International Workshop Meta-Optics and Metamaterials, IBS

Plasmonic Engineering in Subwavelength Space

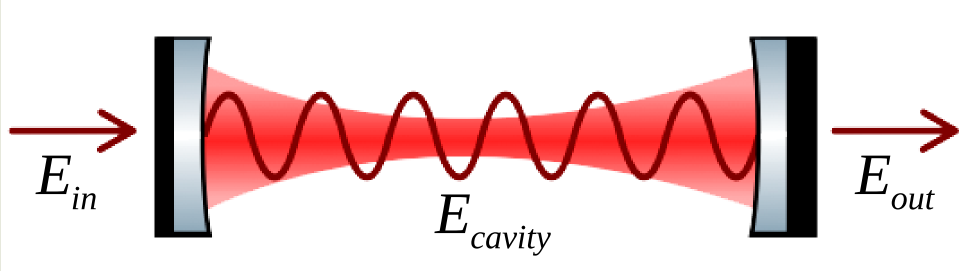
04/ 26/ 2018

Myung-Ki Kim

KU-KIST 융합대학원

KU-KIST Graduate School of Converging Science and Technology

OPTICAL CAVITIES/RESONATORS



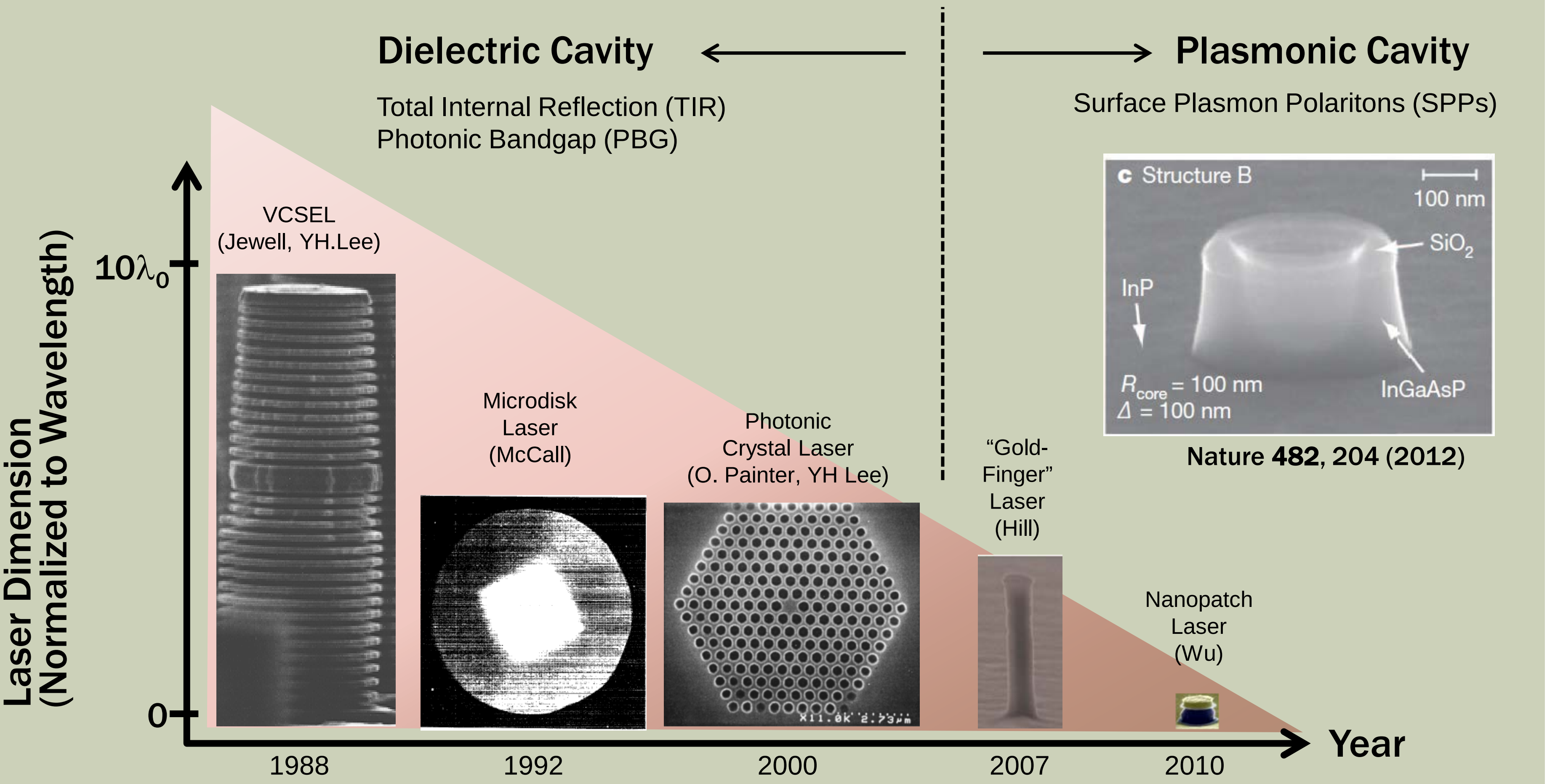
$$\frac{|E_{cavity}|^2}{|E_{in}|^2} = \left[\eta_{coupling} \cdot 4c \cdot \frac{A_{eff}}{n_{eff}} \right] \times \boxed{\frac{Q}{V_m}}$$

Small Volume
High Quality Factor

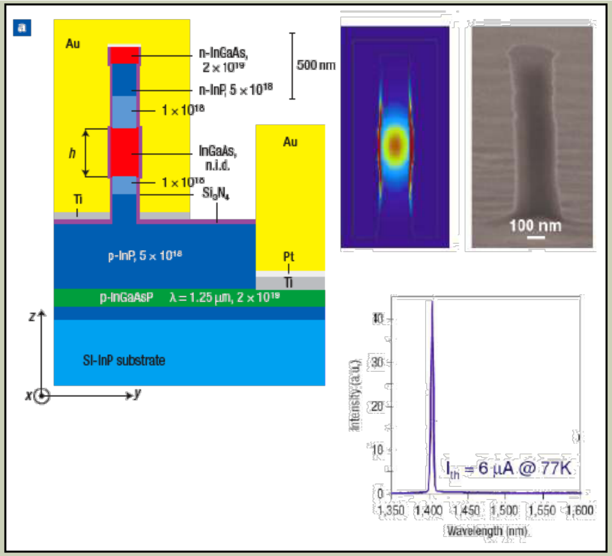
Various Applications with Optical Resonators

- *Small-Footprint, High-Performance Optical Communication Devices*
  - Lasers, Detectors, Modulators, Amplifiers etc.
- *Highly-Sensitive Various Optical Sensors*
- *Efficient Single Photon Sources*
- *Metamaterials*

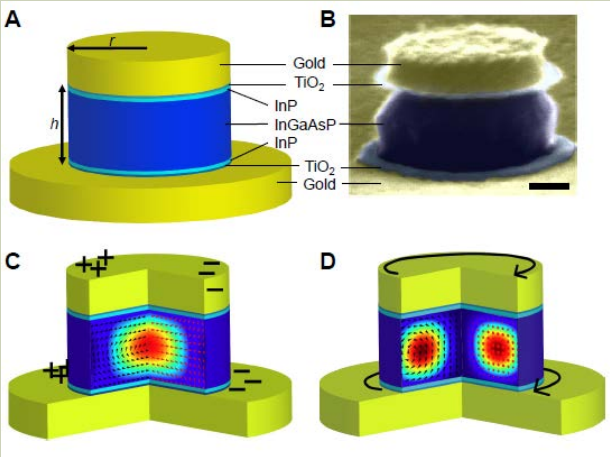
TOWARDS SMALLEST CAVITIES



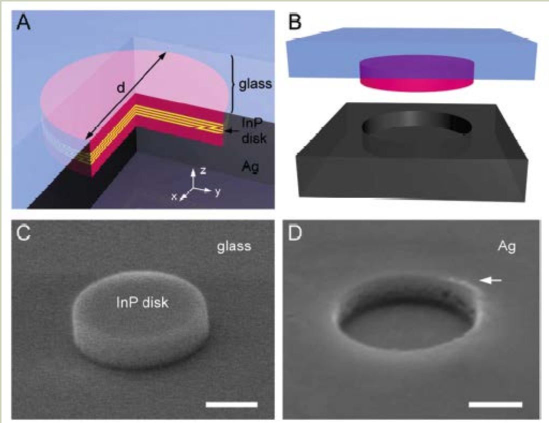
SUB-WAVELENGTH PLASMONIC CAVITIES



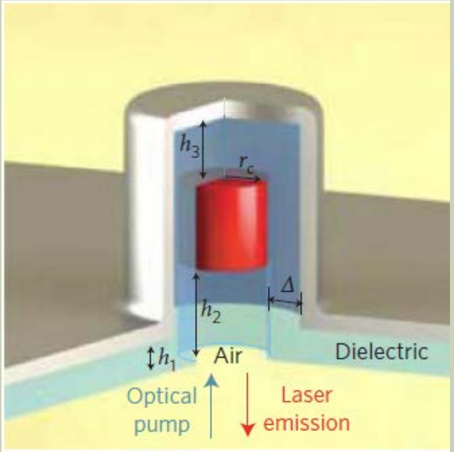
M. T. Hill et al, Nature Photon. (2007)

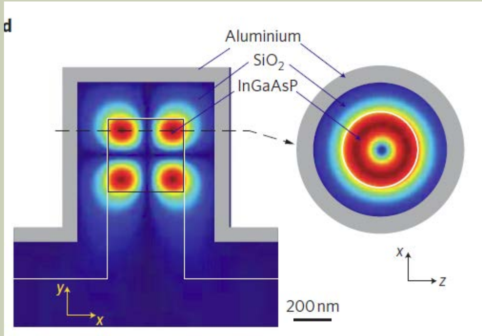


K.-S. Yu et al, Opt. Express (2010)

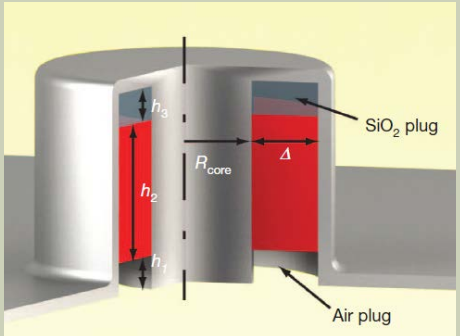


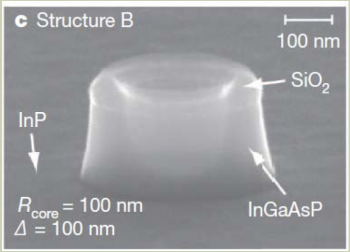
S.-H. Kwon et al., Nano Lett. (2010)





M. P. Zezhad et al, Nature Photon. (2010)



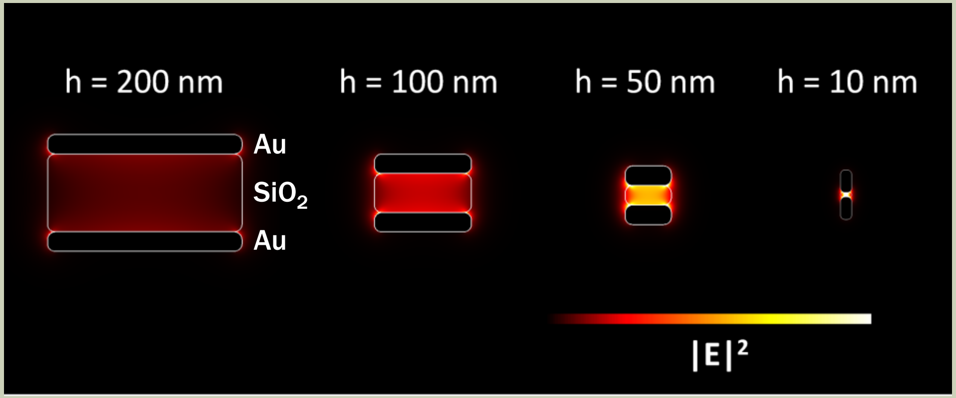


M. Khajavikhan et al., Nature (2012)

PLASMONIC CAVITY LASERS

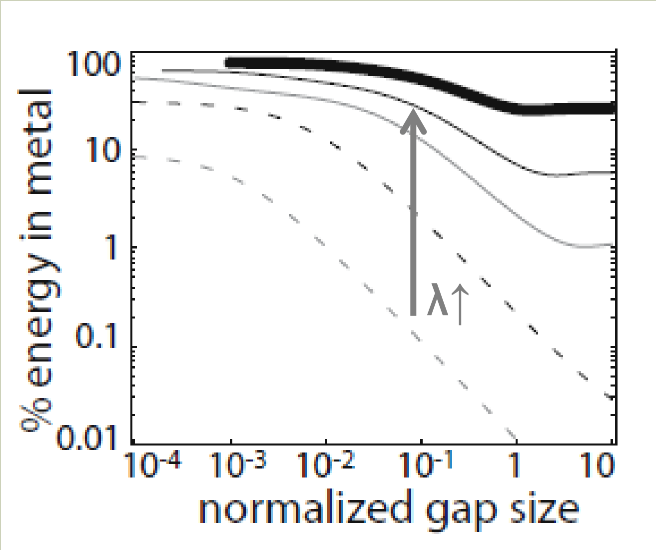
Type	Q (at RT)	V_{mode} $(\lambda/2n)^3$	Γ	Pump.	$\eta_{coupling}$	Temp. (K)
M. Hill	48 (gold)	0.38	43 %	Electrical	N.A.	10, 77K
NanoPatch (UCB)	65 (gold)	0.54	84 %	Optical	N.A.	77K
NanoPan (KAIST)	~110 (silver)	0.56	-	Optical	N.A.	8, 80K
UCSD	1004 (aluminum)	5.2	46 %	Optical	N.A.	300K
UCSD	300 (silver)	0.3	70 %	Optical	N.A.	4.5K

LARGE ABSORPTION LOSS BY METAL

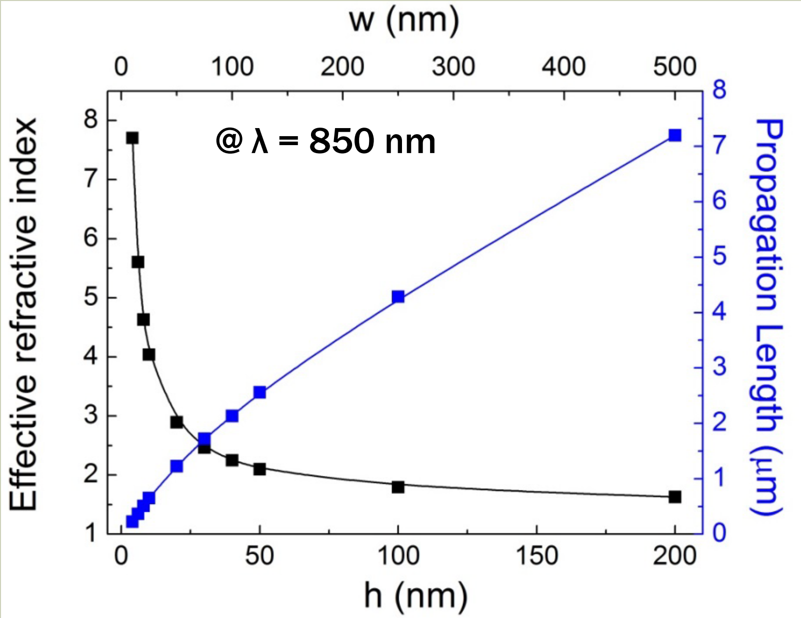


As dimension decreases, the absorption loss and *k*-vector are highly increased.

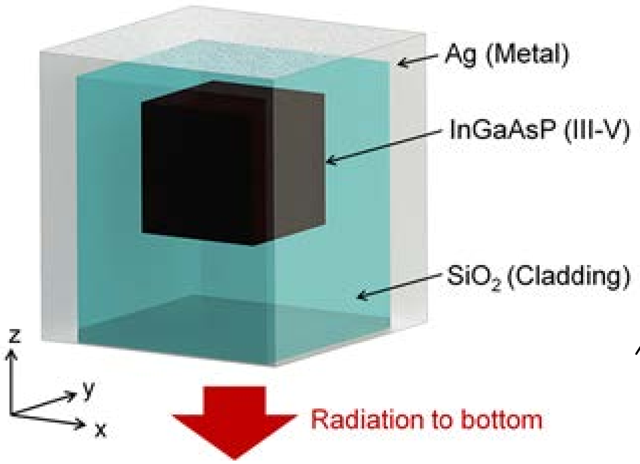
We should find the best way to minimize the losses at this large-*k* regime

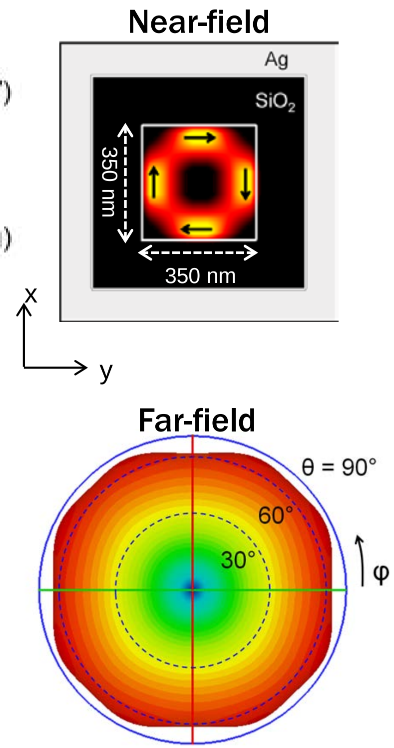


S. Maier, "Plasmonics" (2007)



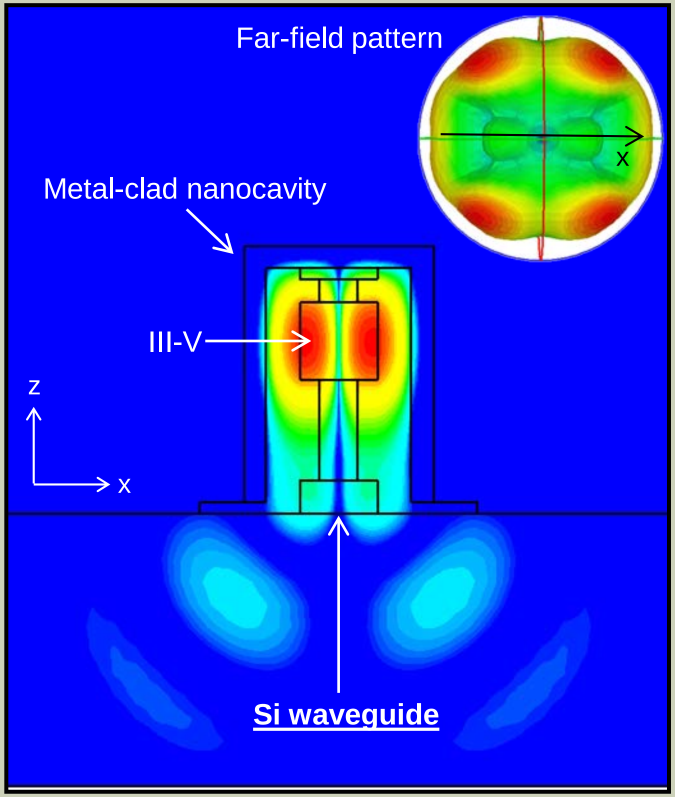
DIFFICULTY IN COUPLING W/ WAVEGUIDE





Because of the **extremely small output aperture** of such a cavity, the **radiation from the cavity diverges very rapidly**.

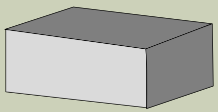
Coupling efficiency **with Si waveguide** < **10 %**



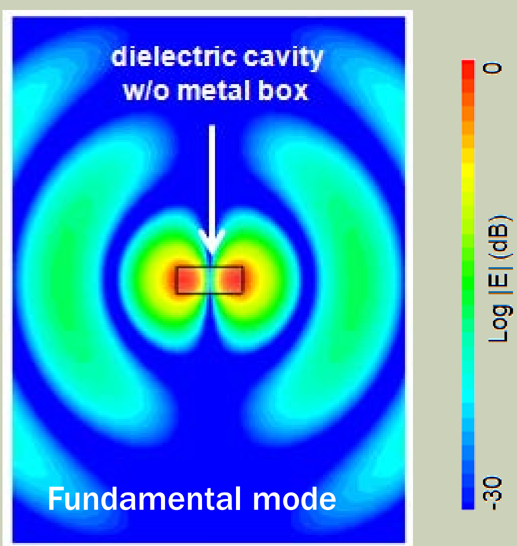
CLADDING ENGINEERING
FOR HIGH-Q AND LARGE COUPLING

METALLIC BOX CAVITY

Dielectric Semiconductor Cavity

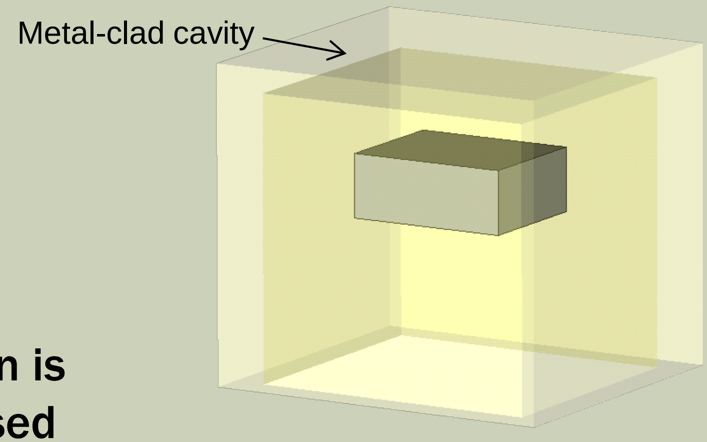


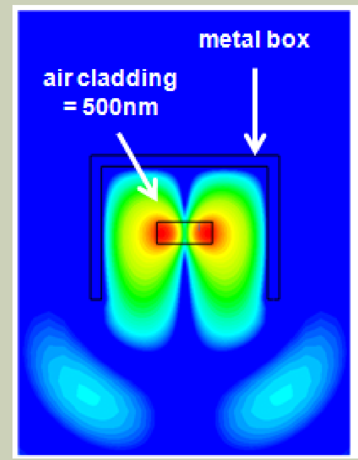
(500nm × 400nm × 200nm)



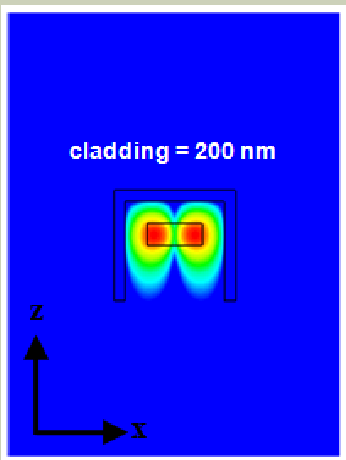
Q = 8
$V_m = 0.35\ (\lambda/n)^3$

Radiation is suppressed by metal





Q = 75
$V_m = 0.29\ (\lambda/n)^3$



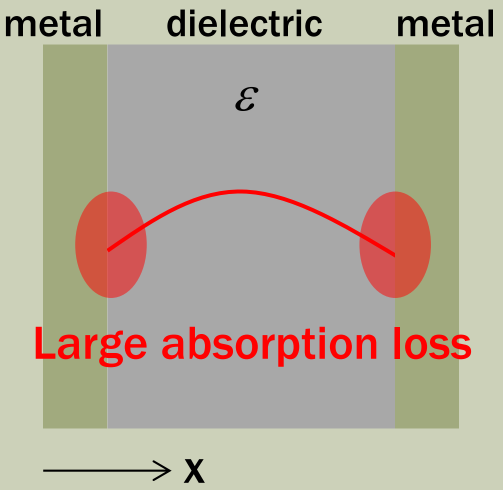
Q = 3100
$V_m = 0.25\ (\lambda/n)^3$

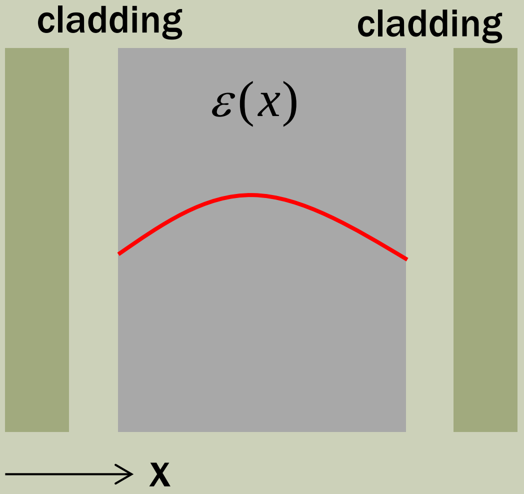
REDUCING ABSORPTION LOSSES WITH LOW-INDEX CLADDINGS

1D wave-equation

$$\left[\frac{\partial^2}{\partial x^2}+\omega^2\mu_0\varepsilon\right]\psi(x)=0$$

$$\left[\frac{\partial^2}{\partial x^2}+\omega^2\mu_0\varepsilon(x)\right]\psi(x)=\left[\frac{\partial^2}{\partial x^2}+V(x)\right]\psi(x)=0$$

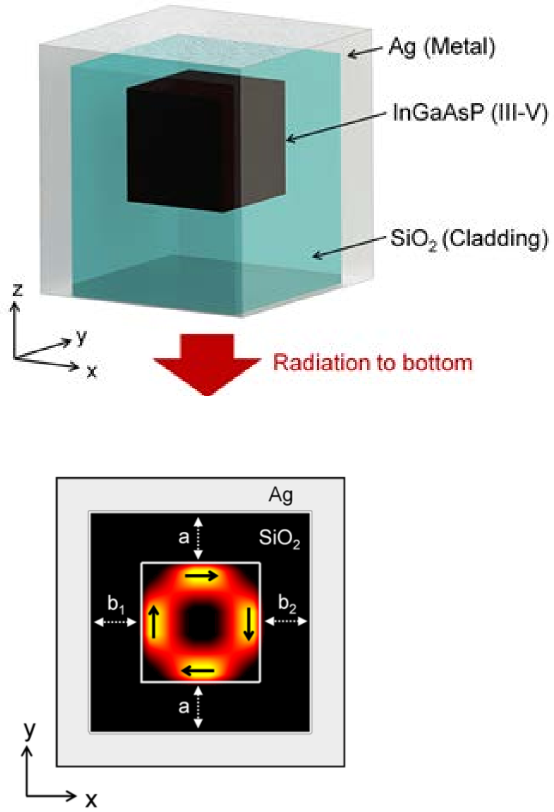


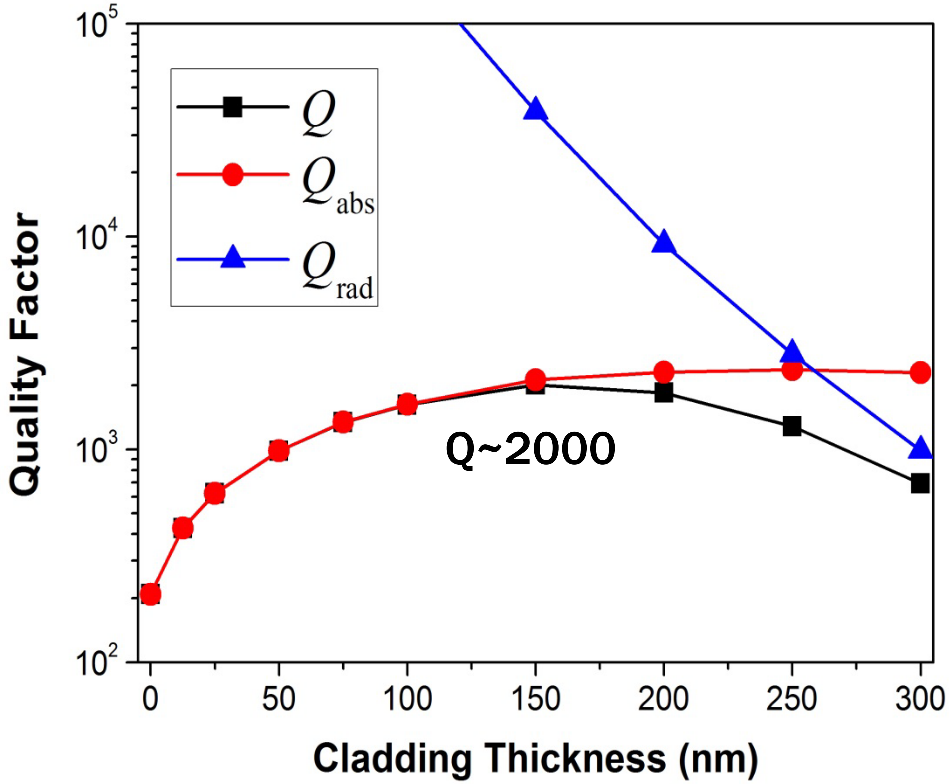


High Reflection (High Q_{rad})
Large Absorption (Low Q_{abs})

High Reflection (High Q_{rad})
Small Absorption (Q_{abs} ↑)

Q VS. CLADDING THICKNESS

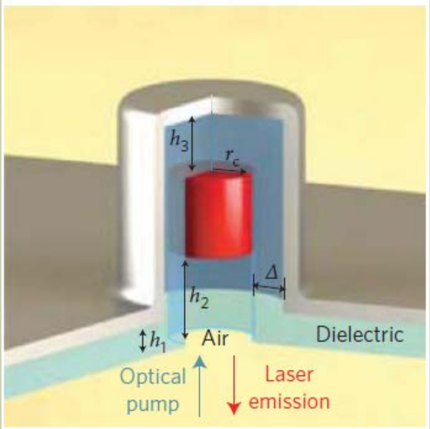


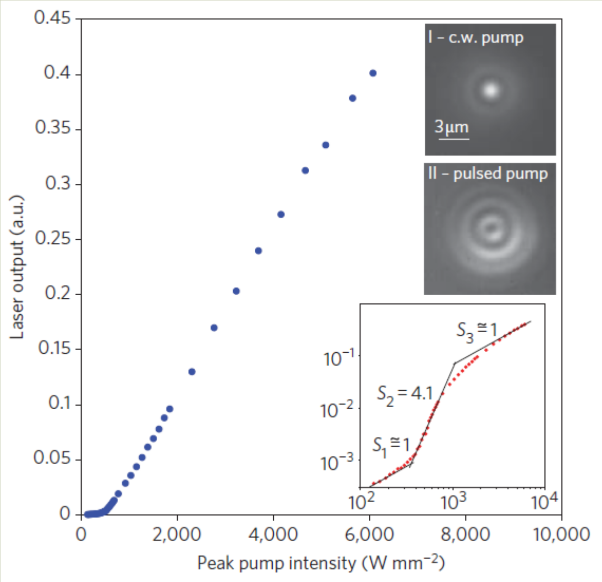


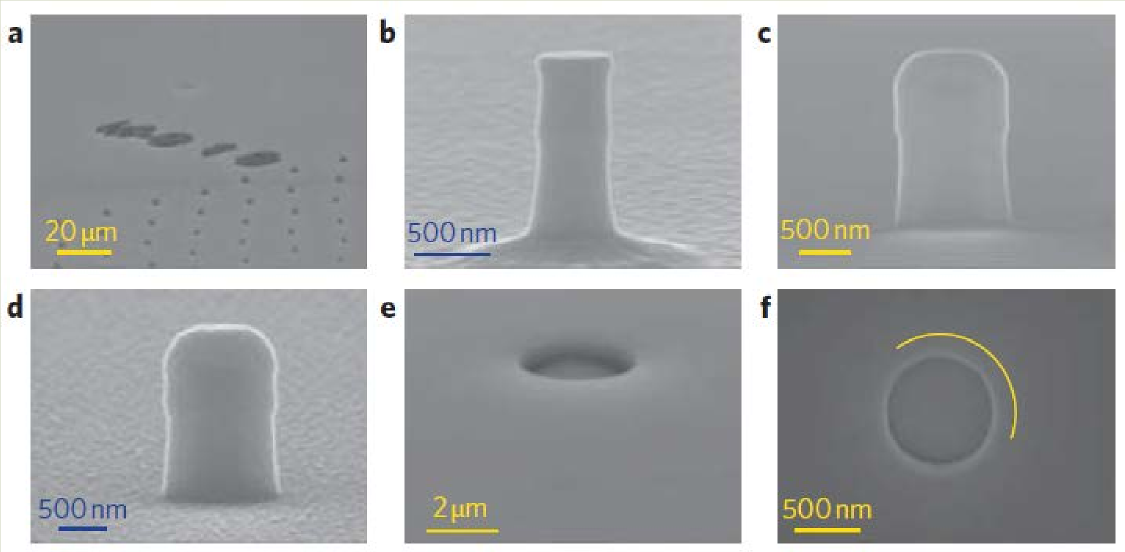
a = b_1 = b_2 = cladding thickness

M.-K Kim et al., Opt. Express **19**, 23504 (2011)

METAL-CLAD CAVITY LASER



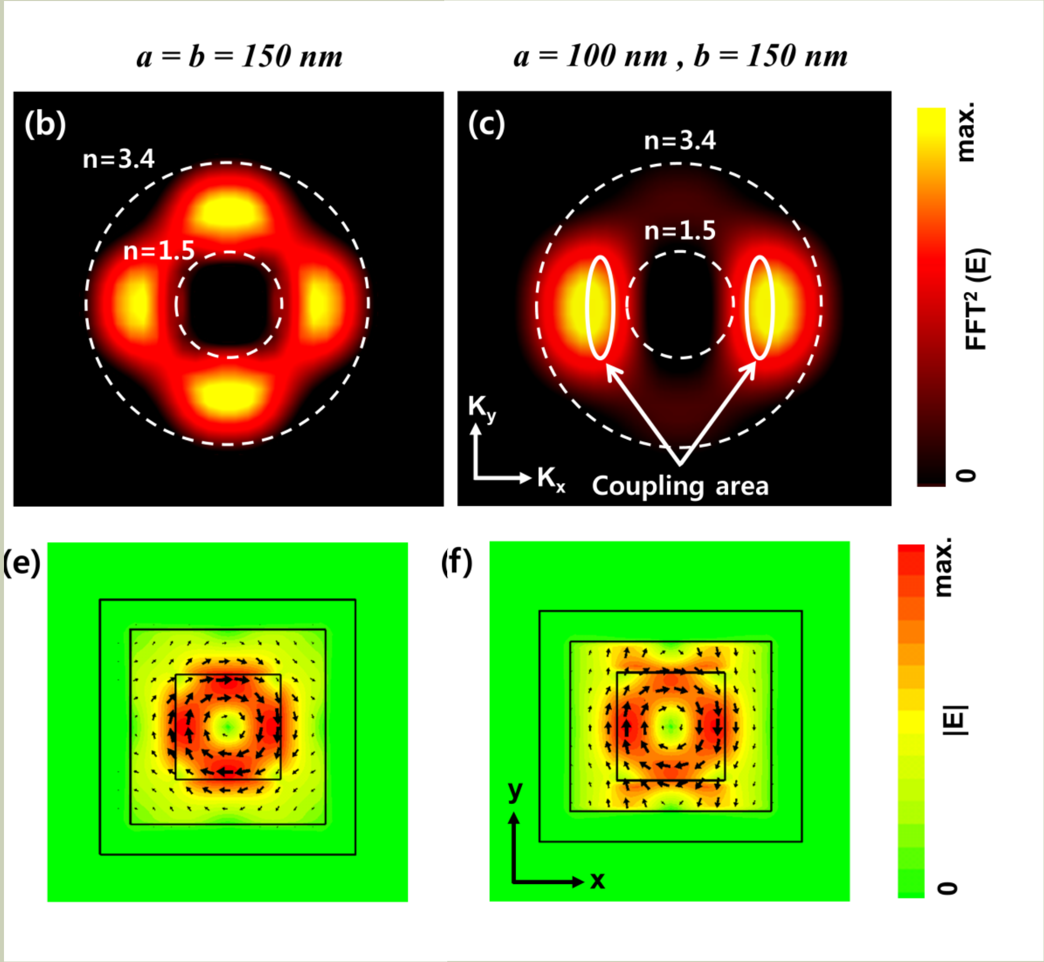




They demonstrated room-temperature pulsed laser emission from optically pumped metallo-dielectric cavities

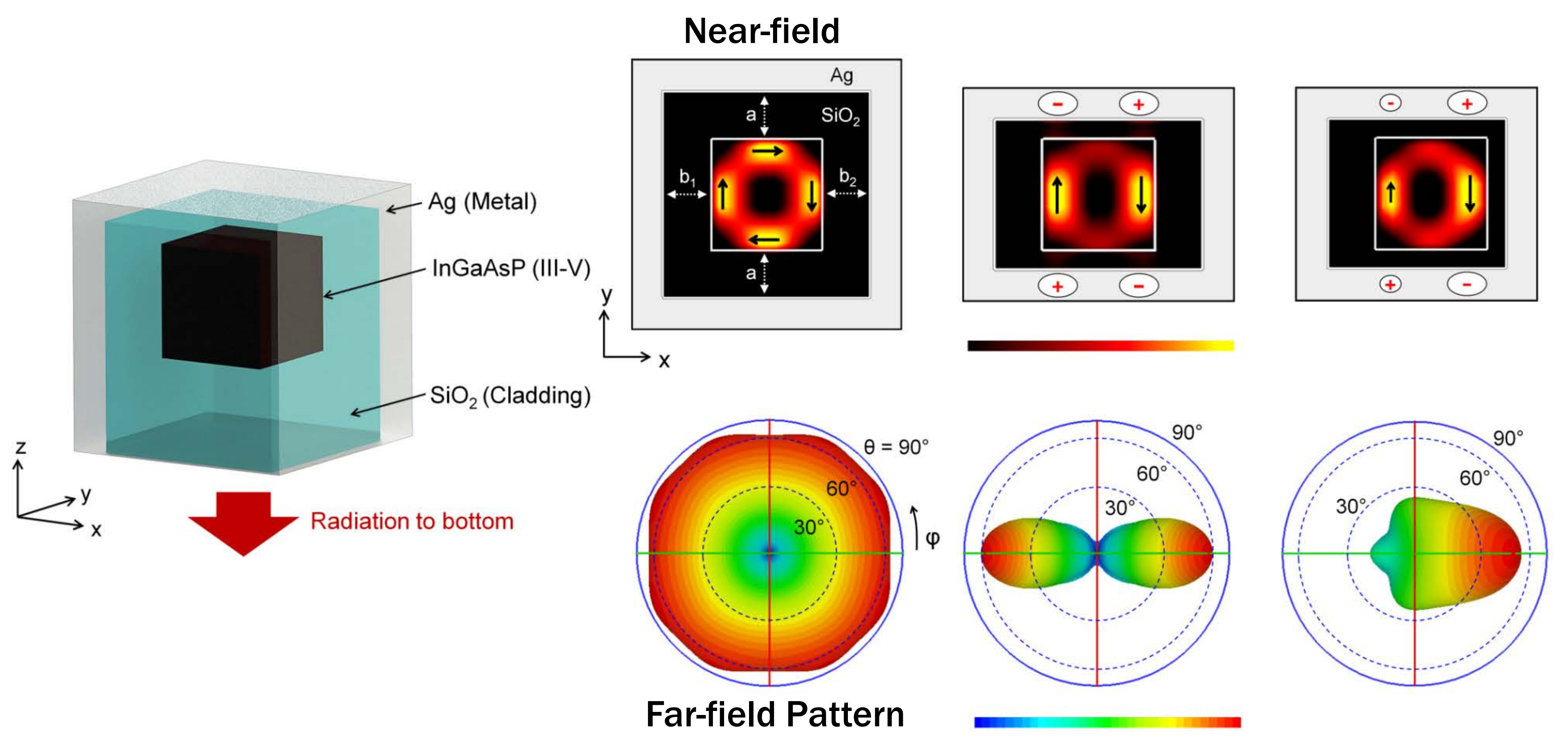
M. P. Zezhad et al, Nature Photon. (2010)

FOR THE EFFICIENT COUPLING



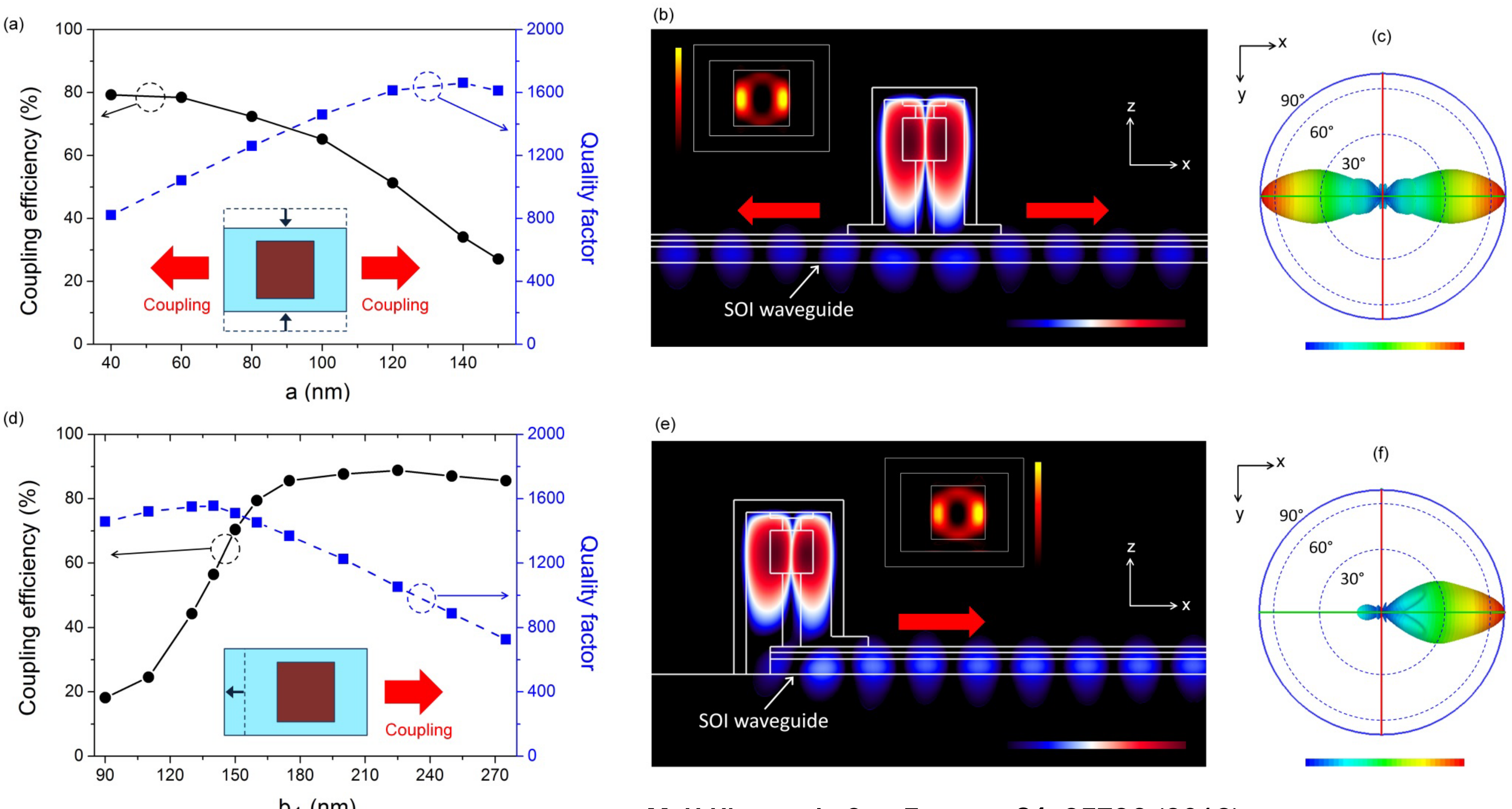
M.-K Kim et al., Opt. Express **19**, 23504 (2011)

BI-/UNI-DIRECTIONAL RADIATION



M.-K Kim et al., Opt. Express 21, 25796 (2013)

EFFICIENT COUPLING IN SI/III-V INTEGRATION

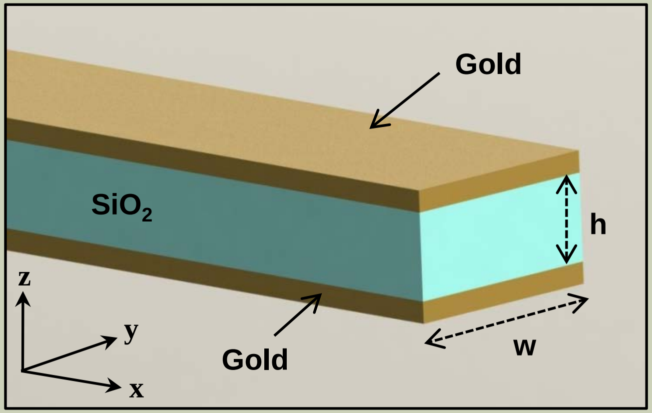


M.-K Kim et al., Opt. Express **21**, 25796 (2013)

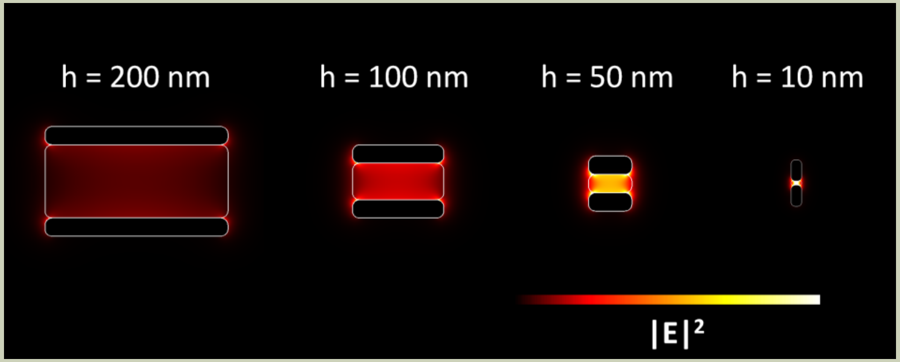
GEOMETRIC ENGINEERING
FOR EXTREME PHOTON SQUEEZING

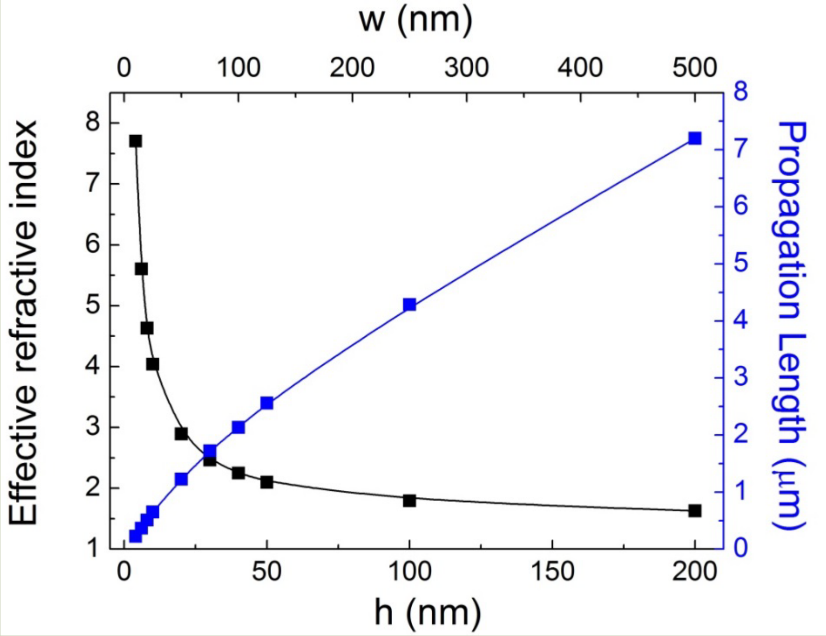
METAL-INSULATOR-METAL PLASMONIC MODE

Metal-insulator-metal (MIM) Plasmonic Mode



$$w / h = 500\ nm / 200\ nm, \quad \lambda = 830\, nm$$

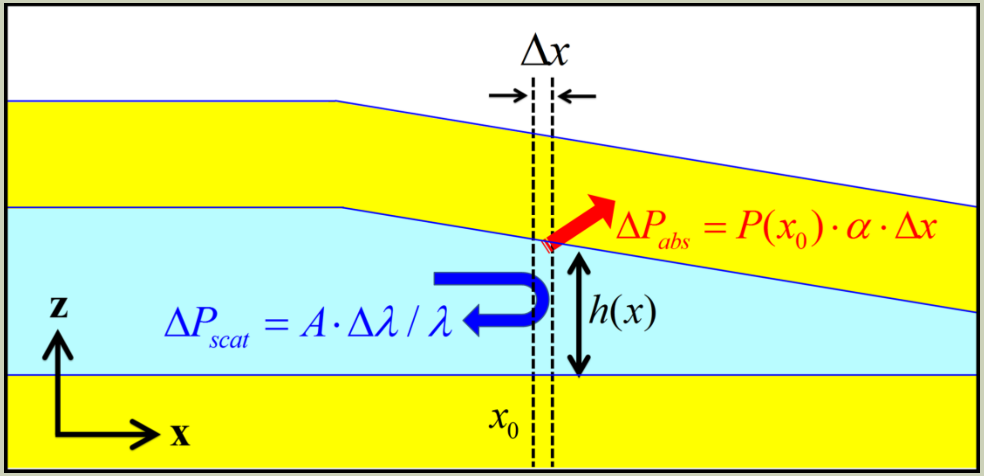




No cut-off dimension (Limitless confinement)

But, Significant Loss at Large-k Regime

OPTIMAL GEOMETRY FOR MINIMIZING LOSSES



$$\Delta P_{loss} = \Delta P_{scat} + \Delta P_{abs}$$
$$= A \cdot \Delta\lambda / \lambda + P_0 \cdot \alpha \cdot \Delta x$$
$$= A \cdot \Delta\lambda / \lambda + B \cdot \mathrm{Im}[k] \cdot \Delta x$$

$$\Delta P_{loss} \approx A \cdot \left(\Delta h / \Delta x\right) + B \cdot \mathrm{Im}[k] \cdot \lambda$$
$$= A \cdot \left(\Delta h / \Delta x\right) + C$$ = constant

At large-k approximation

$k \cdot h = f(\omega)$: dispersion relation

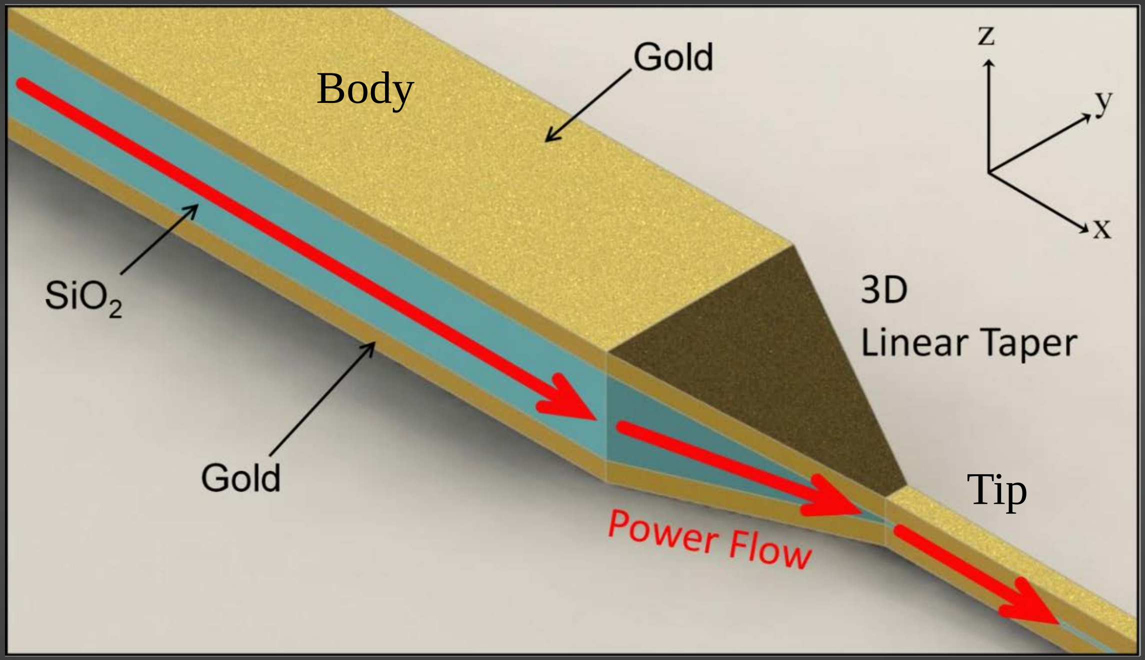
$\Delta x \sim \lambda$

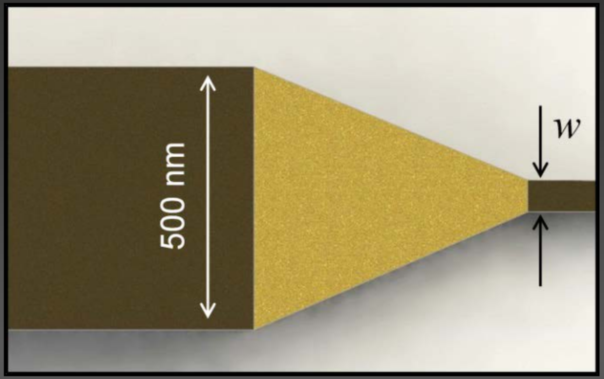
So, "linear-taper geometry" minimizes the losses generated in MIM structure.

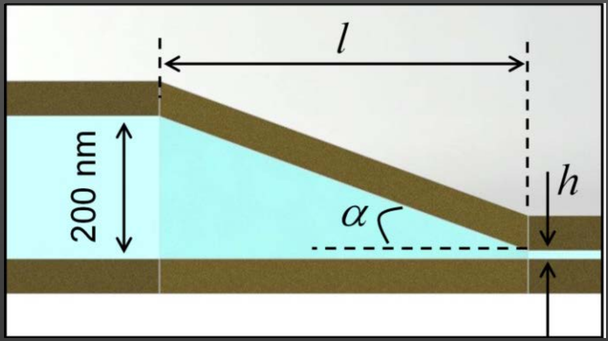
Myung-Ki Kim et al., Nature Photon. **6**(12), 838-844 (Nov. 2012)

Highly Efficient 3D On-Chip Nanofocusing Device

Design of 3D MIM Plasmonic Nanofocusing Device



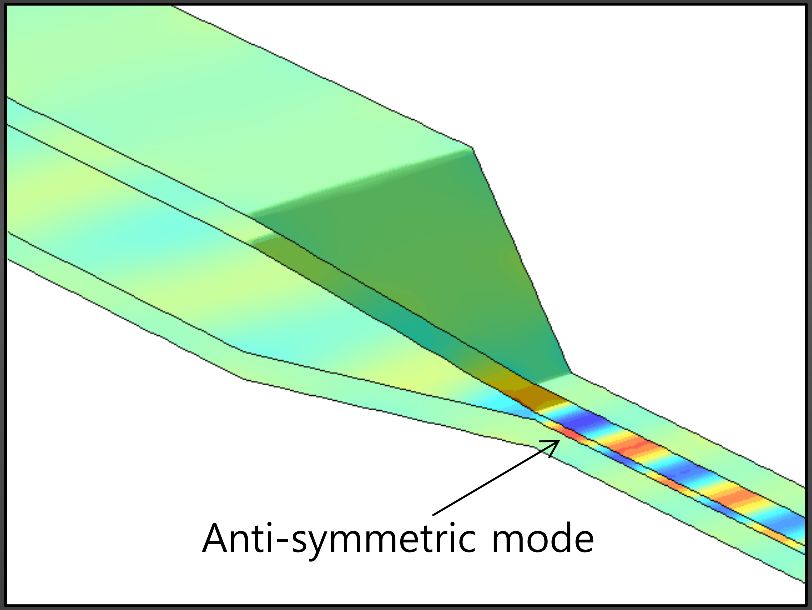




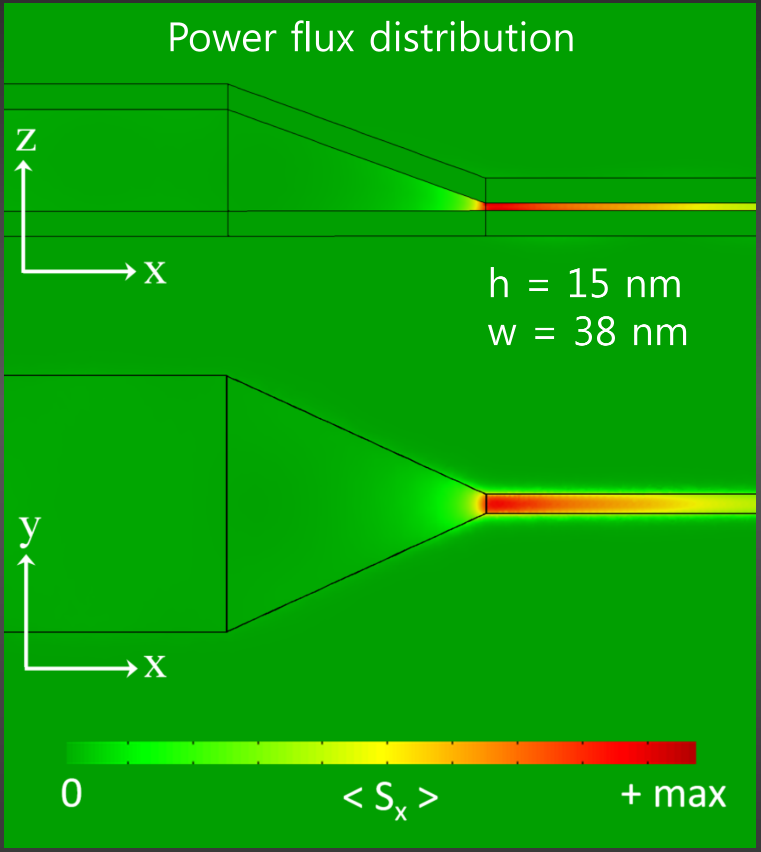
M. Kim, H. Choo, E. Yablonovitch et al. Nature Photonics 6, 838 (2012)

Highly Efficient 3D On-Chip Nanofocusing Device

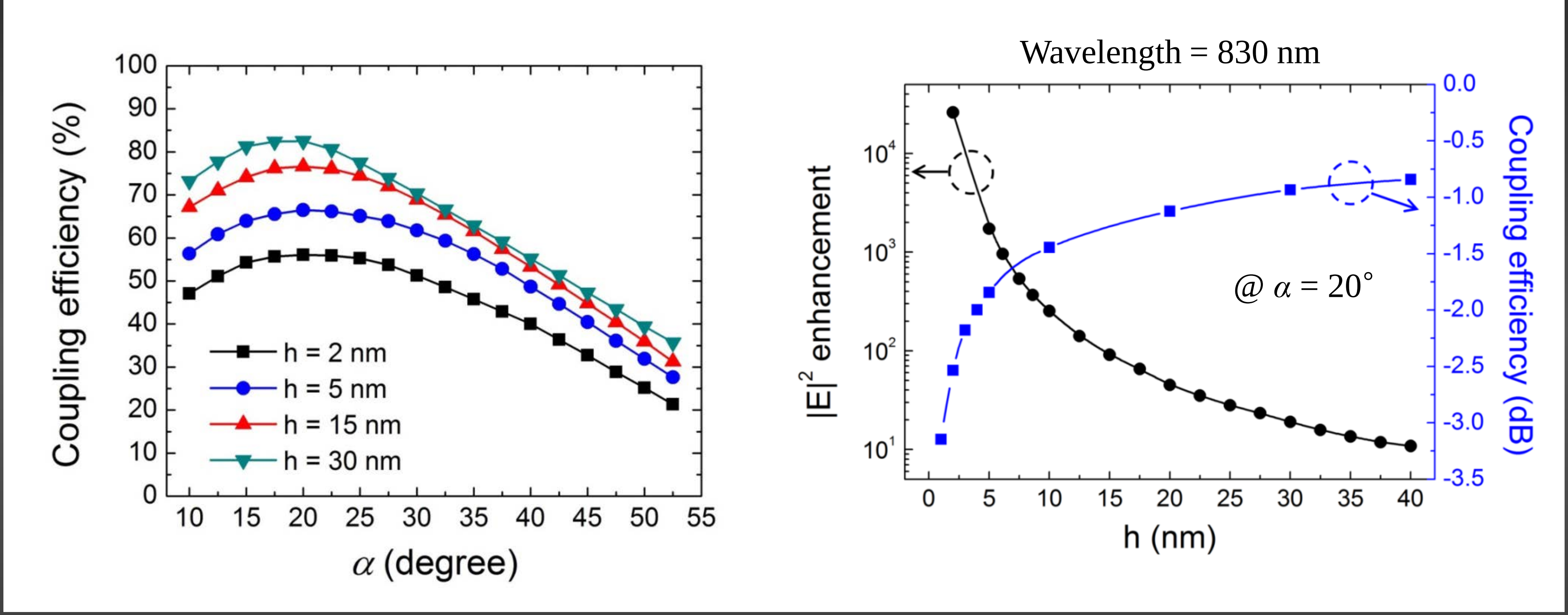
Surface-charge density propagation



Power flux distribution



Highly Efficient 3D On-Chip Nanofocusing Device



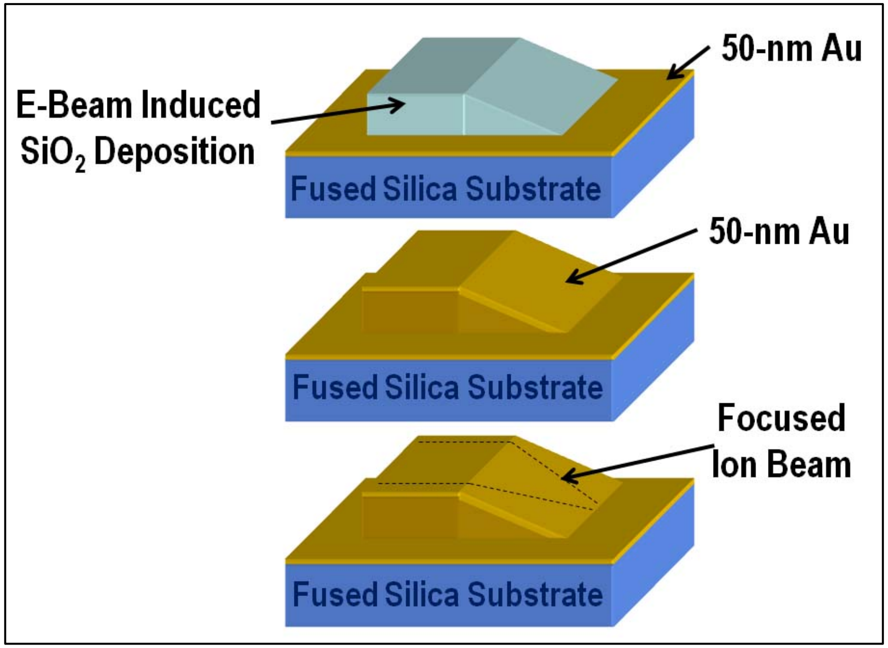
Optimal coupling angle: 10° < *a* < 30°

When focusing into 2 × 5 nm^2 area,
Coupling loss = 2.5 dB
E^2 enhancement ~ 3.0 x 10^4

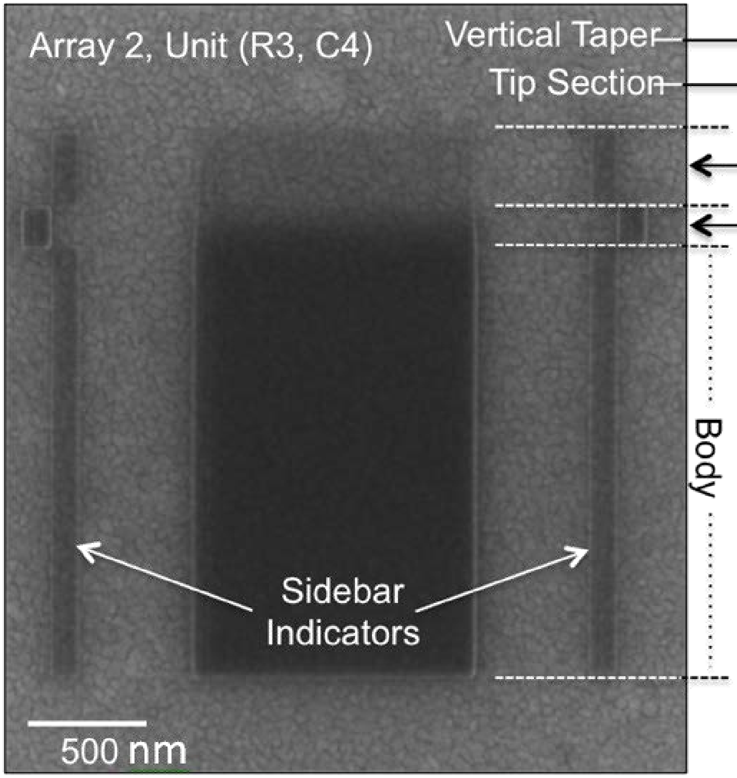
Myung-Ki Kim et al. Nature Photonics 6, 838 (2012)

Fabrications

Fabrication Steps



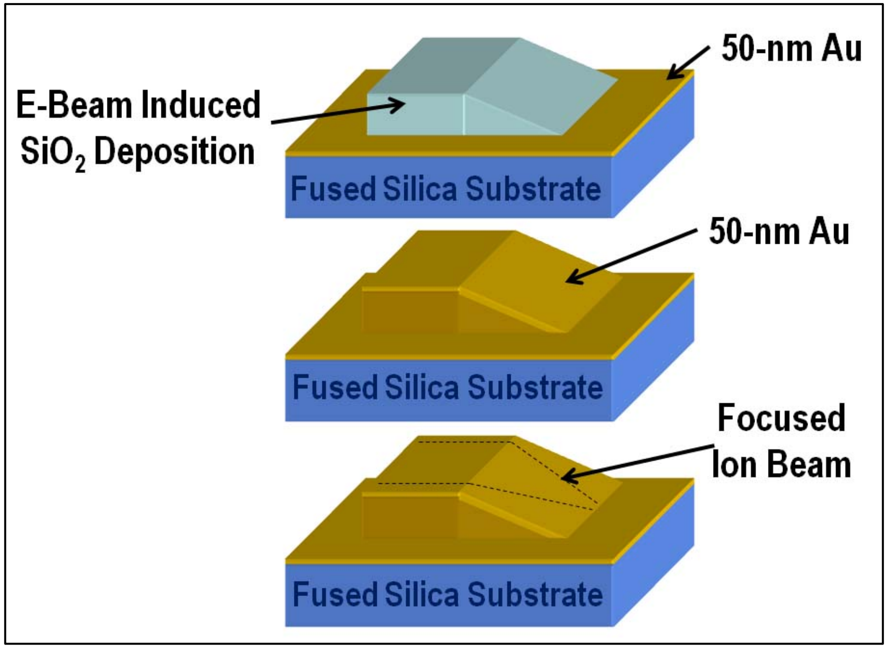
E-beam induced SiO_2 deposition on Au



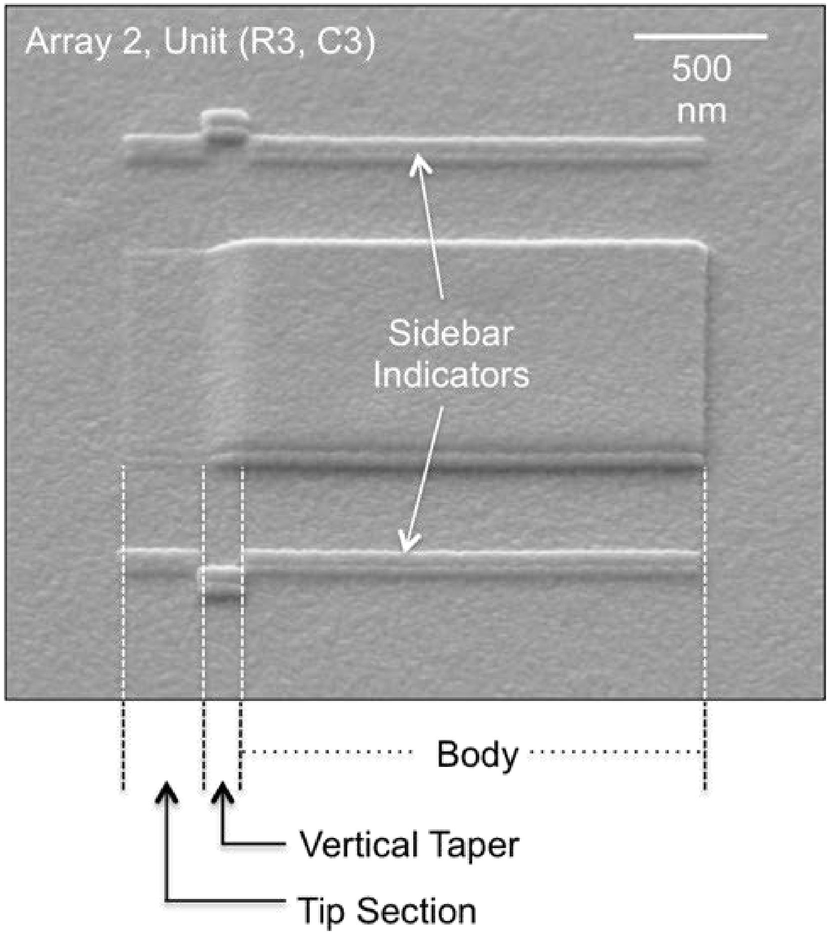
Myung-Ki Kim et al. Nature Photonics 6, 838 (2012)

Fabrications

Fabrication Steps

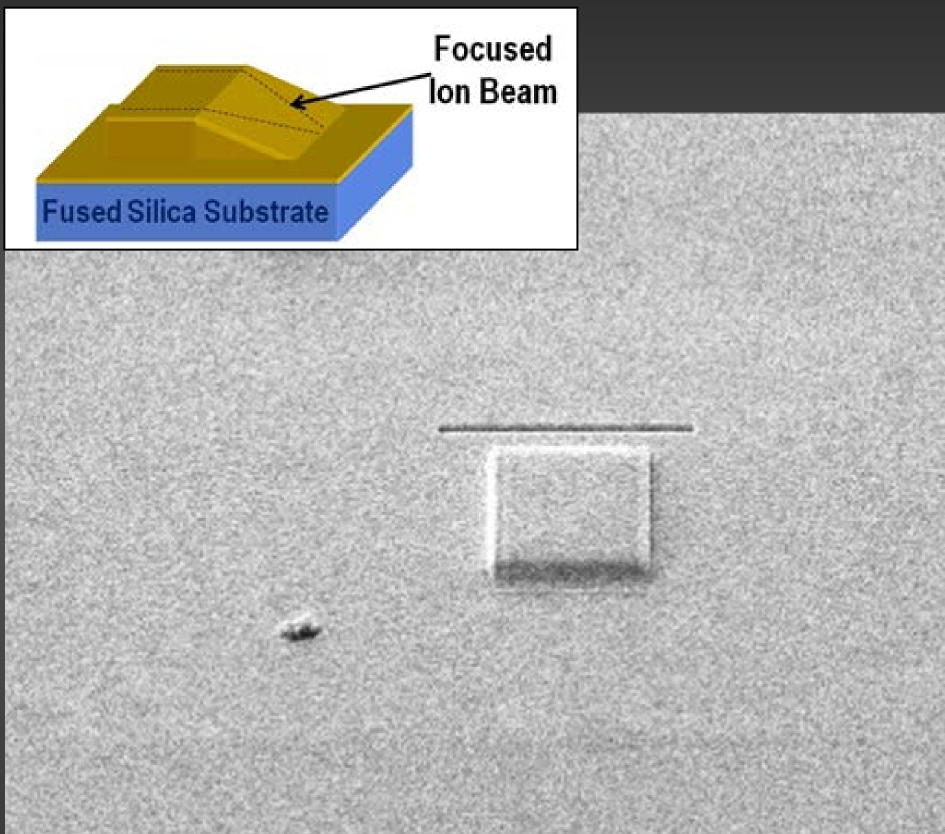


50-nm-Au deposition

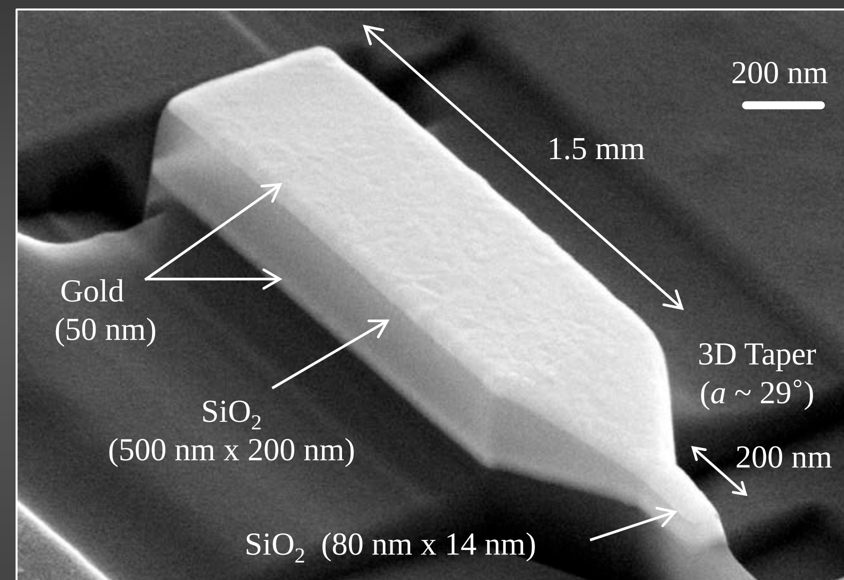


Myung-Ki Kim et al. Nature Photonics 6, 838 (2012)

Fabrications



3D MIM nanofocusing structure

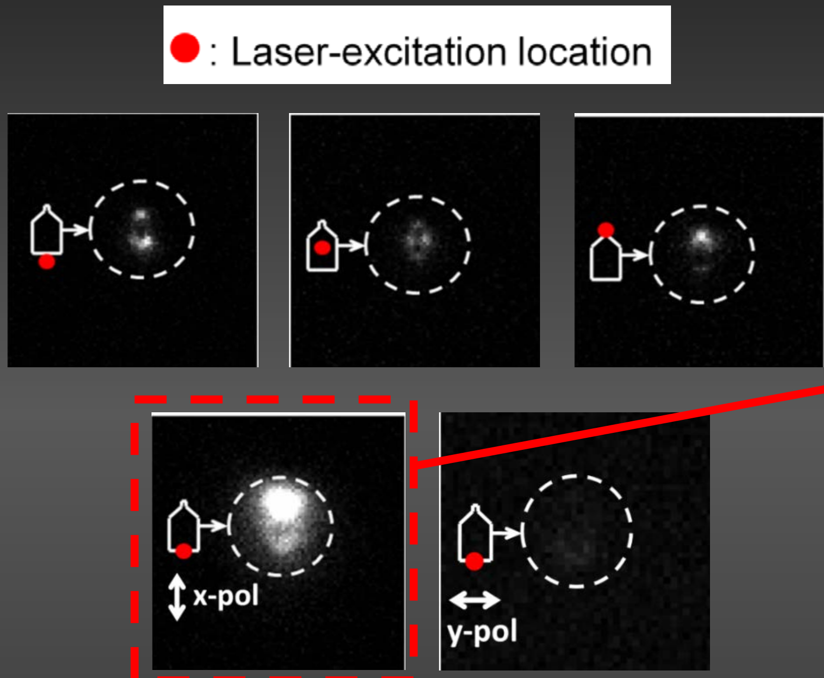


Minimum SiO_2 area = $14 \times 80\ nm^2$

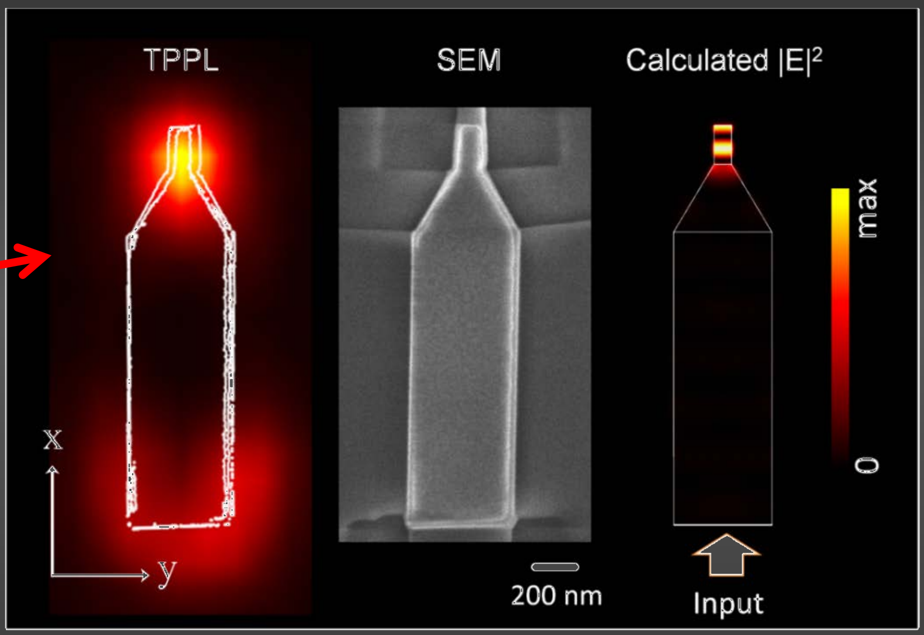
Tapering angle (a) = 29 °

Myung-Ki Kim et al. Nature Photonics 6, 838 (2012)

TPPL measurement

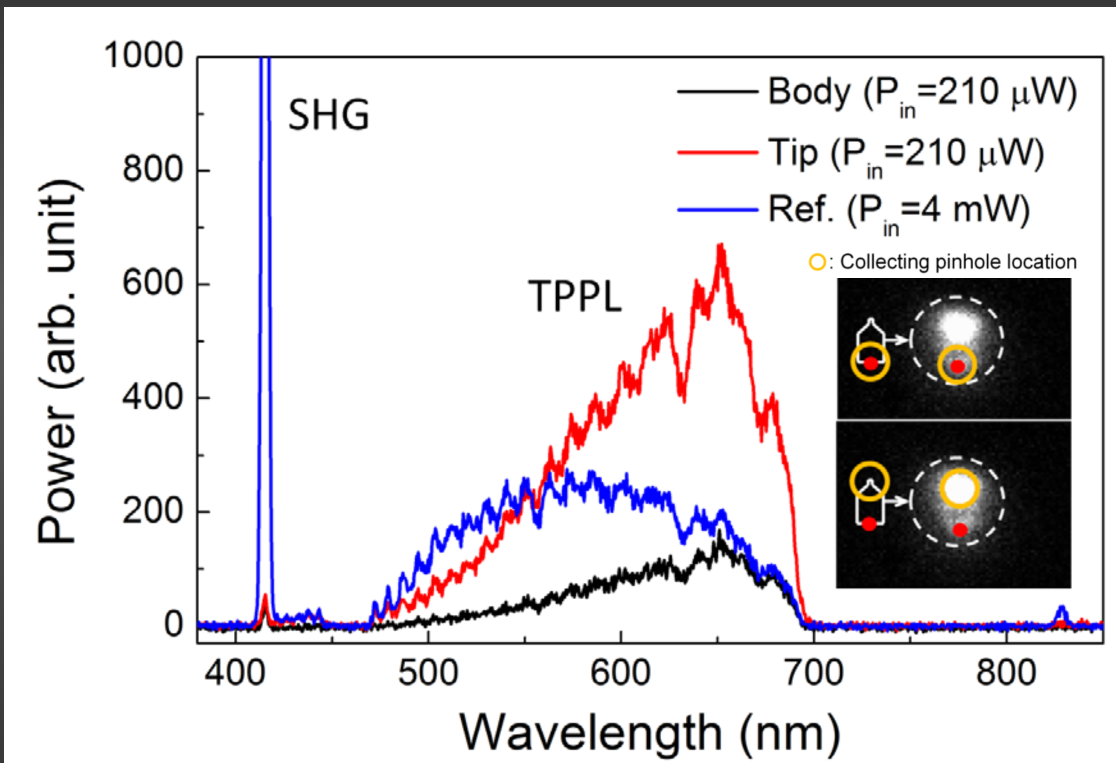


Unsaturated TPPL intensity map



Laser source: 120 fs Ti-sapphire laser at 830 nm
Time-veraged power = 210 μW
Beam diameter ~ 400 nm (100 × 0.90NA)

Estimation of E^2 Enhancement



E^2 enhancement

$$\alpha_{tip/body} = \alpha_{tip/inc}\alpha_{inc/body} \sim 400$$

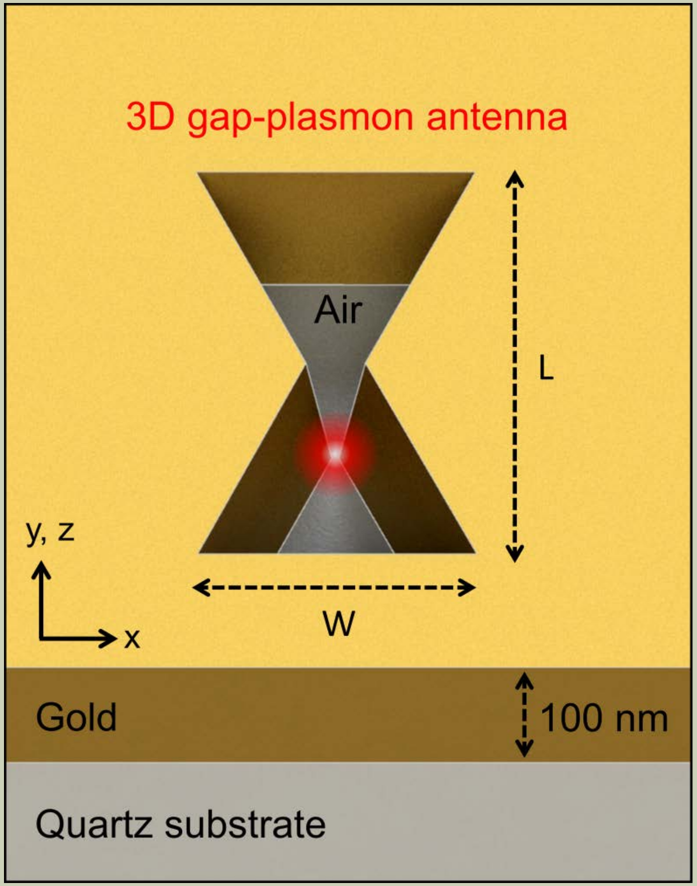
(cf. Simulation value = 410)

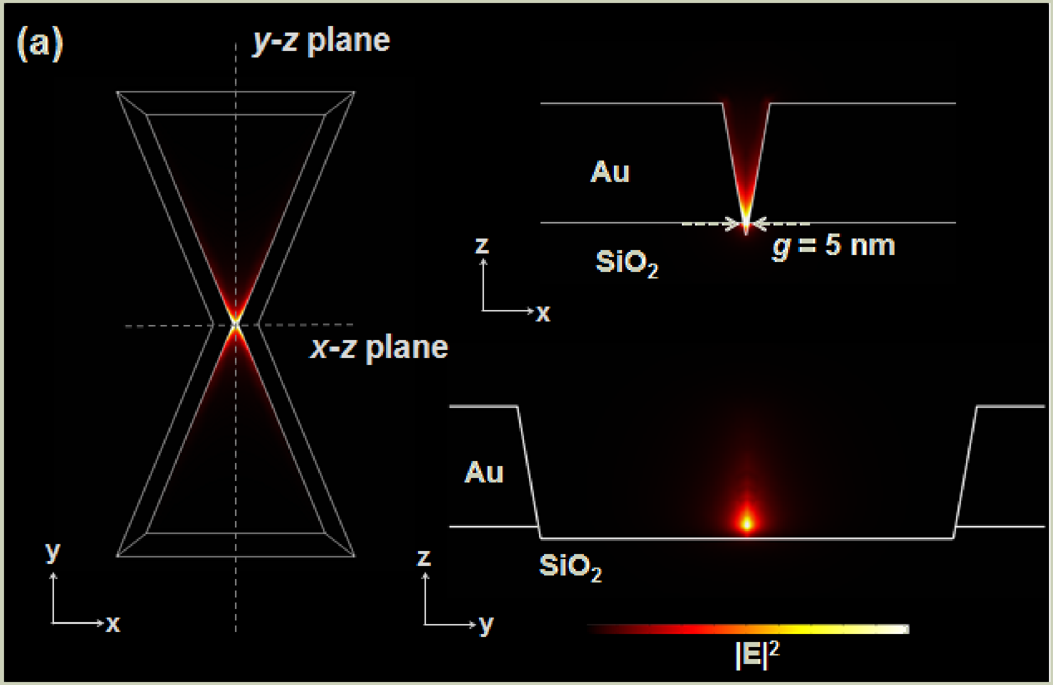
Estimated Transmittance ~ 74%

$$\alpha_{tip/inc} = \left(\frac{A_{ref}}{A_{tip}} \times \frac{\langle TPPL_{tip}\rangle}{\langle TPPL_{ref}\rangle}\right)^{1/2} \cdot \frac{\langle P_{ref}\rangle}{\langle P_{inc}\rangle} \approx 125$$

$$\alpha_{inc/body} = \left(1/\eta\right)\cdot\left(\frac{A_m^{body}}{A_{ref}}\right)\cdot\left(\frac{\varepsilon_{SiO_2}}{n_{eff}^{body}}\right) \approx 3.2.$$

3-D POINT-LIKE CAVITY





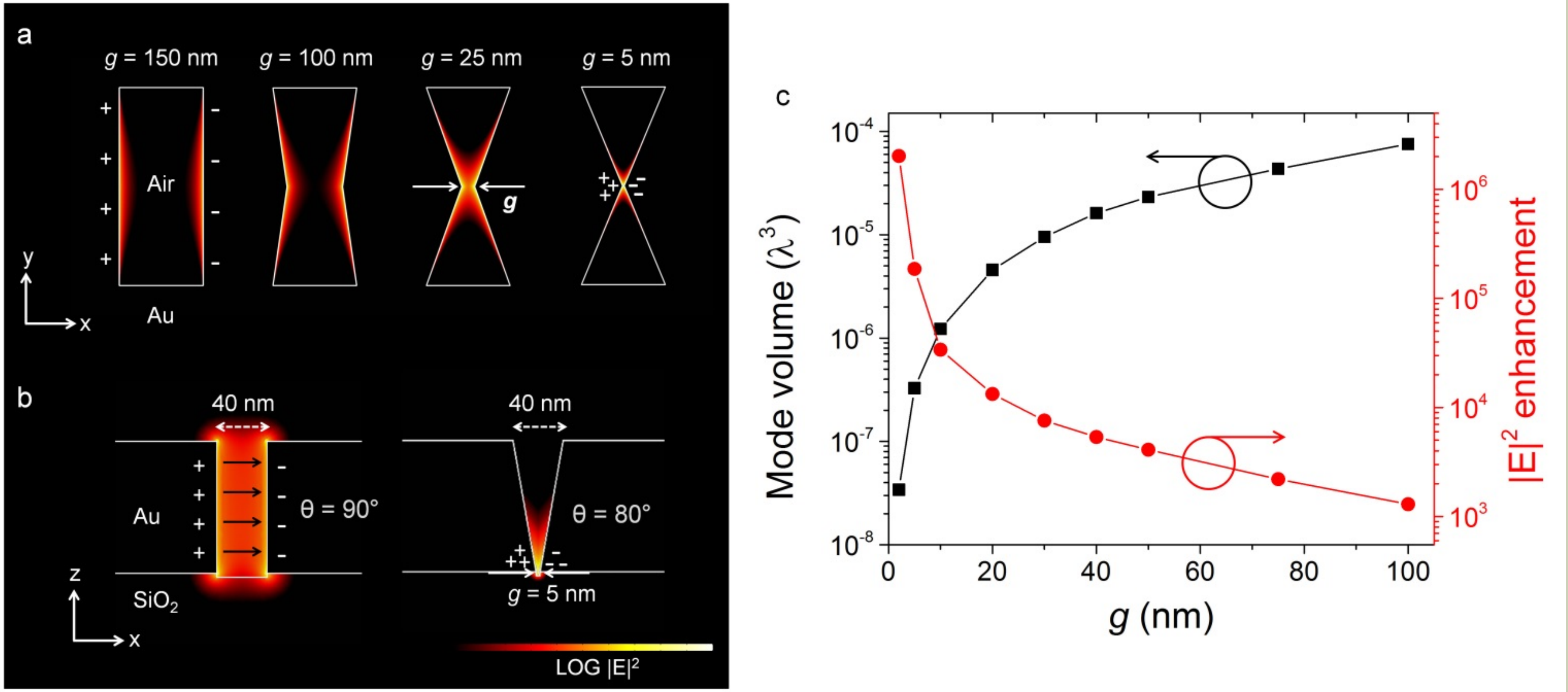
$V_m = 1.3 \times 10^{-7}\ \lambda^3$ **(~ 4 × 10 × 10 nm^3)**

$|E|^2$ enhancement > 400,000

(λ = 1560 nm, g = 4 nm, L = 320 nm, W = 100 nm)

Myung-Ki Kim et al., Nano Lett. **15**(6), 4102−4107 (2015)

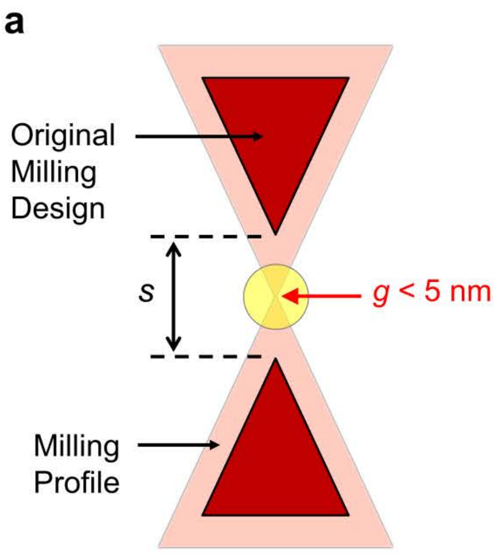
3-D FIELD ENGINEERING & FIELD ENHANCEMENT



$V_m = 1.3 \times 10^{-7}\ \lambda^3$ (~ $4 \times 10 \times 10\ nm^3$)

$|E|^a$ enhancement > 400,000 @ g= 4 nm

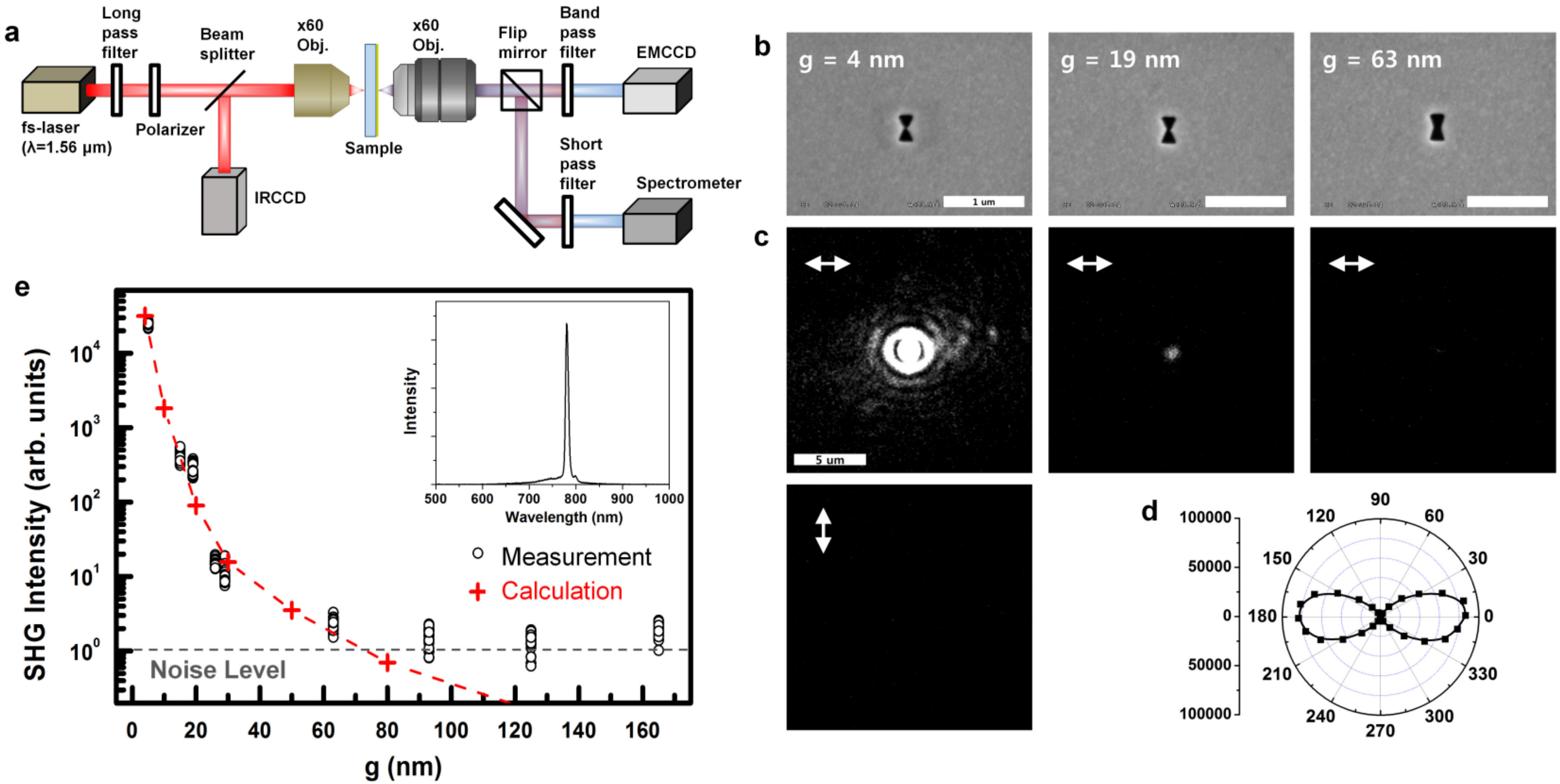
PROXIMAL FIB MILLING TECHNIQUE



Myung-Ki Kim et al., Nano Lett. **15**(6), 4102−4107 (2015)

STRONG FIELD ENHANCEMENT

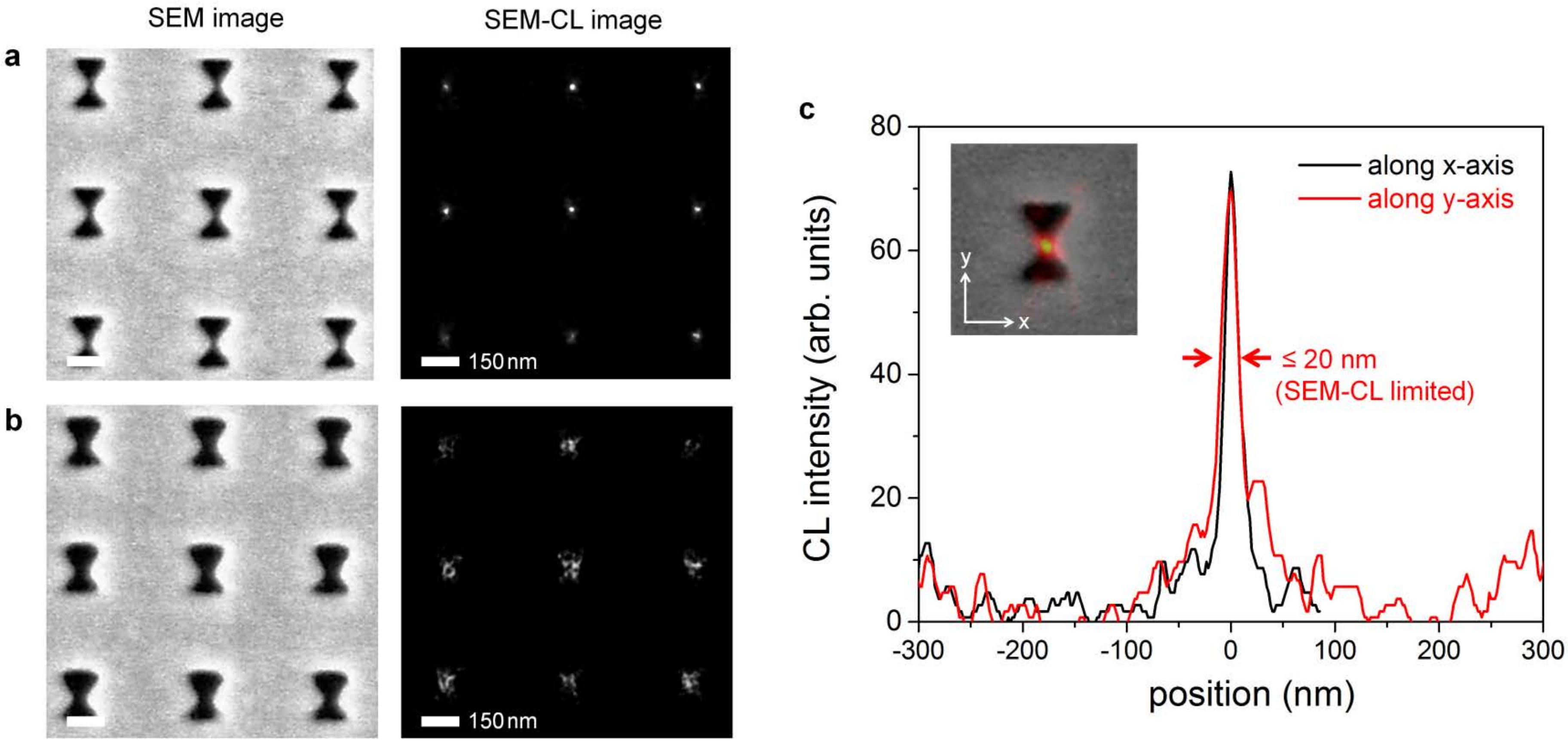
From a 4 nm-gap antenna, a nonlinear second-harmonic signal more than 27,000-times stronger than that from a 100 nm-gap antenna is observed.



Myung-Ki Kim et al., Nano Lett. **15**(6), 4102−4107 (2015)

EXTREME FIELD CONFINEMENT

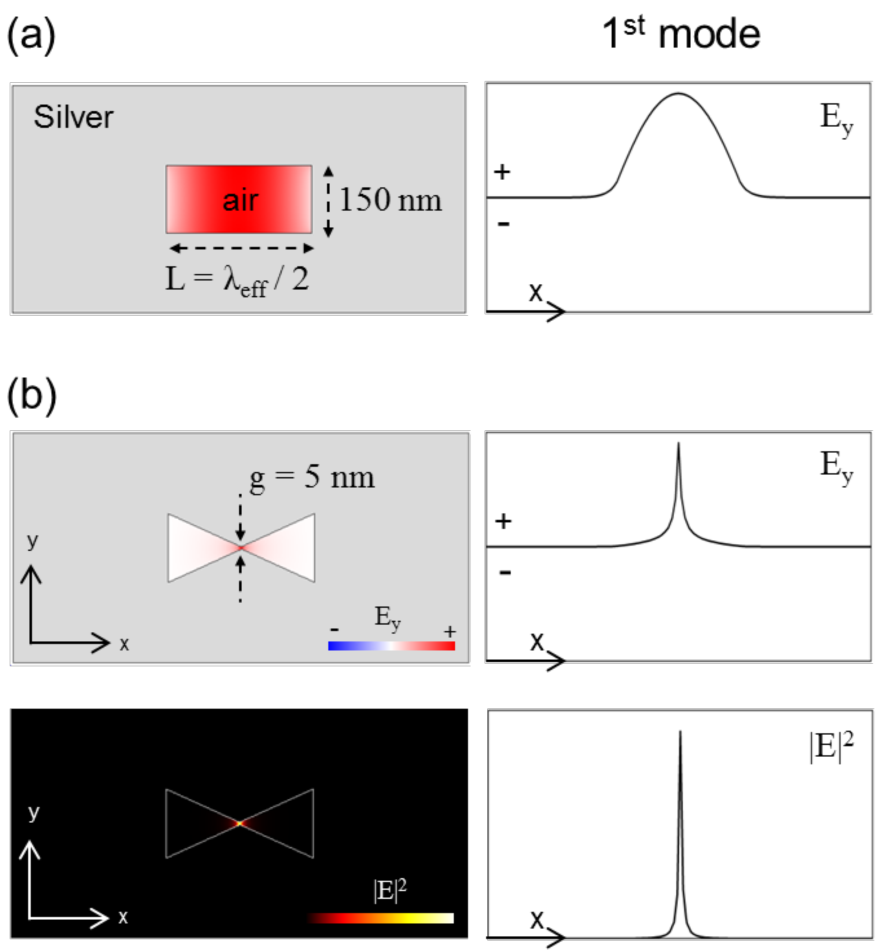
Scanning cathodoluminescence images confirm unambiguous photon confinement in a resolution-limited area 20×20 nm^2 on top of the nano gap.



Myung-Ki Kim et al., Nano Lett. **15**(6), 4102−4107 (2015)

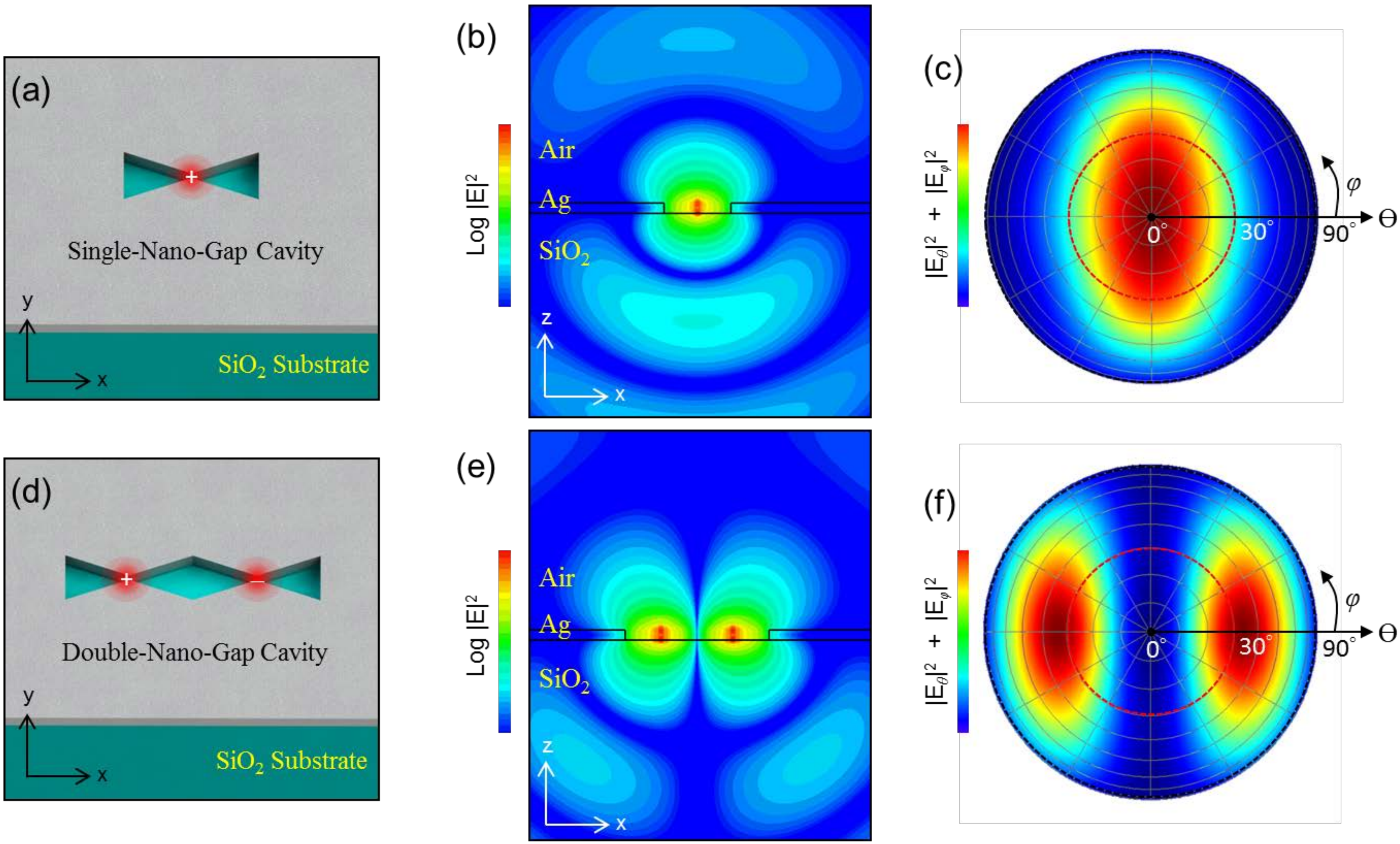
GEOMETRIC ENGINEERING
FOR EFFICIENT COUPLING

Double-Nano-Gap Plasmon Antenna



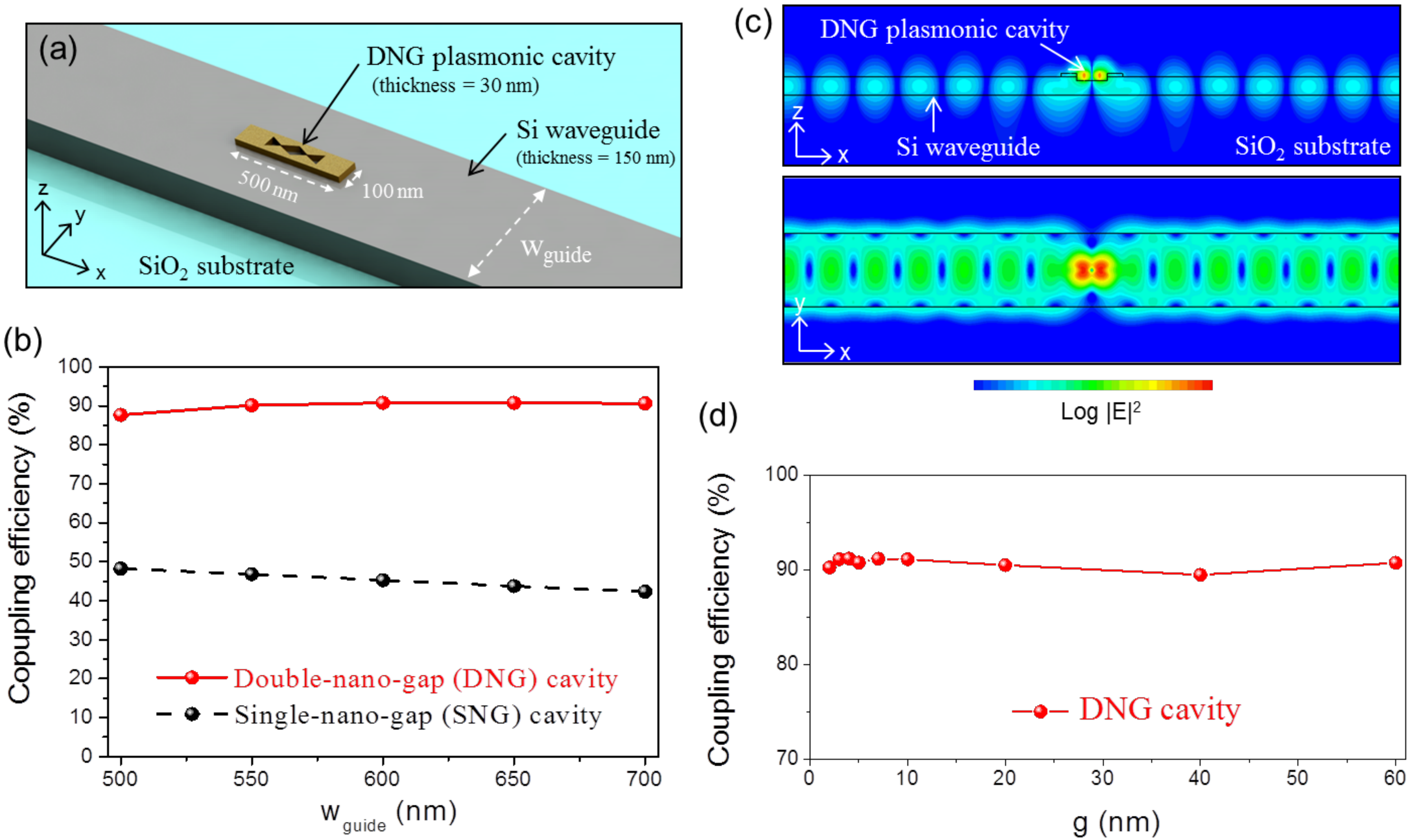
Y. Jin et al., Opt. Express 24, 25540 (2016)

Far-field Radiation Patterns



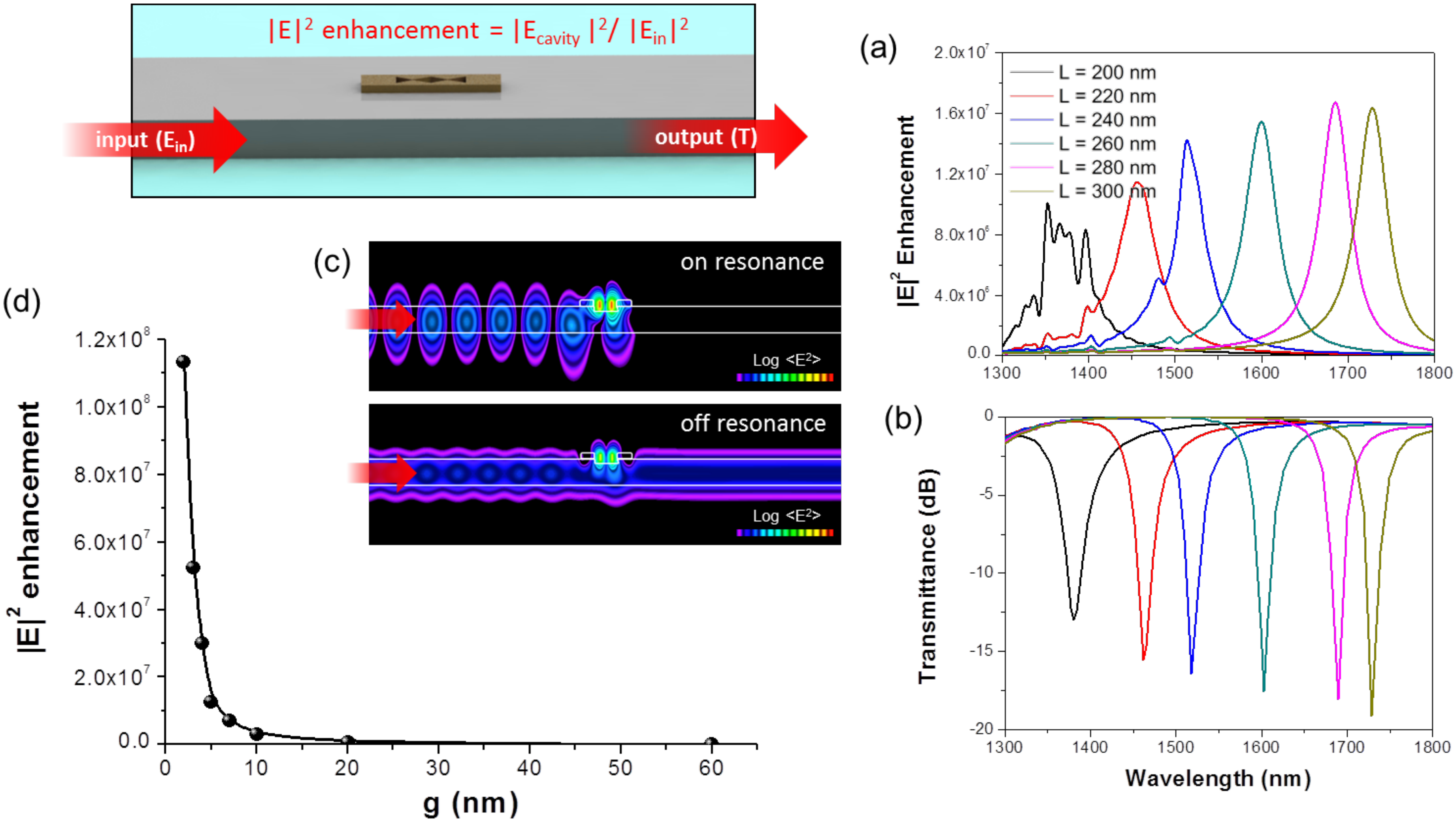
Y. Jin et al., Opt. Express 24, 25540 (2016)

Gap-Plasmon Antenna Coupled with Si waveguide



Y. Jin et al., Opt. Express 24, 25540 (2016)

Extreme Field Enhancement



Y. Jin et al., Opt. Express 24, 25540 (2016)

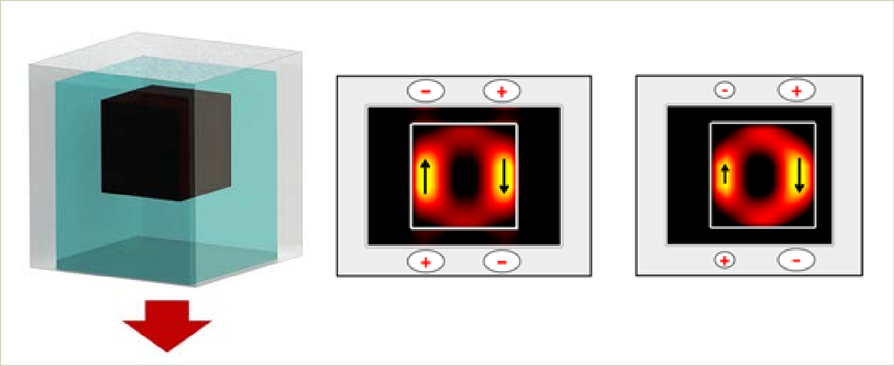
SUMMARY

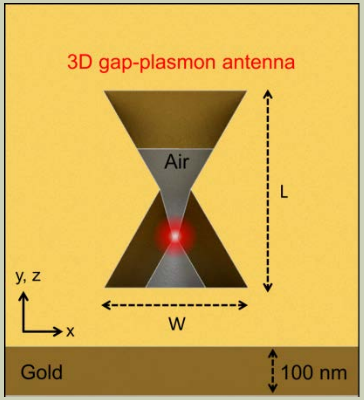
Sub-wavelength Plasmonic Cavities

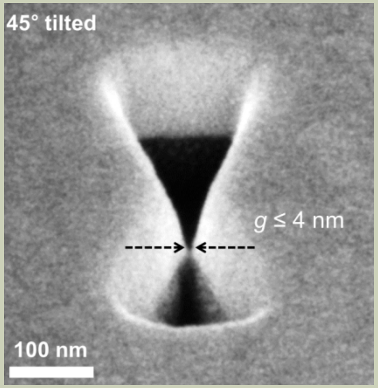
Plasmonic Engineering

Cladding Engineering

Geometric Engineering







고려대학교
KU-KIST 융합대학원


Prof.
Myung-Ki Kim

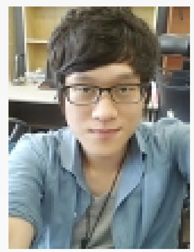

Young-Ho Jin


Byoung Jun Park


Nu-Ri Park

KAIST


Prof.
Yong-Hee Lee


Seung Ju Yoon


Jungmin Lee

KIST
Korea Institute of Science and Technology
한국과학기술연구원

NRF 한국연구재단
National Research Foundation of Korea

SAMSUNG