Nanophotonics : fundamentals and applications

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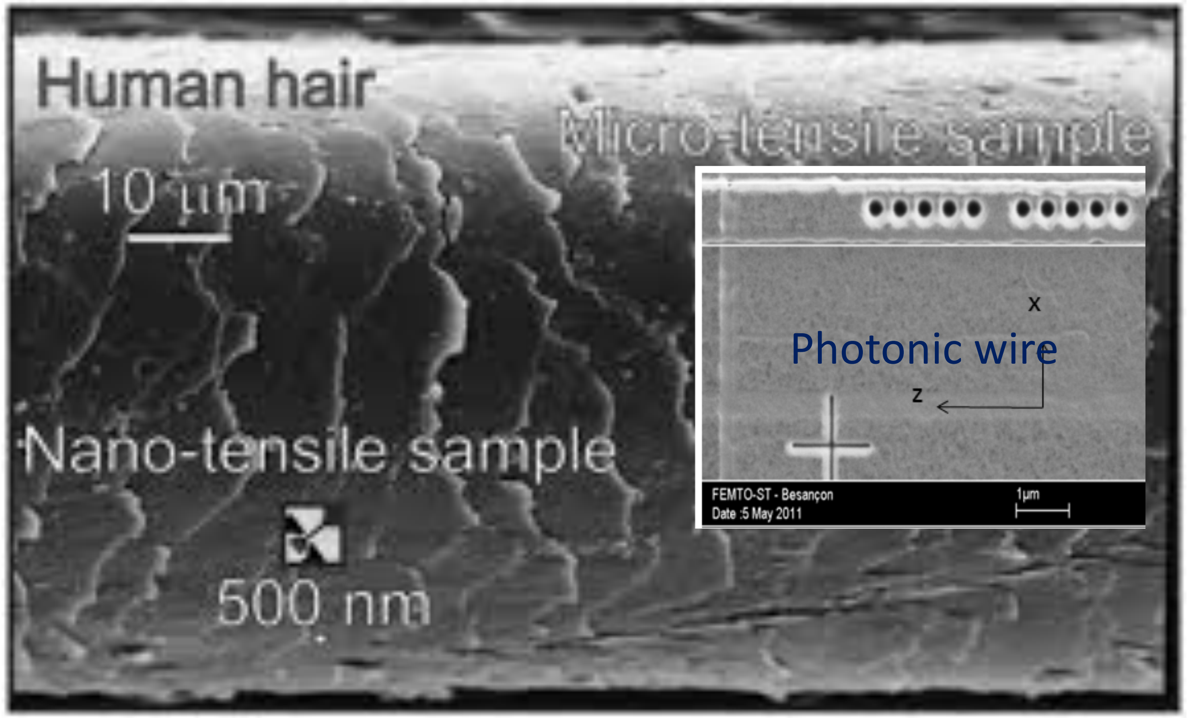
Nano-world

micrometer = 10^{-6} m = 1/1000 millimeter

nanometer = 10^{-9} m = 1/1000 micrometer




SAMSUNG
12:45
Mon, 24 February

What is wrong with the use of electric current ?

Good: electrons are small; devices are potentially scalable to a size of a single molecule

Bad: electric current cannot be changed or modulated fast enough. Speed is limited to nanosecond scale by circuit inductance and capacitance.

Thermal losses!!!!

Thermal losses in electronic circuits: Photons versus electrons

Looking at the energy efficiency of the most advanced microelectronics chip, processing a bit of data consumes roughly a picojoule. When you do this for photon-based technologies, the energy budget is less than a femtojoule per bit – so a factor of a thousand less energy demand.

The other advantage is that when you look at the frequencies you can cover with photons, they are a factor of about 1,000–10,000 higher than the spectrum you can cover with electrons. So you can go to much higher frequencies and you can do that far more energy efficiently.

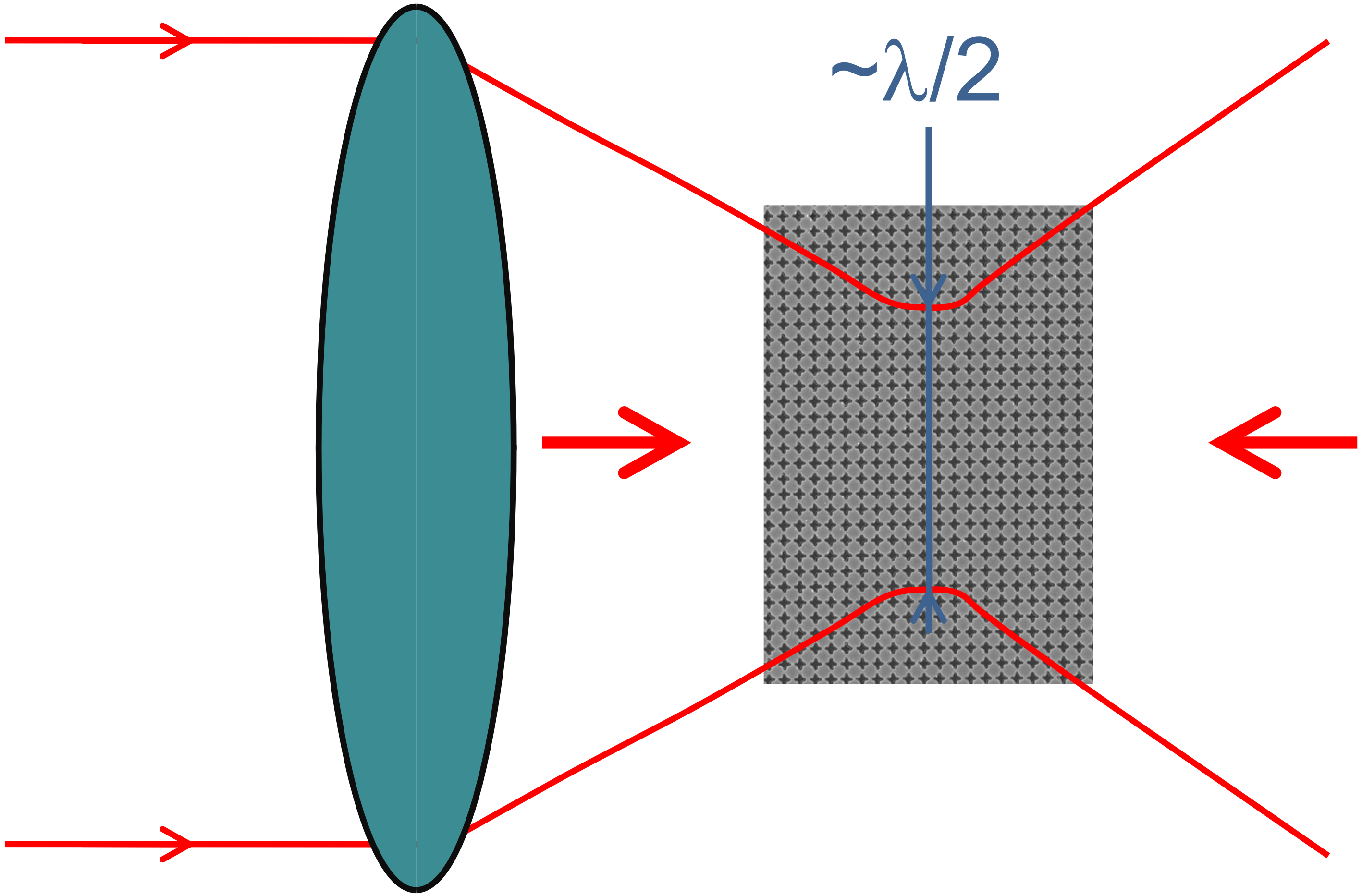
Can electronic circuits and transmission channels be replaced by photonic ones?

Using photons as bits of information instead of electrons would revolutionize data processing, optical communications, and possibly computing

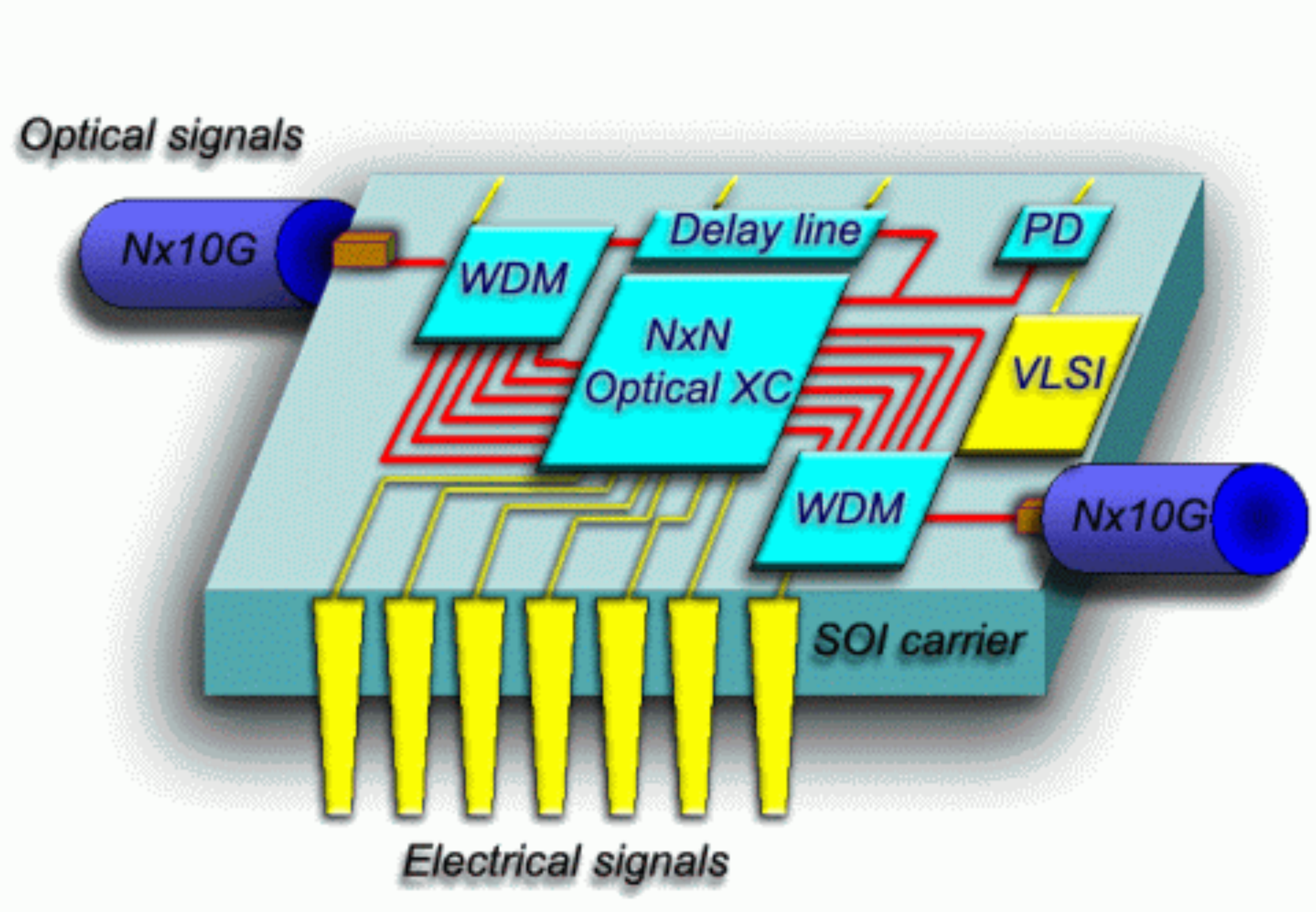
Photons travel much faster and don't dissipate as much power

BUT there is diffraction that limits the smallest light spot…

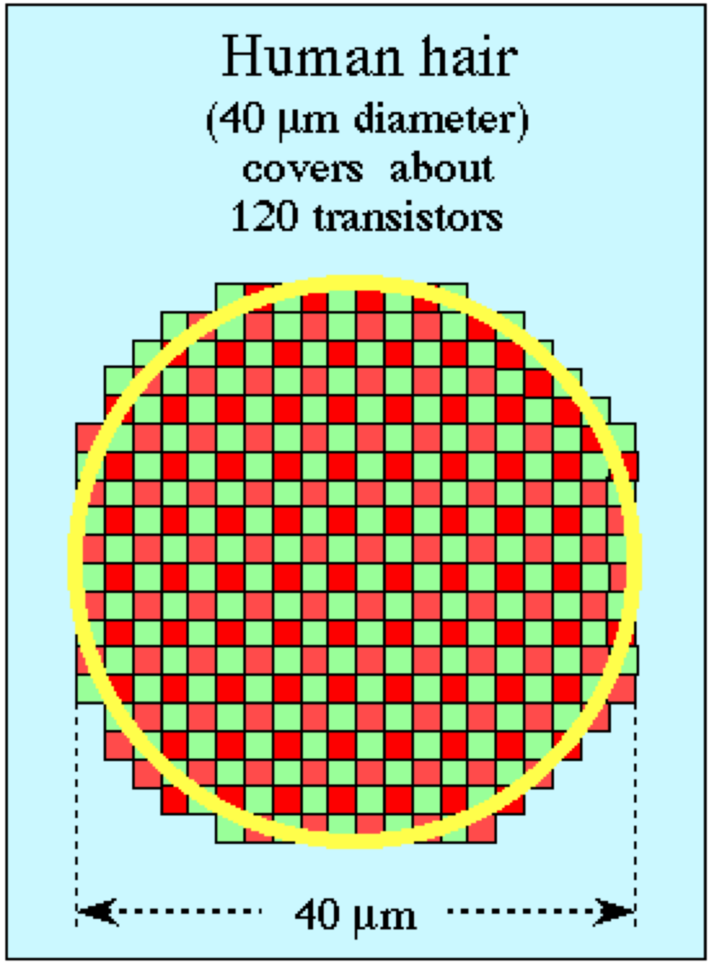
The limits of optics



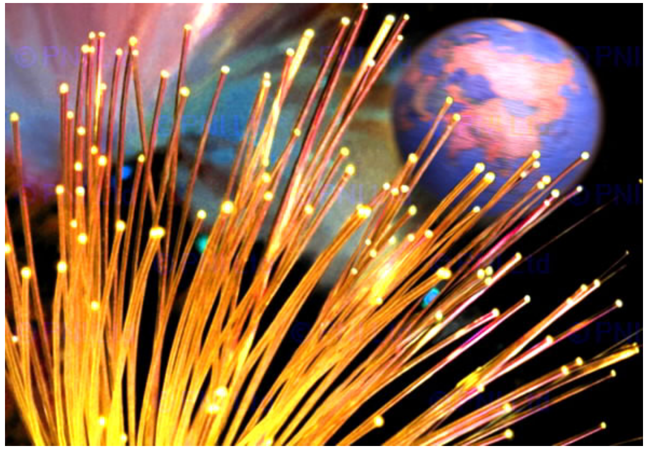
THE DREAM: could we replace electric signal processing by all-optical signal processing?



Optical Fibers open up the path ....
However, dimension of optical "wires" is much larger than that of electric wires



Or optical fiber cross-section

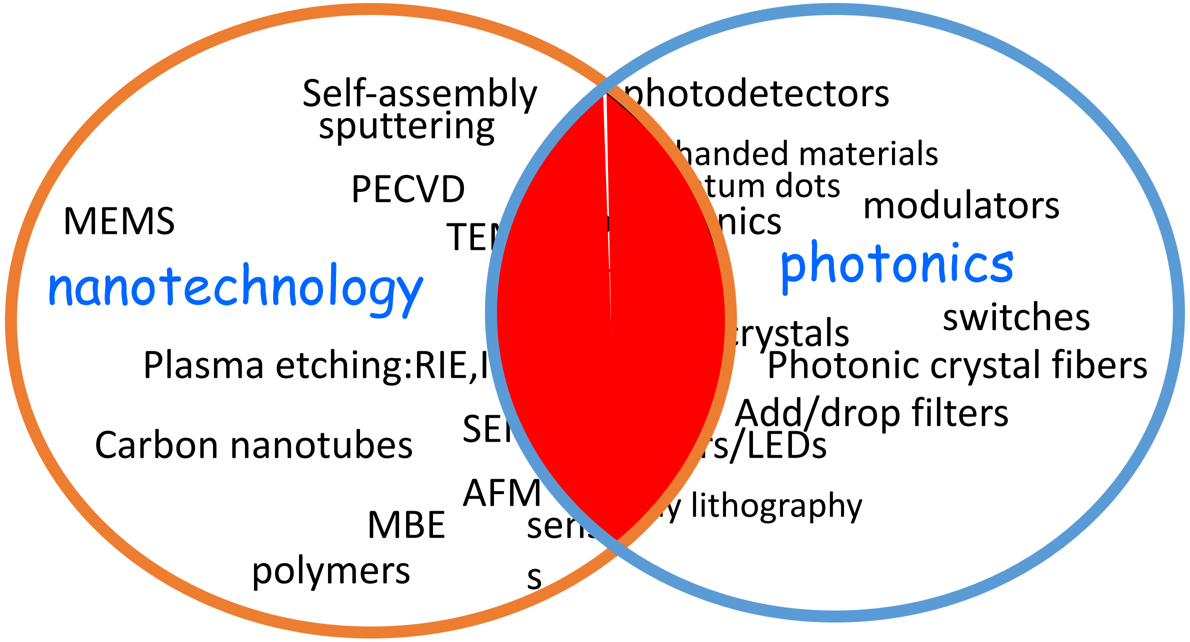


We need to confine light to at least 10-20 times smaller size than the fiber diameter and we need to engineer active/reconfigurable devices

What is nanophotonics?

Nanoscience/nanotechnology: creation of useful/functional materials and devices through control of matter on the nanometer length scale and exploitation of novel phenomena and properties at that length scale

Photonics is the technology and science of light generation, handling and control



Nanophotonics is the interface between the two with optical materials patterned on wavelength-size scales or smaller.

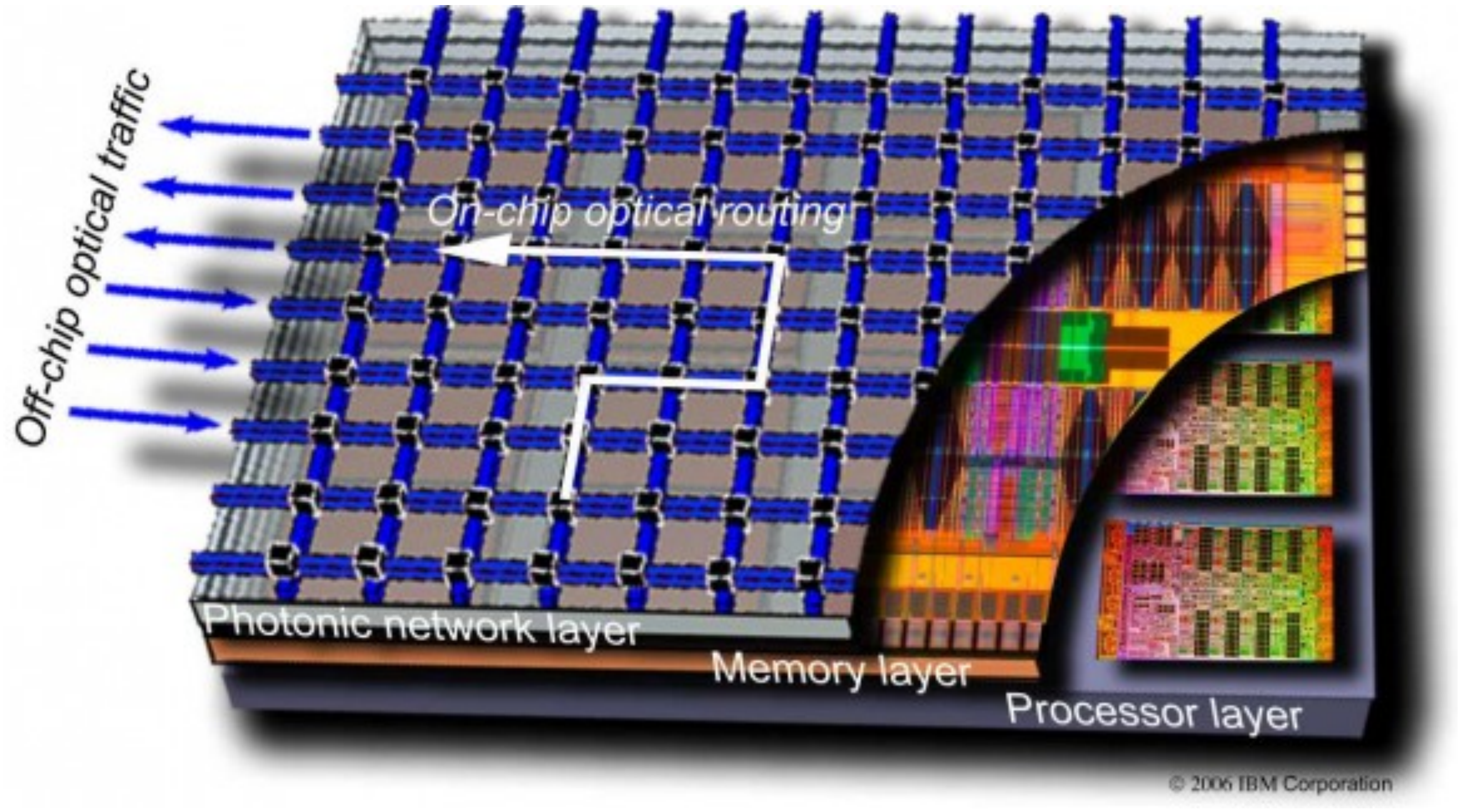
Nanophotonics: defined by its applications

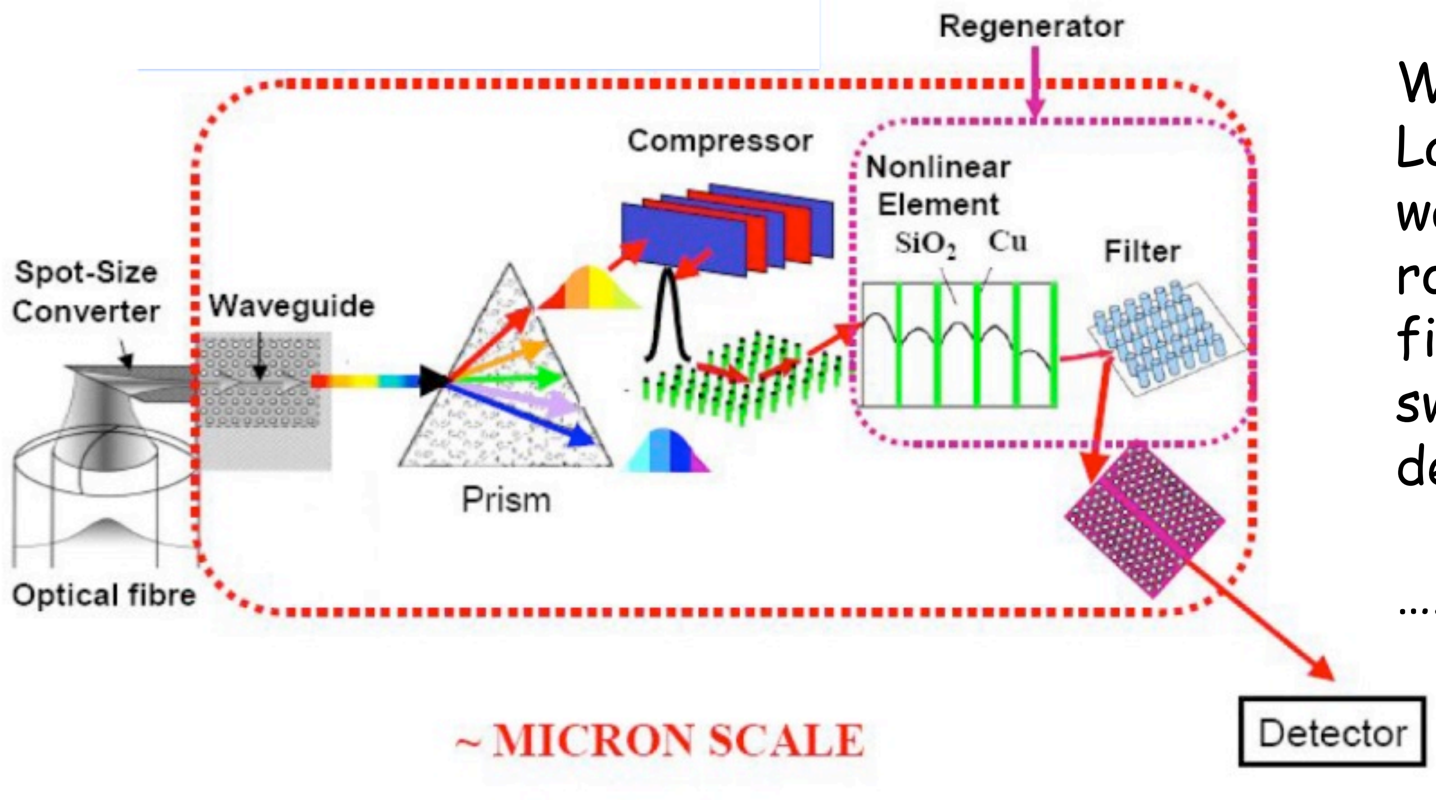
- communications technology
- lasers
- data storage
- (bio-)sensors
- optical computers
- solar cells
- light-activated medical therapies
- displays
- smart materials

Large interest from industry in fundamental research on nanophotonics

Nanophotonics is a unique part of physics/chemistry/materials science because it combines a wealth of scientific challenges with a large variety of near-term applications.

Is it possible to have an all optical processor?



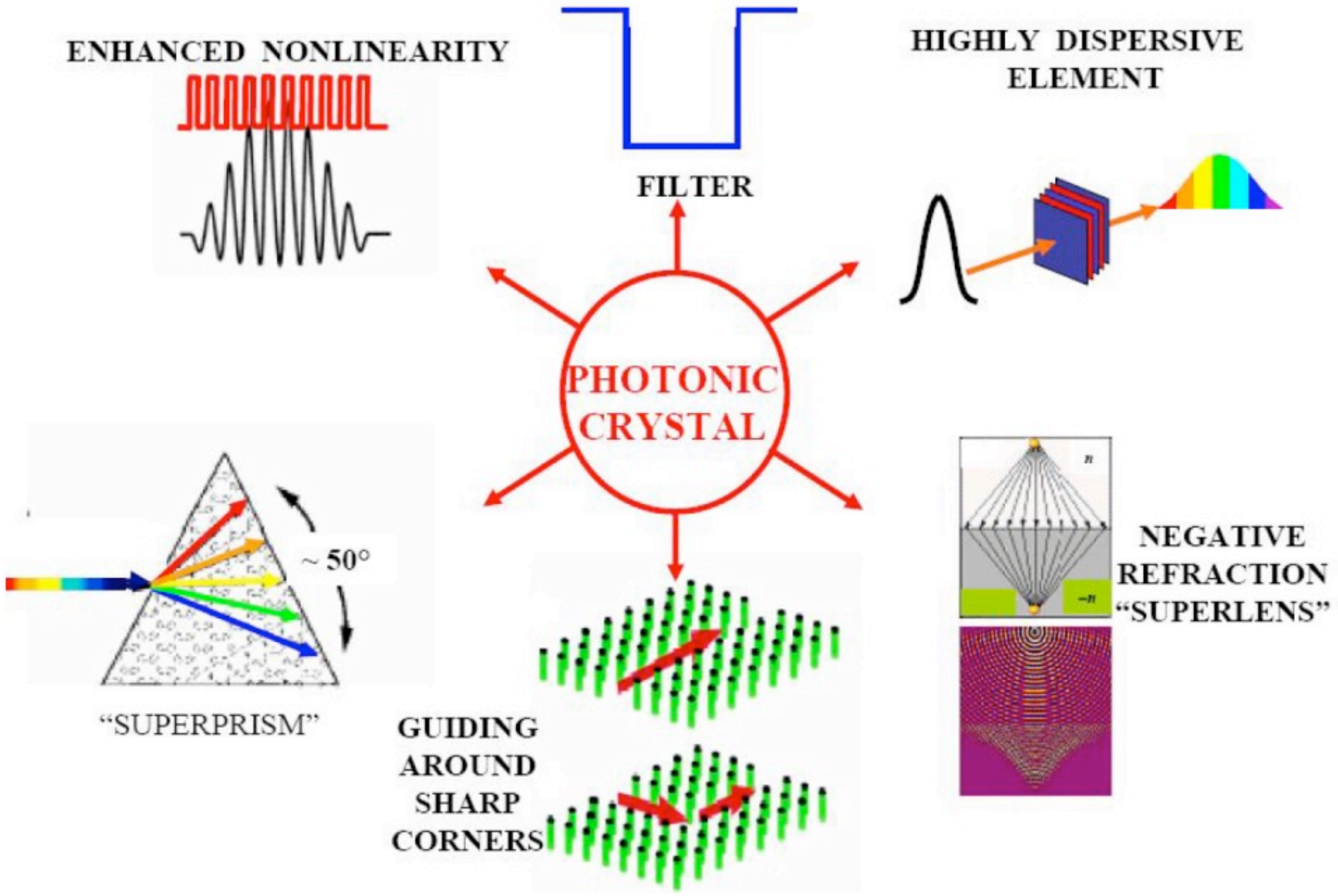


What we need:
Laser sources,
waveguides,
routers, light bending,
filters,
switching, modulators,
detectors

....at the micrometric scale

Already fiber optic cables, which simply guide light, have revolutionized the telecommunications industry

Nanophotonics (mainly based in periodic nanostructures) can do all those optical functions !



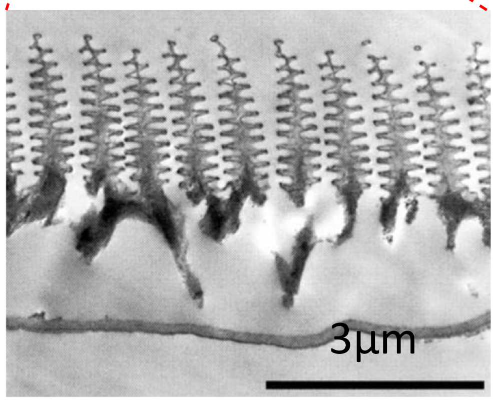
Photonic Crystals in Nature

Morpho rhetenor butterfly

http://www.bugguy012002.com/MORPHIDAE.html

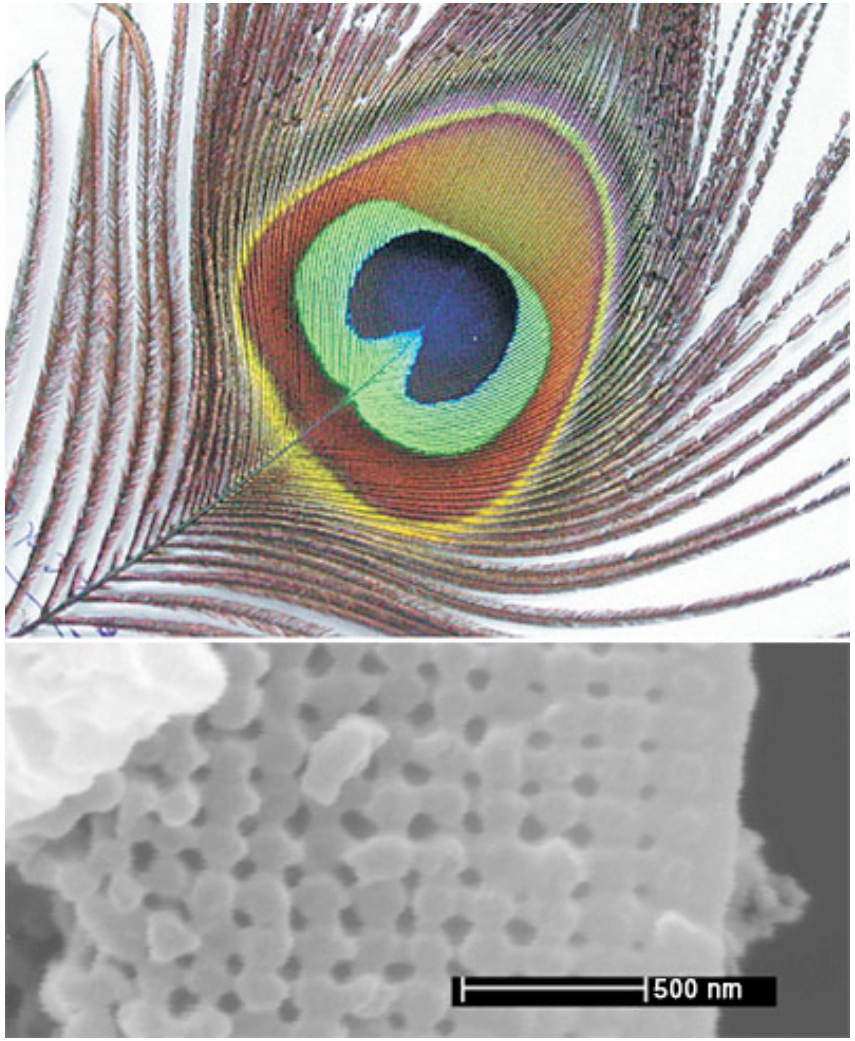
wing scale:

P. Vukosic *et al.*, *Proc. Roy. Soc: Bio. Sci.* **266**, 1403 (1999)



B. Gralak *et al.*, *Opt. Express* **9**, 567 (2001)

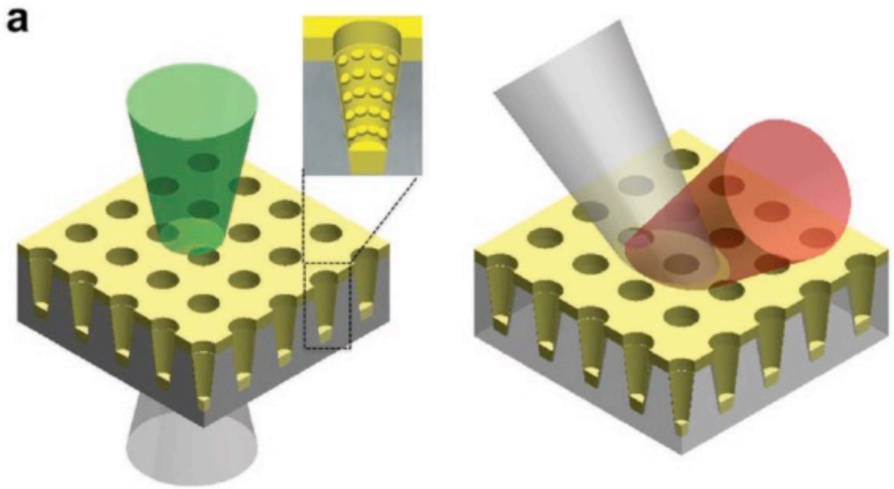
Peacock feather



J. Zi *et al*, *Proc. Nat. Acad. Sci. USA*, **100**, 1257(2003)
[figs: Blau, *Physics Today* **57**, 18 (2004)]

…and in Art

The Lycurgus cup is on display at the British Museum in London. (Images: British Museum)

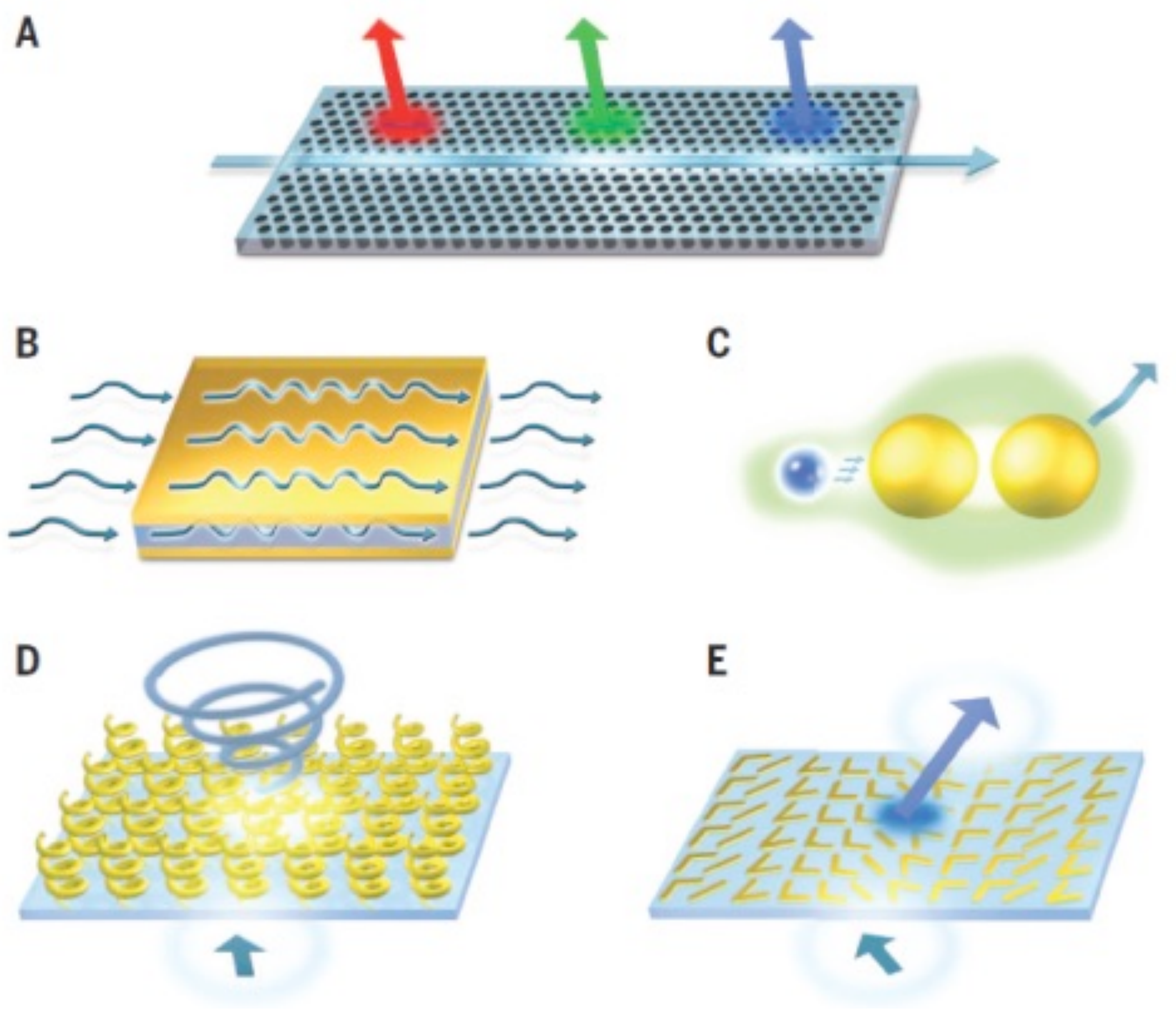


Adv. Opt. Mat. 2013, 1, 68-76

The cup contains metallic nanoparticles that absorb all wavelengths except red light.

Nanophotonic architectures

-Photonic crystals (A)
-Plasmonics (B)
-Nanoantennas (C)
-Metamaterials (D)
-Metasurfaces (E)

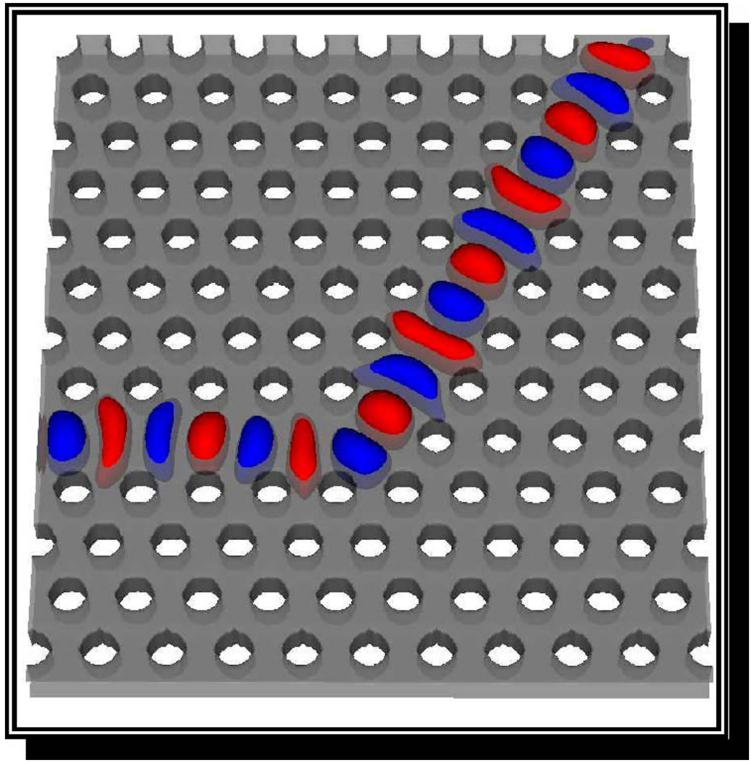


Science 348, 516-521 (2015)

Photonic Crystals

-Dielectric materials, sub-wavelength periodicity
-Photonic band gap
-Band structure engineering provides exquisite control over light dispersion

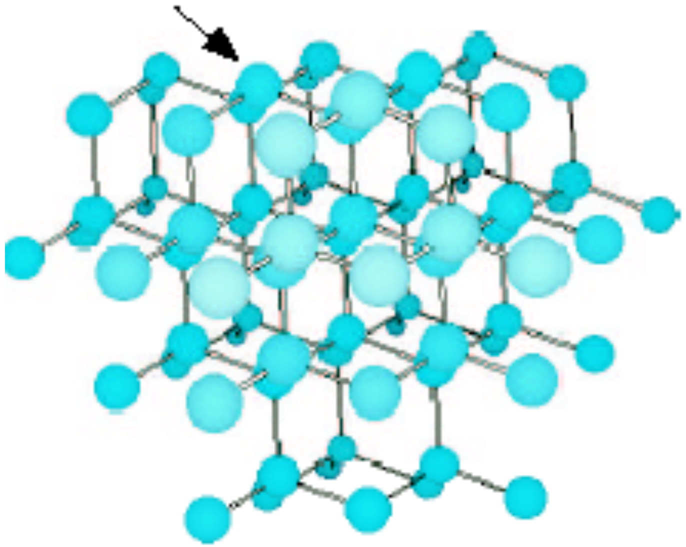
- Slow Light
- Light confinement in nanocavities
- Switch, filter, modulator



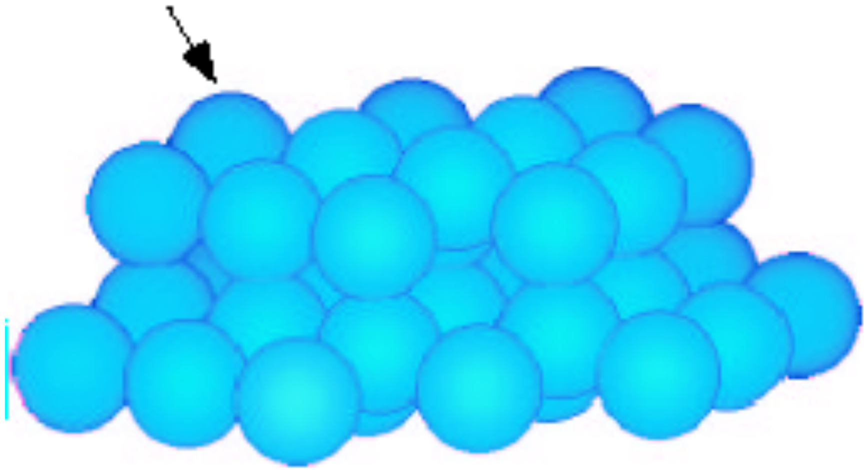
Electronic and Photonic Crystals

Periodic Medium

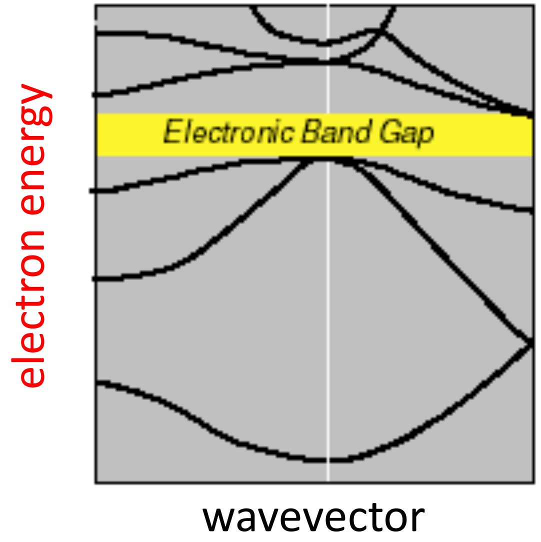
atoms in diamond structure

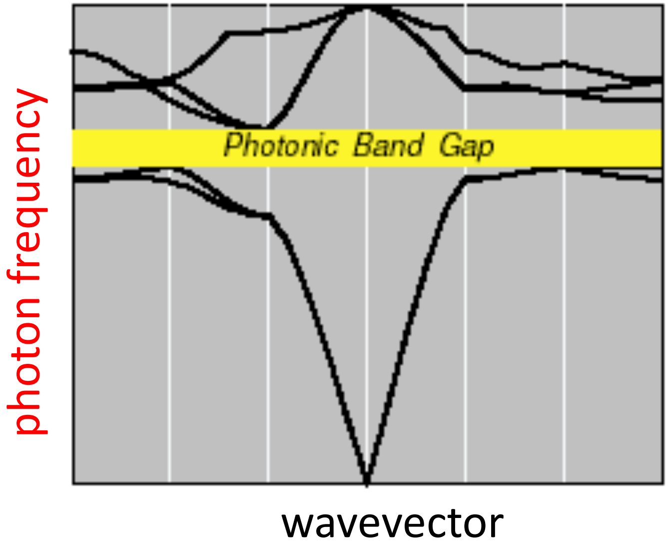


dielectric spheres, diamond lattice

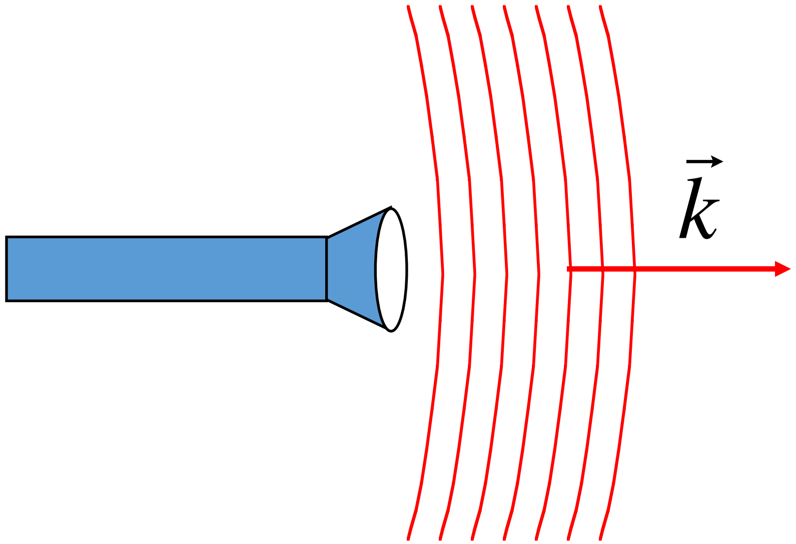


Bloch waves: **Band Diagram**





It is known that light scatters when collides with atoms

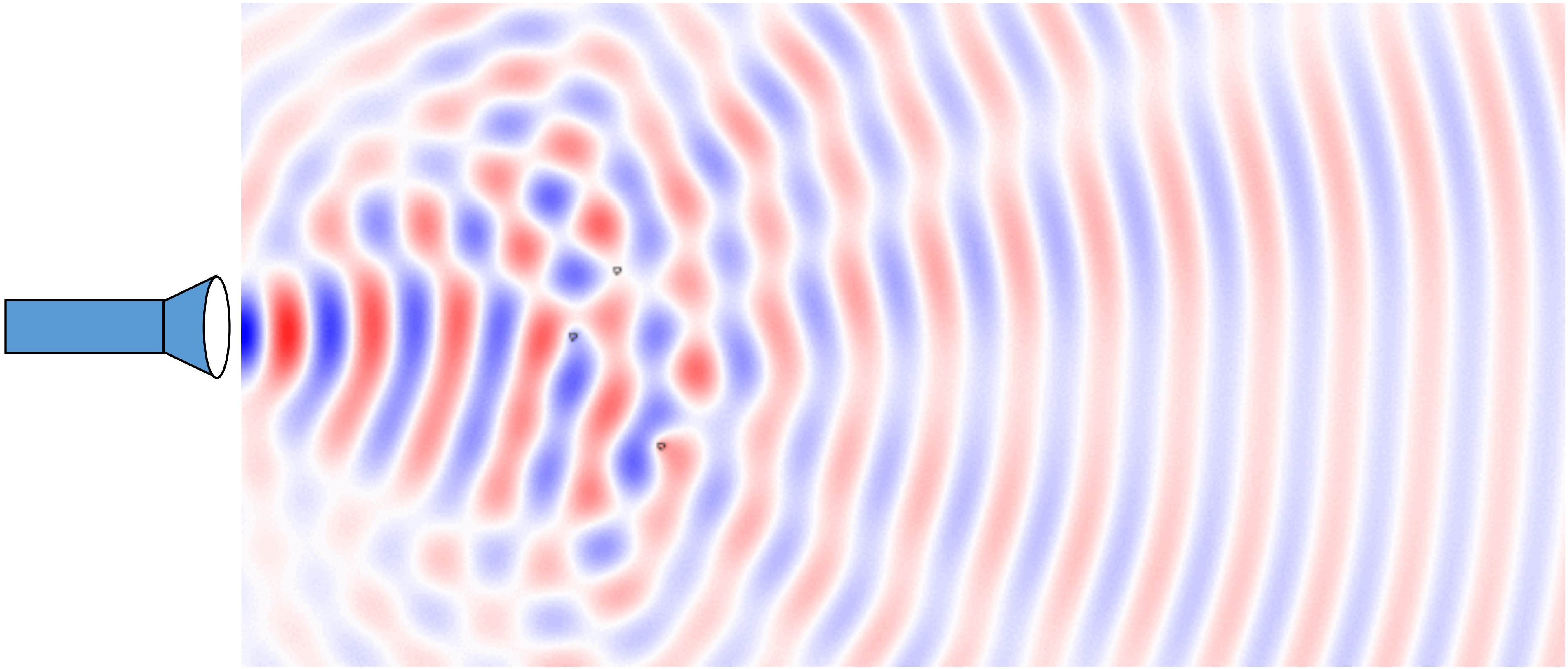


planewave

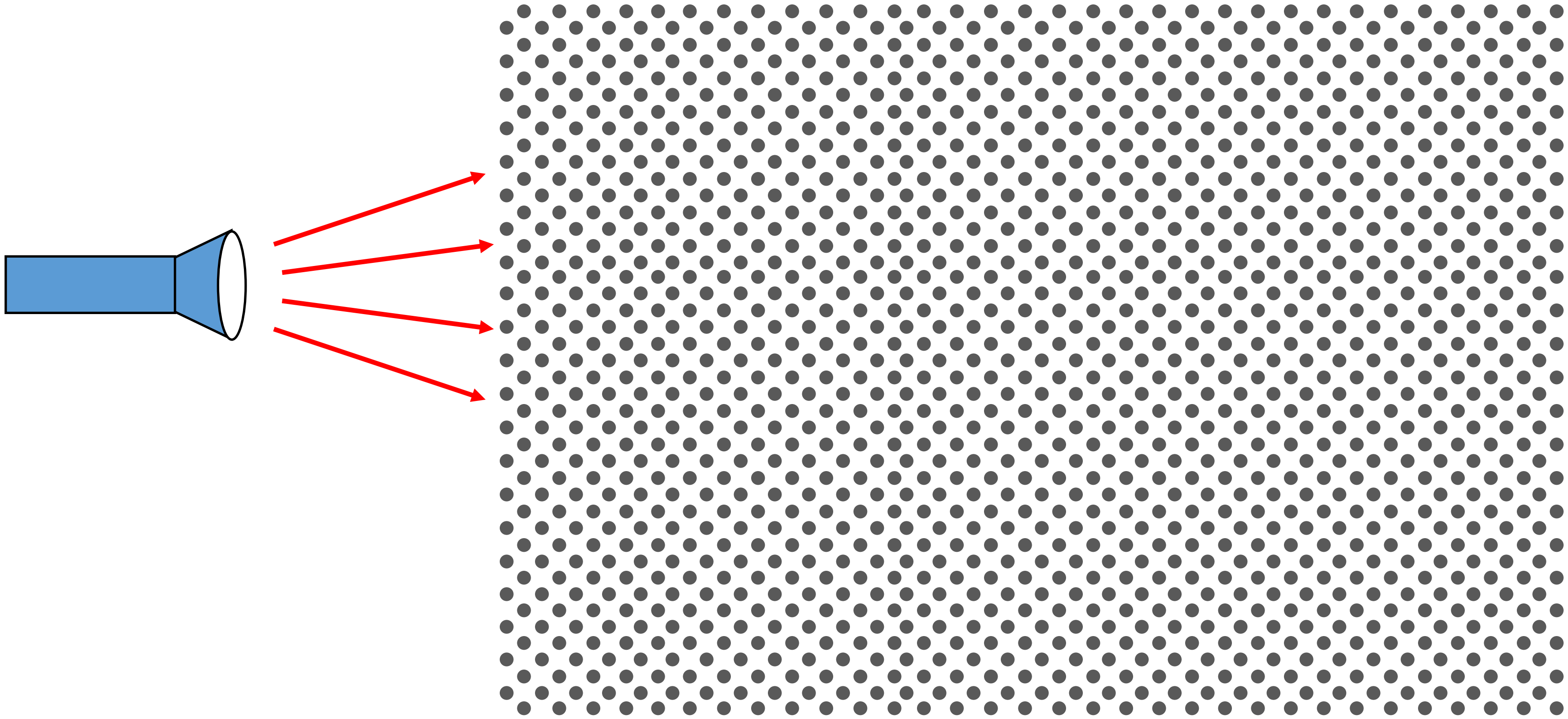
$$\vec{E},\vec{H} \sim e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

$$\left|\vec{k}\right| = \omega / c = \frac{2\pi}{\lambda}$$

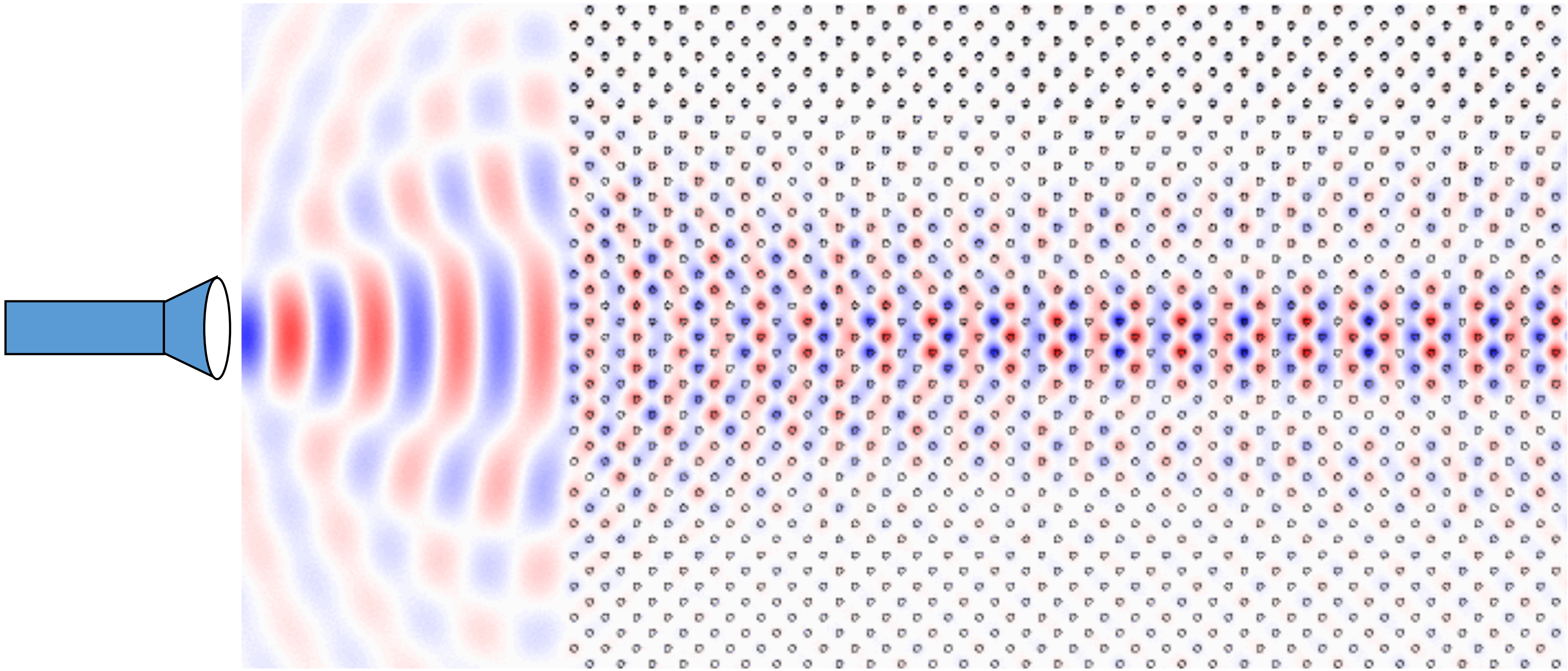
here: scattering off three particles of silicon



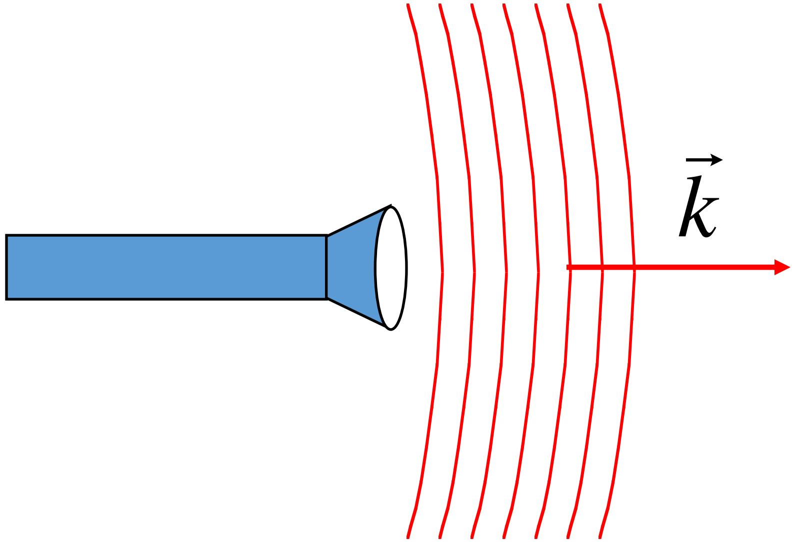
What about many “organized” particles?



Bloch Theorem states that waves in a periodic medium can propagate without scattering



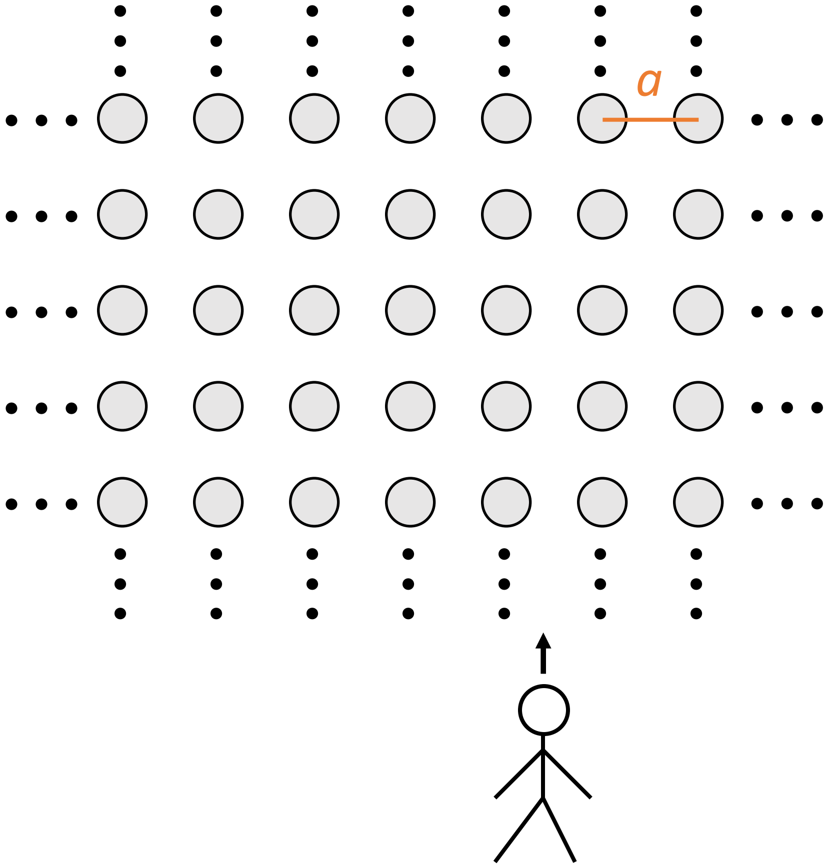
light seems to form several *coherent beams*
that propagate *without scattering*
… and almost *without diffraction* (*supercollimation*)



planewave

$$\vec{E},\vec{H} \sim e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

$$\left|\vec{k}\right| = \omega / c = \frac{2\pi}{\lambda}$$



for most λ, beam(s) propagate through crystal without scattering (scattering cancels coherently)

...but for some λ (~ 2*a*), light cannot propagate: a photonic band gap

What happens?

Periodicity comparable to incident light wavelengths can be responsible for constructive interferences among scattered light by every lattice point. The phenomenon is exactly the same as it happens in diffraction gratings.

Periodically patterned media Vs. Random media

Si wafer top side with devices

Patterned roughness

Random roughness

Resonant reflectivity at given incident angle and wavelengths

Light is scattered in all directions, there is no evidence of frequency or angle dependent response induced by random roughness

Maxwell Equations

Maxwell equation in linear, isotropic, non-magnetic and homogeneous media can be written as:

$$\vec{\nabla} \times \vec{E} = -\mu \frac{\partial}{\partial t} \vec{H}$$

$$\vec{\nabla} \times \vec{H} = \varepsilon \frac{\partial}{\partial t} \vec{E} + \vec{J}$$

$$\vec{\nabla} . \varepsilon \vec{\mathrm{E}} = \rho$$

$$\vec{\nabla} . \vec{\mathrm{H}} = 0$$

In optical materials there is no free charges or currents included so:

$$J = 0$$

$$\rho = 0$$

$$\vec{\nabla} \times \vec{E} = -\mu \frac{\partial}{\partial t} \vec{H}$$

$$\vec{\nabla} \times \vec{H} = \varepsilon \frac{\partial}{\partial t} \vec{E}$$

$$\vec{\nabla} . \vec{\mathrm{E}} = 0$$

$$\vec{\nabla} . \vec{\mathrm{H}} = 0$$

Bloch Theorem

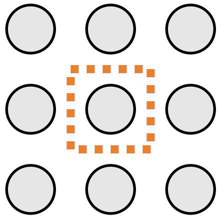
The Bloch-Floquet theorem tells us that, for a Hermitian eigenproblem **whose operators are *periodic* functions of position**, the solutions can always be chosen of the form $e^{i\vec{k}\vec{r}}$

$$\vec{H}(\vec{r},t) = e^{i(\vec{k}.\vec{r}-\omega t)}\vec{H}_{\vec{k}}(\vec{r})$$

Solutions are a **periodic envelope function multiplied by a plane wave**

Corollary 1: **k** is conserved, *i.e.* no scattering of Bloch wave

Corollary 2: $\vec{H}_{\vec{k}}$ given by finite unit cell, so ω are discrete ω_n(**k**)



Mathematical development

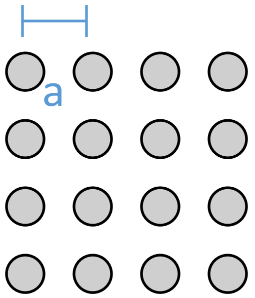
http://www.pbglink.com/software.html

Free

- Meep http://ab-initio.mit.edu/wiki/index.php/Meep
- MIT Photonic Band http://ab-initio.mit.edu/wiki/index.php/MIT_Photonic_Bands
- CAMFR http://camfr.sourceforge.net
- Geo-Radar http://carsten.welcomes-you.com/radarfdtd
- GFDTD http://gfdtd.kldp.net
- BigBoy http://sourceforge.net/projects/bigboy
- EMP3 http://www.fieldp.com/emp3/emp3.html
- EM Explorer http://www.emexplorer.net/news.htm
- GprMax http://www.gprmax.org/

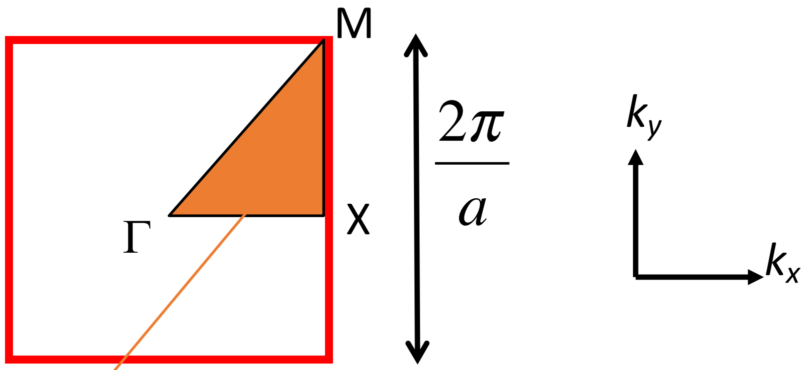
Commercial

- Photon Design (CrystalWave, OmniSim, FIMMPROP) http://www.photond.com/
- COMSOL http://www.comsol.com/
- RSoft http://www.rsoftinc.com/
- ISE / Synopsis http://www.synopsys.com/
- EM photonics http://www.emphotonics.com/
- Optiwave http://www.optiwave.com/
- Apollo Photonics http://www.apollophoton.com/apollo/
- SEMCAD http://www.iis.ee.ethz.ch/research/bioemc/em_simulation_platform.en.html
- Lumerical http://www.lumerical.com/

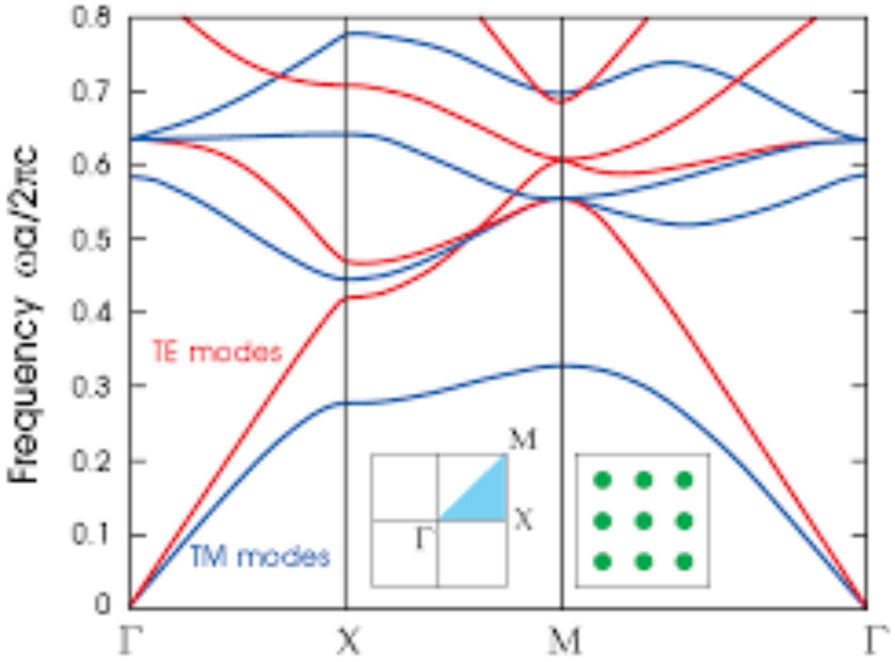


Bloch's theorem: solutions are periodic in **k**

first Brillouin zone
= minimum |**k**|
"primitive cell"

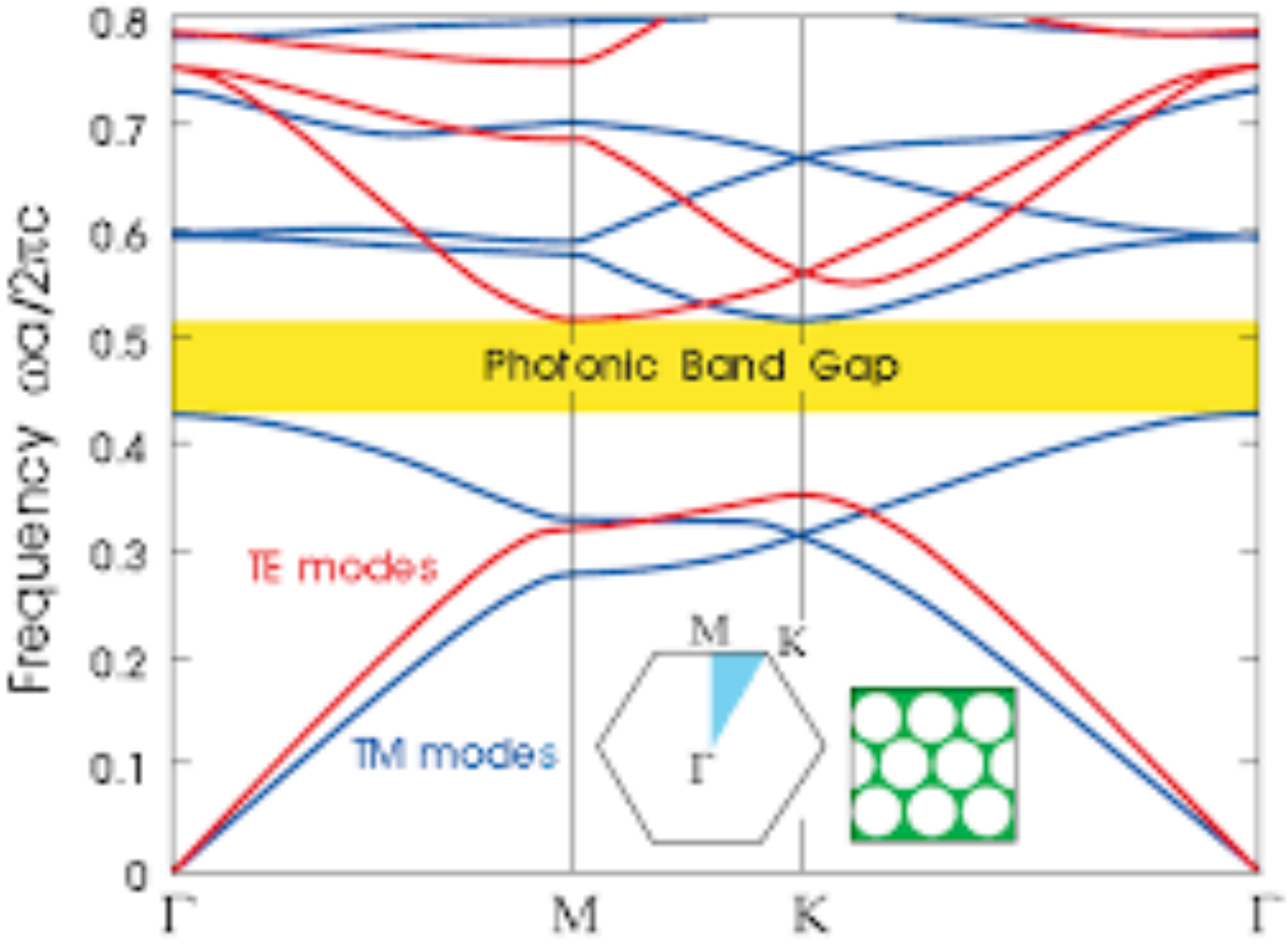


irreducible Brillouin zone: reduced by symmetry



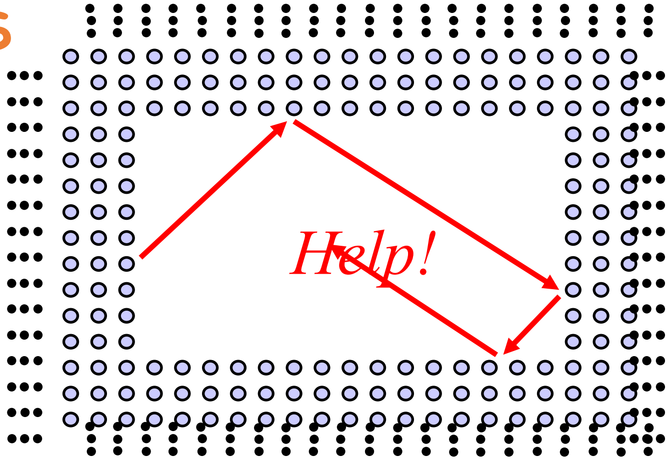
Square lattice of holes do not give photonic band gaps...

In hexagonal lattice we do have a complete photonic band gap!



2D PCs: what can we do with them?

APPLICATIONS



RESONANT CAVITIES

When a point defect is created in a photonic crystal, it is possible for that defect to pull a light mode into the band gap.

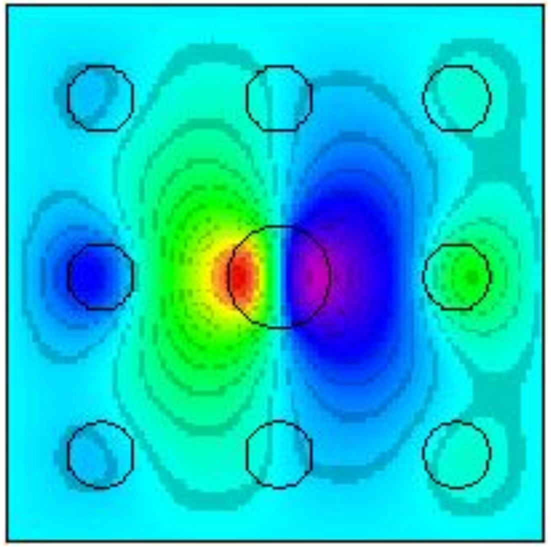


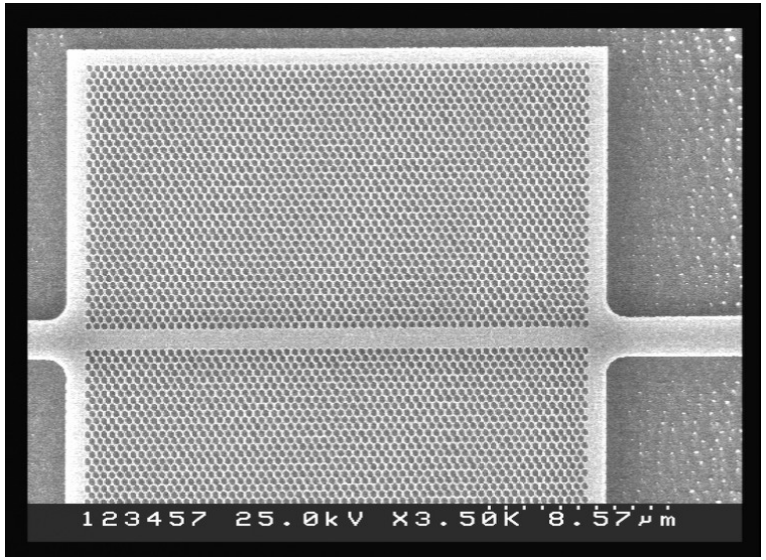
Image: MIT Joannopoulos

Because such a state is forbidden from propagating in the bulk crystal => it is trapped => the mode decays exponentially into the bulk.

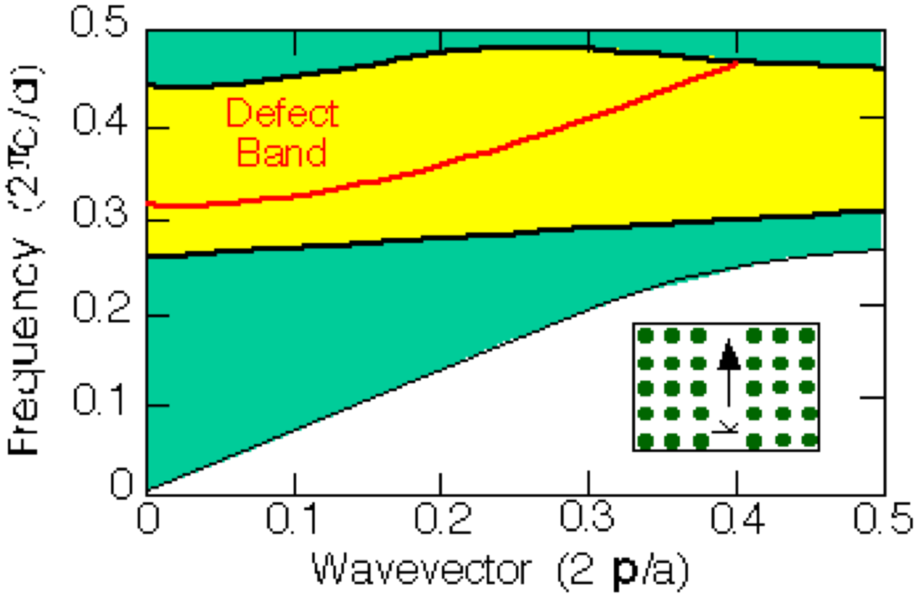
Such a point defect is a resonant cavity. It can be used for example to produce a very sharp filtering through resonant tunneling.
They can also be used as laser enhancement;
By changing the size and/or the shape, its frequency can easily be tunned

2D PCs and Applications

PHOTONIC CRYSTAL WAVEGUIDES



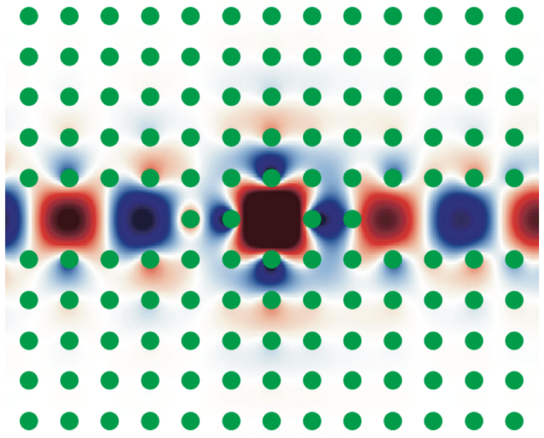
Photonic crystal waveguide
Courtesy of Dr. Martin Kamp
University of Wuerzbug
Germany



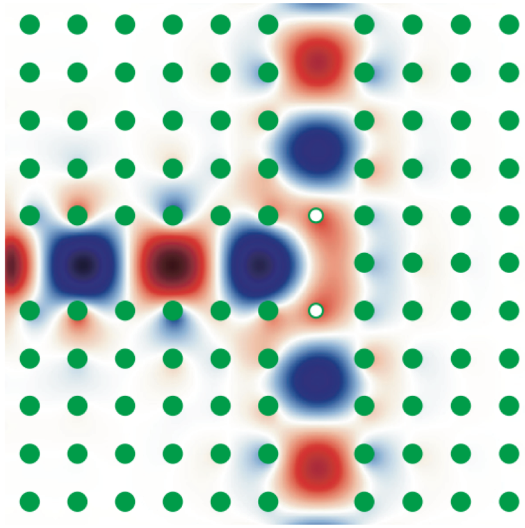
Band diagram of a waveguide
courtesy of Joannnopoulos, MIT

Line defects: when a line defect is introduced a photonic crystal waveguide may be created. Such waveguides can guide light at optical wavelengths with minimal propagation losses.

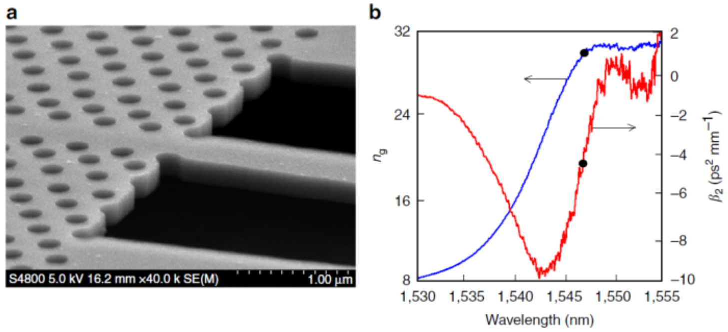
resonant filters



waveguide splitters

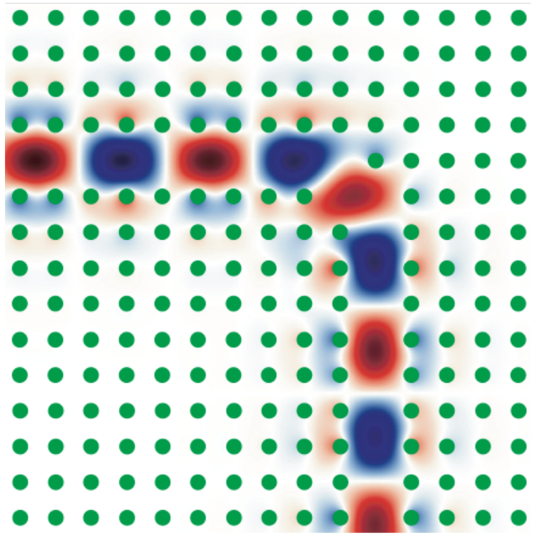


Experimental results

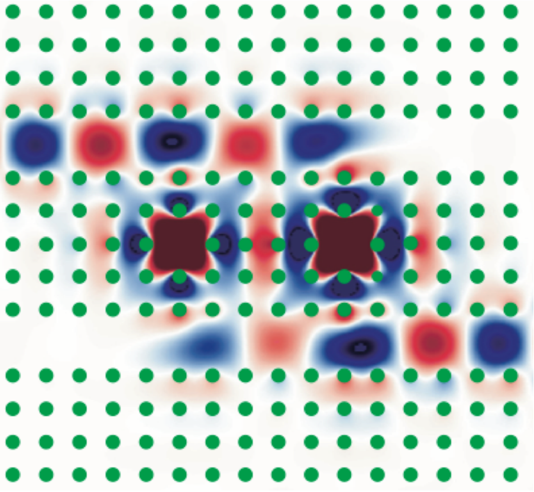


Nature Comm. 5, 3160 (2014)

high-transmission sharp bends



channel-drop filters



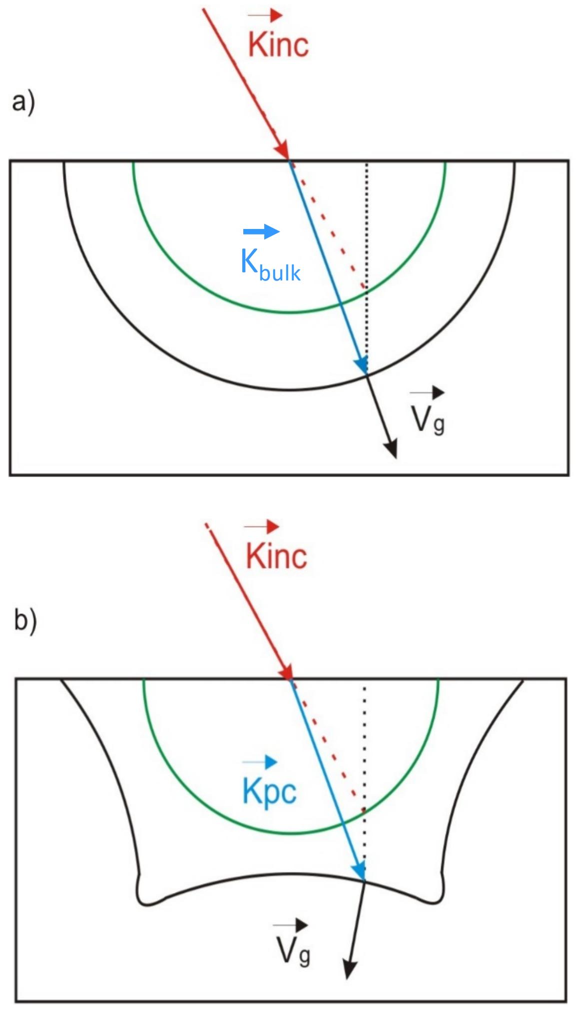
SUPERPRISMS

Group velicity : $\mathbf{V_g}$ = **k .** ω

Phase velocity : $V_\phi = \omega / |k|$ avec $|k| = 2\pi / \lambda$

Propagation direction of a beam is given by the group velocity

Isofrequency curves are the index profile curves n(x,y,z) for a given frequency



Isotropic material

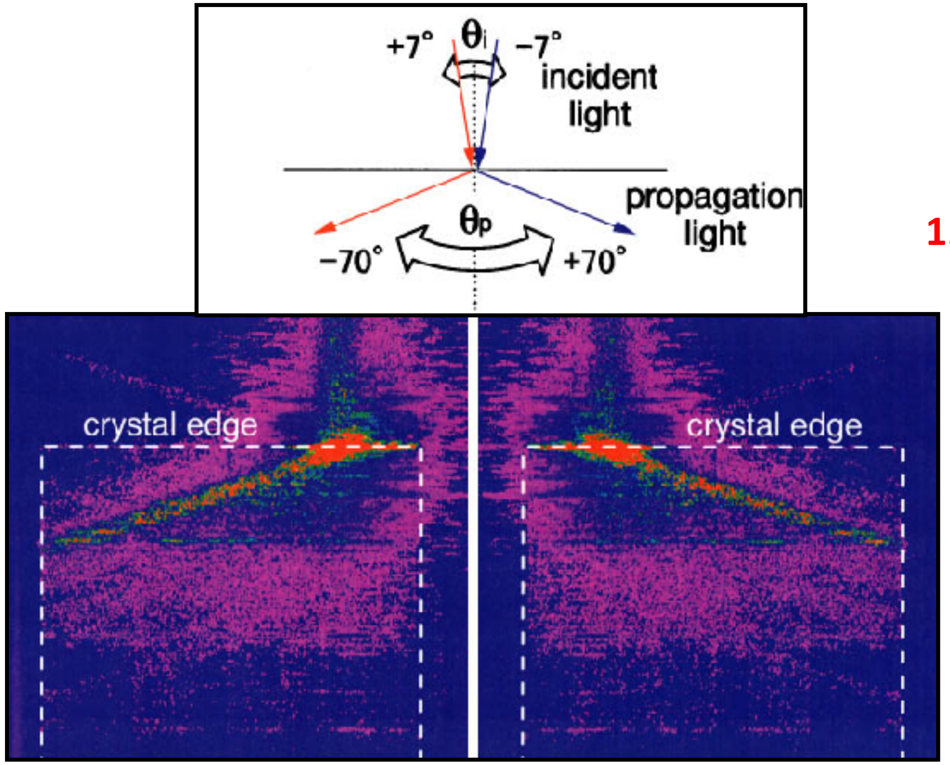
$\mathbf{V_g}$ and **k** have the same direction and depend on the propagation direction and the wavelegth.

Photonic crystals

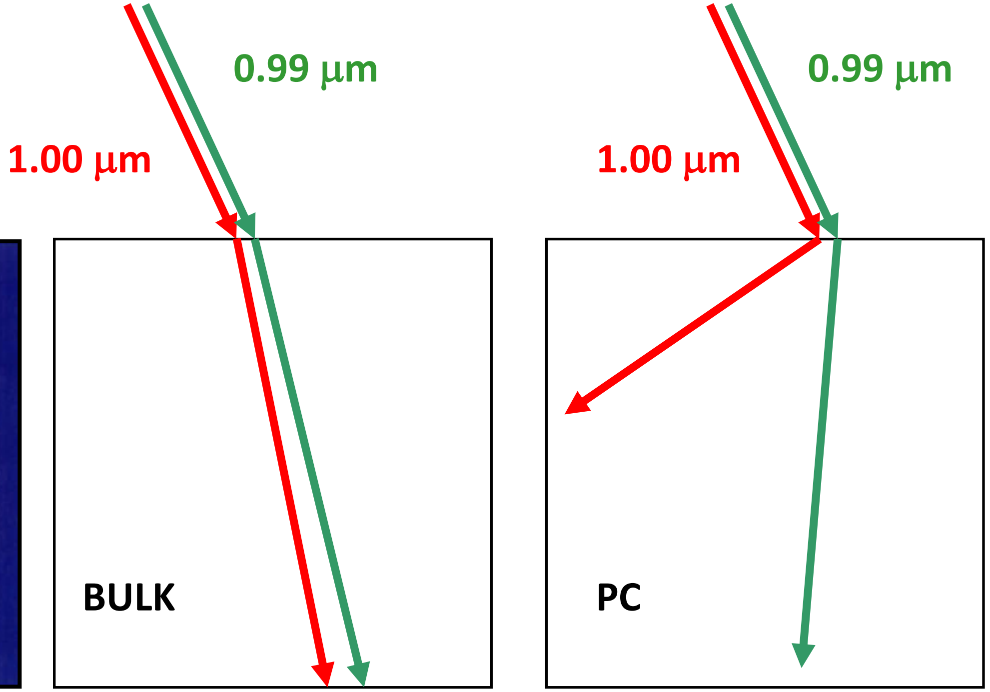
Due to the periodic variations of the dielectric constant:
In a PV $\mathbf{V_e}=\mathbf{V_g}$ (velocity of energy $\mathbf{V_e}$) [1].

$\mathbf{V_g}$ and **k** may have different directions.

[1] P. Yeh «Electromagnetic propagation in birefingent layered media », Jour. Opt. Soc. Am., **69**, 742-756, 1979.



Light propagation on a 3D PC Si/SiO_2 (500µm*500µm) as a fonction of the incidence angle



Light propagation as a fonction of wavelength on a 2D PC Si/SiO_2 [2]

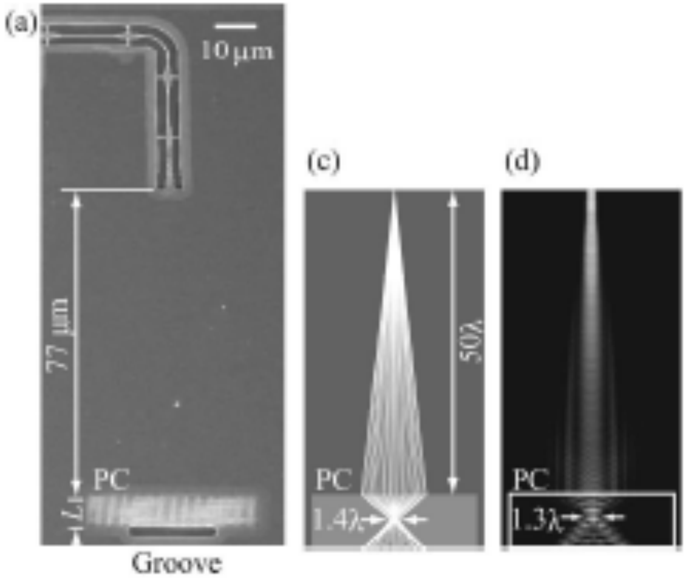
[1] H. Kosaka et al « Superprism phenomena in photonic crystals », Phys.Rev. B, **58**, n°16, 1998

[2] S. Massy : « Contribution à la réalisation de fonctions optiques à base de cristaux photoniques sur $LiNbO_3$ » Université de Limoges, thèse n°4-2004

2D PCs and Applications

Superlens

-PC can behave as if they have a negative index of refraction
-This property is interesting for subwavelength imaging
-How? Optical waves in a periodic lattice can have a Bloch state with its wave vector and group velocity in opposite



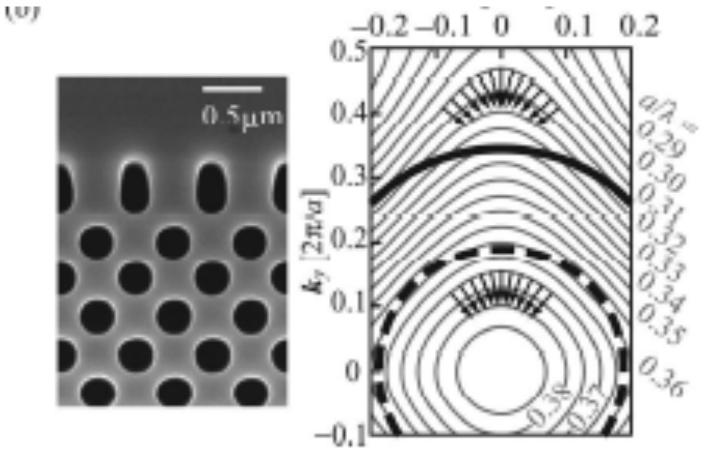
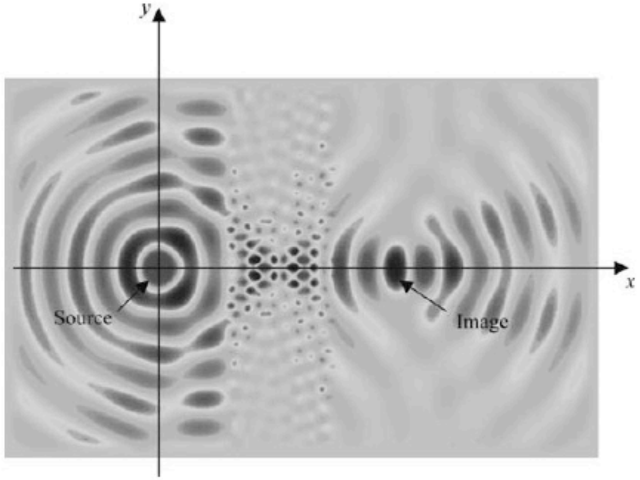


Fig. 1. Device structure and theoretical characteristics.



0. The snapshots of the electric field of a point source and its image across a photonic crystal ith elliptic air-holes.

Belhadji et al, Optical and Quantum Electronics, 37 pp575 (2005).

Matsumoto et al., Opt. Lett. 31, 2786 (2006)

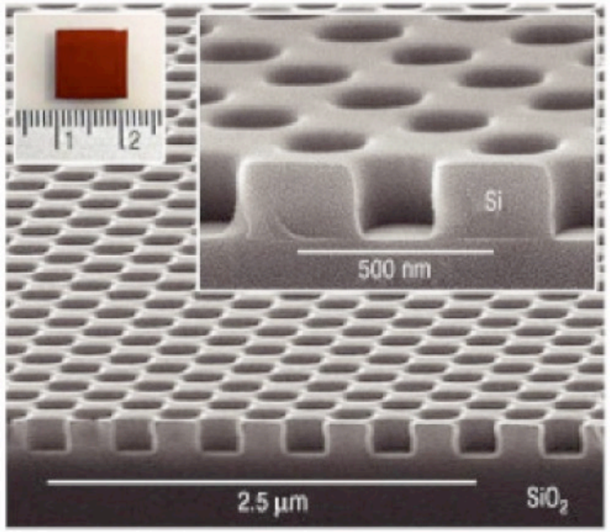
2D PCs and Applications

Autocollimation

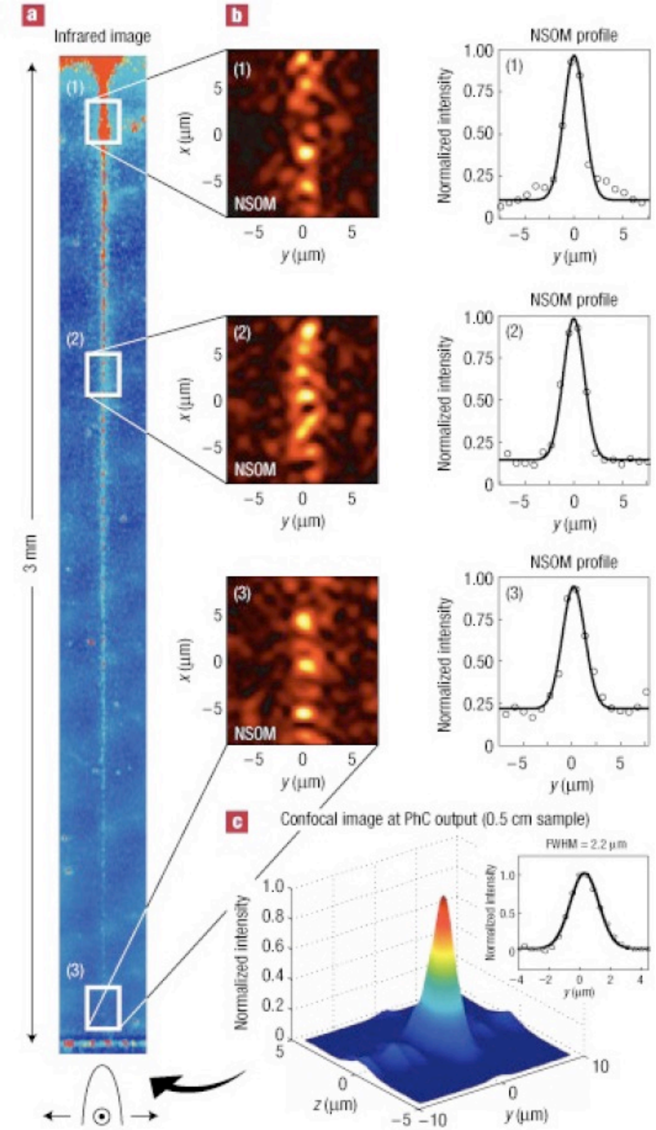
Achieving centimetre-scale supercollimation in a large-area two-dimensional photonic crystal

PETER T. RAKICH*†, MARCUS S. DAHLEM*, SHEILA TANDON, MIHAI IBANESCU, MARIN SOLJAČIĆ, GALE S. PETRICH, JOHN D. JOANNOPOULOS, LESLIE A. KOLODZIEJSKI AND ERICH P. IPPEN

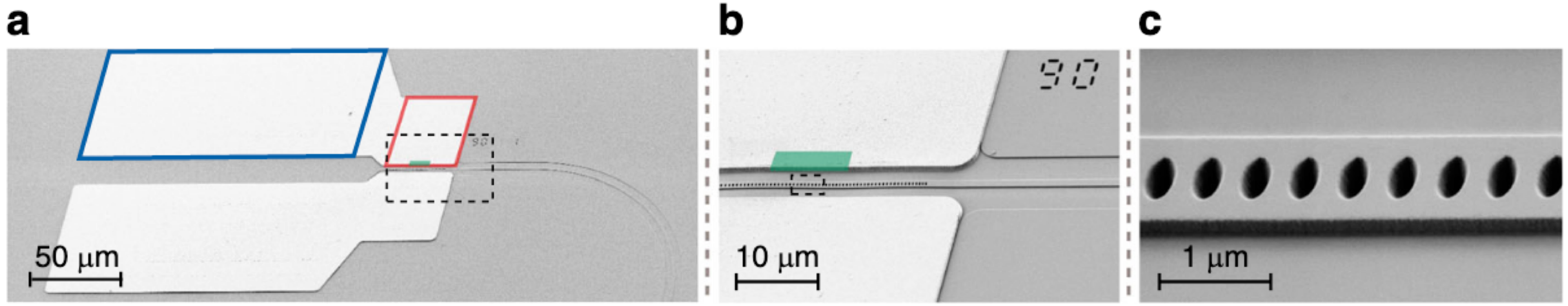
Nature Materials 5, 93–96 (2006)

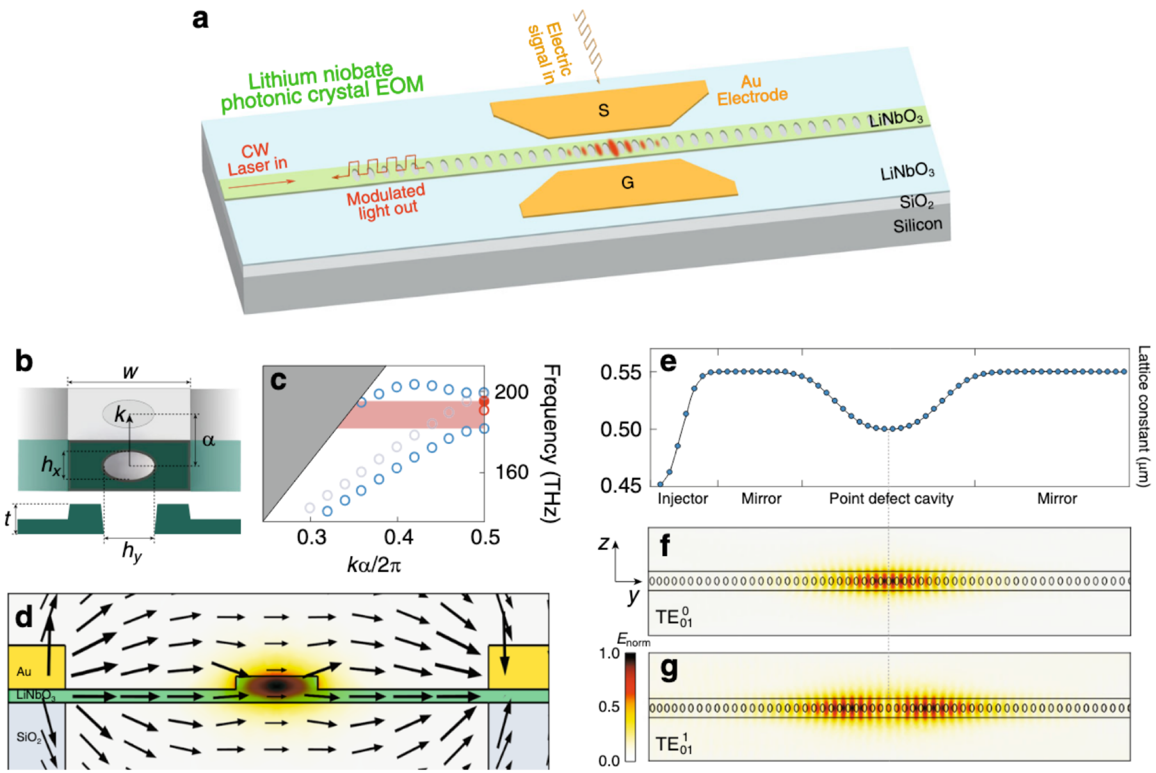


pertes = 3.6 dB/mm



Photonic crystal : Light modulators





Li, M., Ling, J., He, Y. *et al.* Lithium niobate photonic-crystal electro-optic modulator. *Nat Commun* **11,** 4123 (2020).

modulation bandwidth of 17.5 GH

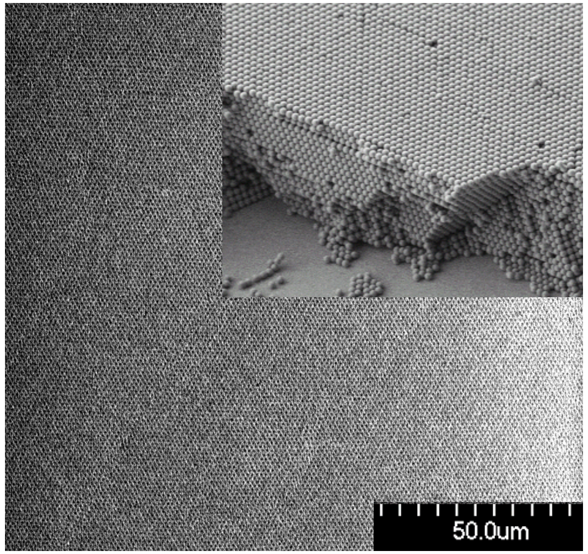
electro-optic modal volume 0.58µm3

3D PCs and Applications

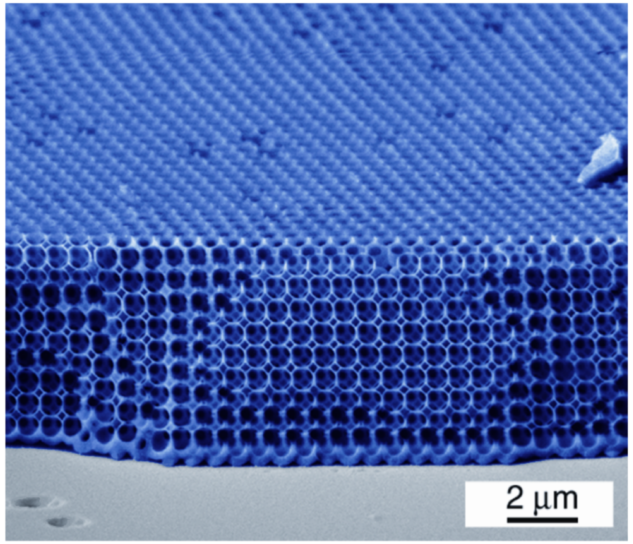
Their fabrication is more complex than that of photonic crystals but their advantage is the omnidirectional confinement.

An interesting example is the colloidal self assembly in which small dielectric spheres in a fluid automatically arrange themselves into close-packed crystalsby surface forces .

These crystals can be back filled with a high index material out of which the original spheres are dissolved to form inverse-opal crystals with a complete gap.

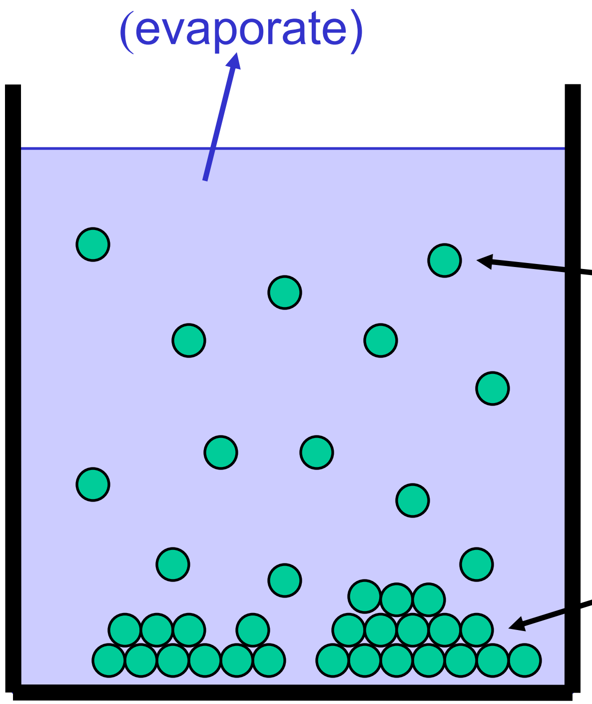


OPALS, fig. courtesy D. Norris, UMN



Y. A. Vlasov et al., Nature 414, 289 (2001)

3D PCs and Applications



microspheres (diameter < 1μm)

silica (SiO_2)

sediment by gravity into close-packed fcc lattice!

Photonic crystals in medicine (drug delivery, biosensing, photodynamic therapy,…)

Polymer Replicas of Photonic Porous Silicon for Sensing and Drug Delivery Applications, Science (2003)

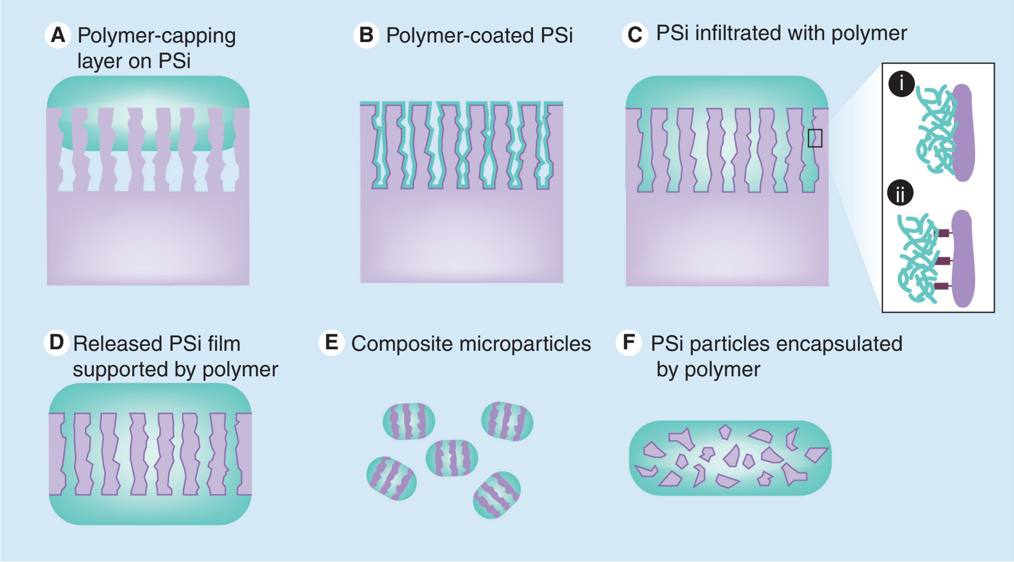
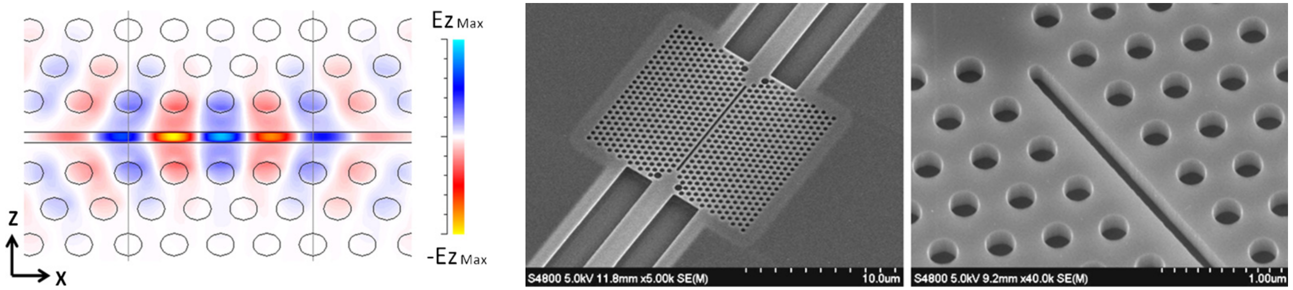


Figure 1. Strategies for design of polymer-porous silicon hybrids. (A–F) Depict different formats of hybrid device design as described above each illustration. Inset illustrates interfacial chemistry where polymer is **(i)** not attached to PSi and **(ii)** is attached to a chemical modification layer on the surface area of the PSi. Schematics are not drawn to scale.
PSi: Porous silicon.

Photonic Crystals for Chemical Sensing and Biosensing (Angewandte Chemie)

Slotted photonic crystal cavities with integrated microfluidics for biosensing applications
M.G. Scullion∗, A. Di Falco, T.F. Krauss



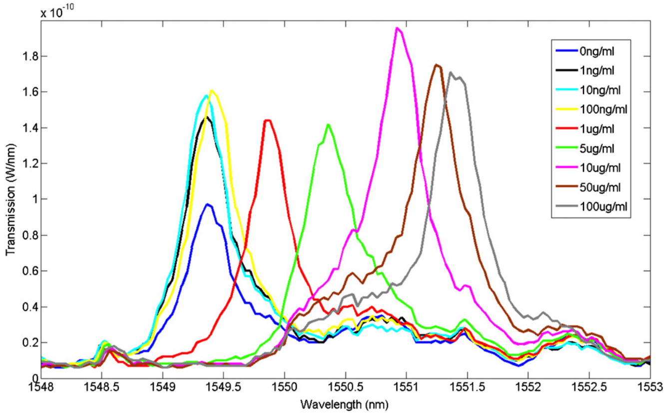
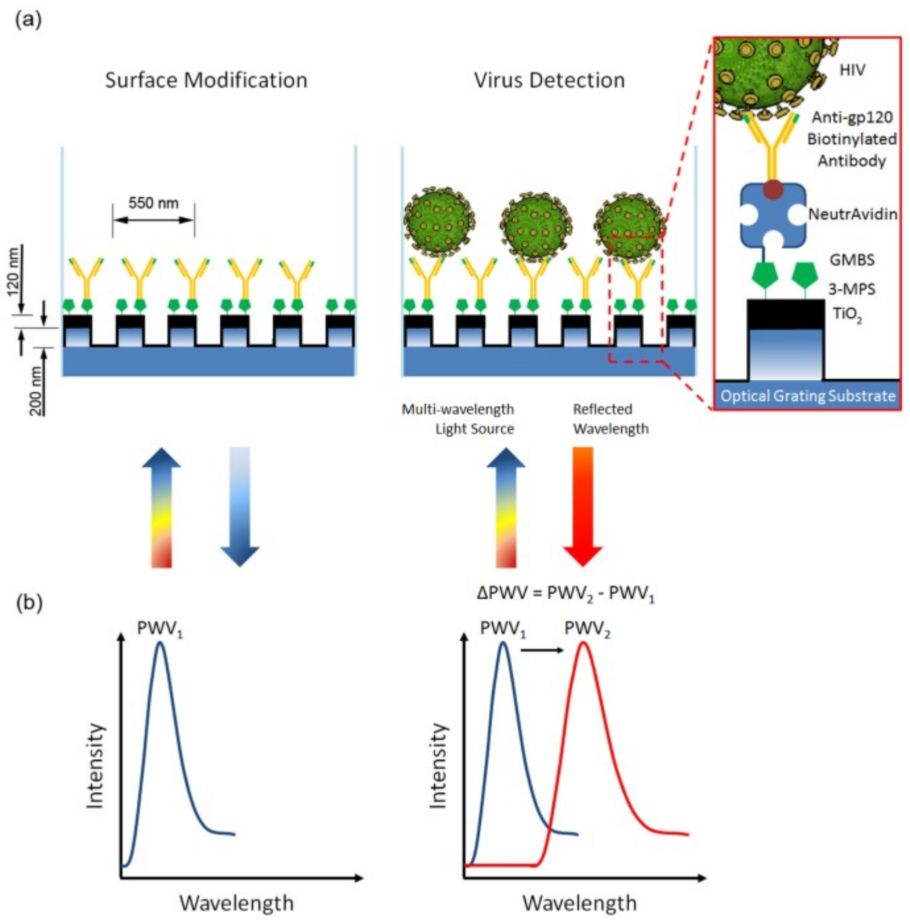
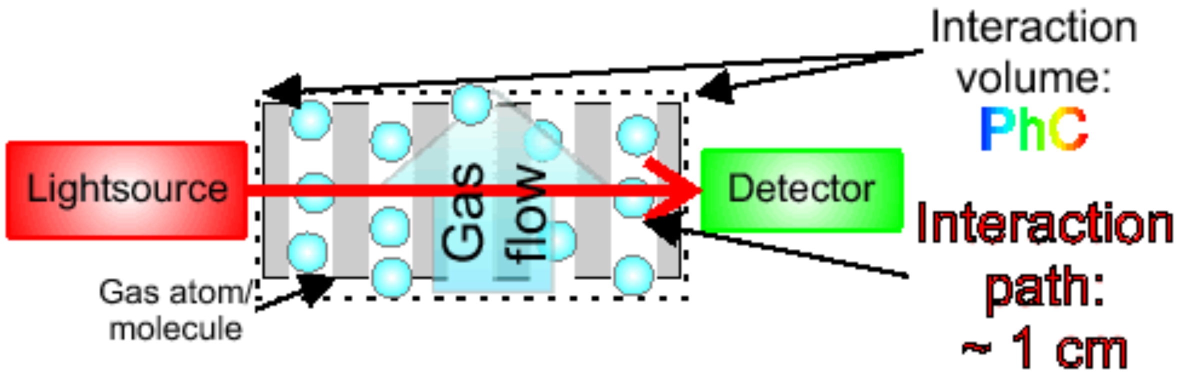


Fig. 5. Cavity peaks recorded at each concentration of dissolved avidin.

Photonic crystals for gas sensors





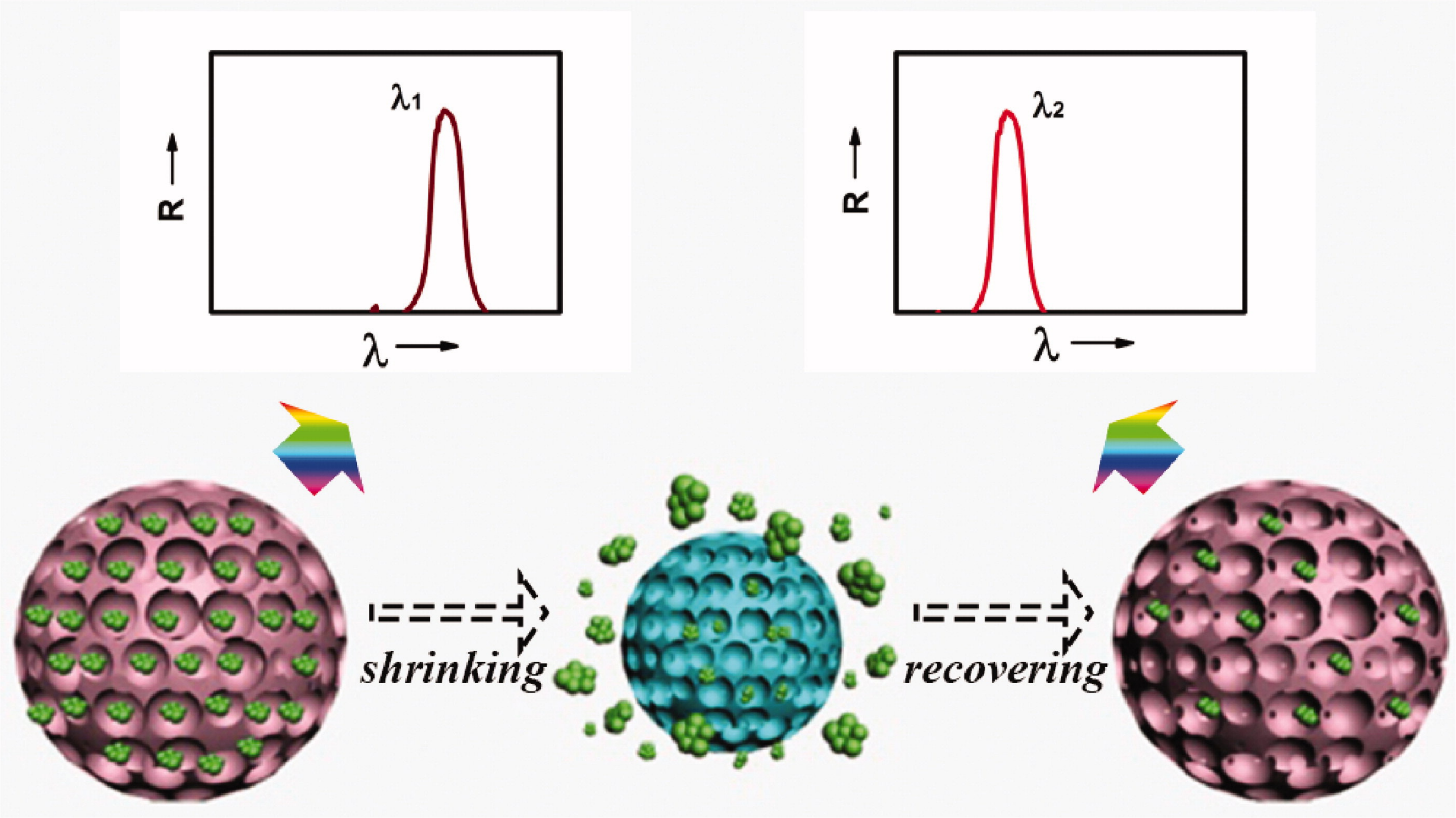
PC materials have attracted more and more attention in the area of biochemistry and biomedicine because of their high sensitivity, selectivity and ability for real-time monitoring

Shafiee, H., Lidstone, E., Jahangir, M. *et al.* Nanostructured Optical Photonic Crystal Biosensor for HIV Viral Load Measurement. *Sci Rep* **4,** 4116 (2014)

DRUG DELIVERY

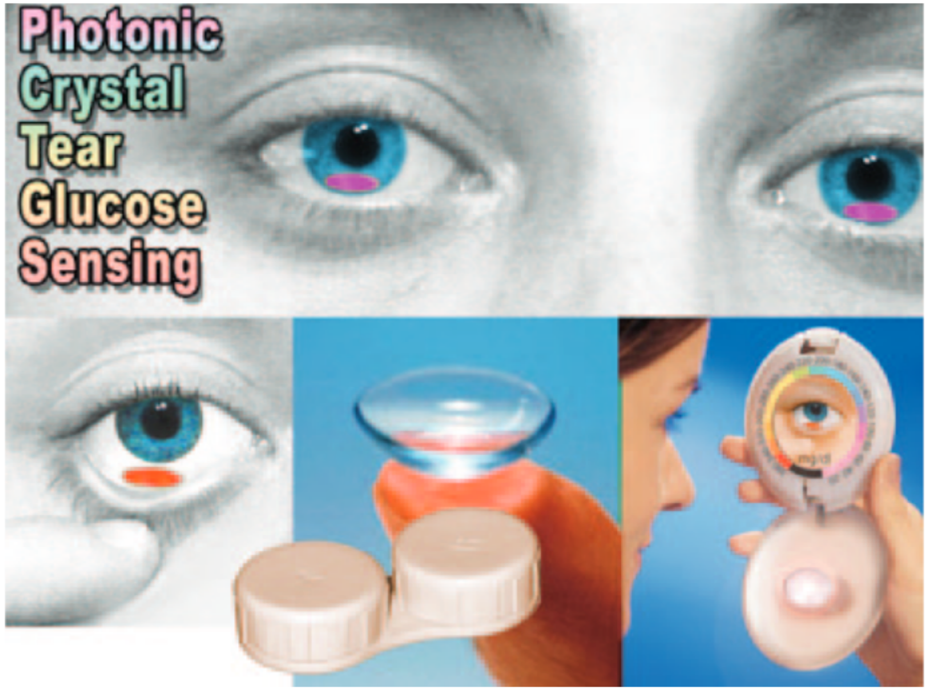
Zhang B, Cheng Y, Wang H, et al. (2015a). Multifunctional inverse opal particles for drug delivery and monitoring. Nanoscale 7:10590–4

As the pNIPAM hydrogel IO scaffolds shrank and swelled at different temperatures, this could make it possible to control the release of drugs by modulating the environmental temperature. In addition, the reflection wavelength of the hydrogel IO would blue shift when the drug was released. Therefore, the process of drug delivery was effectively detected in real time. Such characteristics make IO particles ideal materials for drug delivery systems.



The ability to diagnose diabetes is one of the most successful applications of PC biosensors to date.

lexeev, Vladimir & Das, Sasmita & Finegold, David & Asher, Sanford. (2005). Photonic Crystal Glucose-Sensing Material for Noninvasive Monitoring of Glucose in Tear Fluid. Clinical chemistry. 50. 2353-60. 10.1373/clinchem.2004.039701.



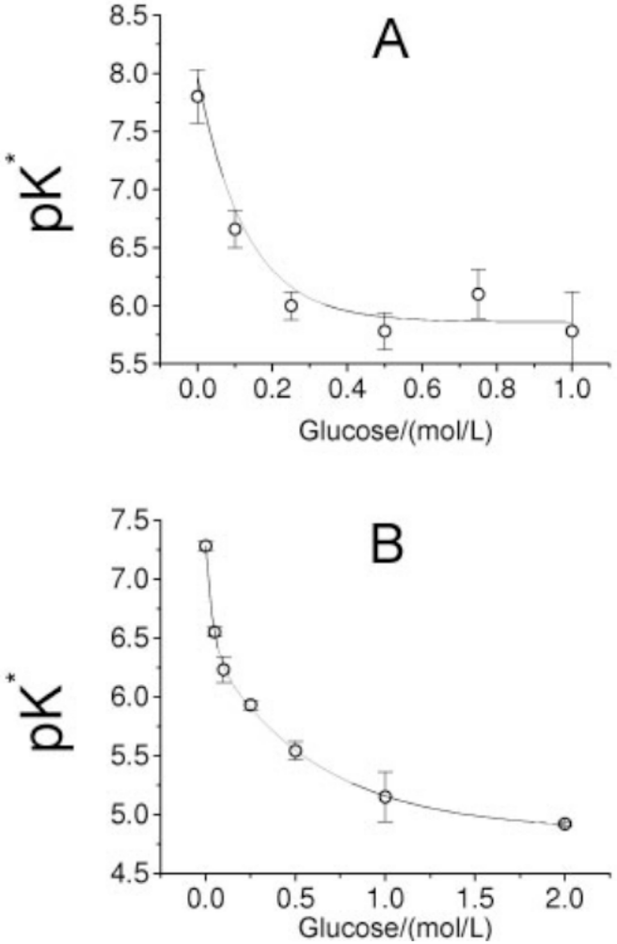
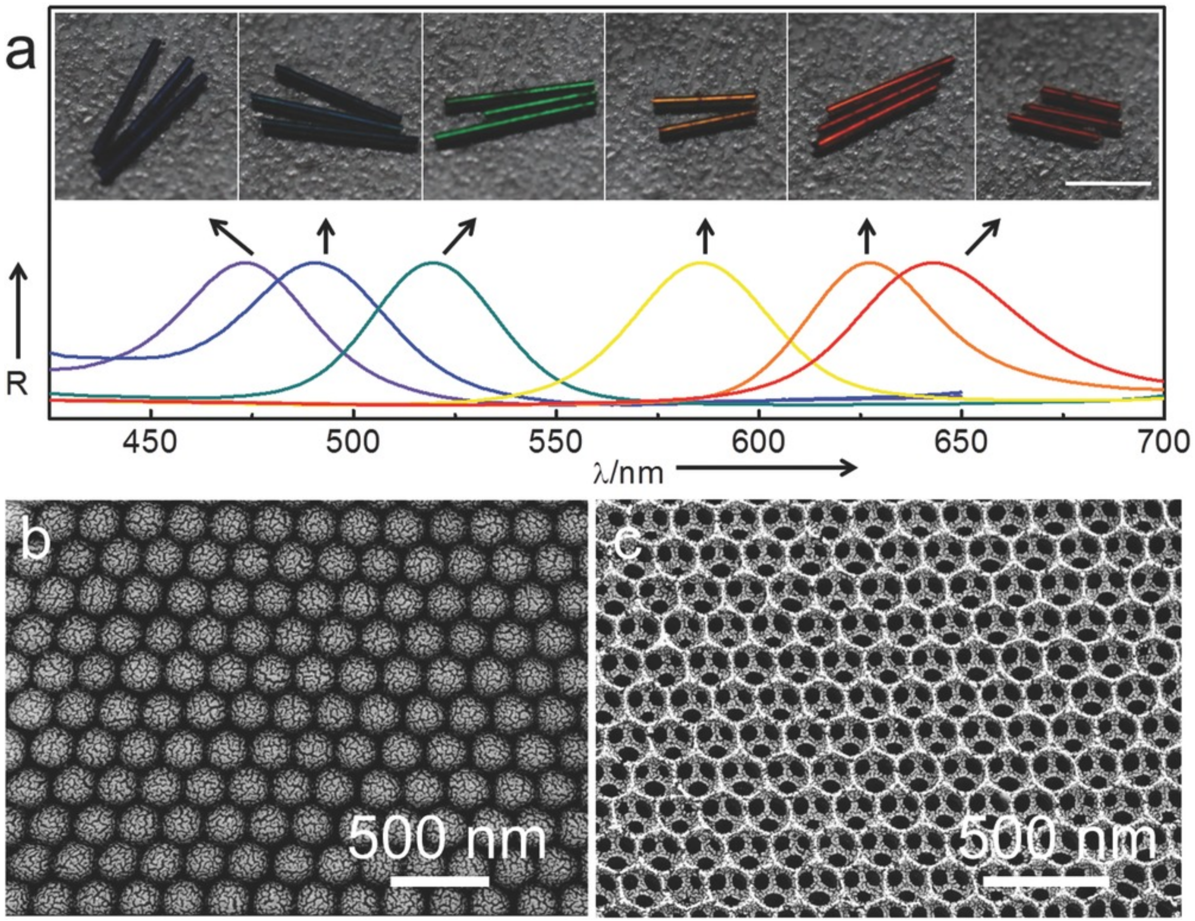


Fig. 4. Effect of glucose concentration on the apparent pK_a values for hydroxylation of 4-acetamido-3-fluorophenylboronic acid (*A*) and 3-fluoro-4-*N*-methylcarboxamide phenylboronic acid (*B*).

The *solid lines* are theoretical best fit of the data as described previously (*8*).

CHOLESTEROL DETECTION

Cholesterol oxidase functionalization of a polymerized crystalline colloidal array. Sensors Actuators B Chem 134:736–42 => When the PCCA was exposed to 5.0 mM cholesterol, the diffraction wavelength was red-shifted ∼60 nm

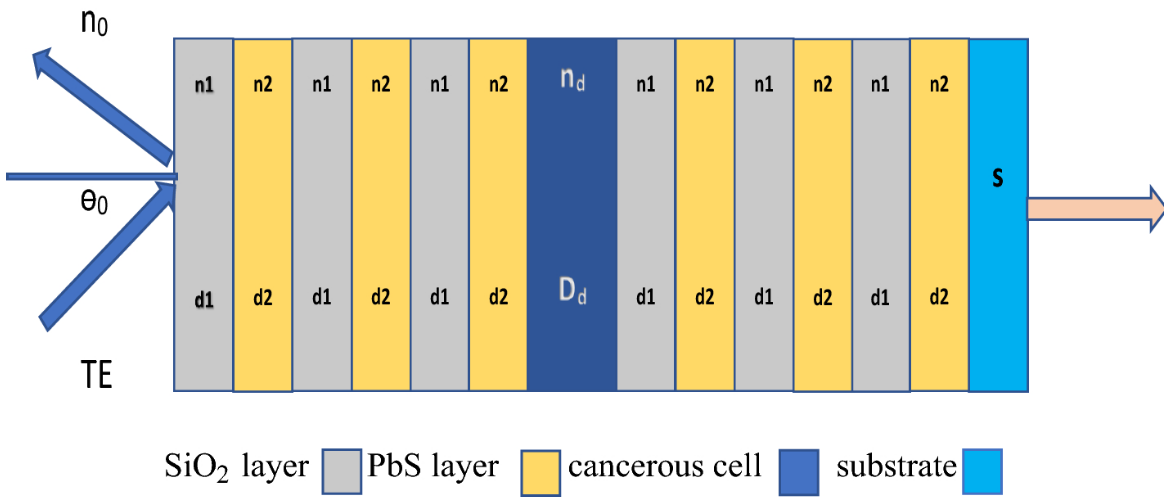


Zhong QF, Xie ZY, Ding HB, et al. (2015). Carbon inverse opal rods for nonenzymatic cholesterol detection. Small 11:5766–70

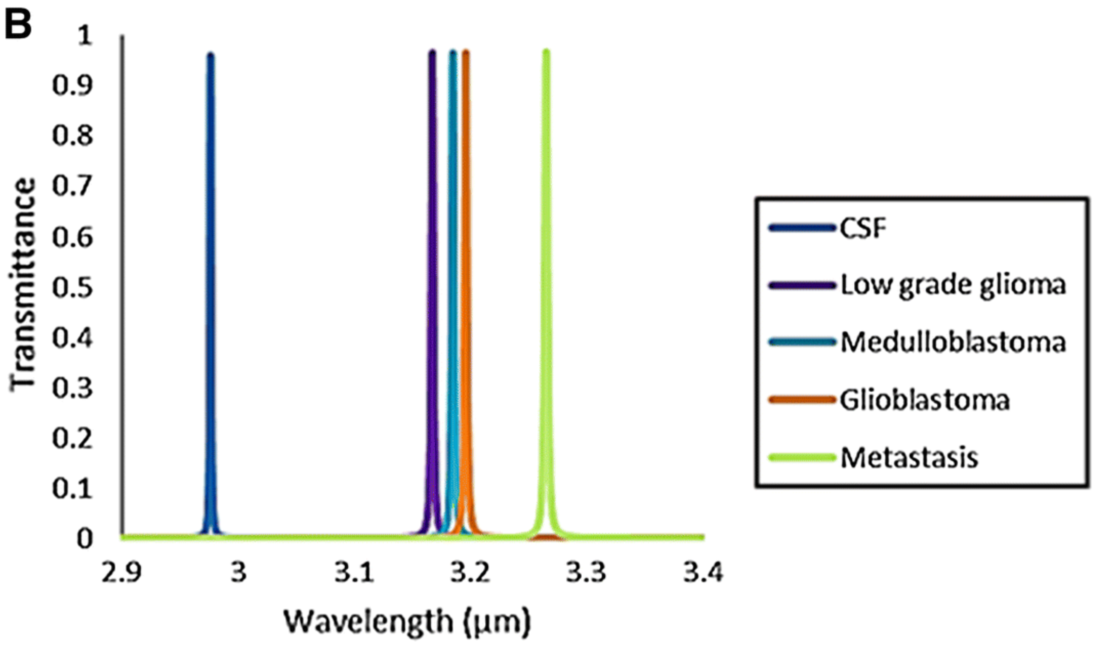
The porous CIORs are permeable to cholesterol but can block out blood cells and proteins that are larger than the pore size, which makes it possible for the detection of cholesterol in human serum and blood.

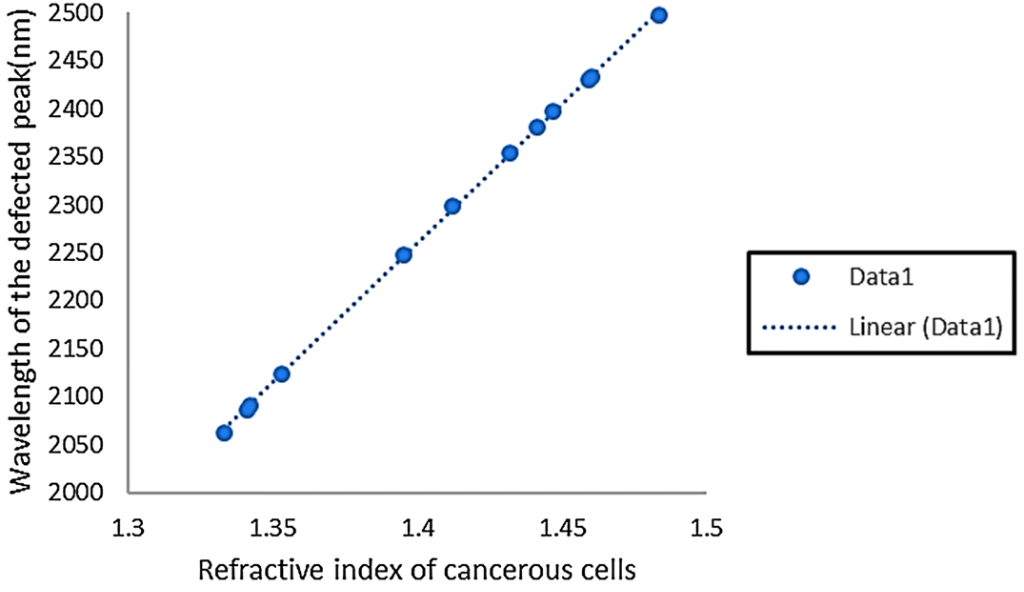
MALIGNANT TUMOR DETECTION

-Malignant tumors are a leading cause of death worldwide
-Early diagnosis and treatment is of vital importance to reduce the mortality of affected individuals

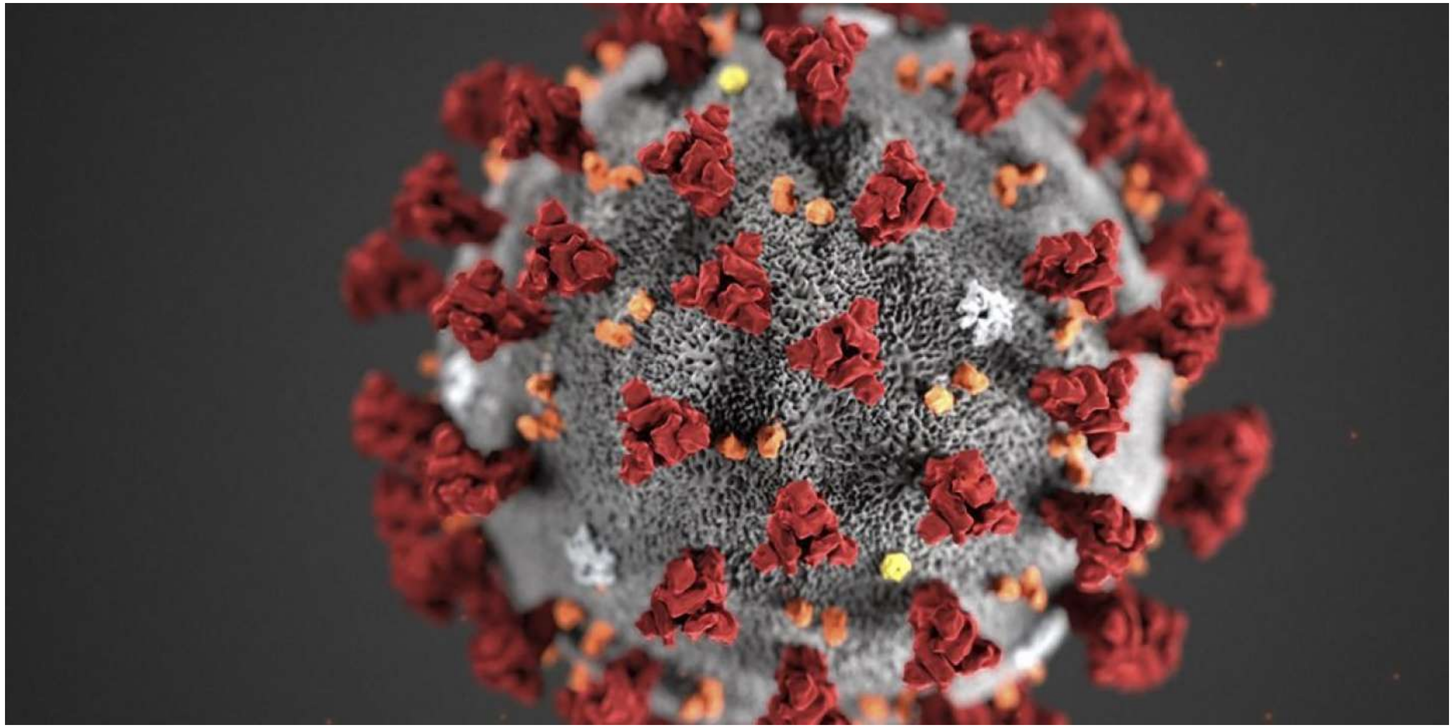


Nouman, W.M., Abd El-Ghany, S.ES., Sallam, S.M. *et al.* Biophotonic sensor for rapid detection of brain lesions using 1D photonic crystal. *Opt Quant Electron* **52,** 287 (2020). https://doi.org/10.1007/s11082-020-02409-2





COVID DETECTION ???



Le virus SARS-CoV-2, responsable de la maladie Covid-19, en image de synthèse, d'après des observations au microscope électronique. CDC / LIZABETH MENZIES / AFP

Maria Soler, Maria Carmen Estevez, Maria Cardenosa-Rubio, Alejandro Astua, and Laura M. Lechuga
ACS Sensors **2020** *5* (9), 2663-2678

Bimodal Waveguide device

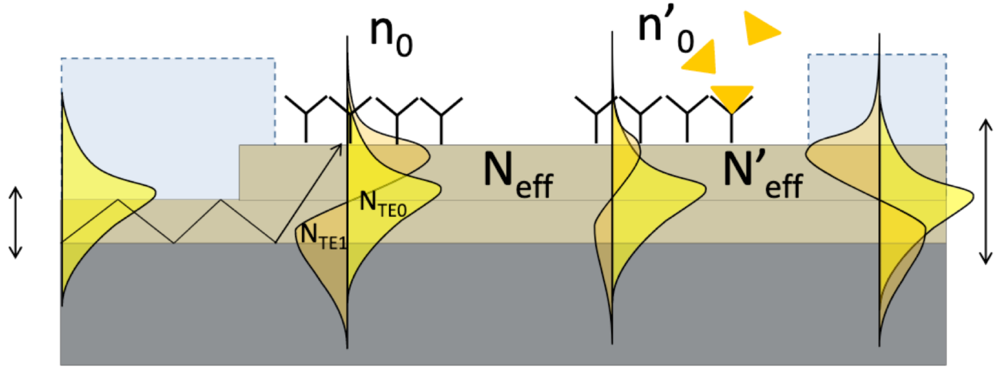
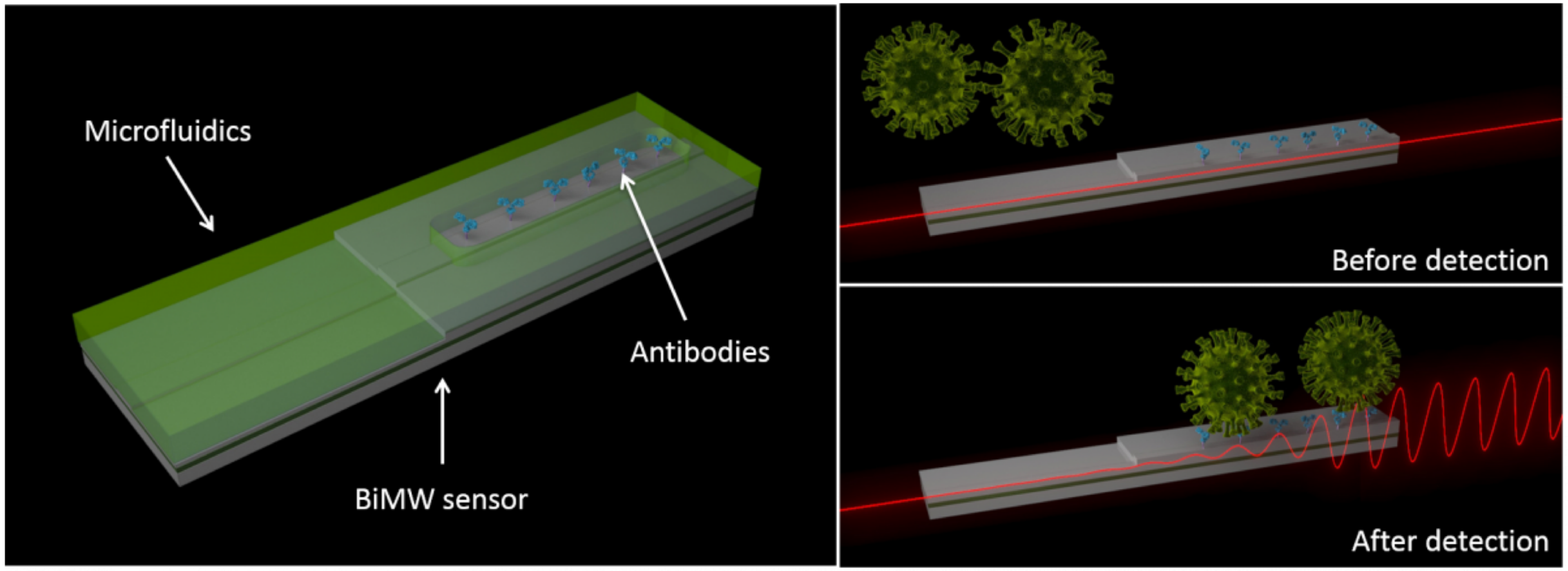


Figure 2.15: Sensing principle of a BiMW biosensor.



Graphic image of the interferometric sensor (credit CONVAT)

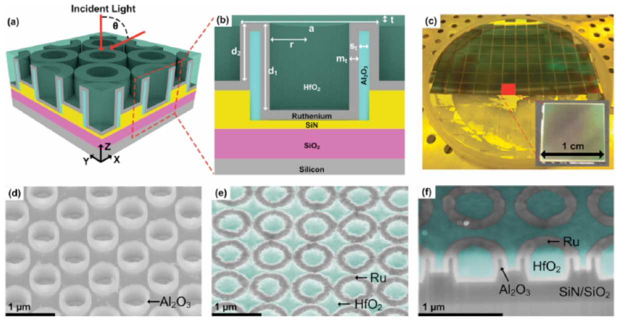
Enabling Ideal Selective Solar Absorption with 2D Metallic Dielectric Photonic Crystals, Adv. Mater. 2014, 26, 8041–8045

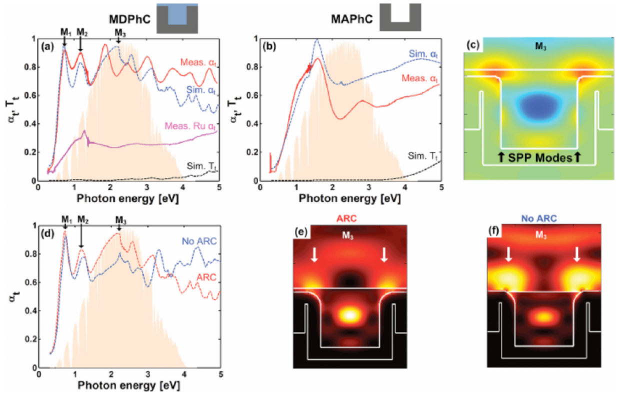
solution which
contains all of the ideal properties of a selective absorber for large-scale and efficient solar energy conversion.

The effective absorption of solar energy requires selective absorption across the solar spectrum, high temperature reliability, omnidirectional absorption, and wafer-scale fabrication for mass scalability.

Here we present our 2D metallic dielectric photonic crystal (MDPhC) structure, which simultaneously demonstrates broadband (visible to near-IR) absorption, omnidirectional absorption, wafer-scale fabrication, and high temperature robustness.

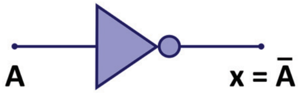
ADVANCED MATERIALS
Materials Views





Logic gates with photonic crystals : photonic crystals + nonlinear effects

NOR

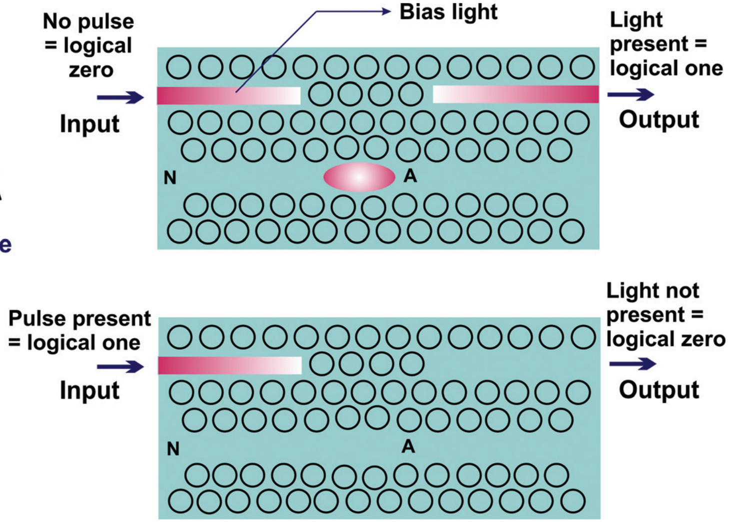


Circuit symbol of NOT gate

A	x = Ā
0	1
1	0

Truth table of NOT gate

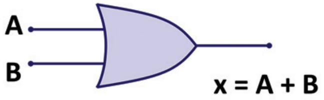
(a)



Implementation of NOT gate in a photonic crystal

(b)

OR

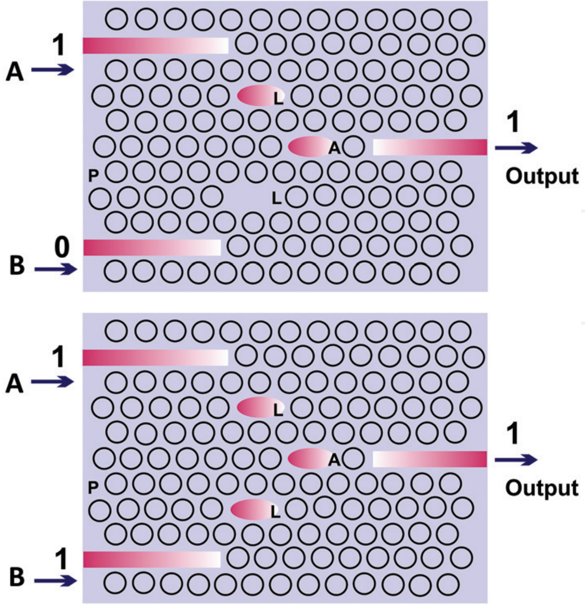


Circuit symbol of OR gate

A	B	x = A + B
0	0	0
0	1	1
1	0	1
1	1	1

Truth table of OR gate

(a)



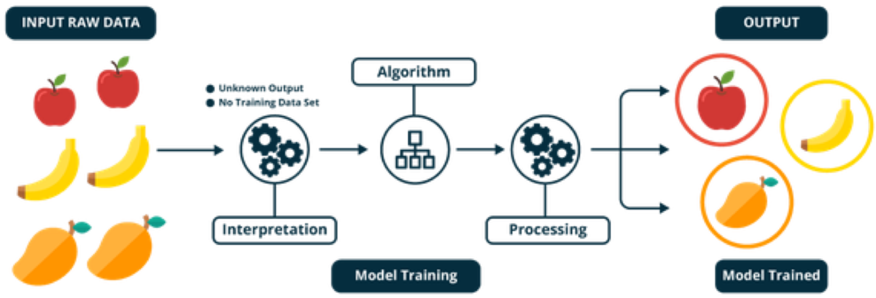
Implementation of OR gate in a photonic crystal

(b)

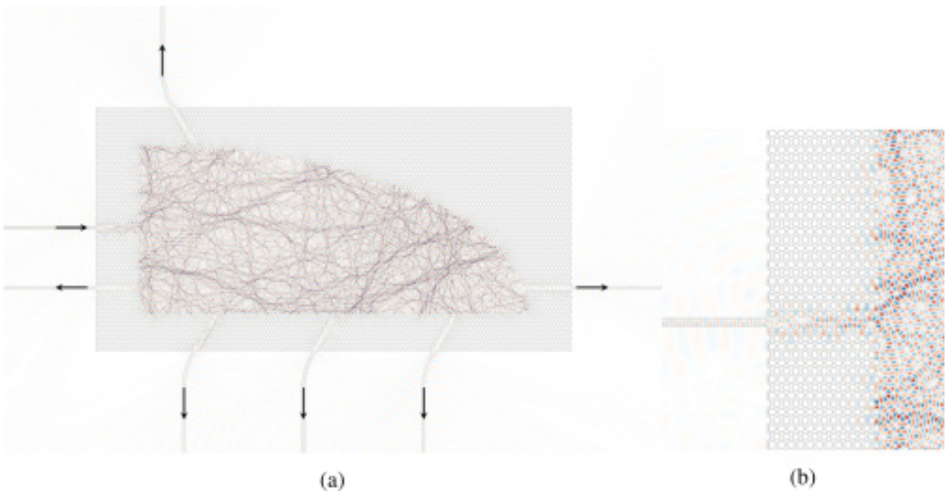
Neuromorphic computing

Floris Laporte, Andrew Katumba, Joni Dambre, and Peter Bienstman, "Numerical demonstration of neuromorphic computing with photonic crystal cavities," Opt. Express 26, 7955-7964 (2018)

Machine learning algorithms use computational methods to "learn" information directly from data without relying on a predetermined equation as a model.



Photonic reservoir computer on a silicon photonic chip.



-The system consists of an on-chip photonic crystal cavity in the shape of a quarter-stadium resonator, which is known to foster interesting mixing of the fields in an almost chaotic manner. -The light is sent through one of the seven standard 450 nm waveguides, which are connected to W1-defects in the wall of the photonic crystal cavity.

-The light inside the cavity subsequently leaks out of the cavity via all of those defects.

-The six other defects are used for readout.

Q1: How you might be able to make a laser that has a diameter one thousandth of your hair's
thickness?

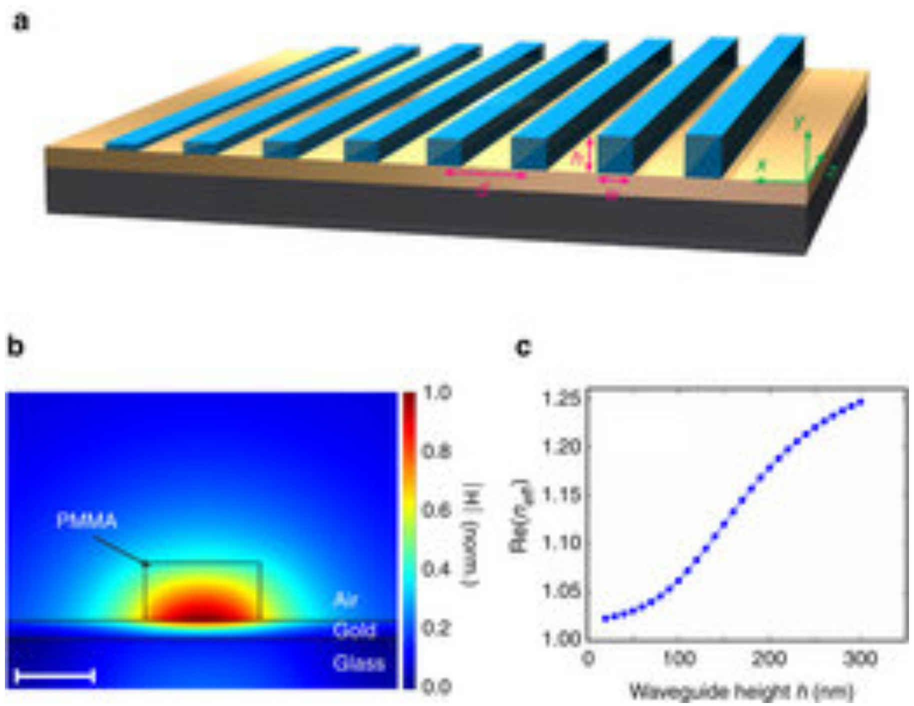
Q2: Can you squeeze a light beam through a hole or a slit that is much smaller than the wavelength?

Plasmonics:

-Allows light confinement beyond diffraction limit by using noble metals

-Metals contain a large density of unbound electrons which experience no restoring force upon being driven by an oscillating electric field.

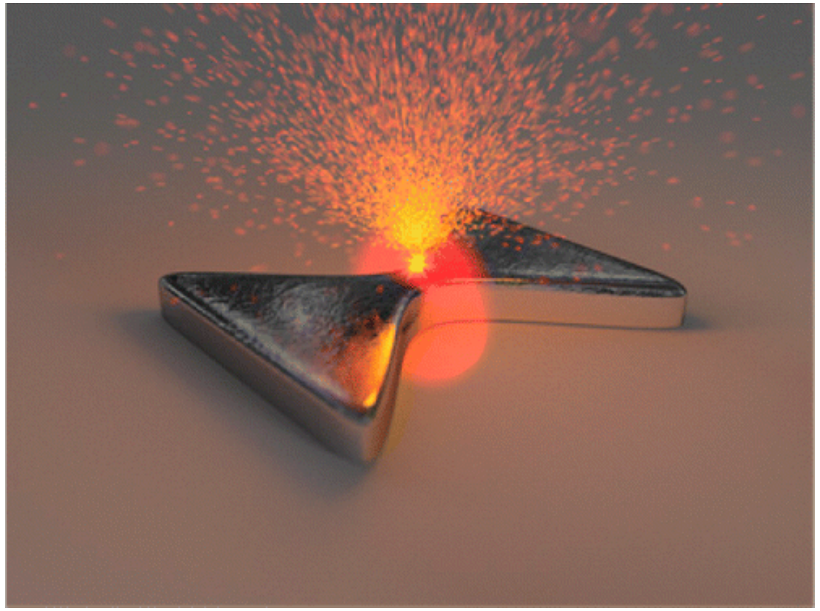
-Light can propagate at a metal-dielectric interface in a form of surface plasmon polariton which are hybrid waves of photons and charge oscillations sustained by electrons near the metal surface.



Dielectric loaded surface plasmon polariton waveguide

Nature Communications 5, 3843 (2014)

Optical Nanoantennas :
Light concentration is even higher in 3D metalic components.
They tansduce free-space, far field radiation to localized electromagnetic energy.
Metallic nanoparticle is the simplest example of optical nanoantennas reciprocally,
an optical excited nanoparticle can eficiently radiate light in a controlled way.
-Antennas coupled to a single quantum emitter can result in highly directional beaming
of spontaneous emission.



Strong modification of magnetic dipole emission
through diabolo nanoantennas

ACS Photonics 2015 2(8), pp.1071-1076

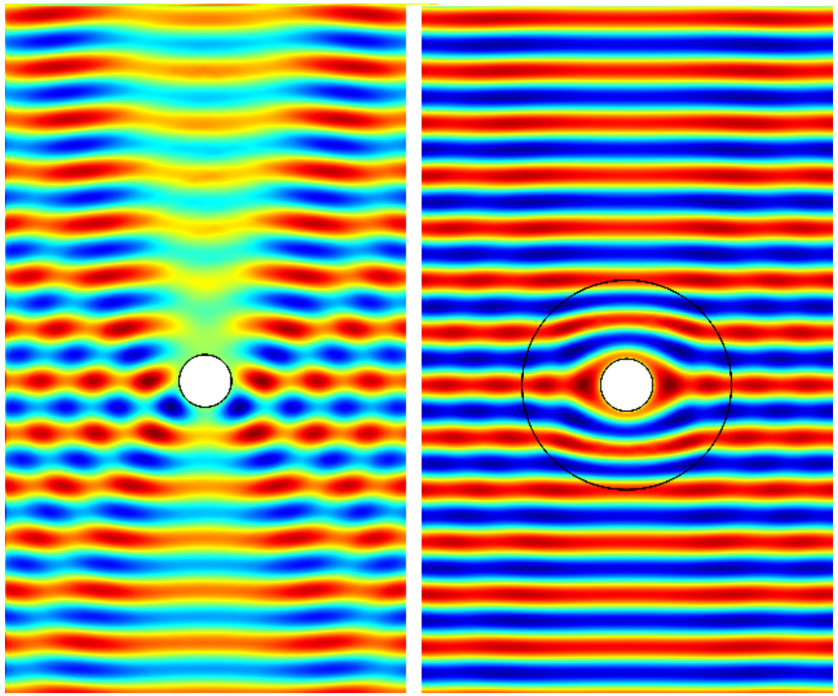
Metamaterial

-Existing materials only exhibit a small subset of electromagnetic properties theoretically available

-Metamaterials can have their electromagnetic properties altered to something beyond what can be found in nature. They can for example achieve negative index of refraction, zero index of refraction, etc.

-A metamaterial is composed of a sequence of elements and spacings, which are much smaller than the selected wavelength of light.

Without metamaterial With metamaterial

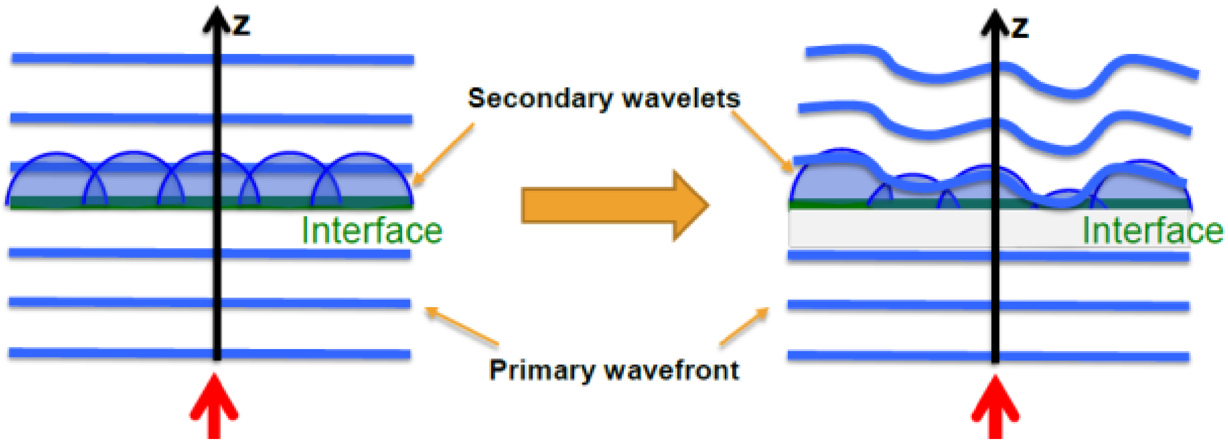


Metasurface:
Optically thin arrays of optical scatteress such as antennas with subwavelength sizes and separations to afford a spatially optical response
They allow wave front engineering (phase control): spatial distribution of different phase discontinuities along the entire interface

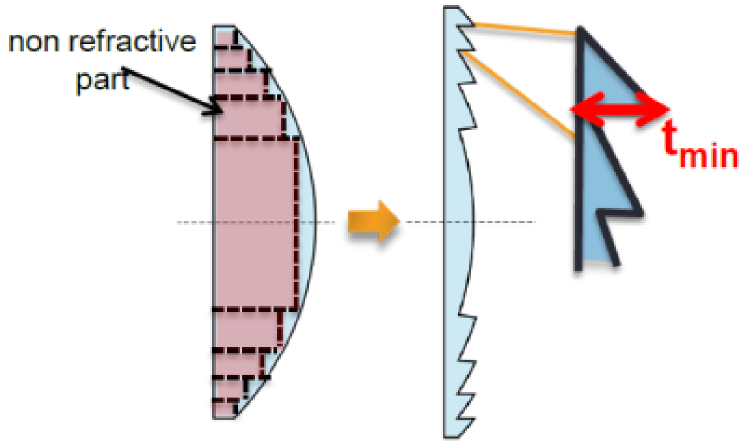
Requirements :

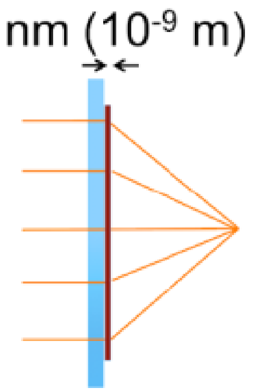
- -deep subwavelength thickness
- -subwavelength separation
- -2Π phase coverage

Huygens principle



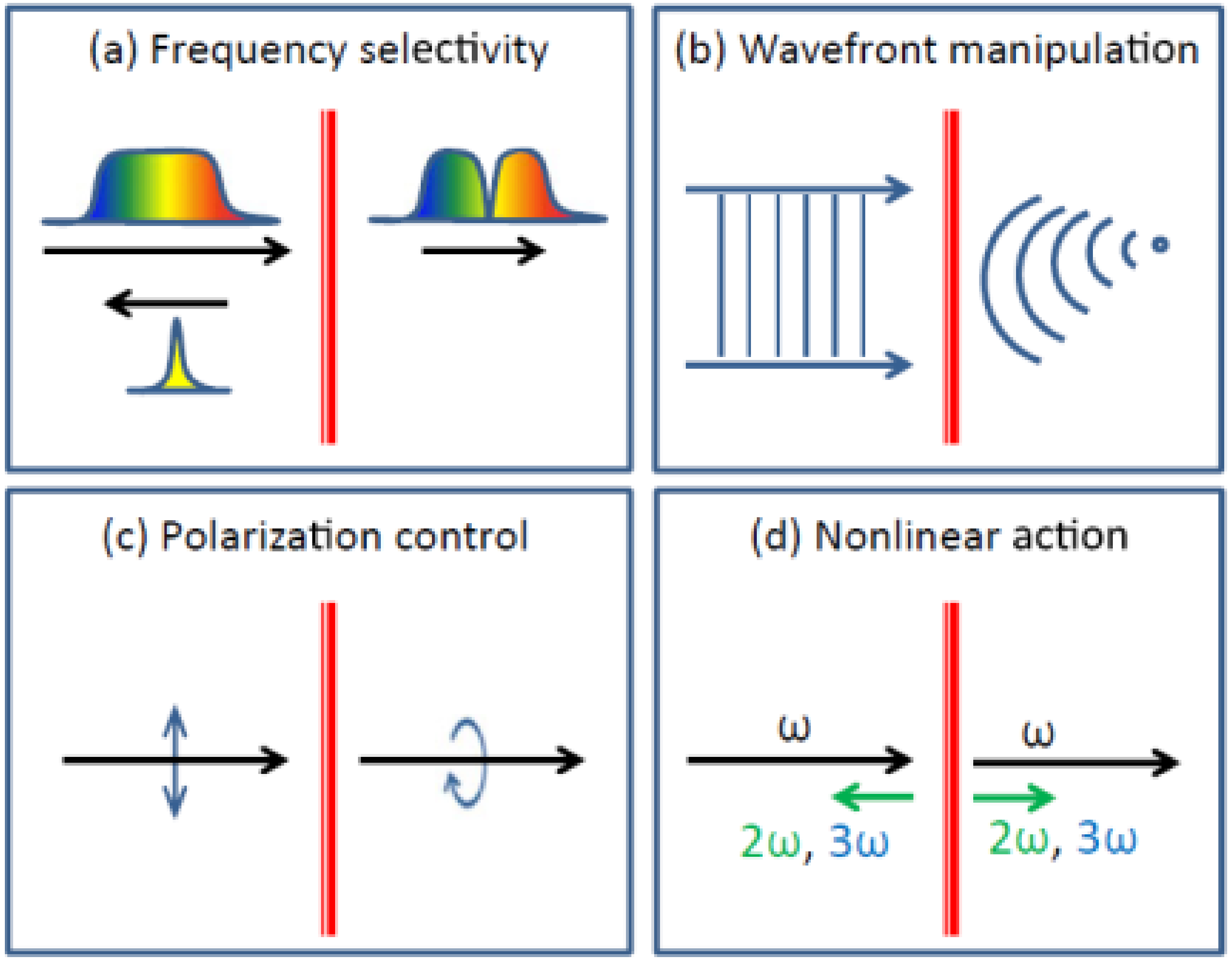
Fresnel Optics vs Metasurface based Optics





Fresnel Optics	Metasurface
thin but finite thickness	ultra - thin
finite lateral phase control	sub wavelength phase control
polarization insensitive	polarization control
diffractive: single wavelength operation	controlled dispersion: achromatic
multiple steps of lithography: N phase level→$\log_2$ N steps	single lithographic step

Functionalities of optical metasurfaces



Linear Optics vs Non Linear Optics

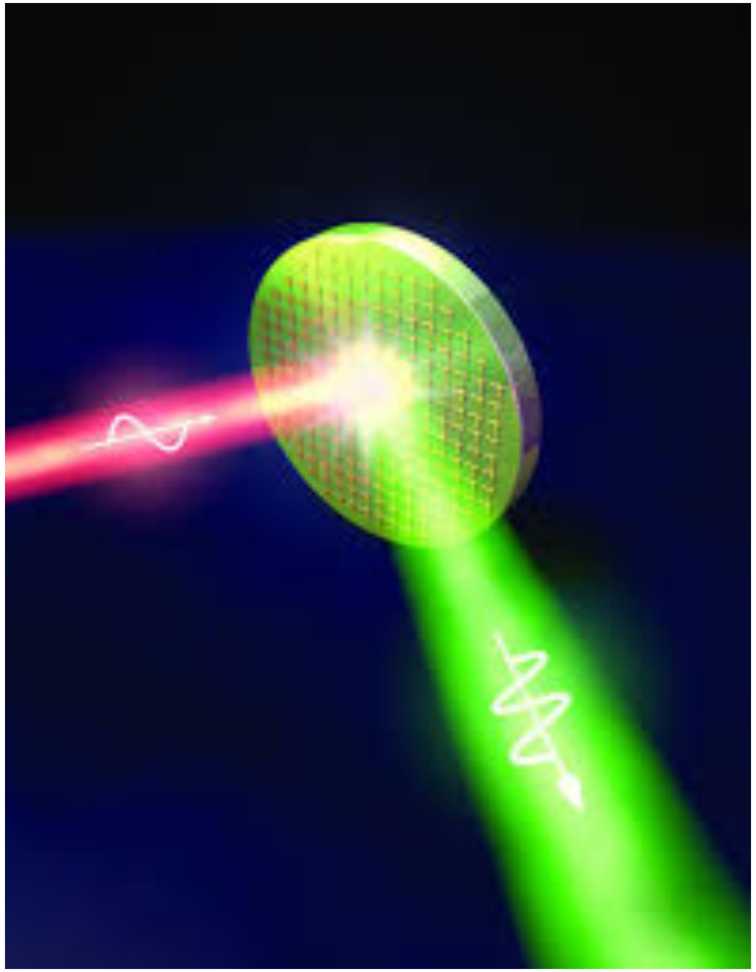
- Linear optics- 'Optics of weak light':
  Light is deflected or delayed but its frequency is unchanged.

- Non-Linear optics-'Optics of intense light':
  We are concerned with the effects that light itself induces as it propagates through the medium.

Nonlinear optics (NLO) is the branch of optics that describes the behavior of light in *nonlinear media*, that is, media in which the dielectric polarization **P** responds nonlinearly to the electric field **E** of the light. This nonlinearity is typically only observed at very high light intensities.
Nonlinear optical effects arise when electronic motion in a strong electromagnetic field cannot be considered harmonic.

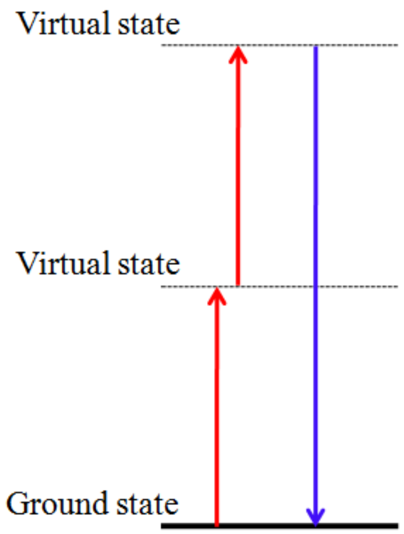
Non-Linear optics produces many exotic events

Nonlinear optics allows us to change the color of a light beam, to change its shape in space and time, to switch telecommunications systems, and to create the shortest events ever made by Man

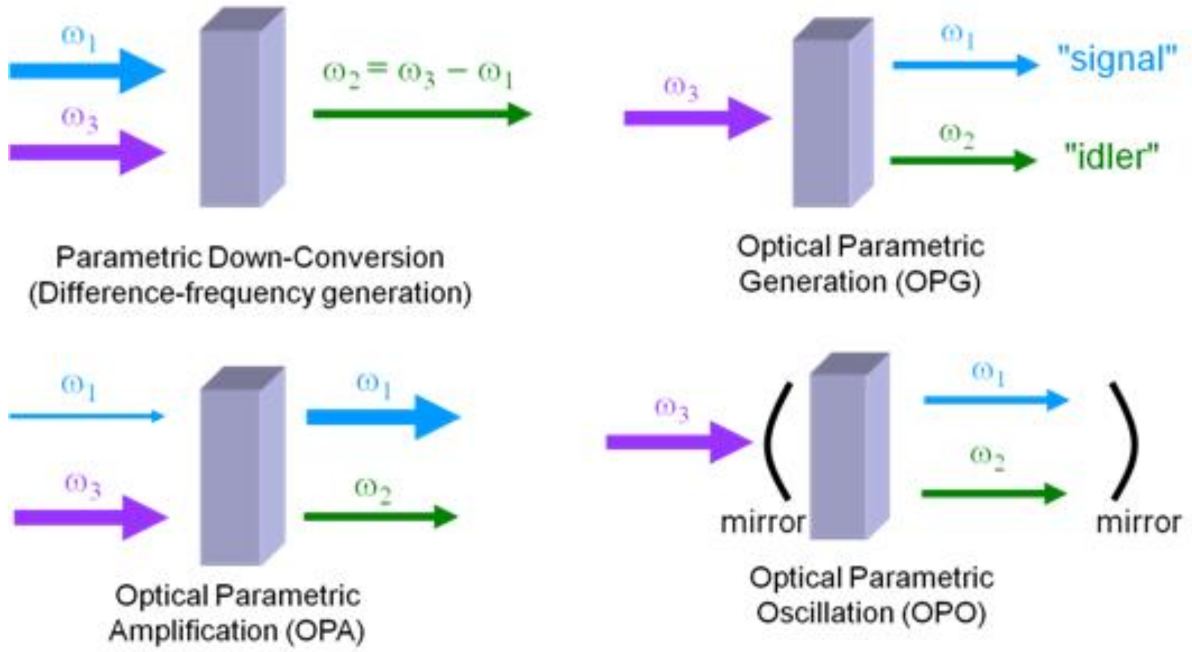


Frequency mixing processes

- Second harmonic generation (SHG), or *frequency doubling*, generation of light with a doubled frequency (half the wavelength), two photons are destroyed creating a single photon at two times the frequency.
- Third harmonic generation (THG), generation of light with a tripled frequency (one-third the wavelength),
- three photons are destroyed creating a single photon at three times the frequency.
- Difference frequency generation (DFG), generation of light with a frequency that is the difference between two other frequencies
- Optical parametric amplification (OPA), amplification of a signal input in the presence of a higher-frequency pump wave, at the same time generating an *idler* wave (can be considered as DFG)
- Optical parametric oscillation (OPO), generation of a signal and idler wave using a parametric amplifier in a resonator (with no signal input)



SHG



Second Harmonic Generation

$$P = \varepsilon_0 \left[\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right]$$

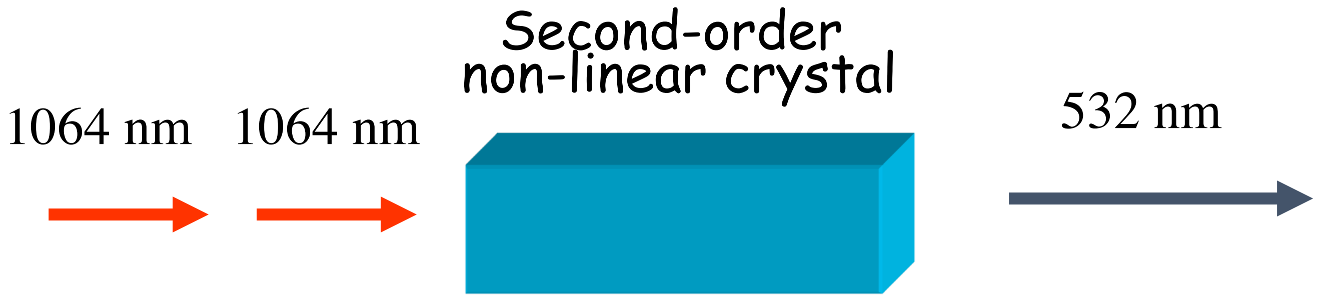
What are the effects of such nonlinear terms?

Since $E(t) \propto E_0 \exp(i\omega t) + E_0^* \exp(-i\omega t)$,

$$E(t)^2 \propto E_0^2 \exp(2i\omega t) + 2\left|E_0\right|^2 + E_0^{*2} \exp(-2i\omega t)$$

↑

2ω = 2nd harmonic!

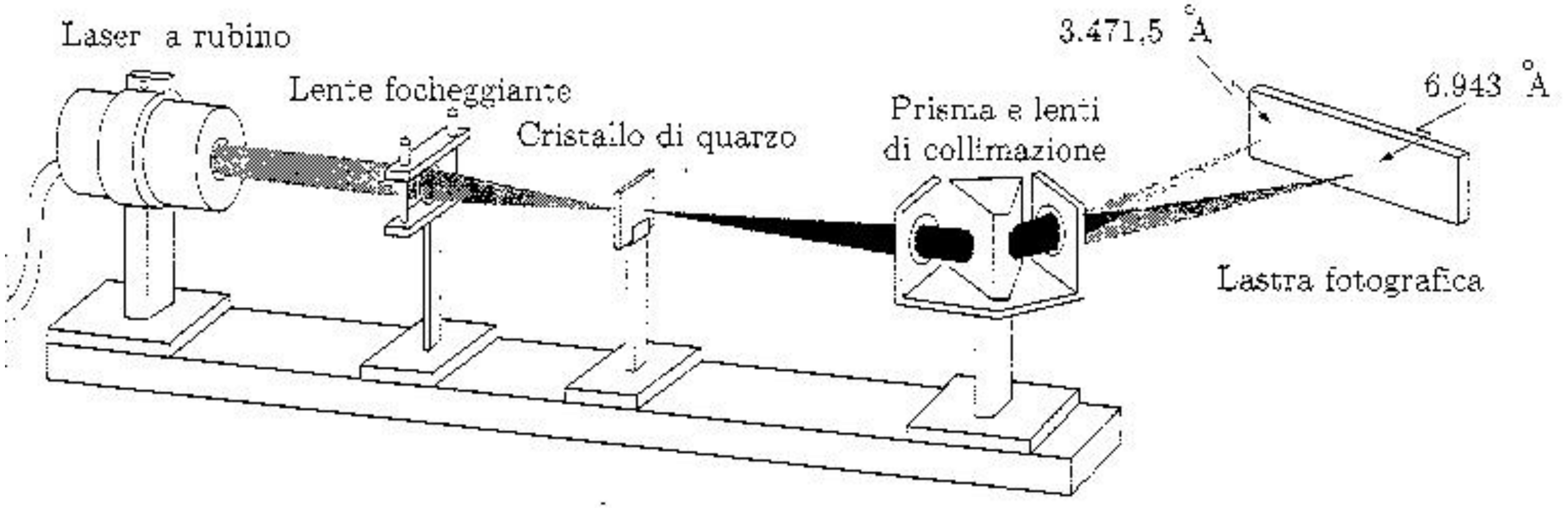


VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)

SHG discovered in 1961 by Franken et al. during an experiment of **second harmonic generation**. Sending red light of a ruby laser (λ = 6.943 Å) onto a crystal of quartz, they observed ultraviolet light



But…the proof reader corrected the photo, suppressing the tiny spot of the second harmonic believing it was just a smash. You may see this on the photo below in which under the arrow you see….nothing!

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

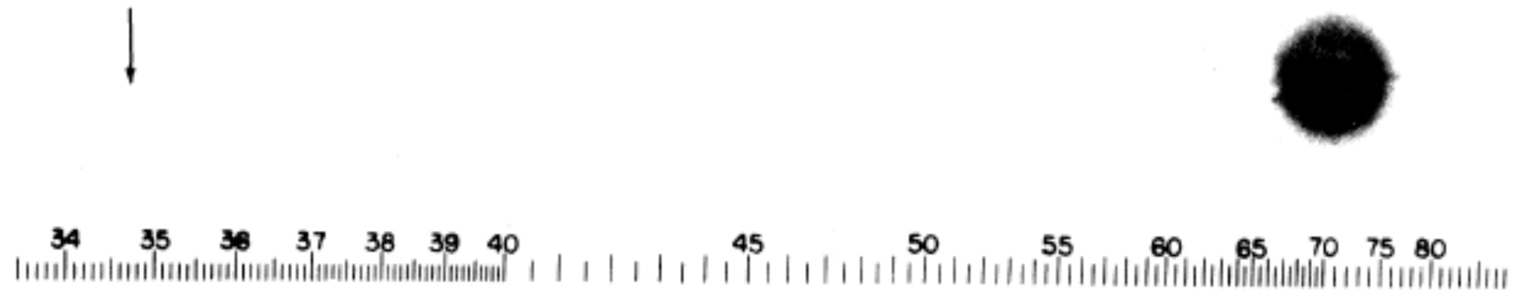


FIG. 1. A direct reproduction of the first plate in which there was an indication of second harmonic. The wavelength scale is in units of 100 A. The arrow at 3472 A indicates the small but dense image produced by the second harmonic. The image of the primary beam at 6943 A is very large due to halation.

Sum and Difference Frequency Generation

Suppose there are two different-color beams present:

$$E(t) \propto E_1 \exp(i\omega_1 t) + E_1^* \exp(-i\omega_1 t) + E_2 \exp(i\omega_2 t) + E_2^* \exp(-i\omega_2 t)$$

So:

$$E(t)^2 \propto E_1^2 \exp(2i\omega_1 t) + E_1^{*2} \exp(-2i\omega_1 t)$$ 2nd-harmonic gen

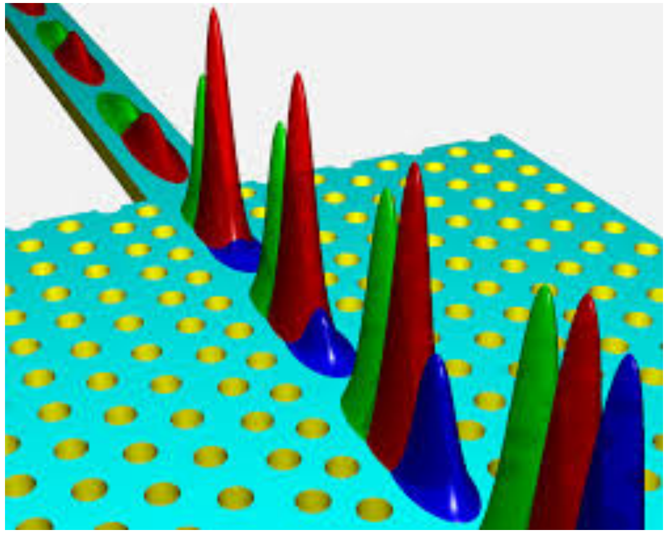
$$+ E_2^2 \exp(2i\omega_2 t) + E_2^{*2} \exp(-2i\omega_2 t)$$ 2nd-harmonic gen

$$+ 2E_1 E_2 \exp(i[\omega_1 + \omega_2]t) + 2E_1^* E_2^* \exp(-i[\omega_1 + \omega_2]t)$$ Sum-freq gen

$$+ 2E_1 E_2 \exp(i[\omega_1 - \omega_2]t) + 2E_1^* E_2^* \exp(-i[\omega_1 - \omega_2]t)$$ Diff-freq gen

$$+ 2|E_1|^2 + 2|E_2|^2$$ dc rectification

And…
what if we combine nanophotonics with nonlinear effects ??



St-andrews.ac.uk

Photonic Crystal (periodic dielectric) → Photonic Bandgap

+

Nonlinear Material → "n" changes with light intensity

↓

New Outstanding Applications

Supercontinuum generation in photonic crystal fibers

A supercontinuum is formed when a collection of nonlinear processes act together upon a pump beam in order to cause severe spectral broadening of the original pump beam, for example using a microstructured optical fiber.

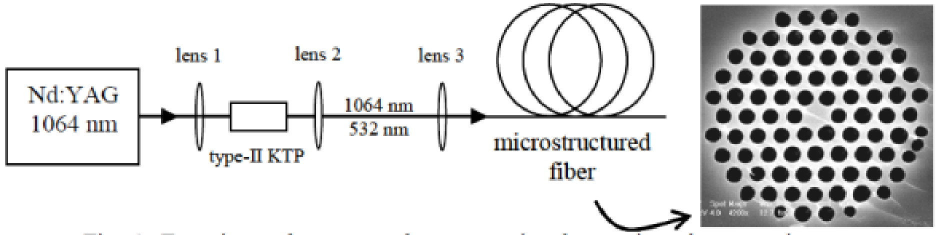
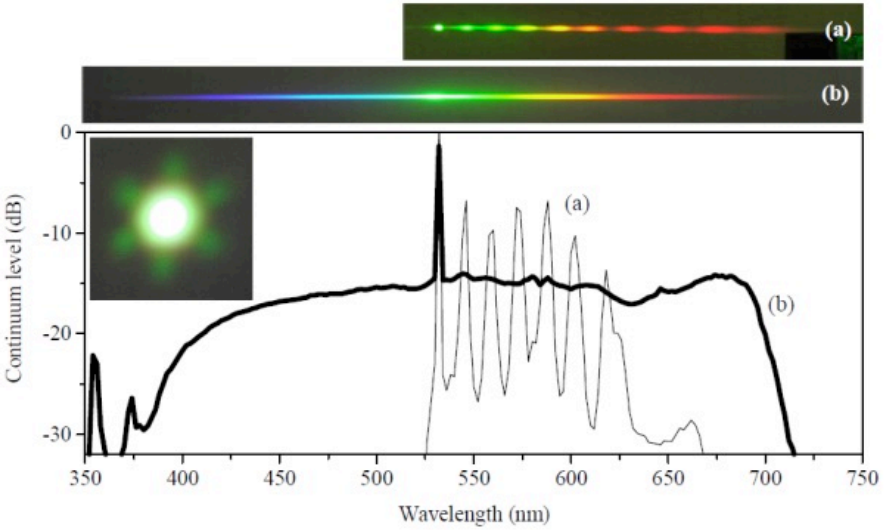
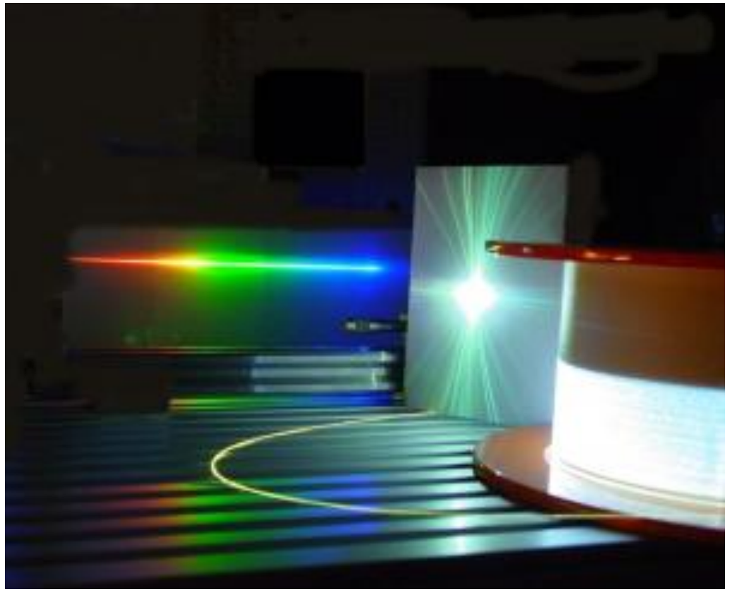


Fig. 1. Experimental set-up and cross sectional scanning electron microscope image of the microstructured air-silica fiber.



Optics Express 12, 4366 (2004)

- Stimulated Raman Scattering
- Self-phase and cross-phase modulation
- Four wave mixing
- High order soliton formation



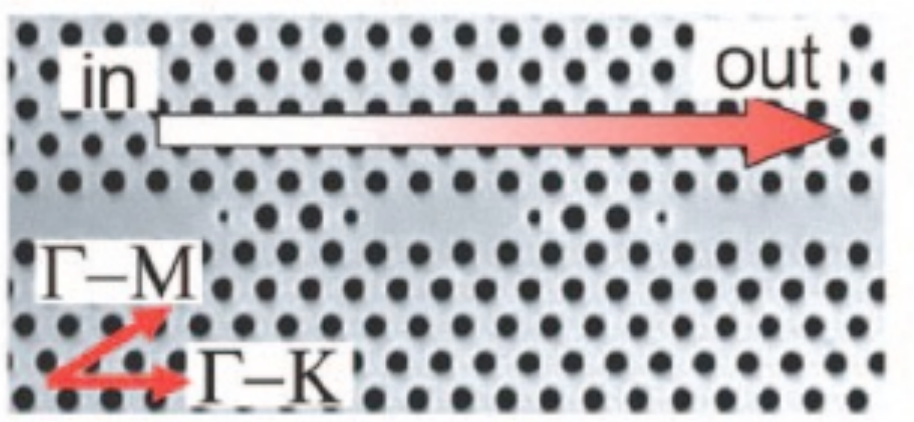
www.femto-st.fr

Nonlinear photonic crystal: an example

All-optical switches on a silicon chip realized using photonic crystal nanocavities

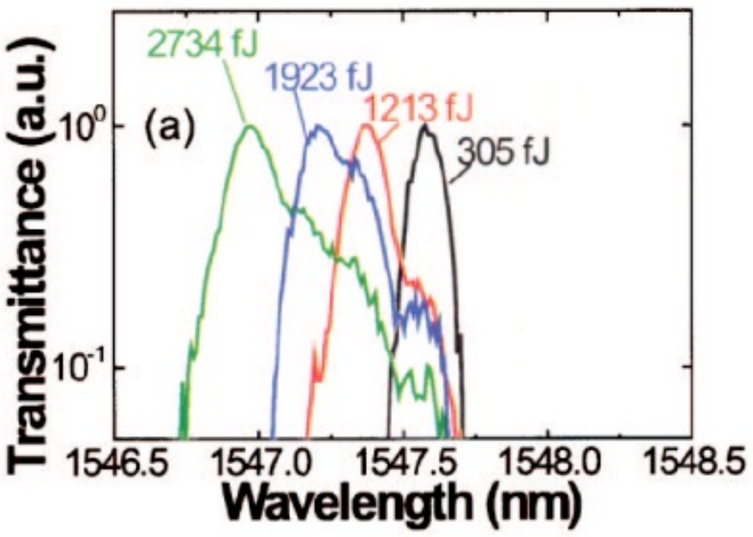
Switching is induced by a nonlinear refractive-index change caused
by the plasma effect of carriers generated by two-photon absorption in silicon

Very low switching energy (a few 100 fJ)



Appl. Phys. Lett. 87, 151112 (2005)

Nonlinear spectrum at various pulse energies



Nonlinear plasmonics

Plasmonic excitations can boost **nonlinear optical effects** in several ways:

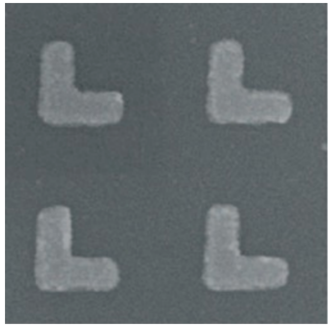
1. The coupling of light to surface plasmons can result in strong local electromagnetic fields, significantly enhancing optical processes.
2. Plasmonic excitations can be extremely sensitive to dielectric properties of the metal and the surrounding medium. Minute modifications of the refractive index near the metal surface result in significant modifications of the plasmonic resonance.
3. Plasmonic excitations can respond on the timescale of few femtoseconds, allowing ultrafast processing of optical signals.

Interesting review paper:
« Nonlinear plasmonics » M. Kauranen and A. V. Zayats, Nature Photonics 6, 737 (2012)

Second Harmonic Generation

Four Wave Mixing

L-shaped gold particles



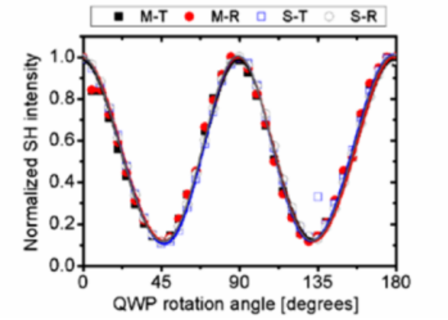
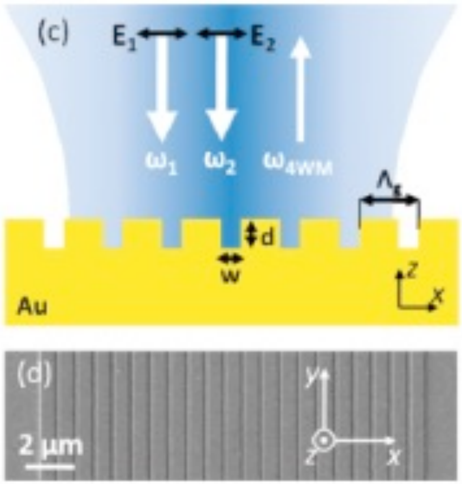


Fig. 3. Normalized transmitted (-T) and reflected (-R) SHG signals from an array of L-shaped gold nanoparticles for metal incidence (M-) and substrate incidence (S-), and from the present high-quality sample. Symbols represent the data from the measurements and solid lines are theoretical fits. The starting and detected linear polarization was x.

Array of noncentrosymmetric gold particles
Strongest SHG signal at the resonance plasmonic wavelegth

Optics Express 19, 26866 (2011)

Gold grating



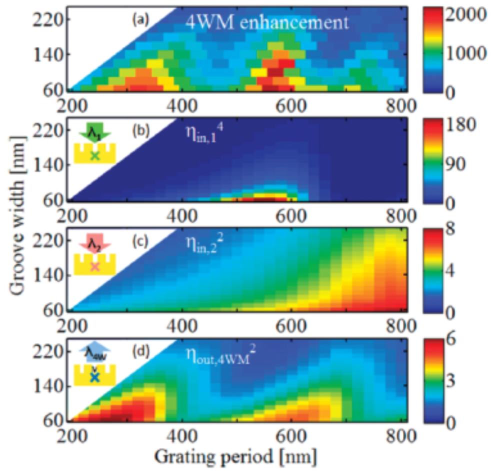


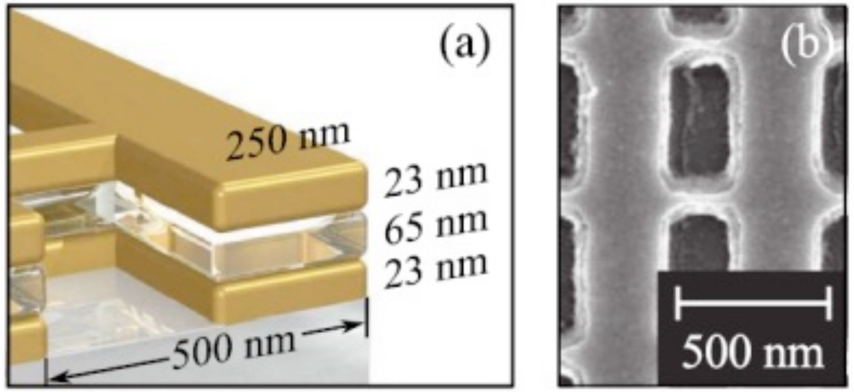
FIGURE 3. (a) Measured 4WM signal as a function of the groove width w and the grating period Λ_G. The experimental data are normalized to the 4WM signal obtained from an unpatterned gold surface and show a maximum enhancement of ≈2000. (b, c) Simulated enhancement factor $\eta_{in,1}^4$ (b) and $\eta_{in,2}^2$ (c), evaluated 5 nm below the groove bottom (see inset). (d) Simulated enhancement factor $\eta_{out,4WM}^2$, evaluated by monitoring the power radiated by a small volume of polarized medium (see inset and Supporting Information). Both $\eta_{in,1}$ and $\eta_{in,2}$ exhibit a maximum when $\Lambda_G = \lambda_{g,i}$, which explains the variation of the 4WM enhancement with Λ_G in (a). In (d), a higher order surface waves coupling condition also appears for $\Lambda_G = 2\lambda_{g,4WM}$.

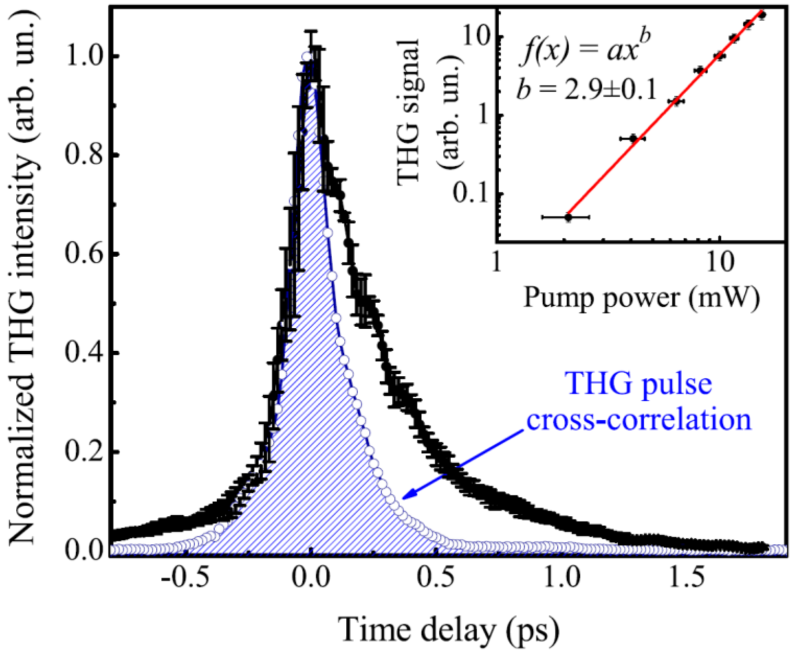
Nano Lett. 10, 4880 (2010)

Nonlinear metamaterials: an example

Experimental observation of ultrafast modulation of the third order optical nonlinearities of a Fishnet material by fs laser pulses

gold and magnesium oxide



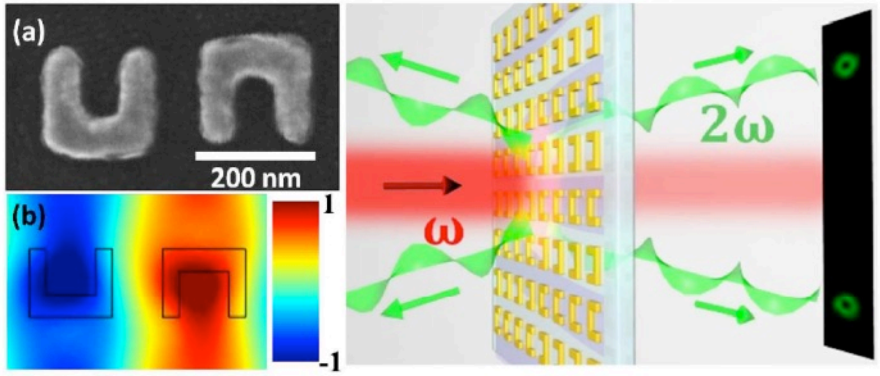


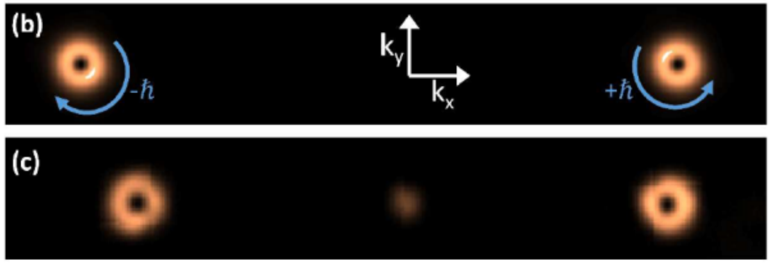
Scientific Reports 6:28440 (2016)

Nonlinear metasurfaces

Example: Nonlinear beam shaping with plasmonic metasurfaces

Generated vortex bessel beams





Simulation

Experiments

Metasurface fabricated on indium tin oxide coated glass

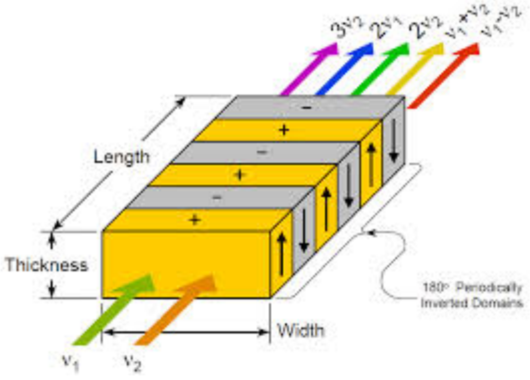
Second harmonic generation with tailored beam profiles using nonlinear metasurfaces based on split ring resonator. By manipulating both the phase and the amplitude of the quadratic nonlinear coefficient, the emitted second harmonic wavefront is perfectly controlled

ACS Photonics 3, 117-123 (2016)

LiNbO3: The Silicon of photonics?

Silicon: ideal material for integrated electronics

What material could play similar role for integrated photonics?
-III-V materials on Si: waveguides on III-V are not tightly confined
-Silicon lacks of second order non linear effect



Lithium Niobate

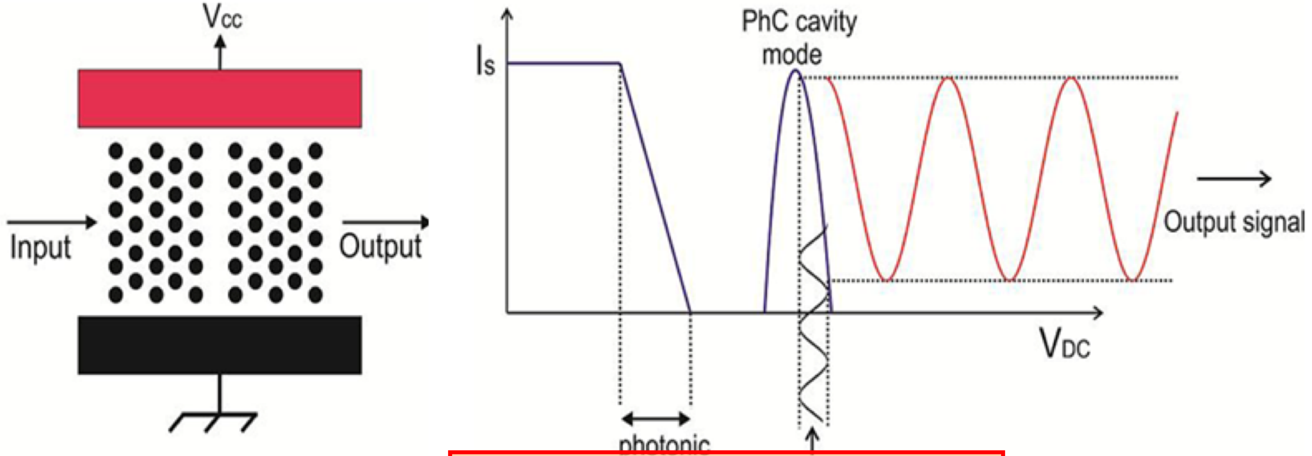
-Transparent from 0.35 to 5 μm
-Optical gain can be achieved by doping LN with rare earth elements
-Strong second order nonlinearity (parametric oscillation, SHG, wavelength conversion)
-EO effect (light modulators)
-Piezo-electric effect (acousto-optic devices)
-Pyroelectric effect
-Photorefractive effect

AO Tunable Filters

What if we combine LN and PhCs ??

Photonic crystals (PC) are **periodic dielectric** structures that have a **band gap** that forbids propagation of a certain range of light.
With PCs one can control light with amazing facility and produce effects that are impossible with conventional optics

The band gap position changes with a, r, and **n ($LiNbO_3$, lithium niobate)**



$$\Delta n = -\frac{1}{2} \times n^3 \times r_{33} \times (V / \Gamma)$$

With slow light the peak shift can be done with a very small external voltage!!

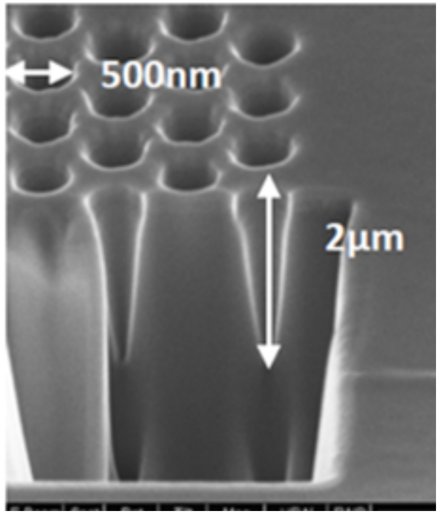
Drawbacks of lithium niobate for nanophotonics:

- It comes in thick wafers (300 microns)
- Etching is very difficult
- Epitaxial growth is even more difficult

Development of photonic crystals in three different LN supports:

- Classical Annealed Proton Exchange waveguide
- Optical Grade Dicing
- Smart-cut
- Wafer Bonding and polishing

Classical Annealed Proton Exchanged waveguides (APE)

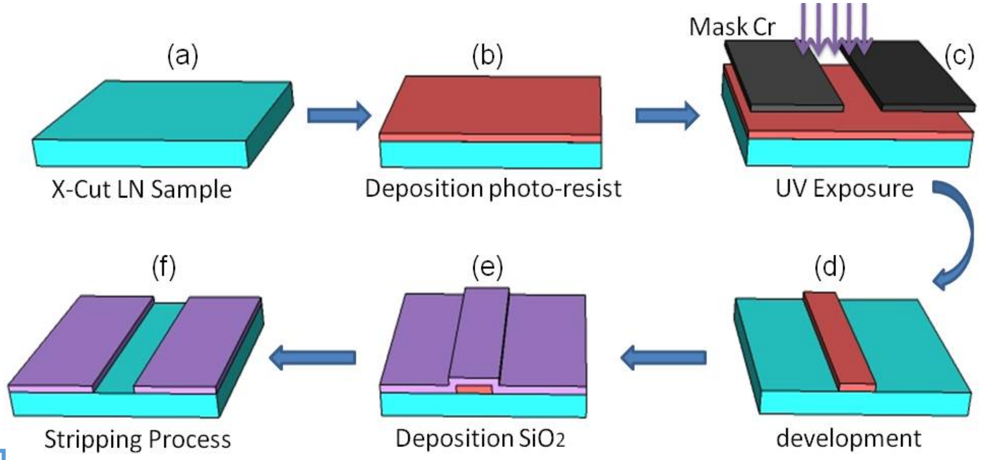


Opt. Mat. 27, (2005)

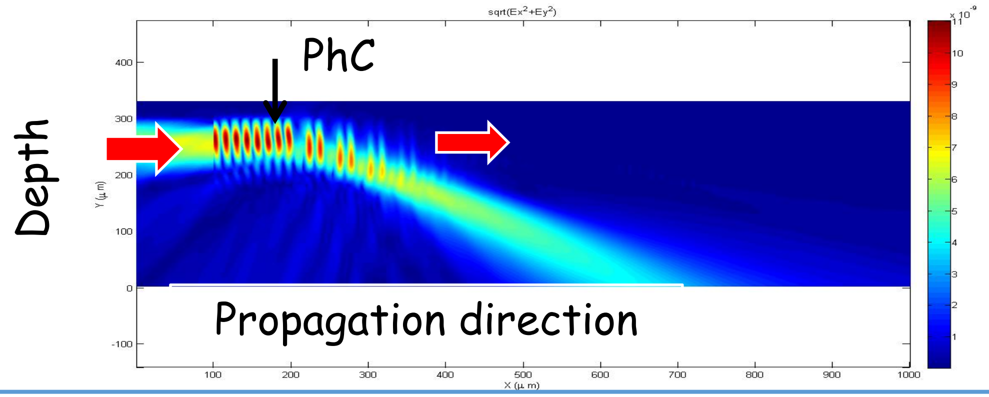
Proton Exchange:

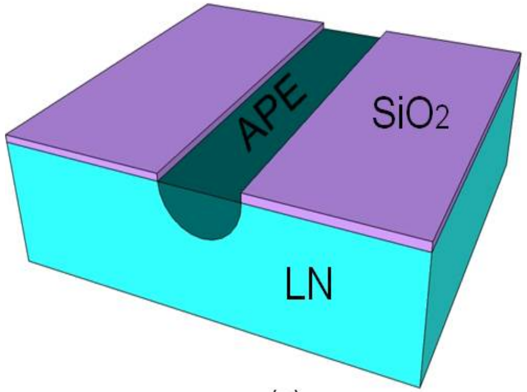
80minutes, 180°C

Annealing time: 6h at 333°C



Propagation through a PhC with a conical shape
(Simulation, FDTD method)

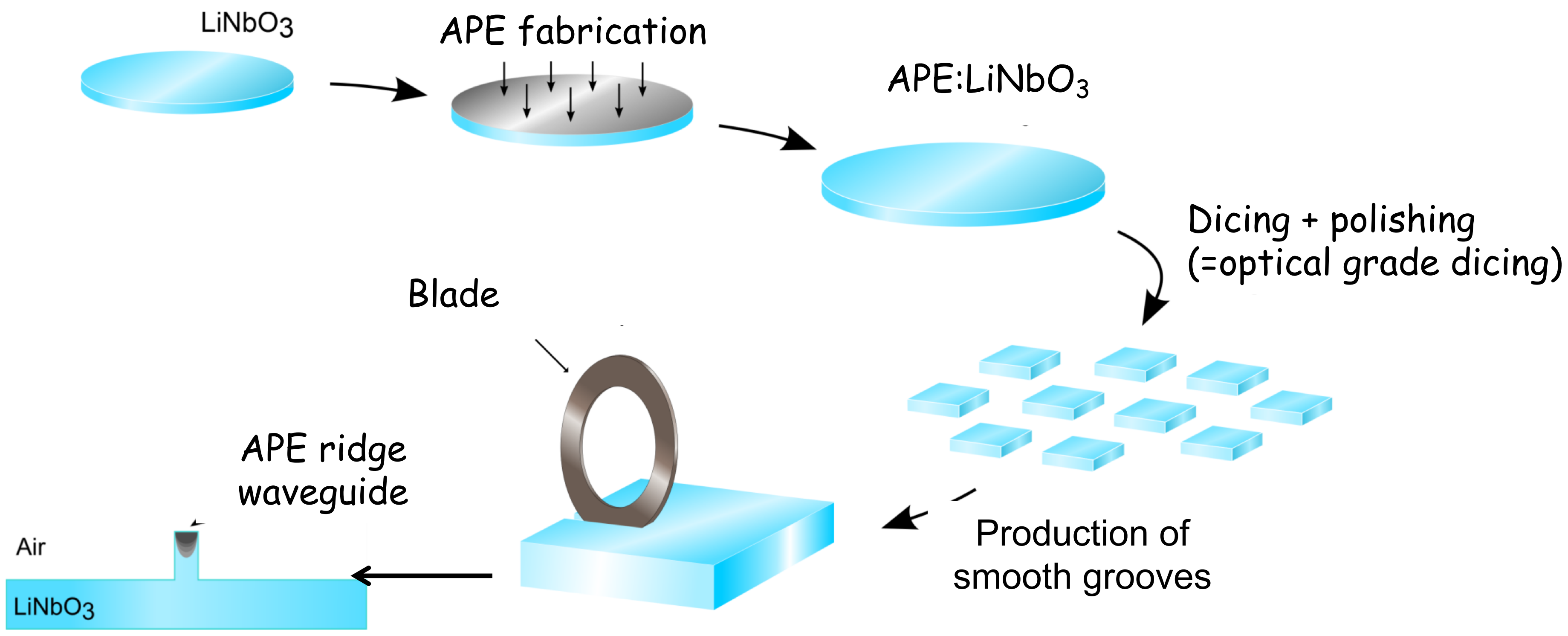




(a)

Large Mode -> Bad interaction between optical guided mode and PhC

Optical grade dicing: flow chart



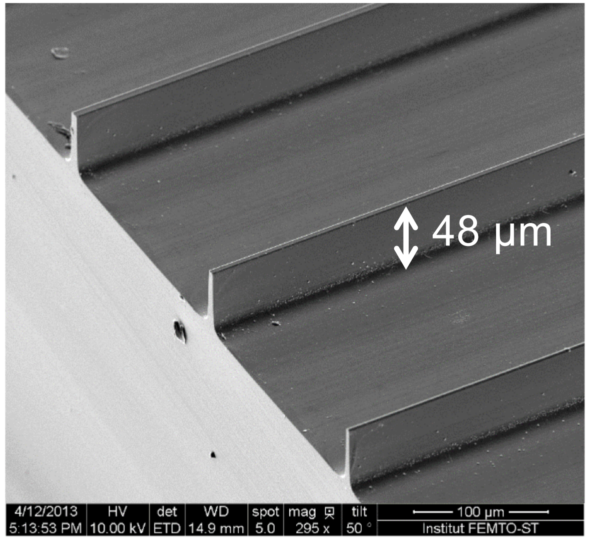
→ APE + optical grade dicing with a circular precision saw
→ The vertical confinement is due to APE
→ The lateral confinement is due to the ridge configuration

Opt. Lett. 39, 37 (2014)
Microelectronic Engineering 97, 185 (2012)
J. Physics D 44, 305105 (2011)

LN waveguide ridges with high aspect ratios

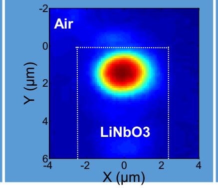
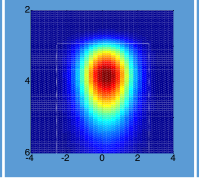
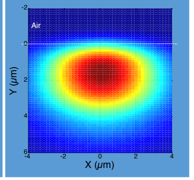
Low propagation losses and strong light confinement:

LiNbO$_3$ ridges
With ultra-high aspect ratios



J. Phys. D: Appl. Phys, **44**, 305101, (2011)

Confinement twofold higher than in a standard wg

Vertical Confinement	Ti-APE	Ti	Ti
			
Width of the ridge (µm)	**6**	**6**	**No ridge**
Lateral FWHM (µm)	3.1	2.8	5.3
Vertical FWHM (µm)	2.5	3.5	5.1
TE propagation losses (dB/cm)	3	0.2	0.1
TM propagation losses (dB/cm)	-	0.3	0.1

→ Roughness < 10 nm
→ Propagation losses lower than 1 dB/cm for both polarizations
→ The lateral confinement is twofold better than in a standard waveguide

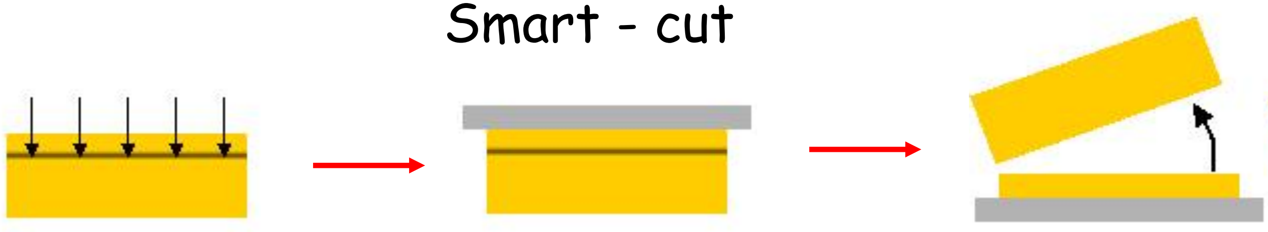
Thin films: smart cut technology

<u>State of the art:</u>

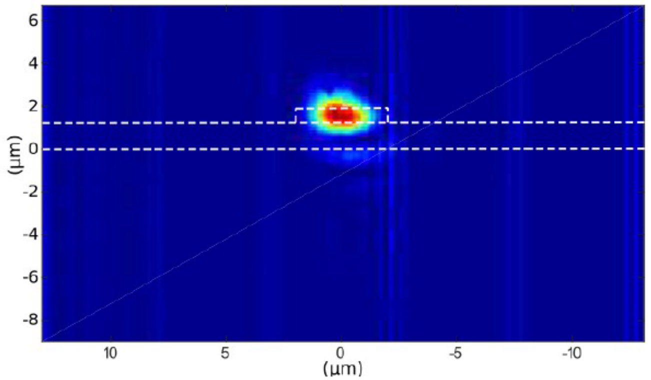
Osgood group: http://www.ee.columbia.edu/richard-osgood
Günter group: http://www.nlo.ethz.ch/staff/gunter/
NanoLN: commercially available: http://www.nanoln.com/

Films of 700 nm thickness can be obtained

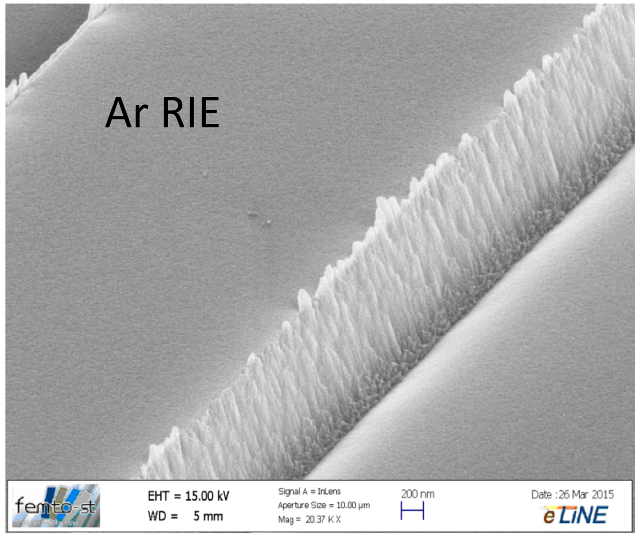
Smart - cut

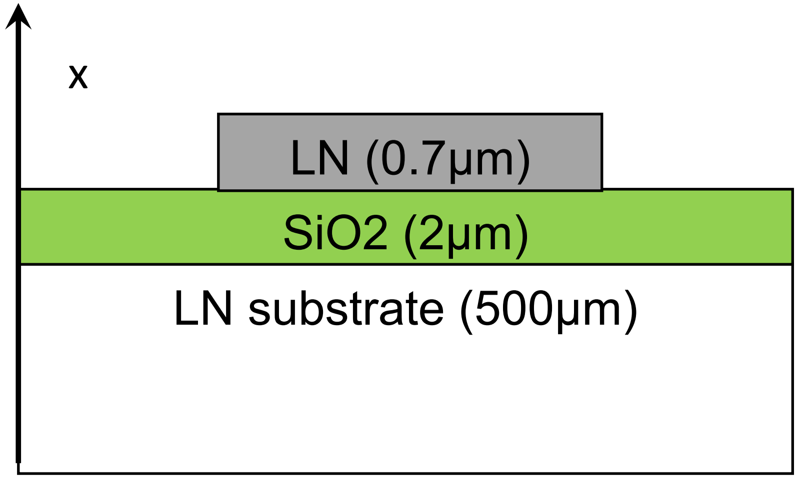


Ion Implantation — Bonding on Si, or LN — Slicing

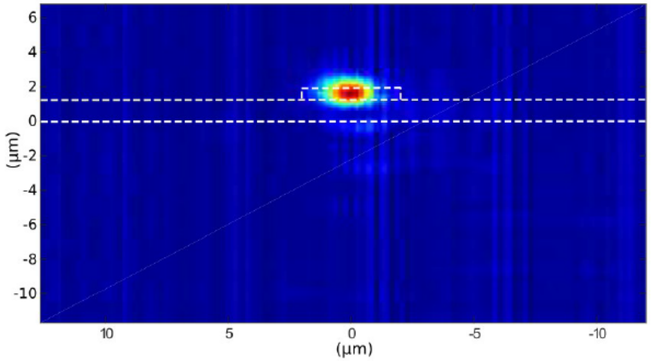


TE-like (experimental)

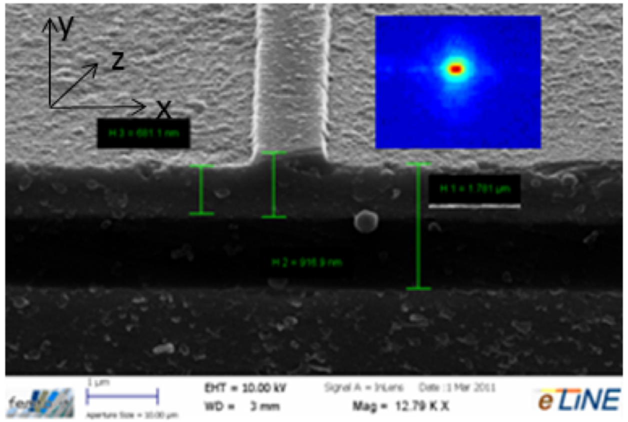


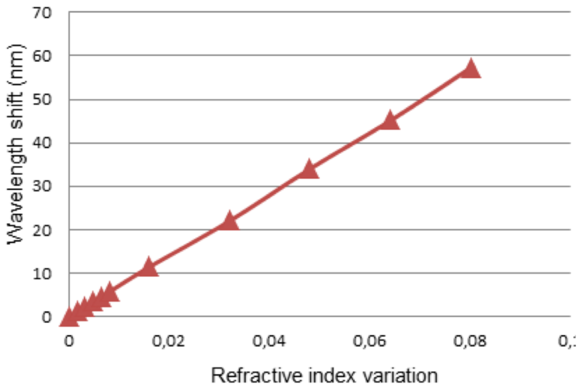


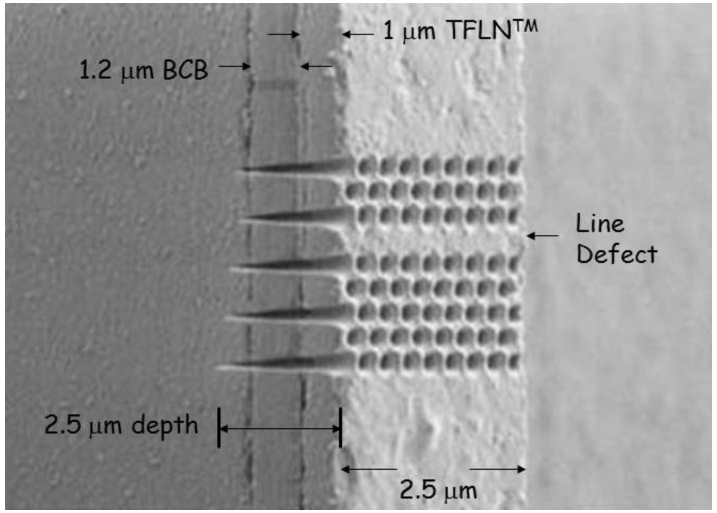
Optical Materials 2015, accepted

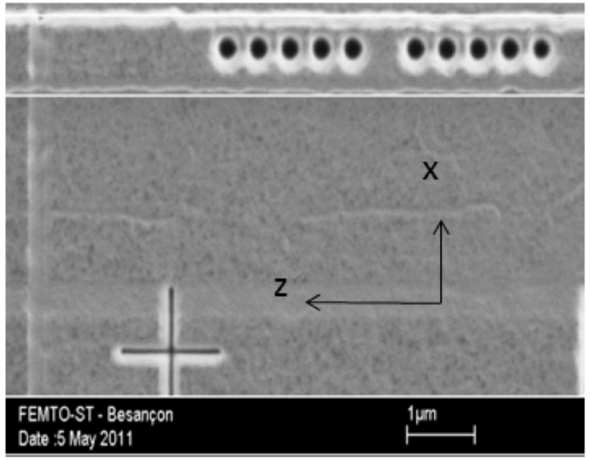


TM-like (experimental)

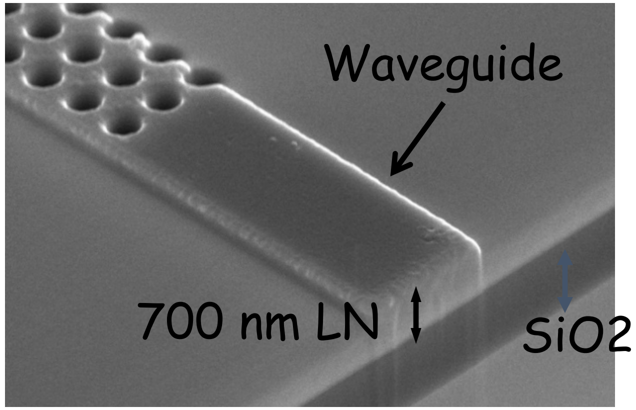








Guide width: 1 μm
Thickness: 200 nm
Fabrication: RIE + FIB



1 μm electrode distance => 0.6 V – Δλ = 1.2 nm

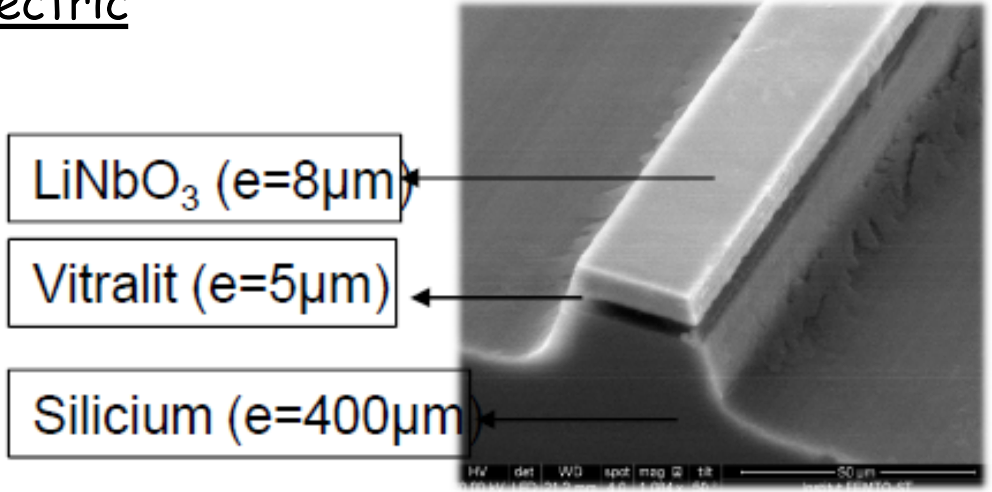
Opt. Exp. **20**(3), (2012)

Thin film: bonding and polishing @ femto-st

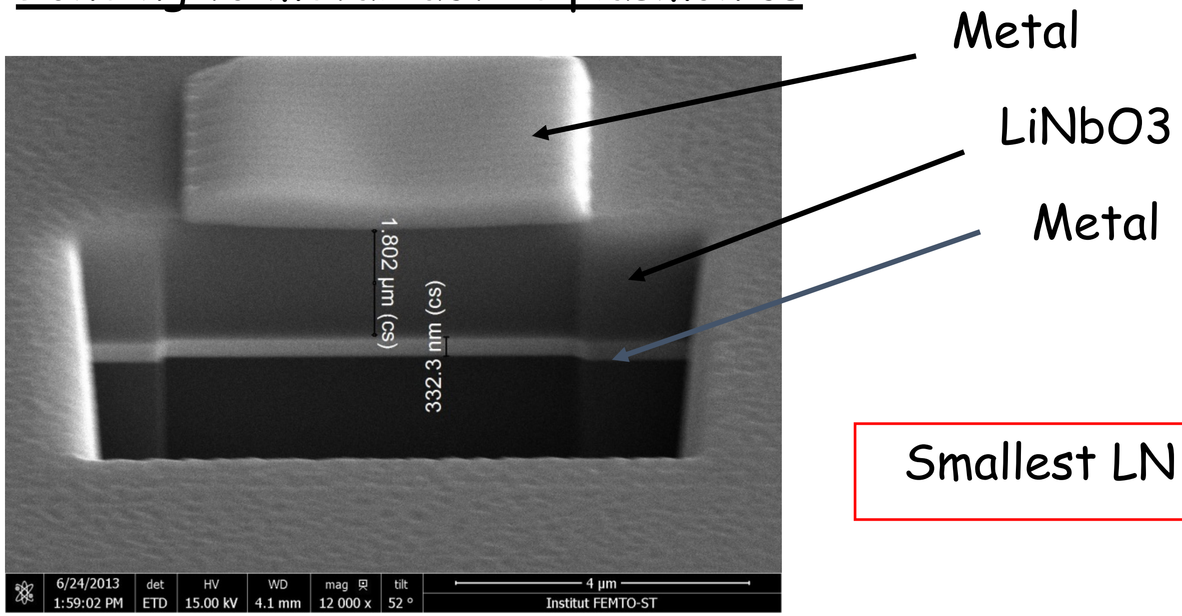
femto ENGINEERING

F. Bassignot
L. Gauthier-Manuel

Bonding to dielectric
Vitralite
SiO2
Si in progress

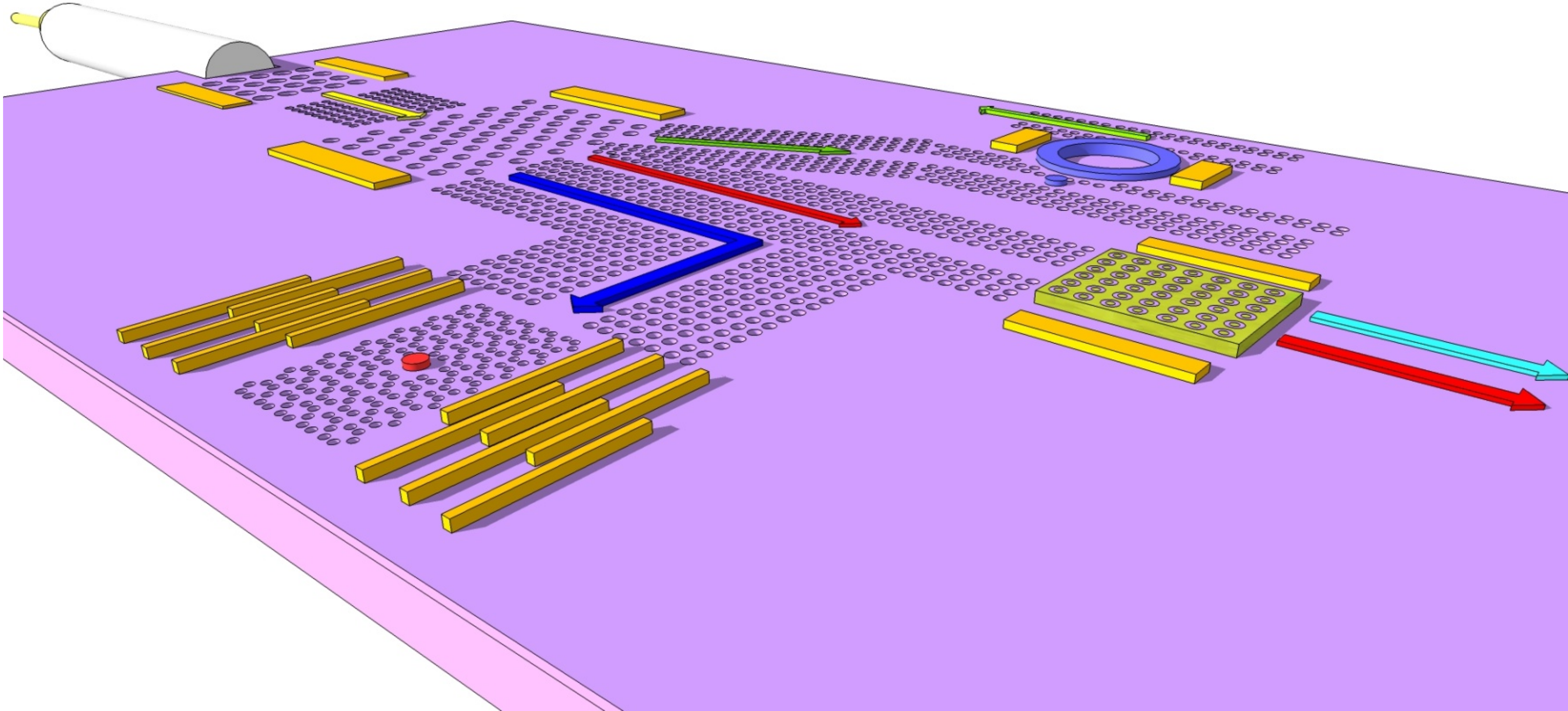


Bonding to metal: active plasmonics

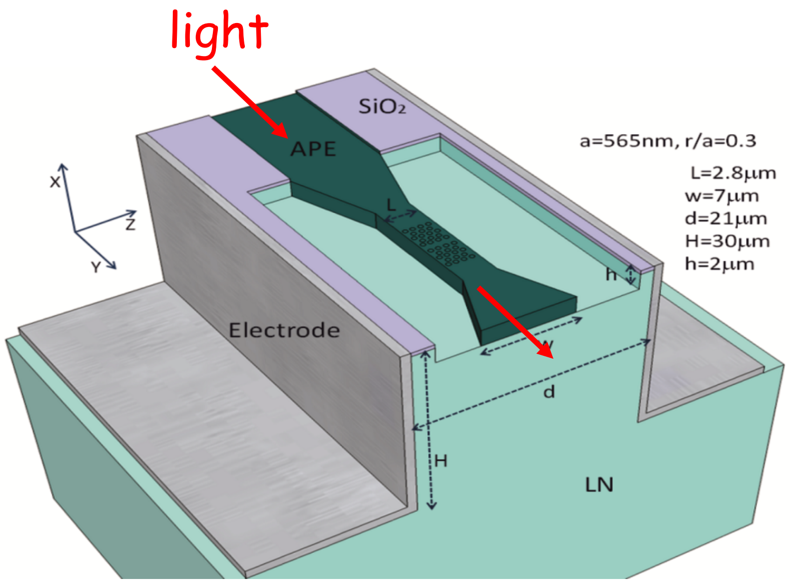


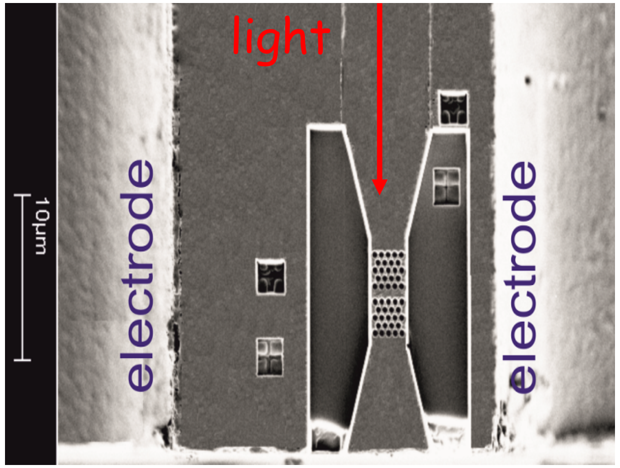
Smallest LN thickness so far~ 1 µm

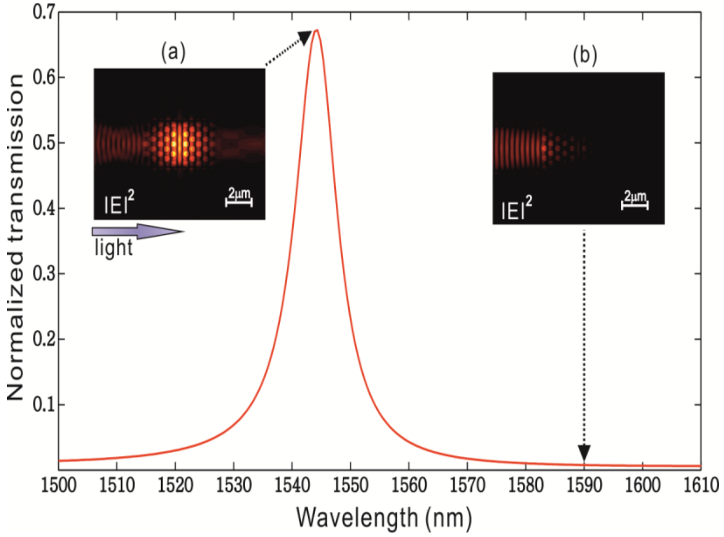
Nanodevices for integrated optics: horizontal light coupling



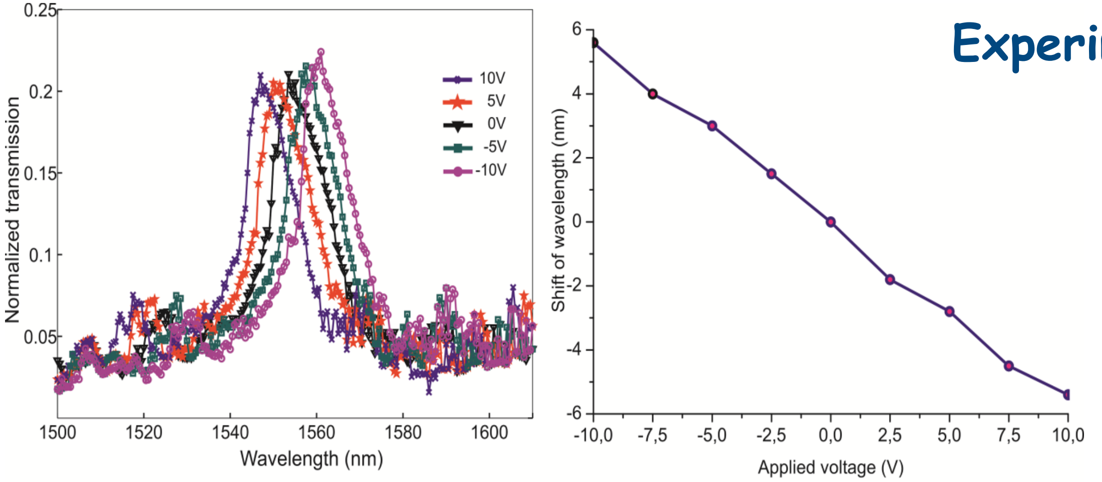
Light intensity filters and modulators







Theory

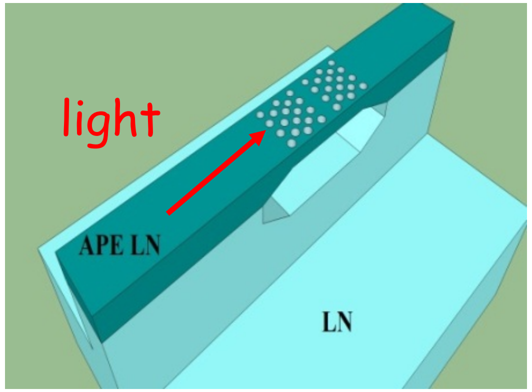


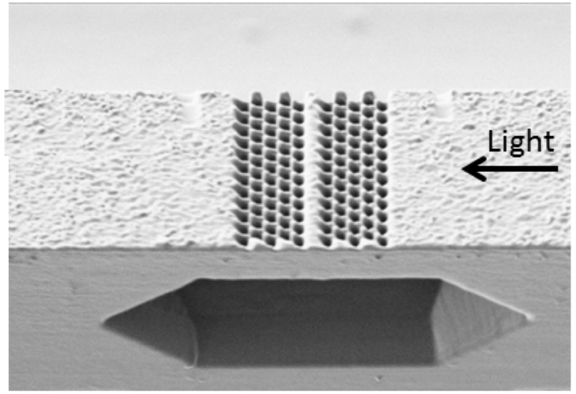
Experiment

EO tunability: **~ 0.56nm/V**, **18 times** more important than bulk LN (30.8pm/V). ***Q* : ~108**,
(theoretical *Q* : ~181) with a interaction size **(5.5 μm * 2.8 μm)**

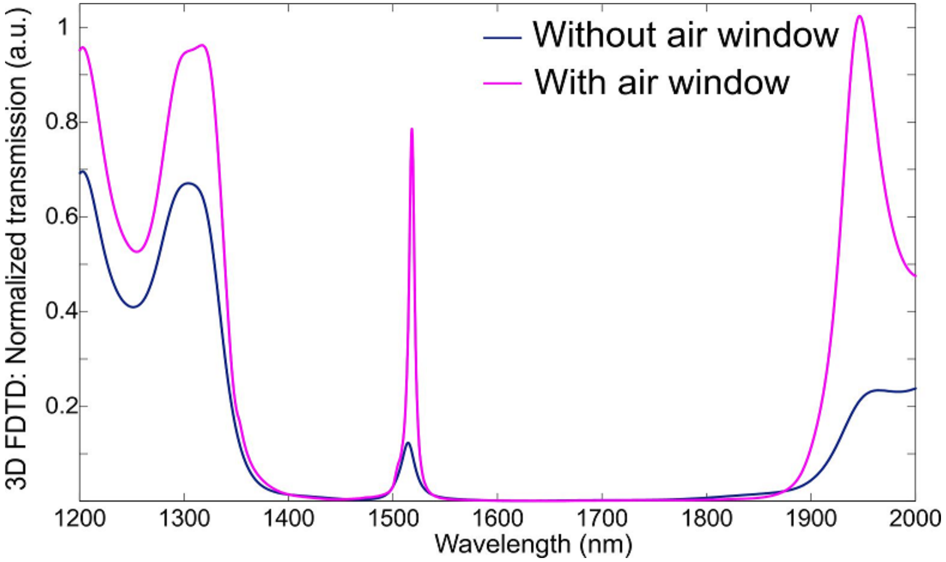
Opt. Exp. **20**(19), (2012)
IEEE Phot. Tech/ Lett. **26**, 1332 (2014)
Appl. Phys. Lett. **101**(15), (2012)

Temperature Sensor



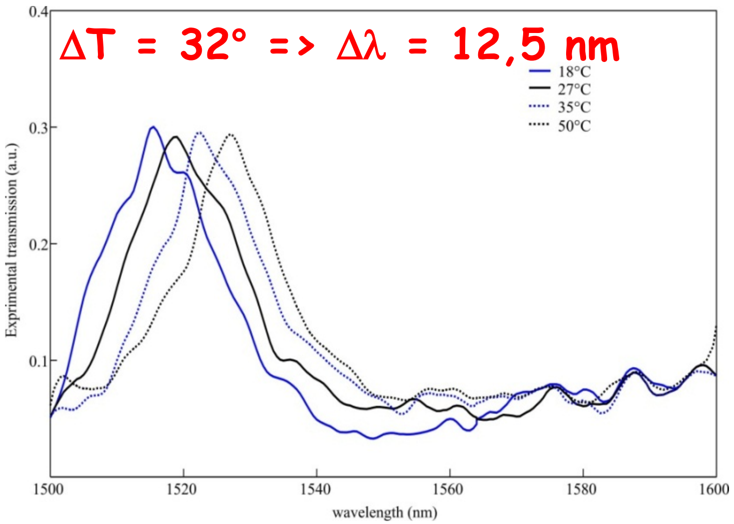


Temperature sensor with sensibility: ~0.36 nm/°C
ENHANCEMENT = 19
Bulk LN ~ 0.019 nm/°C

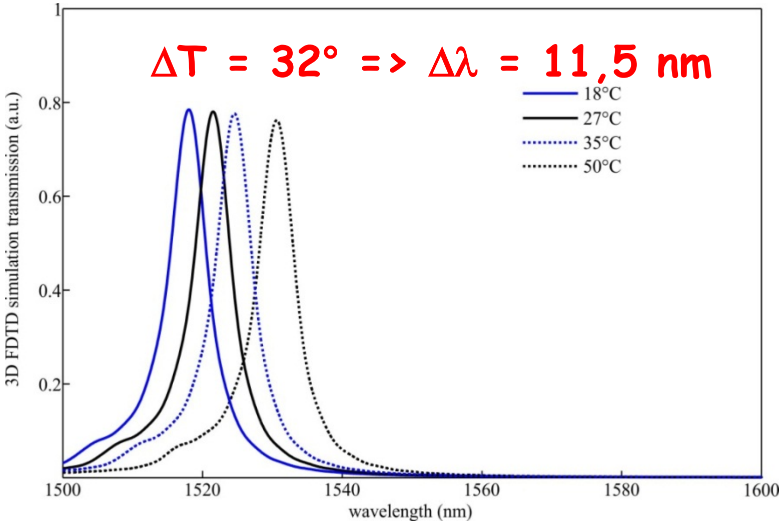


With air window: transmission (78%)
Wihtout air window: transmission (13%)

Experiment



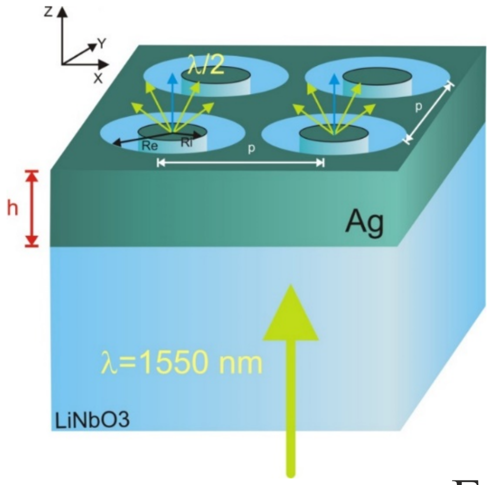
Theory

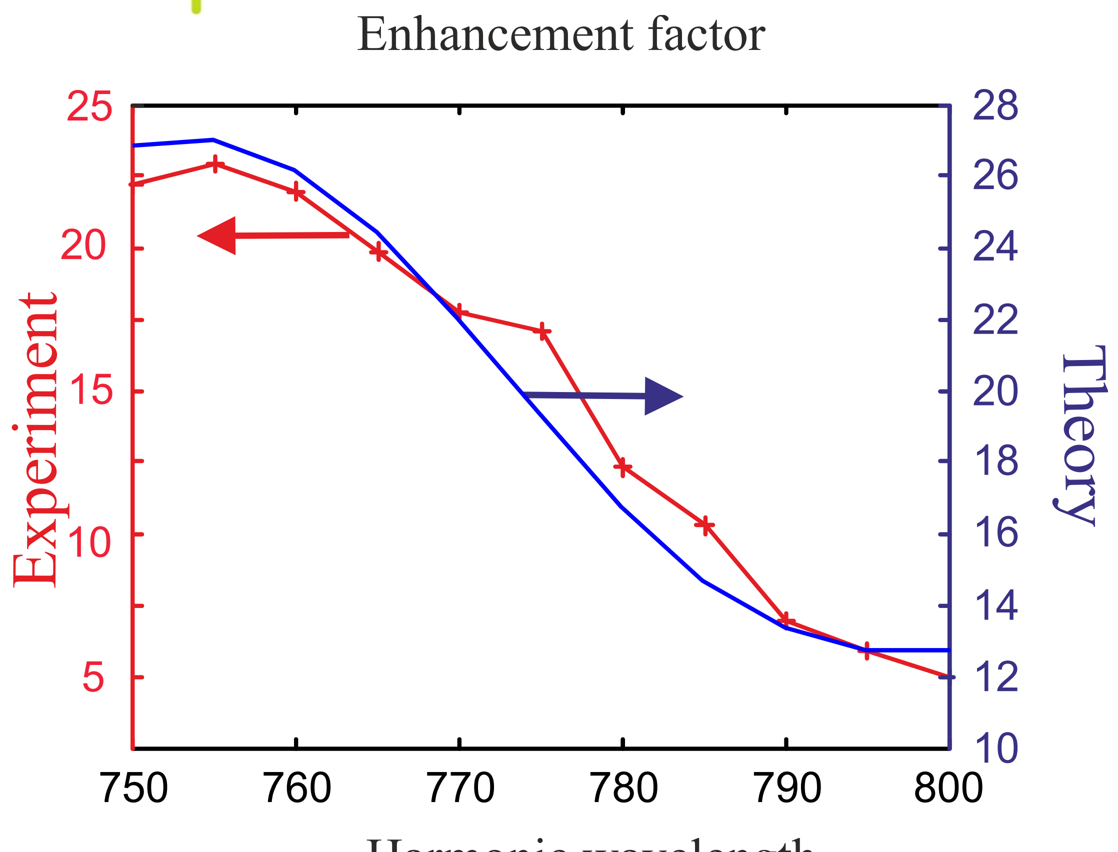


Opt. Express 21, 16311-16318 (2013)

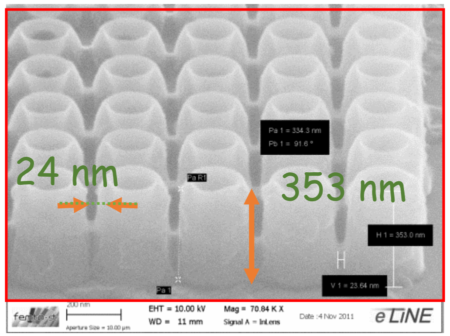
Novel Nonlinear Optical Device in Lithium Niobate

Goal: To increase LN SHG with nanoplasmonics

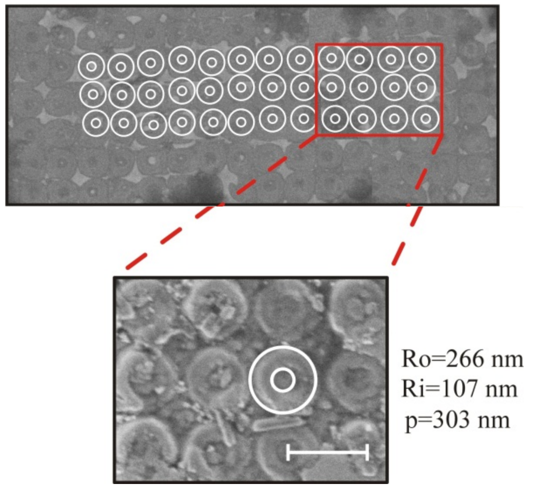




Cylindres in LN



LN cylinders embedded on Ag



SHG is 22 times more important than on bulk LN

Opt. Express, 20,16258 (2012)
JOSA B, 30, 1975 (2013).

E-field sensors based on LN photonic crystals

Applications:

- Electric field characterisation
- Balistic control
- Frequency sensor
- Electromagnetic compatibility
- Biosignal sensing
- Temperature sensing

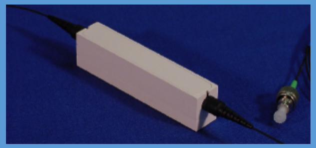
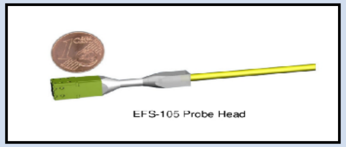
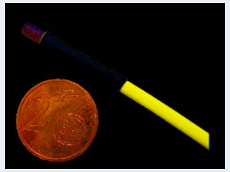
Advantages:

-High sensibility: μV

-Metal free : they are invisible and they do not perturbe the field to be measured

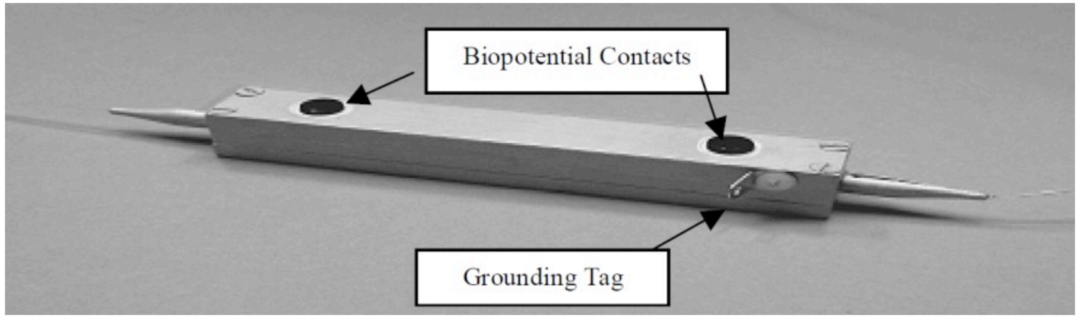
-MRI compatible: no heating because they are metal free

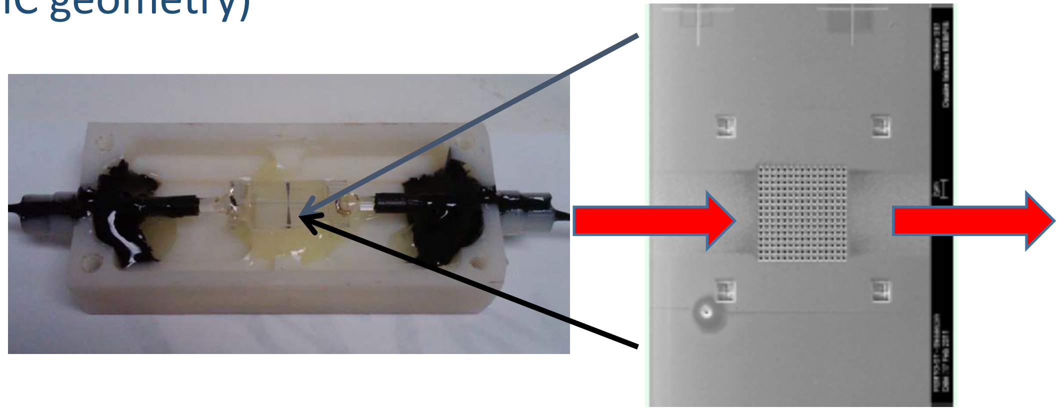
Commercial E-field optical sensors

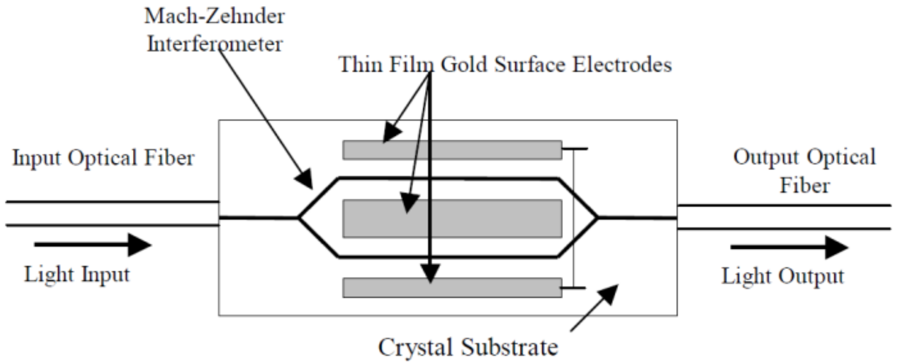
Srico		**~ 5 cm^3**	**25 mV/m/Hz $^{1/2}$** **1 Hz – 2 GHz** **(not flat)**
EnProbe		~ 2 cm^3	30 mV/m/Hz $^{1/2}$ 500kHz – 3 GHz (flat)
Kapteos		< 0,5 cm ^{3}	0,7 V/m/Hz $^{1/2}$ 20 Hz – 10 GHz

E-field sensing with PhC in horizonatal light coupling

Photrode™ (Mach-Zehnder to be replaced by PhC geometry)

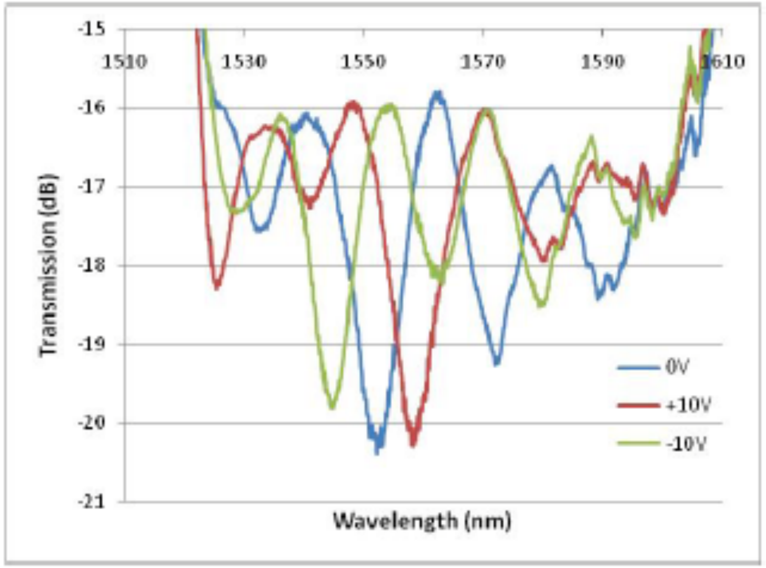






Key Results

- ✓ Relatively low loss (~14 dB)
- ✓ Sharp spectral features
- ✓ Shift of about 1.12 nm/V is <u>140x larger</u> than predicted by Pockel's effect
- ✓ **E-field sensitivity 310 μV/(m.√Hz)**

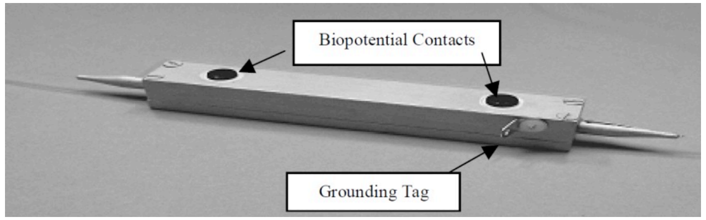


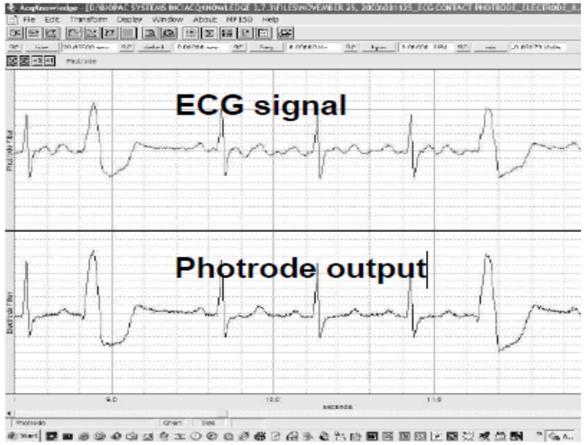
300 times better sensitivity than Photrode™

If we want to use LN PhC for biosensing:
-horizontal coupling is not desirable because it has big optical losses and the packaged device is bulky

A fibered configuration needs to be taken into consideration

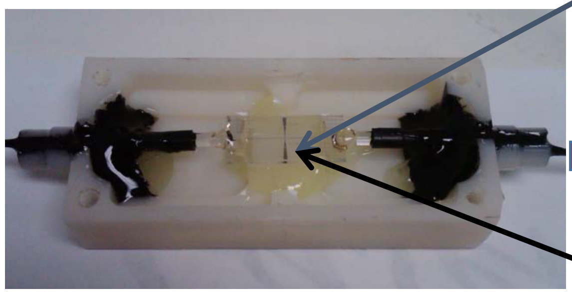
SRICO Photrode™

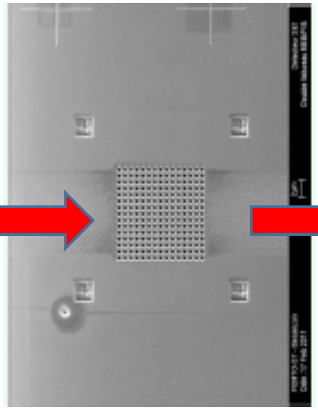




Limité à mV/m !!!

Premier capteur de FEMTO



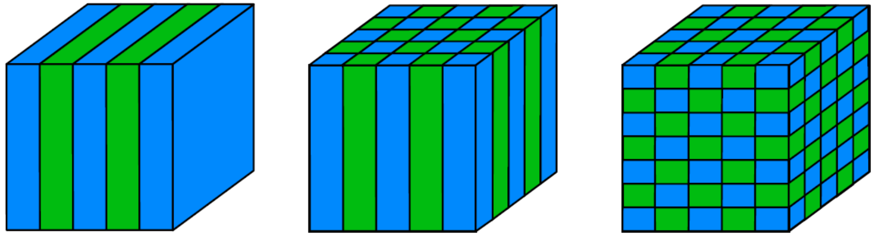


✓ E-field sensitivity 310 µV/(m.√Hz)

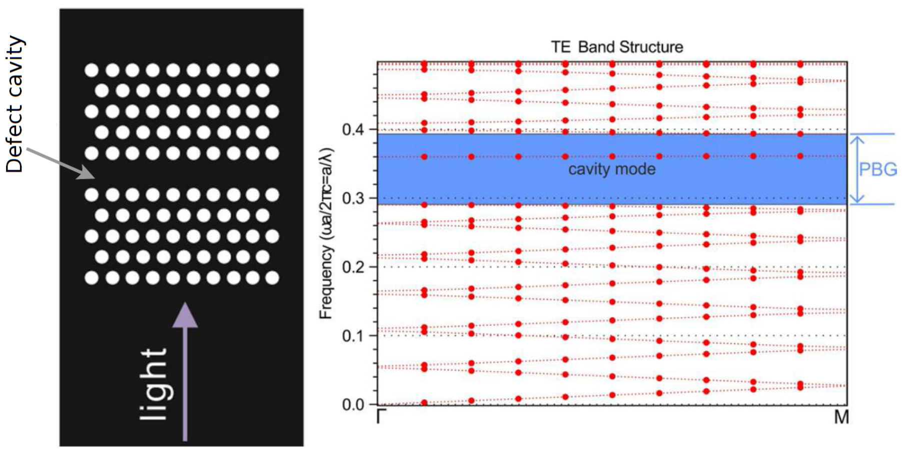
300 times better sensitivity than Photrode™

Proc. of SPIE, Defense Security Sensing, 8376, 8376H (2012)

PHOTONIC CRYSTALS (PhC)

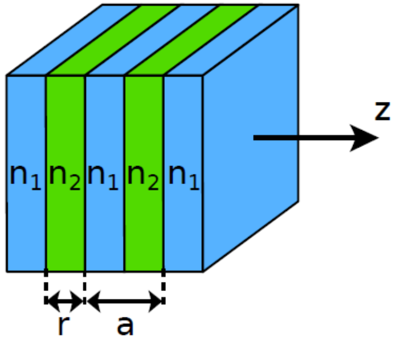


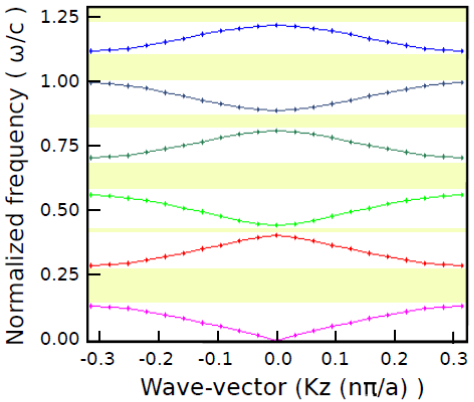
1D **2D** **3D**

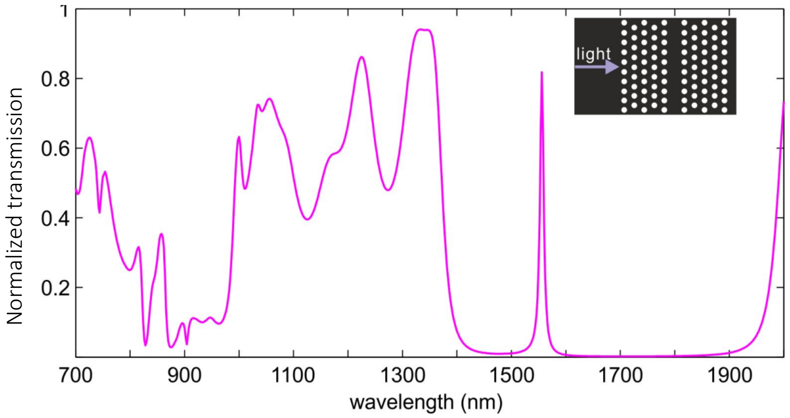


Main Feature: **Photonic Crystals forbid light propagation**

A simple example… BRAGG GRATINGS







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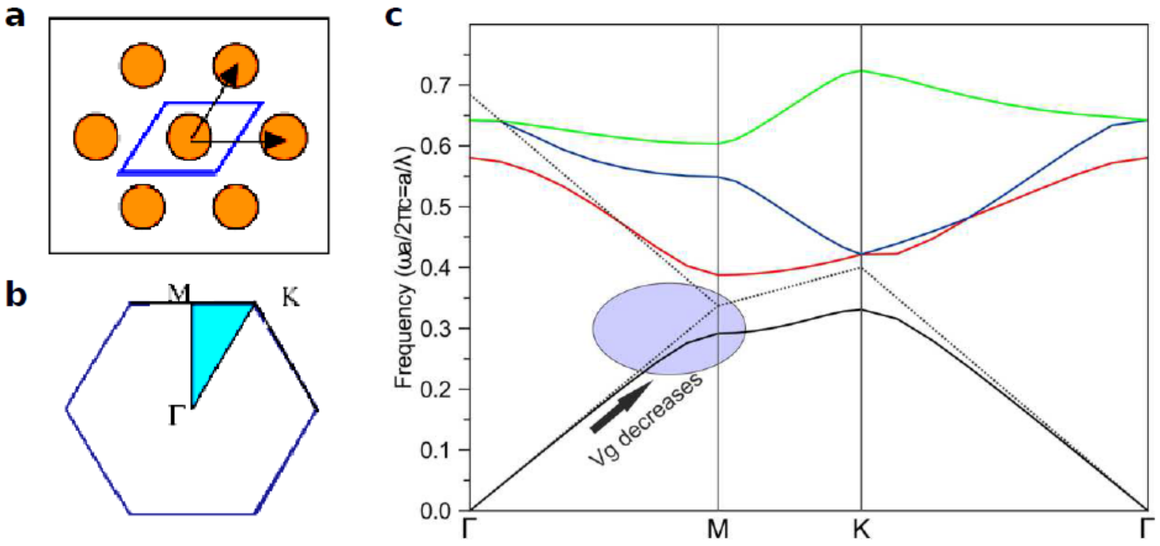
ENHANCED POCKELS EFFECT



$$v_g = \frac{\partial \omega}{\partial k} \qquad f_{opt} = \sqrt{\frac{v_g^{bulk}}{v_g^{PhC}}}$$

Classical
Pockels effect

$$\Delta n = -\frac{1}{2} \cdot n^3 \cdot r_{33} \cdot E$$

Enhanced
Pockels effect

$$\Delta n = -\frac{1}{2} \cdot n^3 \cdot r_{33} \cdot f_{opt}^2 \cdot E$$

Roussey, M., Bernal, M., Courjal, N., Labeke, D. V., Baida, F. I., & Salut, R. Applied Physics Letters, 89(24), 241110 (2006)

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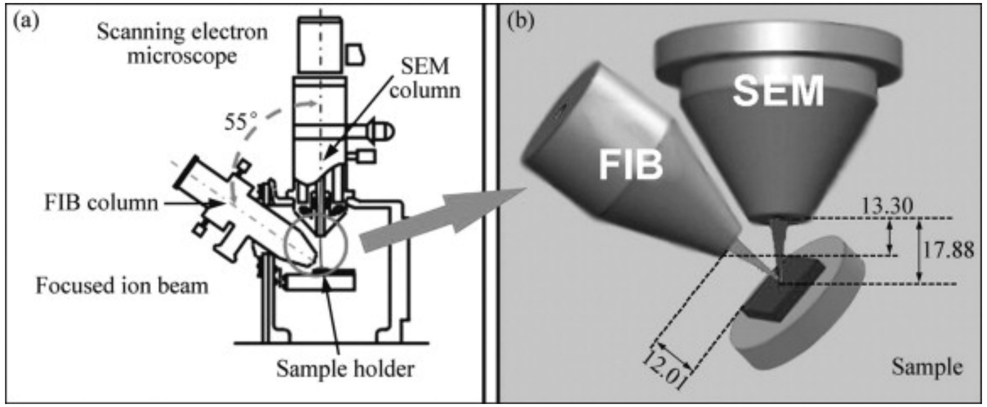
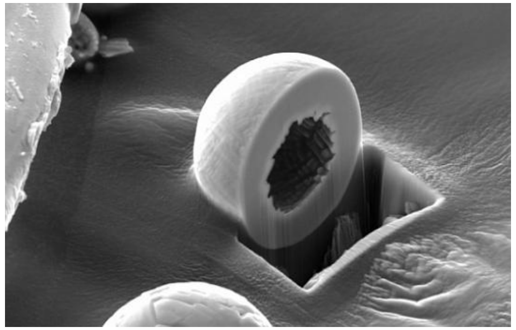
NANOSTRUCTURING IN LITHIUM NIOBATE

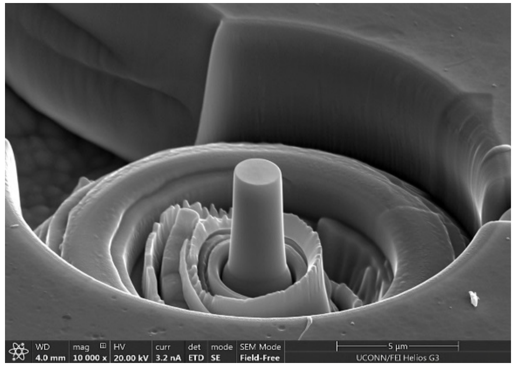


G. Huo, R. Jing, Y. Cui, H. Wang, R. Wang. Progress in Natural Science: Materials International, 20, 111-115 (2010)

Source: http://victorgutierrez.mx

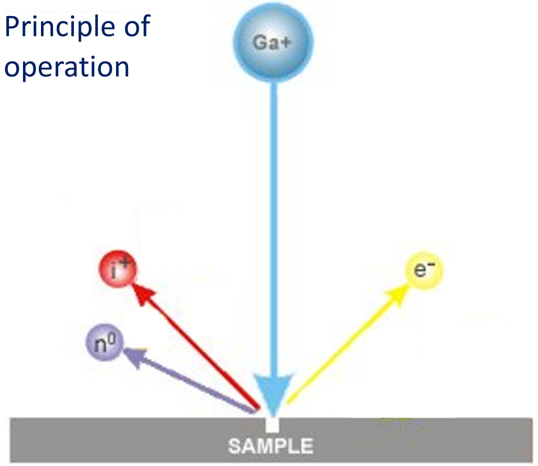


Source: http://microscopy-analysis.com

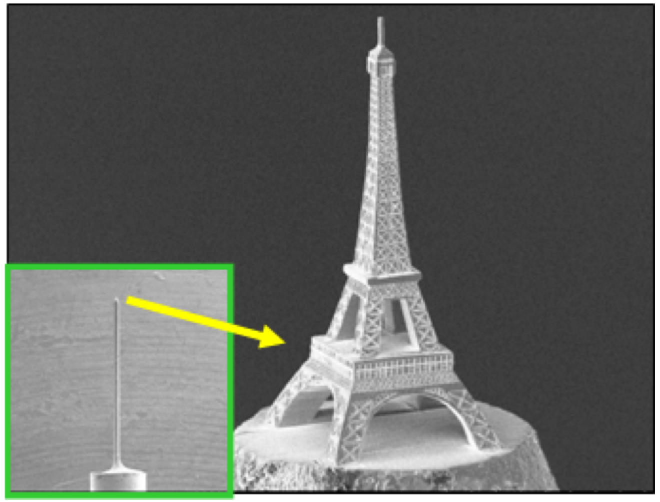


Source: http://sem.elte.hu

Principle of operation



Source: https://en.wikipedia.org



Source: https://www.jfe-tec.co.jp

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TOWARDS LAB-ON-FIBER TECHNOLOGY

Optical Guided Wave (OGW) Technology

FIBER | WAVEGUIDE | EO STRUCTURE | WAVEGUIDE | FIBER

Coupling losses

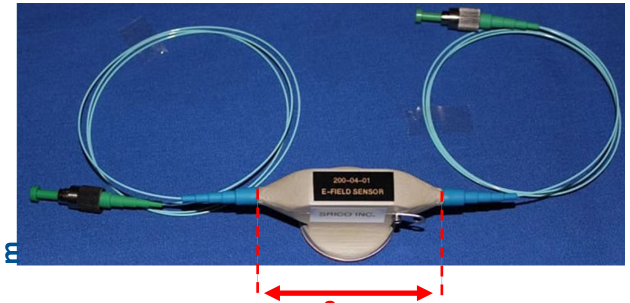
More losses…

Reduced interaction

Massive devices

Bandwidth: DC to 1GHz

srico.com



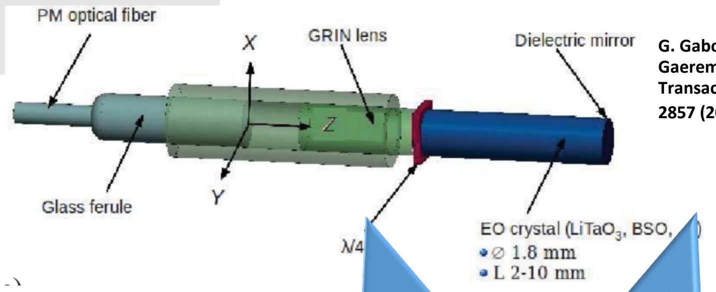
OGW-Reflection based

FIBER | WAVEGUIDE | EO STRUCTURE

Lab-on-Fiber Technology

FIBER | EO STRUCTURE

Bulk-crystal



G. Gaborit, J. Dahdah, F. Lecoche, P. Jarrige, Y. Gaeremynck, E. Duraz, L. Duvillaret. IEEE Transactions on Plasma Science, 41(10), 2851-2857 (2013)

kapteos.com

Lab-on-Fiber → ++++ E-field sensor ← Nanostructuring

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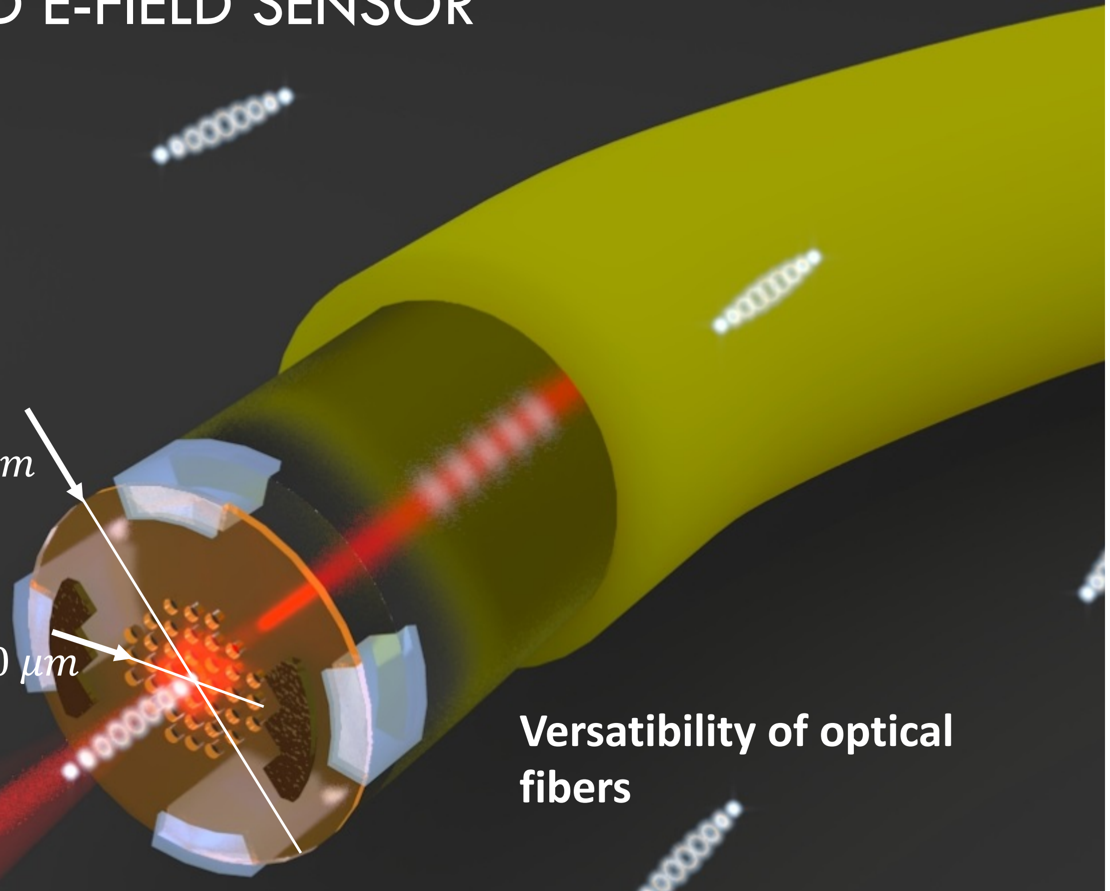
PHOTONIC CRYSTAL FIBERED E-FIELD SENSOR

All-dielectric system

Ultra compact device

Air-coated $LiNbO_3$ thin membrane

Engineered Photonic Structure (Enhanced performances)



Versatibility of optical fibers

Reflection measurement

Easy interface with commercial optical systems

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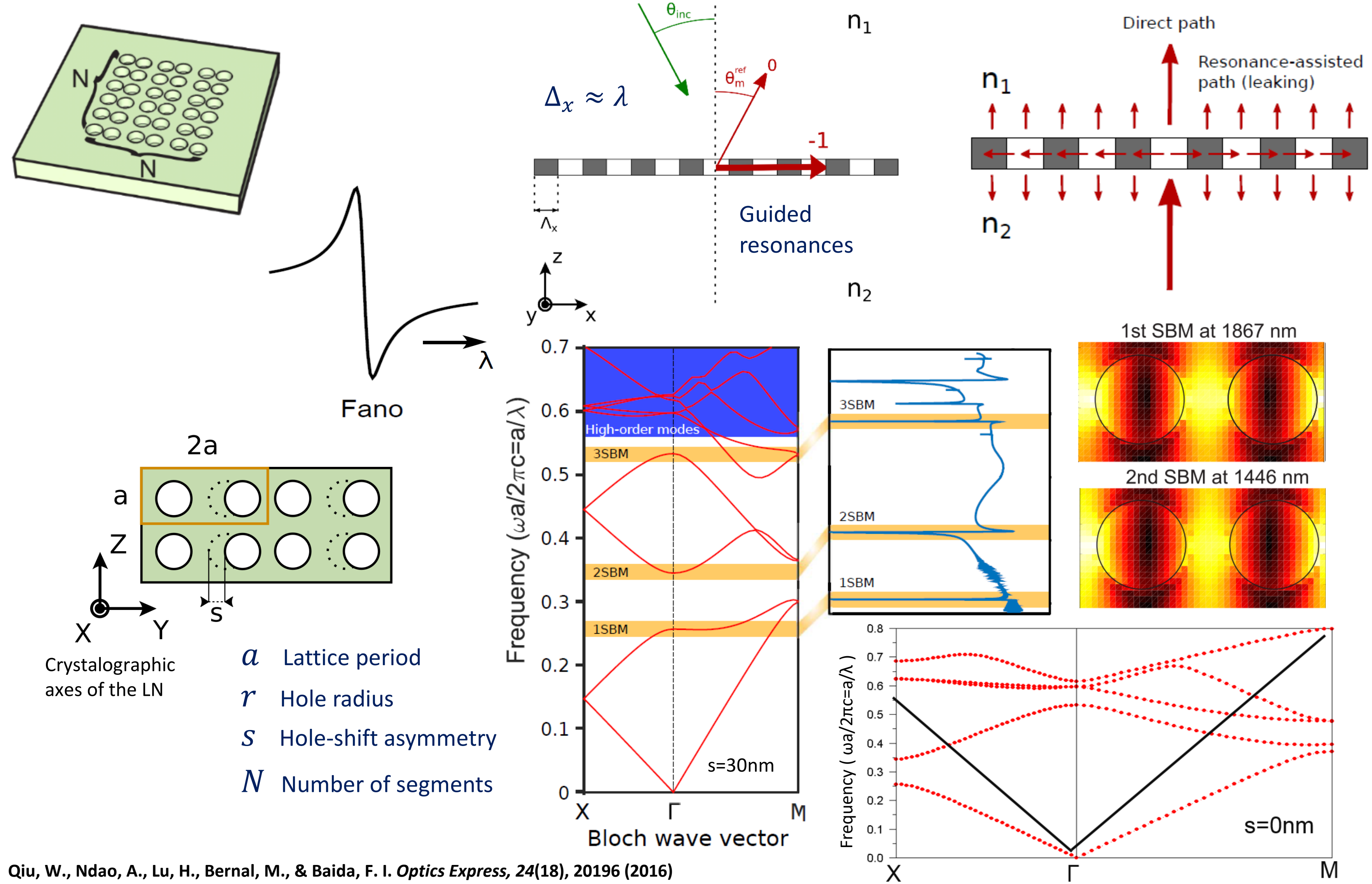
GEOMETRY STUDY



Qiu, W., Ndao, A., Lu, H., Bernal, M., & Baida, F. I. *Optics Express, 24*(18), 20196 (2016)

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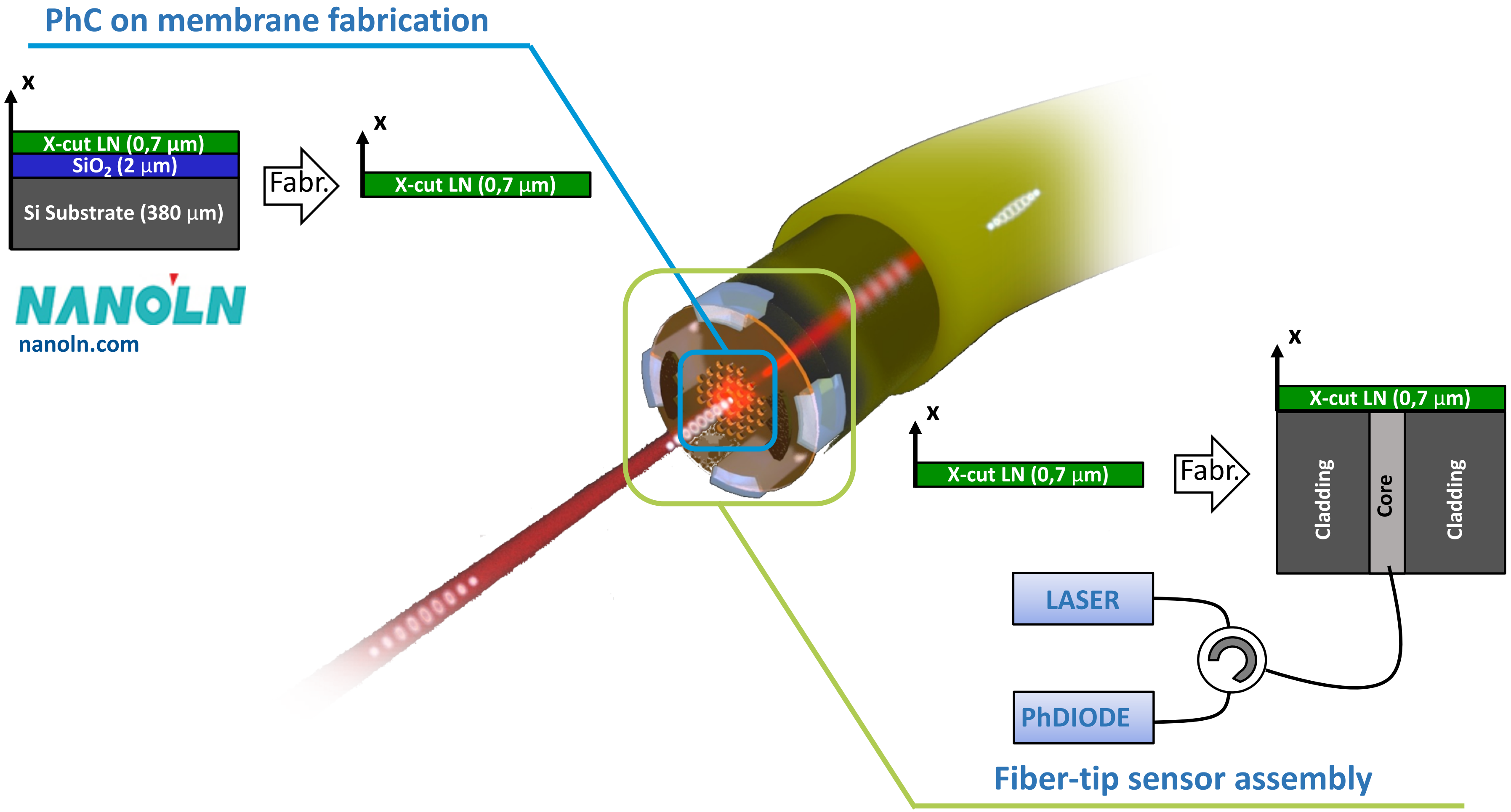
CONCEPT OF THE IMPLEMENTATION



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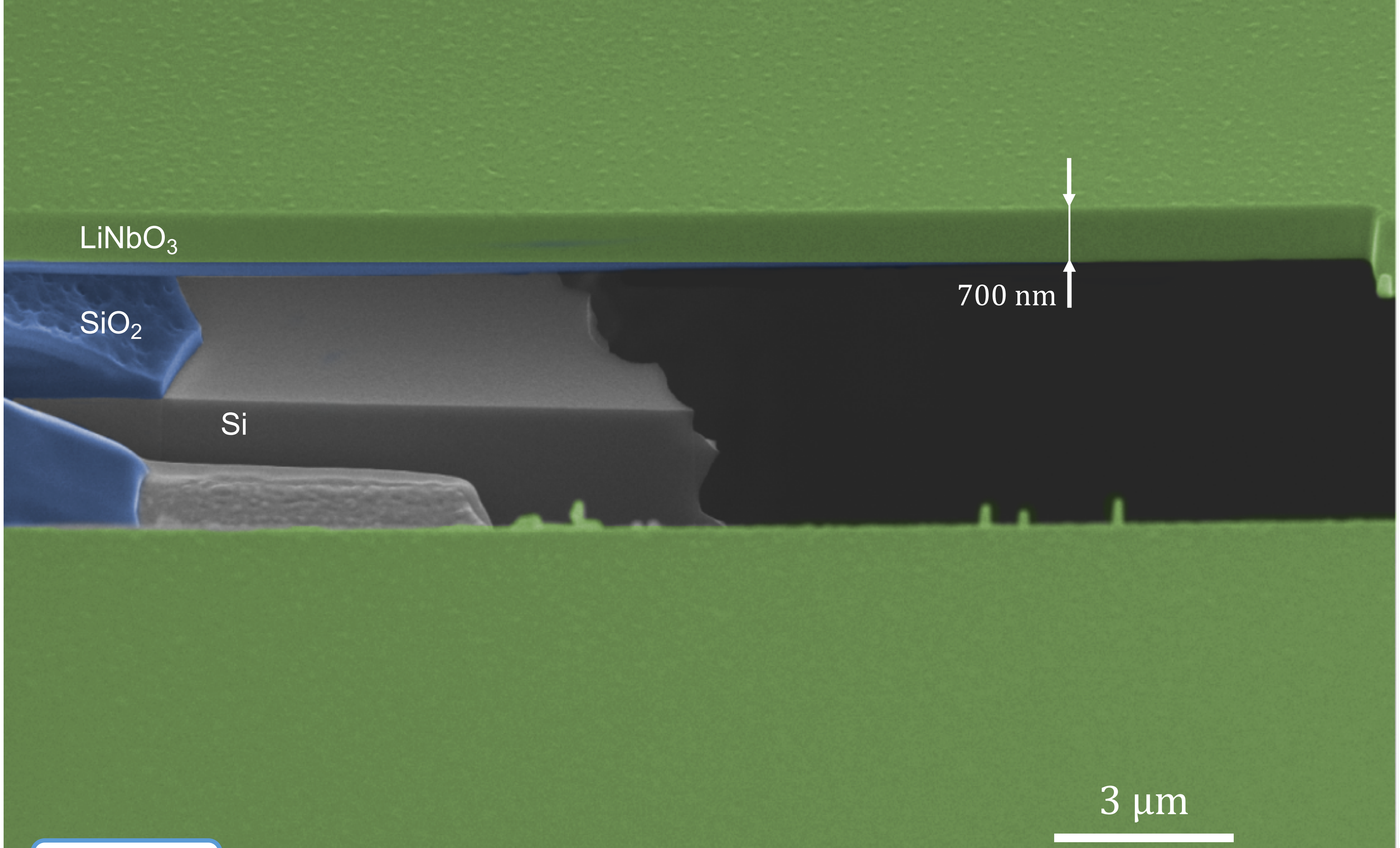
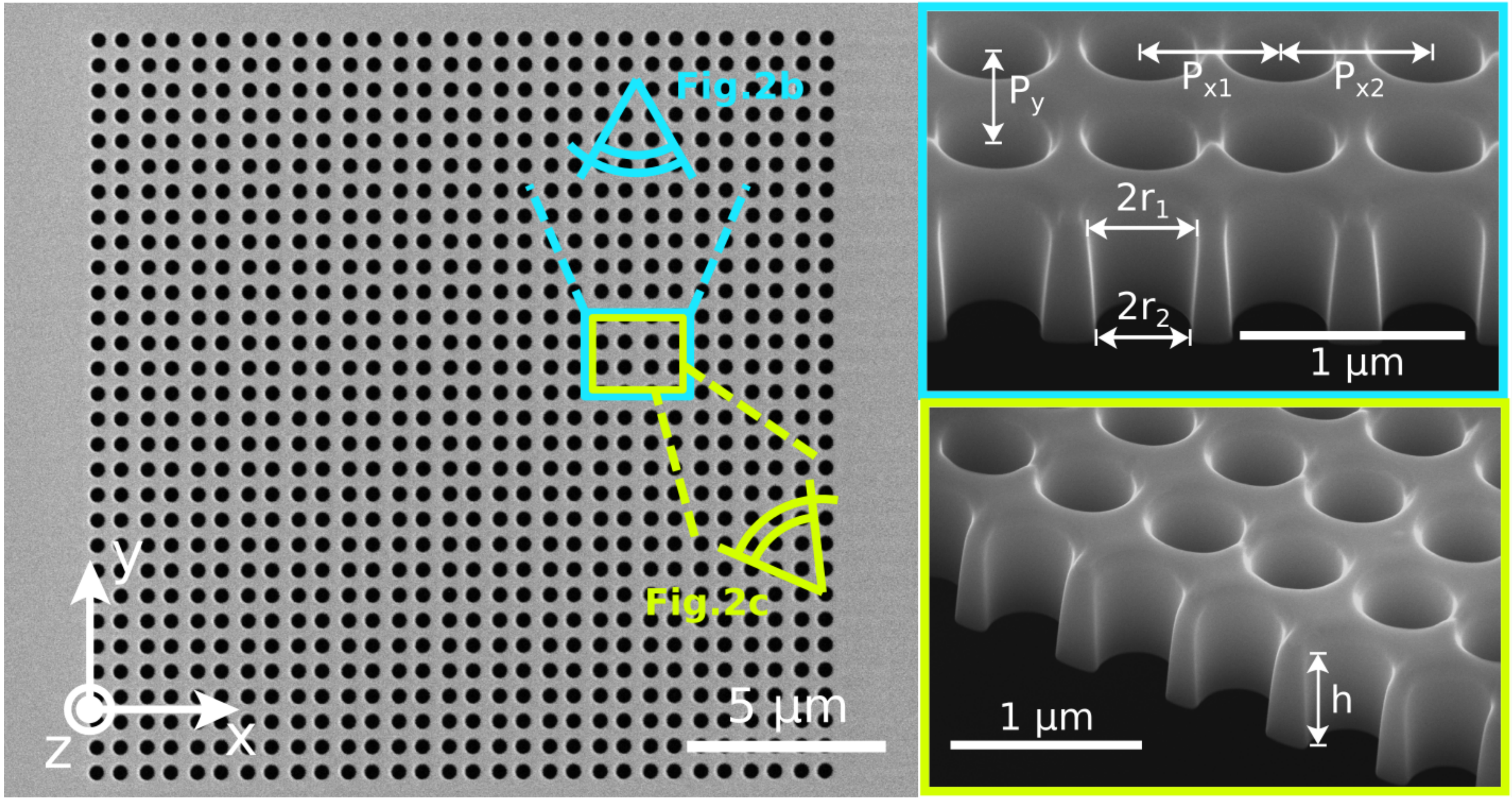
PhC ON MEMBRANE FABRICATION



PhC ON MEMBRANE FABRICATION



RESULTS

a = 630 nm	r = 230 nm	conicity = 3,6º
s = 30 nm	N = 30x30	size = 18,9um x 18,9um

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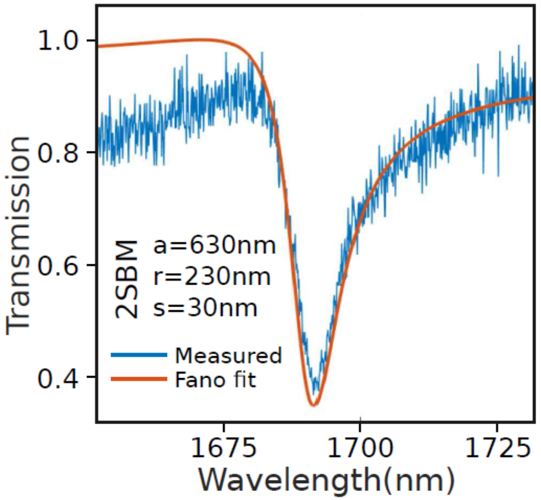
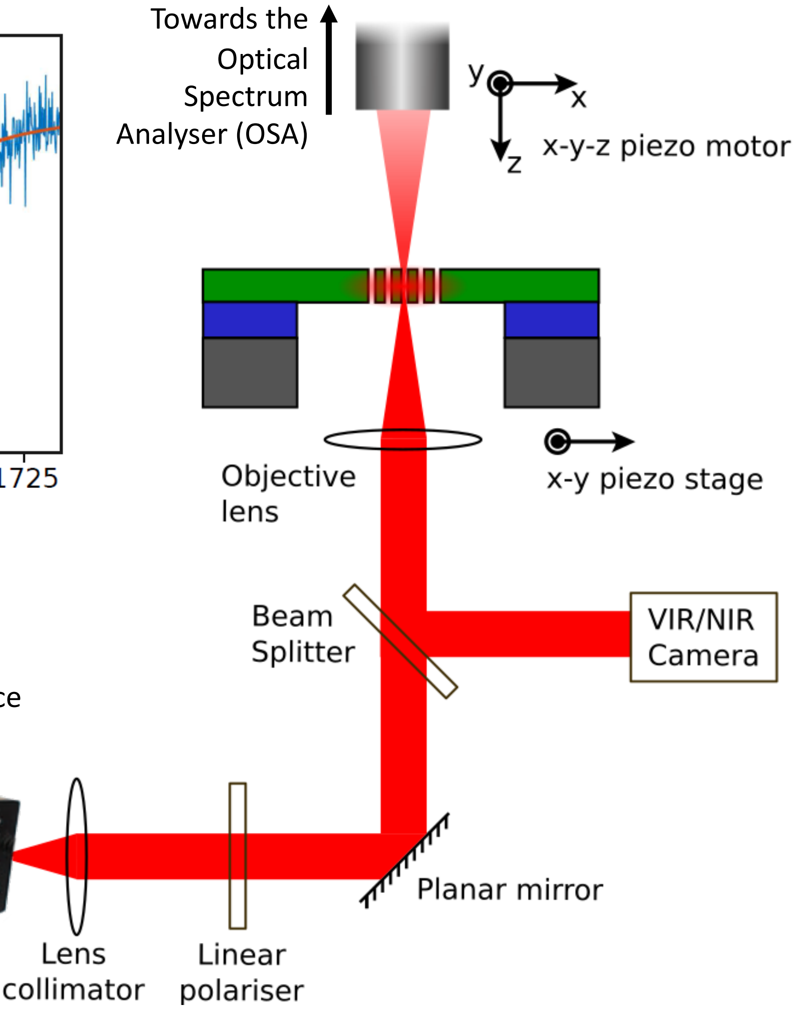
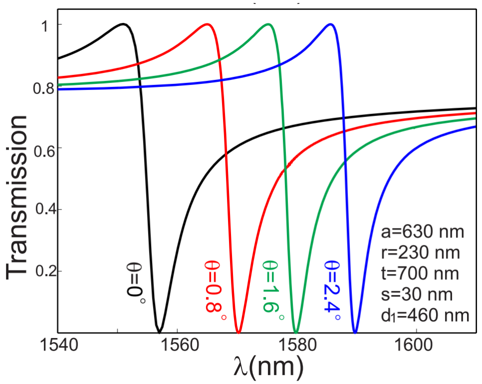
OPTICAL CHARACTERIZATION SETUP





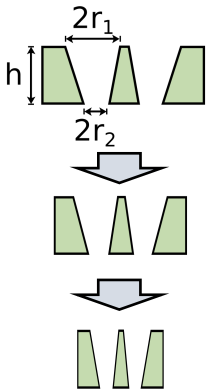
leukos-systems.com

! WARNING
Holes are conical

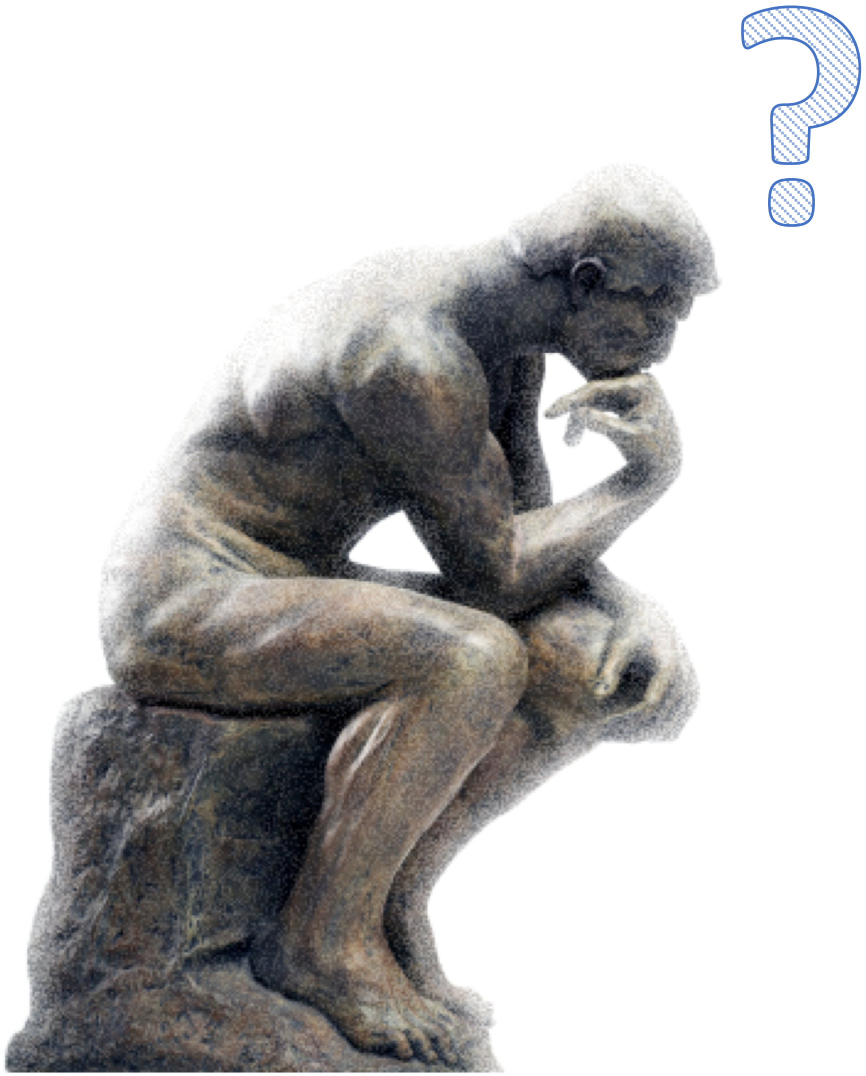


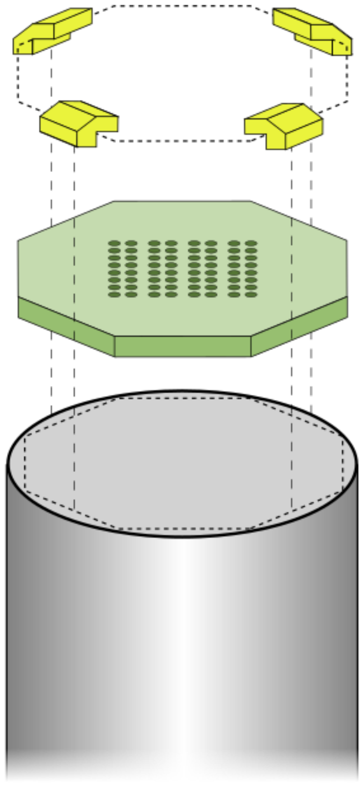
Qiu, W., Ndao, A., Lu, H., Bernal, M., & Baida, F. I. *Optics Express, 24*(18), 20196 (2016)

SOLUTION (re-scaling)

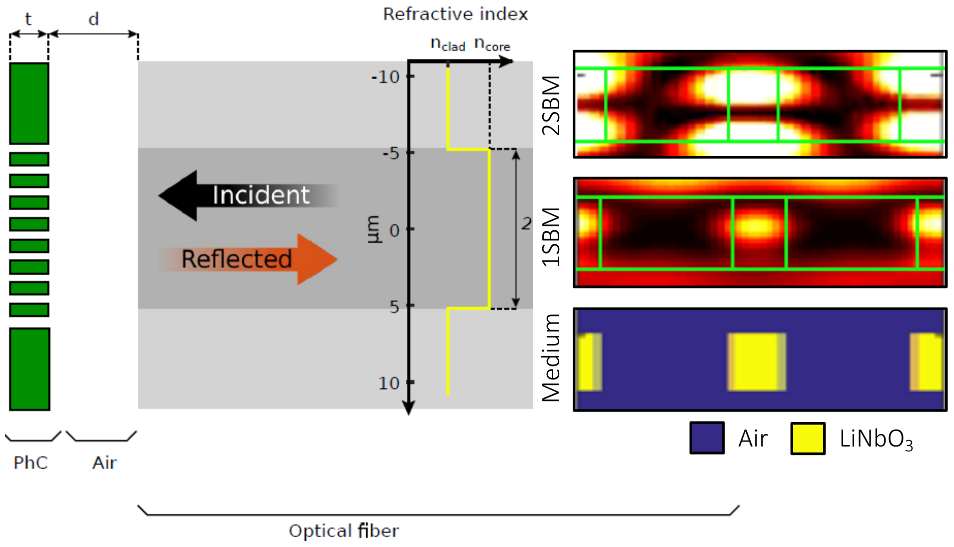


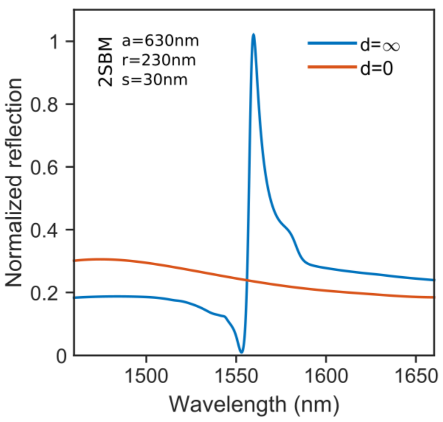
BUT HOW TO INTEGRATE IT?

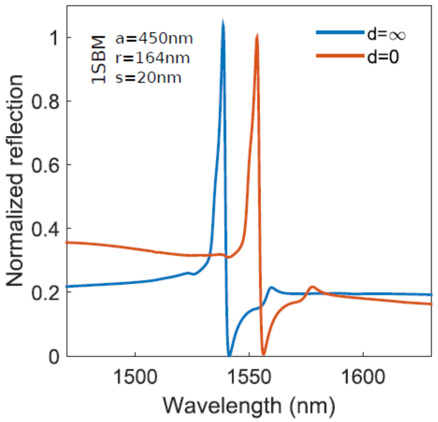




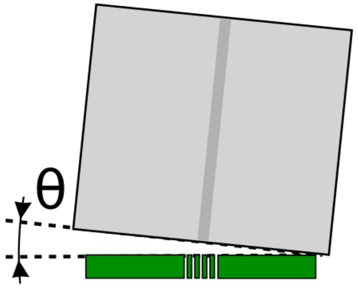
STUDY OF THE INTEGRATION

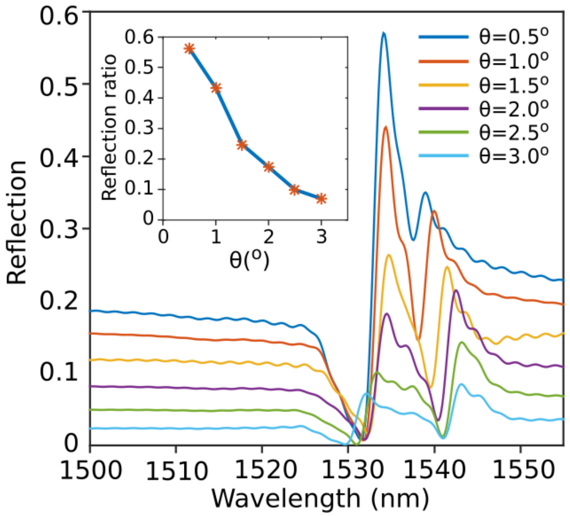






Non-parallelism





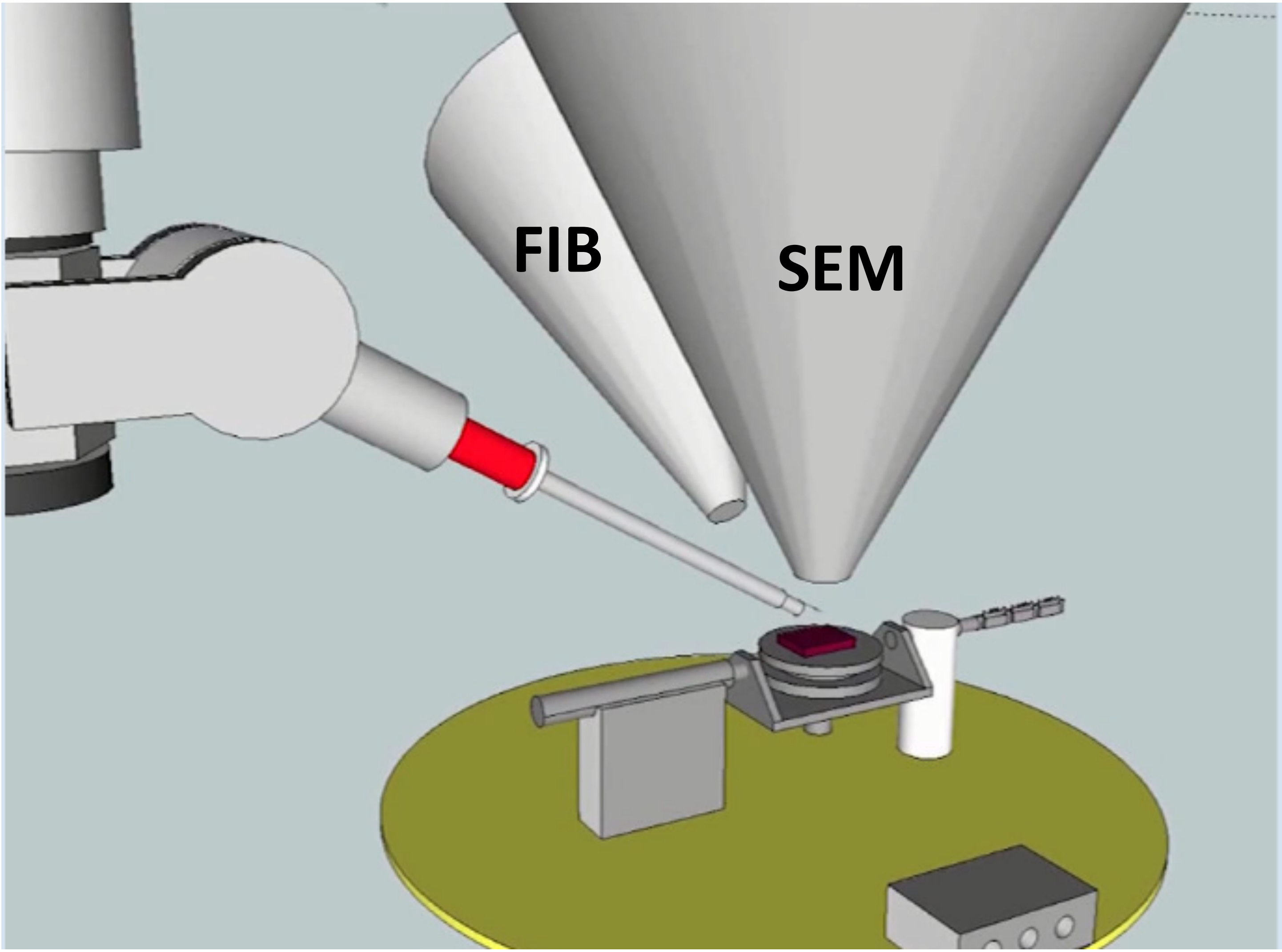
2SBM
a=630nm | r=230nm

- \+ Lower PhC hole conicity
- \+ No thickness erosion
- − Vulnerable under fiber influence
- − An angle may exist between both

1SBM
a=450nm | r=164nm

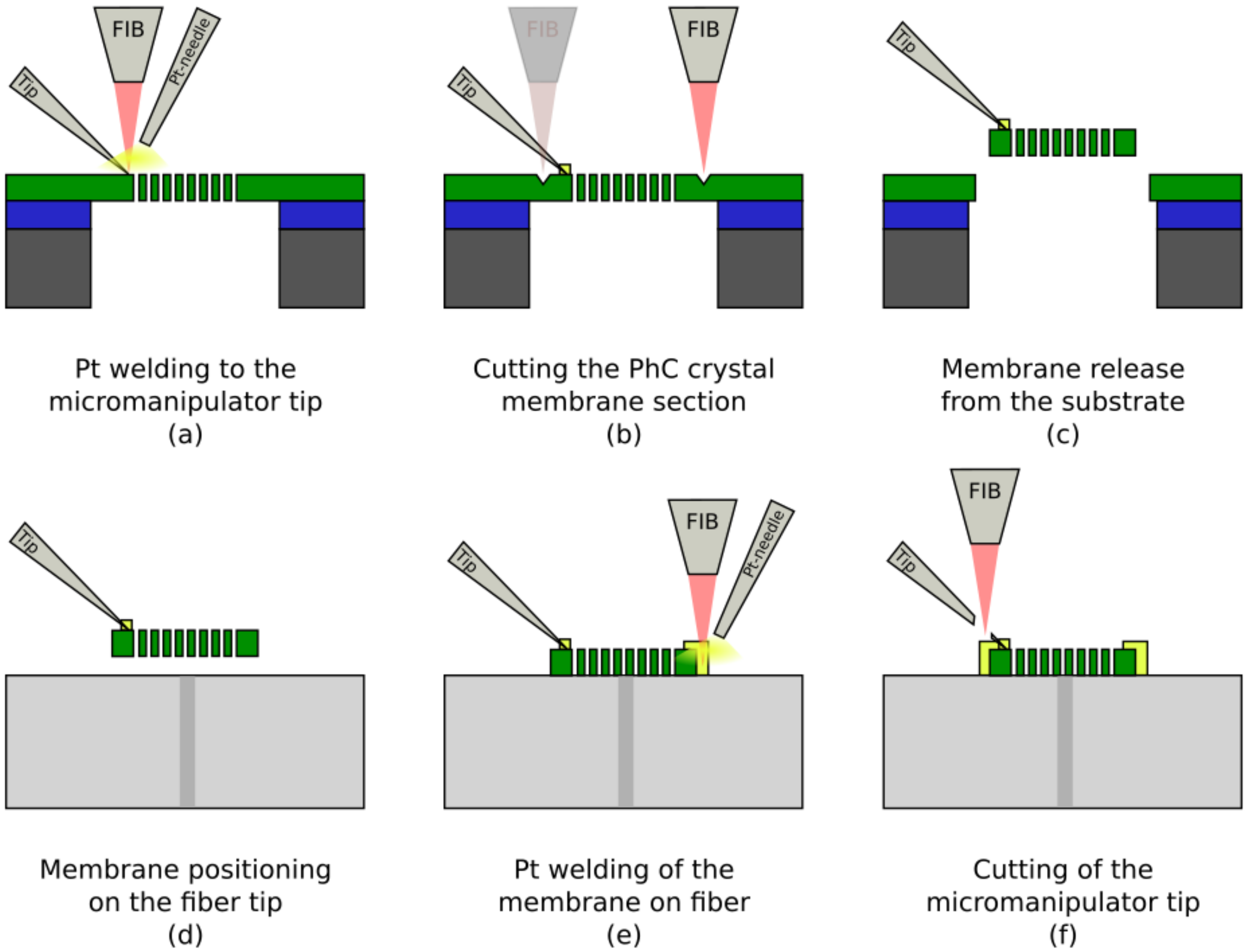
- − High PhC hole conicity
- − Notable thickness erosion
- \+ No influence of the fiber proximity
- \+ Angle error is ensured to minimum

FIB + MICROMANIPULATOR



Source: KleindiekNanotechnik

POINT WELDING ASSEMBLY METHOD



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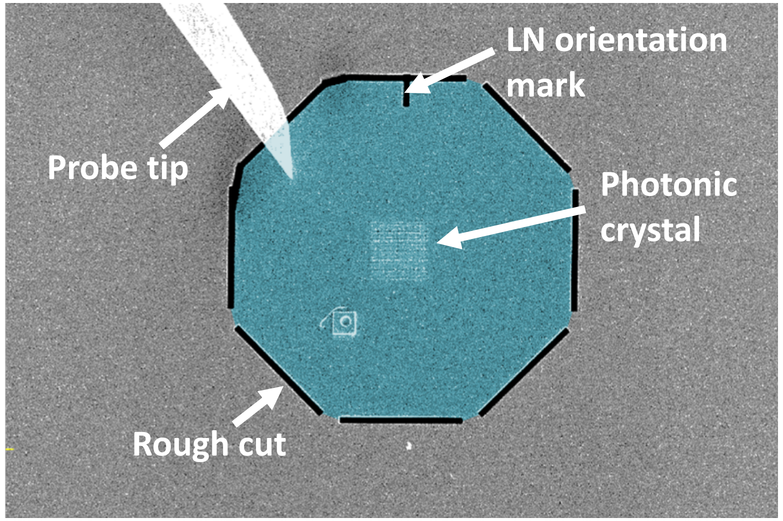
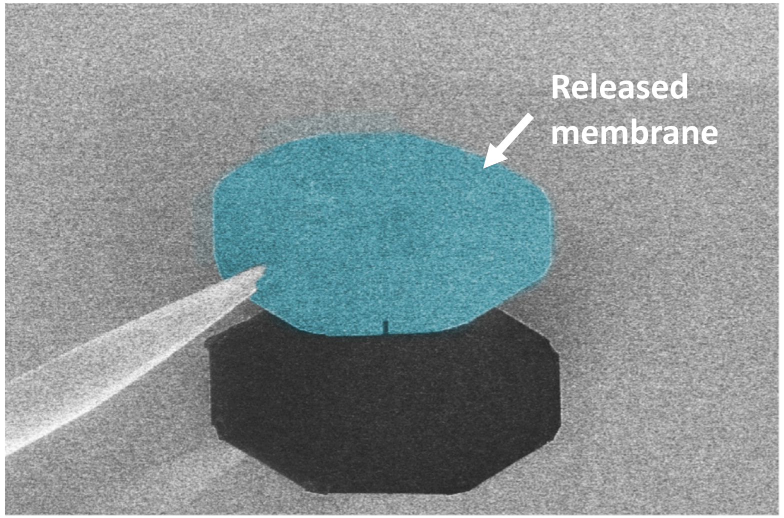
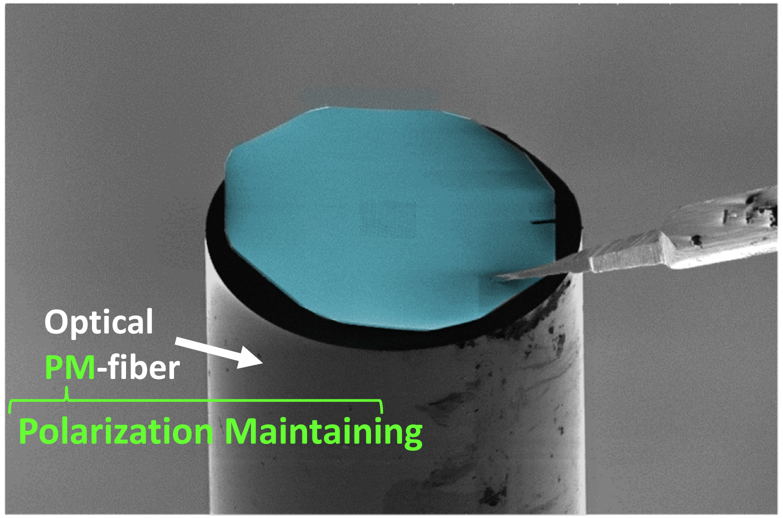
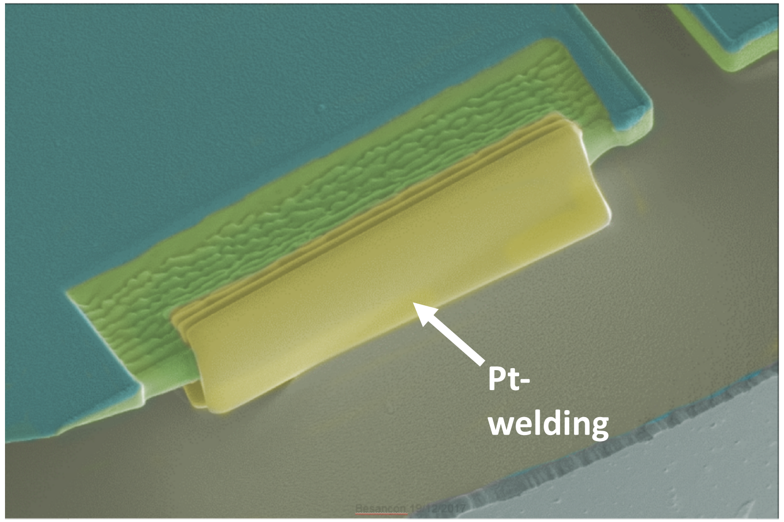
POINT WELDING ASSEMBLY METHOD









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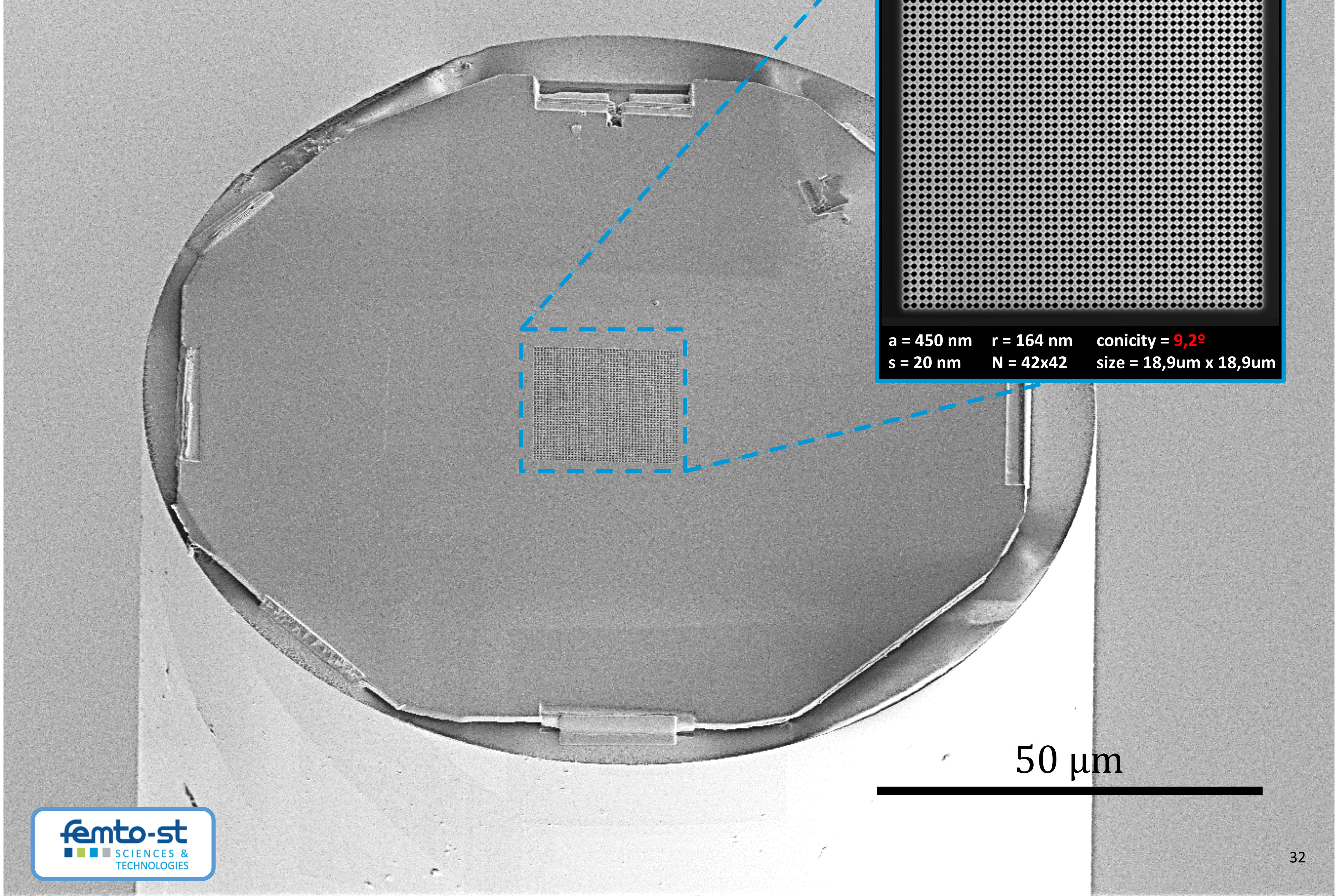
THE FIBER-TIP SENSOR



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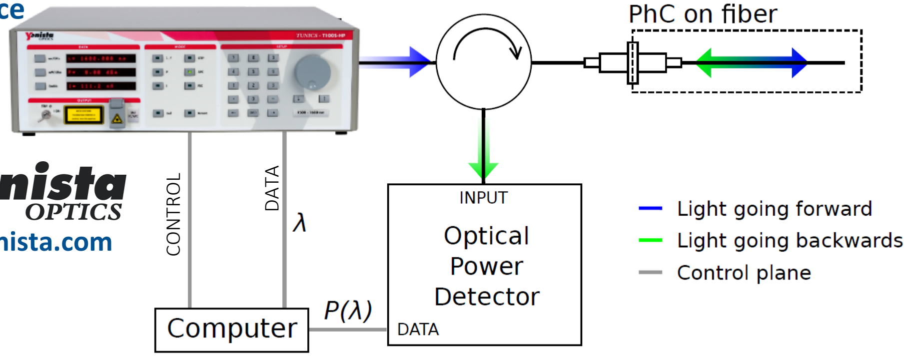
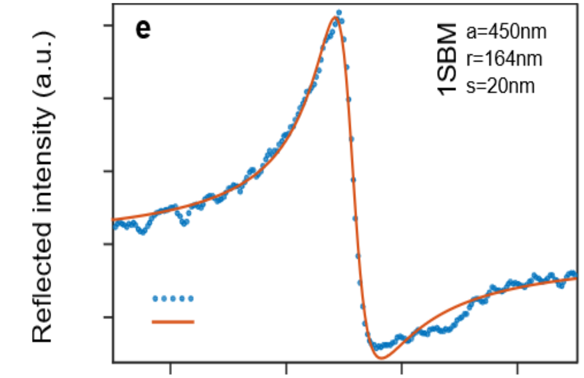
CHARACTERIZATION

Optical verification

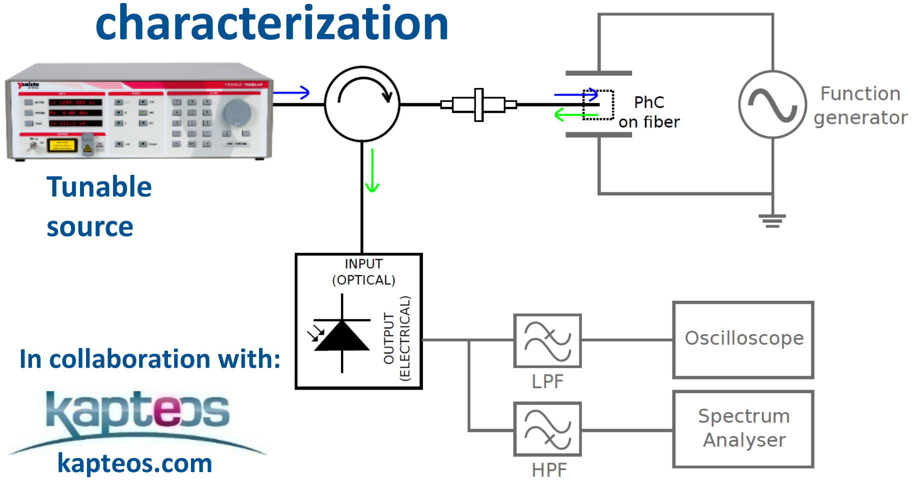
Tunable source **[1470nm, 1660nm]**



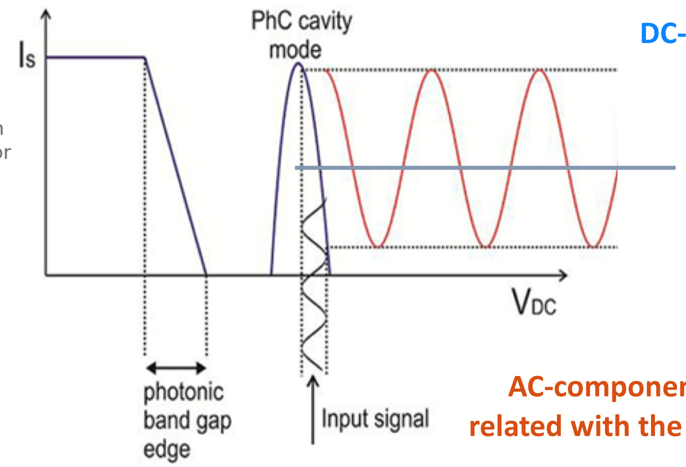
yenista OPTICS
yenista.com



Electro-optical characterization



Tunable source



DC-component gives the working point information

STABILITY

AC-component is directly related with the applied E-field

EO-MODULATION

In collaboration with:

kapteos.com

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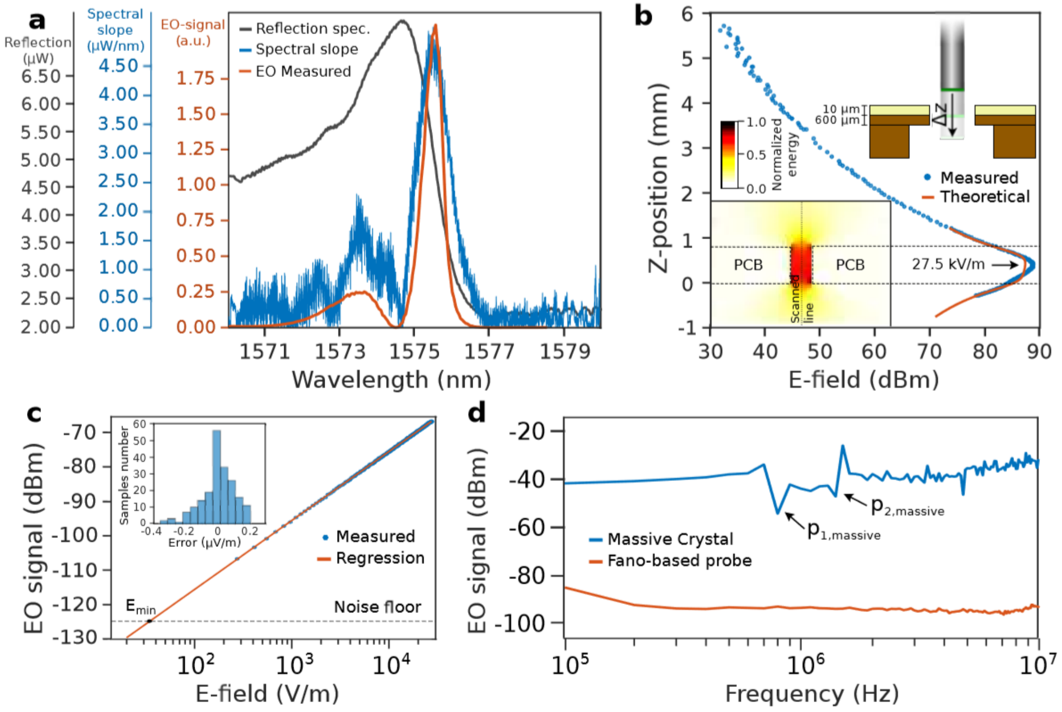
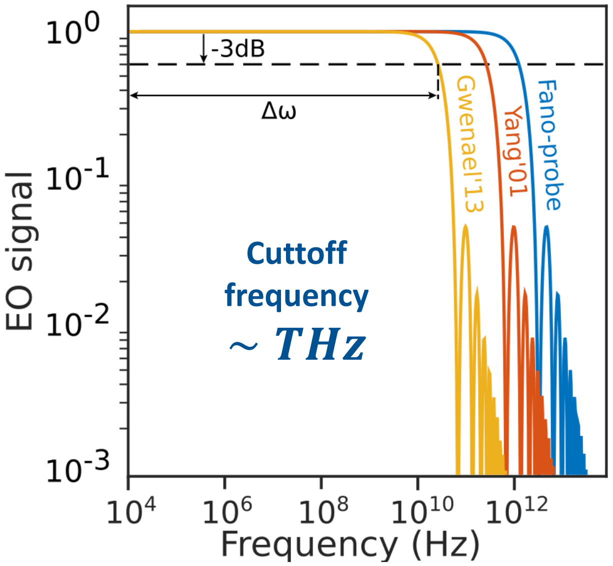
EO behaviour





Sensitivity: $32\ V\ m^{-1}\ Hz^{-\frac{1}{2}}$

Linear response to electric fields

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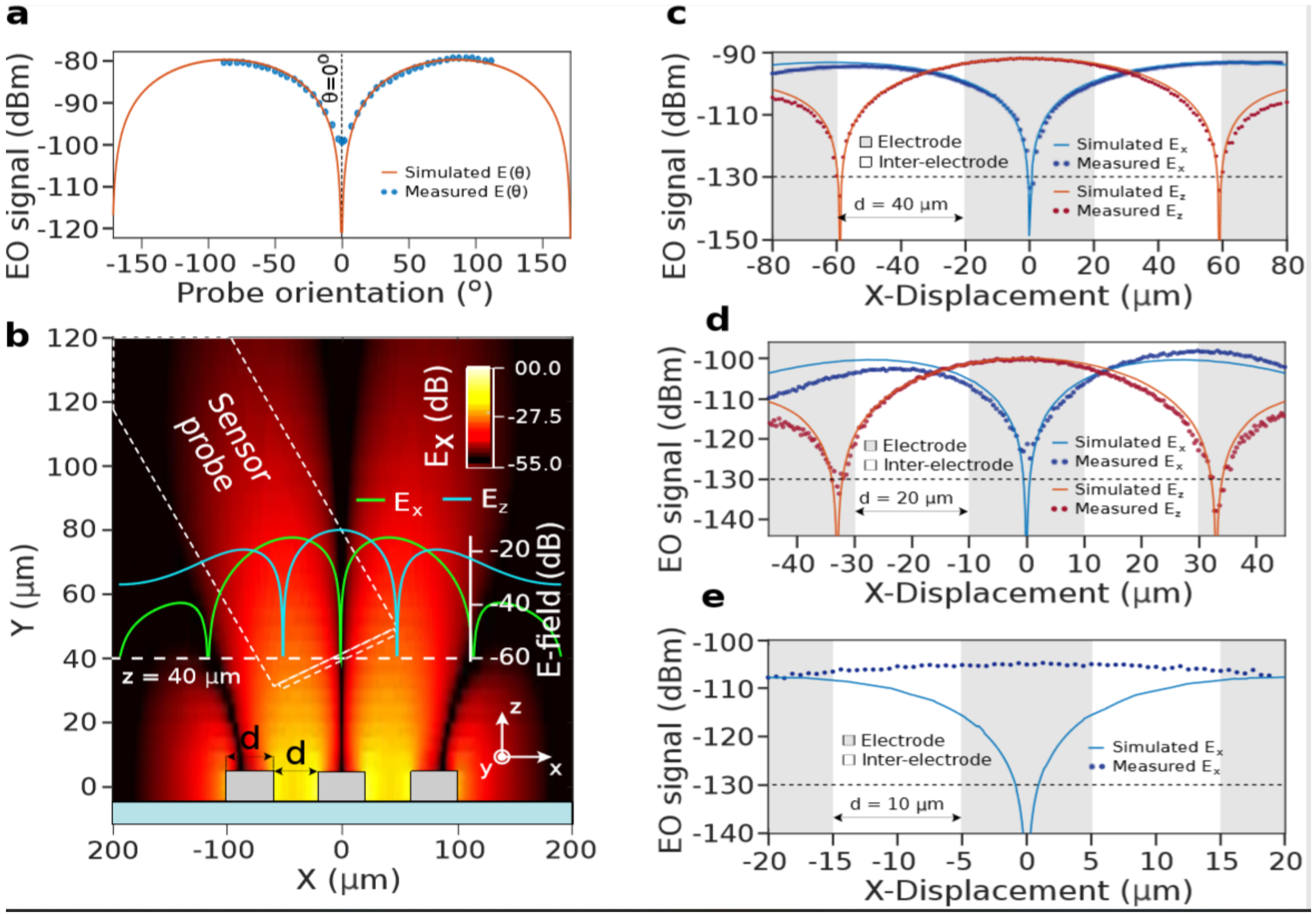
kapteos

Vectorial Sensitivity and spatial resolution

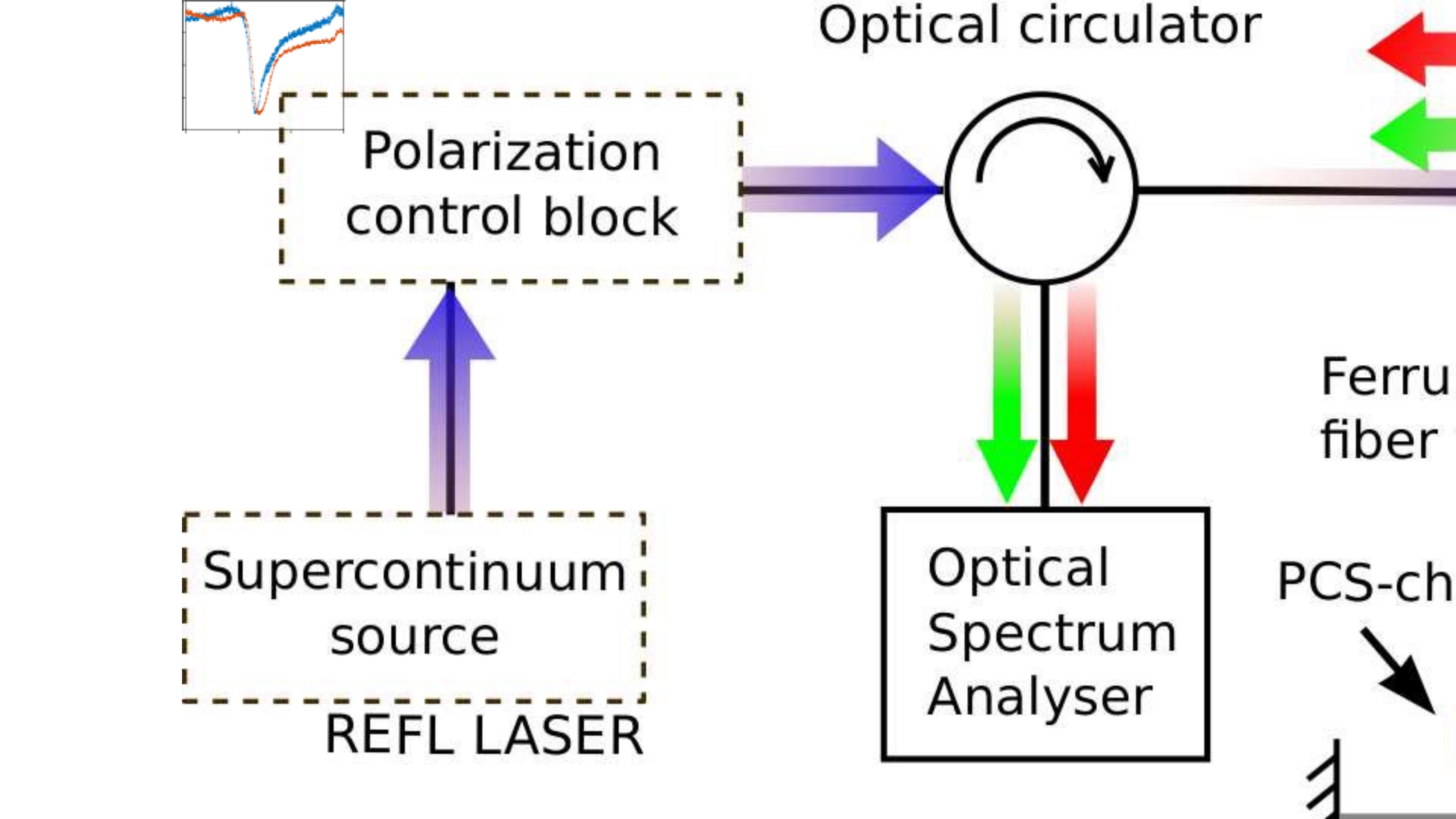
The photonic crystal is rotated between the electrodes around the optical wave vector direction for angles ranging from $-\frac{\pi}{2}$ to $\frac{\pi}{2}$ -- Electrode distance is changed



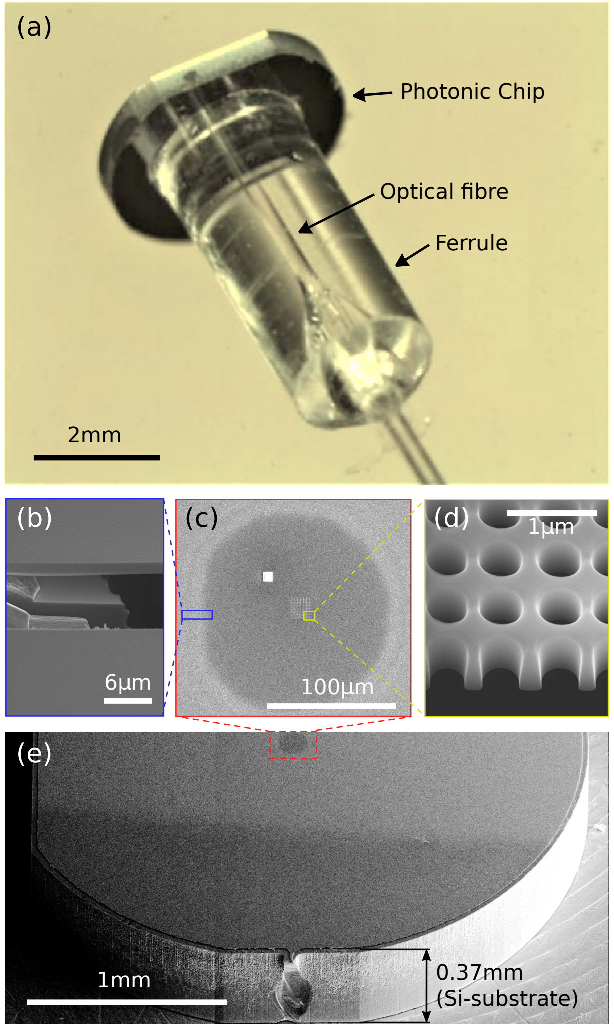
d = 40 um

d = 20 um

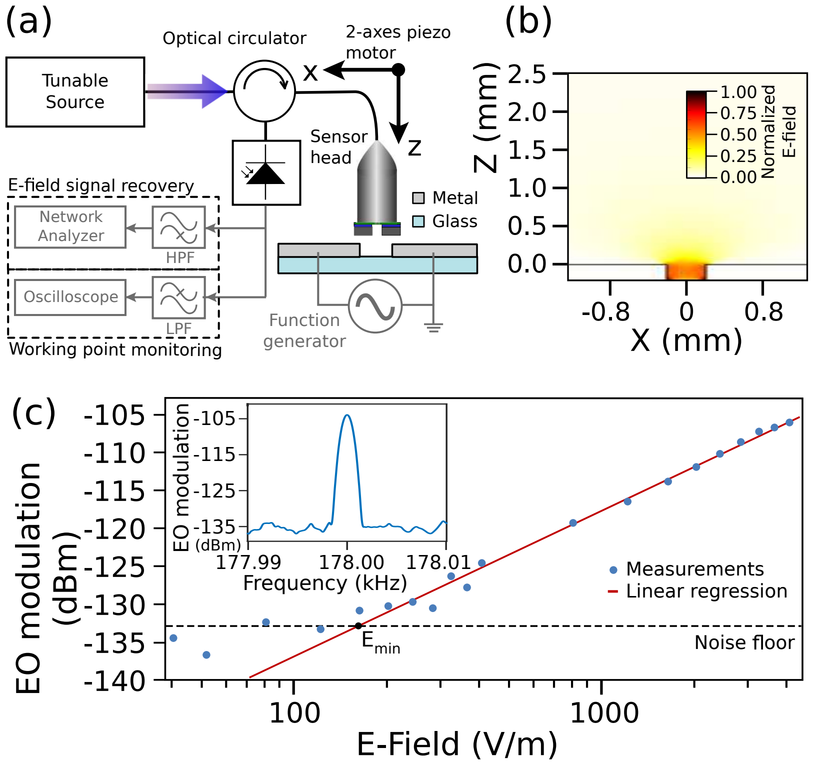
d = 10 um



Optical circulator
Polarization control block
Supercontinuum source
REFL LASER
Optical Spectrum Analyser
Ferru
fiber
PCS-ch



(a)
Photonic Chip
Optical fibre
Ferrule
2mm
(b)
6µm
(c)
100µm
(d)
1µm
(e)
1mm
0.37mm
(Si-substrate)



(a)
Tunable Source
Optical circulator
2-axes piezo motor
X
Z
Sensor head
Metal
Glass
E-field signal recovery
Network Analyzer
HPF
Oscilloscope
LPF
Working point monitoring
Function generator
(b)
Z (mm)
X (mm)
Normalized E-field
(c)
EO modulation (dBm)
E-Field (V/m)
Frequency (kHz)
Measurements
Linear regression
Noise floor
E min

Conclusion

-LN has a serious chance to be the « silicon of photonics »
-Different novel technologies allow today small optical modes with no additional cost in optical losses
-LN combined with nanooptical designs present high potential for applications in high sensitive metal-free E-field optical sensors

Fabrication technologies

What are the steps to follow to fabricate a PC??

Despite the geometrical simplicity, 2D PCs have proven to be a hard task to be accomplished. Just a single pasive device requires a full featured microfabrication facility comprising

- a multilayer deposition system,
- a high resolution lithographic machine, (electron beam, focused ion beam..),
- a plasma etching tool

What is the main difficulty?

For optical wavelengths, the holes or pillars are of several tens of nanometers. Optical lithography is insufficient due to the diffraction limit resolution.

For active devices a further ion implantation step will be necessary

Fabrication technologies

But,……this is not all

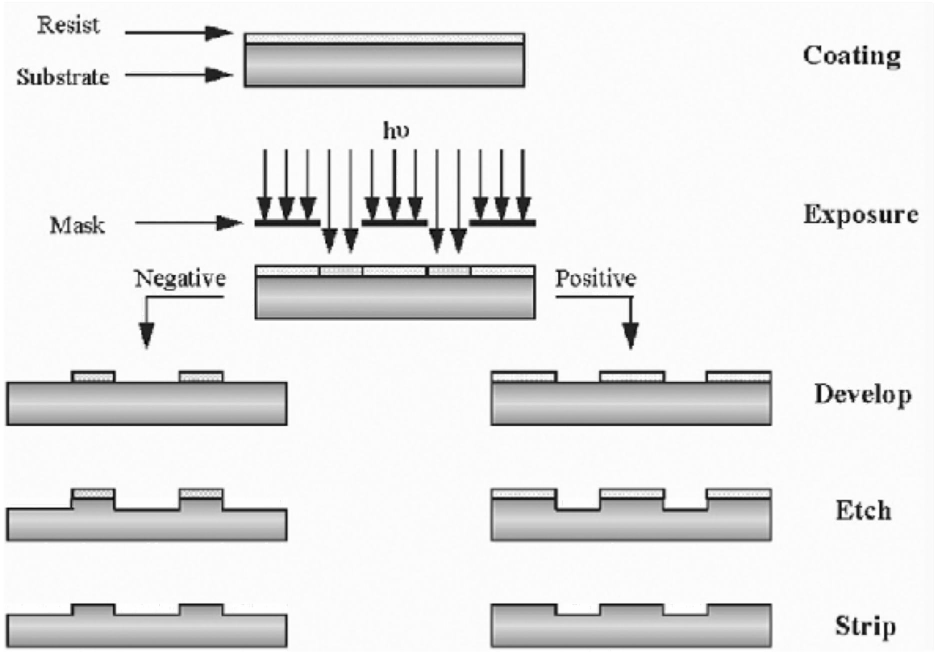
All the fabrication steps require and after process inspection tool so a SEM (Scanning Electron Microscope) is absolutely imprescindible.

And, once the device has been fabricated we need to characterize its optical performance. Two types of experimental set-ups are needed:

1) Transmission or/and reflection measurement (making use of a large band laser or white source supercontinuum.
2) The behavior of the electromagnetic fields on the photonic structure can only be inspected by Scanning Optical Near Field Microscopy (SNOM).

Fabrication technologies

First step: mask fabrication: LITHOGRAPHY



Schematics of a standard lithographic step

The most common method is by lithography.
Lithography is the process of transferring patterns of geometric shapes to a thin layer of a radiation sensitive material (resist).
The exposed/unexposed resist is removed by means of a solvant.

Fabrication technologies

Lithography can be divided in two methods:

1) Parallel lithography: The geometrical patterns are on masks that shadow the incoming radiation and is transfered on the resist in one single shot.

Example: **Optical lithography** (using UV light), the most common technique widely used in semiconductor industry.

Another interesting example: **Nanoimprint**

2) Serial lithography: The pattern, drawn with the help of a computer aided design (CAD) software is directly exposed on the resist.

Example: **EBL (Electron Beam Lithography).** The resist layer is exposed through an electron beam which position is controlled by a computer.

Fabrication technologies

ELECTRON BEAM LITHOGRAPHY

Example of an electron beam lithography equipment from JEOL

EBL offers higher patterning resolution than optical lithography because of the shorter wavelength possessed by the 10-50 keV electrons that it employs.

A typical EBL system consists of the following parts:

1) An electron gun or electron source supplying the electrons.

2) An electron column that « shapes » and focuses the electron beam.

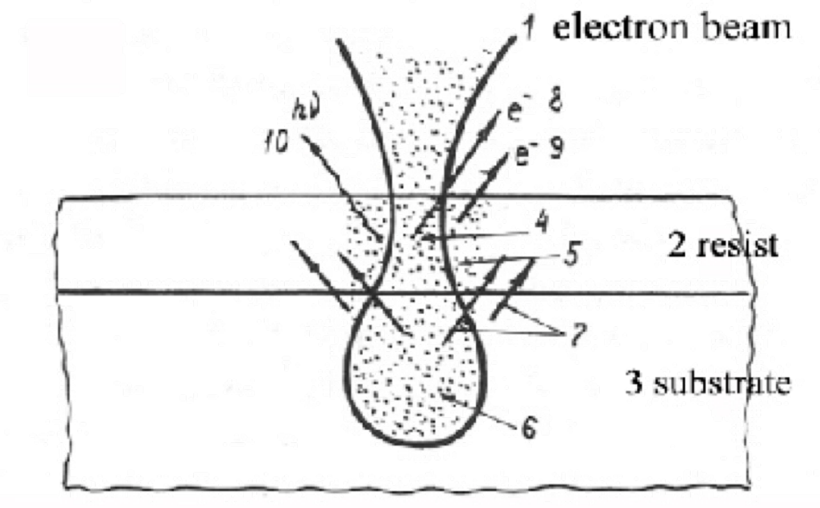
3) A mechanical stage that positions the wafer under the electron beam.

4) A wafer handling system that automatically feeds wafers to the system and unloads them after processing.

5) A computer system that controls the system.

Fabrication technologies

RESOLUTION OF A EBL SYSTEM



Contrary to an optical lithographic system, EBL resolution is not limited by diffraction the reason being the short wavelengths of the electrons (0.2-0.5 A).

However the resolution may be constrained by factors like

4-5	resist layer regions exposed by the passing electron
6	electron scattering area in the substrate
7	electrons reflected from the substrate
8-9	reflected and backscattered electrons

Fabrication technologies

FOCUSED ION BEAM (FIB)

FIB placed in the Optoelectronic Device Group University of Wuerzburg (Germany)

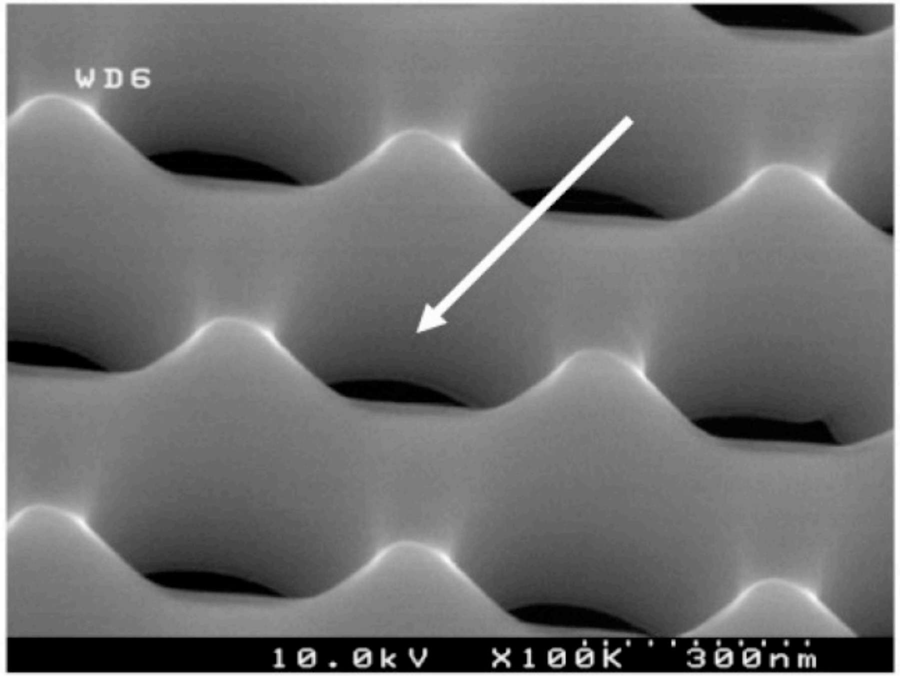
The focused ion beam system uses Ga^{+} ion beam to raster over the surface of a sample in a similar way as an EBL system. The generated secondary electrons (or ions) are collected to form an image of the surface of the sample.

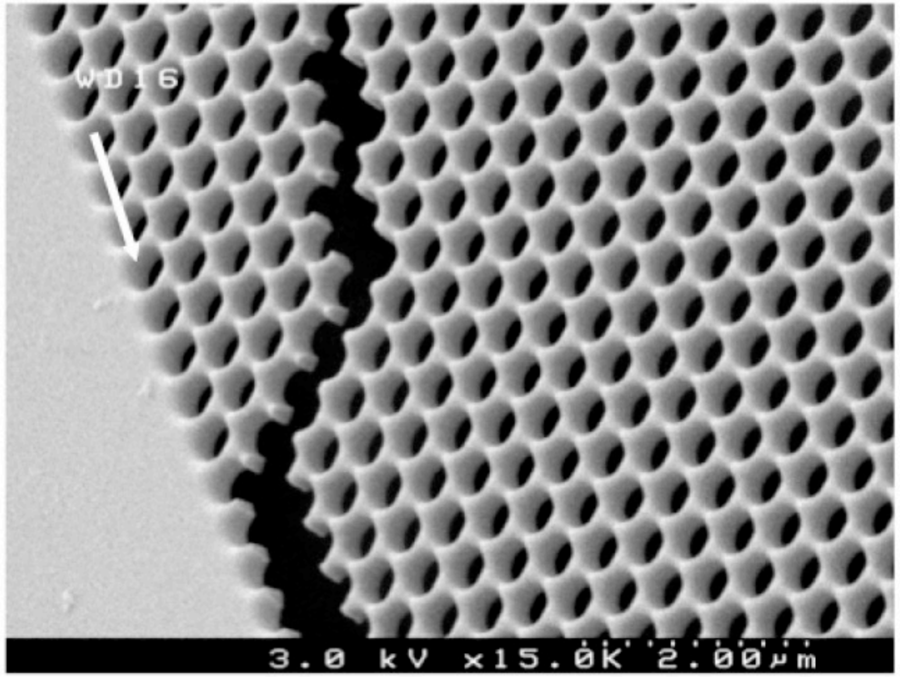
The ion beam allows the milling of small holes in the sample at well localized sites

Ion beam energy range	10-150 KeV
Beam diameter	$<$ 30 nm
FWHM	$<$ 30 nm @ 70 kV
Gaussian like beam shape	

Fabrication technologies

FIB fabrication





D. Freeman et al., Opt. Exp., 13, 3079 (2005)

Fabrication technologies

PATTERN TRANSFER: THE REACTIVE ION ETCHING

MEMS Group
IMES,
ETH Zentrum

Dry etching does not utilize any liquid chemicals or etchants to remove materials from a wafer. It can be accomplished in three ways:

1) Through chemical reactions that consume the material, using chemically reactive gases or plasma.
2) Physical removal of the material, usually by momentum transfer.
3) A combination of both physical removal and chemical reactions.

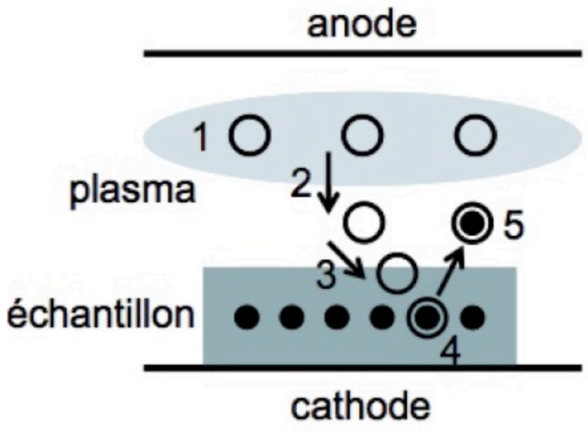
A **plasma** is a quasi-neutral gas of charged and neutral particles which exhibits a collective behaviour.
In plasma, as a ionized gas contains charged particles, while moving around they may generate local concentration of positive or negative charge giving rise to electric fields.

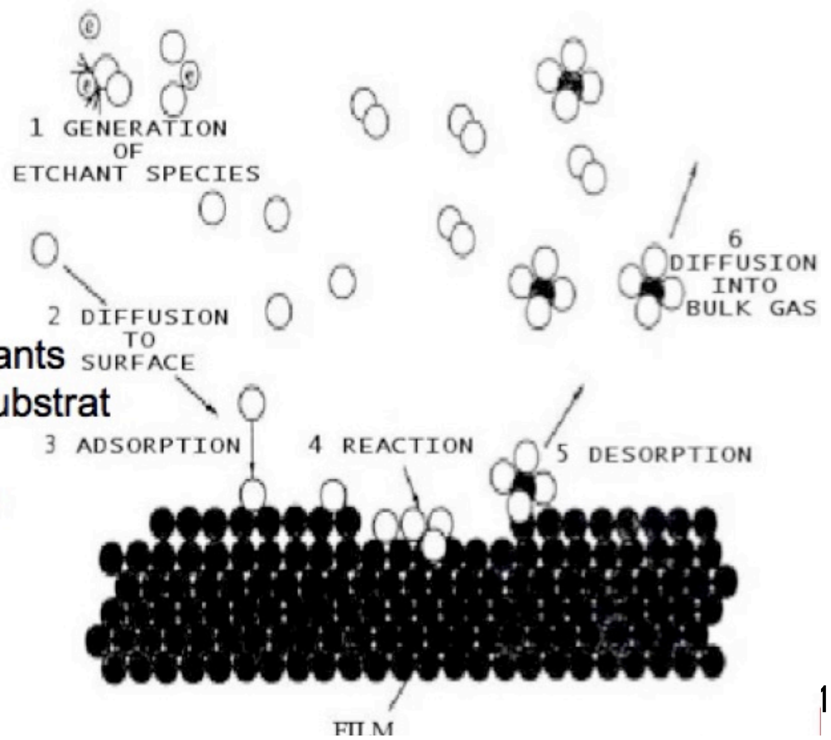
RIE consists then of bombarding the material to be etched with highly energetic reactive ions. Such bombardment with energetic ions dislodge atoms from the material, achieving sputtering of the material.

Fabrication technologies

RIE: Double process

1. Physical etching due to mechanical bombarding
   - Isotropic
   - Generates defects
   - Low selectivity
2. Chemical etching due to chemical reaction of the plasma ions
   - Anisotropic
   - Selective
   - Fast





Fabrication technologies

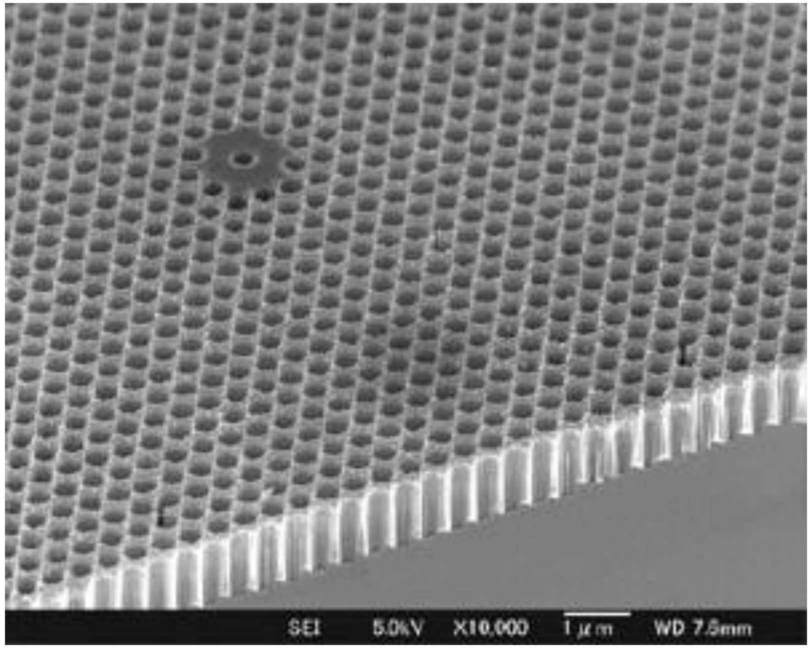
PATTERN TRANSFER: THE REACTIVE ION ETCHING

Examples of Gases Used in the RIE of Common Wafer Materials

Material to be Etched	***Examples of Gases Used in the RIE***
Polysilicon	CF_4; SF_6; Cl_2; CCl_3F; etc. (w/ or w/o oxygen)
Al; Al doped with Si, Cu, Ti	CCl_4; CCl_4+Cl_2; BCl_3; BCl_3+Cl_2
Tungsten	Fluorinated Gases
Refractory Silicides	Fluorinated plus Chlorinated Gases (w/ or w/o oxygen)
TiN; TiC	Same as Al Etch

Realisations

PHOTONIC CRYSTAL LASERS ON InP



Yokohama Nationa University
Baba Reseach Laboratory

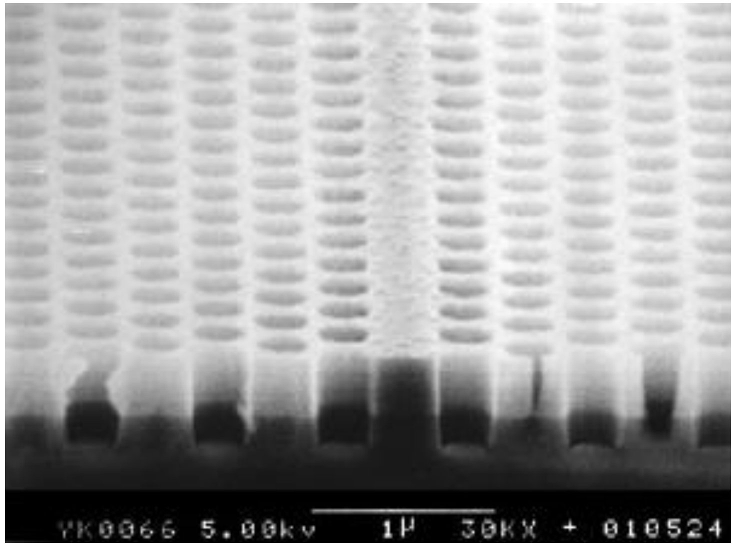
1) A periodic pattern of holes 300nm diameter, 1mm etch is etched in InP using **Inductively Coupled Plasm and chlorine process chemistry.**

2) The laser is formed by making a small ring shaped defect in the hole pattern. Light is trapped in the defect area obtaining the world smallest laser.

3) Laser oscillation was stimulated by an external excitation light source. Laser light is emitted vertically by the resonating area.

Realisations

PHOTONIC CRYSTAL LIGHT WAVEGUIDES ON SOI



Yokohama National University
Baba Research Laboratory

1) A monolithic PC structure is created by etching periodic arrays of holes (300nm diam.) through the Si layer on a SOI substrate

2) A linear row of defects is added to create the light path.

3) **The holes were etched using ICP etching and fluorine chemistry**

Optical characterisation

Goal

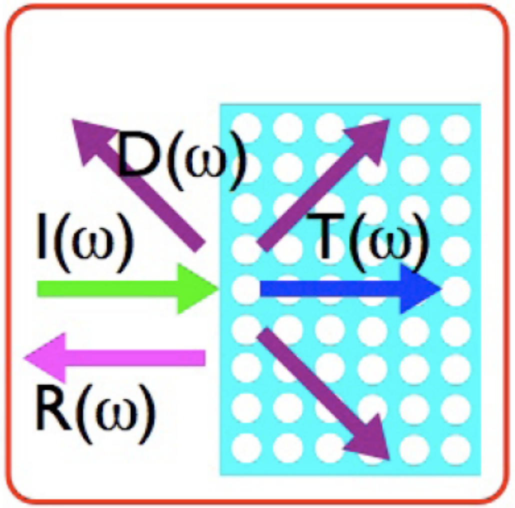
+ Once our photonic crystal structure has been (painfully) fabricated and characterised (SEM, etc…)

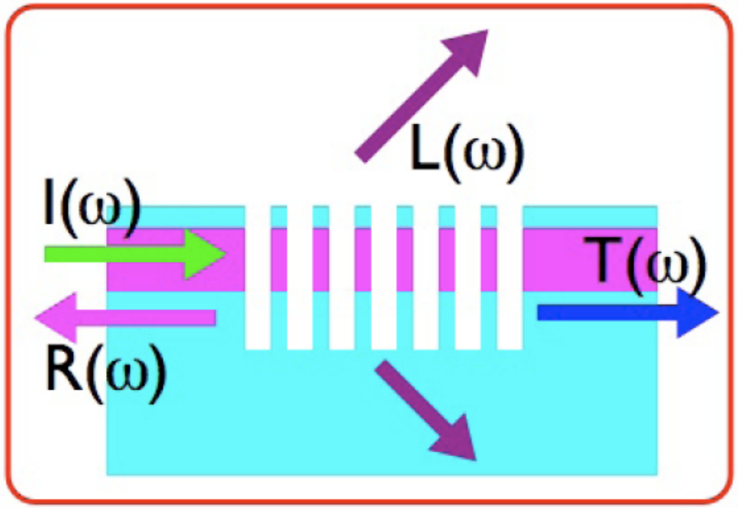
+ How can we measure its optical properties , it was designed for?

Optical characterisation

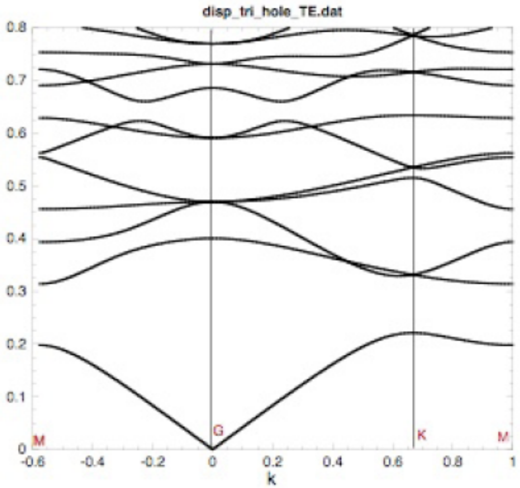
Which optical properties ?

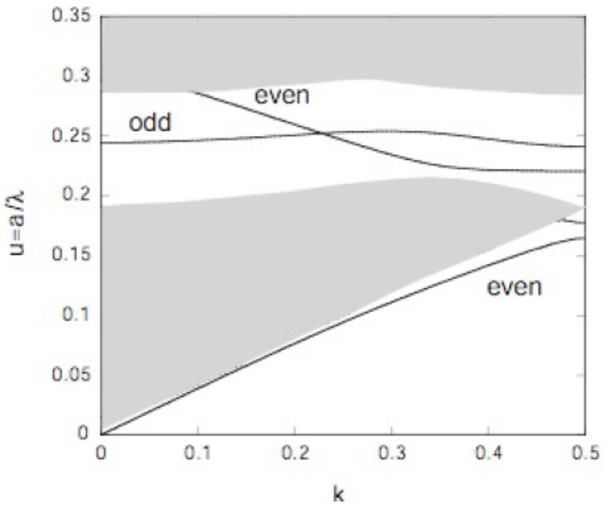
✳ Optical response
- Transmission, T
- Reflection, R
- Diffraction, D
- Absorption, A
- Losses, L=1-T-R-D-A





✳ Band structure
- Dispersion curve
- Group index





Optical characterisation

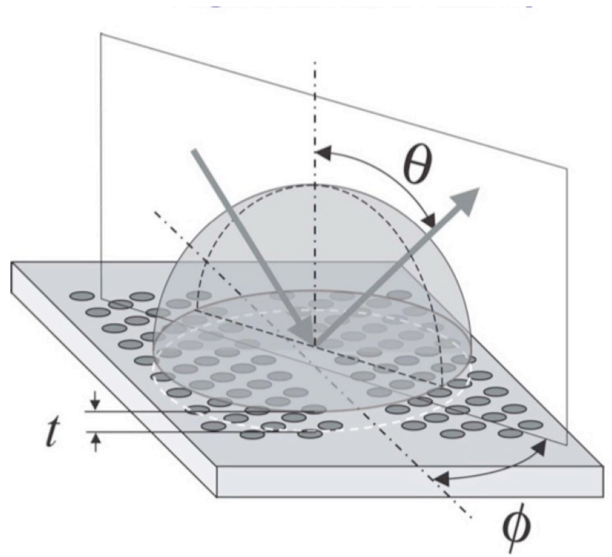
Techniques

1. With an external light source
    - Reflectivity
    - End fire technique
2. With an internal light source
    - Internal light source
    - Luminescence spectroscopy
3. Advanced techniques
    - Local probe, SNOM
    - Time resolved
    - Fourier imaging

Optical characterisation

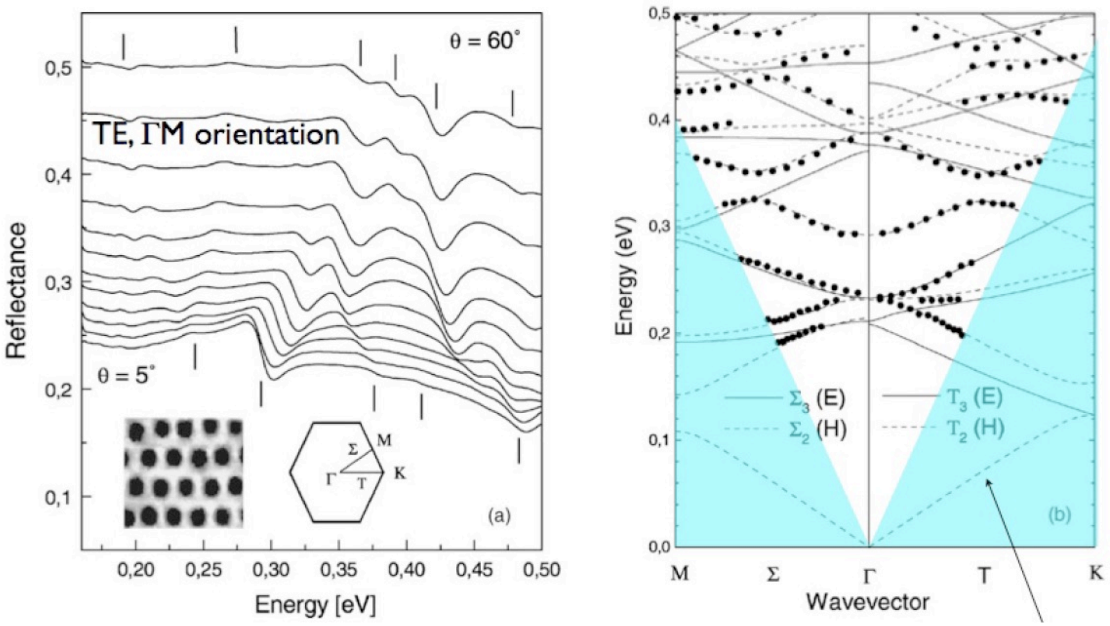
External source: Angular reflectivity

Measurement:
-Intensity vs. Angle(s) at constant wavelength
-Intensity vs. wavelength at constant angle
-Light is reflected according to the grating diffraction law
-It provides information on the band structure k(w)
-Experiments are difficult to interpret due to the complex shape of the reflectivity spectrum



Macroporous silicon

Phys. Rev. B, 65, 113111 (2002)

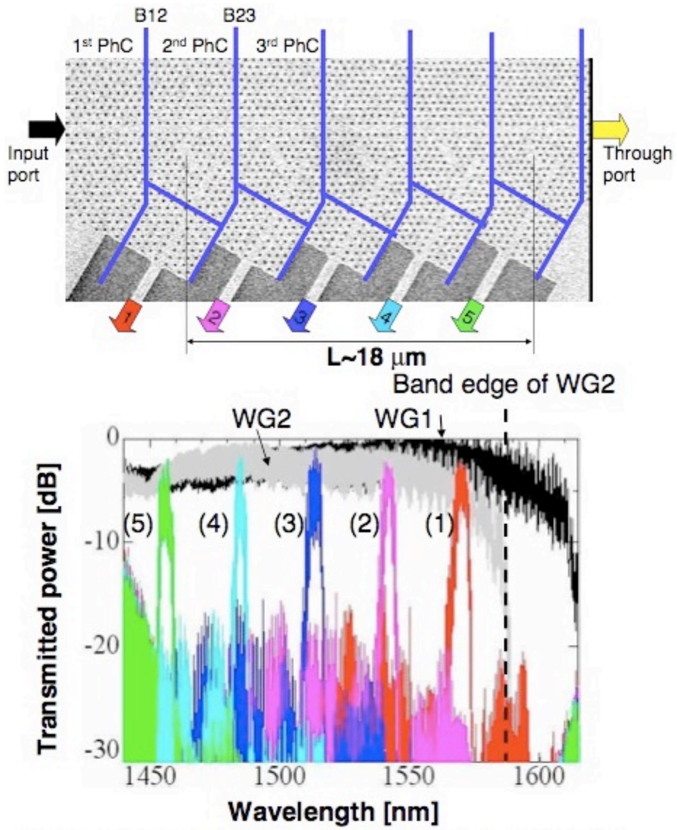


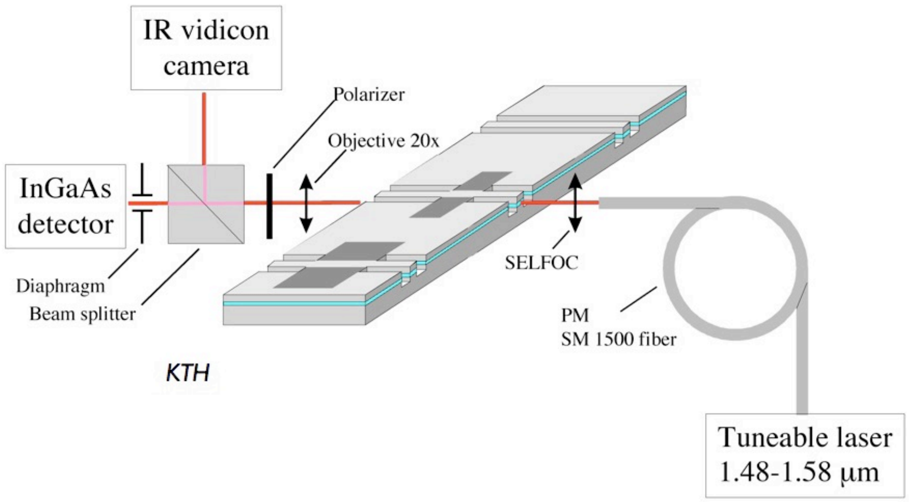
Measurement limited to the radiative cone

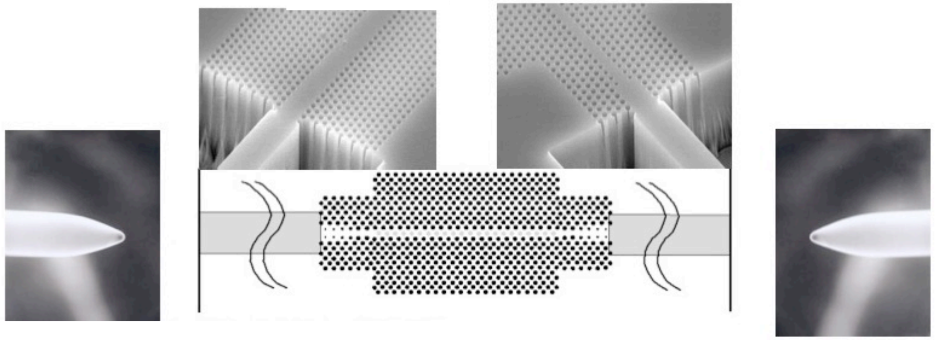
Optical characterisation

External source: end-fire

-Light coupling in/out:
-Microscope objective, free space
-Tapered, microslensed fiber



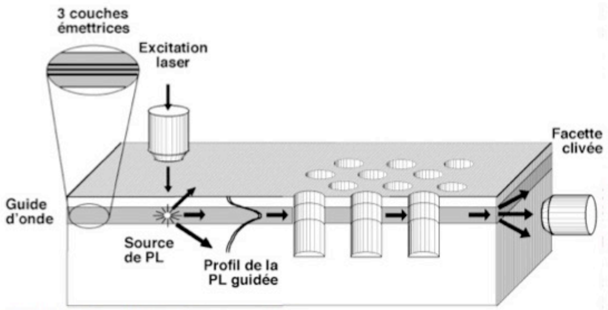




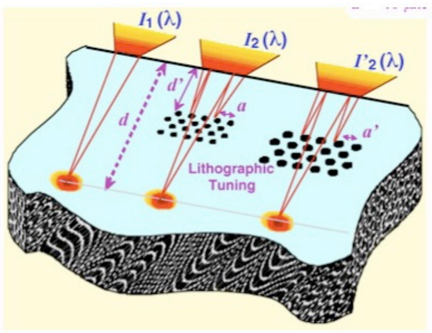
Optical characterisation

Internal source, a versatile technique that:

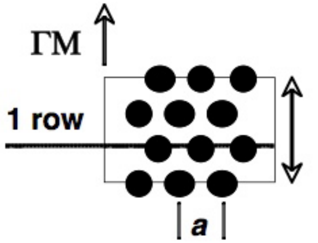
-Does not require acess waveguides, etc..
-Allows the light source to be injected where needed
-The source: quantum dots



D. Labilloy PhD dissertation

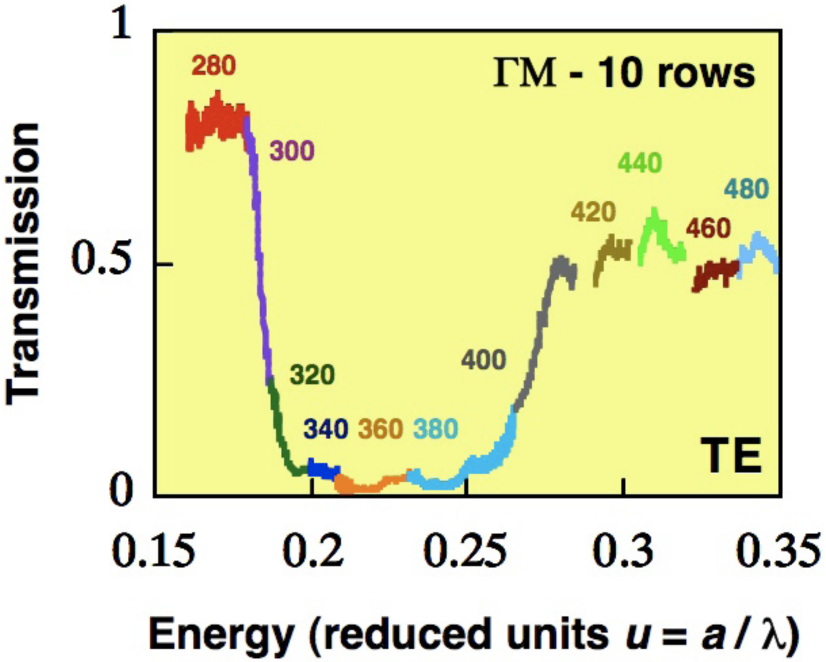


Exemple:



TE polarization

InP/(Ga,In)(As,P) QW
λ=1.55µm f=30%

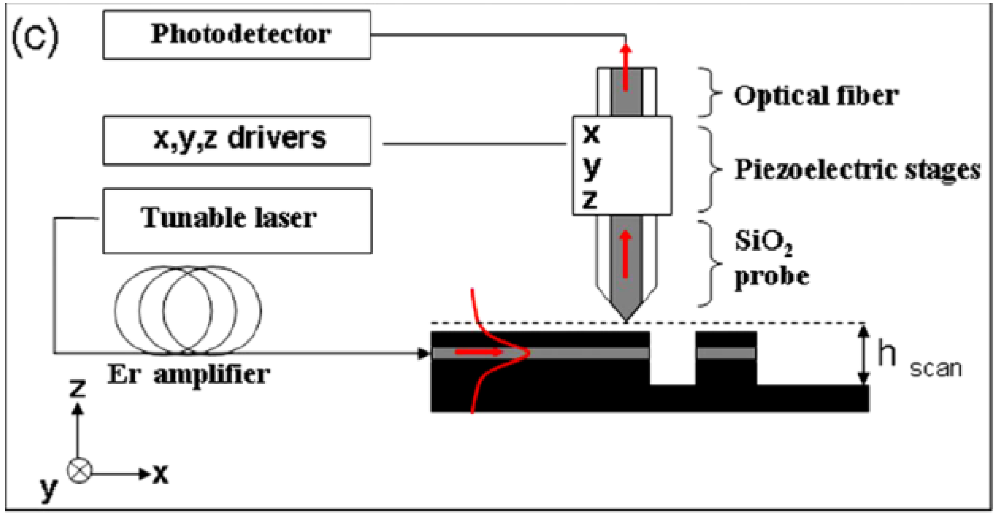


$$T_a(\lambda) = \frac{I_2(\lambda)}{I_1(\lambda)} \rightarrow T\left(u = \frac{a}{\lambda}\right)$$

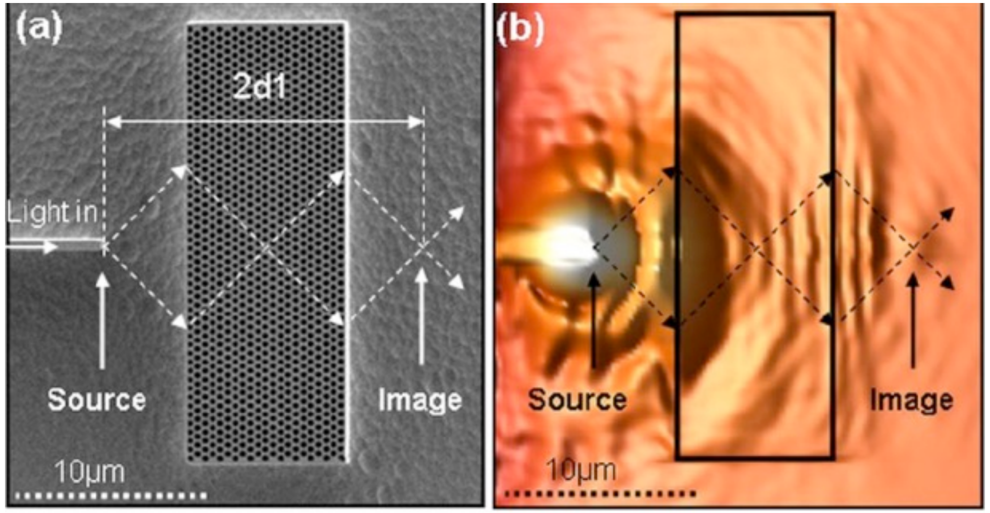
J. Quantum Electron., 38, 786 (2002)

Optical characterisation

SNOM: Scanning Near Field Optical Microscopy
Beyond the diffraction limit



Light focusing through a photonic crystal lens



PRL 101, 073901 (2008)

Thank you for your attention!