Centre Spatial de Liège
Université de Liège

Applications of inorganic photorefractives : marketed systems and potentialities

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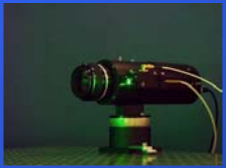
Summary

- The Centre Spatial de Liège
  - Activities with PR materials
- Applications of PR materials :
  - General context
  - Laser mode filtering and enslaving
  - Detection of ultrasound by laser
  - Holographic interferometry

Laser Techniques Group

- Formerly Non Linear Optics
- 3 scientists-engineers + part-time technician
- First activities (start 1988)
  - Photorefractive crystals characterization
  - Applications in optical information processing
- Since 1993 : Development of holographic camera
  - Many projects (Eur. Defense Agency, Walloon Region, European Union, ESA)
  - Creation of Spin-off OPTRION (2001)

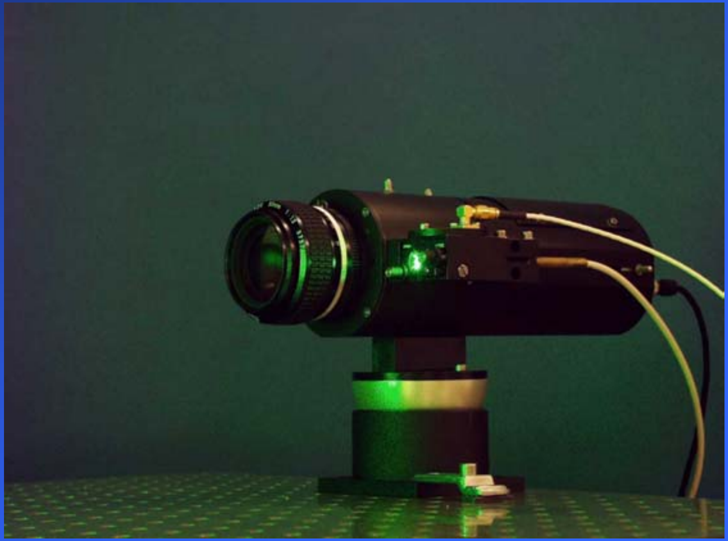


- Since 1998 : Photorefractive Crystal growth
  - Technology transfer from Univ. Bordeaux

- Recent :
  - Digital Holography
  - Laser Induced Breakdown Spectroscopy

Laser Techniques Group

- Photorefractive holographic camera

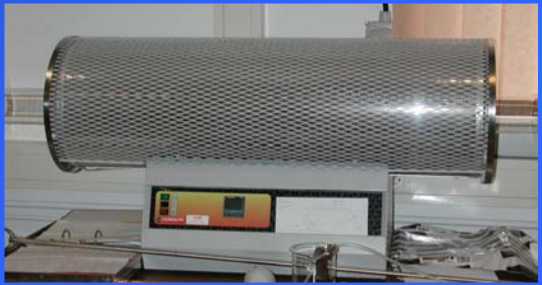


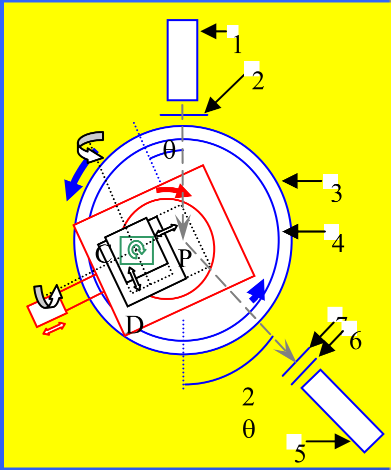
  - Displacement metrology
  - Non destructive testing
  - Compact
  - Userfriendly
    - In-situ recording of holograms
    - Indefinitely reusable

  - High power monomode fiber
    - (World patent)
    - Transmission 80%
    - 5 Watts injected
    - VERDI laser

Laser Techniques Group

- Photorefractive Crystal growth facilities
  - BSO (stopped)
  - CdTe (1 thesis, NATO collaboration)





Applications of inorganic PRCs

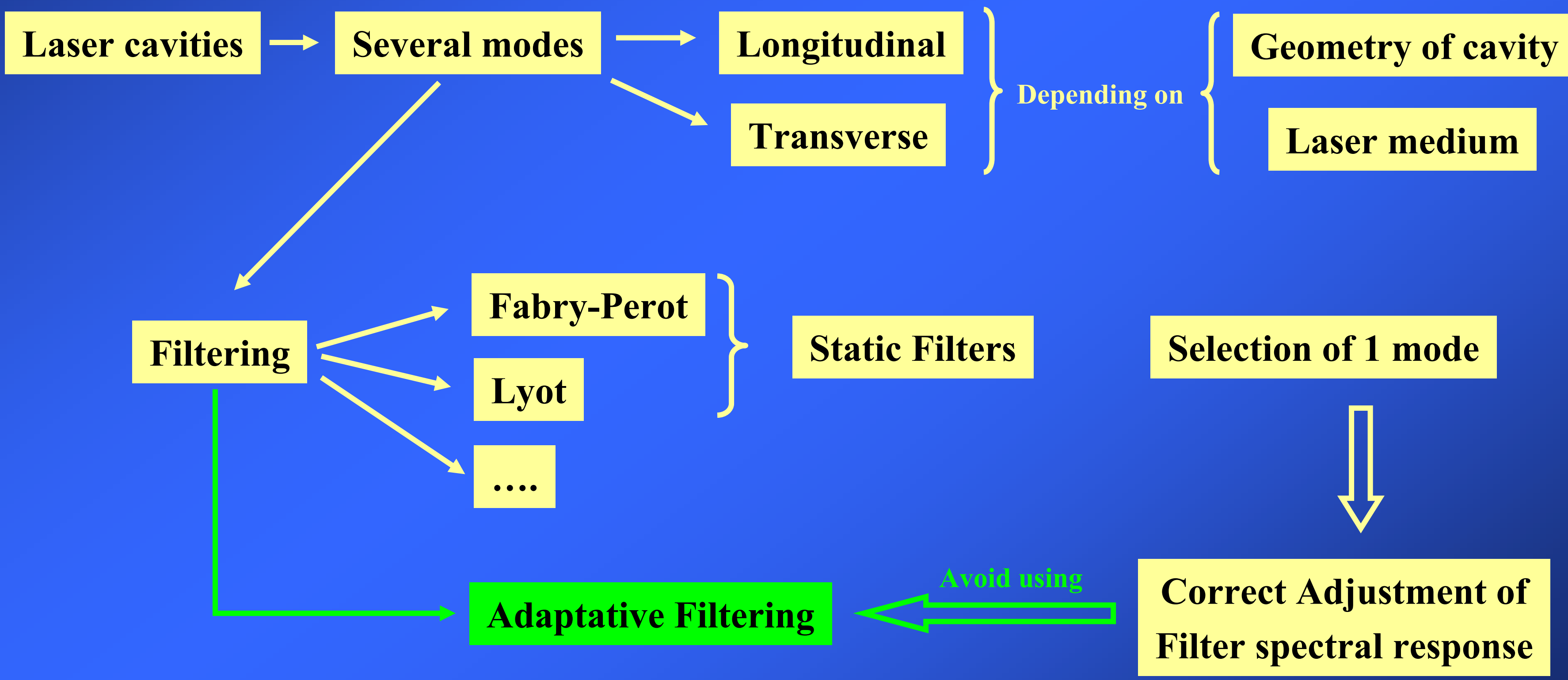
- Many applications
  - Data storage
  - Phase conjugation
  - Optical processing
  - Coherent imagery through turbid media
  - Holographic filtering
  - Non destructive control
  - …..
- Literature : springer Series in Optical Sciences

  « Photorefractive Materials and Their Applications »

- OSA Toptical Meetings on Photorefractive Materials, Effects and Devices : e.g. PR’07, Lake Tahoe
- Best Applications of PR Materials
  - Must be marketed or have a high potential

Holographic adaptative filtering

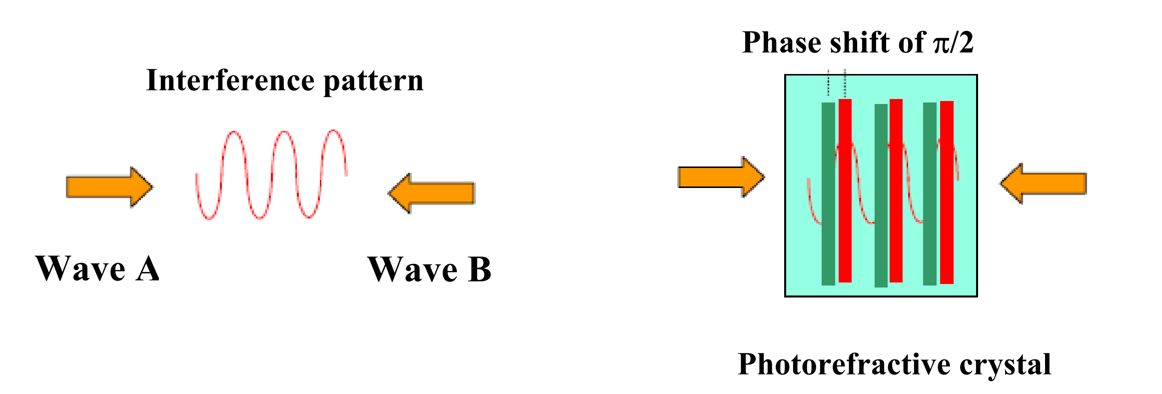
- Filtering of laser modes

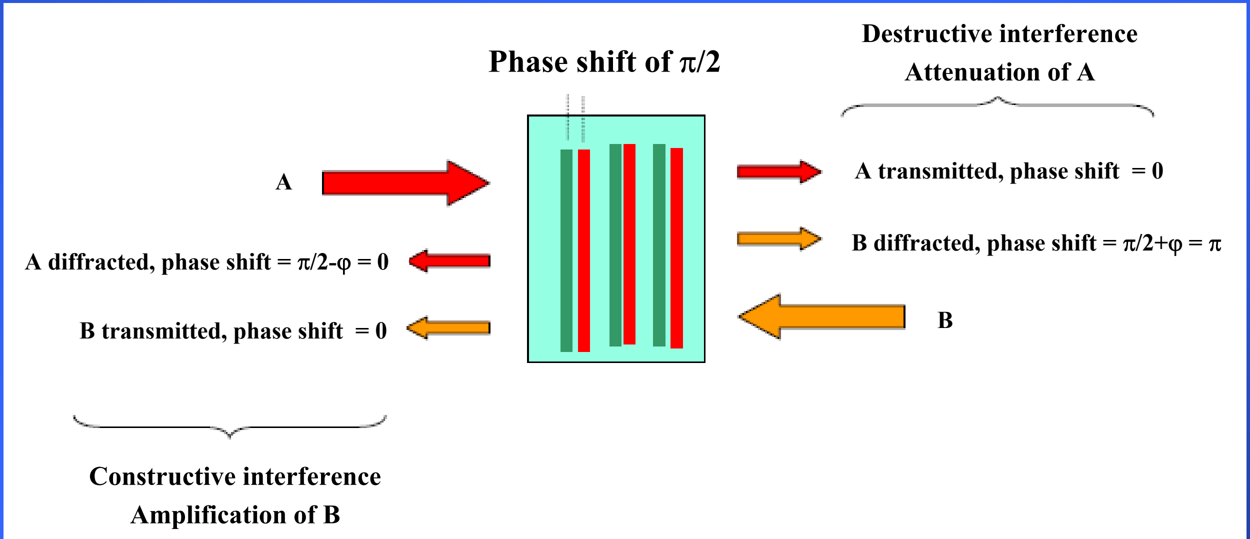


Laser mode filtering and enslaving

Self organized laser cavities

- Filtering of laser modes (courtesy of Gilles Pauliat, Inst. Optique, Palaiseau, Fr)





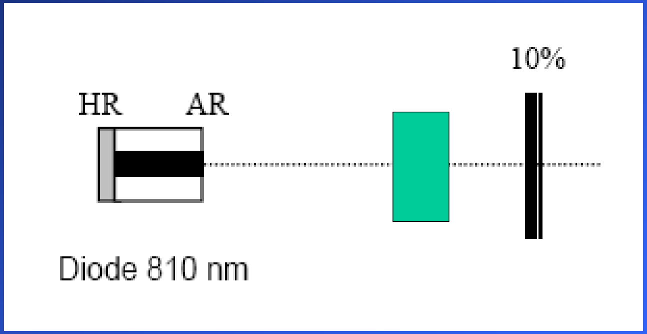
φ : phase shift due to diffraction by refractive index grating
$\varphi = \pi/2$

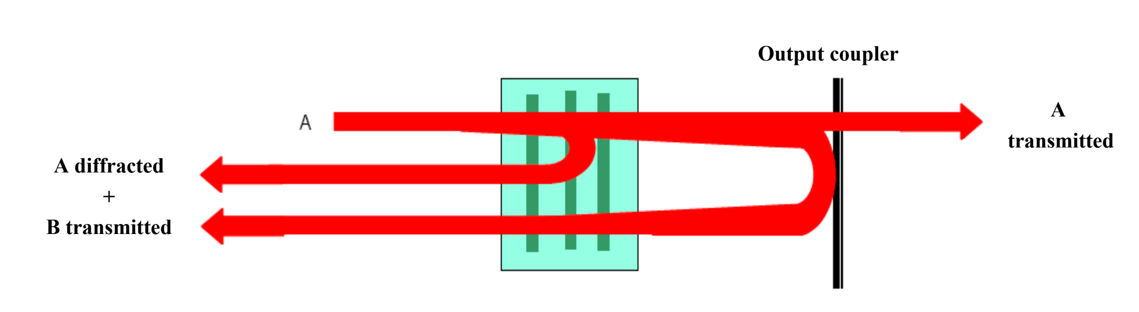
This happens for one wavelength
Other wavelengths do not match

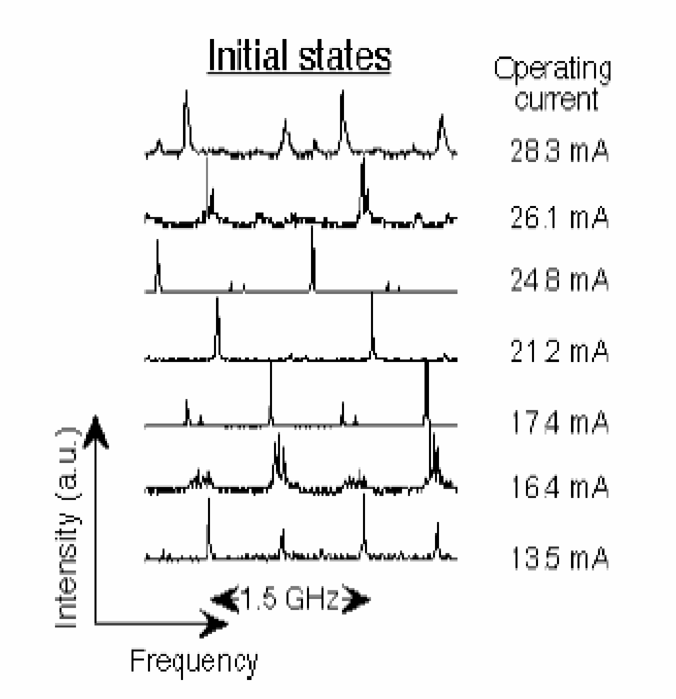
Amplification for a single wavelengt

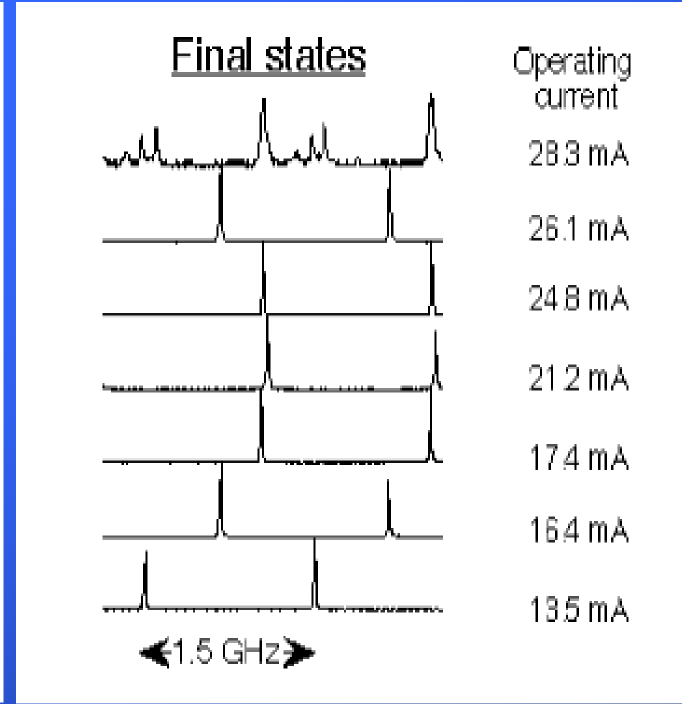
Self organized laser cavities

- Filtering of laser modes (courtesy of Gilles Pauliat, Inst. Optique, Palaiseau, Fr)





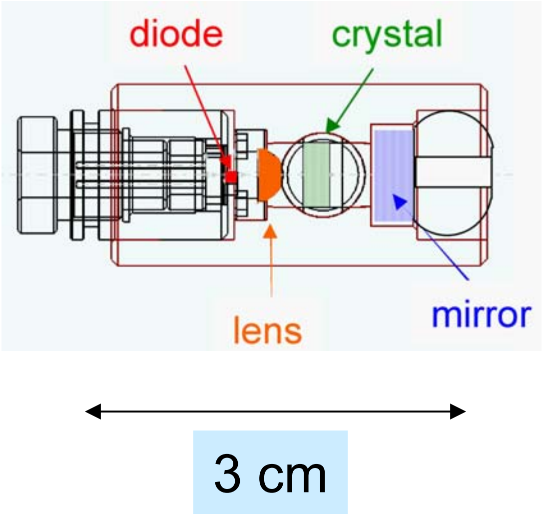


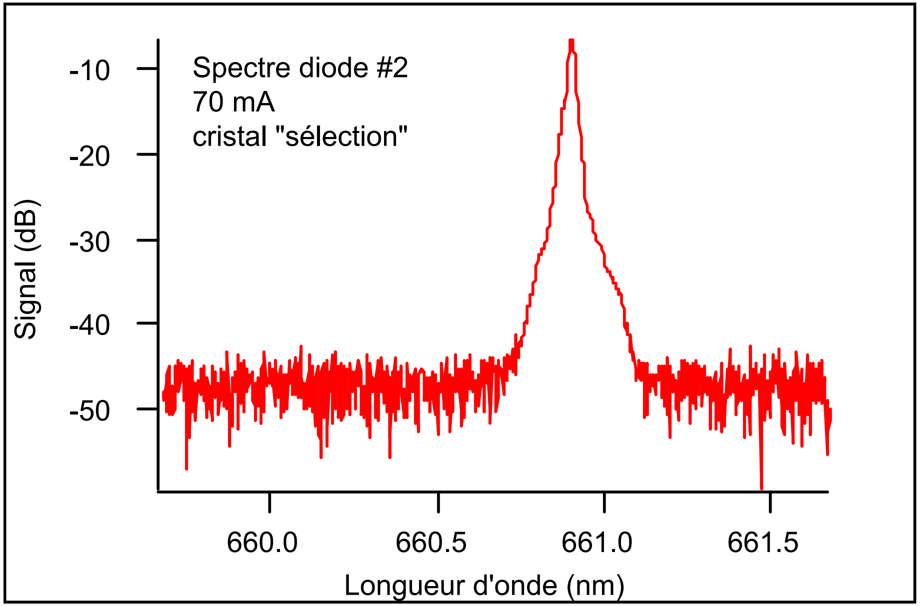


Self organized laser cavities

- Filtering of laser modes (courtesy of Gilles Pauliat, Inst. Optique, Palaiseau, Fr)

Ex : monolithic cavity
15 mW at 660 nm,
with $Co:BaTiO_3$

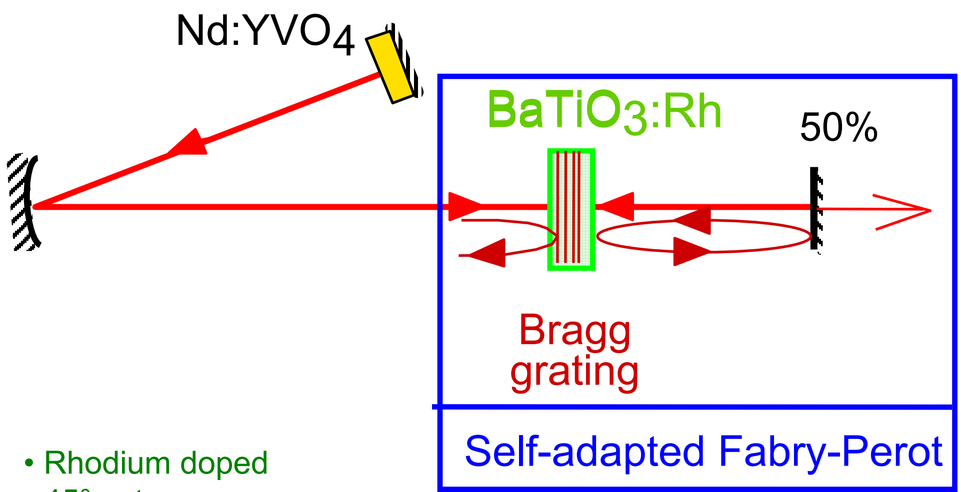




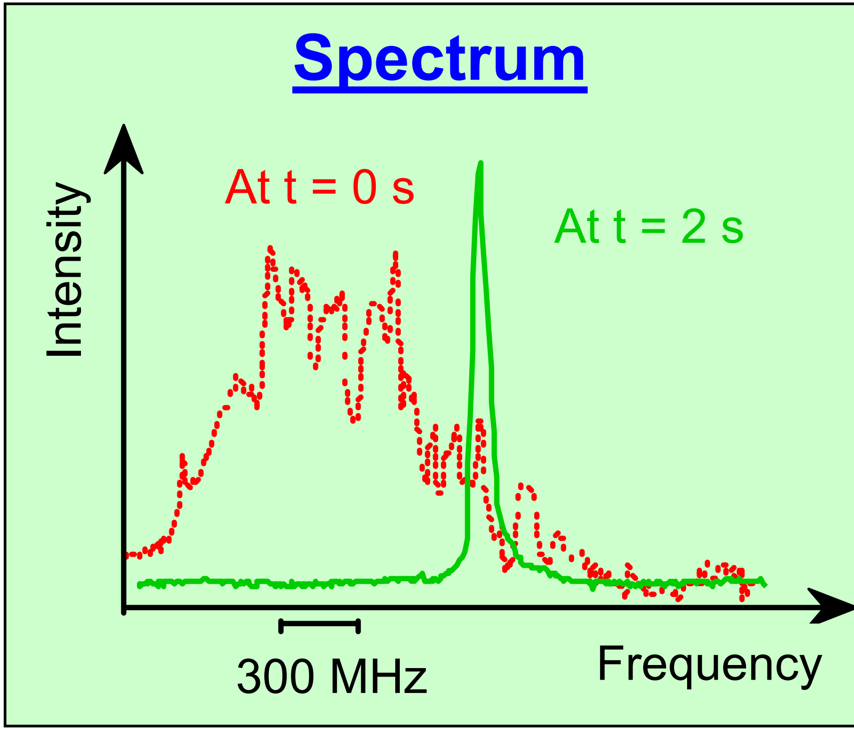
Self organized laser cavities

- Filtering of laser modes (courtesy of Gilles Pauliat, Inst. Optique, Palaiseau, Fr)

Initially : diffraction limited beam, but several longitudinal modes



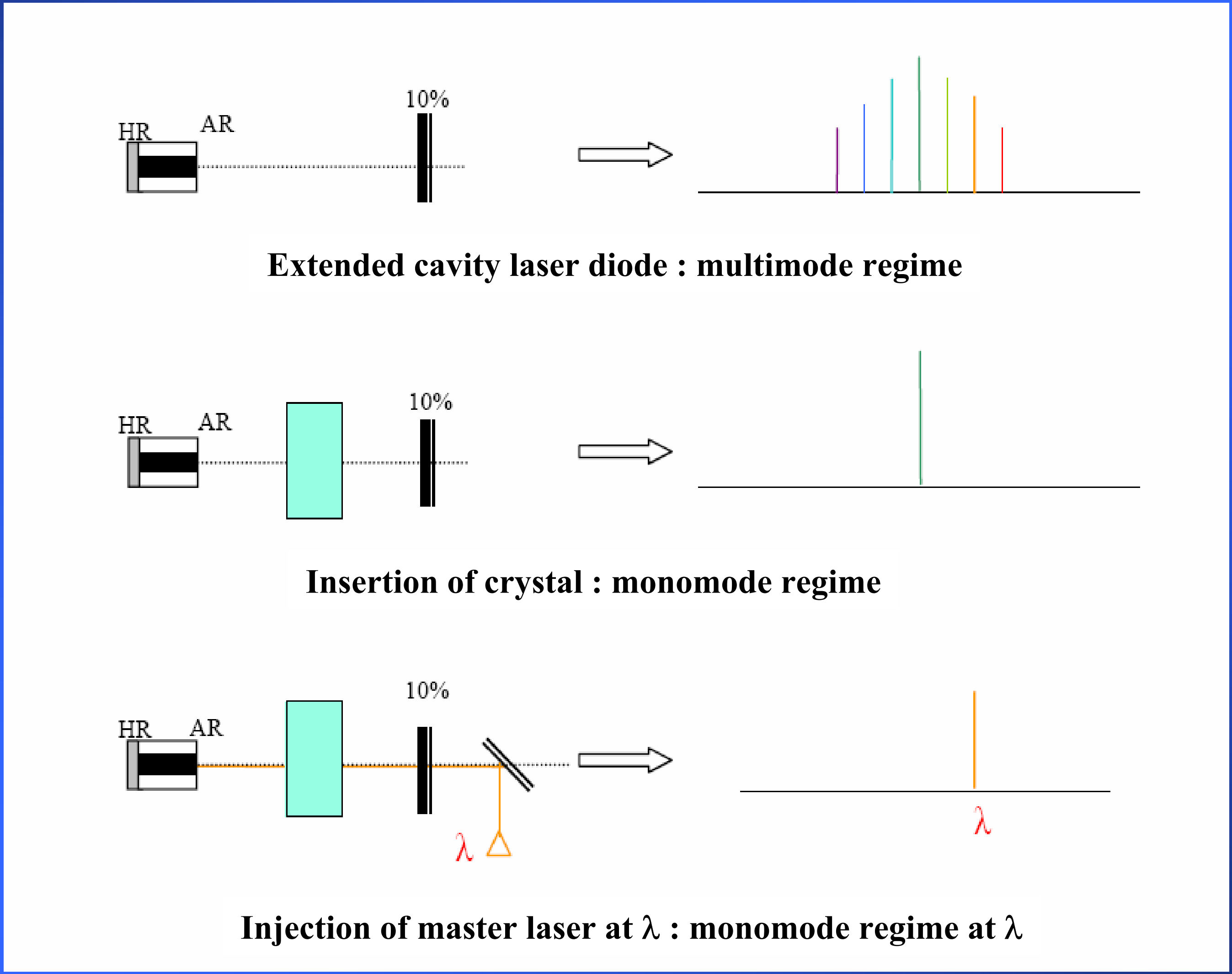
- Rhodium doped
- 45° cut
- thickness = 3.5 mm
- α = 0.1 cm^{-1}, Γl=0.2
- provided by D. Rytz, FEE



Adaptation toward a single longitudinal mode within 2 s

Self organized laser cavities

- Injectable laser with wavelength memory (Gilles Pauliat, Inst. Optique, Palaiseau, Fr)



Extended cavity laser diode : multimode regime

Insertion of crystal : monomode regime

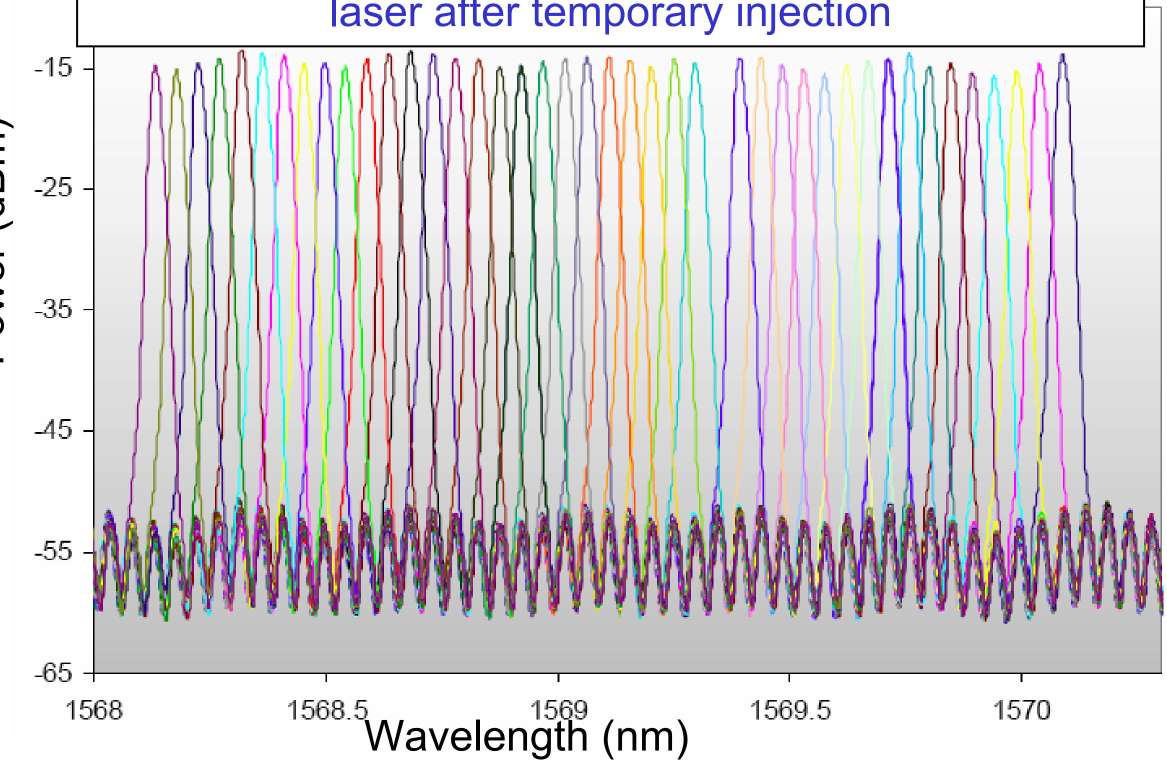
Injection of master laser at λ : monomode regime at λ

Self organized laser cavities

- Injectable laser with wavelength memory

(courtesy of Gilles Pauliat, Inst. Optique, Palaiseau, Fr)

Superposition of spectra memorized by the slave laser after temporary injection



Targeted applications

Telecom source WDM PON

Source for instrumentation

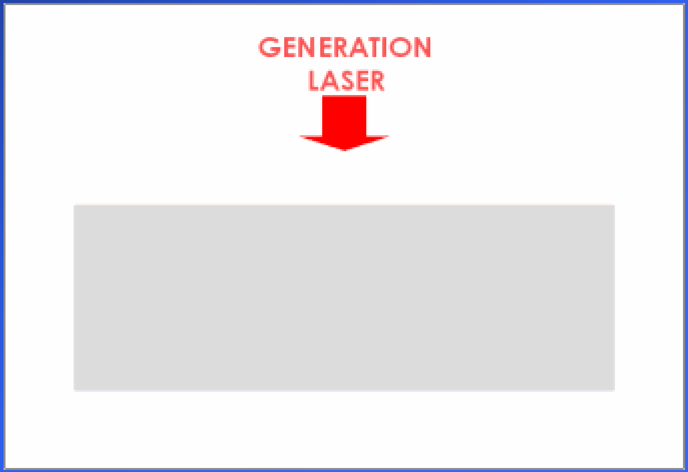
Injection by a master laser
or by a filtered Amplified Spontaneous Emission source

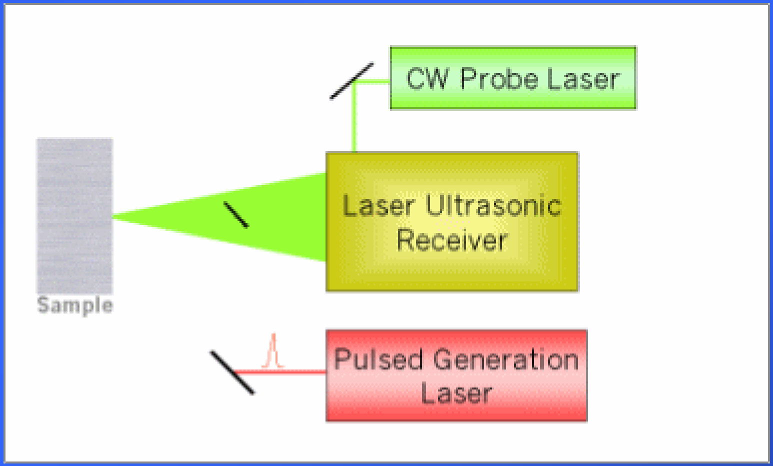
Self organized laser cavities

- Material issues
  - Use crystal matching wavelength of laser (obvious)
  - Reflection Bragg grating : thick enough
  - PR crystal used in diffusive regime :
    - phase-shift = $\pi/2$
    - No electric field
  - $\Gamma l \sim 0.2 - 0.5$ (not higher otherwise unstable)
- Present prospects
  - Grow CdTe crystal for 1.55 µm

Ultrasound detection by laser

- Global principle of Laser Ultrasonics



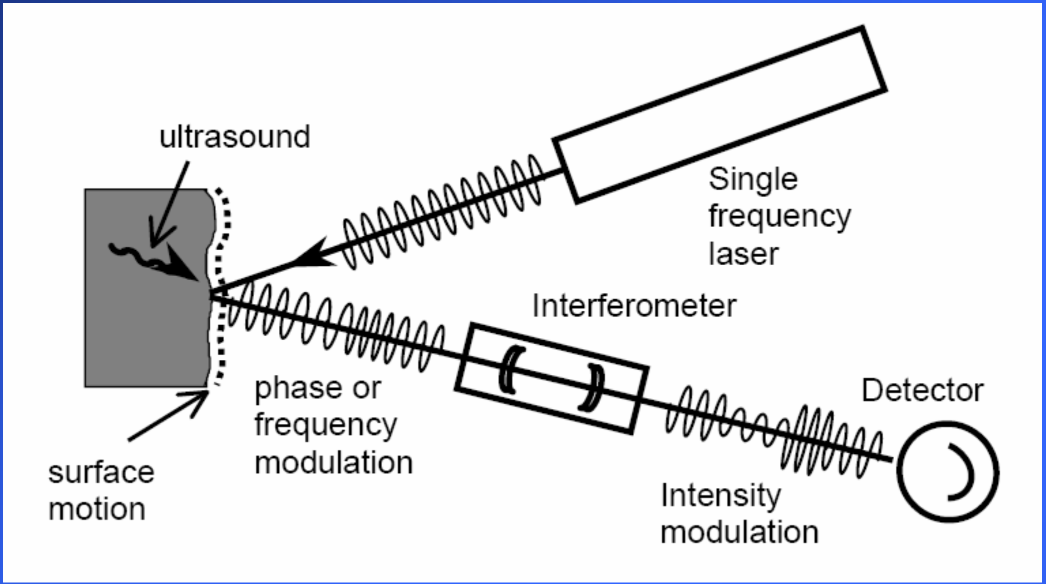


- Interest :
  - Non contact/no couplants
  - Hostile environments
  - Complex shapes
  - Extended bandwidth compared with traditional contact US

Detection of Ultrasound by Lasers

Ultrasound detection by laser

- Confocal Fabry-Perot interferometer

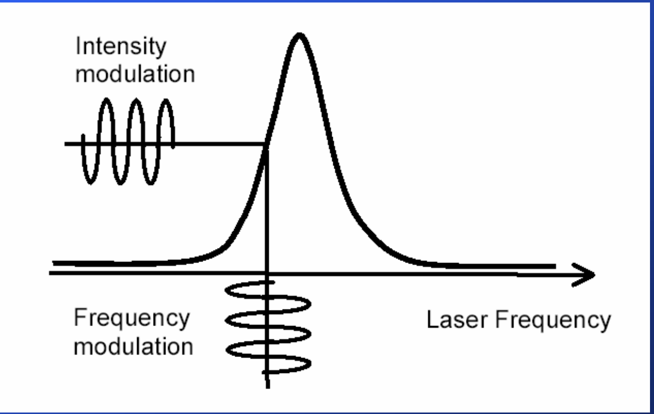


Ultrasonic motion of surface

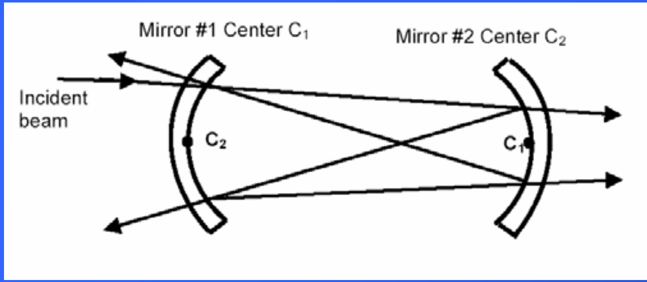
⬇

Doppler shift of laser frequency

Frequency modulation transformed as intensity modulation



Confocal F-P allows large throughput
Ideal for speckled beams (scattering surfaces)



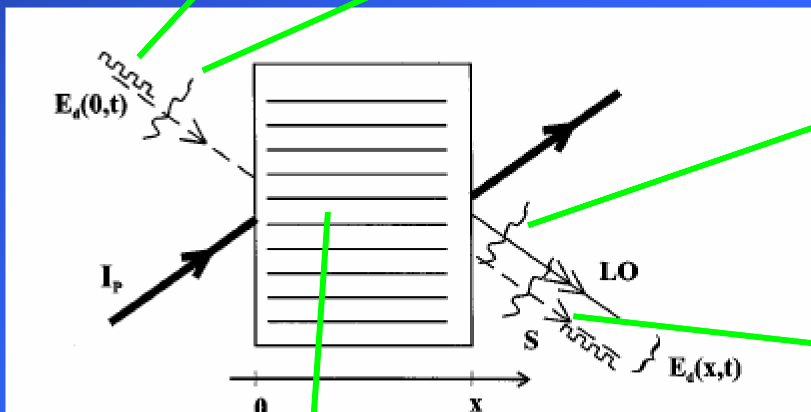
Ultrasound detection by laser

- Confocal Fabry-Perot interferometer : Drawbacks
  - Stabilization of cavity required
  - For MHz bandwidth : long FP cavities (50 cm – 1 m)
  - Complex and cumbersome systems
  - Weak sensitivity to low US frequencies (< MHZ)
  - Not well suited for composites inspection (the increasing market)
- Solution : use adaptative interferometry with PRCs
  - Two Wave Mixing
  - Photo-EMF

Ultrasound detection by laser

- Ultrasound Detection by Two-Wave Mixing

Probe beam : phase modulated + speckled



Diffracted Beam = Local Oscillator

- **No more modulated**
- **Still speckled**

Interference

Transmitted Beam

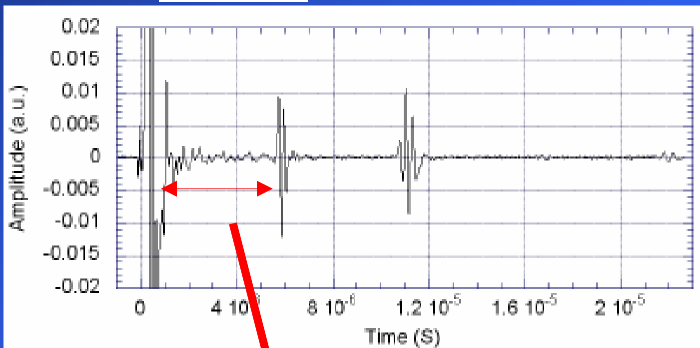
Index grating recorded :

- **Response Time > Phase modulation time**
- **Tuned through Pump Beam**

Ultrasound detection by laser

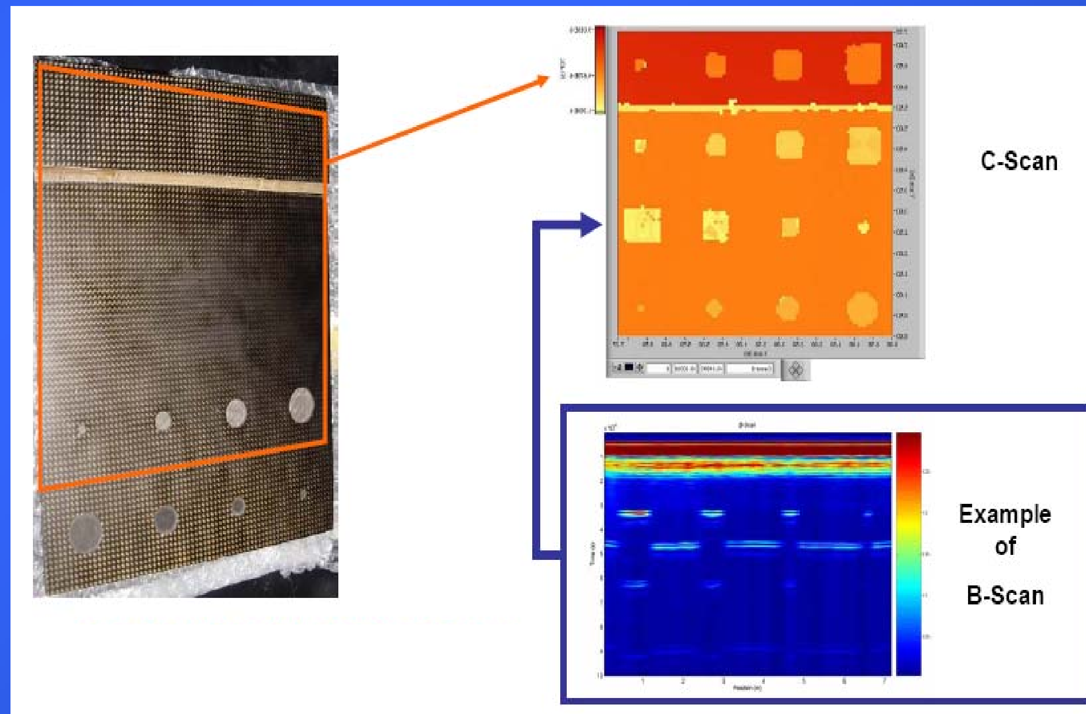
- Typical results (courtesy BossaNova Company)

A-scan



Depth of defect

Thickness of piece

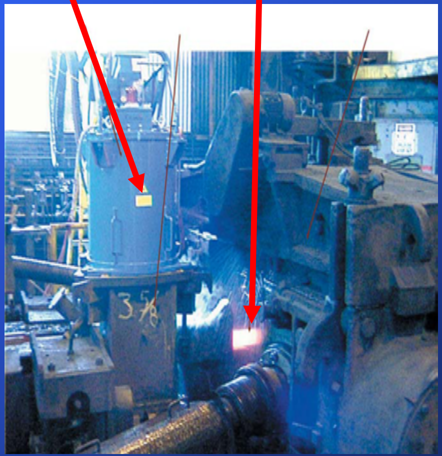


Ultrasound detection by laser

- Ultrasound detection by Two Wave Mixing
- Common works by
  - IMI-CNRC (Boucherville, QC) : J-P. Monchalin, A. Blouin
  - Institute Optics (Orsay, Fr) : G. Roosen, Ph. Delaye
- Best Application of Photorefractive Materials at PR'01
- Other works by USA group B. Pouet, M. Klein
- Good commercial success
  - Bossa Nova, CA
  - Tecnar, QC

Ultrasound detection

Steel tube

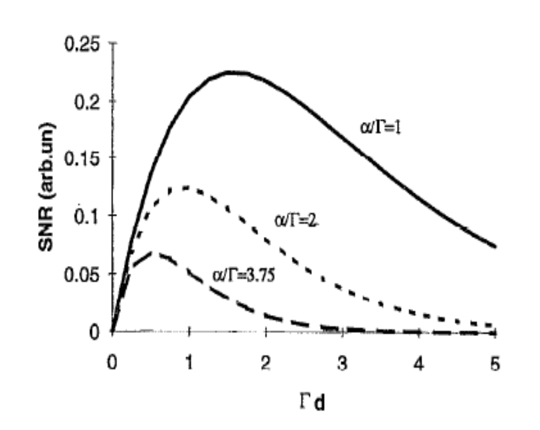


Ultrasound detection by laser

Material issues :

– Response time of grating formation
  - Sufficiently long to record the reference state
    (i.e. If too short, it adapts to the ultrasound motion)
  - Sufficiently short to adapt the interferometer to low ambient vibrations
    (i.e. to record new holograms with new speckled beams during a scan)
  - In practice : $\tau \sim$ 1-10 µs

– Ratio Gain/Absorption
  - GaAs : $\alpha/\Gamma \sim 2$
  - There is an optimal crystal length *d* for a given α/Γ



Ultrasound detection by laser

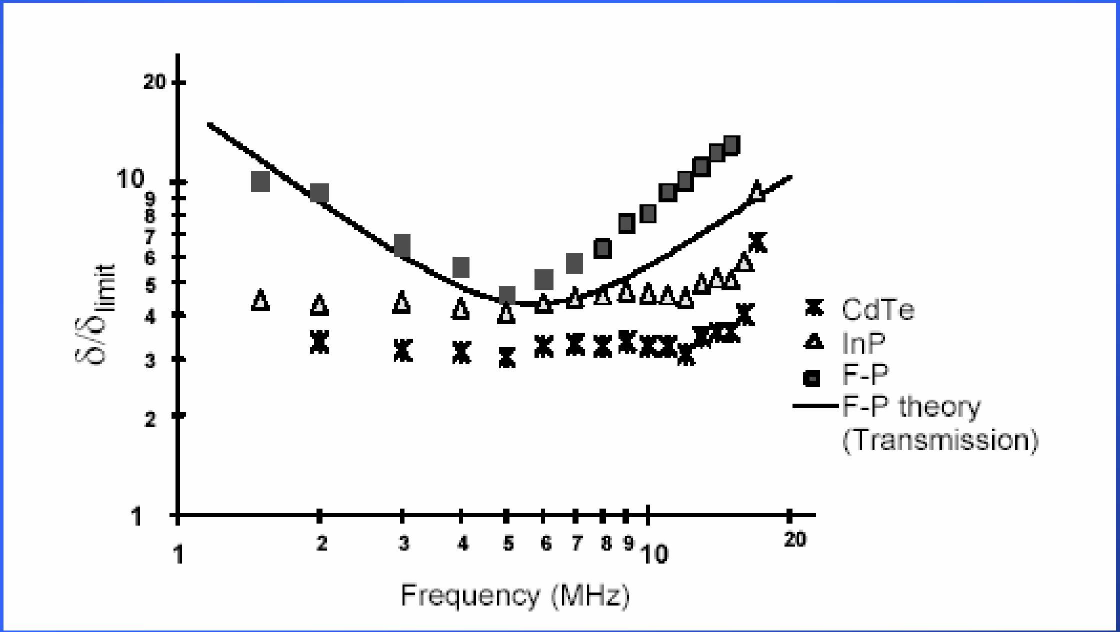
- Material issues : Crystals – Lasers used
  - BaTiO3 : too slow → **Green Laser**
  - GaAs : faster but no DC field possible
  - InP:Fe : faster, DC field possible
  - CdTe : faster, DC field possible, better coupling
  - (GaAs, InP:Fe, CdTe) → **Nd-YAG Laser 1.06 µm**
  - BSO → **Green Laser**

- CW vs. Pulse Lasers
  - Detection only during a few tens of µs
  - Pulsed laser with 50-100 µs sufficient (PDL Laser by Tecnar)
    - Only at 1.06 µm, MOPA
  - CW possible but loss of light
  - Any wavelength, mostly DPSS 532 nm (e.g. BossaNova)

CW : lab systems ⟷ PDL : industry systems

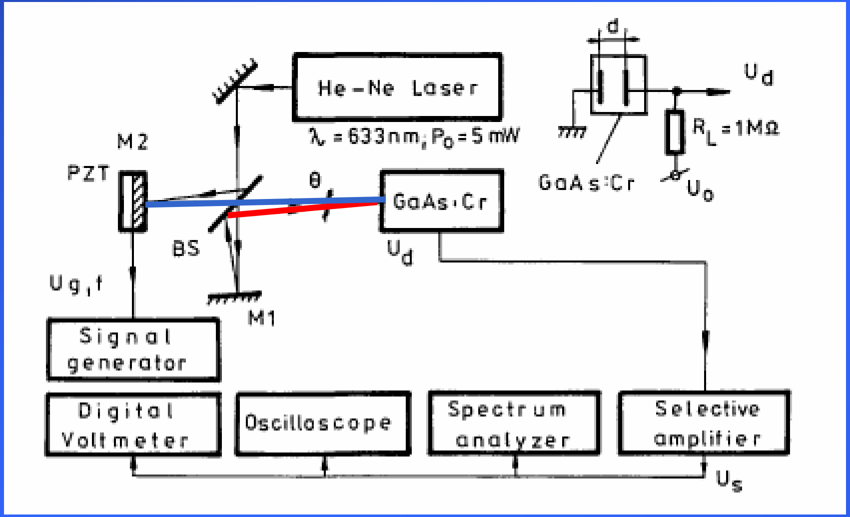
Ultrasound detection by laser

- Comparison of techniques
- Fabry-Perot vs. TWM
- Different crystals



Ultrasound detection by laser

- Photo-Electro Motive Force (EMF) for measuring vibrations



  – First demonstrated by then Soviet group (Stepanov, Petrov,…)
  – Pump + Object Speckled beams interfere at crystal
  – Crystal is used with applied field (drift regime)
  – Motion due to moving target implies moving grating
  – Variations of electric current processed to provide signal
  – Crystal GaAs:Cr = sensor ; No Photodiode

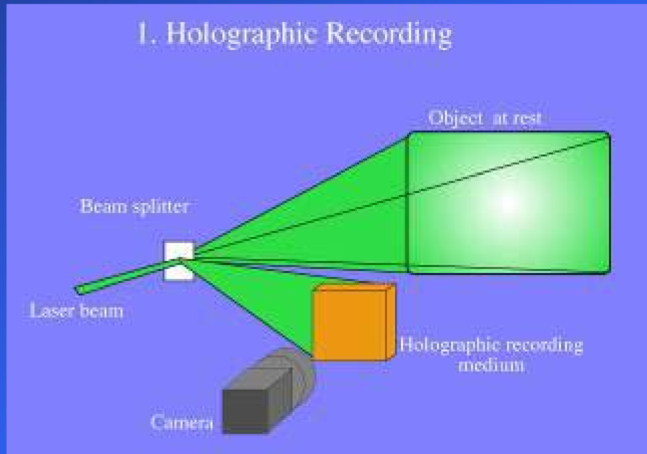
Ultrasound detection by laser

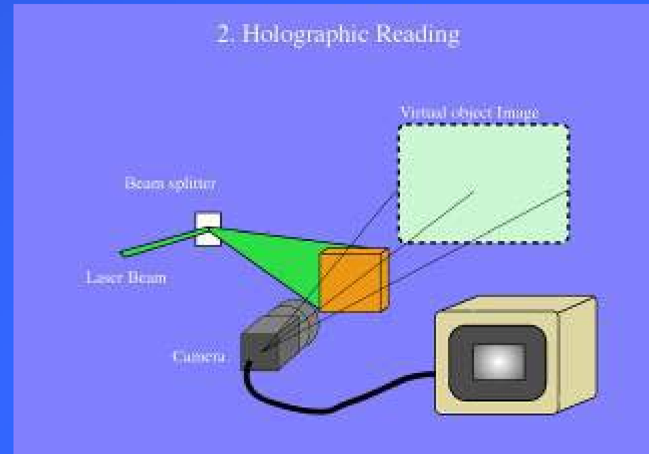
- Photo-EMF used for detecting ultrasonic motions on rough surfaces
- US company LASSON/Intelligent Optical Systems, CA
- Best Application of Photorefractive Materials, PR’99
- First commercial device with PR materials
- Not big success due to weak figures of merit (sensitivity)

Holographic Interferometry

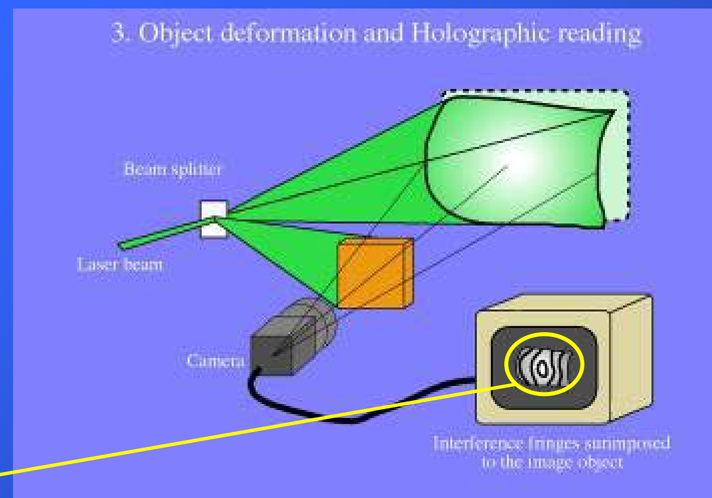
Holographic Interferometry

- Holographic interferometry generalities





  - Object is displaced/deformed
  - Object visualization simultaneous to holographic readout
  - Fringe pattern superimposed to object image



INTERFEROGRAM

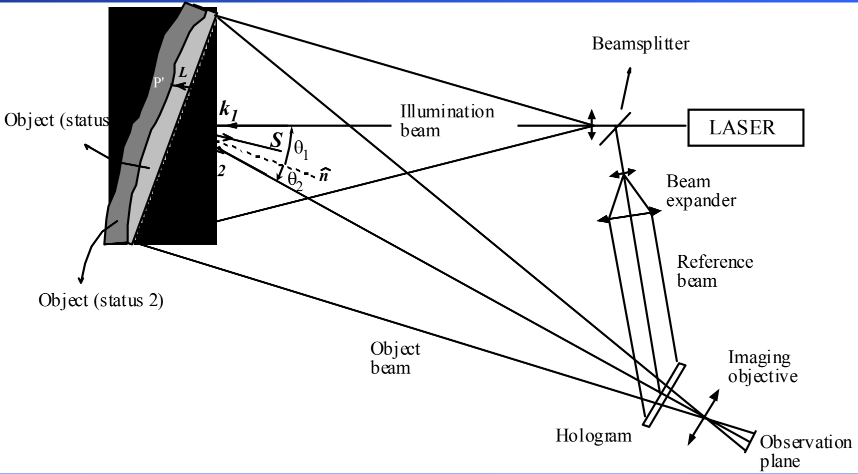
$$I(x,y) = I_0(x,y).[1 + m(x,y)\cos\phi(x,y)]$$

Holographic Interferometry

- What can we measure ?

$$I(x,y) = I_0(x,y).[1 + m(x,y)\ \cos\phi(x,y)]$$

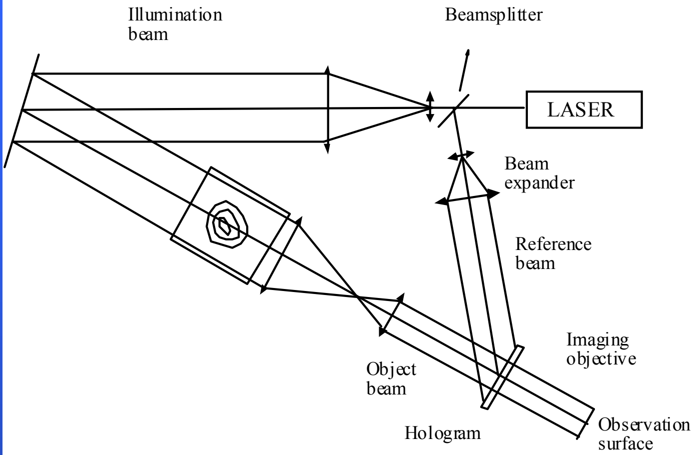
Scattering objects



$$\phi(x,y) = S(x,y).L(x,y)$$

Variation of surface position between 2 instants

Transparent objects

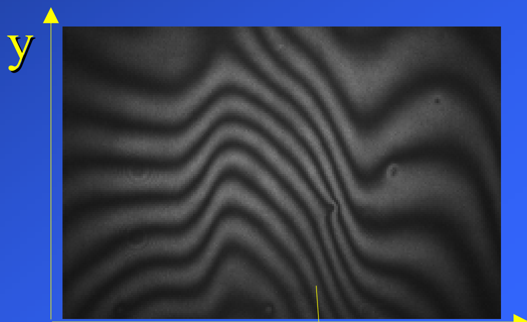


Variations of refractive index between 2 instants and integrated along line of sight

$$\phi(x,y) = \int \frac{2\pi}{\lambda}\left[n(x,y,z) - n_0\right] dz$$

Holographic Interferometry

- Quantification of phase difference



Average Intensity

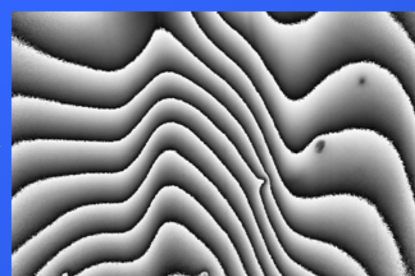
Optical Phase Difference

$$I(x,y)=I_0(x,y)\,[1+m(x,y)\cos(\phi(x,y))]$$

Contrast

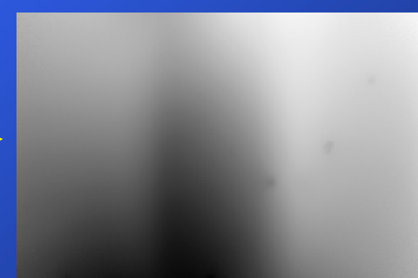
Phase computation technique (phase-shifting, FFT,..)

Optical Phase Difference



(modulo 2π)

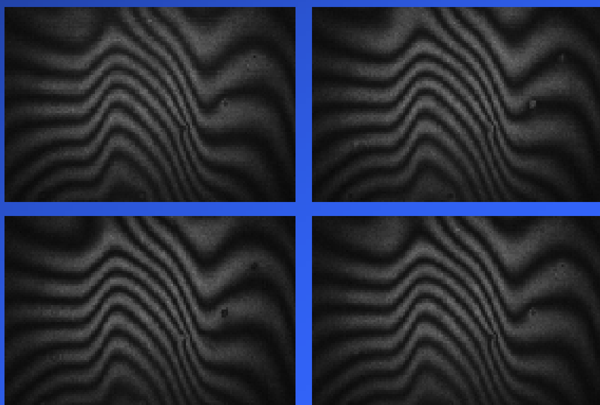
Displacement map

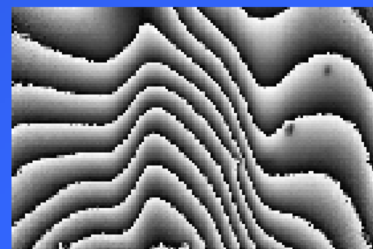


$$\phi(x,y) = \boldsymbol{S.L}$$

Holographic Interferometry

- Quantification of phase difference
  - Temporal heterodyning : « phase shifting »



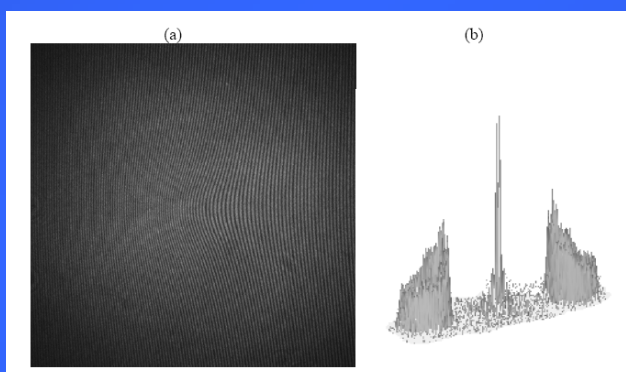


phase modulo 2π

Better accuracy

Requires stability between acquisition

  - Spatial heterodyning : FFT with spatial carrier added

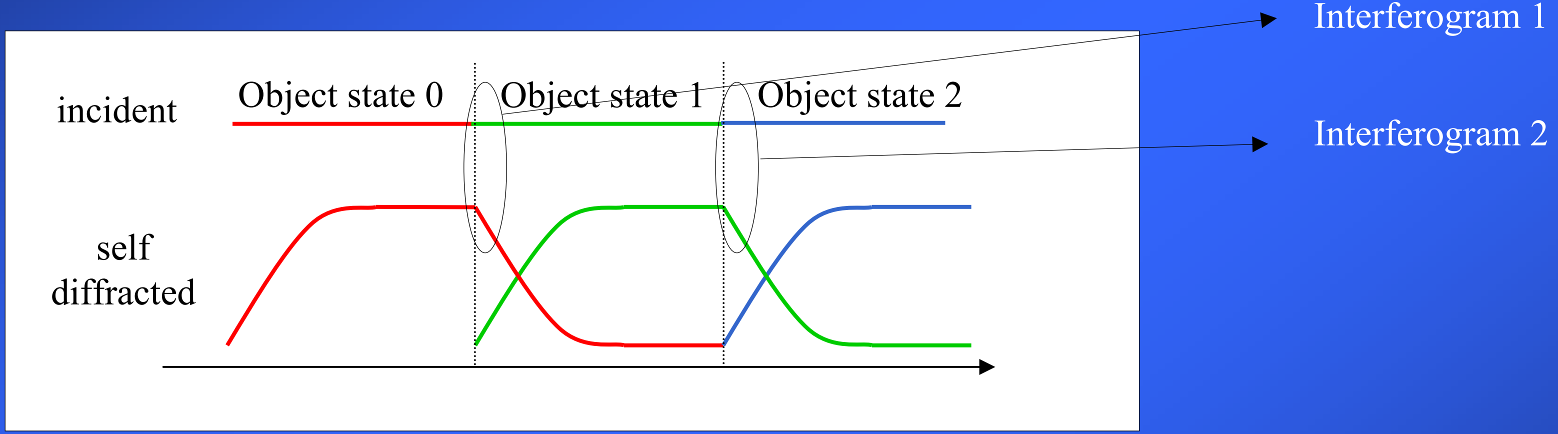


Lower accuracy
Careful choice of carrier

Single Frame analysis

Holographic Interferometry

- « Real-Time » Holographic Interferometry



Recording energy at saturation : $E_s = \tau.I$

- cw lasers
- pulsed lasers

Holographic Interferometry

- Materials issues : inorganic PR used for HI

Visible (blue-green) → Sillenite $Bi_{12}SiO_{20}$ (BSO) → High sensitivity : $E_S \sim$ 1-10 mJ/cm^2; Poorest efficiency : $\eta \sim$ 0.1 %

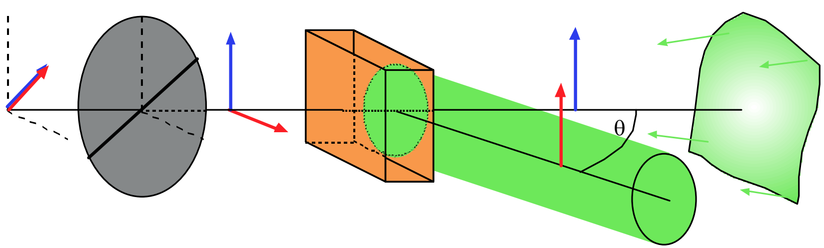
Visible (blue-green) → Ferroelectrics $LiNbO_3$, $BaTiO_3$ → Poor sensitivity : $E_S \sim$ 1 J/cm^2; Highest efficiency : $\eta \sim$ 100 %

NIR (λ=1 µm) → Semiconductors CdTe, GaAs → Highest sensitivity : $E_S \sim$ 0.1-1 mJ/cm^2; Poor efficiency : $\eta \sim$ 1 %

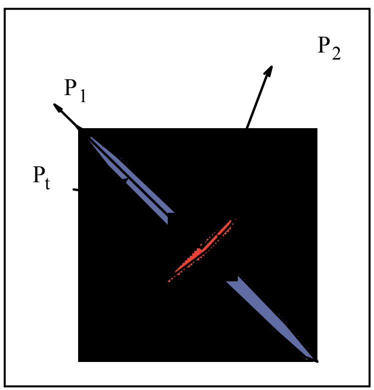
Holographic Interferometry

- Materials issues : Particular properties of diffraction by PRCs

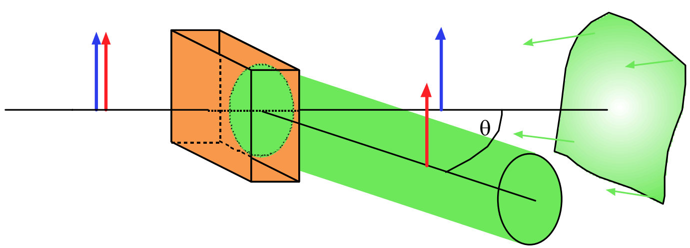
Anisotropic diffraction



Interferogram contrast depends on the analyser orientation



Isotropic diffraction



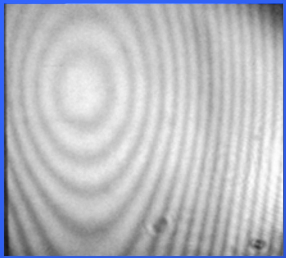
Interferogram contrast depends on the product :
-coupling constant
-crystal thickness

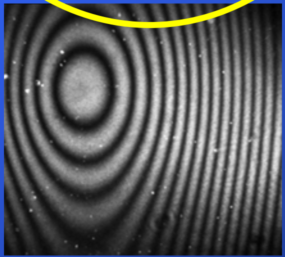
$$\Gamma l = \frac{4\pi \Delta n\, l}{\lambda} \approx 1$$

Holographic Interferometry

- Choice of crystal = BSO
  - The most sensitive
  - Works with DPSS frequency doubled laser (e.g. Verdi)

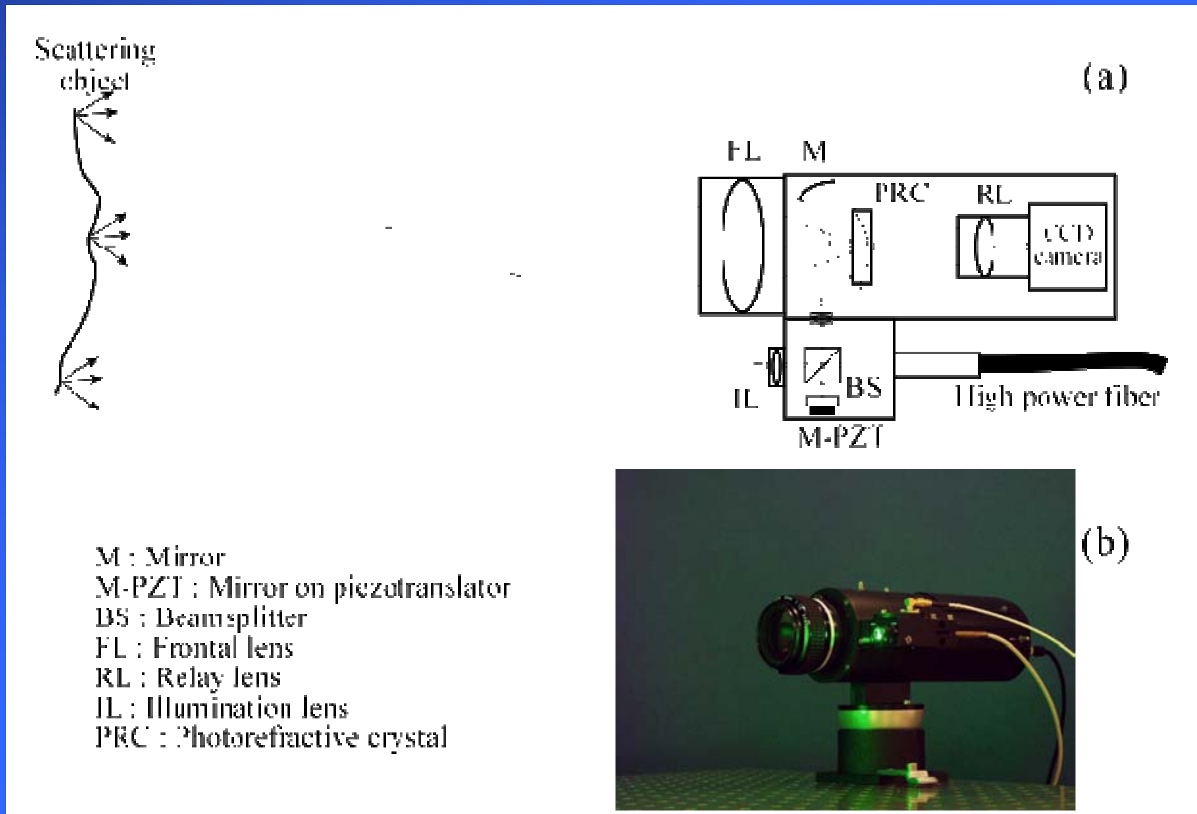
	Isotropic	Anisotropic
Crystal thickness	$l \sim$ 1-2 cm	$l \sim$ 2.7 mm
Average intensity $I_0(x,y)$	High	Low
Contrast $m(x,y)$	Depends on Γl Medium	Easy to control Very High





Holographic Interferometry

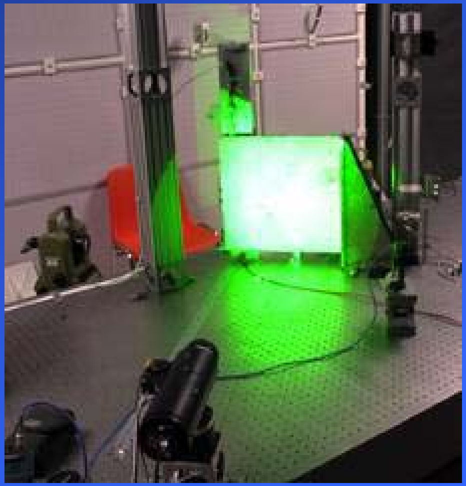
- CW holographic camera

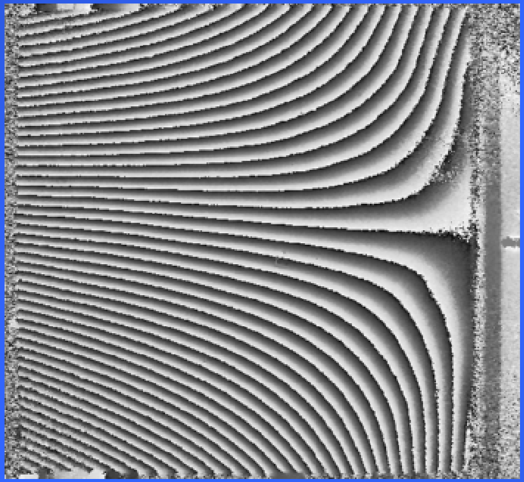


Commercialized by spin-off OPTRION
« Best application of Photorefractive materials »
PR'05

Holographic Interferometry

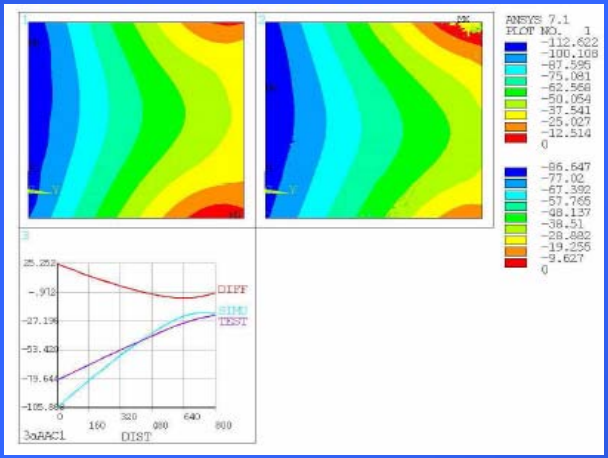
- Applications : displacements metrology

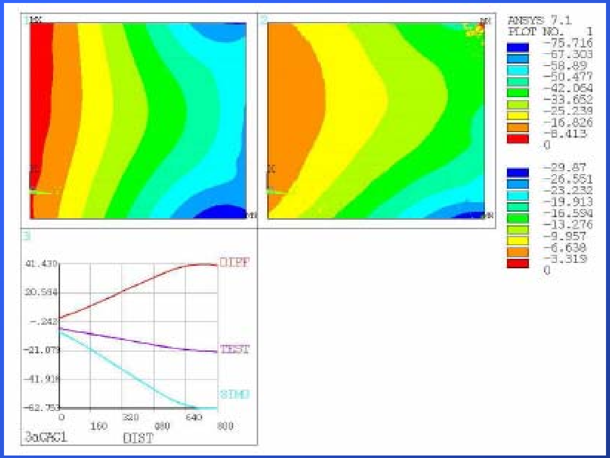




Aluminum + honeycomb

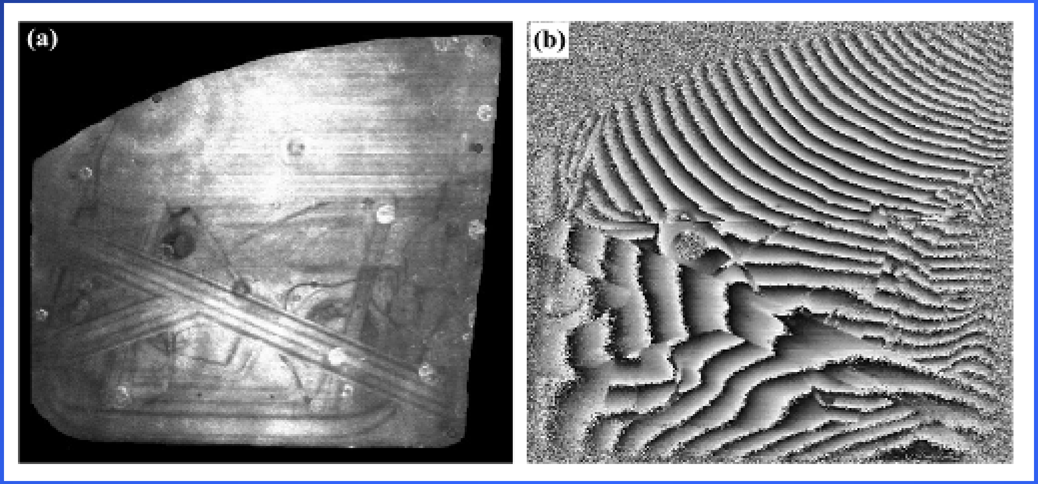
CFRP + honeycomb

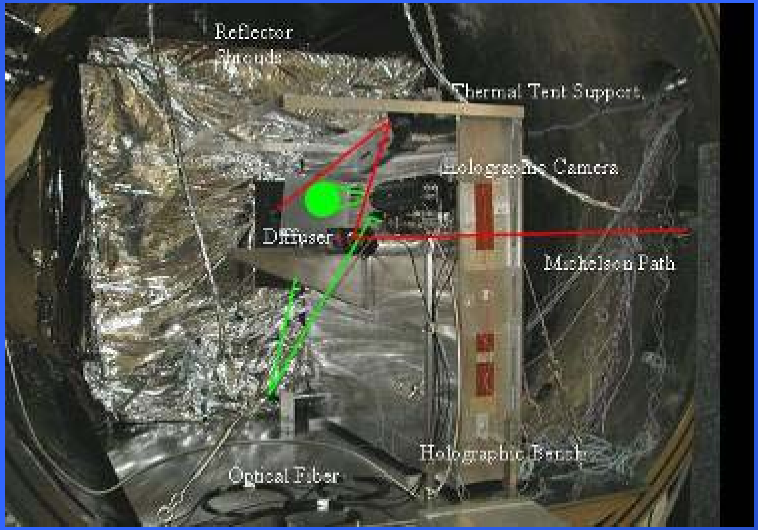


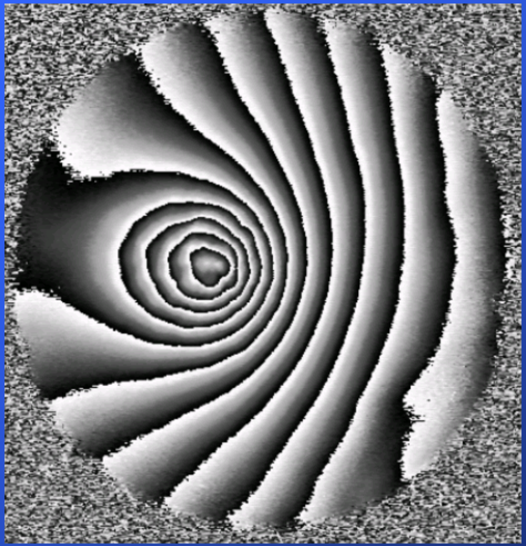


Holographic Interferometry

- Applications : displacements metrology

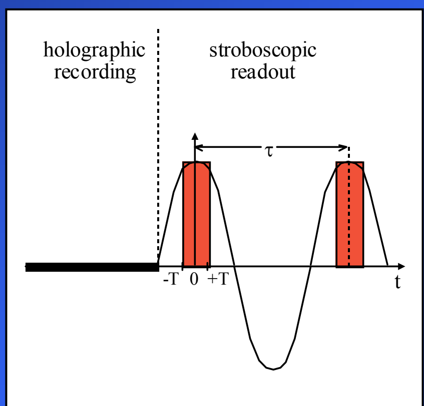


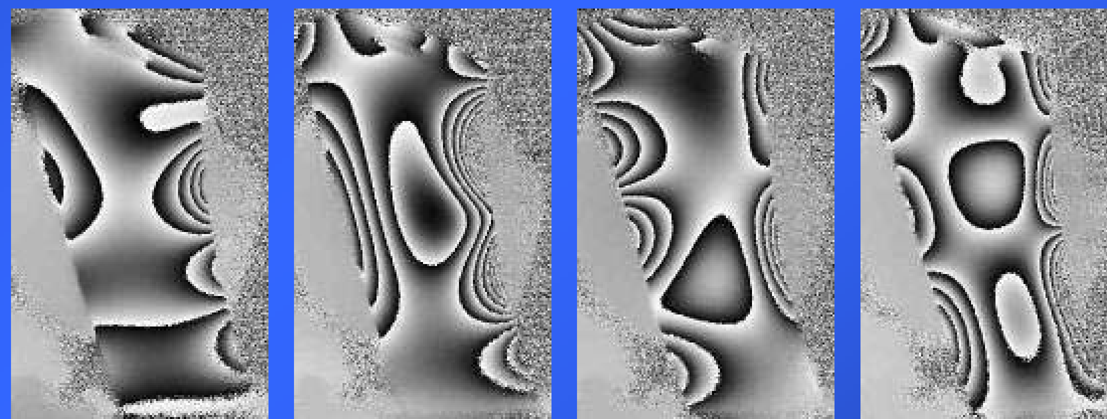


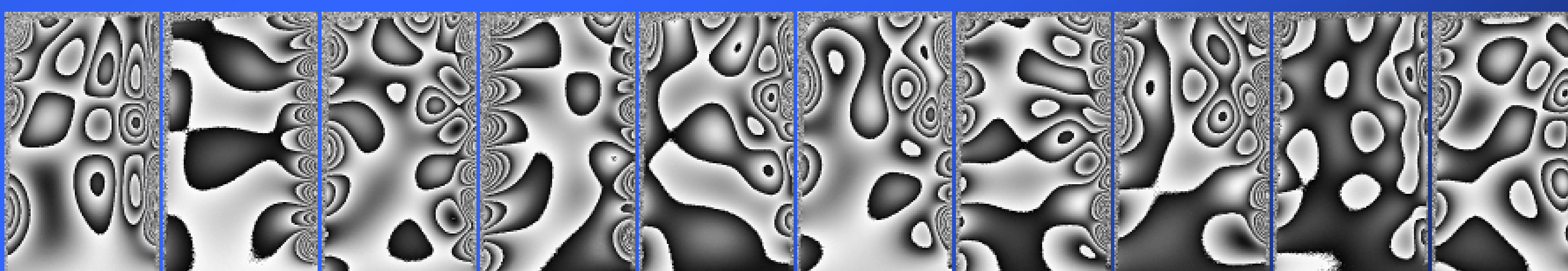


Holographic Interferometry

- Applications : Stroboscopic Real-Time

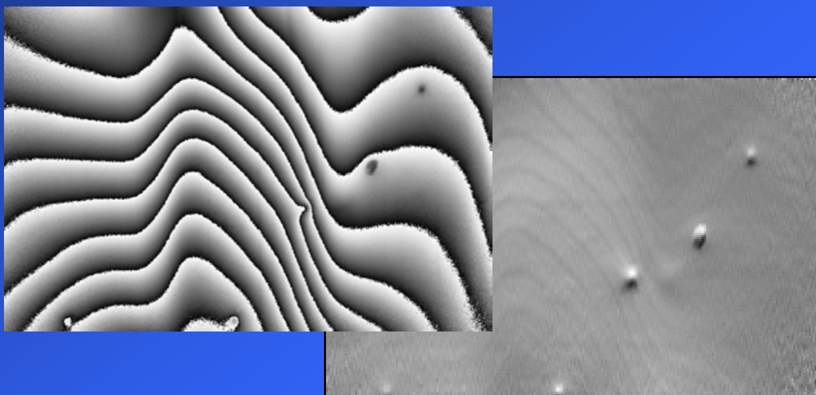


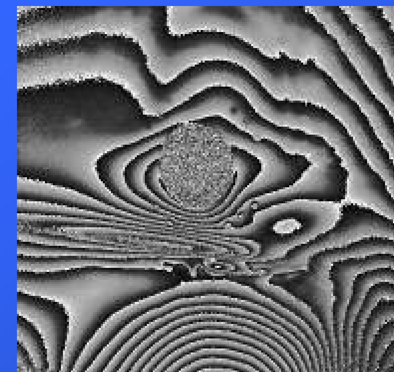
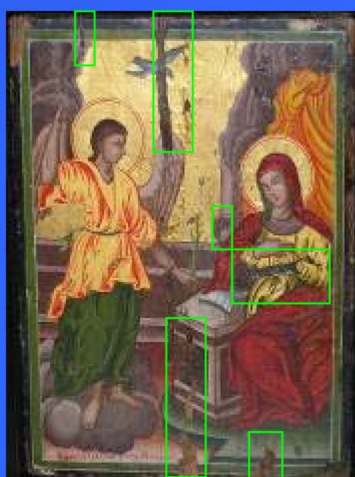
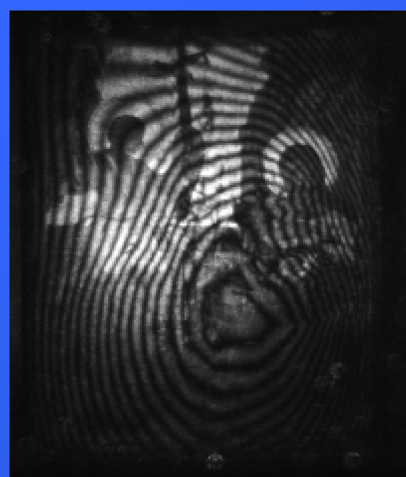
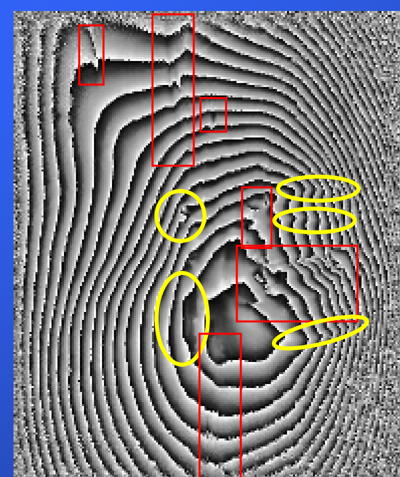




Holographic Interferometry

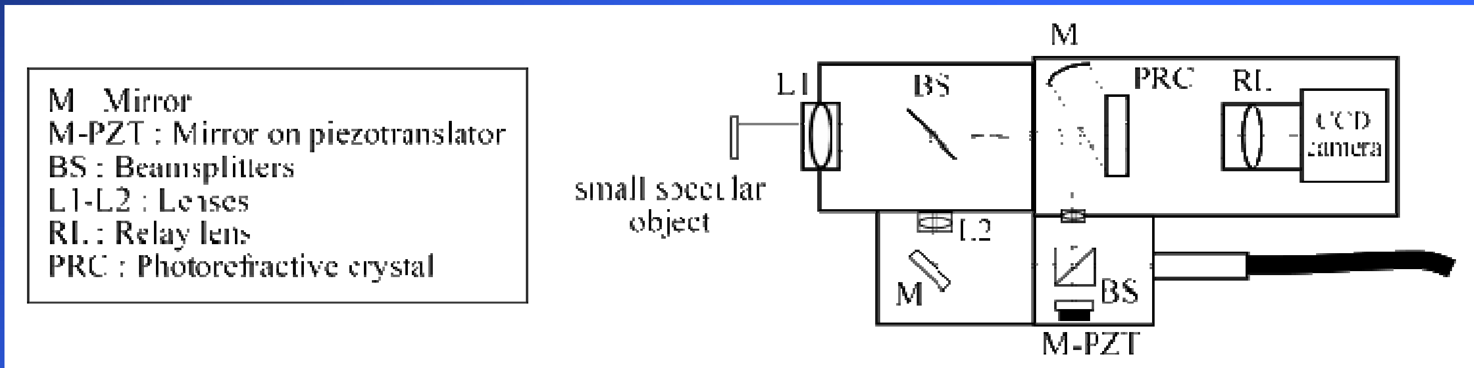
- Applications : NDT (defect detection)

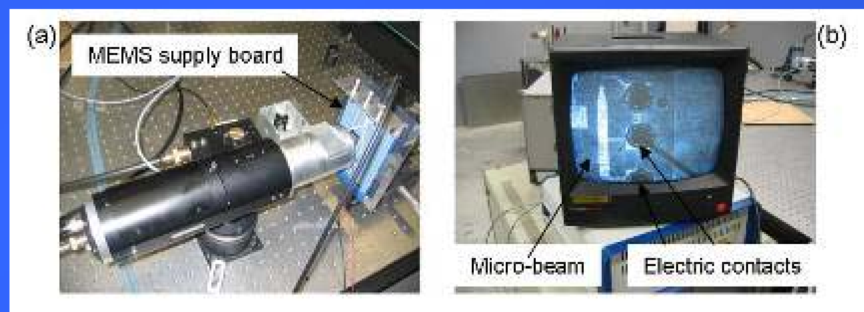


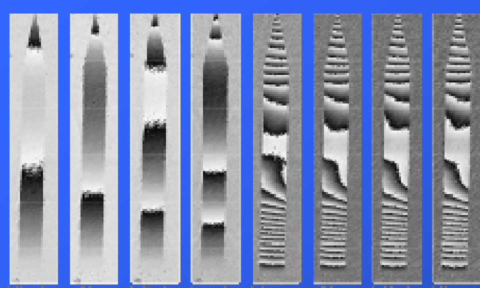





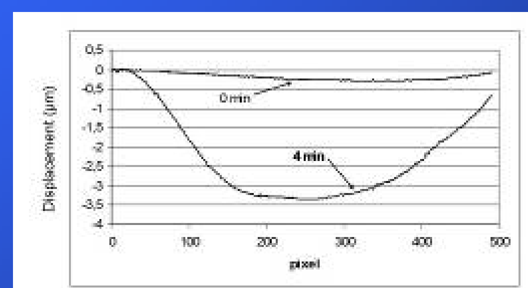
Holographic Interferometry

- Application on MEMS mechanical behaviour



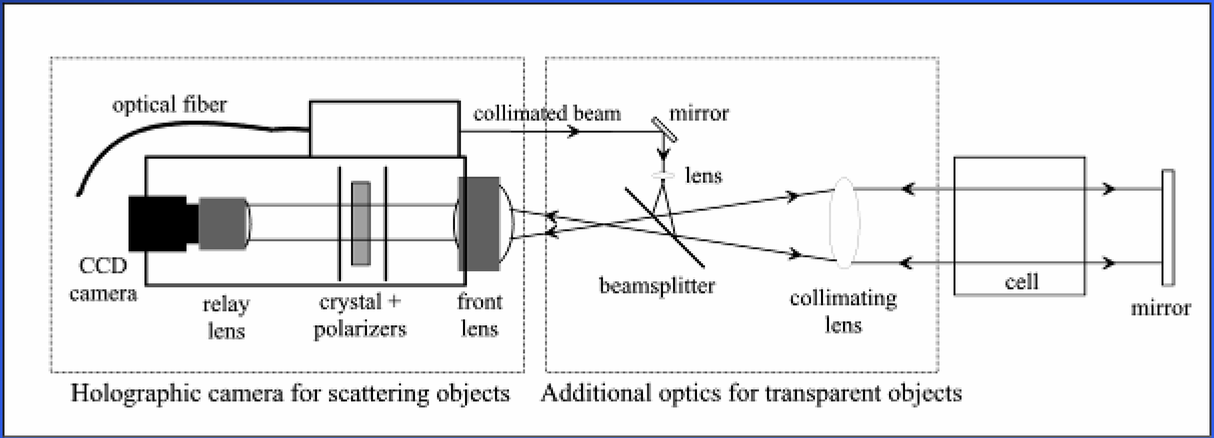


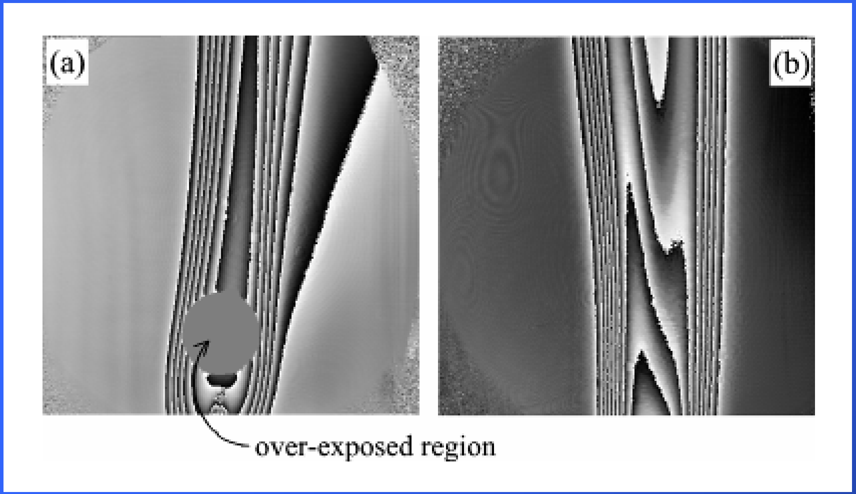




Holographic Interferometry

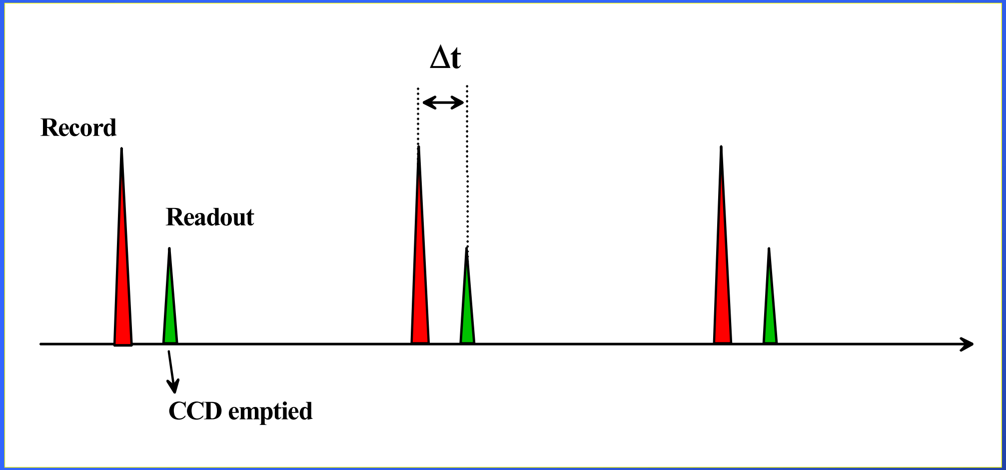
- Application on transparent objects





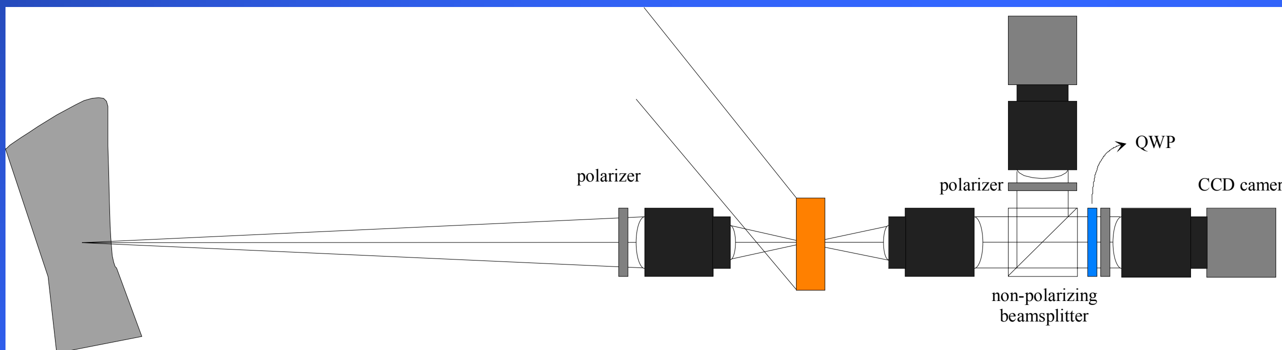
Holographic Interferometry

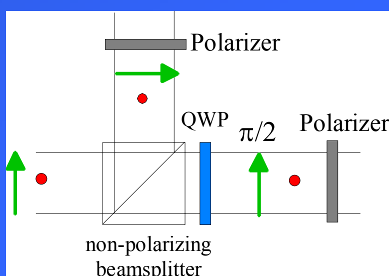
- Use pulse Q-switch YAG laser
  - Nanoseconds recording
  - Allows adressing high speed phenomena : shocks, vibrations,…
- Double pulse lasers,
  - 10-25 Hz repetition rate
  - $\Delta t = 1 - 200\ \mu s$

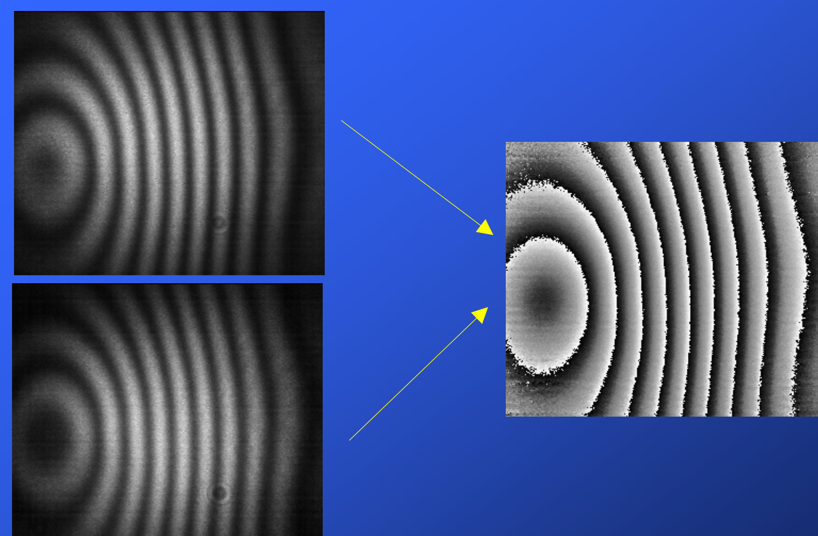


Holographic Interferometry

- Novel phase quantification technique # 1
  - Fully passive simultaneous phase-shifting with 2-cameras





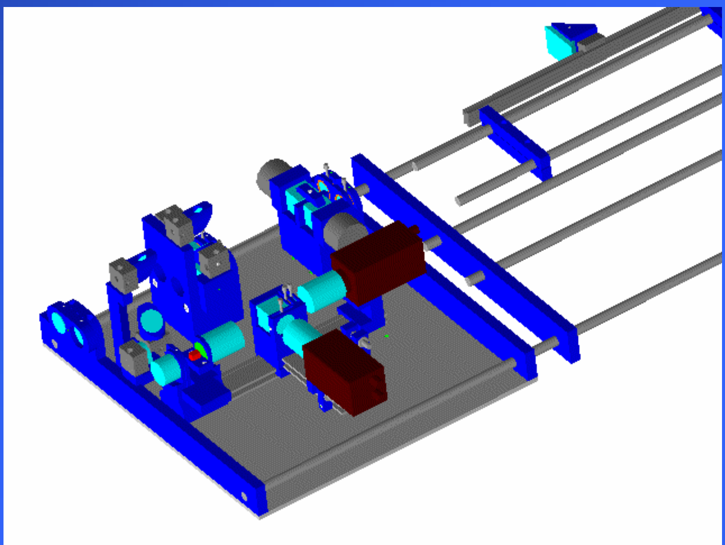


- Cam 1 : $I = I_{01}\,(1+m \sin \Delta\phi)$
- Cam 2 : $I = I_{02}\,(1+m \cos \Delta\phi)$

Holographic Interferometry

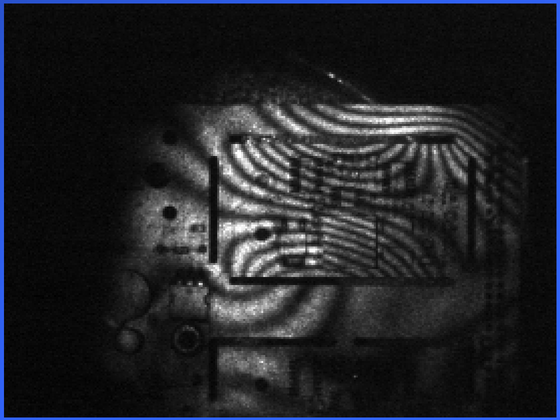
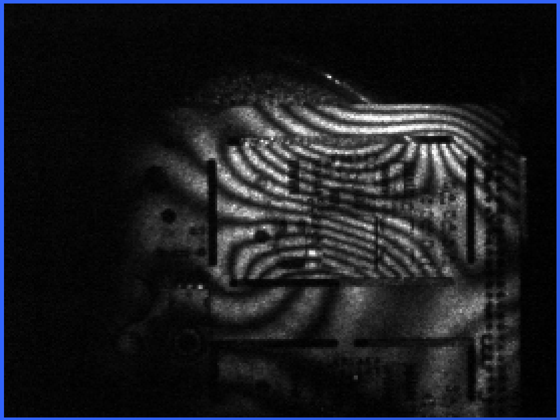
- Industrial prototype = Holographic Head + Laser

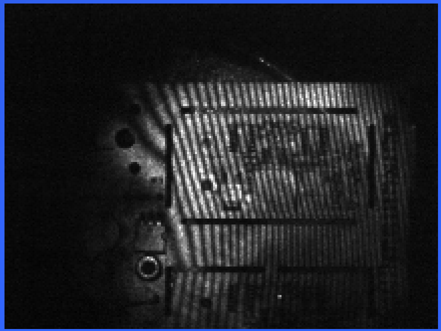
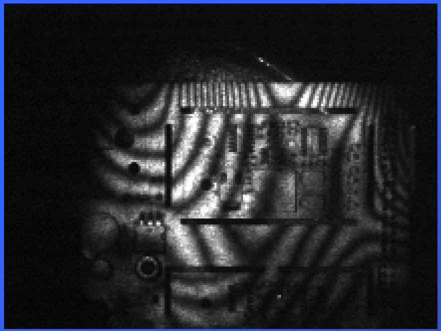
OPTRION
OPTICS & METROLOGY



Holographic Interferometry

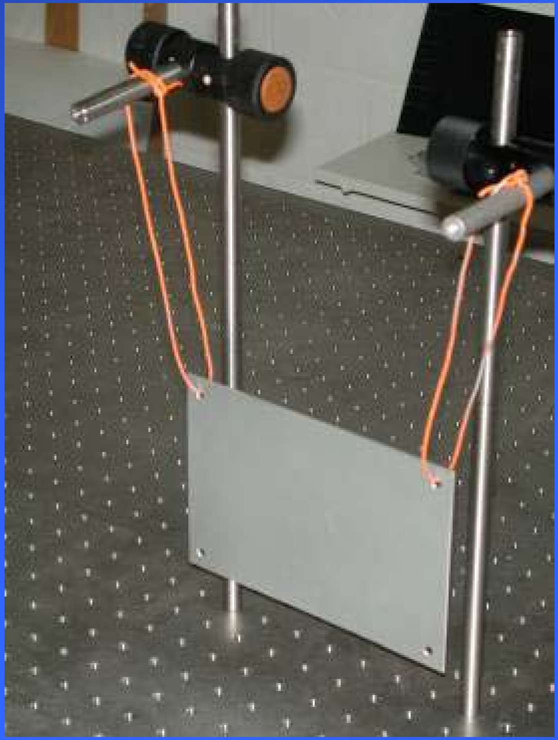
- Vibrations : Electronic board on shaker
  - total amplitude of vibration can be millimeters
  - λ = 1064 nm / AsGa crystal

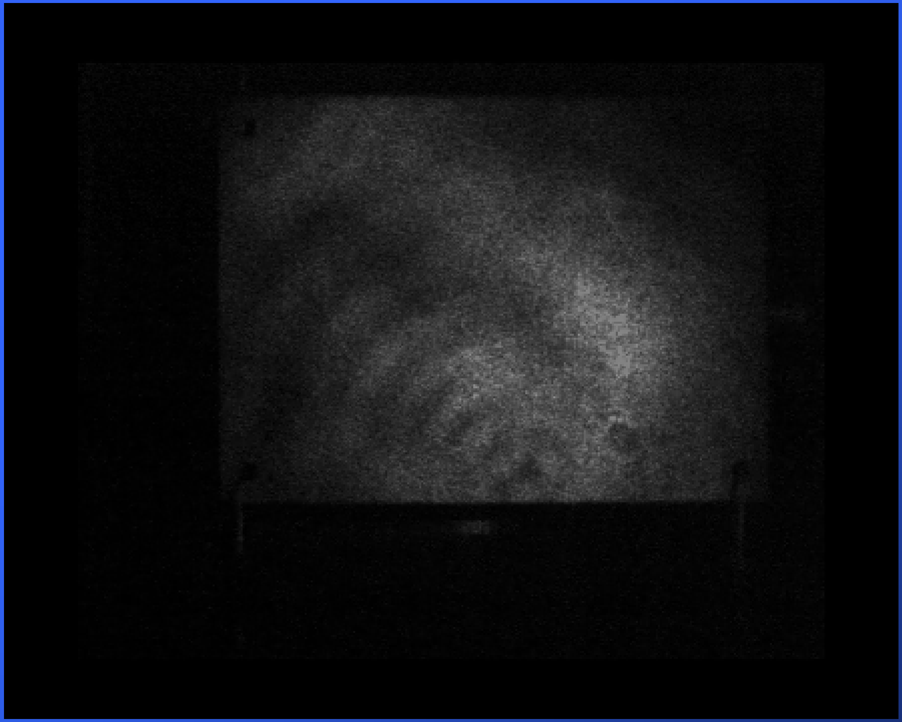



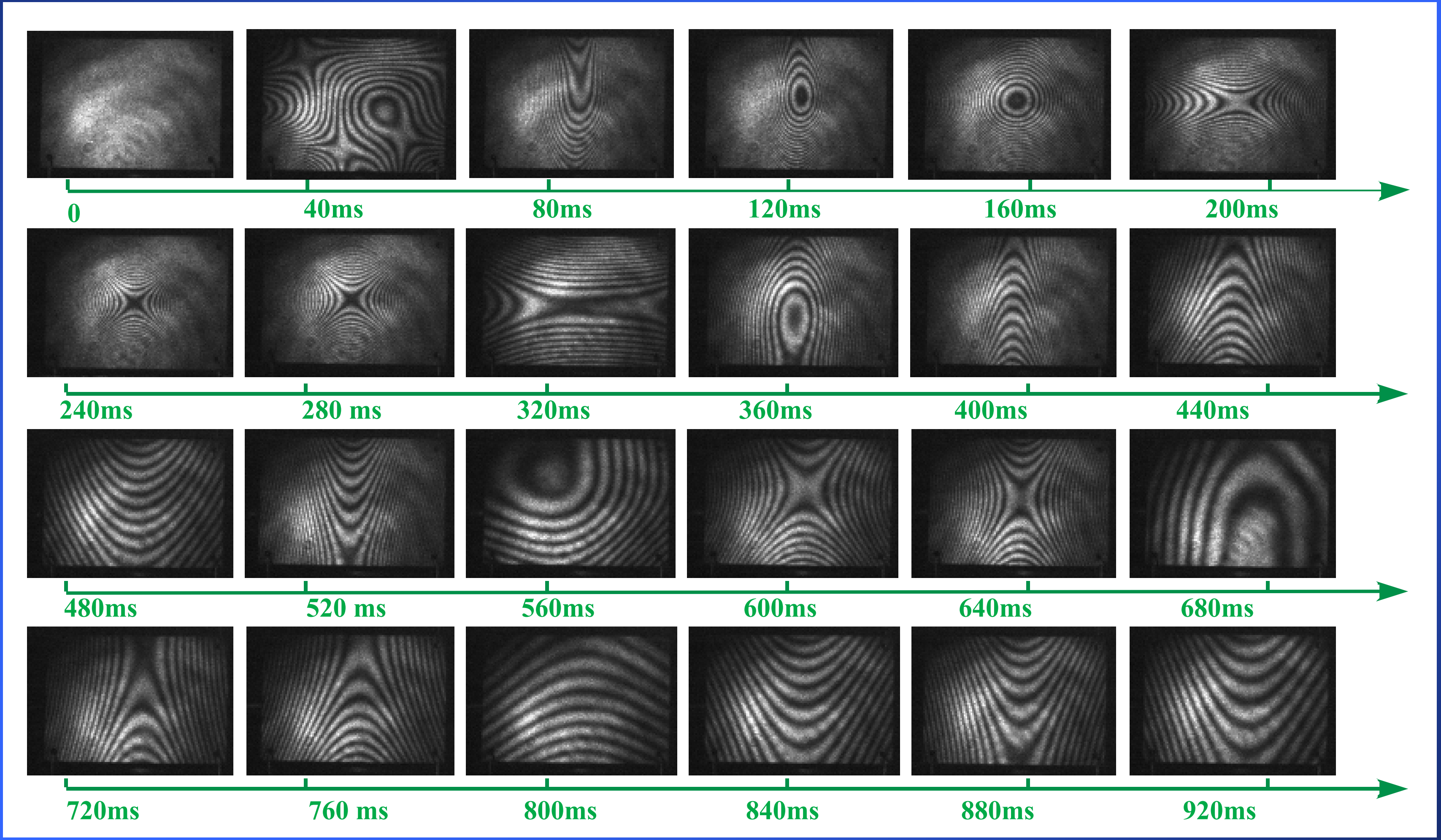
Holographic Interferometry

- Shock : Metallic plate with hammer
  - laser : double pulse sequence (25 Hz rep. Rate, 120 µs delay)





Holographic Interferometry

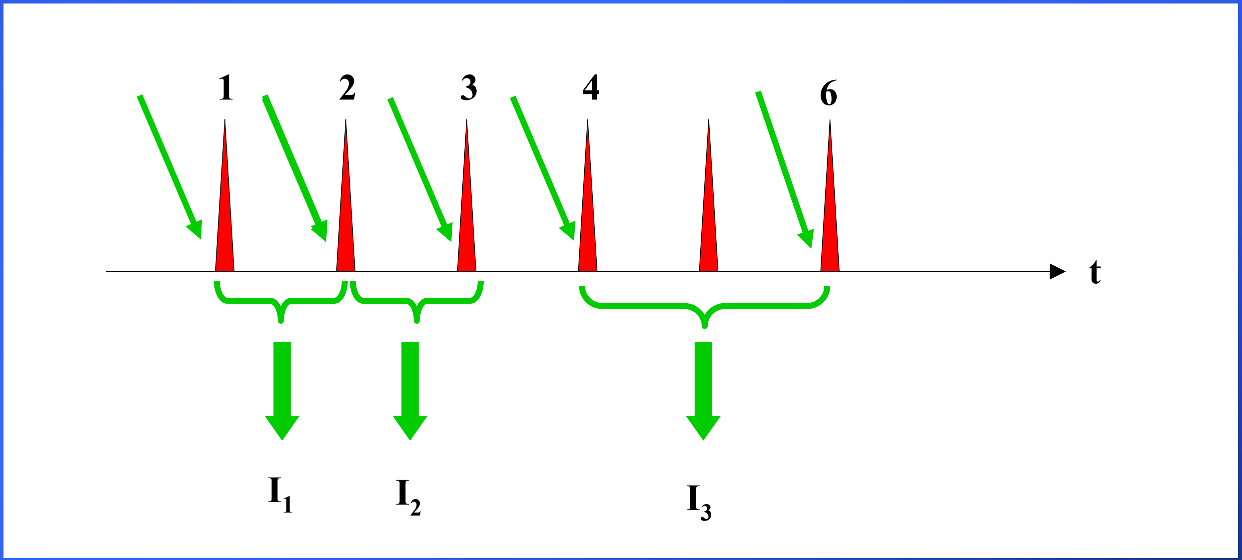


Holographic Interferometry

- Discussion about materials issues
  - Present : BSO/AsGa
    - $E=10\ mJ/cm^2$
    - Weak efficiency : $I_{diffracted} << I_{direct}$
    - Counterbalanced by polarization separation after crystal
    - Contrast m=1
    - I_0 weak : we work at the limit of CCD cameras sensitivity
    - Ratio Surface Observed/Laser Power : small
  - Ideal material :
    - $E<10\ mJ/cm^2$ (not that critical)
    - High efficiency/isotropic diffraction
    - Low scattering noise
    - Laser source :
      - 532 nm, 1064 nm (DPSS)
      - Smaller laser (monomode diode lasers) : material adapted to wavelength

Holographic Interferometry

- Single pulse lasers – High repetition rate
  - 1-10 kHz
  - Allows sampling of fast phenomena
  - Keep track of object/phenomena changes between pulses
  - Readout at slow speed : « Wavefront Buffer Memory »
  - Multiplexing of readout : angular



Pulsed holographic systems

- Material issues :
  - N holograms

$$\eta_i = \frac{1}{N}\eta_0$$

  - Need efficient/fast crystals
    - BSO : fast, not efficient (E. Weidner, G. Pauliat, G. Roosen. *J. Opt. A: Pure Appl. Opt.* 5, pp. 524-528, 2003)
      - A few tens of holograms
      - Limited object size due to low efficiency
    - LiNbO3 : slow, very efficient (X. Wang, R. Magnusson, A. Haji-Sheikh, Appl. Opt. **32** (11), pp. 1983-1986 (1993)
      - High power lasers
  - Need new materials with both qualities
    - Double exposure
    - All holograms have the same polarization
    - Phase quantification : should be a bit more tricky

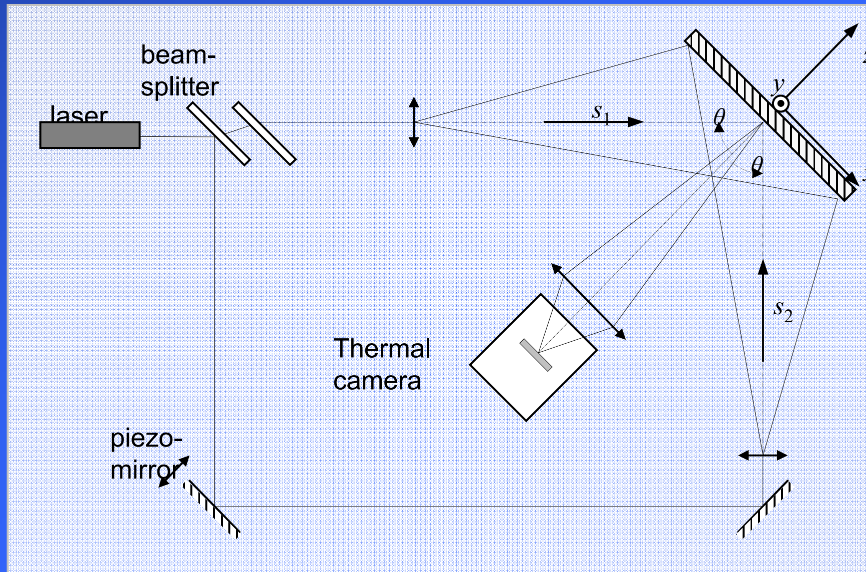
New holographic technique

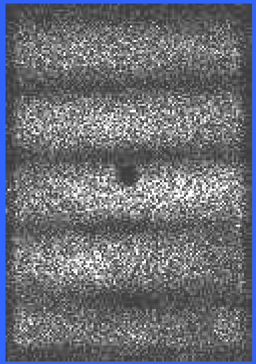
- Use holographic interferometry methods at 10 µm
  - Fill a gap in current optical metrology methods
    - Holography at visible wavelengths
      - Displacement measurement range depends on wavelength
    - Fringe projection/image correlation
      - Displacement measurement range depends on imaging device resolution
  - Decrease stability criteria of Holography (depends on wavelength)
  - Address metrology and NDT with large sollicitation/stress levels

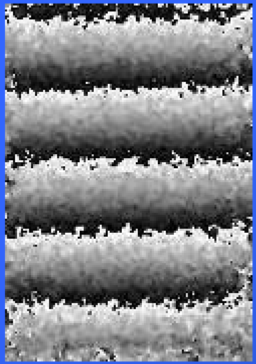
- Photosensitive holographic recording media at 10 µm
  - Examples:
    - Wax & Gelatin Film by S. Kobayashi *et al* (Appl. Phys. Lett. 1971)
    - Thermochromic materials by R. R. Roberts *et al* (Appl. Opt. 1976)
    - Plastics by Rioux *et al* (Appl. Opt. 1977)
  - Recording at 10 µm, readout at 633 nm
  - 10 lines/mm (low resolution)

New holographic technique

- Use digital holography methods at 10 µm







New holographic technique

- No convincing materials
  - In situ recording : thermal processes
  - Not readable by self-diffraction
  - Low resolution
- Is there a PR material at 10 µm ?