



Low-threshold On-chip Yb^{3+} Silica Laser

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Low-Threshold Yb³⁺ Lasers

- Fabry-Perot type *P_{th}* *Finesse*

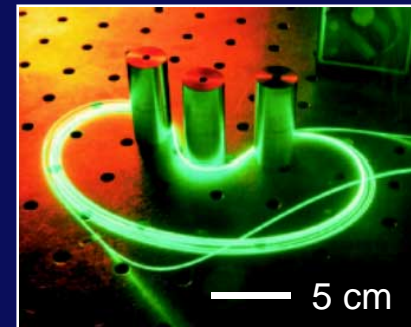
- Microchip lasers - **71 mW** **50**

P. Lacovara et al., Opt. Lett., Vol.16, 14, 1089 (1991)

E. Ostby et al., SPIE Proc. 5707, 72-80 (2005)

- Fiber lasers - **230 μW** **500**

A Asseh et al., Elect. Lett., Vol. 31, 12, 969 (1995)



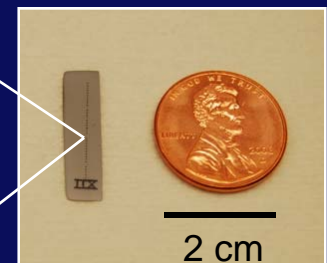
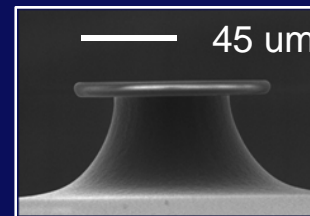
- Ring type

- Microtoroid - ? **10,000**

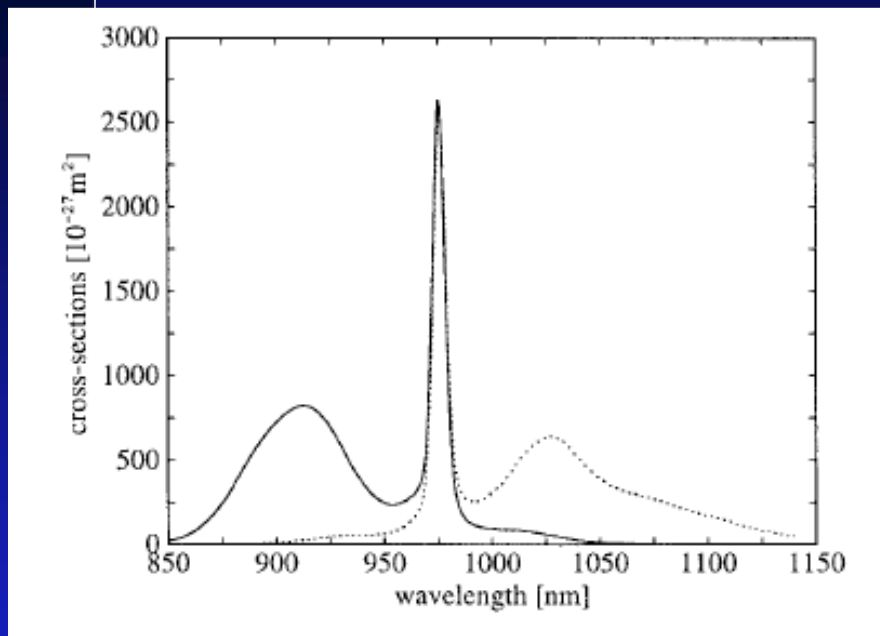
- High Quality Factor ($Q = \lambda / \Delta\lambda$)

- Small cavity length (L)

$$\text{Finesse} = \frac{\text{FSR}}{\text{linewidth}} = \frac{\lambda Q}{nL}$$



Ytterbium (Yb^{3+})

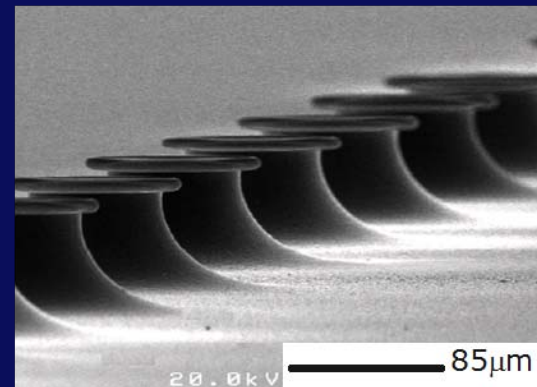
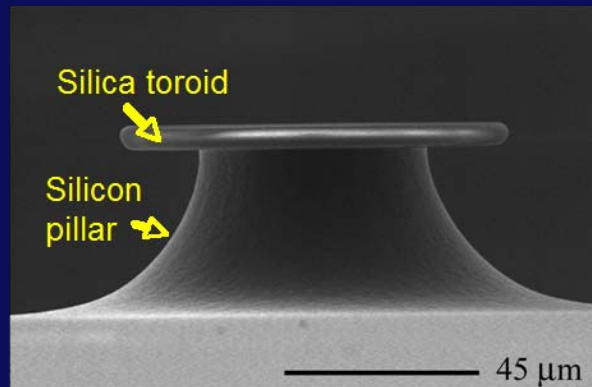


Absorption and Emission Spectra for Yb:SiO_2

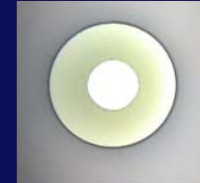
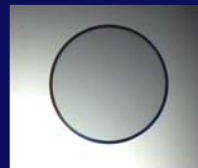
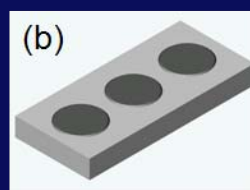
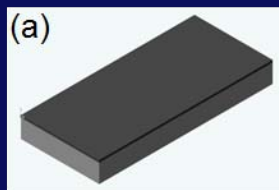
Paschotta et al., IEEE QUANT. ELECT., VOL. 33, NO. 7, 1997

- Pump 970 nm, emission 1040 nm
 - Low quantum defect (7%)
- Simple electronic structure
 - $^2F_{7/2}$ ground state, $^2F_{5/2}$ excited state
 - No up-conversion or concentration quenching expected
 - Quasi 3-level laser (ground state absorption)
- High doping concentrations possible
- Broad emission bandwidth (25 nm)
- 0.7 ms laser lifetime (10 ms for Er)
- Large absorption cross-section
 - $27 \times 10^{-21} \text{ cm}^2$ for Yb:SiO_2
 - $2 \times 10^{-21} \text{ cm}^2$ for Er:SiO_2

Ultra-High-Q Toroid Fabrication



SEM of microtoroid resonator



Thermal silica toroids can have $Q > 10^8$

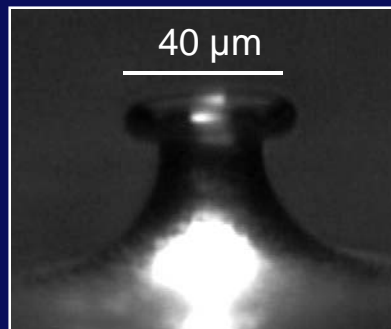
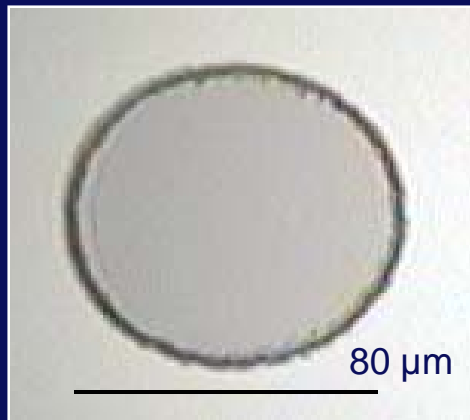


Sol-Gel Film Fabrication

- Metal alkoxide precursor
 - TEOS is hydrolyzed with water at 2:1
 - HCl is added
 - Yb³⁺ ions are introduced
- Solution chemically reacts at 70° C for 3 hours
- Multiple silica sol-gel layers are spin-coated onto a silicon wafer
 - Annealed at 1,000° C for 3 hours to remove organics and solvents
 - 1.5 μm total film thickness (3 layers)

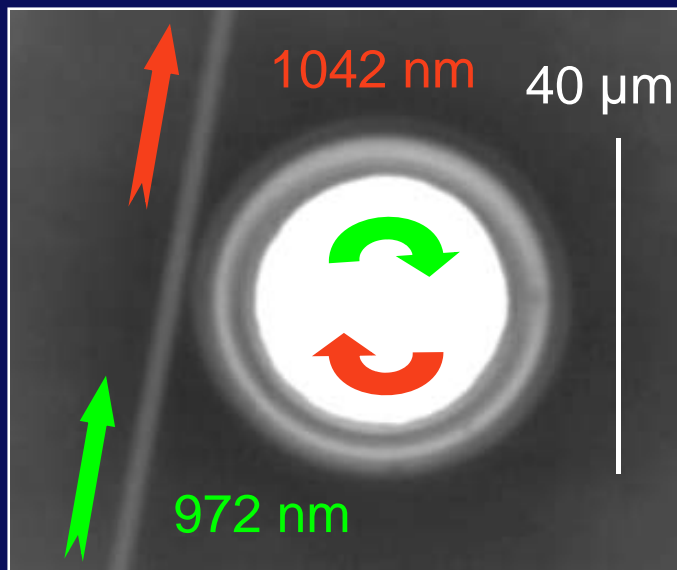
Lan Yang et al., App. Phy. Lett., Vol. 86, p 091114, 2005

Micro-laser Fabrication



- Yb-doped SiO₂ (glass) thin film was chemically fabricated
 - 4×10^{18} Yb³⁺ ions/cm³ (0.01%)
- 80 μm SiO₂ disks were patterned on Si by photolithography, and then exposed by XeF₂ etching
- CO₂ laser annealing produced 40 μm Yb:SiO₂ toroids on a silicon pillar
 - Creates atomically smooth sidewalls in spite of disk roughness caused by etching

Yb:SiO₂ Laser Testing

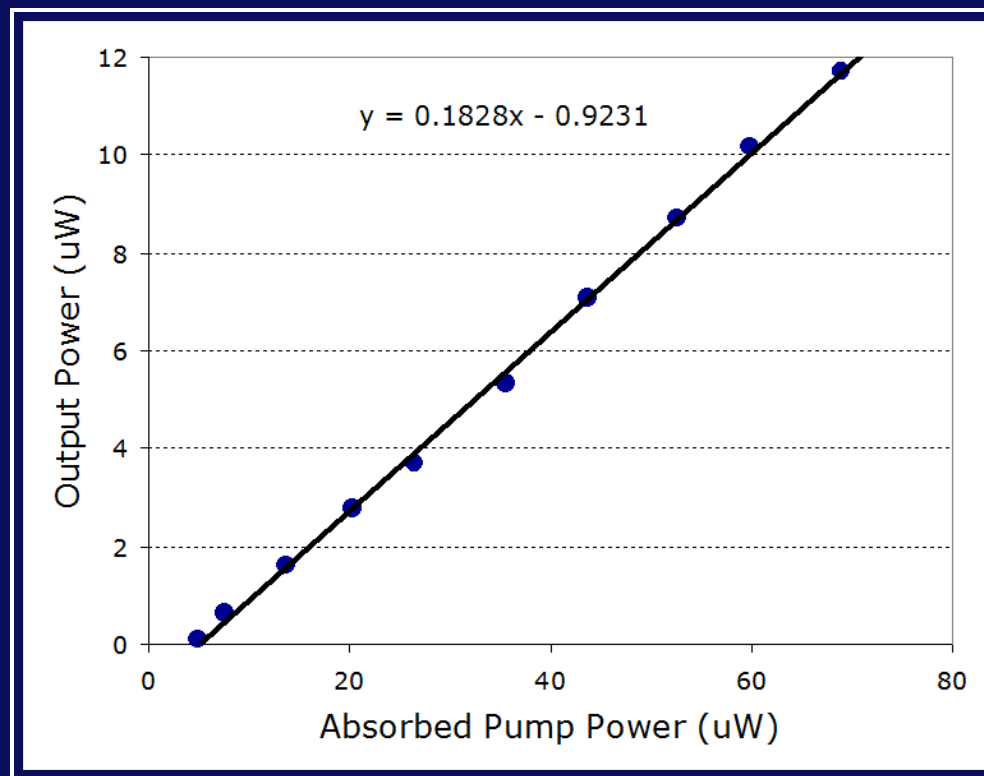


- Fiber taper evanescently couples 972 nm pump light into and 1042 nm laser light out of toroid

M. Cai et al., Phys. Rev. Lett., Vol. 85, 1, 74 (2000)

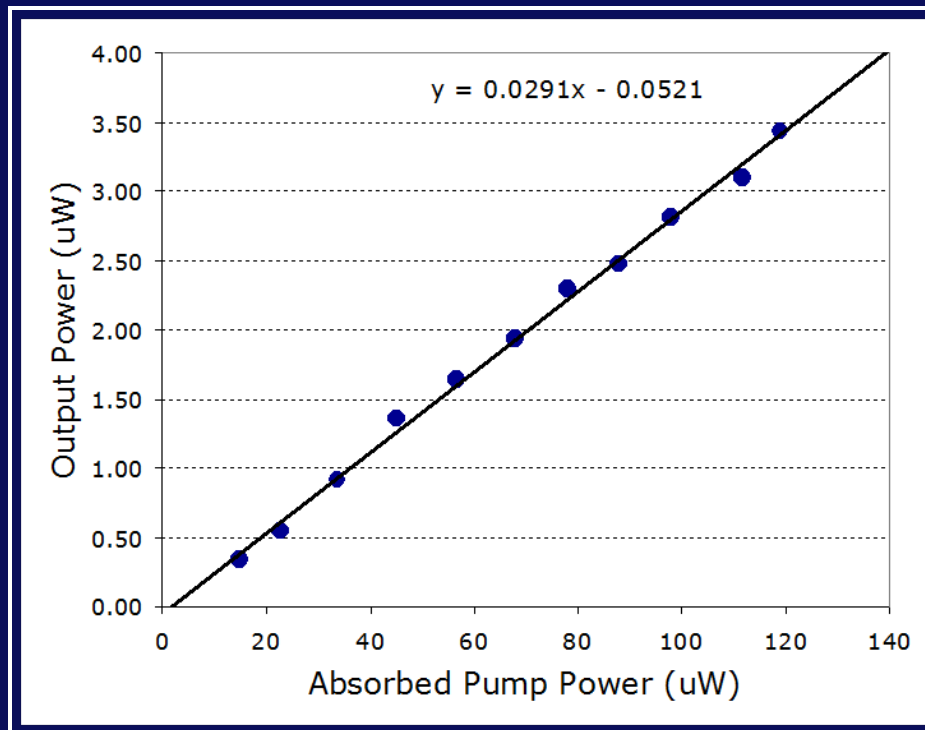
- Coupling is controlled with nanometer resolution stages
 - Critical coupling achieved with air gap
- Under-coupled cavity Quality Factor (Q)
 - = 1×10^6 @ 972 nm
 - Finesse = 10,000
 - = 25×10^6 @ 1558 nm

Result: High Slope Efficiency



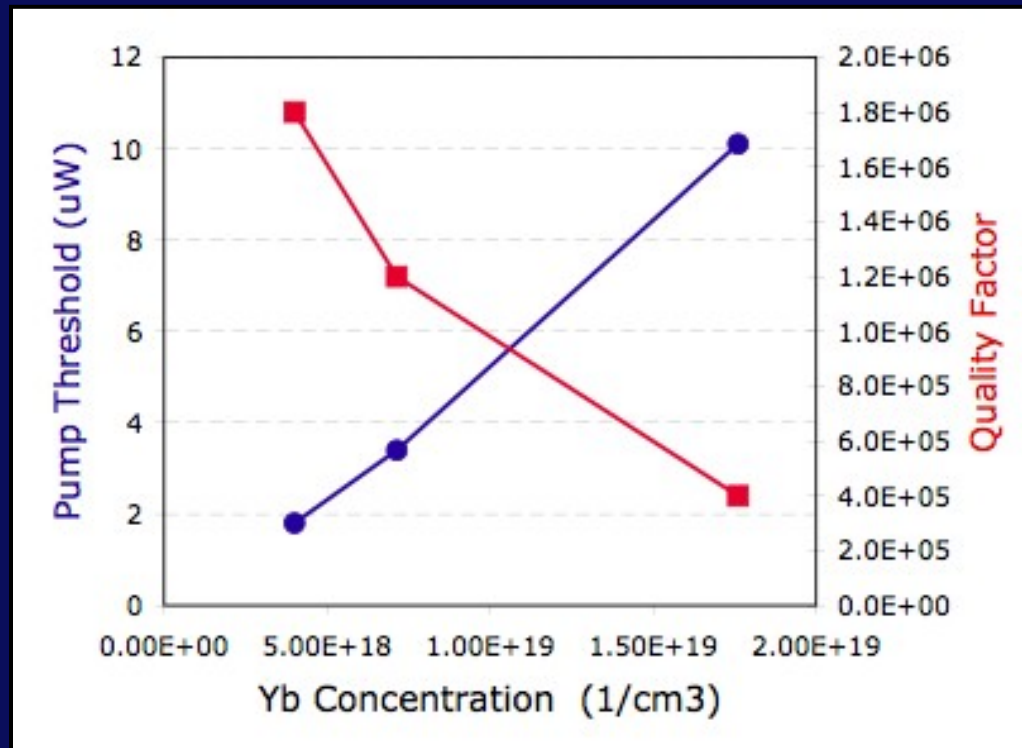
- 18 % slope efficiency
- 12 μW output power
- 5 μW threshold

Result: Low Threshold



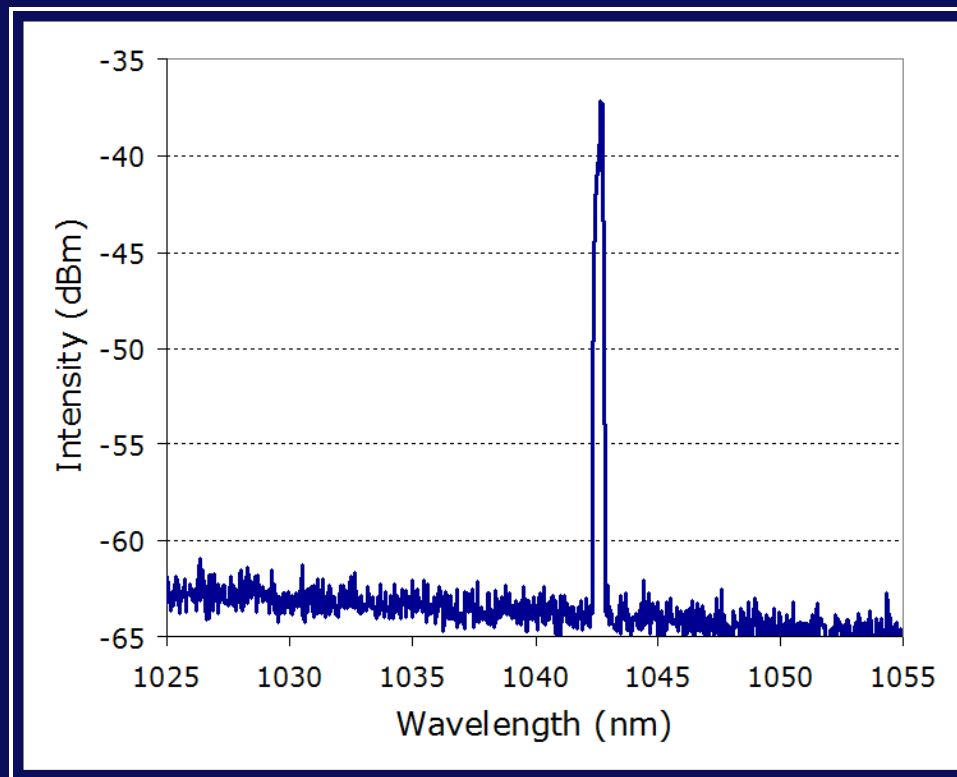
- 1.8 μW absorbed pump power threshold
 - Lowest previously published Yb laser threshold was 230 μW
A Asseh et al., Elect. Lett., Vol. 31, 12, 969 (1995)
- 3 % slope efficiency
- 3.5 μW output power

Effect of Yb^{3+} Concentration



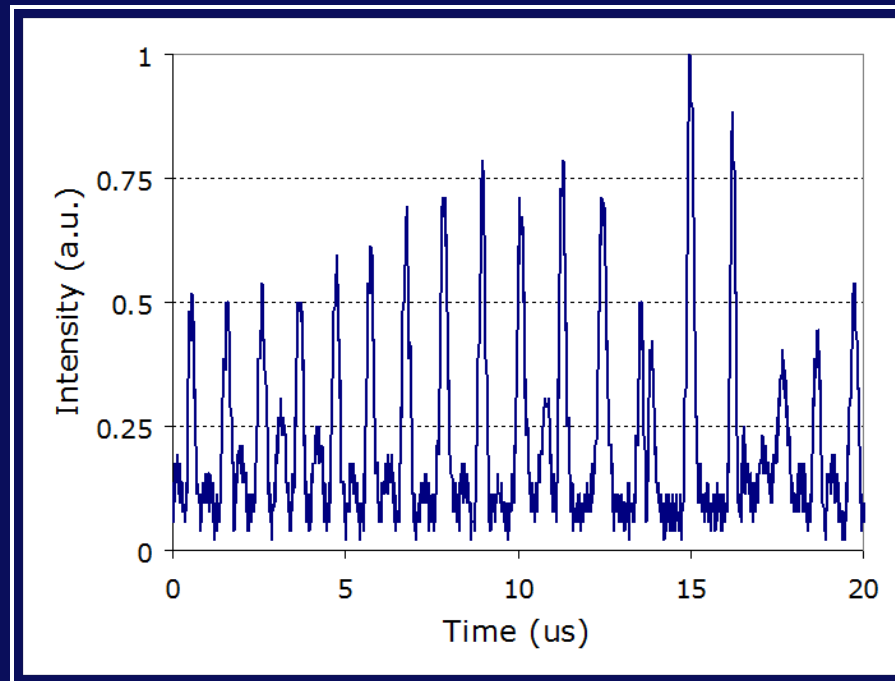
- Goal of current research was to achieve lowest pump threshold
- Future work will maximize laser slope efficiency

Single-Mode Laser Spectrum



- Single-mode pump (972.4 nm), single-mode output (1042.7 nm)
- Multi-mode lasing (1020 - 1060 nm) was observed for certain cavity-taper coupling conditions
 - Cavity FSR = 6 nm

Pulsing at High Concentration



- $2 \times 10^{19} \text{ cm}^{-3}$ concentration:
 - 1 MHz repetition rate, 200 ns pulse width
- $4 \times 10^{18} \text{ cm}^{-3}$ concentration:
 - Continuous-wave operation, no pulsing observed



Future Work and Applications

- Improve toroid cavity Quality Factor
 - 50×10^6 demonstrated in pure silica Sol-Gel toroid laser
Lan Yang et al., App. Phy. Lett., Vol. 86, p 091114, 2005
- Pulsed laser by co-doping silica Sol-Gel with Yb^{3+} and a saturable absorber (e.g. Cr^{3+})
- Er, Yb:SiO₂ (C-band laser)
- Applications
 - Low power lasers on-chip
 - Short-pulse generation



Conclusion

- Wet chemistry fabrication of glass with easy incorporation of rare-earth ions (Er, Yb, Cr, Pr, Tu ,etc.)
- On silicon chip, fiber taper coupled laser
- First Yb³⁺ microcavity laser
 - Pump-band $Q = 1 \times 10^6$
 - C-Band $Q = 25 \times 10^6$
- Record low threshold for any Yb laser (1.8 μW)
 - 12 μW output power, 18% laser slope efficiency (1st device)
 - 3.5 μW output power, 3% laser slope efficiency (2nd device)
- Future work will include efficiency improvements, short-pulse laser, and Yb sensitized Er laser



Thanks for your attention.

For more information:
www.vahala.caltech.edu