Astrophotonics

From laser nanostructuration of electro-optic materials to exoplanet research

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Collaborations:

- **FEMTO-ST: ANR RALIS (N. Courjal)**
- **CEA-LETI: Recombineurs Passifs (P. Labeye)**
- **PHOTLINE: Recombineurs Actifs (J. Hauden, H. Porte)**
- **IMEP-LAHC: Simulations (A. Morand)**
- **LabHC: Femtosecond Laser Writinge (R.Stoian, C. d’Amico)**

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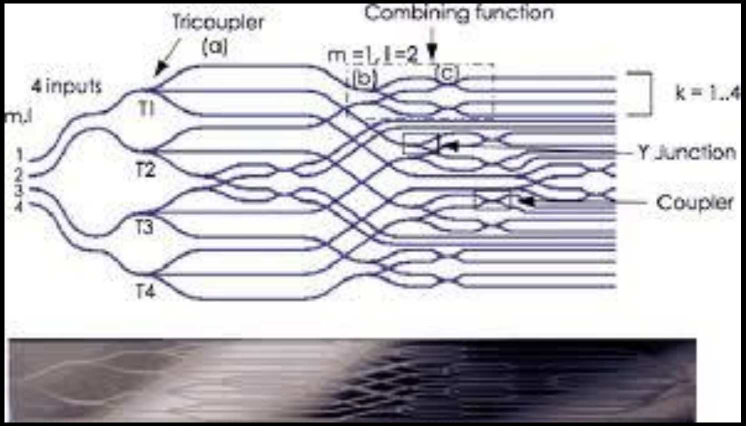
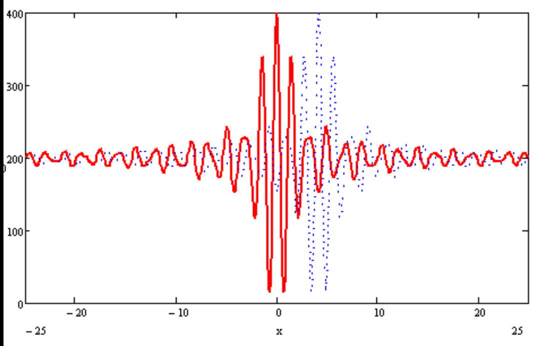
A RAPID OVERVIEW

For astronomical applications (specially, for spatial applications) needs are:

-Integrated optics beam combiners (2D, 3D) & spectrometers (SWIFTS):





Both will generate FRINGES !!!

Can we generate phase modulation without any moving part? ELECTRO-OPTICS

From the Phase and Contrast we will understand the nature of the source

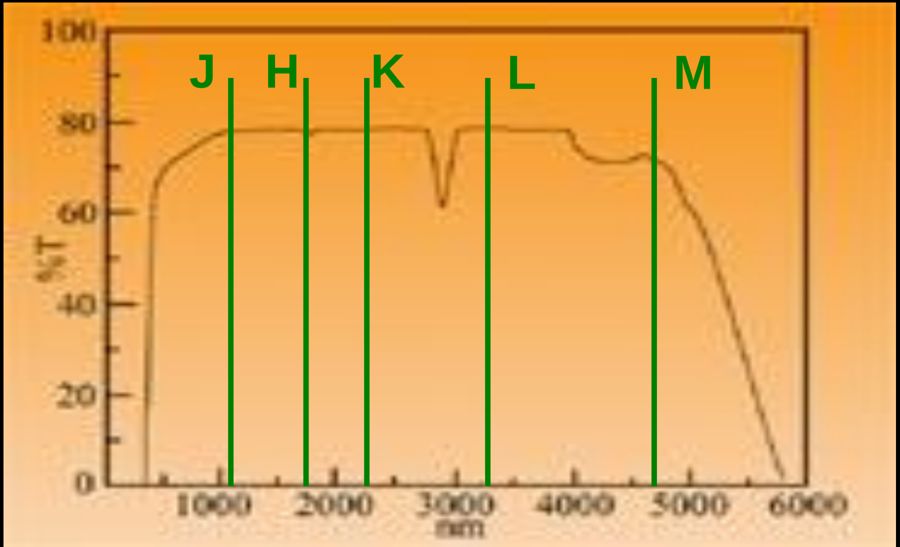
From the Fourier Transform, we will get the emission spectrum of the source

ASTROPHOTONIC (I): MATERIALS

MID IR MATERIALS

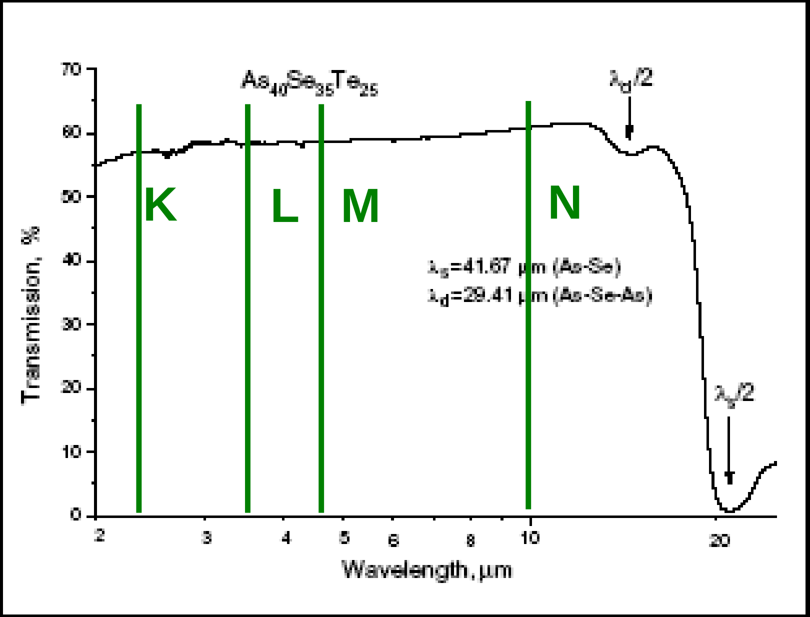
INFRARED MATERIALS

MID-IR MATERIALS



Lithium Niobate

Transmittance $LiNbO_3$: 420-5200 nm



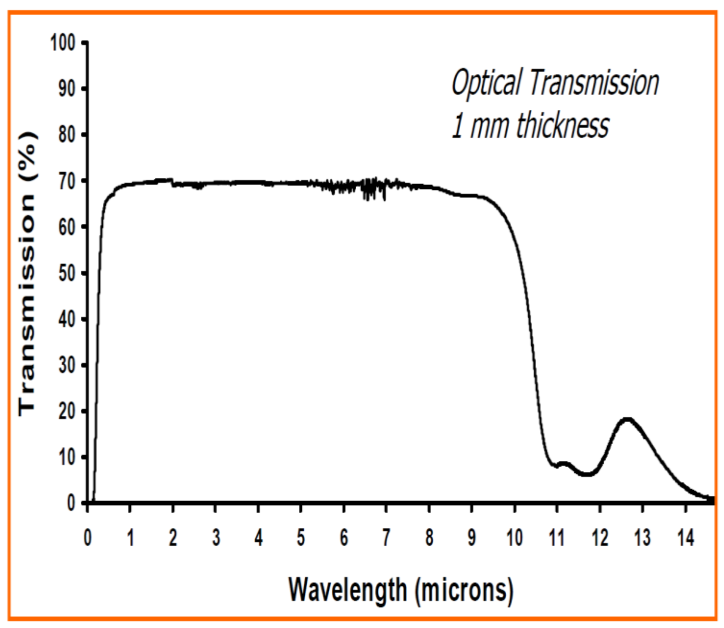
Chalcogenides: TeAsSe, As_2S_3, As_2Se_3…

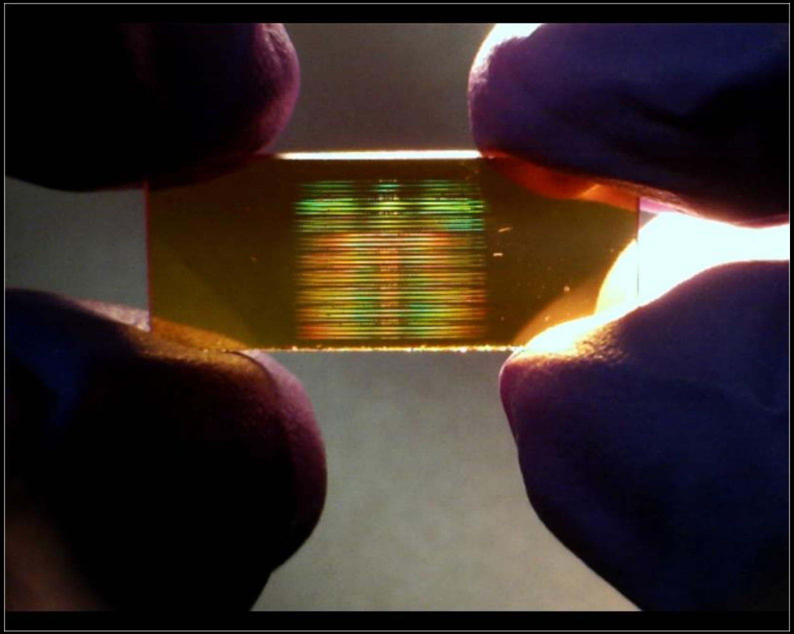
-> **Goal:** Find IR materials that can be turned into waveguides/fibers

INFRARED MATERIALS

MID-IR MATERIALS

Chalcogenides: Te, Ge, La, S, Se





Wide transmission range

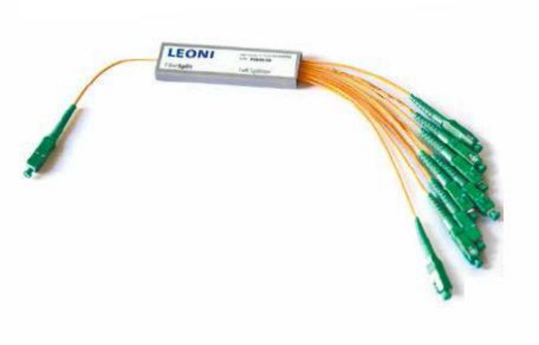
Possibility to change the refractive index by femtosecond laser writing

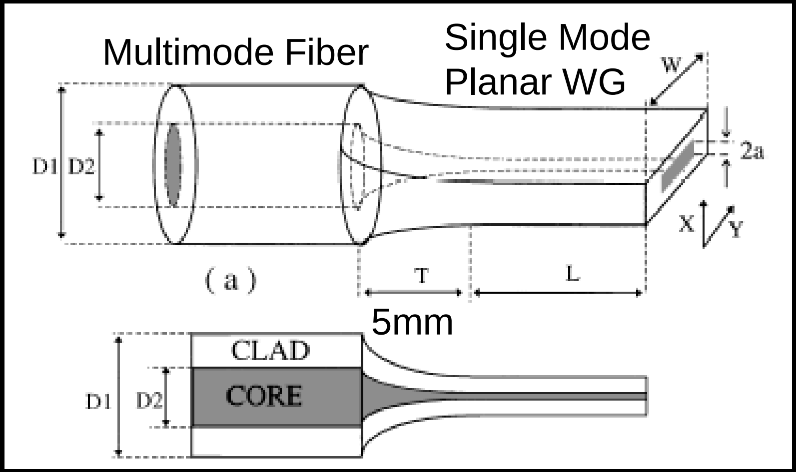
-> Goal: Fabrication of mid-infrared waveguides and beam combiners

INTEGRATED OPTICS WAVEGUIDES

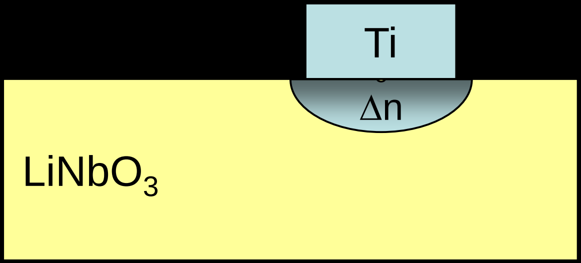
Different technologies:

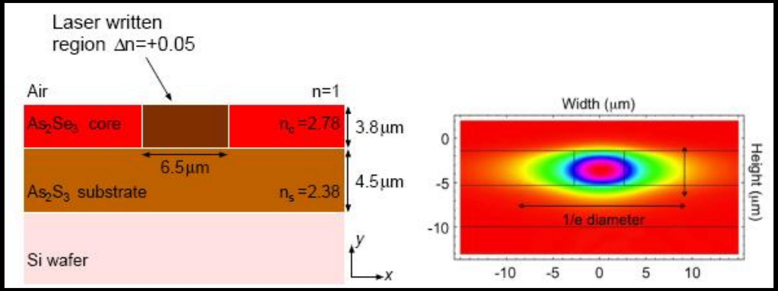
-Fibers, Lanterns



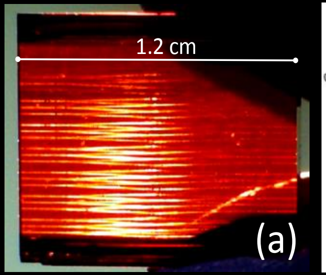


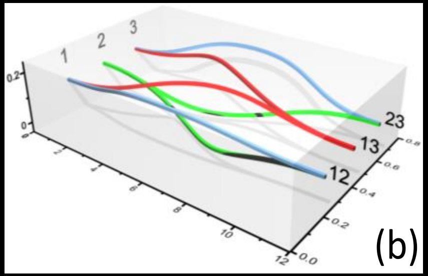
-Channel/Planar 2D Waveguides





-Channel 3D Waveguides





-> **GOAL**: To develop single mode waveguides in the target spectral range

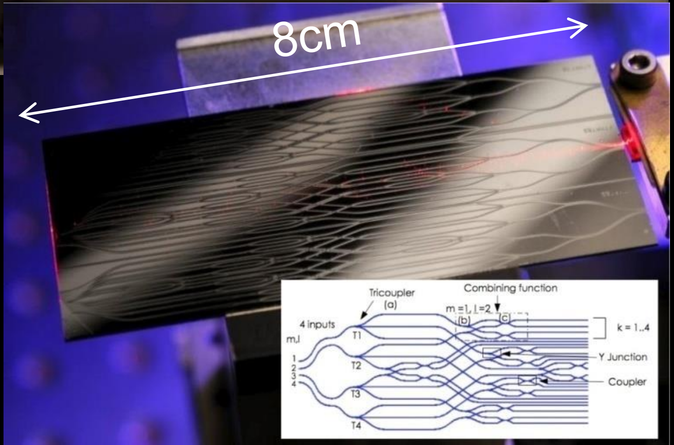
INTEGRATED OPTICS CONCEPTS

BULK OPTICS vs INTEGRATED OPTICS

In order to combine the signal coming from different telescopes, the complexity increases with the number of apertures:

3 Telescopes
250kg
J,H,K bands
(R=10000)
4.2m x 1.5m
Periodical
Re-alignement

Instead, integrated optics can be a useful alternative:



4 Telescopes
One single device
200g
H band (R=8000)
80mm x 15mm
No alignement

INTEGRATED OPTICS FOR SPACE

For spatial applications: Reducing weight, volume and degrees of freedom is compulsory

DARWIN/TPFI

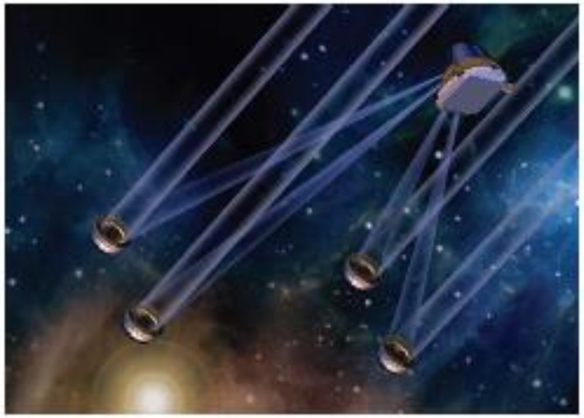


FIGURE 1.6 – Vue d'artiste de DARWIN/TPF-I dans sa solution finale. Source : cnes.fr

4T combination
Mid-IR (5-20um)

PEGASE

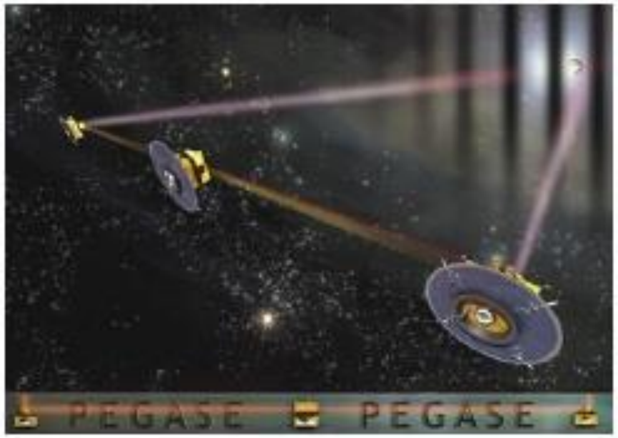
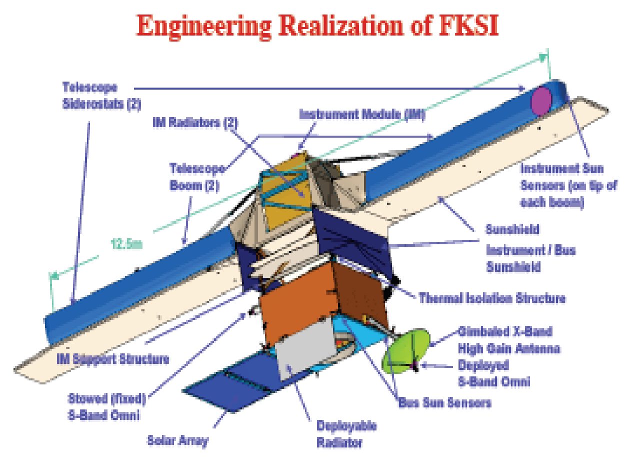


FIGURE 1.7 – Vue d'artiste de PÉGASE. Source : obspm.fr

2T combination
Mid-IR (2.5-5um)

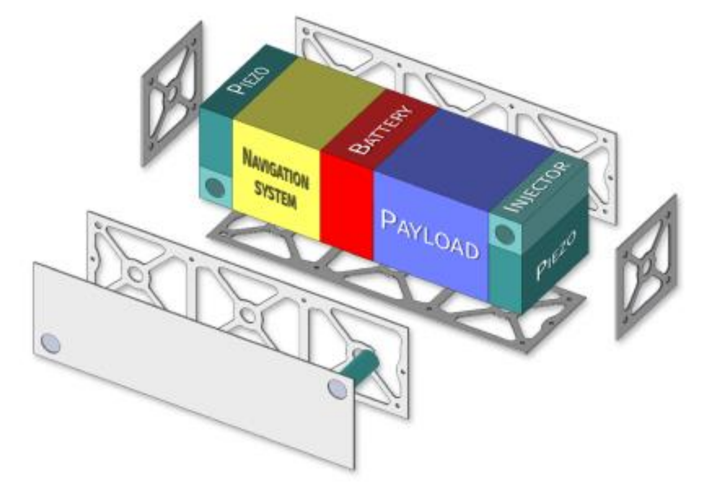


2T combination
Mid-IR (3-18um)

FKSI Proposal. William Danchi

INTEGRATED OPTICS FOR SPACE: CUBESATs

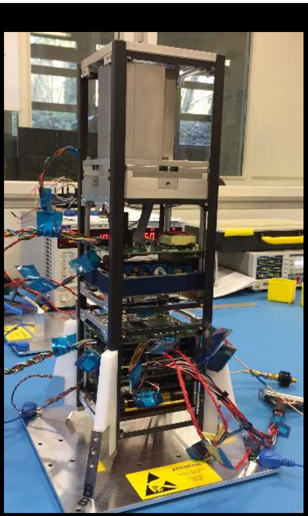
A new era of satellites: Low cost, rapid launch (5 years)

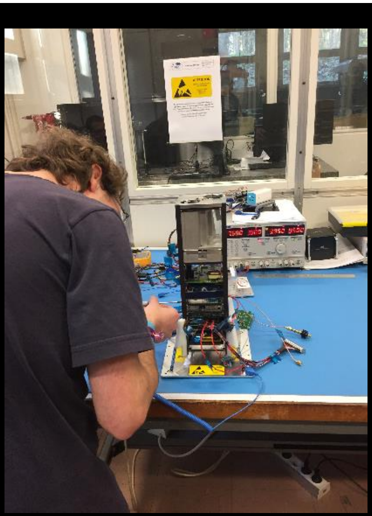


PICSAT and FIRST-Lithium projects

Collaboration LESIA – IPAG

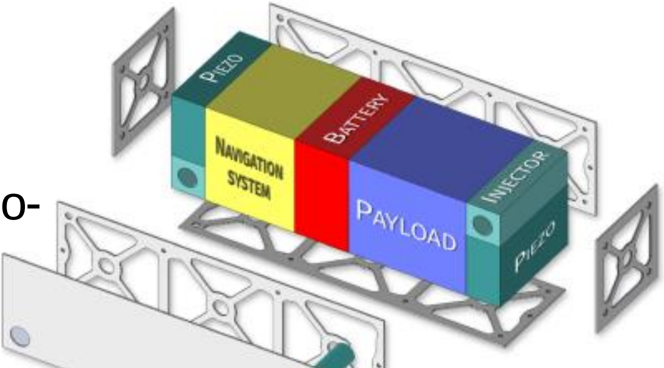
First demonstrations of cubesat interferometry

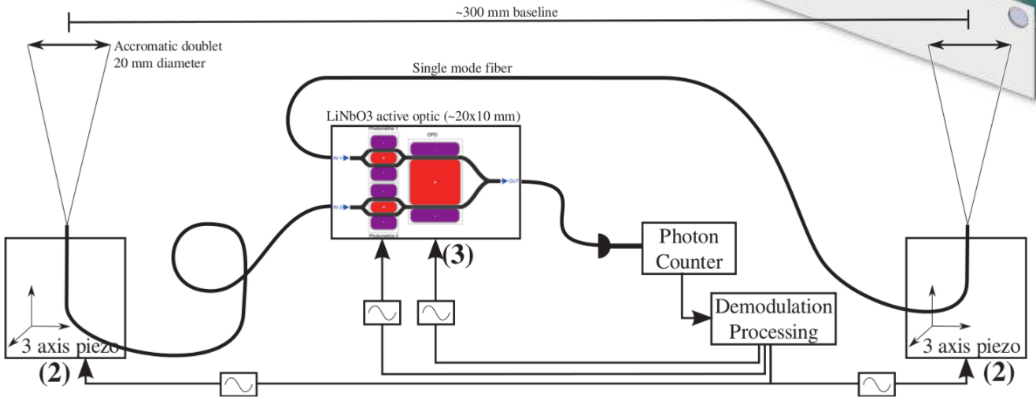


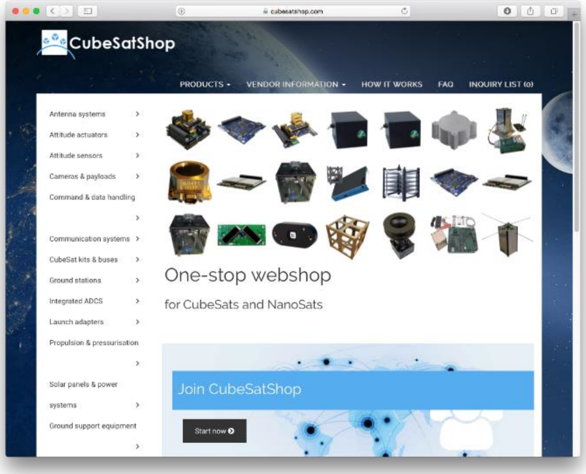


Le projet FIRST-S

- Dérivé de FIRST, autour des composants d’optique active au cœur de l’ERC Lithium
- Cubesat 3U pour caractériser la lumière exo-zodiacale
- Atelier Nanosat à Meudon (Nov. 2013)







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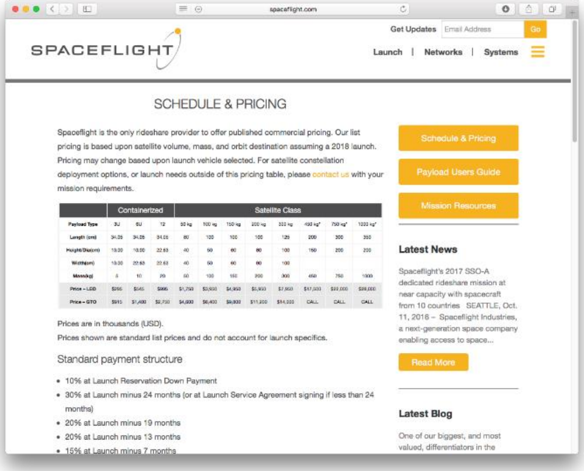

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	Containerized			Satellite Class							
Payload Type	3U	6U	12	50 kg	100 kg	150 kg	200 kg	300 kg	450 kg*	750 kg*	1000 kg*
Length (cm)	34.05	34.05	34.05	80	100	100	100	125	200	300	350
Height/Dia(cm)	10.00	10.00	22.63	40	50	60	80	100	150	200	200
Width(cm)	10.00	22.63	22.63	40	50	60	80	100			
Mass(kg)	5	10	20	50	100	150	200	300	450	750	1000
Price – LEO	$295	$545	$995	$1,750	$2,950	$4,950	$5,950	$7,950	$17,500	$22,000	$28,000
Price – GTO	$915	$1,400	$2,750	$4,000	$6,400	$9,000	$11,200	$14,000	CALL	CALL	CALL

Prices are in thousands (USD).

Prices shown are standard list prices and do not account for launch specifics.

Standard payment structure

- 10% at Launch Reservation Down Payment
- 30% at Launch minus 24 months (or at Launch Service Agreement signing if less than 24 months)
- 20% at Launch minus 19 months
- 20% at Launch minus 13 months
- 15% at Launch minus 7 months

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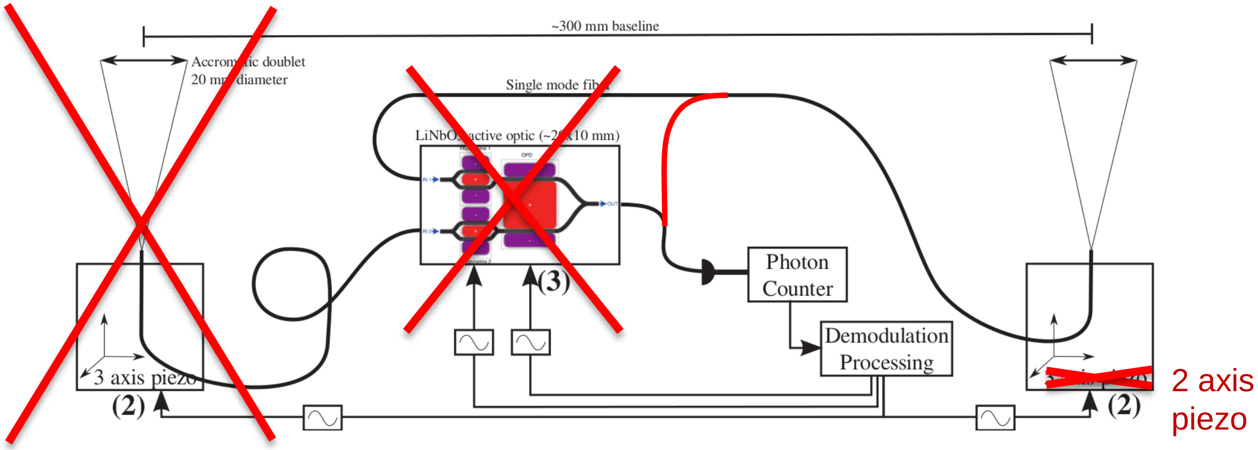
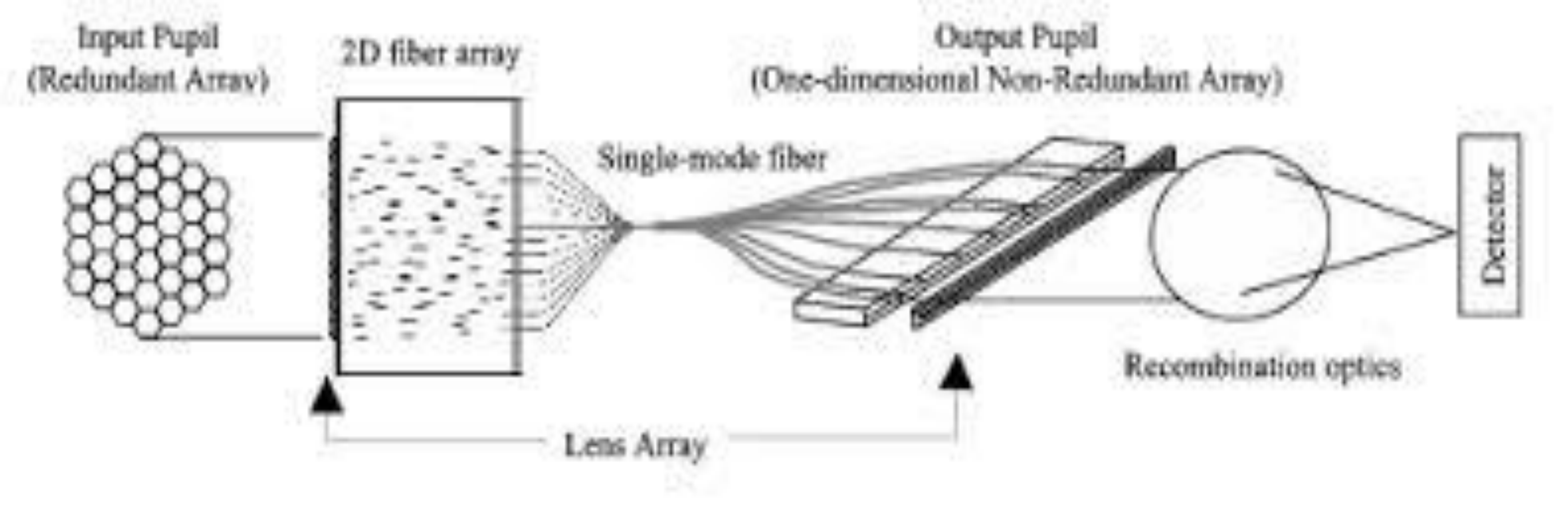
https://www.isispace.nl/cubesats/



SINGLE MODE FIBERS: PHOTONIC LANTERNS

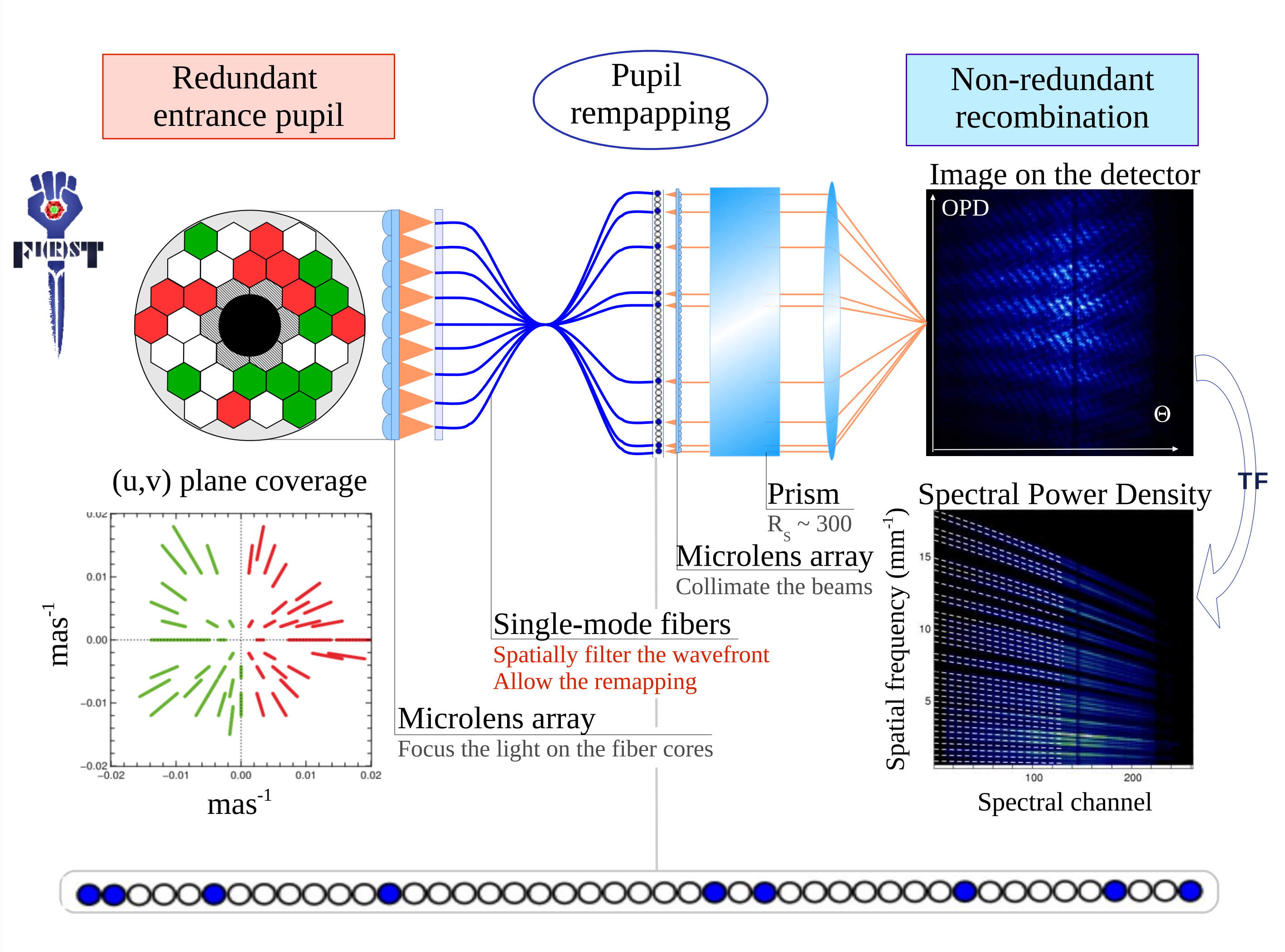
Photonic Lanterns for pupil remapping:



Bundle of single-mode fibers, that will be reconfigured to obtain interference fringes on the detector

For mid-IR applications standard functions (Y junctions, X-couplers, 1xN spliiters are not available).

FIRST (Fibered ImageR for a Single Telescope)



Redundant entrance pupil

Pupil rempapping

Non-redundant recombination

Image on the detector

(u,v) plane coverage

Prism

$R_s \sim 300$

Microlens array

Collimate the beams

Single-mode fibers

Spatially filter the wavefront

Allow the remapping

Microlens array

Focus the light on the fiber cores

Spectral Power Density

Spectral channel

Huby et al. 2012

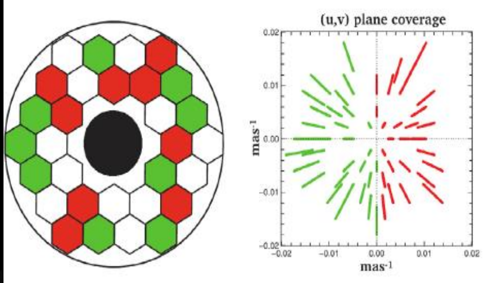
From HDR Sylvestre Lacour

COMPLEX BEAM COMBINERS: Multi-Apertures & Hybridation

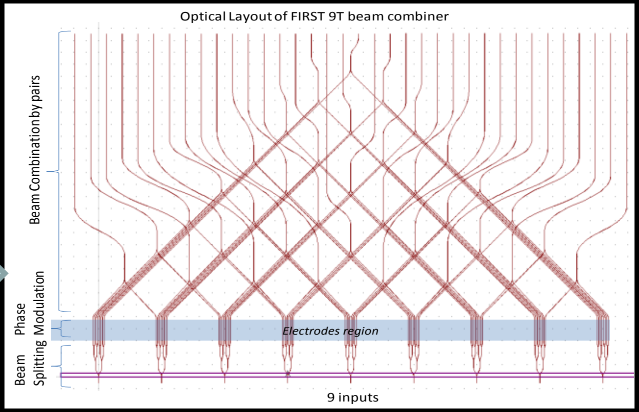
Higher Number of Telescopes : Hybridation Glass-Niobate

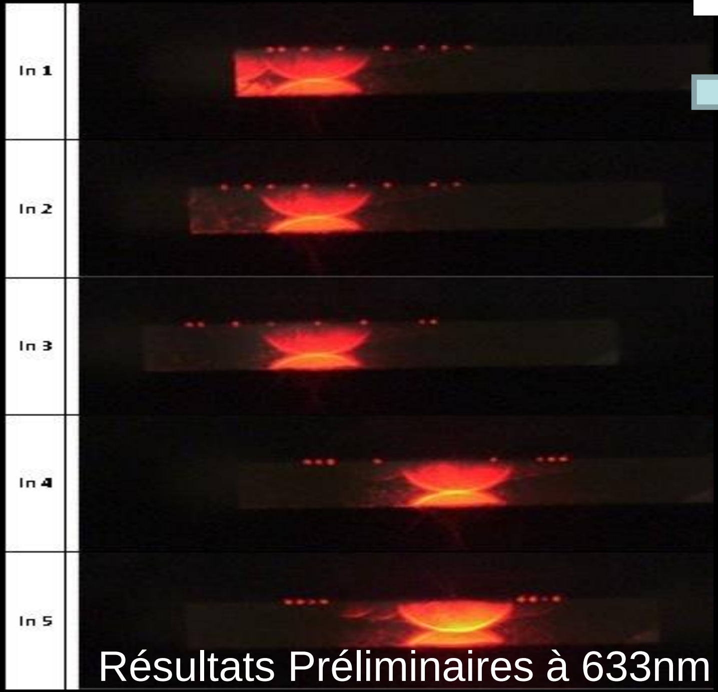
Collab. avec S. Lacour LESIA

Instrument FIRST
(SUBARU Telescope)
3x 9 « télescopes »



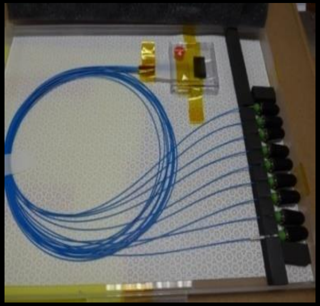
Proposed Design





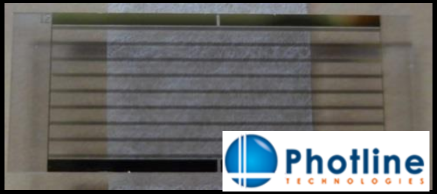
Résultats Préliminaires à 633nm

Assembling photonic elements



V-groove
d’entrée 9T

72 Modulateurs de Phase

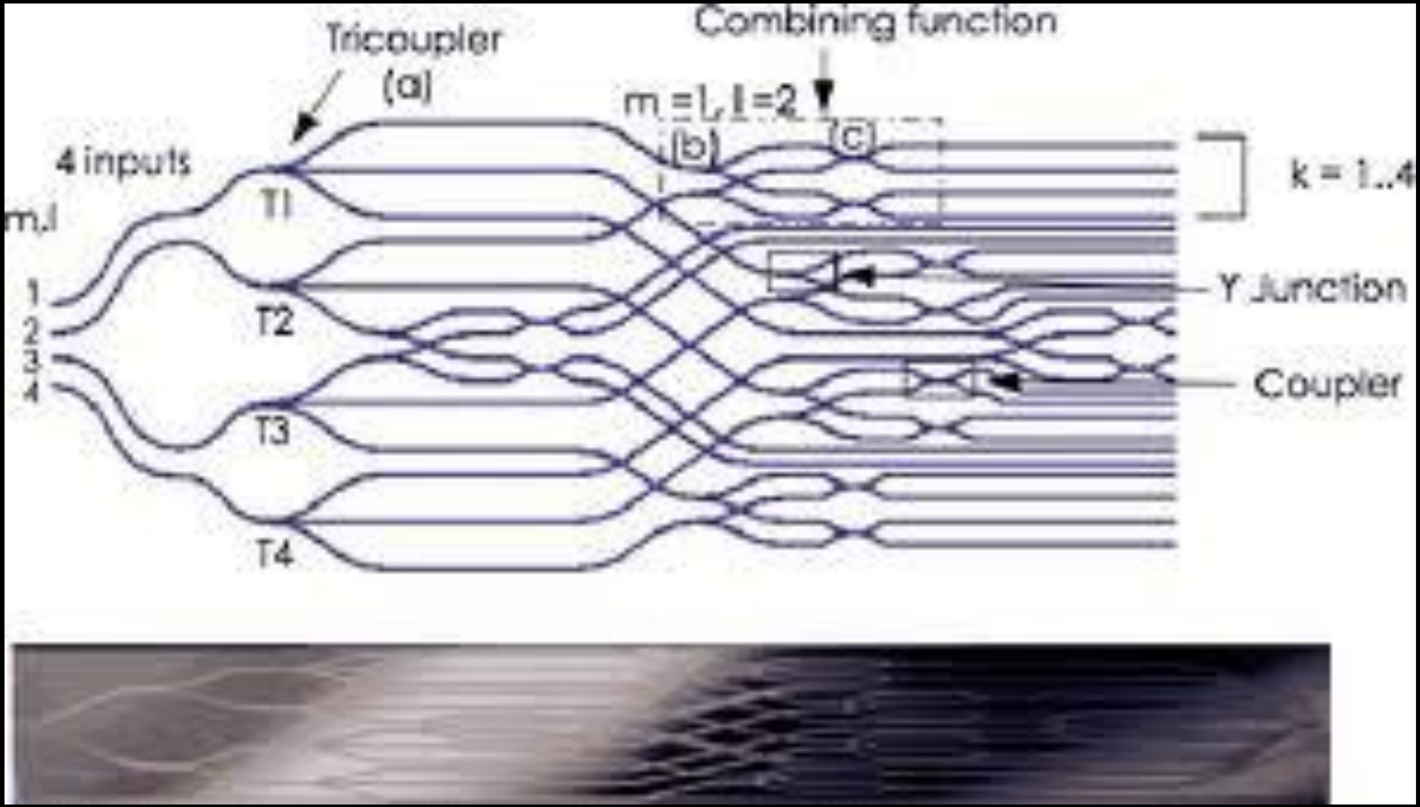


Puce 9 -> 72 -> 36

V-groove de
sortie 36 Y

COMPLEX 2D BEAM COMBINERS

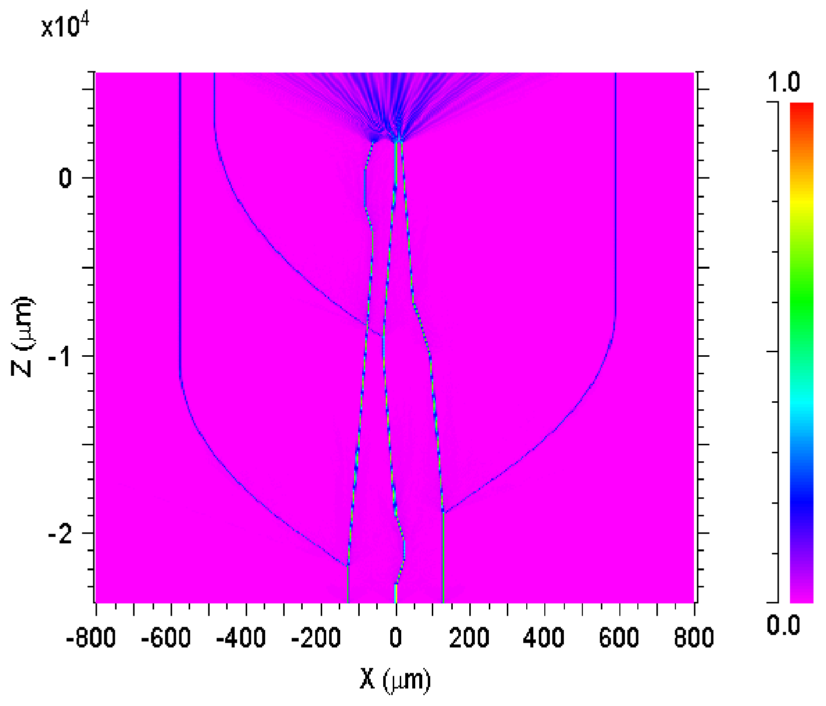
Achieve complex functions in a compact device:



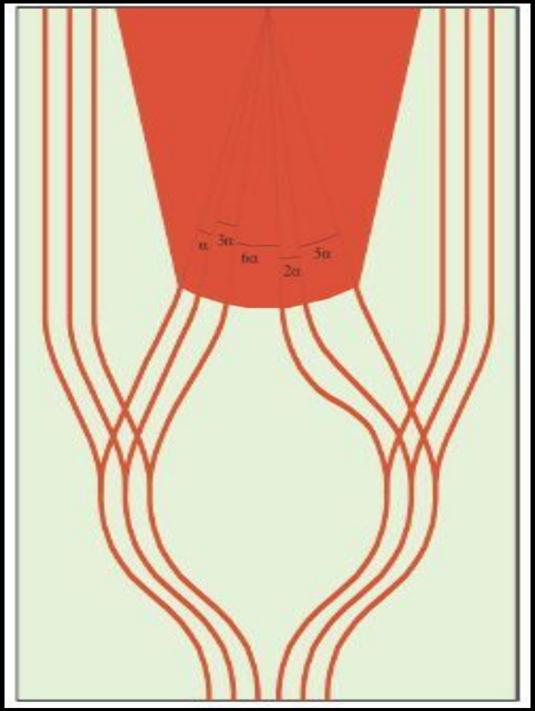
-> GOAL: Obtain good transmission, achromatic functions, avoid polarization issues…

COMPLEX 2D BEAM COMBINERS

Obtain fringes and photometry in a single device: Non redundant combination of input telescopes



3T multiaxial



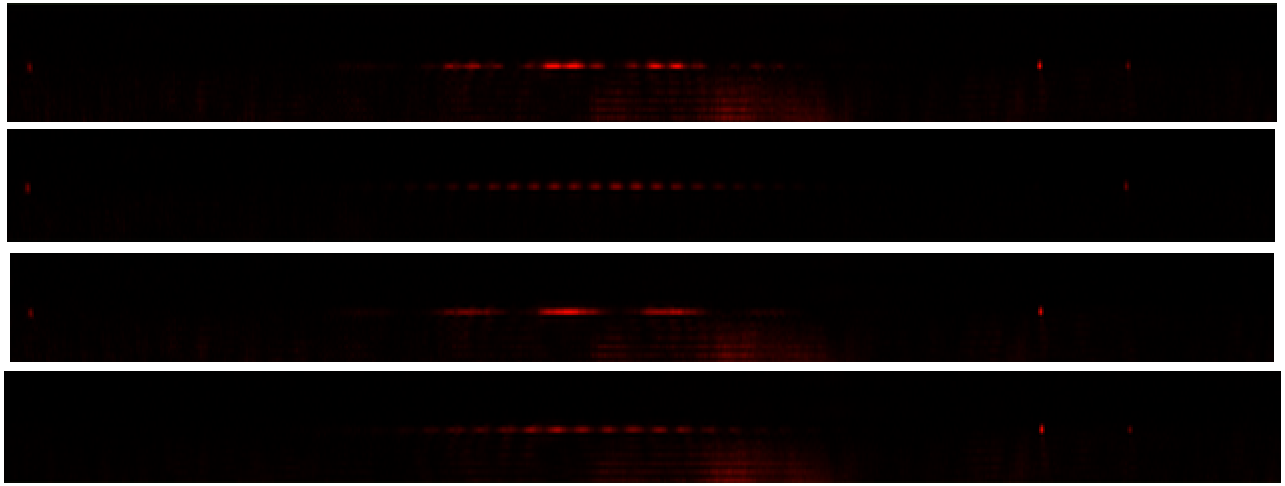
6T multiaxial

-> GOAL: Obtain non-redundant fringes of the inputs

RESULTS ON THE 3T MULTIAXIAL COMBINER

Fringes and Photometry in a single shot measurement: Passive Device (Glass)

- Fringes in monochromatic light (633 nm)



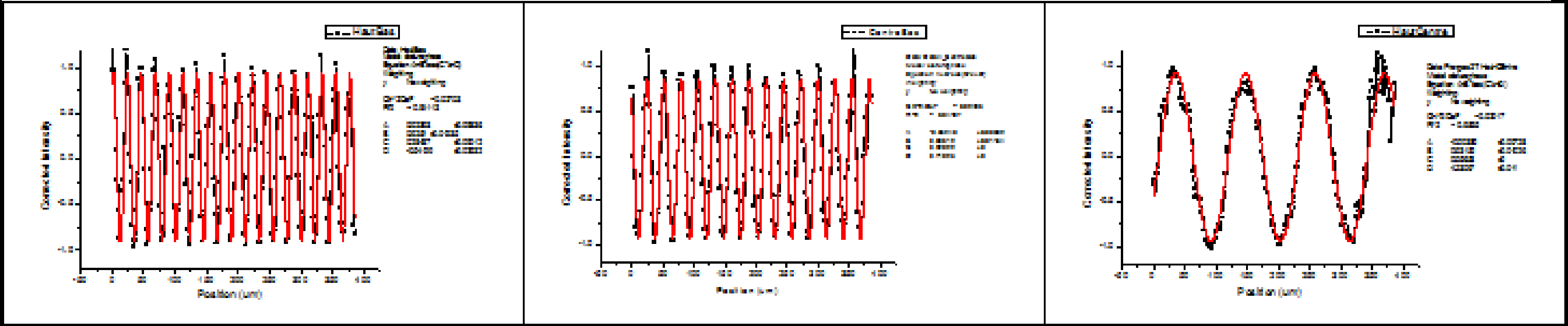
3-T

2-3

1-2

1-3

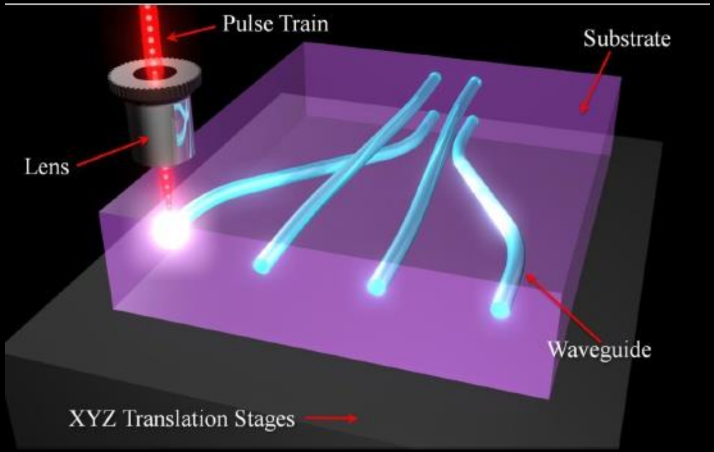
Contrast > 89%



COMPLEX 3D BEAM COMBINERS

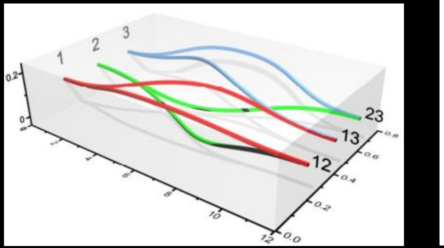
Use the vertical dimension to avoid in-plane crossing and crosstalk:

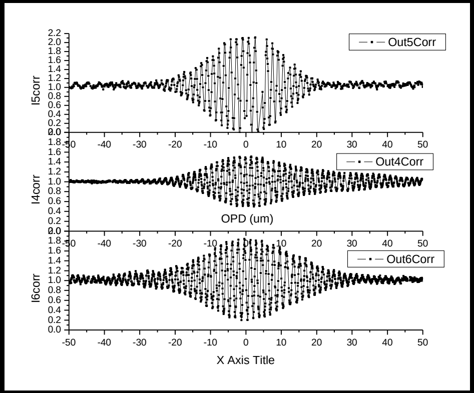
Laser-written waveguides



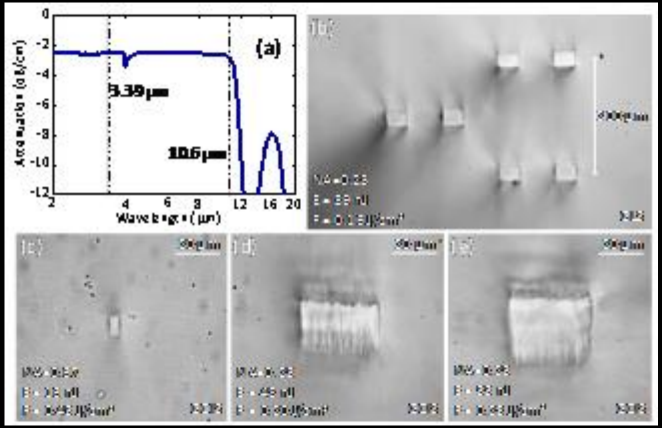
Design of complex multi-T combiners

Simultaneous 3T injection and scan

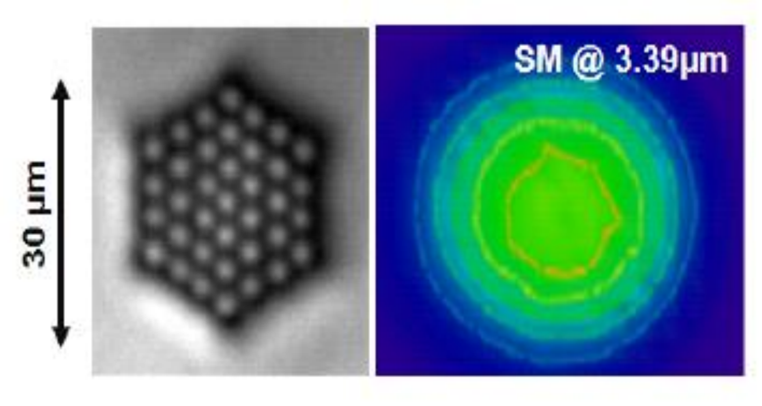




Slit-shaping



Multi-core



LASER WRITING BASICS

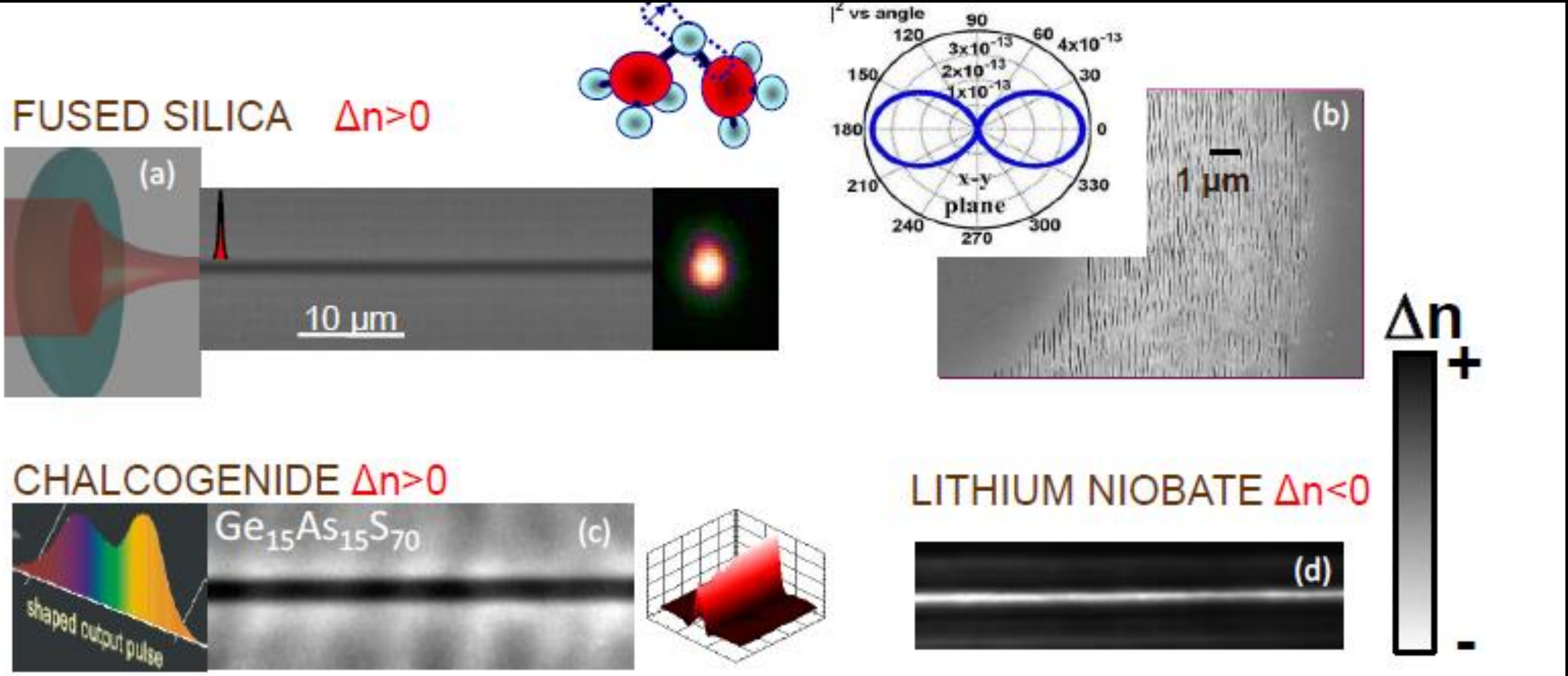
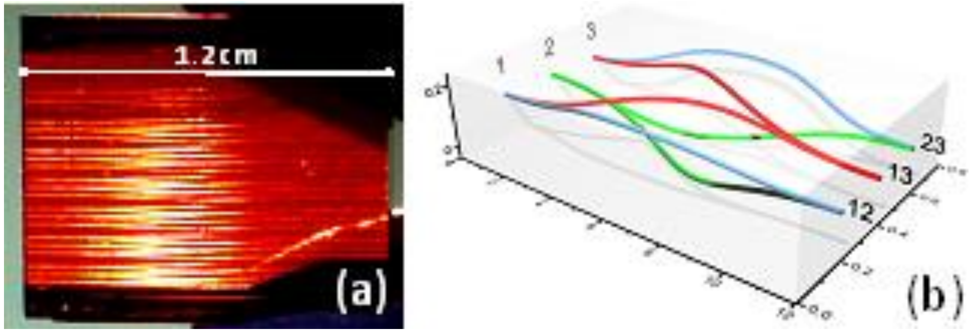


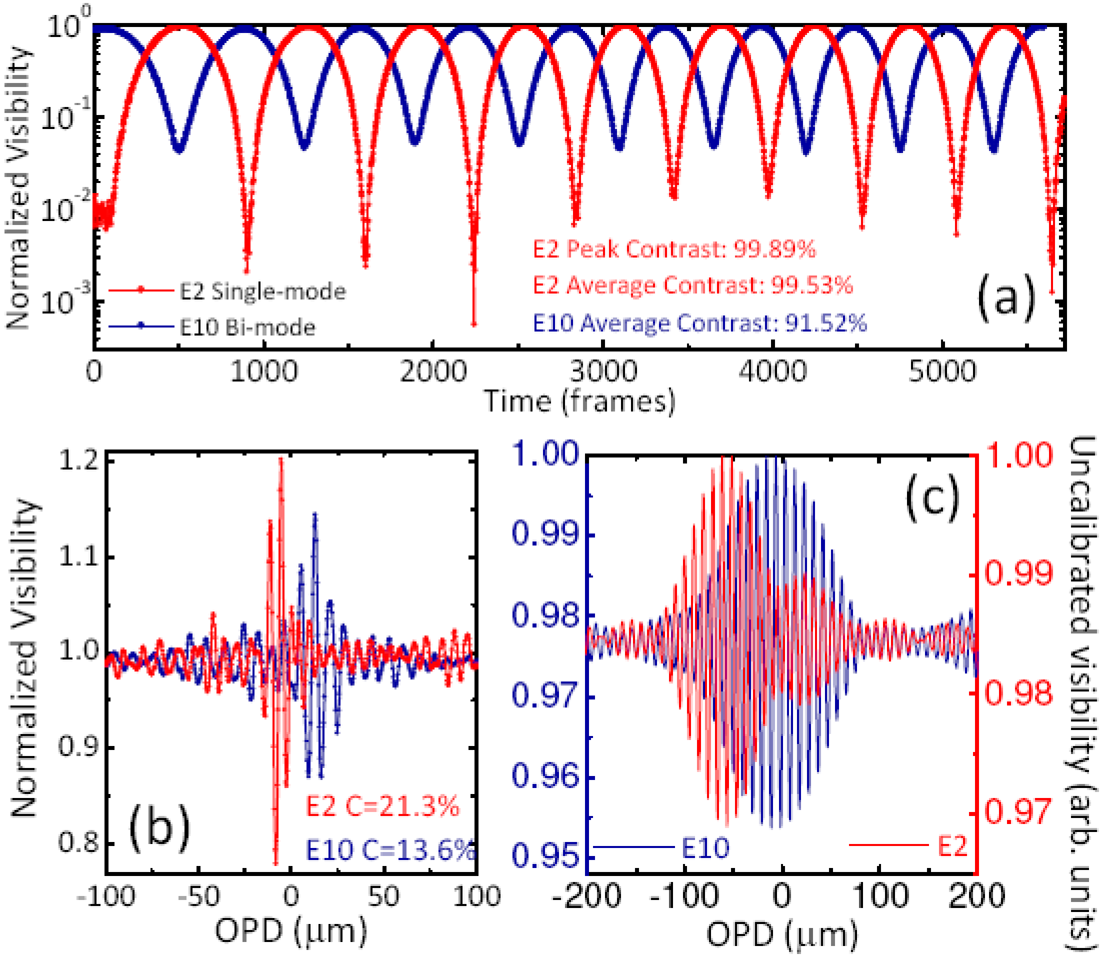
Fig. 8. Example of refractive index changes in the various substrates. (a) Positive index change in fused silica based on defect-driven densification with guided near-IR mode. (b) Spontaneous self-arrangement of nanogratings in fused silica with anisotropic scattering patterns. (c) High contrast index change in Ge-doped S-based chalcogenide glass using shaped ps pulses. (d) Negative index change in LiNbO₃ determined by mechanical rarefaction [source LaHC].

Credits: R. Stoian (IPAG – LaHC project)

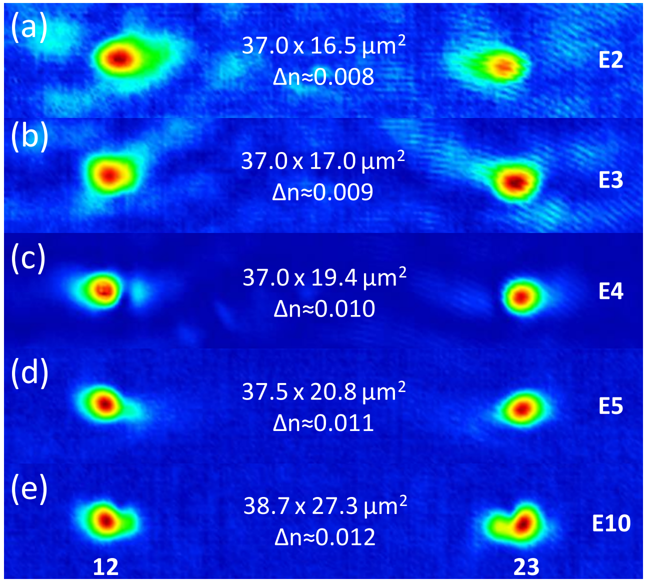
Collab.
Airan Rodenas & R. Thomson



Single vs Multimode
Visibility Fringes



Optical outputs

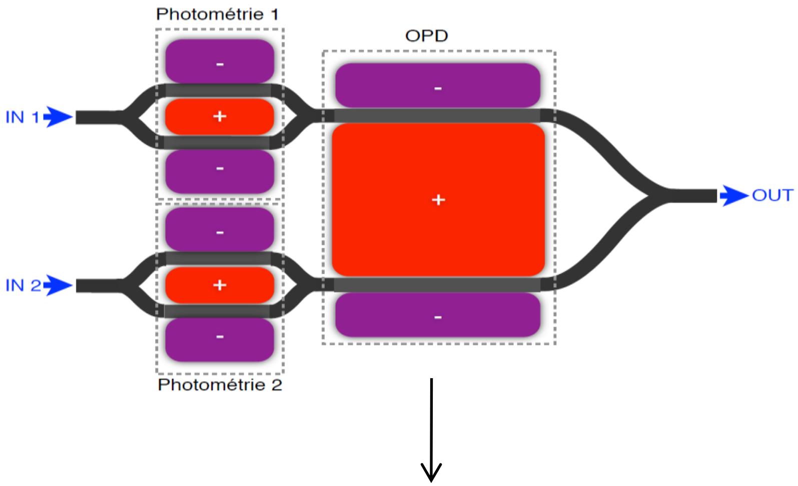


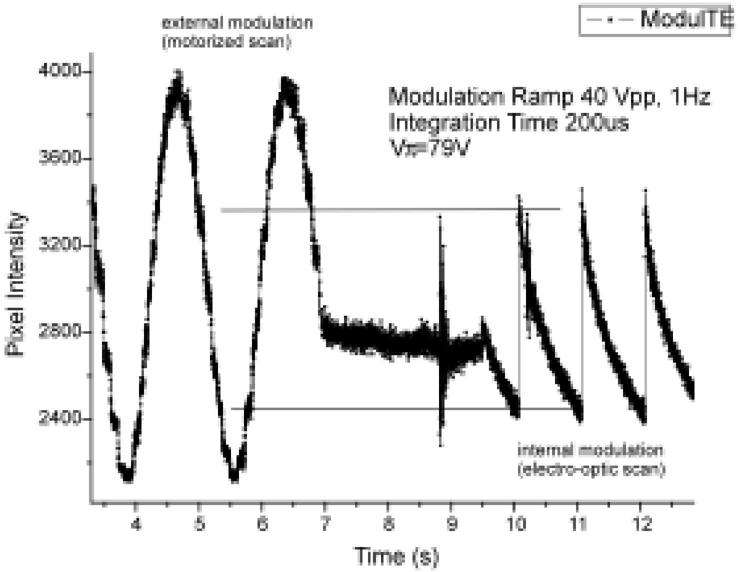
ASTROPHOTONICS (I): CONCEPTS

ELECTRO-OPTICS

Internal Modulation using LiNbO3

Guide Ti:Diff ; w = 14 µm ;
Aluminium sur Silice ; Laser 3.39 µm

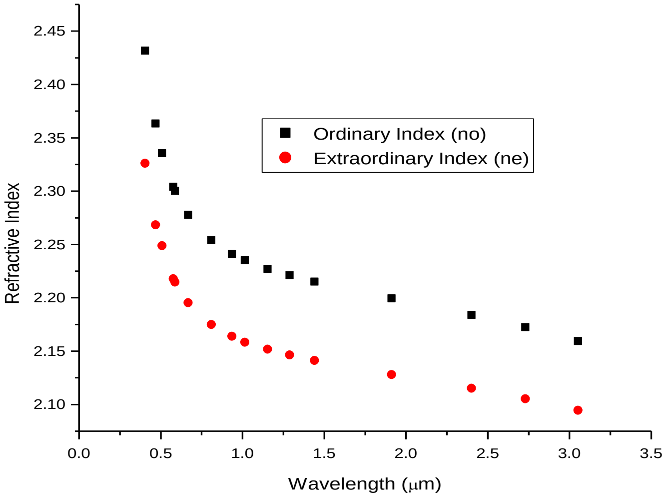




$$\varphi(V,\sigma) = \varphi_0 + 4\pi\sigma \left(\underbrace{-\frac{1}{2} r_{33}(\sigma) n_e^3(\sigma) \frac{V}{d}}_{\Delta n_{EO}(\sigma)} \right) L_{elec}$$

Difficulty: EO effect is chromatic,
Dependence in σ=1/λ

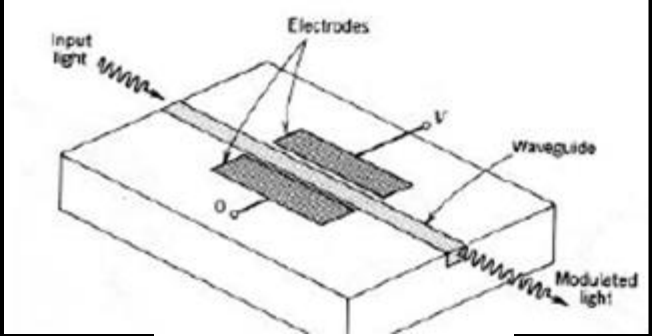
$$n_e(\lambda) = \sqrt{1 + \frac{2.9804 \cdot \lambda^2}{\lambda^2 - 0.02047} + \frac{0.5981 \cdot \lambda^2}{\lambda^2 - 0.0666} + \frac{8.9543 \cdot \lambda^2}{\lambda^2 - 416.08}}$$



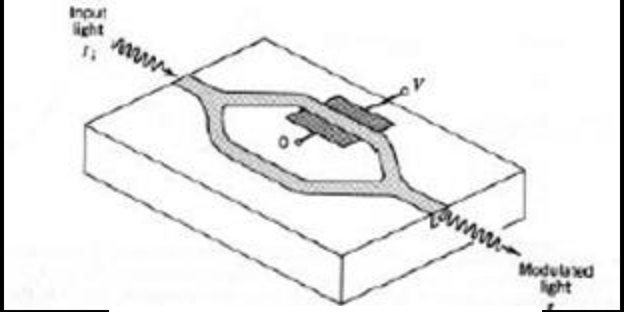
ELECTRO-OPTIC EFFECT

Orders of magnitude:

Internal modification of optical path delay -> phase modulation :

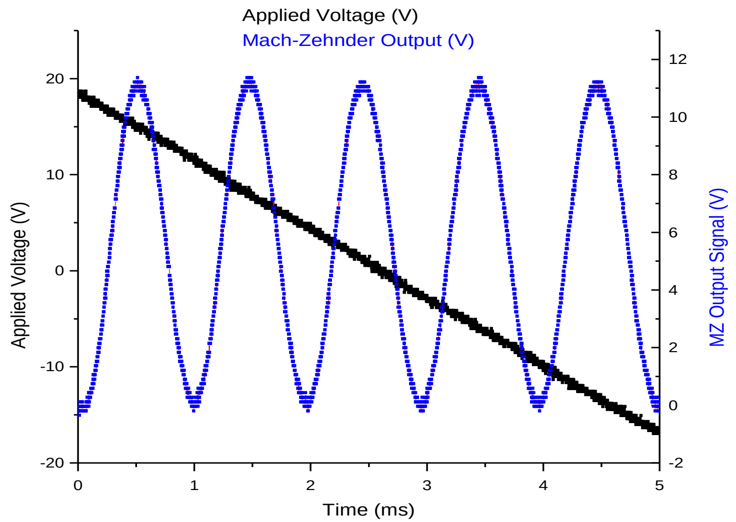


Phase Modulation



Amplitude Modulation

$$I_{out} = 2I_0(1+\cos\phi_k)$$



Modulation Freq 100Hz ; Voltage 34.32V ; Offset 0.44V ; Wavelength 2.2µm

Example: 35V for 5 fringes in a K-band modulator

-Chromatic effect
-Problematic for long OPD scans

ELECTRO-OPTIC WAVEGUIDES

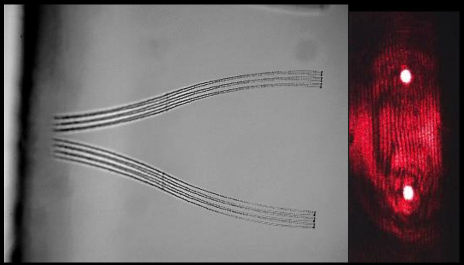
LiNbO3, BGO, SBN, YCOB…

-Classical waveguides (ion in-diffusion, proton exchange)

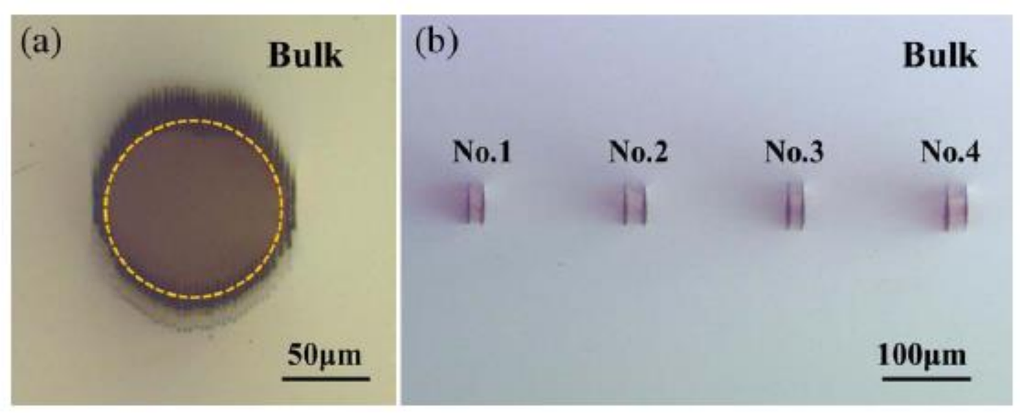
LiNbO3
-Well known
-r=30pm/V
-Anisotropic

BGO
-r= 3pm/V
-Isotropic

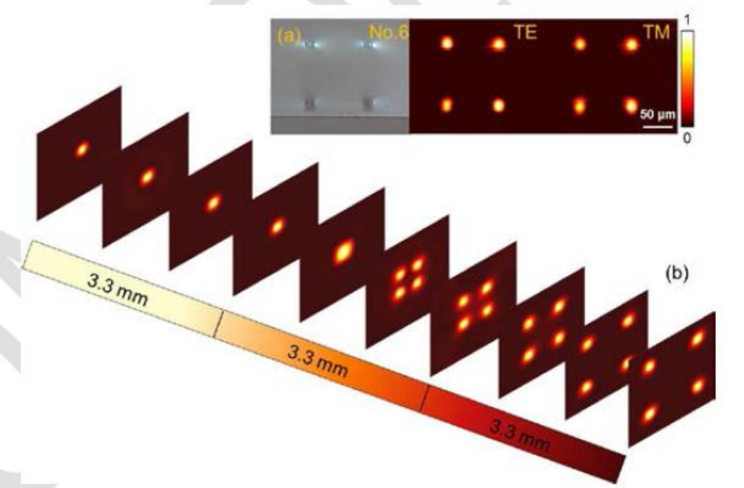
SBN
-r= 1300pm/V
-Anisotropic
-Low Curie T



-Laser-written waveguides: J.R.V. de Aldana, A. Rodenas



Cladding and dual line Type II BGO Waveguides



Multiscan Type I BGO Waveguides

INTEGRATED OPTIC CONCEPTS

Challenge:
-On-chip phase and intensity modulation
-Achieve achromatic phase modulation
-Combine 3 telescopes or more
-Both TE and TM polarizations (no birefringence)
-Low propagation losses
-Low driving voltages

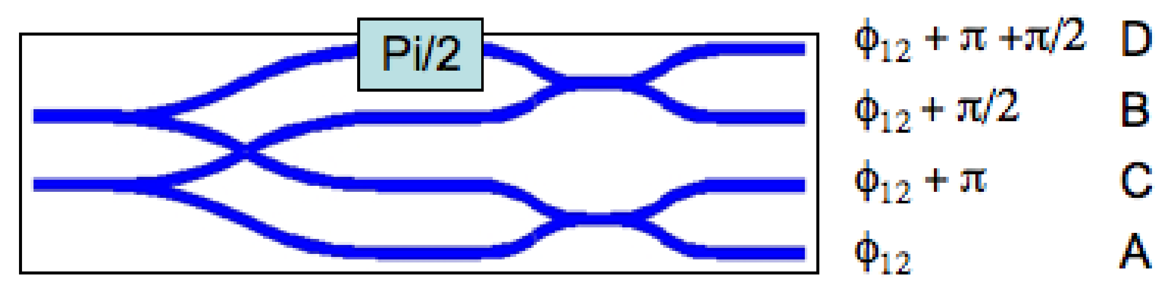
Astrophysical Needs:

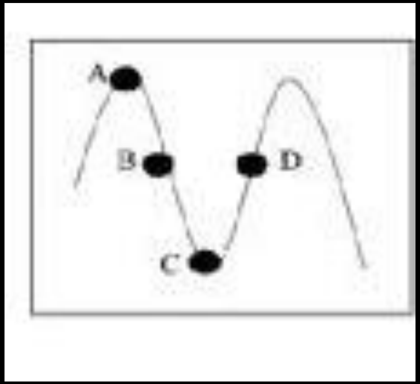
-Acheve high contrast fringes -> Nulling Interferometry
-Achieve High spectral resolution -> Integrated Spectrometers

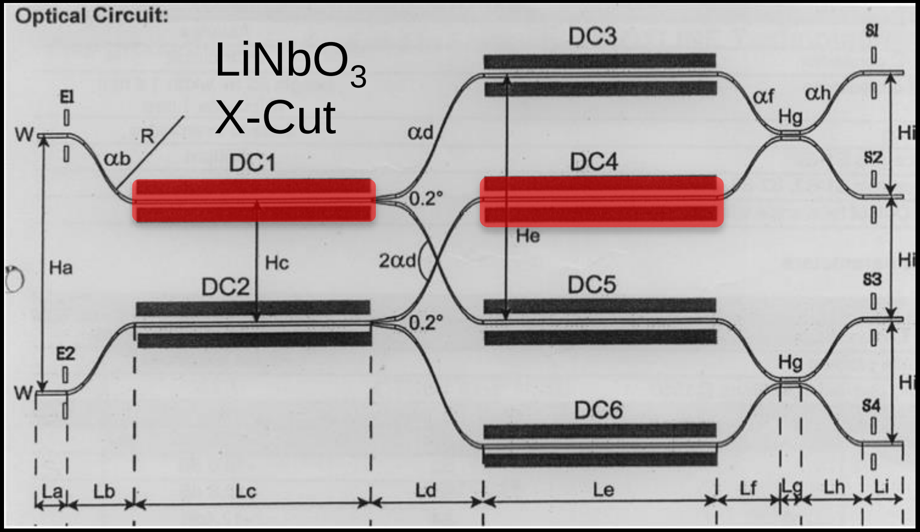
COMPLEX 2D BEAM COMBINERS

The 2T ABCD Concept: **DEMO!**

The interference fringes are sampled using 4 data, phase shifted:



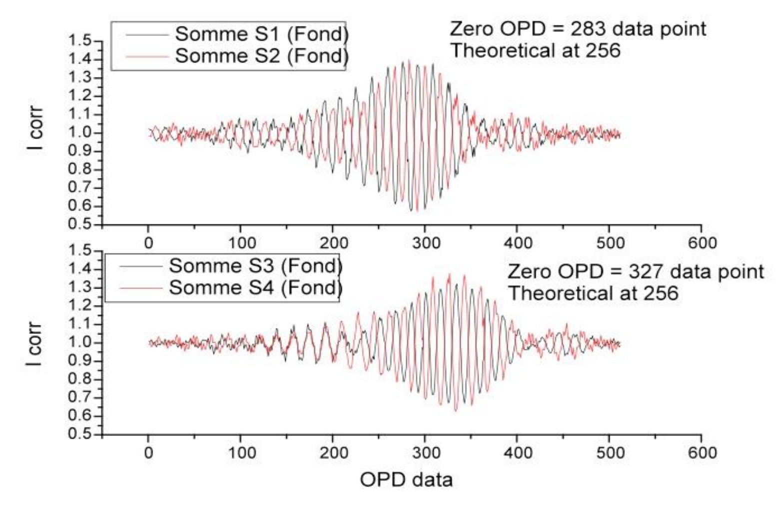




$LiNbO_3$

X-Cut

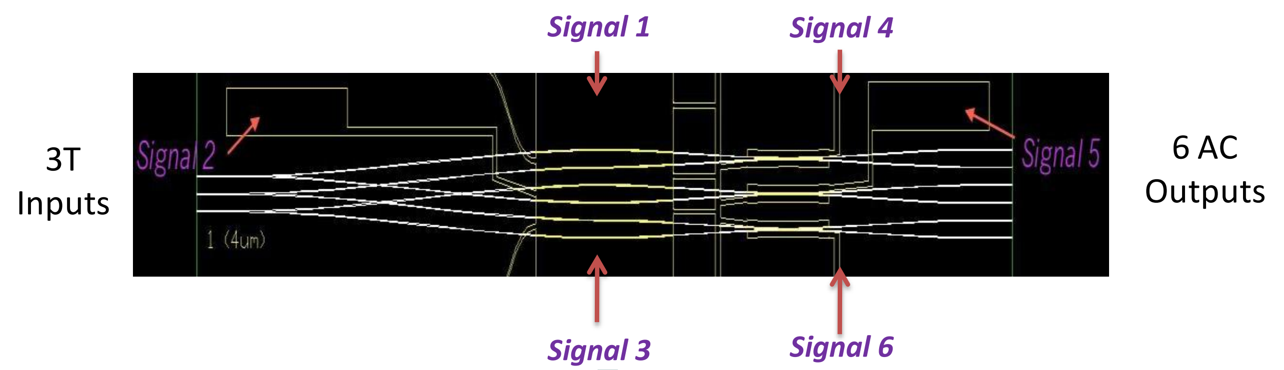
55mm



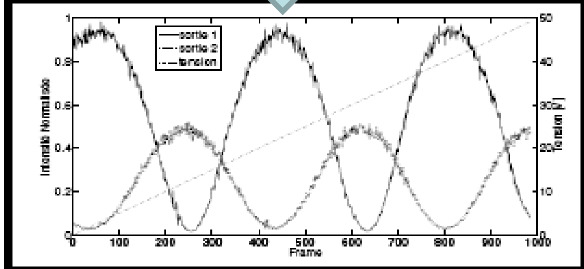
COMPLEX 2D BEAM COMBINERS

The 2T ABCD Concept:

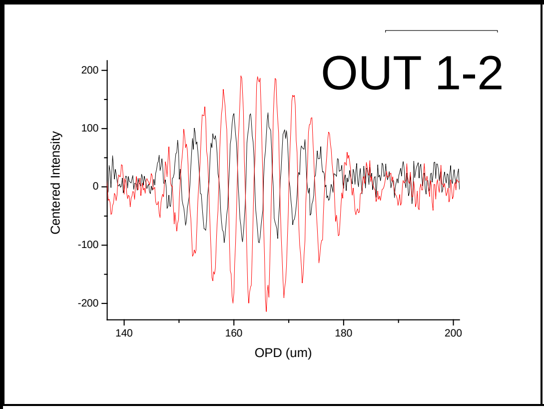
Signal 4-6 modifies the coupling ratio; Signal 1-2-3 shifts the relative phase (fringe scan)

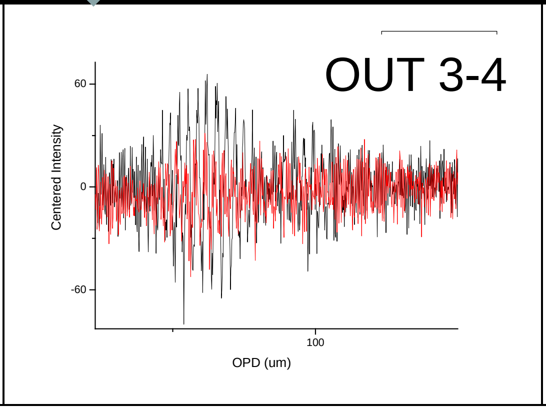


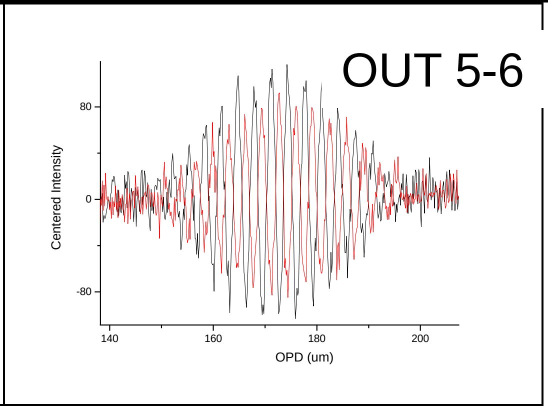
Coupling Ratio Modulation



Modulation de phase



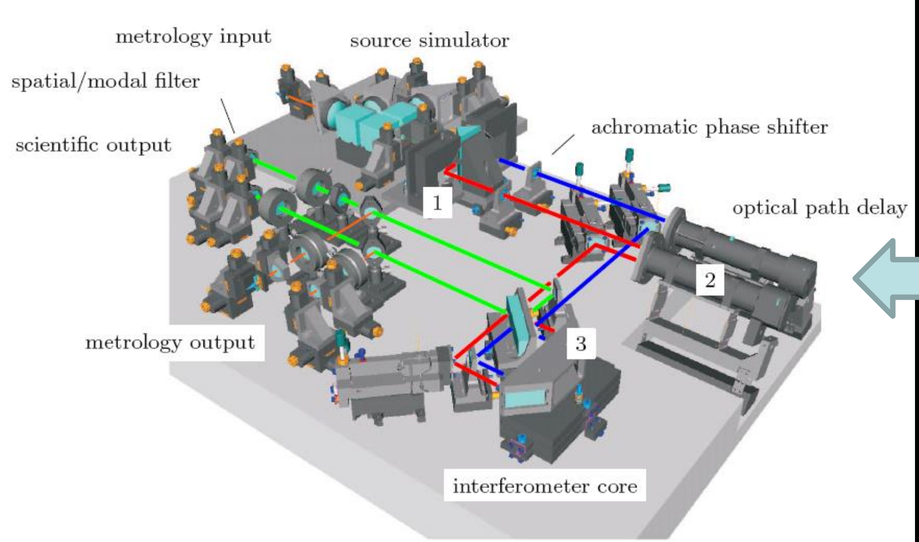


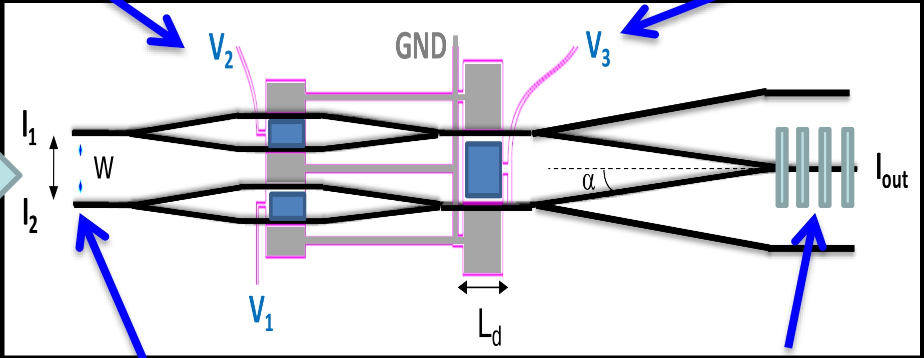


NULLING INTERFEROMETRY IN ASTROPHYSICS

NULLING INTERFEROMETRY: BULK vs INTEGRATED OPTICS

Nuller for DARWIN (Wallner 2003)





Photometry

Phase Modulation

Modal Filtering

Spectrum

Mid IR Waveguides

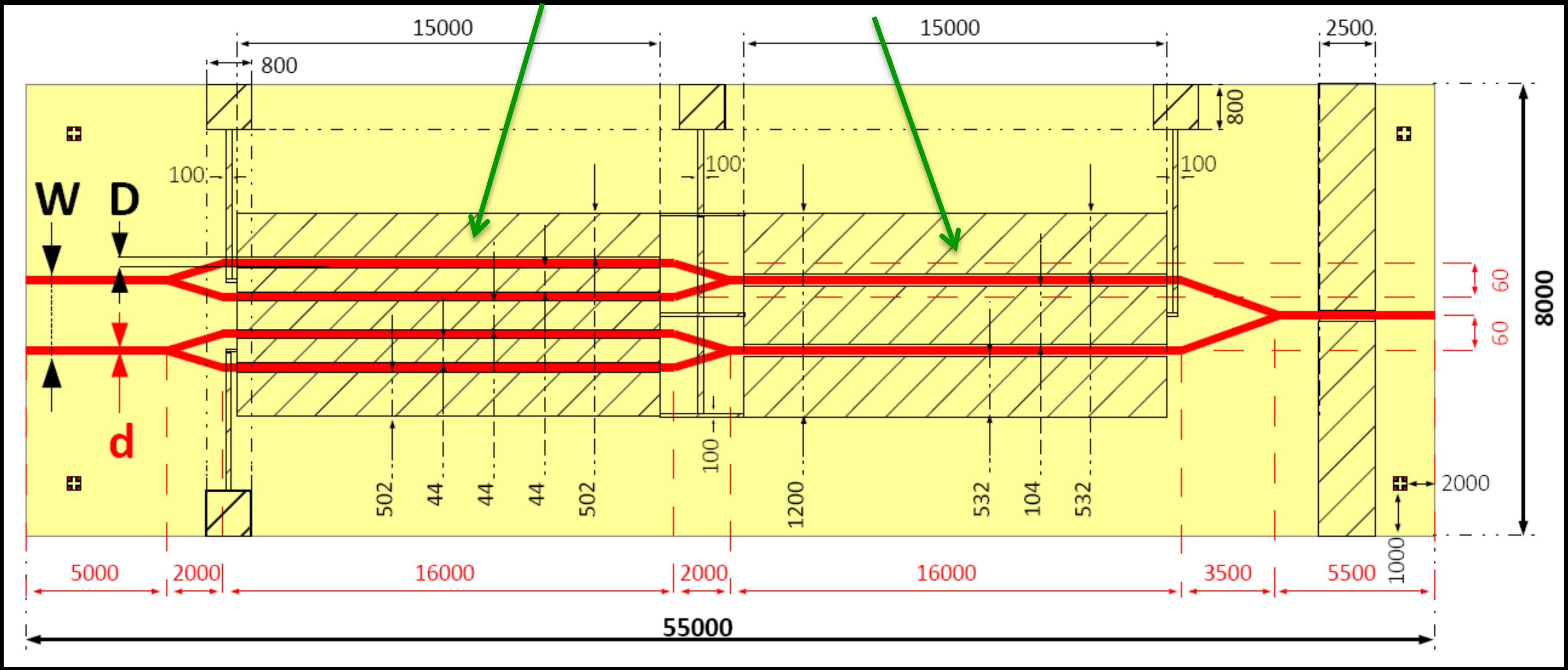
Optical Functions (Coupler, Y…)

High Contrast: 40dB (C>99.98%)

Multiple Beam Combining (2T, 3T…)

CONTROLLING PHASE AND INTENSITY

Active control of relative photometry and phase



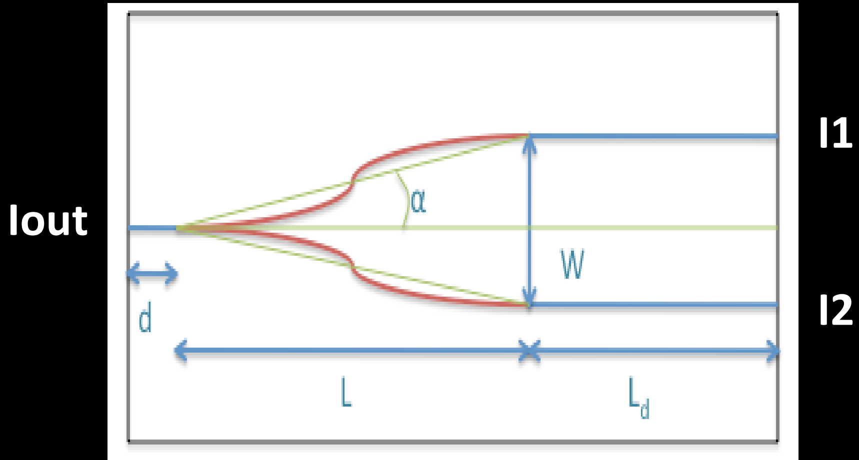
-Difficulty 1: Scan the fringe enveloppe: (typ. 10) -> High modulation V
-Difficulty 2: Achromatic behavior

Niobate de Lithium: Monochromatic MZ Modulation

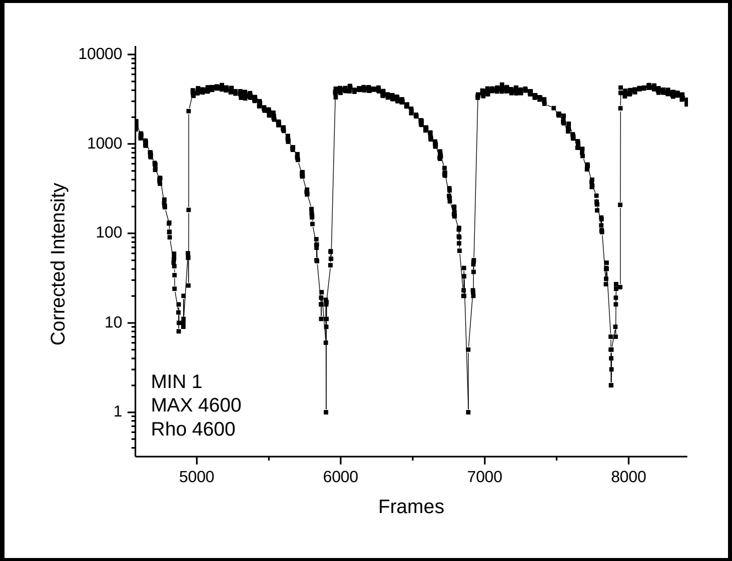
- Fringes modulation at 3.349µm (L Band)

Mach-Zehnder Modulators and Y-junctions: High rejection ratio and on-chip L band scan

20mm x 10mm $LiNbO_3$ sample

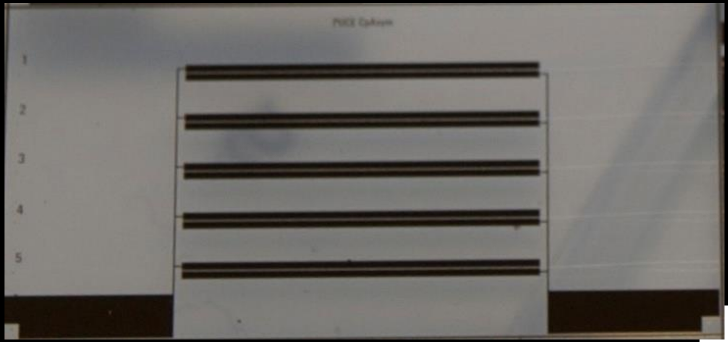


On-Chip mid-IR Nulling (36dB) @ 3.39um

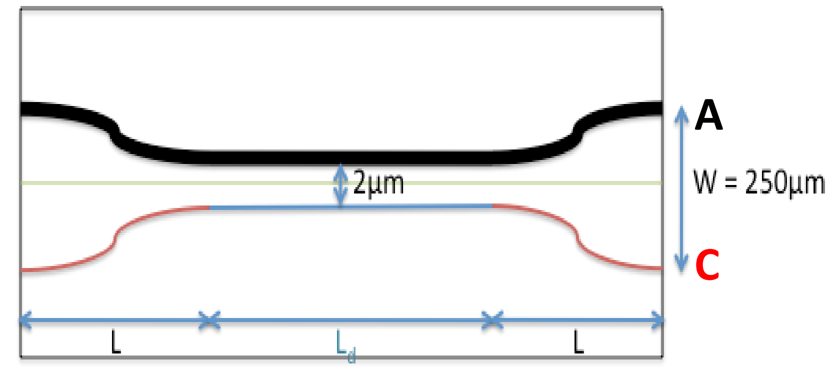


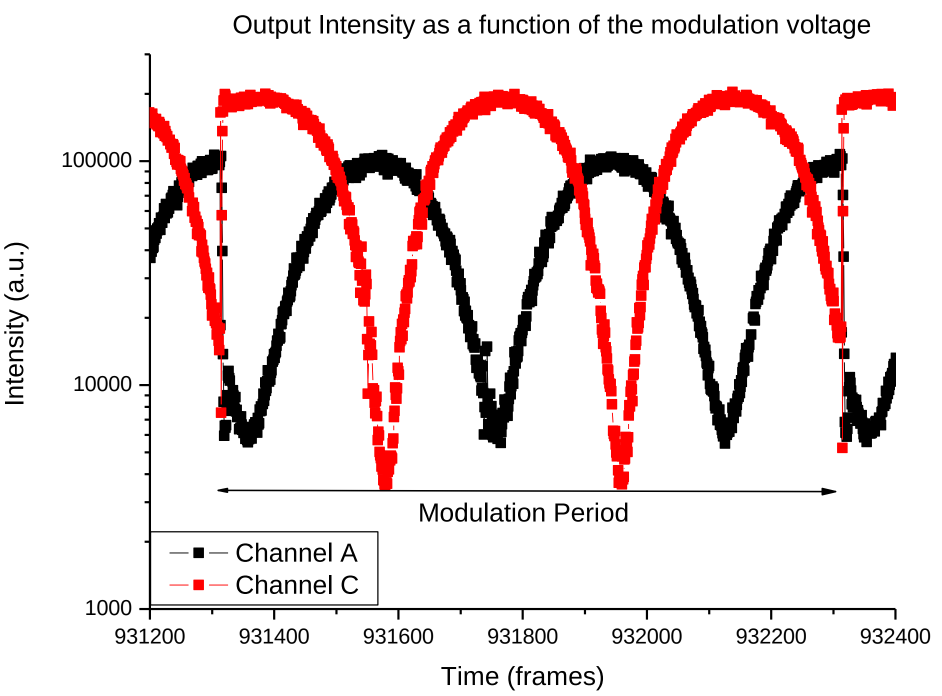
Niobate de Lithium → Directionnal Couplers

Active Directionnal Couplers: On-Chip Amplitude Tuning @ 3.39um



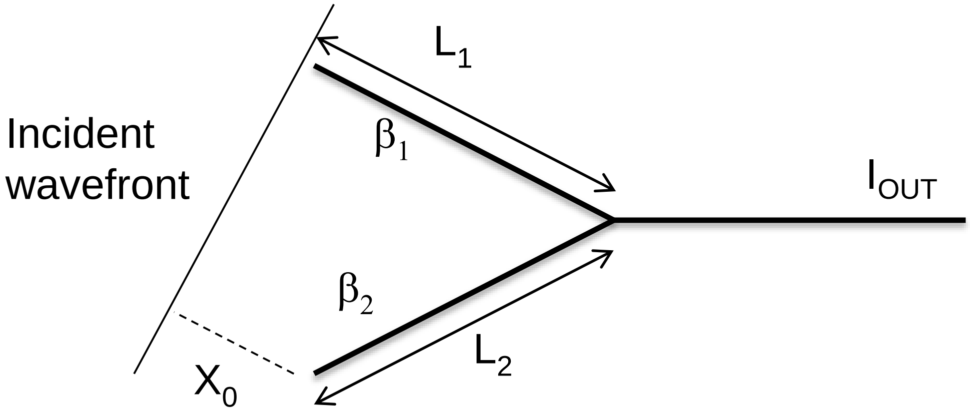
20mm x 10mm $LiNbO_3$ sample





Phase modulation: Differential dispersion

$$I_{OUT}(x)=I_1+I_2+2\sqrt{I_1 I_2}\cos\varphi(x)$$



Both arms are not strictly identical:

$L_1 \neq L_2$ et $\beta_1 \neq \beta_2$

$$\varphi(\sigma,x,E)=\varphi_0+2\pi\sigma\Big((x-x_0)+n_{eff}(\sigma)\Delta L+\Delta n_{eff}L+\Delta n_{EO}(\sigma,E)L_{elec}\Big)$$

- φ_0 ↓ Initial phase difference (pure phase)
- $(x-x_0)$ ↓ Path delay at the entrance of the telescopes
- ΔL ↓ $\Delta L=L_1-L_2$
- Δn_{eff} ↓ Relative effective index difference
- Δn_{EO} ↓ Electro-optic effect over the length of the electrodes

And refractive index also depends on the wavelength

Problem of differential dispersion

$$I_{OUT}(x) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi(x)$$

$$\varphi(\lambda) = A_0 + \frac{A_1}{\lambda} + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^3}$$

$$\Leftrightarrow$$

$$\varphi(\sigma) = A_0 + A_1\sigma + A_2\sigma^2 + A_3\sigma^3$$

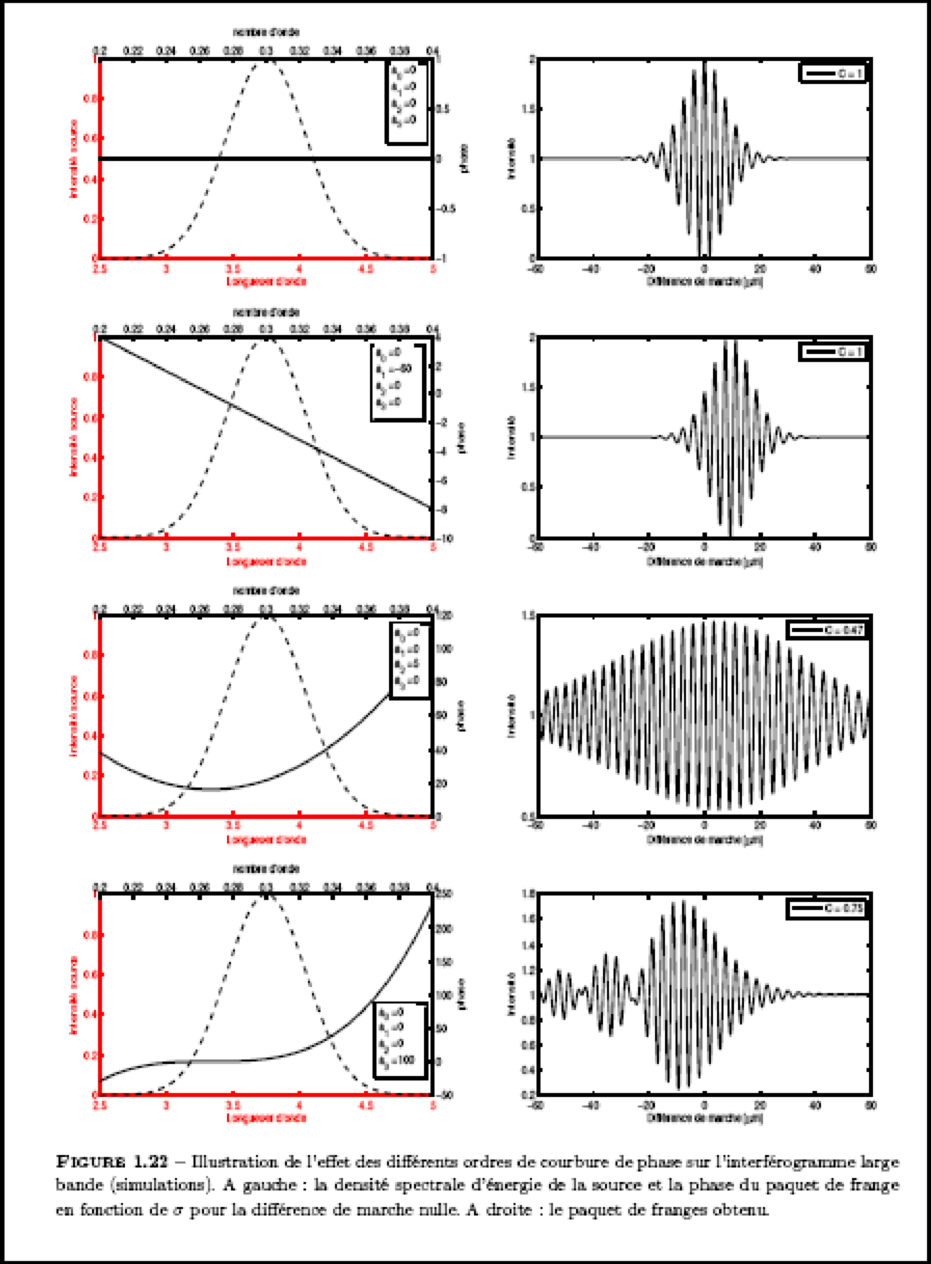
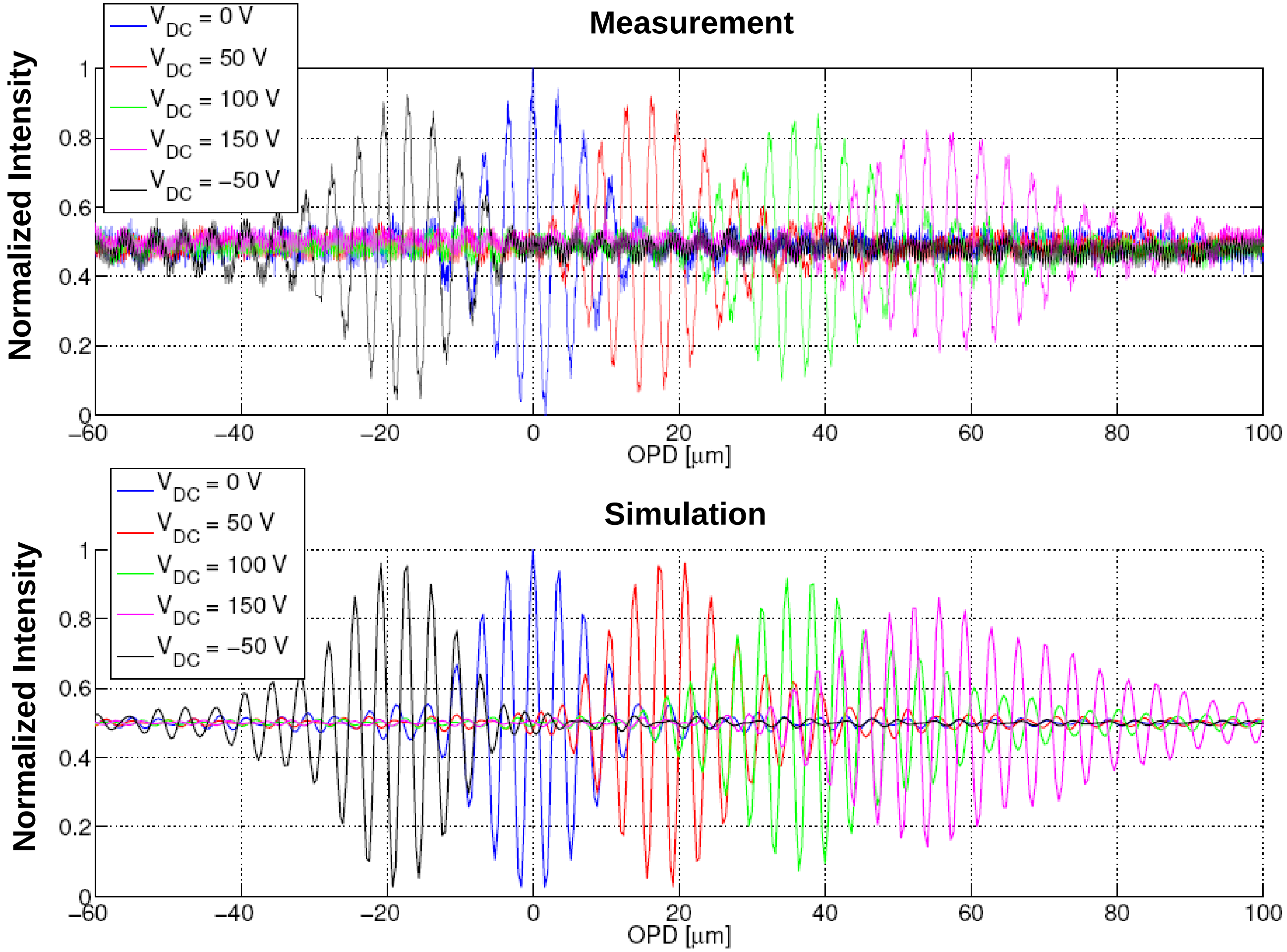


FIGURE 1.22 – Illustration de l'effet des différents ordres de courbure de phase sur l'interférogramme large bande (simulations). A gauche : la densité spectrale d'énergie de la source et la phase du paquet de frange en fonction de σ pour la différence de marche nulle. A droite : le paquet de franges obtenu.

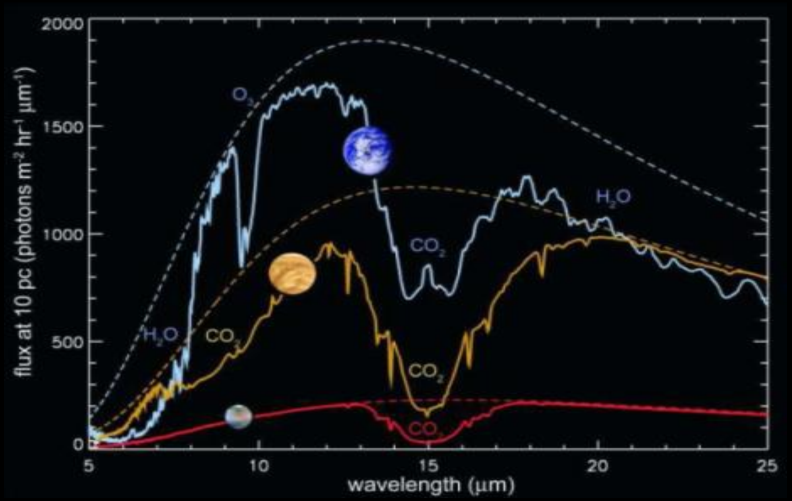
EO effect is chromatic: $r_{33}(\sigma)$ et $n(\sigma)$ -> Even in an ideal Y-junction the dispersion is visible, at high modulation voltages



This can be used to compensate an initial differential chromatic effect

INTEGRATED SPECTROMETERS

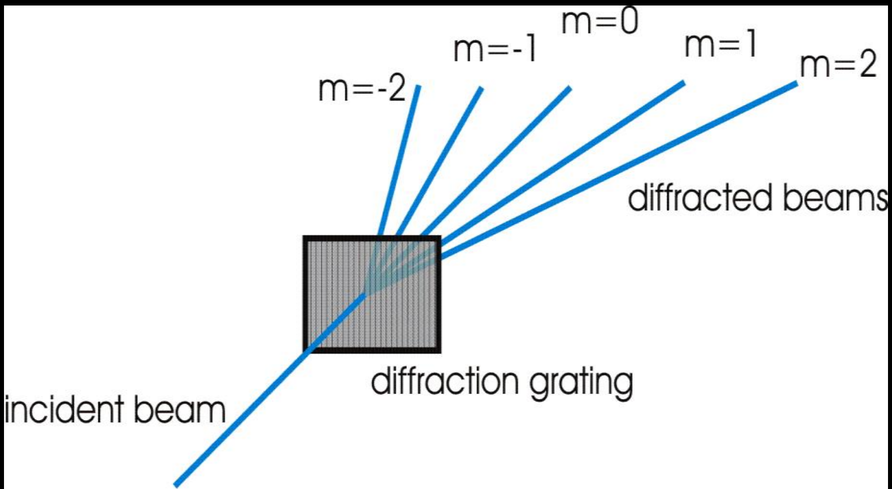
Caractérisation



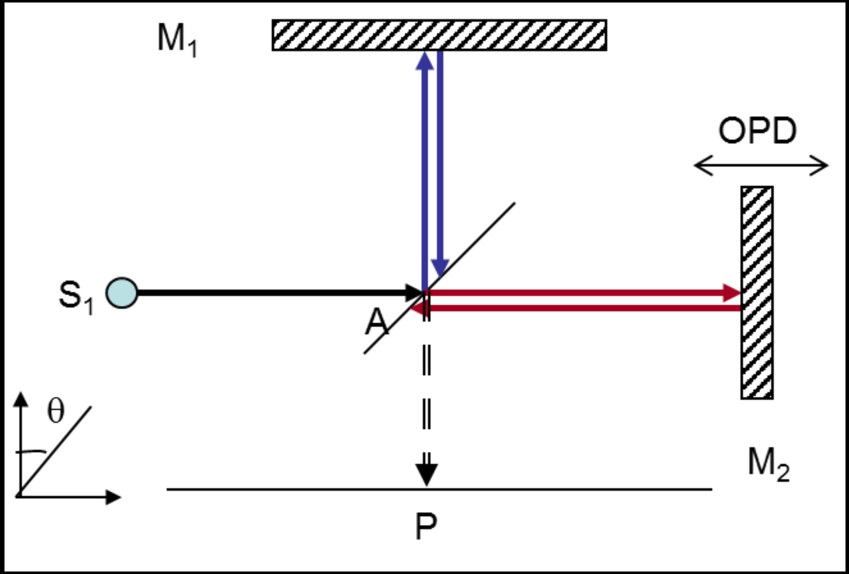
Spectrométrie

Spectrometry Basics

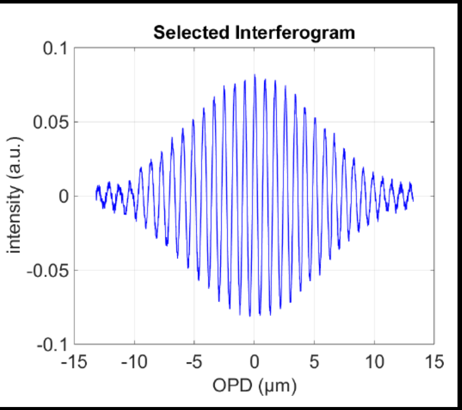
Diffraction Gratings



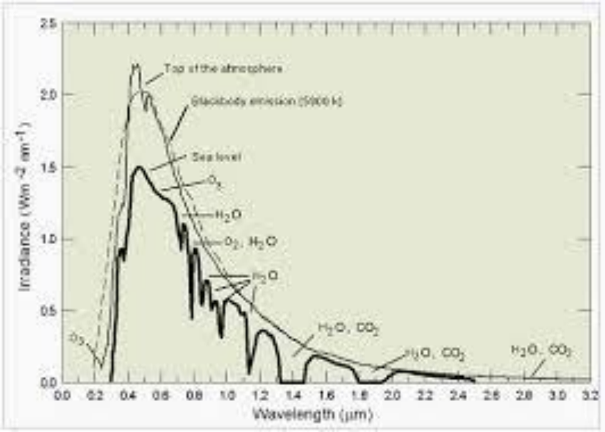
The Michelson approach



Fourier Transform Spectrometers



TF



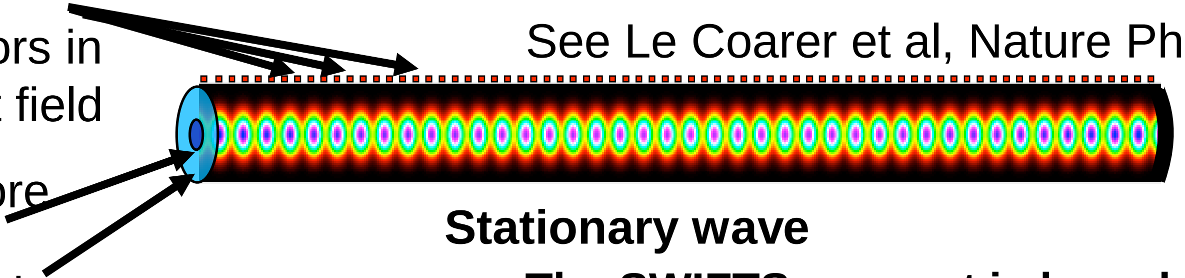
-Résolution Spectrale:

$R \approx L/\lambda = 10000$ for $L=1$cm @ $\lambda=1\mu m$

-Etendue Spectrale:

$\delta\sigma \approx 1/\delta L \Rightarrow \delta\lambda=10nm$ for $\delta L=10\mu m$

Swifts
Stationary-Wave Integrated Fourier Transform Spectrometer



Nano-detectors in evanescent field

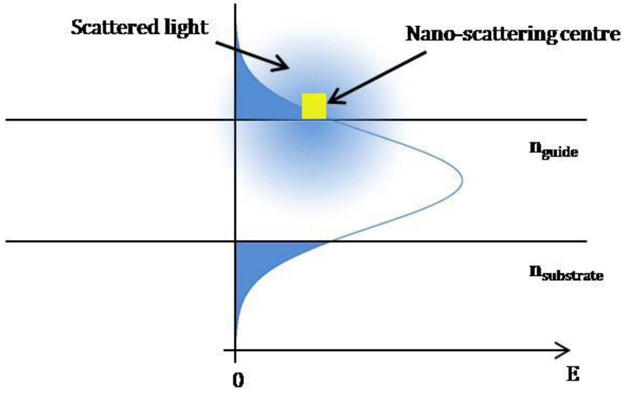
See Le Coarer et al, Nature Photonics 2007

Wave-guide core

Wave-guide Substrate

Stationary wave

- **The SWIFTS concept is based on a weak non-perturbing measurement along a standing interference within a wave guide**
- **where sub-wavelength scale detectors pick up the evanescent field**
- **The overall sensitivity results from a collective effect of the set of nano-detectors, each one detecting a slight amount of the light propagating in the waveguide.**

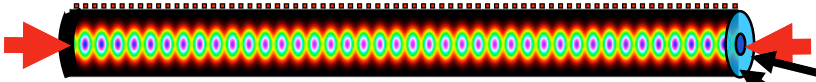


SWIFTS-Principle

SWIFTS-Gabor

SWIFTS-Lippmann

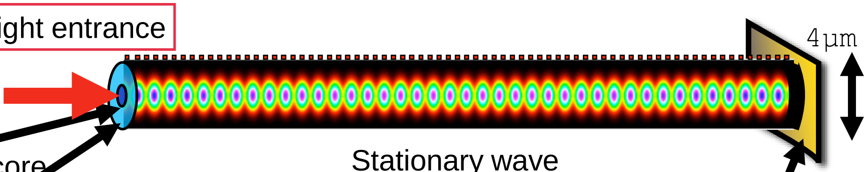
Monochromatic light case



Split Light entrance

Split Light entrance

Stationary wave

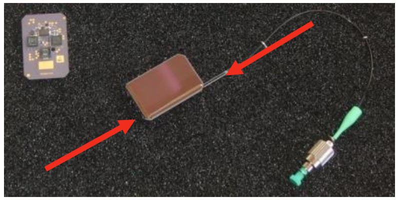


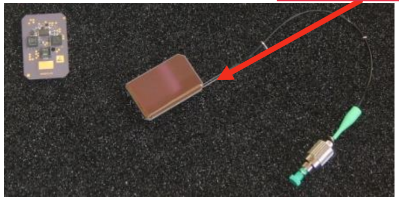
Light entrance

Stationary wave

Wave-guide core

Wave-guide Substrate



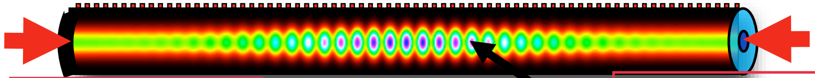


Light entrance

Mirror

White light case

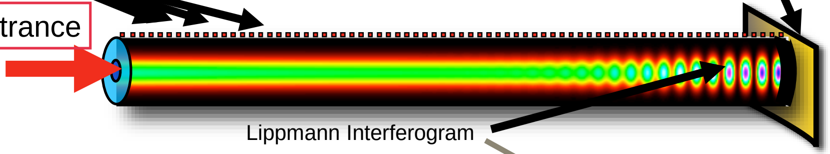
Nano-detectors in evanescent field



Split Light entrance

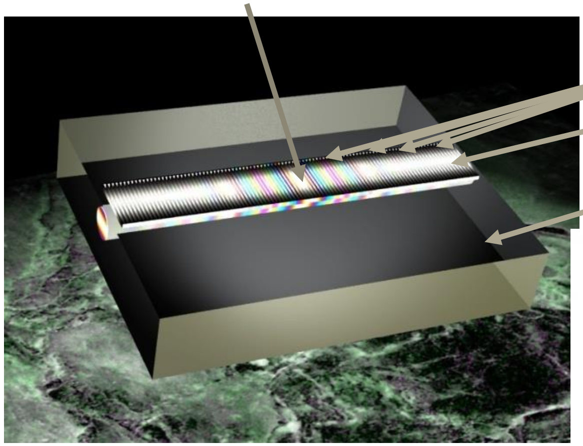
Fourier Interferogram

Split Light entrance



Light entrance

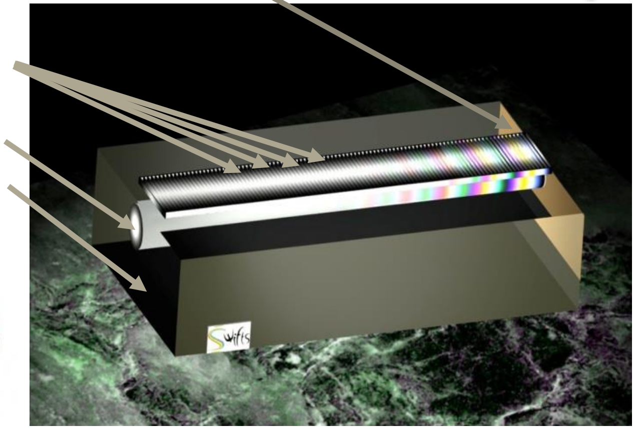
Lippmann Interferogram



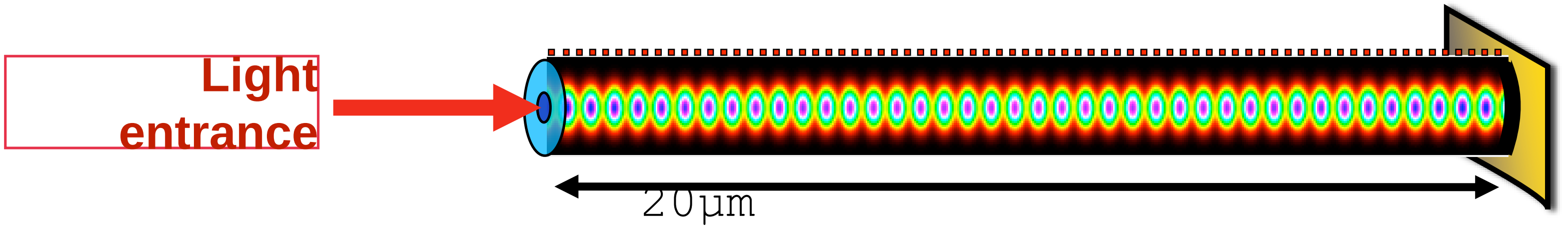
Nano-detectors in evanescent field

Wave-guide core

Wave-guide Substrate



SWIFTS resolution



R: number of fringes between first and last detectors

$\delta\sigma \approx 1/2nL$ $R \approx 2n\,L/\lambda$

L : Length between first and last detector (20 µm)

n : effective index (1.5)

λ : Wavelength (1.5µm)

R= 40 in this example ($\delta\lambda \approx 37.5$nm)

10cm long instrument provide: **R= 200 000 or 0.033 cm^{-1}** ($\delta\lambda \approx 7.5$pm)

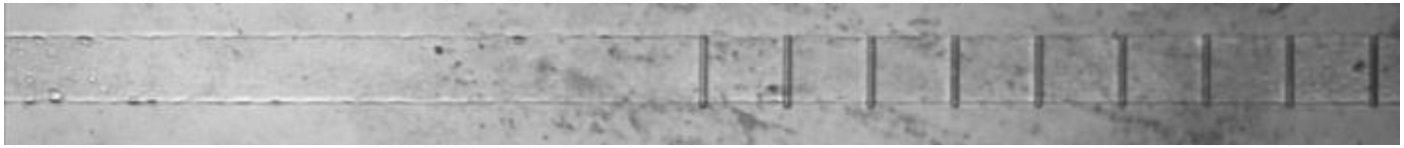
Note: an under-sampling of the fringes results in a reduced operation bandwidth limited by the detector pitch p :

$\Delta\sigma = 1/4n.\Delta z$ or $\Delta\lambda = \lambda^2/4n.\Delta z$

a 18 µm pixel in this case induces **$\Delta\lambda \approx 20$ nm**

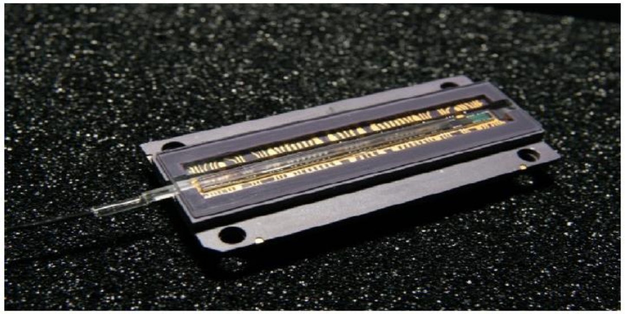
In order to recover the fringes, use of nanodots or nanogrooves

Guide avec centres de diffusion (sans injection): -> **FEMTO-ST**

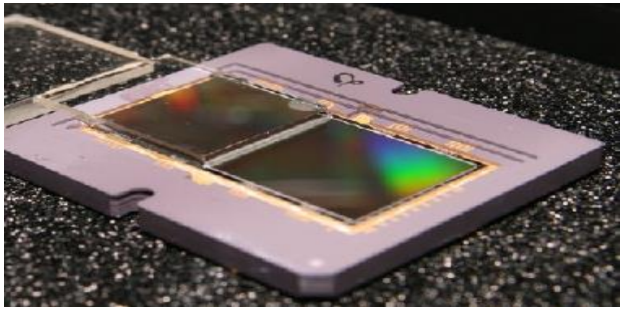


Guide avec centres de diffusion (avec injection):

Le signal échantillonné est alors récupéré par un détecteur collé au dessus du guide:



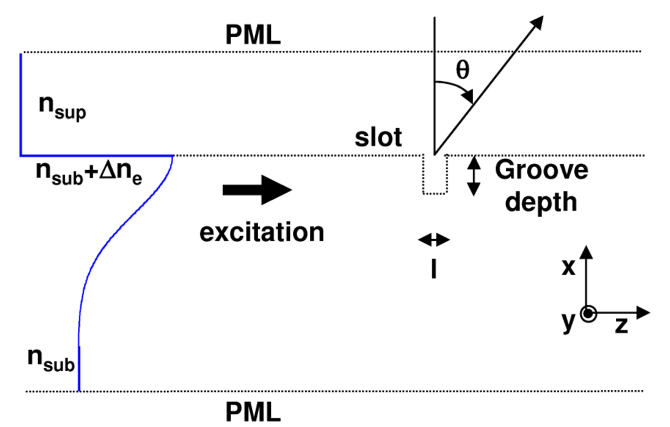
Barrette SWIFTS

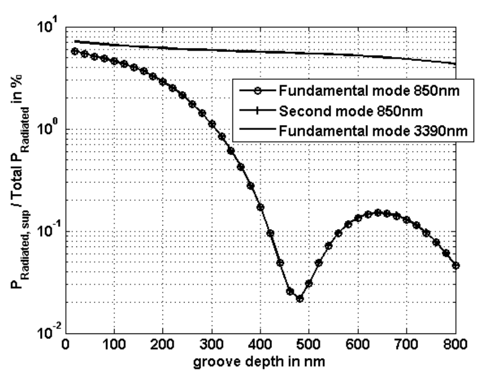


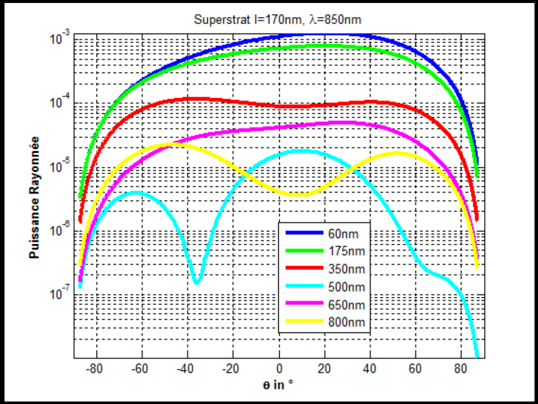
Détecteur sur SWIFTS Matriciel

DIRECTIVITY

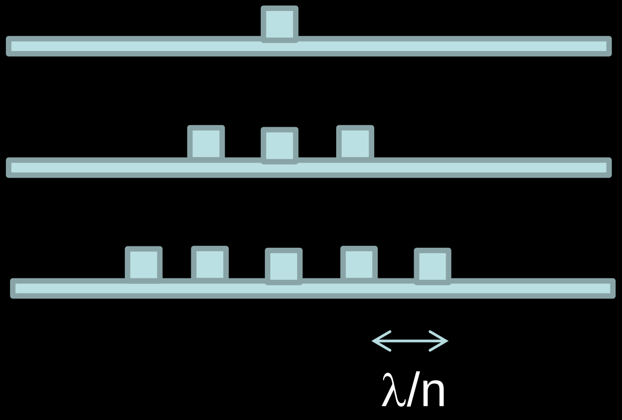
Simulations on the effect of Groove geometry on the diffraction efficiency

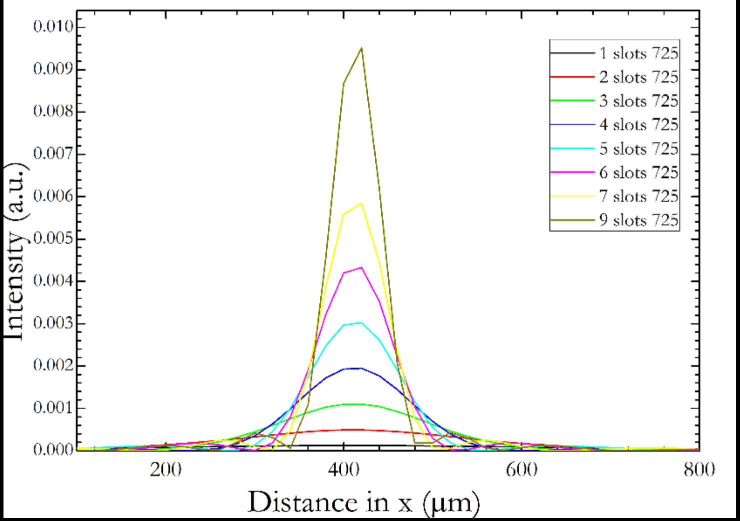






Simulations on the effect of Groove assembling: Antenna Effect





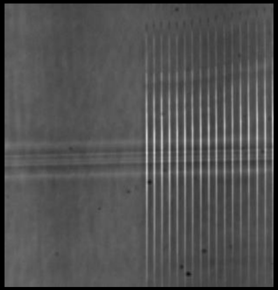
Collaboration with A.Morand (IMEP-LAHC)

LASER WRITTEN SWIFTS: FOR MID-IR

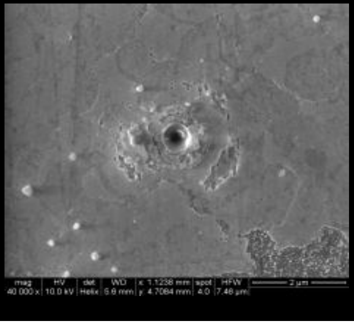
Use fs laser to write the sampling centers

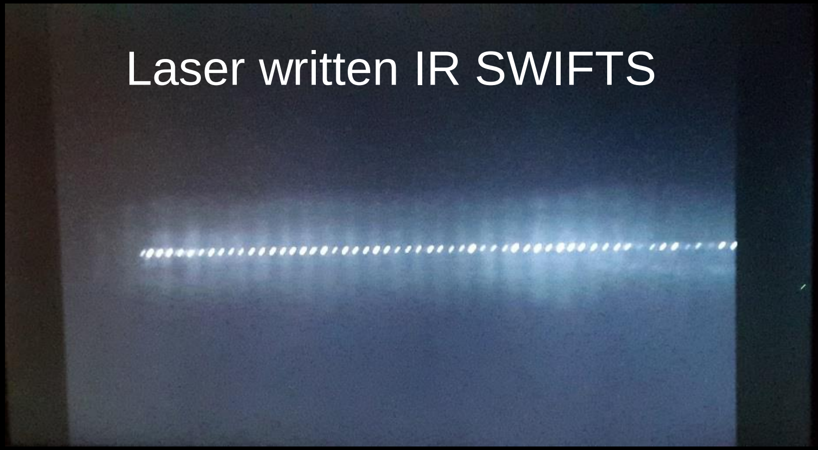
-possibility to obtain large areas

View from top

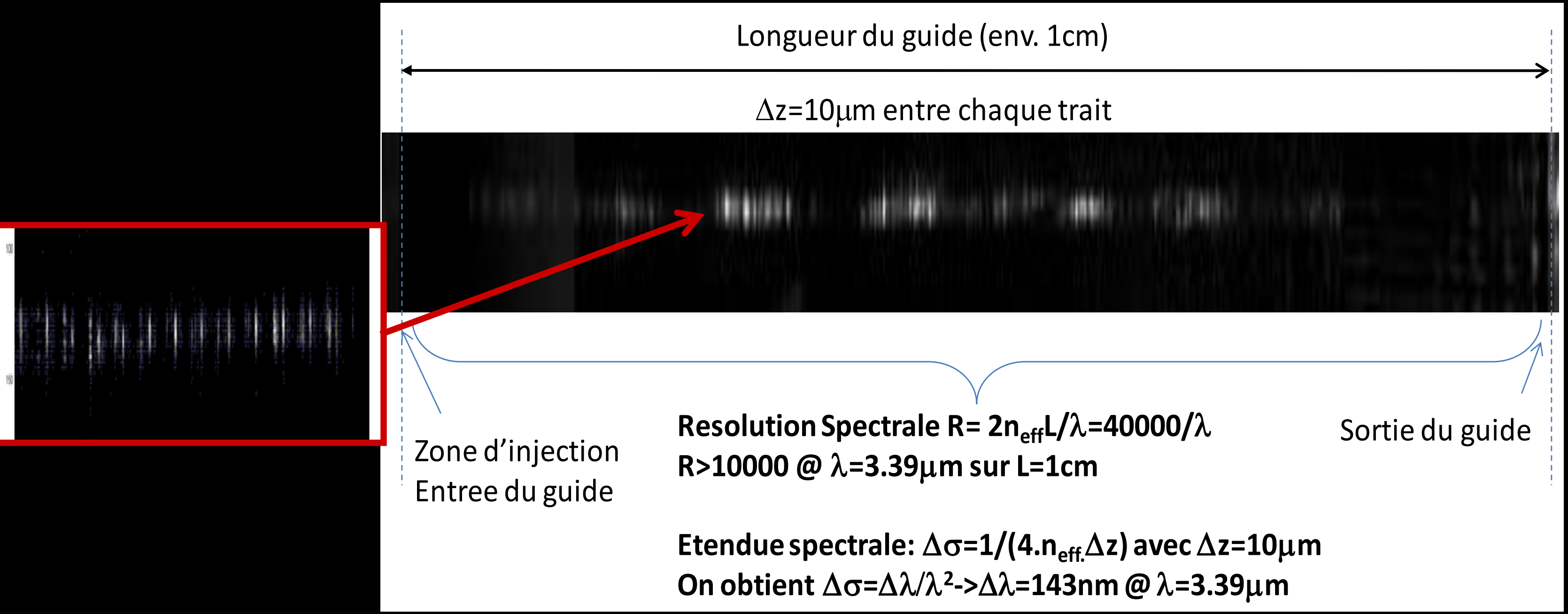


Side view





Laser written IR SWIFTS



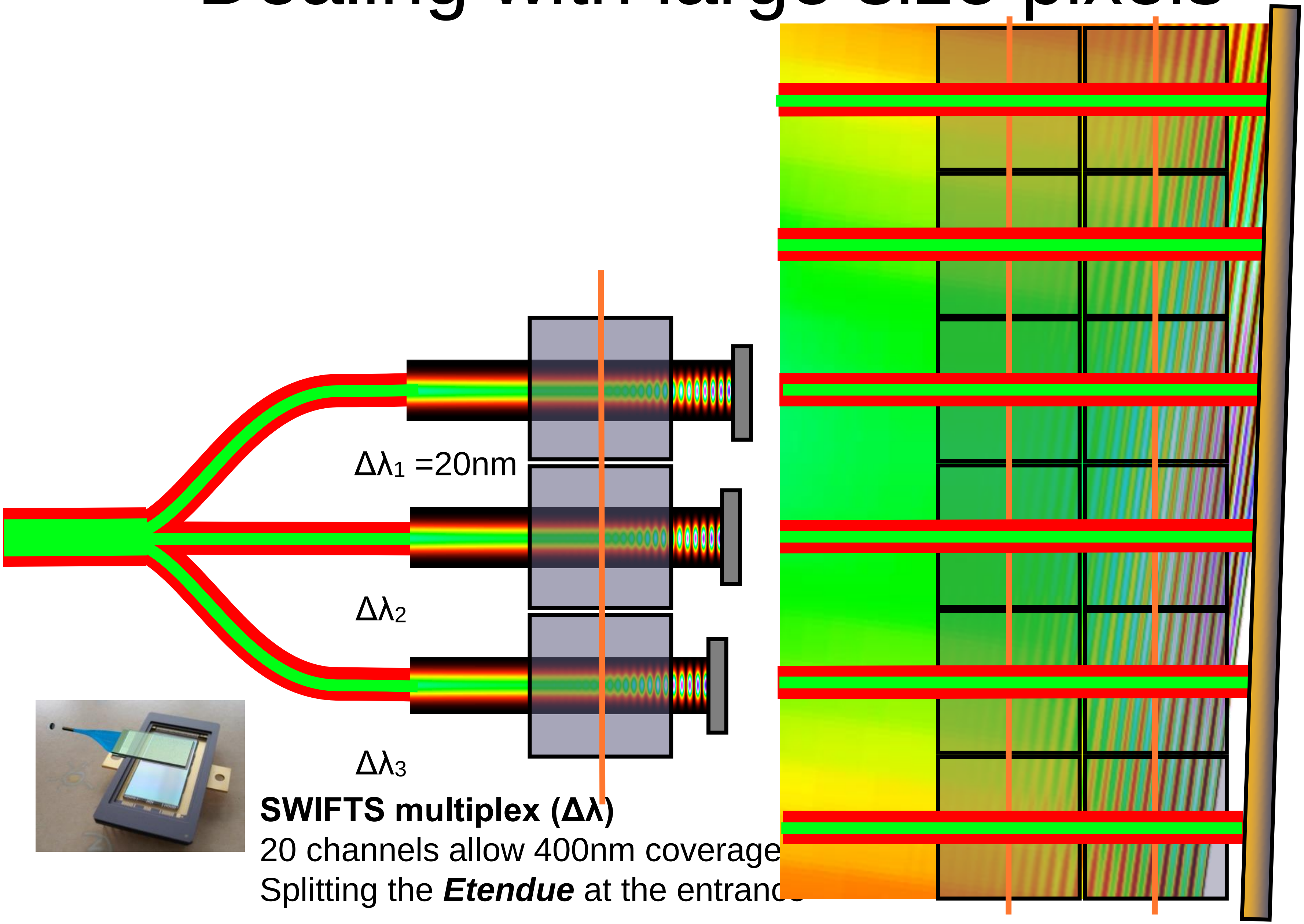
Resolution Spectrale $R= 2n_{eff}L/\lambda=40000/\lambda$

$R>10000$ @ $\lambda=3.39\mu m$ sur $L=1cm$

Etendue spectrale: $\Delta\sigma=1/(4.n_{eff.}\Delta z)$ avec $\Delta z=10\mu m$

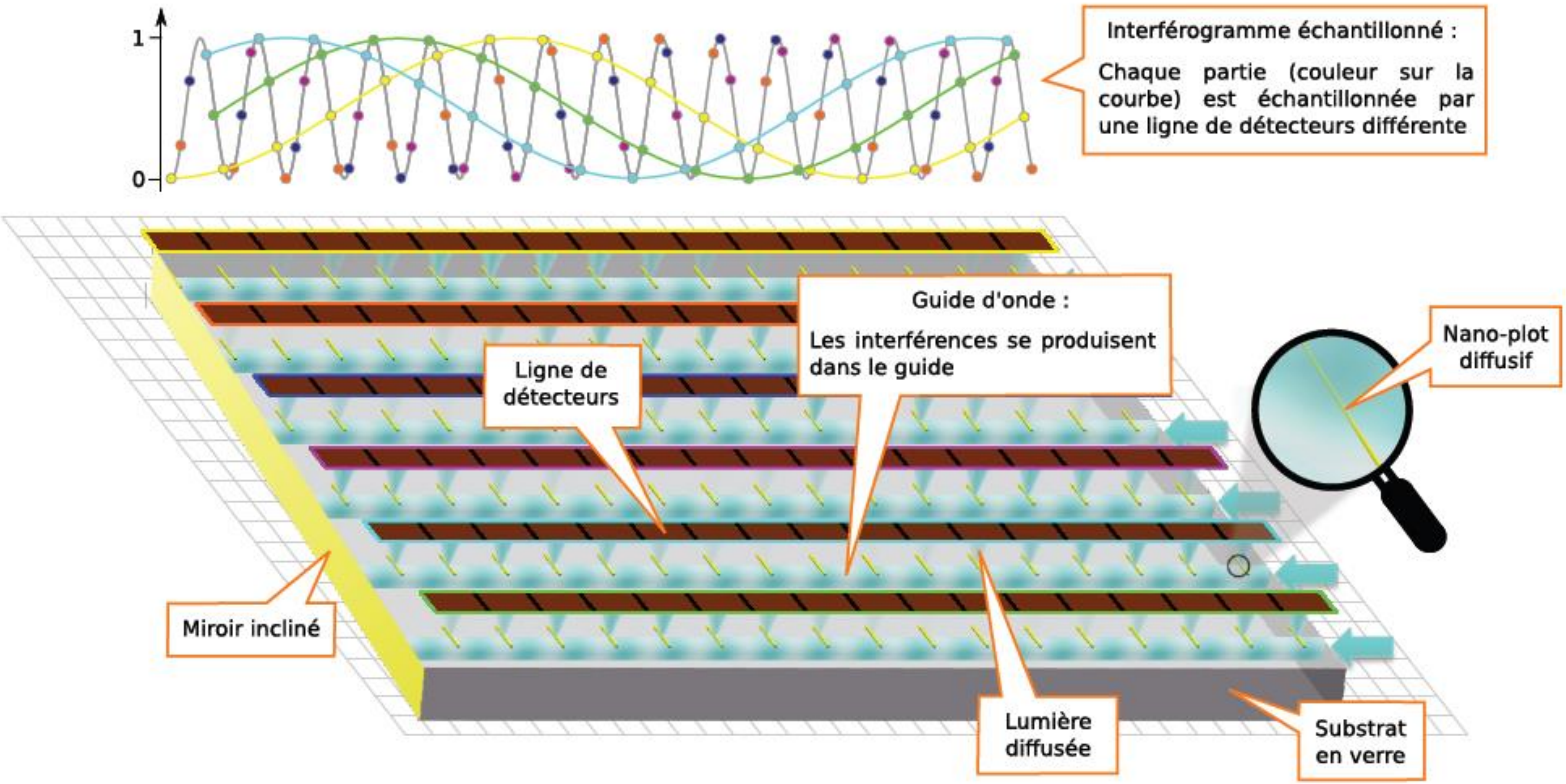
On obtient $\Delta\sigma=\Delta\lambda/\lambda^2 \text{->} \Delta\lambda=143nm$ @ $\lambda=3.39\mu m$

Dealing with large size pixels



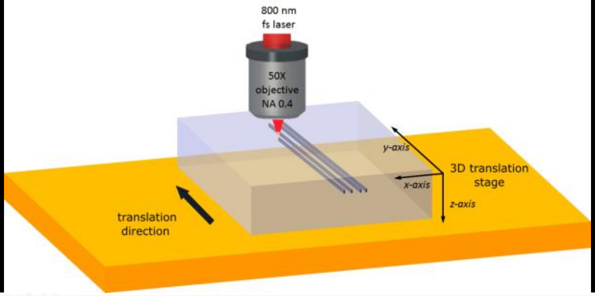
SWIFTS multiplex (Δλ)
20 channels allow 400nm coverage
Splitting the ***Etendue*** at the entranc

Multiplexage: Swifts WIDE



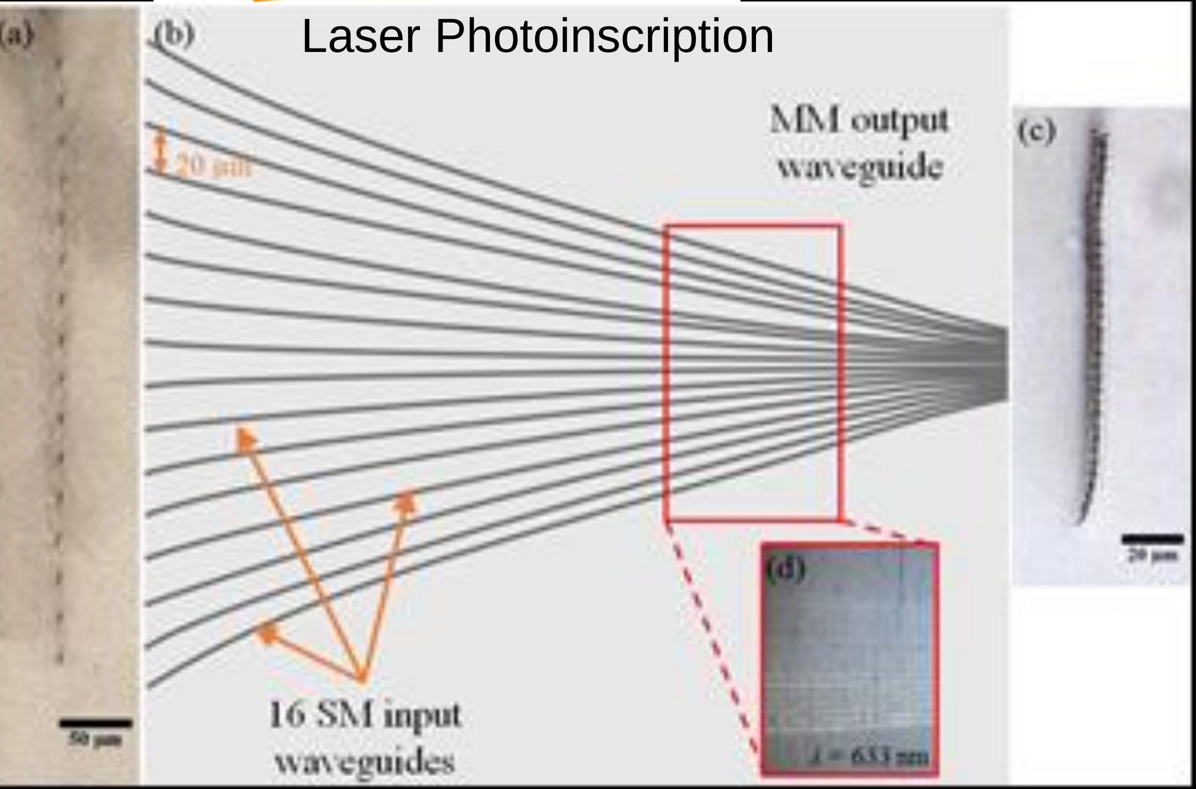
La superposition des interferogrammes sous-echantillones, permet de reconstruire un interferogramme sur-echantillonne

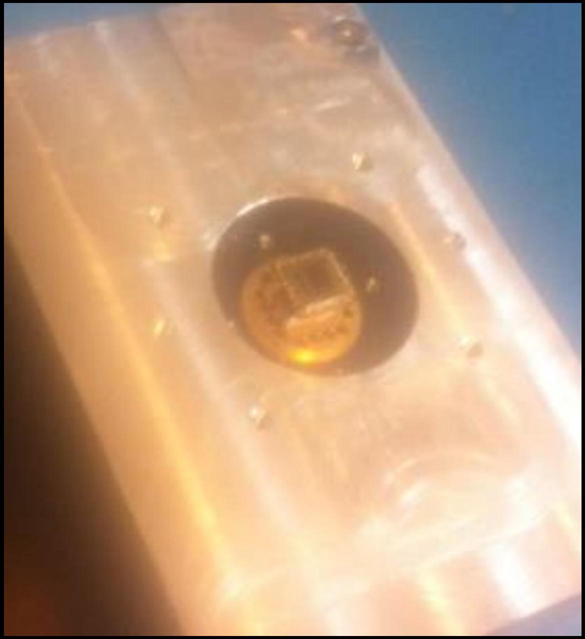
Multiplexage: Swifts WIDE
Collaboration avec IMEP-LAHC (A. Morand)



Couplage avec Détecteur Hamamatsu
128 x 128 (20um pixel pitch)

Laser Photoinscription

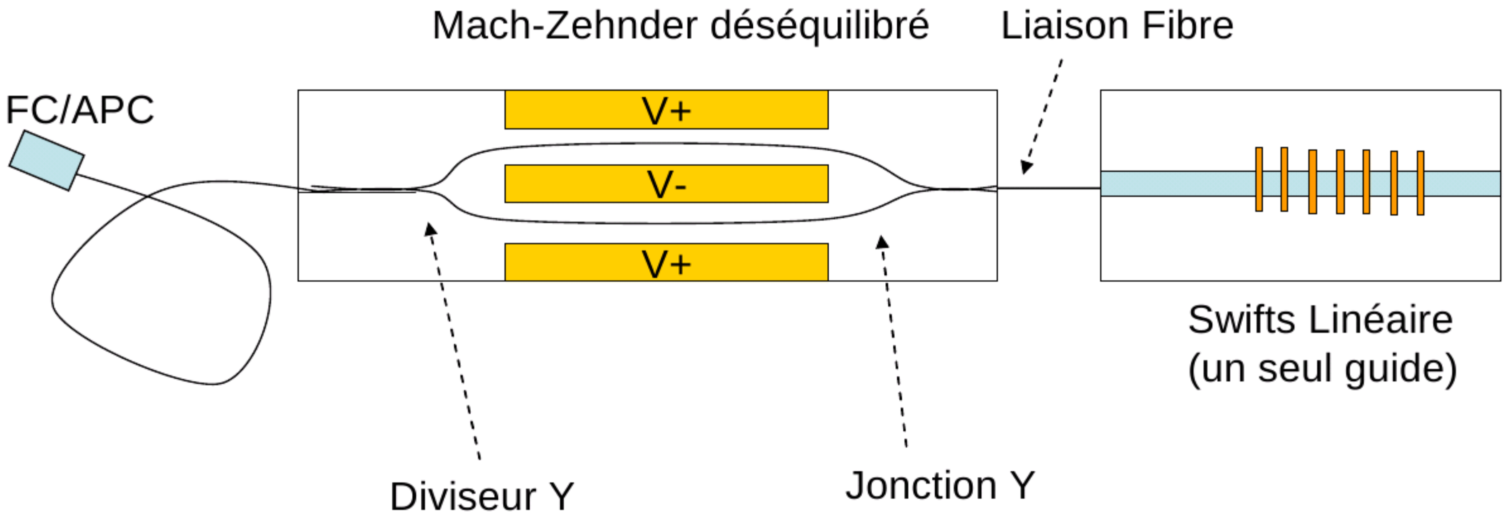




Premiers tests d’une lanterne de 16 guides

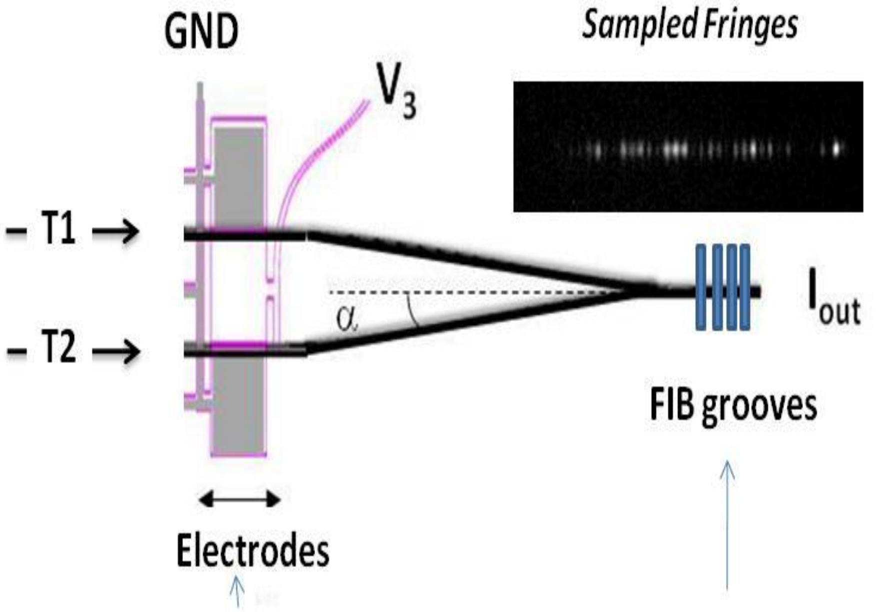
Interest of an internal modulation (electro-optic) to improve sampling efficiency

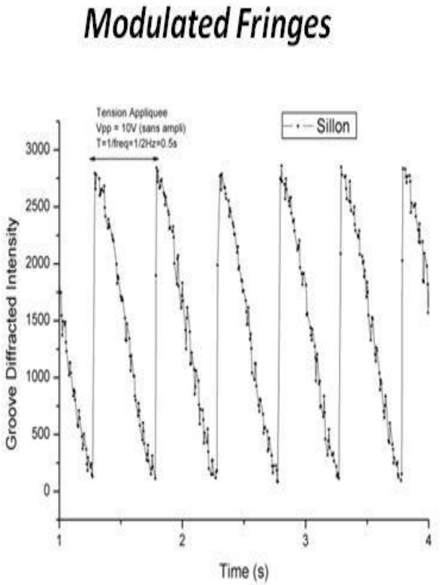
« Static » SWIFTS is limited to $\Delta\sigma$=10nm since distance between sampling centers is too high.



Using an unbalanced MZ allows to set a second « dynamic » fringe pattern over the sampling centers, and scan it actively

Fringe Modulation **in a single chip** using the Electro-optic effect

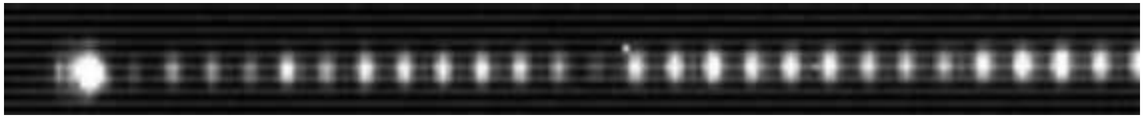




Phase Modulation

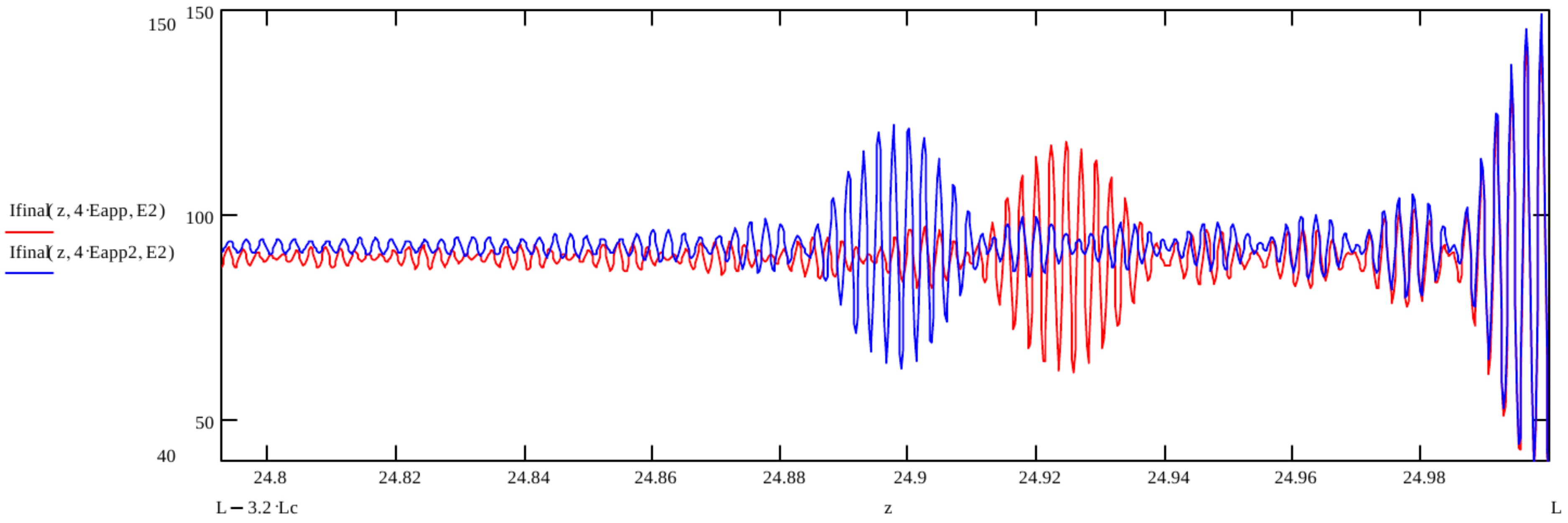
Standing Wave Sampling

$$I(\lambda, z, V_3) = \left[I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi}{\lambda} \Delta n(V_3) L_{elec} \right) \right] \left[1 + R - 2\sqrt{R} \cos\left[\frac{2\pi}{\lambda} n(\lambda, E) 2(z - L) \right] \right]$$



L'interférogramme OCT

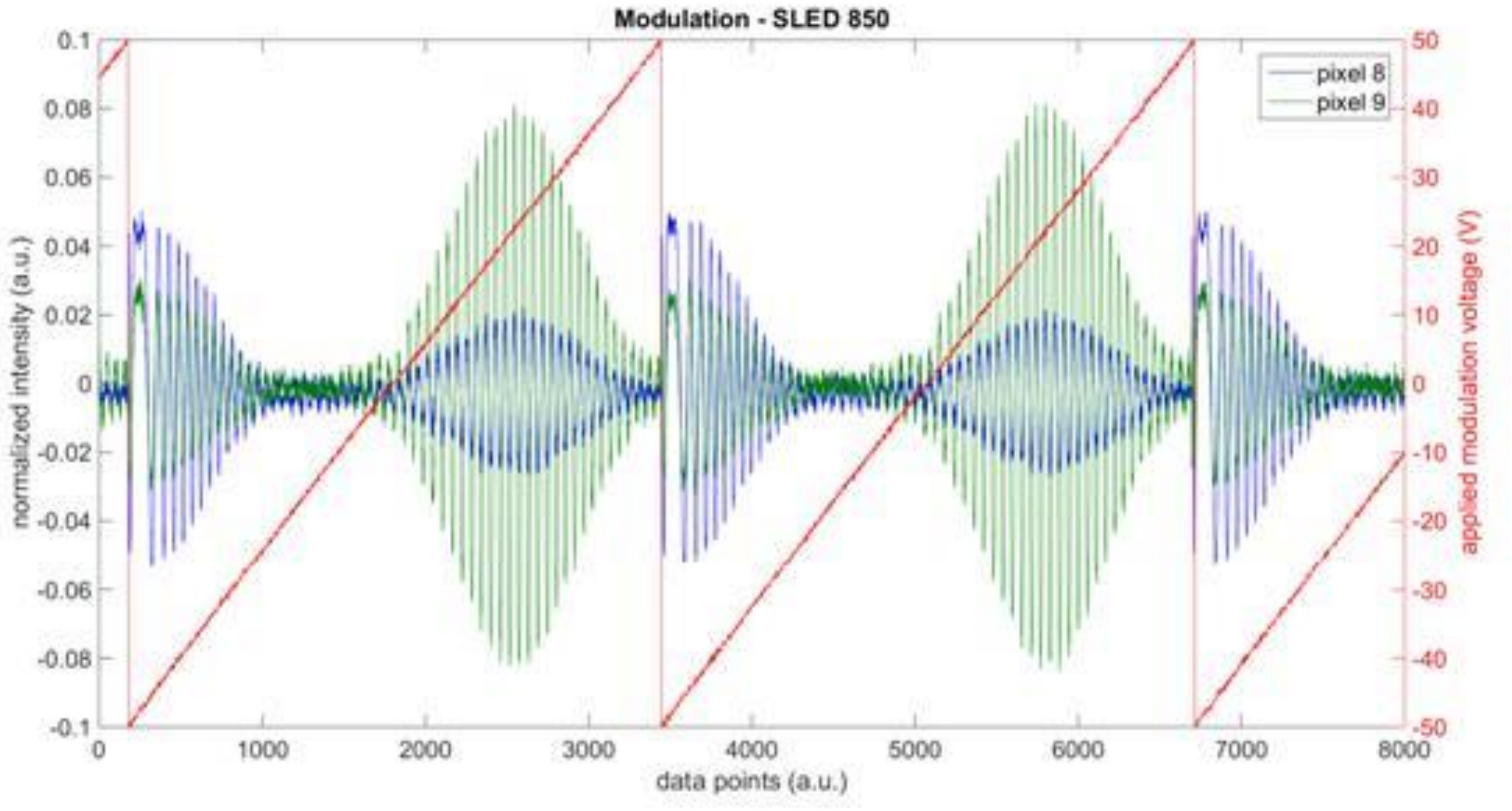
Depending on the initial unbalance in the MZ, we can set the fringes where needed (but not too far from the edge)



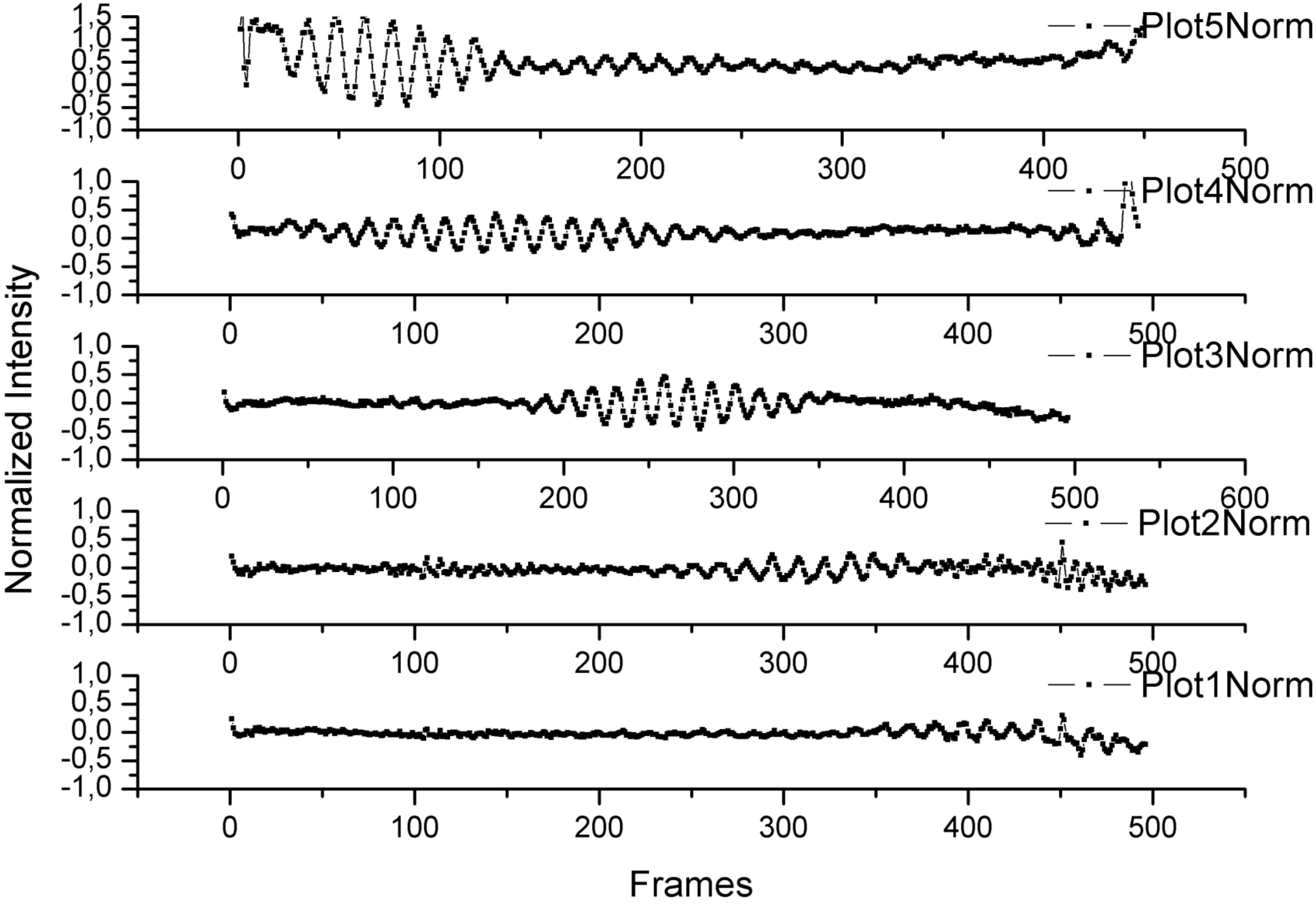
By applying a modulation voltage, we scan the fringes over the grooves

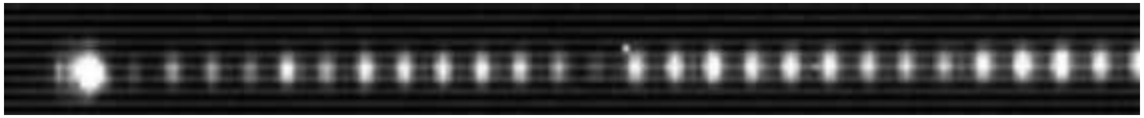
RESULTS:

Recording one sampling center using a Voltage ramp:



Shifting the wide-band fringes under the sampling grooves:

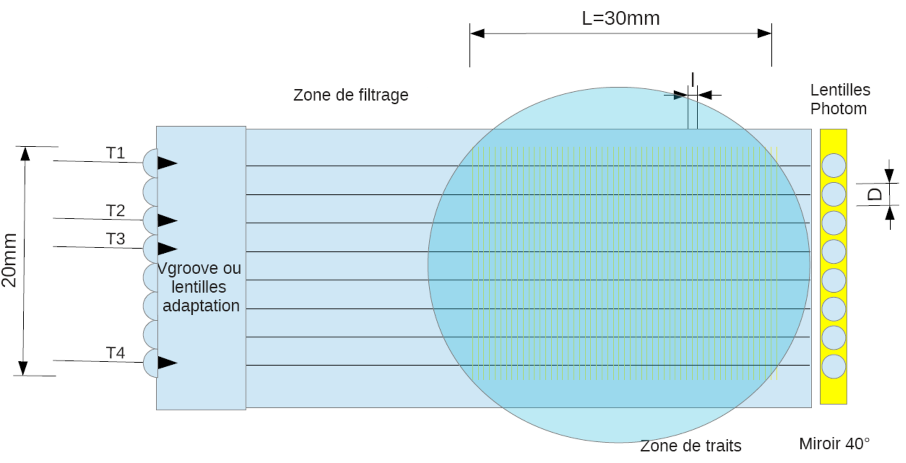




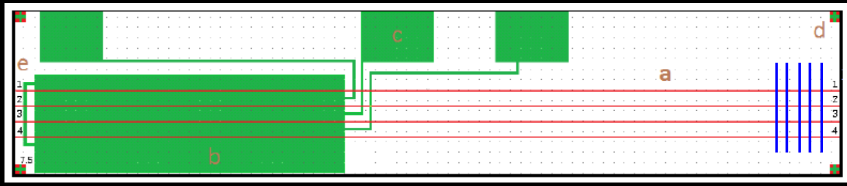
TOWARDS MULTI-T SPECTRO-INTERFEROMETERS

High Spectral Resolution

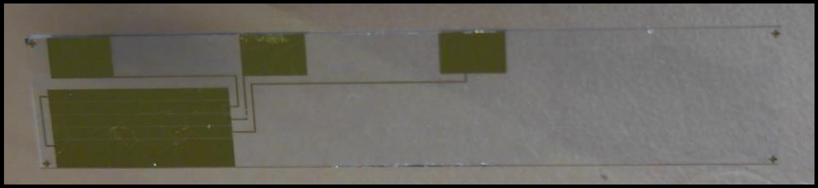
Grating Waveguide Spectro-Interferometer



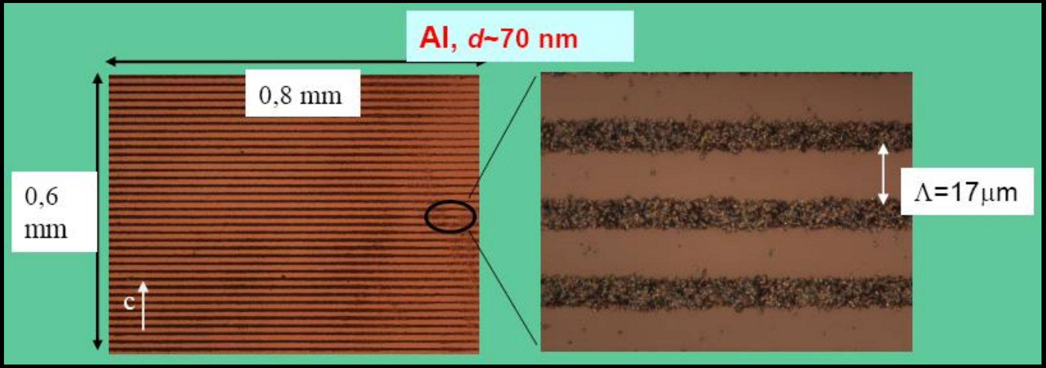
4T Device J. Loridat Master M2



Prototype 4cm x 1cm (FIB)



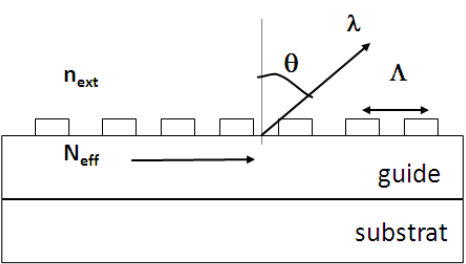
Collaboration with UAM-Madrid: Nanoparticles self-assembling



Wide Surfaces (qq mm^2)
Single Step
-> Visit of J.F. Muñoz Martinez
ETSI Aeronáutica

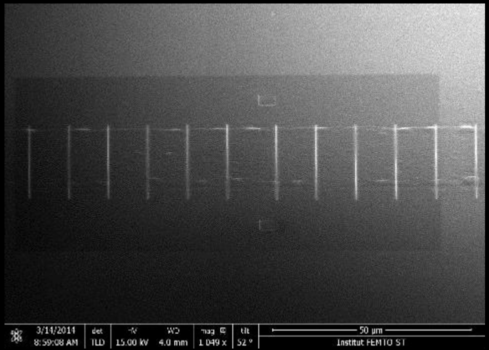
Grating Waveguide Surface Spectrometers

Diffraction Grating Spectrometer

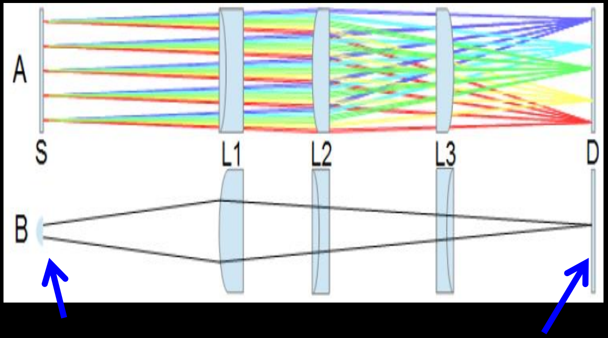


$$N_{eff} - n_{ext} \sin\theta = m \frac{1}{\Lambda} \lambda$$

FIB Grooves

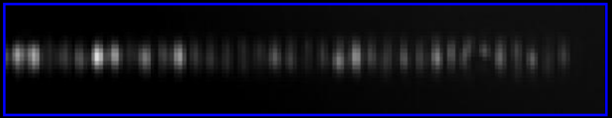


Grooves as seen from the top

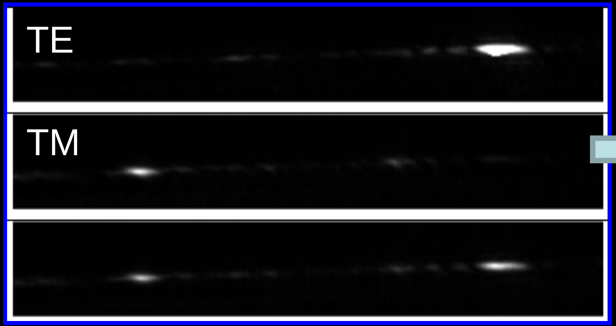


WG+Grating Detector

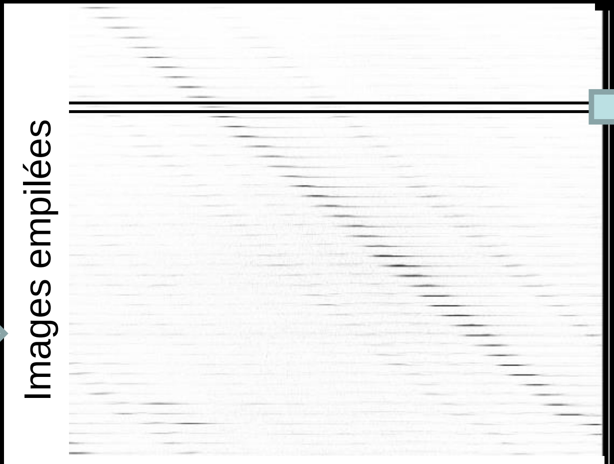
Direct Image



GWS Image

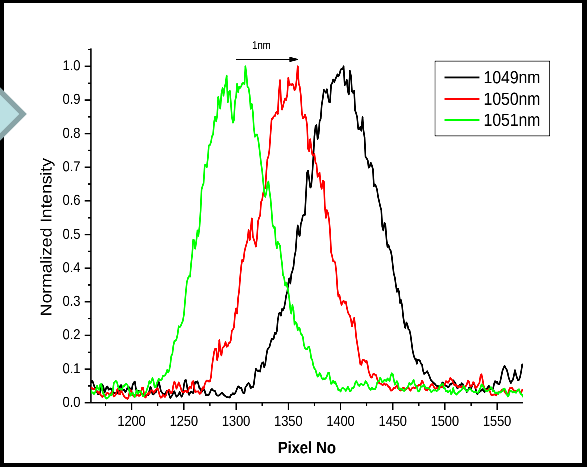


Scan 1030-1077nm



2048 pix x 7µm size

GWS Vision

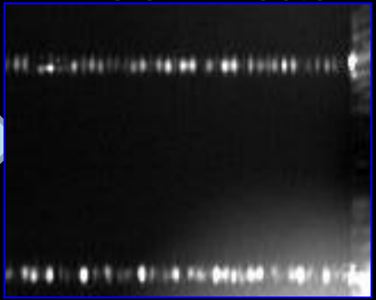


G. Martin et al., JLighTech, 2014

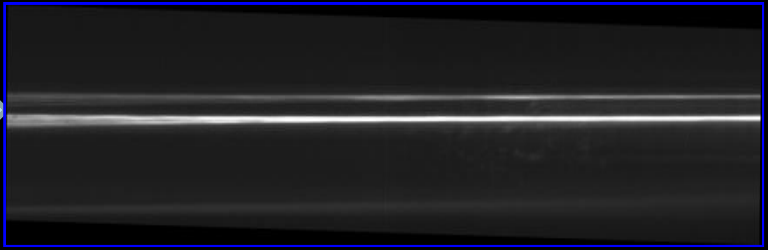
Spectromètres AVRUTKSY

Intérêt Avrutsky: Le Multi Télescopes (Spectro Interferomètre)

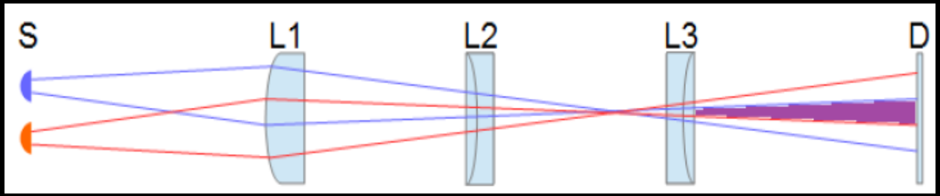
Vision Directe



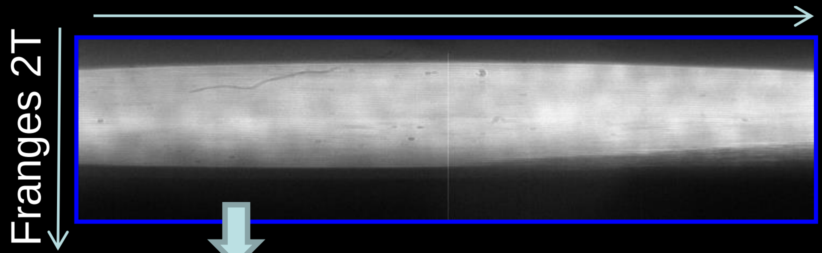
Vision Avrutsky (focalisée)



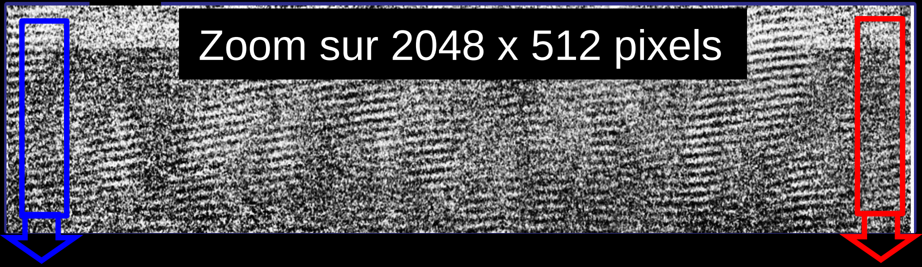
Défocalisation



Longueur d'Onde (820-870nm)

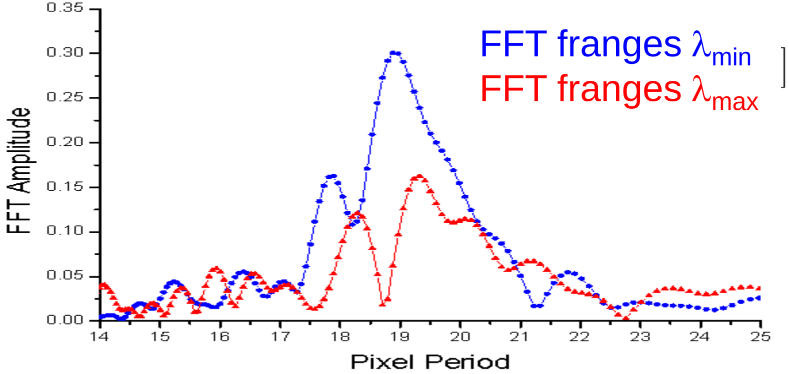


Décalage 1 pix = 40nm (5cm défocalisation)



Franges λ_{min}

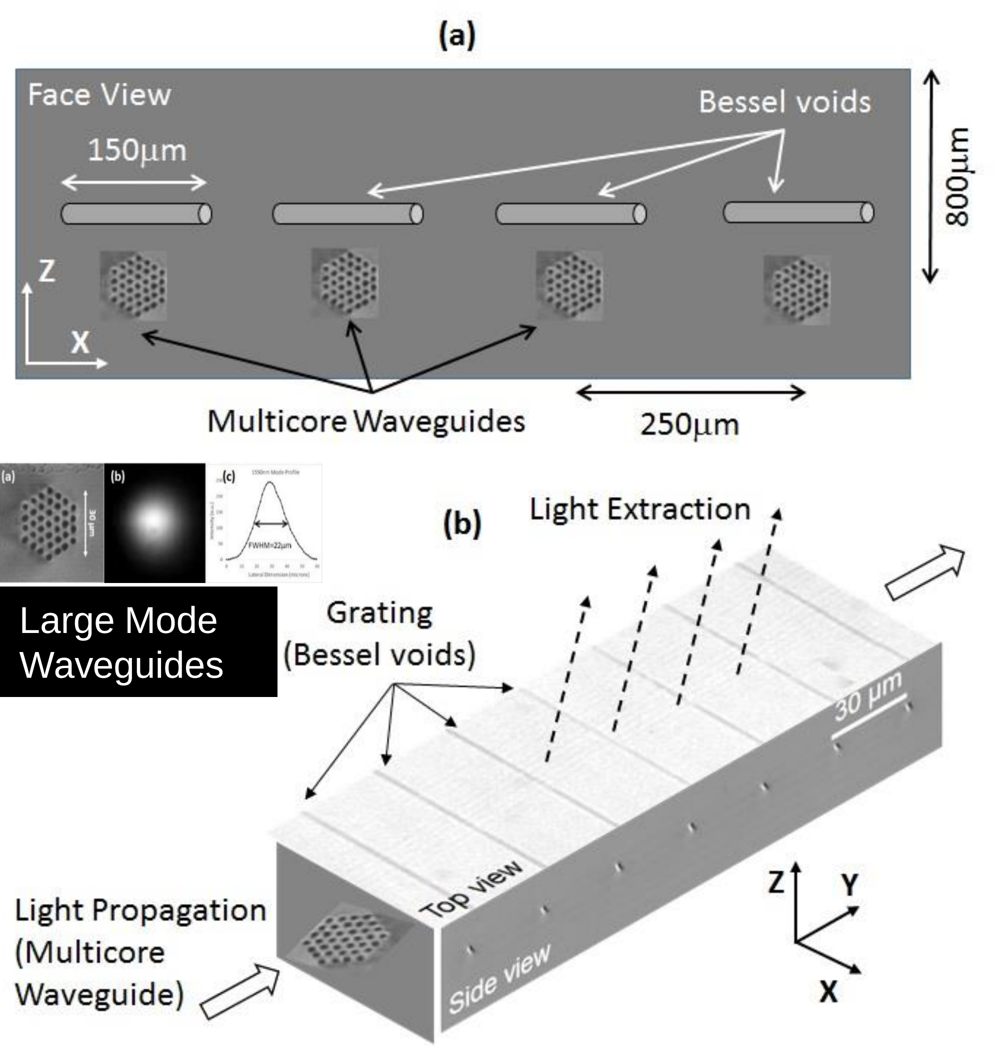
Franges λ_{max}



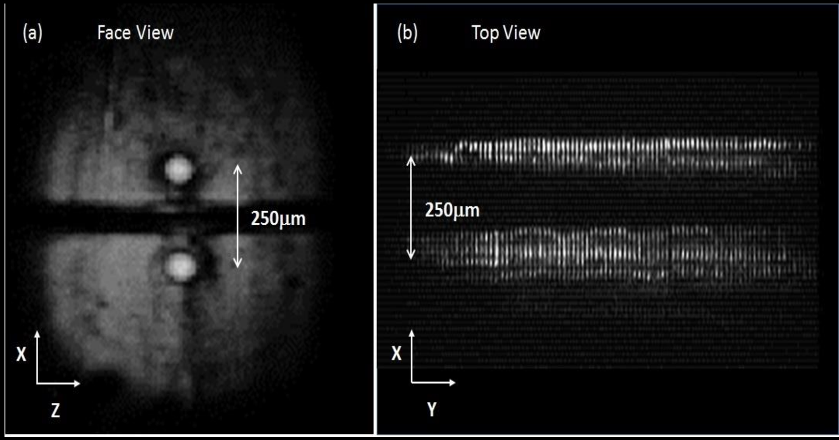
Bilan d'Etape: Amélioration de l'étendue spectrale SWIFTS; Premiers Résultats Avrutsky

Grating Waveguide Spectrometers

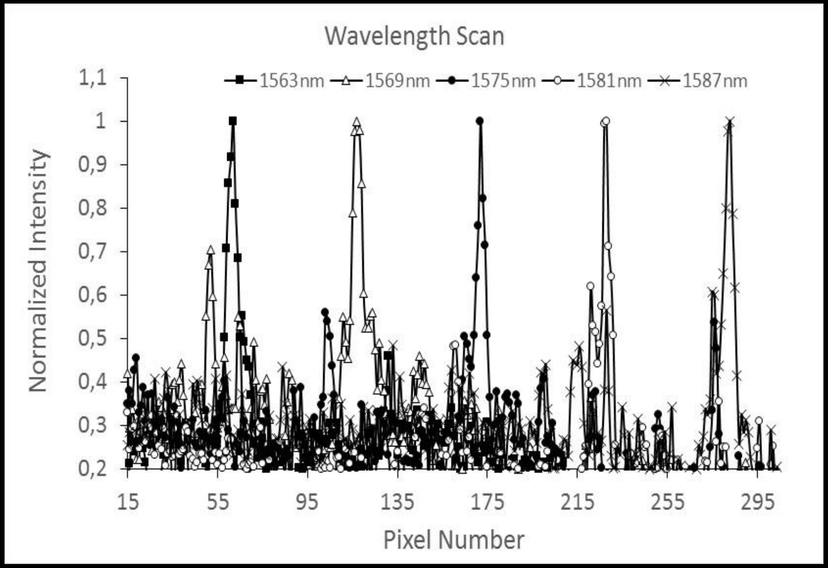
Interest of GWS: Multi Telescope (Spectro Interferometry)



Large Mode
Waveguides



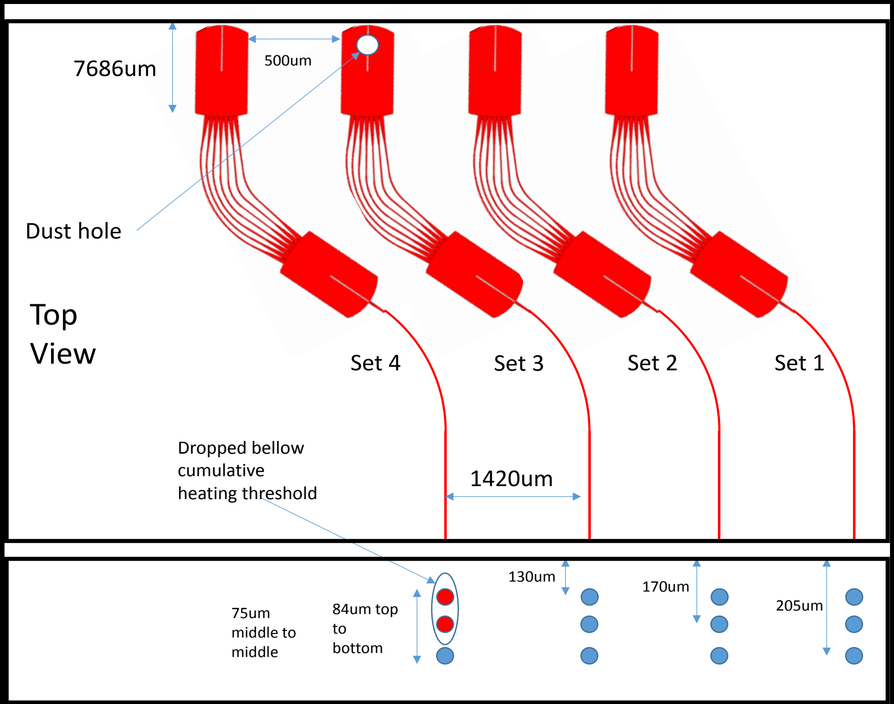
Near Infrared SWIFTS images



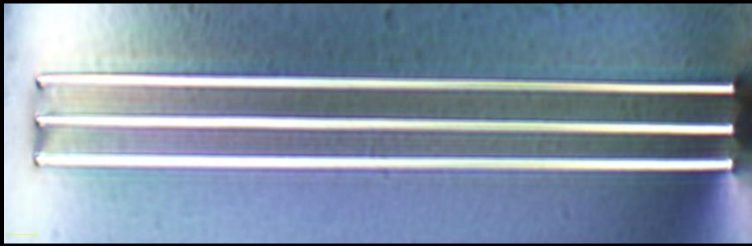
G. Martin et al., Opt. Express 2017

Vers un spectro-interféromètre en propagation directe…

Collaboration avec McQuarie University (Sydney)



Projet PHC Fasic, 2016



Zone planaire de sortie (3 AWG empilés)

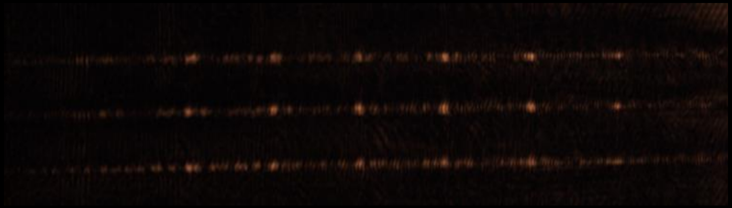


Image focalisée des sorties à 810nm

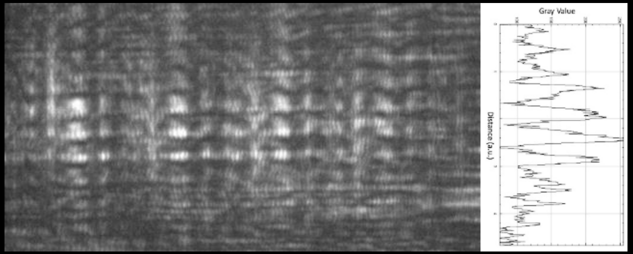
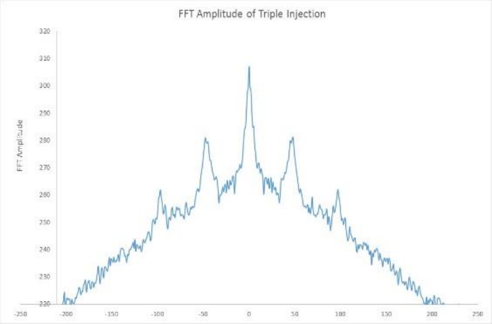


Image défocalisée des sorties à 810nm

TF

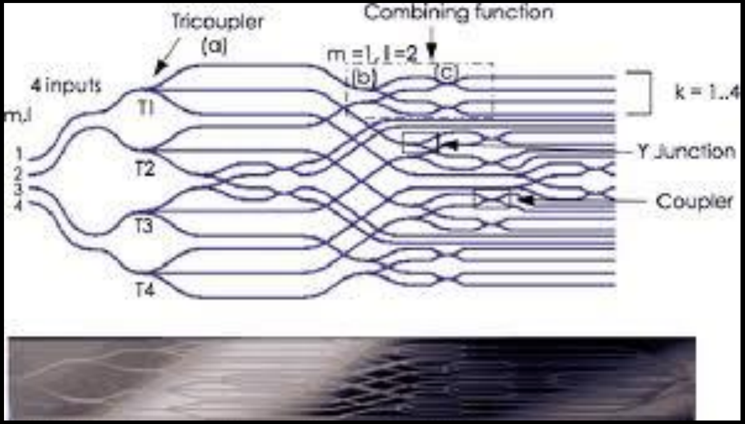


FFT Amplitude:
Pics frange non redondants

CONCLUSION

IPAG context: From technological developements to instruments & observation

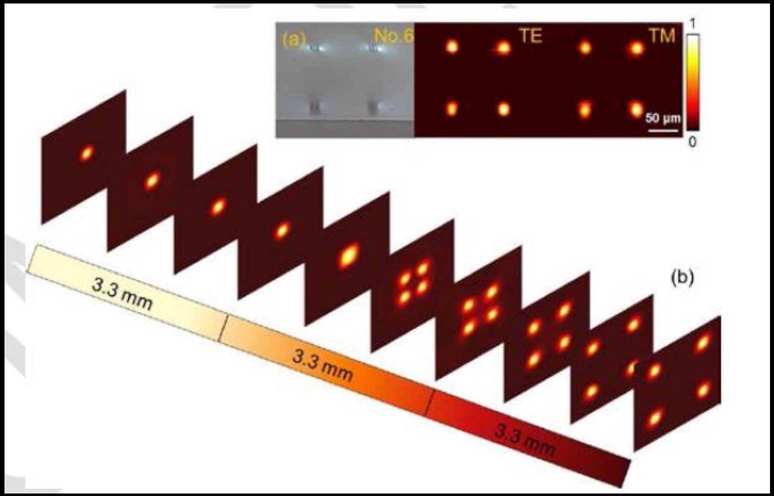
-Integrated optics beam combiners (2D, 3D):



-Integrated optics spectrometers (SWIFTS):

1. **MID-IR MATERIALS**
2. **INTEGRATED OPTICS**
3. **ELECTRO-OPTICS**

- **VIS to N BAND optical benches**
- **WG Simulations**
- **Re-birth of L band!**



Thanks for your attention!