A(n Incomplete) Survey of Some of the Plasmonic Work at Stanford

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outline

- what is a plasmon?
- where is it used?
- what do I work on?
  - photo detectors integrated with plasmonic antennas & waveguides
  - antenna and waveguide modeling
- what do some others at stanford work on?
- discussion

what is a plasmon?

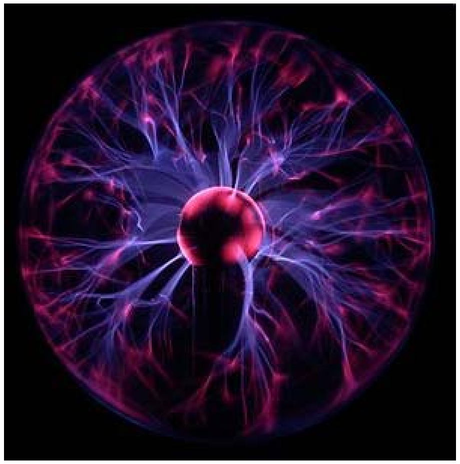
- 1900 *Daily Express 31 July 2/6 Plasmon is nothing more or less than milk dried after removing the cream and sugar. Ibid., The writer has found Plasmon chocolate a most useful preparation in cycling.*

- 1956 D. Pines in *Rev. Mod. Physics* vol. 28. 184/1 *The valence electrons in the solid..are capable of carrying out collective oscillations at a high frequency... The valence electron collective oscillations resemble closely the electronic plasma oscillations observed in gaseous discharges. We introduce the name 'plasmons' to describe the quantum of elementary excitation associated with this high-frequency collective motion.*

http://www.oed.com/

plasmonics

- *plasma:* ionized gas with free electrons
- *–on:* suffix that signifies quantized particles



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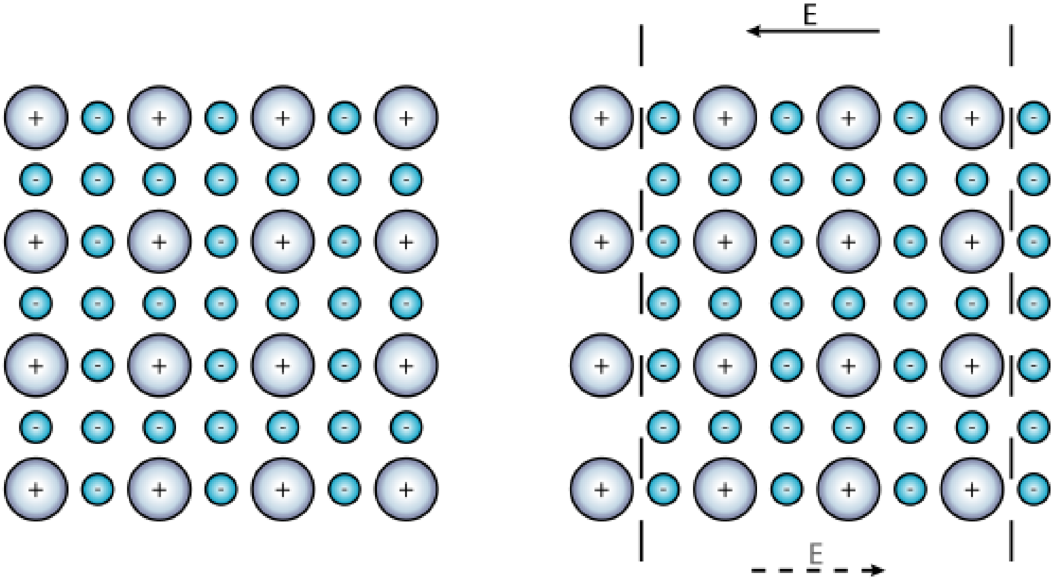


electrons in a metal can be modeled as free and non-interacting

☛ *Drude model*

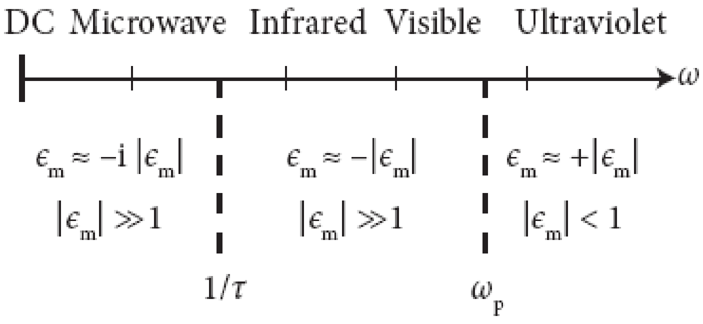
$$\omega_p^2 = \frac{ne^2}{m\epsilon_o}$$ Plasma freq.

(*) http://en.wikipedia.org/wiki/Plasma_(physics)

drude model

- assumes that electrons are bound to ions in the metal with a spring
- τ is the time between collusions with the ions
- ω is the driving EM field frequency

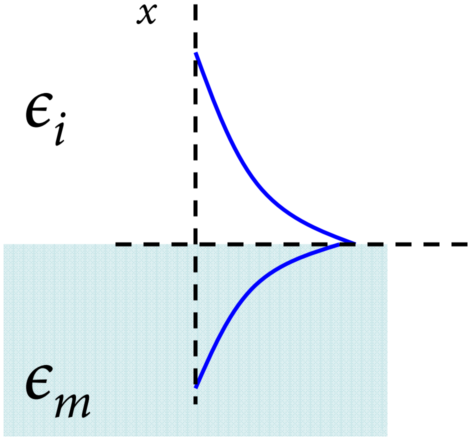
$$\epsilon_m = 1 + \frac{\omega_p^2}{-\omega^2 + \mathrm{j}\,\omega/\tau}$$

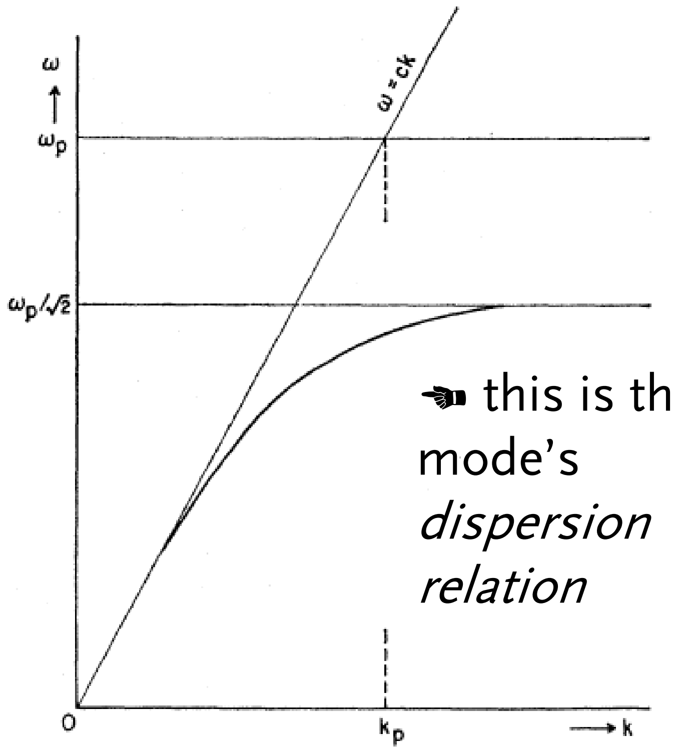


C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*. Wiley Science, 1998.

surface plasmon

- a metal-insulator interface supports a bound electromagnetic mode—*surface plasmon* — which looks like:



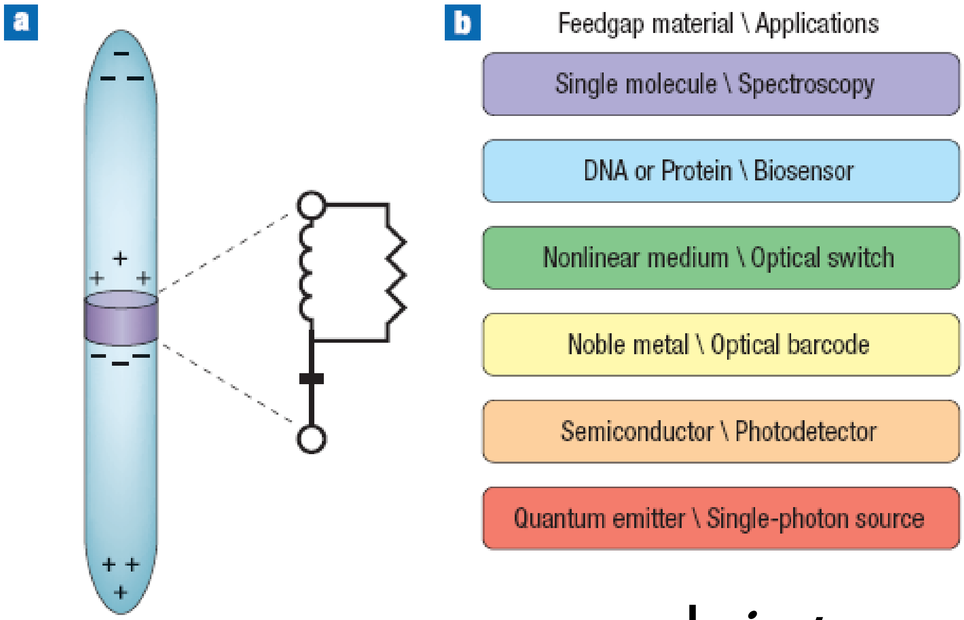


☛ this is the mode's *dispersion relation*

E. N. Economou, "Surface plasmons in thin films." *Physical Review*, vol. 182, no. 2, pp. 539 – 54, 1969.

possible uses of plasmons

- biosensing, waveguiding, spectroscopy, optical switching, optical barcoding, single photon source …



and *interconnects*…

Brongersma, M. L., “Plasmonics: Engineering optical nanoantennas,” *Nature Photonics,* 2008, *vol. 2*, pp. 270-272.

interconnects

- interconnect power limits chip performance
  - ~ 50% of microprocessor power was interconnects in 2002
  - expected to rise to 80% (ITRS)
- chip power limited to ~ 200 W from now on
- to compete with electrical interconnects and to achieve the desired bit rates
  - optical output device target energy 10-20 fJ/bit for off-chip, lower for on-chip

David A.B. Miller, "Device Requirements for Optical Interconnects to Silicon Chips," to appear in *Proceedings of IEEE*.
David A.B. Miller, "Novel devices for optical interconnects to chips", LEOS Talk, 11/10/08.

low capacitance detectors

- given that we want to work with optical output devices with ~ 10 fJ energies
  - then we should expect ~ 1 fJ received optical energy at the detector (presuming ~ 10 dB system loss)
  - therefore we want ~ 1 fF photodetector capacitance
    - allows “receiverless” operation
    - little or no voltage amplification needed
  - 1 fF is possible
    - though it needs very good integration
- 1 micron cube of semiconductor has a capacitance of ~ 100 aF
  - transistor input capacitance is ~ 1 fF now
- hence want
  - integration approaches with transistors
  - ideas for very low capacitance detectors

David A.B. Miller, “Device Requirements for Optical Interconnects to Silicon Chips,” to appear in *Proceedings of IEEE*.
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why optical antennas?

- *antenna*: a metallic apparatus for sending or receiving electromagnetic waves
- *detector*: a device for detecting the presence of electromagnetic waves

what will the advantages be if the two concepts are merged for use at optical frequencies?

- as the size of a detector gets smaller:
  - ✓ Speed increases
  - ✓ Capacitance decreases
  - × Sensitivity decreases
- resonant antennas have an effective area larger than their physical size

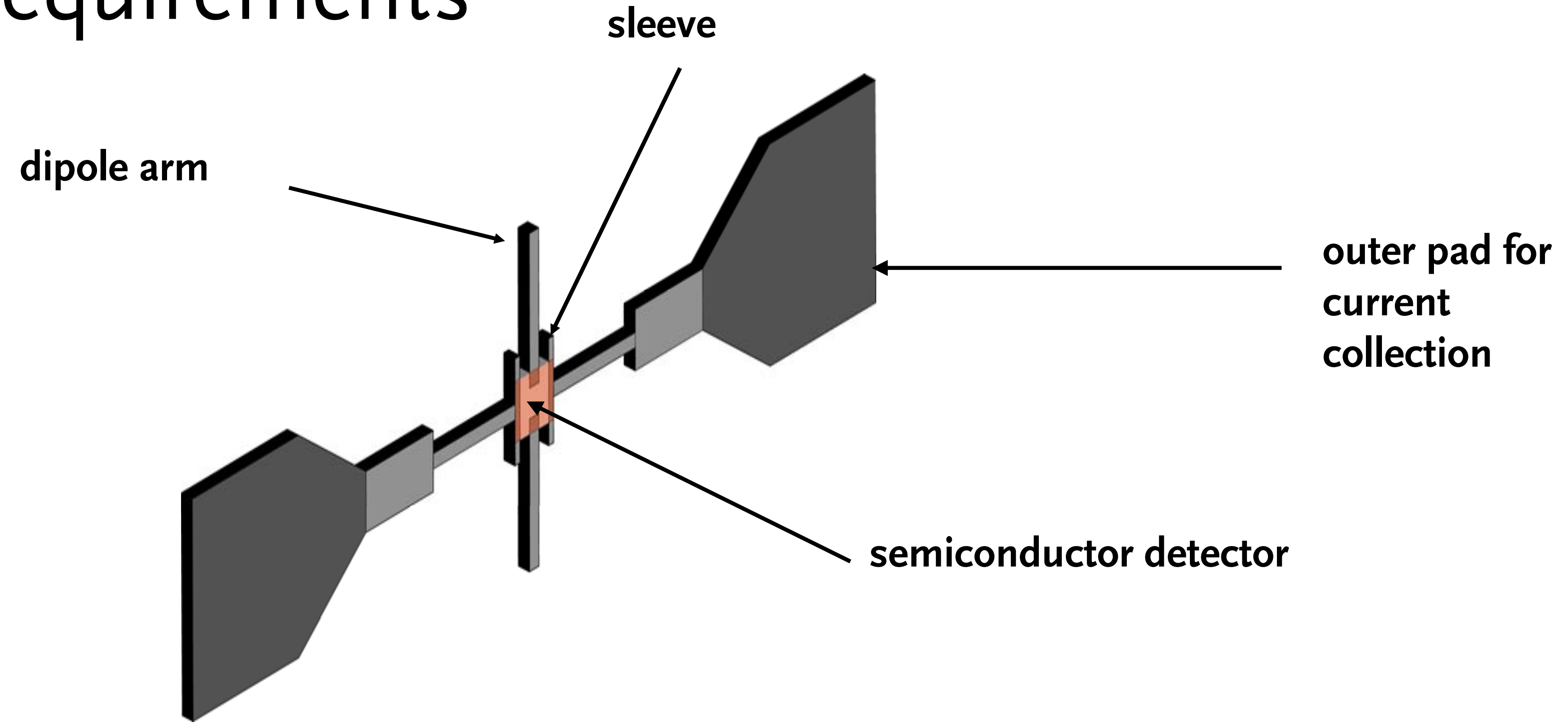
antennas with integrated detectors can overcome the sensitivity degradation of small size detectors

challenges in the design process

modified metallic properties at optical frequencies	properties of metals change as the frequency of operation is increased from RF (100s of MHz) to optical frequencies (100s of THz) classical antenna design techniques need to be modified
integration of the detector without negatively affecting the antenna properties	integrate the detector with the antenna to eliminate the problem of guiding light from the antenna to the detector structure shape and position the detector such that the detection of light and sweeping of electron-hole pairs do not affect each other
substrate effects	for physical support and integration with external circuitry, antennas need to be positioned on a substrate the thickness and permittivity of the substrate affect the antenna properties and should be taken into consideration in the design.

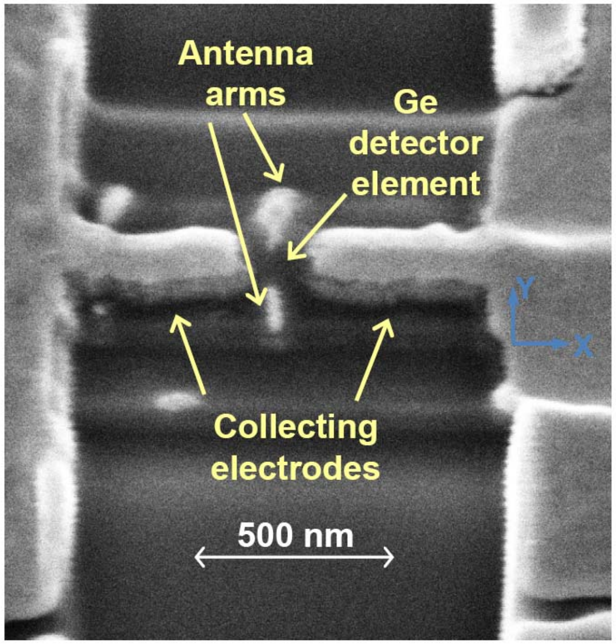
open-sleeved dipoles

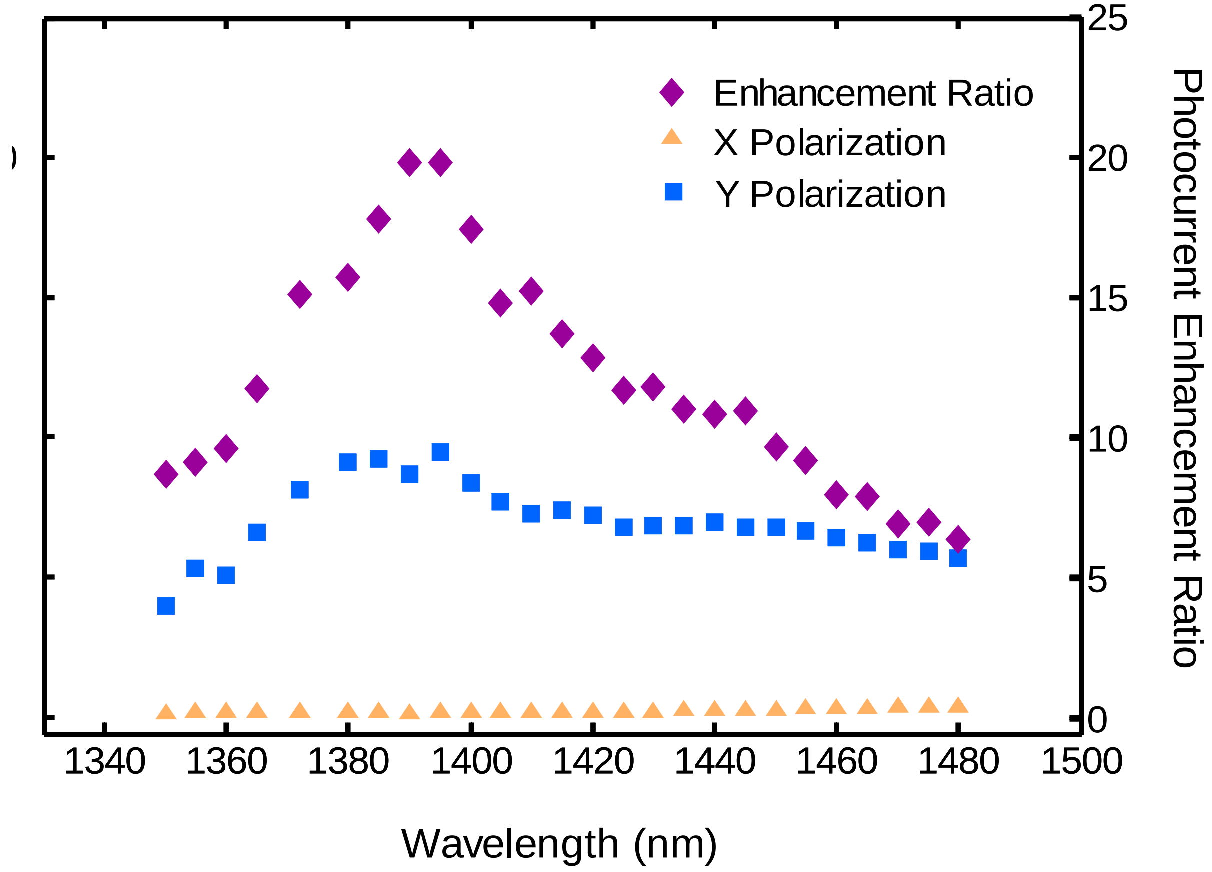
- sleeved dipole structure can meet all these requirements



- designed during WWII, used on airplanes…

fabricated device

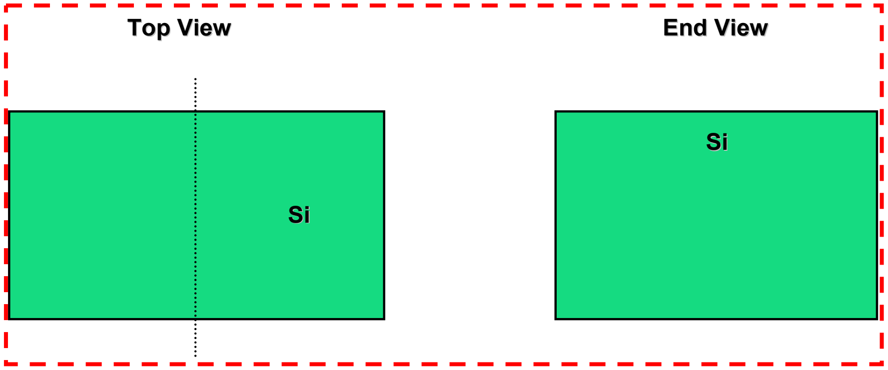




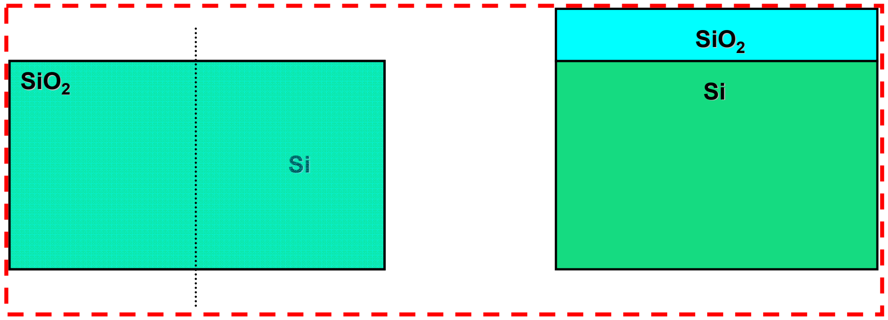
Ge nanowire by FIB + Ti/Au metal for antenna and pads

Liang Tang, et. al., “Nanometre-scale germanium photodetector enhanced by a near-infrared dipole antenna,” *Nature Photonics*, vol.2, pp. 226-229 (2008)

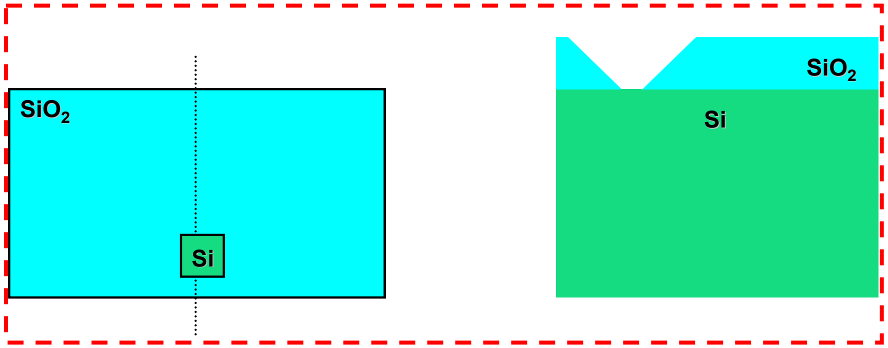
fabrication steps



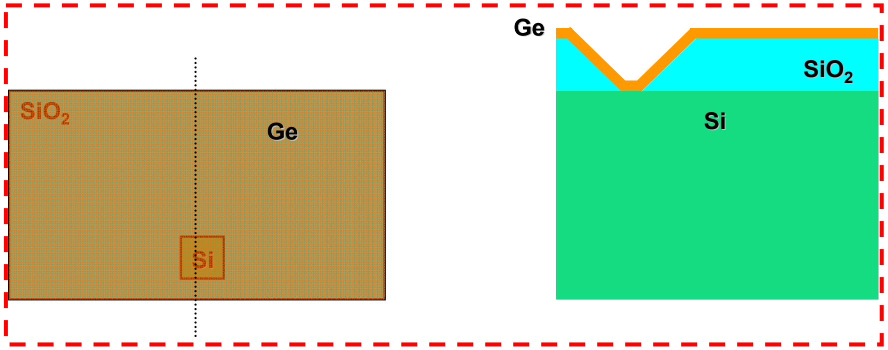
start with bare silicon wafer



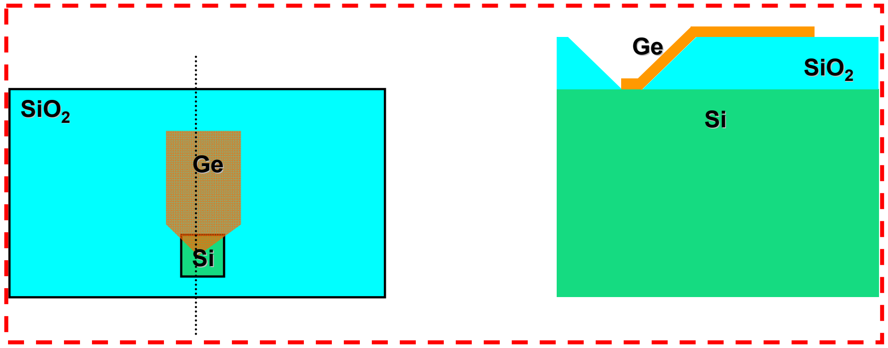
oxidize the silicon



open a window in oxide

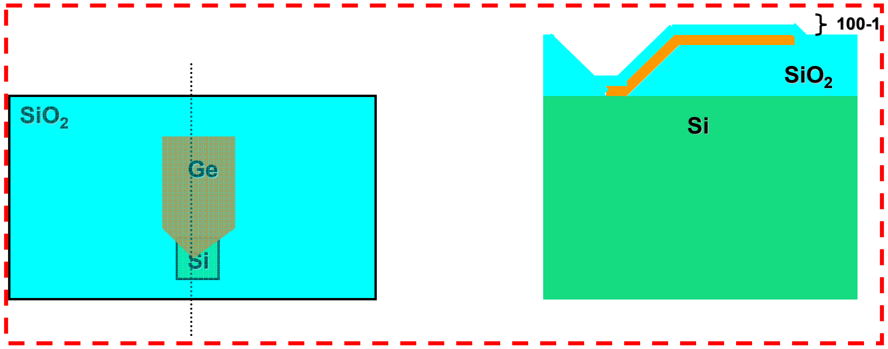


deposit Ge, thickness ~50nm

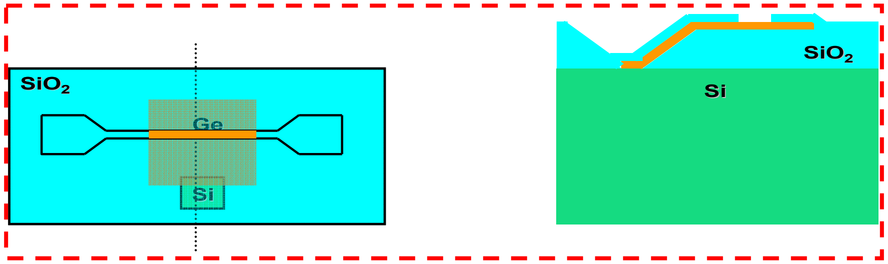


pattern Ge, align to window

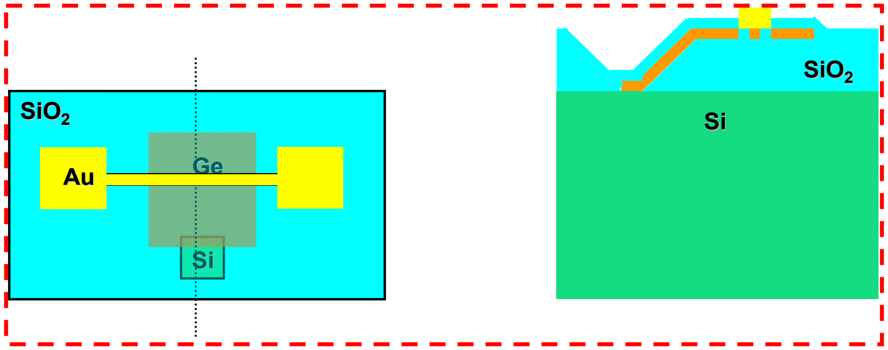
fabrication steps (cont.)



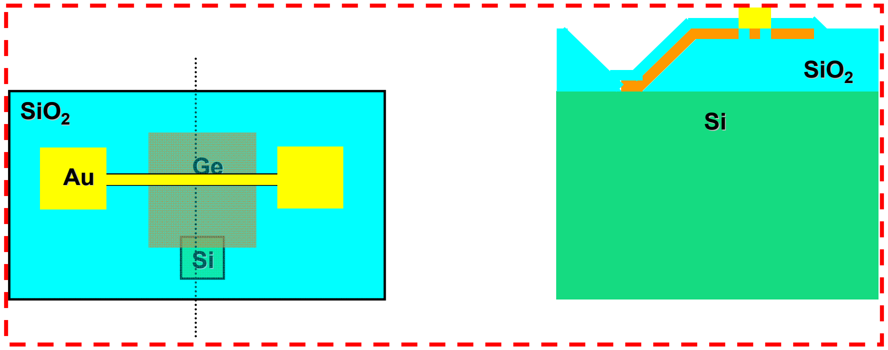
deposit oxide, crystallize Ge by RTA.



remove oxide and pattern



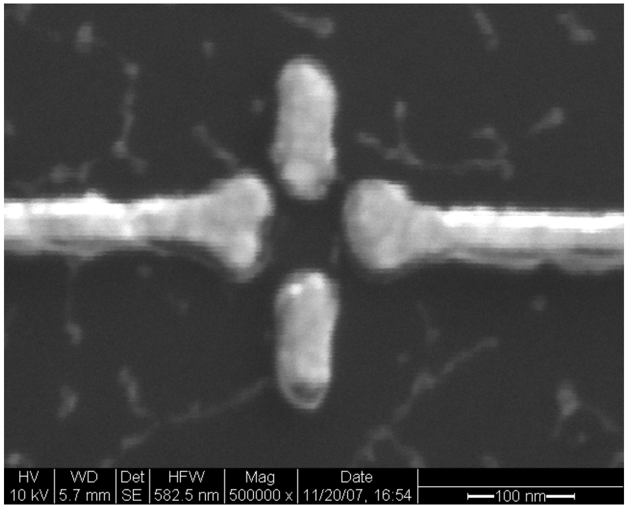
FIB step to carve out Ge from undesired locations
followed by Au deposition



FIB step to carve metal out to shape the antenna

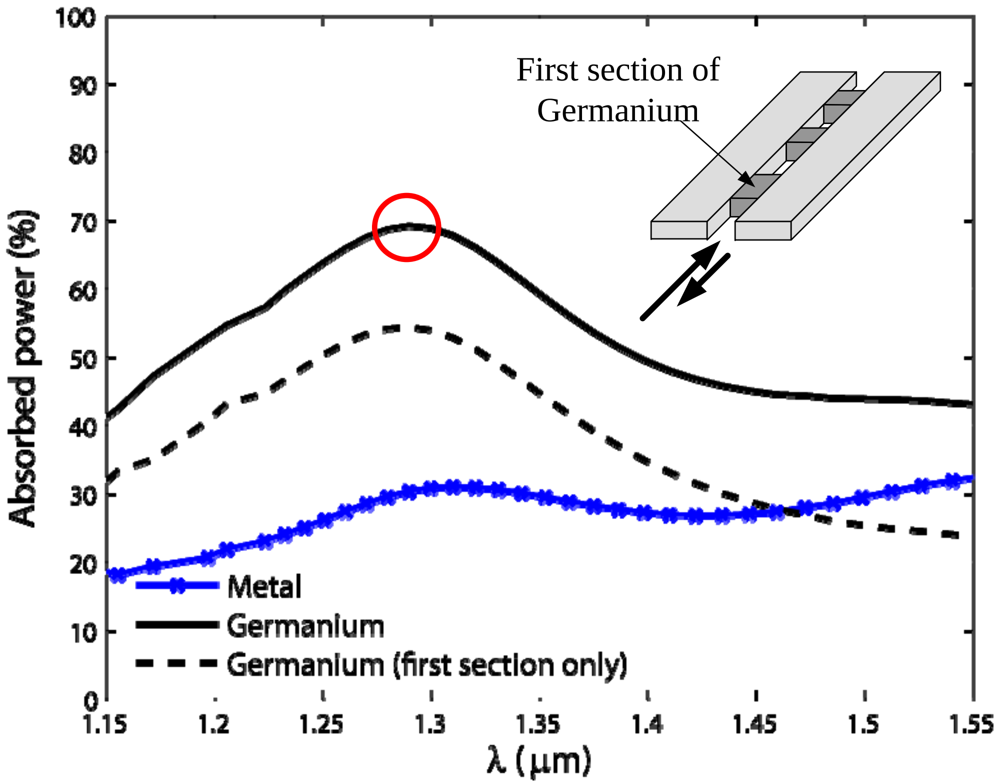
working on the 850nm version

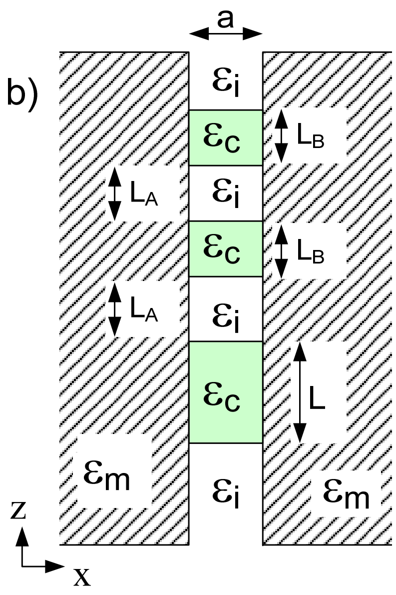
- we now moved to e-beam
- using silicon as the detector (SOI)
- aim is to be able to characterize the antenna properties better by varying size & type of antennas



design of a waveguide detector

70% of incoming power absorbed in
$\lambda^3/500$ Ge volume





$$a = 80nm$$

$$\varepsilon_1 = (1.44)^2$$

$$\varepsilon_c = (4.23 - 7.8 \times 10^{-2} i)^2$$

$$L_A = L_B = 190nm$$

$$L = 260nm$$

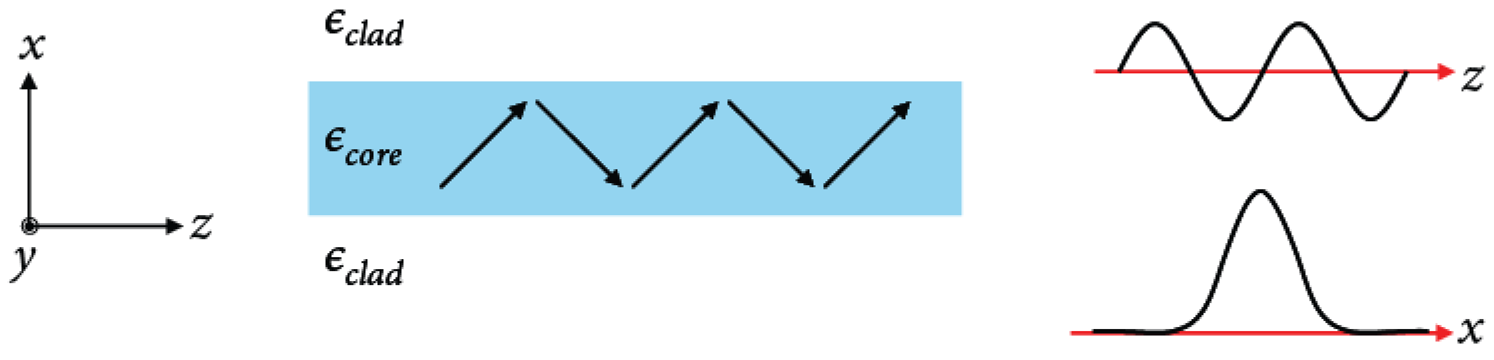
Dany-Sebastien Ly-Gagnon, et. al., "Characteristic Impedance Model for Plasmonic Metal Slot Waveguides", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 14, no. 6, pp. 1473-1478 (2008)

waveguides and modes

- in most communication systems, only a finite number of modes are allowed to propagate
- it is important to understand how an arbitrary optical component affects these communication modes
- descriptions based on the modes of the system lead to the most concise abstractions which are easier to analyze

modes of the dielectric slab waveguide

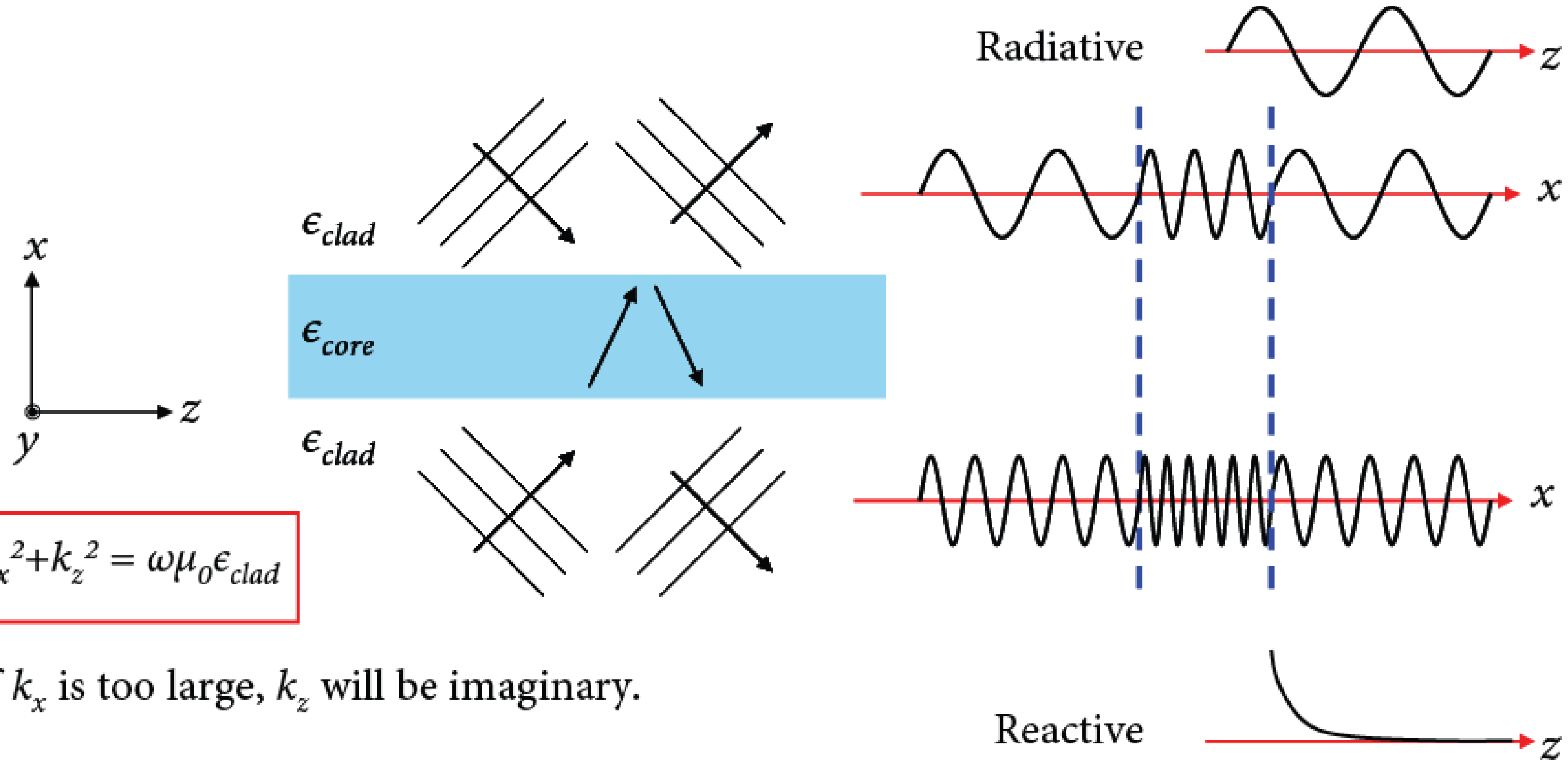
A) Finitely many propagating, discrete modes



Total internal reflection of the plane waves off of the core-cladding surface leads to the guided modes.

modes of the dielectric slab waveguide

B) Continuous modes

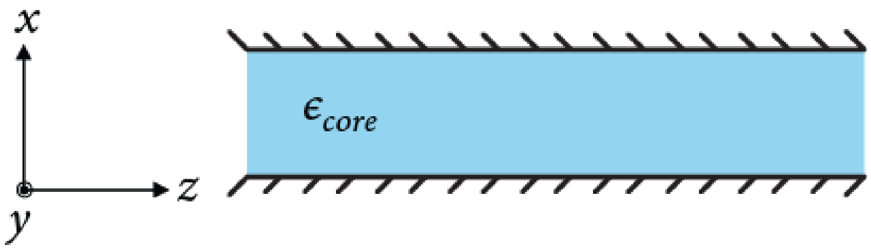


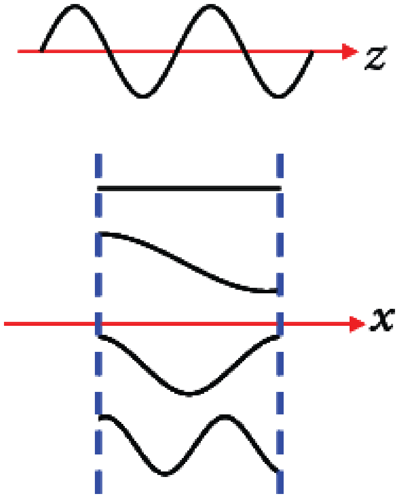
$$\boxed{k_x{}^2+k_z{}^2 = \omega\mu_0\epsilon_{clad}}$$

If k_x is too large, k_z will be imaginary.

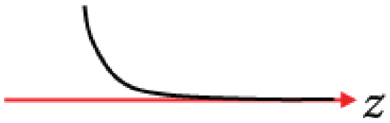
modes of the parallel–plate waveguide

Infinitely many propagating and evanescent discrete modes

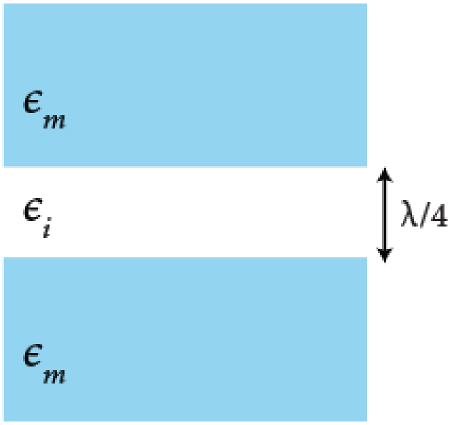




Propagating modes are sinusoidal in z, evanescent modes are exponentially decaying in z.



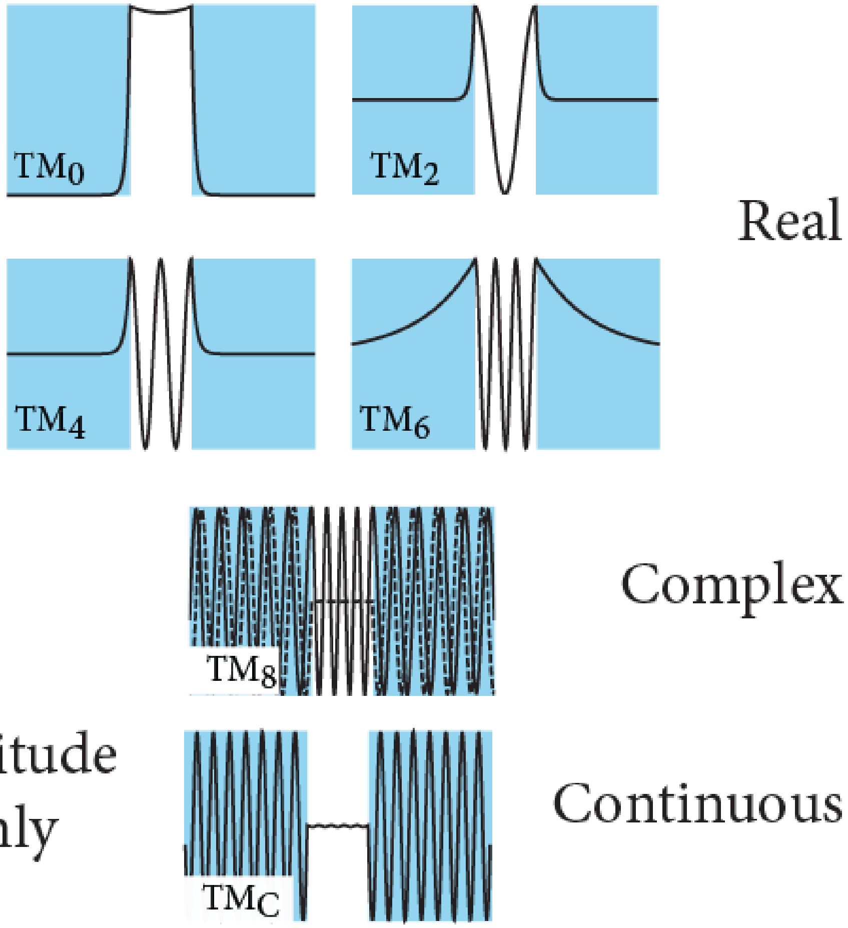
even modes of the MIM



ϵ_m=-143.497

ϵ_i= 1.0

λ = 1500 nm



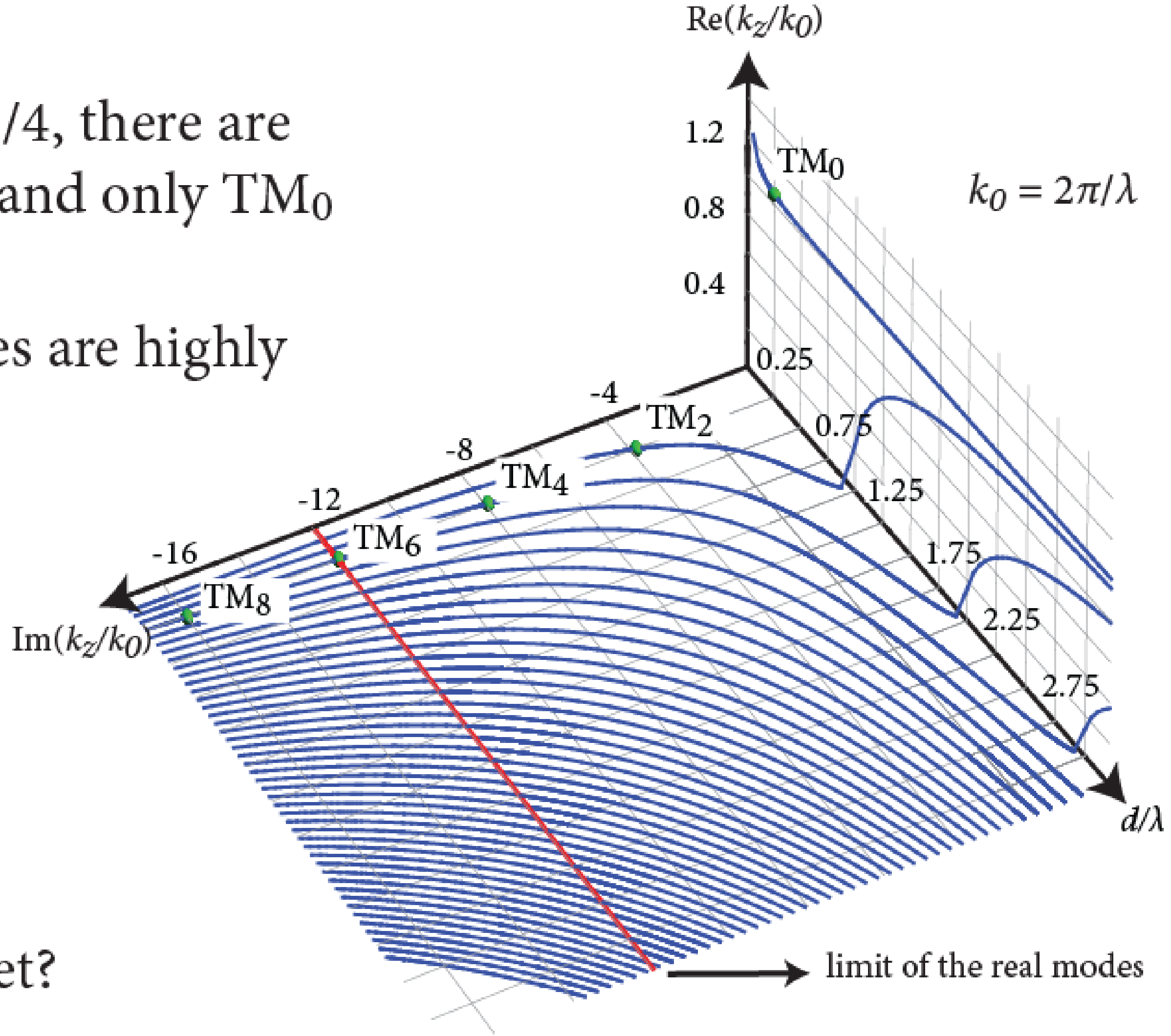
MIM waveguides support a multitude of modes. Most of them are highly evanescent.

Ş. Ekin Kocabaş, et. al., “Modal Analysis and Coupling in Metal-Insulator-Metal Waveguides,” *Phys. Rev. B,* 79, 035120 (2009)

even modes of the MIM

For the case d=$\lambda/4$, there are four real modes and only TM_0 is propagating.

Rest of the modes are highly evanescent.



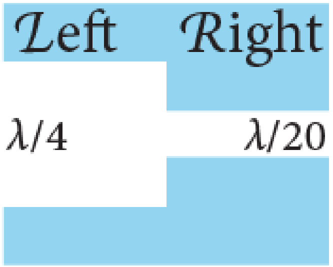
When are these modes useful?

Do they form a complete basis set?

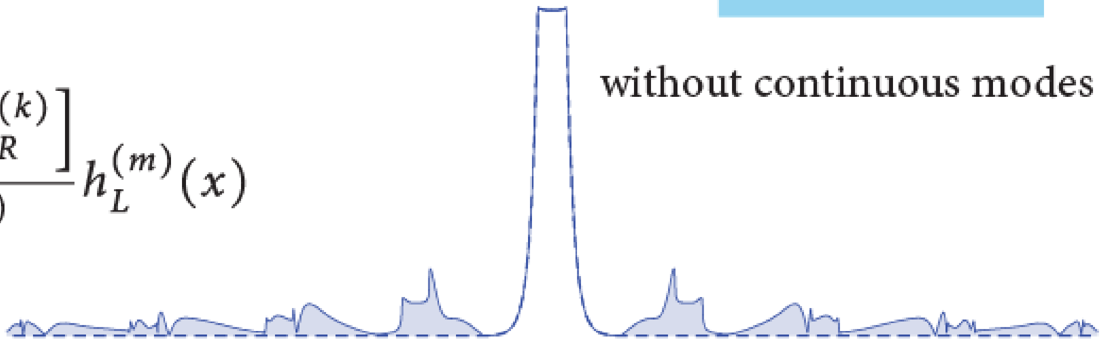
Ş. Ekin Kocabaş, et. al., “Modal Analysis and Coupling in Metal-Insulator-Metal Waveguides,”
Phys. Rev. B, 79, 035120 (2009)

modal expansion at MIM junctions

Expansion of a thin (d=$\lambda/20$) waveguide's main mode in terms of the modes of a thick waveguide (d=$\lambda/4$)

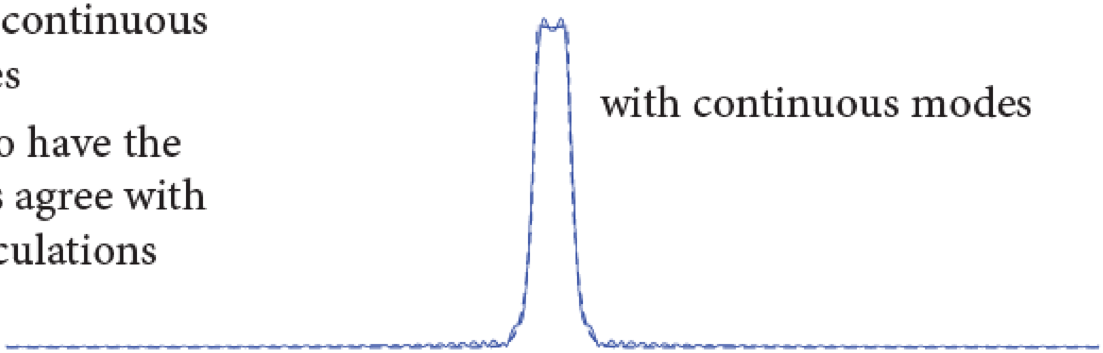


$$h_R^{(k)}(x) = \sum_{m=1}^{L} \frac{\left[e_L^{(m)} \middle| h_R^{(k)}\right]}{\Omega_L^{(m)}} h_L^{(m)}(x)$$



a full basis set requires both continuous and discrete modes

all modes should be used to have the mode-matching calculations agree with brute force numerical calculations (FDFD)



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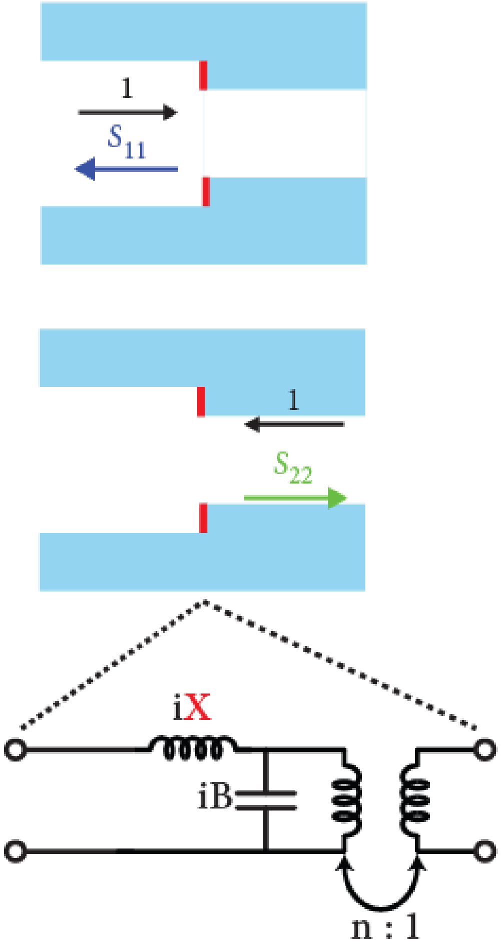
Phys. Rev. B, 79, 035120 (2009)

circuit model for MIM junctions

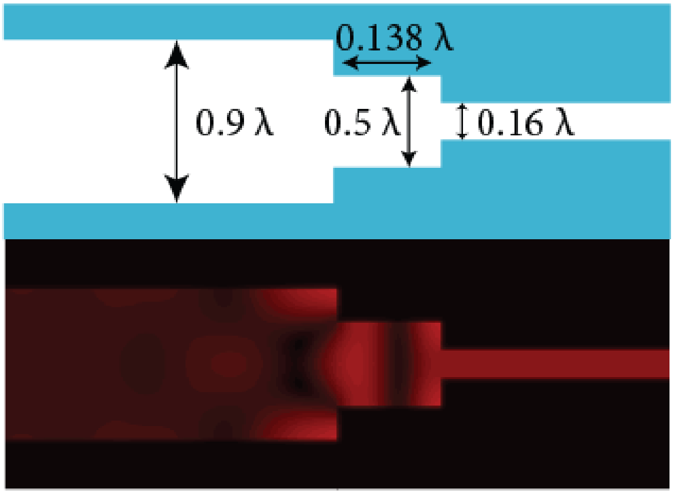


B: equivalent capacitance of the near fields

n: ratio of the impedances on both sides of the junction

X: surface reactance of the metallic sidewalls

The use of the circuit model makes it possible to *design* a perfect mode converter.



Ş. Ekin Kocabaş, et. al., “Transmission Line and Equivalent Circuit Models for Plasmonic Waveguide Components,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 14, no. 6, pp. 1462-1472 (2008).

MIM summary

- Modes of the MIM waveguide are a hybrid of the dielectric slab and the parallel plate modes
  - Discrete (real & complex)
  - Continuous
- Mode-matching calculations show the completeness of the modal structure
- Design of a perfect mode-converter by the use of the modal scattering properties
- Equivalent circuit diagram for MIM junctions

recent work done by others

- Planar Lenses Based on Nanoscale Slit Arrays in a Metallic Film *(Verslegeers2009)*
- Propagating plasmonic mode in nanoscale apertures and its implications for extraordinary transmission *(Catrysse2008)*
- Crosstalk between three-dimensional plasmonic slot waveguides *(Veronis2008)*
- Gain-induced switching in metal-dielectric-metal plasmonic waveguides *(Yu2008a)*
- One-Way Electromagnetic Waveguide Formed at the Interface between a Plasmonic Metal under a Static Magnetic Field and a Photonic Crystal *(Yu2008b)*
- Plasmon-enhanced emission from optically-doped MOS light sources *(Hryciw2009)*
- Nonresonant enhancement of spontaneous emission in metal-dielectric-metal plasmon waveguide structures *(Jun2008)*
- Spectral properties of plasmonic resonator antennas *(Barnard2008)*
- A Nonvolatile Plasmonic Switch Employing Photochromic Molecules *(Pala2008)*

and many many more...

questions? comments?

well, I have some questions

- any one working on nanowires?
  - our devices have ~50nm wide & thick, many microns long EBL defined wires, with metal pieces around them to act as antennas
    - we want to be able to understand their i-v characteristics, any references?
    - contact issues: alternatives to Ti/Au on Si?
- low noise, low current (~tens of pA) photo-current characterization
  - we've built a setup, but would love to see yours, too! come see ours if you wish.

some SEMs of
latest samples