OPTICAL BISTABILITY AND UPCONVERSION PROCESSES IN ERBIUM DOPED MICROSPHERES

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Overview

- Physical mechanisms
- Theory
- Applications
- Microsphere fabrication
- Coupling to a microsphere
- Experimental set-up
- ZBLALiP
- IOG2
- Future work
Physical mechanisms

Light travelling inside sphere, strikes glass-air interface at angle of incidence greater than critical angle – get total internal reflection TIR
If sphere is of good quality light can undergo multiple reflections … leads to long photon storage lifetimes, high Q factor and low mode volume

Resonance condition

\[ 2\pi r = \beta \lambda s \]
Physical mechanisms

Modes in a sphere can be described by 3 integer numbers \( n, l \) and \( m \).

*Propagation constant = \( \beta \)*

Modes can be thought of as zig-zagging about either side of the equatorial plane.

Different \( m \) numbers imply that modes travel in zig-zag paths with different inclinations with respect to the equatorial plane.

In a perfect sphere all path lengths are equal therefore there is degeneracy between polar components.

In reality deformations lift degeneracy
Microspheres theory

Solve scalar wave equation

\[ \nabla^2 \psi(r) + n^2 k^2 \psi(r) = 0 \]

- four solutions corresponding to the TE and TM components of the sphere electric and magnetic fields

Separation of variables gives mode numbers \( n, l \) and \( m \)

\( n \) – described by modified Bessel functions, \( n = 1, 2, 3, \ldots \)
\( l \) – described by spherical harmonics, \( l = 0, 1, 2, \ldots \)
\( m \) – described by sinusoidal variation, \( m = -l, \ldots, 0, \ldots, l \)

View from sphere pole

View from sphere equator

\( n = 1, l = 30 \)

\( n = 2, l = 30 \)

\( n = 2, l - |m| = 2 \)
Active microspheres to realise miniature laser sources: erbium is gain material

Long photon storage times coupled with small mode volumes $\rightarrow$ very high intensities e.g. 1 mW coupled into cavity with $Q \sim 10^8$ and mode volume $V \sim 1000 \, \mu m^3$ yields circulating intensity of $\sim 1 \, GW/cm^2$

Of interest for fundamental studies e.g. cavity quantum electrodynamics and quantum information processing and applied research e.g. optical communications and trace species detection

Acceleration sensor, gas detection, temperature sensor

Optical and photonic filters, electro-optic modulators and photonic storage

Bio sensor – DNA detection and identification
Microsphere fabrication

Microspherical lasers fabricated from two different erbium doped glasses:

ZBLALiP – novel heavy metal fluoride glass – 0.1% Er
Schott IOG-2 – phosphate glass – 2% Er and 3% Yb

Bulk glass sample ground to powder
Powder dropped through microwave plasma torch
Surface tension forces yields sphere sizes in the 10-200 µm diameter range and ellipticity ~ 10^{-3}
Select defect free microspheres
Realisation of useful device requires efficient in/out coupling of light

Achieved via overlap of evanescent fields

Evanescent field occur at surfaces where light undergoes TIR

Even under TIR some light can tunnel across boundary

Light decays exponentially with distance from surface

Evanescent field couplers: prism, polished fibre blocks and tips, tapered optical fibre
Adiabatic length-scale criterion

Local taper angle \( \Omega(z) = \tan^{-1} \left| \frac{dp}{dz} \right| \)
\( \Omega(z) \ll 1 \) so \( Z_t \sim \frac{p}{\Omega} \)

Local coupling length
\( Z_b = \frac{2\pi}{\beta_1 - \beta_2} \)
If \( Z_t \gg Z_b \) negligible coupling will occur
If \( Z_t \ll Z_b \) coupling will occur

\( Z_t = Z_b \) is delineation
\( \Omega = \frac{p (\beta_1 - \beta_2)}{2\pi} \)
Fibre taper fabrication

- CO2 laser: scan beam along fibre: 3 µm T = 90%
- Micro furnace: sapphire tubes: 1 µm T = 50%
- Butane torch: static flame and flame brush: 1 µm T = 60%
- Electric heater: disilicate element: 1 µm 75% - 90%

Length of fibre depends on size of hot-zone
Current multimode pump source linewidth: ~ 17 GHz. The same taper is used to probe for 1.55 μm radiation by evanescent out-coupling, through a WDM and into an optical spectrum analyser.
ZBLALiP

13 separate upconversion signals
320 nm – 850 nm.
IR lasing at 1550 nm.
Lifetime of $^4F_{3,5/2}$ greater than other fluoride glasses.
Intensity ratios agree with calculated branching ratios.
Absorption + Emission spectra for IOG2

Ener

Ytterbium
980nm

1550nm  520nm  550nm  660nm  410nm

Erbium
410nm

Absorption cross section, \( \sigma_{\text{abs}} \)
Emission cross section, \( \sigma_{\text{em}} \)
IOG2 Emission spectra

3 distinct spectra obtained.

660 nm emission in competition with 1.5 µm emission.

Only ever see RGB emission with spheres < 40 µm diameter.

Increased emission at 520 nm due to thermalisation.
Optical bistability

- Intensity at 520.2nm

- Intensity of IR peak

\[ \text{Intensity at 520.2nm} \]

\[ \text{Intensity of IR peak} \]
Optical bistability

Possible mechanisms?

- Temperature dependent absorption cross section of Yb ion
  Temperature increase due to pump.

- Dispersive/ absorptive bistability
  Non linear change in refractive index due to increase in temperature.

- Non linear energy transfer
  Temperature dependent energy transfer between Yb-Er or Yb-Yb.

- Photon avalanche
  Sudden increase in ESA absorption due to intermediate state saturation.
Future work

Bistability - characterisation, temperature dependence
Photonic molecule - effect on lasing and bistability
Integrated devices - microsphere fused to taper
Taper / MOT experiment
Conclusion

Microsphere useful tools for studying light-matter interactions.

Enhanced probability of 3 and 4 photon ESA.

ZBLALiP broad emission spectra for sensing applications.

IOG2 Optical bistability over multiple wavelengths.

IOG2 Good candidate for optical switch.
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