Guided Photons, waveguides, and their Applications

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Photonics Materials Group

Prof. Andy Bell, Dr. S. Milne (Reader),
Prof. P. Harrison, Prof. Bob Miles, Dr. Paul Steenson (School EEE)
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3 Full-time research Support staff.
~£2.5 m Clean room, with £5-6 m equipment and £5-6 m research projects in microelectronics, THz, uv-visible-mid IR Photonics
A suite of micro-fabrication facilities

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OUTLINE

- WHAT IS A PHOTON & PHOTONICS? When did it all begin?
- APPLICATIONS OF PHOTONICS
- Fibres for signal processing e.g. amplification and lasing
  - telecom wavelengths
  - mid-IR wavelengths (beyond 2 μm and longer)
  - schemes for generating light in visible and means for accessing shorter UV wavelengths and X-ray lasers
- Planar optics devices and optical integration and MEMS for inorganic, organic, and biological solid matters
- Materials processing
- Fibres as Chemical Sensing in 1 to 10 micron and then beyond 10 microns
- Bio-photonics and future
- High-power lasers for fusion energy and space communications

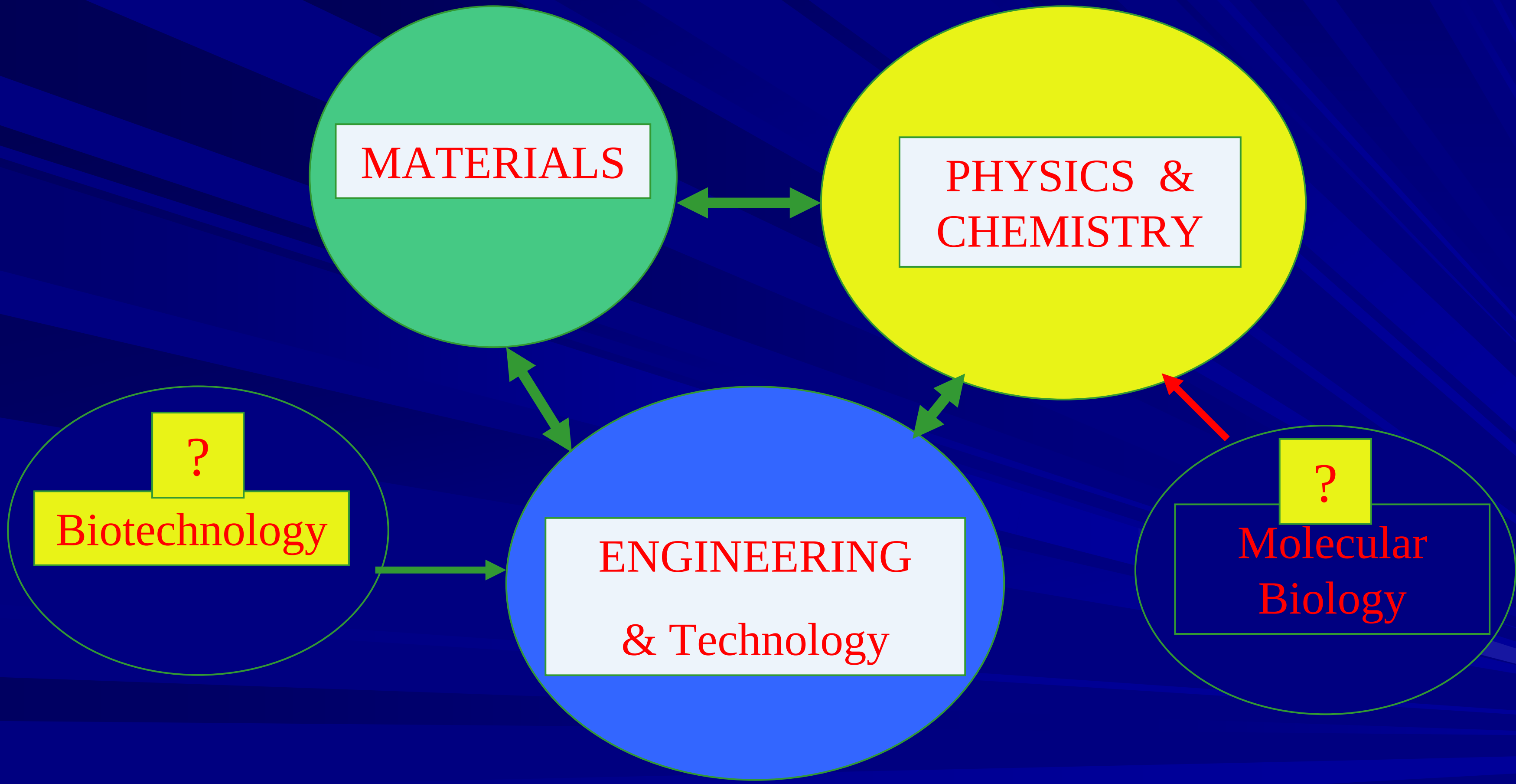
PHOTONICS, Albert Einstein & His Quotations

- Imagination is more important than the knowledge.
- All these 50 years of conscious brooding has brought me no nearer to the answer to the question "what are the light quanta"? Now-a-days every Tom, Dick, and Harry thinks he knows it, but he is gravely mistaken.

  Moral is: Knowledge must bring humility so that we continue imagining new science for the good of the well-being of everyone on the planet.

WHAT IS PHOTONICS? Interaction of photons (coherent and incoherent) with matter, and of its consequences: linear and non-linear interactions. Follows conservation of momentum and energy.

THE HOLY TRINITY IN PHOTONICS- a multidisciplinary subject



Electromagnetism & Electrodynamics

Name	Partial differential form	Integral form
Gauss's law:	$\nabla \cdot \mathbf{D} = \rho$	$\oint_A \mathbf{D} \cdot d\mathbf{A} = Q_{encl}$
Gauss's law for magnetism:	$\nabla \cdot \mathbf{B} = 0$	$\oint_A \mathbf{B} \cdot d\mathbf{A} = 0$
Faraday's law of induction:	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_S \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$
Ampere's law + Maxwell's extension:	$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	$\oint_S \mathbf{H} \cdot d\mathbf{s} = I_{enc} + \frac{d\Phi_D}{dt}$

Where

ρ is the *free* electric charge density (SI unit: C/m^3), not including dipole charges bound in a material

B is the magnetic flux density (SI unit: tesla, T), also called the magnetic induction.

D is the electric displacement field (SI unit: C/m^2).

E is the electric field (SI unit: V/m),

H is the magnetic field strength (SI unit: A/m)

J is the current density (SI unit: A/m^2)

$\nabla \cdot$ is the divergence operator (SI unit: m^{-1}),

$\nabla \times$ is the curl operator (SI unit: m^{-1}) **Ref: h**ttp://encyclopedia.laborlawtalk.com/Electromagnetic_theory

Summarise Photon-Matter Interaction

I think – it is relevant to quote Richard Feynman "***How clever we are to have found it all out, but on how clever nature is to pay attention to it***" .

R P Feynman also said: " when a law is right it can be used to find another" and Maxwell's genius, like that of Einstein and Feynman later on in the 20th Century, set a wonderful example of successfully exploiting the knowledge of ELECTROMAGENTISM for "ELECTRODYNAMICS".

It removed the mystery of Newtonian Ether which was confusing in a similar manner when 15th century priests thought that the "*Biblical Angels fly the planets around "earth" before Newton and Kepler brought the concept of Gravity and begin to define its scale"*.

Photon-Matter Interaction

- Different scales of interactions in the medium
- Linear interaction (low photon intensity regime)
  - Guided propagation
  - Scattering in the linear regime (elastic and inelastic scattering)
  - Reflection, refraction, polarisation, diffraction
- Nonlinear interaction (High photon intensity regime)
  - Photon absorption at band gap and molecular frequencies
  - Raman and Brillouin effects (conservation of energy)
  - Conservation of momentum (electronic transitions; e.g. self-phase modulation, four-wave mixing etc)
  - Photon interaction at very large intensities

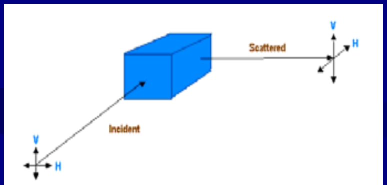
Examples

- OPTICAL FIBRES and WAVEGUIDES
- Semiconductor and rare-earth doped devices
- Guiding light in a periodically controlled defect structures
- High power laser interaction with matter
- Achieving ultra-high power beyond 10^{15}W cm^{-2} – commercial systems
- Photons and biological systems – our eyes
- High-energy photons as surgical tool

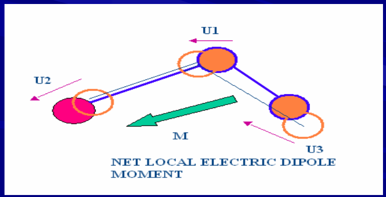
VIBRATIONAL SPECTROSCOPY

- <u>Raman Spectroscopy:</u>
- Symmetric and anti-symmetric stretching modes are determined,
- Follow crystal analogues for CN and nearest neighbours.
- Raman Intensity strongly depends on the **polarisability** of molecular structure, ie cation/anion size and charge.

V – Vertical, H - horizontal



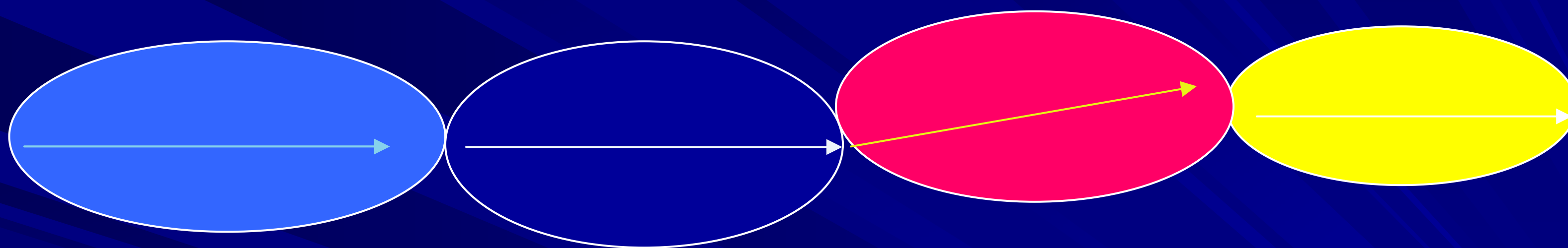
- <u>Infrared Absorption and Reflection Spectroscopy:</u>
- Asymmetric and anti-symmetric vibrational modes can be determined, hence it is complementary to Raman.
- It is a **Dipole-induced vibrations**, therefore by combining the two vibrational techniques (IR and Raman) a detailed phonon and molecular structure can be determined.



BOSONS in Physics

- The Bosons are considered soft-mode or weak-mode phonons in the glass structure, which have vibrational energies in the range of 5-100 cm^{-1}.
- Few less comprehensive reports on the evidence for Boson peak in the crystalline materials.
- Bosons in the glass structure support the propagation of acoustic phonons.
- By comparison Optical Phonons have larger energies.

PROPAGATION OF ACOUSTIC PHONONS



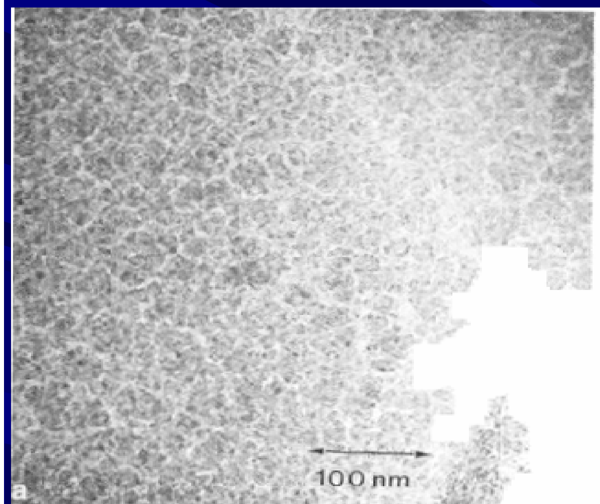
Medium Range Order can be determined by equation, which connects the velocity of sound in a medium with the Boson peak frequency. Each cluster represents the MRO, which support the Boson coupling, or the acoustic phonon propagation.

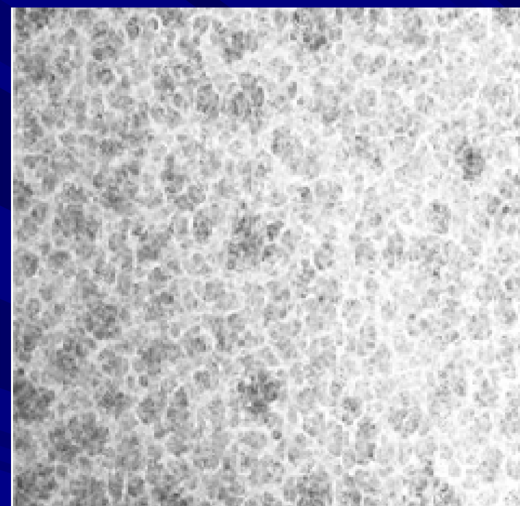
$$\omega_{Boson} = \frac{1}{2\pi} \cdot \sqrt{\frac{f}{\mu}},$$

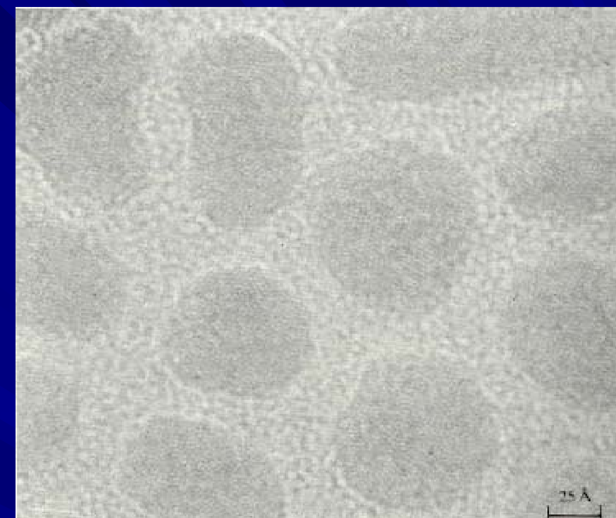
$$\mu = \frac{m^{+} . m^{-}}{m^{+} + m^{-}}$$

$$MRO = \frac{V_{acoustic}}{C.\omega_{BOSON}}$$

Cluster formation glass and local ordering in GLASSY materials







Low concentration (< 1 mole%)

High dopant concentrations (>5 mole%)

Pd-Si amorphous alloy

Ref: Physics of amorphous Matls. &

Fibre Amplifiers and their applications

Clustre Formation In Pd-Si amorphous alloy produced via PVD technique 500kV accelerating voltage. Clustres are 7.5 – 10 nm in size.

Table 2: A comparison of data for the dominant Raman (υ_R) and Boson peaks (υ_B) in various glasses, their acoustic velocities (V_{ac}) and calculated Boson mean free path (l_B, nm).

Glass Name	υ_R, cm^{-1}	M^+-A^{n-}, nm	V_{ac}, ms^{-1}	υ_B, cm^{-1}	l_B, nm
SiO_2	1120[b]	0.162[b]	3800[a]	55[d]	2.3
GeO_2	880[b]	0.170[b]		36[b]	
B_2O_3	1500[b]	0.137[b]	1780[a]	24[a]	2.47
Tellurite	760, 660	0.185[b]		35	
Ge-S-I	350	0.220[b]	1750[a]	25	2.87
50 GeS_2 - 50 GeS	350	0.220[b]	1750[as1]	25	2.87
Ge-2	350, 420	0.220[b]	1750[as1]	25	2.87
98 GeS_2, 2 Ga_2S_3	480, 350	0.220[b]	1750[as1]	25	2.87
As_2S_3	340	0.228[b]	1400	25	1.87
70 Ga_2S_3 30 La_2S_3	350	0.246[est]	1750[as1]	80	0.72
ZBLAN	580[c]	0.209[c]	2100[a]	45[a]	1.55
ALF-126	620	0.180 (avg)	2100[as2]	140	0.52
) $ZnBr_2$, 40 KI, 10 $BaBr_2$[a]	155, 144	0.232[b]	1300	23[a]	1.89

Guided Waves and signal degradation mechanisms

- Satisfies the condition of total internal reflection and follows the Maxwell's equations for electrodynamics; based on Faraday's law of electromagnetism. Single-mode and multimode waveguiding.
- Loss mechanism :

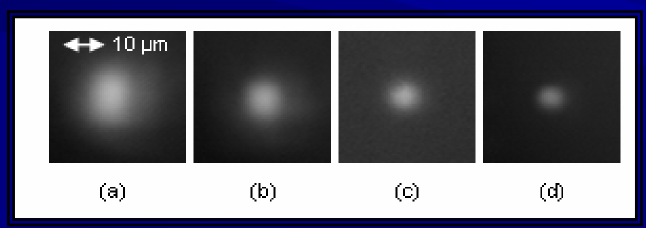
$$\alpha_{TOTAL} = \alpha_{IR} + \alpha_{UV} + \alpha_{Rayleigh}$$

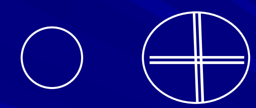
$$\alpha_{IR} = A\exp\left(-\frac{a}{\lambda}\right)$$

$$\alpha_{UV} = B\exp\left(\frac{b}{\lambda}\right)$$

$$\alpha_{Rayleigh} = C.\lambda^{-4}$$

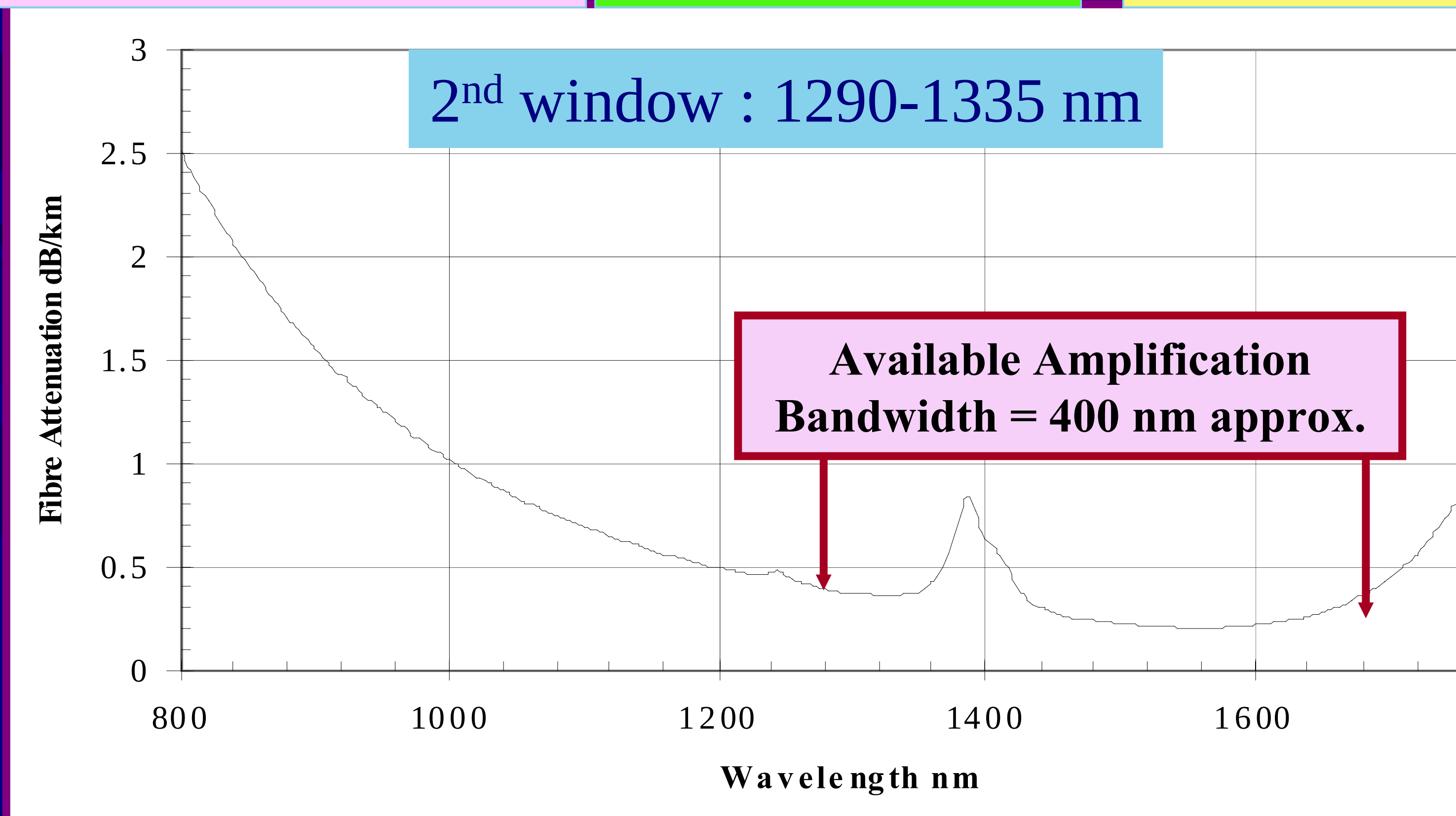
- Dispersion: Electromagnetic interaction with the medium



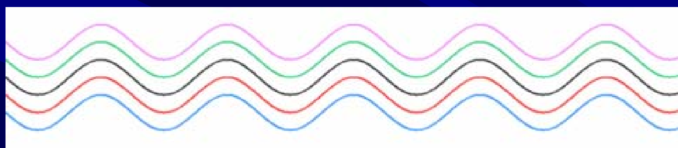


Silica Fibre Loss Curve: (Capacity+Reach)/£

S band : 1445-1505 nm | C: 1510-1565 nm | L: 1575-1615 nm

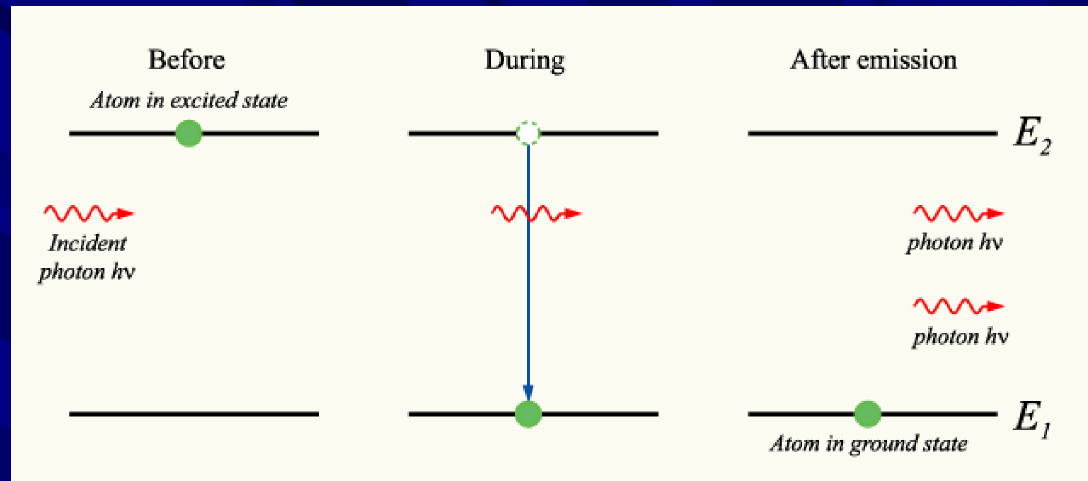


Loss = intrinsic + extrinsic factors + dispersive effects (depends on system) – limits the reach and hence the capacity.



Coherent

Incoherent



- Stimulated emission and coherence are the two main properties of lasers.
- A wave can also be coherent with itself, a property known as temporal coherence. If a wave is combined with a delayed copy of itself, the duration of the delay over which it produces visible interference is known as the coherence time of the wave, Δ*tc*. From this, a corresponding coherence length can be calculated: where *c* is the speed of the wave.

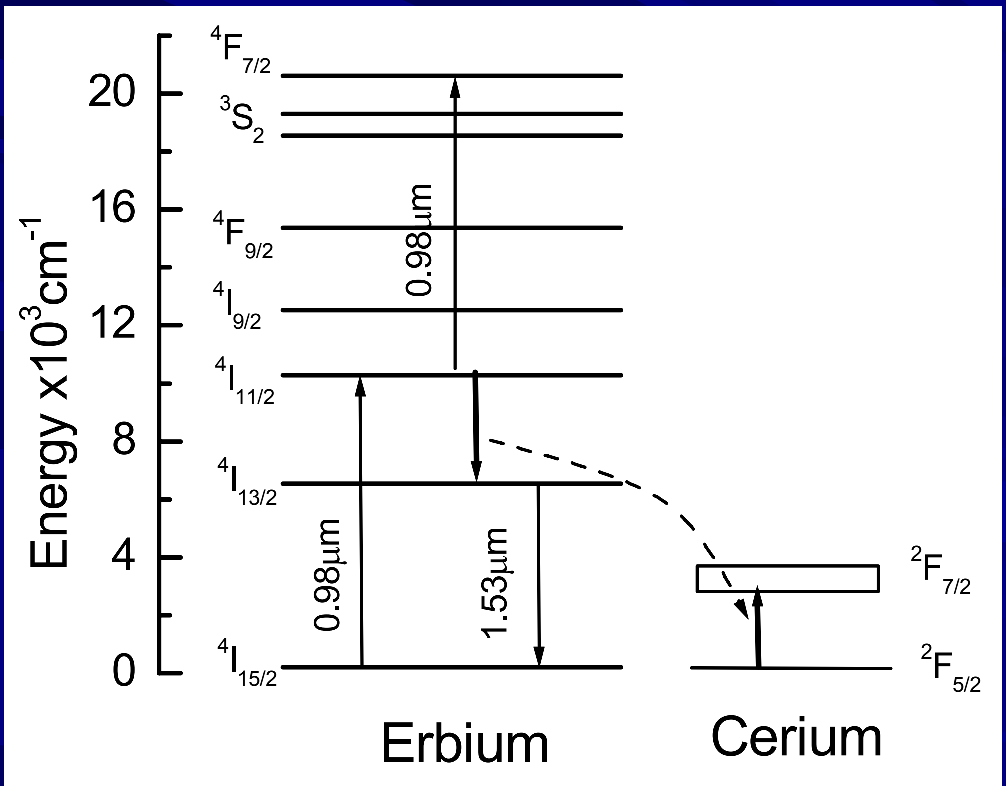
$$\Delta x_c = c\Delta t_c$$

Fibre based devices

- Rare-earth and transition metal fibres for lasers and amplifiers.
- Passive fibres for optical fibre sensors, power delivery
- Hollow-core fibres for long-wavelength transmission
- Fibres with periodic defect structures

Device Costs And Optical Integration

How to shorten the Er-device & yet increase wavelength capacity for CATV applications?



Challenges:

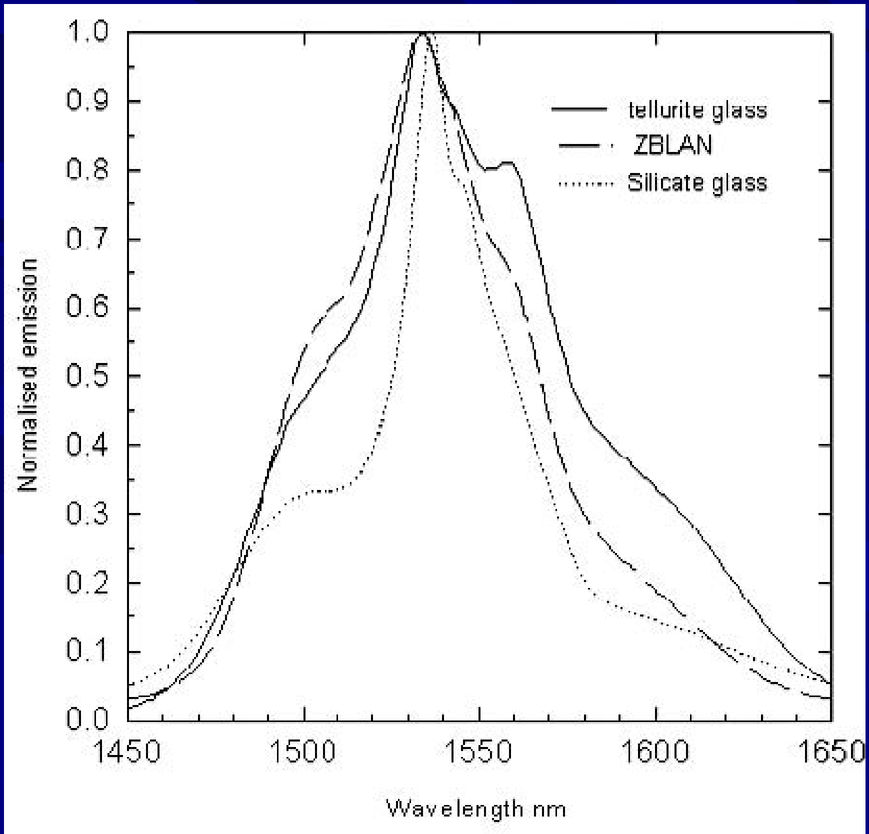
How to reduce pump ESA so that the gain can be maximised?

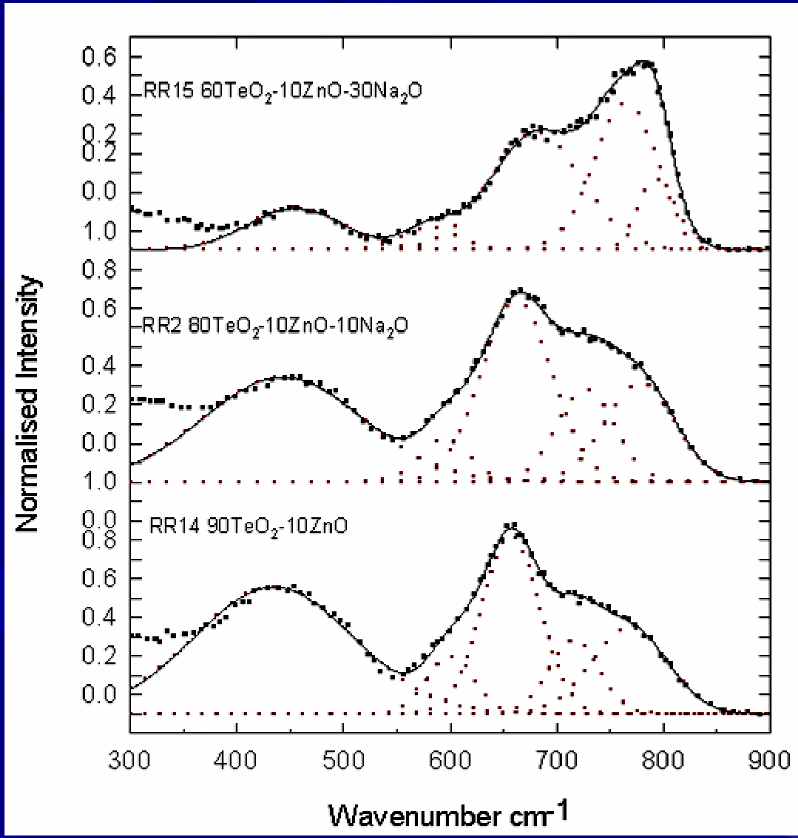
1480 nm pump is better for longer wavelengths than the 980 nm for reducing the noise figure.

ESA at signal wavelengths beyond 1610 nm

Energy Level Diagrams of Er^{3+} and Ce^{3+}

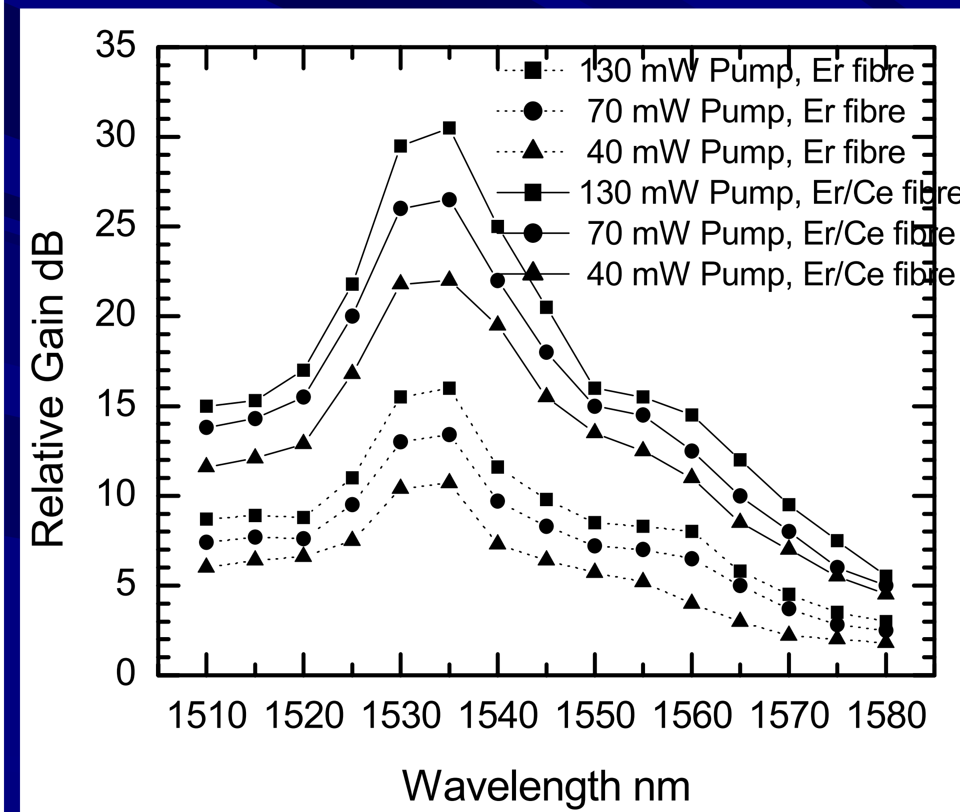
COMPARISON OF Er EMISSION LINES DIFFERENT GLASSES & STRUCTURE



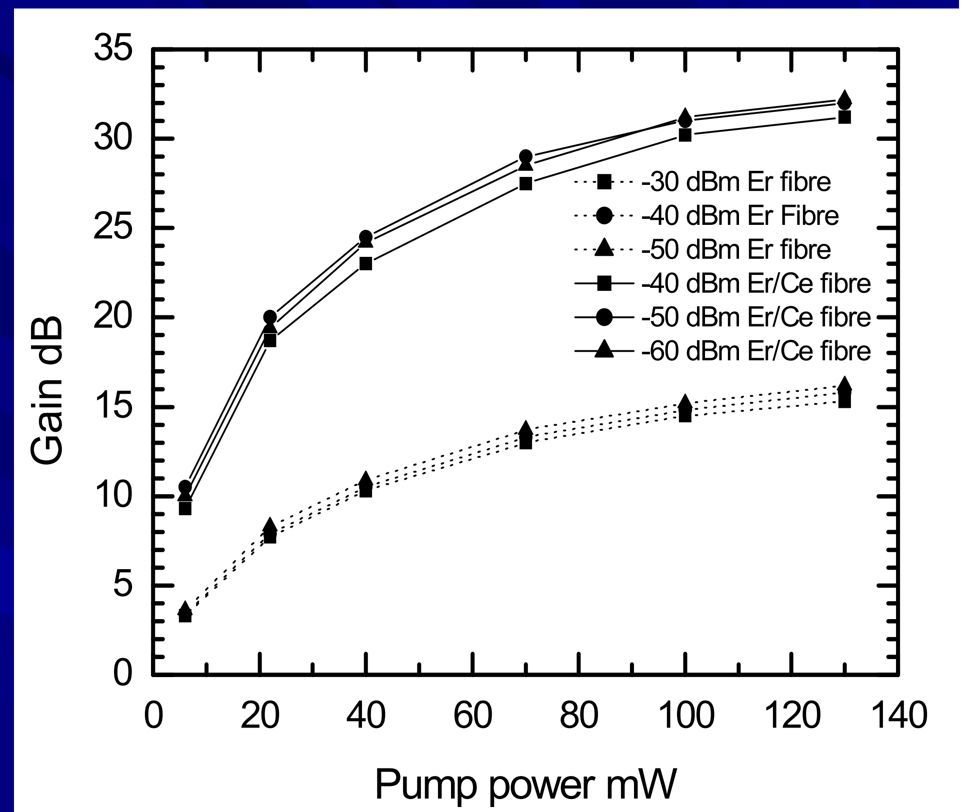


Phys Rev B, 2000, , vol.62, No 10, pp.6215-6227.

Gain spectra in Er-Ce fibres

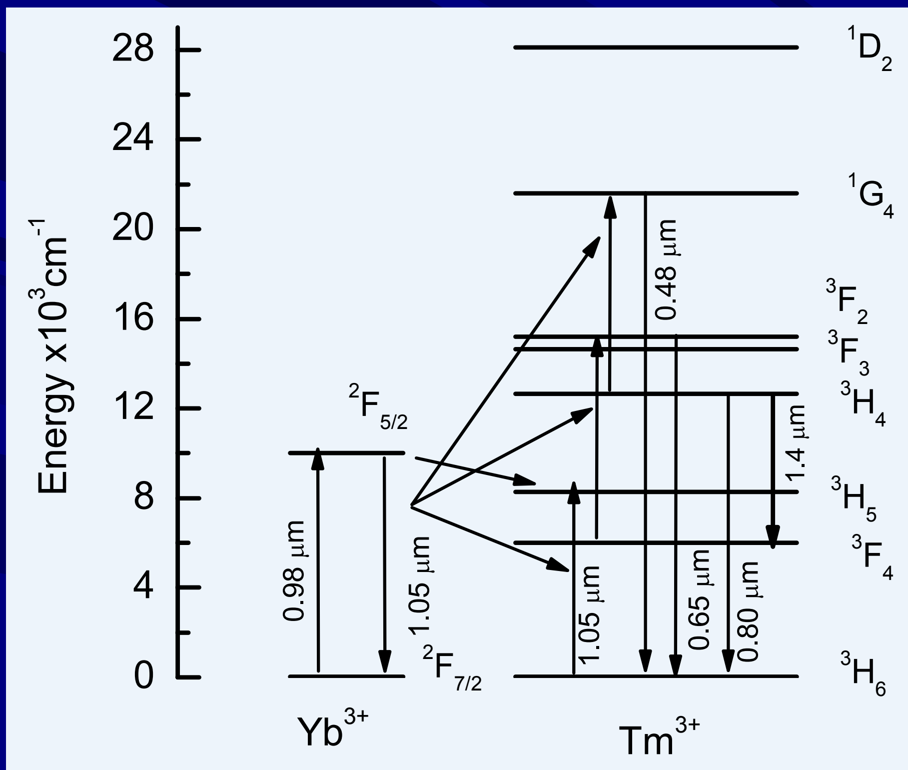


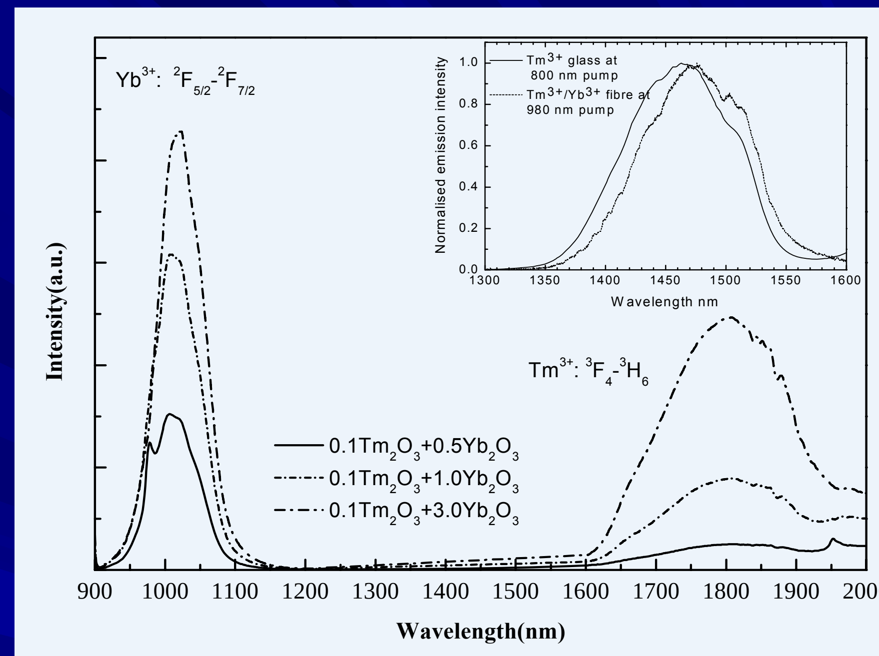
Comparison of the gain spectra in Er^{3+} and Er^{3+}/Ce^{3+} fibers



Variation in gain with different input signal and pump powers

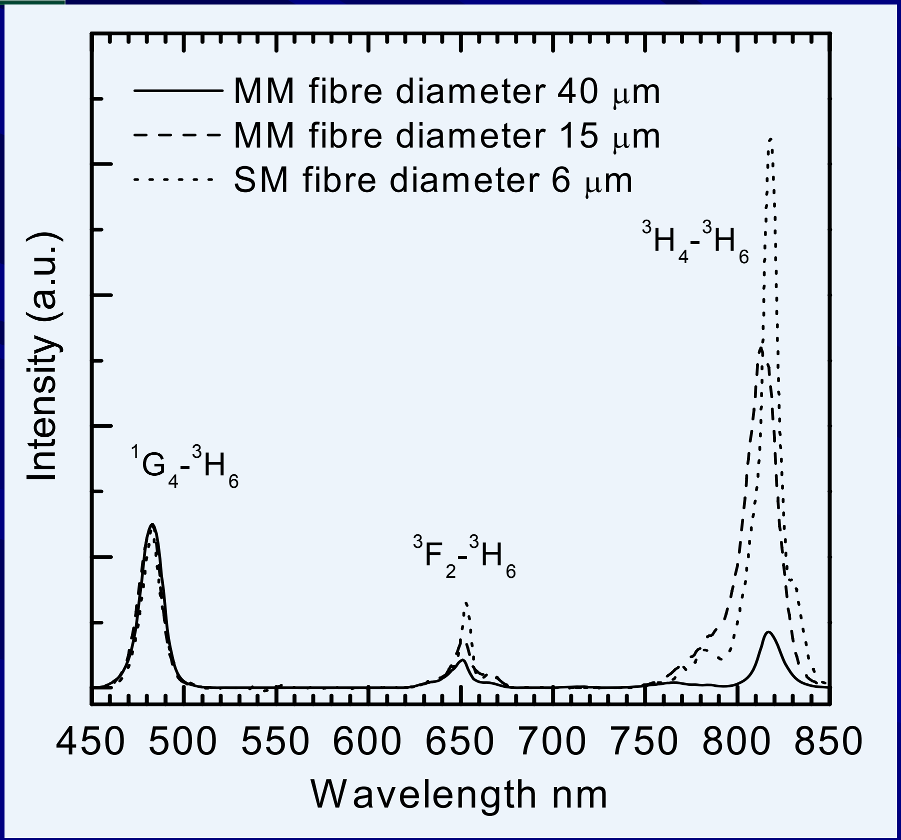
Visible, NIR, and Mid-IR Emission in TeO_2 Fibres

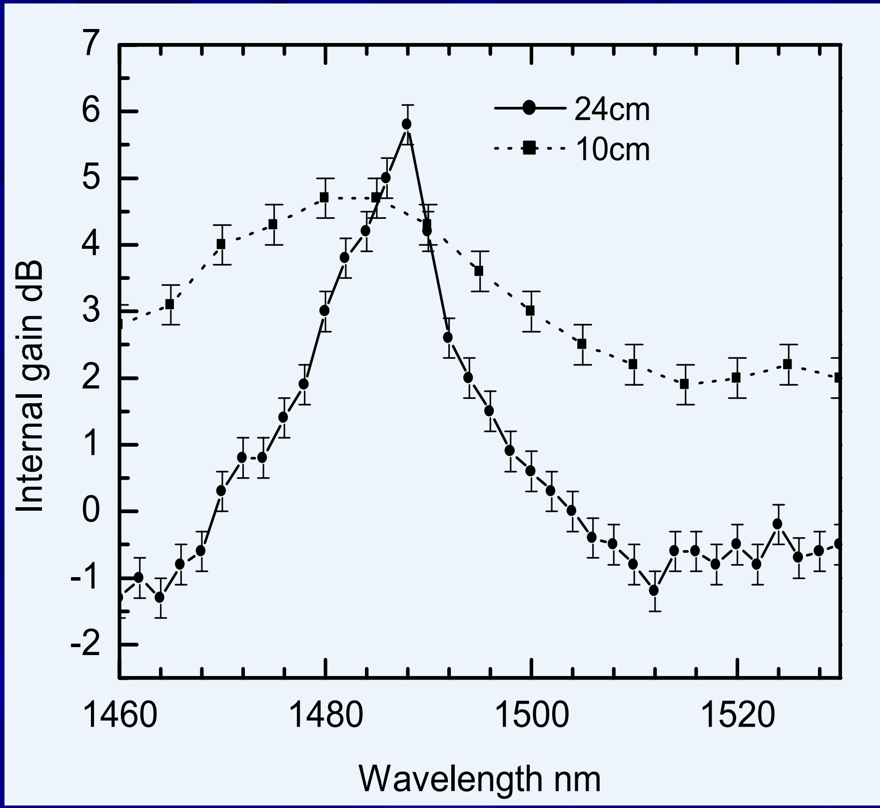




J. Non-Crystalline Solids, vol. 345-46, 2004, Oct (349-353).

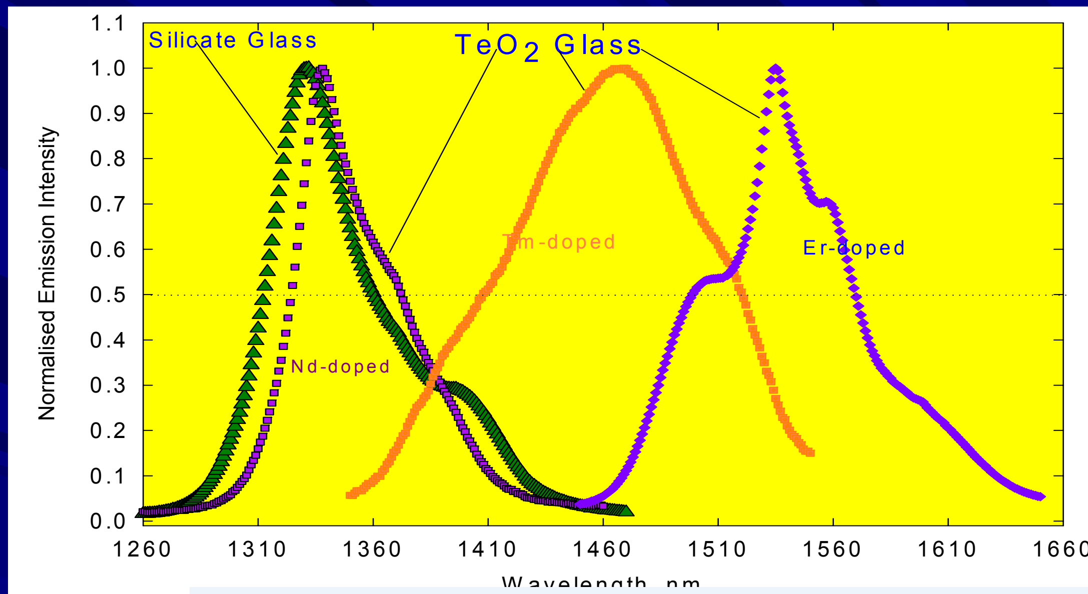
Amplification and Blue Upconversion

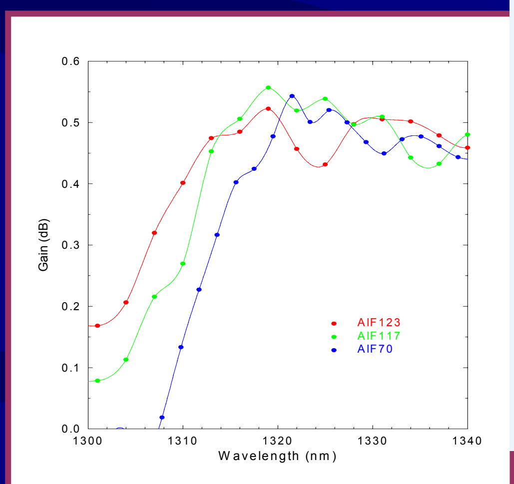


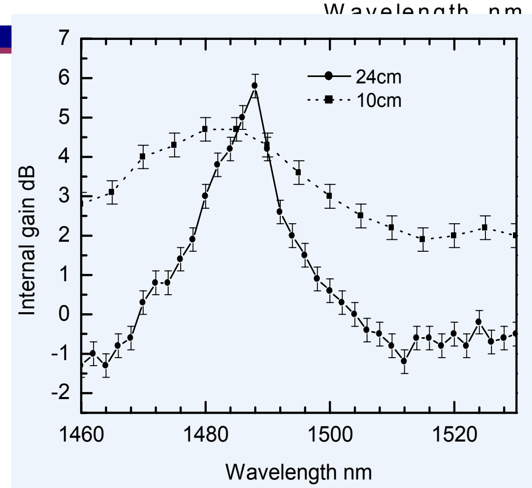


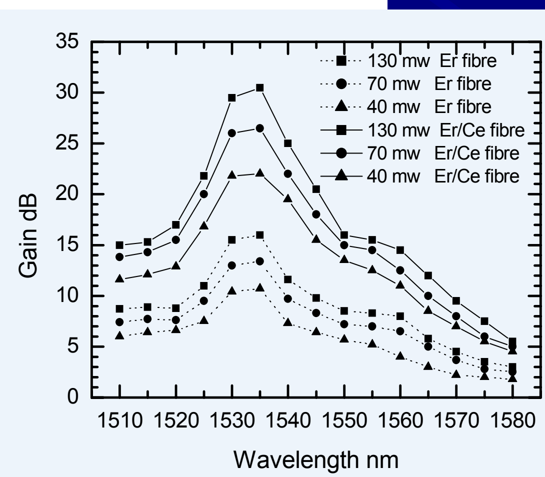
Internal gain measurements in Tm-Yb doped fibres using 980 nm pump, pump power: 120 mW. **Optics Lett 2005 , June**

Amplification Targets achieved

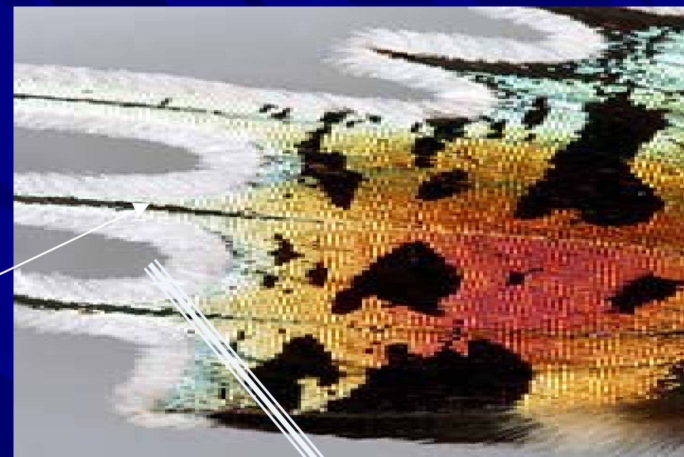


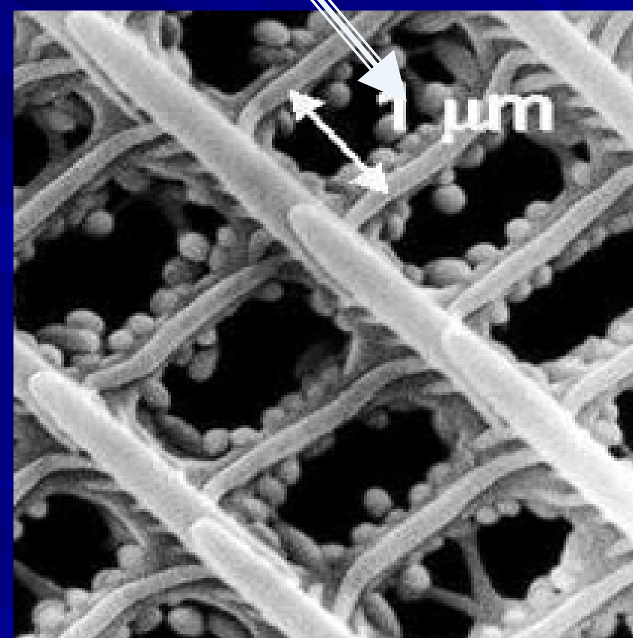


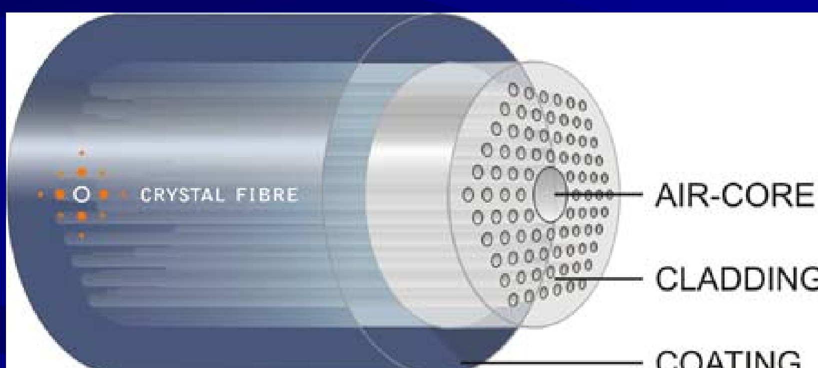




PERIODIC DEFECTS IN WAVEGUIDES







Website : crystalfibre.com

MOTIVATION FOR ENGINEERING DEFECTS

Virtual Absence of
Low Loss THz and MIR Waveguides

Plastic Photonic Crystal Fiber
- **Low Loss**
- **Flexible Interconnection bet. THz/Mid IR Devices & Systems**
- **THz Analogue to Optical Fiber**

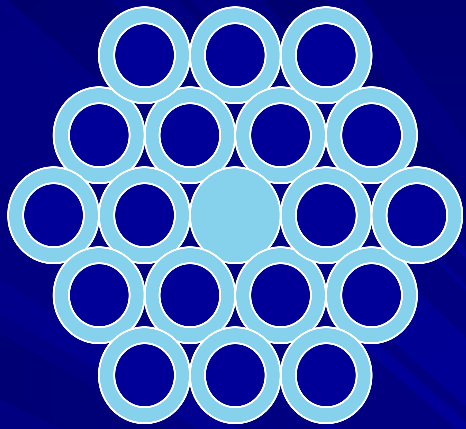
THz Waveguides	Loss @ 1 THz (cm^{-1})	GVD @ 1 THz (ps/THz·cm)	Field Confinement	Mechanical Flexibility
Free Space	0	0	-	-
Coplanar Strips (CPS)	> 20	> 2	2D	X
Coplanar Waveguide (CPW)	> 20	> 2	2D	X
Metallic Hollow Waveguide	< 1	?	2D	Δ
Crystalline Sapphire Fiber	~ 1	?	2D	O
Plastic Ribbon Waveguide	< 1	?	1D	O
Plastic Photonic Crystal Fiber	< 0.5	~ - 0.2	2D	O

Acknowledgement from : Prof. Martin Han, Seoul, Korea

Guiding Mechanism

High Index Defects

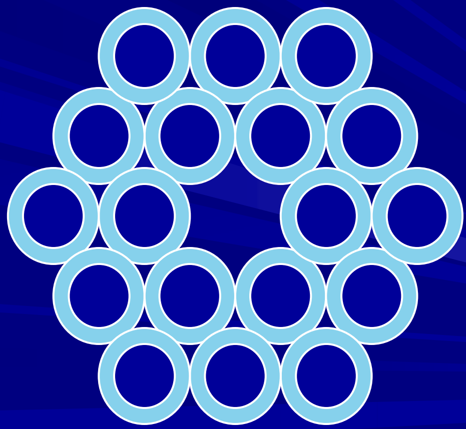
- Total Internal Reflection
- Broad Band



Low Index Defects

- Photonic Bandgap Effect
- Narrow Band
- Ultralow Loss

⇨ "Vacuum Guiding"



Photonic Crystal Fibers

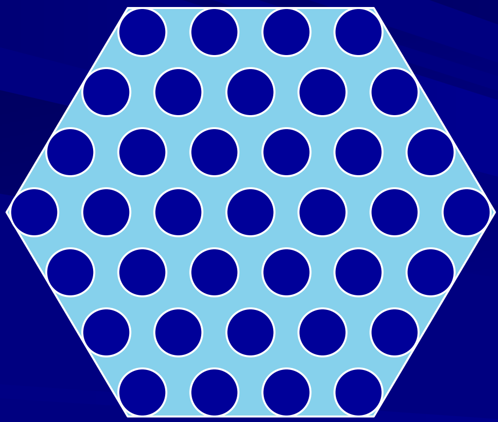
2D Photonic Crystal with Defects

↓

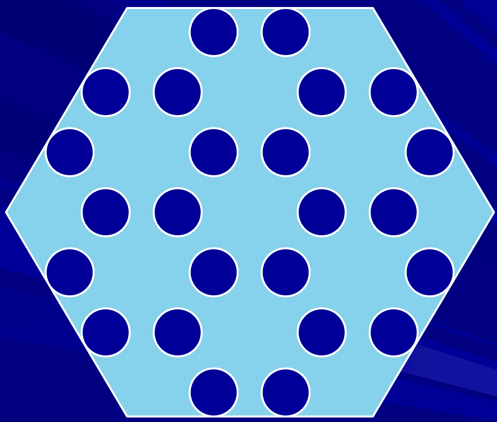
Field Localization around Defects

↓

Photonic Crystal Fiber



Triangular Lattice



Honeycomb Lattice

In TeO_2 Glass

- Improve the manufacturing processes to further reduce the propagation loss
- Dispersion-management in PCF
- Vacuum Guiding Plastic and Glass PCF

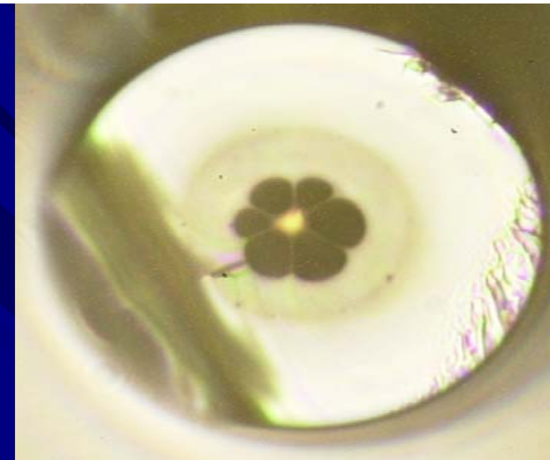
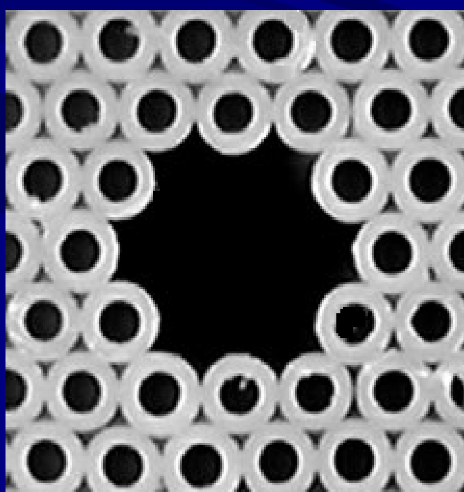
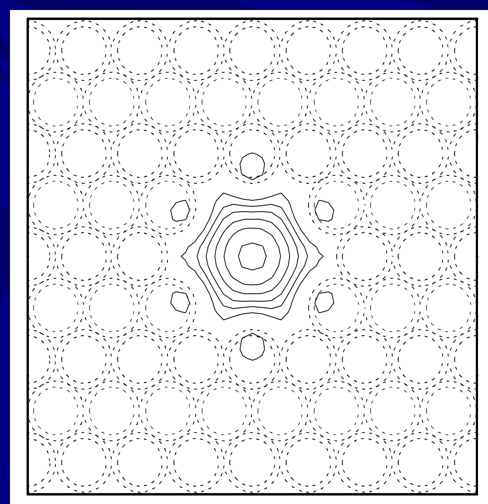


Figure 1 Tellurite glass microstructured fibre made under the feasibility study. The fibre shown has a core diameter of 5µm. The sample of several centimetres length is illuminated from both above and below, and the brightly-lit core is a clear confirmation of guided optical transmission





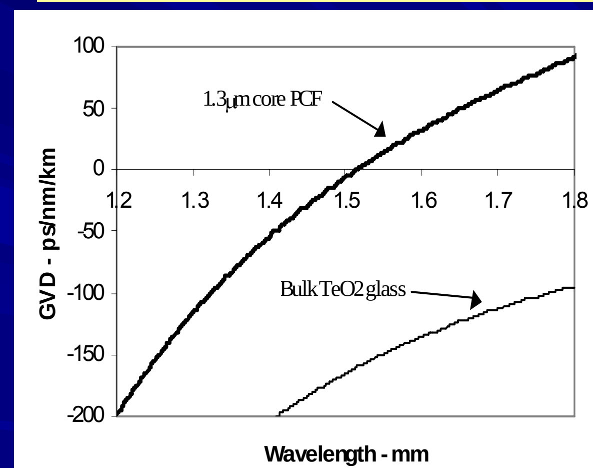


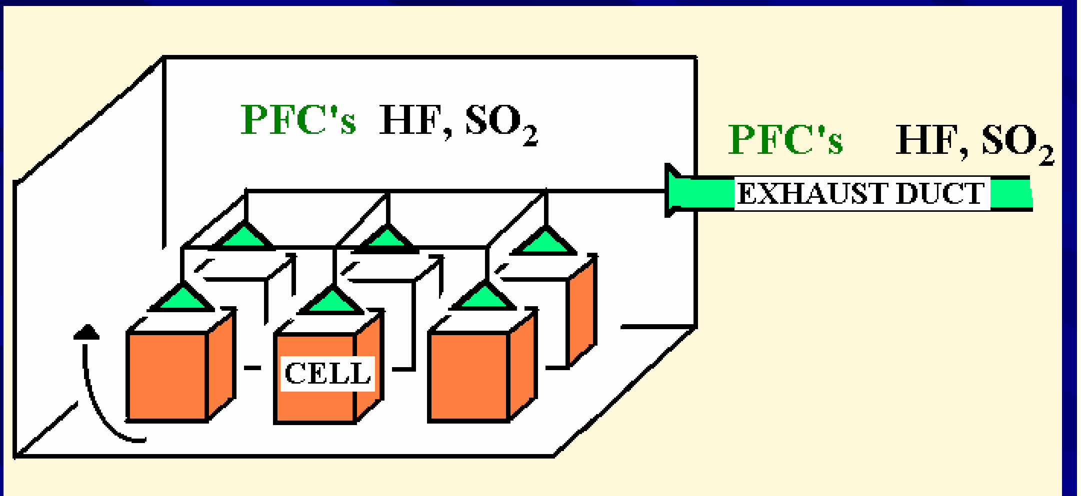
Figure 2 Calculated group velocity dispersion in a 1.3µm core PCF, engineered to be zero at a wavelength of 1.5 microns

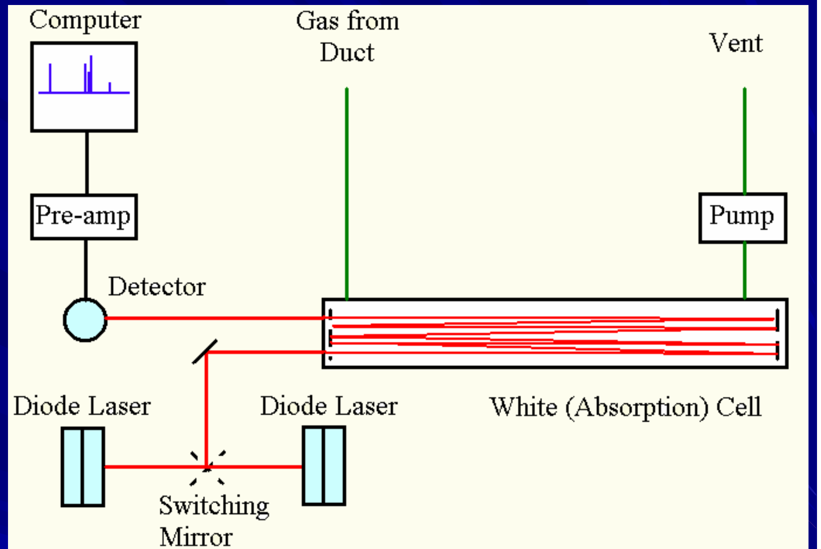
APPLICATIONS OF FIBRES IN SENSORS TECHNOLOGY

Approach to Environment Monitoring, Management and Mitigation

- To carry out chemical analysis using the spectroscopic technique for meeting the minimum pollution specification.
- To develop a database and real-time pollution monitoring tool for an intelligent waste management and pollution warning system.
- Provide data to National Database for Pollution Control.
- Monitor processes for pollution management.

The Basic Plan For Fugitive Gas Analysis: WDM system for chemical sensing

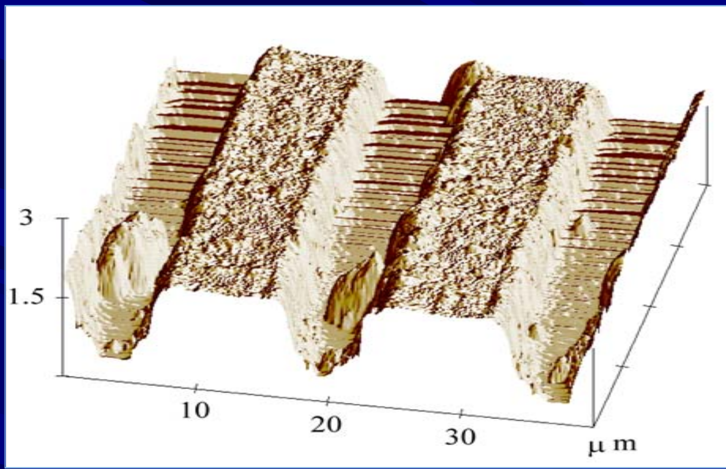


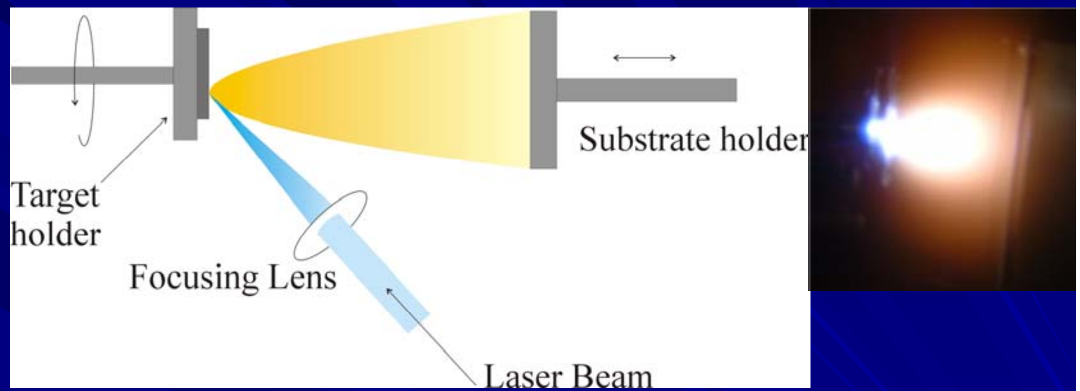


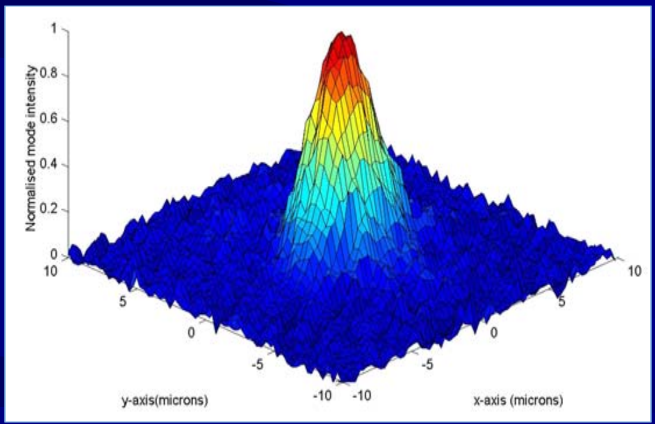
Measure PFC's and greenhouse gases which escape into the pot room (fugitive emissions)

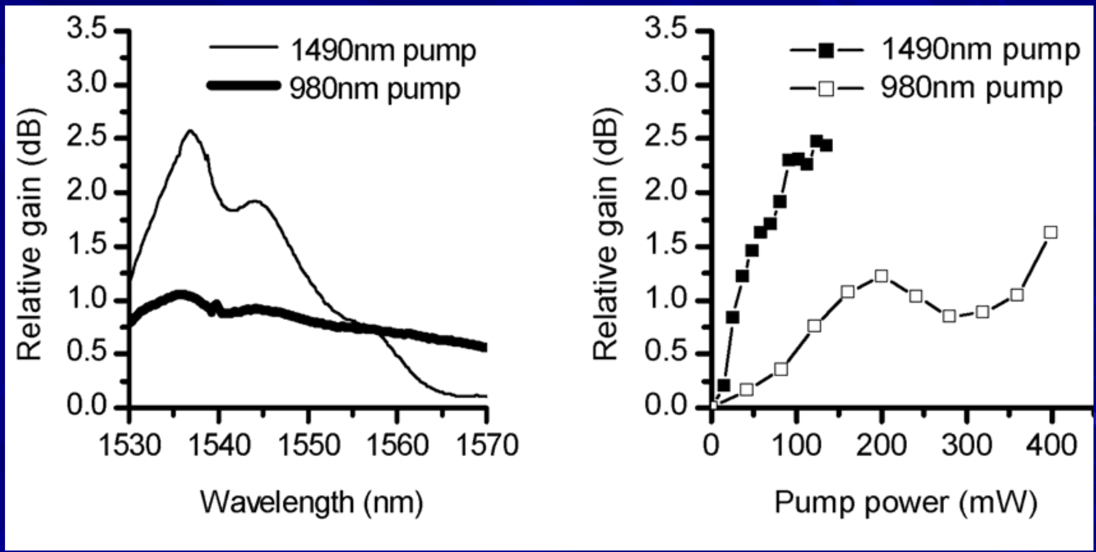
$$I = I_o.\exp(-\varepsilon.C.\ell)$$

2D- and 3D Optical Circuits and Integration via Laser processing









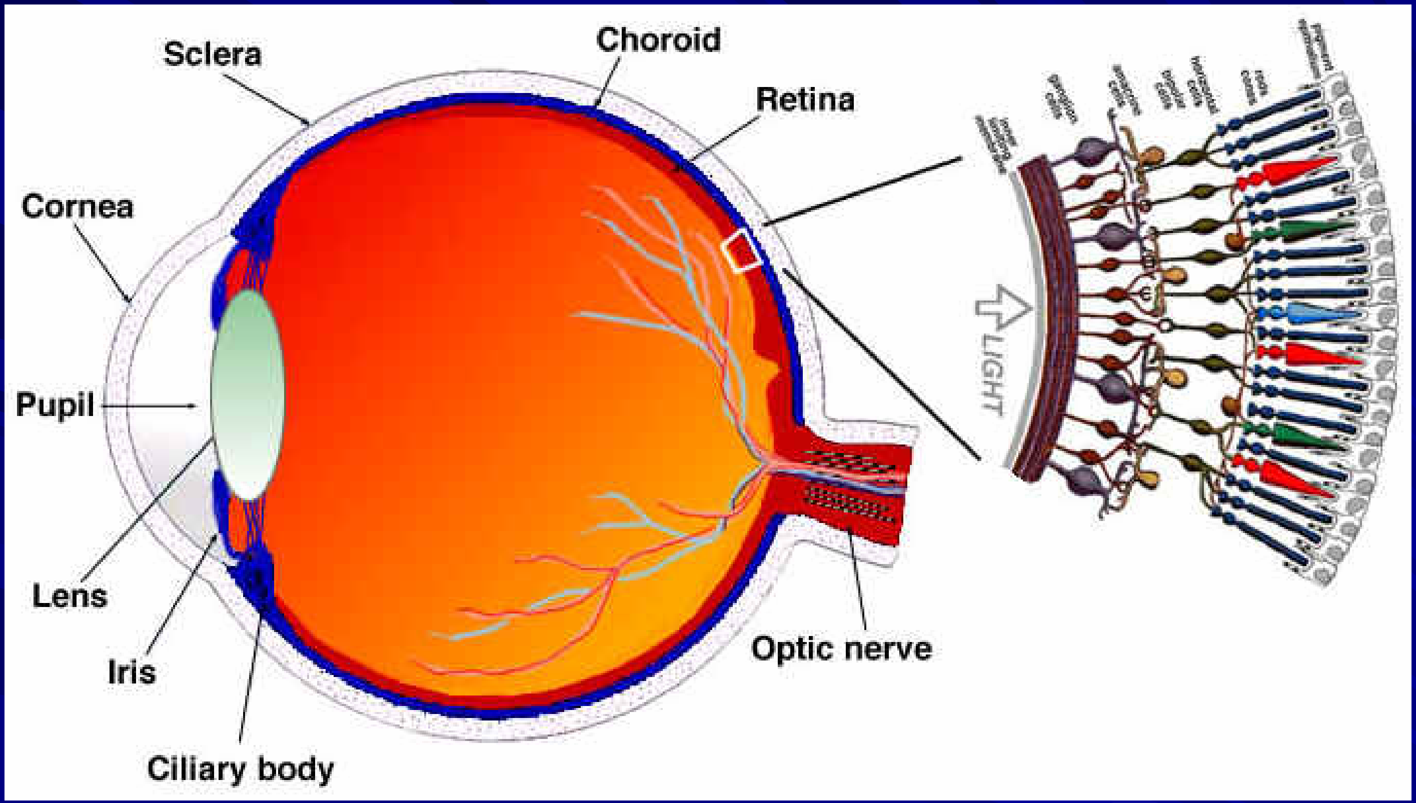
Biophotonics: a land of imagination and for future technology

- Can we use lasers as a tool to do the necessary diagnostics; e.g. in mid-IR, THz, UV
- If so, what we can then learn from it?
- Are there any ethical issues? If yes! Then we must sort out to design new diagnostic tools for helping patients for clinical trials and wider use of new technology.
- Use biophotonics for environment sensing

Photons: A source of healing waves

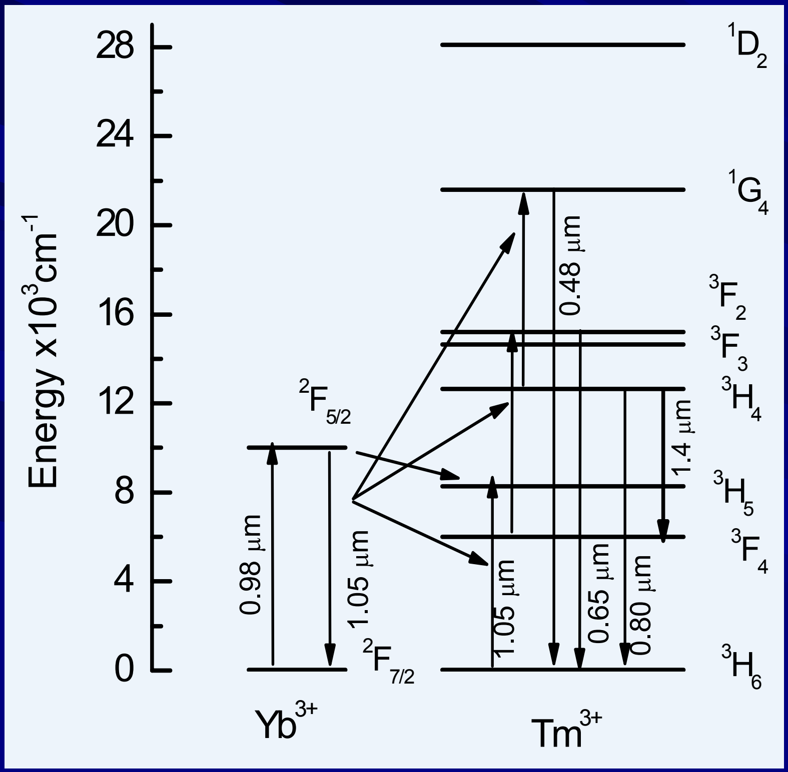
- Lasers for arterial plaque removal – (Er-line at 2870 nm, Tm @ 2000 nm good tunability)
- Lasers for key hole surgery (soft and hard tissue incision) Er-lasers.
- Dental care (low power) and denture machining (high power) – *Is it possible to make a laser tooth brush?*
- Improvements in laser dynamic therapy for skin care – psoriases, eczema, skin cancer.
- Drug delivery via nonlinear absorption and optical tweezing effects.
- Analyze macromolecules and learn how to functionalize them.

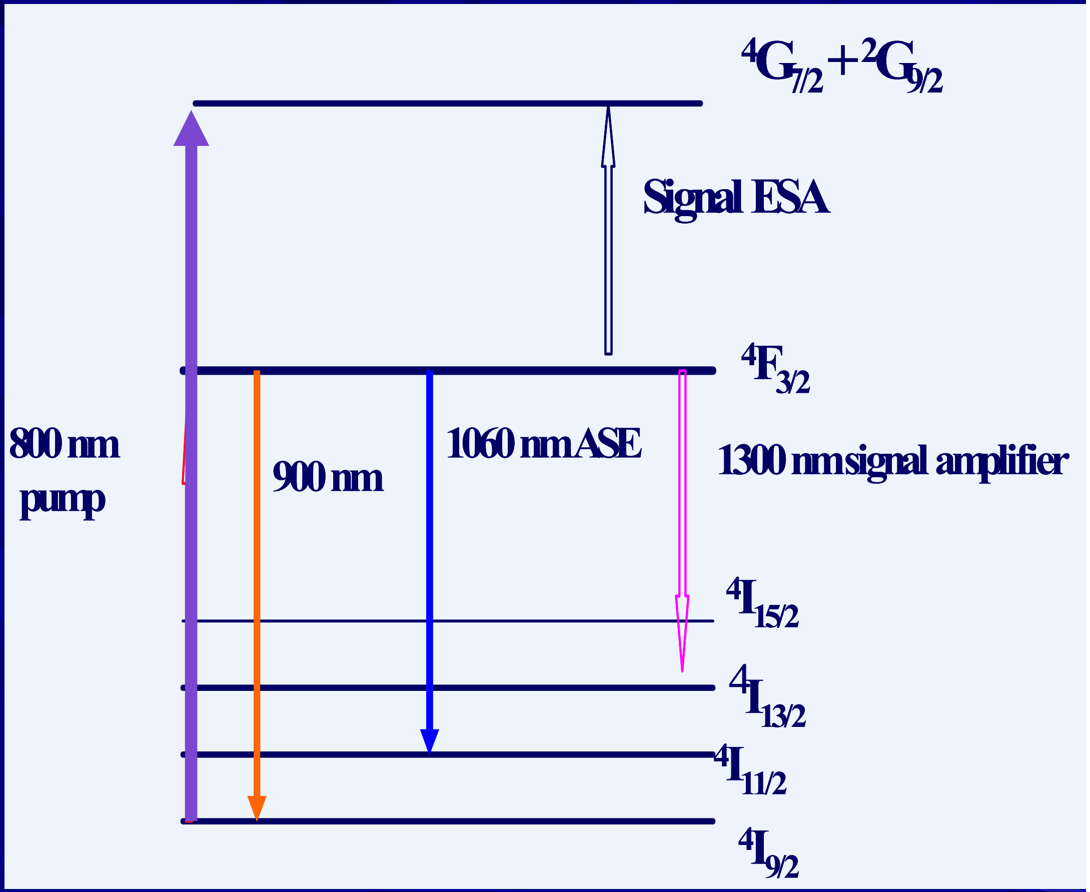
The Ultimate in Future of Bio-photonics



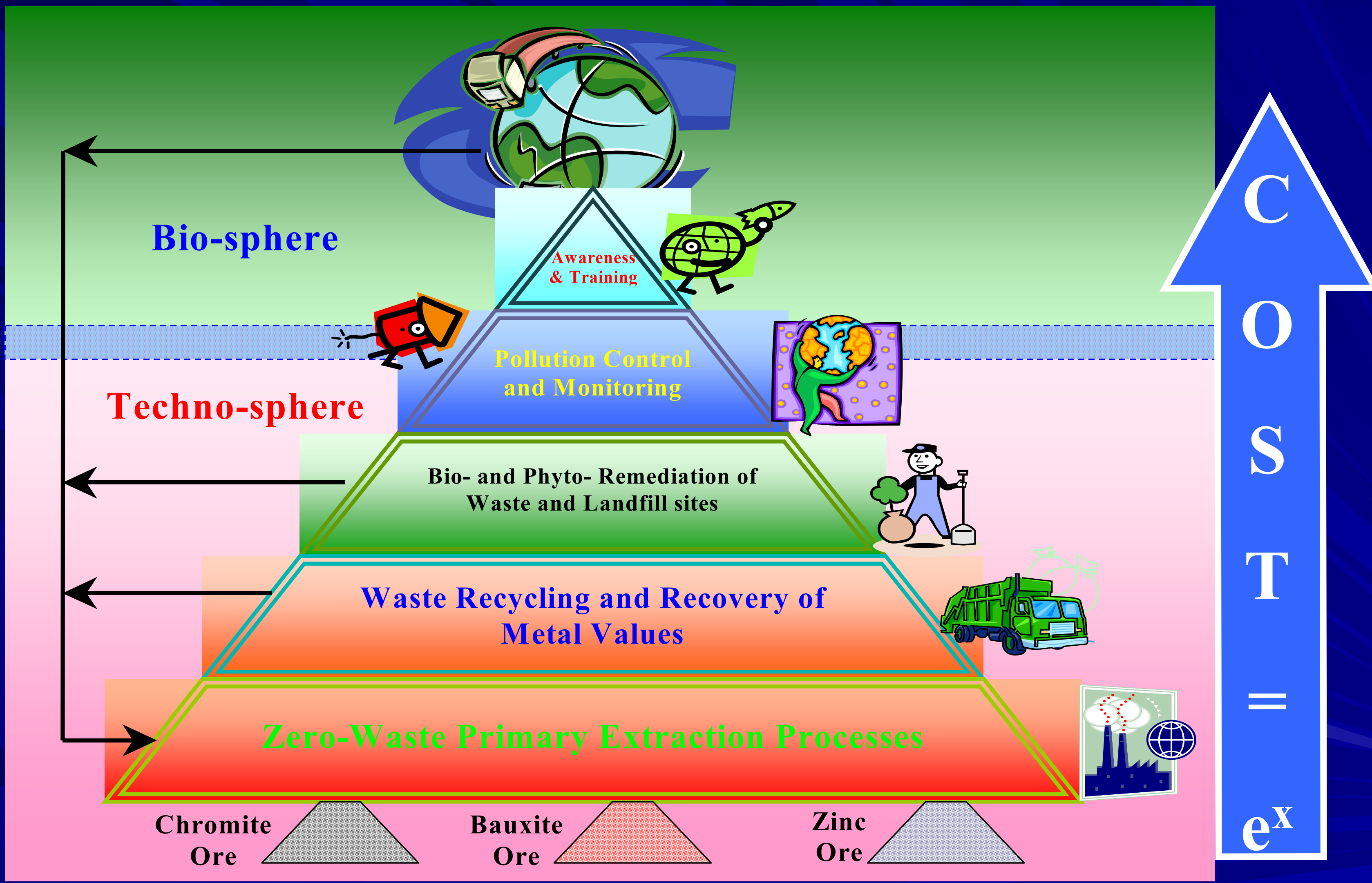
Magical proteins and their multifunctional properties: photo-active, electromechanical: an opto-mechanical devices.

High-Power Lasers: Kilowatt, Megawatt and beyond





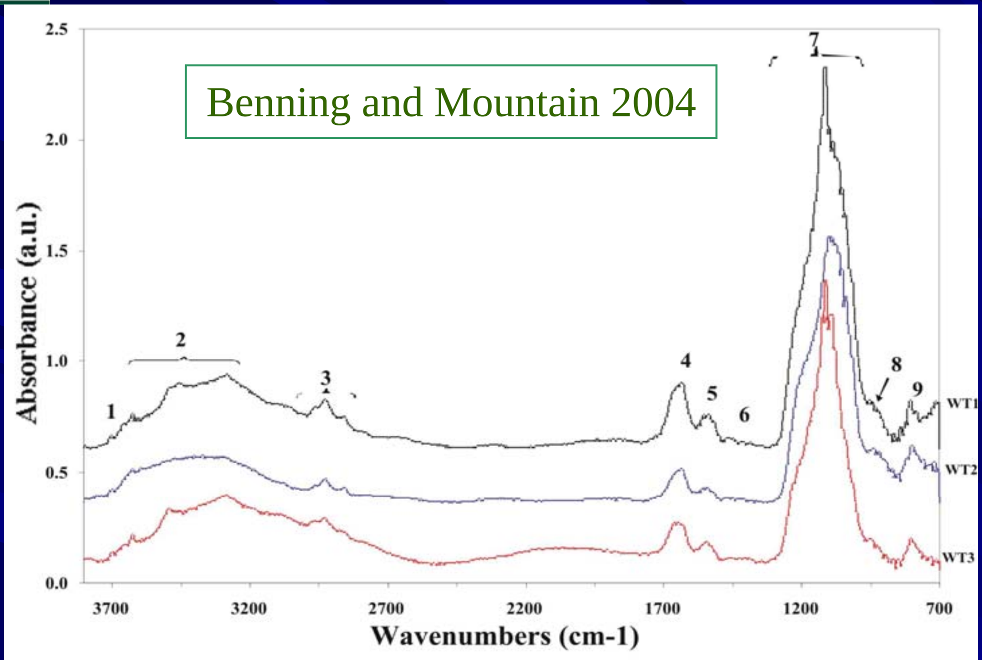
THE COST OF CLEANING UP

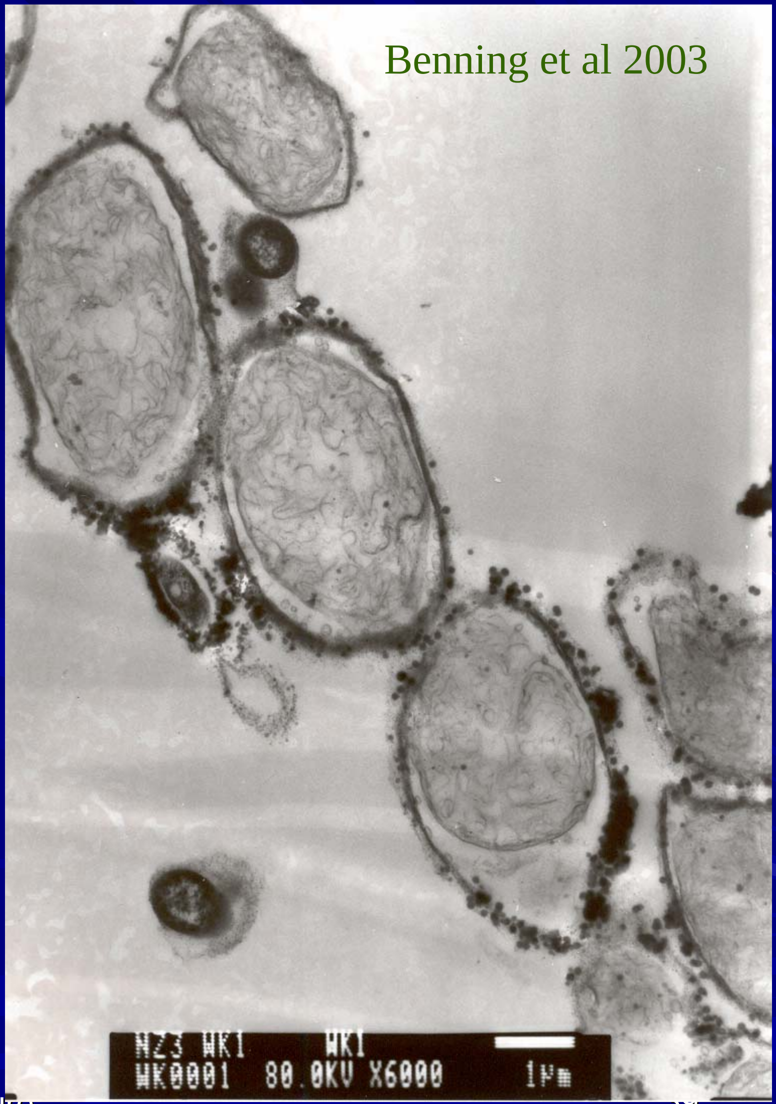


LEEDS-CGCRI-CSIR (INDIA) Lab

- Bring our materials and device knowledge to tackle water pollution problem in the region.
- Metal ion pollution to be remedied are As^{5+}, As^{3+}, Cr^{6+} and their chemical companions , e.g. iron.
- Why we worry about these ions and their potential adverse effects?

Spectroscopic applications for As bacterial interactions





Conclusions & Future

- *A number of fibre and planar waveguide based technologies would emerge in future which would be capable of providing broadband amplification via for CWDM technology.*
- *Optical integration is essential for reducing the cost of data transmission with increased capacity. Silicate, oxide and chalcogenide glasses are capable of meeting some aspects of OICs.*
- *In future similar technologies may emerge for mid-IR including THz for communication, sensing , imaging and clinical diagnostics, where we may rely on signal processing at different wavelengths.*
- *Future also holds in providing top quality health care and maintaining the health of environment via chemical sensing using LIDAR, RADAR , and ground base sensing stations.*
- *Development of molecular circuits for information processing will be only possible unless we attempt to understand DNA and other complex molecules.*

Thank you