Status and prospects of integrated nanophotonics circuits

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Outline

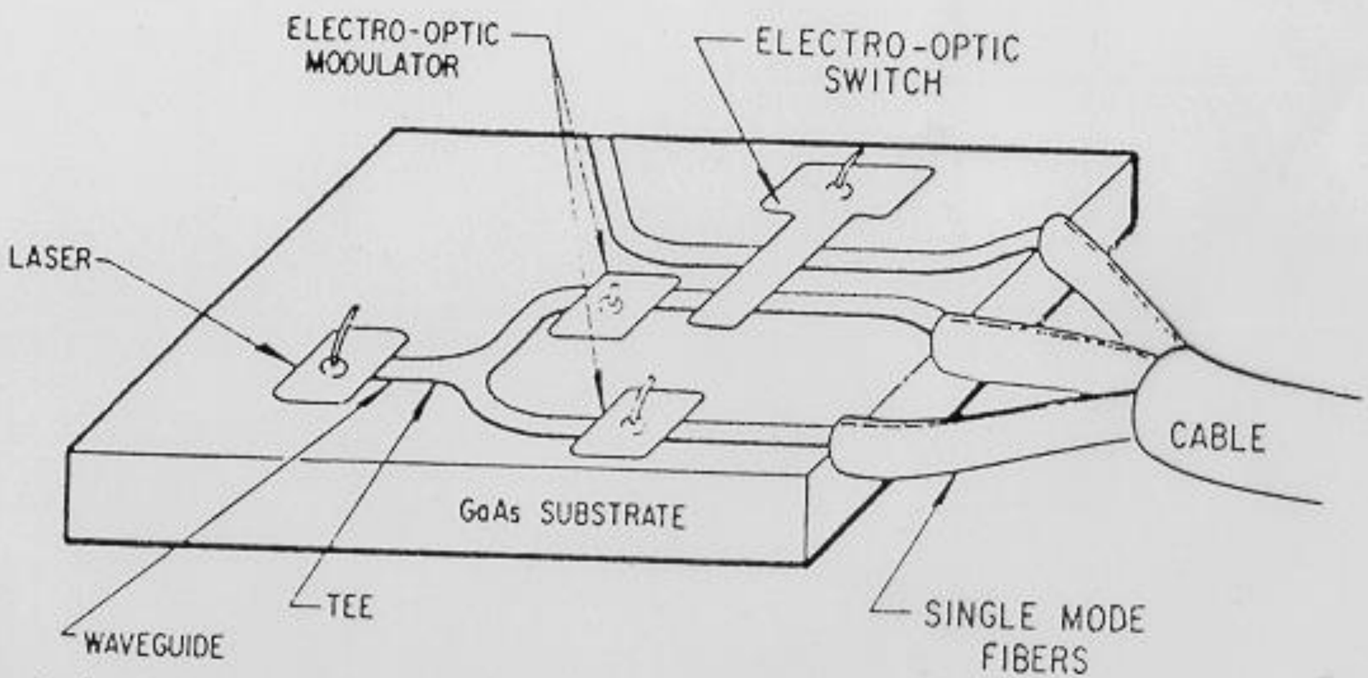
- **Integrated photonics:**
  - **Developments over the years and a ”Moore’s” law for integrated photonics**
  - **Further progress?**
- **Nanophotonics and plasmonics:**
  - **Basic principles, waveguide properties**
  - **Performance limitations due to dissipative losses in passive circuits***
- **High optical confinement waveguides and photonic circuits**
  - **Metamaterials, what and why?**
- **Loss compensating gain, quantum dots and power dissipation in active circuits**
- **Conclusions**

* *Note: There are numerous applications of plasmonics where optical losses are not so important , e g sensors and SERS (Surface enhanced Raman scattering)*

Integrated photonics

Vision in the mid 70s

when the term ***Integrated optics*** was coined..

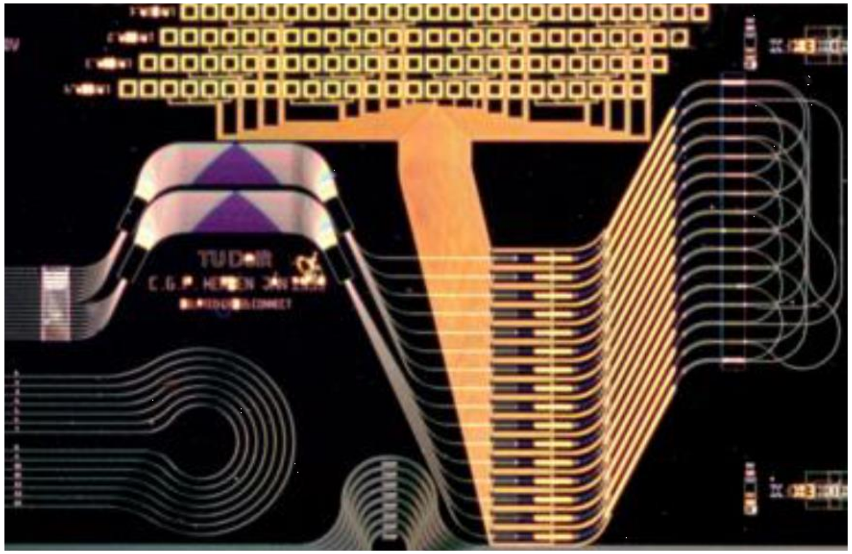


$\Delta n\, k0$
$L=\pi$

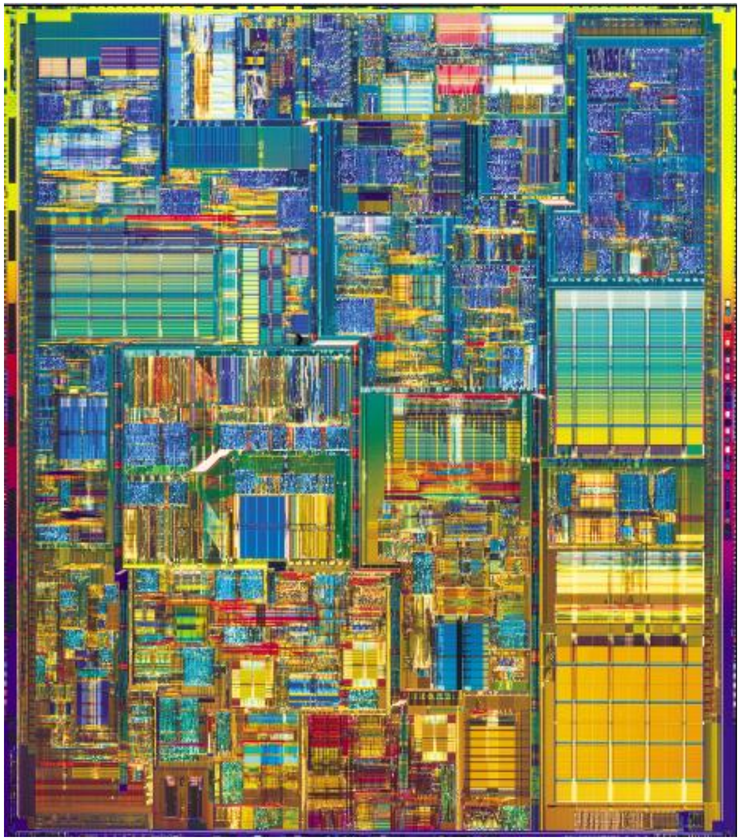
Fig. 1.2. Artist's sketch of a monolithic integrated GaAs transmitter. (After BLUM et al. [1.54])

Photonics is far behind electronics in maturity, But excellent research and business opportunities!

After ~30 years of development ....



State - of- the Art Photonic IC (U of Eindhoven)
Optical Cross-connect: 100'ish components



State-of the Art Electronic IC (Intel Website)
Pentium 4: 42 M Transistors

"Moore´s law" for photonic light wave circuits

- Moore´s law for electronic ICs pertains to circuits with generic elements (transistors, resistors, capacitors), some fraction of which are active

- "Moore´s law" for PLCs:
  - No generic elements like in electronics but lots of ***different*** active and passive device structures with ***different*** functions, in ***different*** materials. (hence transform PLCs to some "equivalent elements")
  - Assess ***Integration density*** for PLCs rather than ***total number of elements*** in our "Moore´s law"

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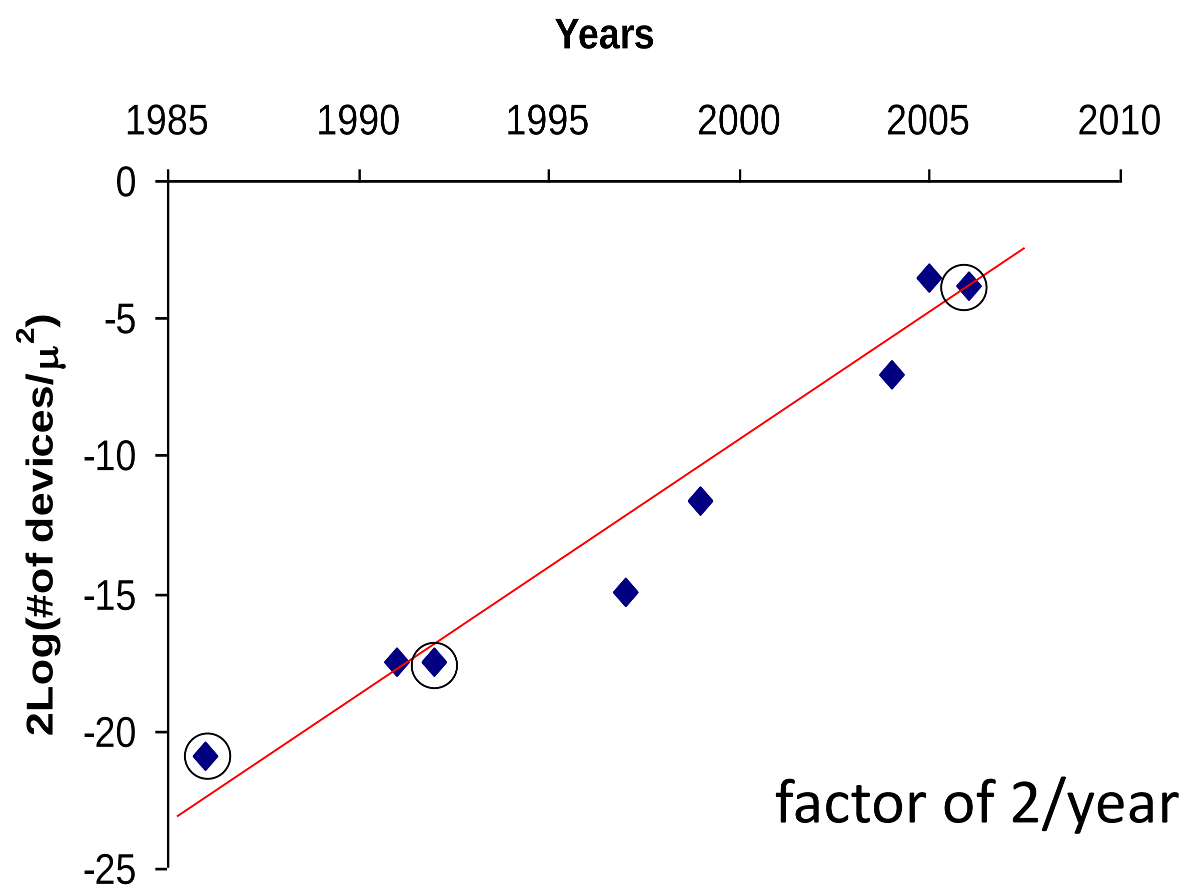
A Moore´s law for integration density in terms of equivalent number of elements per square micron of integrated photonics devices:

Growing faster than the IC Moore´s law!



J. Zhejiang Univ SCIENCE 2006 7(12) p.1961-1964
http://www.zju.edu.cn/jzus/

Total *minimum* field width vs core width, planar waveguide, wavelength =1.55 μm

(core index, cladding index)

Silica waveguide	(1.5,1.4)	3 μm
III V	(3.4,3.1)	1 μm
Silicon/air	(3.5,1)	***appr 400 nm***

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So how continue increasing integration density?
Or
What comes after Si?

- Photonic crystals?
  - But wavelength sized waveguides and resonators…
- High refractive index?
  - But have to beat e g Si…
- Metals or negative epsilon materials?
  - Losses…
- ??

What will integrated nanophotonics circuits bring (for telecom and interconnect)?

<u>The classical issues for integrated photonics</u>

- **Insertion loss**
- **Polarization sensitivity**
- ***Drive power***
- **Interfacing**
- ***Functionality***
- ***Footprint***
- **Power dissipation**
- **Cost**

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Nanophotonic integrated circuits based on negative ε materials

(plasmonic or metal optics)

for high density lateral and longitudinal device integration

PLASMONICS

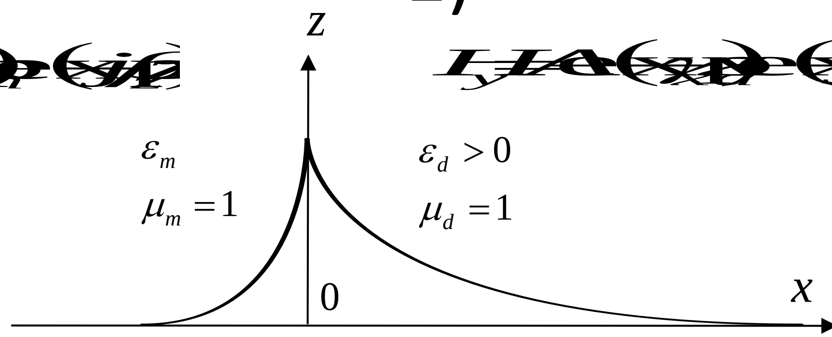
…to be the key nanotechnology that will combine electronic and photonic components on the same chip…

- Optical frequency subwavelength metallic wired circuits with propagation loss comparable to conventional optical waveguides;
- Highly efficient plasmonic LEDs with tunable radiation properties;
- Active control of plasmonic signals by electro-optic, all-optical, and piezoelectric modulation and gain mechanisms to plasmonic structures;
- 2D plasmonic optical components for coupling single mode fiber directly to plasmonic circuits;
- Deep subwavelength plasmonic nanolithography over large surfaces.
- Subwavelength imaging

Ekmel Ozbay, SCIENCE VOL 311 13 JANUARY 2006

Dispersion equation for TM surface waves (TM-1)

$H_y = A\exp(\gamma_{xm}x)\exp(i\beta_z z)$ $\qquad$ $H_y = A\exp(-\gamma_{xd}x)\exp(i\beta_z z)$



Wave equation and continuity of *Ez* gives:

$$\frac{\gamma_{xd}}{\varepsilon_d} = -\frac{\gamma_{xm}}{\varepsilon_m}$$

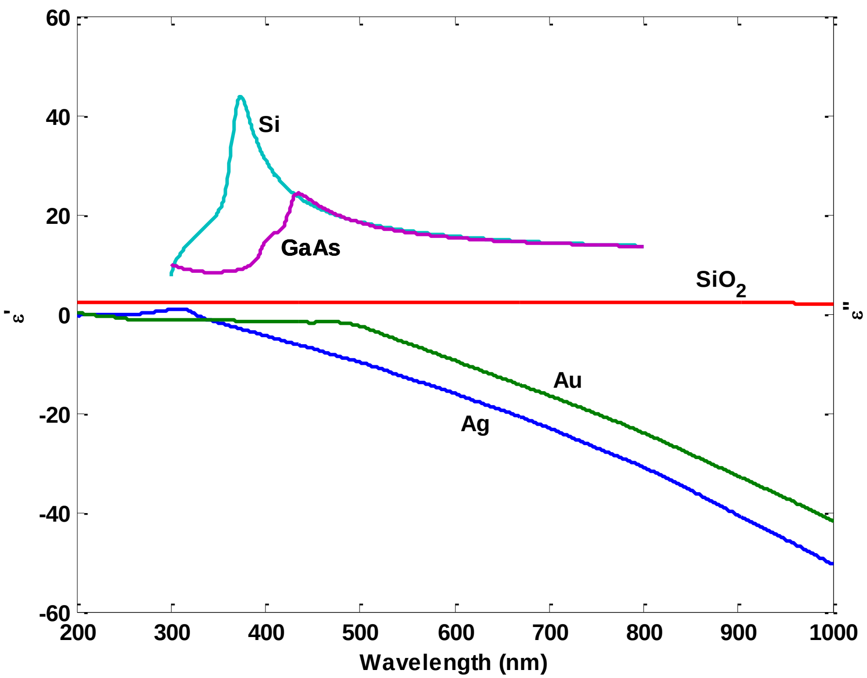
$$\gamma_{xd}^2 + \varepsilon_d k_0^2 = \beta_z^2$$

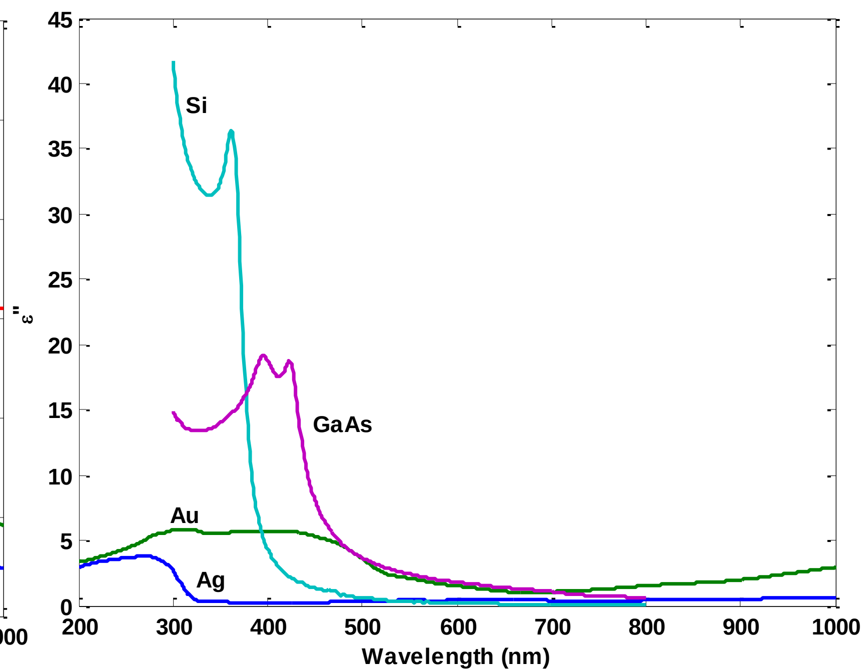
$$\gamma_{xm}^2 + \varepsilon_m k_0^2 = \beta_z^2$$

$$\begin{cases} \beta_z^2 = k_0^2 \dfrac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} = (\dfrac{2\pi}{\lambda_{eff}})^2 \\ \gamma_{xd}^2 = -k_0^2 \dfrac{\varepsilon_d^2}{\varepsilon_m + \varepsilon_d} \\ \gamma_m^2 = -k_0^2 \dfrac{\varepsilon_m^2}{\varepsilon_m + \varepsilon_d} \end{cases}$$

Also called Surface Plasmon Polariton

Real and imginary parts of epsilon of some metals and semiconducors





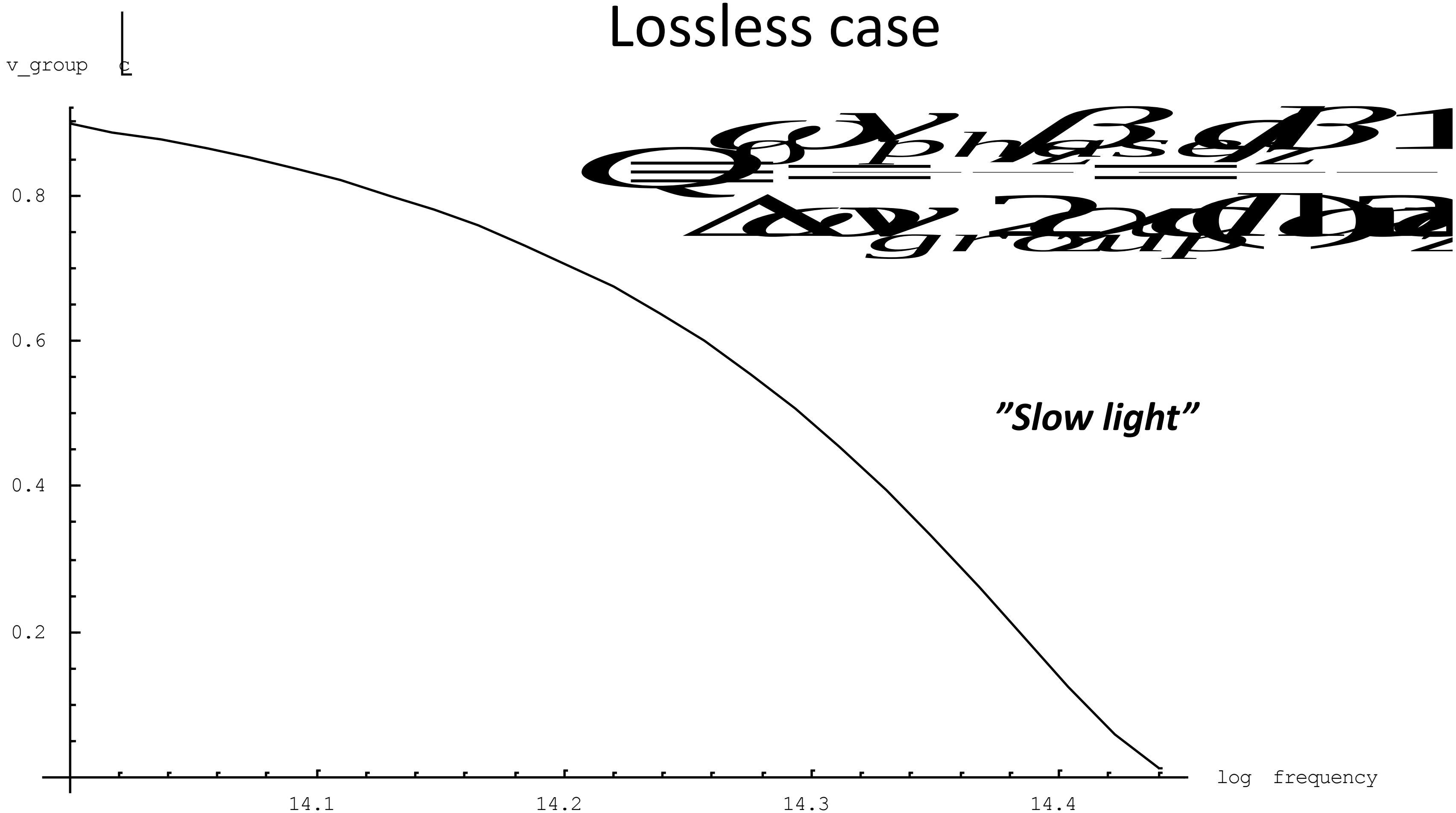
ε'' !!

- Trade off between optical confinement and photon life time (and Q)
- Group velocity converts photon lifetime to propagation distance

Metal/dielectric interface surface waveguide

Group velocity dispersion

Lossless case



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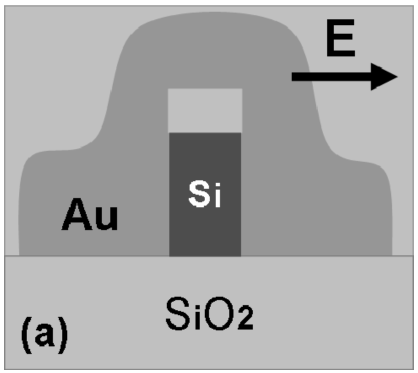
Examples of ultra compact waveguides and a suggested roadmap for integrated optics devices

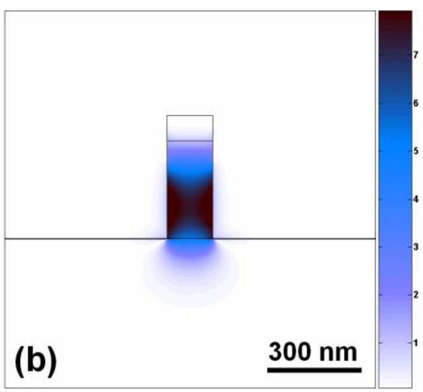
Fabrication and Characterization of sub-wavelength structures

L. Chen, J. Shakya, and M. Lipson, "Subwavelength confinement in an integrated metal slot waveguide on silicon," Opt. Lett. 31, 2133-2135 (2006)

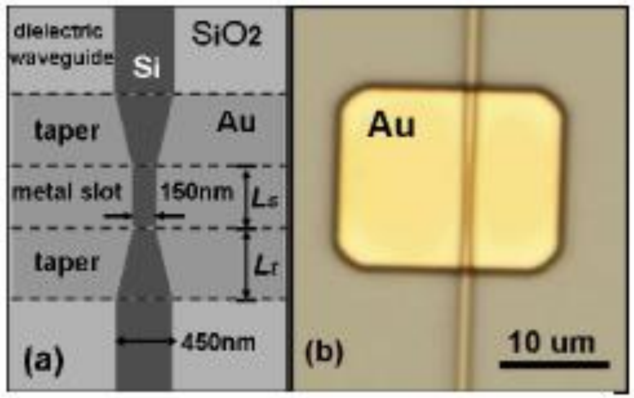
Propagation loss of less than 0.8dB/µm in a metal slot waveguide on Si with predicted confinement below the optical wavelength (1.55µm.

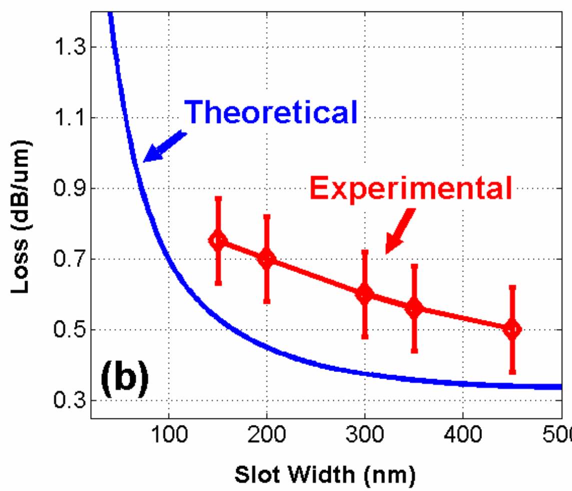


The

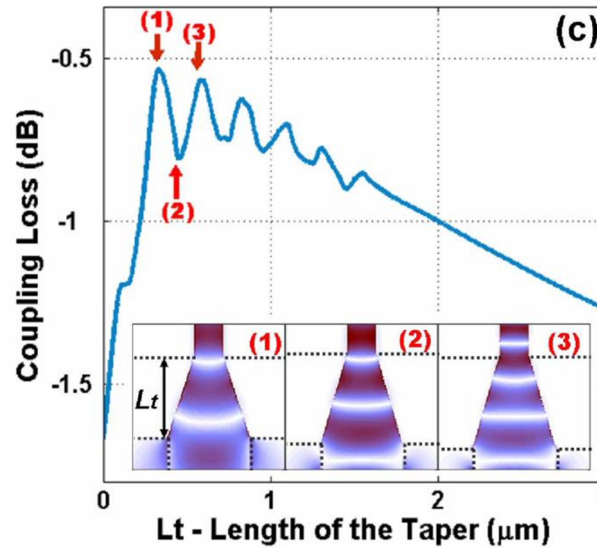


Schematics (a) and |Ex | mode profile (b) of the metal slot waveguide with a 150-nm-wide silicon core.



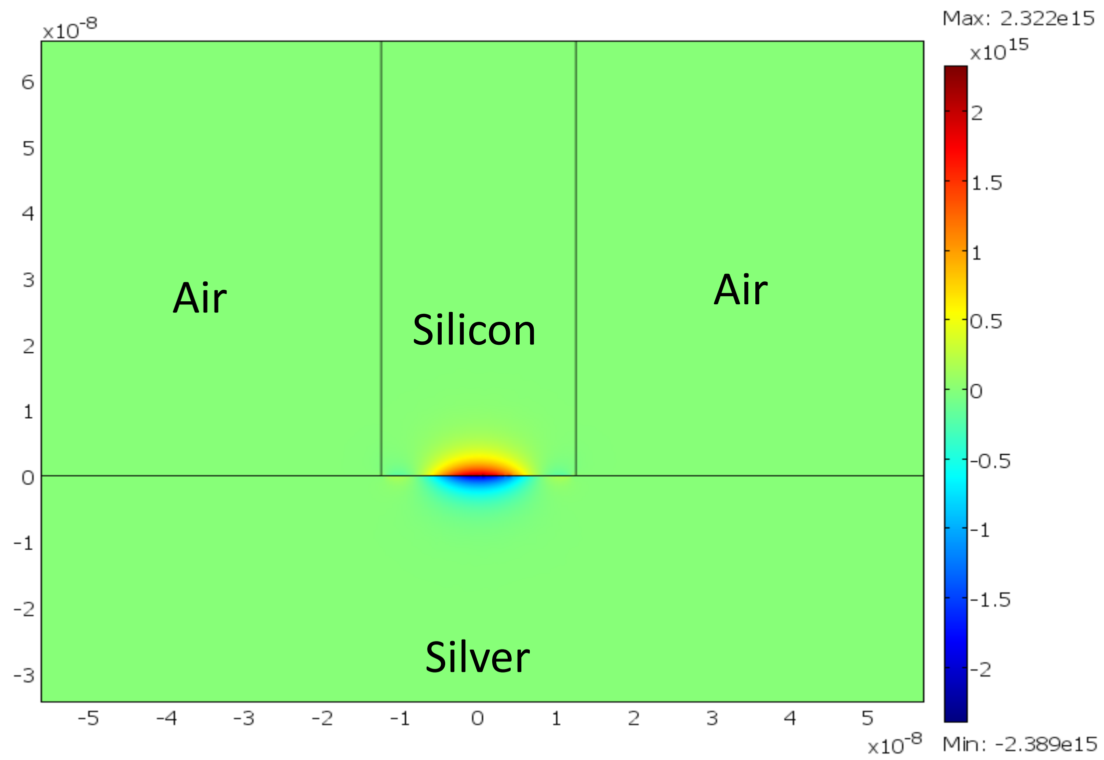


Theoretical and experimental propagation losses for several slot waveguides with different slot width



FDTD simulation of the coupling loss versus the taper length for the 150-nm-wide slott. Inset: |Ex | field distribution of the taper coupler for various taper lengths: (1) Lt= 325 nm, (2) 450 nm, (3) 575 nm.

Time-average power flow along propagation direction



Field size: 10 x 20 nm2

Vacuum wavelength 1000 nm

M Yan, L Thylén, M Qiu, D Parekh, Optics Express 2008

Energy flow around a metal nanosphere

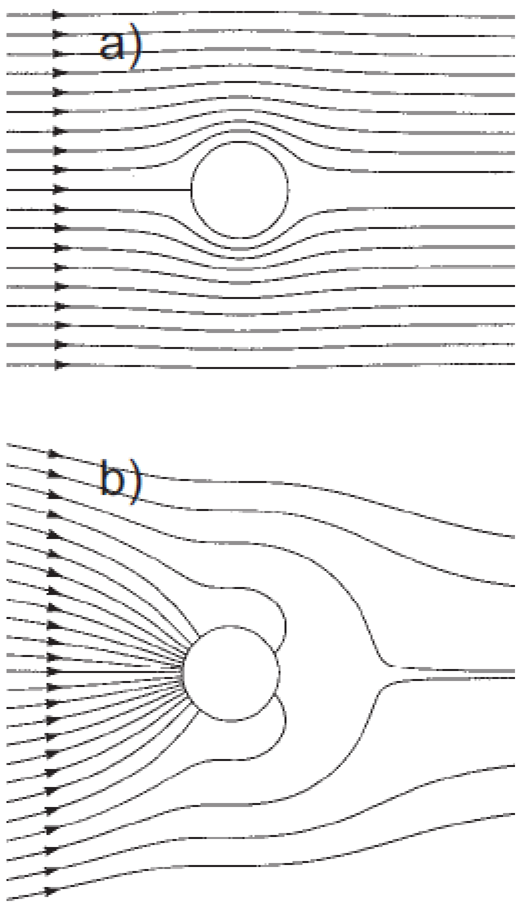


Fig. 1. Energy flux (Poynting vector) around a metal nanoparticle under plane wave excitation at two frequencies: a) When the excitation occurs far from the plasmon resonance frequency, the energy flow is only slightly pertubed. b) When the excitation occurs at the plasmon frequency, the energy flow is directed towards the particle. This resonant field enhancement is a key element of plasmon waveguides. Image taken from C. F. Bohren, D. R. Huffman, Absorption and Scattering of Light by Small Particles, copyright Wiley, New York 1983; this material is used by permission of John Wiley & Sons, Inc.

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Plasmonics: A Route to Nanoscale Optical Devices

By Stefan A. Maier, Mark L. Brongersma,
Pieter G. Kik, Sheffer Meltzer, Ari A. G. Requicha, and Harry A. Atwater

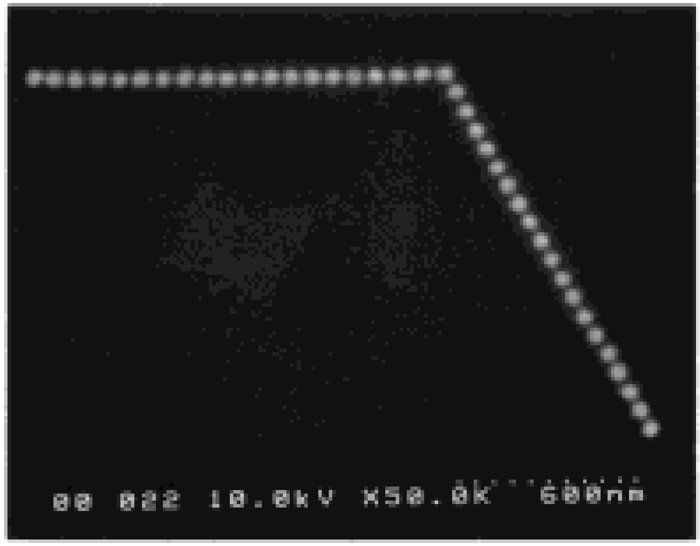
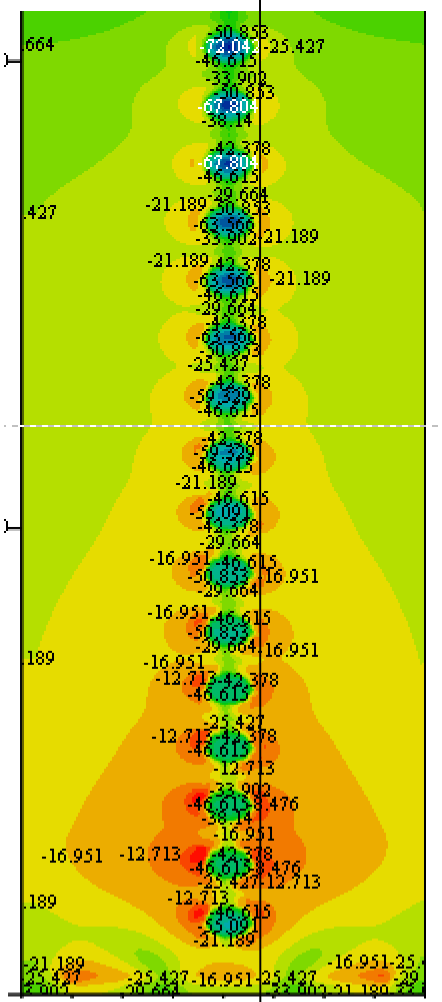
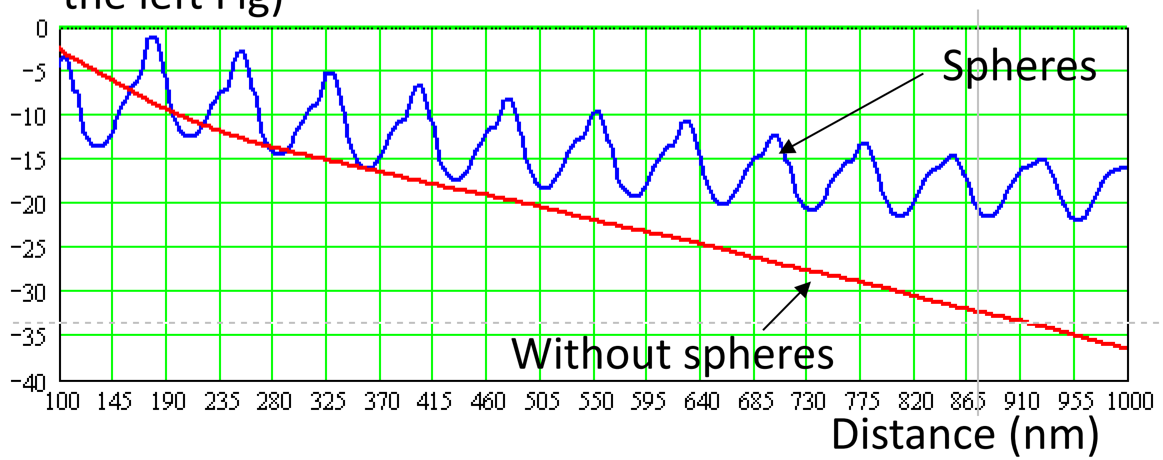


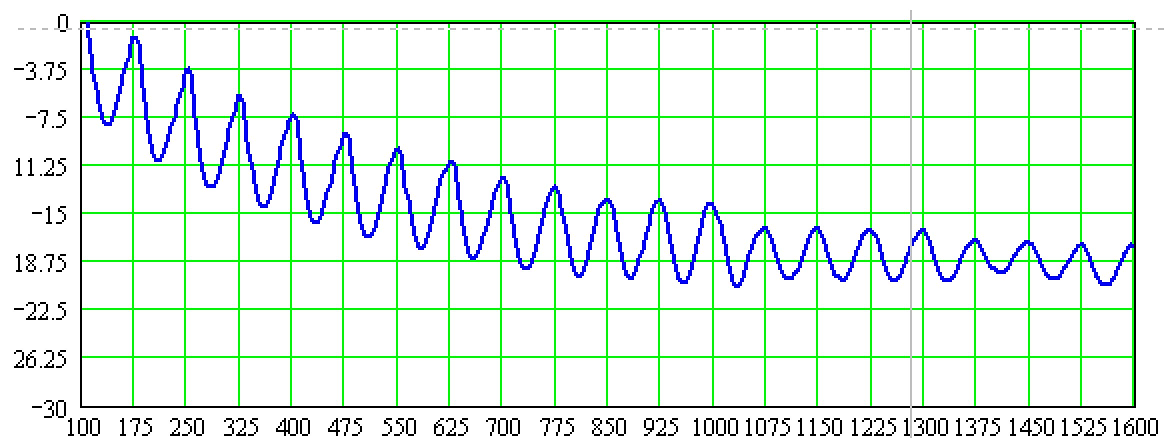
Fig. 5. a) Scanning electron microscopy image of a 60° corner in a plasmon waveguide, fabricated using electron beam lithography. The gold dots are ~50 nm in diameter and spaced by ~75 nm (center-to-center). b) Straight plasmon waveguide made using 30 nm diameter colloidal Au nanoparticles. The particles were assembled on a straight line using an atomic force microscope in contact mode, and subsequently imaged in non-contact mode.

Log of E-field intensity in dB averaged by period



Intensity along the chain of spheres (along black line in the left Fig)





Metamaterials

- **Artificial manmade materials**
- **Properties based on e g nanoparticle inclusions (much smaller than the wavelength) in a host medium**
- **Properties based on structural rather than material characteristics**

Effective medium epsilon

Maxwell Garnett:
Relation between macroscopic epsilon and dielectric constants of spherical particles and the matrix, where they are immersed, with fill factor η

$$\varepsilon'_{MAC} = \varepsilon_R \left[\frac{(1+2\eta)\varepsilon_d + 2(1-\eta)\varepsilon_R}{(1-\eta)\varepsilon_d + (2+\eta)\varepsilon_R} \right]'$$

$$\varepsilon''_{MAC} = \varepsilon_R \left[\frac{(1+2\eta)\varepsilon_d + 2(1-\eta)\varepsilon_R}{(1-\eta)\varepsilon_d + (2+\eta)\varepsilon_R} \right]''$$

" Colours in Metal Glasses and in Metallic Films." By J. 0. ***Maxwell Garnett****, BA, Trinity College, Cambridge Proceedings of the Royal Society of London 1904*

Loss happens...

Try optical amplification

(*There are other possibilities*)

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Geometrical parameters

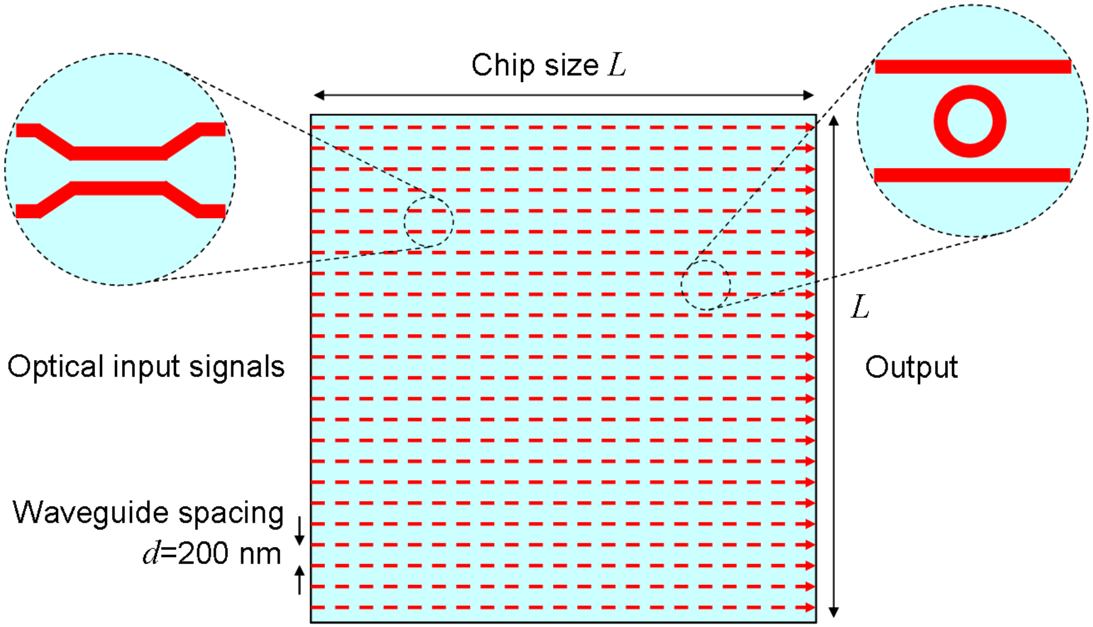
- Cubic lattice of QDs + Ag wires
- lattice parameter = 13 nm,
- QD diameter = 10 nm (radius=5nm),
- packing fractions: QD fraction = 0.24, Ag wire fraction=0.11 (1 Ag wire per u.c.)
- wire diameter = 3.4 nm

Power dissipation in loss compensated amplifier systems

- **Power dissipation due to**
  - Dissipative losses of the metal structure
  - Auger recombination in the quantum dots.

- **Nonradiative dissipation** per unit propagation length limits lateral packing density (say to 200 nm)

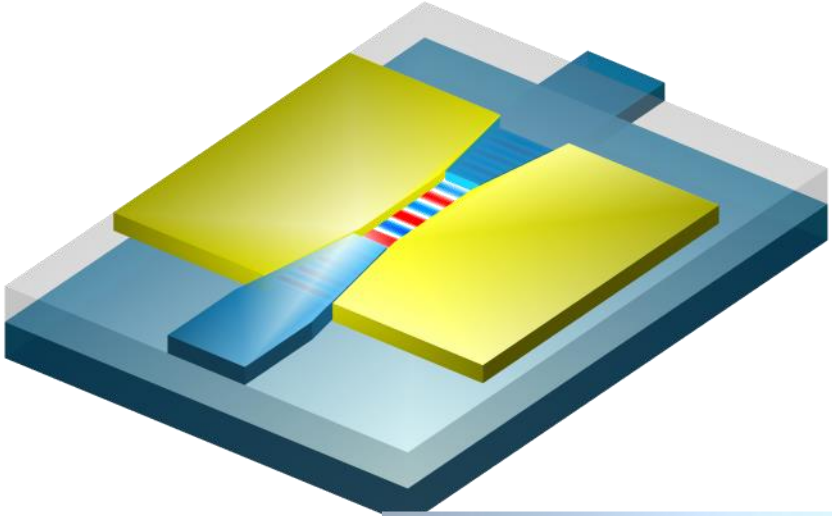
- The **gain** to offset losses **limits input signal power**, which will in turn, for SNR reasons, limit the information capacity of the chip => trade off between ***low power dissipation*** and ***signal to noise ratio***

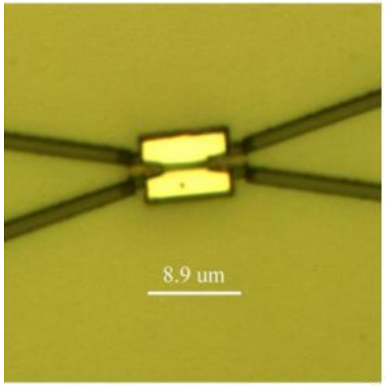


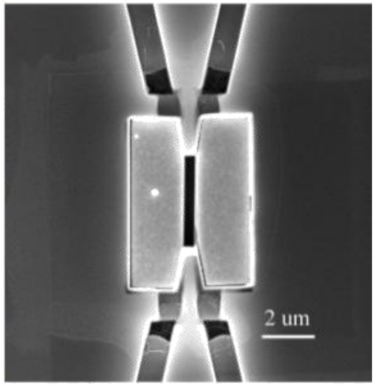
Model circuit used in integration density calculations.

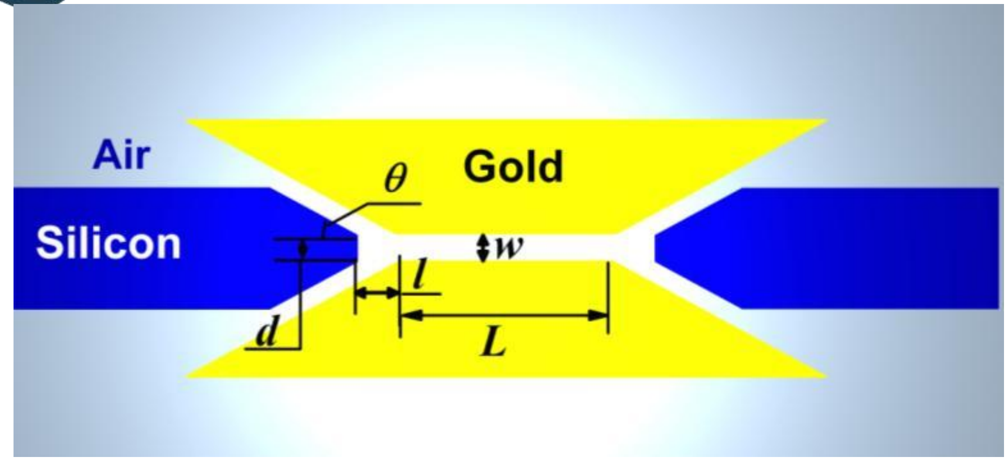
Interfacing

Silicon-gold slotline coupler

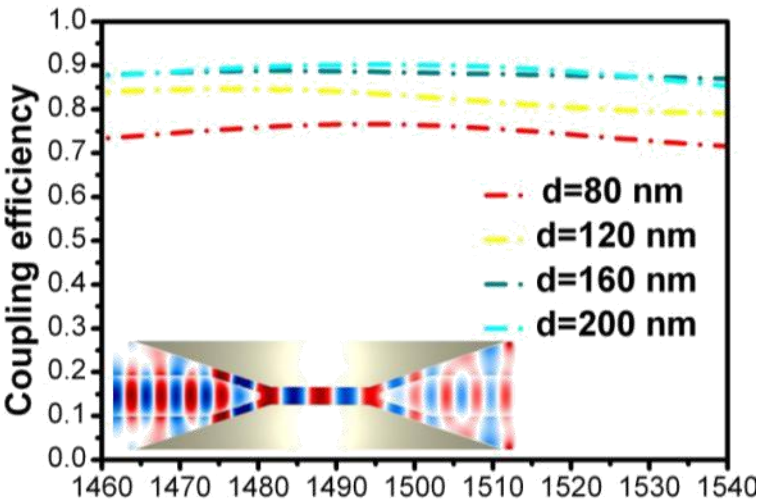


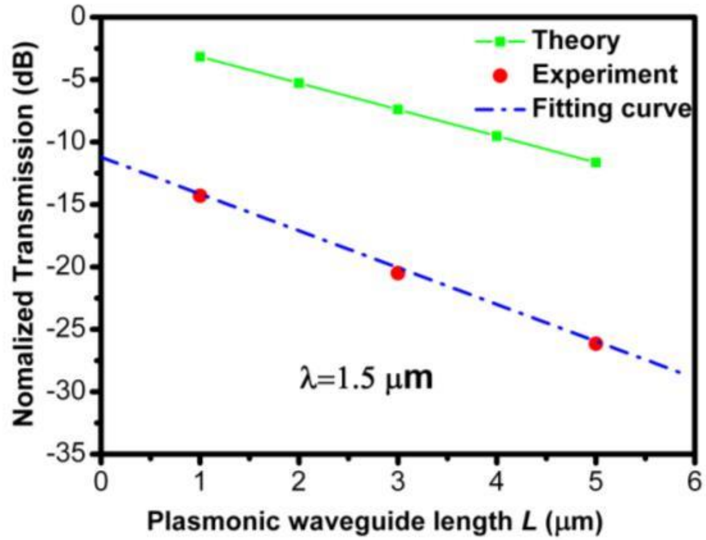






Mini Qiu et al, KTH: Broadband high-efficiency surface plasmon polariton coupler with silicon-metal interface





Theory

Experiment

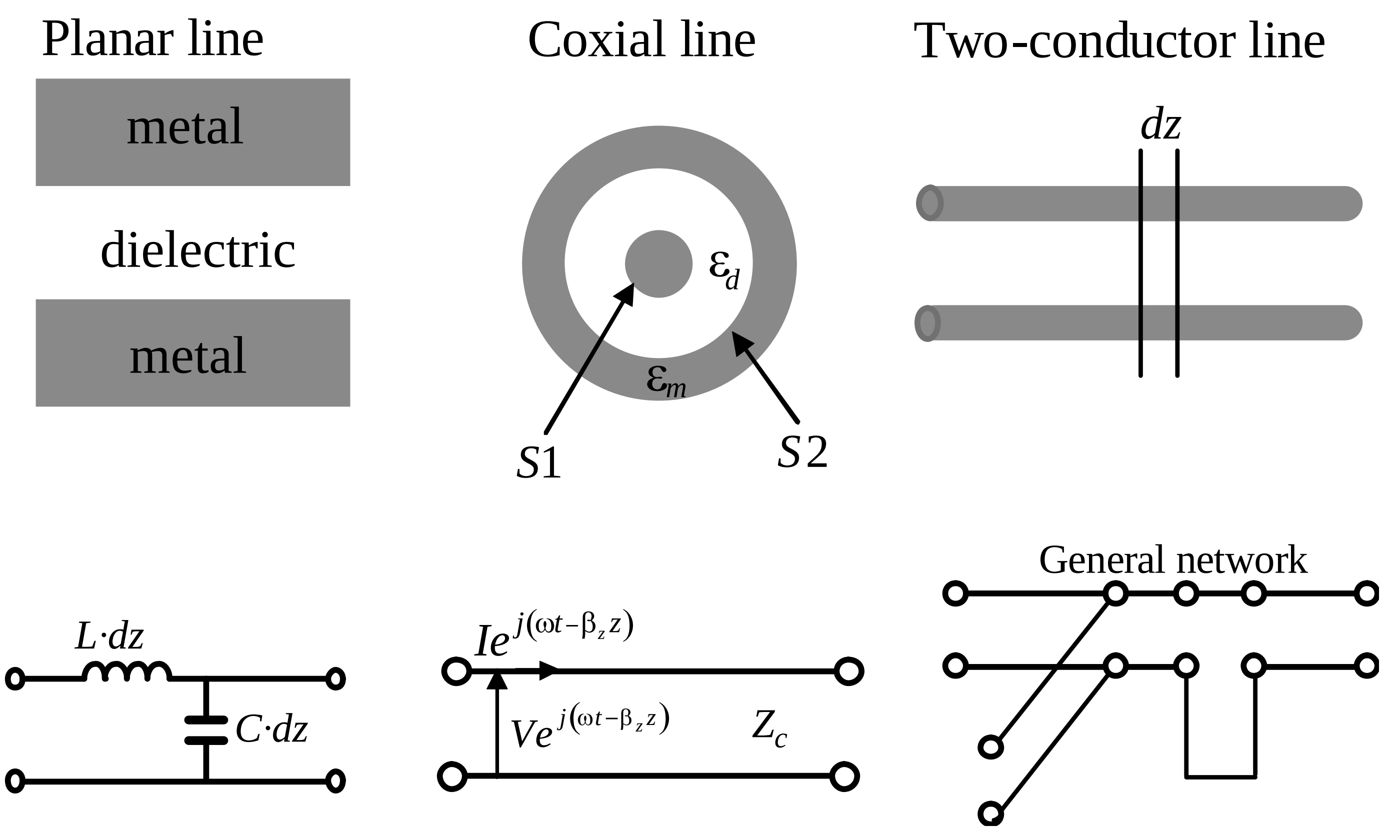
Coupling efficiency:

Theory: 88%/facet

Experiment: 28%/facet

***w*:200 nm,**
***ϑ*:10º,**
***l*: 0.25 μm**
***d*: 200 nm**

Plasmonics and microwaves and the role of TEM waves



Eilert Berglind, Lars Thylen, and Liu Liu,
"Plasmonic/Metallic Passive Waveguides and Waveguide Components for Photonic Dense Integrated Circuits: A Feasibility Study Based on Microwave Engineering", to appear in IET Optoelectronics (previous IEE optoelectronics)

- **Devices based on negative epsilon and compensated loss metamaterials, as accomplished by e g gain in QDs:**
  - *=>Limits on integration density due to power dissipation due to gain*
- **If we require dimensions of circuits < Si photonics circuits**

=> epsilon<0 is required

- ⇒ optical loss
- ⇒ (for circuits) gain required
- ⇒ {trade off *low power dissipation* vs. *SNR*}

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So to return to the statement above…

- ***Optical frequency subwavelength metallic wired circuits with propagation loss comparable to conventional optical waveguides?***

Alternative approaches to this :

- Gain with monodisperse quantum dots with small linewidth to give large amplification
- T=4K and less gain
- Si waveguides for transport in photonics circuits, plasmonics for functional elements
- …..

Nanophotonics target performance data: A ”roadmap”

- **Waveguides: Field width laterally < 75 nm,**
  - This gives lateral packing of waveguides that rivals that of electronics.
  - Has to be significantly lower than the Si one (appr 350 nm for Si/air at 1550 nm vacuum wavelength)

- **Waveguide components: Effective index significantly in excess of indices of conventional waveguide materials, say >10**
  - This gives generally tightly confined optical fields as above
  - And short resonators and other wavelength selective devices, since the wavelength in the medium will shrink with higher effective indices.

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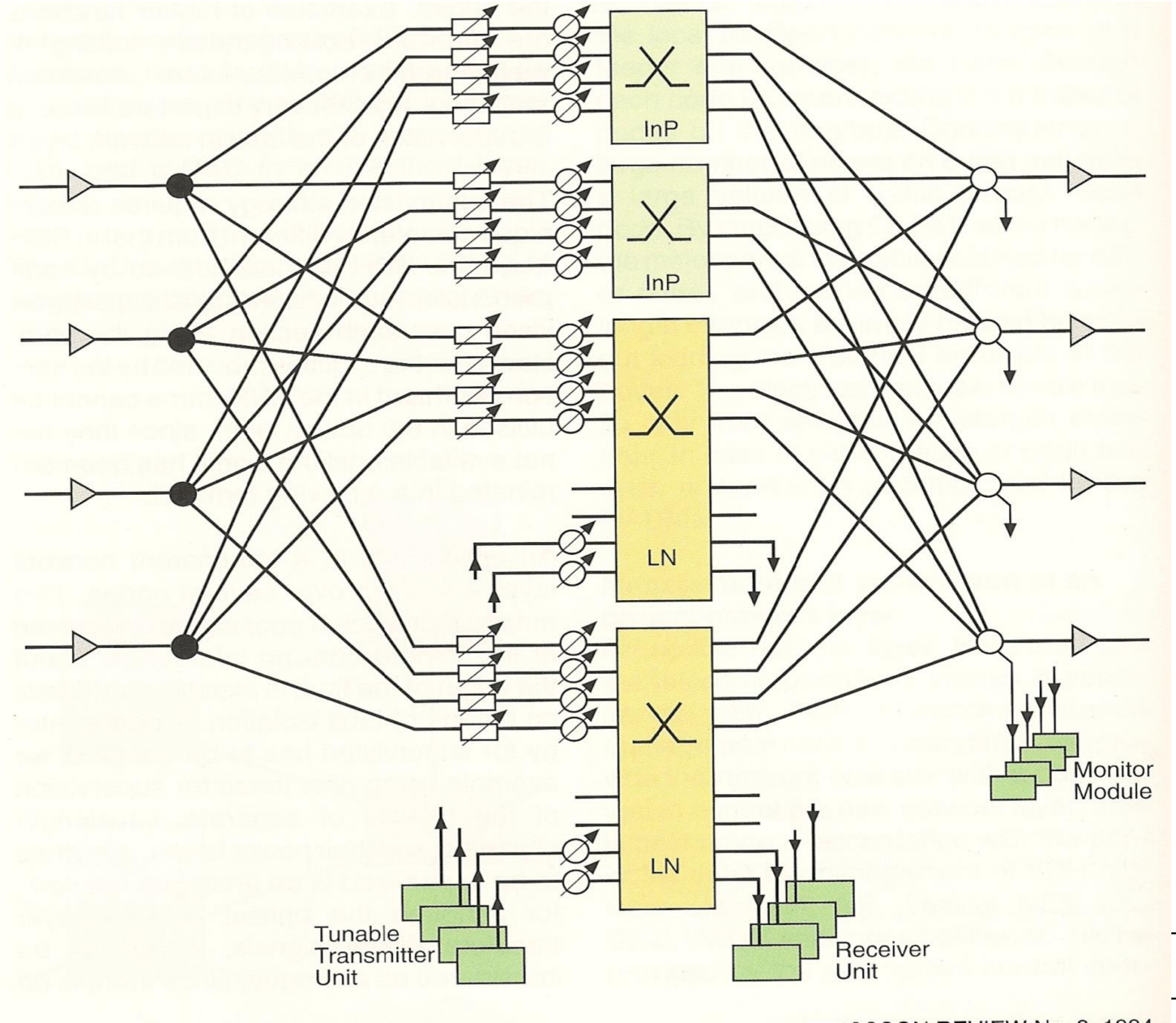
one telecom application vision…

EU project Multiwavelength transport network, the first managed Multiwavelength test bed (Ericsson, BTRL, Pirelli, Uni Paderborn.., 1992-96)



...to paraphrase Archimedes...

......Give me a real, negative and practically implementable ε, over some wavelength range, and I will (perhaps) be able to use it as a massive leverage for integrated photonics....

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