Photosensitivity of Optical Materials for Photonics and Integrated Optics

Raman Kashyap

Advanced Photonics Concepts Laboratory
Ecole Polytechnique de Montreal
Canada

Functional Glasses:
Properties and Applications for Energy and Information
January 6 – 11, 2013
Siracusa, Sicily, Italy
Learning To Love the Materials that Make Glass – SAND in Sergipe

Prof. Peter Kazansky learns to love sand
Outline of Talk

- Introduction to Photosensitivity:
  - Historical Perspective:
    - Art, Photography, Photosensitivity
  - Photo Refractive materials
    - Charge generation in Electro Optic Crystals: change in refractive index
    - Grating Formation

- Photosensitive Materials:
  - Defects in glass
    - Two Photon and Single photon excited charge generation: Ge doped Silica
    - Holographic Glass: Silver doped glass, Photothermal Refractive Glass
  - Photoresist, Polymers: Dichromated gelatin (DCG: 1830s), photochromics, Photopolymerisable resins (PR)
  - Chalcogenides: phase transitions

- Femtosecond pulsed laser recording vs CW
  - Imaging of moving biological samples
- Laser Cooling with Quantum Dots in Glass

- Future Prospects
Introduction

- Our fascination with *Capturing the Image*: Since time began.....painting was an inexact art...........has had its advantages!

- Photosensitivity:
  Paintings fade when exposed to light: well known Paper colours when exposed to light..c.f. Kodak Museum.
  - The **REVERSE** process: *Photo-Darkening*
    Daguerre-type photographic process captures images permanently on glass coated with silver-halide emulsion : 1820
    • Changing absorption into refractive index change by bleaching: Lippmann: 1894....... **More later.....**
    - However,.....**All materials** change properties when exposed to electro-magnetic radiation of some frequency!
    - High Energy FEMTOSECOND LASER INTERACTION!

Nude lady combing her hair, Picasso, 1940
Louis-Jacques Mande Daguerre: Born Cormeilles, Normandie region, 1787:
DATA STORAGE: Boulevard du Temple, 1838

Basic Material is Silver Nitrate, **fixed** as Silver Oxide with an **associated** Refractive Index change
Another Material From Sicily can also Change Your Refractive Index
Photorefractivity

- Photoexcitation of low lying defects in Electro-Optic crystals
  - Charge migration:
    - Under external field (enhanced effects)
    - Without external field (weak effect)
  - Elevated temperature allows ionic diffusion to neutralise charges
    - Room temp diffusion of ions is slow.
    - Electrons remain in deep traps quasi permanent E-field.

\[ \text{Defect sites (Fe}^{2+}/\text{Fe}^{3+}) \]
\[ \text{Conduction band} \]
\[ \text{Valency band} \]
Process of phase grating formation

- Optical Radiation
- Interference
- Thickness of grating defined by overlap and absorption depth
- Electro optic crystal
- Refractive index modulation

• Development of internal field through charge separation
## Energy requirements for 1% diffraction efficiency: EO photorefractives

<table>
<thead>
<tr>
<th>Material</th>
<th>1% eff mJ/cm²</th>
<th>Dark Storage time (yr)</th>
<th>Wavelength (nm)</th>
<th>Ext. E-field (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiTaO$_3$;Fe</td>
<td>11</td>
<td>10</td>
<td>351</td>
<td>15</td>
</tr>
<tr>
<td>LiNbO$_3$;Fe</td>
<td>200</td>
<td>1</td>
<td>351</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>0.1</td>
<td>488</td>
<td>0</td>
</tr>
<tr>
<td>Sr$<em>{0.75}$Ba$</em>{1.25}$Nb$_2$O$_6$;Ce</td>
<td>1.5</td>
<td>0.1</td>
<td>488</td>
<td>0</td>
</tr>
<tr>
<td>Bi$<em>{12}$SiO$</em>{20}$</td>
<td>0.3</td>
<td>0.003</td>
<td>514</td>
<td>6</td>
</tr>
<tr>
<td>KTa$<em>{0.65}$Nb$</em>{0.3}$O$_3$</td>
<td>0.05</td>
<td>0.001</td>
<td>530</td>
<td>6</td>
</tr>
</tbody>
</table>

Glass Photosensitivity
Photosensitivity

• Definition:
  – *the change in the optical transmission properties of a material on the exposure to light*
  – Transient or *Permanent*

• *Indirect* process
  Charge trapping, self electro-optic induced refractive index change: *Photorefractive, photothermal*

• *Direct* process
  Creation of defects and free charges, breakage of molecular bonds, stress alteration
  > changes in absorption (*photochromic*) and refractive index

*PHOTOSENSITIVITY IS A TOOL FOR CREATING DEVICES*
Photosensitive Inorganic glasses:

• Photo bleaching Glasses:
  • Historical inorganic glasses for phase holograms:
    – Bleaching of color centers by UV radiation: 2 and single photon. 3mm thick, diffraction efficiencies: 1%, up to 6000L/mm*
      • Borosilicate glass (BK-7) also low refractivity (stress/differential etching)
    – Porous silica impregnated photo-polymer† – residual photosensitivity and high scattering (Sol-Gel)
    – Ge doped silica fibre: bleaching and stress relief
    – Excellent stability and low loss: Something to Bragg about!
      • Bulk gratings difficult
      • Hydrogen loading and formation of GeH, GeOH….

• Photothermal Refractive (PTR) Glass:
  Li-Al-SiO₂:Ce, Na-Zn-Al-SiO₂:Ce

  ➢ Process…aka…Daguerre
    ➢ UV exposure and & heat treatment**
    ➢ Greater than 95% reflection gratings: 10,000L/mm

†Cheben P and Calvo M, ‘APL78, 1490-1492, 2001
Fibre Bragg Gratings Basics

- Most glass is photosensitive to UV laser light
- A diffractive interference pattern can be printed in glass using phase mask

![Transmission Spectrum](image)

**Transmission (dB)**

- Wavelength (nm)

---

Raman Kashyap ECI Functional Glass Conference
6-11 January 2013
FBG basics

- Fiber Bragg grating: periodic modulation of the index in the core of an optical fiber that allows a Bragg wavelength to be reflected.

Bragg wavelength:
\[ \lambda_B = 2n_e \Lambda \]

Reflection:
\[ R = \tanh^2(\kappa_{ac}L) \]

Bandwidth:
\[ 2\Delta\lambda = \frac{\lambda^2}{\pi n_e L} \sqrt{(\kappa_{ac}L)^2 + \pi^2} \]

Phase mask technique

- Grating period fixed by phase mask
  \[ \Lambda_g = \frac{N \lambda_{\text{Bragg}}}{2n_e} = \frac{\Lambda_{pm}}{2} \]
- Very simple to align
- Length is limited by phase mask (10cm)

Silica

Diffractive phase mask
Reflection Spectra: FBG types

Uniform

Phase shifted (DFB)

Chirped
High Temperature Chemical Composition Gratings in F:Ge: Silica

1 m long FBG Writing Station
1 Meter Long FBG: Simulation

1 Million Periods
Full Bandwidth = 2 pm

300 MHz
Impact of non-uniformities

• Can we achieve Perfect Device characteristics?
• What is an acceptable random variation?
• How uniform does a material have to be?
Reflection & Transmission of 1M periods: \( dn = 10^{-6} \)
1m Long FBG (Bandwidth < 80pm)
Summary on Uniformity

• A refractive index modulation of only $10^{-6}$ is needed for meter long gratings....

• However
  – $10^{-6}$ random change in refractive index visibly affects performance
  – 0.1% variation in the core diameter is equivalent to a change of $\sim 1.5 \times 10^{-6}$ in refractive index!
  – SO ???????
Photosensitivity & Materials Requirements
Photonics in Action: Applications of UV processed silica

VCSEL, DFB, FP, ECL

EDFA

GFF

Mzi Modulator EOM, EAM

Dispersion compensating chirped grating

DCF

λ-C

Photodiode Receiver

PMD compensator

isolator DFB Filter

South

West

Femto-second Continuum Generator

UV written waveguide devices:
interleavers, couplers, multiplexers,
gain equalising filters, lasers, sensors,
ASE rejection filters...etc

AWG
Photosensitive Material Issues For Photonics Applications

- High Transparency in region of interest
- Low Scatter loss
- Zero Absorption loss
- Resistant to Bleaching
- Large controllable refractive index change
- High Optical Damage Threshold
- Low Dispersion
- High Stability with temperature and time
- Good Reliability & Lifetime (10-20 years)
- Durability
- Process Repeatability and Adjustability
- Low Reversability
- Ease of Handling
- Long Storage & large operating temperature range
Photosensitivity: Challenging Device Issues

- Uniform characteristics
- Guided wave devices with CONSTANT properties: Ultra-low variation in dimensions ~ few nm over meter lengths...0.1% .... ~ 5nm in 5 micron!
- Low variation in refractive index with distance: $< 10^{-7}$ over meter lengths: ~0.01% in waveguide refractive index difference

- Increase Change in Refractive Index to 0.1
Some words about Ge:Silica

- **Fascinating material!**
  If you thought you knew everything about silica….wait!
  It has ALL the properties one would lust after!

**Makes:**
- Near perfect waveguides…..but we are at the limit
- Dope with all sorts of materials: lasing
- Make complex near-perfect grating filters optically in waveguide core
- Infinitely adaptable for device fabrication
- Stable >500ºC
- High Quality and…………well…….er…….understood?

So…..why do we need other materials?
Lets consider some other materials & applications……..
Photosensitive Glass: Foturan ® Schott: Silver loaded silicate

1. UV radiation between 290-330nm @ 2 Joule/cm²

2. Silver atoms formed in illuminated regions. Heat treatment between 500° and 600°C crystallizes glass around silver atoms.

3. Room temperature etch in 10% HF:
   - Etching rate of crystalline 20 x higher than vitreous regions.
   - High aspect ratios: 25 micron feature size with micron size roughness.

Main application: Masking and feature formation: NEW APPLICATIONS??
Foturan Glass

- Excellent processability
- Excellent aspect ratios
- Durable
- Transparent

- But not acceptable as Optical glass….loss due to scattering

- Is there anything else……????
PhotoThermal Refractive (PTR) Glasses

• Probably most promising material Properties:
  – Inorganic glass
  – Stable to greater than 400°C
  – Index change 0.001 ….on low end of scale
  – Low loss
  – Bulk processing
  – High optical damage resistance
  – Volume phase holograms
  – Commercial applications in lasers and beam combiners
Photo-Thermal Refractive Process

• Na-Zn-Al-SiO$_2$: Ag, Ce, F
  – Precipitation of dielectric micro-crystals in the bulk of glass exposed to UV radiation.
  – Electron released by
    \[ \text{Ce}^{3+} = \text{Ce}^{4+} + e^- \]
    is trapped at nearby Ag ion \(\Rightarrow\) neutral atom (latent image)
  • But NO significant change in refractive index or coloration....

• UNTIL HEATING:
  – 3 Hrs at 450-550°C \(\Rightarrow\) diffusion of Ag atoms to form tiny crystals \(\Rightarrow\) nucleation site for NaF crystal growth
    \(\Rightarrow\) \(dn\)

Transparency and Photosensitivity windows in PTR Glass

Absorption in Unexposed PTR Glass

From: Glebov L B et al., SPIE 4724, pp101-109
Optical damage and diffraction in PTR glass

From: Glebov L B et al., SPIE 4724, pp101-109
Summary: Processed PTR Glass

- Transparent between 350 – 2700nm (contamination: OH\(^-\) group)
- Extra loss in UV due to mixtures of Ce & Ag
- Fluoride crystals are transparent but scatter light:
  - Additional absorption < 0.3 cm\(^{-1}\) in blue region
  - < 0.03 cm\(^{-1}\) in red region
- Index change ~ 10\(^{-3}\)
- Ideal for PLANE WAVES
Photosensitive glass: Application

• Laser mirror for locking semiconductor diode arrays

FROM: PDLD website
Waveguide Fabrication by Direct Laser Writing
But First......
Optical Fibres…25 years ago.....
Plasma Generation in Glass
...Optical Fibre Damage at Low Powers*: ‘Fibre End’

Molecular oxygen in cavities

Stationary Temperature Profile of Damage Filament

- Self-Propelling Damage
- Absorption of light by glass at elevated temperatures
- Thermal runaway

Calculated using a heat diffusion model

Refractive Index Increase After Damage

*Damage Summary*

- Wild Temperatures…10,000K!
- Almost no heat loss: Only Conductive Heat
- Creates Sub Oxide of Ge/Si
- Refractive index modification….
- Catastrophic Damage….
- Similarities to fs laser processing.

So what else can we do?

......Laser Ablation
Laser Written Waveguides*

High magnification picture of ablated waveguide
Cascaded Multimode Interference Filters (Six Ports)

\[ L = \frac{p}{N} \left( \frac{3L\pi}{4} \right) \]

1 x 2 MMI

2 x 4 MMI
5 port devices using 2 configurations

Straight Waveguide Loss: 0.36dB/cm

G. V. Vázquez, A. Harhira, R. Kashyap and R. G. Bosisio, Micromachining by CO₂ Laser Ablation: Building Blocks for a Multiport Integrated Device, Accepted in Optics Communications
Movie of MMI Fabrication
L’impact est du à un laser CO2 (P=1,05W). Le shift est déterminé par le shift du centroïde. Les spectres sont enregistrés le long de la ligne ci-dessus a partir du centre de l’impact. La densité du verre de silice dopé germanium augmente lorsque le Raman shift augmente.
Refractive Index Change (Reflectometry)
Annealing!

• Waveguide is *buried* due to Heat Affected Zone Lowering Refractive Index!

• **THEREFORE:**
  Pre-annealed planar samples *do not work!*
CHANGE OF PACE FROM CW ILLUMINATION...

Femtosecond pulse photoinduced effects in glasses

Acknowledgement: Prof Hirao, Ravi Bhardwaj
Question of Maximum Optical Power Limitation

20ns Pulses

Commensurate with fs modification: 30mJ/20ns OR 60nJ/100fs

Fabrication platform

**Laser parameters**
- Power: 300 mW
- Wavelength: 800nm
- Pulse duration: 40-50 fs
- Rep rate: 10 – 250 KHz
- Scan rate: 10 – 500 μm/s
Fs laser induced refractive index changes

Laser induced generation of ODC (II) generation and optical damage in the form of scattering centers in the volume of the sample, whereas the generation of Si $E'$ only left the samples scatter free. Finally, Raman spectroscopy confirmed the generation of threefold and fourfold rings and revealed a decrease in the Si-O-Si angle distribution as a result of the photoinduced disruption of strained bond upon IR femtosecond laser irradiation.

Zoubir et al., PR B 73, 224117, 2006.
Material Modification with fs lasers

Provided by courtesy of Dr. Réal Vallée, U Laval

Femtosecond Interaction with solids: Originally demonstrated by Prof. Hirao

On solids
- Material ablation
- No heat diffusion
  - Rapid solid to vapour transitions
- Micromachining

Inside glass
- No material ablation
- Localized refractive index change
  - Only at the focal spot
  - IR photosensitivity
- Integrated optics

Threshold for refractive index modification

Threshold agrees with the atomic ionization energy
Fabrication of nanostructures

Closely spaced microwells in fused silica
Well densities ~ 33 million/cm² !!!


Mixing biological fluids in 3D microfluidic channels

50 μm
Femtosecond pulse interaction with glass

Courtesy: Prof. Hirao
Novel Observations with fs lasers

- **Preferential crystallisation in Ge: glass** *(c.f. A. Stone et al., “New advances and current challenges in femtosecond laser-induced crystallization for 3D precision patterning of nonlinear optic structures inside glass” [Poster, This Conf.])*

- **Refractive Index Modification and Self Structuring**
Fs Laser Generated Void Formation: Similar to Optical Fibre

ISSUES in fs structuring

• High propagation Loss
• Control of waveguide shape
• Birefringence
• Better understanding of glass chemistry
• Relationship and similarity to low power damage
• ……
Other Photosensitive Materials of Potential Interest for Photonics Applications:

Photopolymers
Chalcogenides
PhotoPolymers: Issues for devices

- Low Energy for cross-linking
- Once fixed: high reversal energy
- Low scatter….multiple gratings
- Polarisation sensitivity
- Transparency
- Relaxation
- Stability…….
Optically recorded mechanically tunable gratings on azo-elastomers

Before

Light

After

Collaboration T. Galstian & Y. Zhao
High diffraction efficiency (>95%) photopolymers sensitive to 850 nm light

- Infrared photo-polymerization
Self-growing of a single waveguide in photopolymerizable resin

photopolymerizable resin: SCR500 (JSR Co., Ltd.)

He-Cd laser 
(441.6 nm)

N.A. : 0.23
Power : 0.1mW
exposure time : 2s

Self-Guiding in Photo-polymerising resin:

SELF-WRITTEN WAVEGUIDES IN PHOTOSENSITIVE MATERIALS
ANDREY A. SUKHORUKOV, SATORU SHOJI and YURI S. KIVSHAR
Nonlinear Physics Group, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia

SATOSHI KAWATA
Department of Applied Physics, Osaka University, Yamadaoka 2-1, Suita, Osaka 565-0871, Japan
Nanophotonics Laboratory, RIKEN, Wako, 351-0198, Japan

Refractive index profile for different values of $I_{th}$

- $P=0.1$
- FWHM=1.5
- exposure time $\tau=1200$
Bragg gratings in amorphous semiconductor waveguides

Integrated IR components (semiconductor glasses As$_2$S$_3$)
First order Bragg grating filter (L=353 nm) in waveguides

*Prof. Younes Messaddeq, U Laval

R. VALLÉE, S. FRÉDÉRICK, K. ASATRYAN, M. FISCHER, T.V. GALSTIAN,
« Real-time Observation of a Bragg grating formation in As2S3 chalcogenide ridge waveguides »,

**Sandor Kokenyesi et al. “In situ surface relief recording in light sensitive chalcogenide glasses, This conf. Poster

6-11 January 2013  Raman Kashyap ECI Functional Glass Conference
## League Table of Photosensitive Materials For Photonic Devices

<table>
<thead>
<tr>
<th>Material</th>
<th>Processing</th>
<th>Refractive index change</th>
<th>Comment</th>
<th>Long term Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge doped Silica</td>
<td>UV laser</td>
<td>~ +0.02</td>
<td>Waveguide</td>
<td>&gt;500-1000ºC</td>
</tr>
<tr>
<td>Silica, Borosilicate glass</td>
<td>Femtosecond laser, Visible-IR</td>
<td>+/- 0.01-0.001</td>
<td>Bulk and waveguide</td>
<td>&gt;900ºC</td>
</tr>
<tr>
<td>Foturan ® Schott</td>
<td>UV 290 – 330nm, Chemical</td>
<td>0.001</td>
<td>Bulk, Low resolution</td>
<td>&gt;500ºC</td>
</tr>
<tr>
<td>PTR Glasses</td>
<td>UV 300nm, Heat treatment</td>
<td>0.006</td>
<td>Two step process</td>
<td>&gt;500ºC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Lossy</td>
<td>Bulk</td>
<td></td>
</tr>
<tr>
<td>Photopolymer LC doped polymer</td>
<td>Self-inducing blue-red radiation</td>
<td>0.001</td>
<td>Two step process</td>
<td>Poor 150ºC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcogenides</td>
<td>Self-inducing red λ</td>
<td>0.1</td>
<td>Single step</td>
<td>Poor ~70ºC</td>
</tr>
</tbody>
</table>
Laser Cooling
Solid and *Liquid* State COOLING WITH LASERS

Laser

Cool Projet

K_B T

Jerome Poulin: Cold Atom Guiding

Elton Soares

Sebastien Loranger

Galina Nemova

More People

6-11 January 2013
Solid State Laser Cooling

- Absorption of energy at long wavelengths

  Thermalization

  Pump

  Fluorescence

  Heat Removal

  Tilted grating in Yb3+ doped ZBLAN Fibre

- HEAT Removed by Emission of photon at SHORTER WAVELENGTH
Maximum Cooling Efficiency (ANTI-STOKES RADIATION)

\[ \eta = \frac{\Delta \lambda}{\lambda_f} \left( 1 - \frac{k_B T}{h \nu_f} \right) \]

\[ \Delta \lambda = \lambda_{\text{fluorescence}} - \lambda_{\text{pump}} \]
Cooling in Yb: YLF to 110 K

PROBLEMS:
- Need very pure sample
- Non-radiative rate must be LOW
- Low phonon energy material
- Need laser to match absorption
- No tunability

CANNOT USE SIMPLE DOPED GLASSES!

\[ CE = \frac{P_{\text{cool}}}{P_{\text{absorbed}}} \]

Laser Cooling: The Challenges

• MATERIAL REQUIREMENTS:
  – Low Phonon Energy glasses: $E_g > 8$ phonons
  – Very high purity of materials
  – High quantum efficiency of fluorescence
  – Low background absorption
  – Low NON-RADIATIVE decay rates
  – Low Auger recombination rates
  – Pump wavelength selection
  – Reabsorption of Fluorescence
Cooling with QDs

- How can we improve cooling efficiency?
  - Through reduced radiative lifetime of the excited level

- How to improve the figure of merit?
  - By increasing the absorption cross section

- How can we use new materials with higher phonon energy as hosts?
  - When we reduce the radiative lifetime

- How to tune the absorption properties of material?

Solution: quantum dots (artificial atoms)

Quantum Dots and Size Dependent Effects

14th © Glass from Damascus

QD Doped Filter

15th © QD Stained Glass Windows

The First Nanotechnologists

Gold particles in glass

Silver particles in glass

Raman Kashyap ECI Functional Glass Conference
Quantum dots (*artificial atoms*)

- Small size semiconductor (of order exciton Bohr radius) becomes a quantum dot (QD)
- States become quantized

- Bulk semiconductors have fixed band-gaps – material structure dependent.
- QD band gap becomes a function of the size of the QD.

\[
E_g(R) = E_g + \frac{2 \hbar^2 \pi^2}{m_{eh} D_{QD}^2},
\]

where \( m_{eh} = \frac{m_e m_h}{m_e + m_h} \),

\( m_e = \text{effective mass of electron} \)

\( m_h = \text{effective mass of hole} \)

\( D_{QD} = \text{diameter of QD} \)
Advantages of PbSe QDs for cooling

- Lead-salt QDs (e.g. PbS, PbSe, and PbTe) have strong quantum confinement

- Exciton Bohr radius of a PbSe QD is huge: \( a_{\text{exc}} = 46\,\text{nm} \)

- Due to high permittivity \((\varepsilon = 23) + \text{small effective masses} (< 0.1\,m)\) of electron/hole, where \( m = \text{rest mass of the electron} \)

- Radiative lifetime of 1Sh level of the PbSe QDs doped glass is microseconds

- Radiative lifetime of rare-earth (RE) ions is miliseconds \((1000x)\)

- Size of QDs, as artificial atoms, changes distance between the 1Se and 1Sh levels to match any available pump sources

- Large absorption cross section makes QDs very attractive for laser cooling
Cooling with quantum dots (spectra)

\[ D_{QD}^{(1)} \approx 5.0 \text{ nm}, \]
\[ D_{QD}^{(2)} \approx 5.5 \text{ nm}, \]
\[ D_{QD}^{(3)} \approx 6 \text{ nm}. \]

Robodots
CdSe QD
with CdS, CdZnS and ZnS shell
From Laval University
Absorbance and emission spectrum

Absorbance and Emission (λ_p = 532 nm)
Anti-Stokes emission in QDs

Pumped at 670 nm
Pumped at 628 nm

Intensity (a. u.)
Wavelength (nm)

0,6
0,4
0,2
0

Pumps
Anti-Stokes Emission in PbS QDs in SNAB Glass

Results

• Despite ~80% efficiency of QDs no Cooling yet!
• Work is progressing to change this with better QDs.
Challenges with Semiconductor QDs

- High QE of passivated QDs in liquids >80%
- Excellent Control of QD size in liquids
- Control sizes to 1% in glass
- Reduce Non-radiative effects in glass
- Increase QE to 95% in glass
- Passivate QDs in glass host: Core-Shell?
CONCLUSIONS AND SOME THOUGHTS FOR THE FUTURE

• Materials must have a *key* advantage over existing solutions
• It is not just necessary to be better in *one* respect
• Applications can be *very* demanding of material properties
• With the correct materials, photosensitivity must lead to:
  – Direct writing of interconnect….point to point/ multipoint
  – 3D-ICs: High density chips
• Bio-compatible photosensitive materials are needed
  – Integrated functionality for micro-fluidics and waveguides
• Need Techniques for Passivation of QDs in solids
• Bubble Formation in Optical Fibres for Nuclear Fusion…….???
The Advanced Photonics Concepts Group
Acknowledgements:

- Dr. Kivshar, *Australian National University, Canberra*
- Mr Shoji, *Department of Applied Physics, Osaka University*
- Prof. Tigran Galstian, U Laval, Canada
- Prof. Real Vallee, U Laval, Canada
- Dr Ravi Bhardwaj, NRC, Canada
- Prof. Hirao, Japan
- Prof. Peter Kazansky, U. Southampton
Mille Grazie!