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"Workshop on Ion Beam Studies of Nanomaterials:
Synthesis, Modification and Characterization"

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Tailoring of Optical Properties of $LiNbO_3$ by ion implantation

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Tailoring of optical properties of $LiNbO_3$ by ion implantation

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Outline

The material

- Optical properties
- Linear (LO) and nonlinear (NLO) optical response

Exploitation of ion implantation for nanoclusters formation

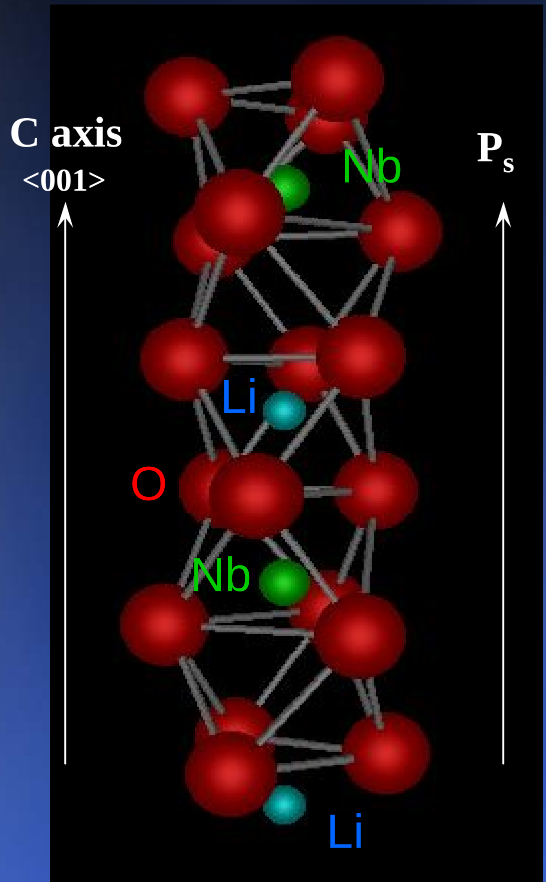
Exploitation of ion implantation for waveguides formation

- Applications: optical modulator for gas tracing

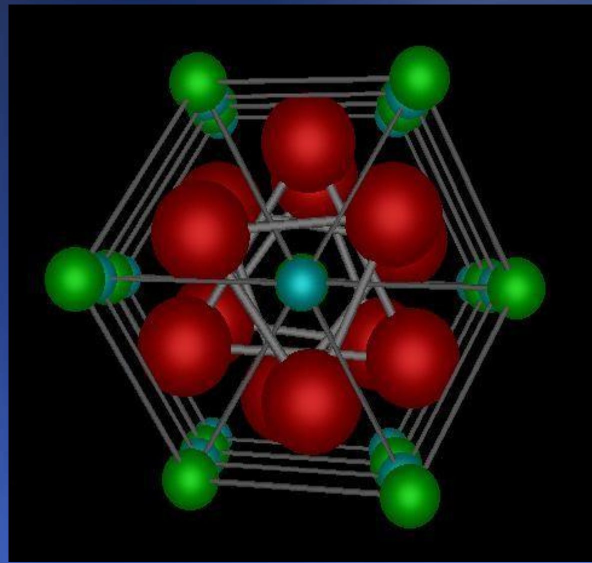
Exploitation of ion implantation in photonics

- Photonic structures
- Realisation and characteristics
- Applications

The material



Lithium Niobate
($LiNbO_3$)



Ferroelectric with a spontaneous polarization P_s=0.71 C/m^2 parallel to the c-axis

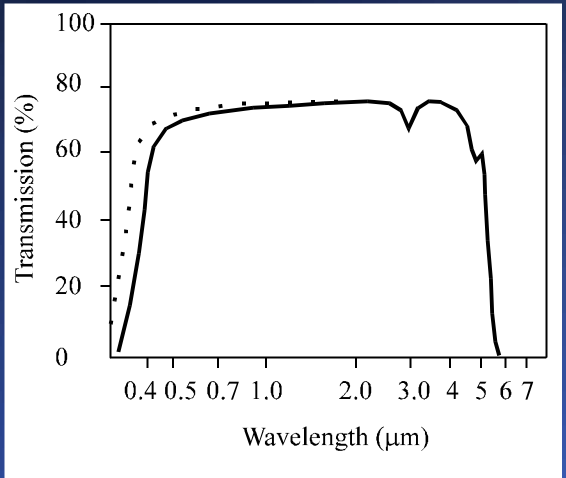
Due to its large Electro-Optic and Acousto-Optic coefficients, $LiNbO_3$ is used for optical applications:

1. Optical modulators
2. Pockel Cells switches,
3. Integrated waveguides
4. Second harmonic generation

Optical properties

Linear optical properties

Ordinary refractive index n_o (**E** $\perp$ c axis)
Extraordinary refractive n_e (E // c axis)



Negative birifrangence (at 633n)

n_e=2.2219
n_o=2.2878

Transmission:
80% in the range
350nm-4000nm

Nonlinear optical properties

$\chi^{(2)}=2d$ d=non linear optical coefficient

	d_{31} *(pm/v)*	d_{33} *(pm/v)*	d_{22} *(pm/v)*
$LiNbO_3$	-5.95	-34.4	4.08

Ion Implantation on $LiNbO_3$

$LiNbO_3$

LO properties

NLO properties

Induced NLO properties

Optical waveguides

Modification of the local composition and structure to confine the light

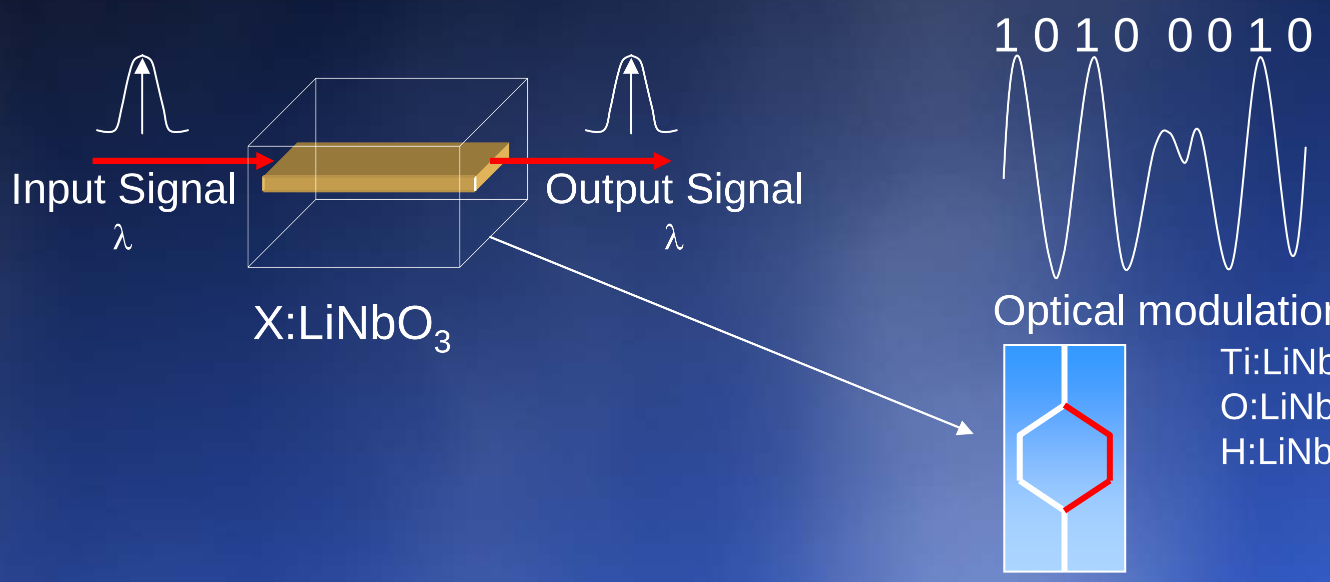
Application in integrated optics

Metal nanocluster in $LiNbO_3$

Application in nanotech

Applications of ion implantation on $LiNbO_3$

Local doping with passive elements (metals, H,He,..)



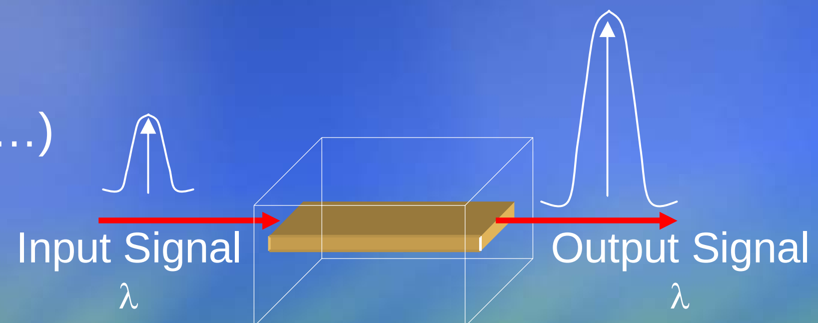
Optical modulation

$Ti:LiNbO_3$
$O:LiNbO_3$
$H:LiNbO_3$

Optical recording

$Fe:LiNbO_3$
$Cu:LiNbO_3$

Local doping with active elements (rare earths…)

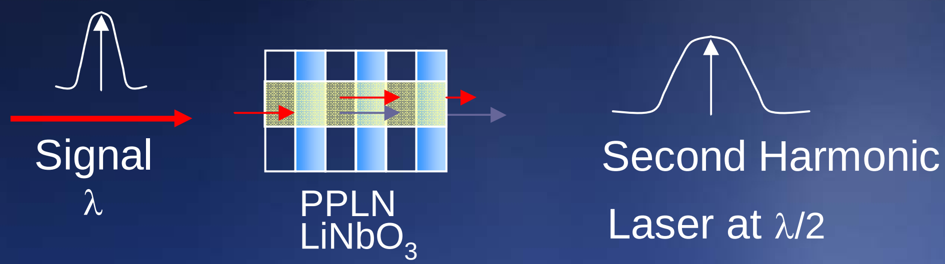


Amplification and lasing

$Er:LiNbO_3$
$Er:glass/SiO_2$

Applications of ion implantation on $LiNbO_3$

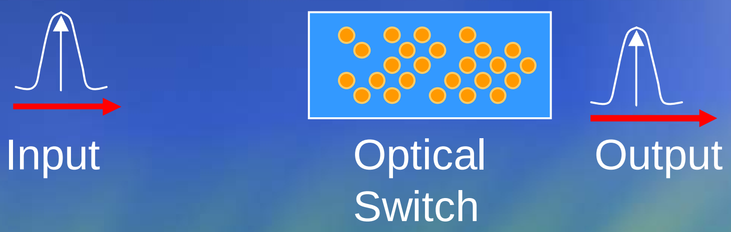
Native nonlinear properties



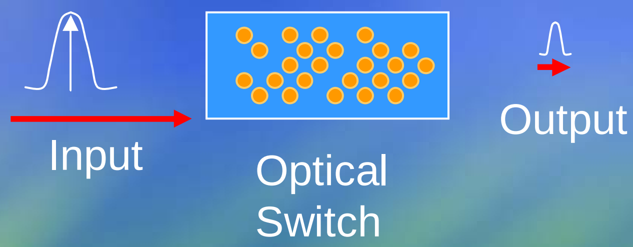
Blue-green wavelenth for
Optical recording

Induced nonlinear properpies

ON configuration



Off configuration



Induced nonlinear properties

Ion implantation of metals in $LiNbO_3$ for realisation of metal nanoparticles

Works reported in literature: implantation of Au, Ag, Cu in the KeV region

Best results obtained on Cu:$LiNbO_3$

Induced nonlinear optical properties

Stability of nanoparticles in $LiNbO_3$ induced by negative Cu ions and ultrafast nonlinear optical property

N. Kishimoto [a,*], N. Okubo [b], O.A. Plaksin [c], N. Umeda [b], J. Lu [a], Y. Takeda [a]

Nuclear Instruments and Methods in Physics Research B 218 (2004) 416–420

Cu- implanted at E=60KeV I=10-50 $\mu A/cm^2$

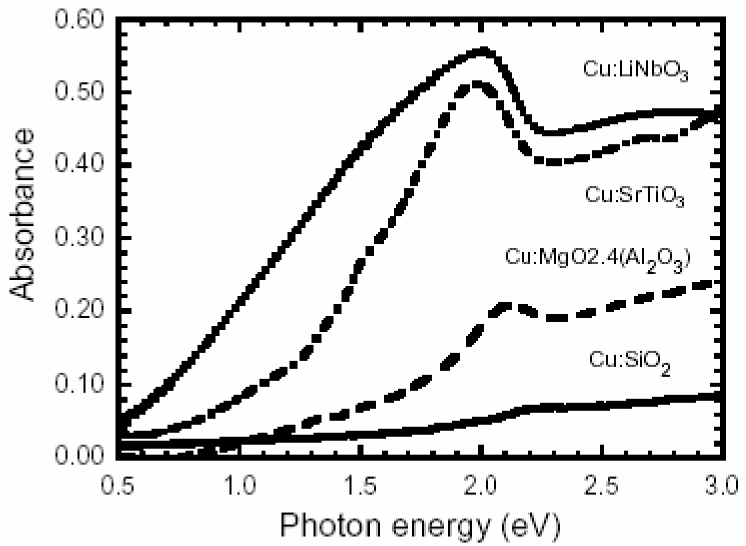


Fig. 1. Optical absorbance spectra of various dielectric substrates implanted with 60 keV Cu^- at 10 $\mu A/cm^2$ to 3.0×10^{16} ions/cm^2.

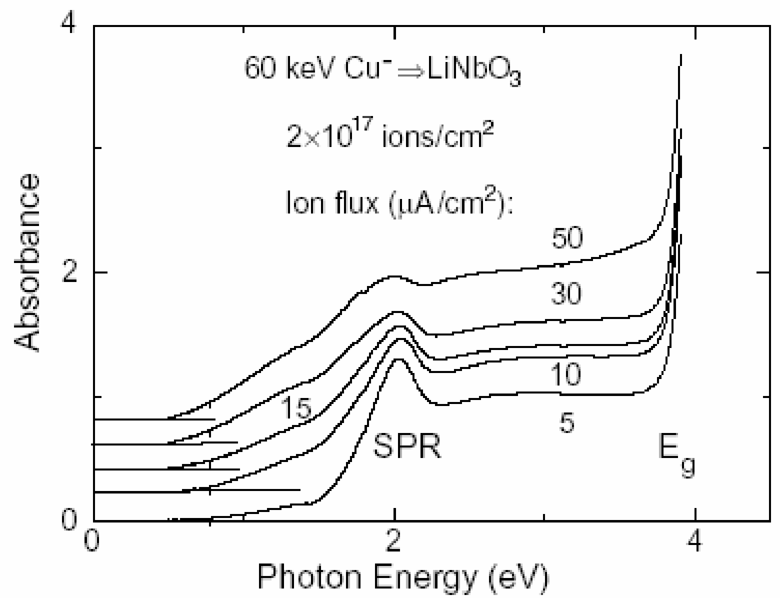


Fig. 2. Optical absorbance spectra of $LiNbO_3$ implanted with 60 keV Cu^- at various fluxes to 2×10^{17} ions/cm^2.

Induced nonlinear optical properties

Ion-induced metal nanoparticles in insulators for nonlinear optical property

N. Kishimoto [a,*], Y. Takeda [a], N. Umeda [b], N. Okubo [b], R.G. Faulkner [c]

Nuclear Instruments and Methods in Physics Research B 206 (2003) 634–638

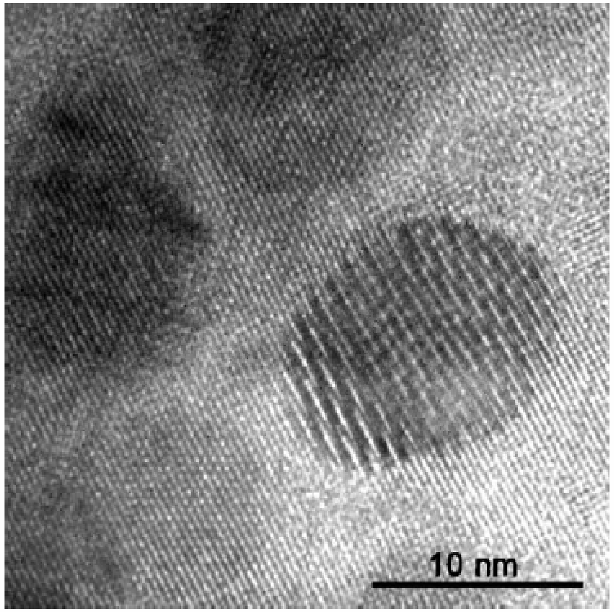


Fig. 1. Cross-sectional TEM image of $LiNbO_3$ implanted with 60 keV Cu^- ions at a dose rate of 10 $\mu A/cm^2$ to a dose of 3×10^{16} ions/cm^2.

Cu- implanted at:

E=60KeV
I=10-50 $\mu A/cm^2$

Non spherical nanocluster D=10nm

Sub-picosecond nonlinear response

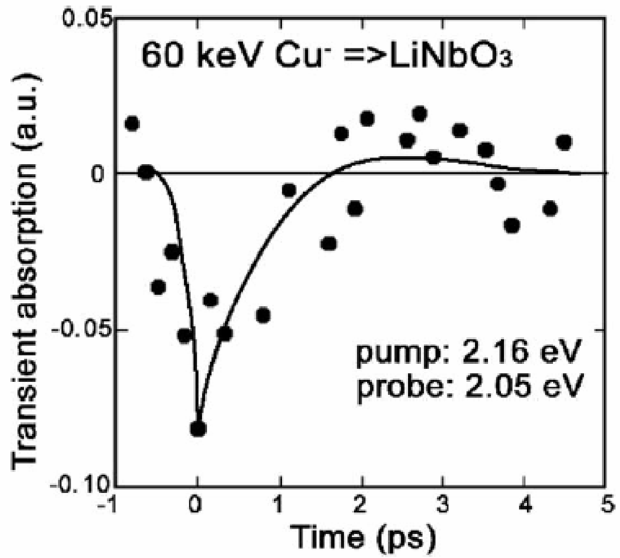


Fig. 5. Non-linear transient absorption of $LiNbO_3$ implanted with 60 keV Cu^- at 10 $\mu A/cm^2$ to 3×10^{16} ions/cm^2. The pumping and probing energies are 2.16 and 2.05 eV, respectively.

Linear optical properties

Ion implantation of: heavy elements (Si 30KeV),
medium light (C,O,N 3-5MeV)
light elements (H, He 0.5-1MeV)

to modify locally the refractive index of the medium and guarantee the light confinement

⬇

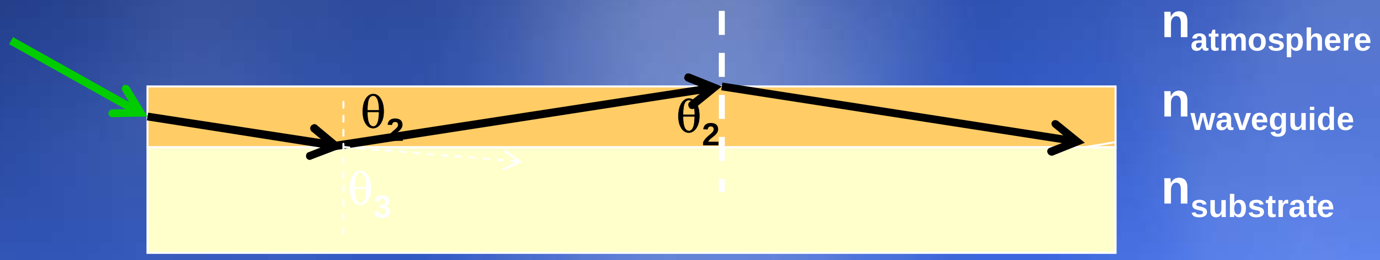
Waveguides for integrated optics

Linear optical properties: waveguide

Light confinement in optical waveguides

$n_{waveguide} - n_{substrate} > 0$

Total internal reflection

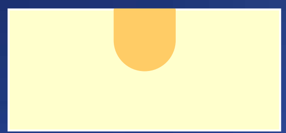


Integrated optics: optical waveguide

How to prepare an optical waveguide

Standard approach

Introduction of suitable dopant



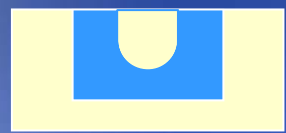
$= n > n_{substrate}$

$= n_{substrate}$

Methods:
Thermal diffusion
Ion exchange
Ion implantation

Alternative approach

Modification of the surrounding



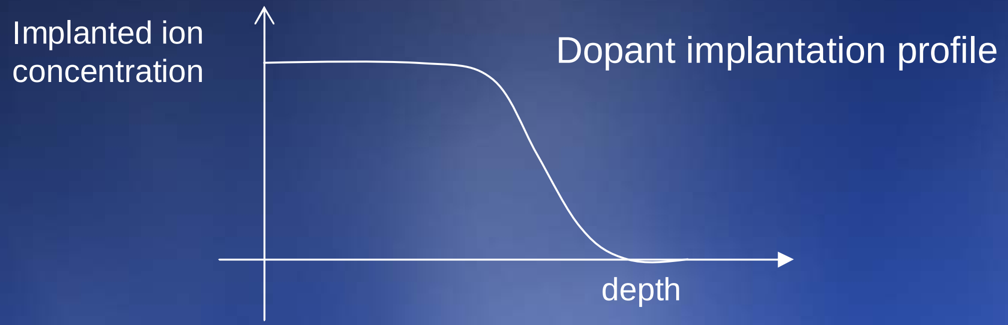
$= n < n_{substrate}$

$= n_{substrate}$

Methods:
Ion implantation

Standard approach

Increase of the refractive index in the doped region



Ion implantation of light elements

Refractive index behaviours of He implanted optical waveguides in $LiNbO_3$, $KTiOPO_4$ and $Li_2B_4O_7$

P. Bindner et al, NIMB 142 (1998) 329-337

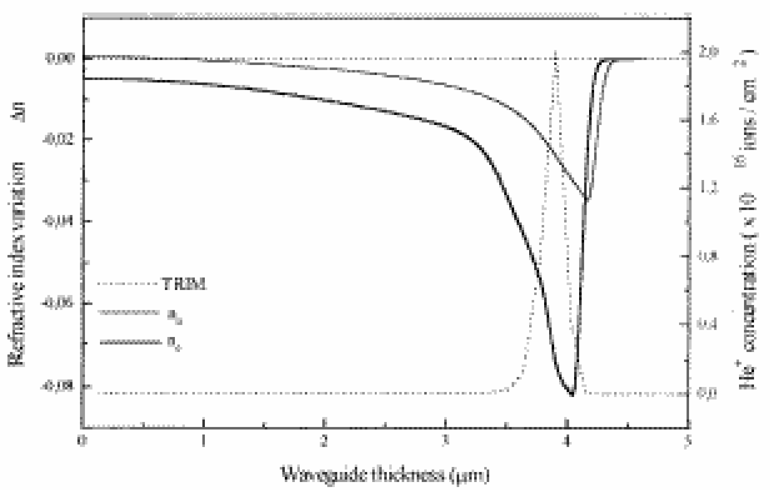


Fig. 6. Extraordinary (n_e) and ordinary (n_o) index profiles of He^+ implanted $LiNbO_3$ waveguide (solid lines) with the implanted helium concentration profile (dashed line) obtained by TRIM simulation.

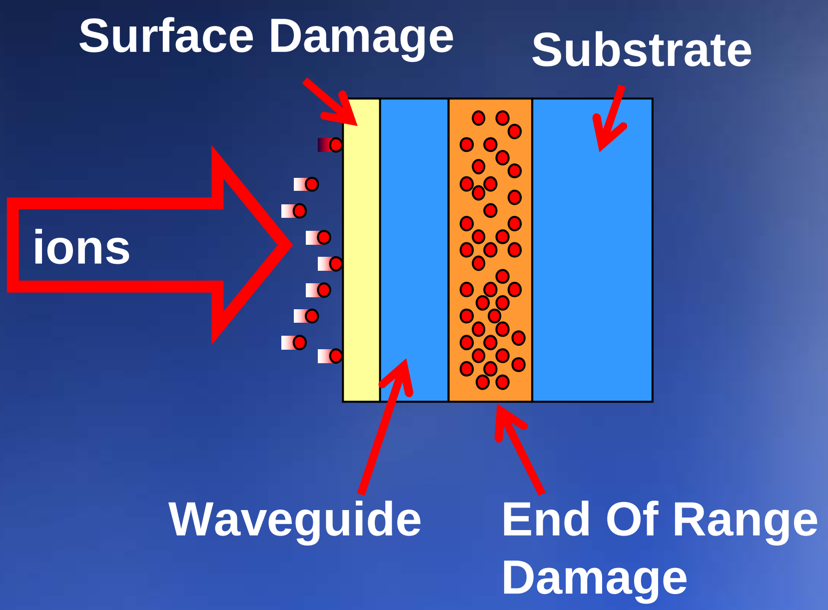
Implantation parameters: Energy and helium dose

	Dimensions (mm^3)	Implantation parameters	
		Energy (MeV)	Dose ($\times 10^{16}$ ions/cm^2)
$LiNbO_3$	$20 \times 10 \times 1$	2	2
KTP	$6.87 \times 10 \times 2.1$	2	1
LTB	$1 \times 4 \times 10$	2	1.5

Concerning the He^+ implanted $LiNbO_3$ waveguide, at the surface, the index variations observed are: a decrease in the extraordinary profile ($\Delta n_e = -0.5\%$) and a slight increase in the ordinary one ($\Delta n_o = +0.07\%$). The index barrier is more pronounced in the extraordinary ($\Delta n_e = -6\%$) case than in the ordinary one ($\Delta n_o = -2\%$). The corre-

Ion implantation: alternative approach

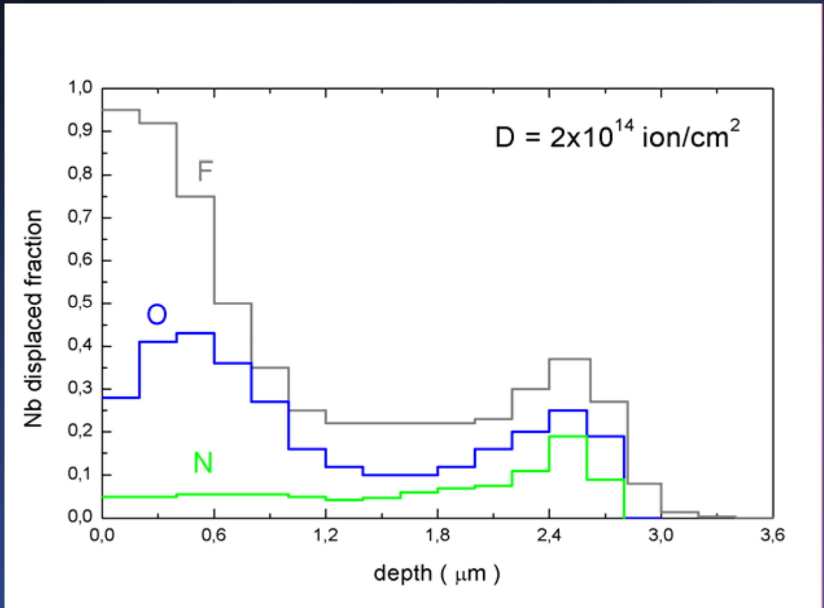
Interaction of the medium light elements with the material



Surface damage due to the electronic energy loss

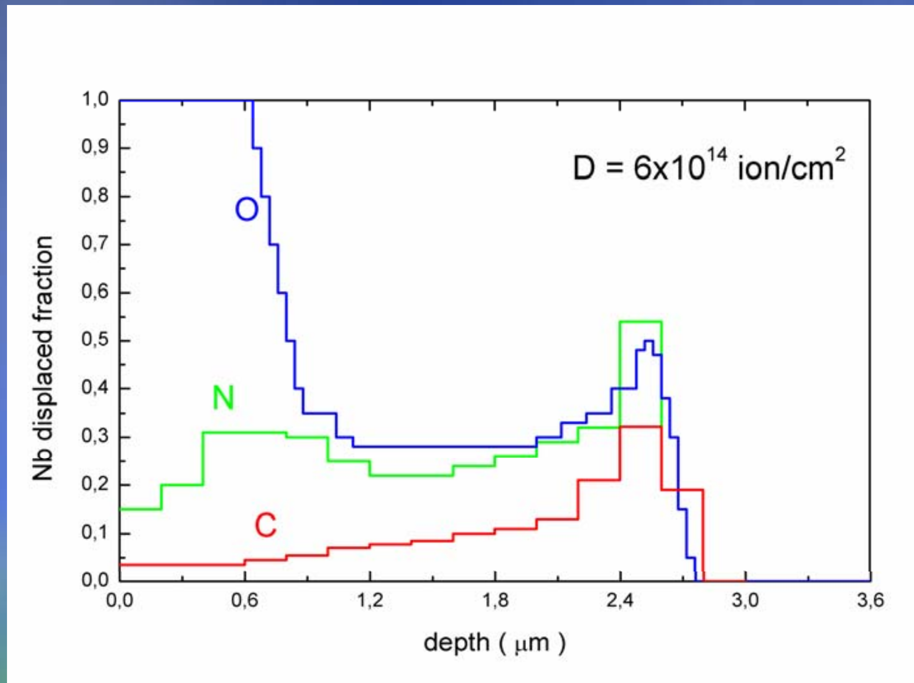
End of range damage due to the nuclear energy loss

Ion implantation of medium light elements



High implant fluences of medium light elements increase the surface damage

Higher damage with increasing atomic number of the implanted species



Questions

1. Origin of the surface damage
2. Dependence of the surface; damage on the implantation conditions.

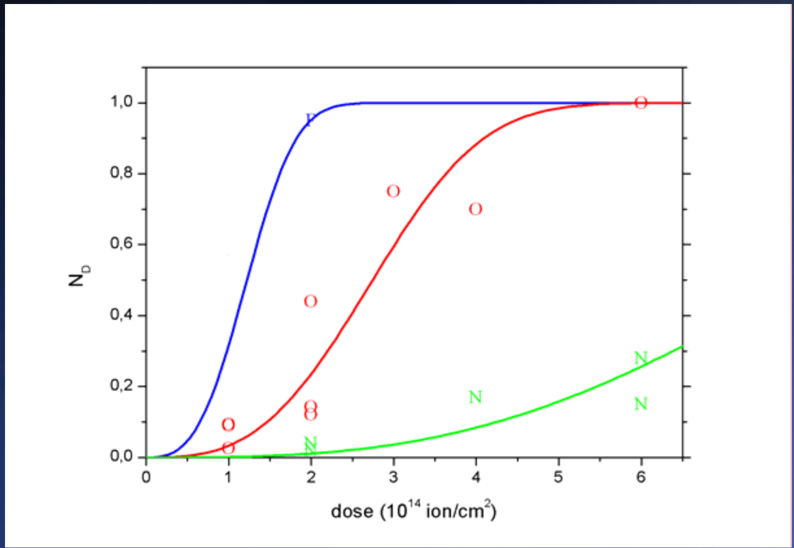
Ion Implantation:

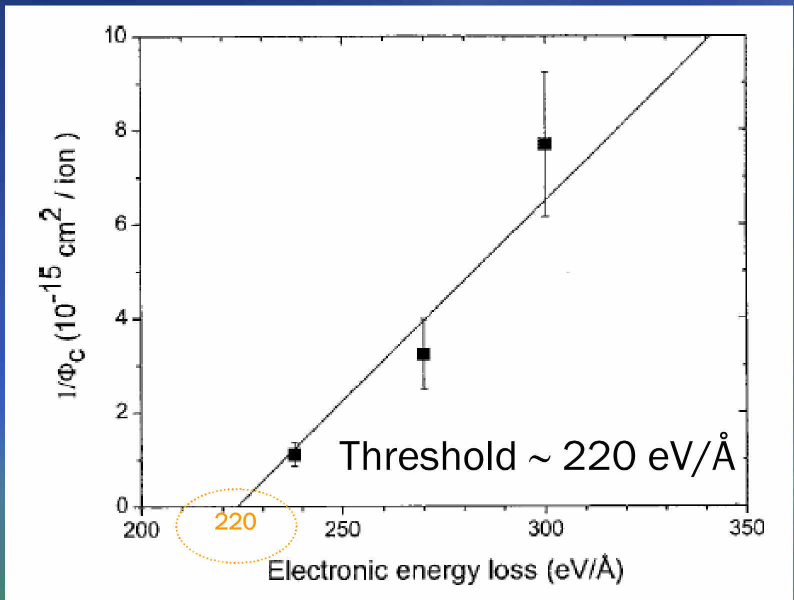
i) The energy lost by electronic interaction mostly generates localised colour centres and/or few structural isolated defects. These defects can be easily annealed at lower temperatures than the more complex defect clusters generated at the End-of-Range by nuclear interaction.

ii) This is a general trend rather independent of the target material.

iii) The energy lost by Nuclear interaction, generates collision cascades and large defect clusters.

Ion implantation of medium light elements





Surface damage

$$N_D = 1 - \exp\left[-\left(\frac{\Phi}{\Phi_c}\right)^n\right]$$

N_D defects density in the region nearby the surface

Φ fluence

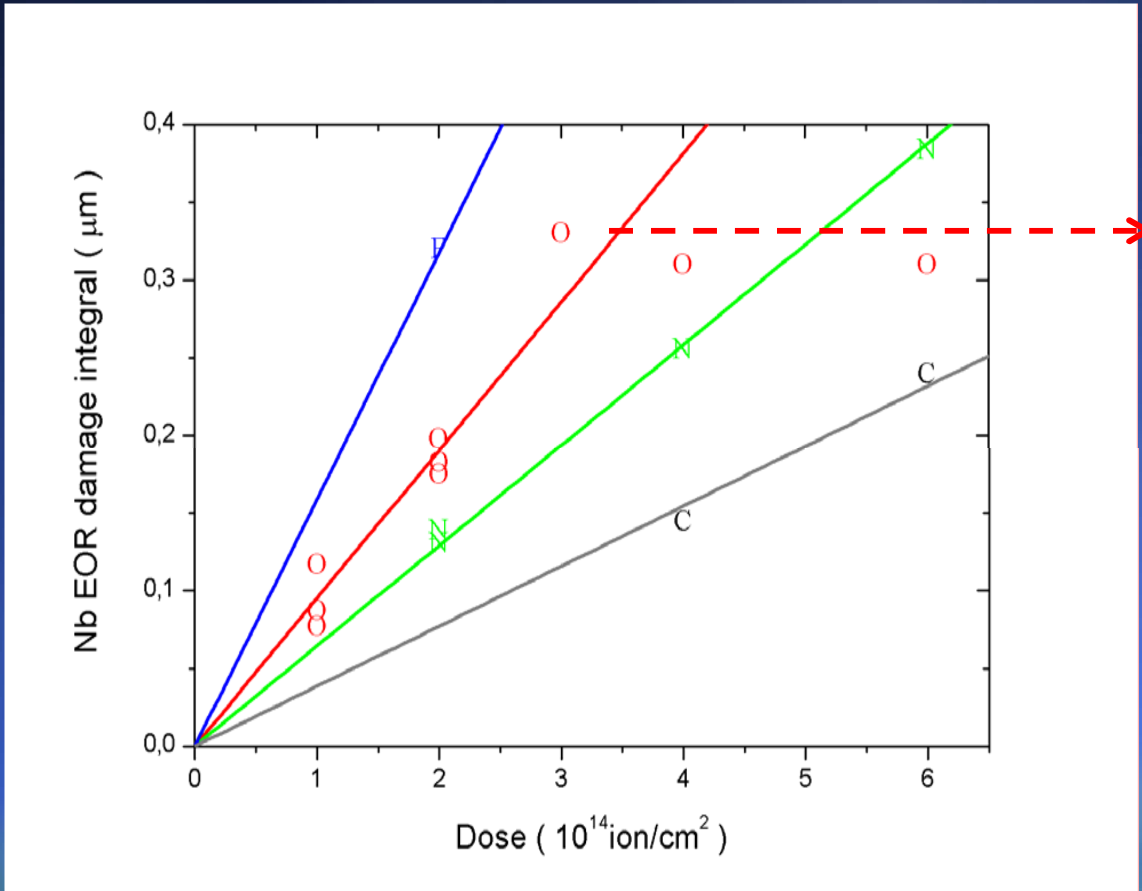
Φ_C critical fluence

$\Phi_c = (3.1 \pm 0.6) \cdot 10^{14}/cm^2$
$n = (2.75 \pm 0.25)$,

n=1	1-D defect
n=1.5÷2.5	2-D defects
n=3-4	3-D defects

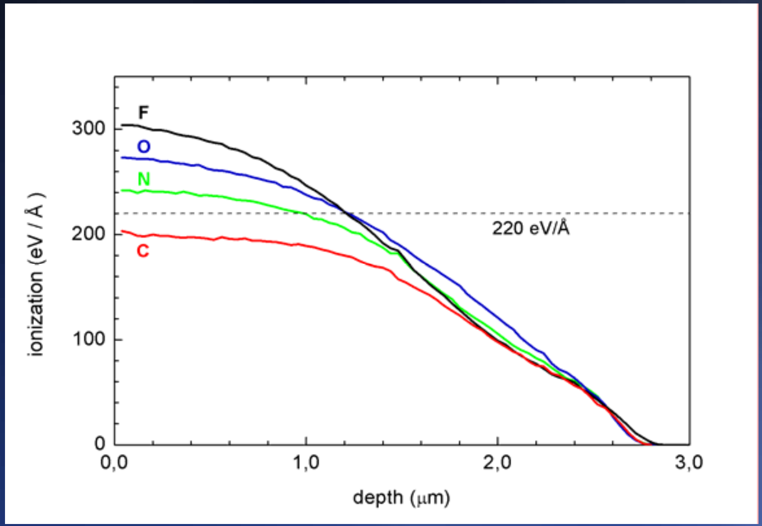
Ion implantation of medium light elements

End of range damage

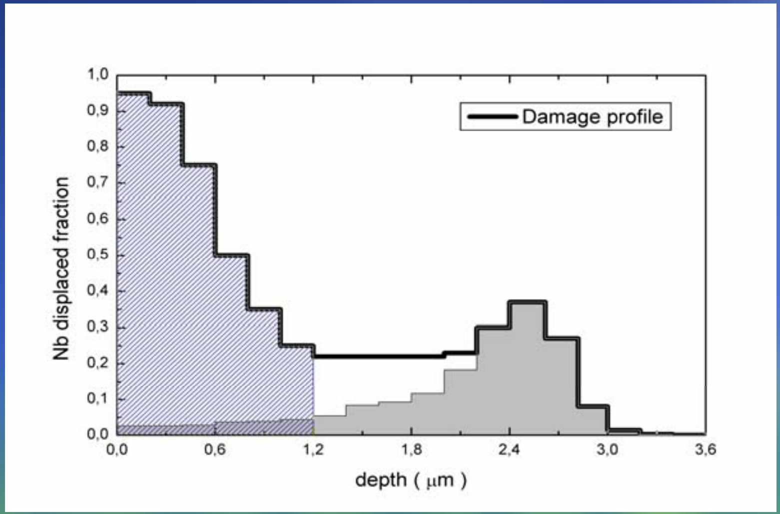


Linear dependence of the end of range damage up to a threshold value that depends on the implanted species

Ion implantation of medium light elements

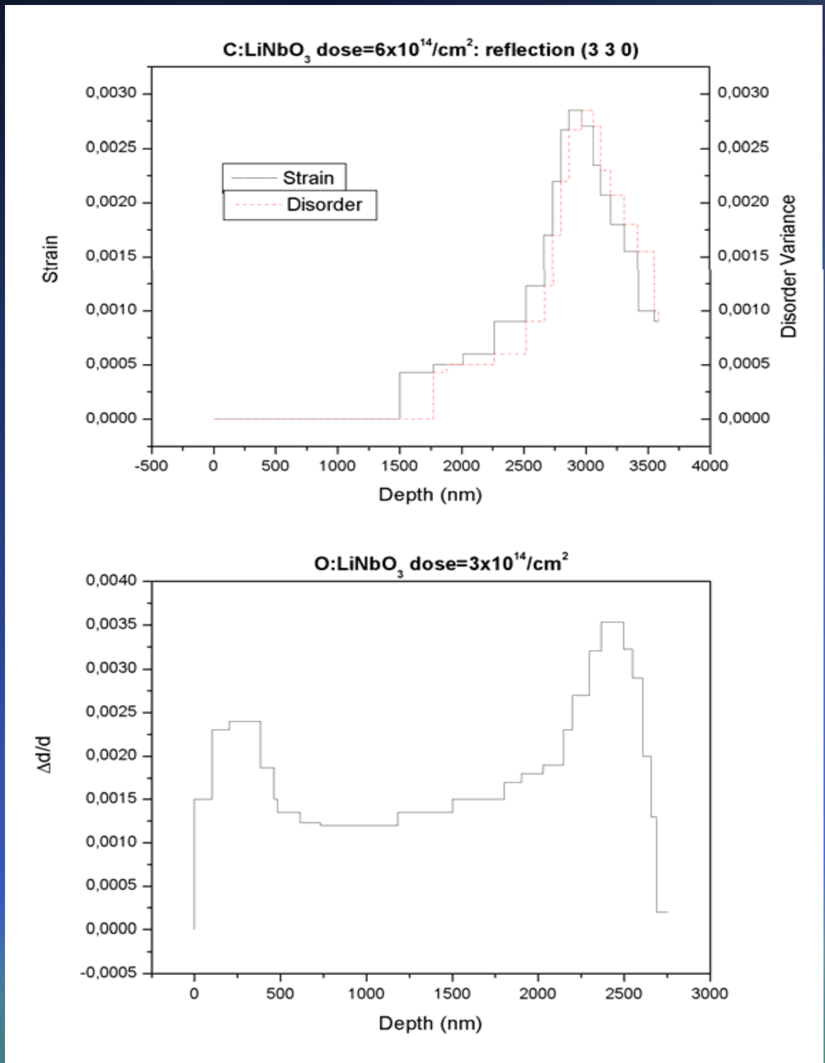


Above a give threshold in the electronic energy loss the surface damage occurs



The overlap between the damage due to the electronic regime and the nuclear one give the final damage profile

Ion implantation: alternative approach



Structural modification

relative lattice mismatch $\Delta d/d$

$$\Delta d = d_{film} - d_{substrate}$$
$$d = d_{substrate}$$

$C:LiNbO_3$

Surface region: $\Delta d/d<0.0002$

End of range (EOR):
peak: $\Delta d/d \sim 0.00255$

$O:LiNbO_3$

Surface region: peak at $\Delta d/d \sim 0.0025$

End of range damage peak at $\Delta d/d \sim 0.0035$

Ion implantation: alternative approach

Optical properties

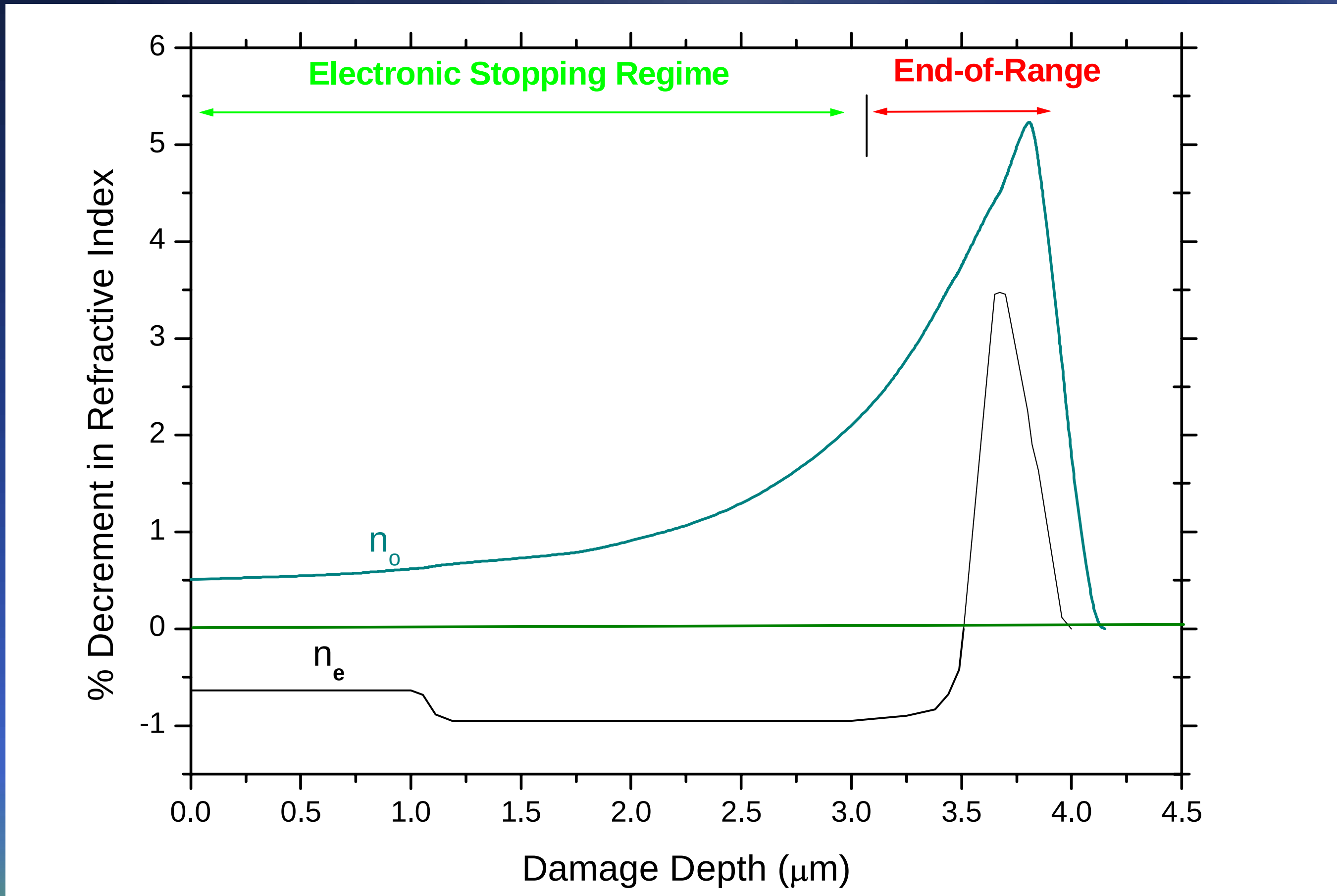
The variation in the refractive index can be due to the following contributions:

Variation in the optical refraction due to composition and ion polarizability	Δn^R
Variation in the molar volume	Δn^V
Variation in the spontaneous polarization	Δn^P
Variation due to the structural modification Elasto-optic effect	Δn^ε

$$\boxed{\Delta n^{tot} = \Delta n^R + \Delta n^V + \Delta n^P + \Delta n^\varepsilon}$$

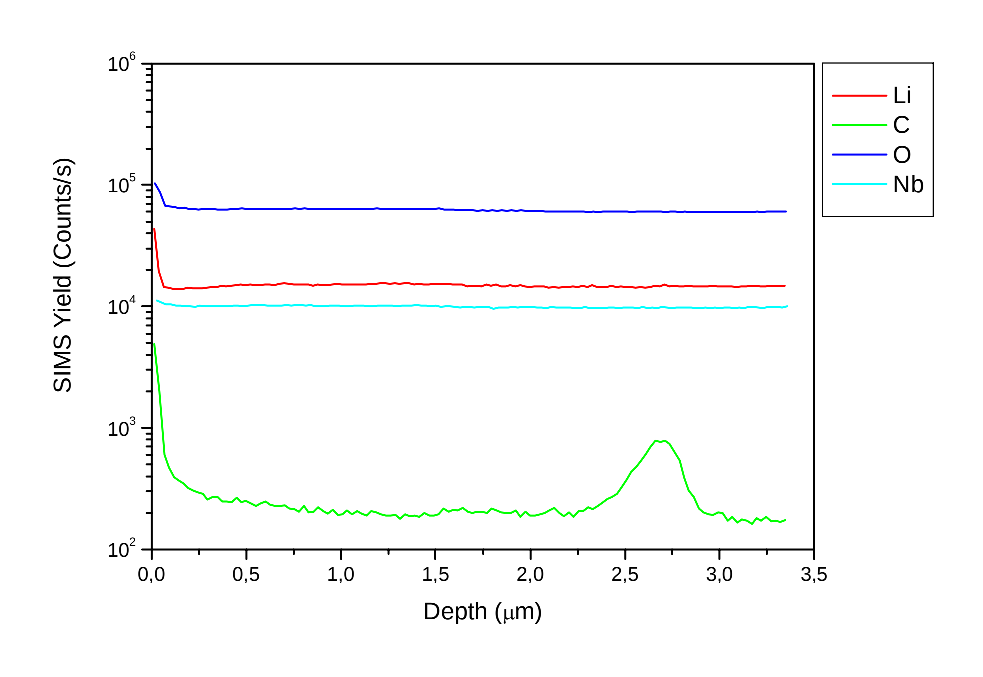
Ion implantation

Effect of implantation on the optical properties

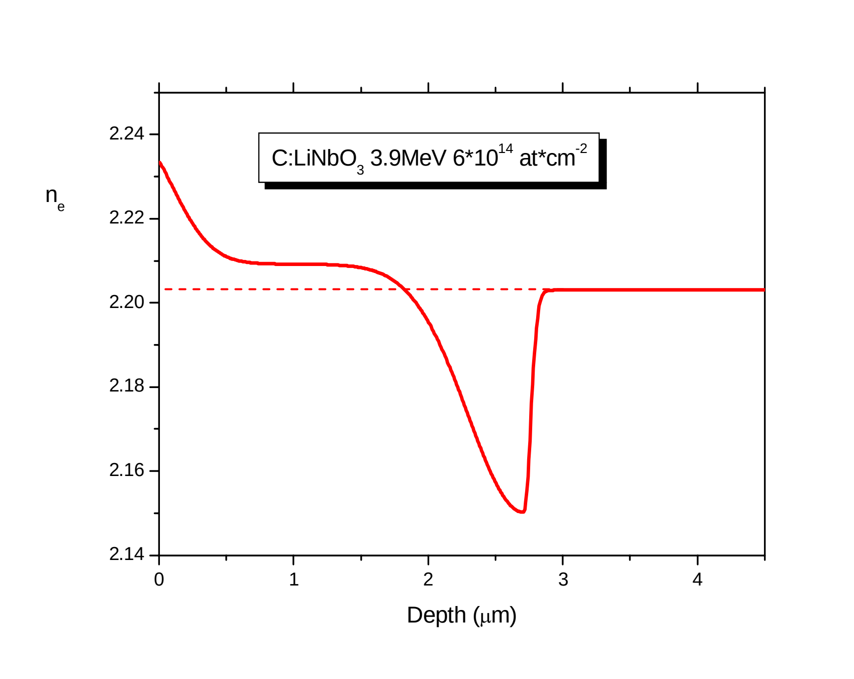


Results of ion implantation

Compositional analysis

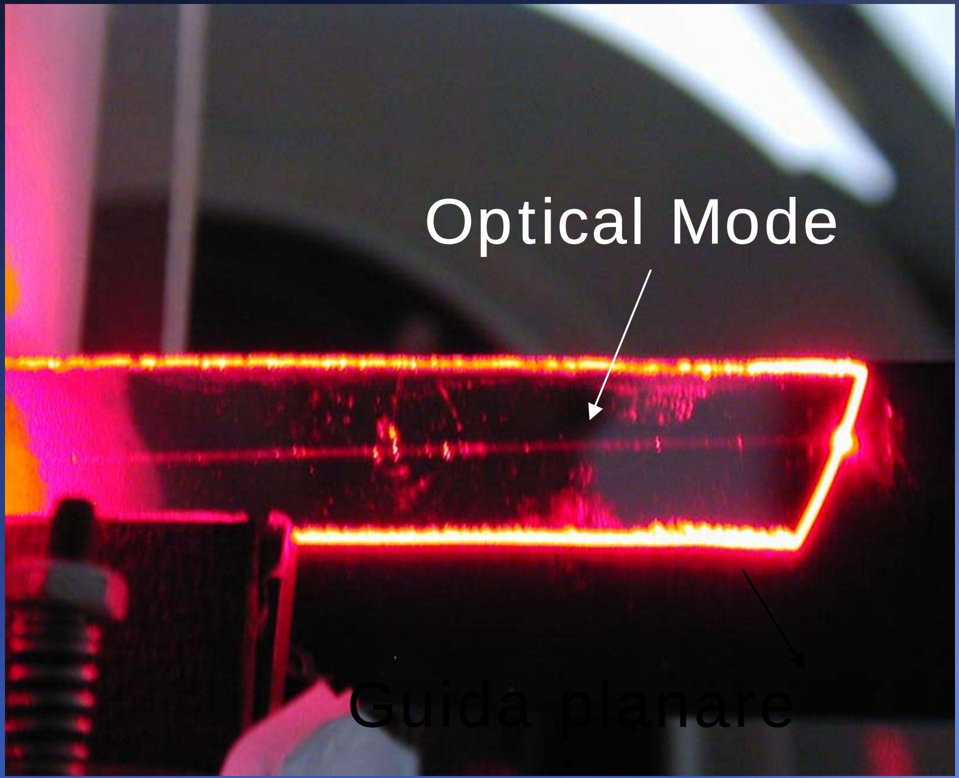


Refractive index



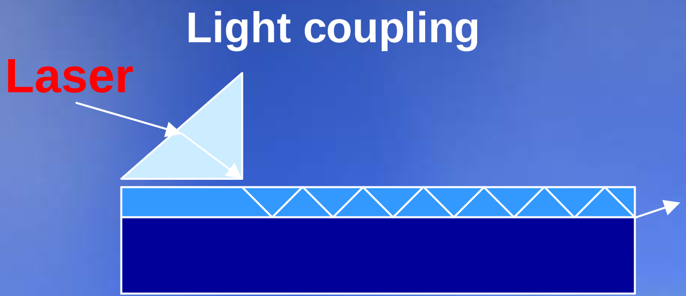
- C excess in the EOR region, $LiNbO_3$ composition unaltered
- Low optical losses <3dB/cm)

Optical waveguide



O:LiNbO$_3$ waveguide

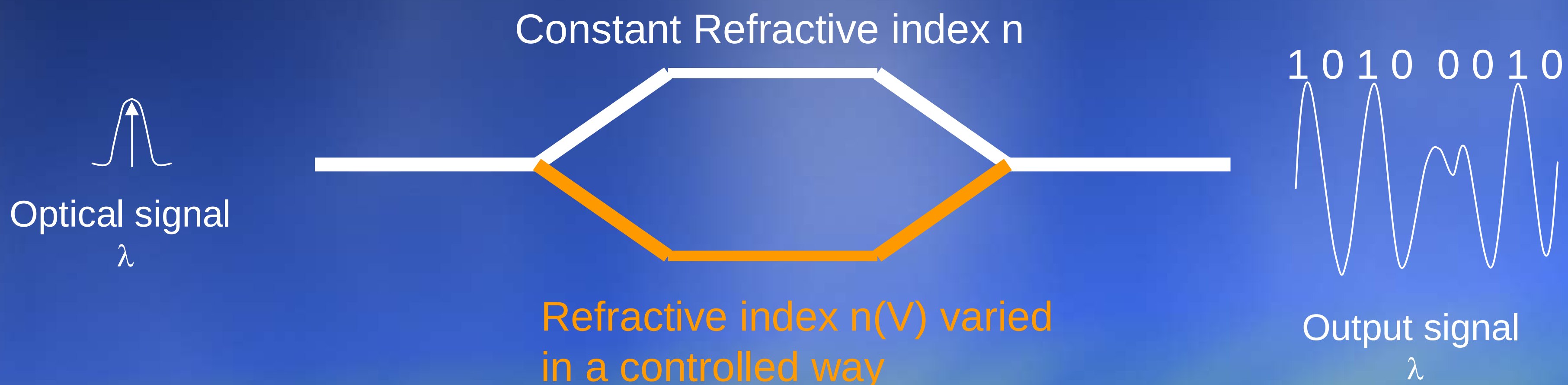
- 3 inch
- Losses < 3dB/cm



Ion implantation of medium light elements

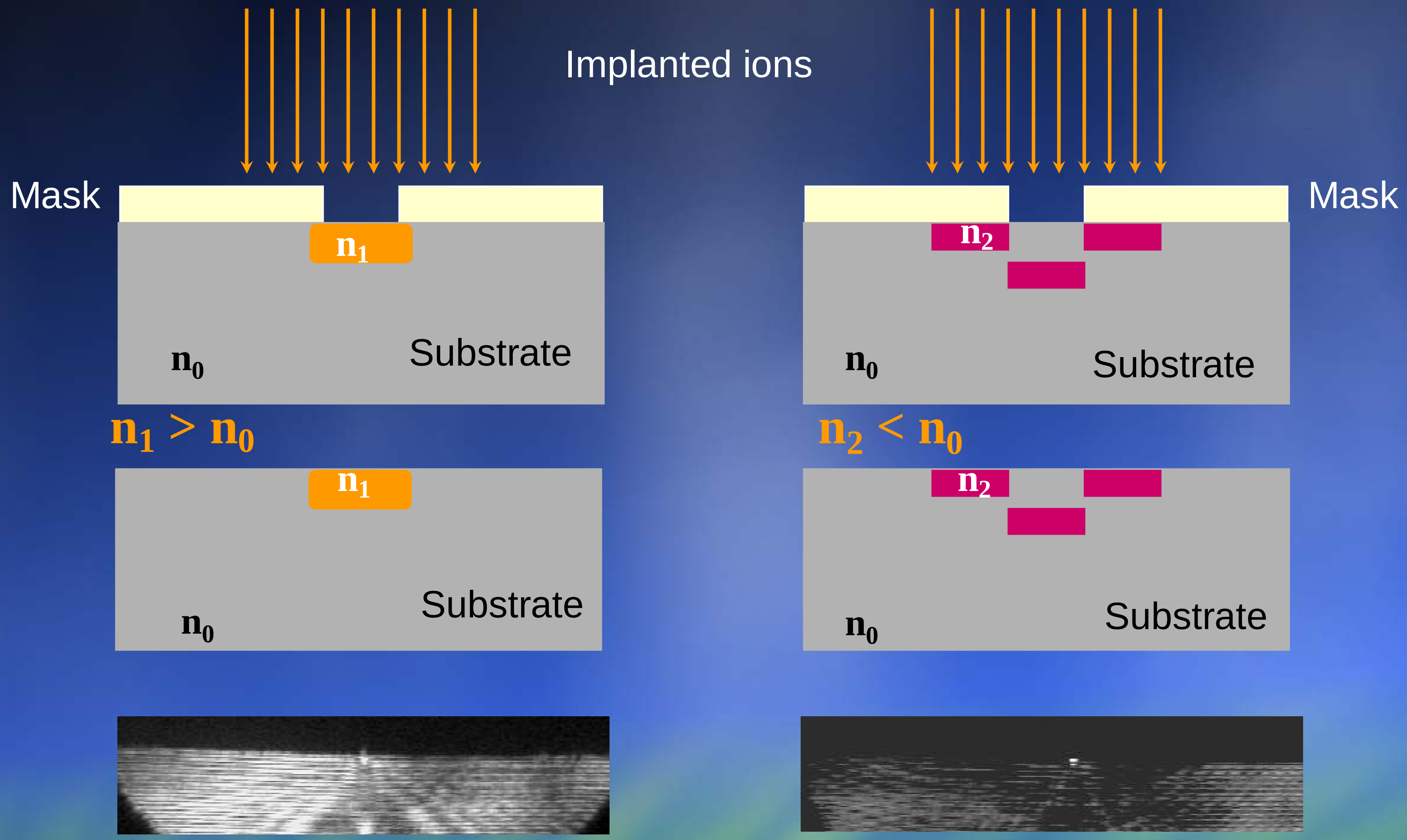
Ion implantation combined with photolitographic process can be used to prepare optical circuit and devices

One of the most important application is the optical modulator: the input signal is modulated by interference effect due to the different refractive index value in the two optical branches



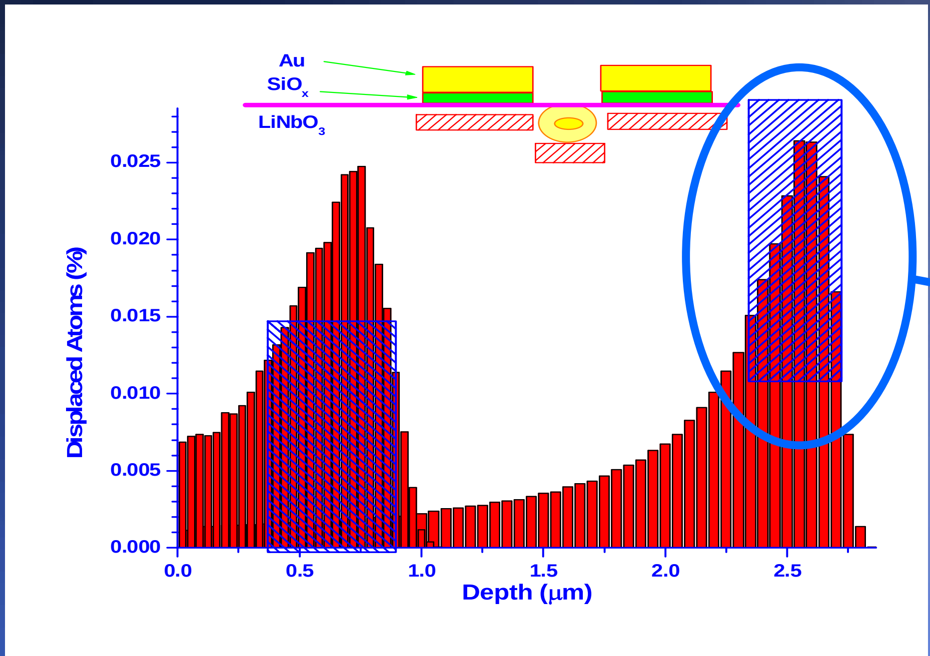
NEED of realizing channel patterns

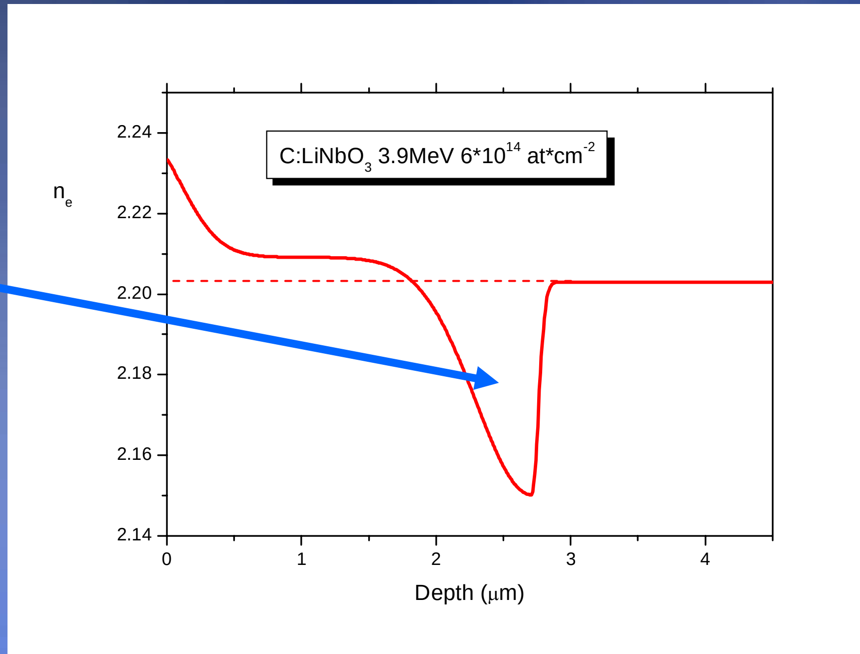
Ion Implantation of medium light elements



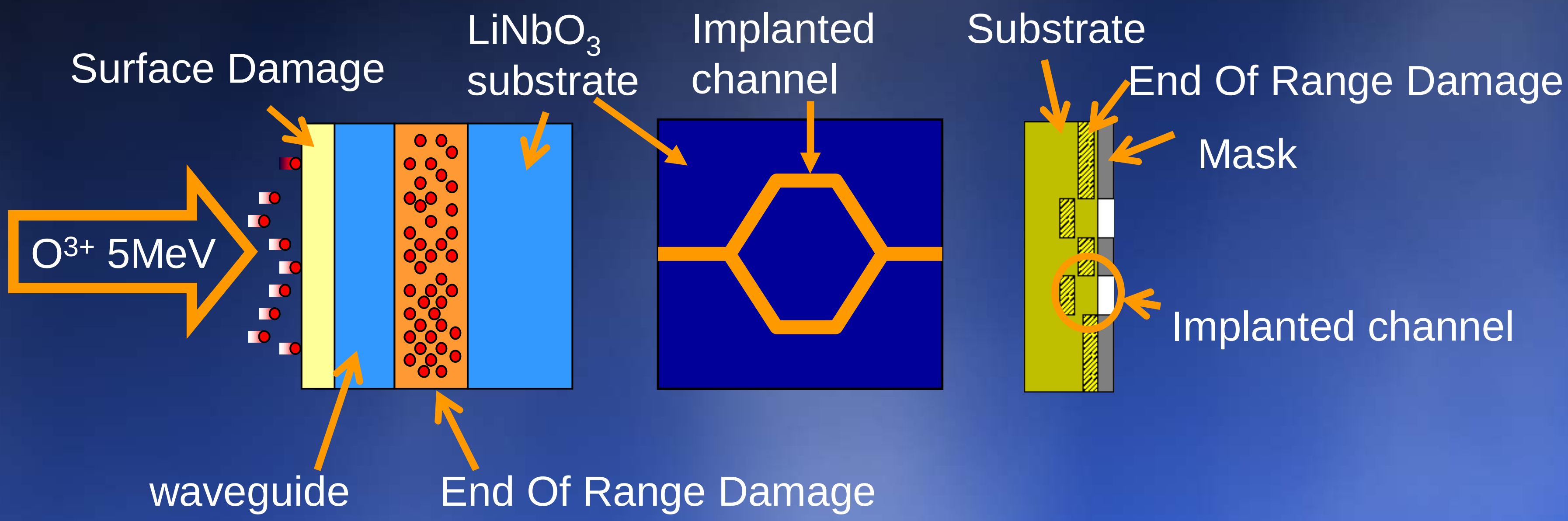
Ion Implantation of medium light elements

Damage Profile of a Channel Waveguide realized by High Energy Ion Implantation





Application: optical modulator



How to change the refractive index in one branch?
Via the **electro-optic effect**

Electro-optic effect

Change in refractive index with the applied electric field:

$$\Delta(1/n^2) = r \cdot E + P \cdot E^2$$

Pockel effect

Kerr effect

Where:

n= Refractive index

r = Linear Electro-Optic coefficient

P = Quadratic Electro-Optic Coefficient

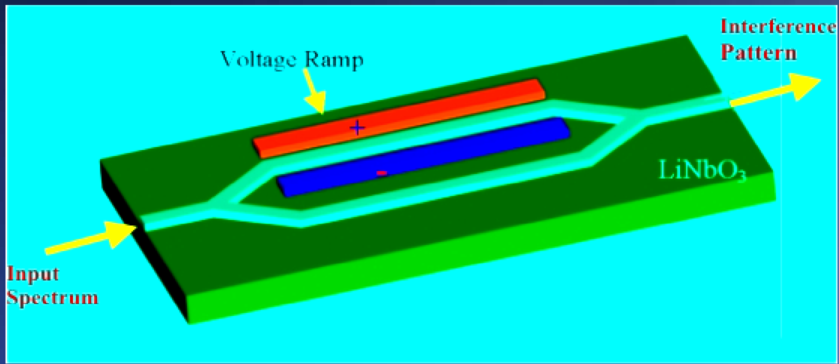
E = Applied Electric Field

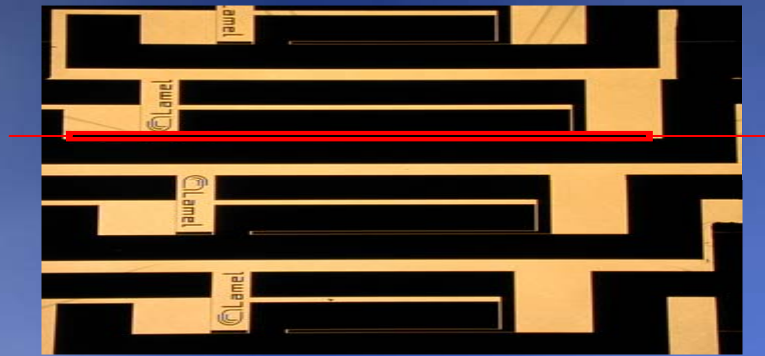
Electro-optic effect

Modulation of the refractive index through the applied electric field

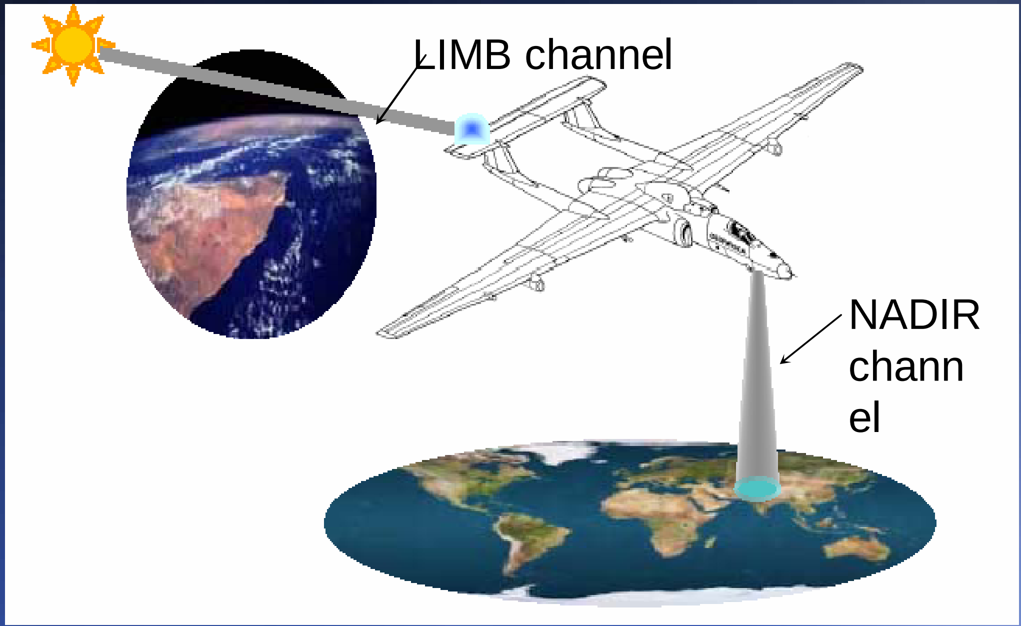
Material	*r* (pm/V)	*n*
KTP	35	1.86
$KNbO_3$	25	2.17
$LiNbO_3$	29	2.2
$Ba_2NaNb_5O_{l5}$	56	2.22
SBN (25-75)	56-1340	2.22
GaAs	1.2	3.6
$BaTiO_3$	28	2.36

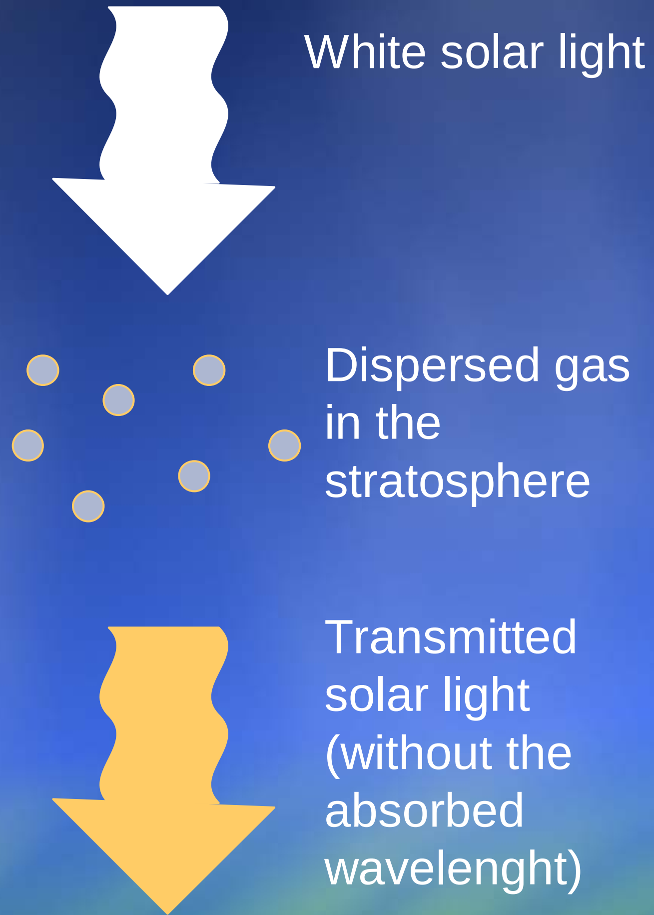
Ion implantation: application to gas tracing





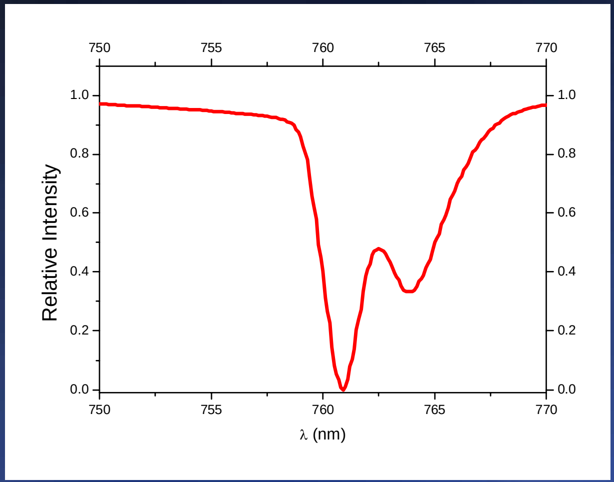
Ion implantation: application to gas tracing



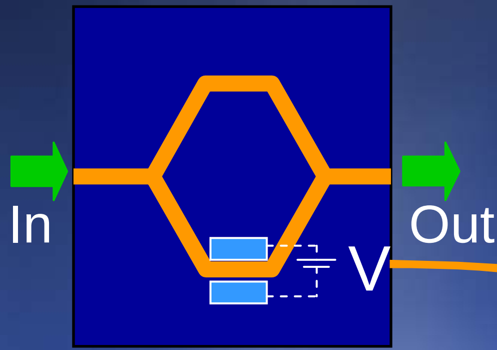


Application to gas tracing

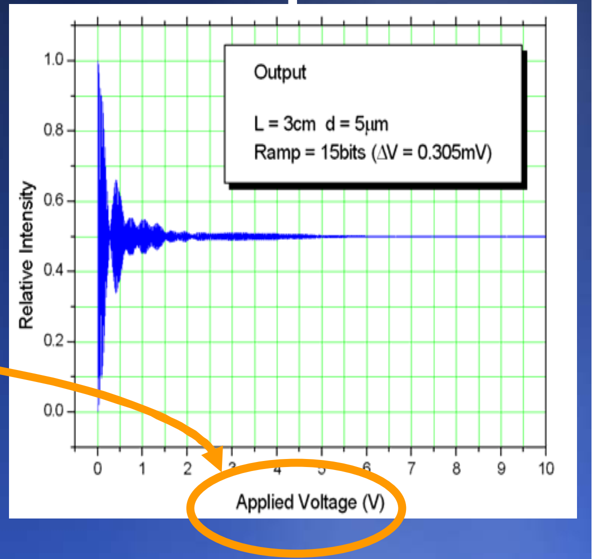
Input



Mach-Zehnder



Output



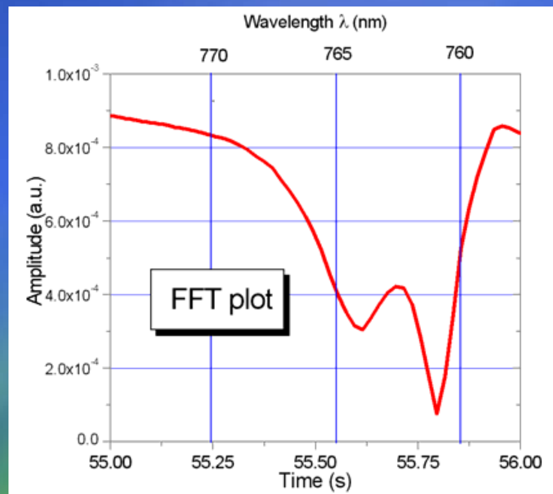
Different refractive index in the two branches=different phase velocity of the optical beams

At the output, beams recombination gives light interference

The interference pattern contains the information on the input signal

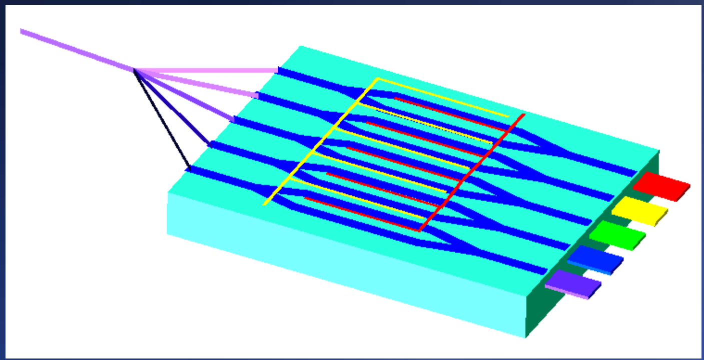
Post analysis of the interference pattern allows the identification of the input signal, i.e gas element

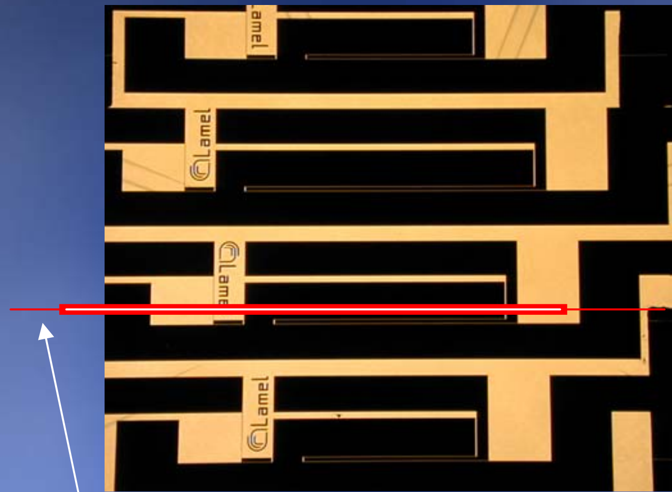
Reconstruction



Application to gas tracing

High selectivity on the wavelength

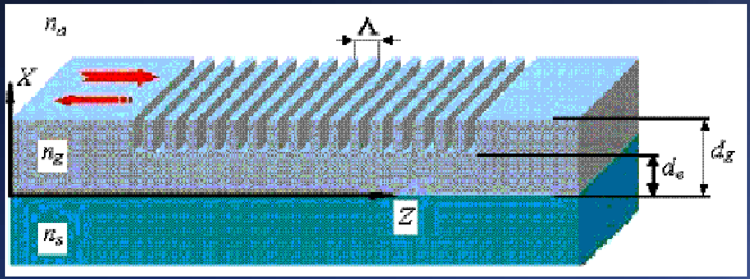


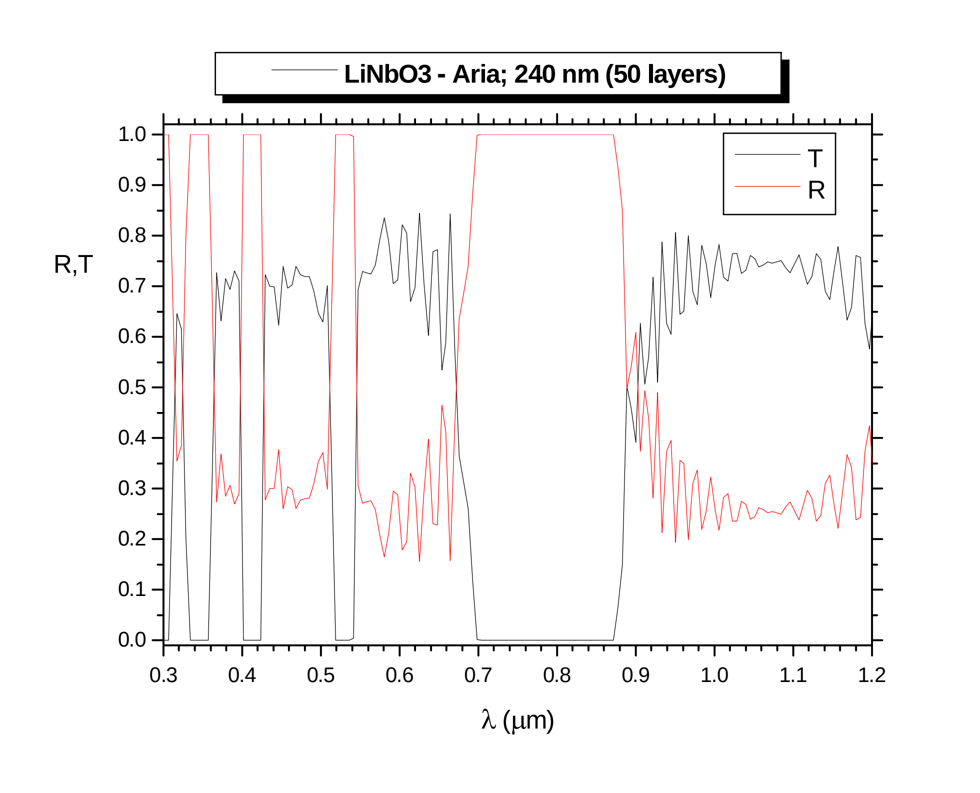


Position of the waveguides below the driving electrodes

Nanotech applied to $LiNbO_3$

Realization of periodic grating acting as wavelength filters

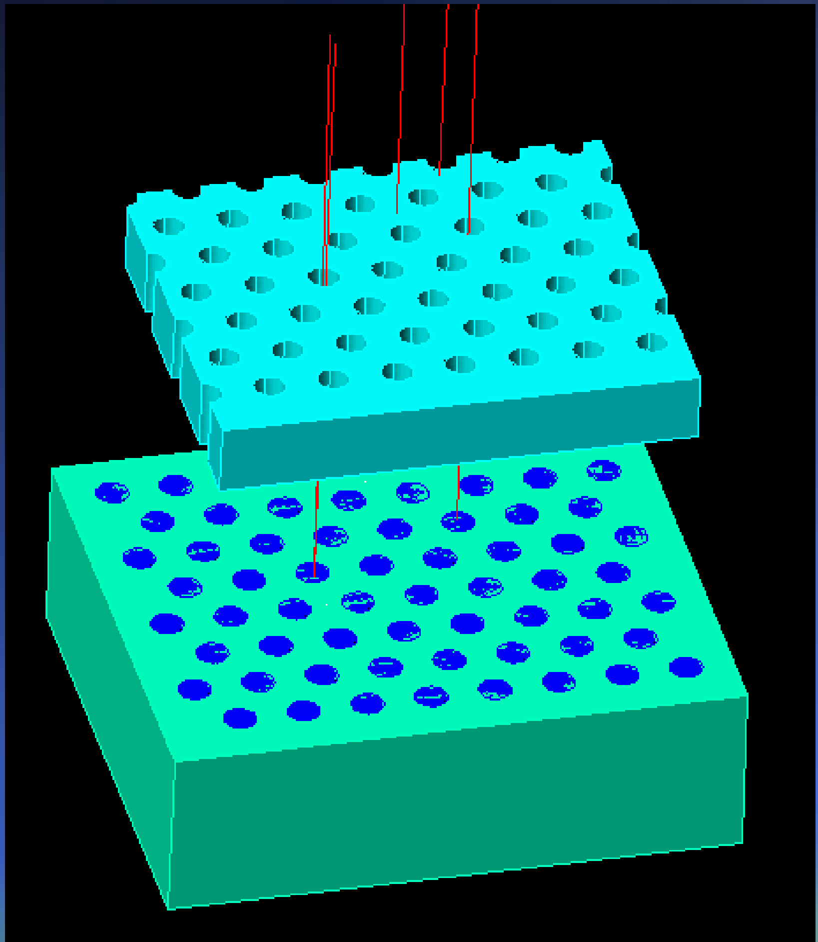




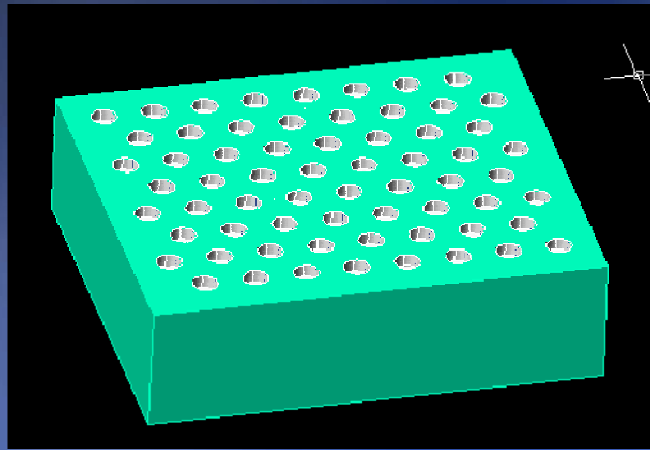
Periodic structure in the nanoscale region obtained by laser irradiation: band pass filter

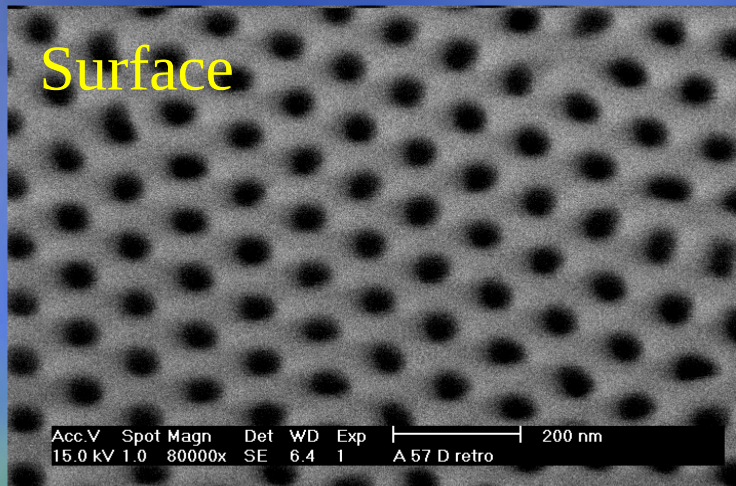
Ion implantation: application in nanotech

Ion implantation through a mask



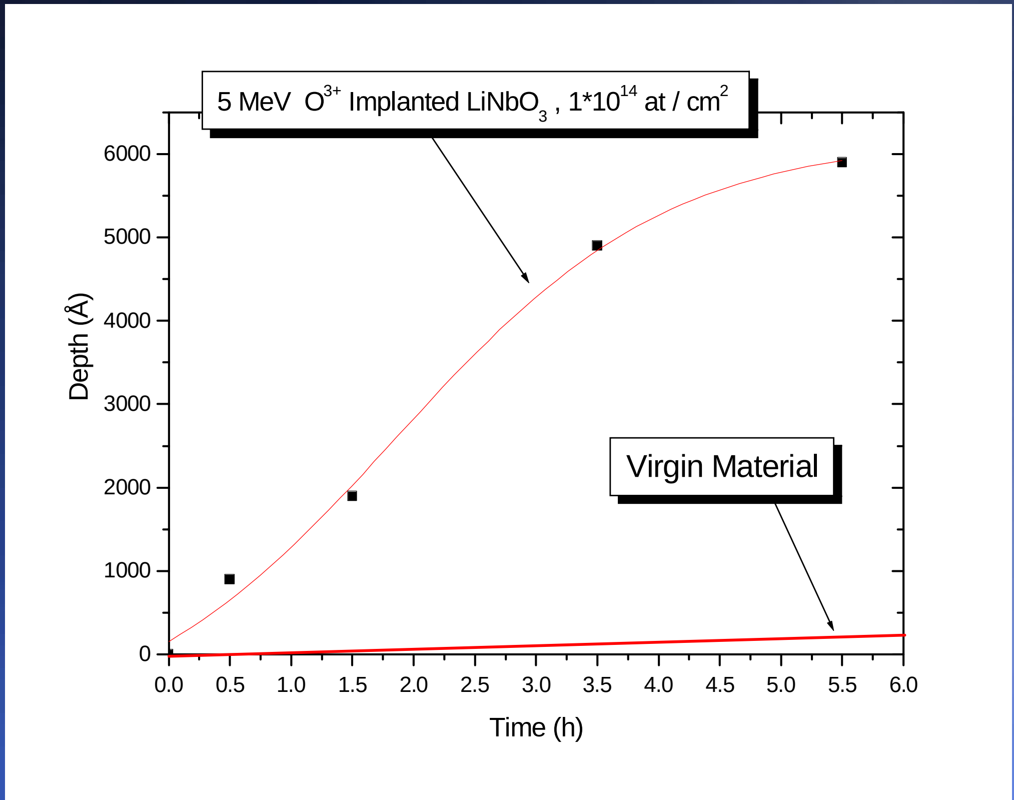
Chemical etching on the implanted surface





Ion implantation: application in nanotech

Effect of the damage on the etching rate

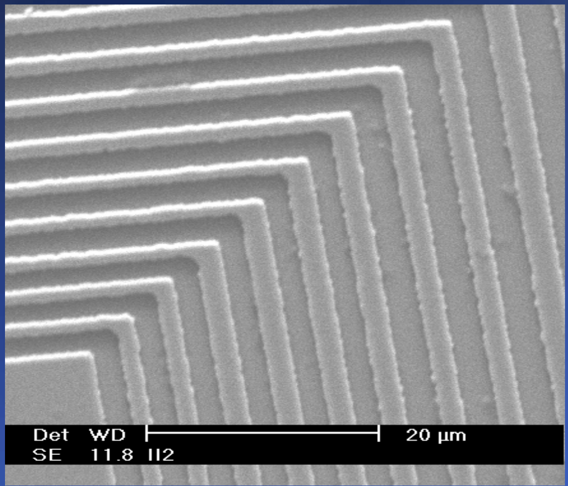


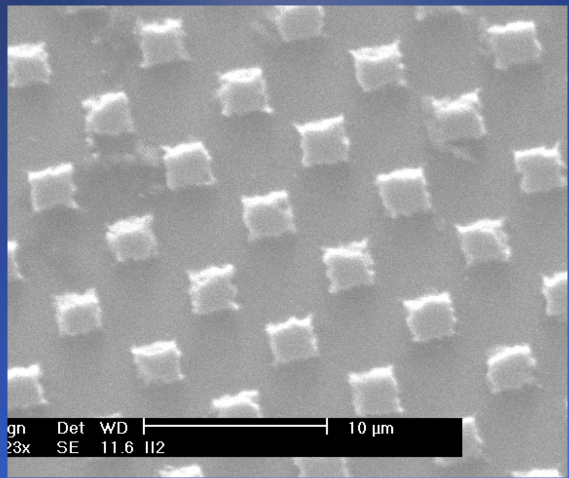
Implanted region are chemically attached faster than unimplanted ones

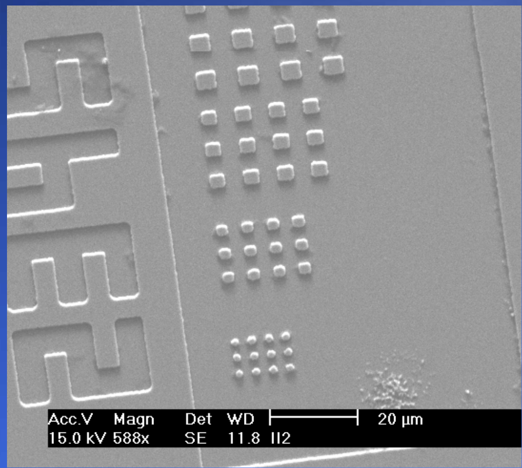
Selective etching!

Ion implantation: application in nanotech

Patterns obtained on $LiNbO_3$ by ion Implantation and selective etching

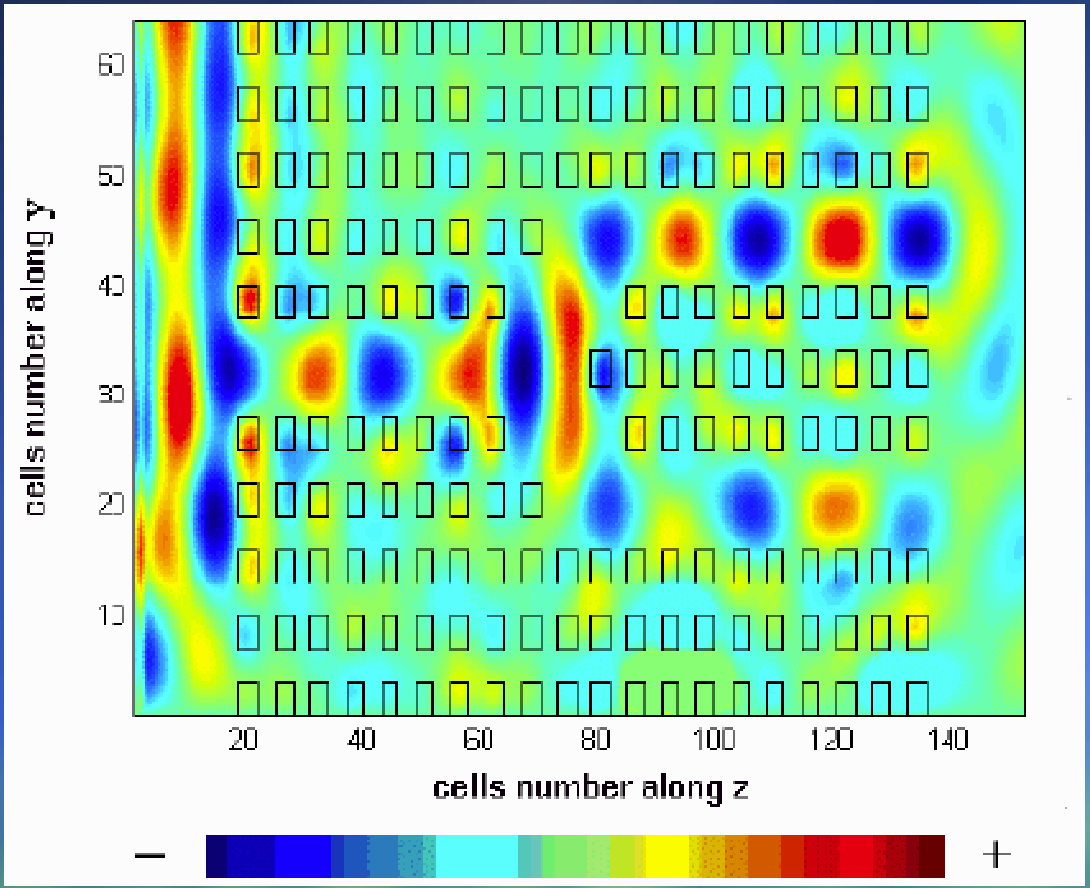




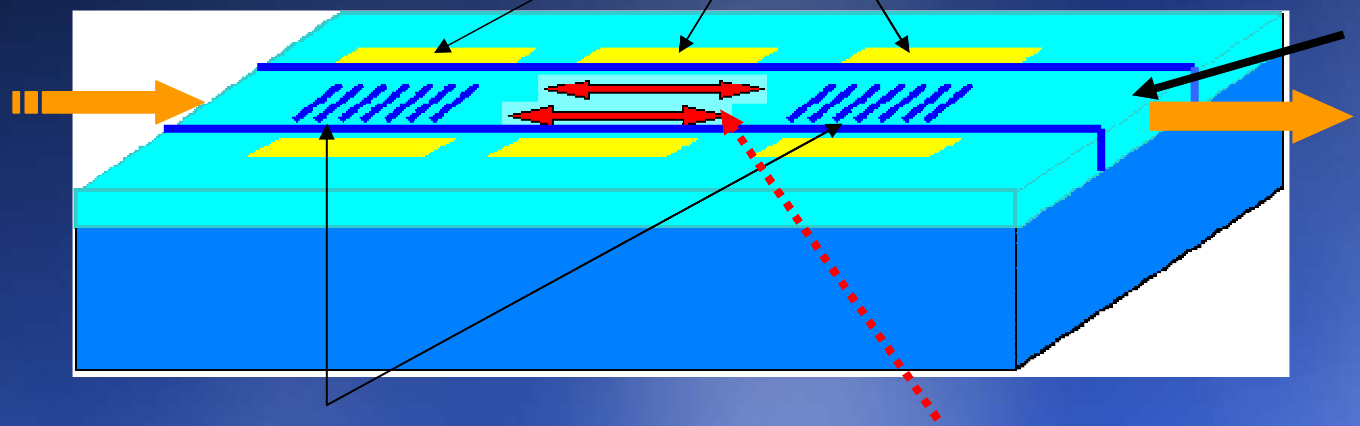


Ion implantation: application to nanotech

Simulation of the electromagnetic field propagation in a Photonic Device obtained by ion implantation + selective etching



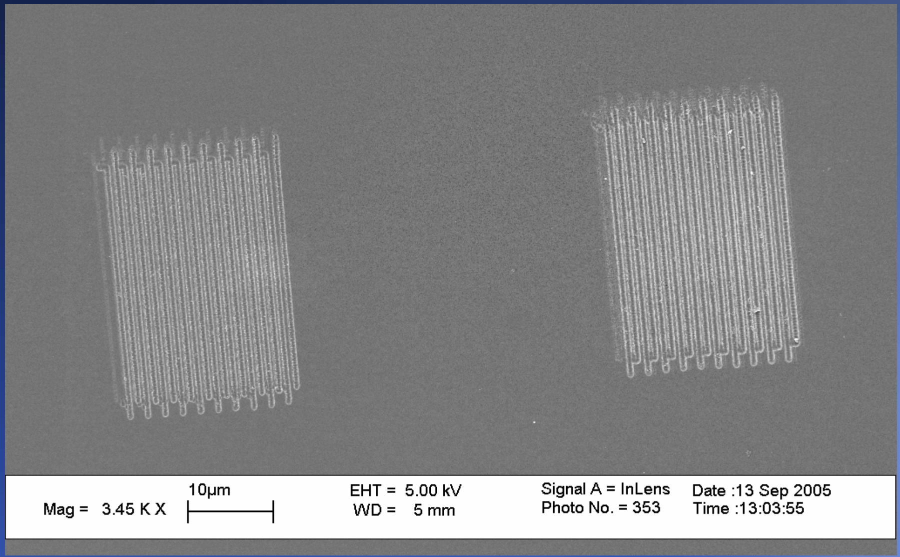
Perspectives

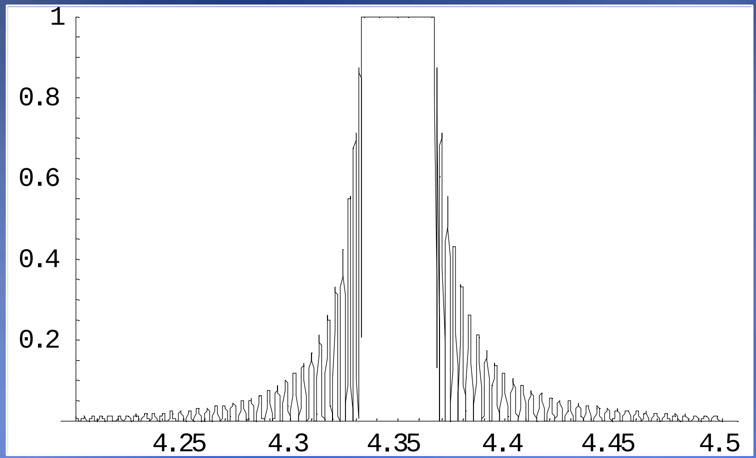


Obtained by periodic structures

Outline

Resonant Cavity

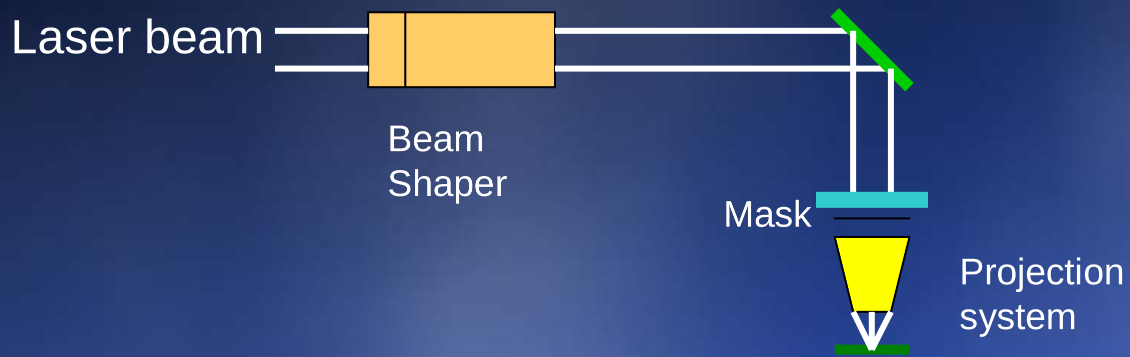


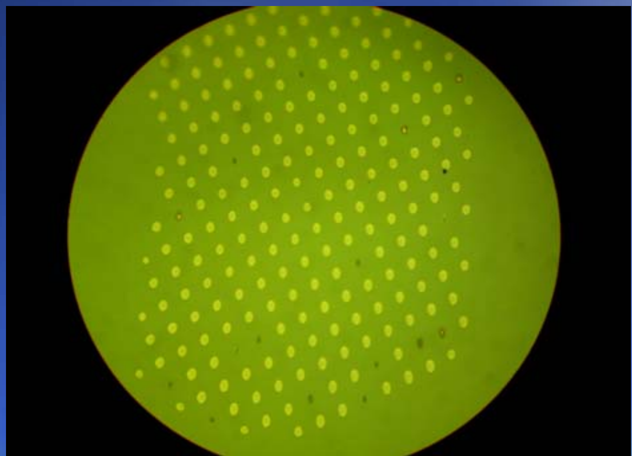


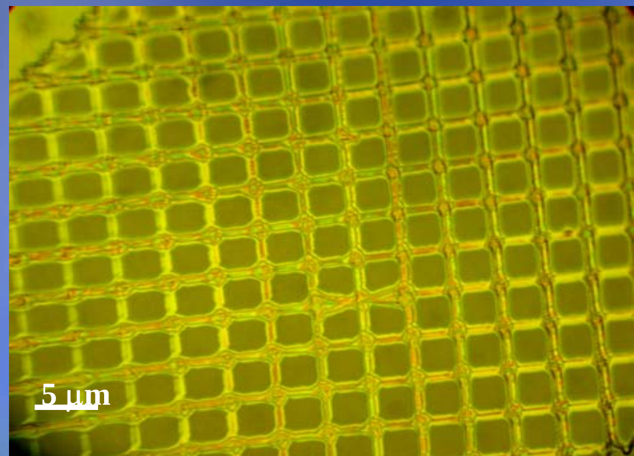
Resonant Cavity, periodicity of the Photonic Structures: 600 nm

Photonic Band Gap of the cavity, (Theory)

Nanotech applied to $LiNbO_3$







Lower period can be obtained by laser irradiation

Conclusions

Ion implantation is a very versatile techinique to modify the $LiNbO_3$ properties

In combination with photolitography it allows for the relaization of optical pattern

In principle any complex optical device can be realised, with tailored performances and functionalities