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
  – Creation of Spin-off OPTRION (2001)
♦ Since 1998 : Photorefractive Crystal growth
  – Technology transfer from Univ. Bordeaux
♦ Recent :
  – Digital Holography
  – Laser Induced Breakdown Spectroscopy
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 Topical 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 cavities → Several modes → Longitudinal
  Depending on
  Geometry of cavity
  Laser medium

Filtering
  Fabry-Perot
  Lyot
  ....

Static Filters

Adaptative Filtering

Avoid using

Correct Adjustment of Filter spectral response
Laser mode filtering and enslaving
Self organized laser cavities

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

- Interference pattern
- Photorefractive crystal
- Phase shift of $\pi/2$
- Constructive interference: Amplification of B
- Destructive interference: Attenuation of A
- $\phi$: phase shift due to diffraction by refractive index grating
  $\phi = \pi/2$

This happens for one wavelength
Other wavelengths do not match

Amplification for a single wavelength

$\varphi$ : phase shift due to diffraction by refractive index grating

$\varphi = \pi/2$
Self organized laser cavities

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

Initial states

Operating current
- 28.3 mA
- 26.1 mA
- 24.8 mA
- 21.2 mA
- 17.4 mA
- 16.4 mA
- 13.5 mA

Frequency (1.5 GHz)

Final states

Operating current
- 28.3 mA
- 26.1 mA
- 24.8 mA
- 21.2 mA
- 17.4 mA
- 16.4 mA
- 13.5 mA

Frequency (1.5 GHz)
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:BaTiO₃

Spectre diode #2
70 mA
crystal "sélection"

Signal (dB)

660.0 660.5 661.0 661.5
Longueur d'onde (nm)

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Self organized laser cavities

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

Initially: diffraction limited beam, but several longitudinal modes

\[
\text{Spectrogram}
\]

- At \( t = 0 \text{ s} \)
- Adaptation toward a single longitudinal mode within 2 s

\begin{itemize}
  \item Rhodium doped
  \item 45° cut
  \item thickness = 3.5 mm
  \item \( \alpha = 0.1 \text{ cm}^{-1}, \Gamma/t = 0.2 \)
  \item provided by D. Rytz, FEE
\end{itemize}
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 $\lambda$: monomode regime at $\lambda$
Self organized laser cavities

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

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 $\mu$m
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

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

Ultrasonic motion of surface
Doppler shift of laser frequency
Frequency modulation transformed as intensity modulation
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

Index grating recorded:
- Response Time > Phase modulation time
- Tuned through Pump Beam

Diffracted Beam = Local Oscillator
- No more modulated
- Still speckled

Interference

Transmitted Beam
Ultrasound detection by laser

- **Typical results** (courtesy BossaNova Company)

  - **A-scan**
  - **Depth of defect**
  - **Thickness of piece**

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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 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: $\tau \sim 1\text{-}10 \mu s$
  - Ratio Gain/Absorption
    - GaAs: $\alpha/\Gamma \sim 2$
    - There is an optimal crystal length $d$ for a given $\alpha/\Gamma$
Ultrasound detection by laser

- **Material issues: Crystals – Lasers used**
  - BaTiO3: too slow
  - GaAs: faster but no DC field possible
  - InP:Fe: faster, DC field possible
  - CdTe: faster, DC field possible, better coupling
  - BSO

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

Ultrasound detection by laser
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

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

♦ What can we measure?

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

\[ \phi(x,y) = S(x,y) \cdot L(x,y) \]

Variation of surface position between 2 instants

Scattering objects

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

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

Transparent objects
Holographic Interferometry

- Quantification of phase difference

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

- Optical Phase Difference
- Average Intensity
- Contrast
- Phase computation technique (phase-shifting, FFT, ...)
- Optical Phase Difference (modulo 2\(\pi\))
- Displacement map

\[
\phi(x,y) = S.L
\]
Holographic Interferometry

- Quantification of phase difference
  - Temporal heterodyning: «phase shifting»
  - Spatial heterodyning: FFT with spatial carrier added

- Better accuracy
  - Requires stability between acquisition

- Lower accuracy
  - Careful choice of carrier
  - Single Frame analysis

Phase modulo $2\pi$
Holographic Interferometry

« Real-Time » Holographic Interferometry

Recording energy at saturation: \( E_s = \tau I \)
Holographic Interferometry

- Materials issues: inorganic PR used for HI

Visible (blue-green)
- Sillenite $\text{Bi}_{12}\text{SiO}_{20}$ (BSO)
  - High sensitivity: $E_S \sim 1-10 \text{ mJ/cm}^2$
  - Poorest efficiency: $\eta \sim 0.1 \%$
- Ferroelectrics $\text{LiNbO}_3$, $\text{BaTiO}_3$
  - Poor sensitivity: $E_S \sim 1 \text{ J/cm}^2$
  - Highest efficiency: $\eta \sim 100 \%$

NIR ($\lambda = 1 \mu m$)
- Semiconductors $\text{CdTe}$, $\text{GaAs}$
  - Highest sensitivity: $E_S \sim 0.1-1 \text{ mJ/cm}^2$
  - 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

\[
\Gamma l \approx \frac{4\pi \Delta n l}{\lambda} \approx 1
\]
Holographic Interferometry

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

<table>
<thead>
<tr>
<th></th>
<th>Isotropic</th>
<th>Anisotropic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal thickness</td>
<td>$l \sim 1-2 \text{ cm}$</td>
<td>$l \sim 2.7 \text{ mm}$</td>
</tr>
<tr>
<td>Average intensity</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>$I_0(x,y)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast $m(x,y)$</td>
<td>Depends on $\Gamma l$</td>
<td>Easy to control</td>
</tr>
</tbody>
</table>
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

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Holographic Interferometry

- Applications: Stroboscopic Real-Time
Holographic Interferometry

- Applications: NDT (defect detection)
Holographic Interferometry

- Application on MEMS mechanical behaviour

Diagram:
- M: Mirror
- M-PZT: Mirror on piezotranslator
- BS: Beam splitters
- L1-L2: Lenses
- RL: Relay lens
- PRC: Photorefractive crystal

Images:
- MEMS supply board
- Micro-beam
- Electric contacts
- Graph showing displacement over time
Holographic Interferometry

- Application on transparent objects
Holographic Interferometry

- Use pulse Q-switch YAG laser
  - Nanoseconds recording
  - Allows addressing 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

  ![Diagram of interferometer system]

- 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
Holographic Interferometry

- Vibrations: Electronic board on shaker
  - total amplitude of vibration can be millimeters
  - $\lambda = 1064$ 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
    • $E=10 \text{ mJ/cm}^2$
    • Weak efficiency : $I_{\text{diffracted}} << I_{\text{direct}}$
    • 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 :
    • $E<10 \text{ mJ/cm}^2$ (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
      – A few tens of holograms
      – Limited object size due to low efficiency
      – 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 solicitation/stress levels

- Photosensitive holographic recording media at 10 µm
  - Examples:
  - 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?