Plasmonic Circuitry

[Circuit] :
a two-way communication path between points

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France

The drive for optical telecommunication

Electric Datacom interconnects & RC Latency

R ~Length / Area

=> 1 / RC ~Area / Length^2

C ~Length

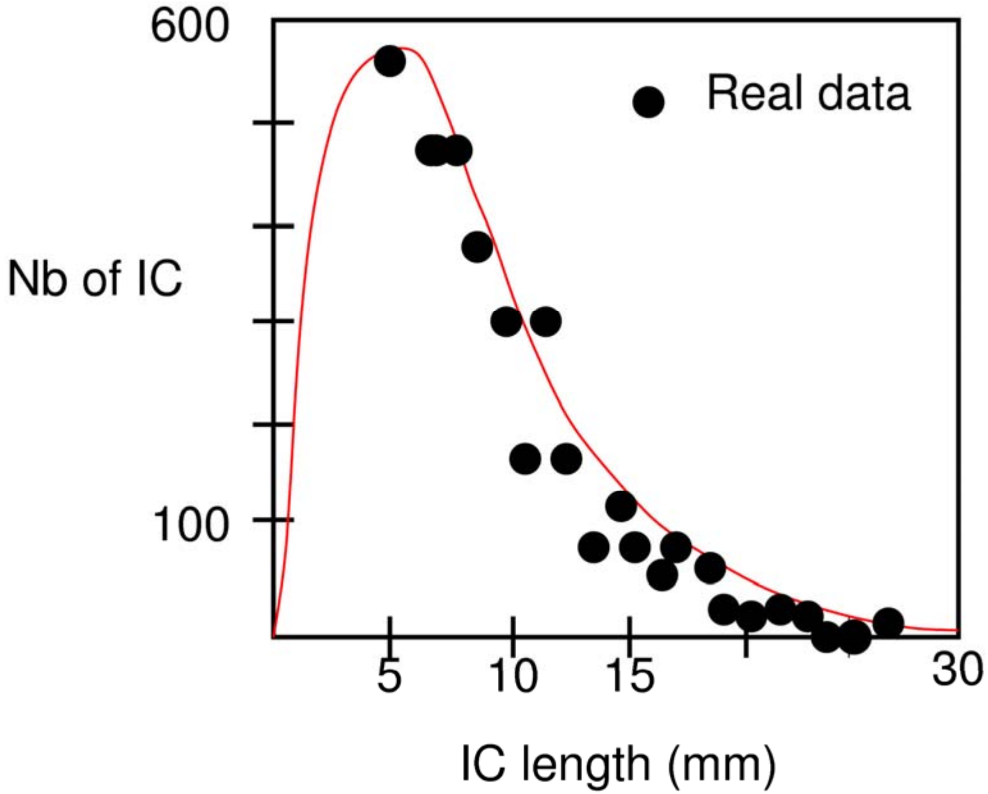
where A << L

Table 1 MOSFET and interconnect latency for 1.0-μm, 100-nm, and 35-nm-technology generations [3].

Technology generation	*MOSFET switching delay* ($t_d = CV/I$) (ps)	*RC response time* (L_{int} = 1 mm) (ps)	*Time of flight* (L_{int} = 1 mm) (ps)
1.0 μm (Al, SiO_2)	~20	~1	~6.6
100 nm (Cu, k = 2.0)	~5	~30	~4.6
35 nm (Cu, k = 2.0)	~2.5	~250	~4.6

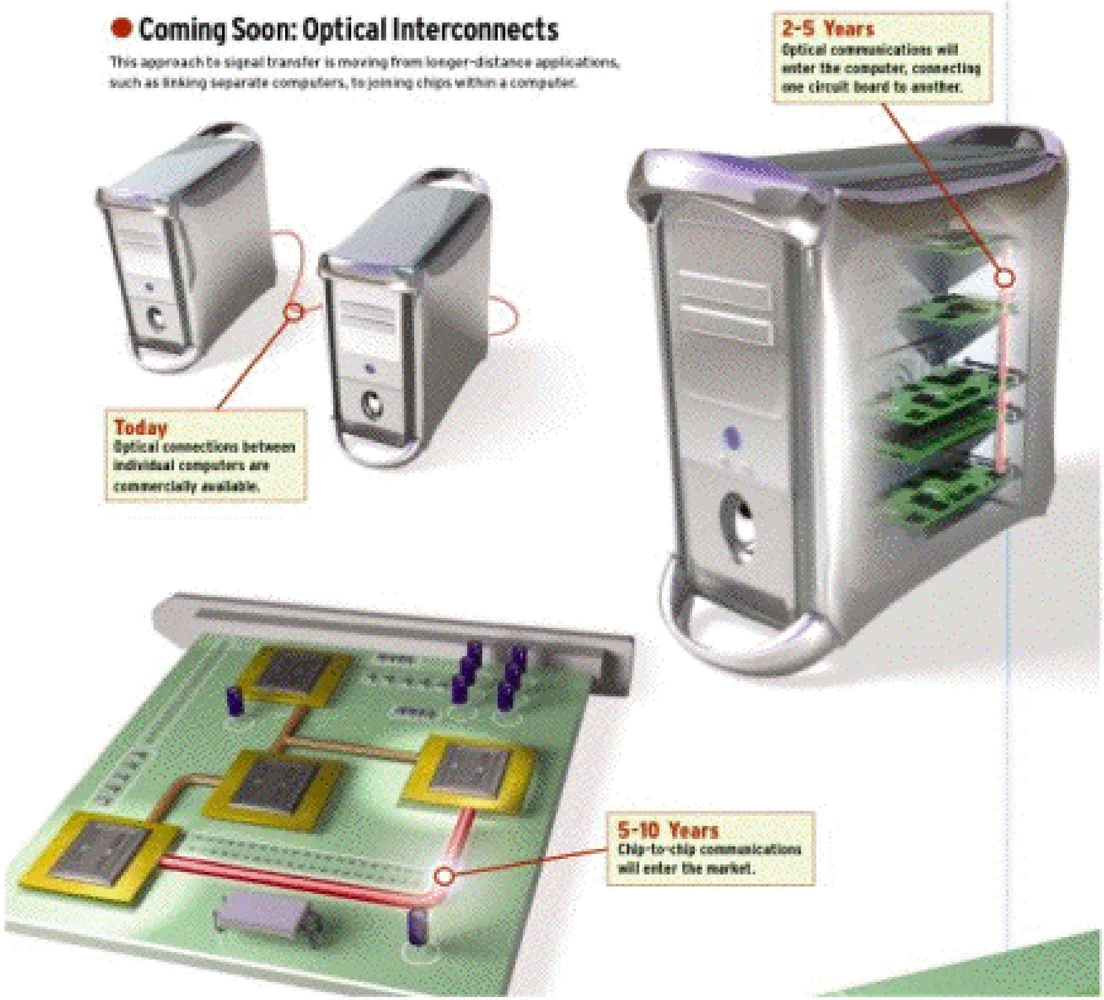
J. D. Meindl et al. IBM J.Res. & Dev. 46, 245 (2002)

Interconnects on boards vs length



Observed distribution of electrical interconnects as a function of their lengths (average over 20 commercial microprocessors – adapted from IBM J. Res. & Dev. ***46****, 245 (2002))*

Anticipation of short-haul optical datacom



(by N. Savage, IEEE-Spectrum, vol. 39, Aug.2002)

Optical interconnects on boards

Advantages of optical IC at the cm length scale and around 10 GHz clock :

***Attenuation*:**

Optical guide-wave losses < electrical lines losses.

But coupling in/out losses !

***Latency*:**

-RC effects of electrical line => longer delays than time-of-flight of signals.

- In optics : electro-optical conversion ~ time of flight of optical signal (~ 5 ps).

But, if cm-long scale, the interfacing and packaging issues are critical !

Advantages plasmon technology vs classical integrated-optics technology :

- Plasmonic device are very short and present intrinsic large bandwidth;
- Many plasmonic structures allow an efficient bending of the light wavevector.

Why plasmon interconnects?

Metal stripes surface plasmon waveguides sustain modes which are strictly confined to the width of the stripes => Advantage to avoid cross-talk.

Passive components such as surface plasmon beam splitters featuring right-angle bents have been recently demonstrated

In the case of Long-Range Surface Plasmon Polaritons (LR-SPP) modes, the typical attenuation lengths are in the mm or cm range *which is compatible with the distribution of chip-to-chip interconnect lengths.*

Compatibility with today silicon electronics technologies

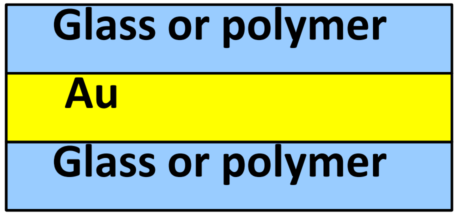
(oxide and metal deposition, lithographic processes).

Plasmonics is also compatible with current board substrate technology.

Plasmon propagation length

SPP

LR-SPP



Wavelength (nm)	Au Index			SPP propagation length (µm)	LR-SPP propagation length (µm)
850	0.196+ i 5.590	Sapphire Index	1,75	7,5	122
		Glass index	1,50	7,6	220
1310	0.411+i 8.347	Sapphire Index	1,74	24,7	502
		Glass index	1,50	25,1	902
1550	0.559+i 9.810	Sapphire Index	1,73	40,0	811
		Glass index	1,50	40,6	1169

- The reference system is a 25 nm thick Au film.

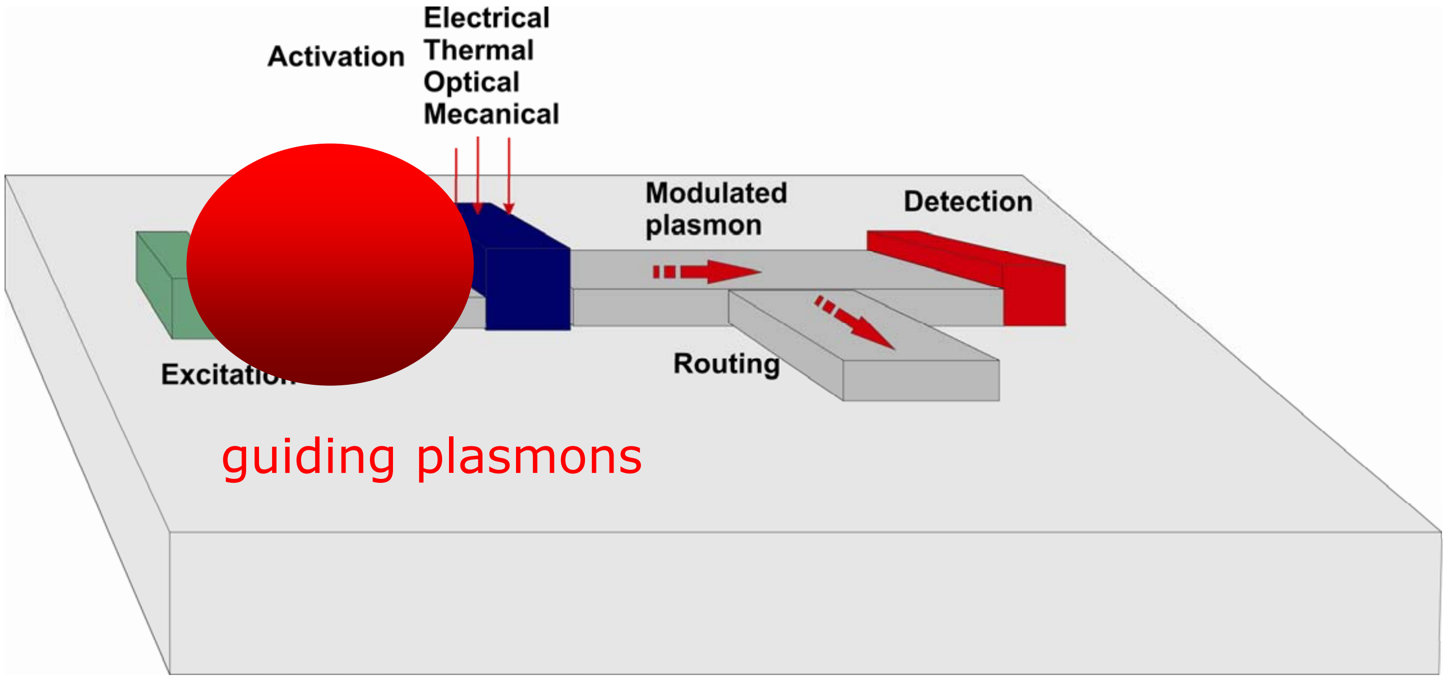
- SPP data corresponds to this film deposited on sapphire or glass substrate while the upper interface is exposed to air.

- LR-SPP data are related to the same film covered by the same material as the substrate.

Plasmonic circuitry: a recipe

Ingredients:

An excitation scheme (optical or electrical)
A waveguide
An active area to encode information
Some routing, filtering…
A detection mechanism



Waveguiding strategies

Plasmonic Crystals Kitson (Barnes' group) et al, PRL 1996; Bozhevolnyi et al, PRL 2001
Thin films/ TIR coupling

Metal Stripes Theory: Berini (Ottawa), PRB 2000 ; Weeber & Dereux (UB) (2001)

Thin films /TIR or end-fire coupling

Diel. WG on metal Hohenau (Krenn's group) et al, Opt. Lett. 2005

Bozhevolnyi, Zayats & Dereux groups

Thin or thick fims / coupling : TIR, end-fire

Crystalline metal nanowires Ditlbacher (Krenn's group) et al, PRL 2005

Very thin nanostructures / coupling : end-fire

Hole arrays & hole arrays components

Ebbesen's group et al (UAM,UZ, UB) , APL 2003

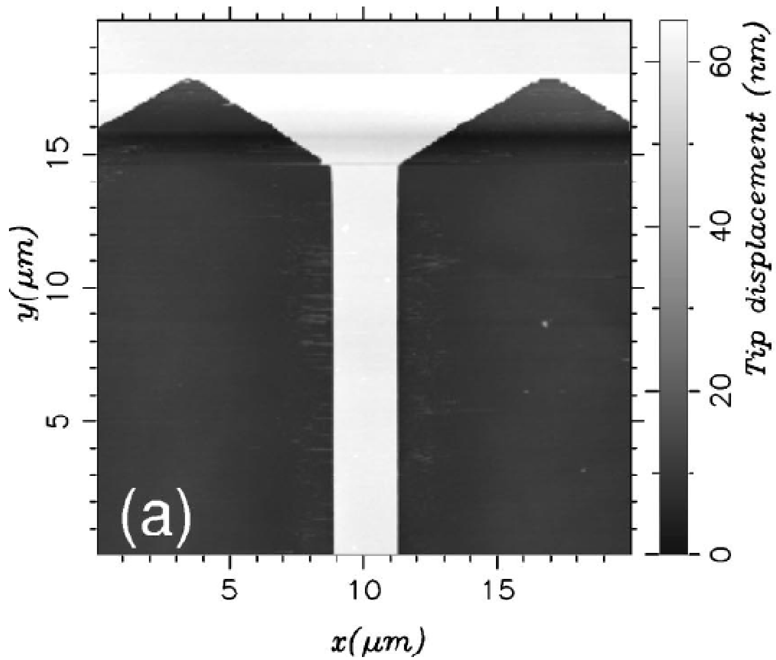
Thick films / coupling : normal incidence

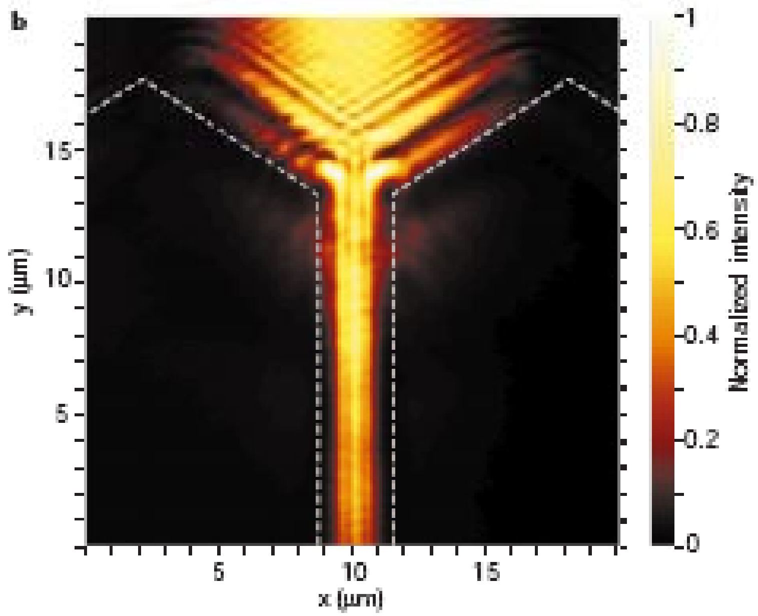
Channel SPP WG Theory: Novikov & Maradudin (Irvine), PRB 2002;

Bozhevolnyi et al (Ebbesen's group), Nature 2006

Thick films / coupling : end-fire

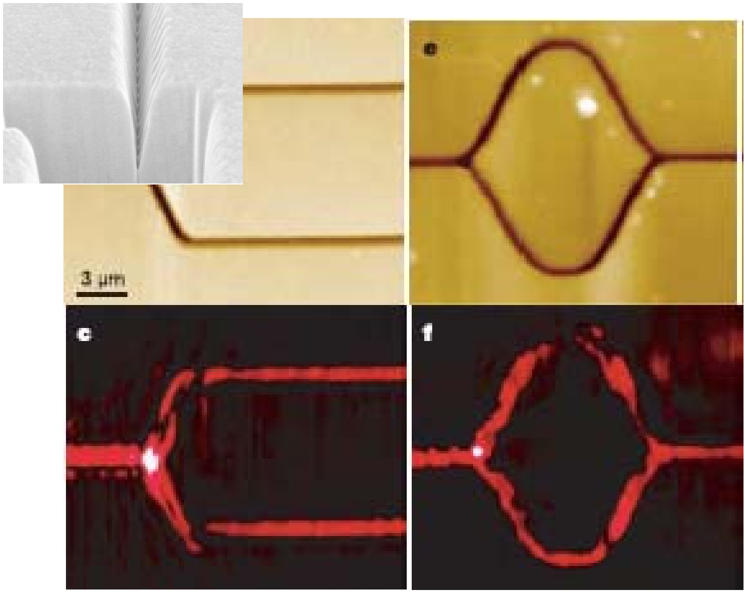
Stripe waveguides



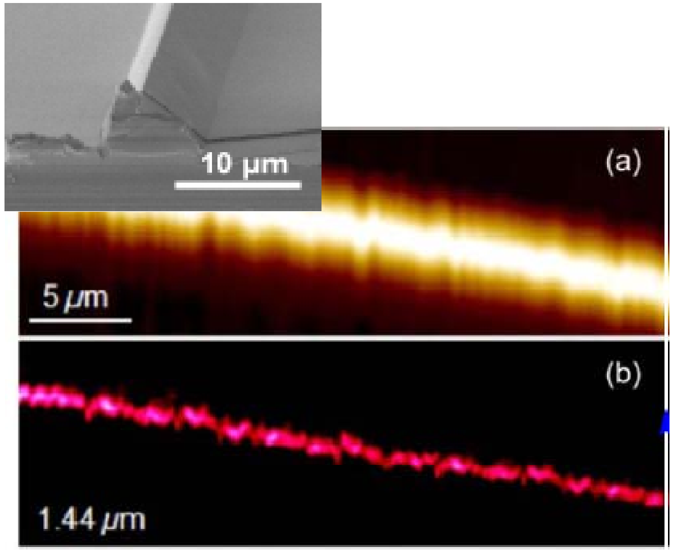


Charbonneau et al. Opt. Lett. 25, 844 (2000)
Lamprecht et al. Appl. Phys. Lett. 79, 51 (2001)
Weeber et al. Phys. Rev. B. **68,** 115401 (2003)
Zia et al. Phys. Rev. B **74,** 165415 (2006)

V-groove and wedge

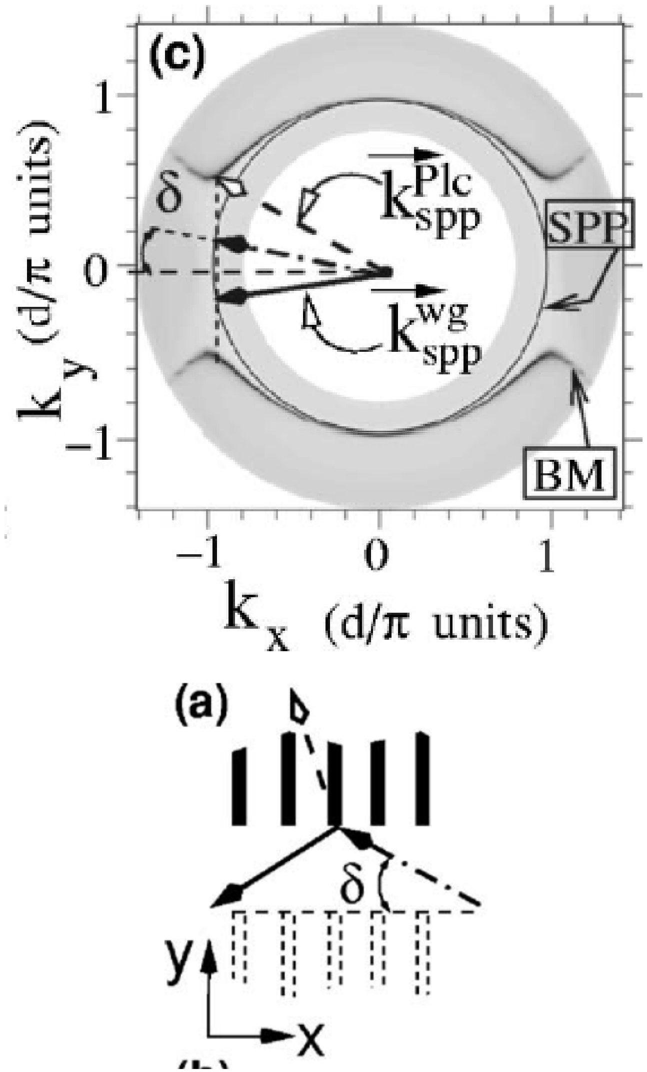


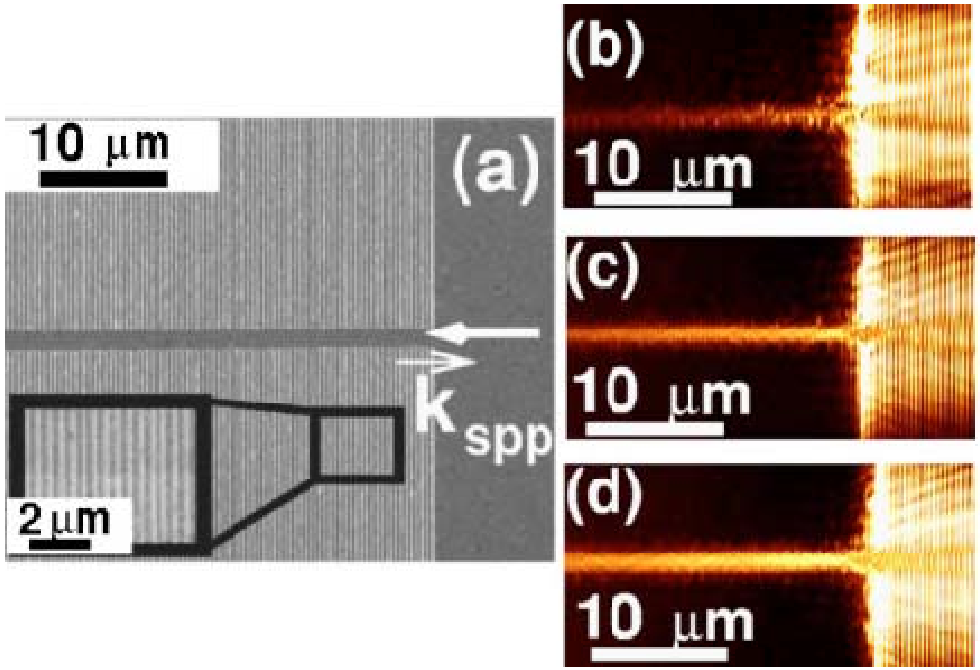
Novikov et al. Phys. Rev. B **66**, 035403 (2002).
Pile et al. Opt. Lett. **29**, 1069 (2004)
Bozhevolnyi et al. Phys. Rev. Lett. **95**, 046802 (2005)
Bozhevolnyi et al. Nature, **440** 508 (2006)



Moreno et al. Phys. Rev. Lett. **100**, 023901 (2005)
Boltasseva et al. Opt. Exp., **15** 5252 (2006)

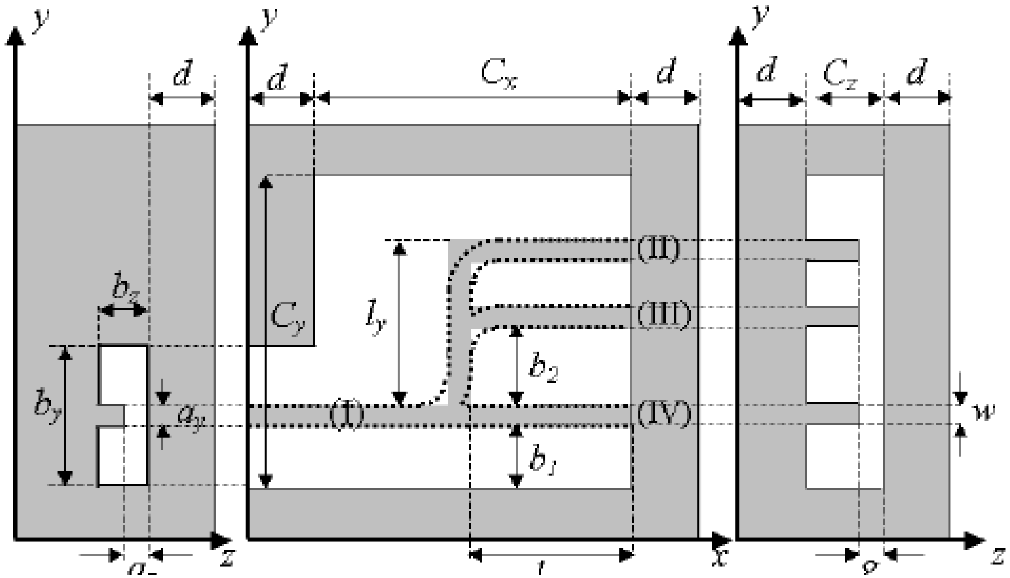
Plasmonic crystal waveguides

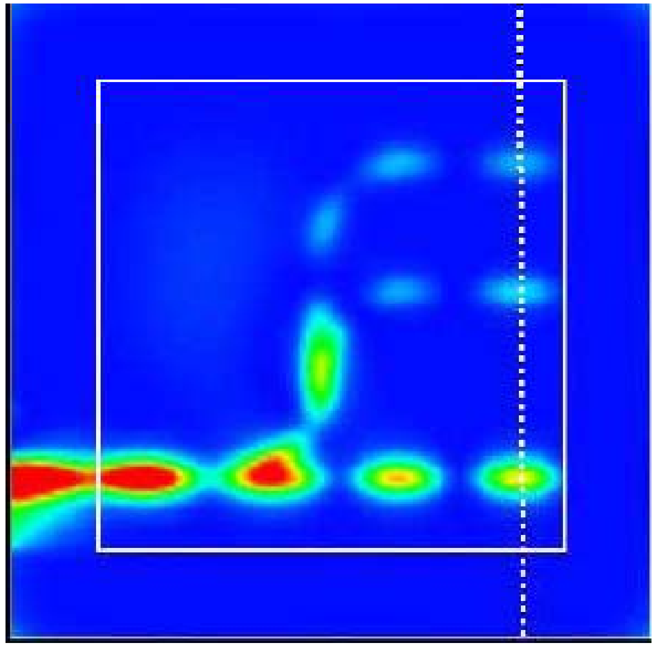




Bozhevolnyi et al. Opt. Lett, **36** 734 (2001)
Weeber et al. Appl. Phys. Lett **89**, 211109 (2006)

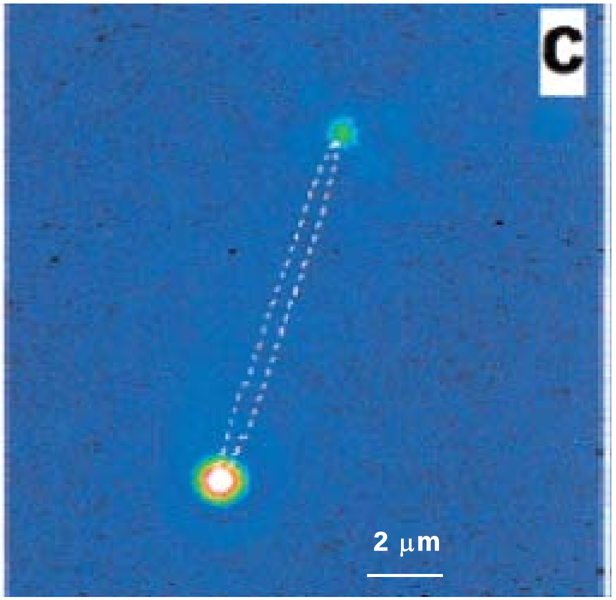
Slot waveguides

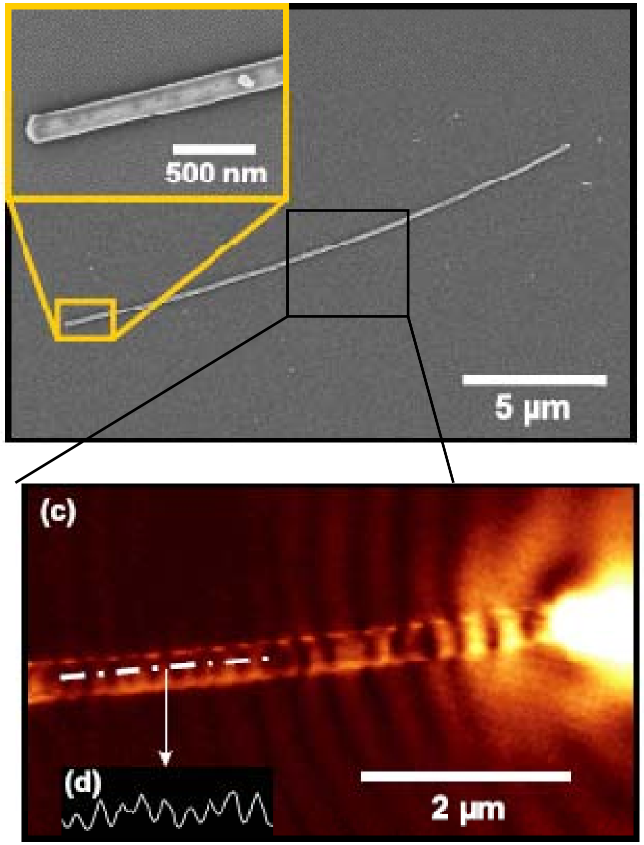




Tanaka et al. Appl. Phys. Lett. **82**, 1158 (2003)
Wang et al. Opt. Lett. **29** 1992 (2004)
Tanaka et al. Opt. Exp **13**, 256 (2005)
Dionne et al. Nano. Lett. **6**, 1928 (2006)

Nanowires



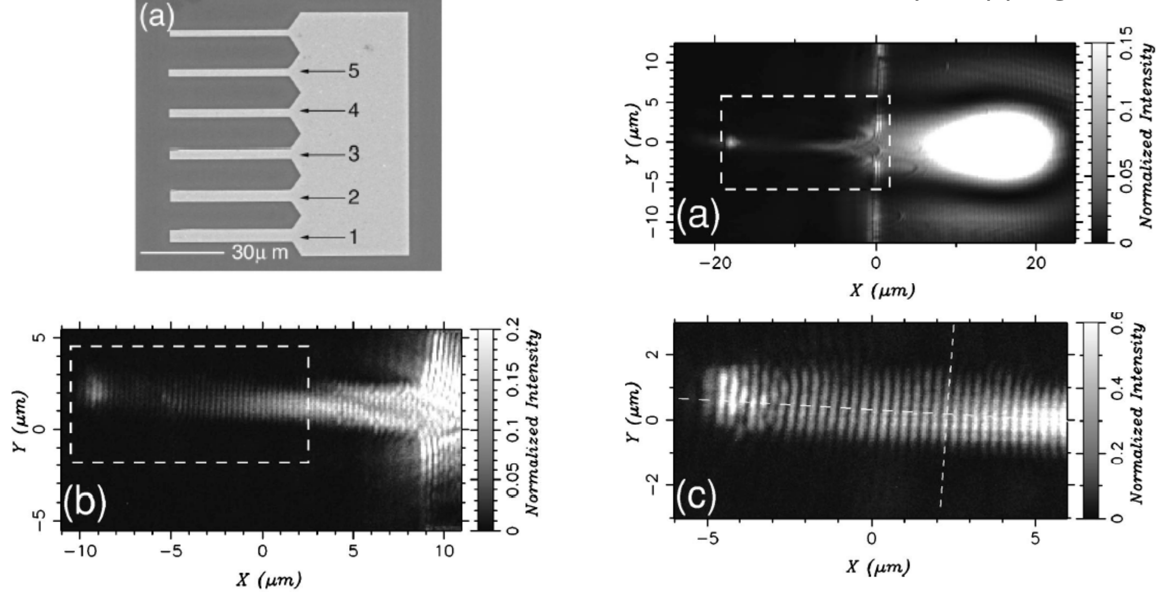


Weeber et al. Phys. Rev. B **60**, 9061 (2000)
Dickson et al. J. Phys. Chem. B **104**, 6095 (2000)
Ditlbacher et al. Phys. Rev. Lett. **95**, 257403 (2005)
Gunn et al. Nano. Lett, **6,** 2804 (2006)

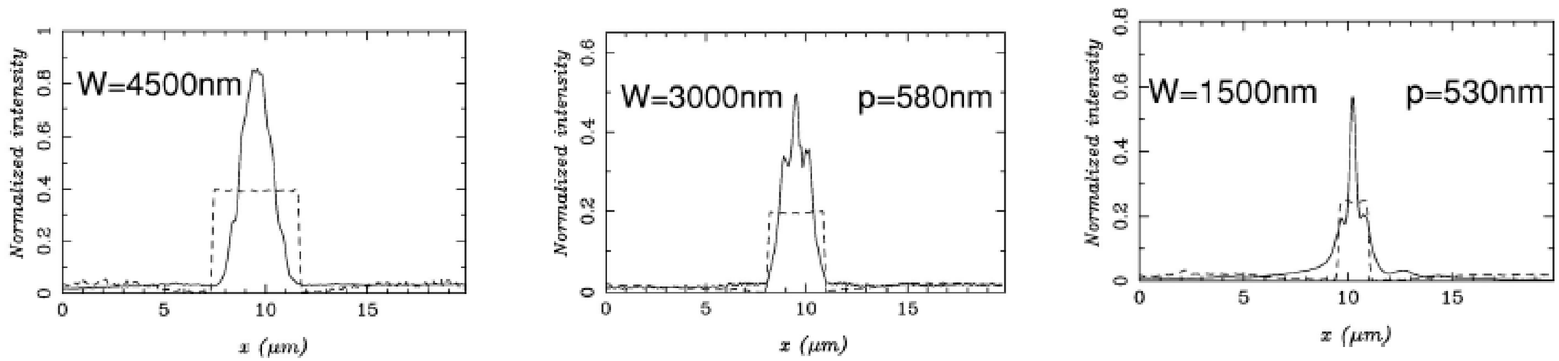
Waveguiding in metal stripes

Near-field intensity mapping:

<u>Need:</u>
Good confinement and
significant propagation!
(issue raised by Kobus!)

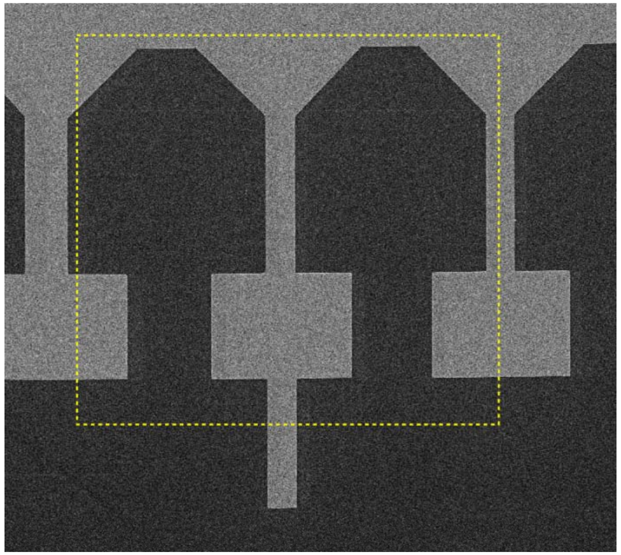


- Plasmon is confined and propagates, but the mode has a cut-off width:

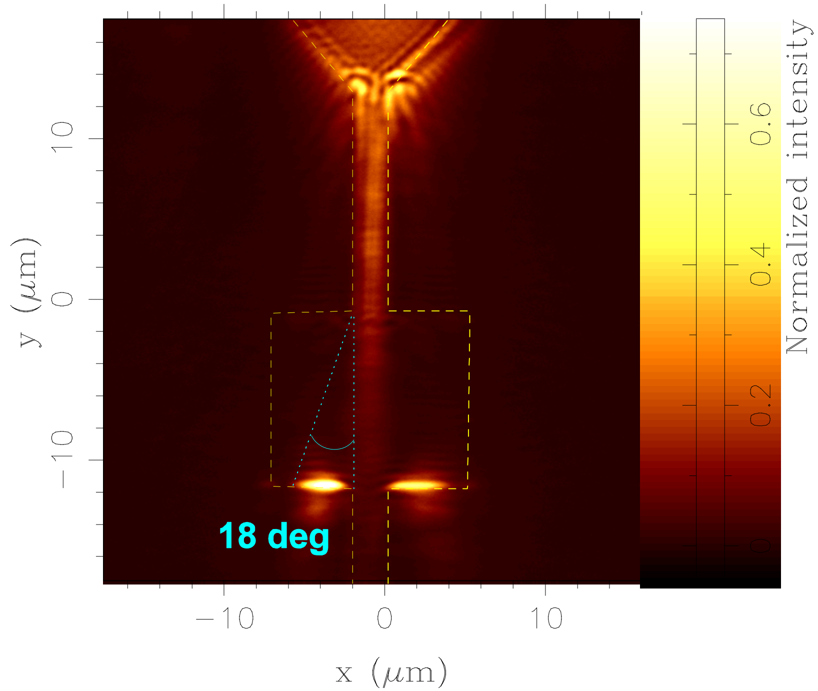


Phys. Rev B <u>68</u>, 115401 (2003)

Confinement



Stripe SP mode spreading



Strong field confinement => large spreading

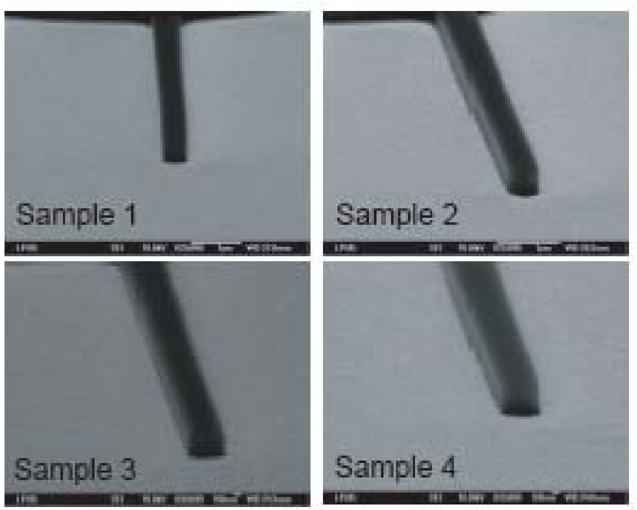
Alternative technology: DLSPPW

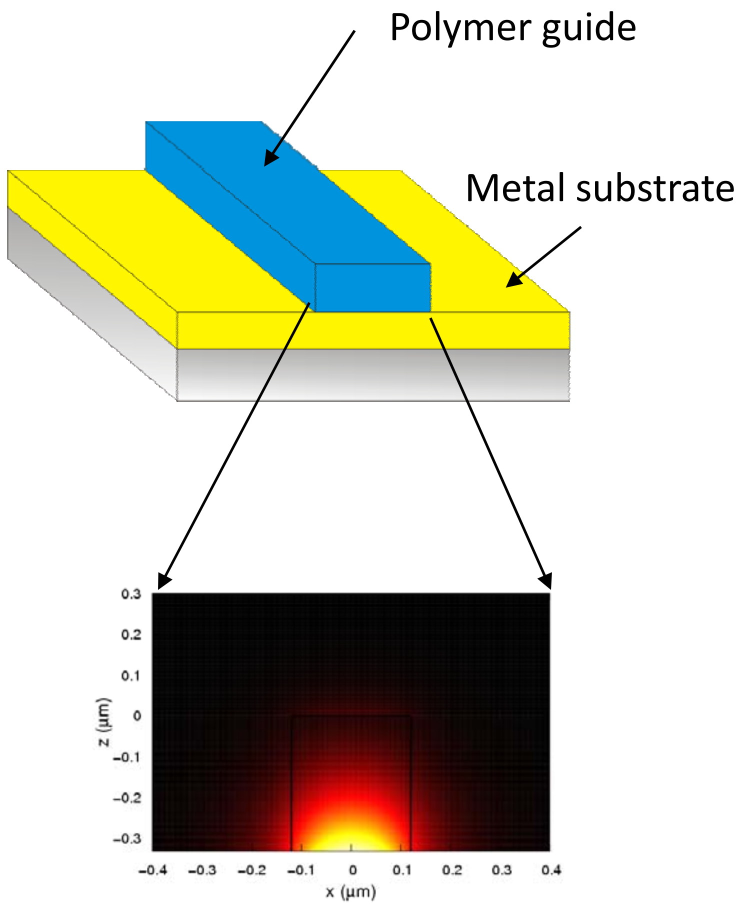
DLSPPW: dielectric-loaded surface plasmon waveguide

- High-density photonic circuitry
- Perspective for reduced losses

- Can be doped!

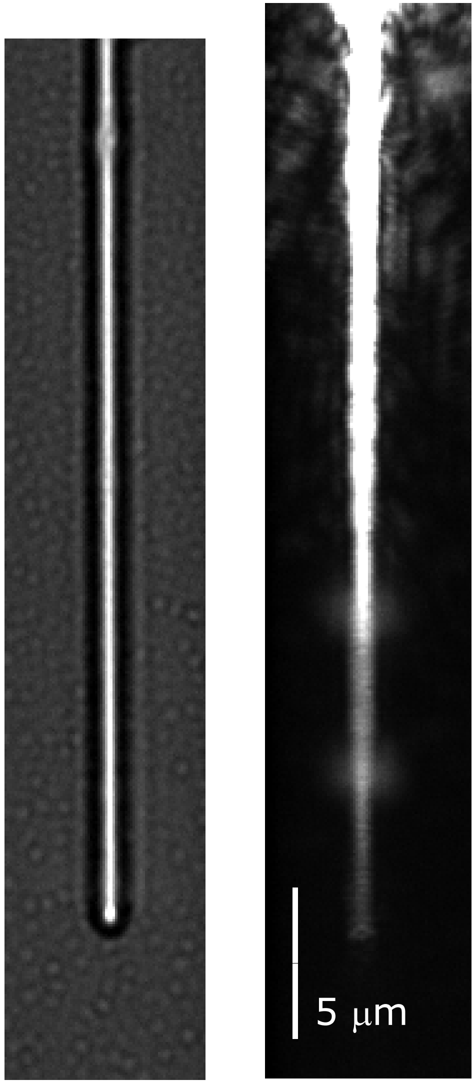
  - Electro-optical
  - Photo-switchable
  - Non-linear

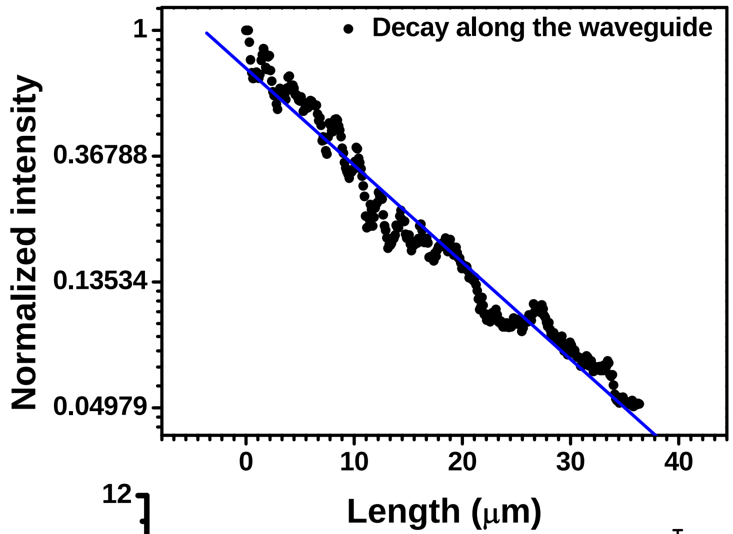


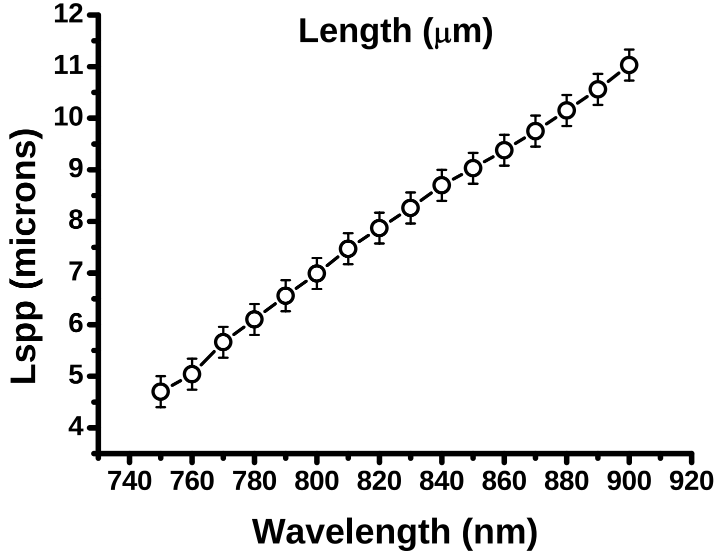


Propagation

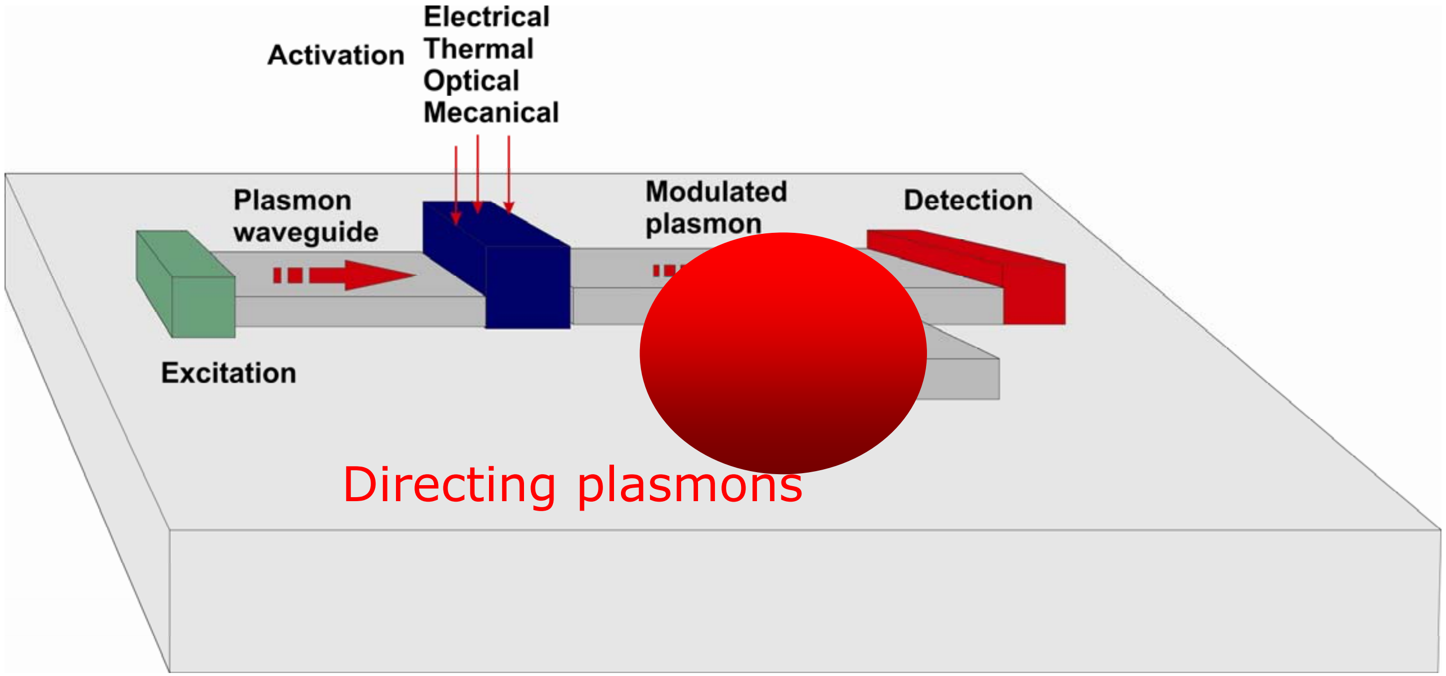
- Surface plasmon decay length





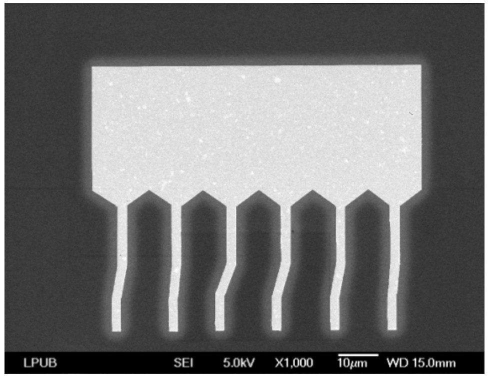


Plasmonic circuitry

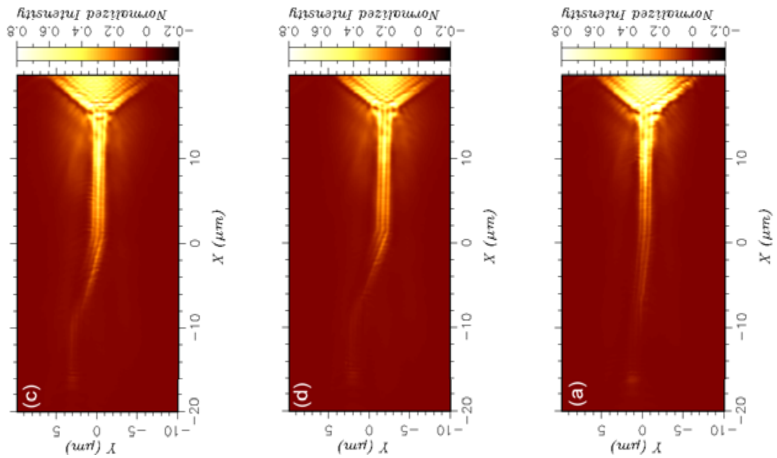


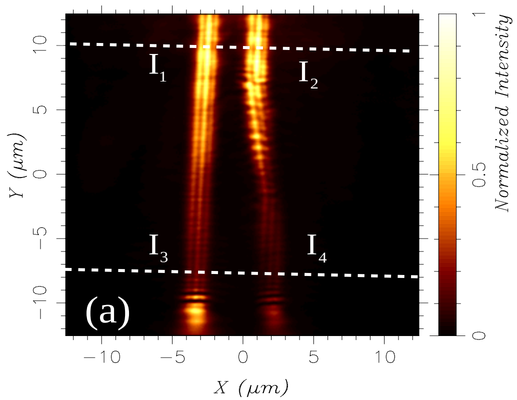
Routing with metal stripes

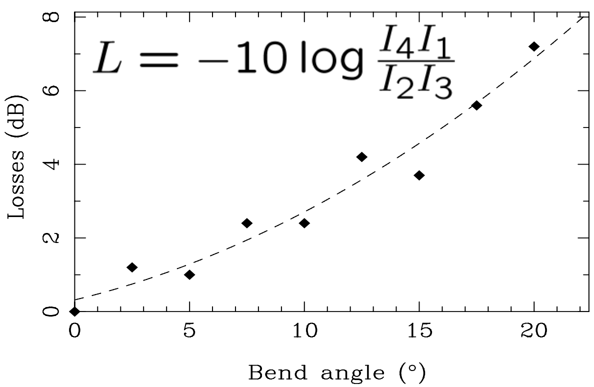
- Routing by bends



15° 10° 5°





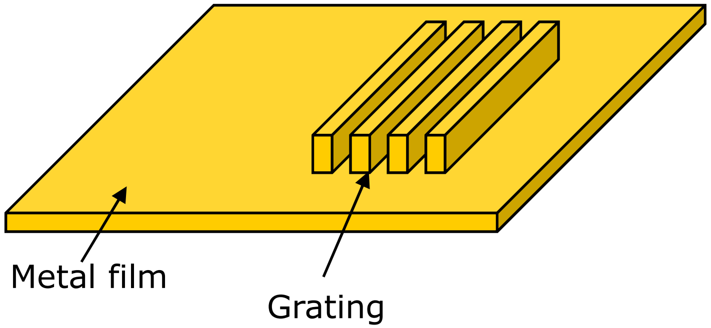


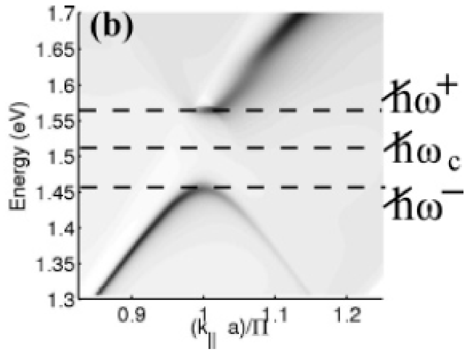
- Large bend losses (7db~20%)

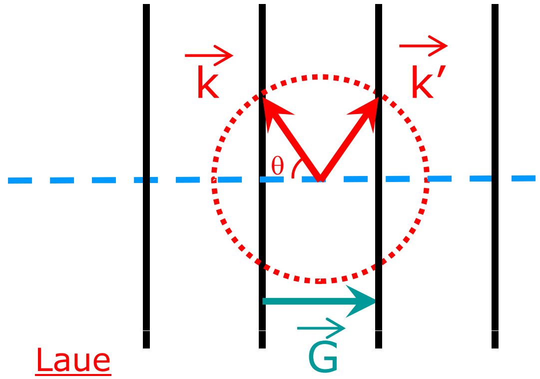
➡ Need better routing mechanism

Integrated surface plasmon Bragg mirrors

- Bragg mirrors

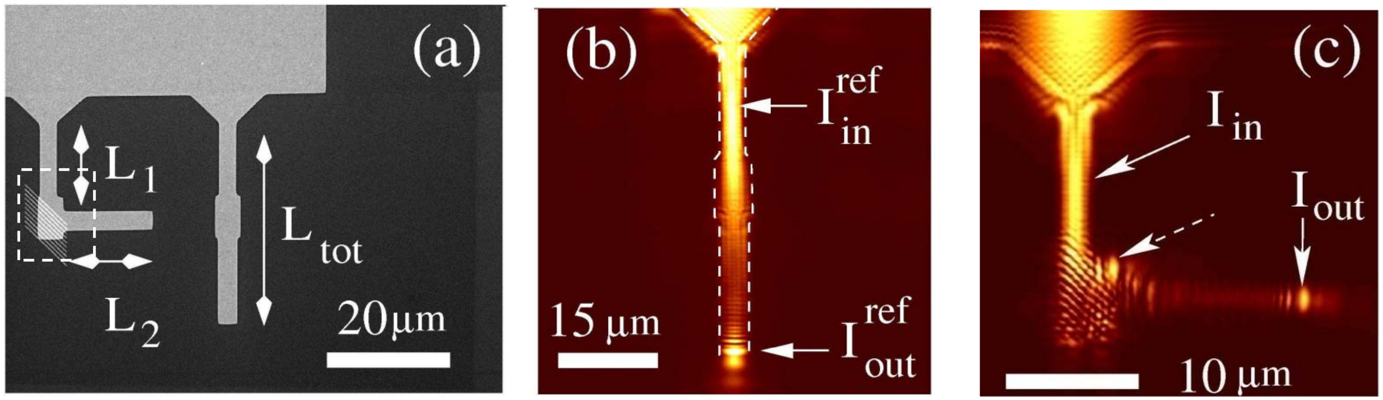


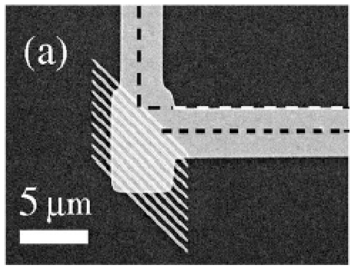




Laue condition

$$\vec{k} - \vec{k}' = \vec{G} = n\frac{2\pi}{d}$$



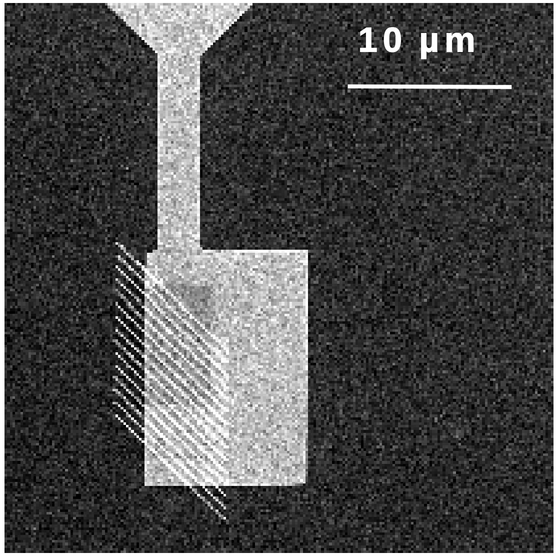


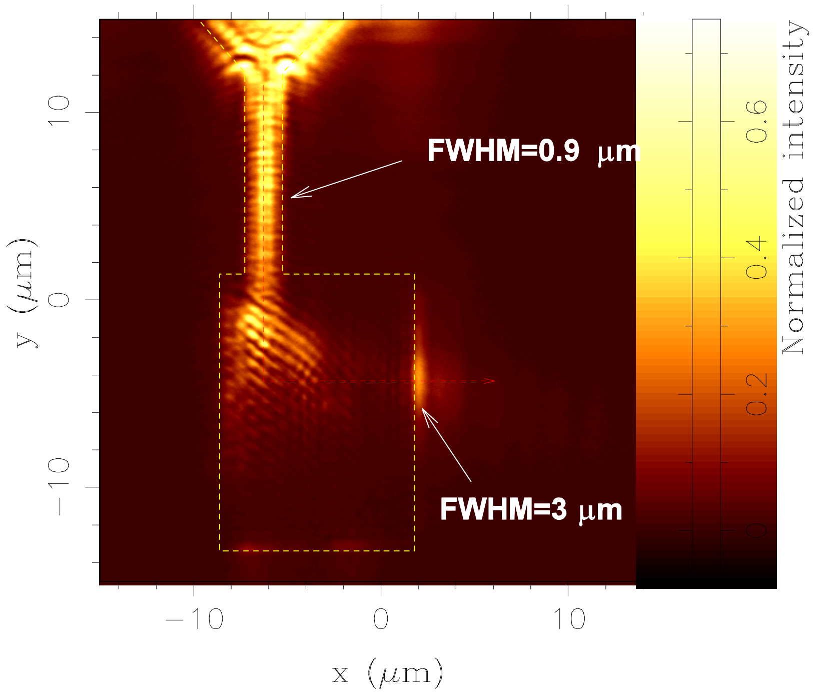
Reflectivity=65%

Bend loss<2dB for 90° bends

Appl. Phys. Lett. 87, 221101 (2005)

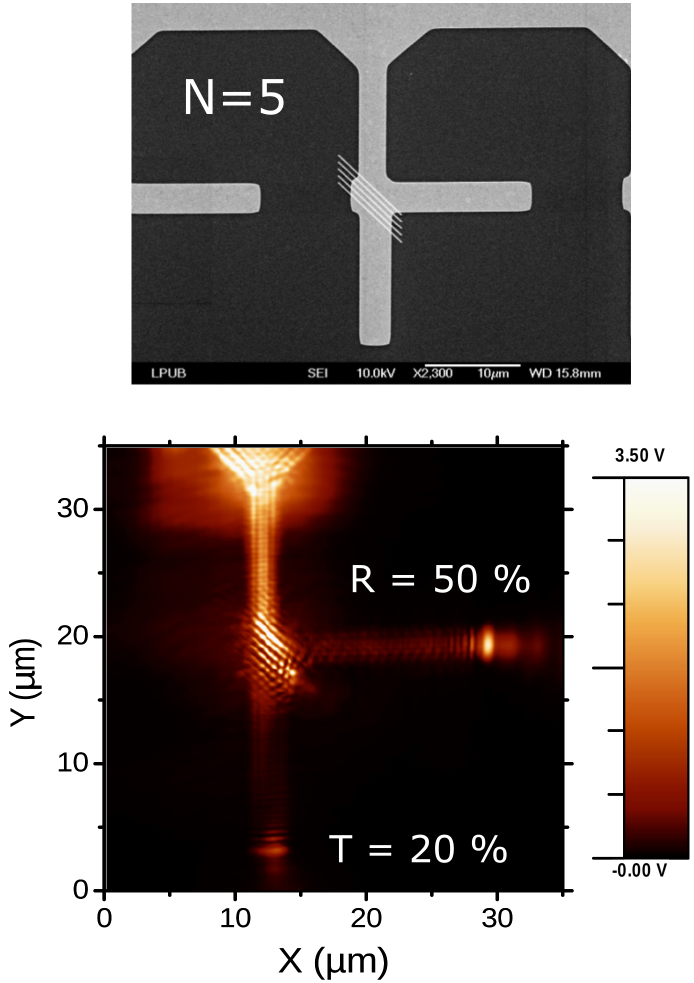
SP Goos-Hänschen effect

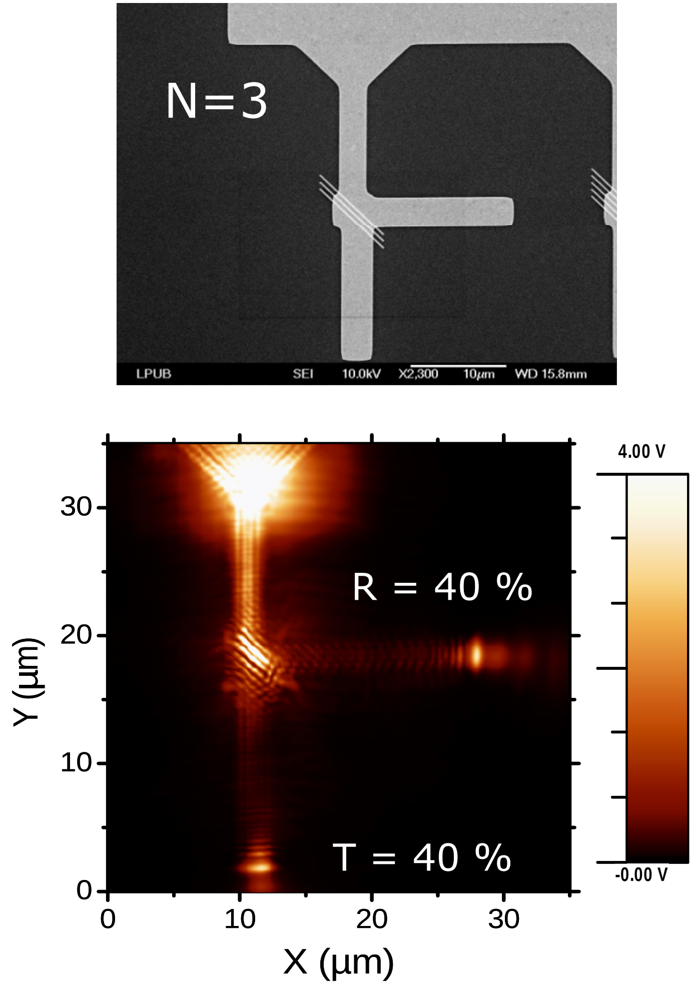




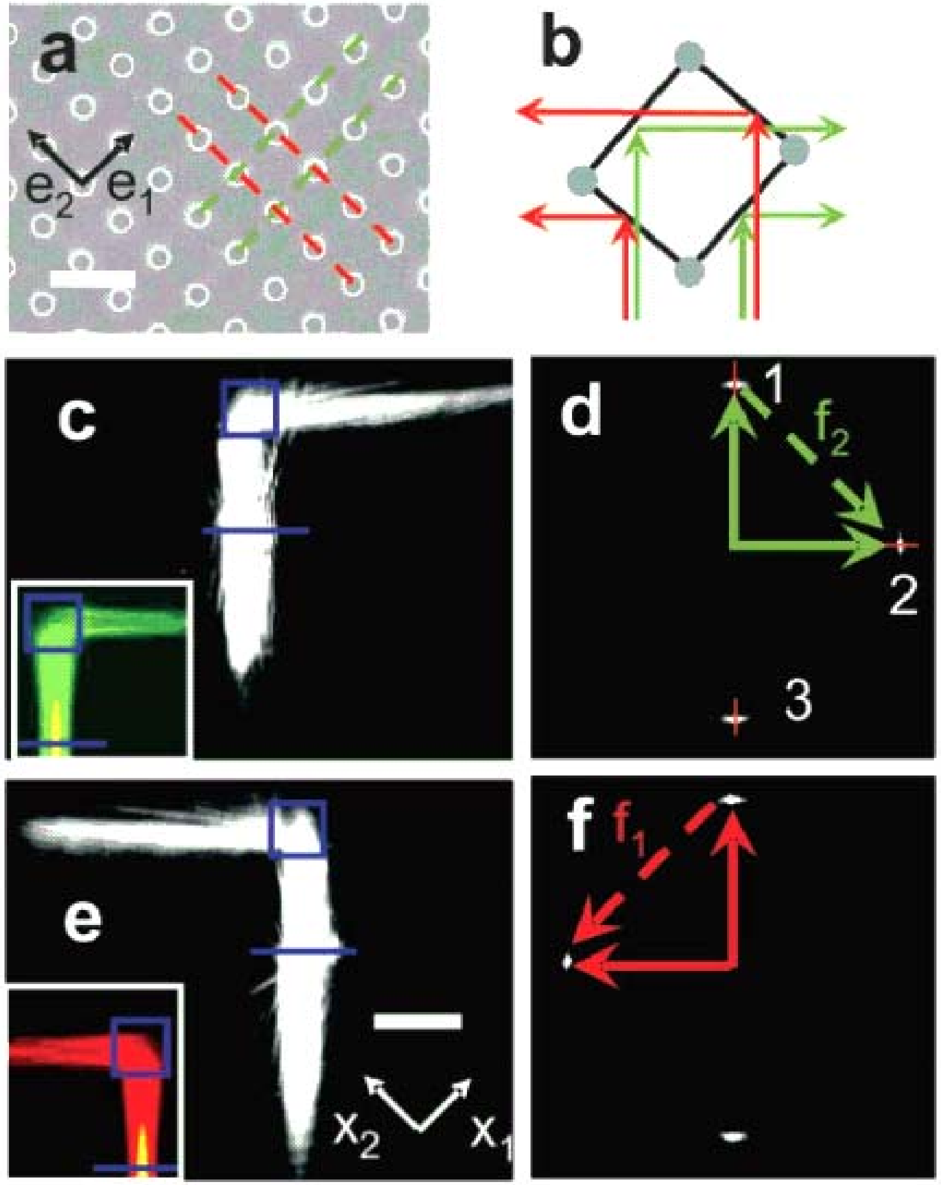
Integrated SP splitters

- Bragg splitters (reflectivity depends of the number of Bragg lines)





Integrated SP multiplexers



A. Drezet et al., *Nano Lett.*, 7, 1697(2007)

Routing with DLSPPW: couplers

PHYSICAL REVIEW B **78**, 045425 (2008)

Three-dimensional numerical modeling of photonic integration with dielectric-loaded SPP waveguides

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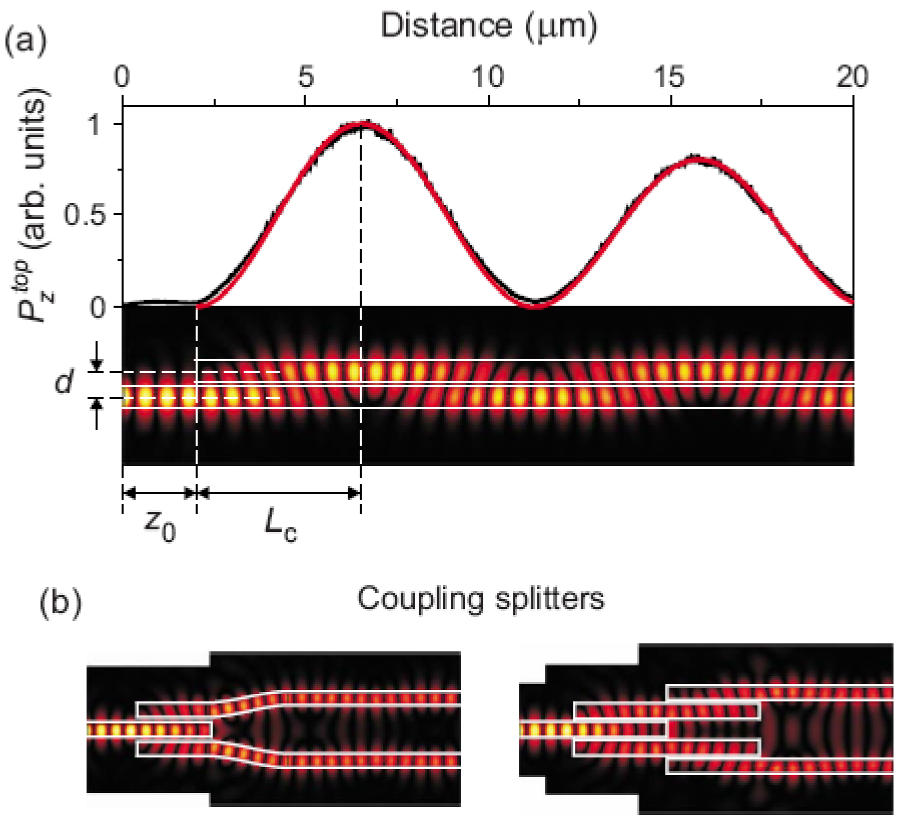
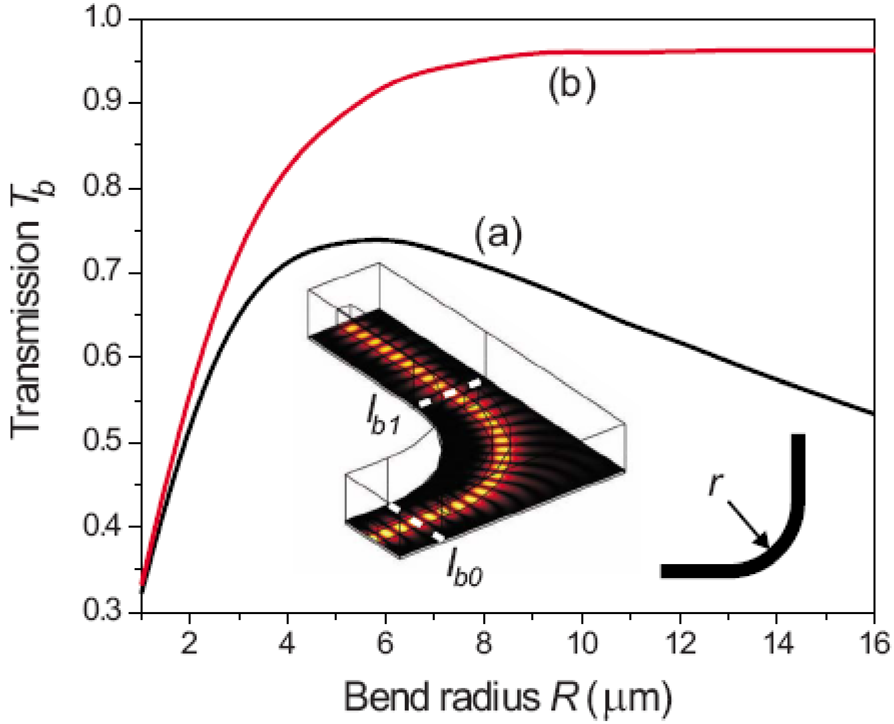
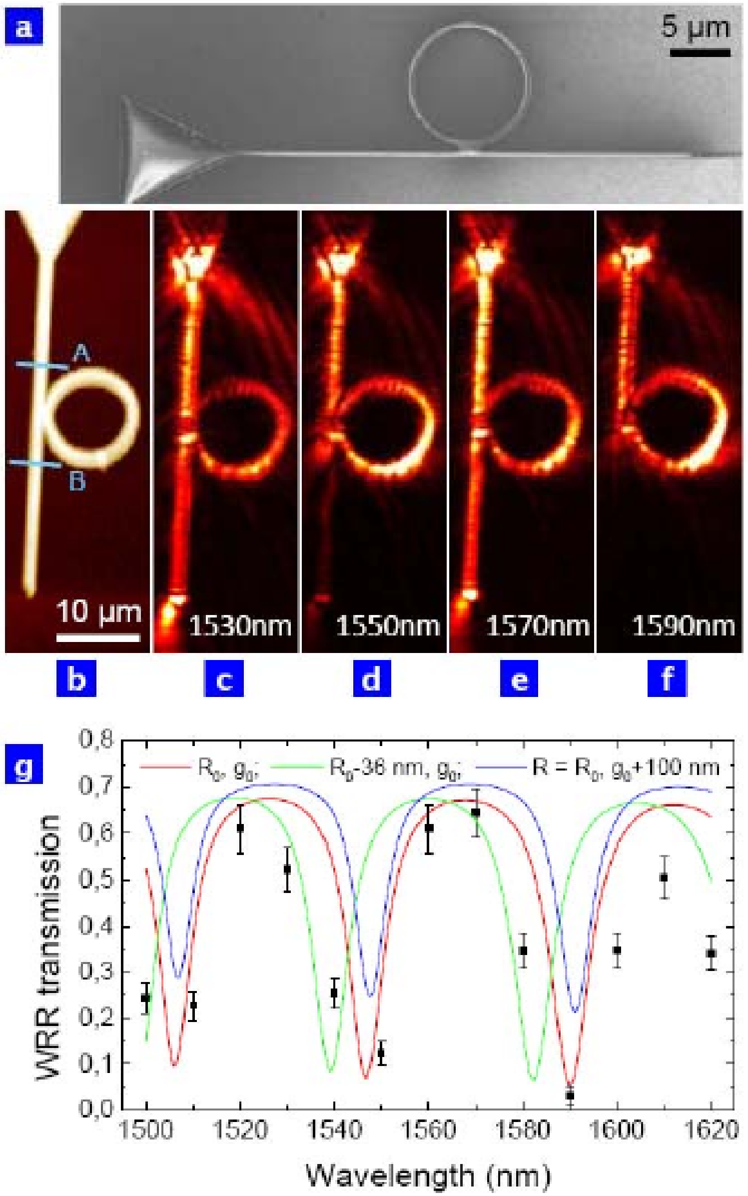
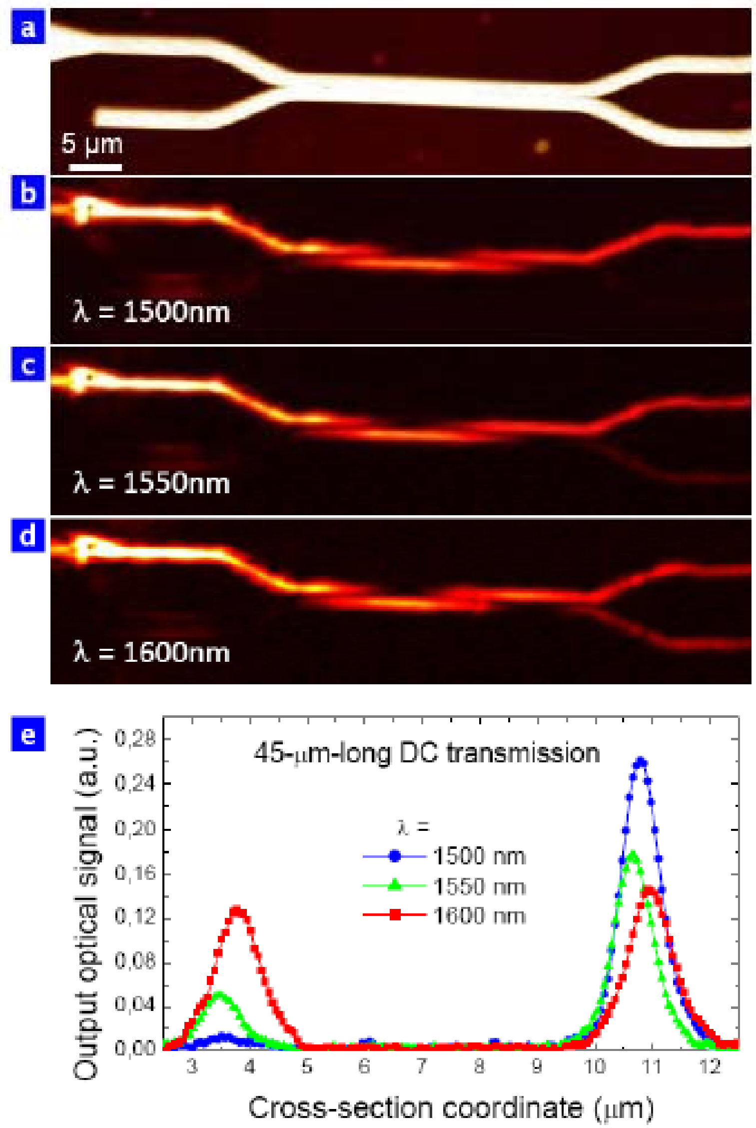
Centre for Nanostructured Media, IRCEP, The Queen's University of Belfast, Belfast BT7 1NN, United Kingdom
(Received 4 April 2008; revised manuscript received 30 April 2008; published 22 July 2008)



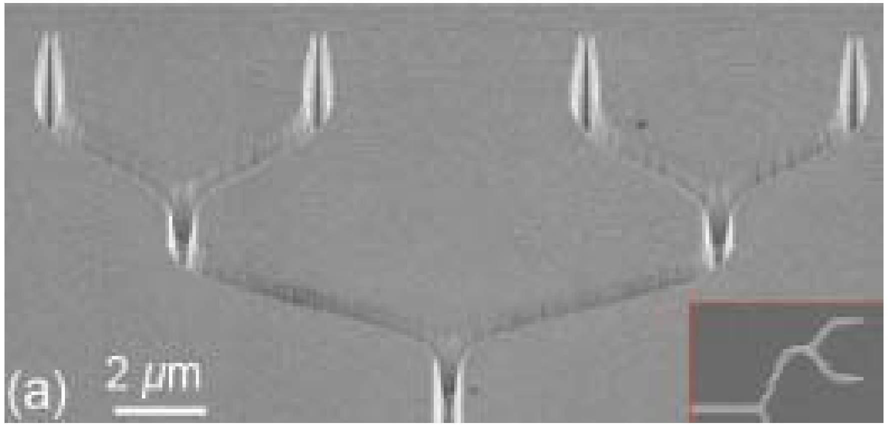


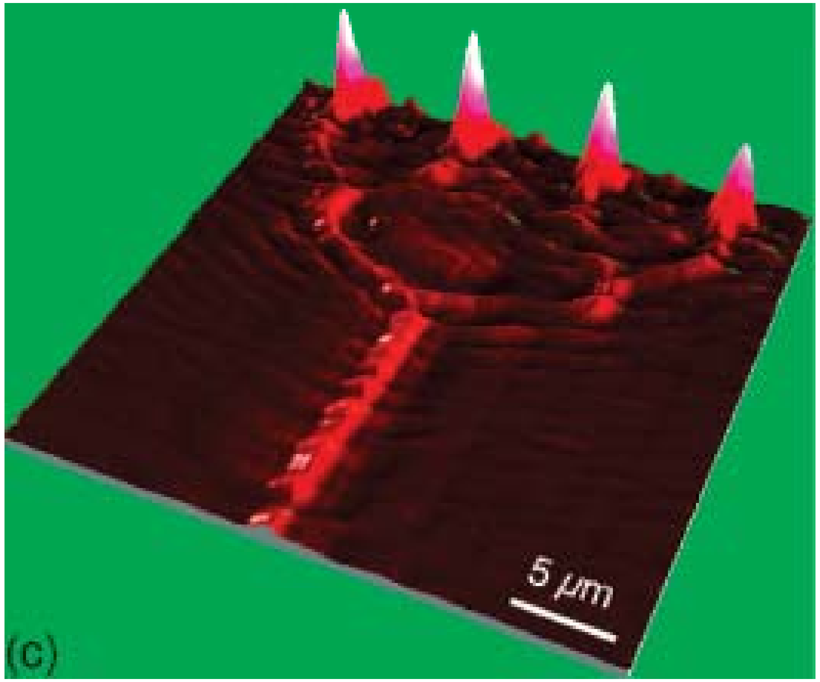
Routing with DLSPPW: filters, couplers





Routing with V-grooves

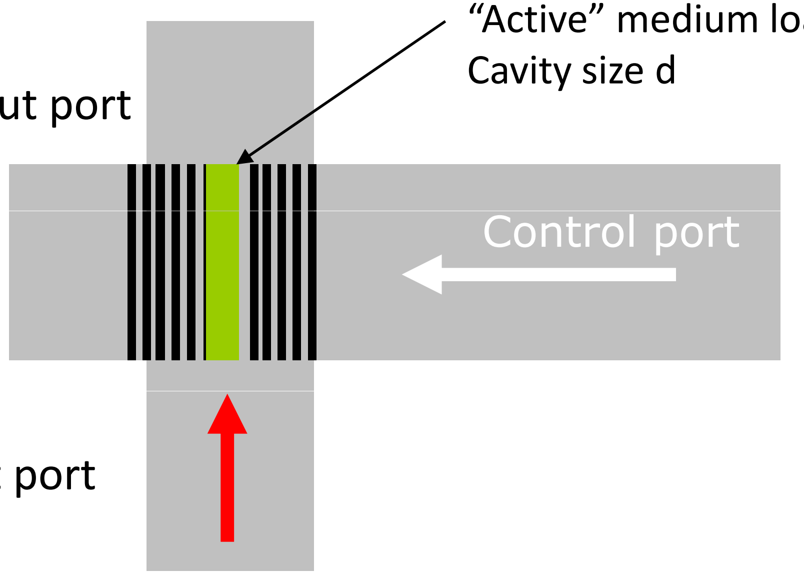


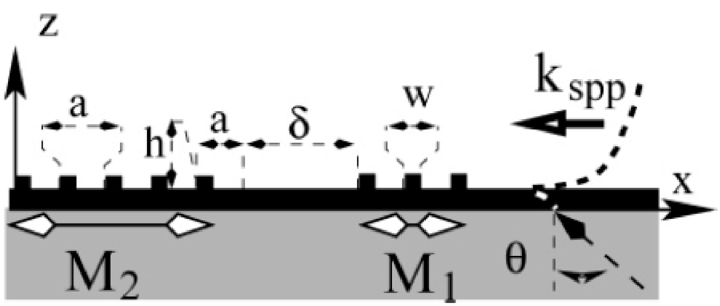


V. Volkov et al., *Nano Lett,* asap (2009)

Surface plasmon cavity

- Locally enhancing plasmon interactions

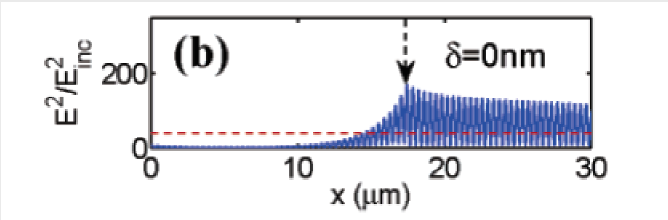


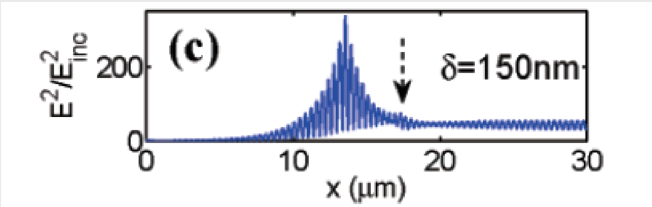


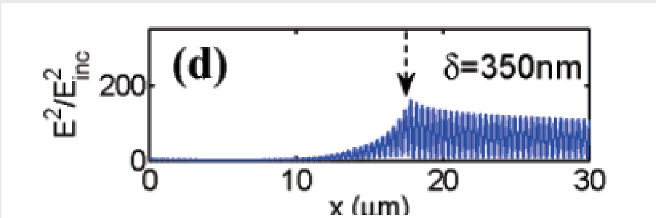
- Resonant conditions
- Field enhancement
- Quality factor

Resonance condition

Model (differential method)



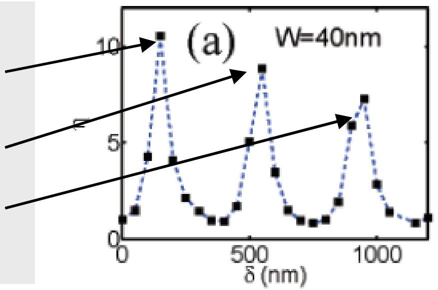




δ=150nm

δ=550nm

δ=950nm

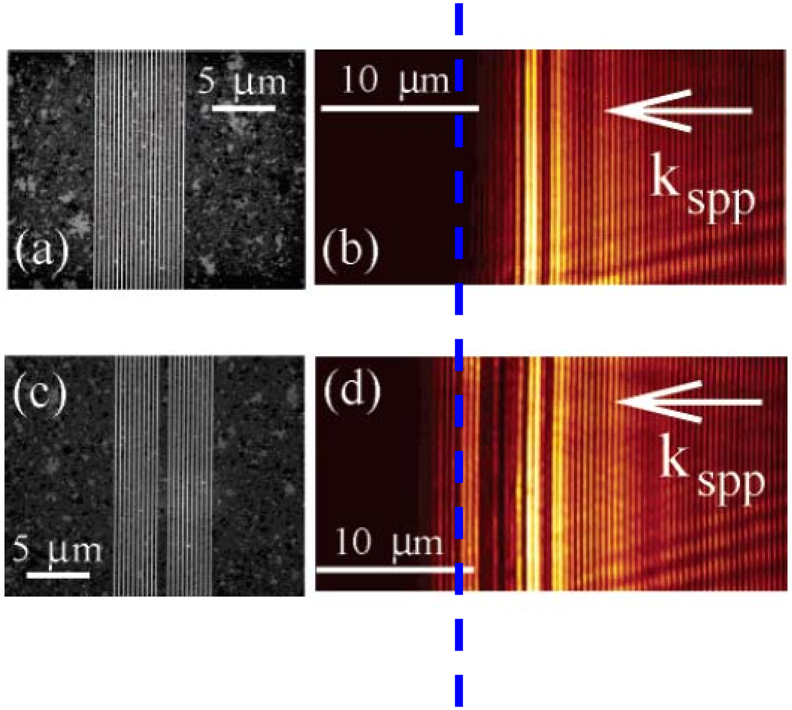


Experiments

Cavity

δ=0nm

δ=550nm



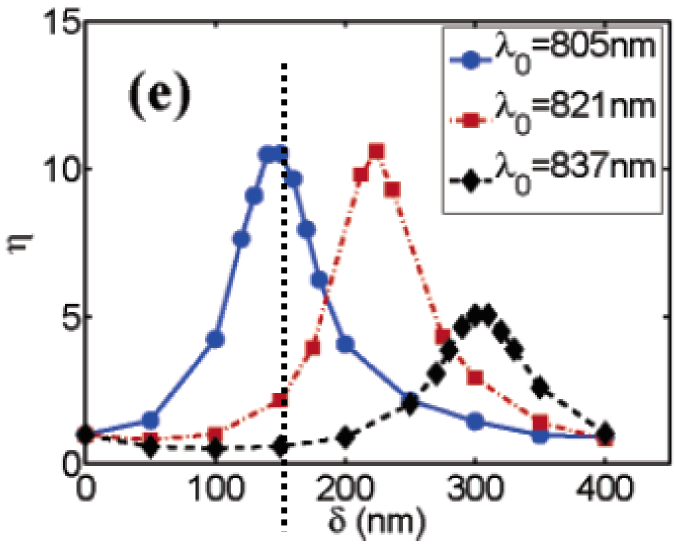
Resonance for $\delta = (2k+1)\frac{\lambda_{spp}}{4}$

Nano Lett. 7, 1352 (2007)

Field enhancement and quality factor

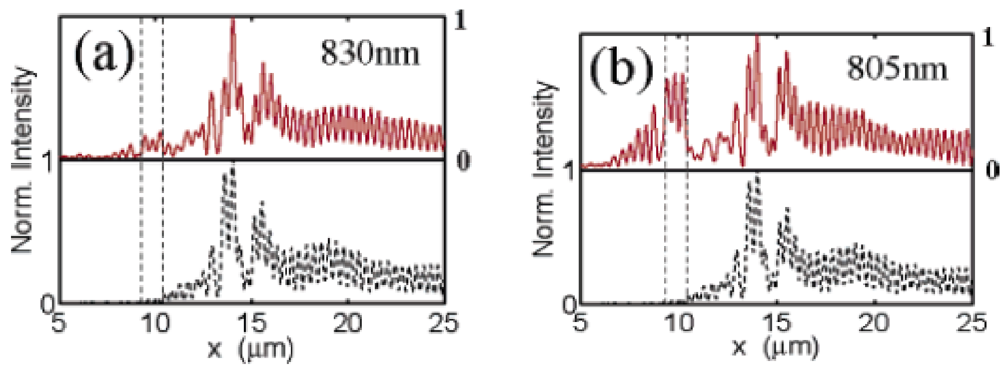
- Predictions

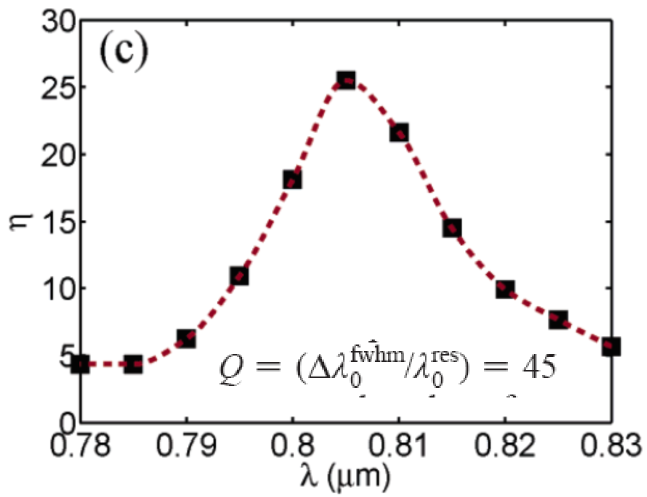
$$\eta = \frac{\int_{\Omega} E^2_{\mathrm{cavity}}(x)\,\mathrm{d}x}{\int_{\Omega} E^2_{\mathrm{mirror}}(x)\,\mathrm{d}x}$$



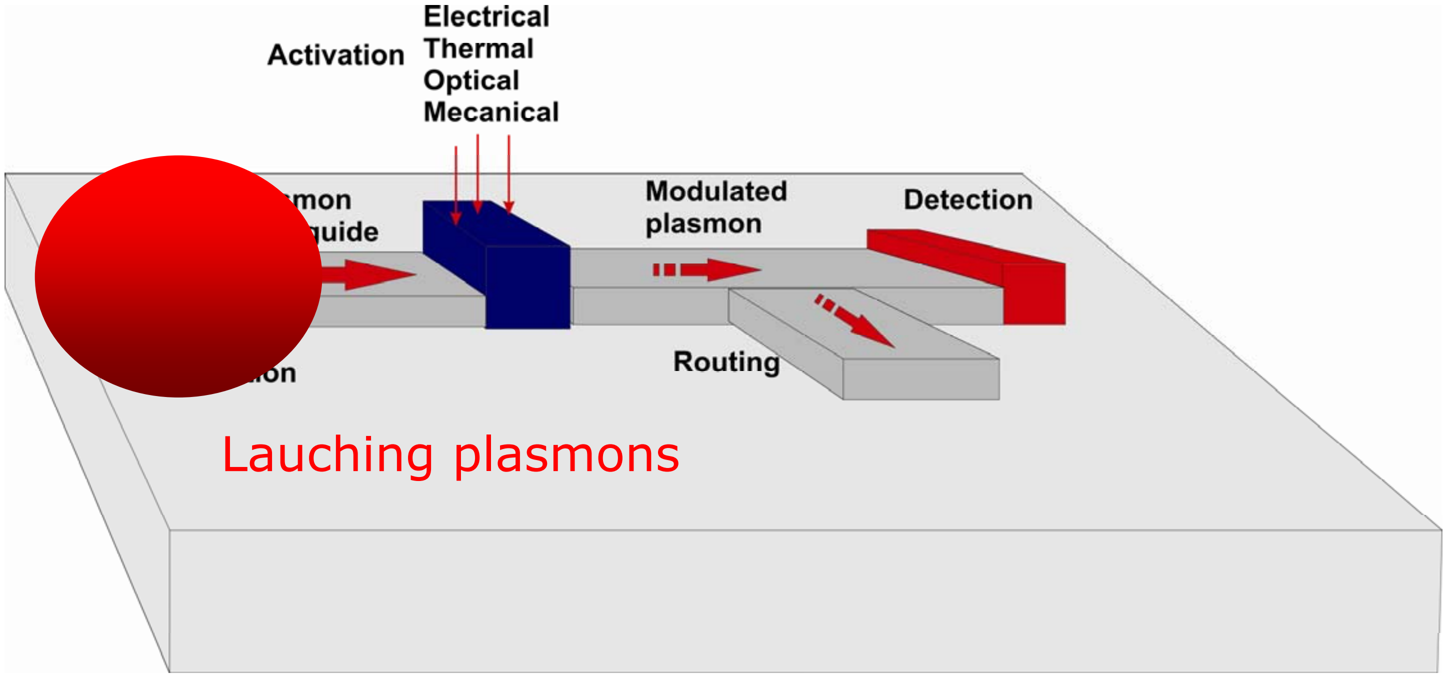
Phys. Rev. B 76, 113405 (2007)

- Experiments





Plasmonic circuitry



Surface plasmon launchers: hole arrays

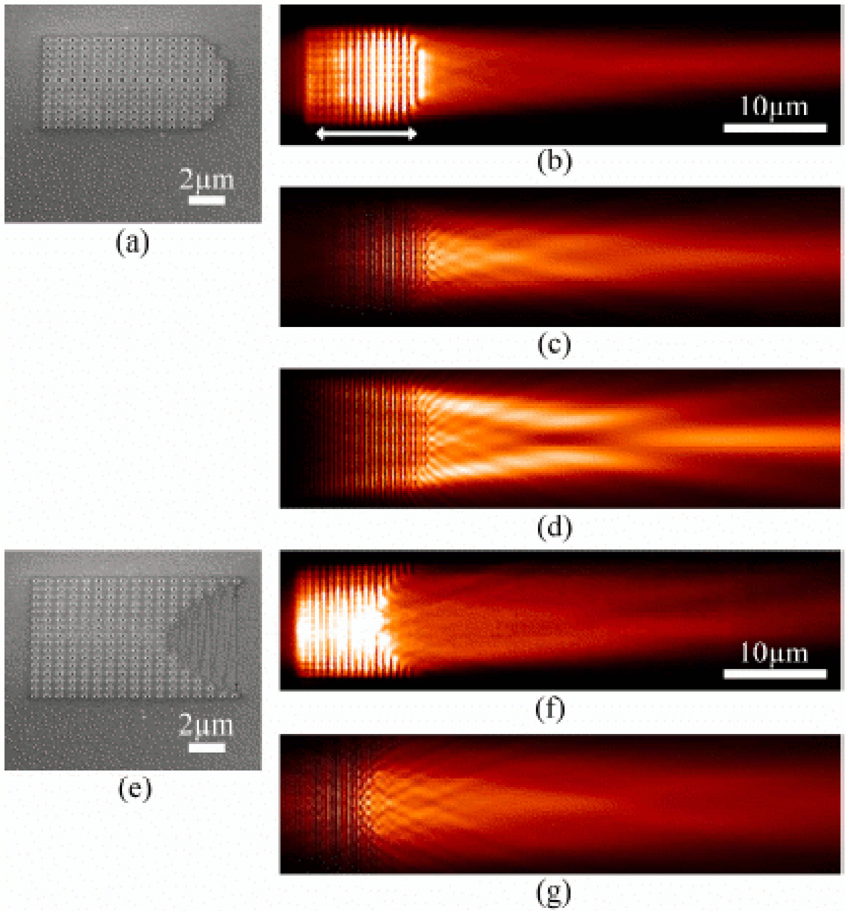
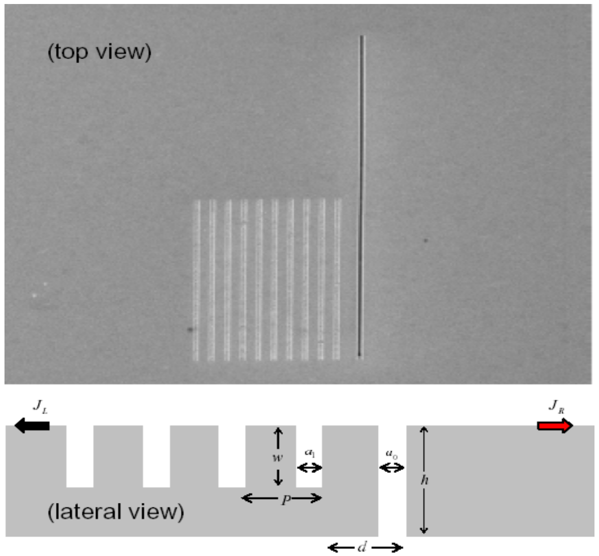


Fig. 4. (Color online) (a) SEM image (52° tilt) of a convex shaped source array with the corresponding NFO image (b) and simulations taking into account the finite size of the illumination spot (c) versus uniform illumination (d). (e) SEM image (52° tilt) of a concave shaped source array with the corresponding NFO image (f) and simulation (g). Simulations have the same scale as NFO images.

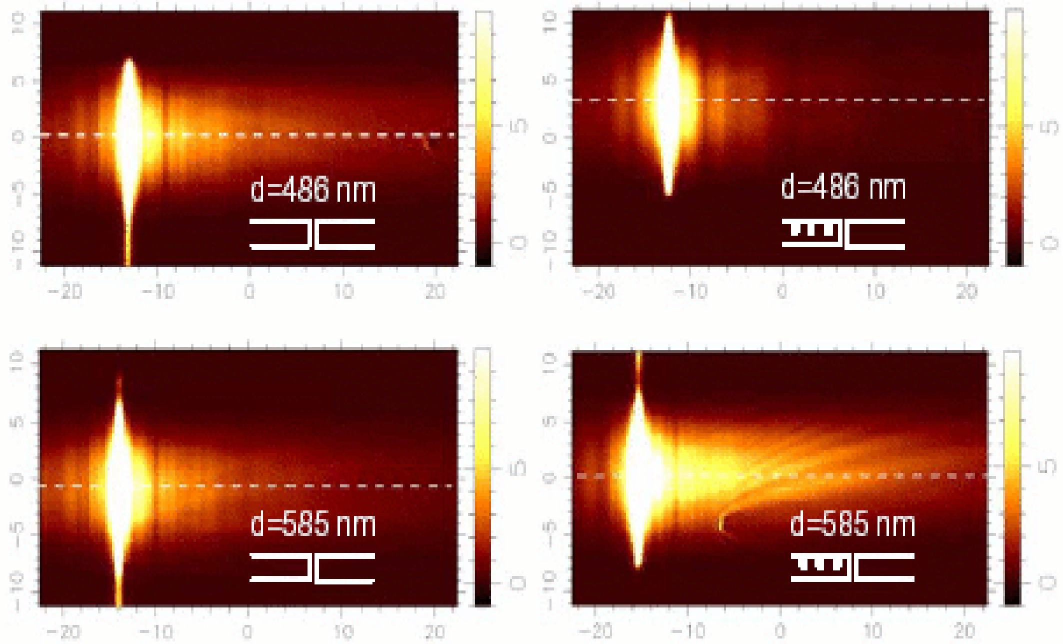
Surface plasmon launchers: slits/grooves

Nature Physics (2007)



Left column: isolated slit.

Right column: slit+grating.

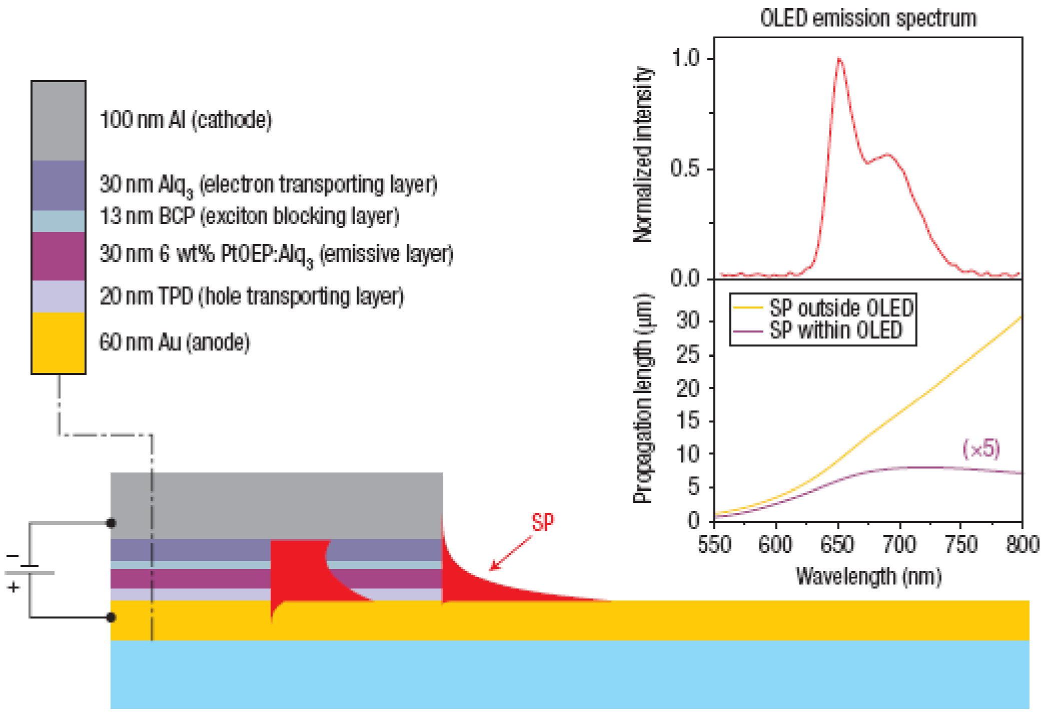


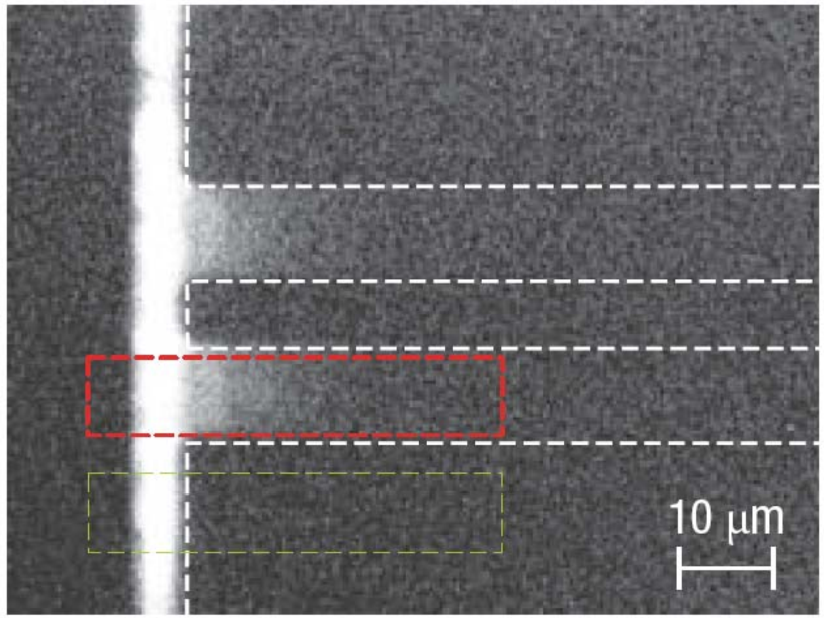
PSTM images recorded at lambda=800 nm for two different slit-grating distances.
Slit and groove widths a=160 nm
groove depth w=100 nm
array period P=390 nm

Electrical injection of SPP

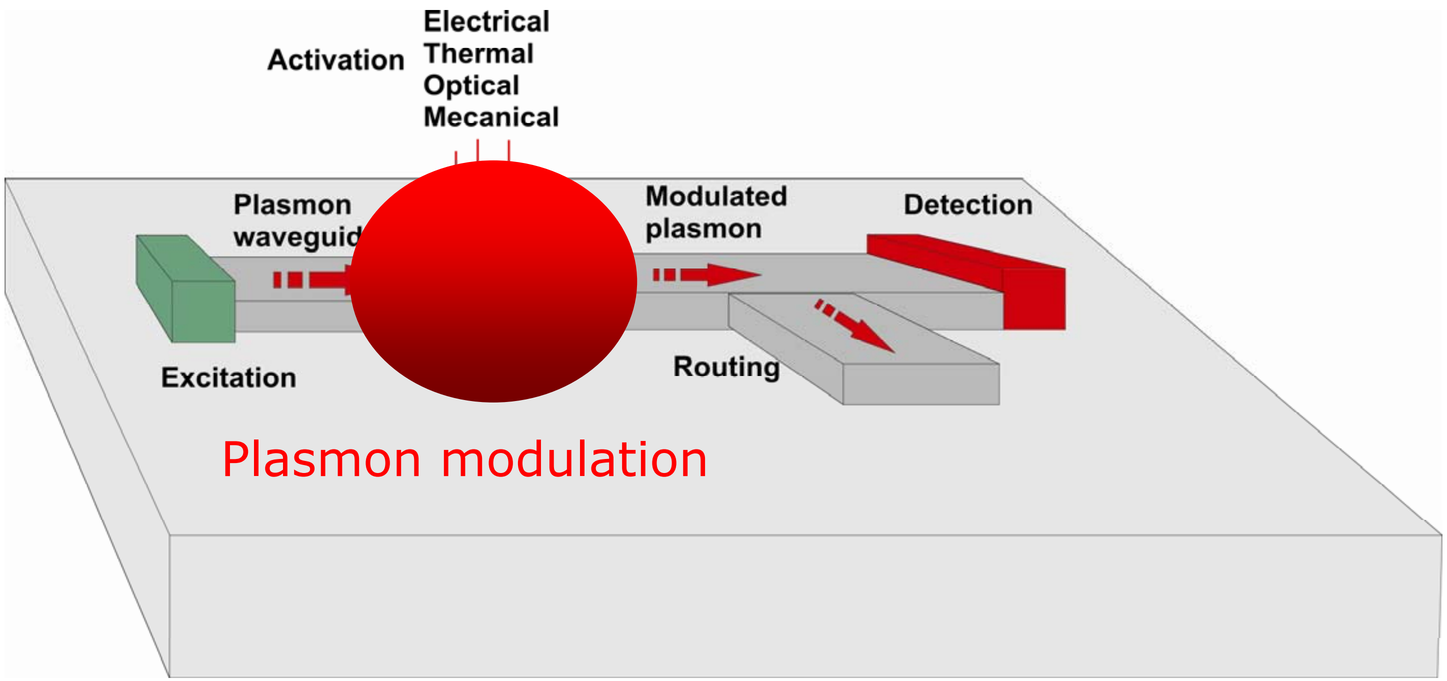
Organic plasmon-emitting diode

D.M. KOLLER[1,2], A. HOHENAU[1,2], H. DITLBACHER[1,2], N. GALLER[1,2], F. REIL[1,2], F.R. AUSSENEGG[1,2], A. LEITNER[1,2], E.J.W. LIST[2,3,4] AND J.R. KRENN[1,2*]
[1]Institute of Physics, Karl-Franzens-University, A-8010 Graz, Austria
[2]Erwin Schrödinger Institute for Nanoscale Research, Karl-Franzens-University, A-8010 Graz, Austria
[3]Christian Doppler Laboratory for Advanced Functional Materials, Institute of Solid State Physics, Graz University of Technology, A-8010 Graz, Austria
[4]NanoTecCenter Weiz Forschungsgesellschaft mbH, A-8160 Weiz, Austria
*e-mail: joachim.krenn@uni-graz.at

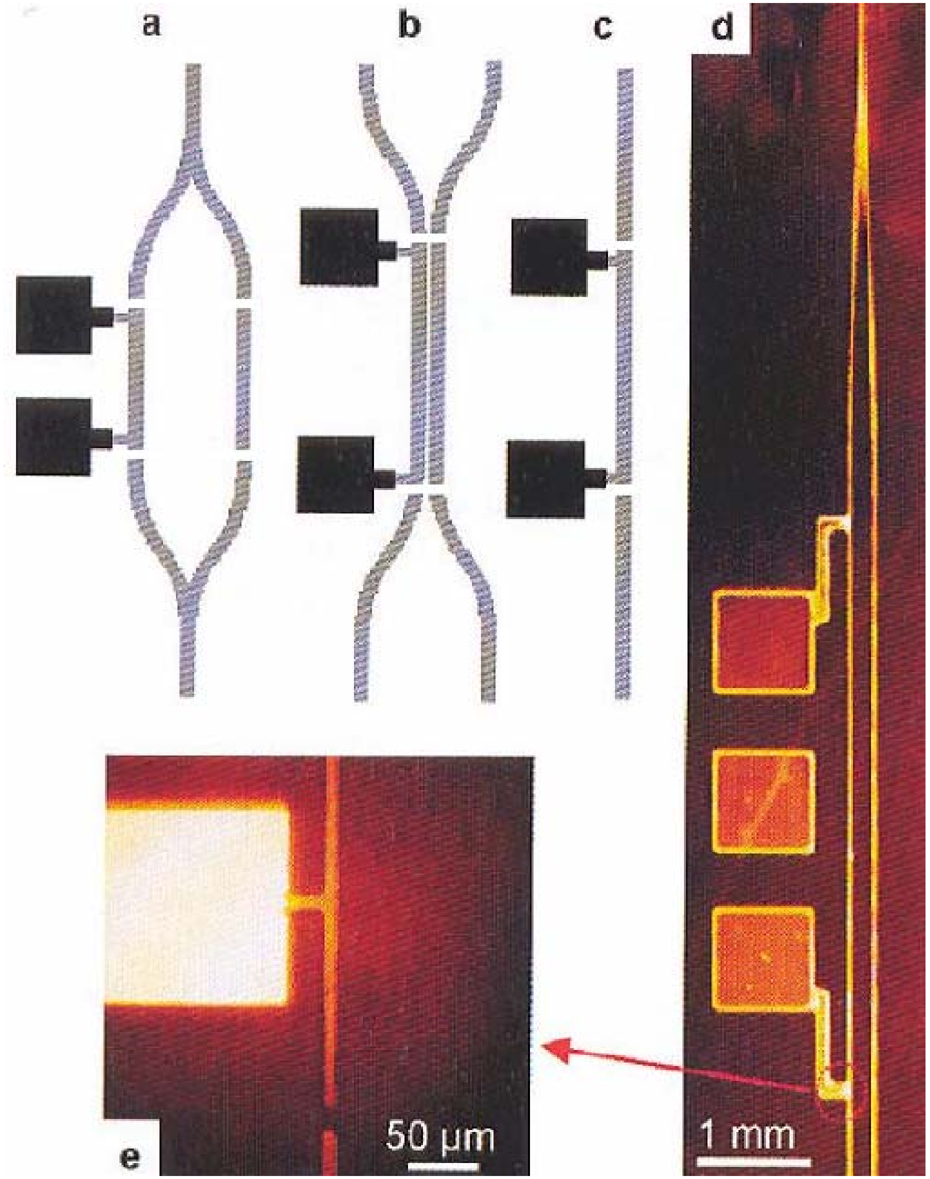


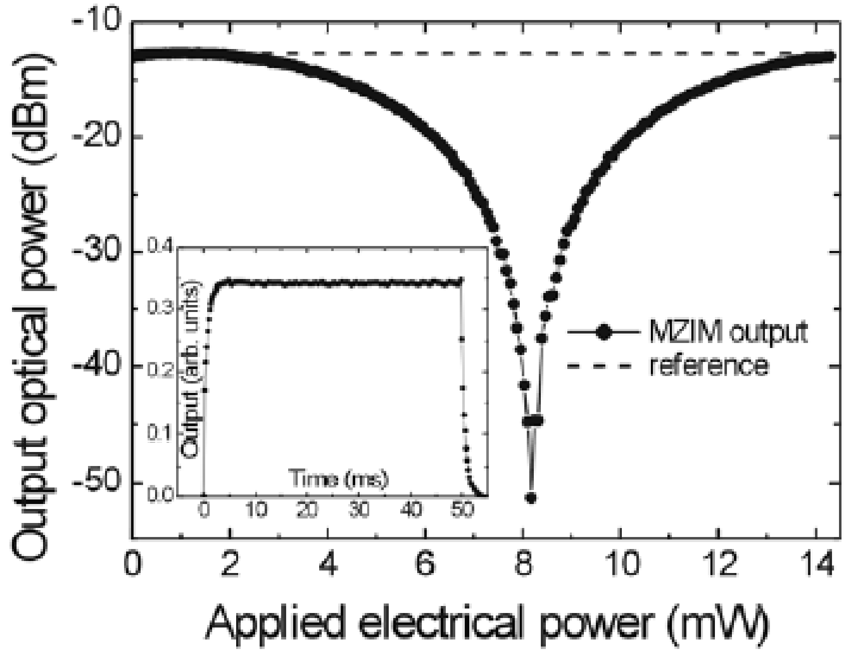


Plasmonic circuitry



Thermo-optical modulation

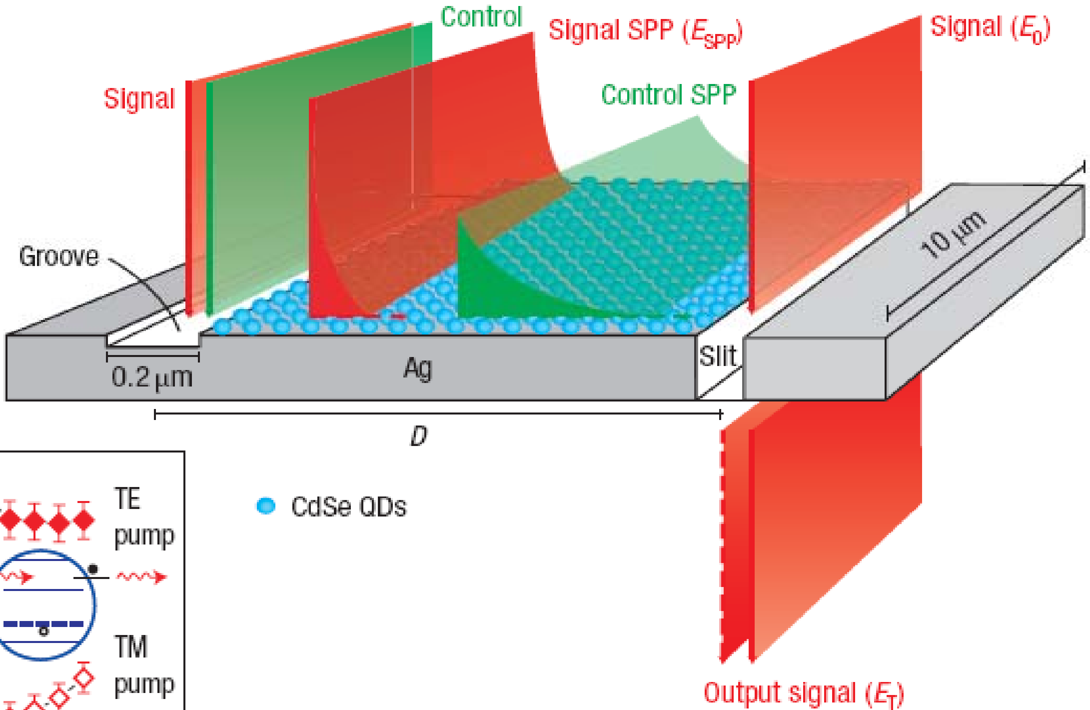


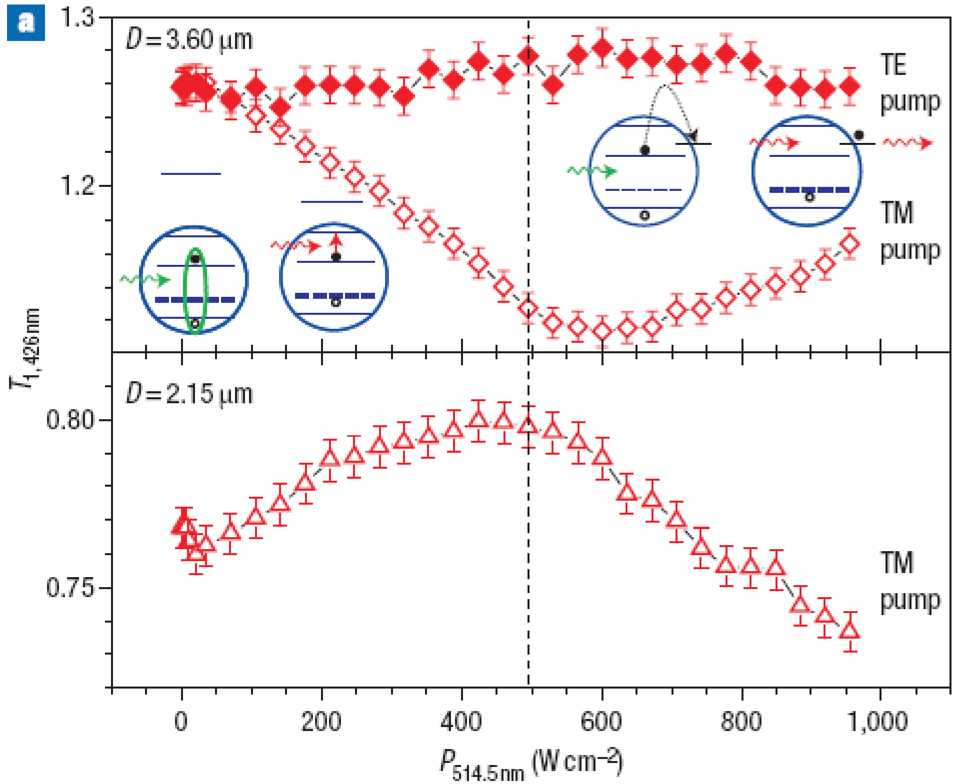


Th. Nikolasjen et al.,
Appl. Phys. Lett. 85, 5833(2007)

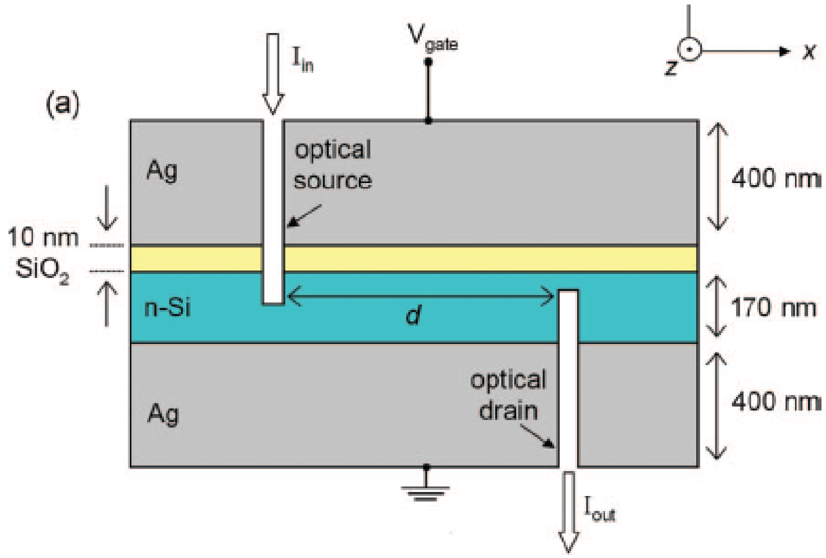
All-optical modulation

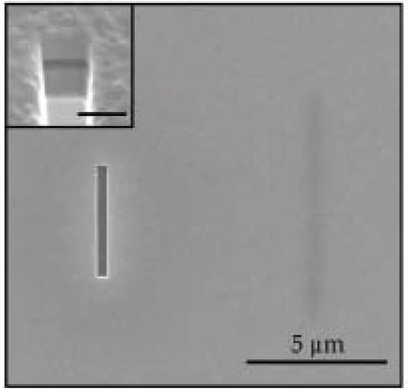
D. Pacifici et al.,
Nature Phot. 1, 402
(2007)



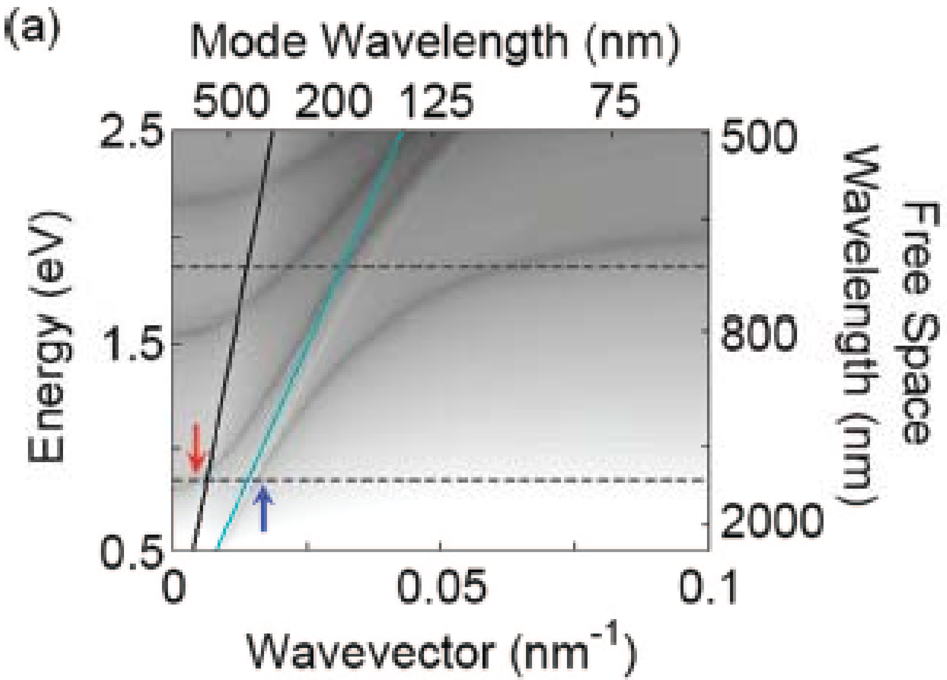


Field-effect modulation





A. Dionne et al., *Nano Lett*. asap (2009)

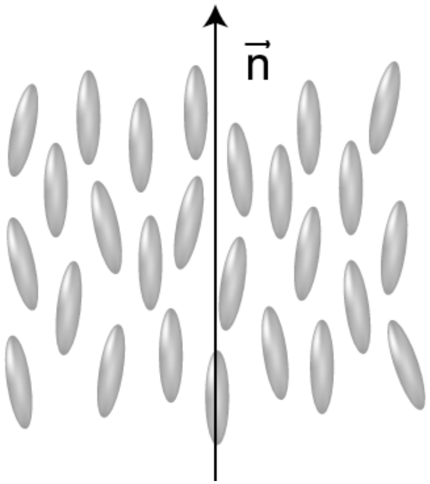


λ=1.55µm	|E| mode profile	Mode Index	Loss (dB/µm)
Off state (V=0) *depletion*	Ag, SiO_2, Si, Ag	3.641	0.207
		0.375	2.37
On state (V>0.7V) *accumulation*	Ag, SiO_2, Si, Ag	3.649	0.228
		0.033	28.14

Liquid crystal modulation

- Liquid crystal = Mesophase (intermediary between liquid and crystalline states)

⇨ Present orientational or / and positional order



Nematic

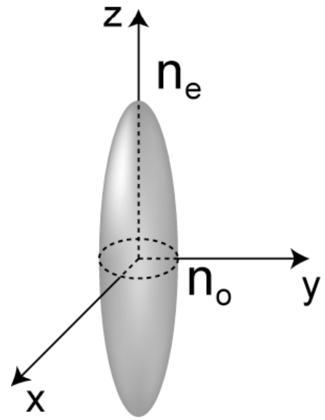
⇨ Anisotropic behaviour

⇨ Modification of their optical properties with the application of an electric field

- Nematic LC ~ Uniaxial medium

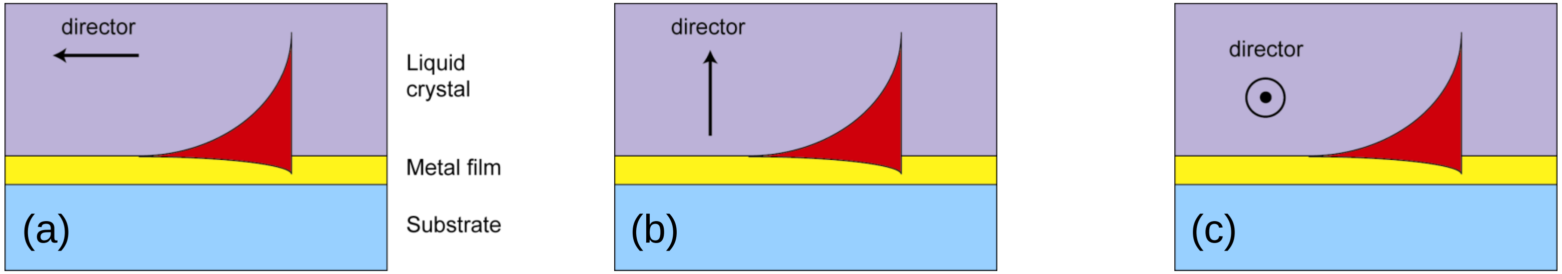
⇨ $$\Delta n = |n_e - n_o| > 0.1$$

(0.2 for E7)



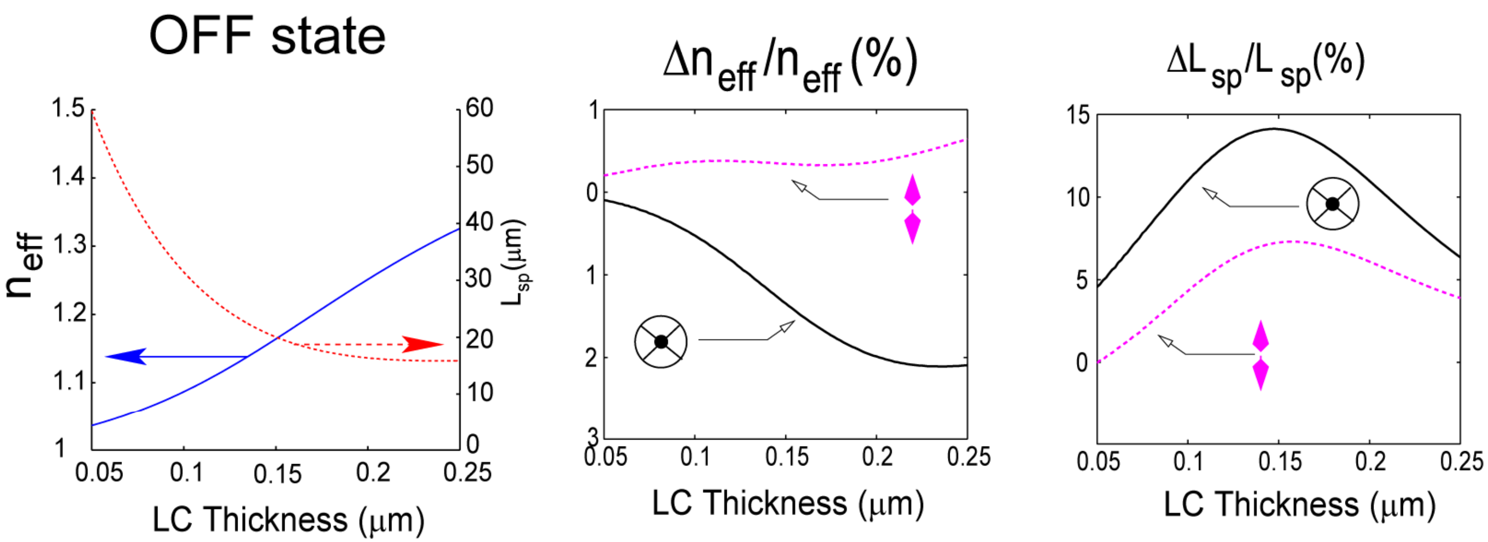
Propagation distance

- Possible interactions between a plasmon and a birefringent medium:

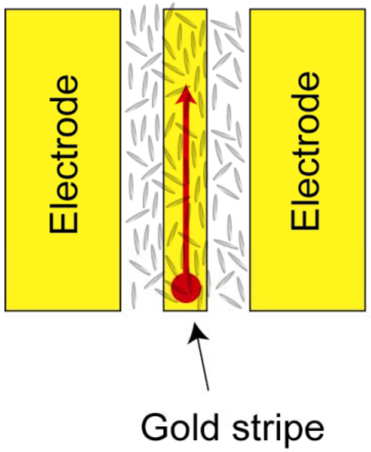


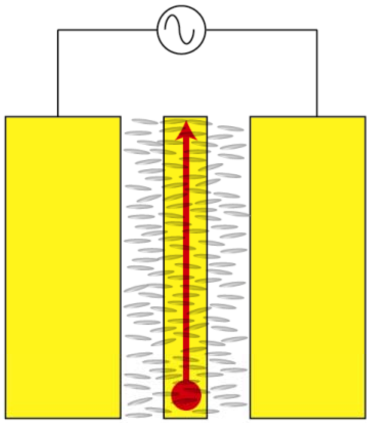
Modification of the SPP propagation constant (real and imaginary parts) when an electric field is applied on the LC.

- Relative variations for n_{eff} and L_{sp} for In plane and Out of plane configurations:

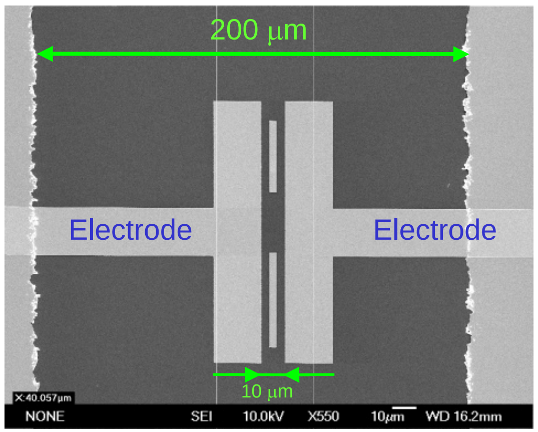


In-plane switching: proof-of-principle

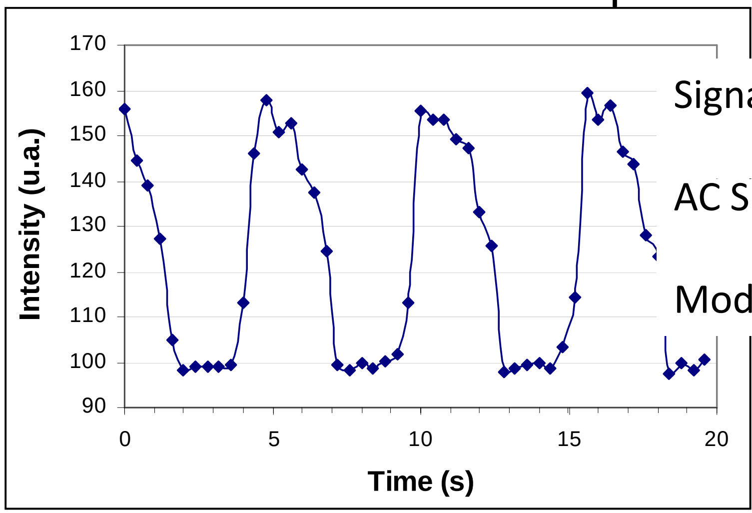




- Modulation of the coupling conditions (real part of n_{eff})
- Modification of the propagation length



Square wave modulation :



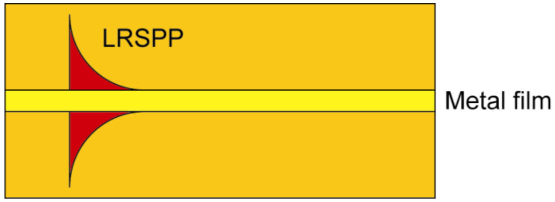
Signal Amplitude: 10 V

AC Signal frequency 1 kHz

Modulation Frequency: 0.2 Hz

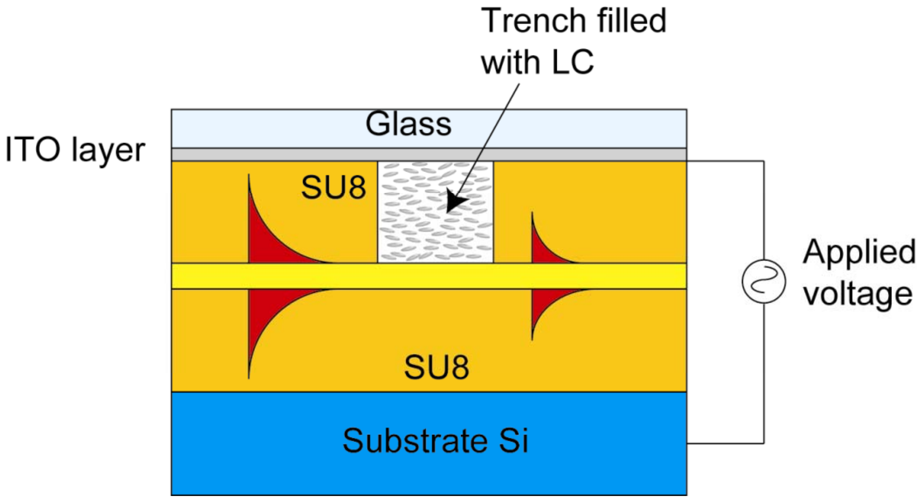
Possible device based on LR-SPP

- Long-range surface plasmon polariton propagation:



- Thin metal film (~15 nm)
- Symmetric configuration
- Propagation length expected : ~ cm

- Principle of the device:

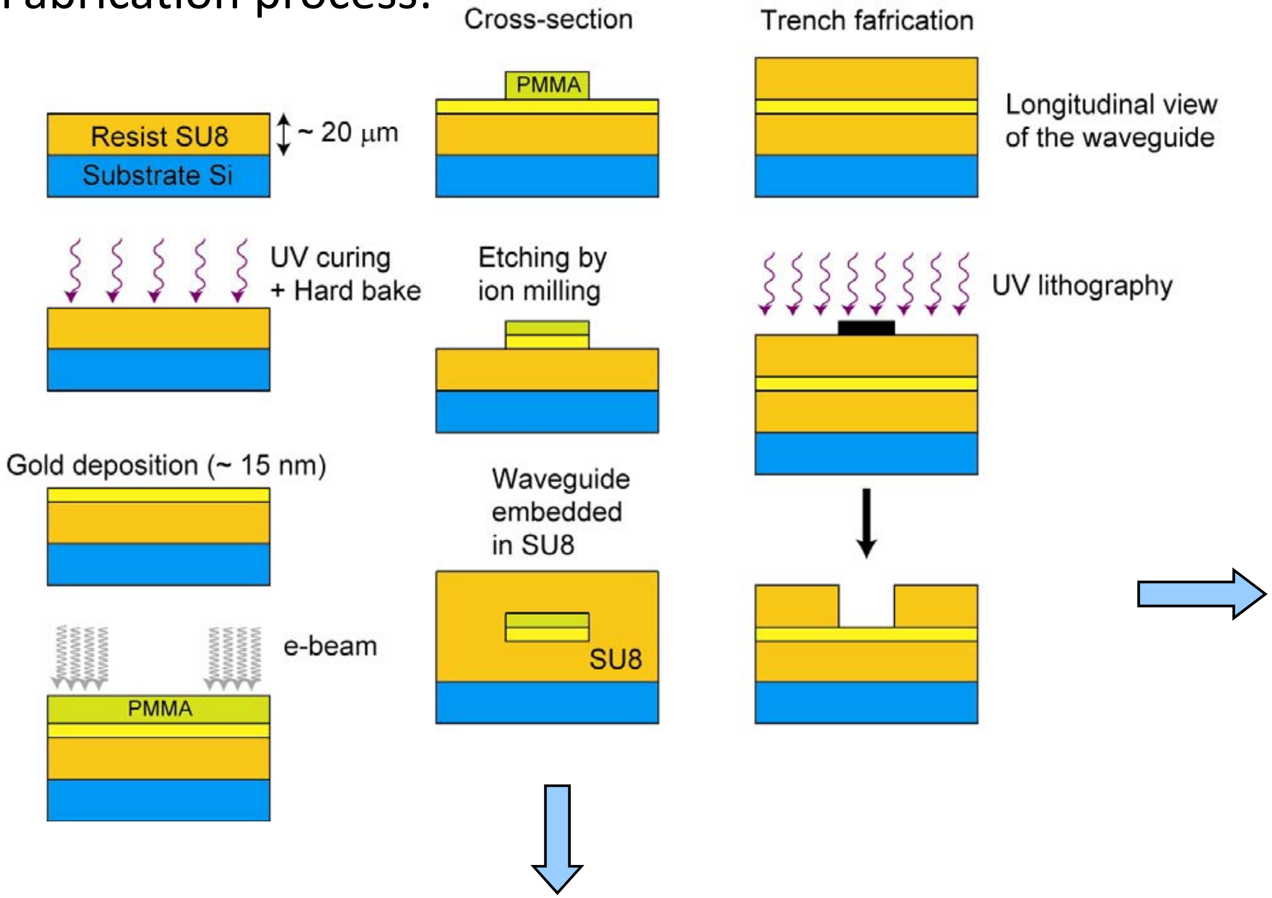


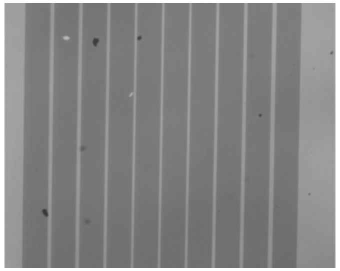
Insertion of a trench filled with LC in order to:

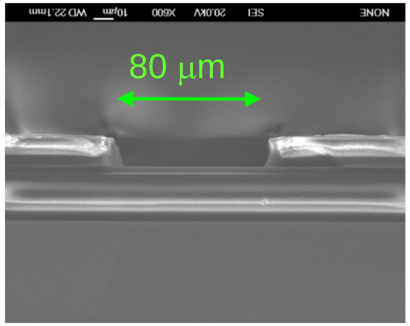
- break the index matching between the two layers surrounding the metal film
- bring a polarization rotation of the signal

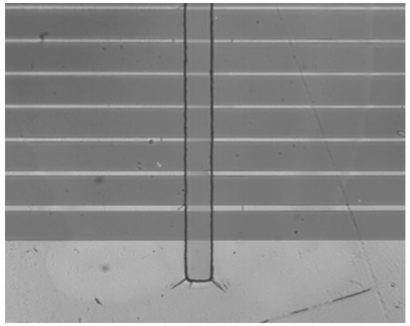
Device fabrication

- Fabrication process:





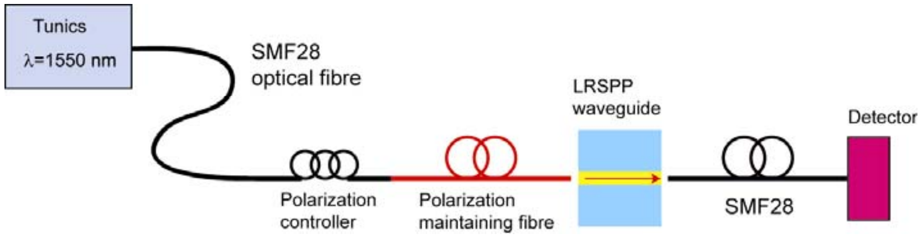


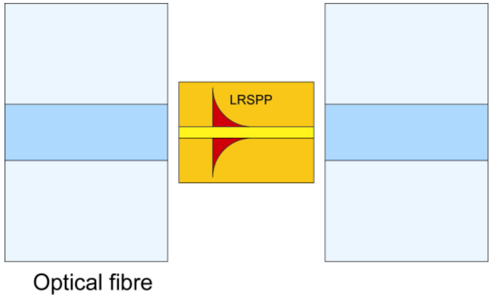


Width : 10 µm
Length : 6 mm

In-out coupling

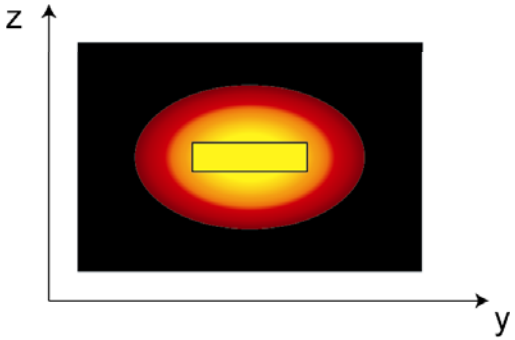
- LRSPP excitation by butt-coupling technique:

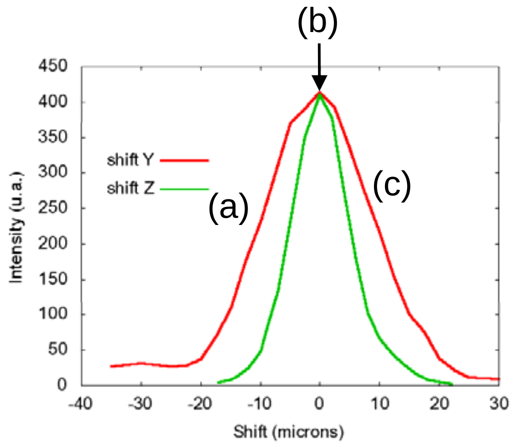




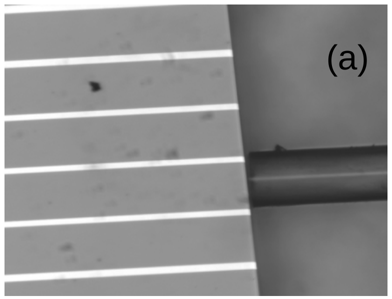
- LRSPP mode characterization:

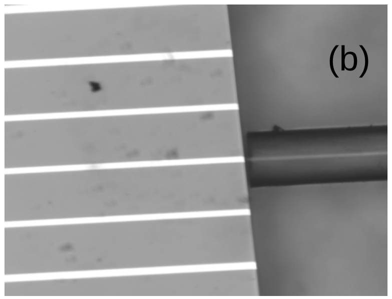
Mode profile illustration

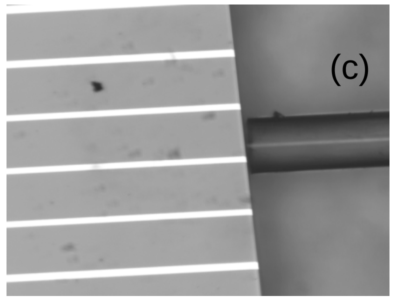




Intensity at the end of the waveguide

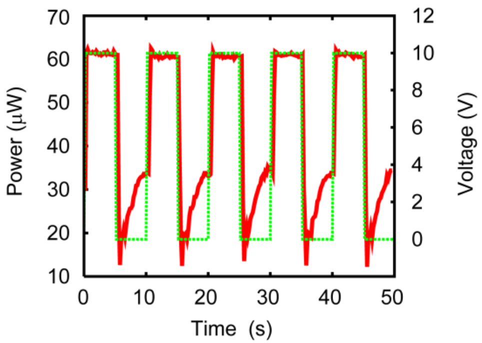




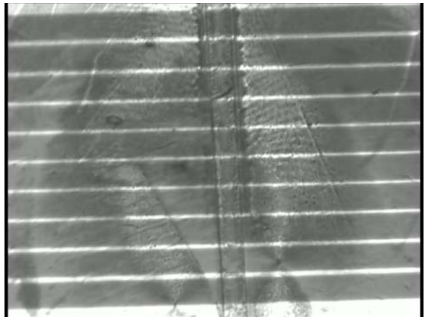


LR-SPP modulation

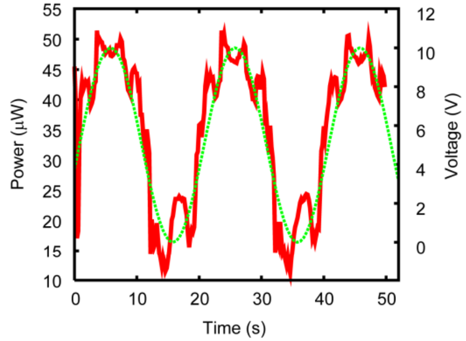
- « Slow » modulation frequency:



Square wave

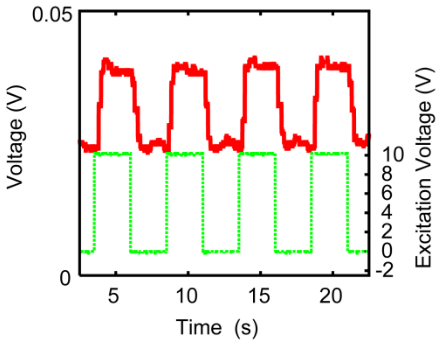


Between crossed polarizers

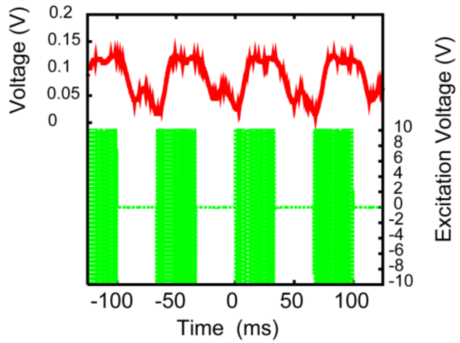


Sine wave

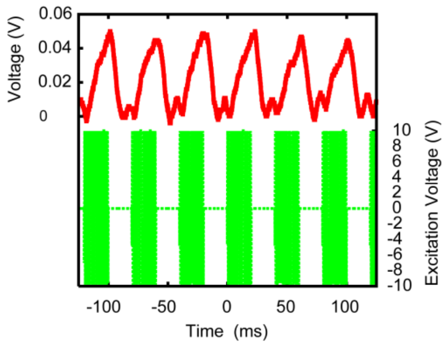
- Response with different modulation frequencies:



0.2 Hz

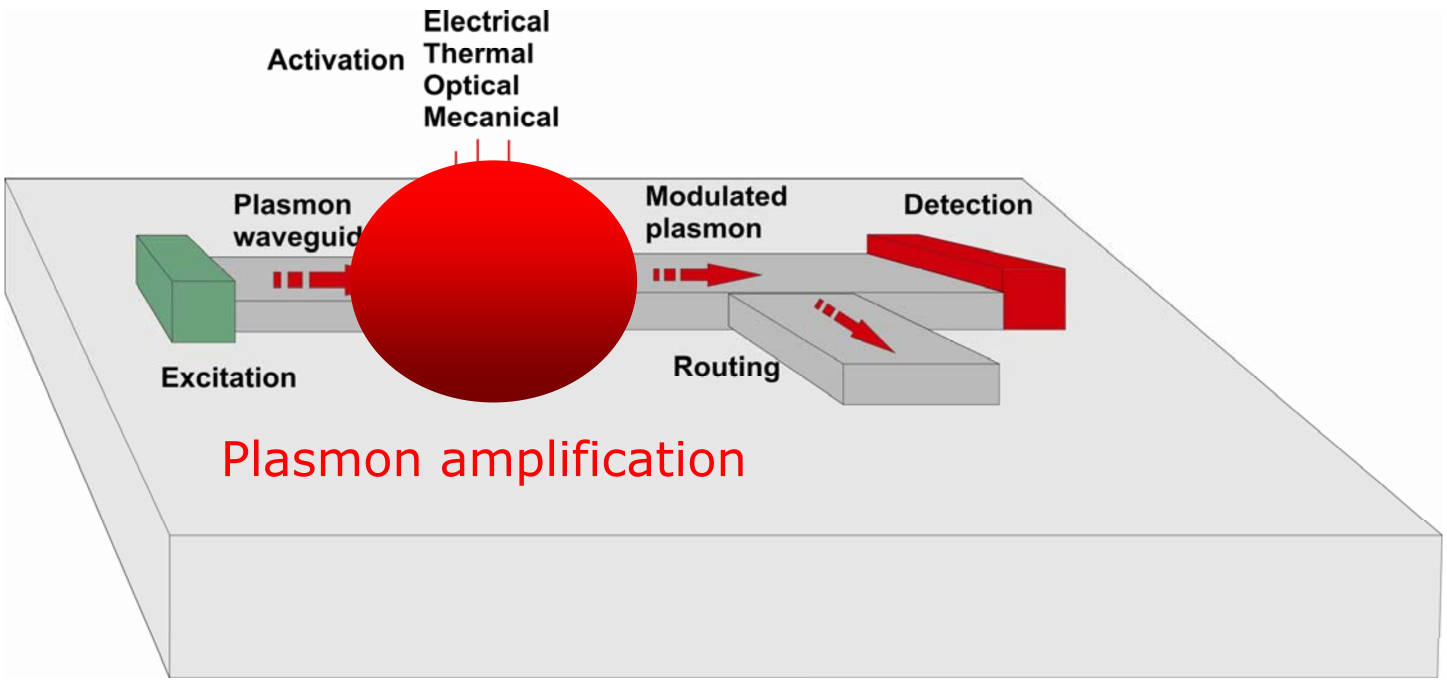


15 Hz



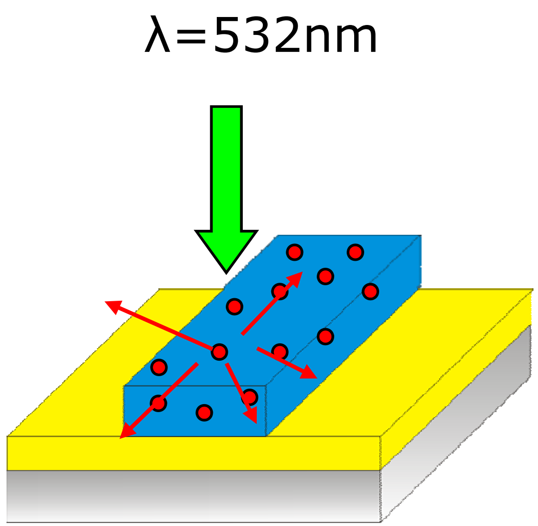
25 Hz

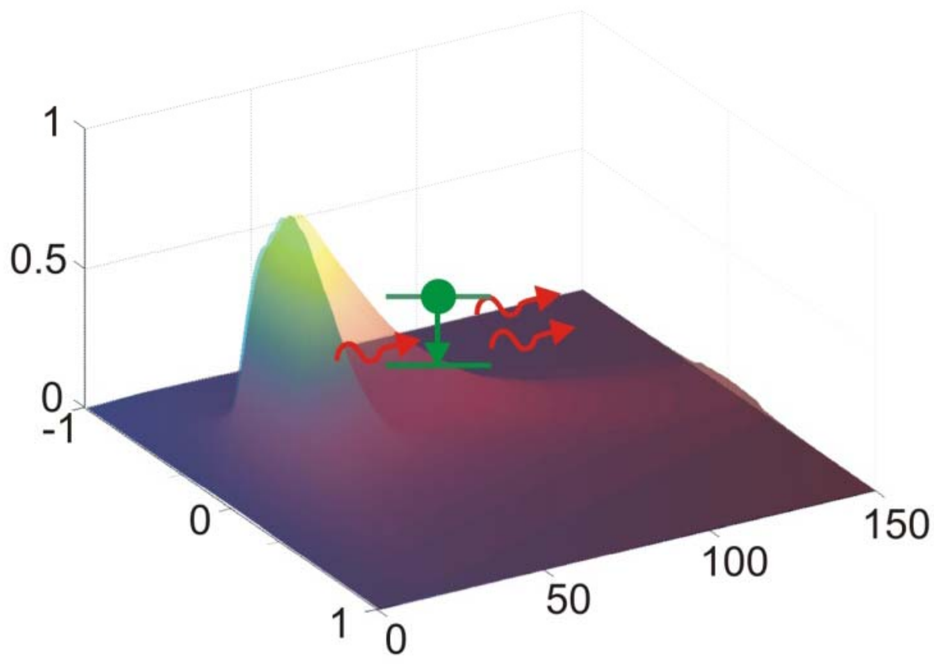
Plasmonic circuitry



Gain medium: polymer-doped with QDs

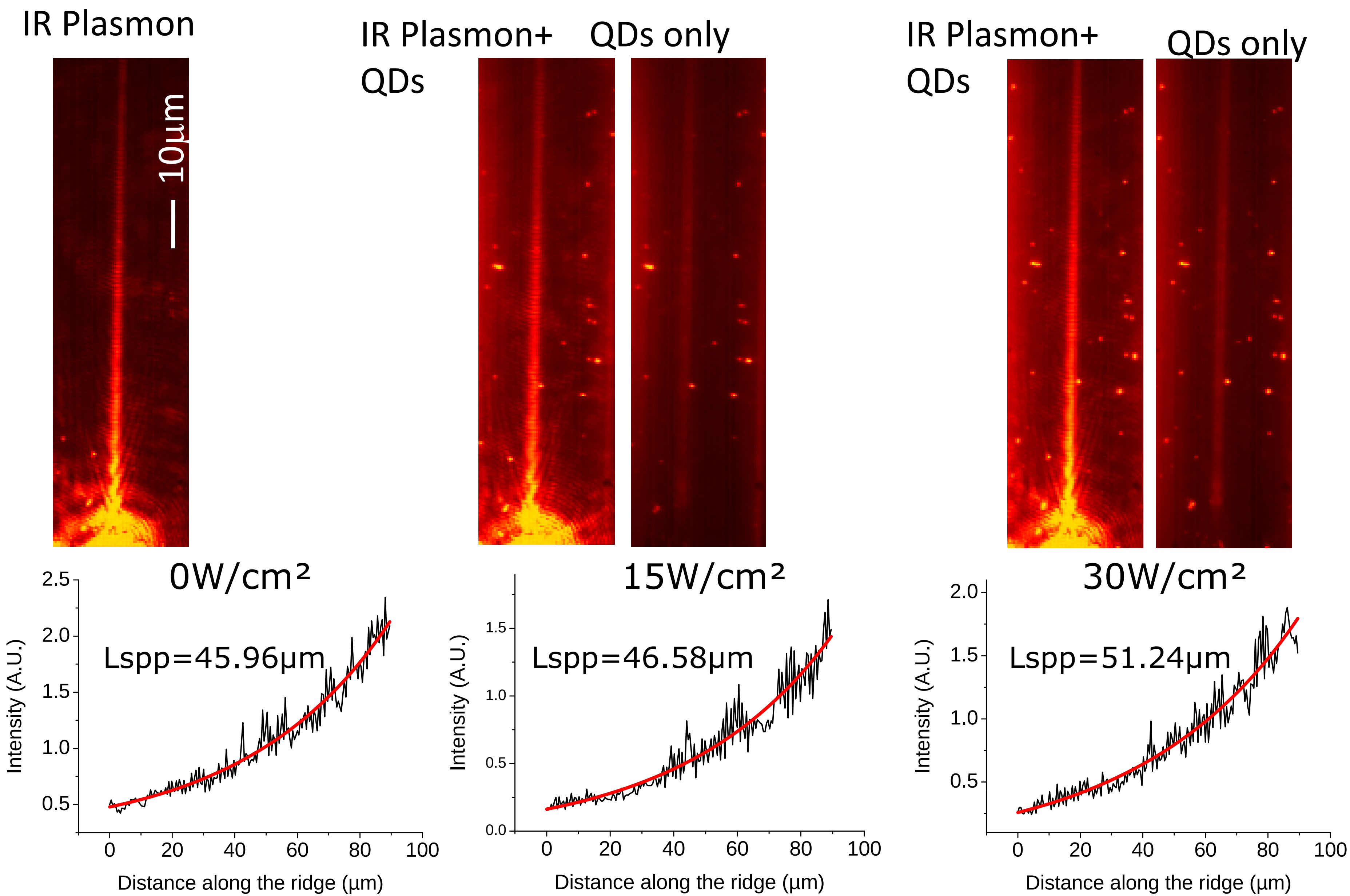
Optical pumping



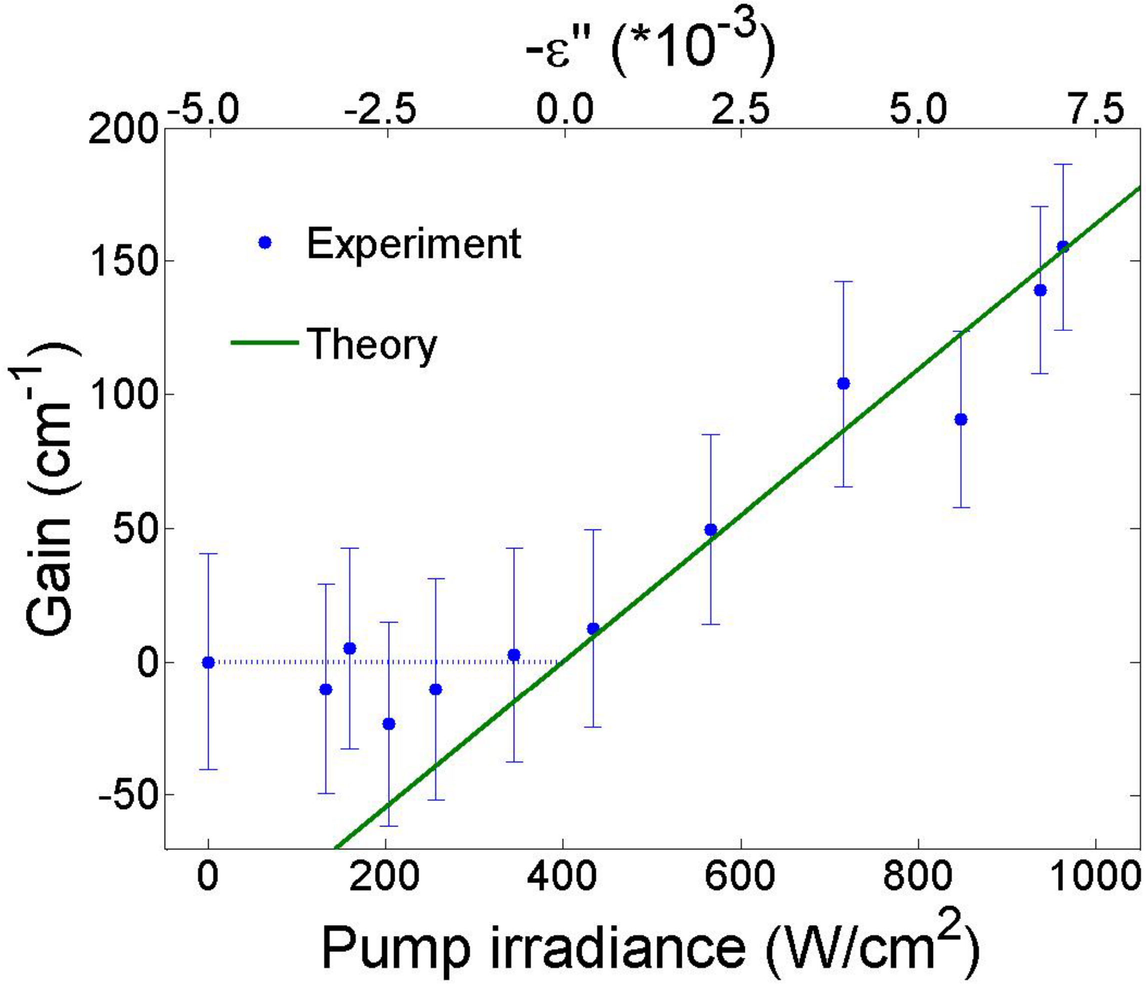


J. Grandidier et al., Nano Lett. 9, 2935 (2009)

Stimulated emission of SPP



Optical gain



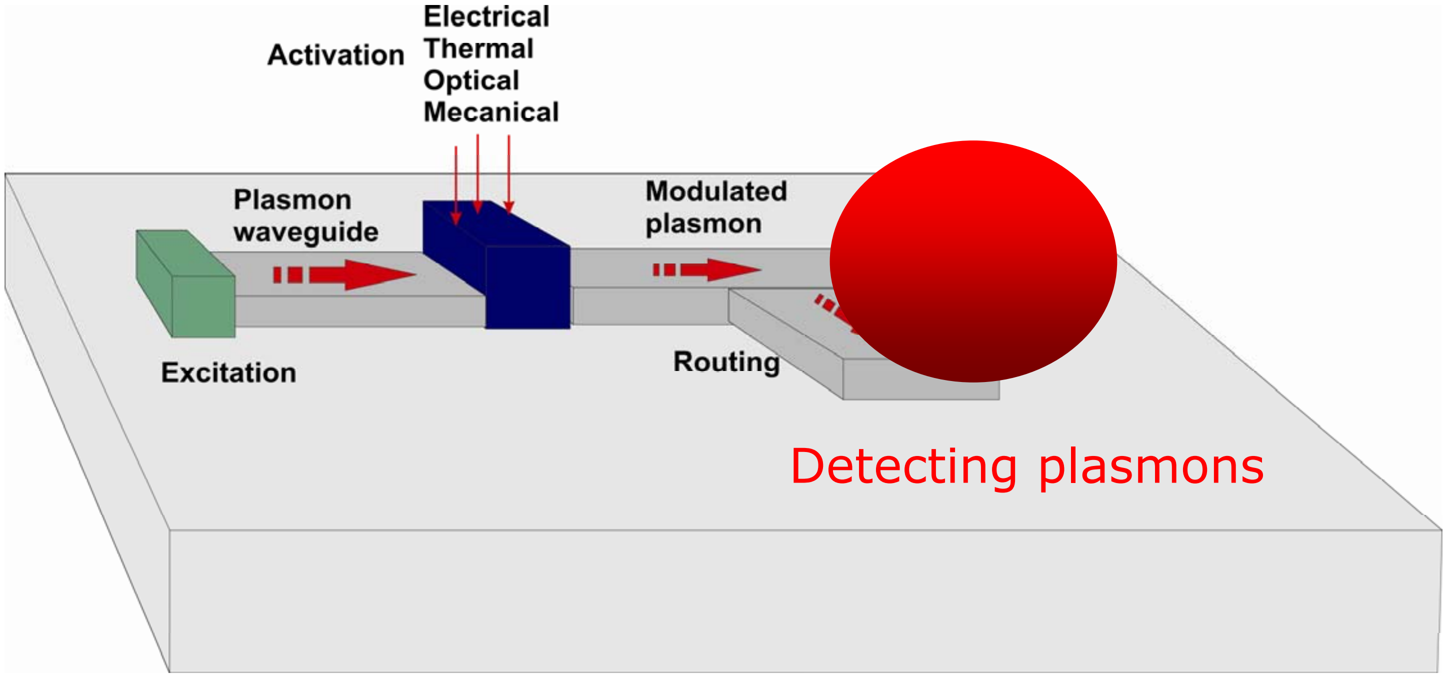
Imaginary part of dielectric constant

Optical gain coefficient

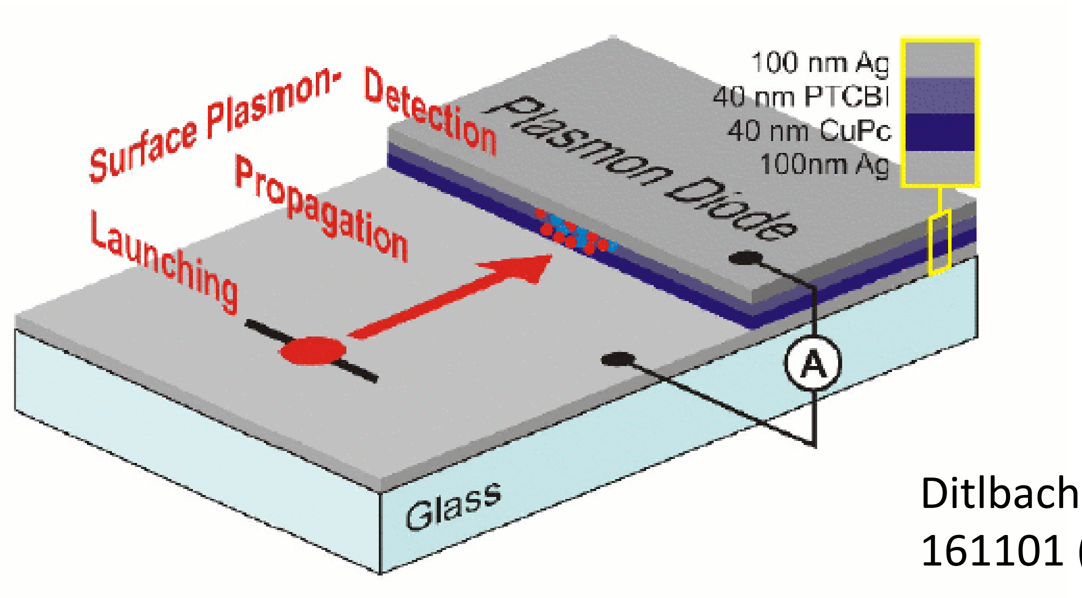
Intrinsic optical gain coefficient

$$g(I_p) = \frac{1}{L_{sp}(0)} - \frac{1}{L_{sp}(I_p)}$$

Plasmonic circuitry



Plasmon diode



Ditlbacher, H. et al. Appl. Phys. Lett. 89, 161101 (2006).

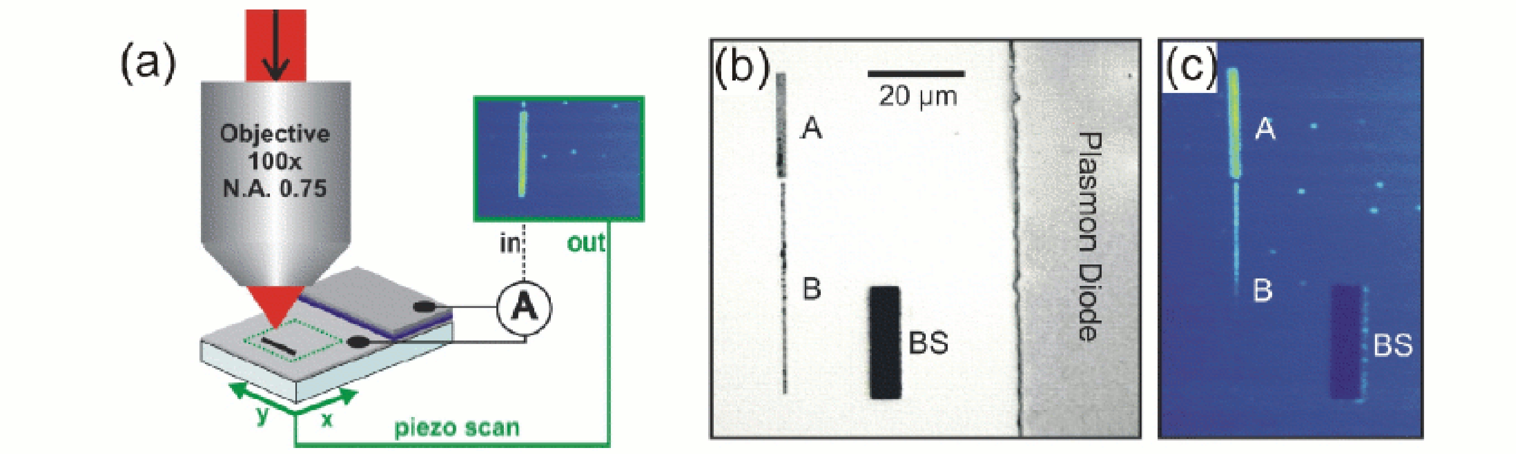


Fig.2 (a) Experimental setup, (b) optical reflection microscopy image, (c) corresponding induced current map. For details see text and supplementary file.

Plasmon power monitor

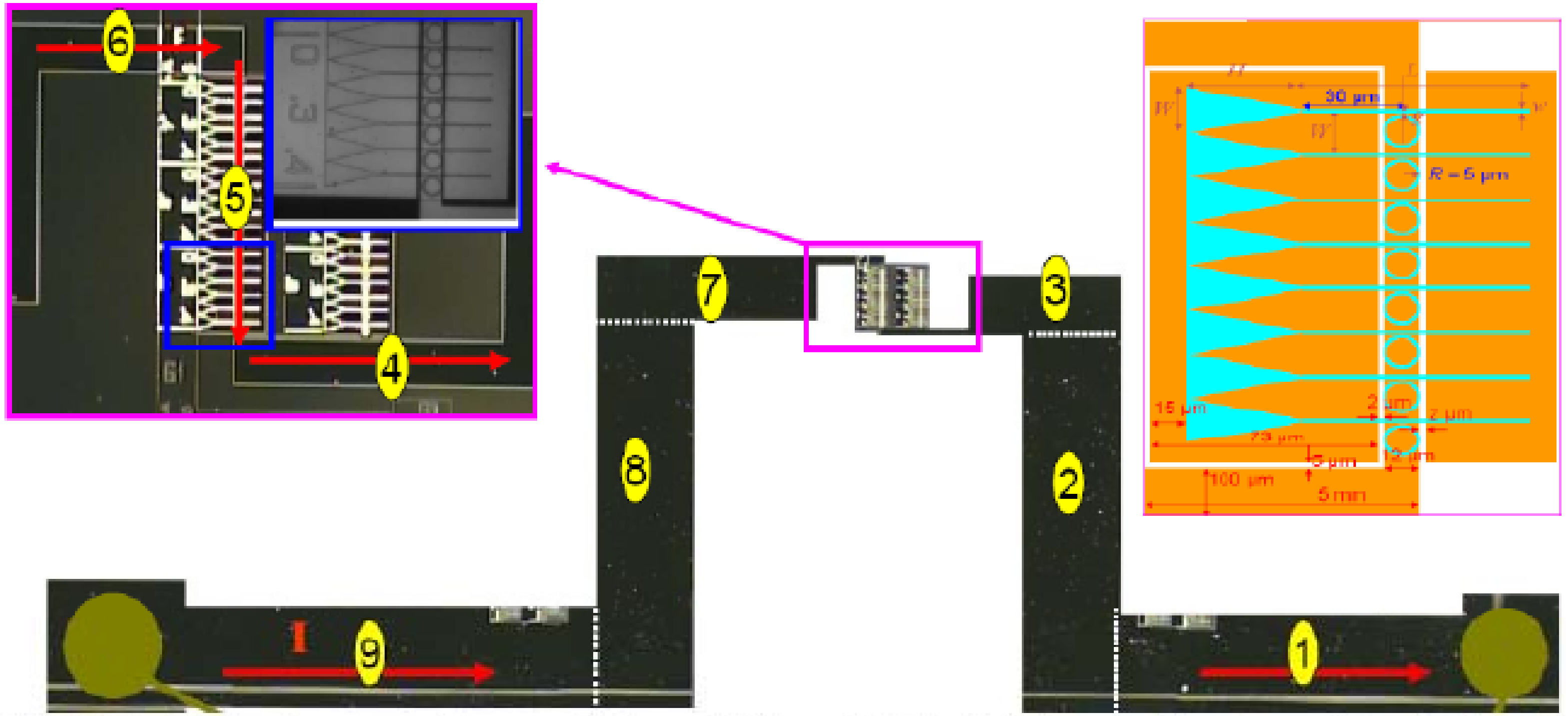
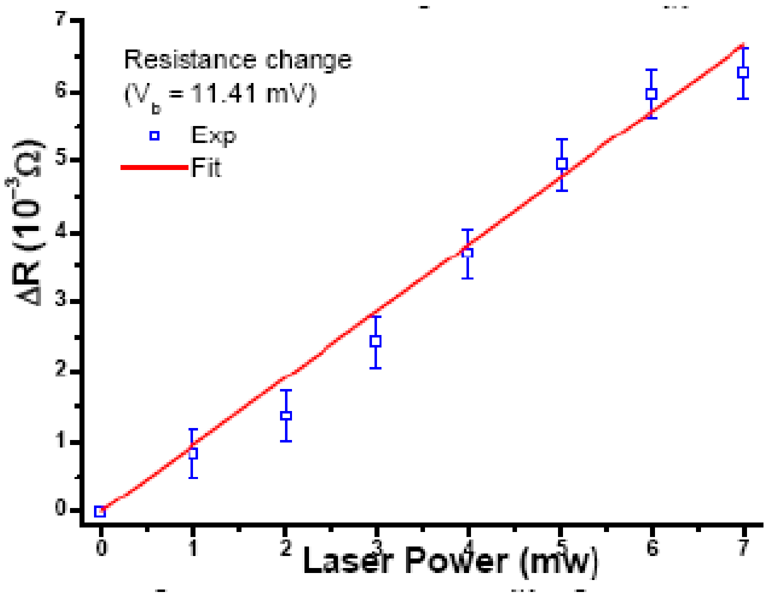
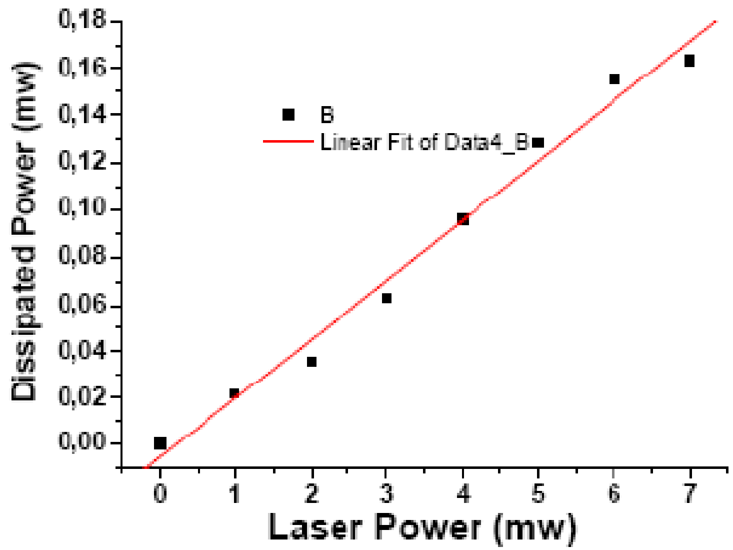


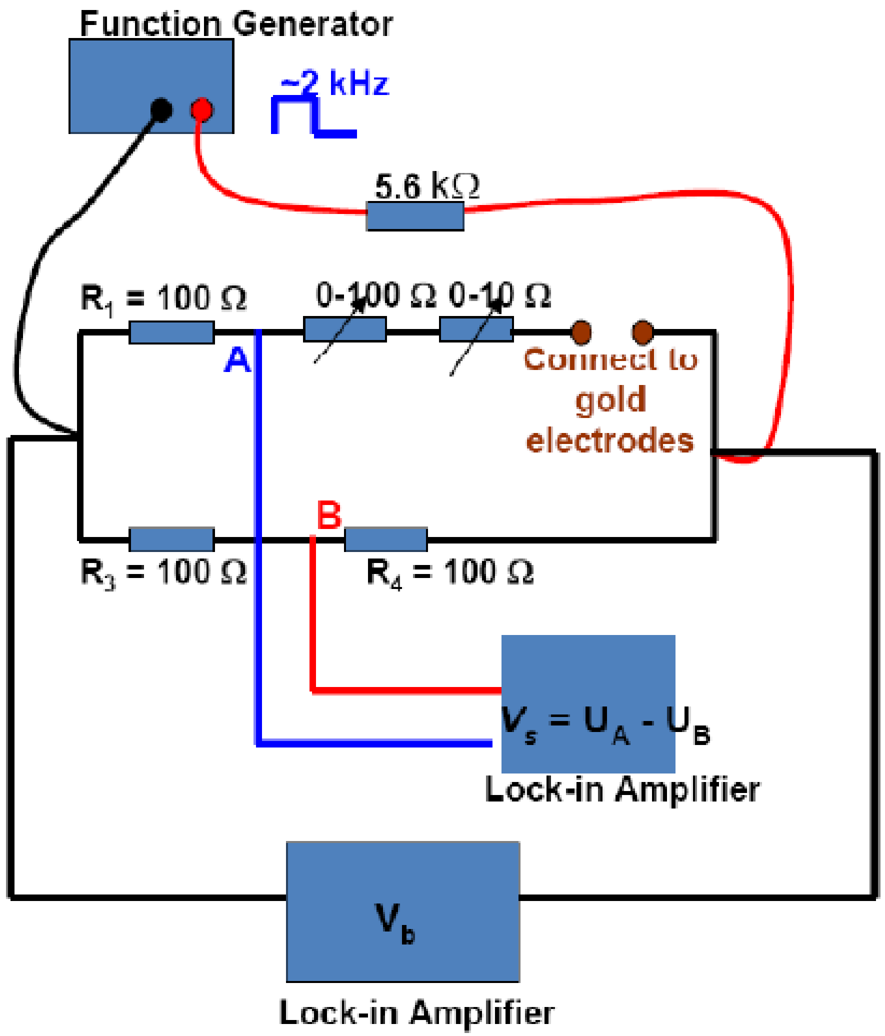
Fig. 2. Optical microscopy images with low (left) and high (right) magnifications of the fabricated WRR structures having rings with separate electrical access for the purposes of (thermo-optic) control of the WRR operation or to monitor the transmitted power via measuring the signal electrode resistance (whose change is determined by the absorbed power).

Bozhevolnyi (SDU)

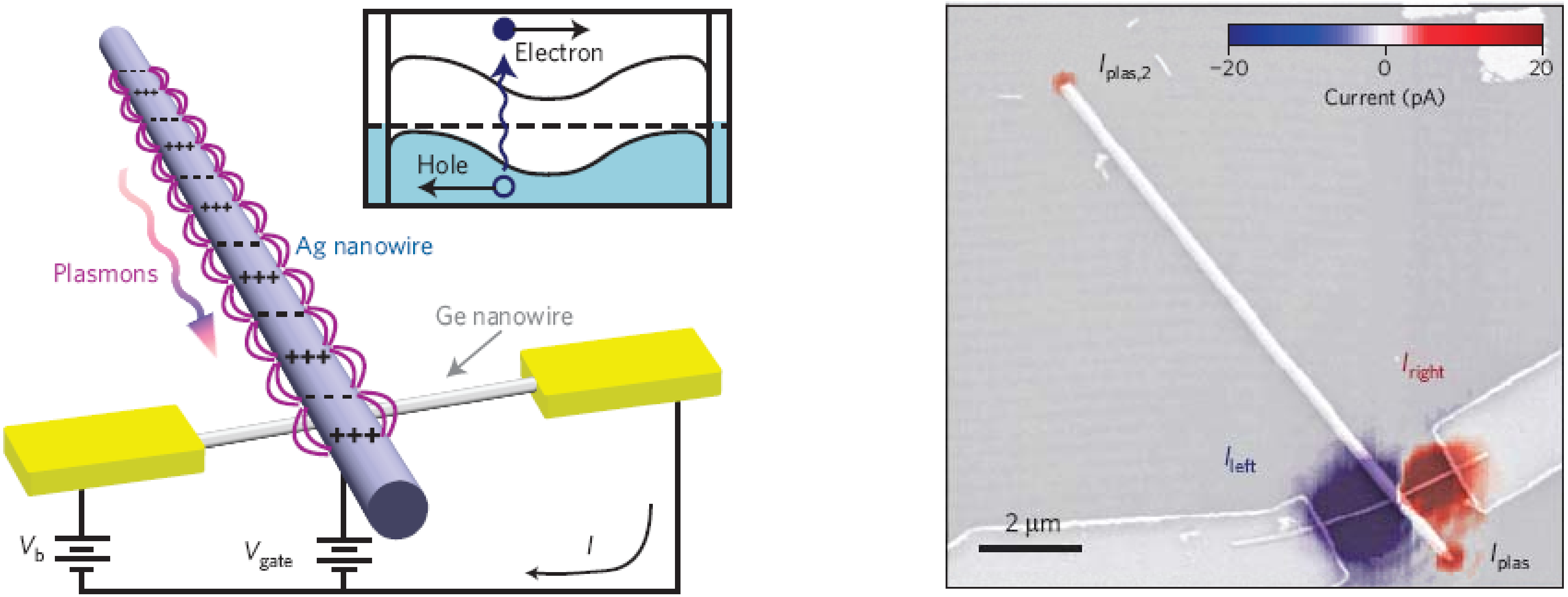
Plasmon power monitor







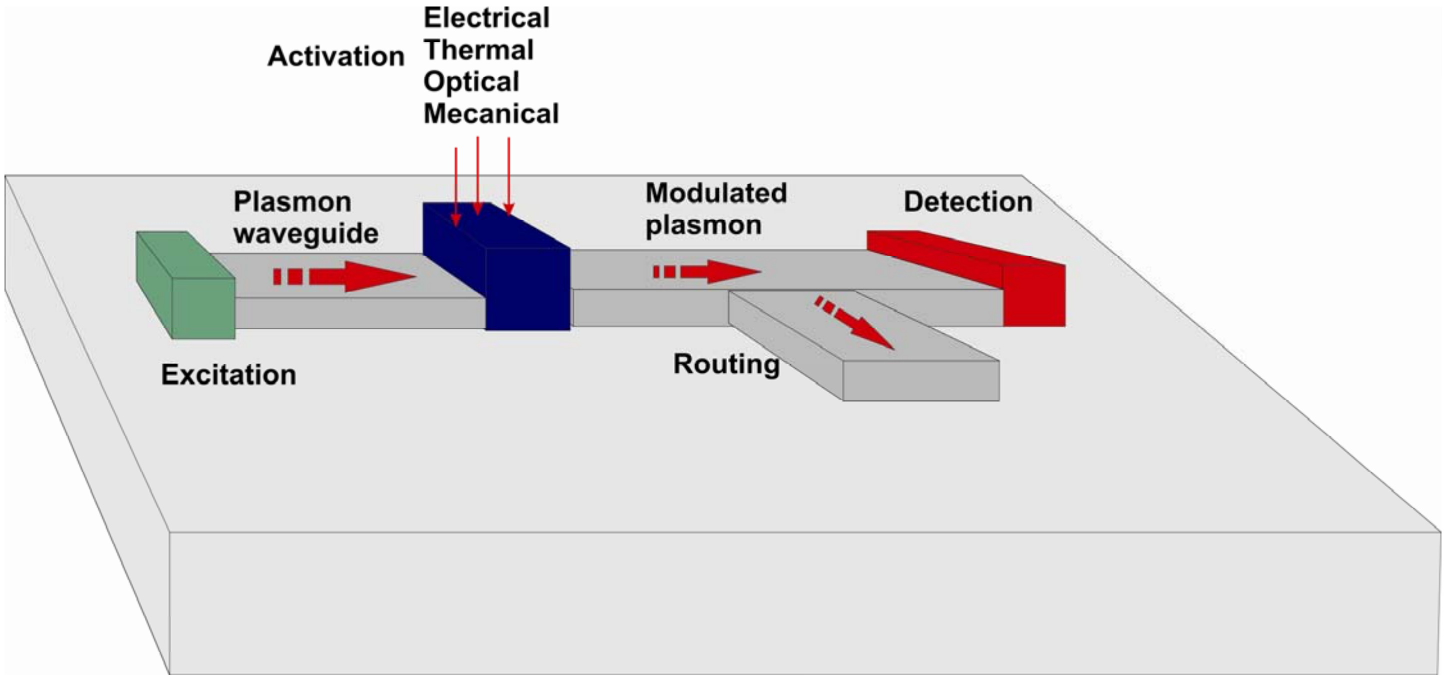
Electrical detection



A. Falk. et al. Nat. Phot. DOI 10.1038 (2009).

Figure 1 | Electrical plasmon detection. a, Schematic diagram of electrical plasmon detector operation. Inset: Electron–hole pair generation and separation in the Ge nanowire detector. **b**, Scanning electron micrograph of device 1, overlaid with the current through the Ge nanowire as a function of excitation laser position. Excitation laser power $P = 2.0\ \mu W$, wavelength $\lambda_{ex} = 532$ nm, $V_b = 0$, $V_{gate} = 0$.

Plasmonic circuitry



So, where are we?

SPP interconnect demonstrator

VCSEL coupling test using self supported LR-SPP waveguide

2.5 Gbps/channel; 6dB/cm propag. Loss

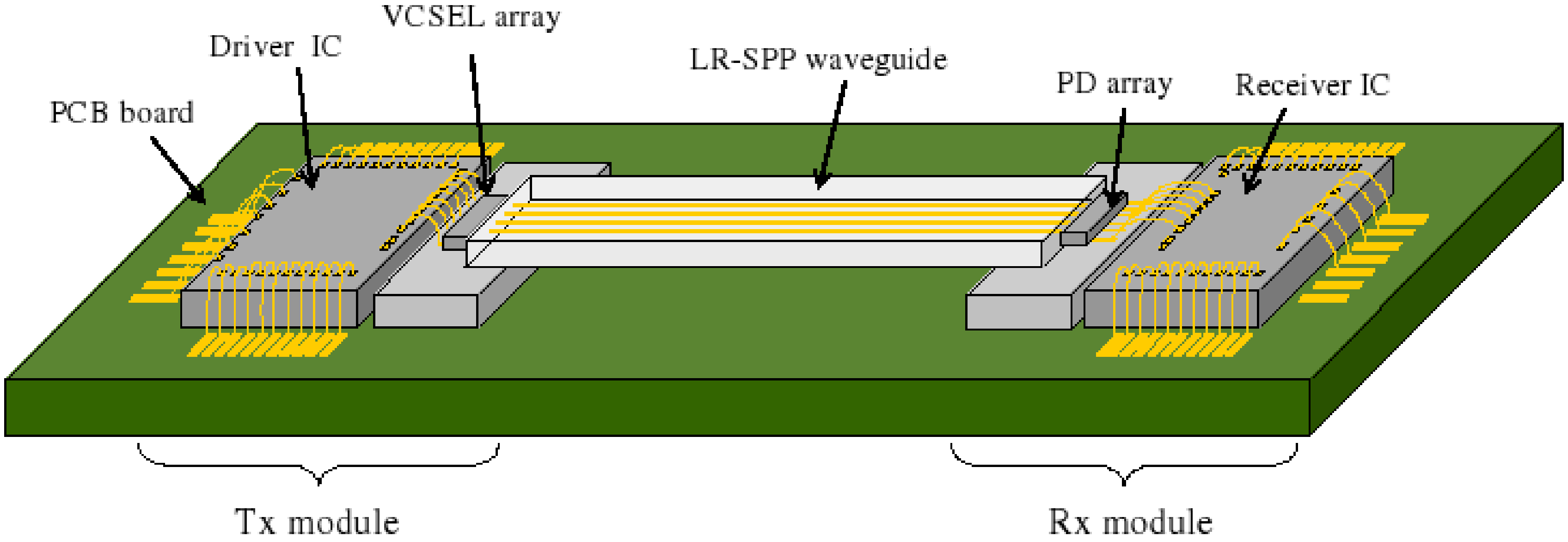
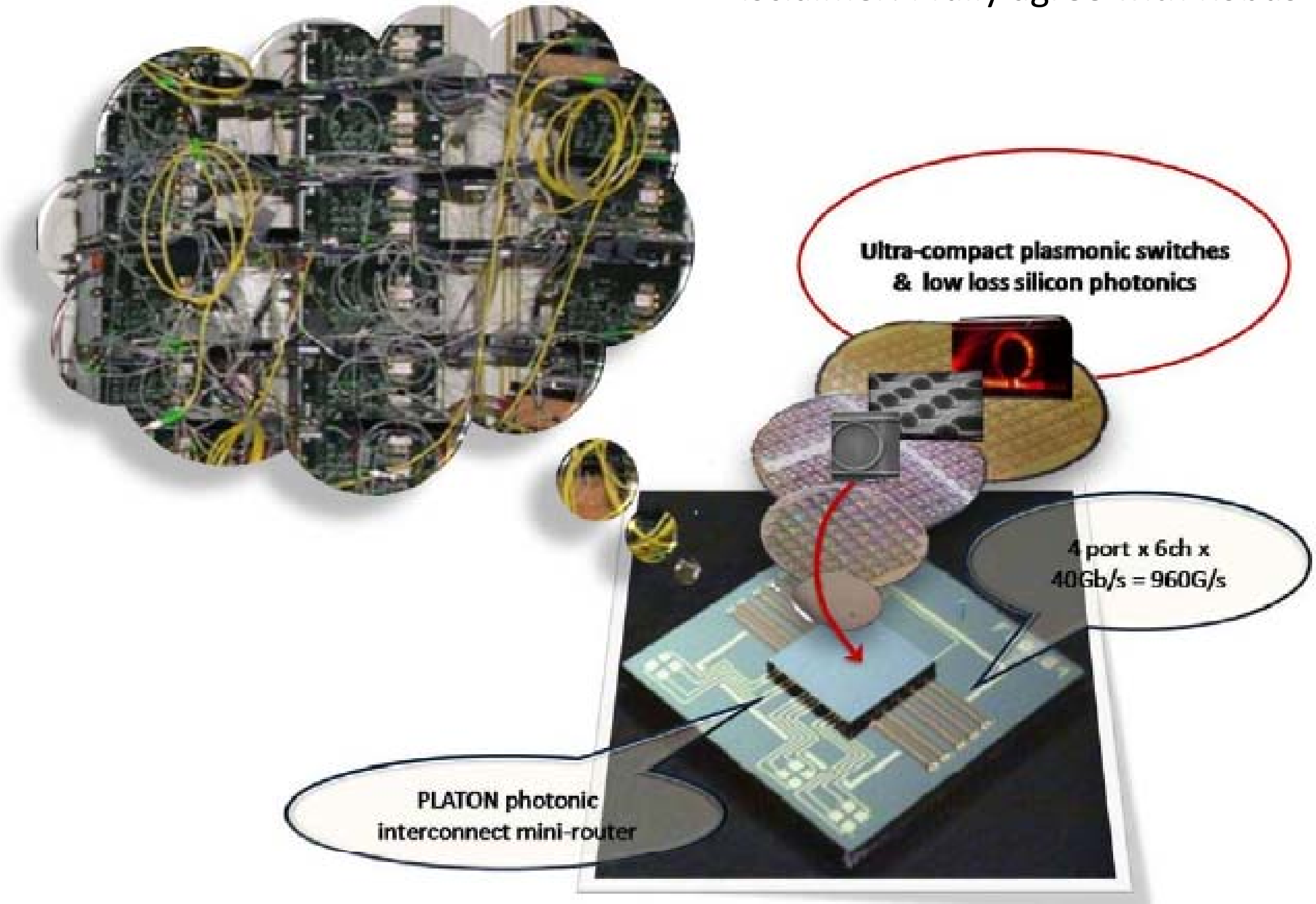


Fig. 1. Architectural view of on-board chip-to-chip optical interconnect using polymer-based Au long-range surface plasmon polariton (LR-SPP) waveguide.

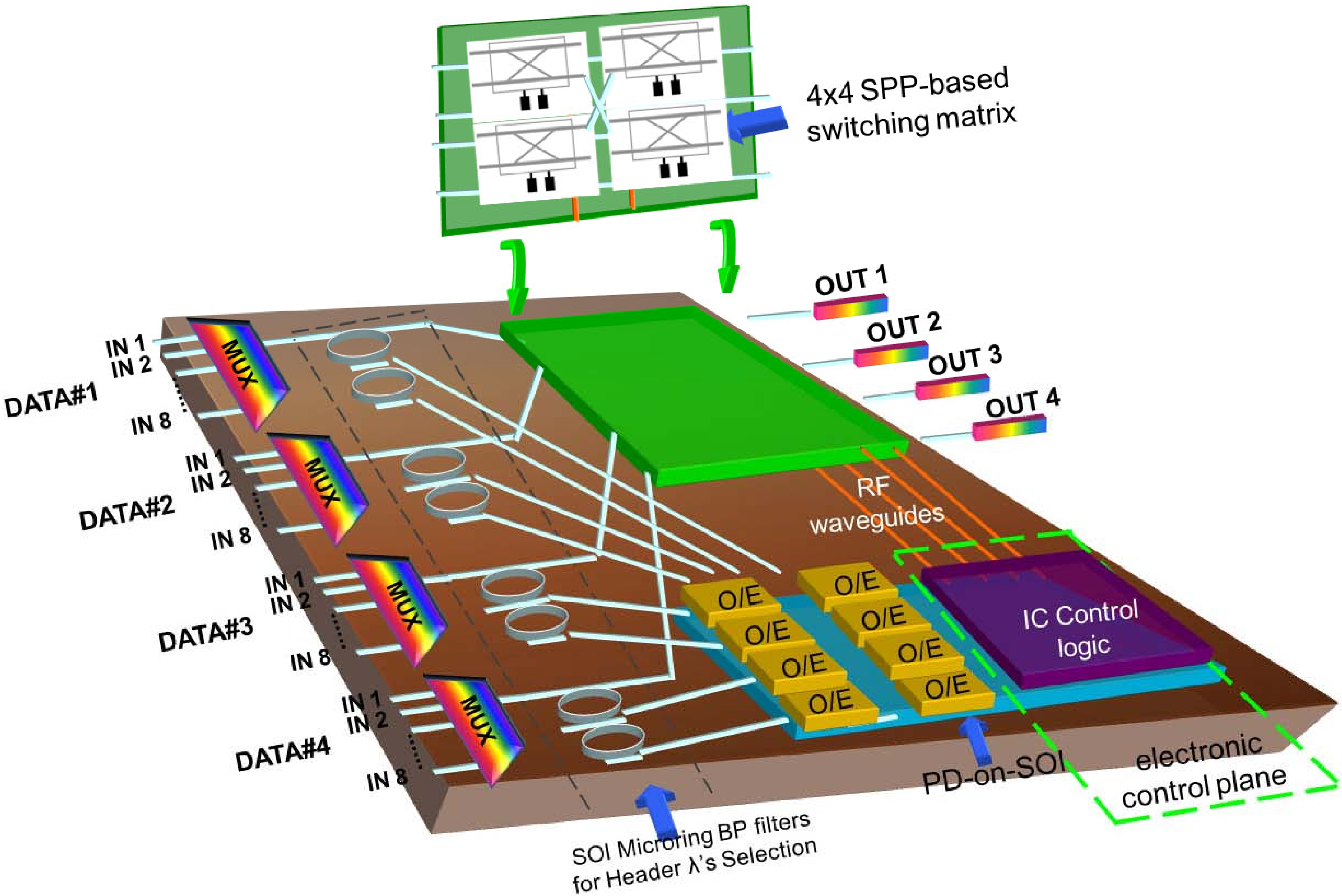
Optics Express, 16 13133 (2008)

Interconnects for Tb control boards

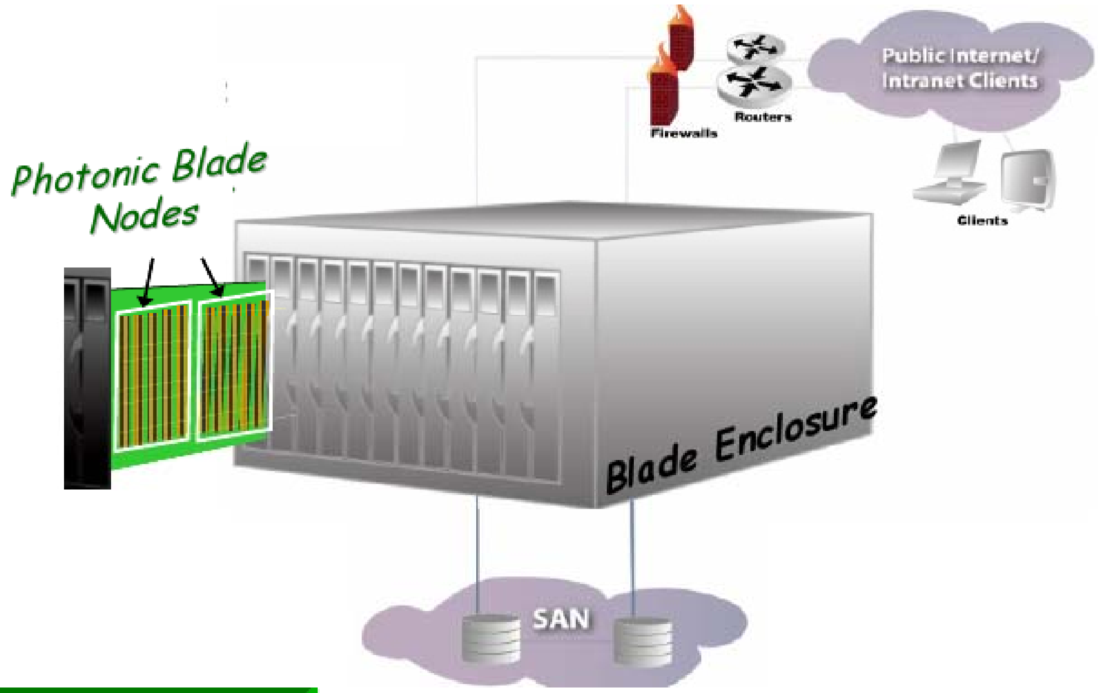
Disclaimer: I fully agree with Kobus' remark

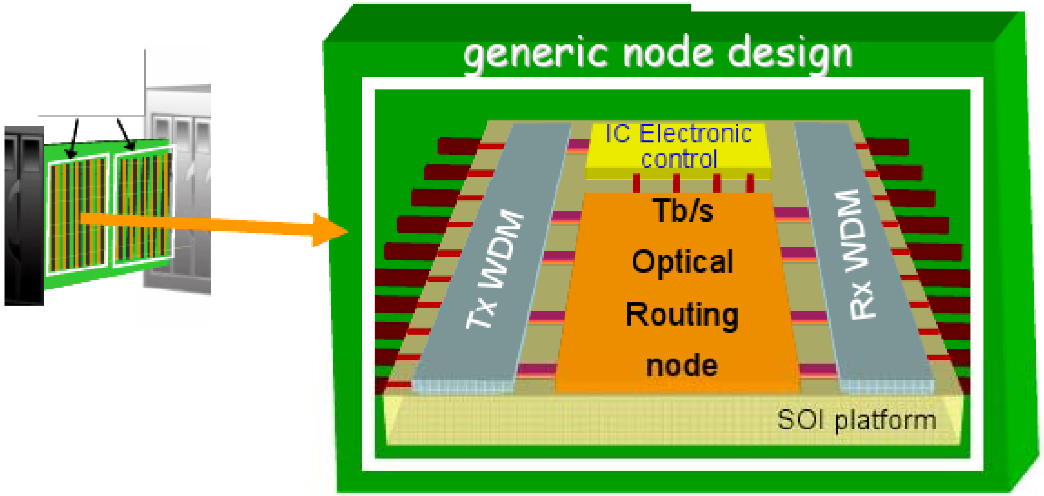


Interconnects for Tb control boards



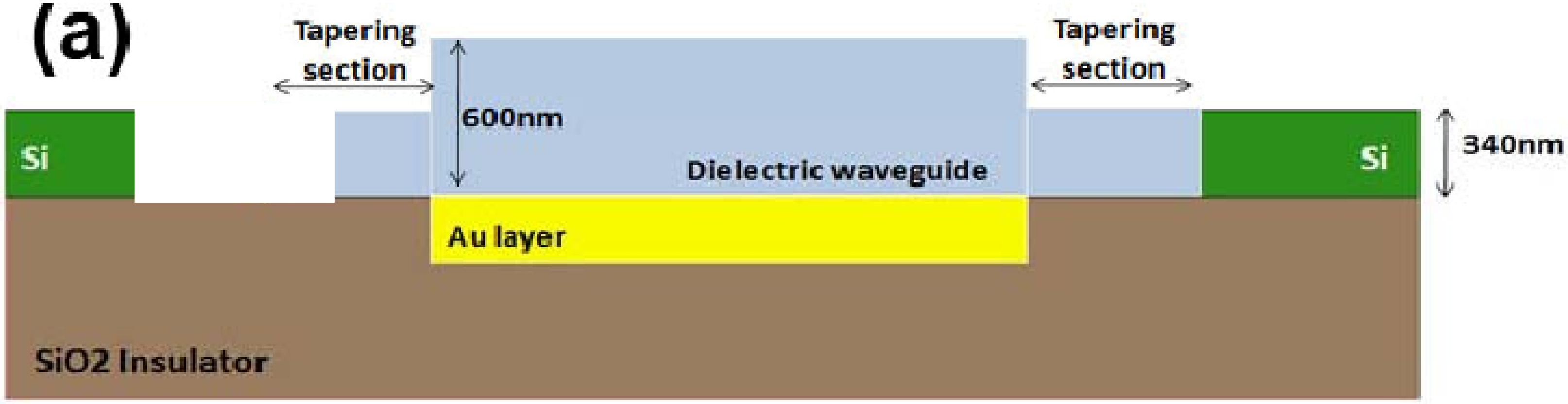
Interconnects for Tb control boards



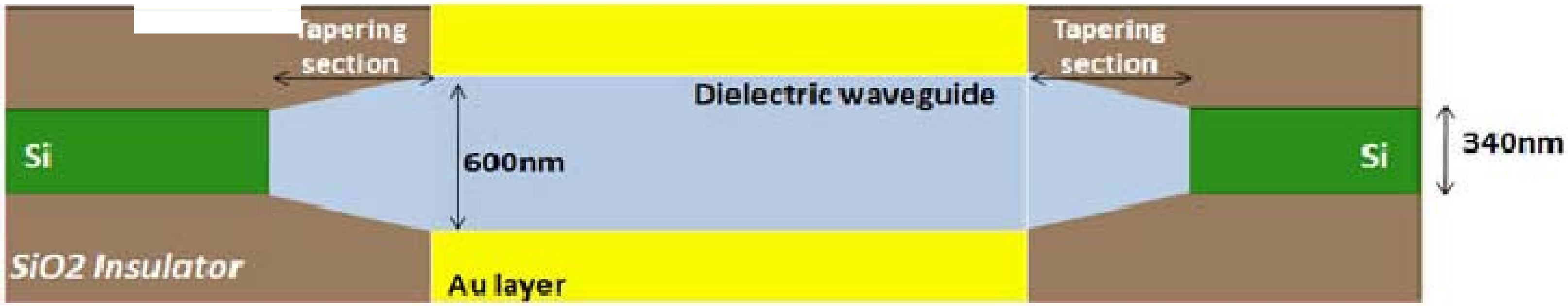


Hybrid technology: Silicon (SOI)+DLSPPW

(a)



(b)



Conclusion

Surface plasmon-based circuitry is becoming a technological reality!
The toolkit is practically complete (inc. SP Lasers)

POST-DOC(S)
AND
PHD(S) WANTED!!

Bio-plasmonics, integrated plasmonics
& molecular plasmonics

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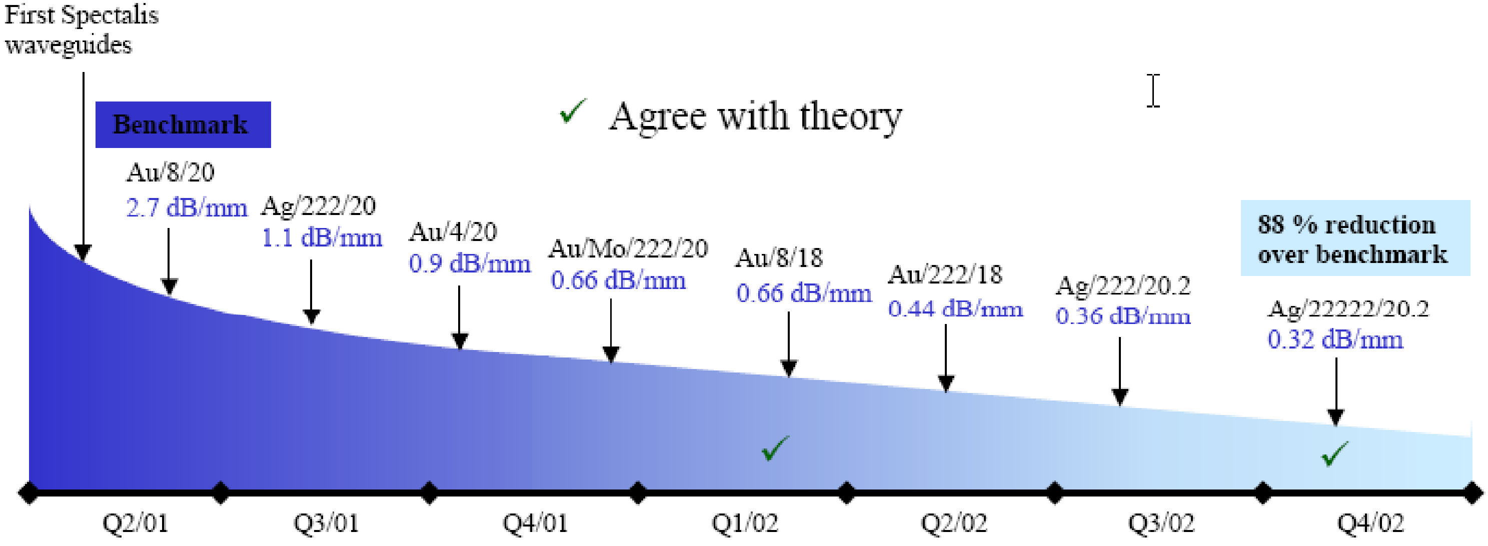
Microwave attenuation

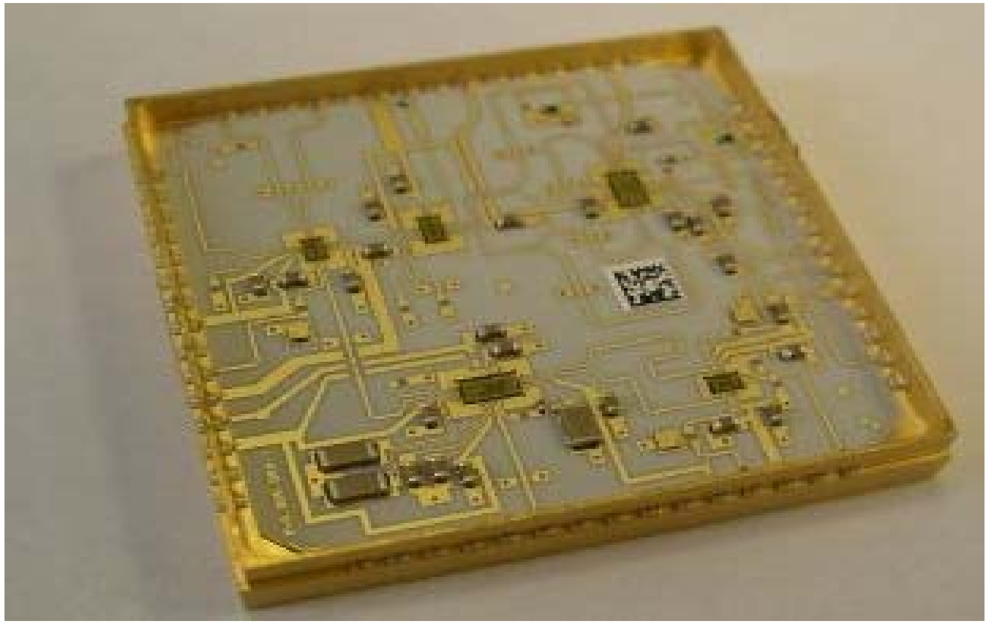
Straight Waveguide: Progress on Attenuation Reduction

- History of attenuation measurements.
  - Measurements at $\lambda_0 \sim 1.55$ µm on SiO_2 with gel upperclad.
  - GoTo: AttenuationSummary.xls



- Further reduction in attenuation is expected as fabrication processes are optimised.

Board technology with Au is Si-compatible



Example of currently available Microwave Au circuit printed on Sapphire.

Both the substrate and the metal stripes are potentially suitable for plasmon propagation if downsizing to micrometre widths and to millimetres lengths is mastered.