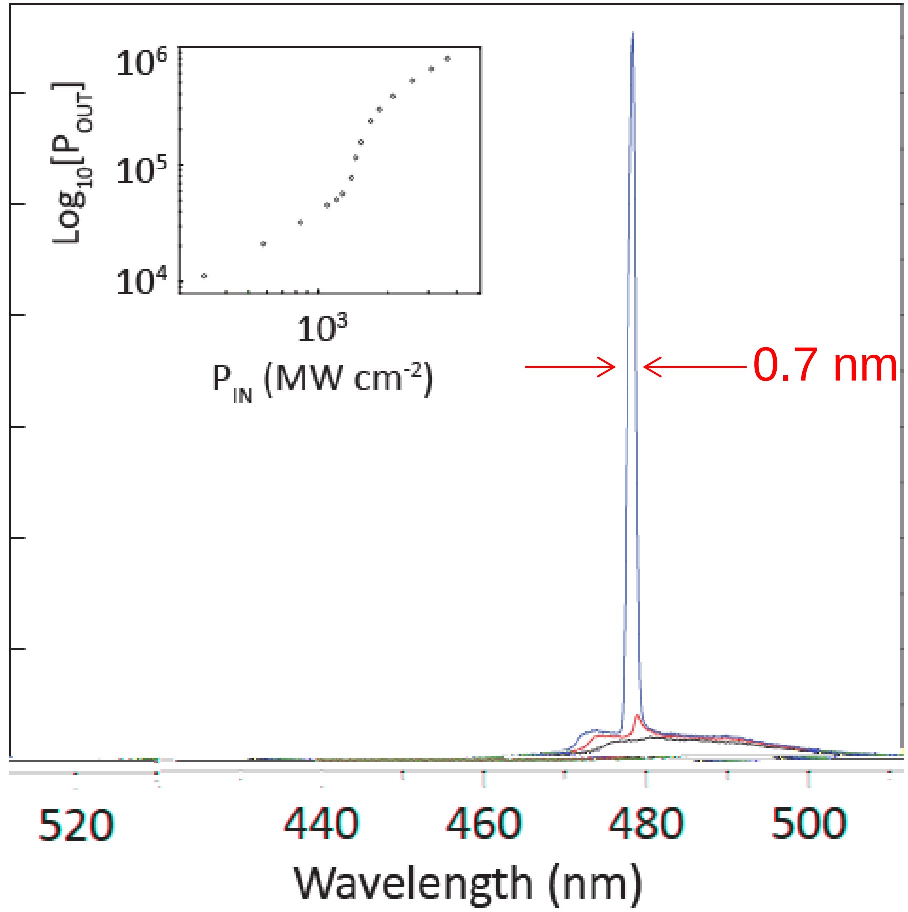
Plasmon mode has lower loss than photonic mode


Q = 82
Q = 74
Q = 95
Q = 130
b
10^6
10^5
10^3
10^4
P_{IN} (MW cm^{-2})
440
460
480
500
520
Wavelength (nm)


500 nm



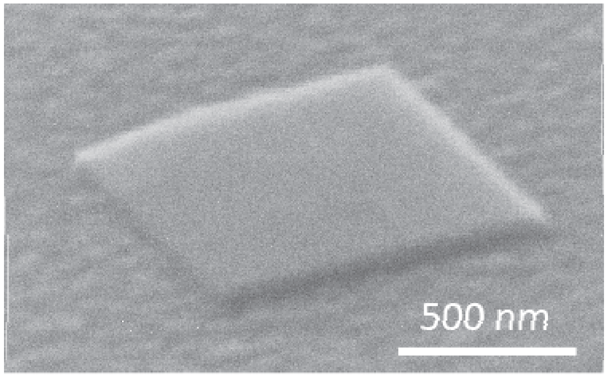




Room temperature, single mode

Plasmon mode has lower loss than photonic mode

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



Fermi's Golden Rule:

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

Field Enhancement

Modified PDOS

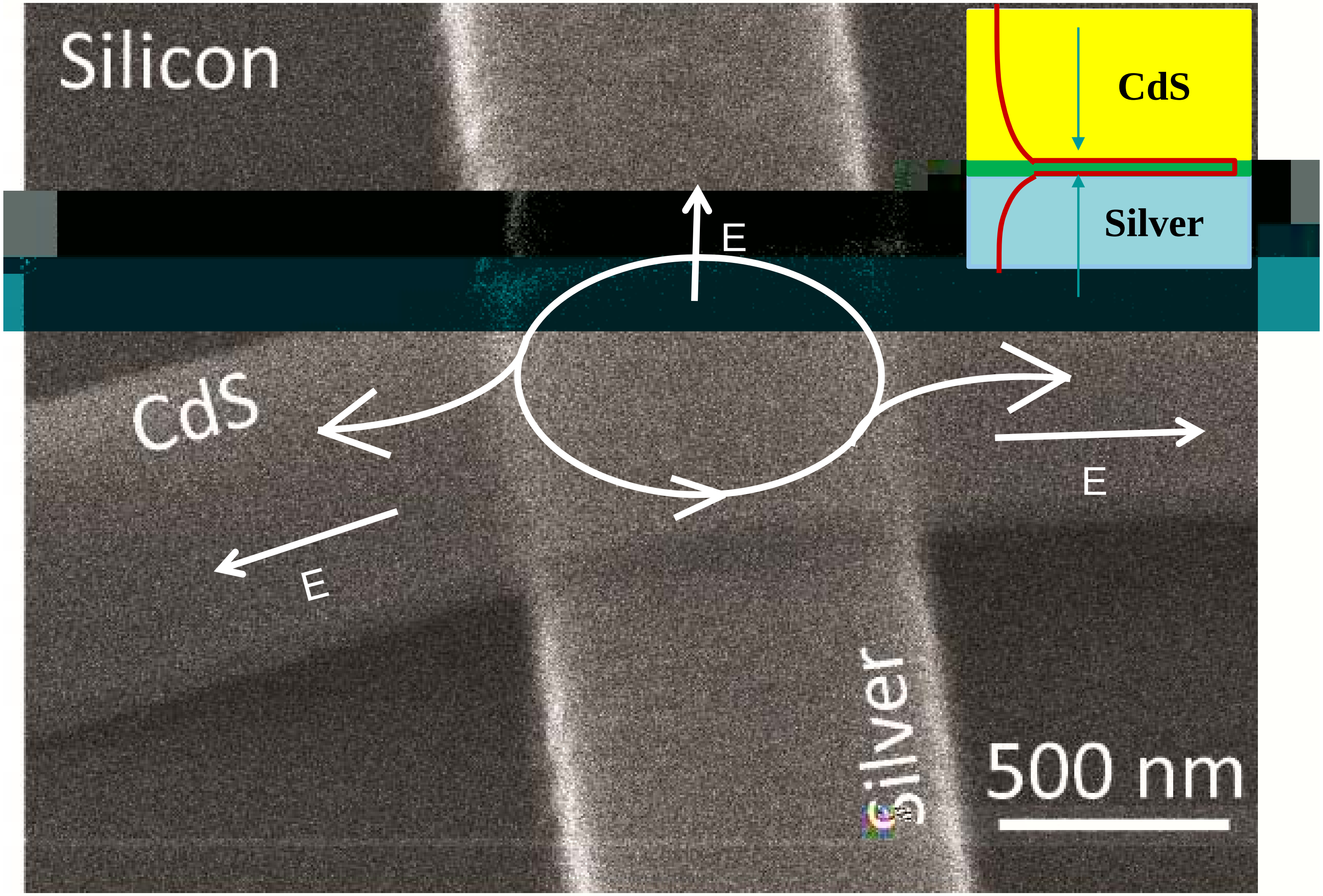
New configuration: Waveguide Embedded (WEB) Plasmon Laser

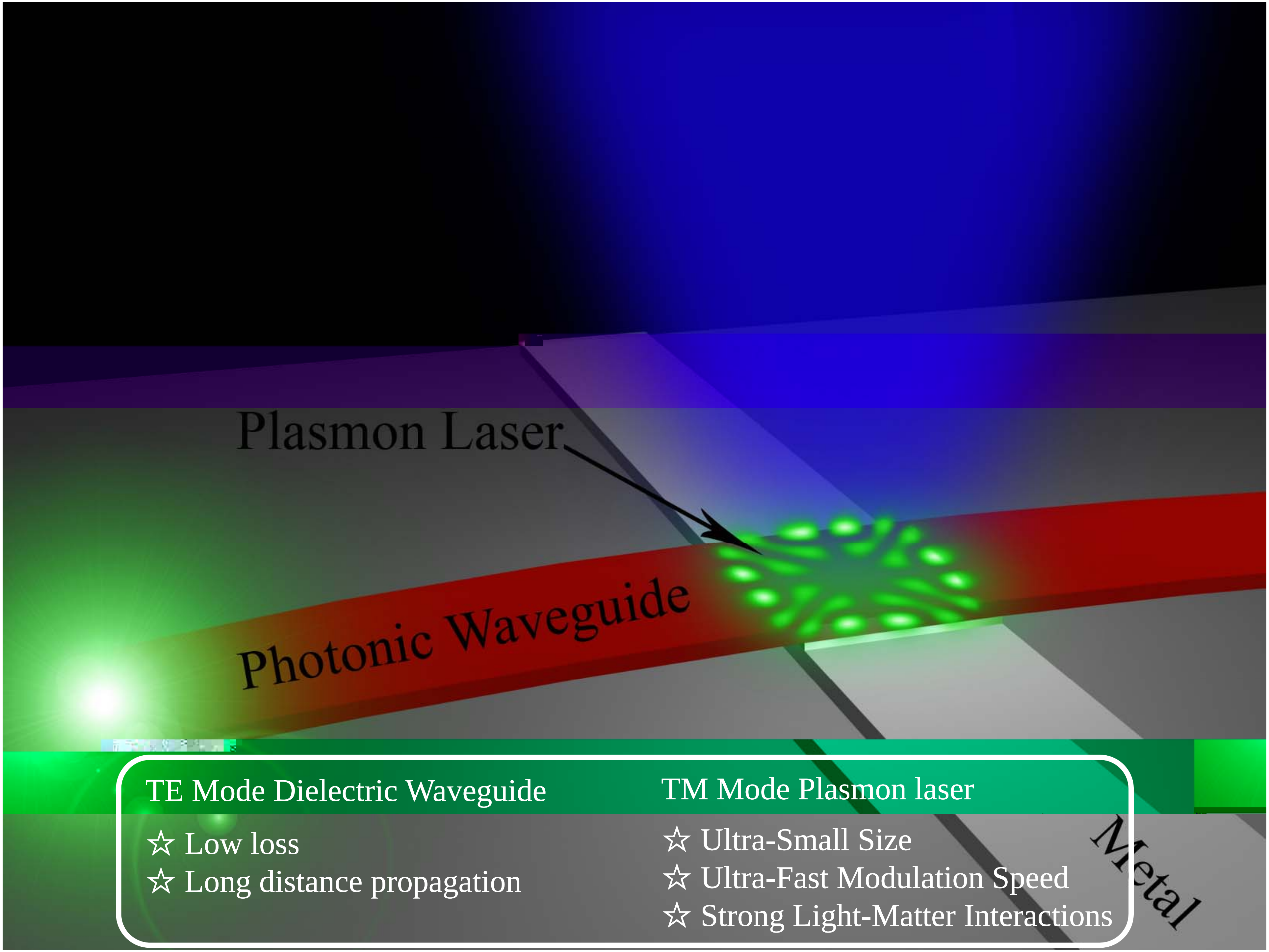
Key Features

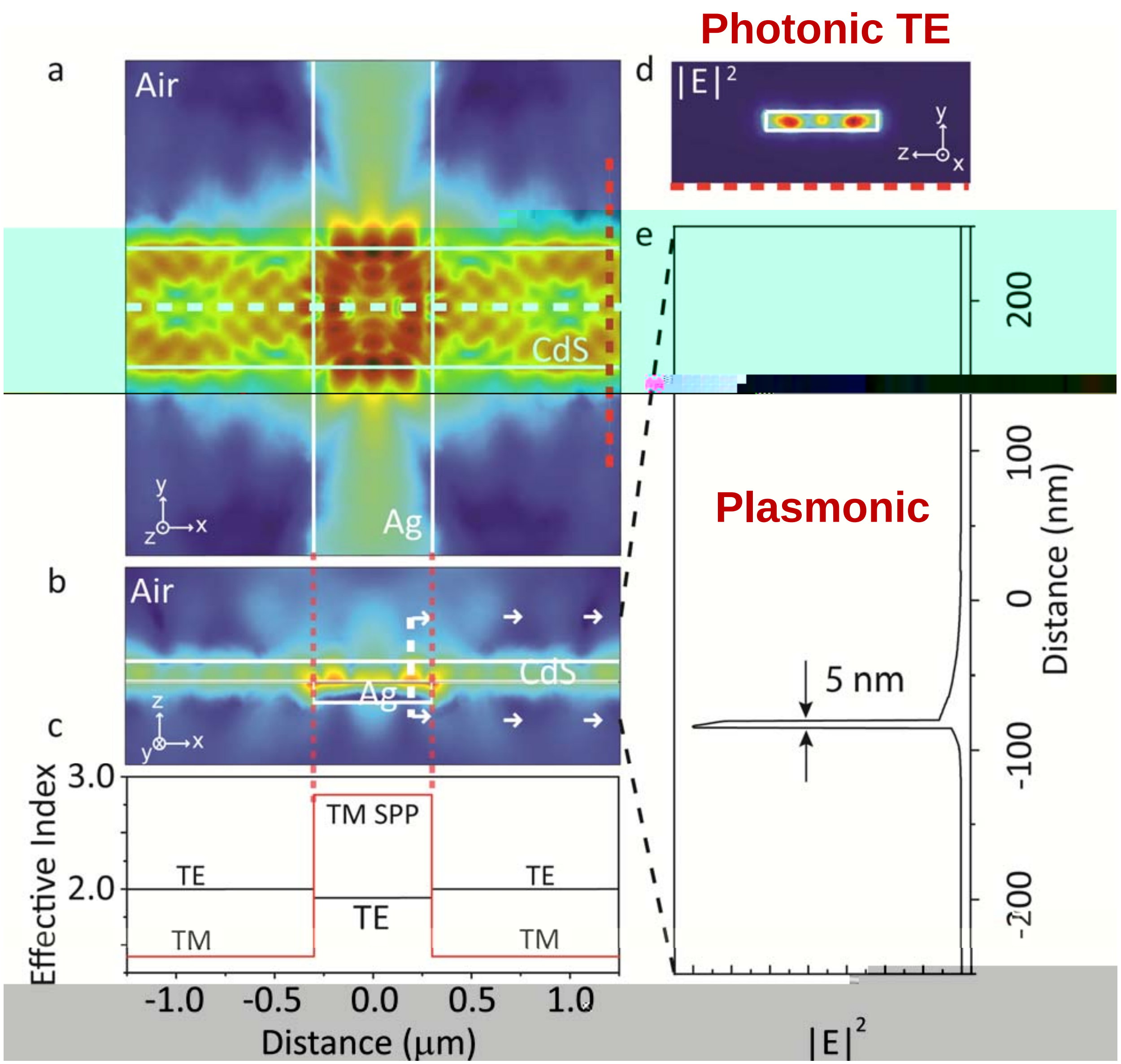
- **First directionally emitted plasmon laser**
- **High extrinsic efficiency**
- **Break parasitic loss limitation**

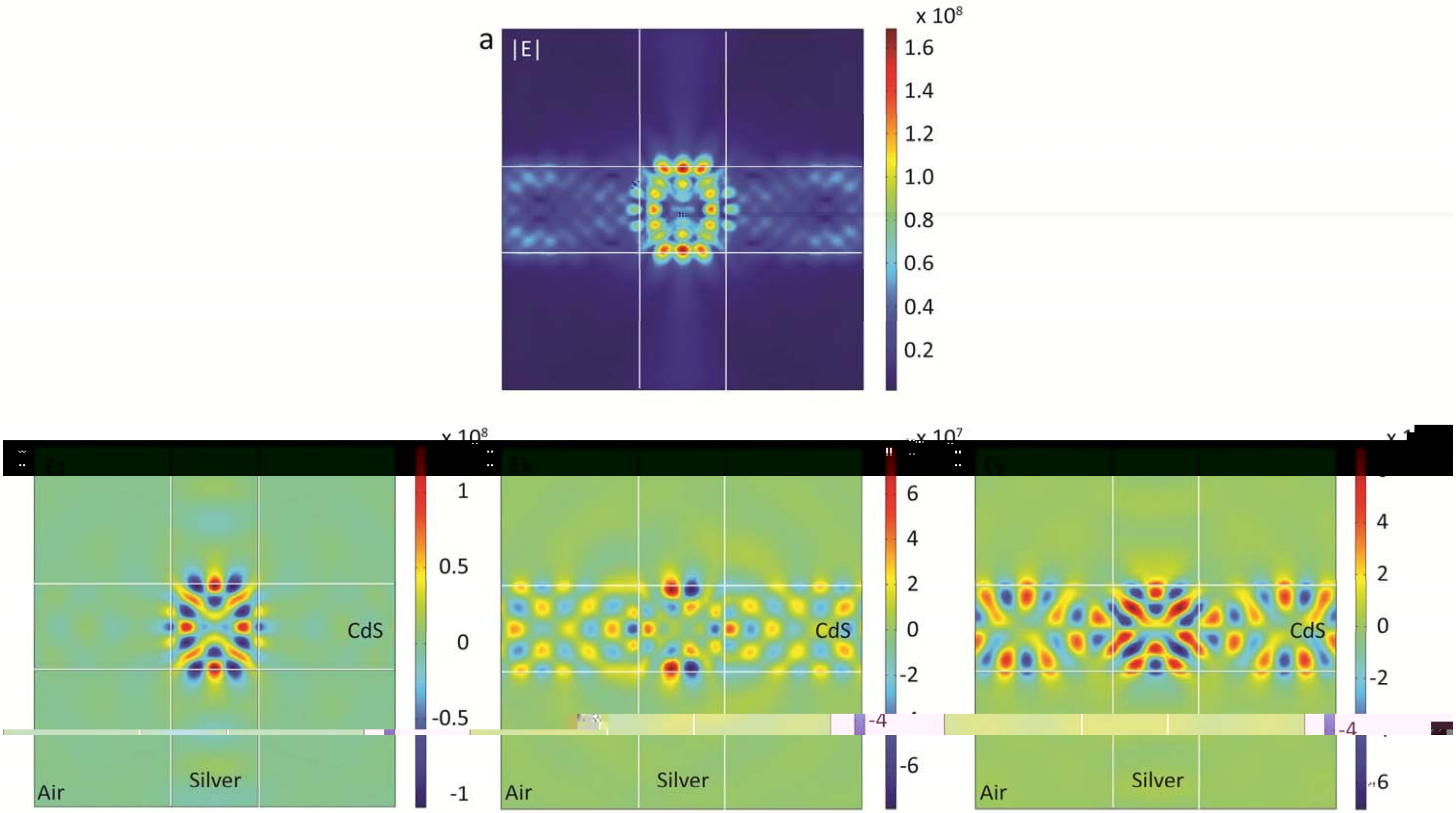
R. M. Ma et al. ***Nano Letters*** **12 (2012) 5396.**

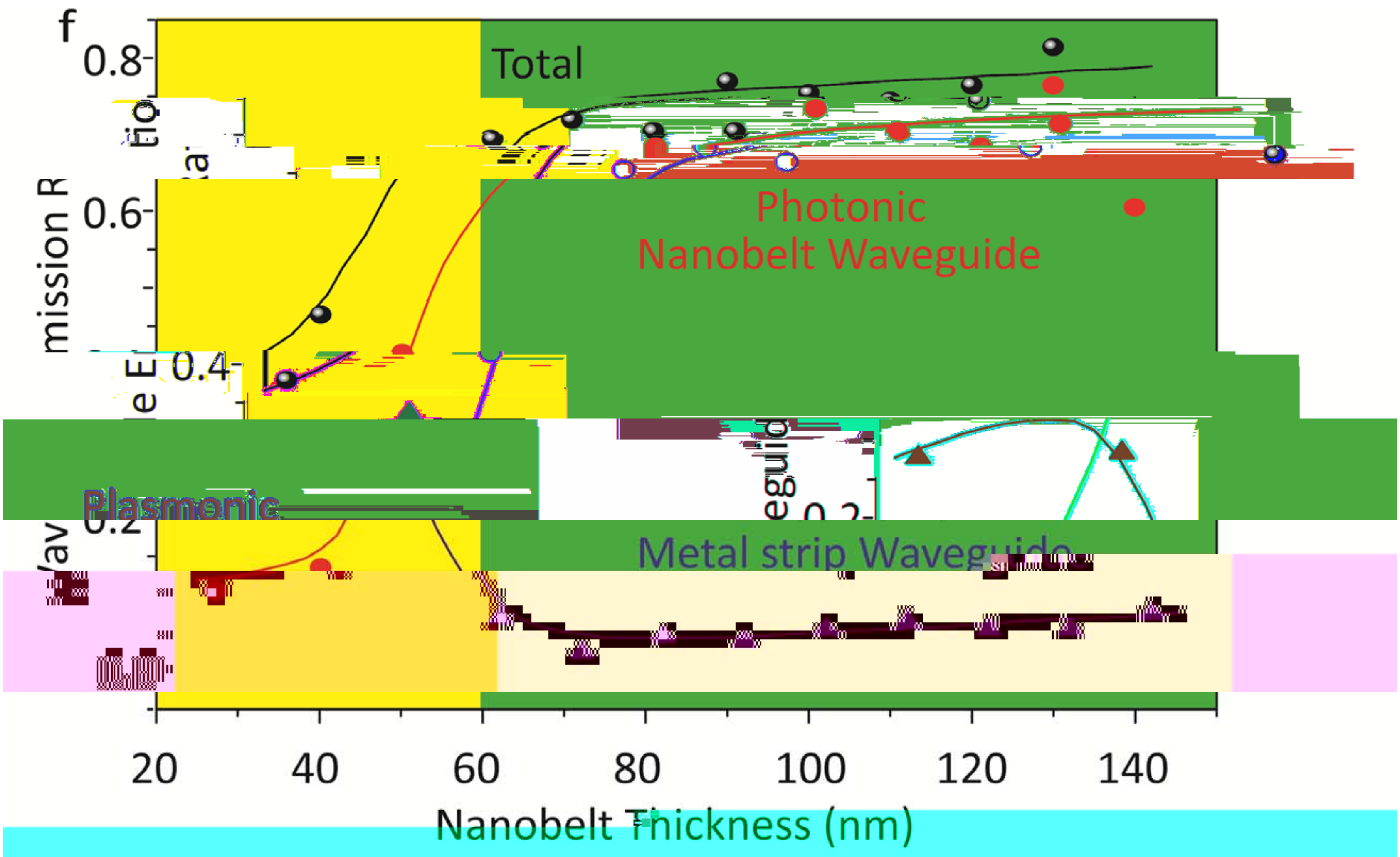
Plasmon TM mode cavity photonic TE mode waveguide?



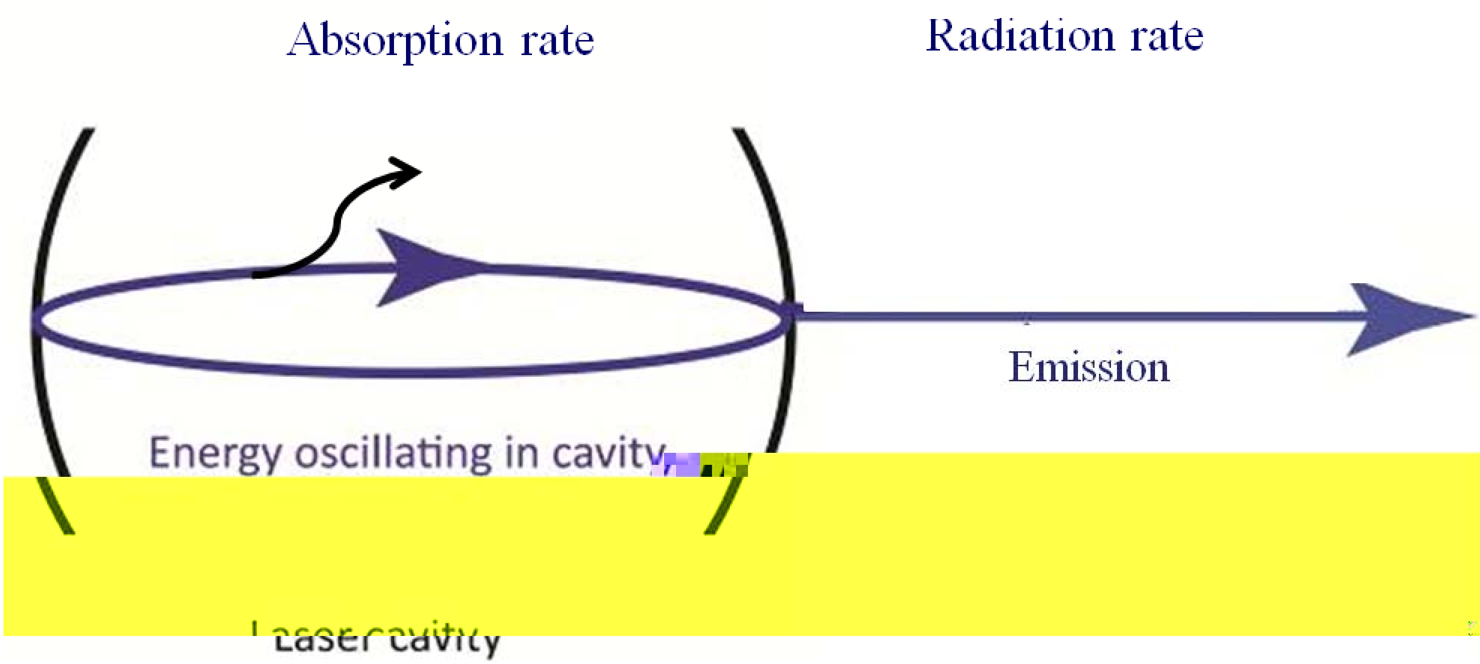

Plasmon Laser
Photonic Waveguide
Metal
TE Mode Dielectric Waveguide
☆ Low loss
☆ Long distance propagation
TM Mode Plasmon laser
☆ Ultra-Small Size
☆ Ultra-Fast Modulation Speed
☆ Strong Light-Matter Interactions


Photonic TE
a
Air
CdS
Ag
b
Air
CdS
Ag
c
Effective Index
3.0
2.0
TM SPP
TE
TE
TE
TM
TM
-1.0 -0.5 0.0 0.5 1.0
Distance (μm)
d
|E|²
e
200
100
0
-100
-200
Distance (nm)
Plasmonic
5 nm
|E|²


a
|E|
x 10^8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
1
0.5
0
-0.5
-1
CdS
Air
Silver
6
4
2
0
-2
-4
-6
CdS
Air
Silver
4
2
0
-2
-4
-6
CdS
Air
Silver



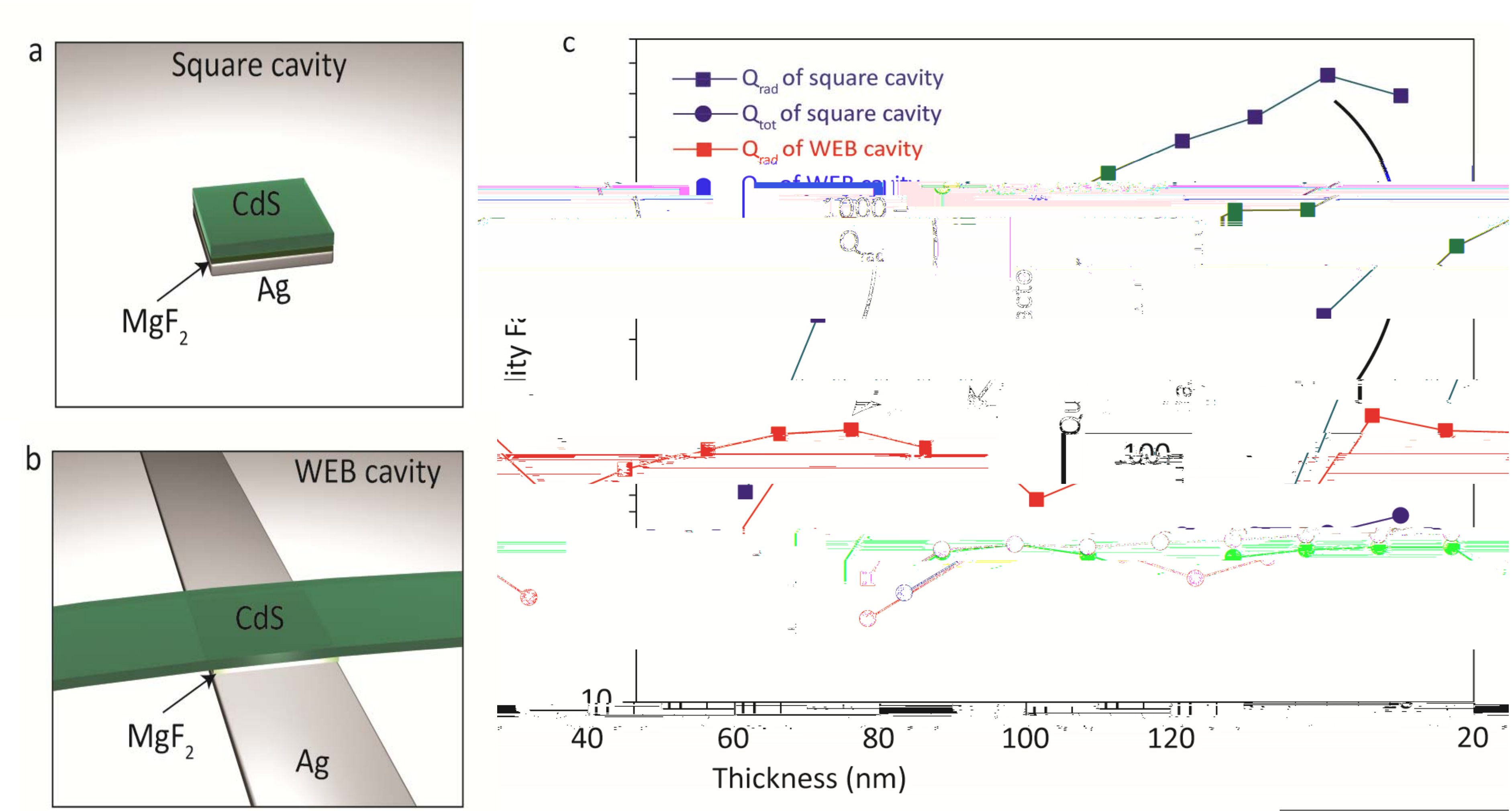
>70% radiation of **Plasmon laser** launched to **Photonic waveguide**



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!

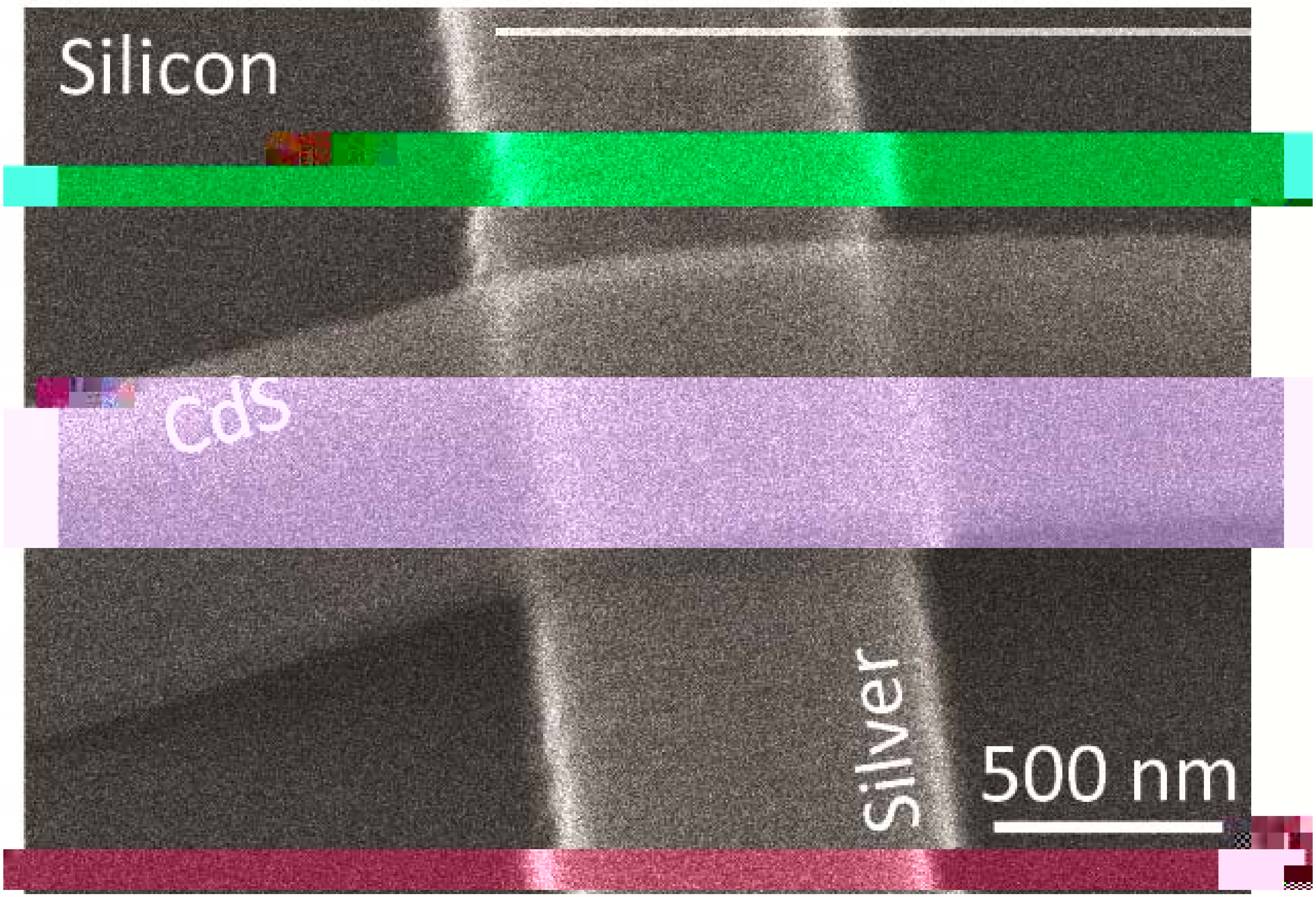


Radiative efficiency 2 % 40 %

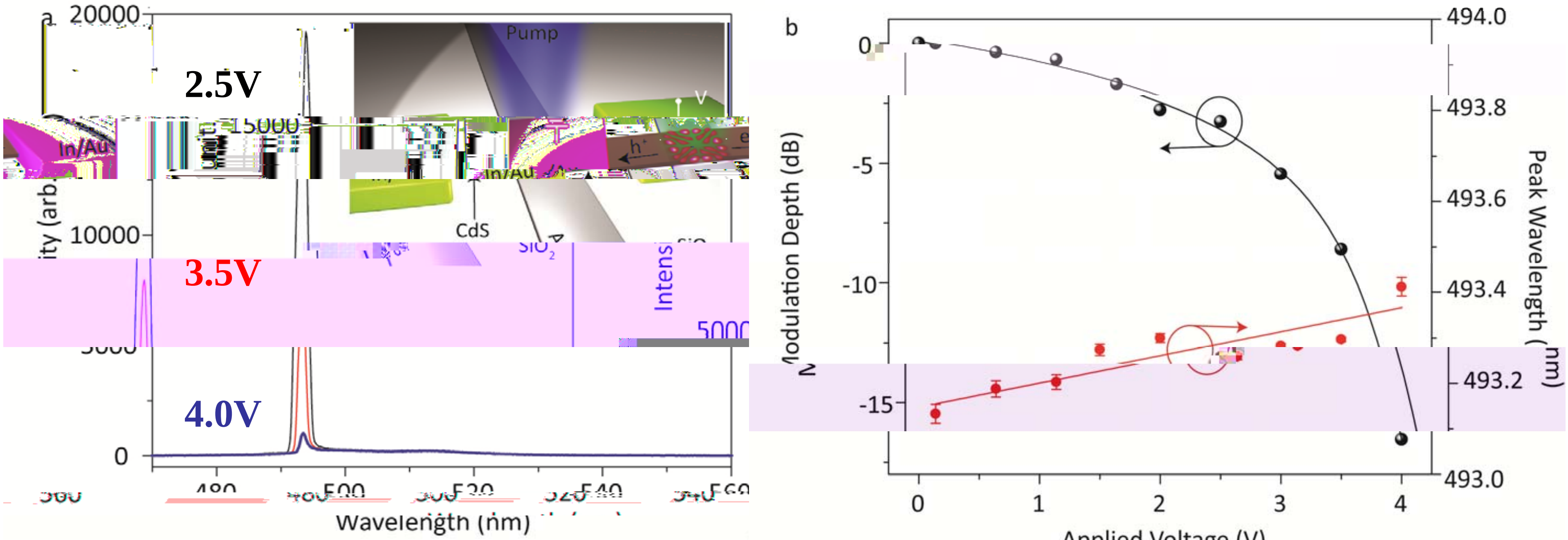
WEB plasmon laser circuits

Key Features

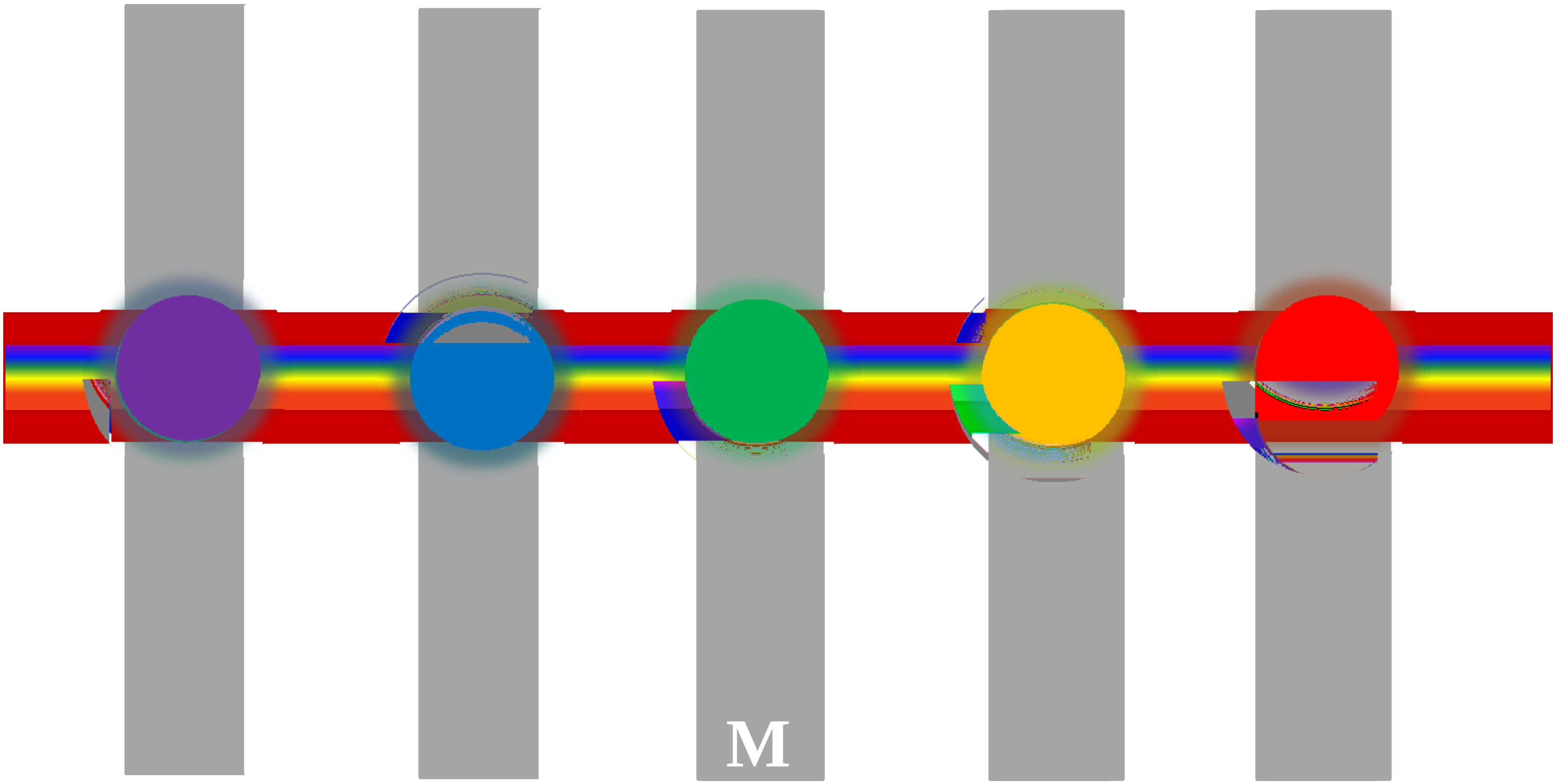
- **New architecture for ultra-compact circuits**
- **Four key**



Electrical interface without jeopardizing the plasmon modes

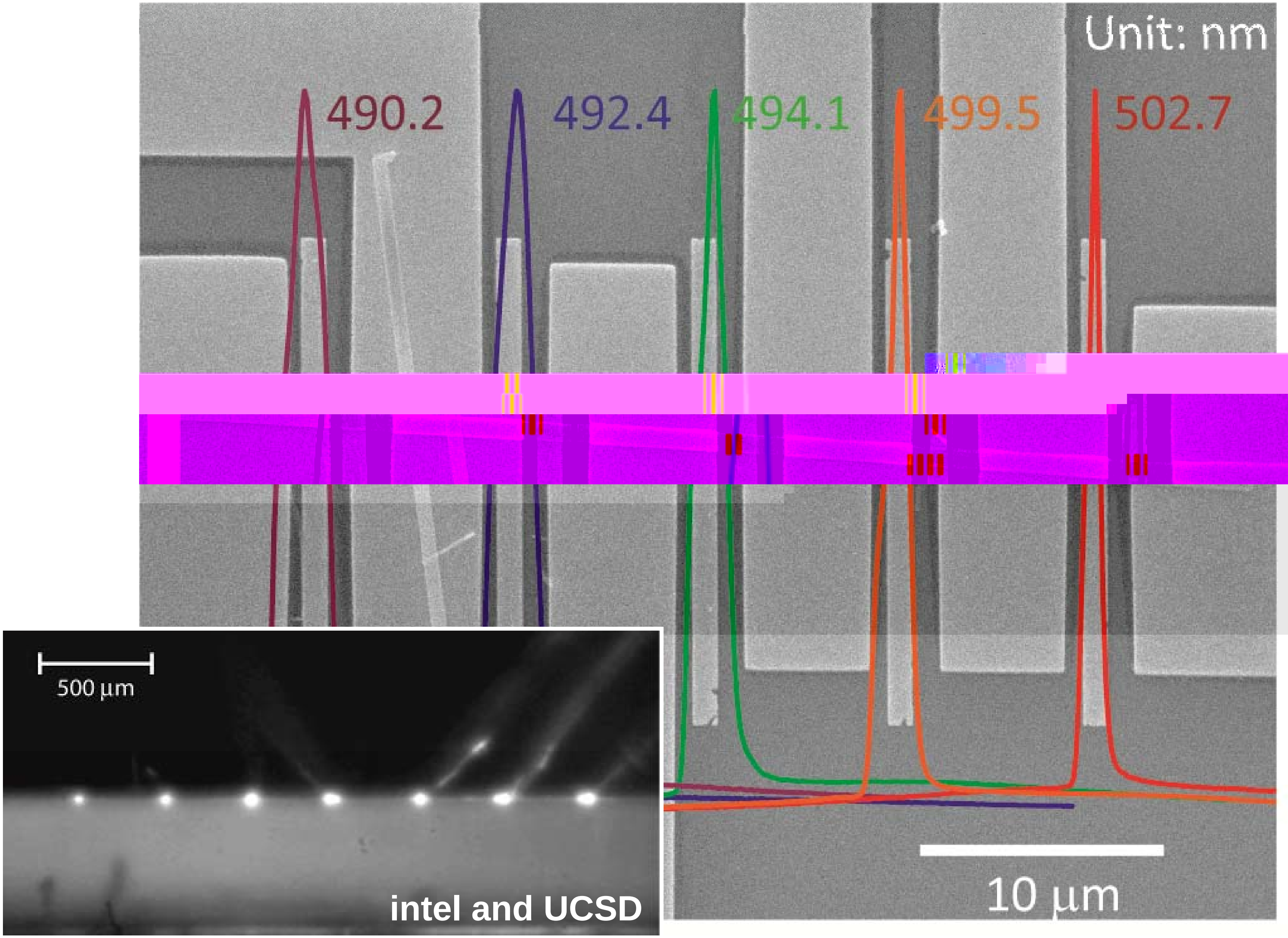


Modulation depth: 16 dB for a peak bias of 4 V

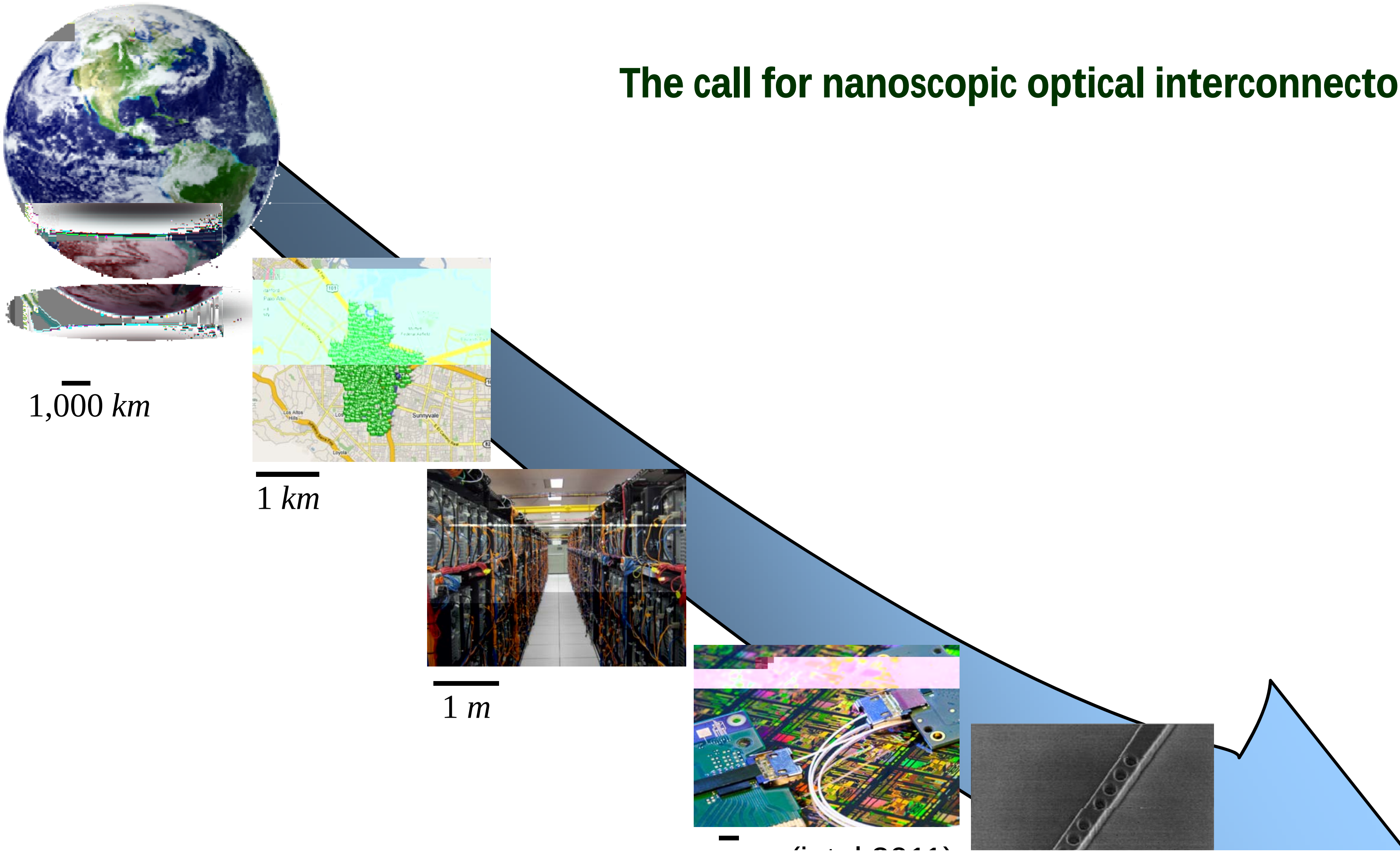


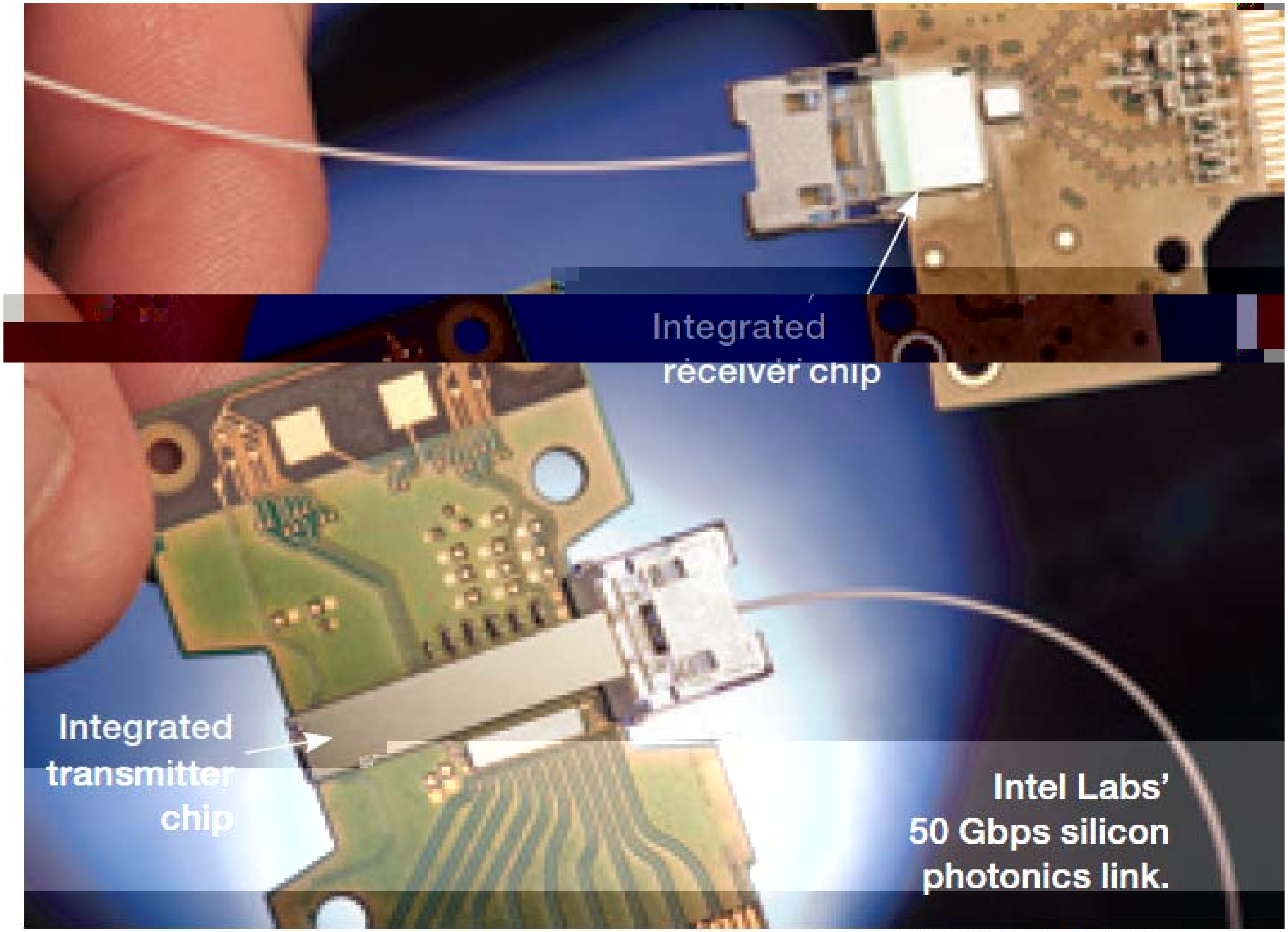
Multi-Color Plasmon Laser Array

Wavelength Multiplexing


Unit: nm
490.2
492.4
494.1
499.5
502.7
10 µm
500 µm
intel and UCSD

The call for nanoscopic optical interconnector:

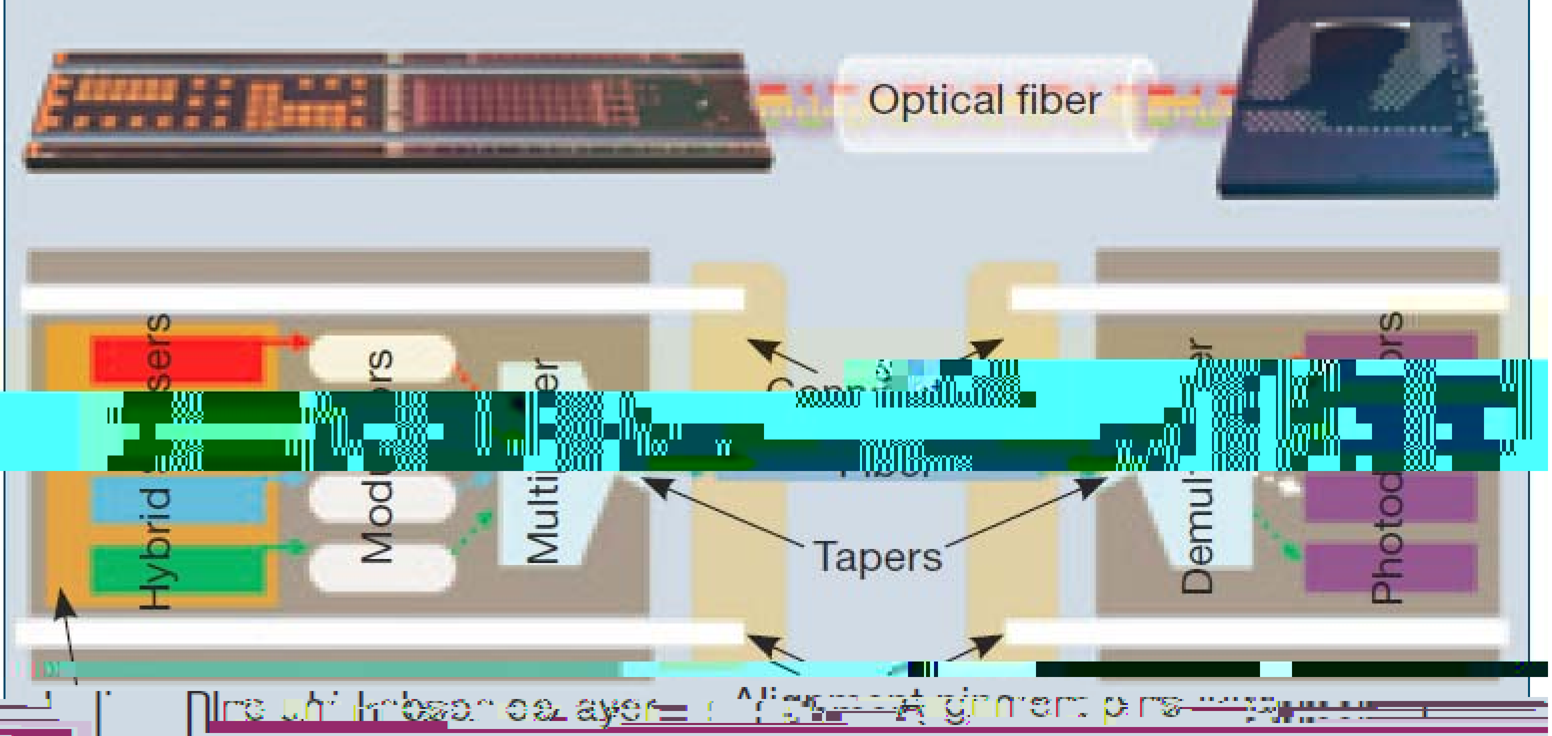




Courtesy of Intel Corp.

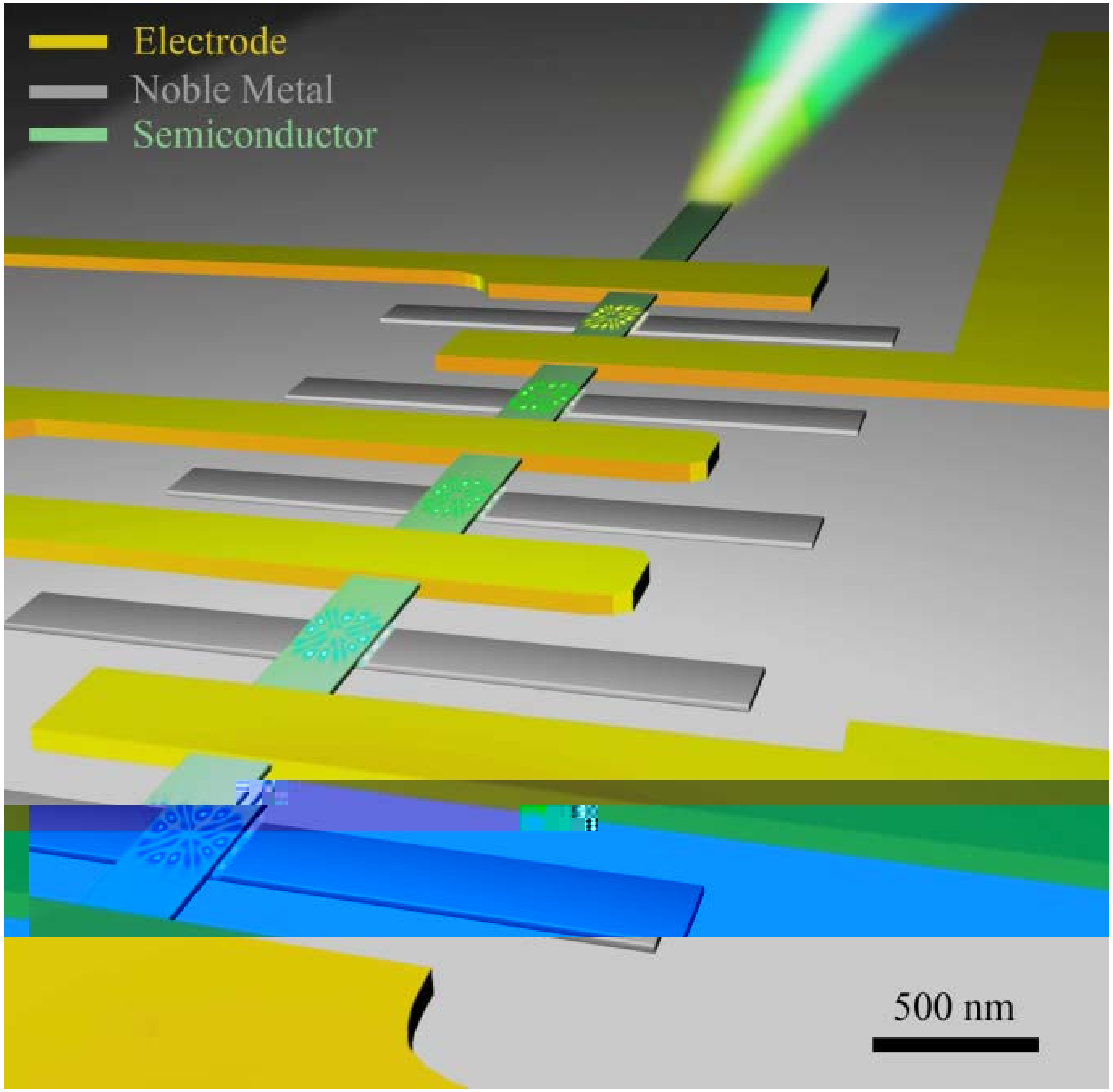
[Key silicon photonic elements]

Courtesy of Intel Corp.

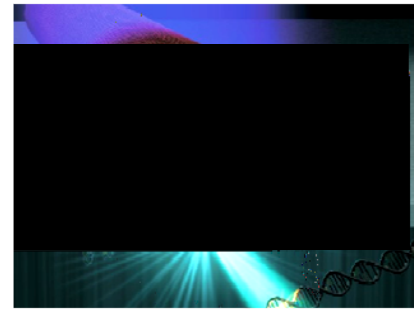


itter

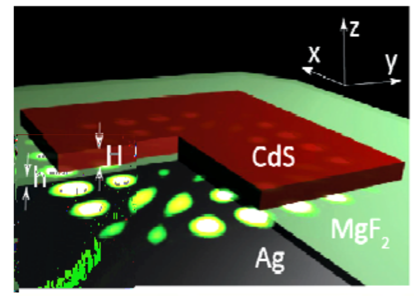
The link’s key silicon photonic elements, with the silicon photonic transm
chip on the left and the silicon photonic receiver chip on the right.


Electrode
Noble Metal
Semiconductor
500 nm

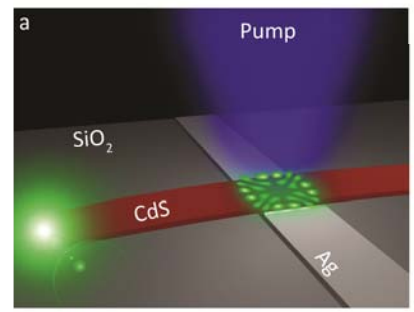
- First plasmon laser
- λ^2/400 optical confinement



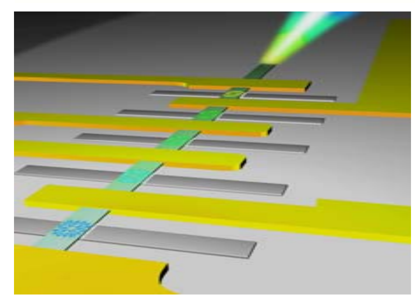
- First room temperature operated plasmon laser
- Single mode
- Strong light-matter interaction
- Ultrafast speed



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



- **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. Yu Ye, Ms. Ania Labno, Mr. David Barth

Thanks for your attention!

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