Geometries for surface plasmon-polariton amplification in the context of the EU project NAVOLCHI

E. P. Fitrakis[1], I. Suarez[2], P. Rodriguez-Canto[2], J. Martinez-Pastor[2], and Ioannis Tomkos[1]

1 Networks and Optical Communications group – NOC
Athens Information Technology (AIT), Greece

2 Unit of Materials and Optoelectronic Devices (UMDO)
Instituto de ciencia de los materiales, University of Valencia

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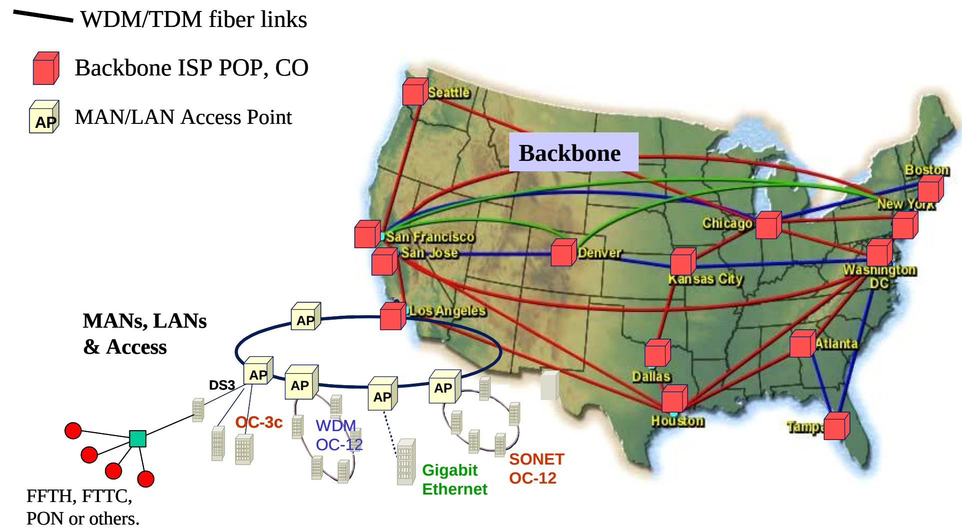
Section I:
The NAVOLCHI project

NAVOLCHI

Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

Optical networking everywhere!

- Backbone/Core networks
  - Terabit per second capacities
  - Automated operation
  - Need for less CAPEX/OPEX costs
- Metro/Access networks
  - Higher access (symmetric) bit-rate (>300Mb/s)
  - Converged wireless/wireline networks
  - Low cost
- In-building networks
  - Very low cost
- Intra data-center networks
  - Higher switching capacities
  - Reduced size – Cable management
- On-chip networks - Interconnects
  - High throughput
  - Small size and power consumption



Market-field for the "usual" players (i.e. network operators and equipment vendors)

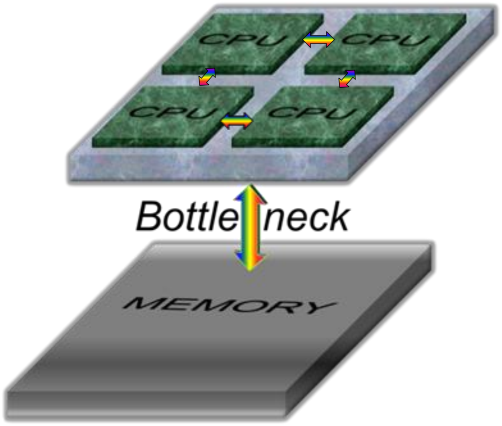
New market-field for industry-giants like:
• Google, Facebook, Microsoft, …
• IBM, Oracle, Intel, …

Focus of EU project NAVOLCHI

Chip-to-Chip Interconnects

- *Chip-to-chip optical interconnection requires high speed transceivers that are monolithically integrated with electronic ICs*, which can convert digital information from electrical domain to optical domain and vice versa.
  - Such transceivers should be compact, offer large bandwidth and consume little power in order to be economically and technologically efficient.
- *The most promising technology for realization of such transceivers is the CMOS compatible silicon photonics platform* whose low cost and large scale fabrication is ensured by well-developed advanced CMOS fabrication techniques.
- *Unfortunately, there is a size mismatch between silicon electronics and silicon photonics*. Even state-of-the-art Si photonic transceivers are bulky comparing to electronic transistors. Therefore, the integrated silicon photonic transceivers would occupy large portion of the optoelectronic ICs making them not economically viable…

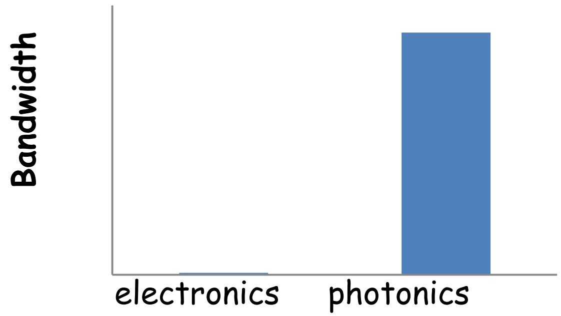
NAVOLCHI motivation



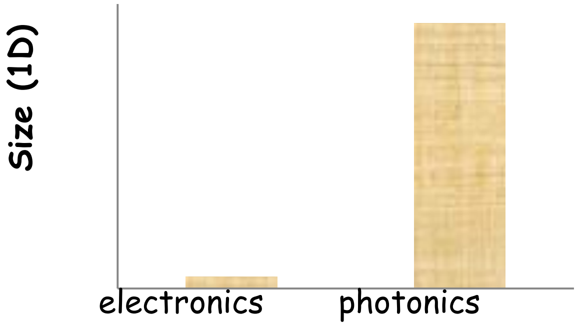
In multi-core processor systems there is a bandwidth bottleneck in the interconnection among the various CPU-cores and an additional bottleneck in the interconnection of the cores with the memory…

Novel high-speed chip-to-chip interconnects should be developed to overcome the mismatch between silicon photonics and silicon electronics!

Photonics offers much superior bandwidth than electronics!...



…But conventional photonic devices are much larger than electronics.



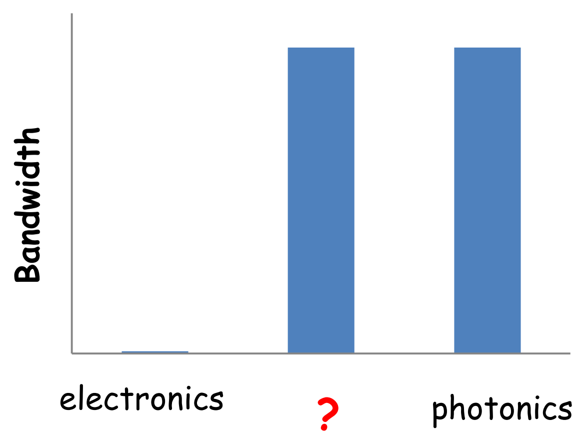
Photonics have 1000 times larger bandwidth, but are 100 times larger in area in comparison to electronics...

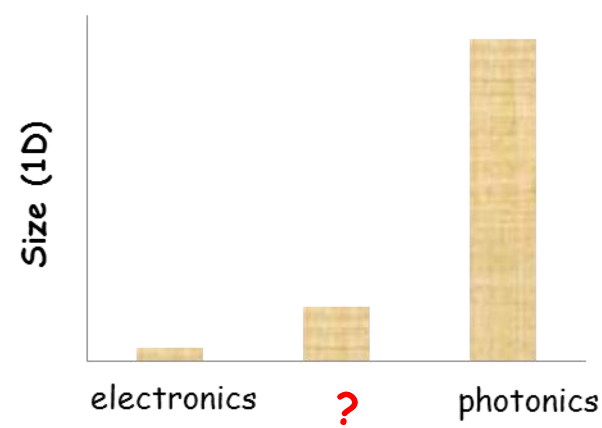
Let's shoot for the moon!

We want:

- *the <u>bandwidth</u> of photonics, and*
- *the <u>miniaturization capability</u> of electronics!*

We want something like…

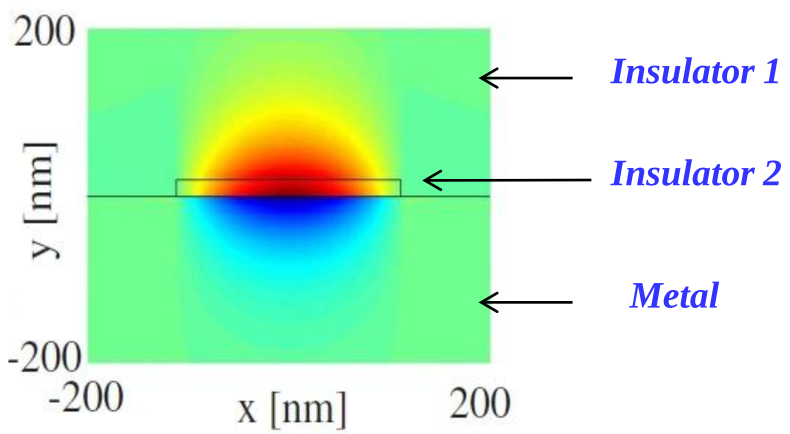


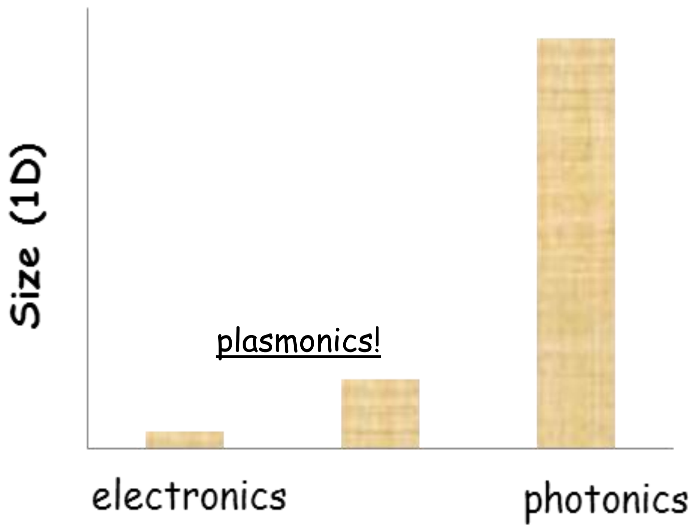


Here comes plasmonics!

Surface plasmons (SP) are coherent oscillations of free electrons present at the boundary between a metal and a dielectric.

Under appropriate conditions when SPs are exposed to a flow of visible or infrared light, they can be coupled to the incident photons leading to a hybrid electromagnetic-wave and charge-surface state known as surface plasmon polariton (SPP). SPPs can propagate along the metal-dielectric interface, while showing unique properties.

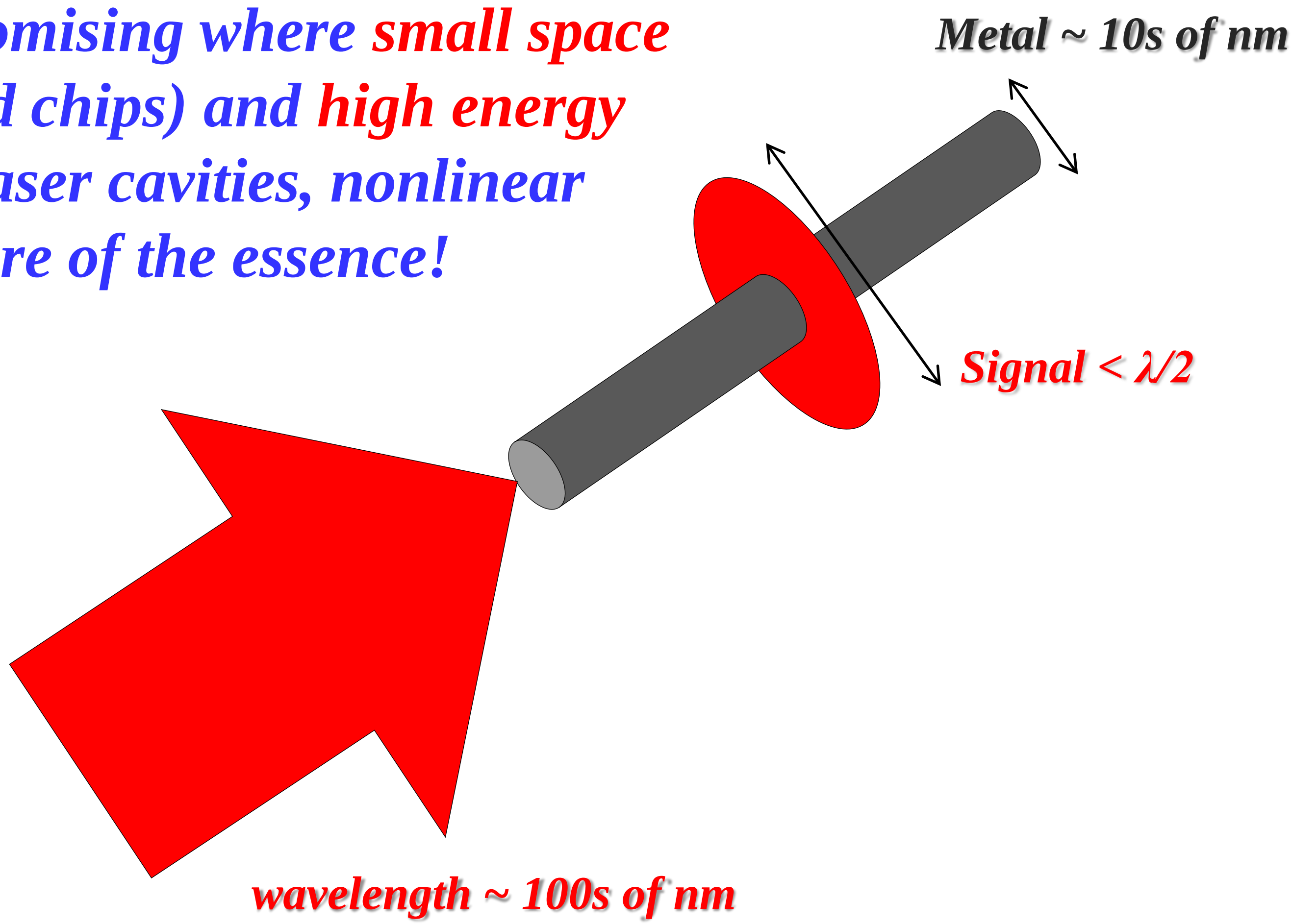




Plasmonics retains the bandwidth superiority of photonics!

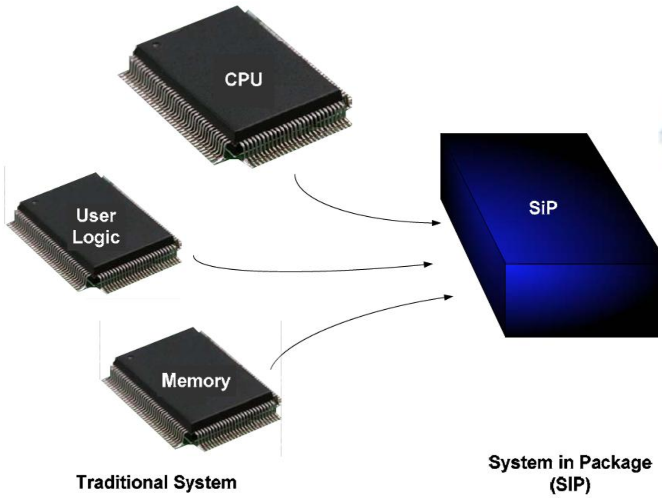
Applications of plasmonics

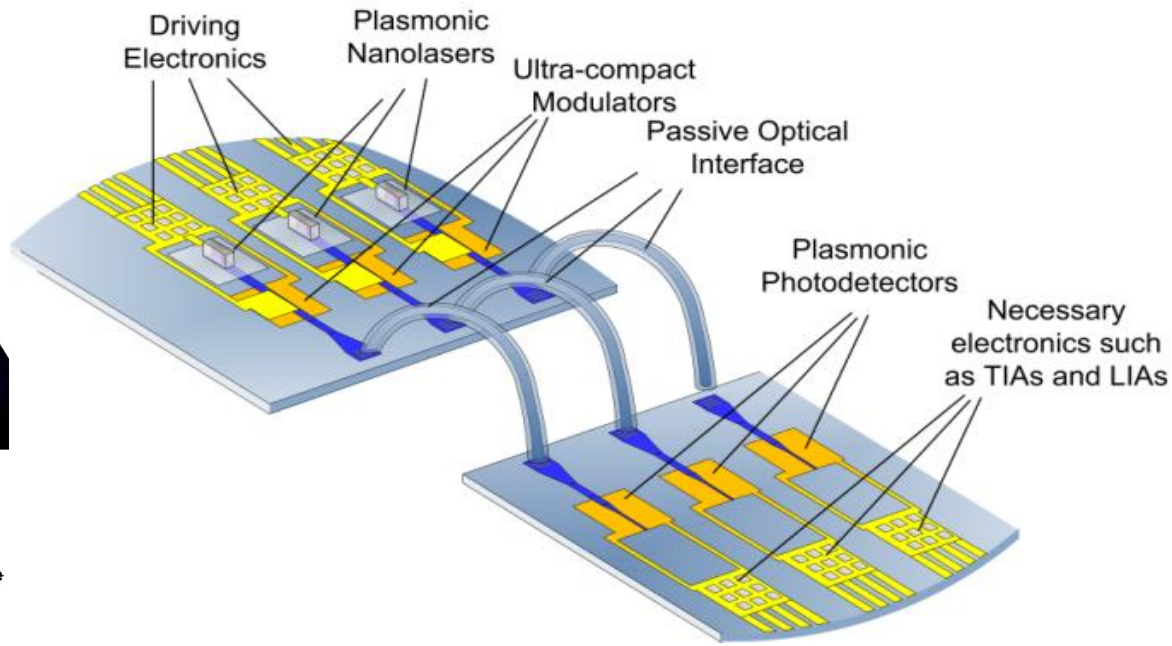
Because of the compactness in transverse dimensions, plasmonics are especially promising where small space (i.e integrated chips) and high energy density (i.e. laser cavities, nonlinear processing) are of the essence!



The NAVOLCHI project goal

Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection



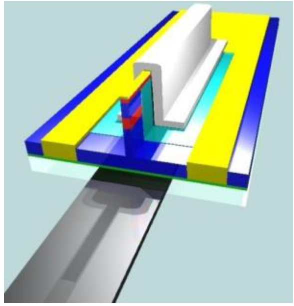


NAVOLCHI Researches & Develops:
A fabrication platform for all-plasmonic chip-to-chip interconnect

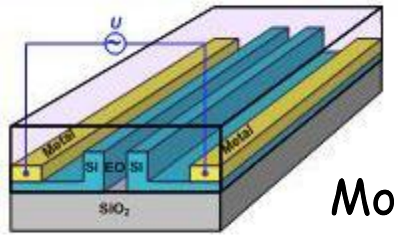
SEVENTH FRAMEWORK PROGRAMME
FP7-ICT-2011-7 (Project #288869)

Devices under development

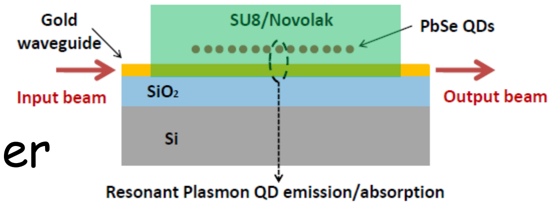
The key plasmonic components studied by NAVOLCHI are the plasmonic nanolaser and the modulator which make the plasmonic transmitter and the plasmonic amplifiers and photodetectors which are the key components of the receiver



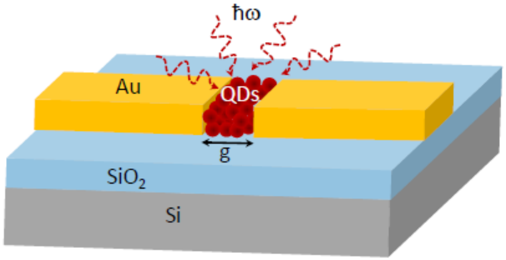
Laser



Modulator



Amplifier



Photodetector

In the NAVOLCHI Si-plasmonic interconnection architecture light generated in plasmonic nanolaser is coupled into a Si nanowire waveguide which feeds a continuous wave signal in the modulator. The light is then coupled out from the chip using a grating coupler. The optical signal is then transferred to the neighbouring chip through a passive optical link. Finally the signal is detected by the plasmonic photodetector of the transceiver located on the second chip.

The NAVOLCHI consortium

Karlsruhe Institute of Technology (Germany)

IMEC (Belgium)

Technical University of Eindhoven (Netherlands)

Athens Information Technology (Greece)

University of Valencia (Spain)

ST Microelectronics (Italy)

Ghent University (Belgium)

However, there is a catch…

Plasmonic devices are extremely lossy, because part of the optical power propagates in the metal…

Three ways to alleviate the problem:

- ***Designs with less power traveling in the metal and more power in the insulator. Works, but may loose the plasmonic properties…***

- ***Metals or other plasmonic materials (i.e. semiconductors) with fewer losses. Work for the future…***

- ***Our approach: Plasmonic amplifiers based on amplification in the adjacent material!***

State-of-the-art in Plasmonic Amplifiers

- The idea of obtaining lossless SPP propagation by a gain assisted dielectric was initially studied theoretically in planar geometries with the use of *III-V multiple quantum wells* proposed as a gain medium adjacent to metal layers.

- Then, *organic dyes* were suggested as a medium with strong gain able to increase propagation length in metal films. More recently, the dielectric gain material consisted of *organic dyes embedded into a polymer matrix*. Such a multicomponent material (polymer+active medium) is called nanocomposite and has the advantages of joining the active properties of the dyes with the technological feasibility of polymers (coating, lithography...). *Organic dyes dispersed in PMMA* were then investigated.

- Besides dyes, other kind of active centres can be selected to provide gain in a SPP. For example *erbium doped glass* can offer stimulated emission in a metal stripe.

- Other sorts of nanoparticles that can be a good choice to provide gain in a SPP are *colloidal quantum dots (QD)*. These kinds of nanostructures are semiconductor nanocrystals synthesised by colloidal chemistry, and are able to offer unique properties. In this way plasmonic amplification has already been demonstrated in dielectric waveguides dispersing the *QDs in sol-gel matrixes*.

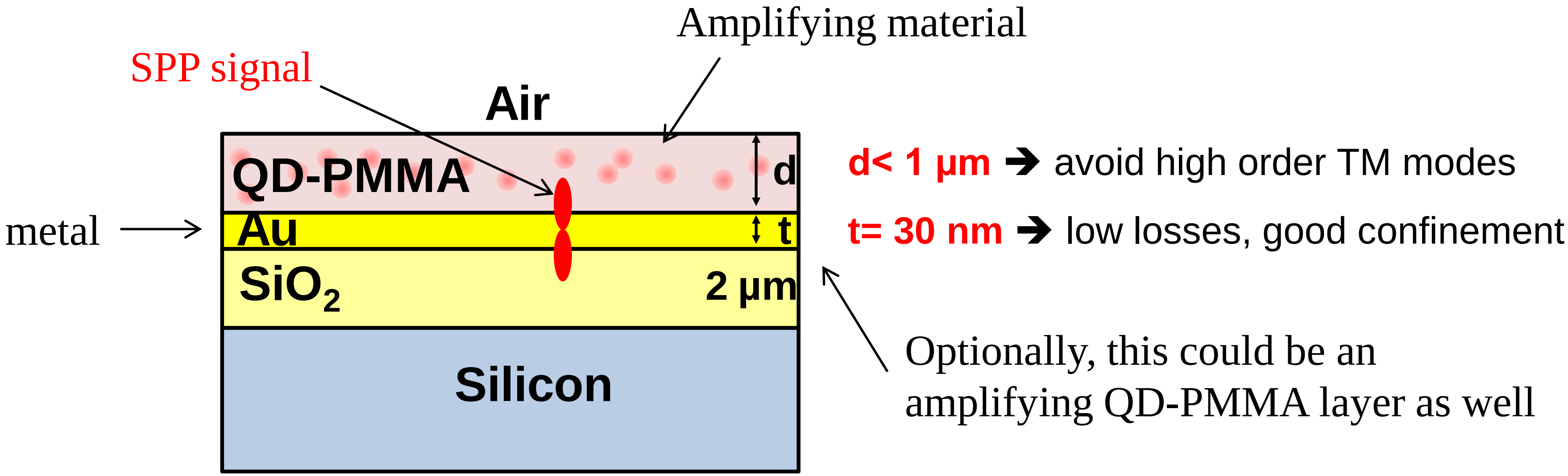
Section II:

Surface plasmon-polaritons amplifiers (*plasmonic amplifiers*) in the framework of NAVOLCHI

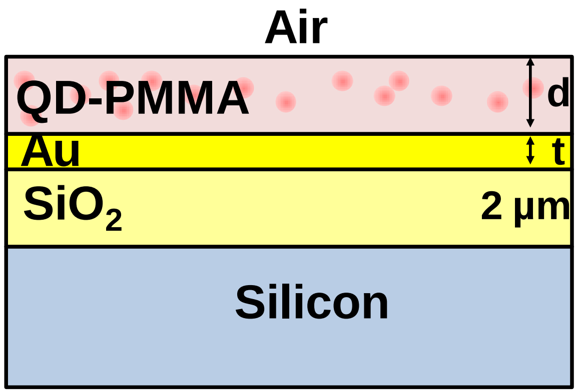
Plasmonic Amplifiers in NAVOLCHI

In NAVOLCHI a novel gain material based on the incorporation of colloidal quantum dots in a PMMA (transparent plastic, alternative to glass) matrix is proposed.

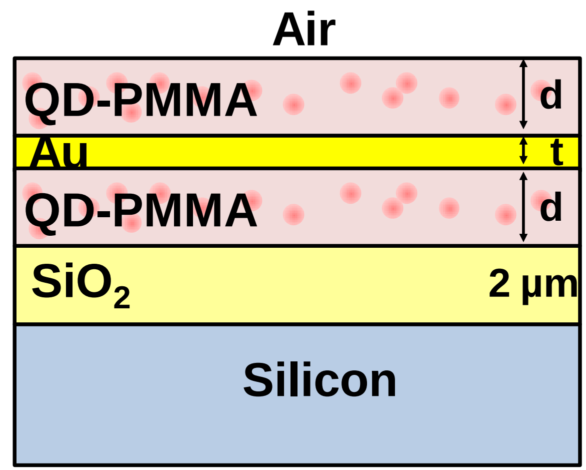
This kind of nanocomposite is important because it combines the novel properties of colloidal quantum dots (temperature independent emission and color tuning with the base material) with the technological feasibility of polymers.



Initial designs for amplifier



Asymmetric IMI
(easier to build)



Symmetric IMI
(better amplification)

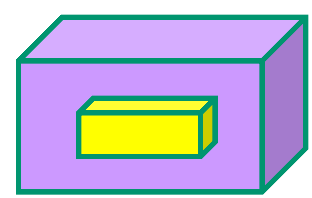
Colloidal Quantum dots (QD):

- Visible QDs: CdS, CdSe, CdTe
- IR QDs: PbS, PbSe, PbTe

Polymer: technologically feasible host matrix

- lithography: UV, ebeam

The above structures can also be modified by using a metal film of finite width



Amplifier simulations

The simplest method to simulate and predict the propagation characteristics of a signal in plasmonic waveguides is by calculating the propagation constant of supported modes

- ***We calculate the dispersion relation (DR) by solving Maxwell's eqs.***

- ***Then, we solve the DR numerically, so that we calculate the complex propagation constant vs frequency.***

- ***Loss and gain are modeled by the imaginary part of the propagation constant.***

- ***For gain materials, the imaginary part of the refractive index has an opposite sign in comparison to the sign in lossy materials.***

DR for the long-range mode in the symmetric IMI.

$$\tanh(k_1 a) = - k_2\varepsilon_1/(k_1\varepsilon_2)$$

ε_i: permittivities for metal and insulator,

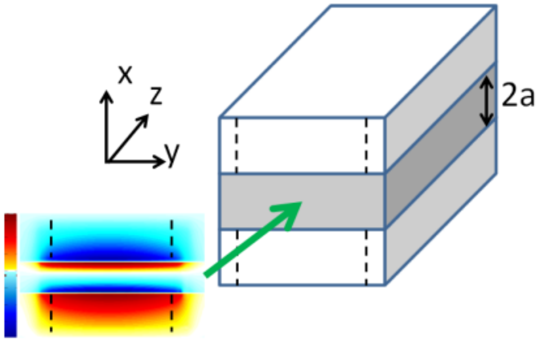
$k_i=(\beta^2-\varepsilon_i k_0^2)^{1/2}$

β: propagation constant,

k_0: wave number

a: metal half-width

Simulation methods



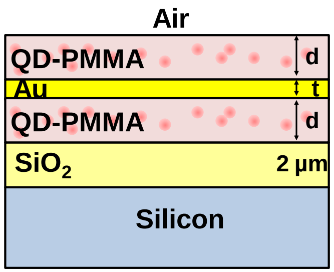
- Simulation methods under use:
  - Numerical I: **FDFD** (2D mode solver)
  - (Semi-)**Analytical** (approx.), for sanity check of simulation results
  - Numerical II: **Muller's method** (solves equations for complex solutions)
  - Modified Effective Index Method (for 2D structures)
  - Transfer Matrix Method (for more than 3 layers)

Modeling assumptions

Assumptions made:

- metal permittivity: Drude model
- insulators: dispersionless
- gain coefficient: constant with frequency
- amplification is assumed to reach peak value instantly

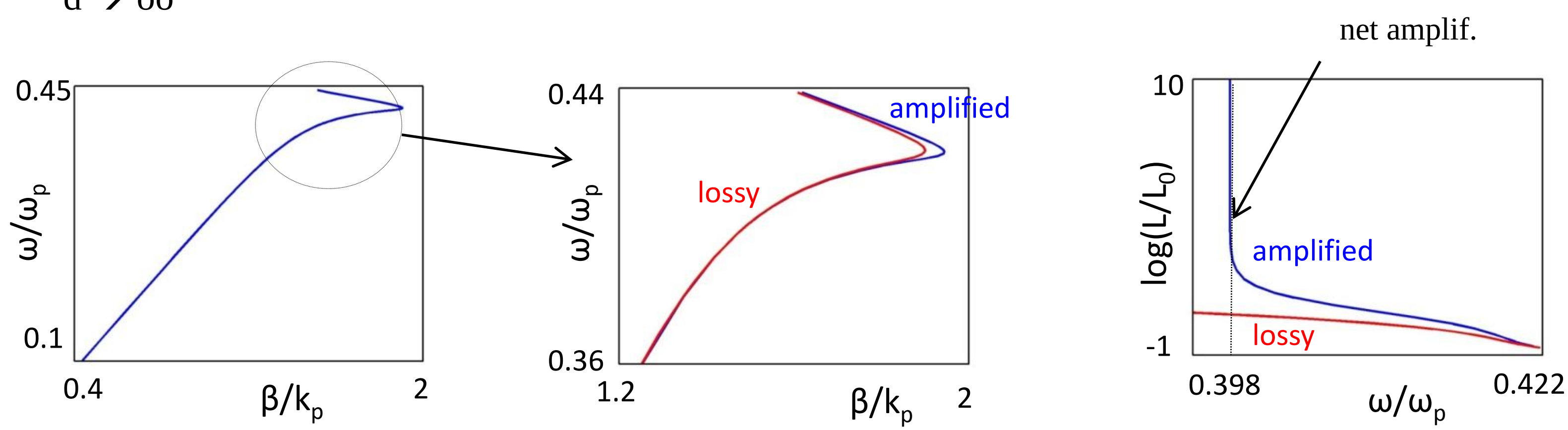
Symmetric IMI



- Easiest structure to simulate

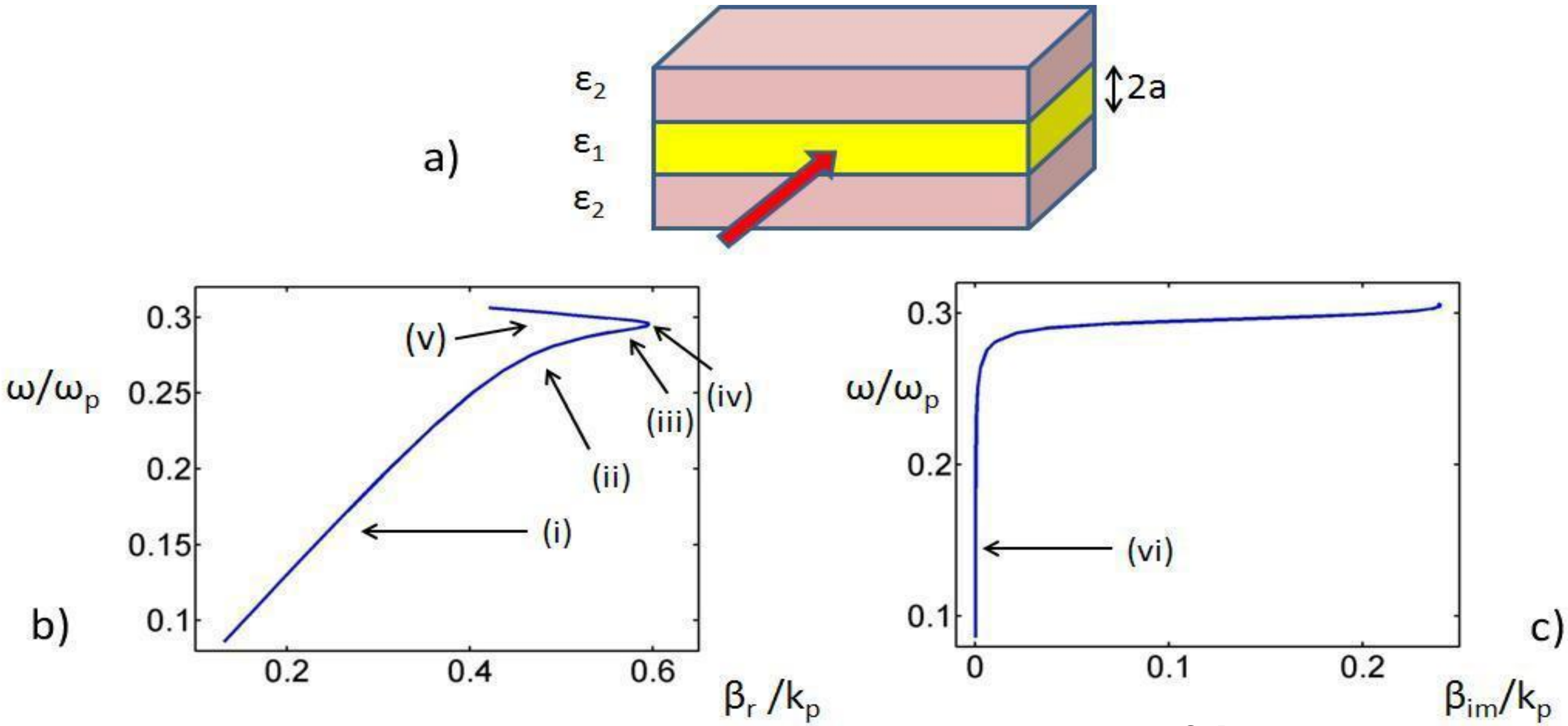
DR: $\tanh(k_1 t/2) = - k_2\varepsilon_1/(k_1\varepsilon_2)$

t = 30 nm
d → oo



- Dispersion properties are qualitatively similar in the cases with and without amplification. Physical properties are retained! (middle figure)
- At a certain wavelength, propagation length becomes infinite. For greater wavelengths, device acts as amplifier. (last figure)

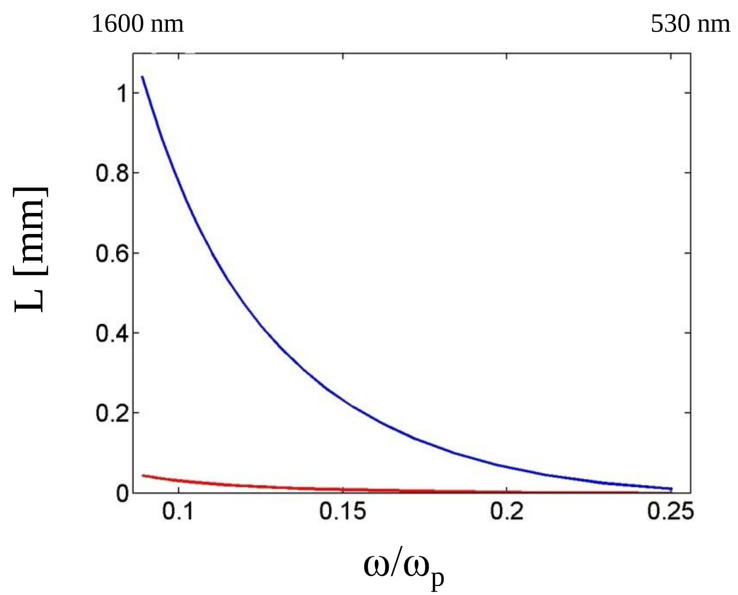
Interesting findings beyond amplification

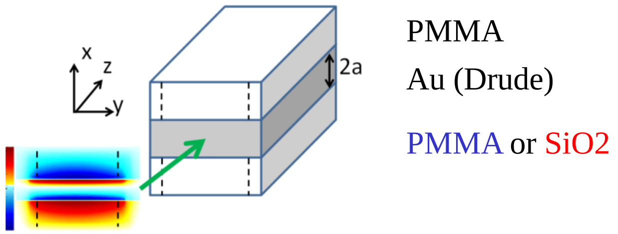


Real part of the propagation constant *Imaginary part of the propagation constant*

a) IMI waveguide. b) Real part of the propagation constant. (i) normal dispersion region (ii) slow light (iii) anomalous dispersion (iv) infinite group velocity (v) fast light. c) Imaginary part of the propagation constant. (vi) the frequency where the curve crosses the βim=0 axis. PMMA gain and metal loss cancel out at that point. For lower frequencies (i.e. wavelength longer than 1072 nm), the waveguide presents net gain.

IMI: symmetric vs. asymmetric





blue: symmetric structure PMMA-Au-PMMA

red : asymmetric structure PMMA-Au-SiO2

PMMA refr. index: 1.48

SiO2 refr. index : 1.45

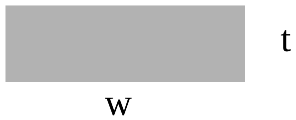
Au width : 30 nm

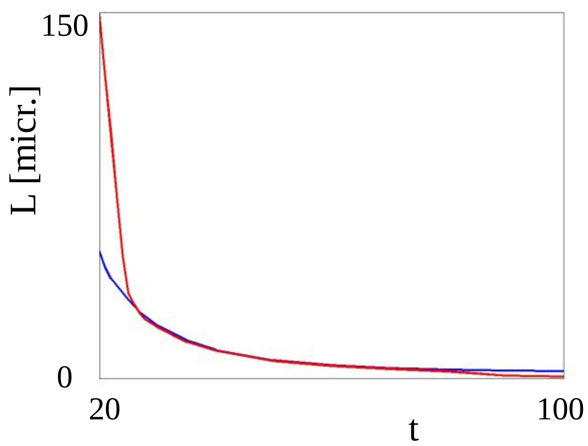
Propagation lengths are clearly longer in the symmetric case, especially for longer wavelengths.

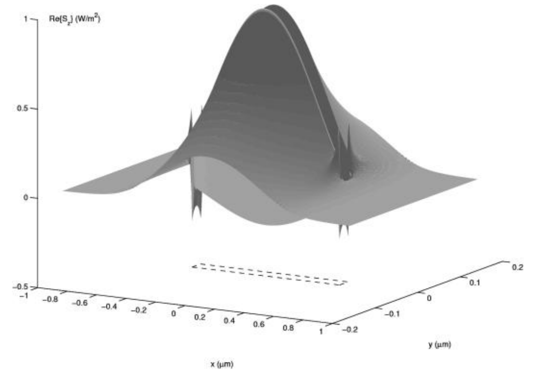
However, the asymmetric structure is easier to build.

Metal stripe (finite width)

The metal-stripe waveguide presents the lowest losses







P. Berini, Phys. Rev. B 61, p. 10484 (2000)

blue: symmetric IMI, PMMA-Au-PMMA, w→oo

red : metal stripe (Au in PMMA), **w = 1 micr.**, acc.   3.7%

The finite-width structure's propagation lengths are superior for small thicknesses!

Trade off: However… more energy away from the metal, therefore less compactness.

Simulation conclusions

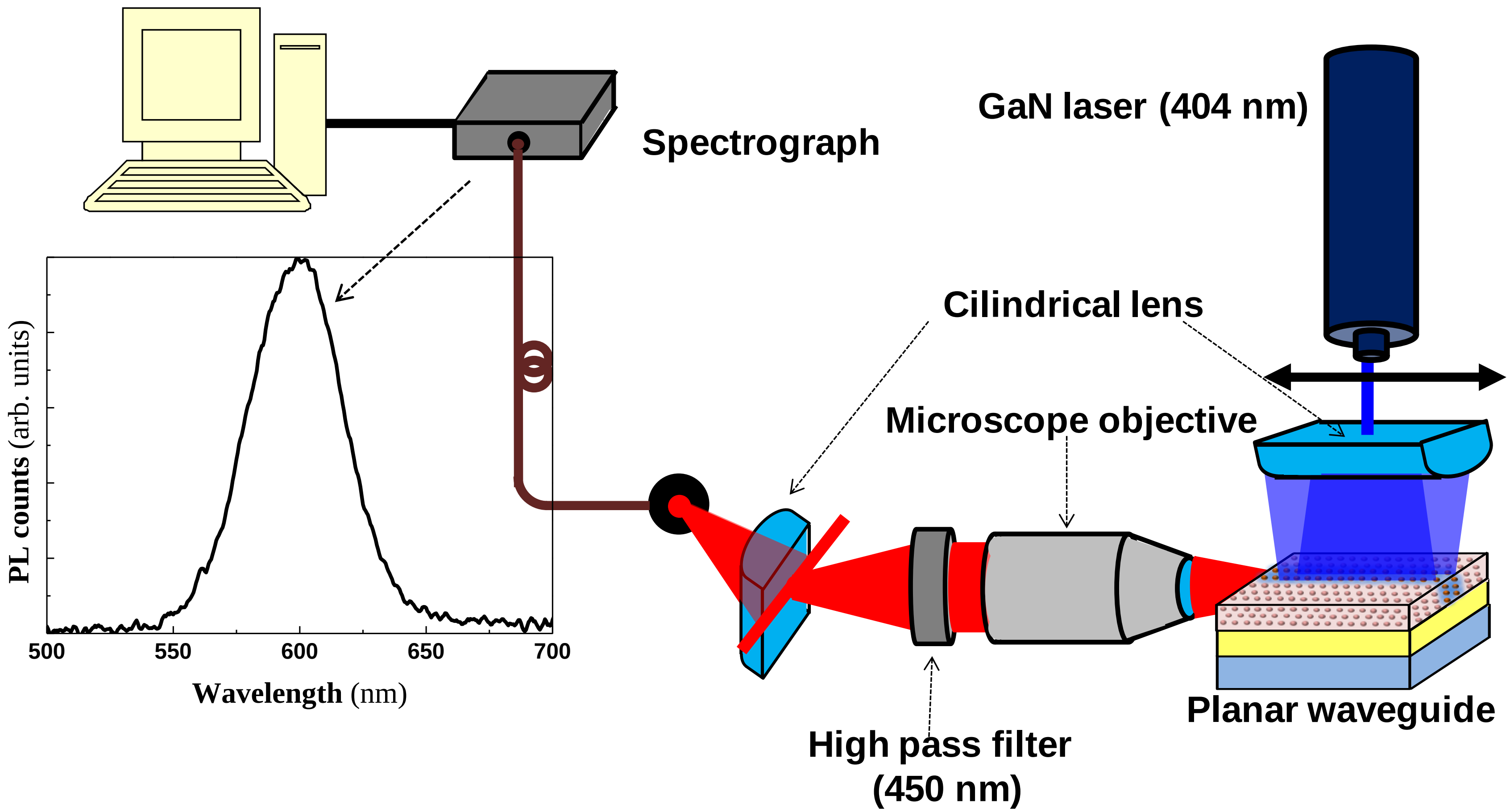
• When amplification is utilized, propagation lengths are increased but other physical properties (e.g. dispersion characteristics) are retained (qualitatively).

• The symmetric IMI and the metal-stripe waveguides are the structures with best propagation lengths and therefore easiest to amplify (depending on thickness)

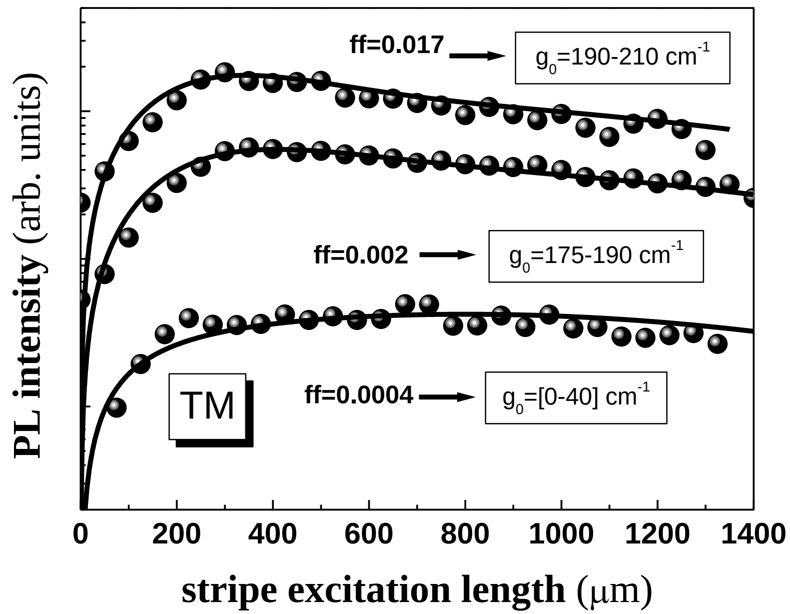
• However, Asymmetric IMI is the easiest to fabricate.

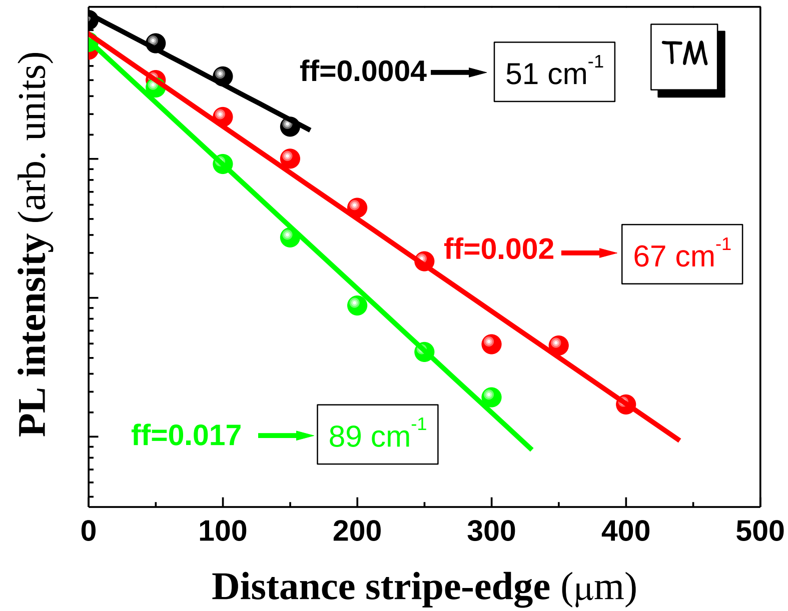
• A trade-off was identified: Geometries with better propagation lengths are less compact…

Experimental set-up



Gain and loss measurements





- Gain increases with the filling factor in the polymer
- Gain Saturation by Auger effect
- Losses increase with filling factor due to reabsorption
- Targeted spec for final project-device: 100 cm^{-1}

Summary

In this presentation we talked about:

- The EU-funded project NAVOLCHI that focuses on plasmonic interconnects.
  - We showed how plasmonics may provide the great bandwidth of photonics and the small size of electronics.
  - But plasmonic devices are lossy…

- Plasmonic Amplifiers
  - …so we are also working on plasmonic amplifier designs to alleviate the loss problem!

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NAVOLCHI

ICMUV INSTITUT DE CIÈNCIA DELS MATERIALS de la Universitat de València

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AND EDUCATION

Perceptum ex Optimus

Thank you!

Dr. Ioannis Tomkos
itom@ait.gr

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