Integrated Optics:
for single mode interferometry

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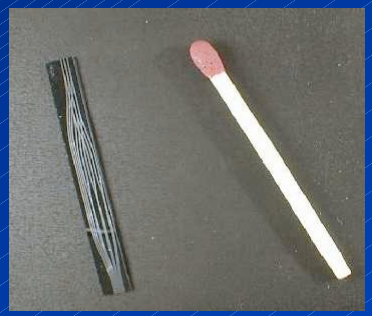
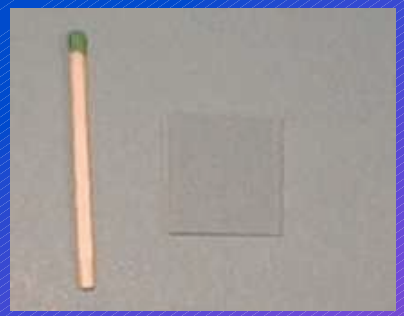
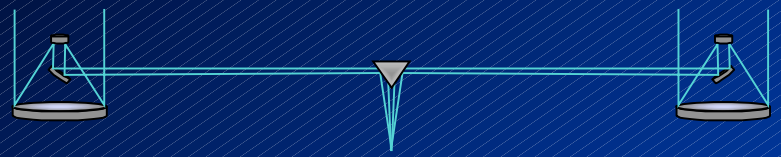
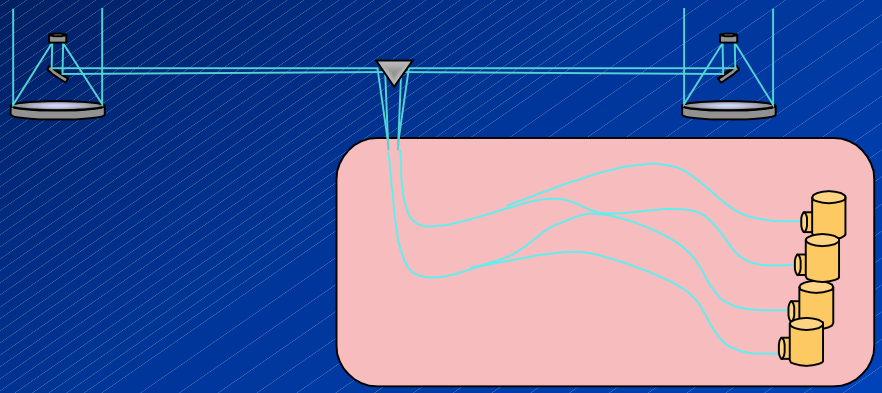




Transportation and Combinaison of the beams

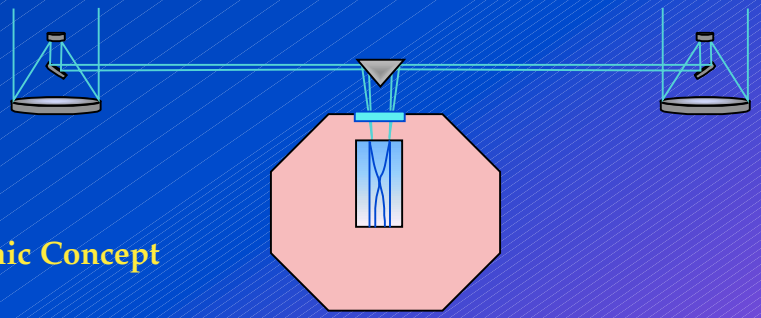


All mirror solution: Fizeau 1867, Michelson 1919



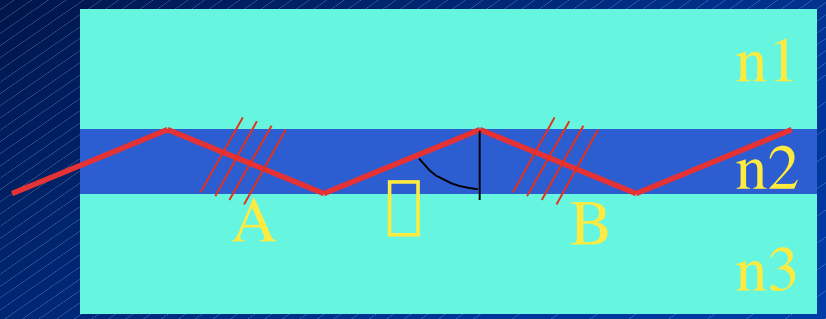
Fiber optics combiner: Fluor Concept

Fiber optics solution: Froehly 1981



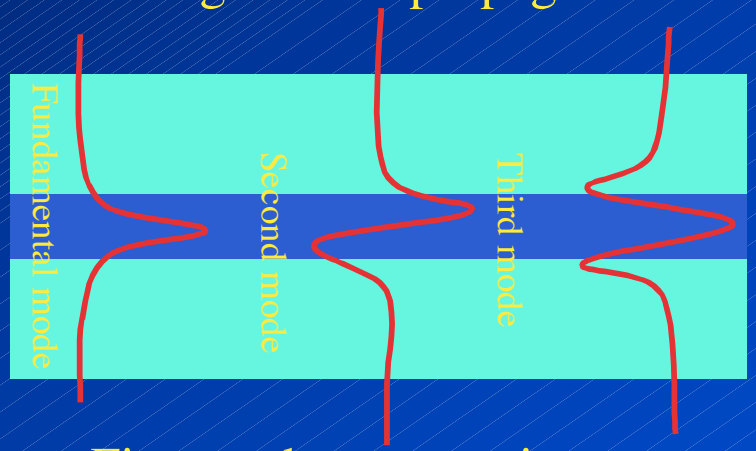
Planar Optics combiner Ionic Concept

Single mode wave-guide

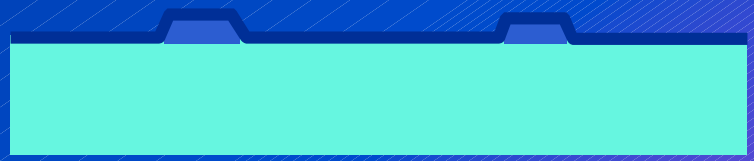


Single mode propagation

Ion exchange technique

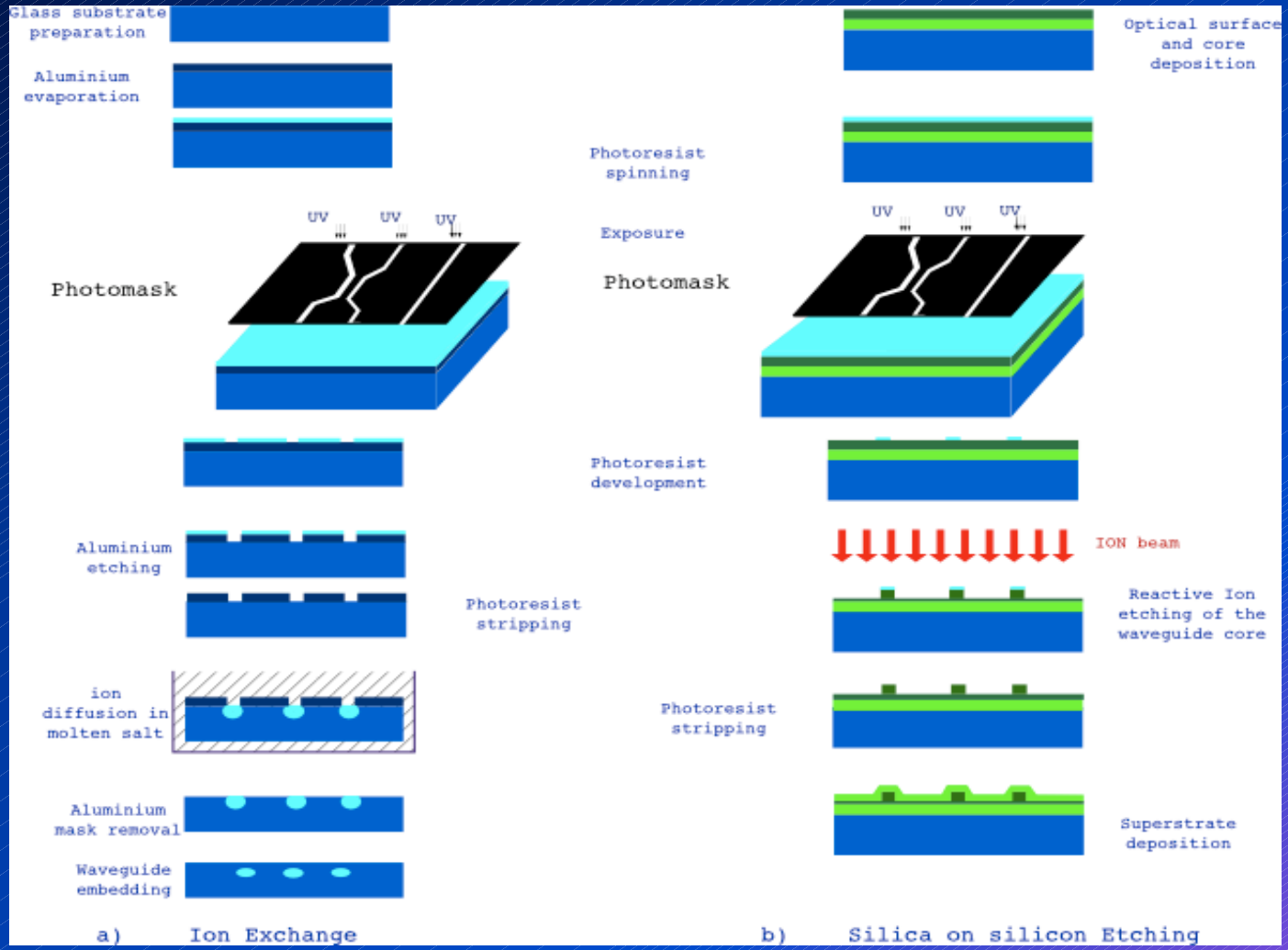


First mode propagation

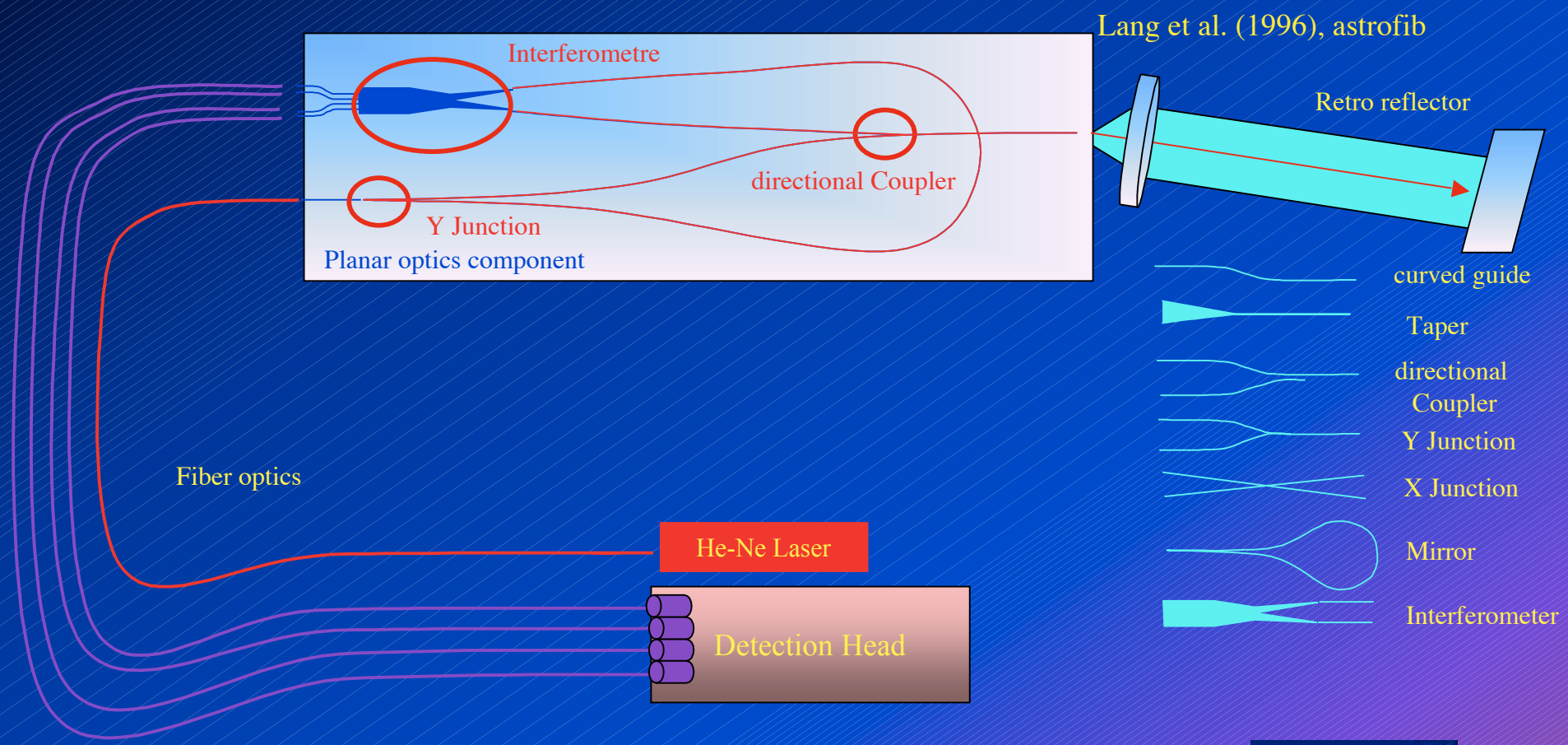


Etching technique

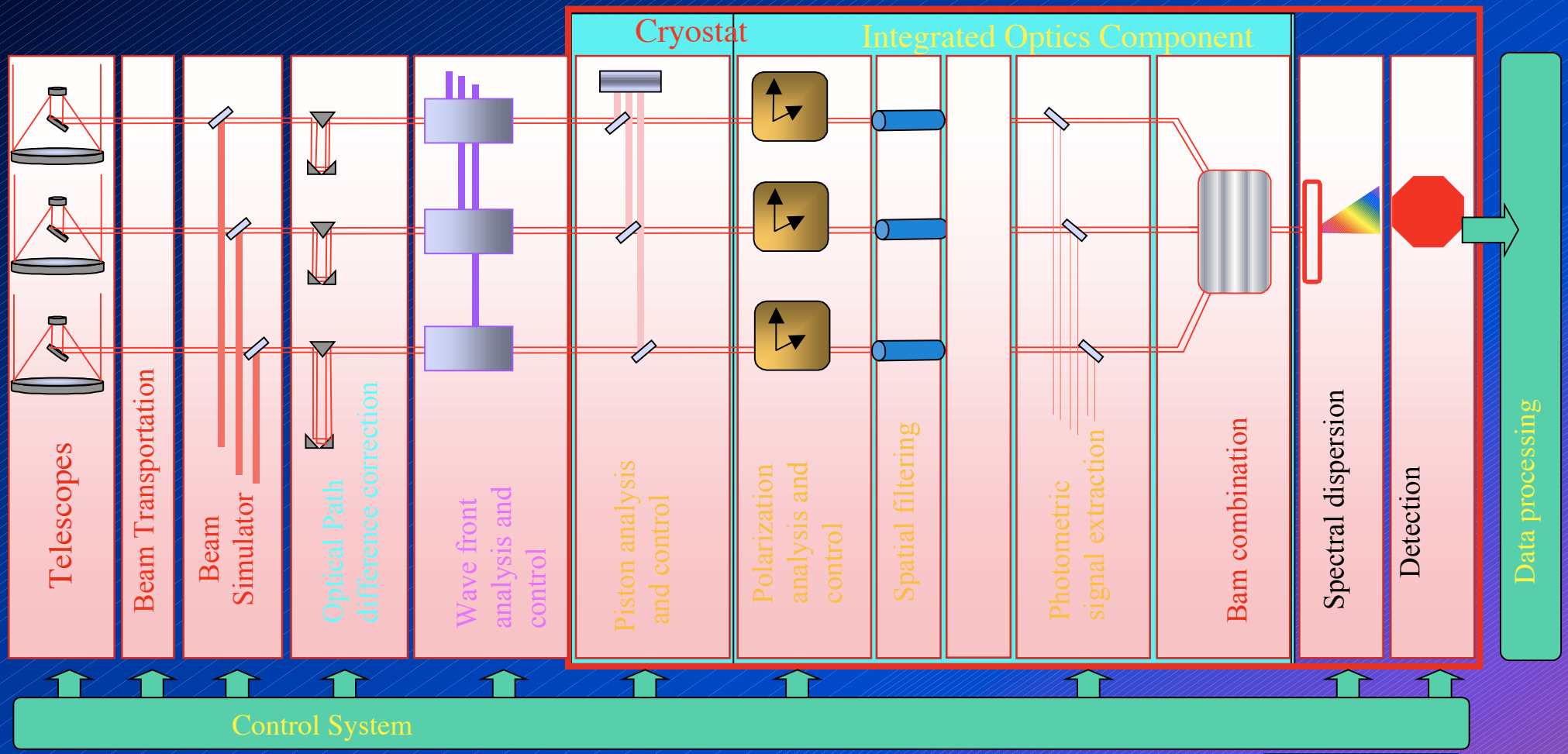
Integrated Optics available Technologies



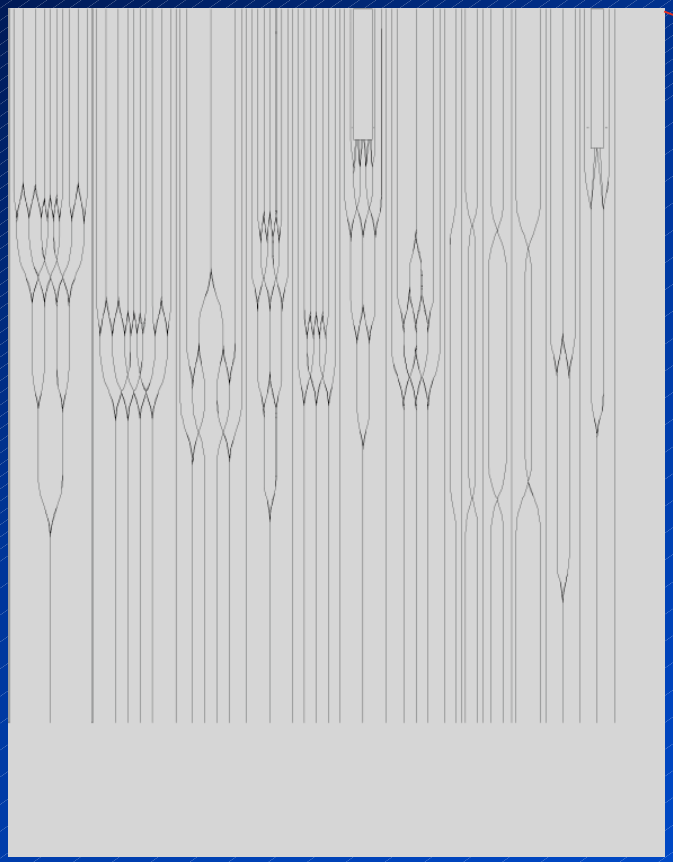
Example of a displacement sensor

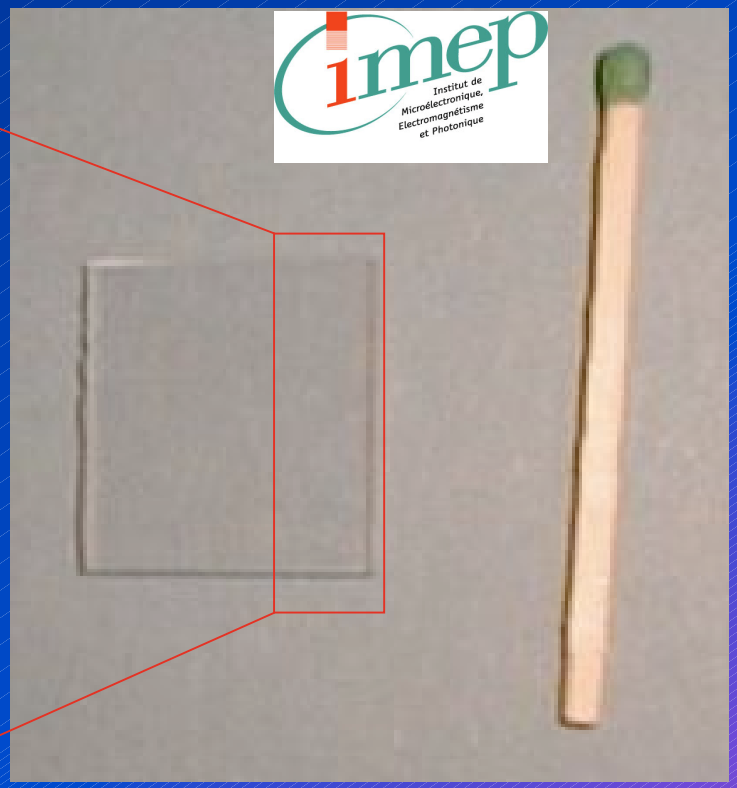


Required functions for stellar interferometry



Beam combiners on a chip !



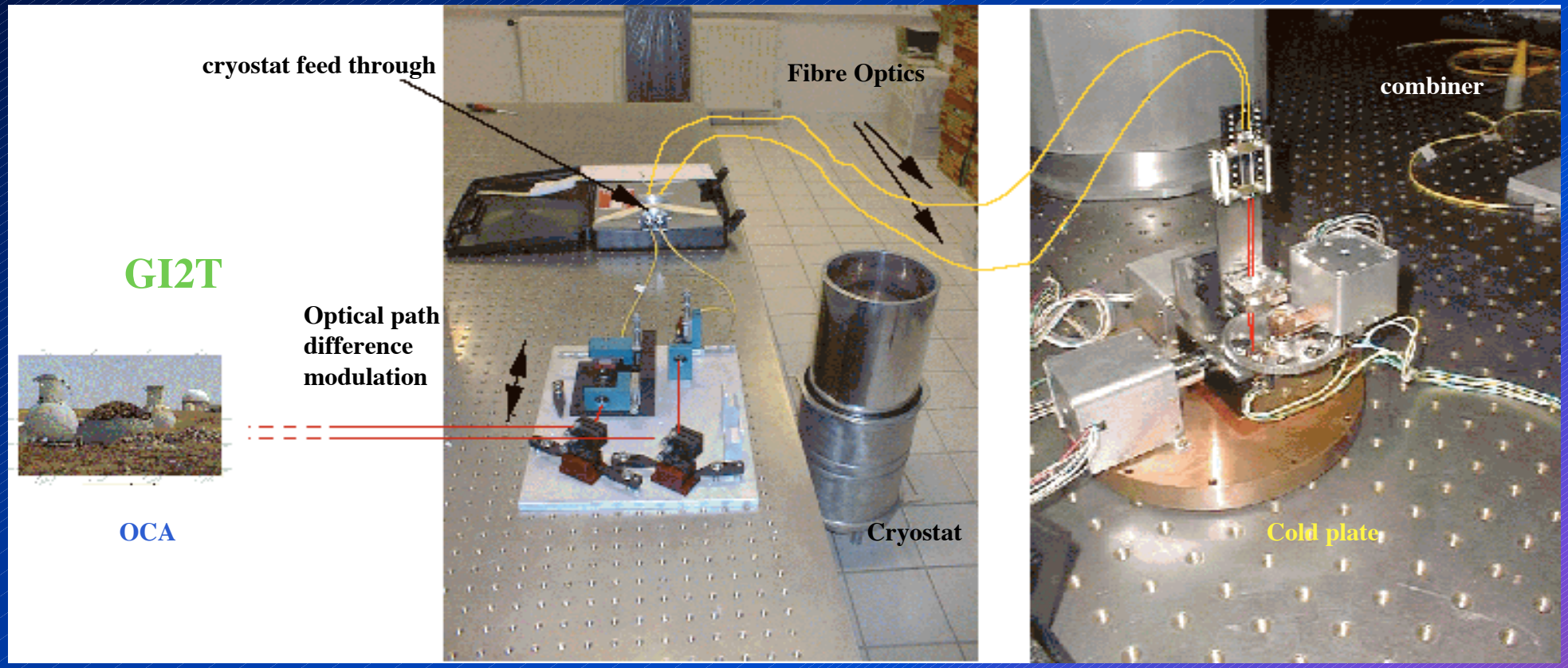


IONIC Camera Prototype for GI2T validation tests

Collaboration: LAOG
IRCOM
GI2T

Telescope interface

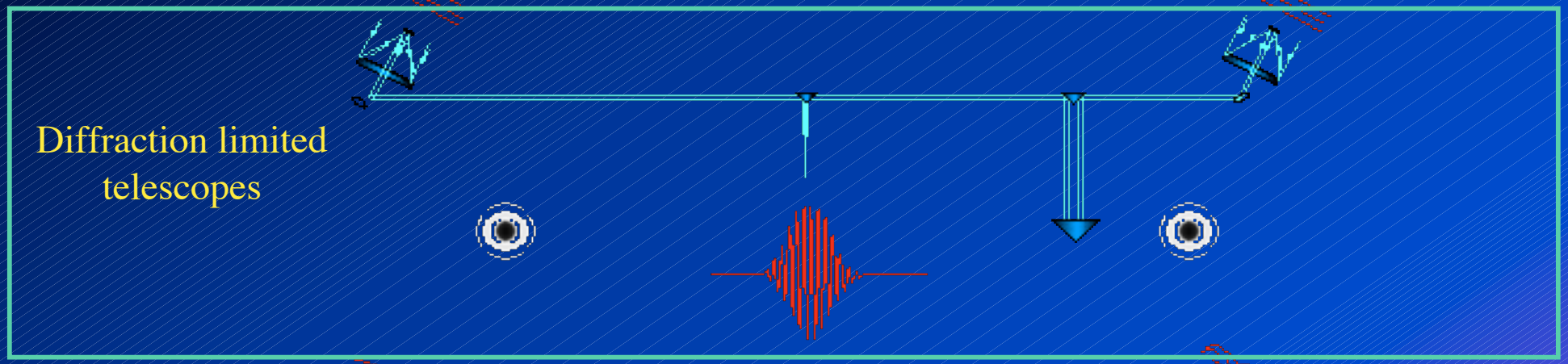
Interferometric Camera

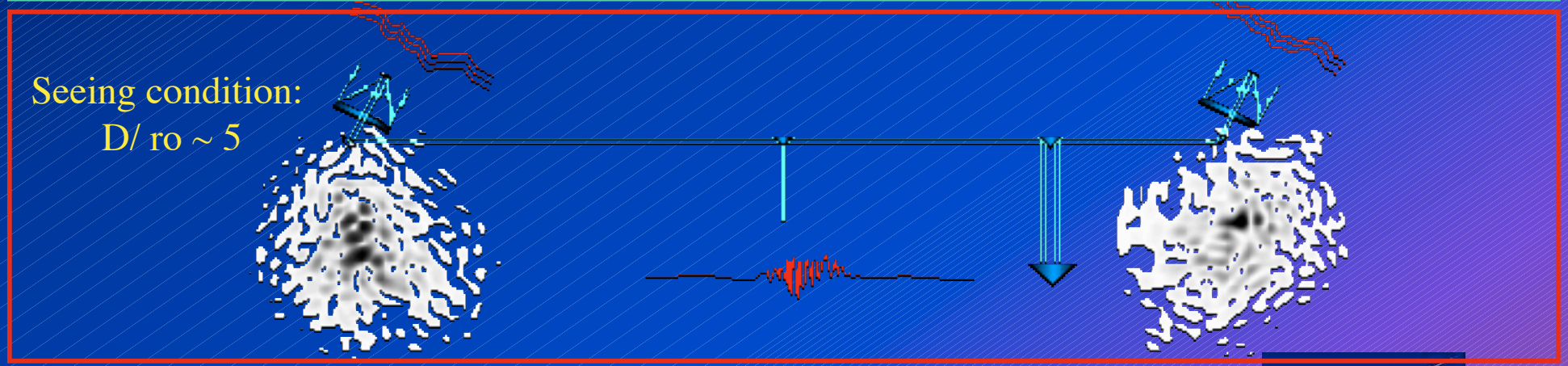


Rousselet et al. (2000) 4006-122

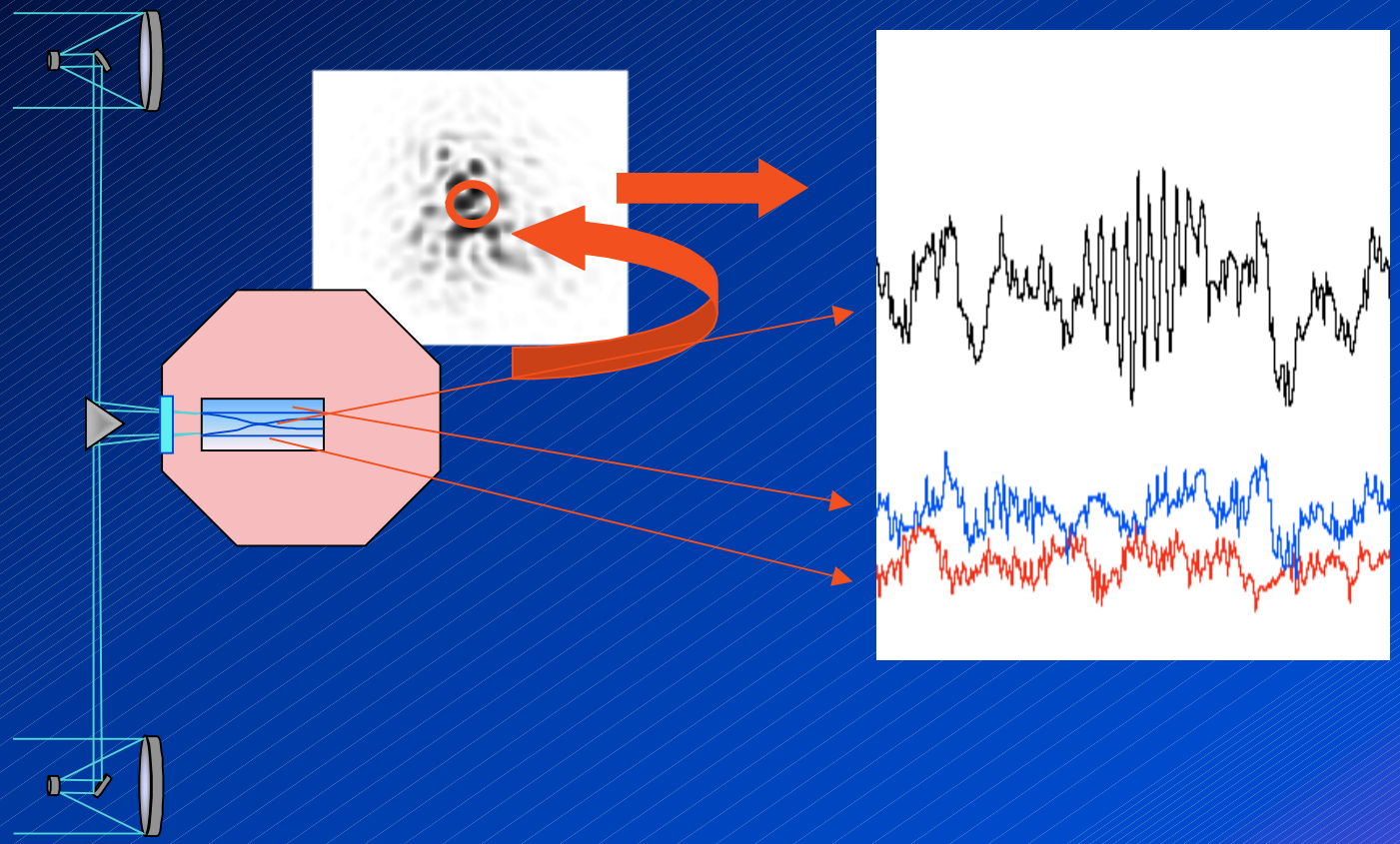
Atmospheric turbulence effects

Degradation of the interferometric signal





Atmospheric turbulence effects:
Modal filtering and photometric calibration



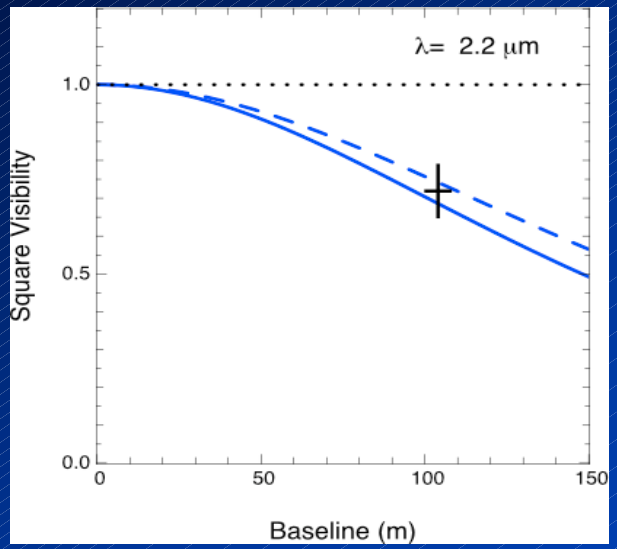
Interferometric channel

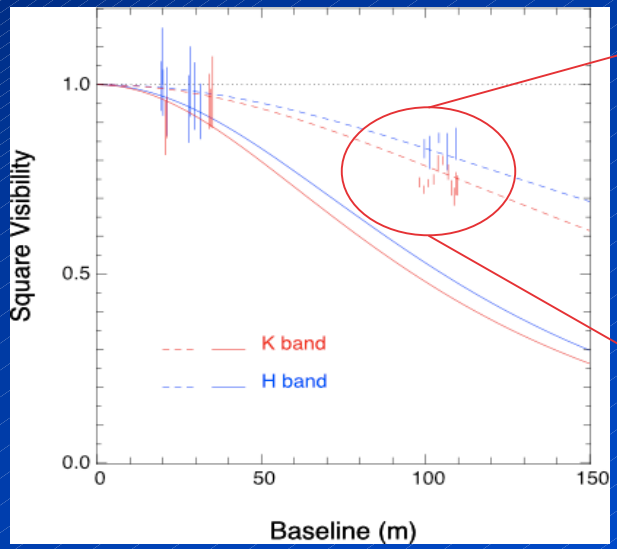
Photometric channel I

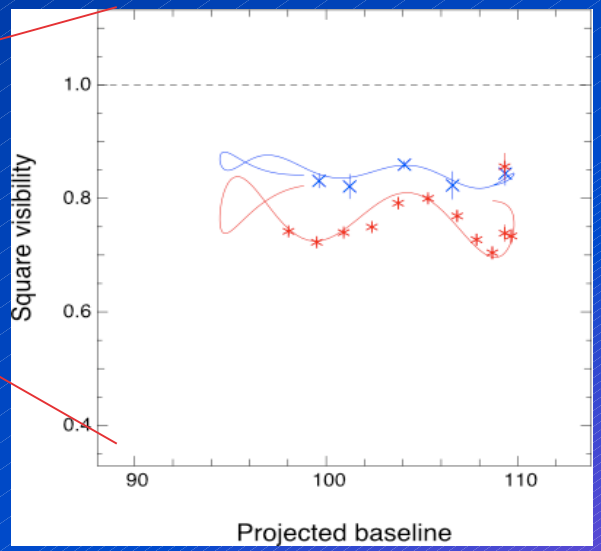
Photometric channel II

FU Orionis

Importance of visibility measurement accuracy





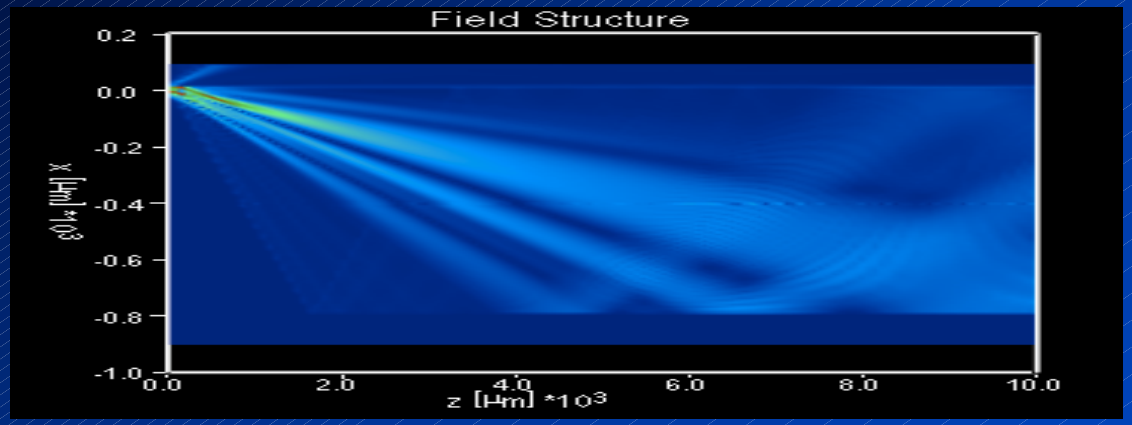


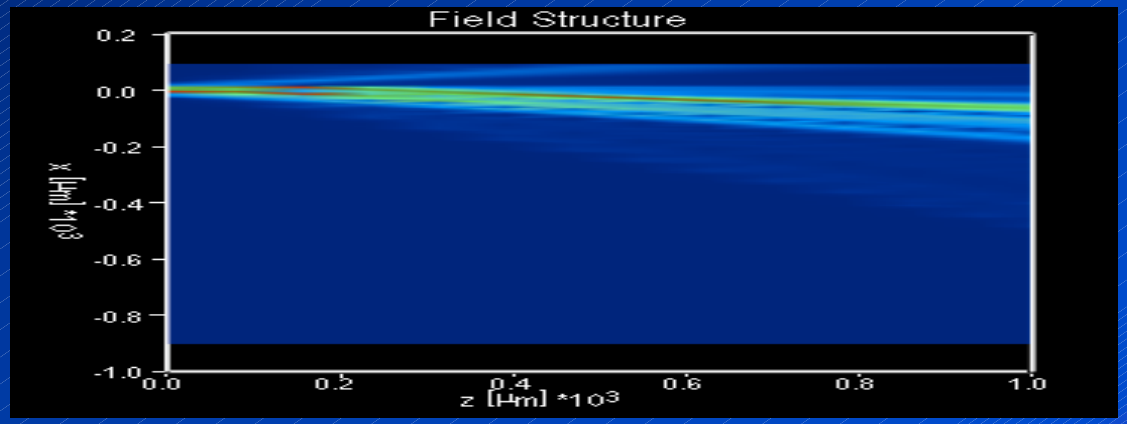
Malbet et al 1998, ApJ letters

Berger et al 2000, SPIE 4006-72

Numerical simulation using Finite Difference Beam Propagation (FD-BPM)

Isabelle Schanen IMEP (Grenoble, France)

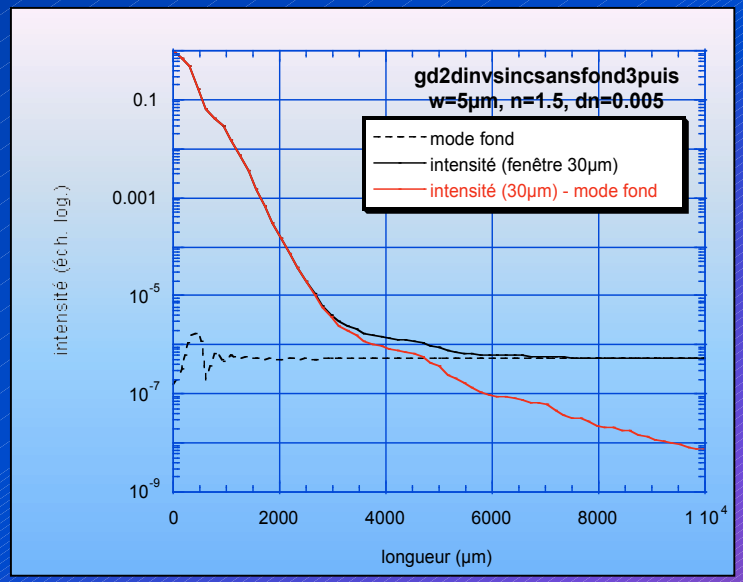




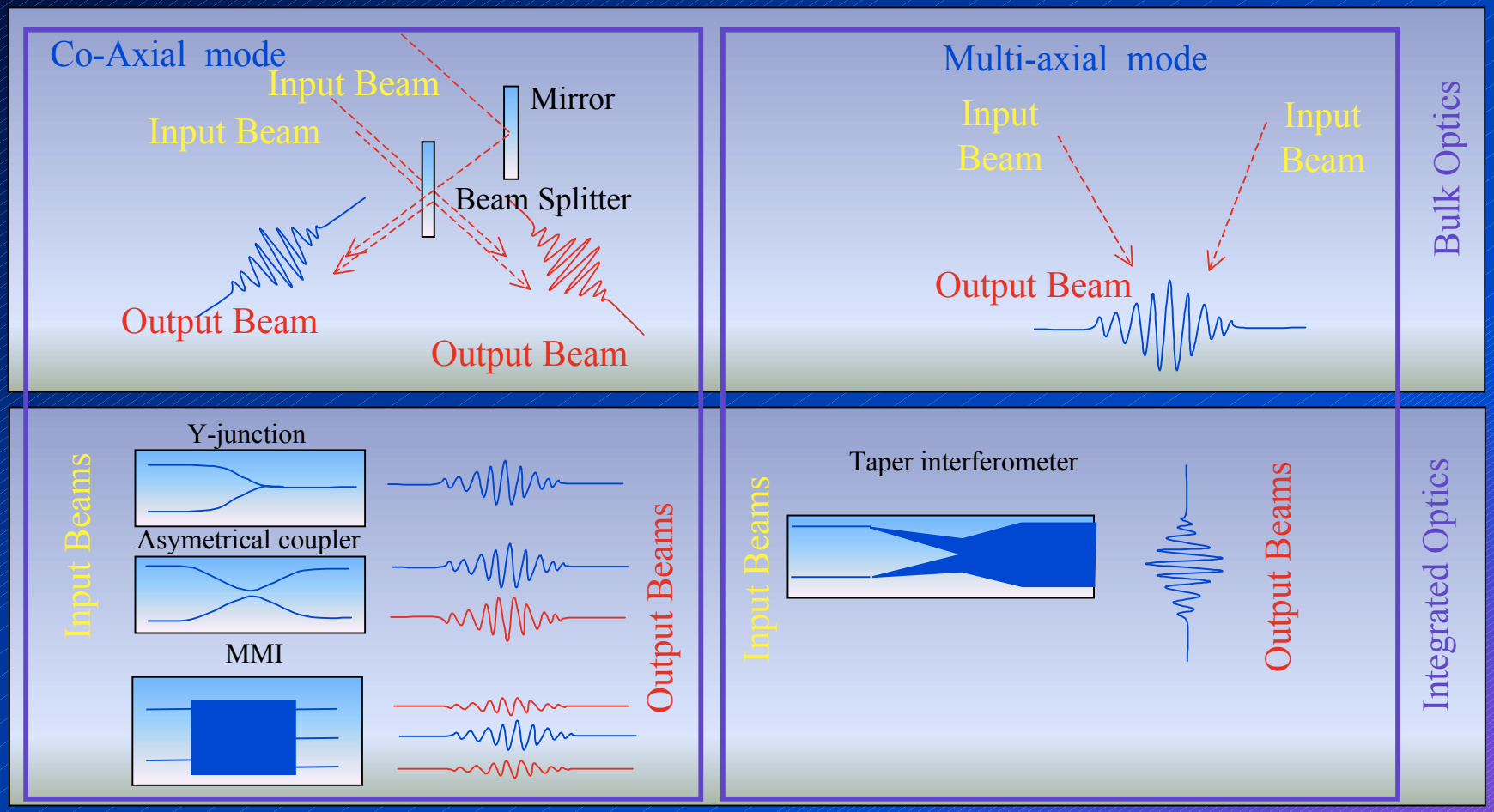
10^{-7} (70dB) filtering after 1 cm propagation

Power analysis

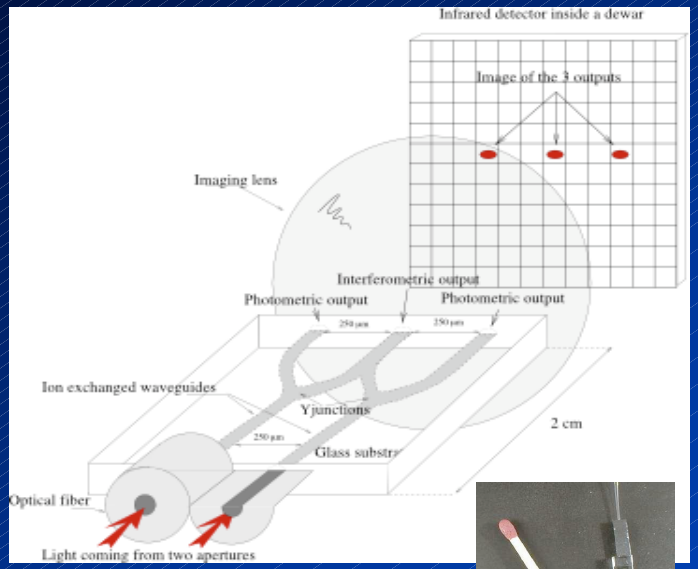
Evolution of the output flux in a 30 μm window

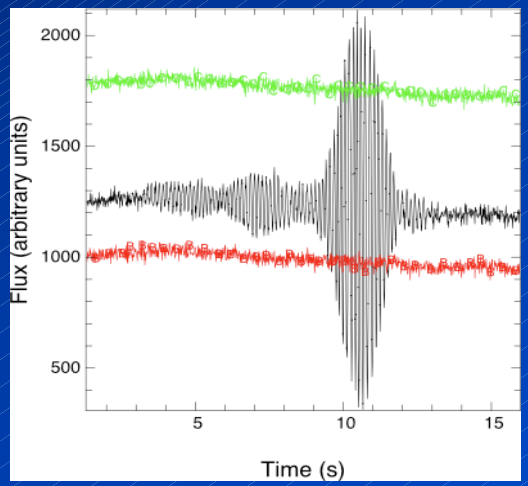


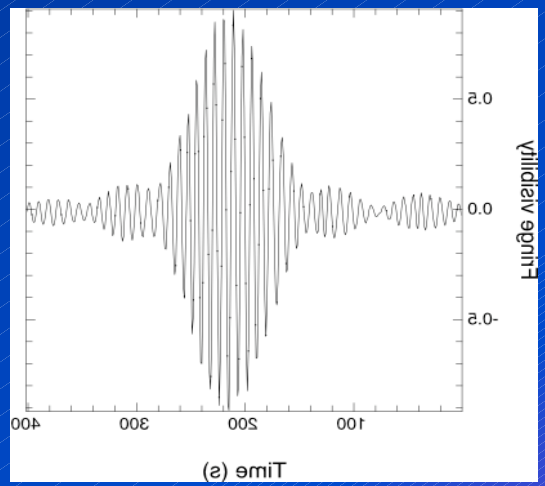
Beam combination for interferometry



2 telescope beam combiner







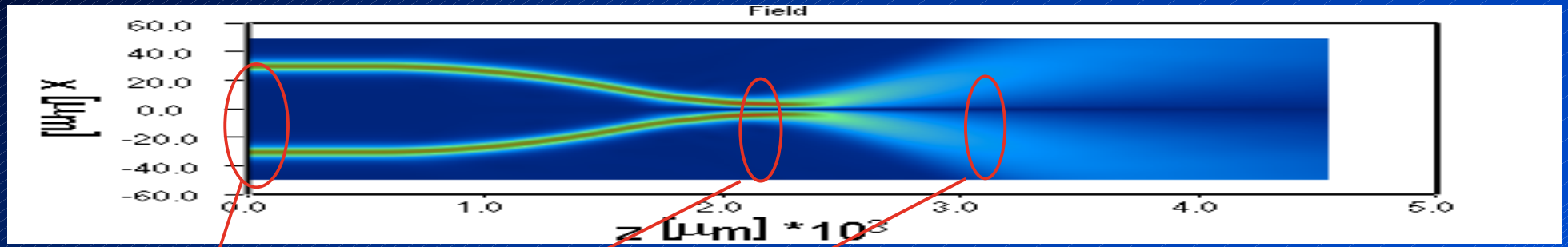
3 output signal:
2 photometric
1 interferometric

Signal corrected from photometric fluctuations

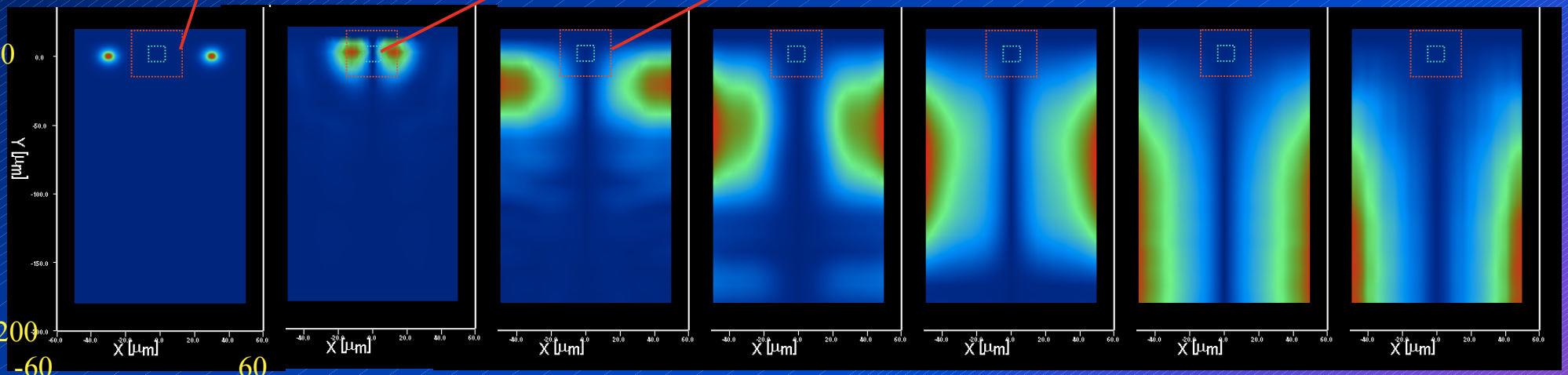
Berger et al. (1999) A&AS, Haguenauer et al.(2000) Appl. Opt.

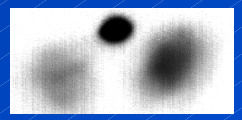
Y-Junction signal rejection simulatin using Finite Difference Beam Propagation (FD-BPM)

Isabelle Schanen - IMEP (Grenoble, France)



Input field | Y junction edge | 1200µm | 2500µm | 3750µm | 6300µm | 10000µm

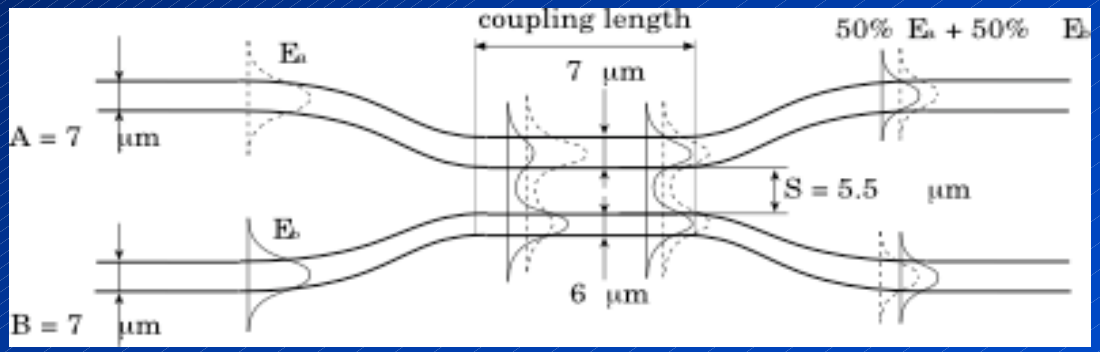


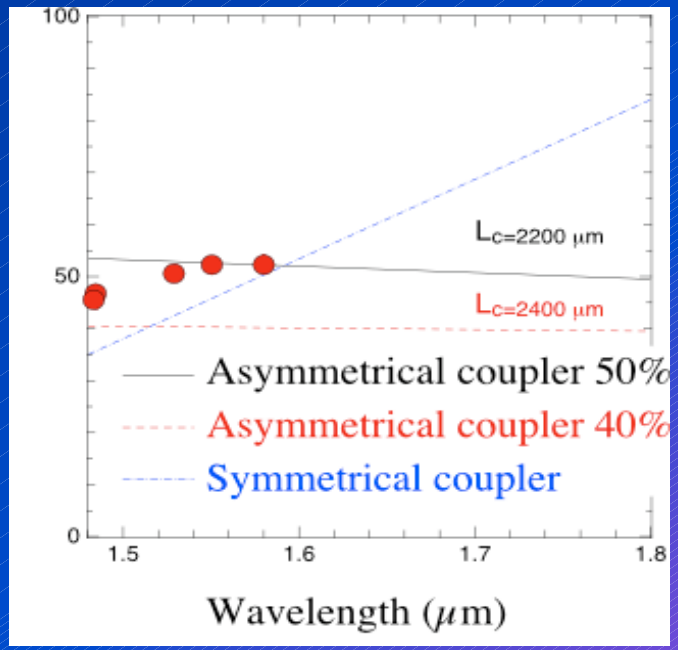


Measured output field of Y junction.
Symetric input field.
Length of the output waveguide 500µm

Pierre Kern

Beam combiner chromatism reduction



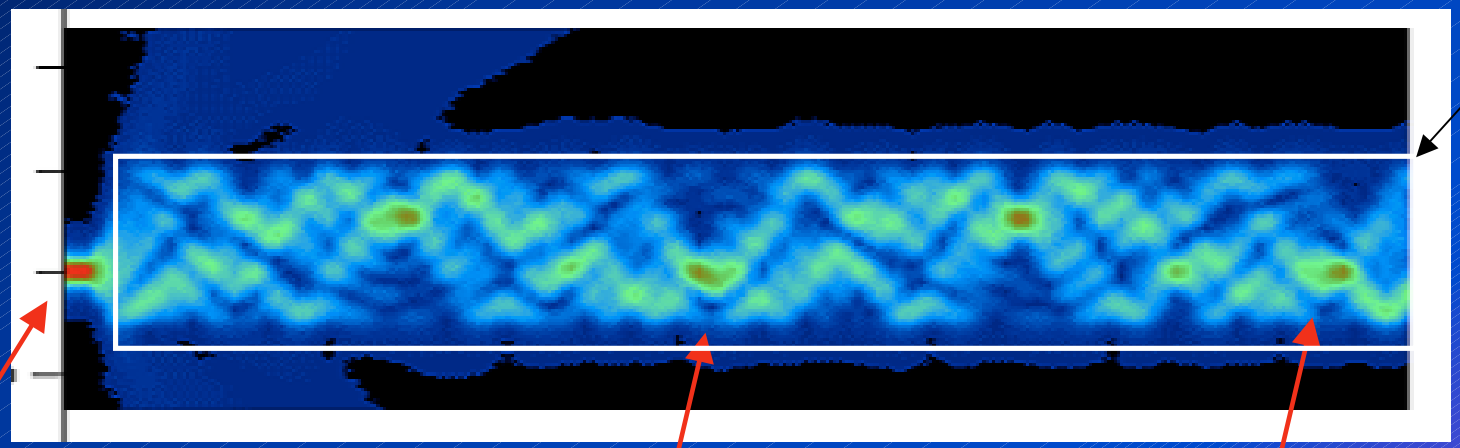


Severi et al.(1999), Torino

Multi-Mode Interference (MMI)

- ➔ each mode propagates with its own speed
- ➔ beating phenomenon

MMI waveguide



Injected Field

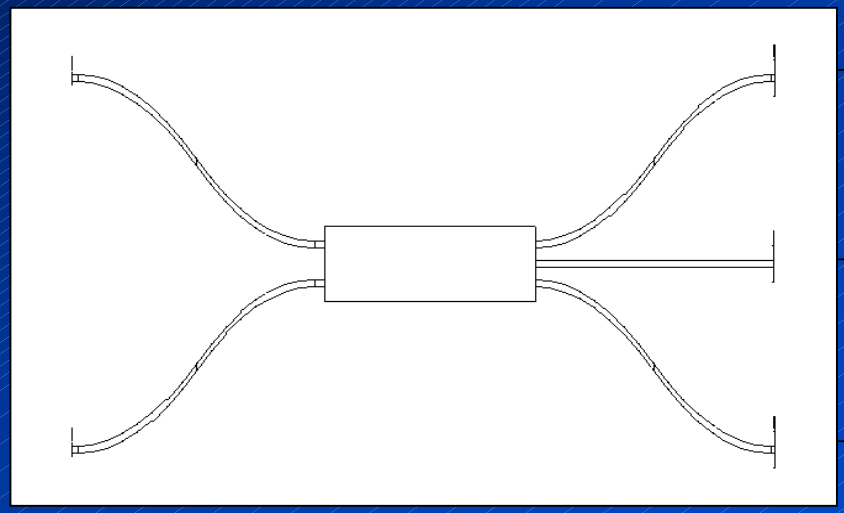
First image

Second image

Two Telescopes Recombiner

E1 →

E2 →

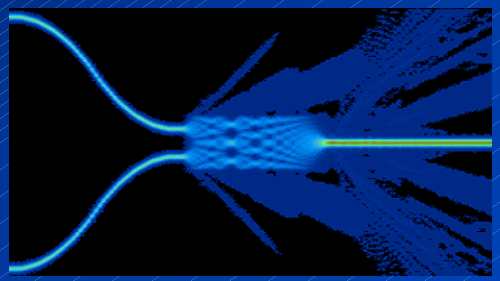


→ E1 - E2

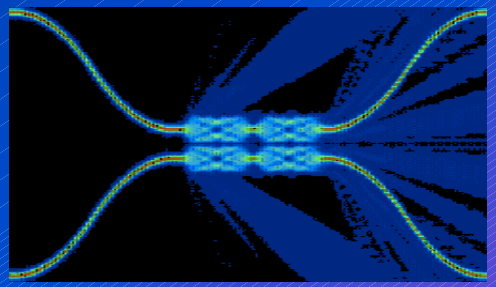
→ E1 + E2

→ E1 - E2

Simulations: Two input fields in phase

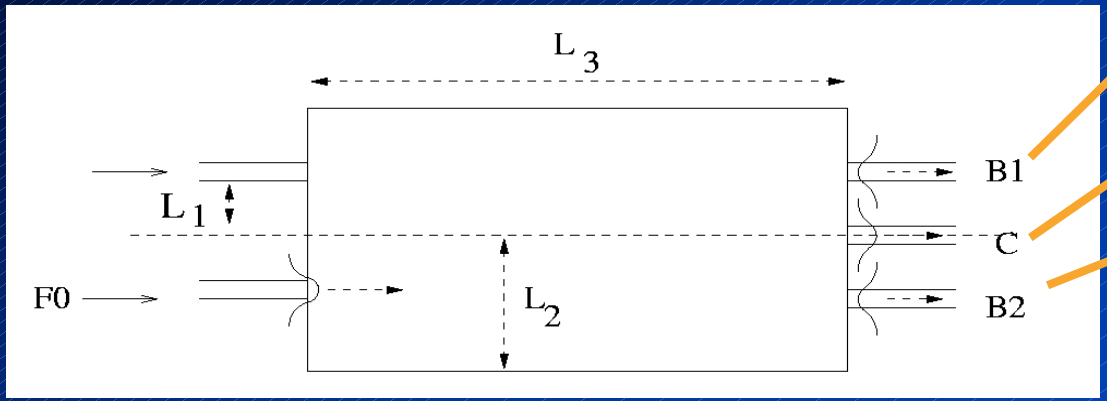


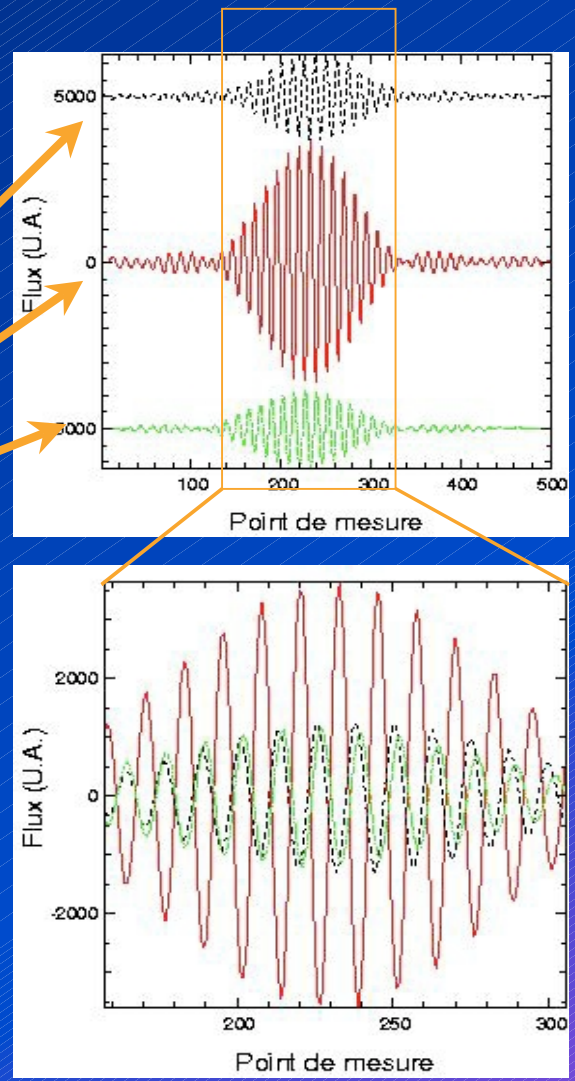
Simulations: Two input fields in phase opposition



El Sabban et Al, Design of an Integrated Optical Magic T Using the Multimode Inerference Phenomena, SPIE vol 3620

MMI (Multi-Mode Interferometer)





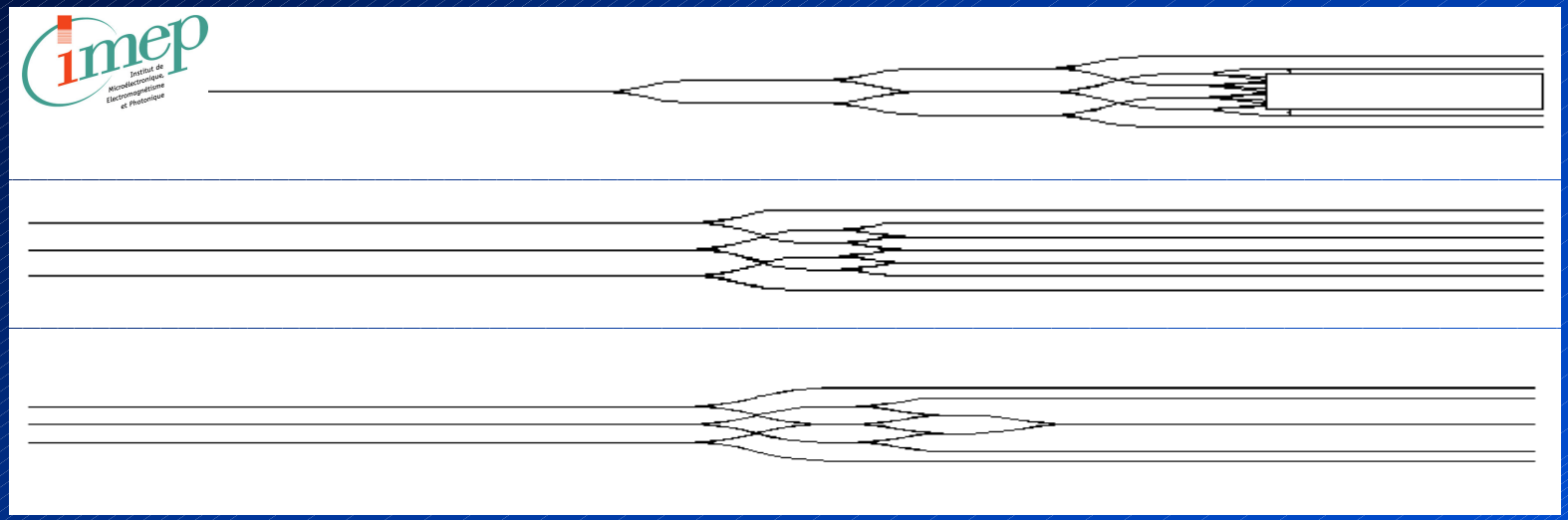
93%

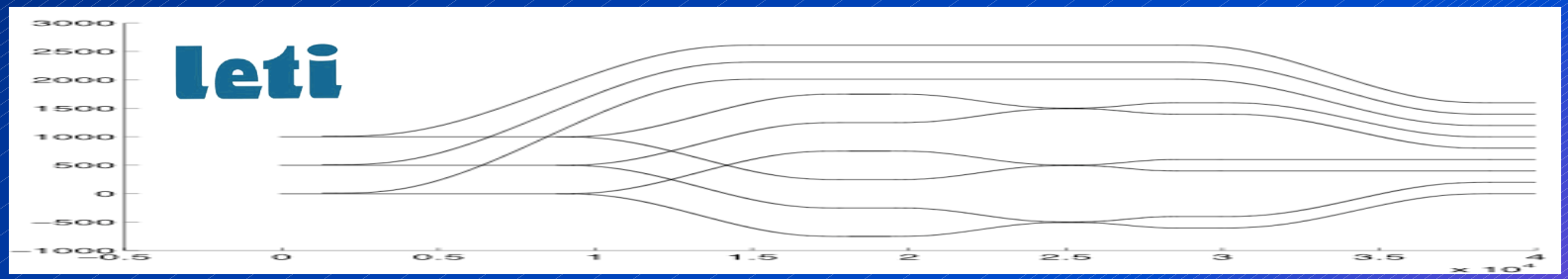
95%

87%

- Single mode waveguide injection (F0).
- Multi mode structure (L3 area).
-At the structure output the flux is injected in 3 single mode wave guides (B1, C, B2).
-B1 and B2 output return signal in phase opposition with C.

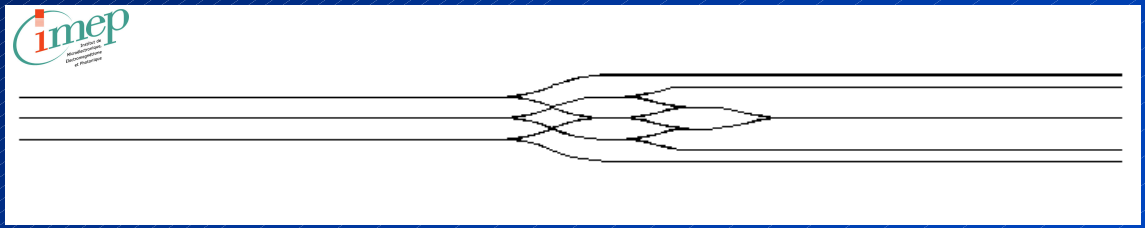
3 telescope combiners

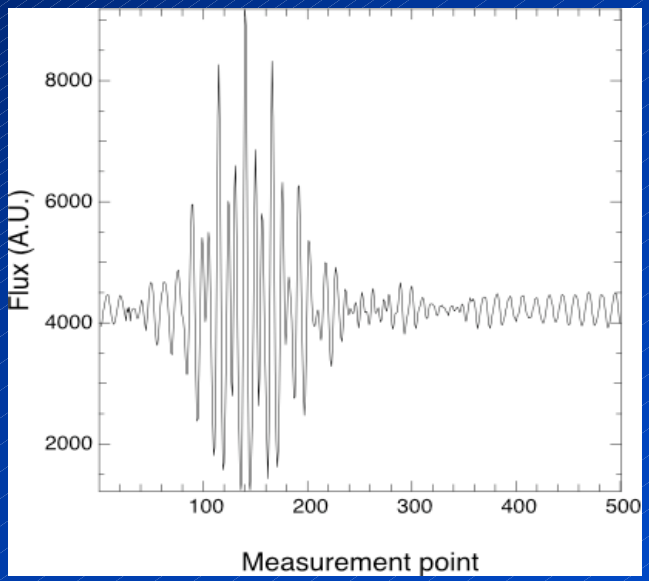




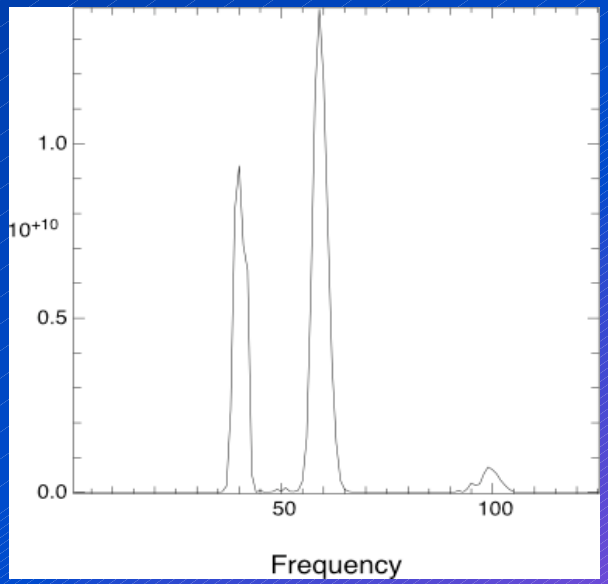
Haguenauer et al. (2000), SPIE 4006-131

Co-axial 3 telescope combiner



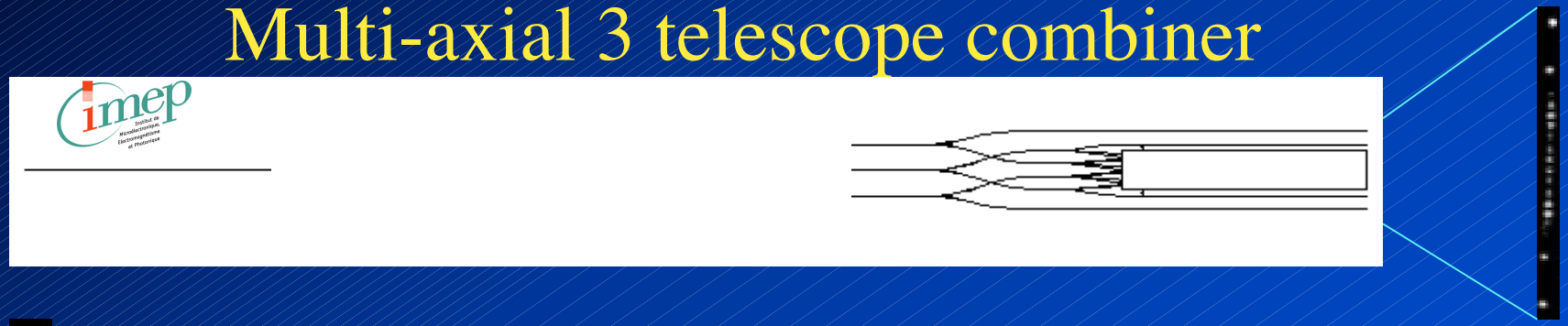


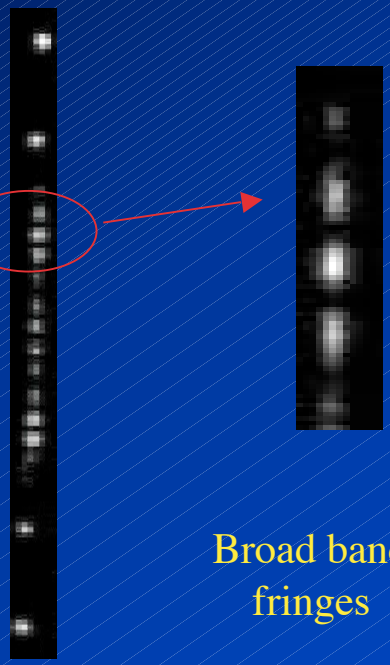
Recorded signal



FFT

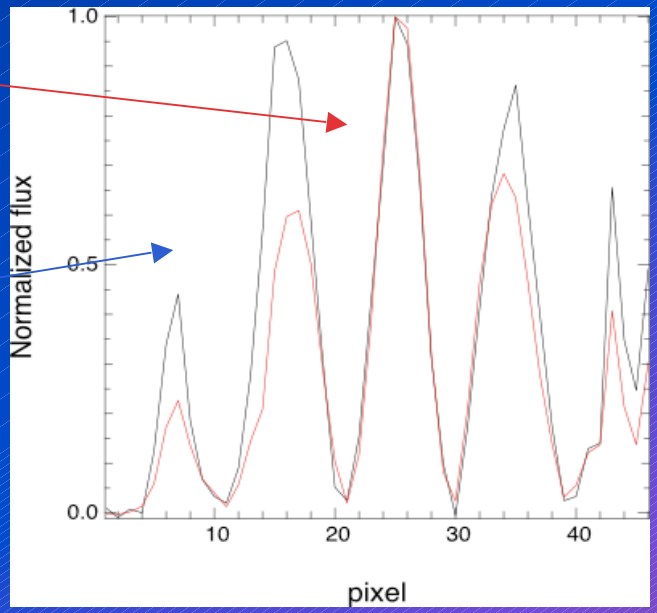
Multi-axial 3 telescope combiner





Broad band fringes

Laser diode fringes



Haguenauer et al. (2000), SPIE 4006-131

Three Telescopes MMI combiner

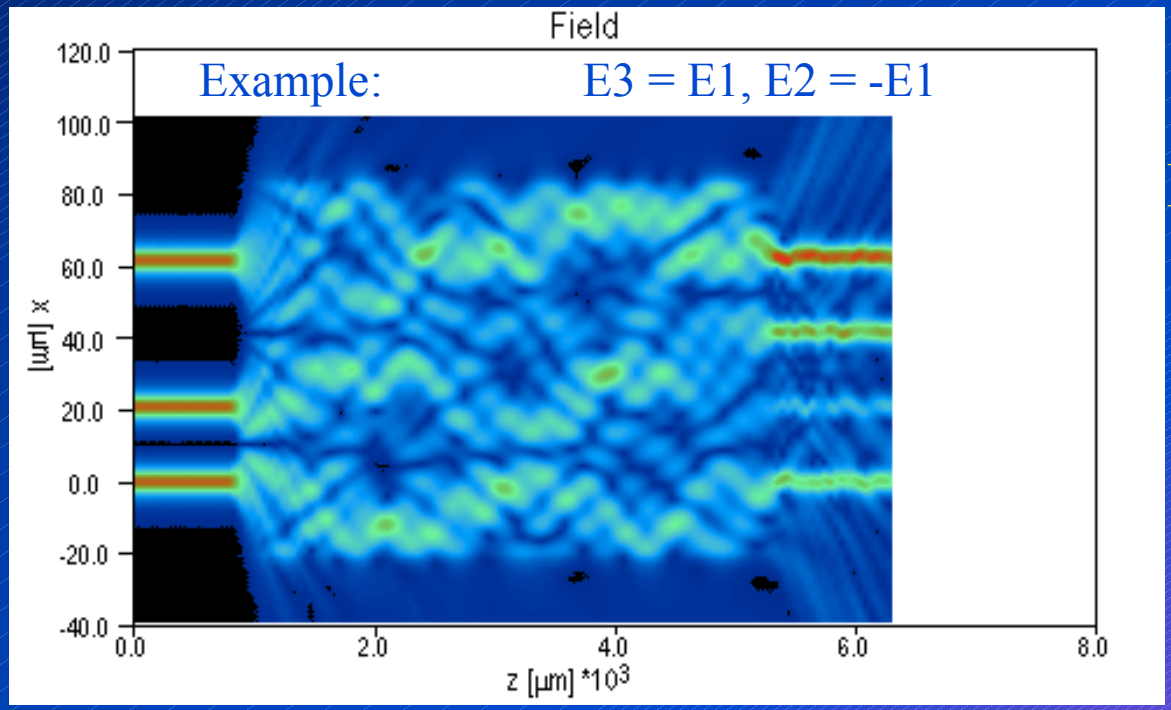
Three inputs and four outputs linked by a complex matrix

Frederic Rooms, Design of a three telescopes interferometer using a multi-mode interference waveguide, SPIE vol 4640

E1 →

E2 →

E3 →



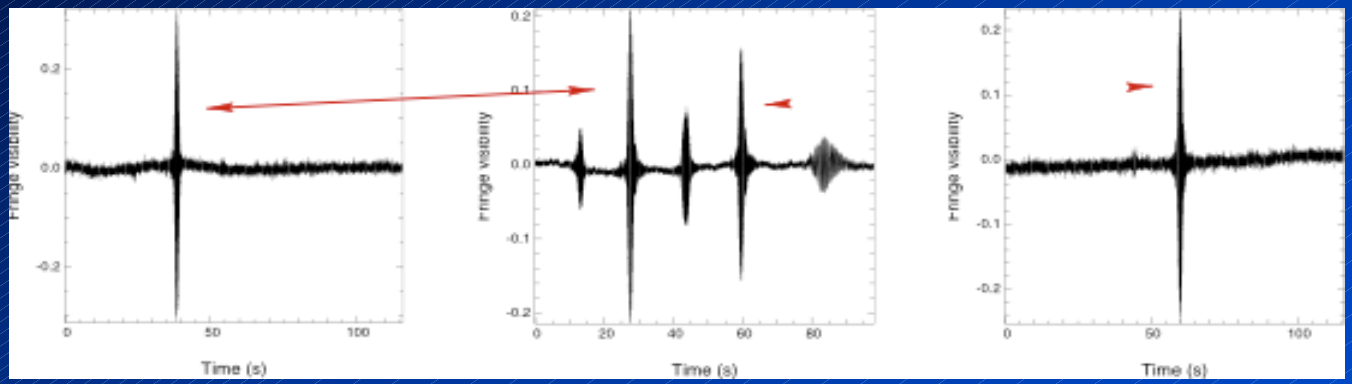
F(E1,E2,E3)

G(E1,E2,E3)

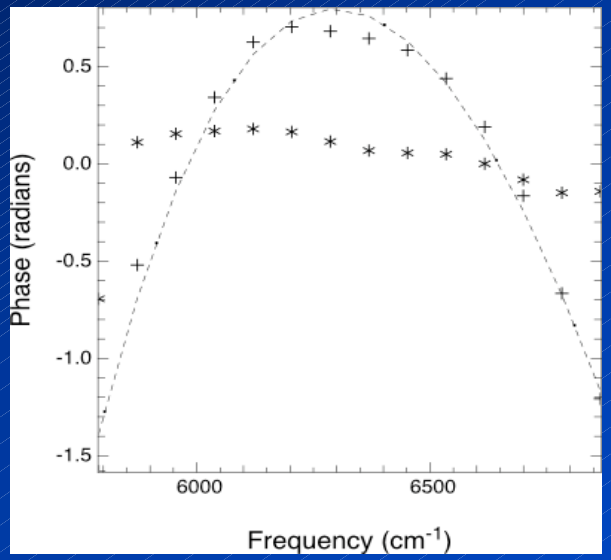
H(E1,E2,E3)

I(E1,E2,E3)

Effects of the **fiber Optics** length difference



Vertical polarization | No polarization control | Horizontal polarization

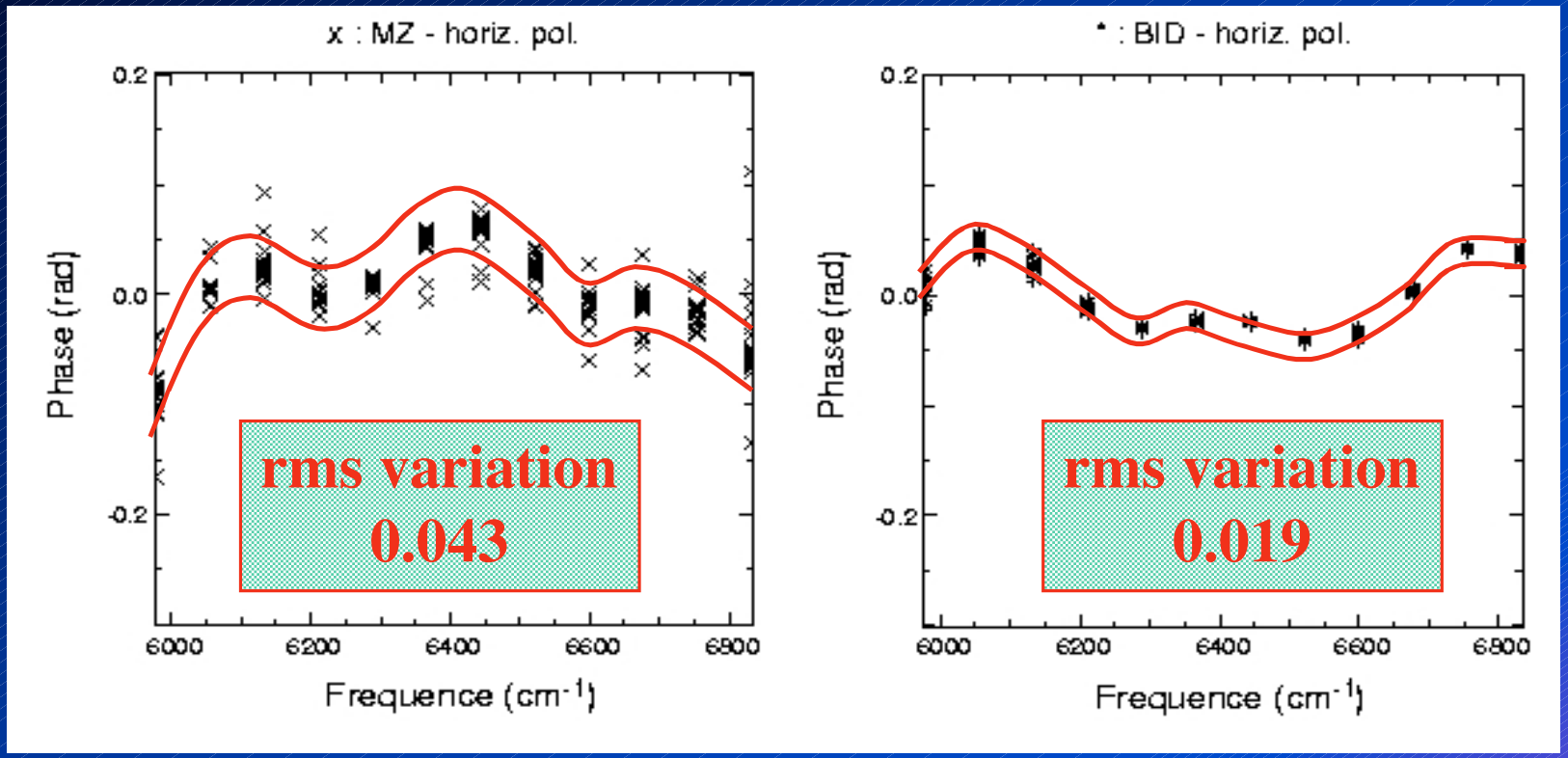


Contrast measurements according to the polarization state, and birefringence behavior demonstration :
Here the measurements have been performed with a 7 cm fiber length difference between the two interferometer arms.

Phase mesurements:
+ with 2 cm fiber length difference
* with equalized fibers

Berger et al. (1999) A&AS, Haguenauer et al.(2000) Appl. Opt.

Phase stability

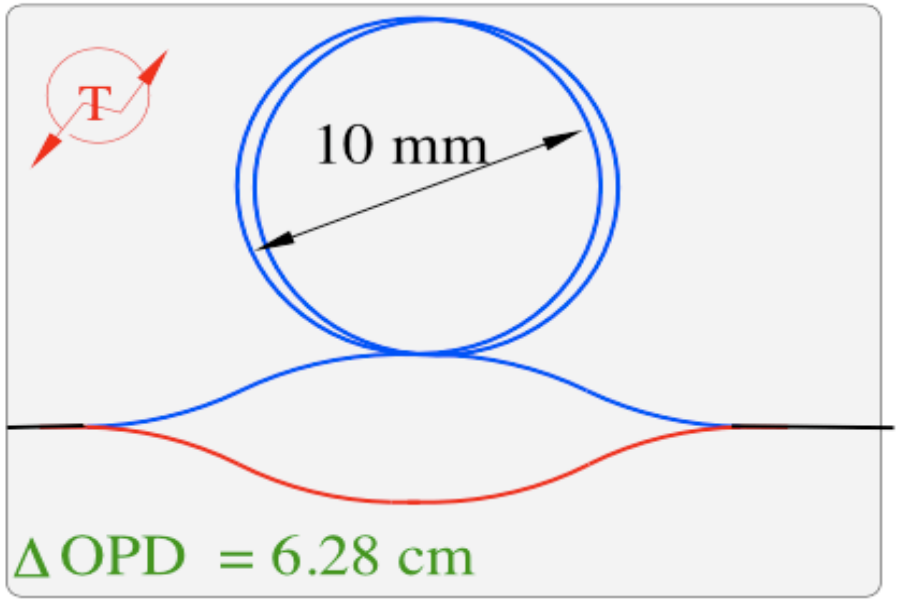


Injection with a fiber optics

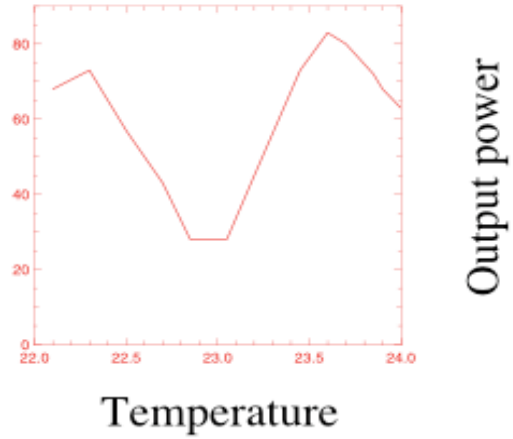
Direct injection

The phase is obtained thanks to a Fourier transform of the interferograms

Temperature dependence of OPD



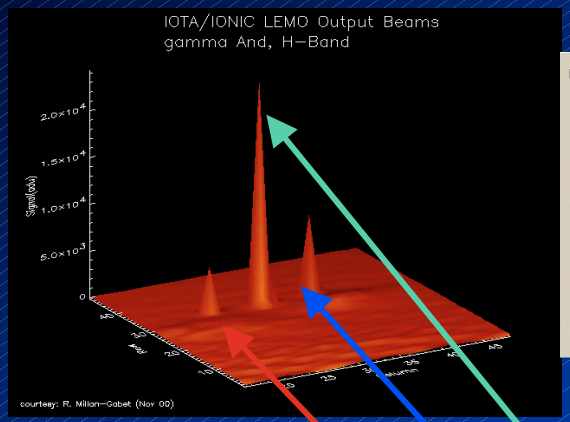
A stability test

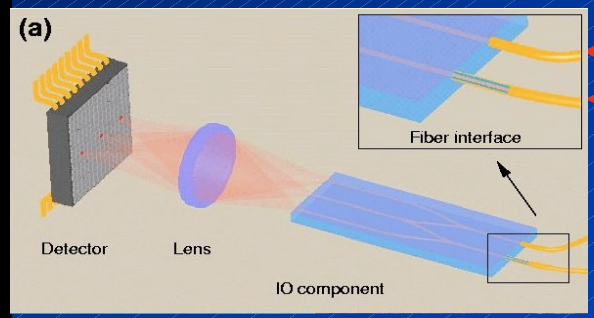


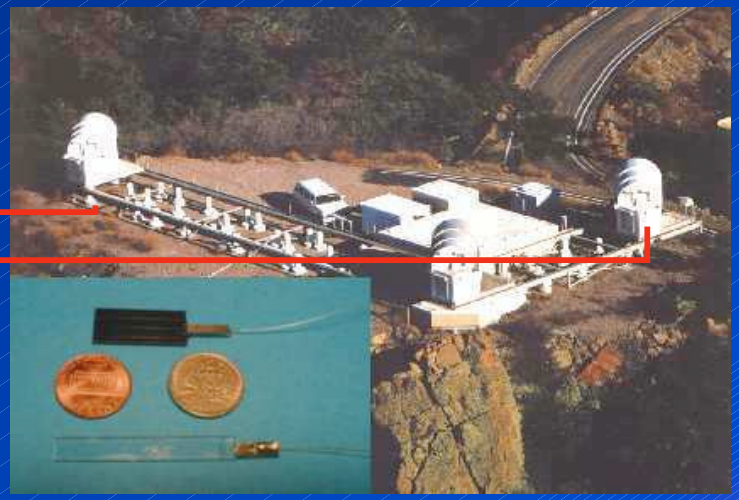
- Δ OPD = 1.6 pm/ (°C . OPD)
  OPD in microns

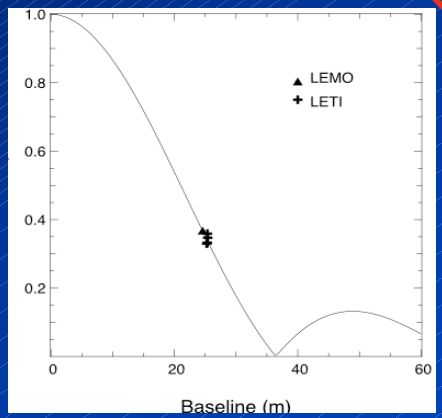
Courtesy of J.P Berger

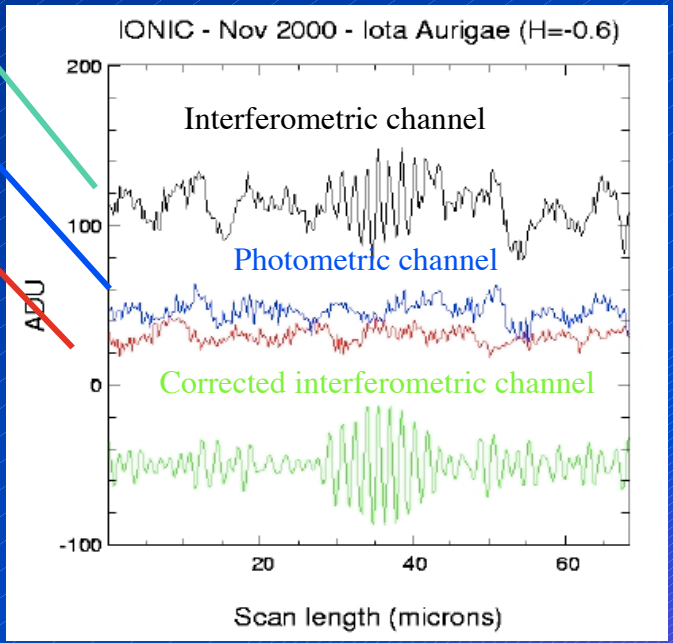
2Telescope beam combiner Tests on IOTA







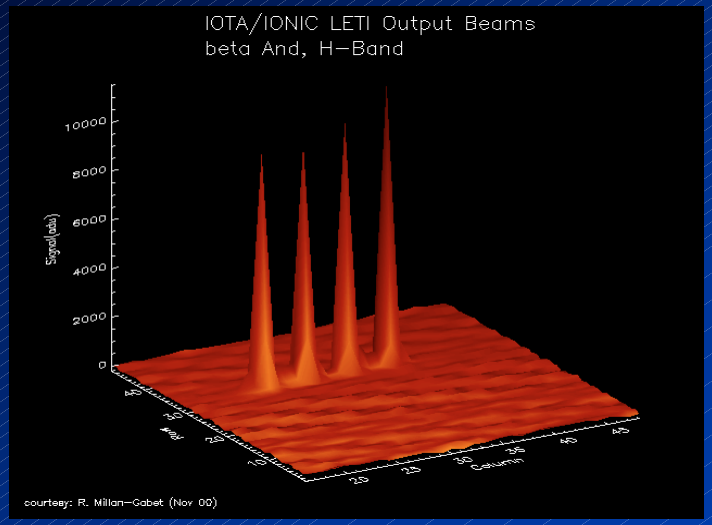


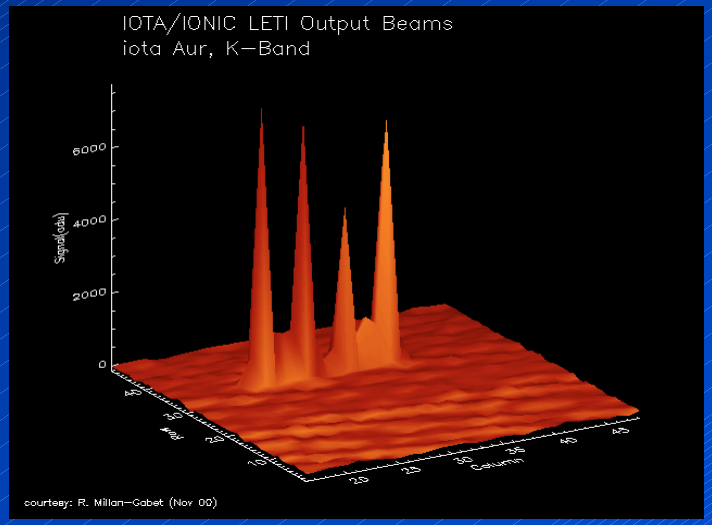


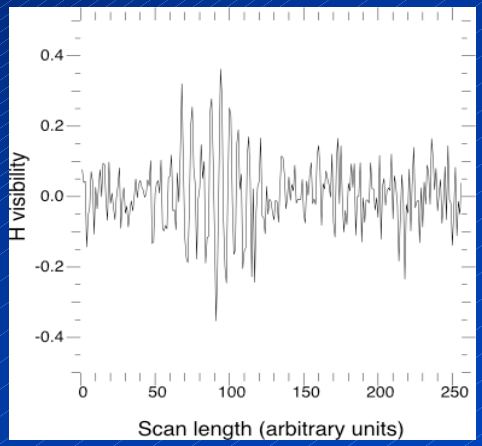
Measurements on UOri

- Instrumental contrast : 80% (H band)
- Accuracy $\leq$ 1%
- Measured diameter: 11.0 ± 0.5 mas
- Limiting magnitude H = 2
- 2 components tested with a exchange time of 2 hours (polarization alignments)

1 single component for H and K' band

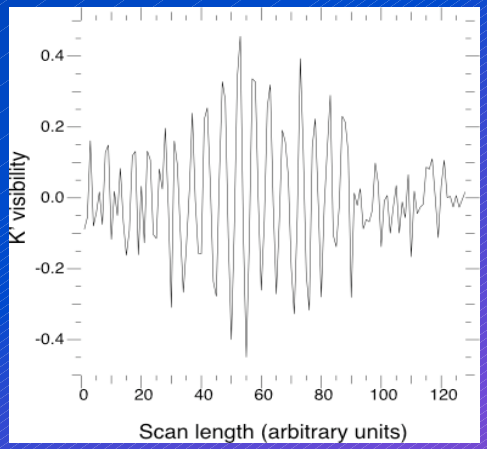






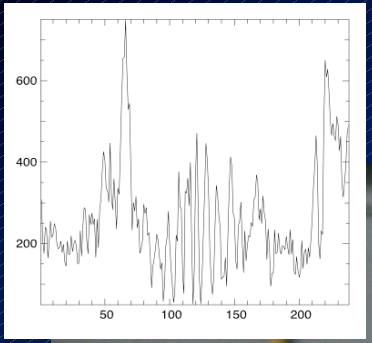
T(H) / T(K') = 1.4 ± 0.2

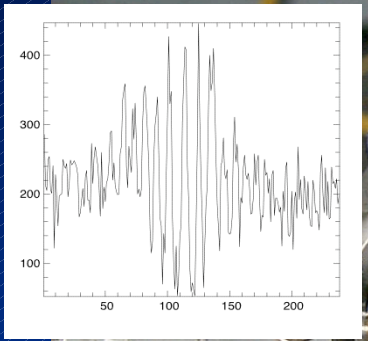
E.Laurent et al, A&A 2002

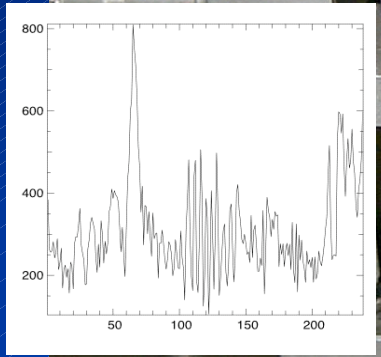


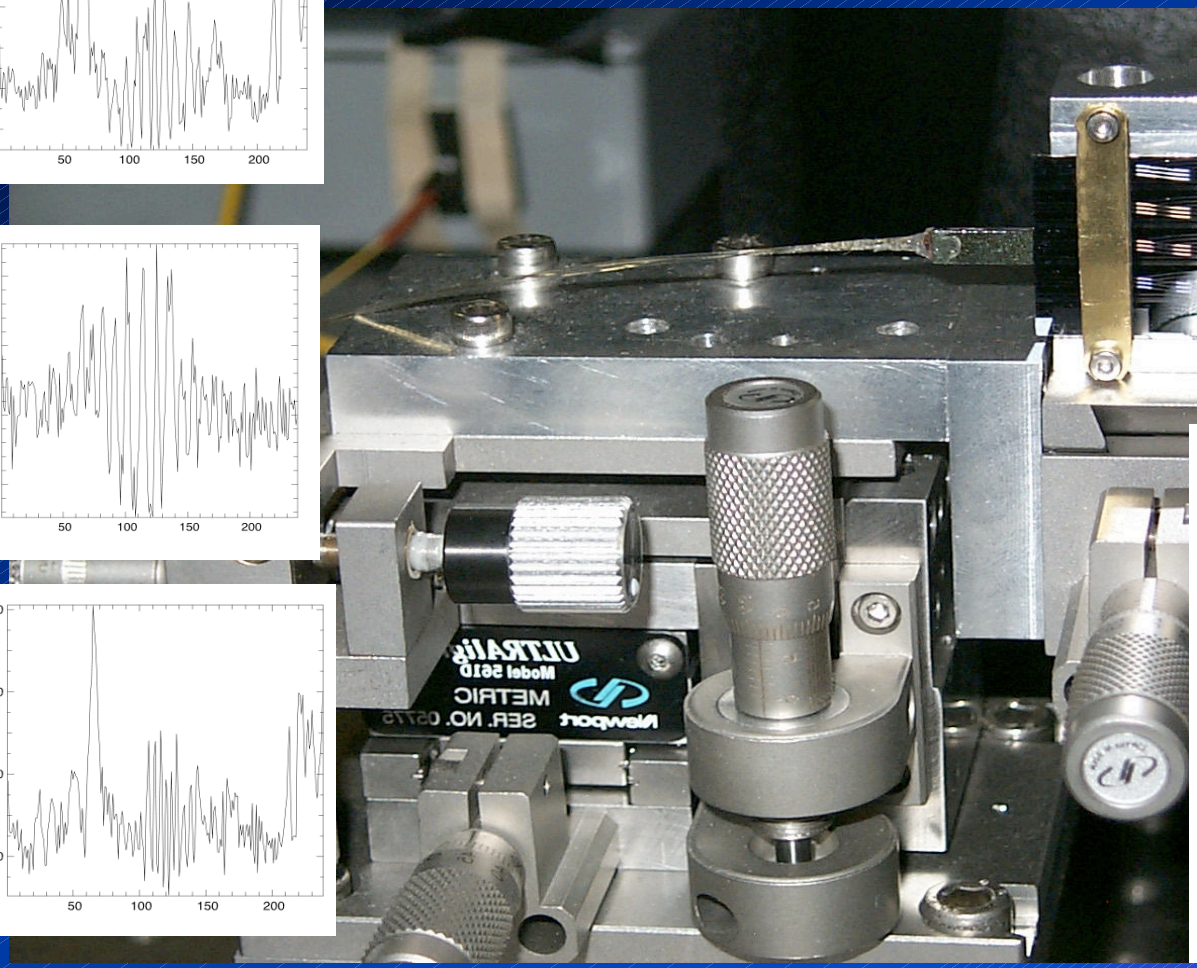
IONIC as IOTA 3T beam combiner

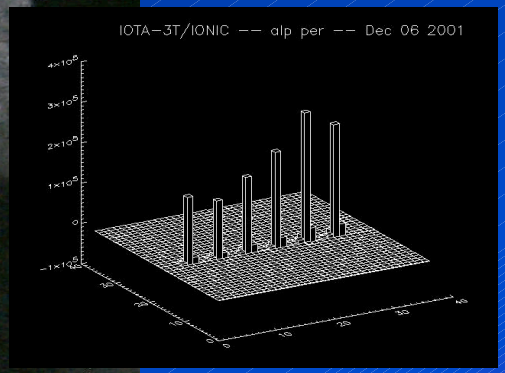
results obtained by the IOTA group ….

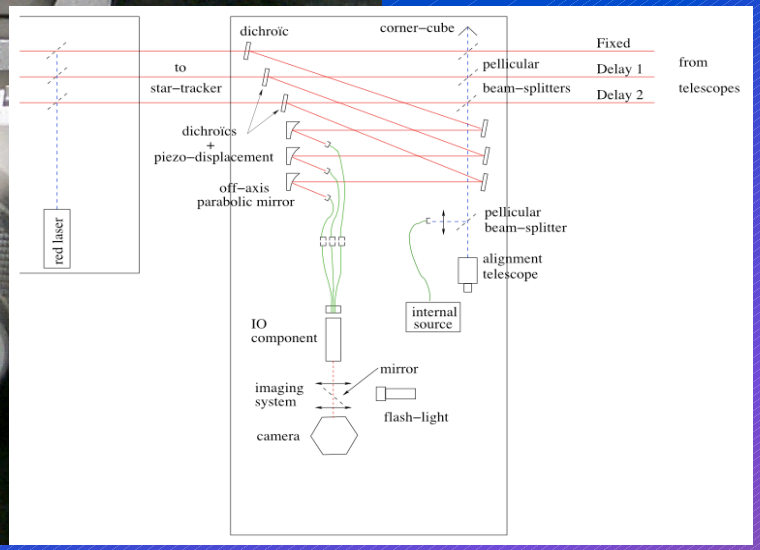








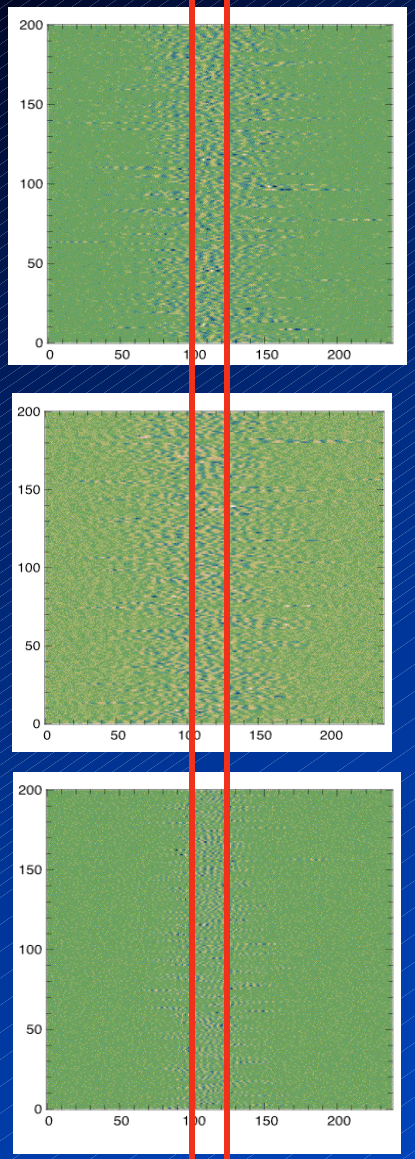


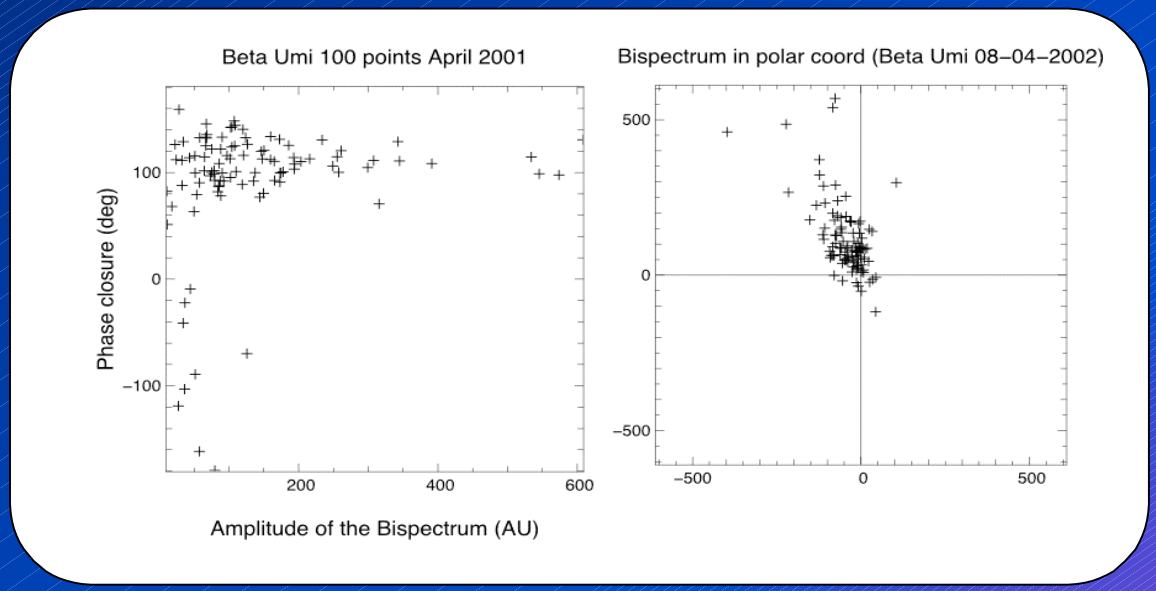


Phase Closure

Bispectrum estimation in a temporal sub window:

signal is considered as coherent



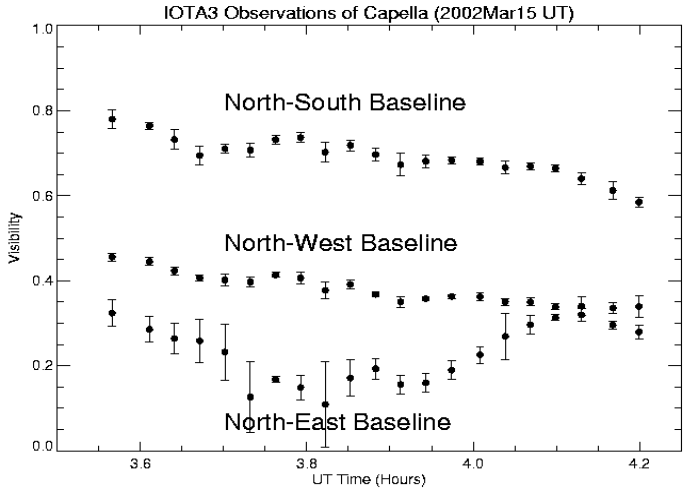


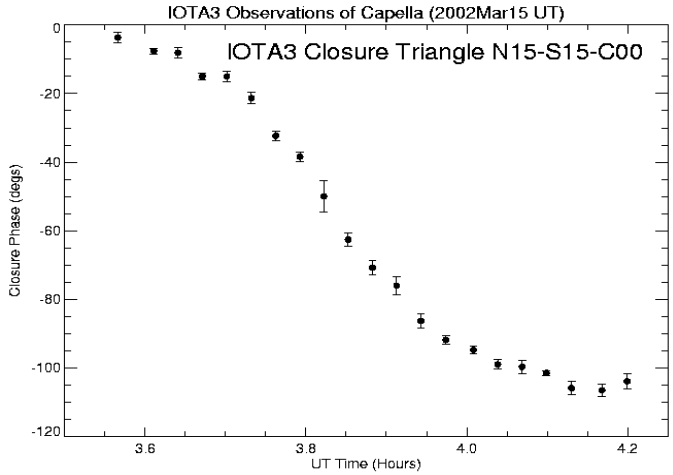
Instrumental phase closure:

119+/- 1.4 degrees

Courtesy of J.Monnier (IOTA/ CfA group)

Capella (IOTA-IONIC)

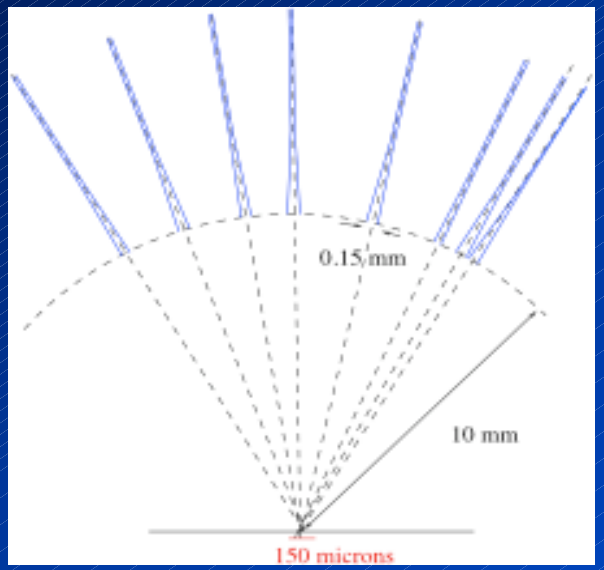


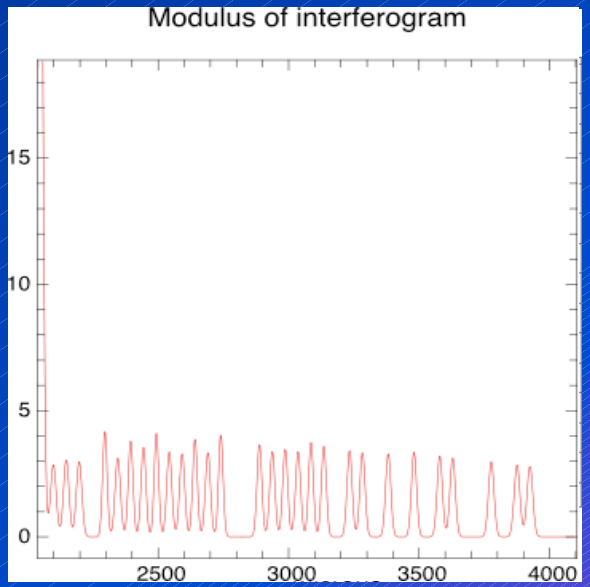


Courtesy of J.Monnier (IOTA/ CfA group)

Design for 8 T combiner

(J.P. Berger et al. 2000 SPIE)





Y junction transmission

(Techno IMEP, Ag+ ions components)

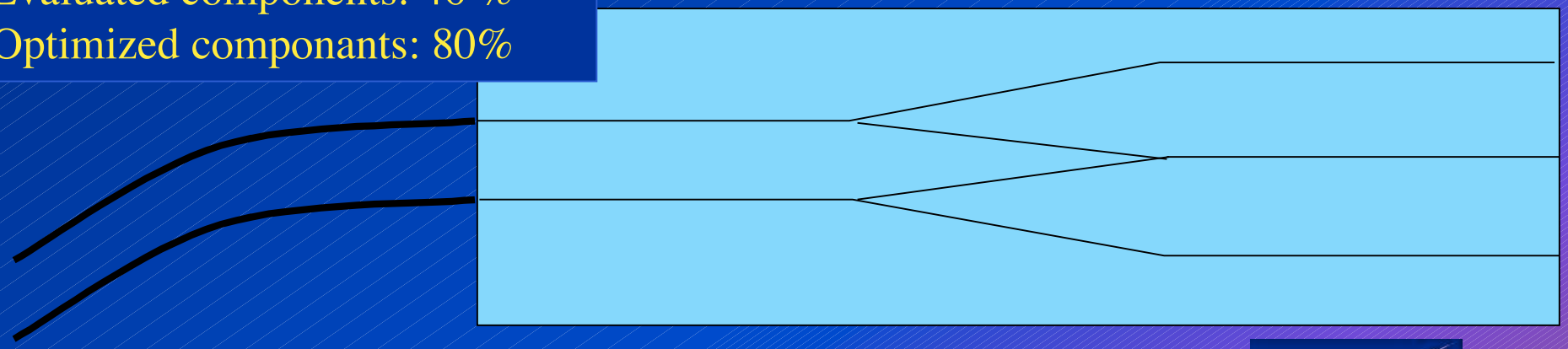
fiber-guide coupling: Actual measurement 80%
Possible improvement thanks to guide/fiber core size adaptation : >95%

Propagation : 91 % for a 4 cm wave guide (0,1 dB/cm for Ag+)

Typical function efficiency: 95 %

Y Junction : 50 % (X and MMI up to 100%)

Overall transmission:
Evaluated components: 46 %
Optimized componants: 80%

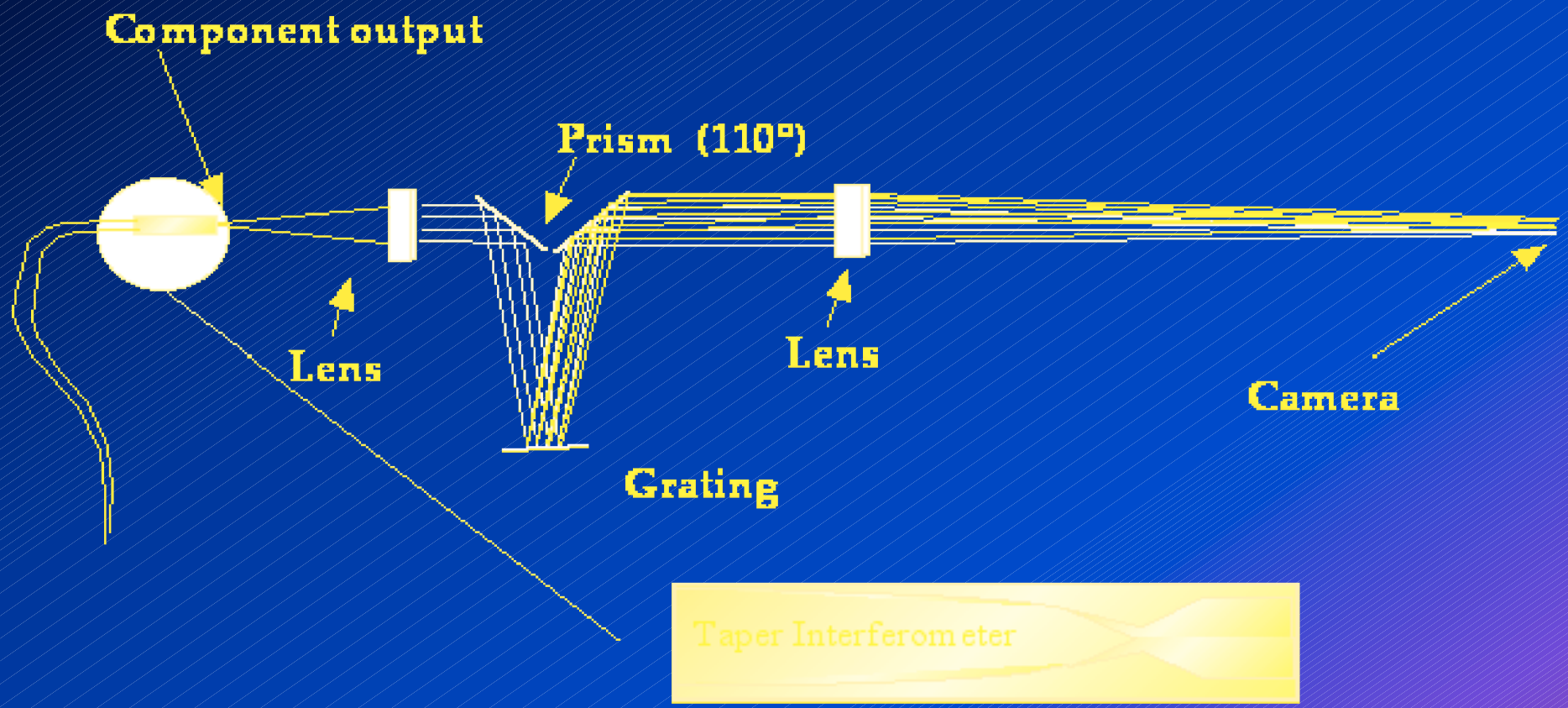


Nulling interferometry

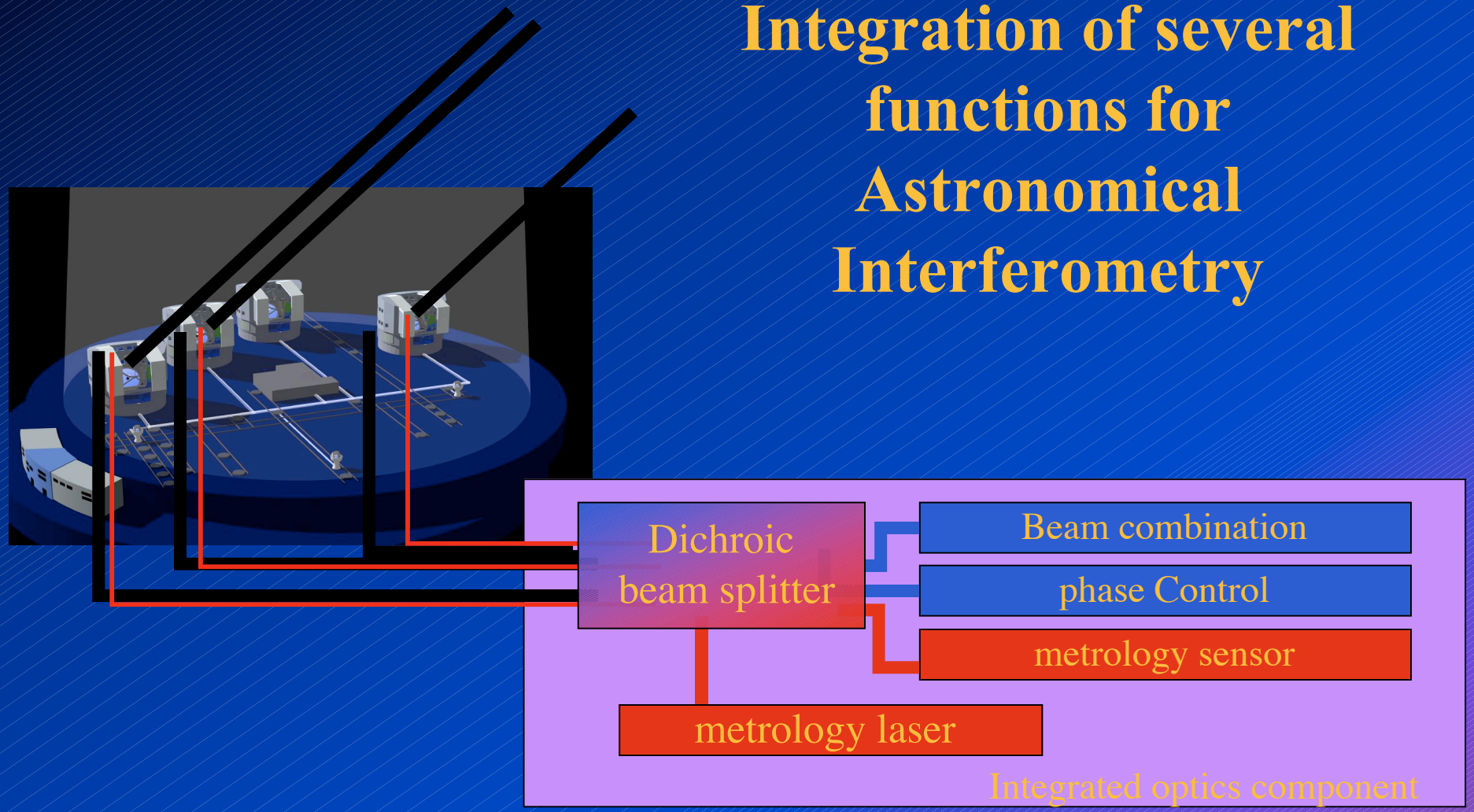
Specifications to achieve a 10^{-6} Nulling and measured performances

	Specifications	Performances
Spectral range	1.3 - 1.6 µm	OK - 1.17 - 2.3 µm
Power Transmission	36 %	OK 58 %
Chromatic transmission	DT (λ) ≤ 10^{-3}	OK ≤ 10^{-2} (limit of bench)
Geometrical path difference	≤ 10 µm	OK ≈ 1 µm
Polarization	≤ 10^{4}	OK ≤ 10^{5}
WFE filtering	10^{-7}	OK (simulations)

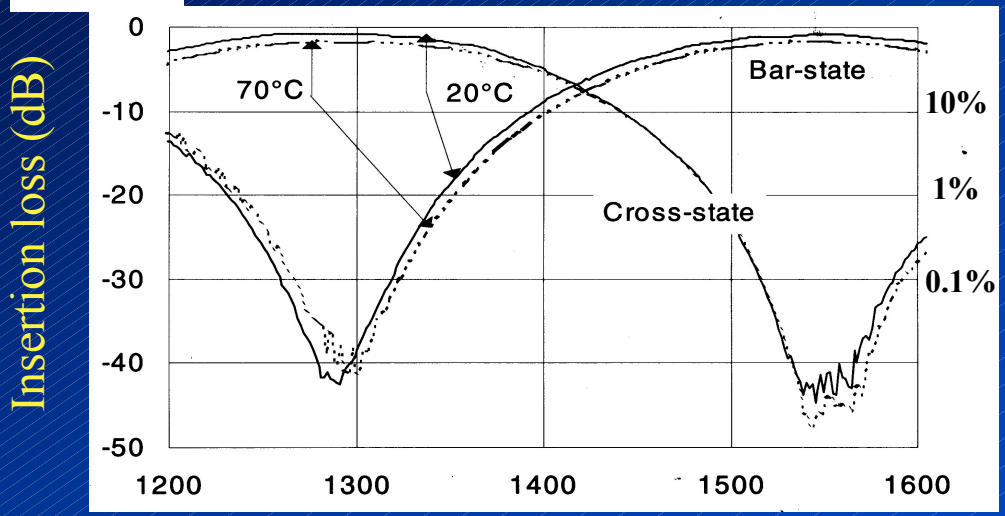
Integrated optics fringe sensor principle



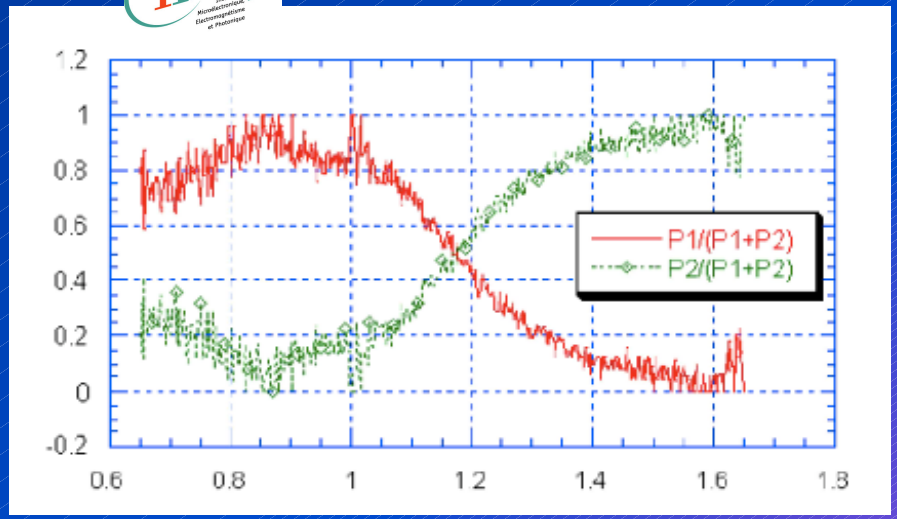
Integration of several functions for Astronomical Interferometry



Wavelength (de) multiplexer



Wavelength



Wavelength

Conclusions (1/2)

- Apart from its compactness Integrated Optics offers very stable optical behavior (polarization, phase, OPD variation, alignment). It allows to obtain very suitable solutions for beam combiner instrument.
- IO flexibility, allow easy and fast exchange between existing instruments according to the observing conditions (beam combiner arrangement, operating wavelength range).
- Main IO functions are available for λ ranging from 0.8 μm to 1.6 μm which correspond to wavelength required for telecoms and sensors. IO use can be easily extended to the 0.5-2.5 μm range without major developments using available technologies.
- Either lab and on the sky demonstrations have been done for the H and K atmospheric bands

Conclusions (2/2)

- Developments of dedicated functions for astronomical interferometry are in progress, mainly beam combiners for several telescopes (3 and more).
- 2 and 3 beam combiners were tested successfully on the sky using IOTA facilities in the H band (H and K band for 2 telescope beam combiner).
- Further developments are also in progress to extend IO application to larger wavelengths (thermal IR in the 4-18 μm range)
- Fully integrated instruments, including internal metrology, will be possible as soon as dedicated dichroïc IO beam splitter will be available for astronomical purpose, i.e. for atmospheric band separation (J, H, K).