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Er-doped Si nanocrystal/silica Microresonators using Optical Fiber

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Outline

- Introduction
- Experiments
- Results and Discussion
  - SEM Images
  - Photoluminescence measurement
  - Transmission Spectrum
  - Q factor Measurement
- Conclusion

Introduction

❑ Compact integrated microphotonics

- The need for active optical components that can be integrated into planar optical circuits using standard processing techniques

❑ Si, the principal semiconductor material

- Most of all semiconductor devices

  → Benefits in cost, functionality, reliability

- Inefficiency of light emission due to indirect band gap

  → Limited use for optoelectronic applications

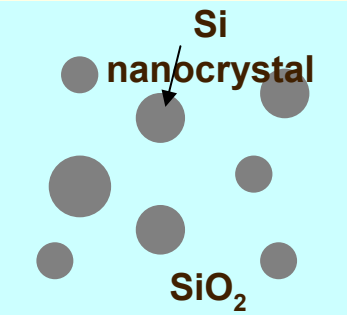
- Increasing importance of combining optical and electronic technology

  → Intense research on Si-based light emitting materials*

* *Light Emission in Silicon: From Physics to Devices*, Semiconductors and Semimetals, **49**

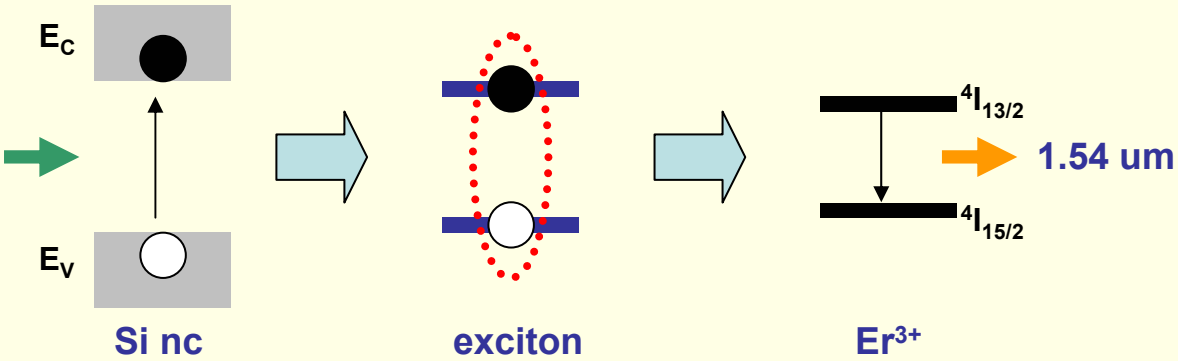
Introduction

❑ Si nanocrystal/silica



- Light emission due to quantum confinement (Canham, 1990)
  - Broad luminescence in visible range
- Rare earth doping of Si
  - Increase luminescence efficiency of rare earth (ex. Er)

❑ Carrier mediated Er^{3+} excitation mechanism

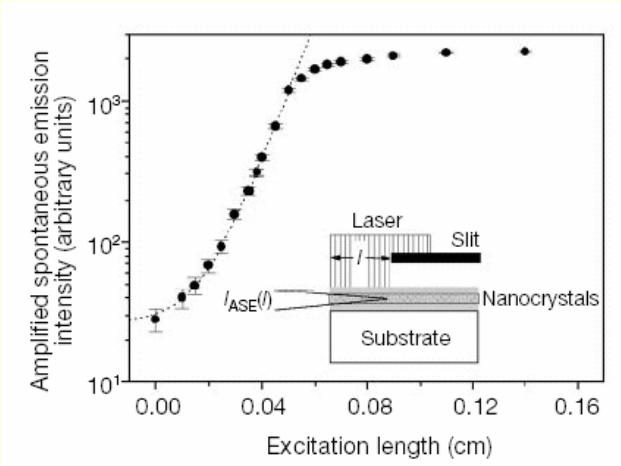


- Any carrier generation mechanism can work: laser, broadband, current injection
- Very strong carrier-Er^{3+} coupling: $\sigma_{carrier} / \sigma_{photon} > 10^6$

Introduction

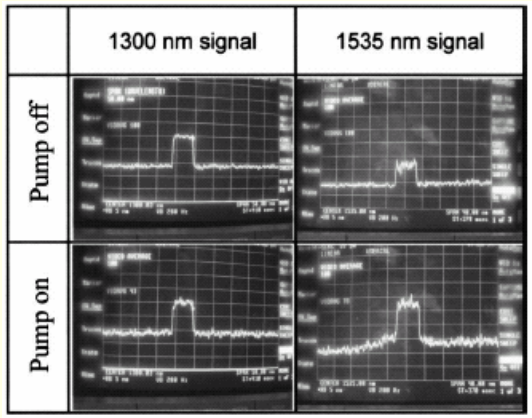
- **Optical gain in Si nanocrystal/silica (with or without Er)**

Optical gain in silicon nanocrystals



L. Pavesi *et al.*, Nature, 2000

Optical gain Si nanocluster sensitizing Er-doped optical amplifier



Han *et al.*, APL, 2002

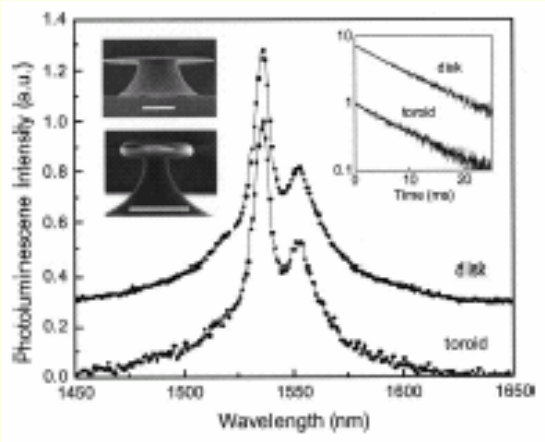
Introduction

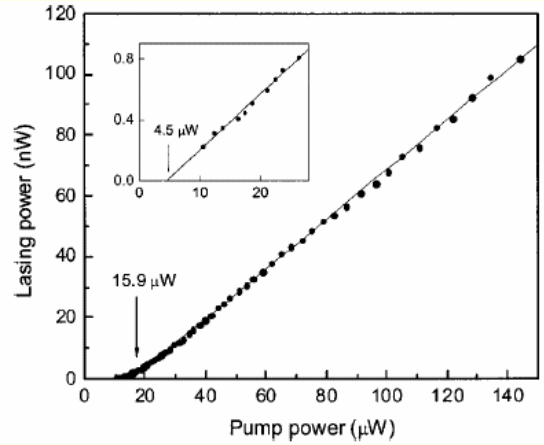
- **Whispering-gallery (WG) type microlasers**
  - Structure for replacement of the functionality of a purely electronic large-scale integrated circuit*
    - low power consumption for the constituent devices
    - light confined to micron size dimensions for integrability
  - Microdisks, Microtoroids, Microspheres, etc.

* S. L. McCall *et al*., Appl. Phys. Lett., **60**, 1992

Introduction

❑ Ultralow-threshold Er-implanted toroidal microlaser on Si*





- Pumped at 1480 nm using an evanescently coupled tapered optical fiber
- Launched pump threshold: 4.5 μW
- Cavity quality factor: 3.9×10^7

* A. Polman *et al.*, Appl. Phys. Lett., **84**, 2004

Introduction

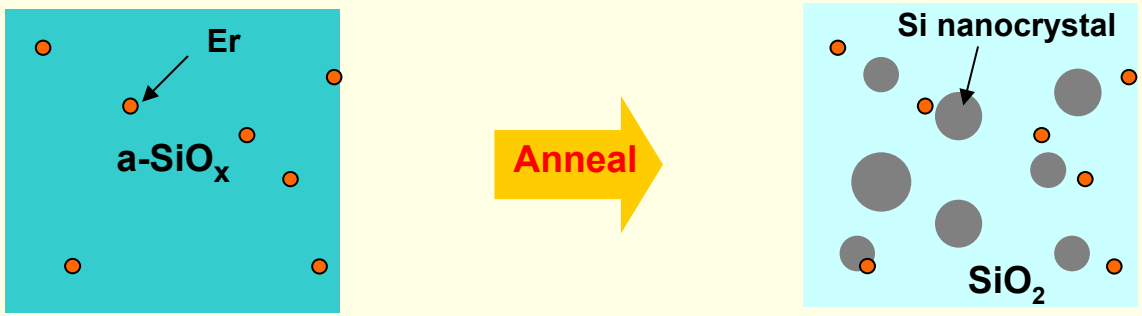
- **Advantages of Si nc/silica WG type microresonators**
  - Top pumping and broad band pumping
  - One of the most promising methods for realizing Si-based laser

- **In this work**
  - Microresonator fabrication by the deposition of Si nc/silica (with or without Er) on optical fiber
  - Measurement and analysis of Photoluminescence, Transmission and Q factor

Fabrication of Si nc/silica

- **Deposition** (ECR-PECVD system*)
  - Gas flow: Ar(3.5 sccm), SiH_4(1.14 sccm), O_2(1.6 sccm)
  - Er co-sputtering voltage (in the case of Er-doped Si nc/silica): -100V
  - Deposition temperature: 450 ℃
  - Pressure: ~ 1×10^{-7} Torr (base), ~ 1×10^{-5} Torr (deposition)

- **Post-dep. Processing**
  - Annealing to precipitate Si nc (at 1100℃ or 900℃ for 30min)
  - Hydrogenation to passivate defects in SiO_2 (at 650℃ for 1hour)



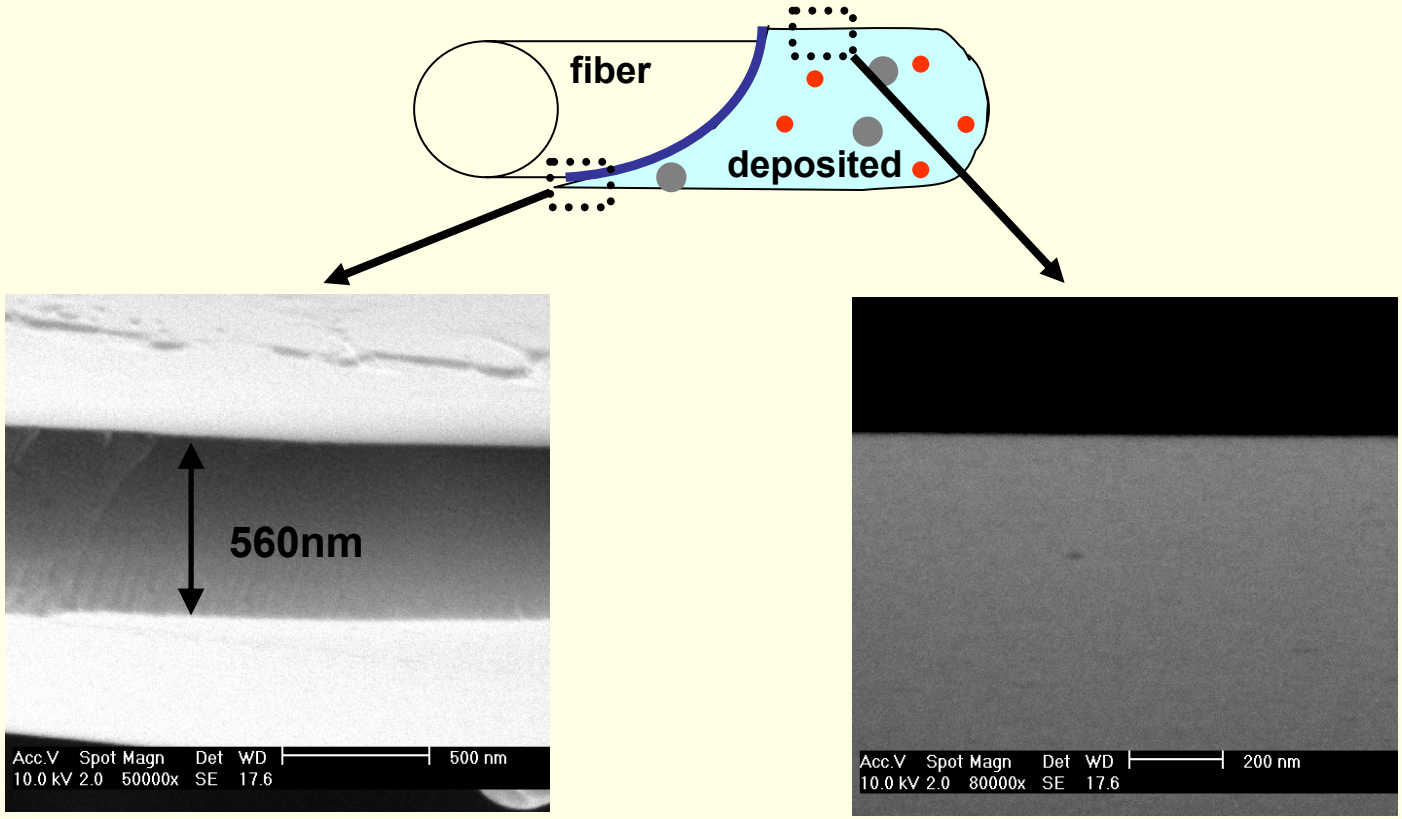
* Jung H. Shin *et al.*, Appl. Phys. Lett., **72**, 1998

Experimental Details

- **Photoluminescence Measurement**
  - Pumping source: 477 nm single line from Ar-ion laser
  - Signal detection: InGaAs(Cs) photomultiplier tube or InGaAs detector with lock-in system

- **Mode spectrum and Q factor Measurement**
  - Light source: ASE (THORLABS ASE-FL7003), Tunable laser (Agilent 81689A)
  - Tapered fiber with 2.8 μm in waist diameter
    - made by heating and stretching a standard SMF-28 fiber
    - attached to a piezo-electric translation stage
  - Power measurement: OSA (Agilent 86142A)

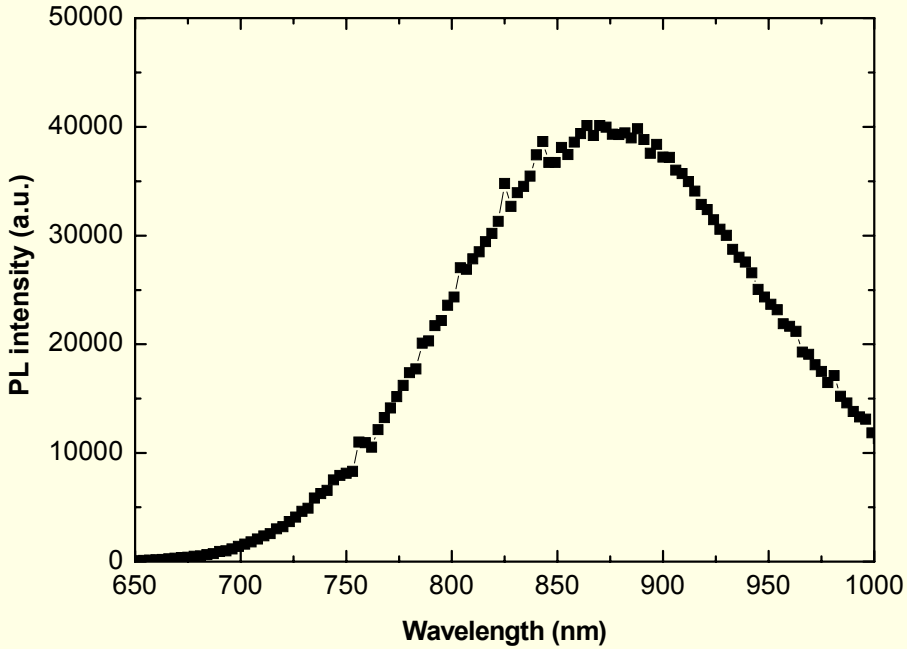
SEM Images of Er-doped Si nc/silica



- Thickness of Er-doped Si nc/silica film deposited on optical fiber is 560 nm without visible degradation of the smooth fiber surface.

PL of Si nc/silica microresonator

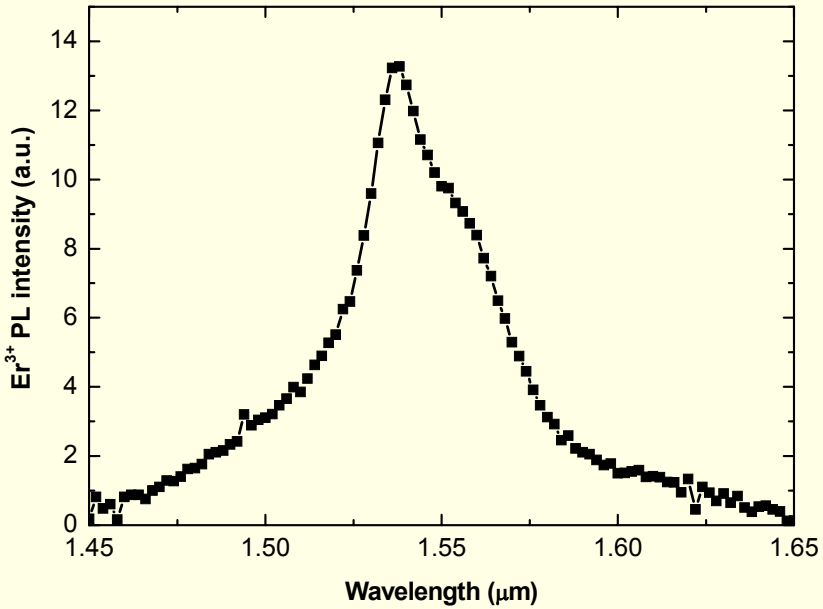
477 nm, 200 mW, RT



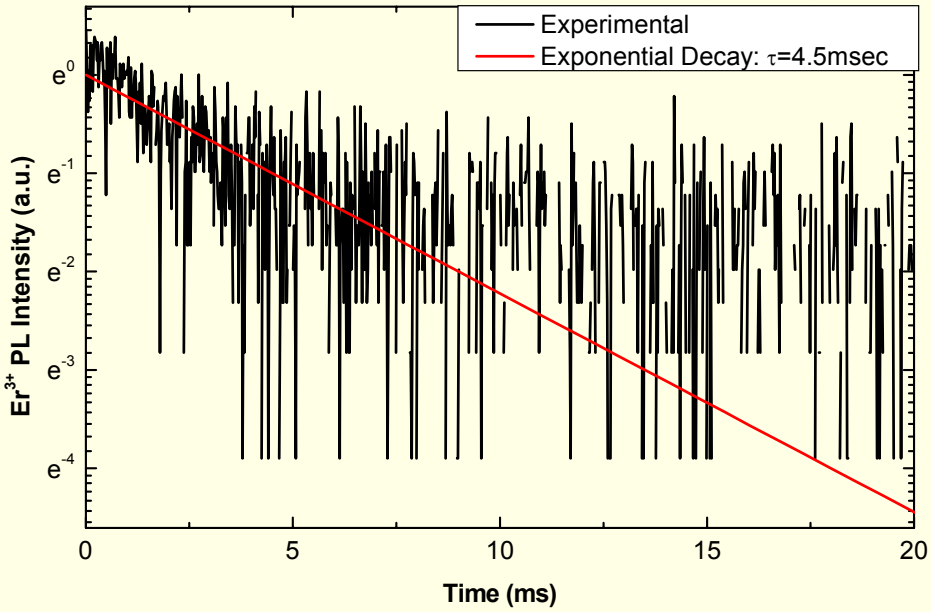
- The PL spectrum shows typical Gaussian-shape Si nanocrystal luminescence.

PL of Er-doped Si nc/silica microresonator

PL spectrum



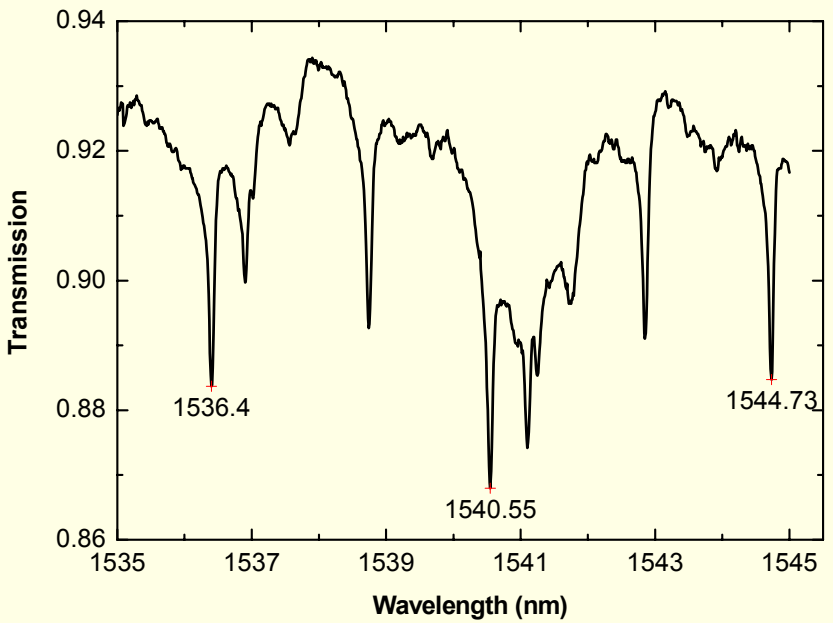
PL decay trace



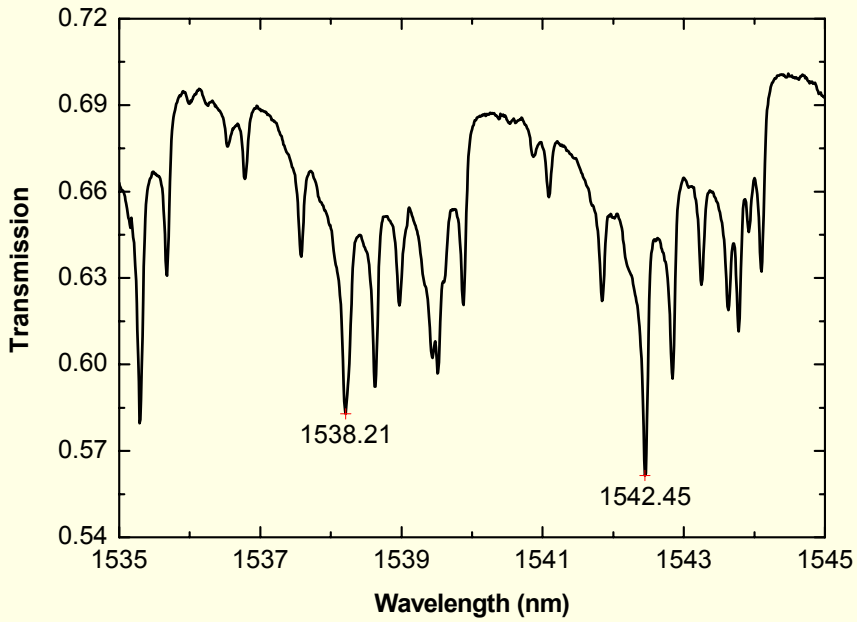
- The PL spectrum shows typical Er^{3+} luminescence and lifetime is about 4.5 ms.

Transmission Spectrum

Fiber deposited Er-doped Si nc/silica

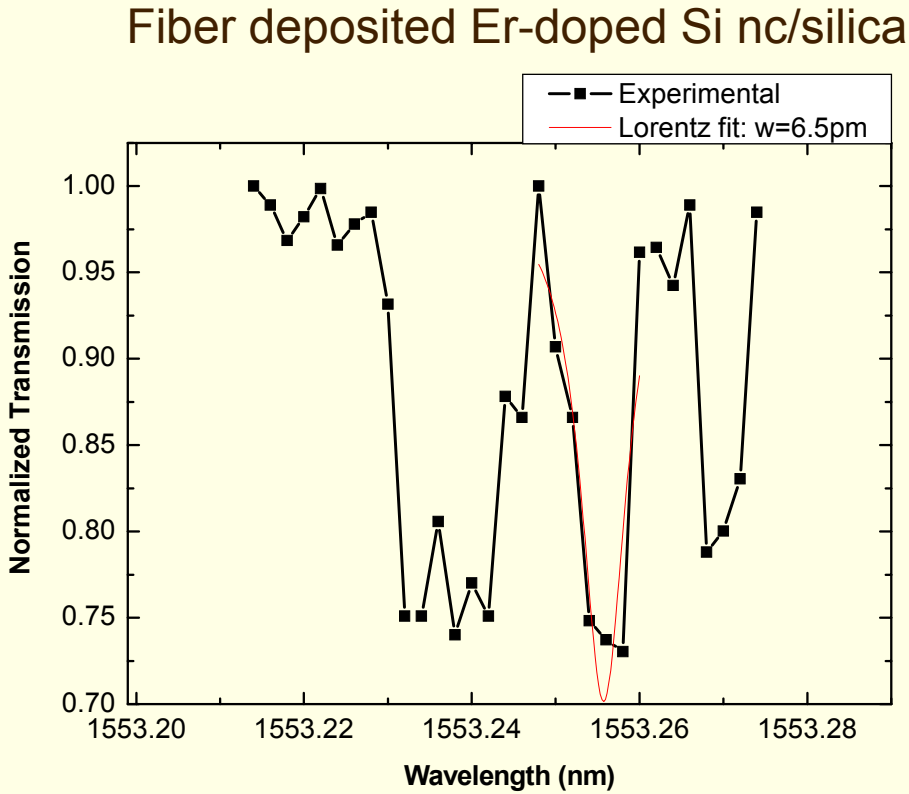


Bare fiber with 125 μm of diameter



- Free Spectral range
  - Fiber deposited Er-doped Si nc/silica: 4.16 nm
  - Bare fiber with 125 μm of diameter: 4.24 nm
  - Mode width limited by the OSA bandwidth

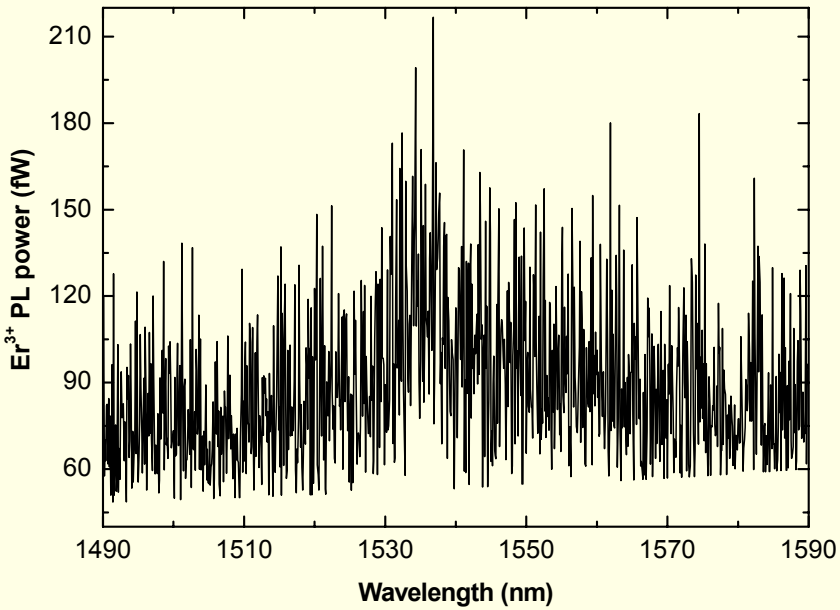
Q factor Measurement



- High-resolution transmission measurements
  - Scan using a tunable laser
  - Cavity Q-factor: > 2.4×10^5

Discussion

Photoluminescence of the fiber obtained with the tapered fiber coupling



- Clear Er^{3+} PL spectrum, but no lasing: material limitation
  - ➔ But is lasing from Er-doped Si nc/silica in principle possible?

Discussion

Gain and necessary Q-factor for lasing

Q ($x10^4$)

n \ G	3	4	5	6	7
1.5	8.9	6.6	5.3	4.4	3.8
1.6	9.5	7.1	5.7	4.7	4.1
1.7	10	7.5	6.0	5.0	4.3
1.8	11	8.0	6.4	5.3	4.6

- Reported gain figures for Si nc
  - Si nc alone: >10 dB/cm
  - Er-doped Si nc/silica: 3-5 dB/cm

➔ Lasing possible with the present fabrication steps and methods

Conclusion

- Microresonator, formed by the deposition of Si nc/silica (with or without Er) on optical fiber are fabricated.

- The PL spectra of Si nc/silica (with or without Er) microresonator show typical luminescence and the PL decay trace of Er-doped Si nc/silica microresonator shows lifetime of 4.5 ms.

- The free spectral range of Er-doped Si nc/silica microresonator is 4.16 nm and Q factor is 2.4×10^5.

- With the right material, current fabrication steps and methods capable of producing lasing