Electrically Pumped SPASER

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OUTLINE

- Data-Processing Devices
- SPPs and SPP losses
- SPP Amplififcation
- SPASER
- Active Plasmonic Interconnects
- Summary

Data-Processing Devices

Nvidia GeForce GTX 680

Number of CUDA cores: 1536

Performance: 3.09 TFLOPS

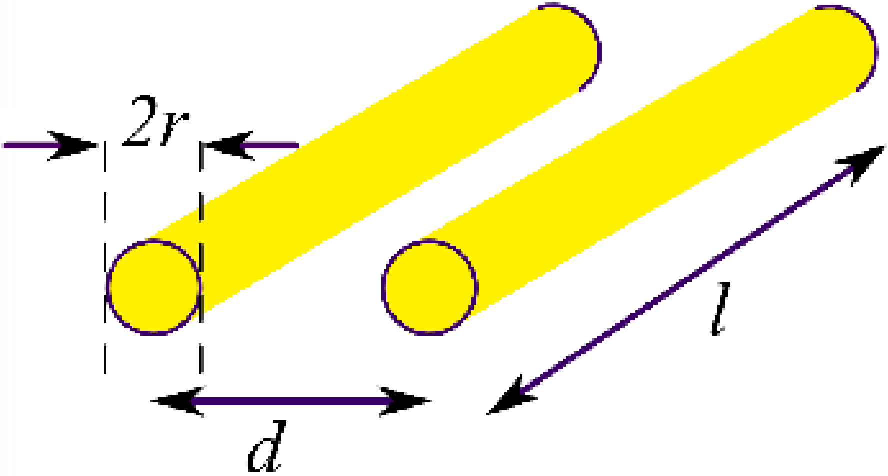
The problem is that after each 1-5 float point operations, one have to write or read information or transmit data to another core.

Ideally, the required bandwidth for the memory interface should be equal to **3090 GB/s** keeping a ratio of 1 byte/FLOP.

Actual bandwidth is only **192.2 GB/s**, but memory interface width is **256-bit**.
So, we have **only 0.75 GB/s per line.**

Data-Processing Devices: Copper Interconnects

Twin-Wire Line Model



Electrical interconnect limitations:

1) Propagation losses.
2) $\tau = RC$ results in a delay and a rise time.
3) Miniaturizing the system doesn't reduce RC delay.

$$B < B_0 \frac{d^2}{l^2}, \text{ where } B_0 < 10^{16} \text{ bit/s}$$

$$\text{If } d < \frac{l}{1000}, \text{ then } \boldsymbol{B < 1\,\text{GB/s}}$$

-D. Miller, H. Ozaktas, *Limit to the Bit-Rate Capacity of Electrical Interconnects from the Aspect Ratio of the System Architecture*, J. Parallel Distrib. Comput. **41**, 42–52 (1997).
-D. Miller, *Optical interconnects to electronic chips*, Appl. Opt. **49**, F59 (2010).

Data-Processing Devices: Copper Interconnects

Twin-Wire Line Model Electrical interconnect

We have almost achieved the bandwidth limit of a single copper line (wire)

We can further increase the total bandwidth only by increasing the number of lines (wires)

But it is not possible, since today we have more than 256 lines in chip-to-chip interconnects and much higher number in on-chip interconnects.

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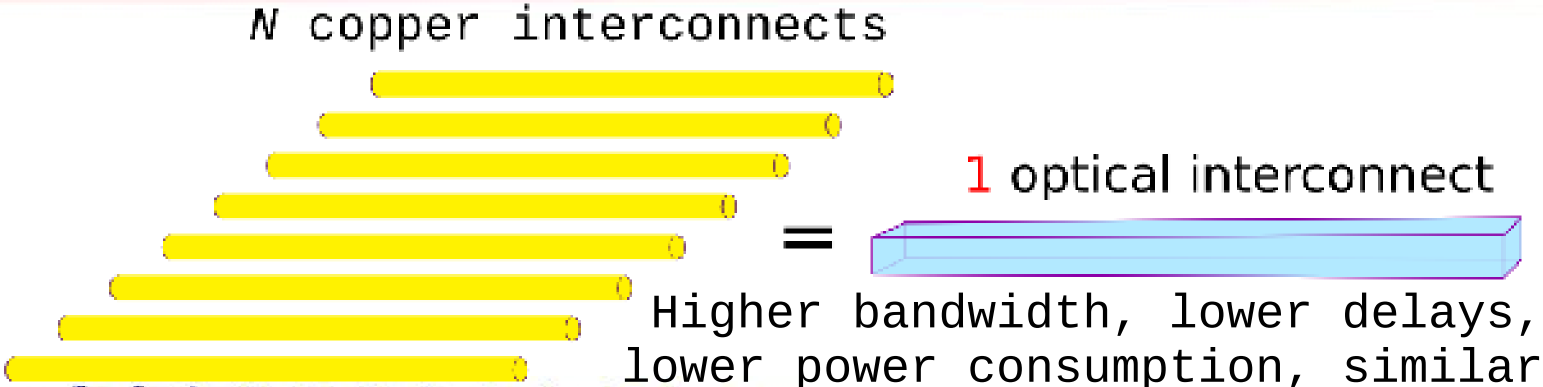
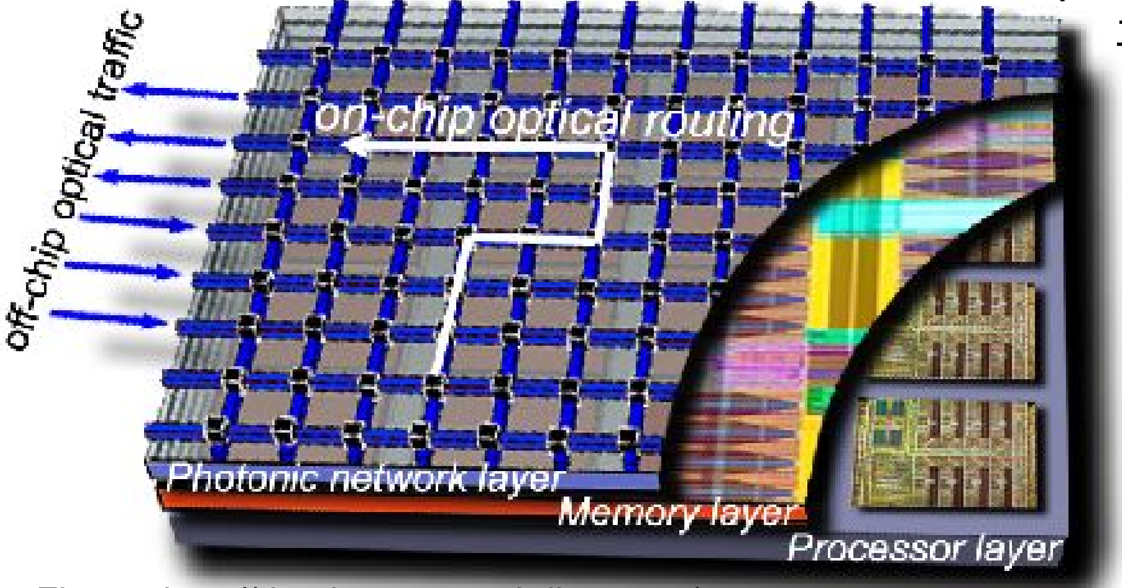
Data-Processing Devices: Optical Interconnects



Higher bandwidth, lower delays, lower power consumption, similar interconnect dimensions, lower cross-talk

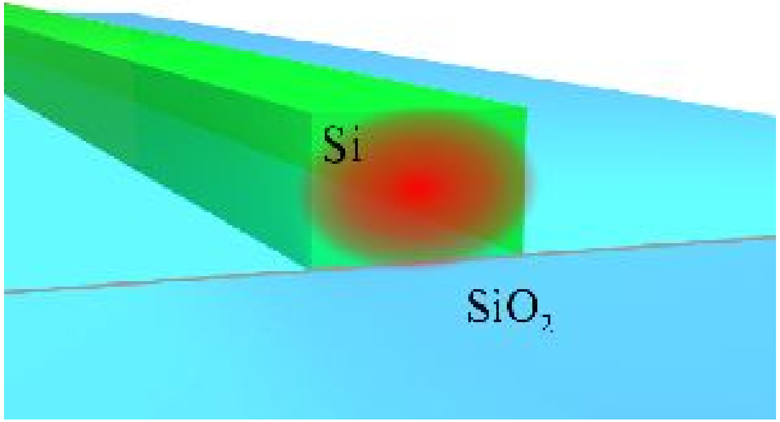


Utilizing on-chip optical interconnects, it becomes possible to achieve exaflop computing on a single chip.

Figure: http://domino.research.ibm.com/

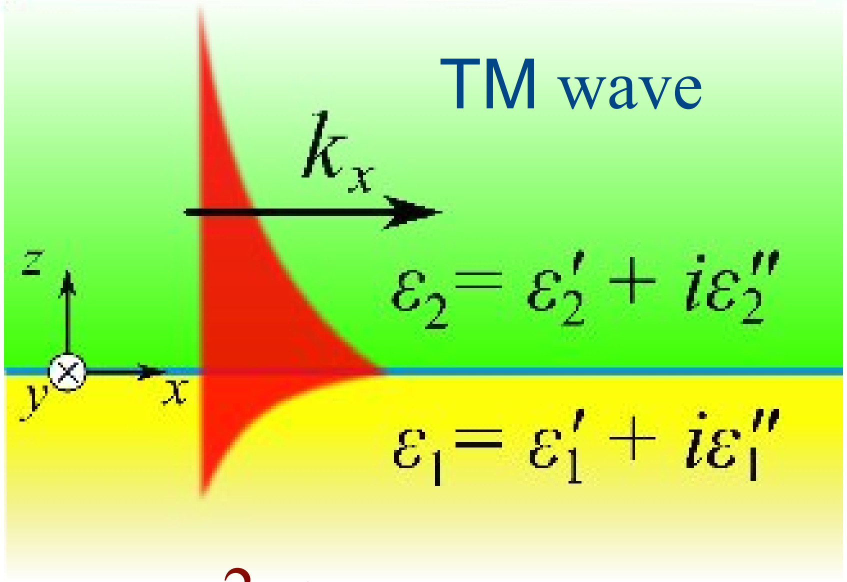
Data-Processing Devices: Silicon Nanophotonics

CMOS integrated silicon nanophotonics gives silicon nanophotonics devices a possibility to share the same silicon layer with silicon transistors and design On-Chip and Chip-to-Chip interconnects.



Is it possible to suggest another approach, which is more compact, have the same bandwidth and the same delays?

SPPs



Drude model:

$$\varepsilon_1(\omega) = \varepsilon_r - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega}$$

$$\varepsilon_1 = \mathrm{Re}(\varepsilon_1) + i\,\mathrm{Im}(\varepsilon_1)$$

$$\mathrm{Re}(\varepsilon_1) < 0$$

$$k_x = \mathrm{Re}(k_x) + i\,\mathrm{Im}(k_x)$$

$$\kappa_i = \sqrt{k_x^2 - \left(\frac{\omega}{c}\right)^2 \varepsilon_i}$$ - penetration constants

$$\lambda_{\mathrm{SPP}} = \frac{2\pi}{\mathrm{Re}(k_x)}$$ -SPP wavelength

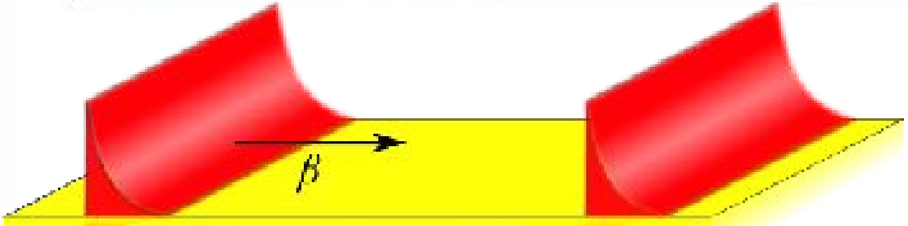
$$L_{\mathrm{SPP}} = \frac{1}{2\,\mathrm{Im}(k_x)}$$ -propagation length

$$\rho_i = \frac{1}{\mathrm{Re}(\kappa_i)}$$ -penetration depths

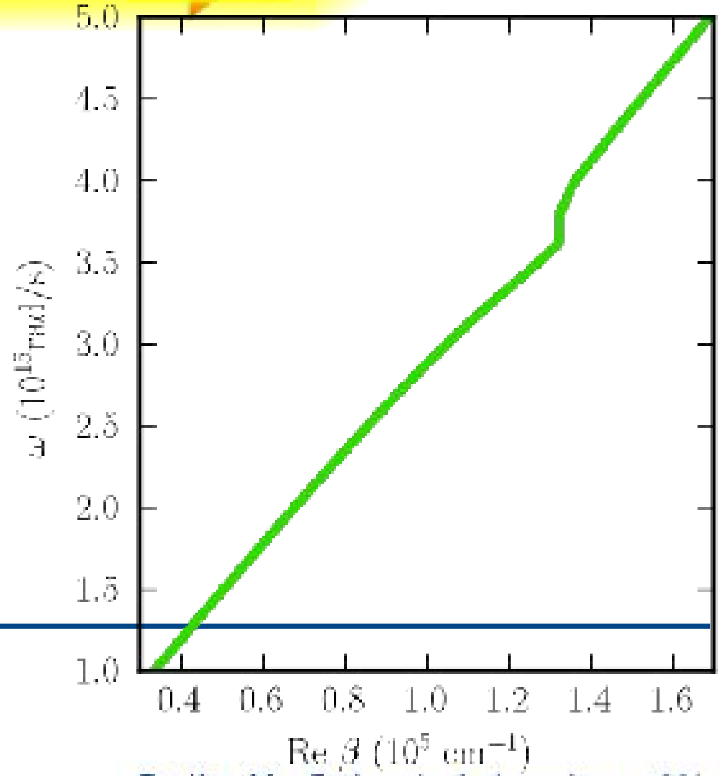
SPP dispersion

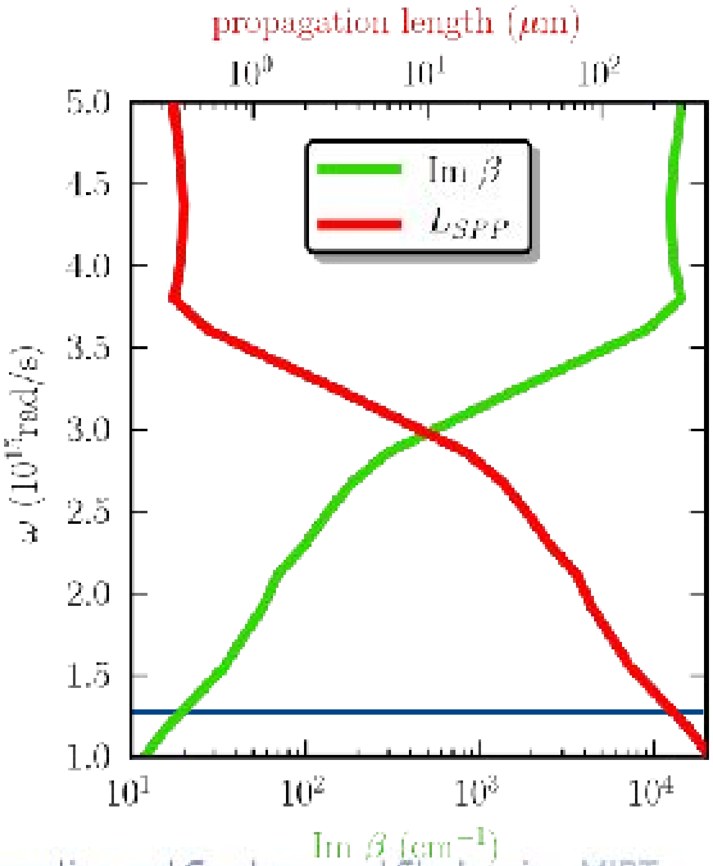
$$\kappa_1 \varepsilon_2 = -\kappa_2 \varepsilon_1$$

SPP losses

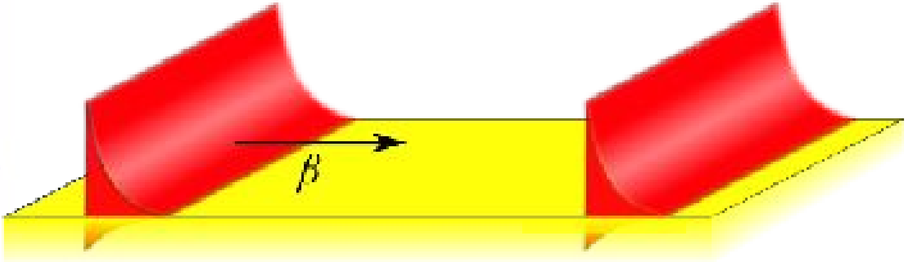


1550 nm





SPP losses



$\lambda = 1.55\ \mu m$

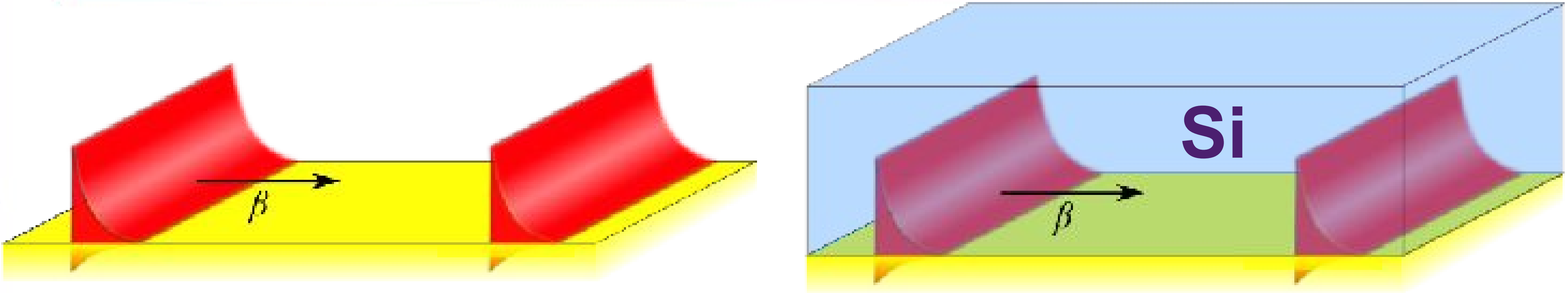
$\lambda_{SPP} \approx 1.5\ \mu m$

$L_{SPP} \approx 270\ \mu m$

$\rho_{Air} \approx 2.5\ \mu m$

$\rho_{Au} \approx 0.023\ \mu m$

SPP losses



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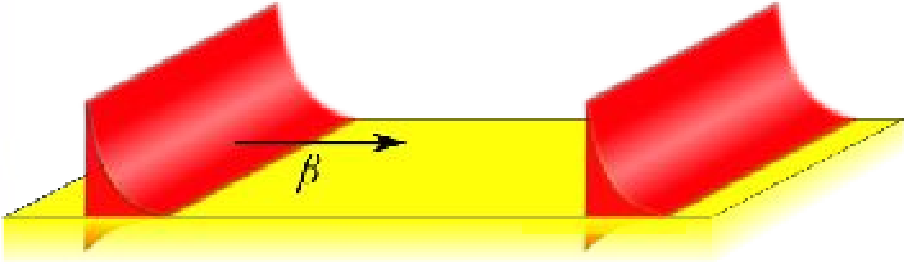

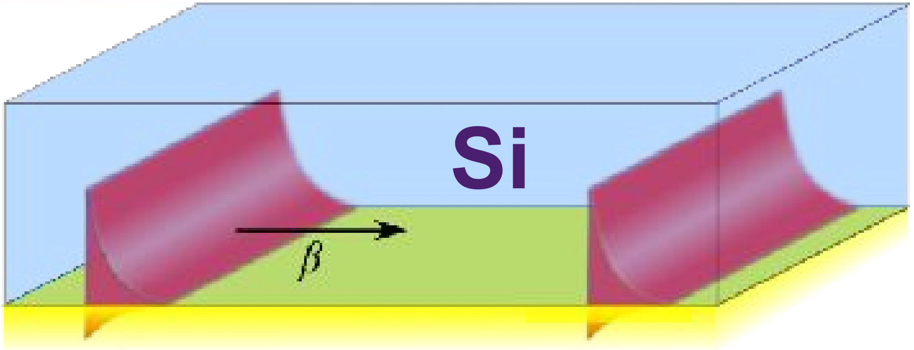

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$\lambda = 1.55\ \mu m$

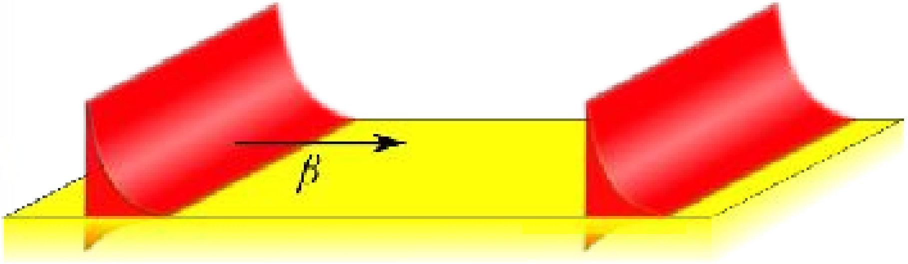
$\lambda_{SPP} \approx 0.42\ \mu m$

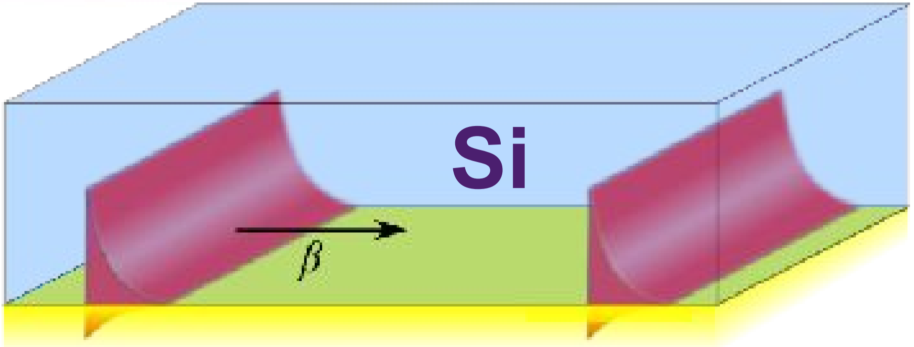
$L_{SPP} \approx 5.8\ \mu m$

$\rho_{Si} \approx 0.2\ \mu m$

$\rho_{Au} \approx 0.022\ \mu m$

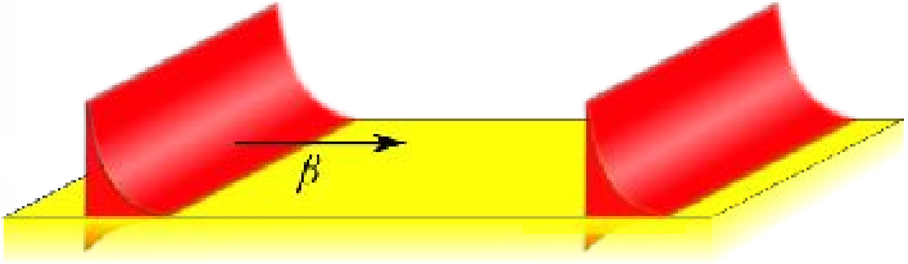
SPP losses





$$\operatorname{Im}\beta \approx \frac{\omega}{2c}\,\frac{\boldsymbol{\varepsilon}_2^{3/2}}{\left(1+\dfrac{\varepsilon_2}{\operatorname{Re}\varepsilon_1}\right)^{3/2}}\,\frac{\operatorname{Im}\varepsilon_1}{\left(\operatorname{Re}\varepsilon_1\right)^2} \quad => \quad L_{\mathrm{SPP}} \propto \frac{\left(1+\dfrac{\varepsilon_2}{\operatorname{Re}\varepsilon_1}\right)^{3/2}}{\boldsymbol{\varepsilon}_2^{3/2}}$$

SPP losses



Low-loss

Not-confined

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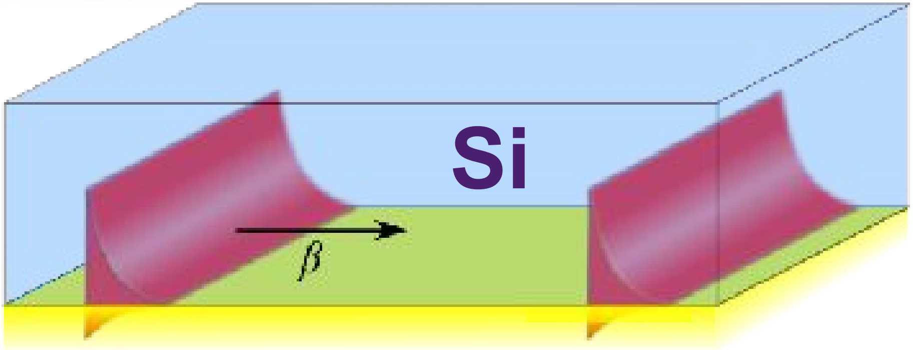

Very lossy

Highly confined

$\lambda = 1.55\ \mu m$

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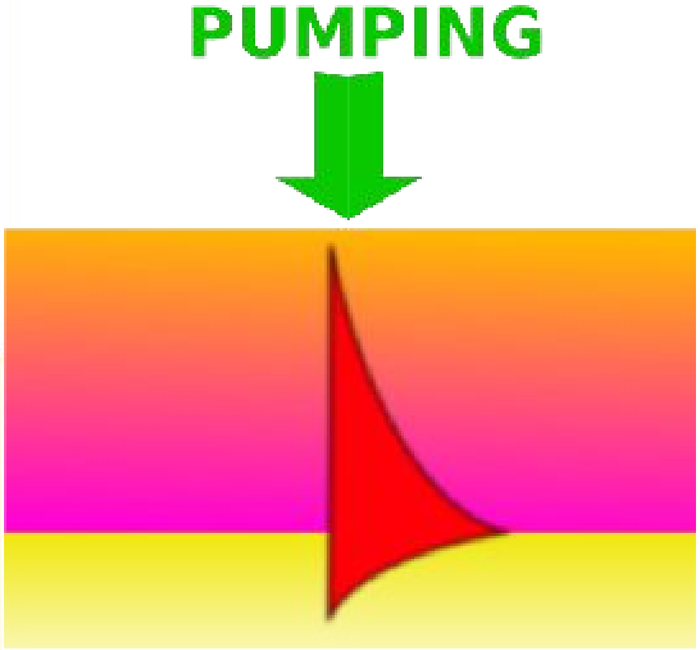
SPP Amplification

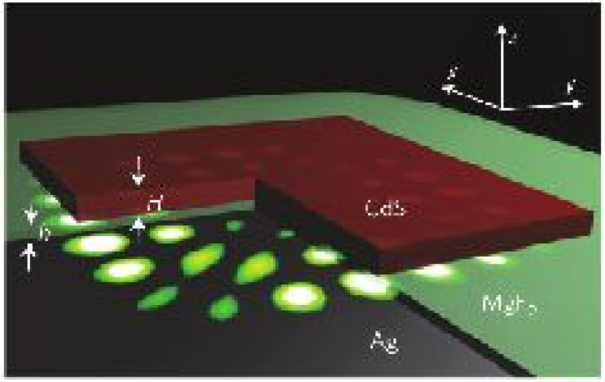
High propagation losses due to Joule heating restrict the application of SPPs. **Thus, one only way to overcome propagation losses is to partially or fully compensate Joule heating losses in the metal.** This can be done by using an active gain medium placed near a metal surface and pumping it.



- A.M. Lakhani et al., *Plasmonic crystal defect nanolaser*, Opt. Express 19, 18237 (2011).
- R.A. Flynn et al., *A room-temperature semiconductor spaser operating near 1.5 μm*, Opt. Express 19, 8954 (2011).
- R.-M. Ma et al., *Room-temperature sub-diffraction-limited plasmon laser by total internal reflection*, Nat. Mat. 10, 110 (2011).
- J.K. Kitur et al., *Stimulated Emission of Surface Plasmon Polaritons in a Microcylinder Cavity*, Phys. Rev. Lett. 106, 183903 (2011).
- and many other papers

SPP Amplification: Optical Pumping

-R.-M. Ma, R.F. Oulton, V.J. Sorger, G. Bartal & X. Zhang, *Room-temperature sub-diffraction-limited plasmon laser by total internal reflection*, Nat. Mat. 10, 110 (2011).



Pumping: frequency-doubled, mode-locked Ti:Sa laser (λ=405 nm, pulse length 100 fs).
Threshold: of the order of **1 GW/cm^2** at **room temperature** and about **60 MW/cm^2** at **10 K**.

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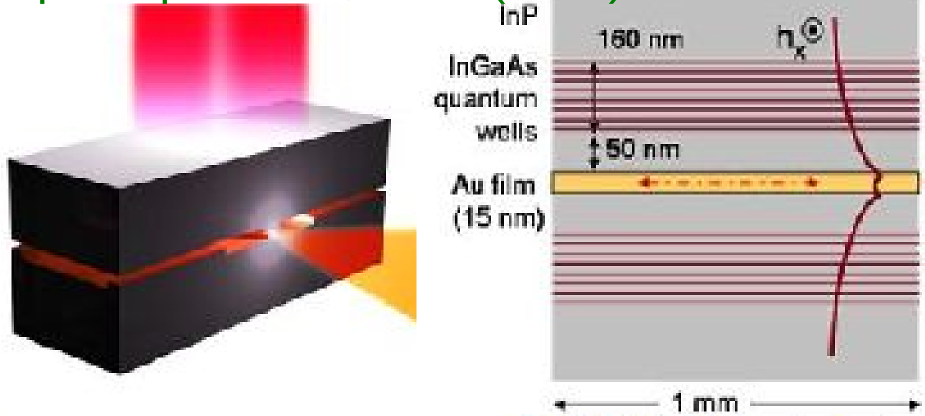

Pumping: pulsed laser (λ=1.06 μm, pulse length 140 ns)
Threshold: about **60 kW/cm^2** at **room temperature**

SPP Amplification: Optical Pumping

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Pumping: frequency-doubled, mode-locked Ti:Sa laser (λ=405 nm, pulse length 100 fs).

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Pumping: pulsed laser (λ=1.06 μm, pulse length 140 ns)

Threshold: about **60 kW/cm²** at **room temperature**

Optical pumping requires the use of external high-power bulky pump lasers and is not feasible in ultracompact on-chip optical circuits

SPP Amplification

Is it possible to design a COMPACT plasmonic structure with NEGLIGIBLY SMALL PROPAGATION LOSSES?

Requirements:

- Compact pumping
- Full loss compensation
- Compatibility with compact plasmonic and optical waveguides

SPP Amplification

Is it possible to design a COMPACT plasmonic structure with NEGLIGIBLY SMALL PROPAGATION LOSSES?

Requirements:

- Compact pumping
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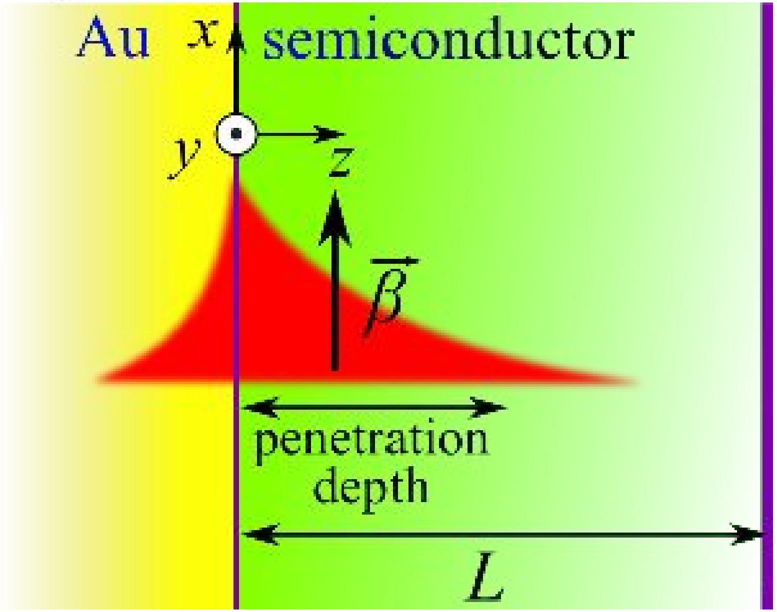
- Compatibility with compact plasmonic and optical waveguides

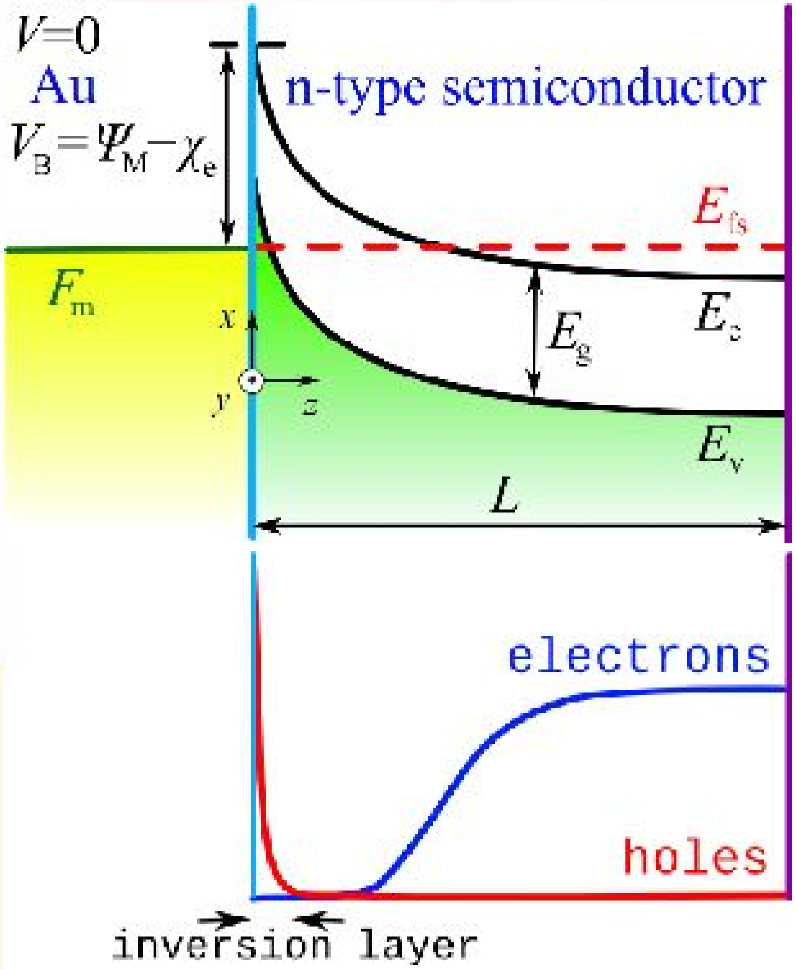
The answer is electric pumping!

-D.Yu. Fedyanin, *Toward an electrically pumped spaser*, Opt. Lett. **37**, 404 (2012).
-D.Yu. Fedyanin, A.V. Arsenin, *Surface plasmon polariton amplification in metal-semiconductor structures*, Opt. Express **19**, 12524-12531 (2011).
-D.Yu. Fedyanin, A.V. Arsenin, *Au/InAs Surface Plasmon Polariton Amplifier and SPASER* // AIP Conf. Proc. **1398**, 70-72 (2011).
-D.Yu. Fedyanin, A.V. Arsenin, *Semiconductor Surface Plasmon Amplifier Based on a Schottky Barrier Diode* // AIP Conf. Proc. **1291**, 112-114 (2010).

SPP Amplification



SPP Amplification: Electric Pumping



Usually, Schottky diodes are treated as majority carrier devices. However, the situation changes drastically when the barrier height exceeds the half of the bandgap. In this case an inversion layer is formed near the metal-semiconductor contact. Under sufficient forward bias this carriers are injected into the bulk of the semiconductor and recombine with majority carriers.

Condition for net stimulated emission or gain

$$F_e - F_h \geqslant \hbar\omega \geqslant E_g$$

-K.W. Nill et al., Appl. Phys. Lett. **16**, 375 (1970).
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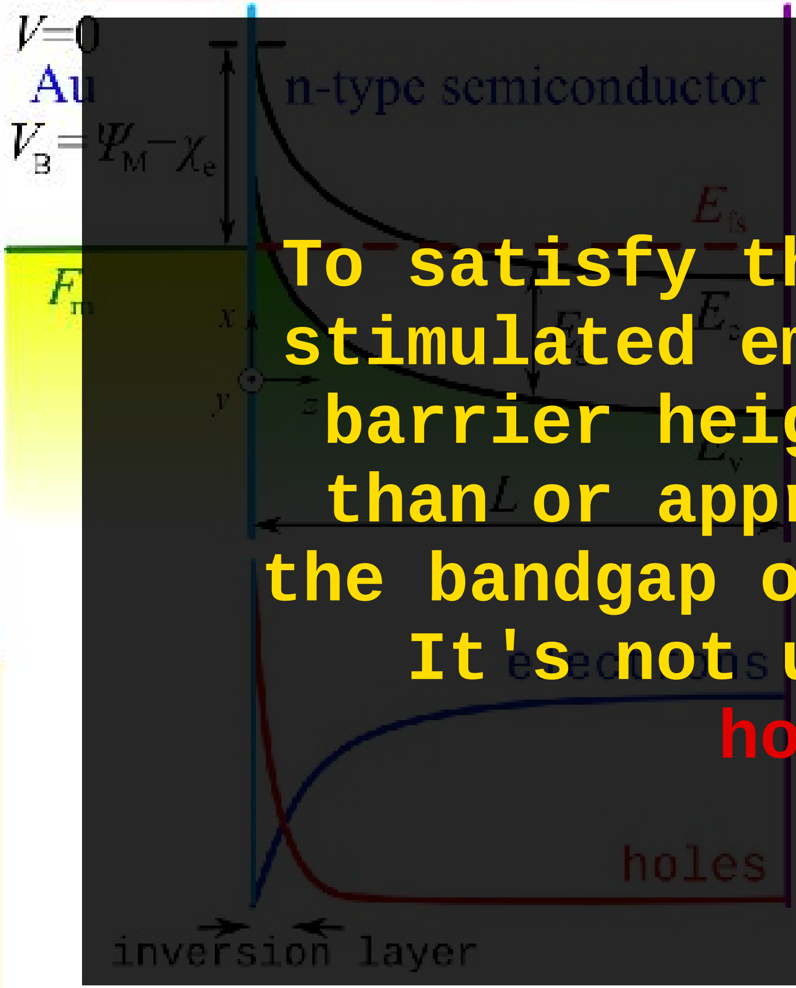
SPP Amplification: Electric Pumping



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Condition for net stimulated emission or gain

$$F_e - F_h \geqslant \hbar\omega \geqslant E_g$$

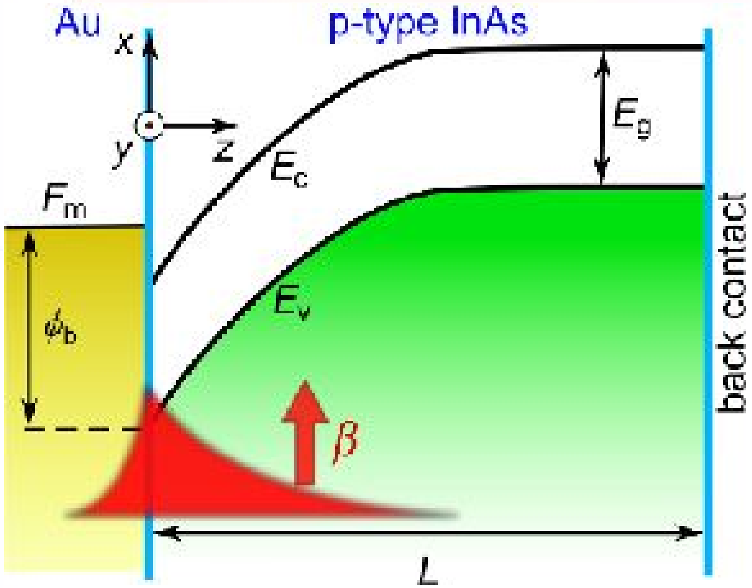
To satisfy the condition for net stimulated emission or gain, the barrier height must be greater than or approximately equal to the bandgap of the semiconductor.

It's not usually possible,

however ...

- K.W. Nill et al., Appl. Phys. Lett. **16**, 375 (1970).
-D.Yu. Fedyanin and A.V. Arsenin, AIP Conf. Proc. **1291**, 112 (2010).

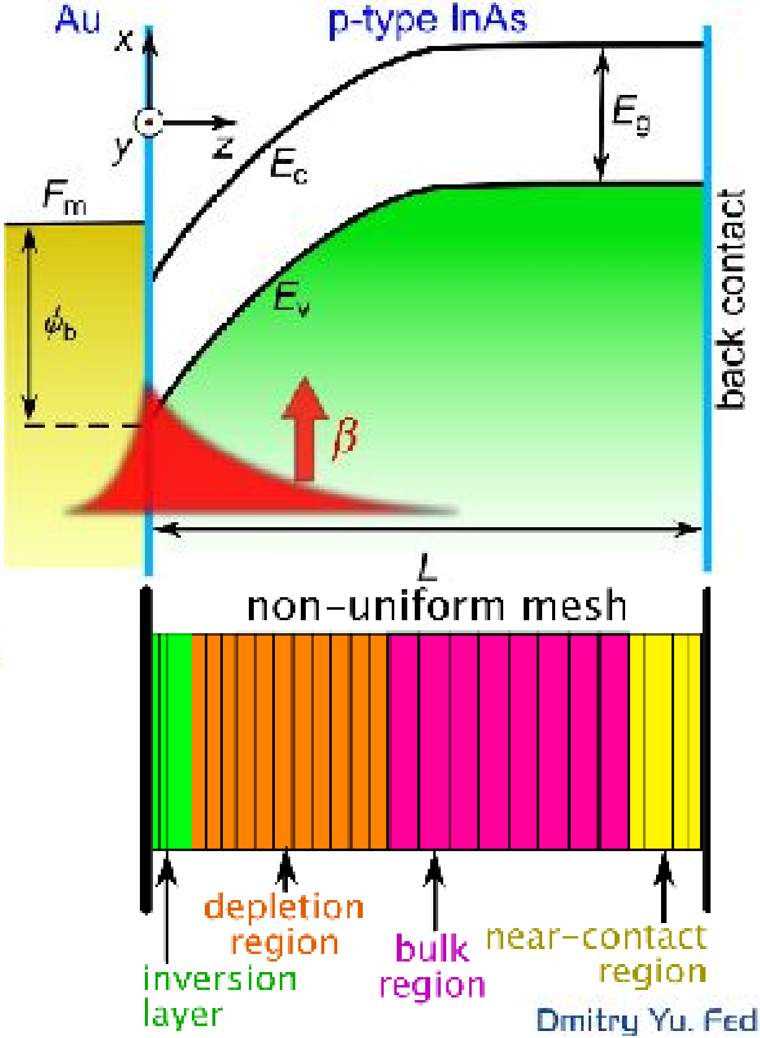
SPP Amplification: Electric Pumping



Fermi level in the metal occurs 130 meV above the conduction band edge of InAs (E_g=0.40 eV at 77K). Consequently, the barrier height of an Au/p-InAs contact is greater than the bandgap.

-D.Yu. Fedyanin, *Toward an electrically pumped spaser*, Opt. Lett. **37**, 404 (2012).
-D.Yu. Fedyanin, A.V. Arsenin, *Au/InAs Surface Plasmon Polariton Amplifier and SPASER* // AIP Conf. Proc. **1398**, 70 (2011)

SPP Amplification: Electrical Pumping

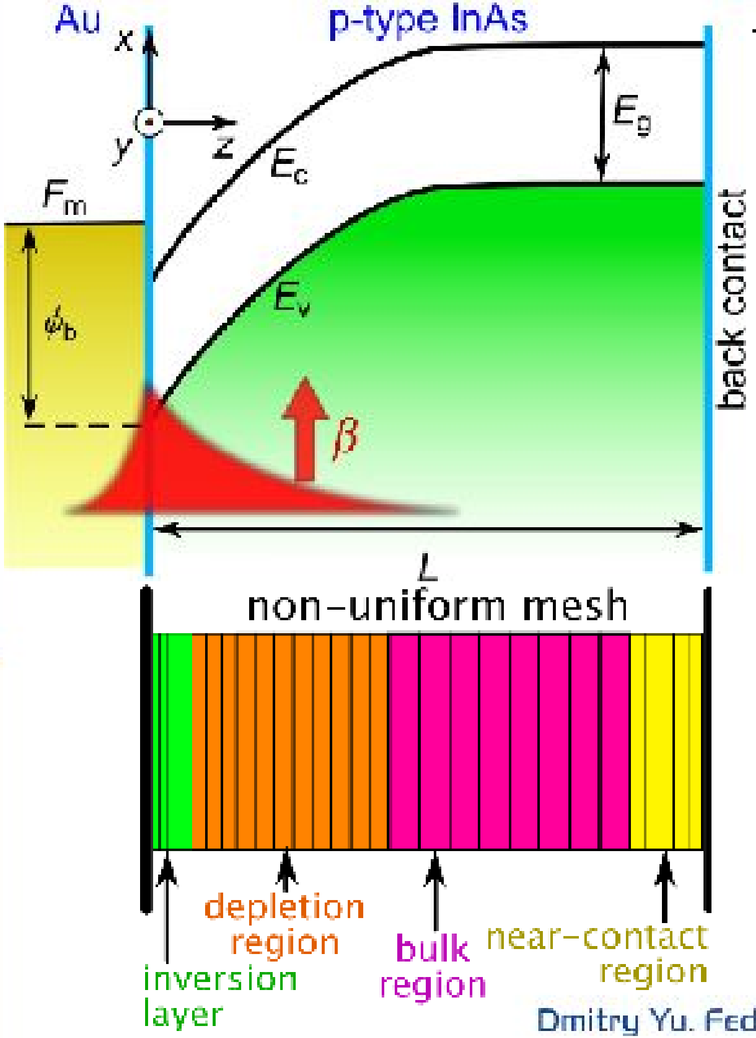


We solve six nonlinear first order differential equations that describe the carrier behavior within the semiconductor

$$\begin{cases} d\varphi/dz = -E_z \\ dE_z/dz = 4\pi e\left(p - n + N_d\right)/\varepsilon_{st} \\ \dfrac{dn}{dz} = \dfrac{1}{eD_n} J_n - \dfrac{\mu_n n}{D_n} E_z \\ \dfrac{dp}{dz} = -\dfrac{1}{eD_p} J_p + \dfrac{\mu_p p}{D_p} E_z \\ dJ_n/dz = eU \\ dJ_p/dz = -eU \end{cases}$$

where $U = U_{\mathrm{stim}} + U_{\mathrm{spont}} + U_{\mathrm{Auger}}$

SPP Amplification: Electrical Pumping

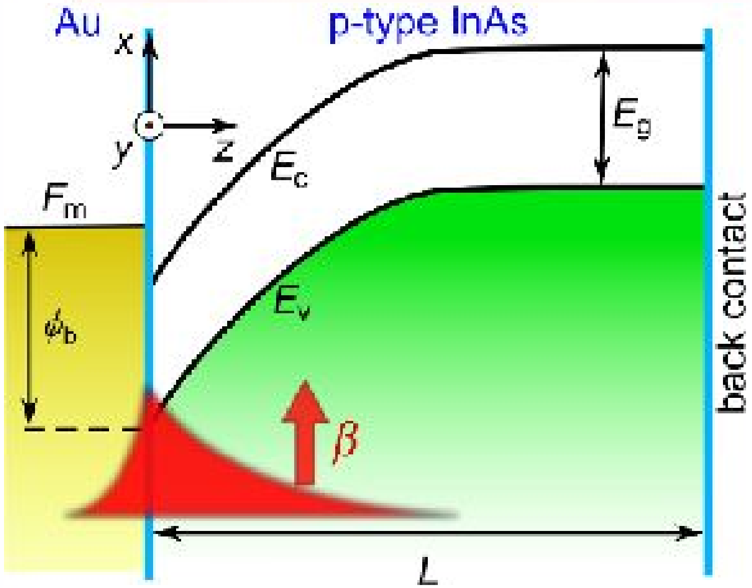


together with six boundary conditions

$$\begin{cases} J_{\mathrm{n}}\big|_{z=0} = e\upsilon_{\mathrm{nr}}\left(n\big|_{z=0} - n_0\right) \\ J_{\mathrm{p}}\big|_{z=0} = -e\upsilon_{\mathrm{pr}}\left(p\big|_{z=0} - p_0\right) \\ \varphi\big|_{z=0} = -\dfrac{\psi_{\mathrm{M}} - \chi_{\mathrm{e}}}{e} \\ \varphi\big|_{z=L} = V + \dfrac{k_{\mathrm{B}}T}{e}\ln\left(\dfrac{n_L}{N_{\mathrm{c}}}\right) \\ n\big|_{z=L} = n_L \\ p\big|_{z=L} = p_L \end{cases}$$

where $\upsilon_{\mathrm{nr}} \approx \dfrac{1}{4}\sqrt{\dfrac{8k_{\mathrm{B}}T}{\pi m_{\mathrm{n}}}}$; $\upsilon_{\mathrm{pr}} \approx \dfrac{1}{4}\sqrt{\dfrac{8k_{\mathrm{B}}T}{\pi m_{\mathrm{p}}}}$

SPP Amplification: Electrical Pumping



N_a=2.33×10^{18} cm^{-3}

$\hbar\omega$=0.3925 eV (λ=3.16 μm)

$\tilde{n}$=3.50

L=2.0 μm

T=77 K

Stimulated emission and gain

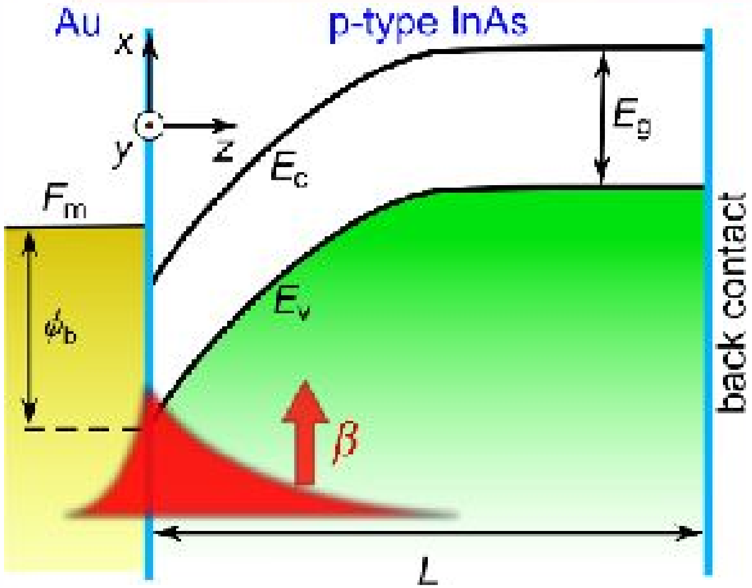
$$U = U_{\text{spont}} + U_{\text{Auger}} + U_{\text{stim}}$$

$$U_{\text{stim}}(z) = g\left(F_{\text{e}}(z), F_{\text{h}}(z)\right) S/\hbar\omega$$

$$g = \frac{4\pi^2 e^2}{c\bar{n} m_{\text{e0}}^2 \omega} |M_{\text{b}}|^2 \int_0^{+\infty} |M_{\text{env}}(E, E-\hbar\omega)|^2 \rho_{\text{c}}(E-E_c)\,\rho_{\text{v}}(E_v - E + \hbar\omega) \times \left\{ \frac{1}{1+\exp\left[(E-F_{\text{e}})/k_{\text{B}}T\right]} - \frac{1}{1+\exp\left[(E-\hbar\omega-F_{\text{h}})/k_{\text{B}}T\right]} \right\} dE$$

- Gaussian Halperin-Lax band-tail (GHLBT) model
- Stern's envelope matrix element M_{env}

SPP Amplification: Electric Pumping



N_a=2.33×10^{18} cm^{-3}

$\hbar\omega$=392.5 meV (λ=3.16 μm)

$\tilde{n}$=3.50

L=2.0 μm

T=77 K

Stimulated emission and gain

$$U = U_{\text{spont}} + U_{\text{Auger}} + U_{\text{stim}}$$

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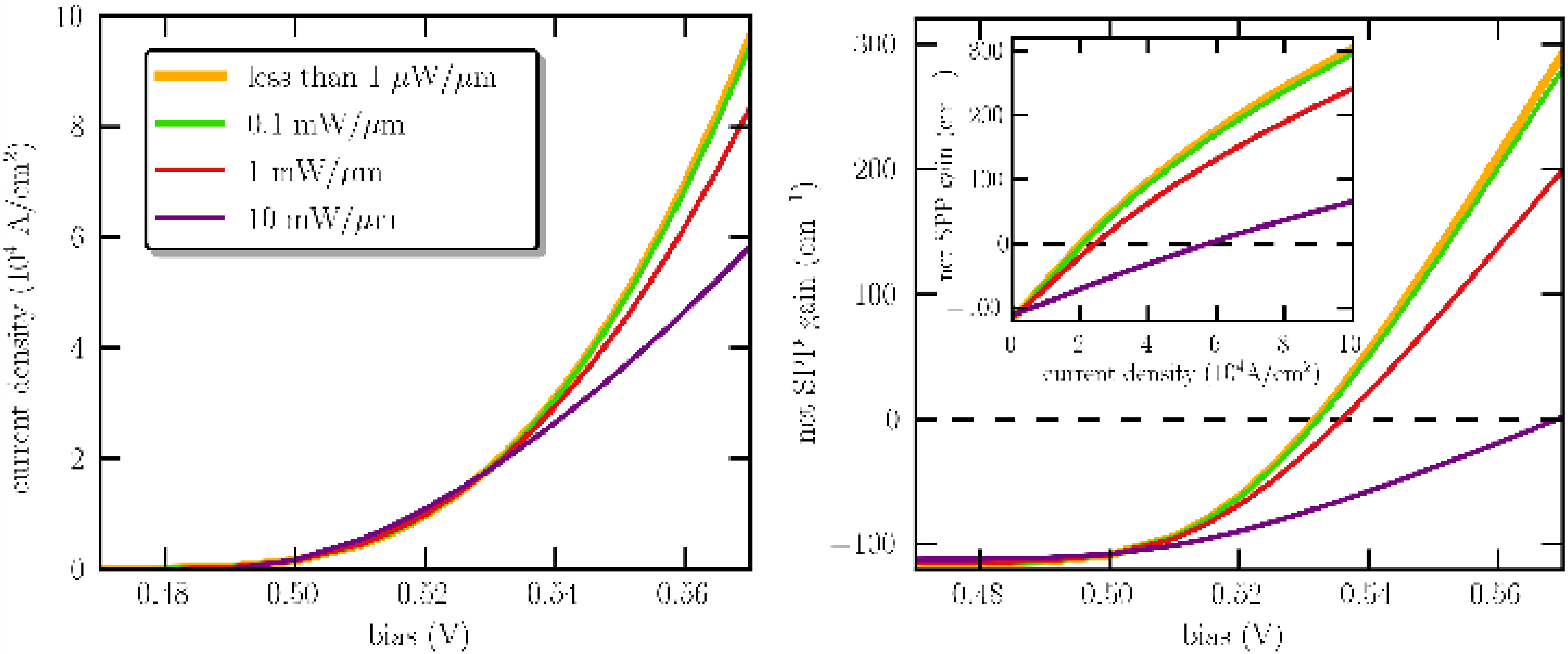
$$\approx 1.41\times10^{-14}\left[\min(\boldsymbol{n}, p) - 5\times10^{14}\right]$$

-D.Yu. Fedyanin, *Toward an electrically pumped spaser*, Opt. Lett. **37**, 404 (2012).

SPP Amplification: Electric Pumping



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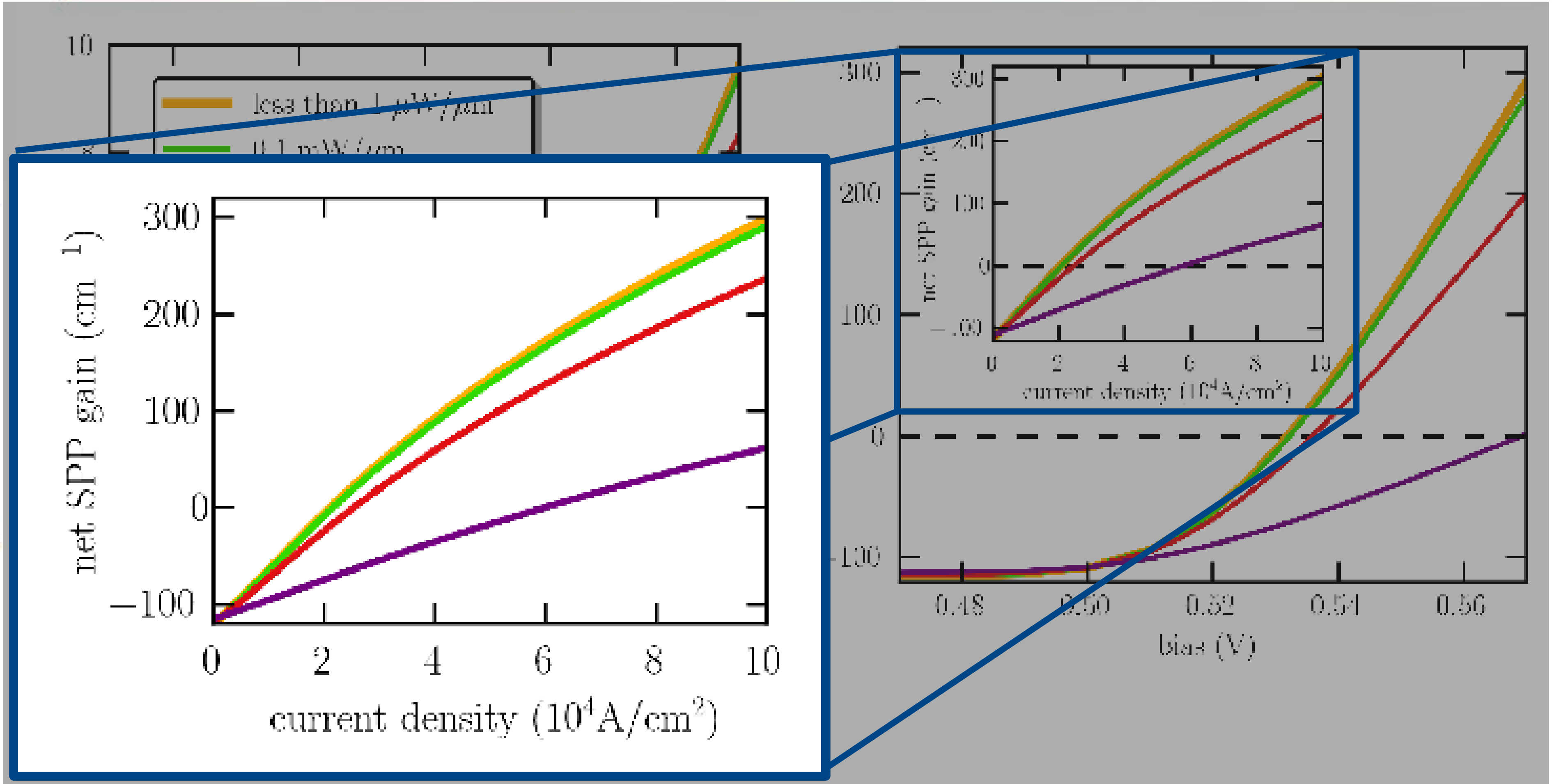

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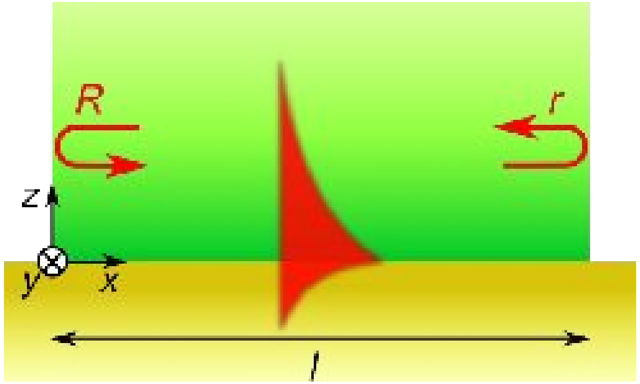
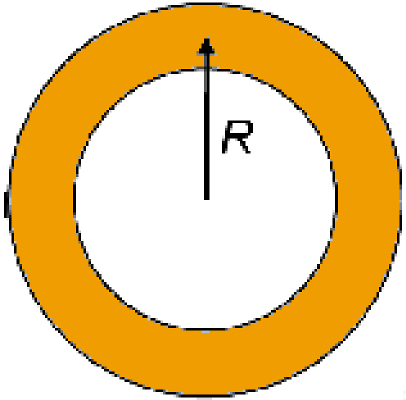
Coherent SPP Sources

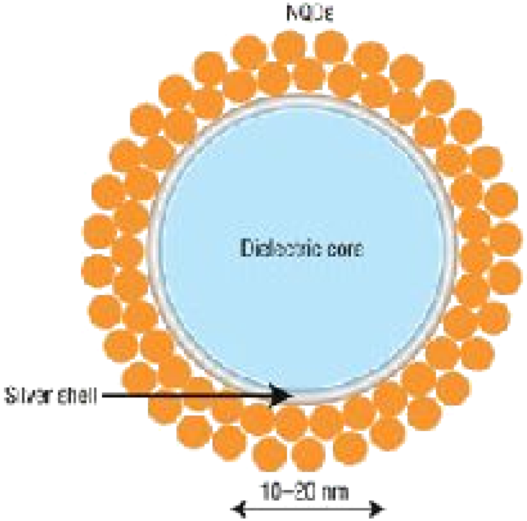
SPPASER and SPASER

Propagating plasmons

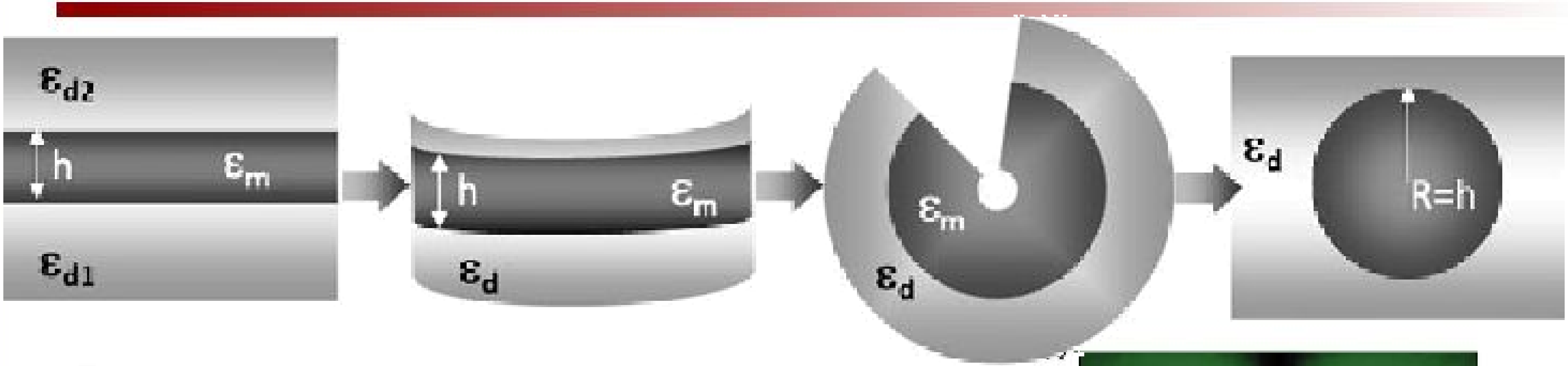
Localized plasmons

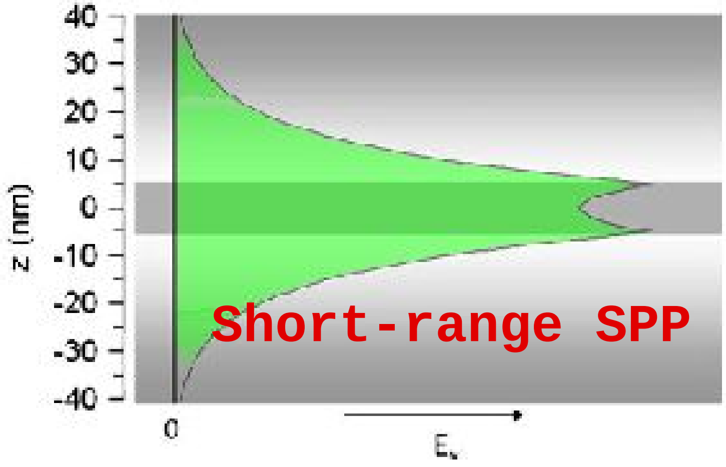


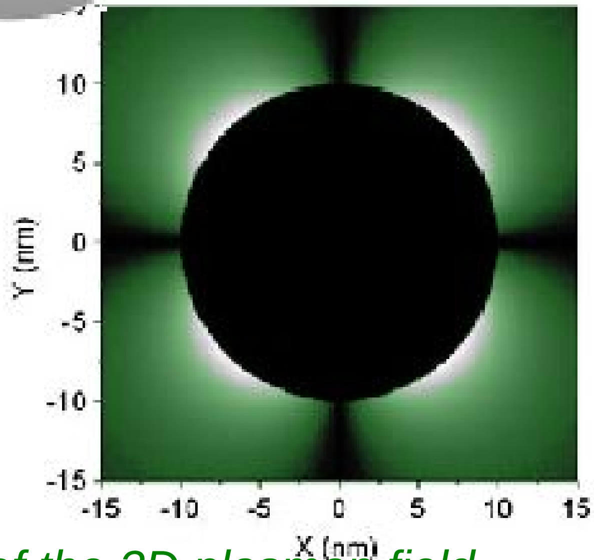




SPPASER and SPASER

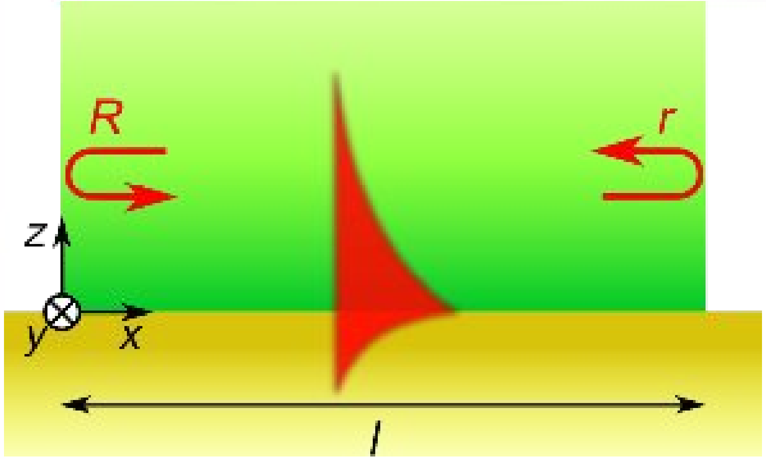






-S. Benghorieb, R. Saoudi, A.V. Tishchenko, *Extraction of the 3D plasmon field,* Plasmonics **6**, 445 (2011)

SPPASER



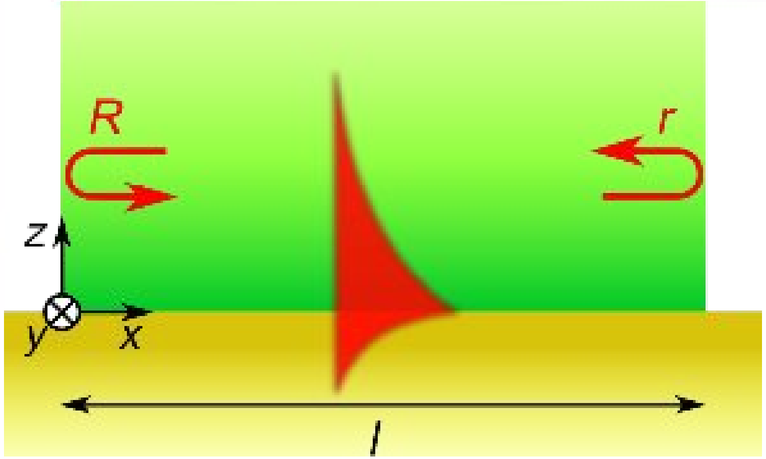
Threshold condition in a steady state:

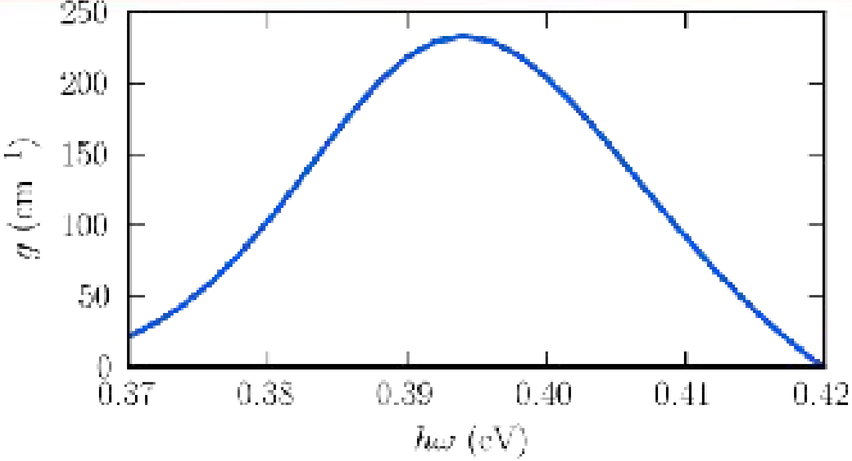
$$G_{\mathrm{th}}=\frac{1}{2l}\ln\left(\frac{1}{|r|^2|R|^2}\right)$$

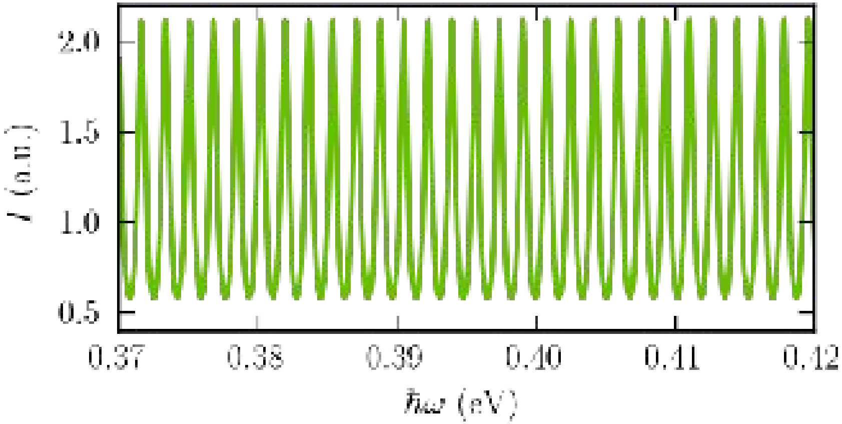
Smooth facets:

$$|r|^2=|R|^2\approx\left|\frac{\frac{\beta c}{\omega}-1}{\frac{\beta c}{\omega}+1}\right|^2=0.31 \;=>\; G_{\mathrm{th}}=115\,\mathrm{cm}^{-1},\, J_{\mathrm{th}}=4.4\times10^4\,\mathrm{A/cm}^2 \text{ at } l=100\,\mu\mathrm{m}$$

SPPASER







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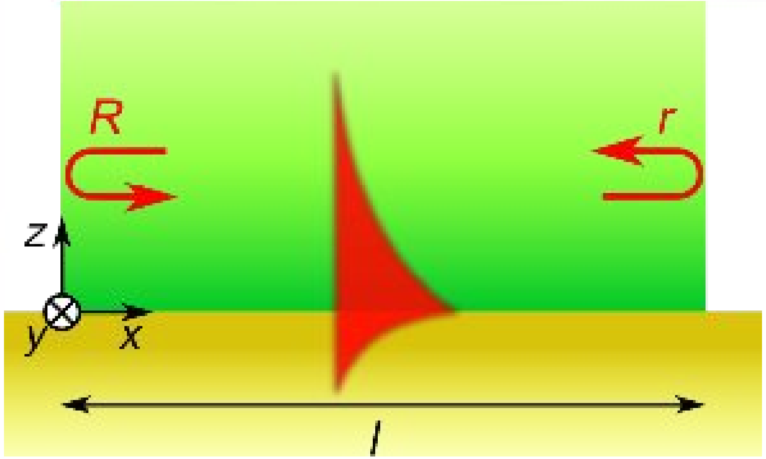
SPPASER



Threshold condition in a steady state:

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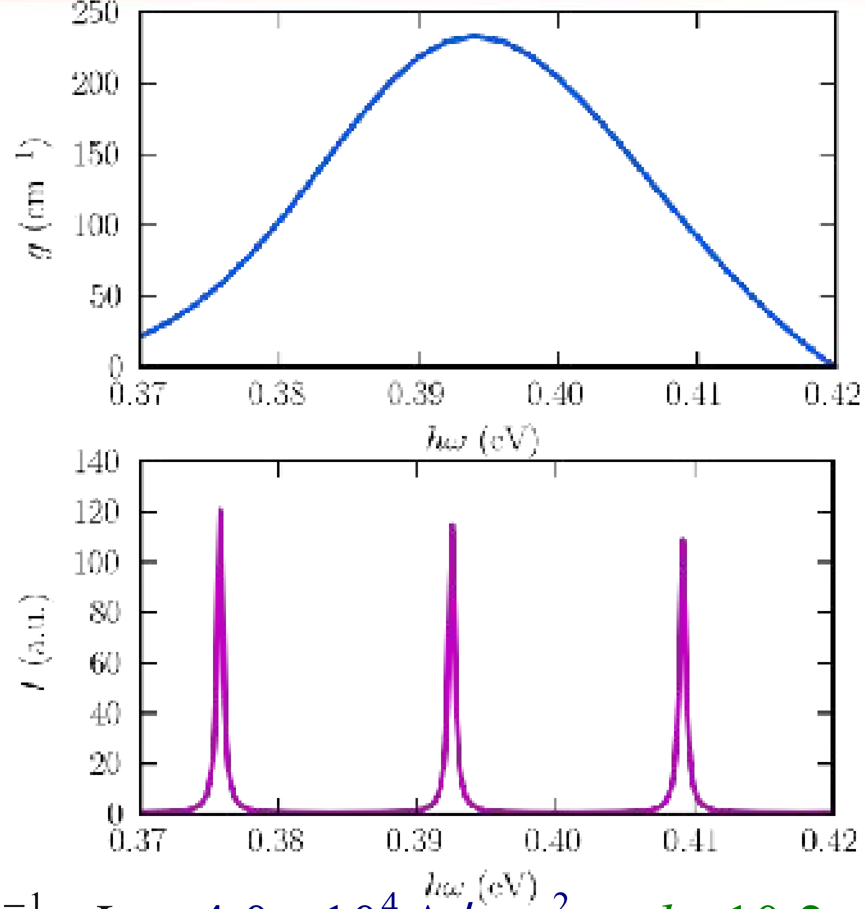
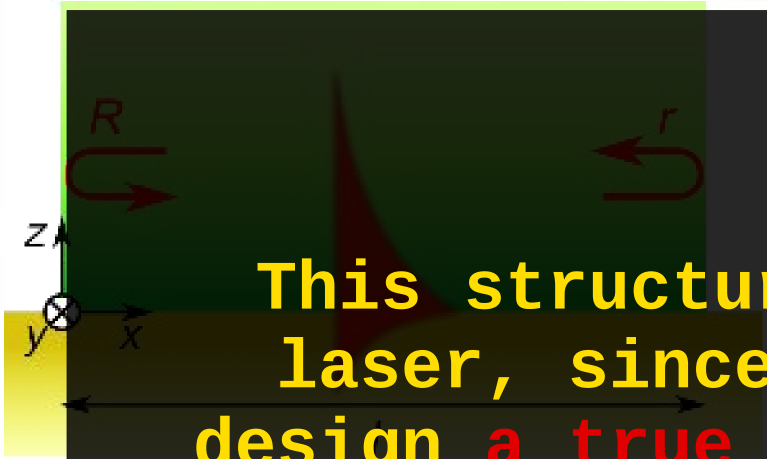
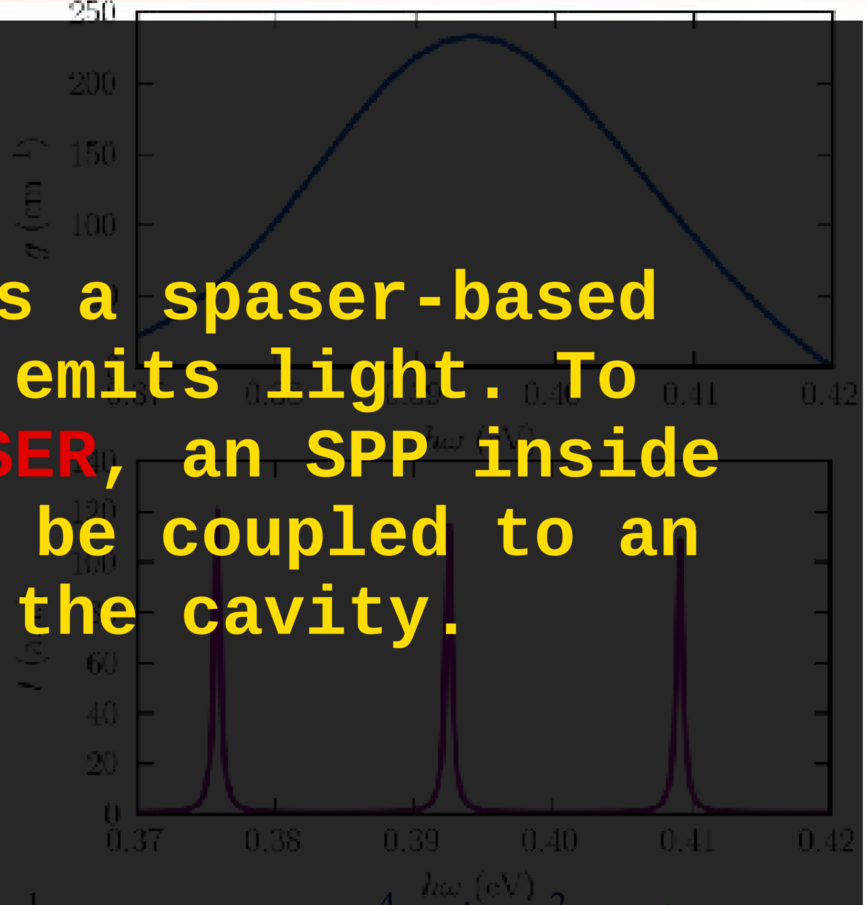
15-nm Au coating:



$$|r|^2 = |R|^2 \approx \left|\frac{\frac{\beta c}{\omega} - 1}{\frac{\beta c}{\omega} + 1}\right|^2 = 0.9 \Rightarrow G_{\text{th}} = 95\,\text{cm}^{-1},\ J_{\text{th}} = 4.0 \times 10^4\,\text{A/cm}^2 \text{ at } l = 10.2\,\mu\text{m}$$

SPPASER





Threshold condition in a steady state:

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15-nm-thick Au mirrors:

$$|r|^2 = |R|^2 \approx \left|\frac{\frac{\beta c}{\omega} - 1}{\frac{\beta c}{\omega} + 1}\right|^2 = 0.9 \Rightarrow G_{\text{th}} = 95\,\text{cm}^{-1}, J_{\text{th}} = 4.0\times10^4\,\text{A/cm}^2 \text{ at } l = 10.2\,\mu\text{m}$$

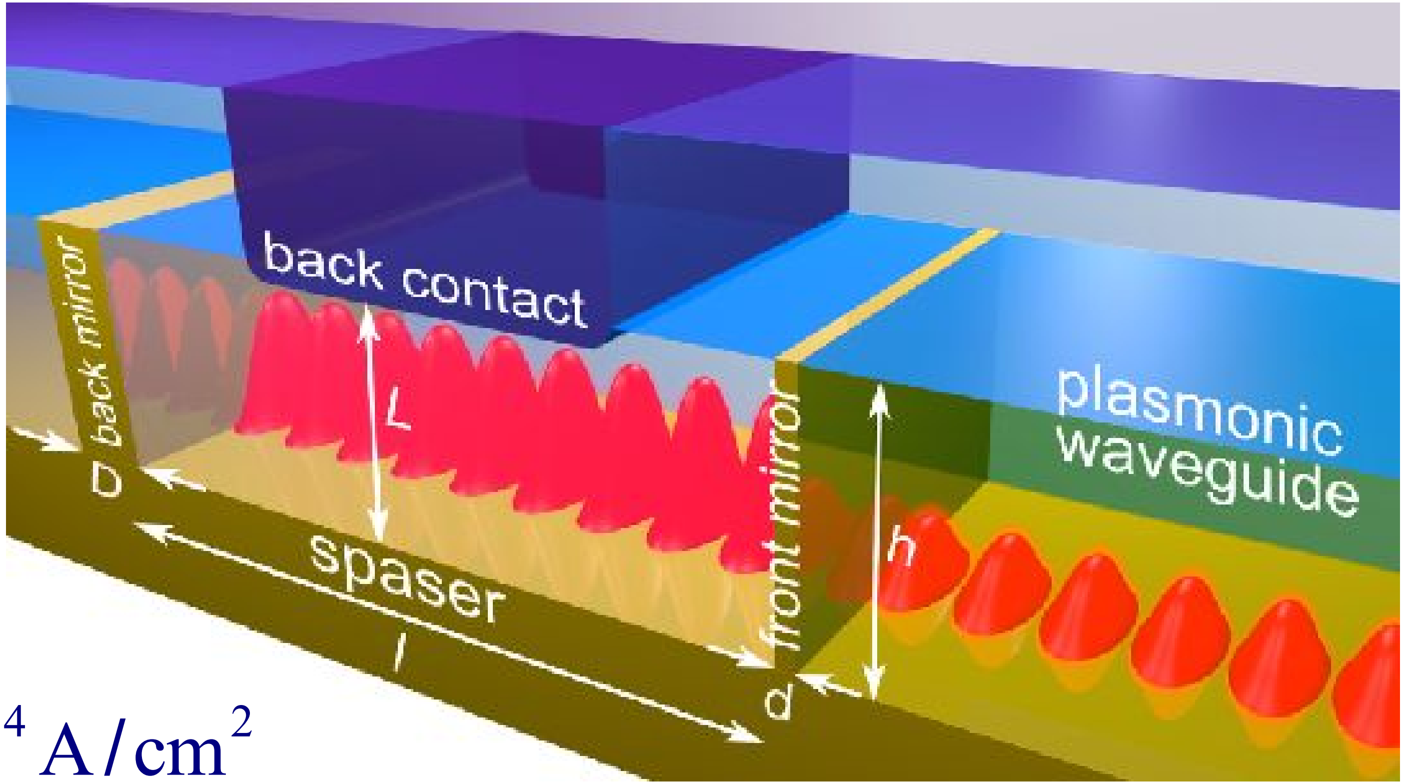
This structure is a spaser-based laser, since it emits light. To design a true SPASER, an SPP inside the cavity should be coupled to an SPP outside the cavity.

SPPASER

$$l = 10.2\,\mu\text{m}$$
$$d = 20\,\text{nm}$$
$$D = 100\,\text{nm}$$
$$L = 2\,\mu\text{m}$$
$$h \sim 2\,\mu\text{m}$$

$$|R|^2 = 0.98$$
$$|r|^2 = 0.89$$
$$|t|^2 = 0.07$$

$$J_{\text{th}} = 3.3 \times 10^4\,\text{A/cm}^2$$



-D.Yu. Fedyanin, *Toward an electrically pumped spaser*, Opt. Lett. 37, 404 (2012).

Active Plasmonic Interconnects

What about of shrinking the lateral (y) dimension?

Active Plasmonic Interconnects

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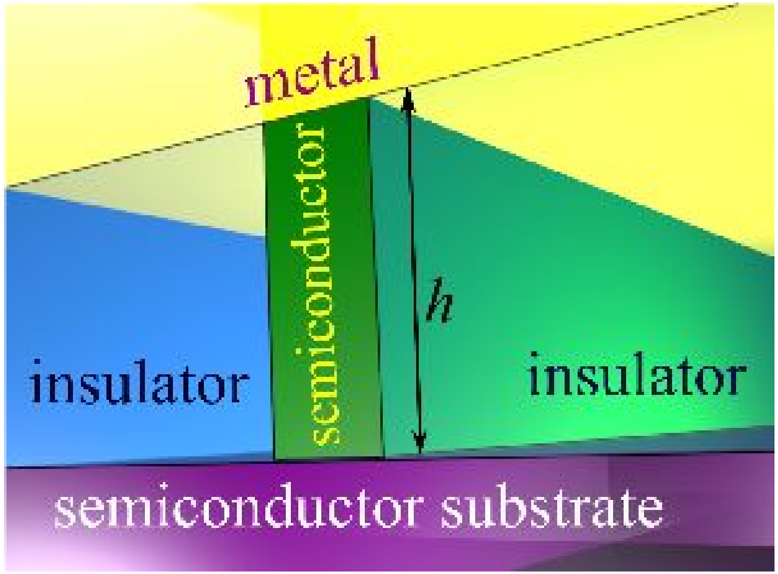
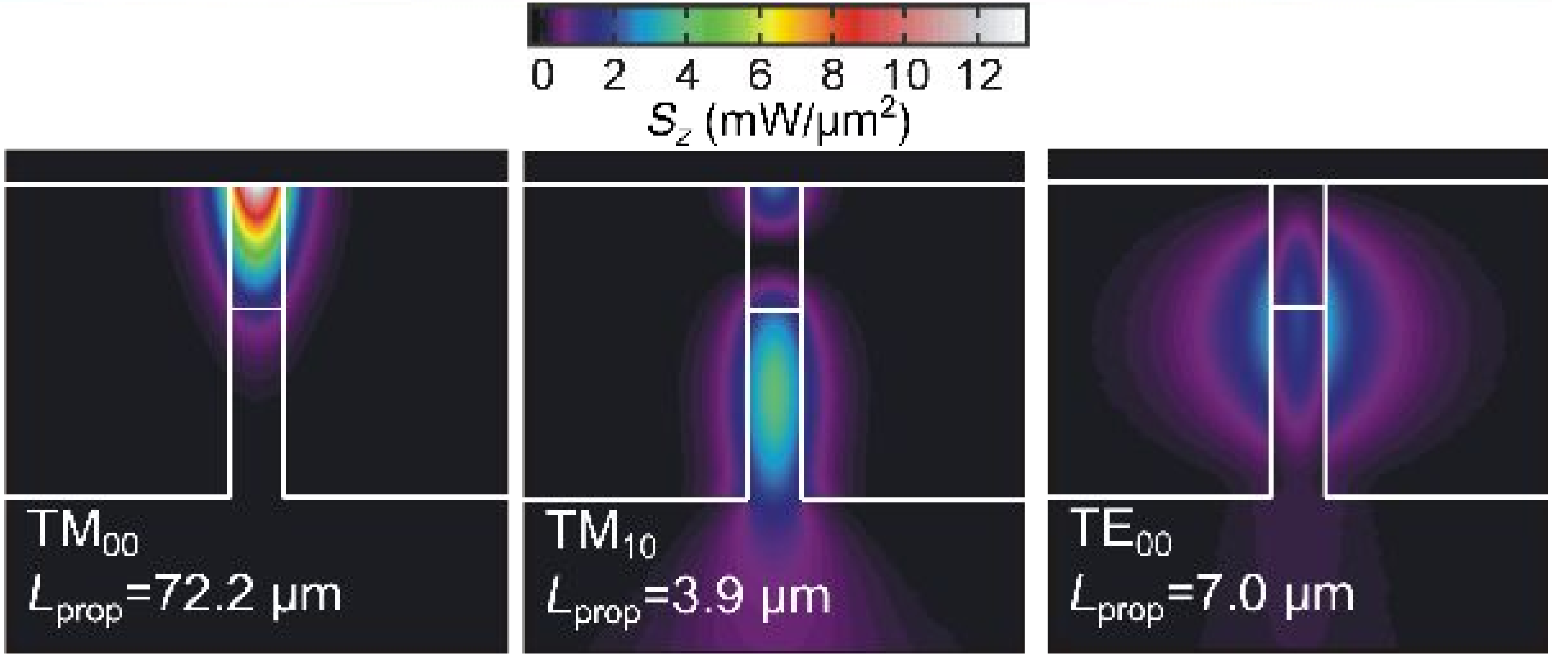


All integrated circuits (both optical and electrical) are actually planar, 2D dimensional circuits. It means that *the mode height is not as important as the mode width*, which actually determines the crosstalk and integration density. So, we should decrease the waveguide width. In the present approach, there are no fundamental and technological limitations for shrinking the lateral (y) dimension of the considereda structure down to several hundred nanometers, since there are only 2 characteristic dimensions: thickness of the inversion layer and thickness of the depletion region. Both of them are appreciably less than 100 nm.

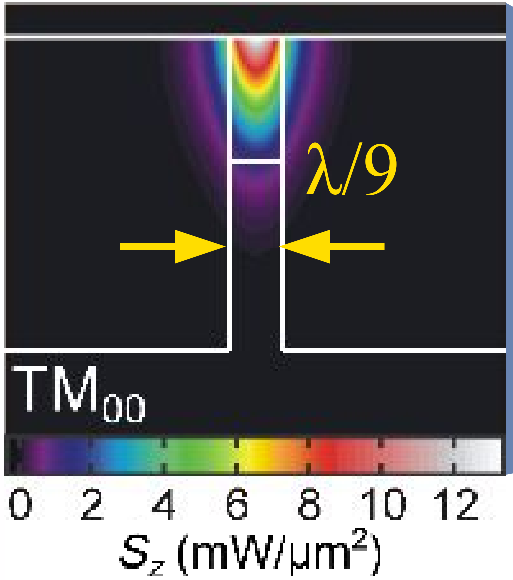
Active Plasmonic Interconnects

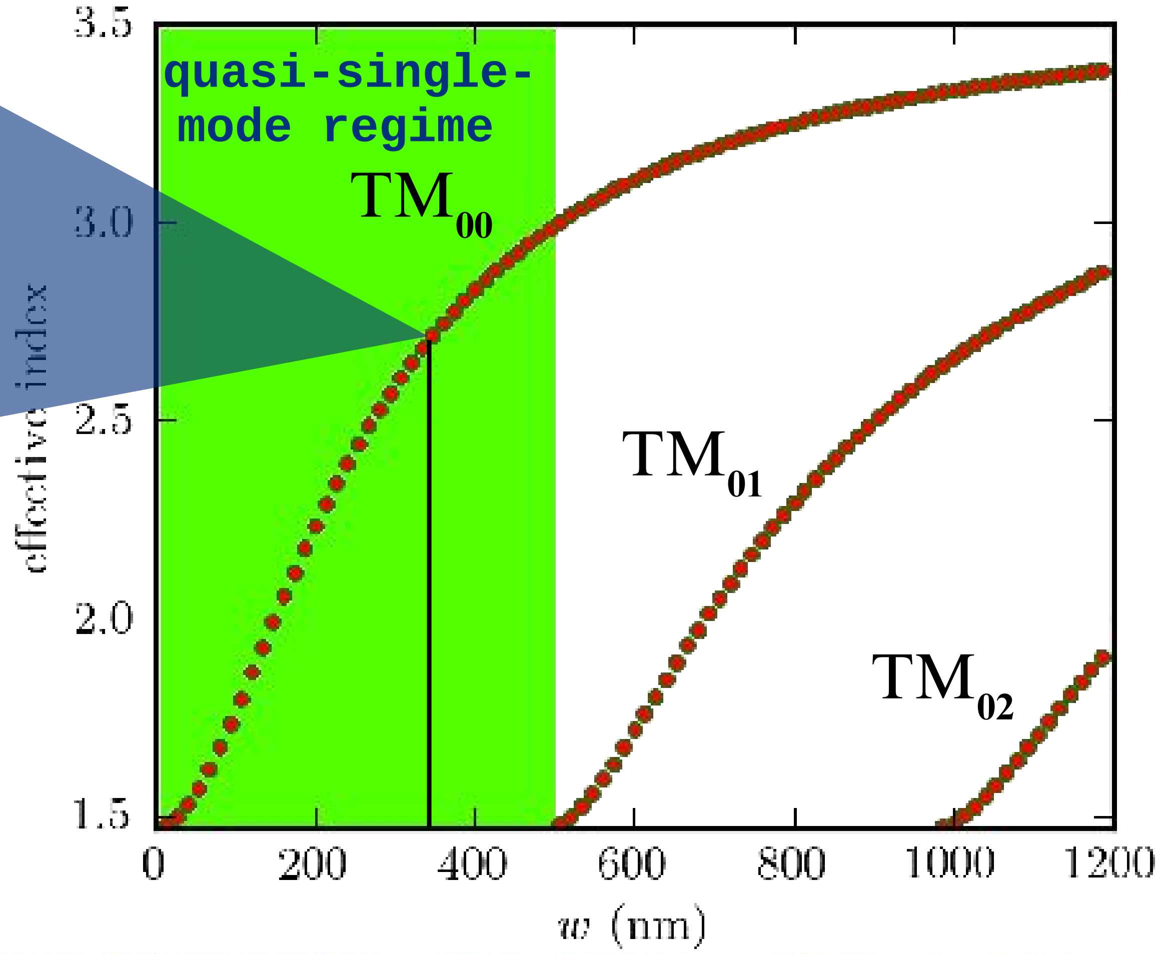


Photonic TE$_{00}$ and TM$_{10}$ modes are very leaky modes and their propagation lengths are much shorter than propagation length of the plasmonic TM$_{00}$ mode.

-D.Yu. Fedyanin, A.V. Krasavin, A.V. Arsenin, A.V. Zayats, *Surface plasmon polariton amplification upon electrical injection in highly integrated plasmonic circuits*, Nano Lett. (2012).

Active Plasmonic Interconnects





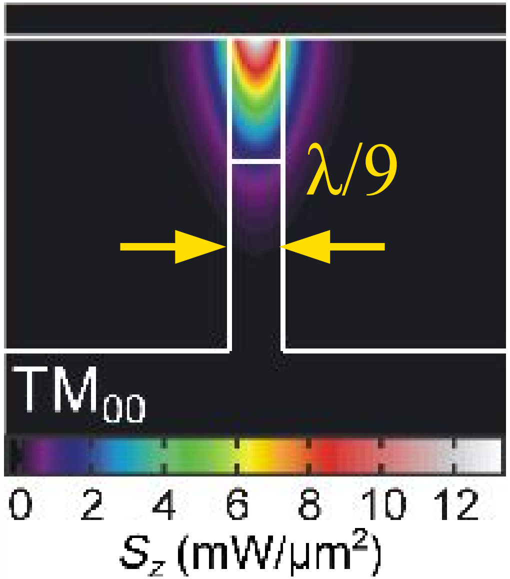
$\varepsilon_m = -535 + 35i$ (Au)

$\varepsilon_d = 2.16$ (SiO_2)

$\varepsilon_s = 12.25$ (InAs)

$\lambda = 3.16\ \mu m$

Purcell Factor



$\tilde{n}(x,y)$ is real part of the refractive index of the medium at (x,y)

υ_g is the SPP group velocity

$\xi(x,y)$ is approximately equal to $\tilde{n}^2(x,y)$ in the semiconductor and and in the insulator and equals $1+\omega_p^2/(\omega^2+\Gamma^2)$ in the metal.

$$F_p(x,y) = 1 + \frac{c^3\left|E(x,y)\right|^2}{4\bar{n}(x,y)\omega^2\upsilon_g \int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty}\frac{1}{16\pi}\left(\xi(\tilde{x},\tilde{y})\left|E(\tilde{x},\tilde{y})\right|^2+\left|H(\tilde{x},\tilde{y})\right|^2\right)d\tilde{x}\,d\tilde{y}},$$

$$F_p(x,y) < 3.5$$

Summary

- Despite the advantages of silicon photonics, even smaller interconnects are achievable with SPP based waveguides, which have the similar bandwidth and delays.
- SPP waveguides are quite lossy. However, one can partially or fully compensate losses using an active medium placed near the metal surface.
- Optical pumping is very bulky and cannot be used in nanoscale on-chip circuits and we should move to electric pumping.
- I've demonstrated an amplification scheme, which is based on a Schottky barrier diode that give a possibility to obtain net SPP gain.
- The presented approach give a possibility do design an electrically pumped SPASER.
- The obtained threshold current is relatively small for a pulsed and even a cw SPASER.
- There are no physical limitations for shrinking the lateral dimension of the proposed structure down to deep-subwavelength scale and development of on-chip plasmonic interconnects.

Thank you for your attention!

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