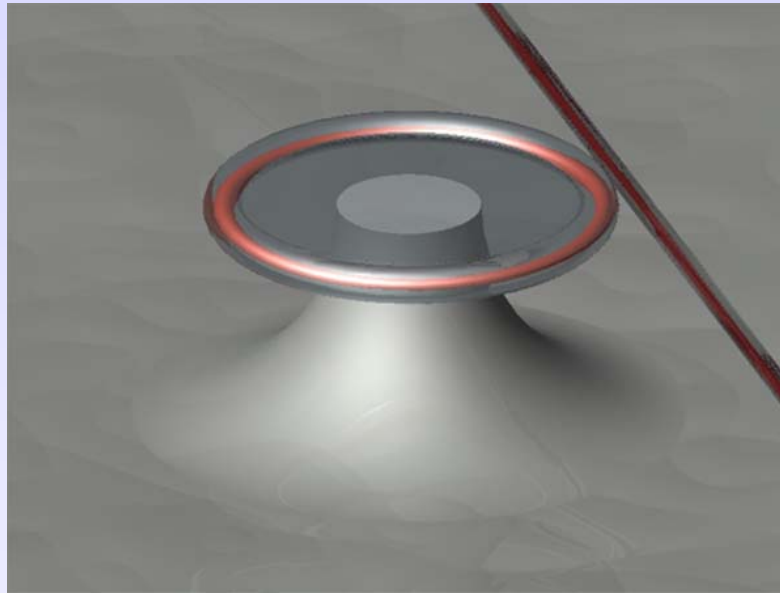


D₂O Detection using Ultra-high Q Toroidal Microcavities



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California Institute of Technology



D₂O detection methods



- **CO₂ Laser Absorption**

10% D₂O in H₂O

Radak, B., et. al., *J. of Rad. and Nucl. Chem.*, **129** 2 (1989).

- **Protonic Conductor**

5% D₂O in H₂O

Hibino, T., et. al. *J. Electrochem. Soc.*, **141** 9 (1994).

- **Optothermal Radiation**

30 ppmv (0.003%)

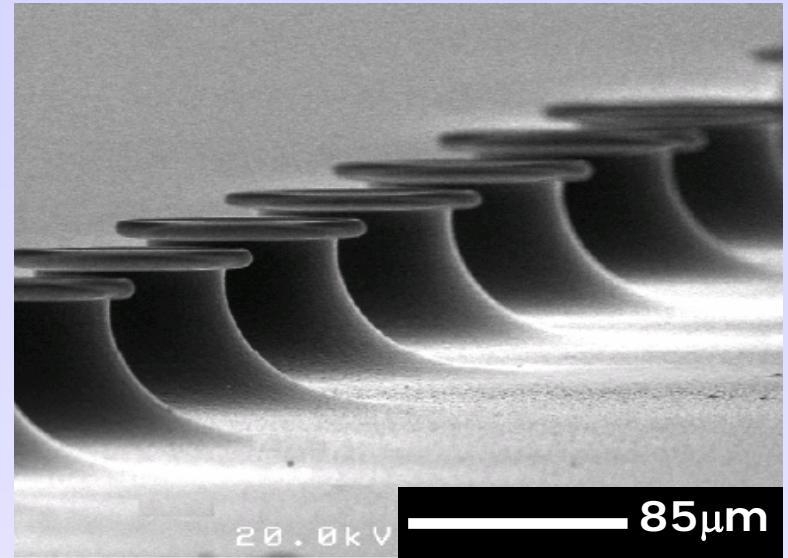
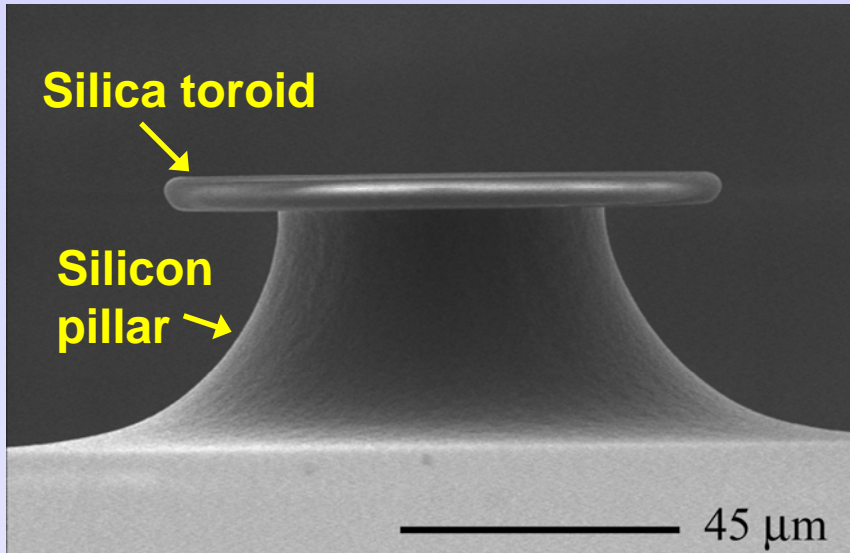
Annyas, J., et. al. *Appl. Spec.*, **53** 3 (1999).

- **UHQ Microtoroid Resonant Detection**

1 ppmv (0.0001%)

Armani, A. M., *Opt. Lett.*, **31** 12 (2006).

Ultra-high-Q microtoroid resonator



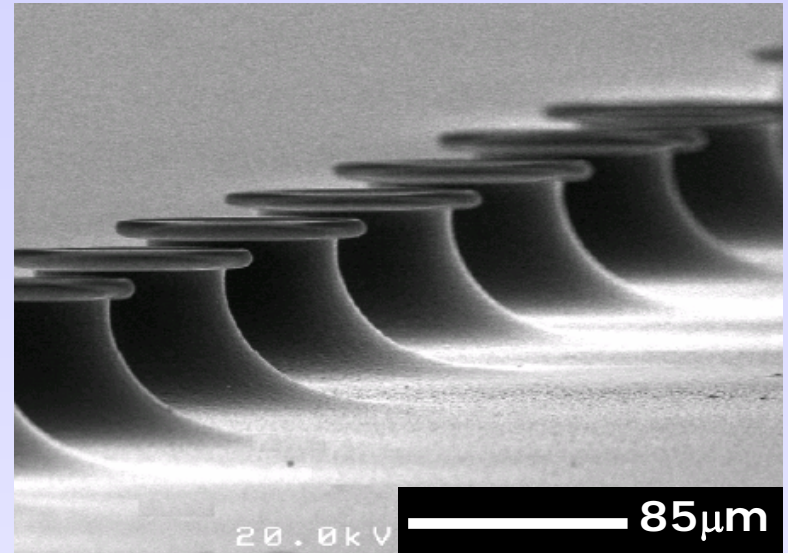
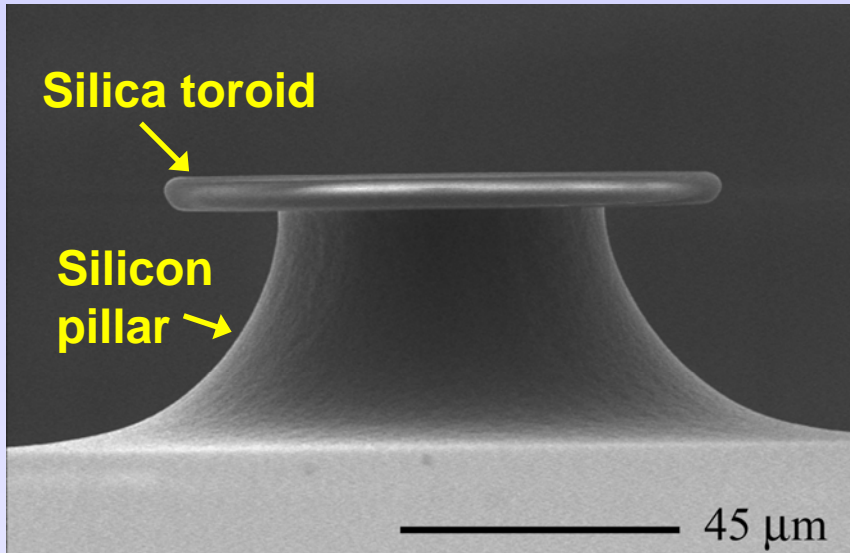
SEM of microtoroid resonator

- Silica on Silicon process
- Q~500 million (5,000X larger than all prior chip-based optical filters)
- Possibility to integrate with electronic control functions and MEMS

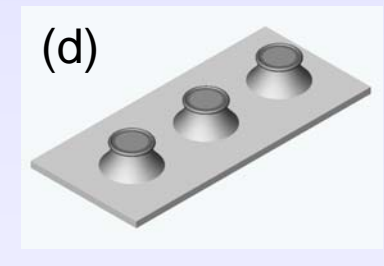
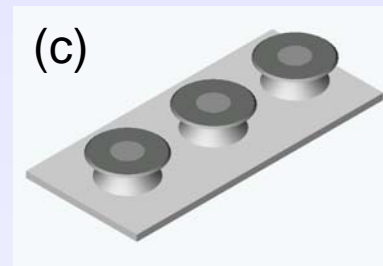
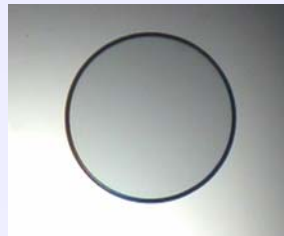
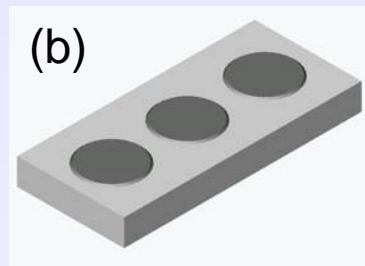
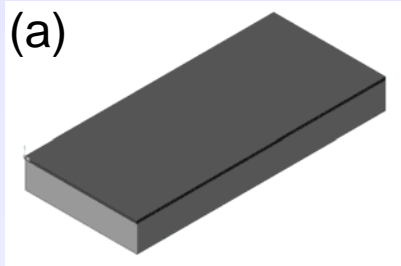


Armani, D. K., et. al. *Nature* 421, 925 (2003).

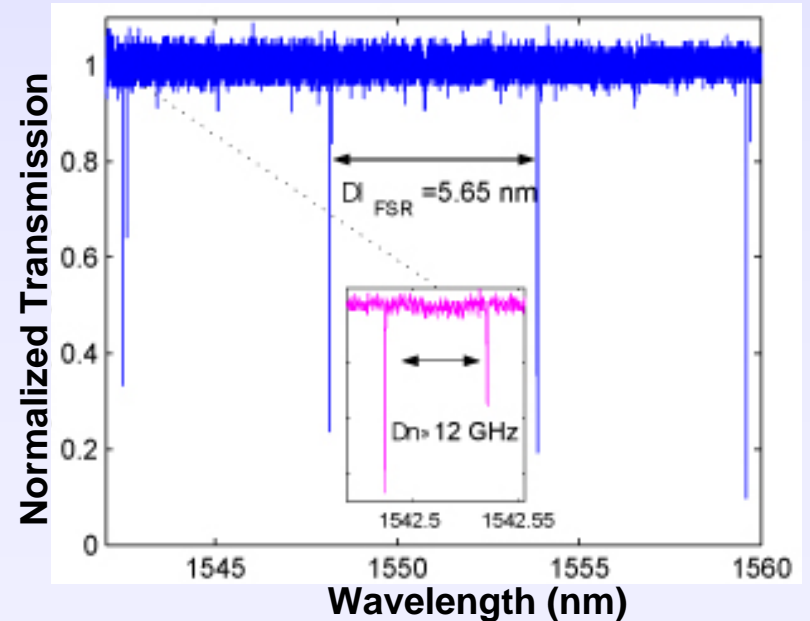
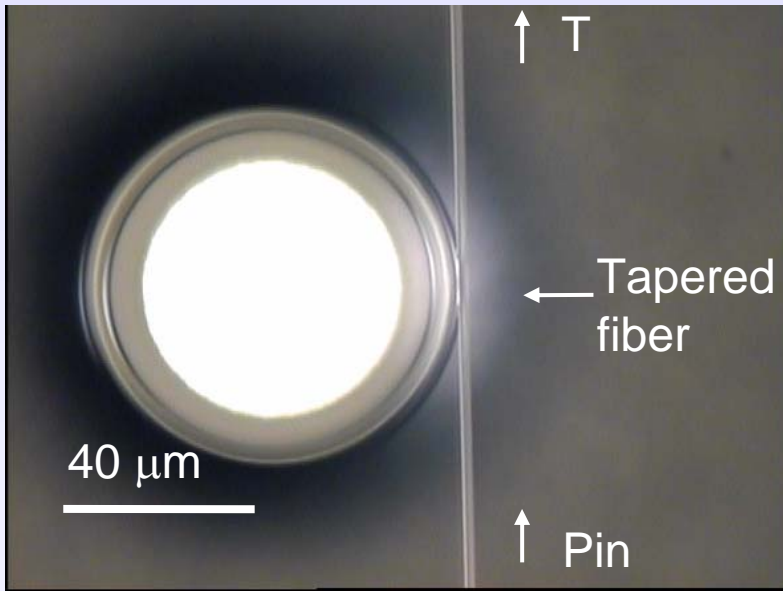
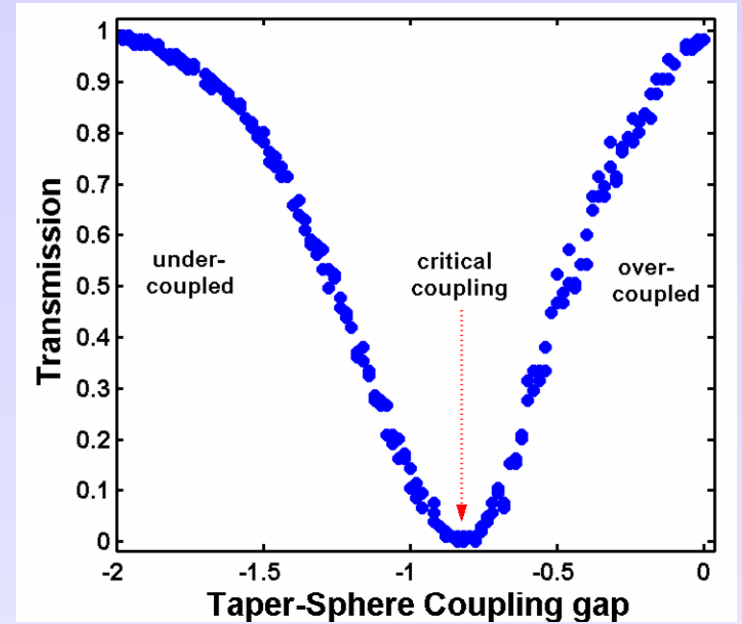
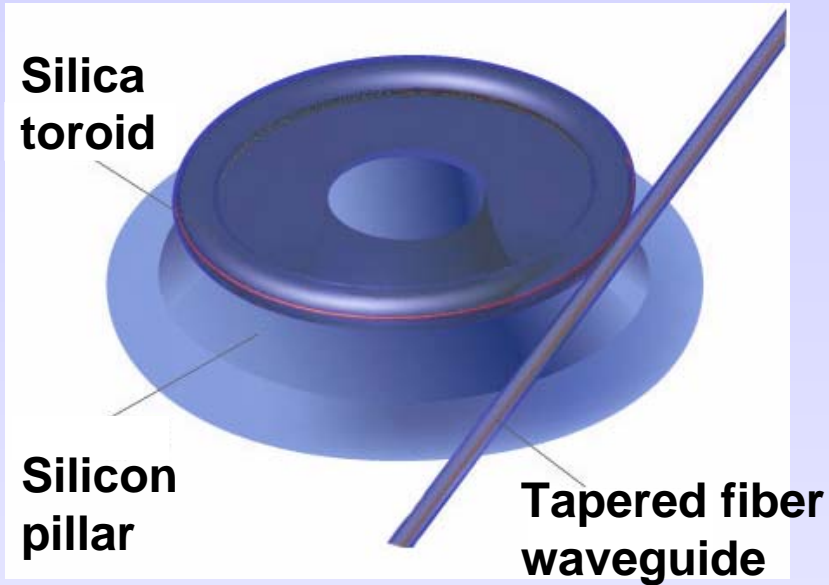
Microtoroid resonator fabrication



SEM of microtoroid resonator



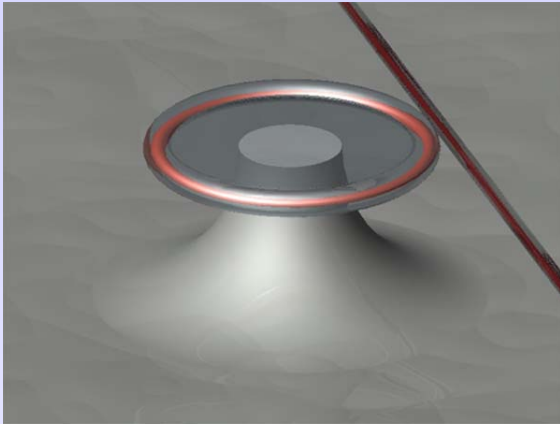
Tapered optical fiber coupling



Quality factor



$$Q_{tot}^{-1} = Q_{mat}^{-1} + Q_{ss}^{-1} + Q_{coup}^{-1} + Q_{rad}^{-1} + Q_{cont}^{-1}$$



$1/Q_{mat}$ = loss due to material loss

$1/Q_{ss}$ = loss due to surface roughness

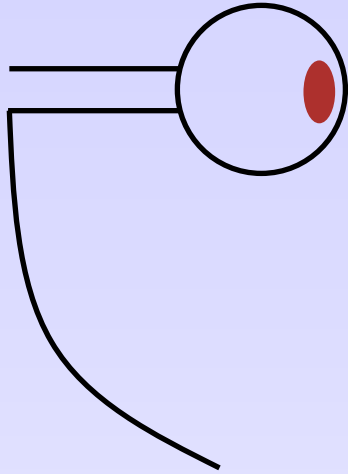
$1/Q_{coup}$ = coupling loss

$1/Q_{rad}$ = bending loss

$1/Q_{cont}$ = contamination loss

- Low loss of silica from the visible through the near-IR (300nm-1600nm) reduces $1/Q_{mat}$
- Reflow of surface reduces $1/Q_{ss}$
- Tapered optical fibers reduce $1/Q_{coup}$
- $1/Q_{rad}$ is controlled by using “large” resonators
- $1/Q_{cont}$ is reduced by keeping microtoroids clean

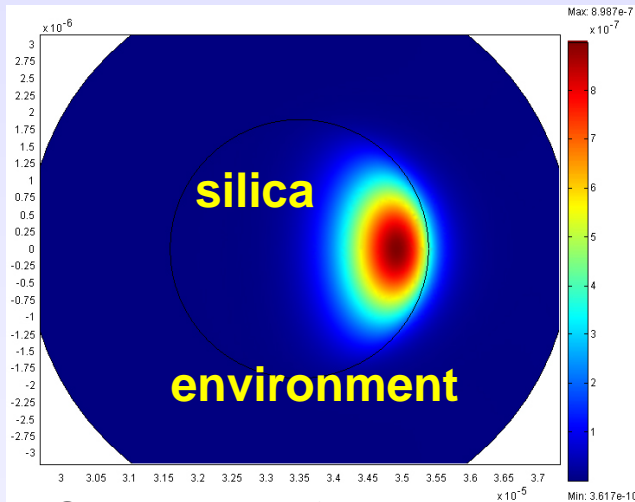
Quality factor regimes



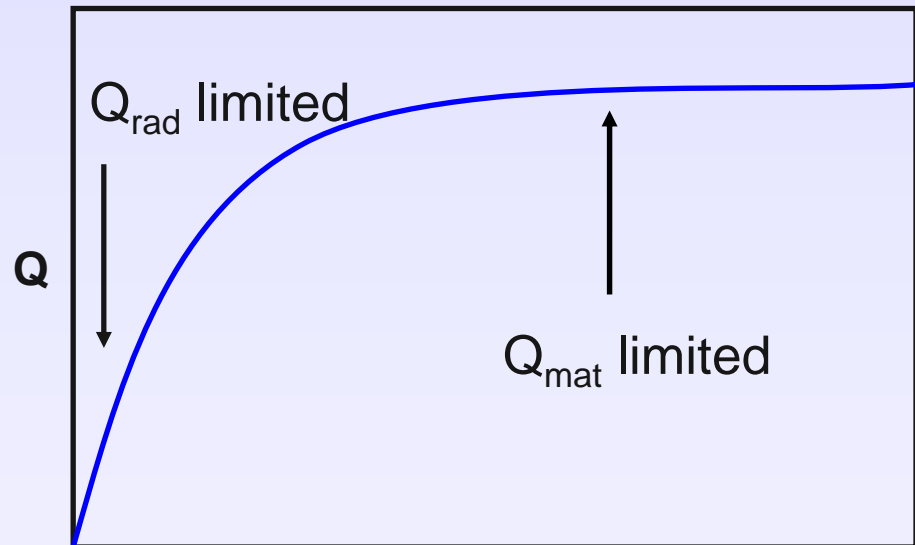
Cross section of microtoroid

$$Q_{tot}^{-1} = \boxed{Q_{mat}^{-1}} + \cancel{Q_{ss}^{-1}} + \cancel{Q_{coup}^{-1}} + \boxed{Q_{rad}^{-1}} + \cancel{Q_{cont}^{-1}}$$

- Q_{abs} limited at large R
- Q_{rad} limited at small R



Simulation of whispering gallery mode in water



Toroid Diameter

Modeling the new environment



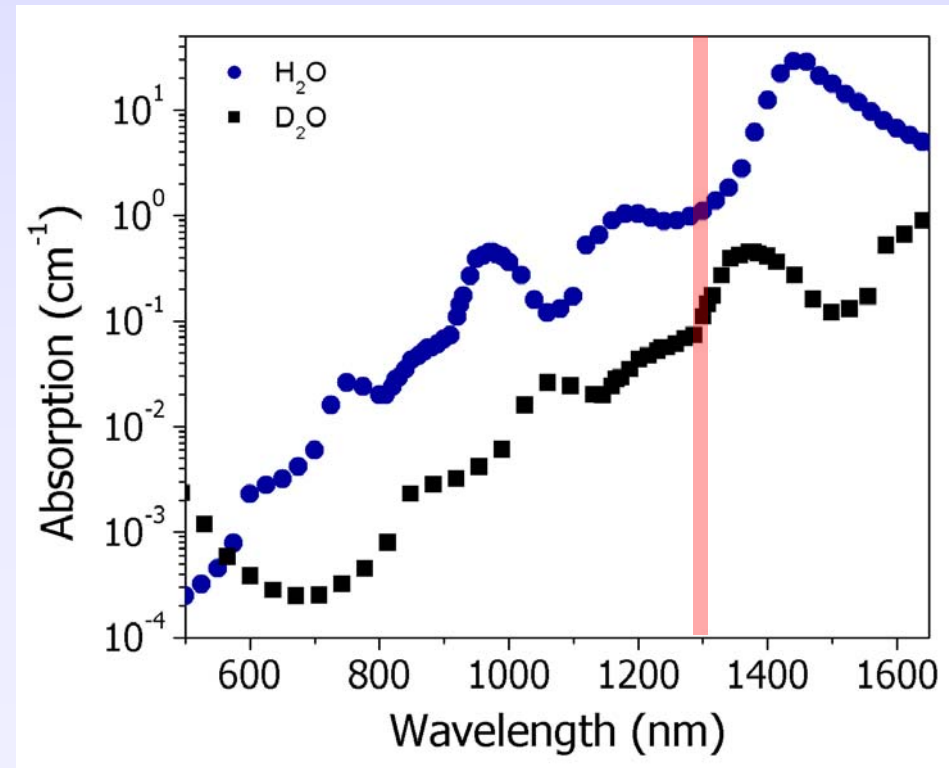
Modeled system numerically using two liquids: D_2O and H_2O

D_2O is H_2O with 2 additional neutrons

D_2O and H_2O are ideal for this system because:

- *same refractive index*
- *different absorption*

$$Q_{\text{tot}}^{-1} = Q_{\text{mat}}^{-1} + Q_{\text{rad}}^{-1}$$



New system – modeled and verified



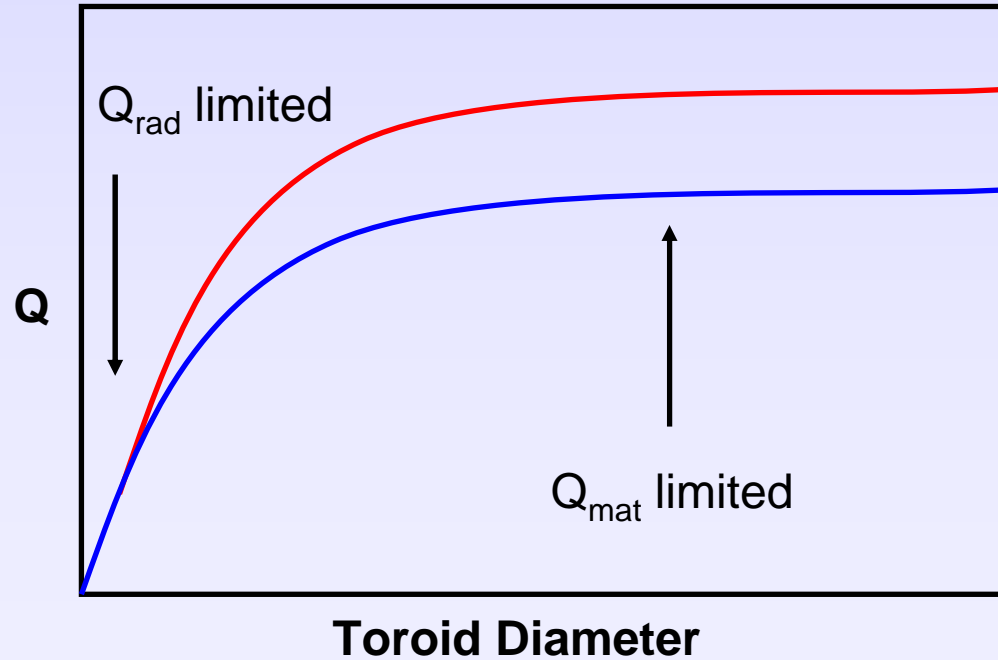
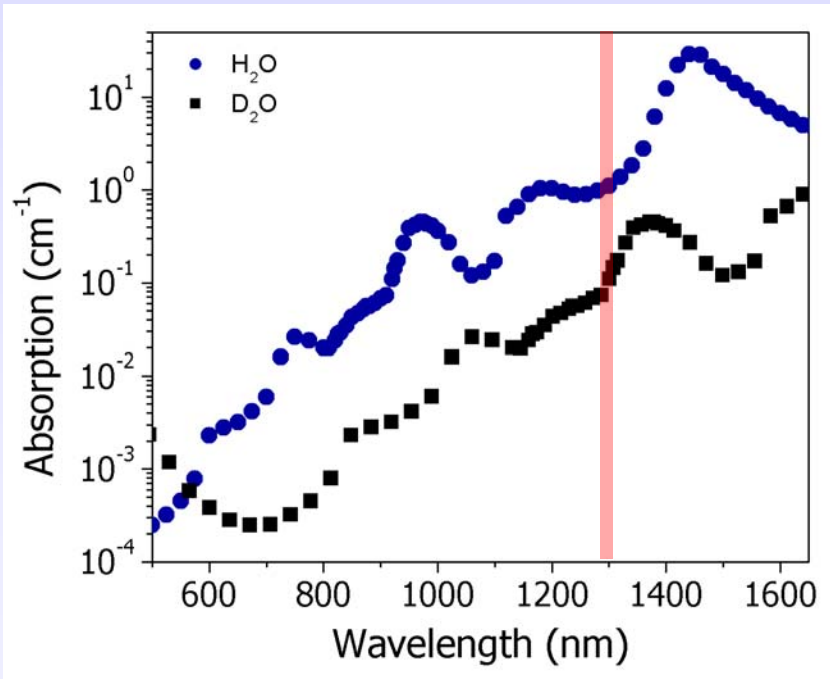
Q_{rad} is dependent on **toroid diameter**, wavelength and refractive index

Q_{mat} is dependent on **absorption**, wavelength and refractive index

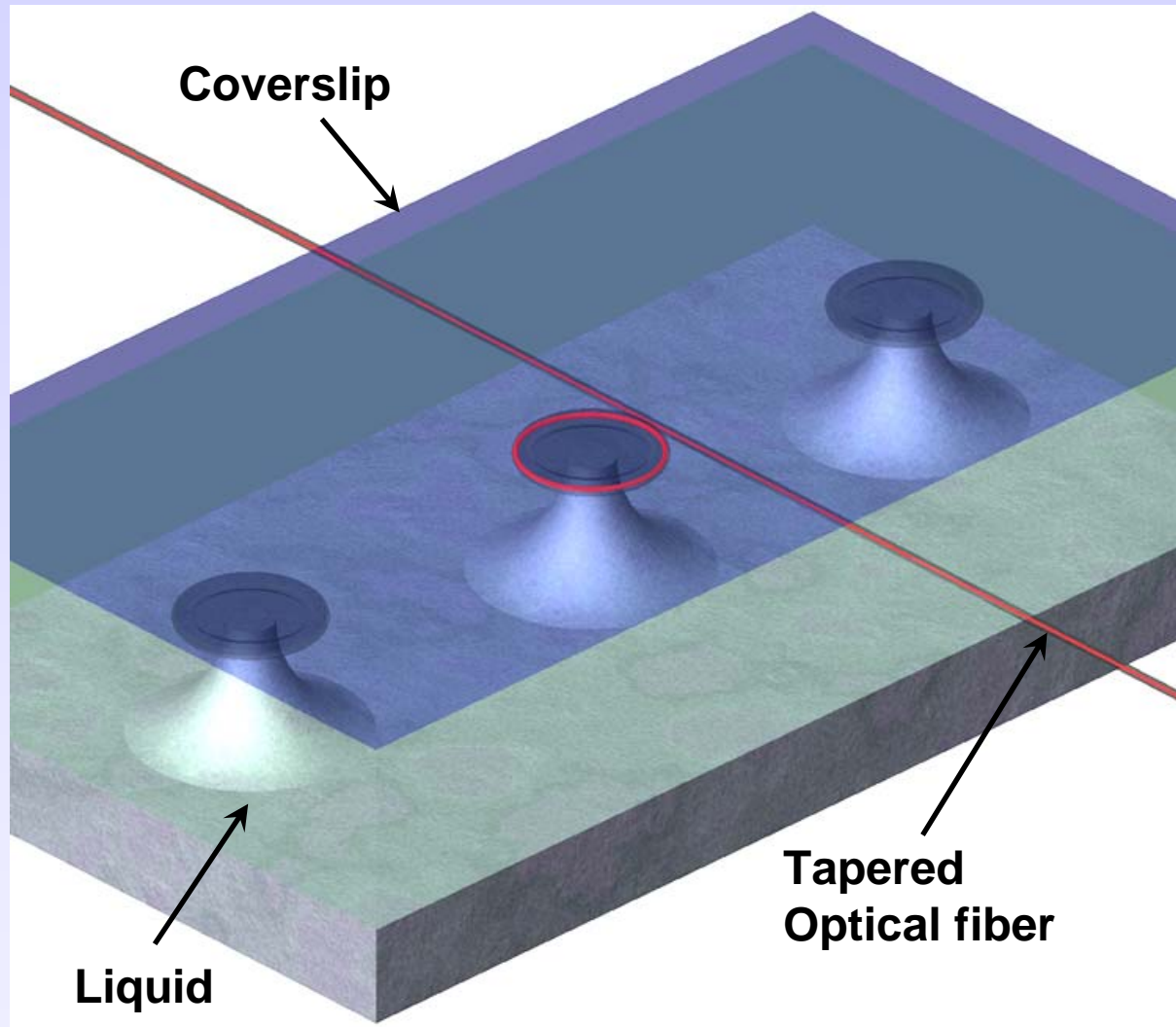
$$Q_{\text{tot}}^{-1} = Q_{\text{mat}}^{-1} + Q_{\text{rad}}^{-1}$$

$\text{H}_2\text{O absorption} > \text{D}_2\text{O absorption}$

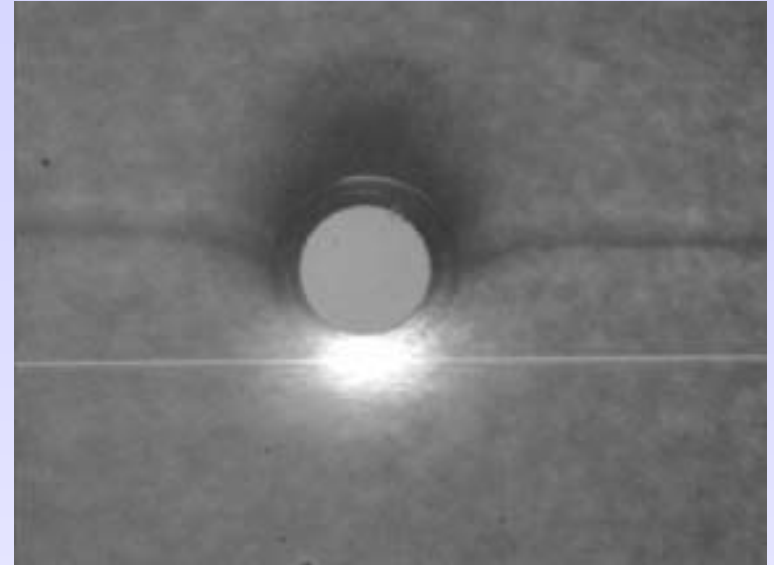
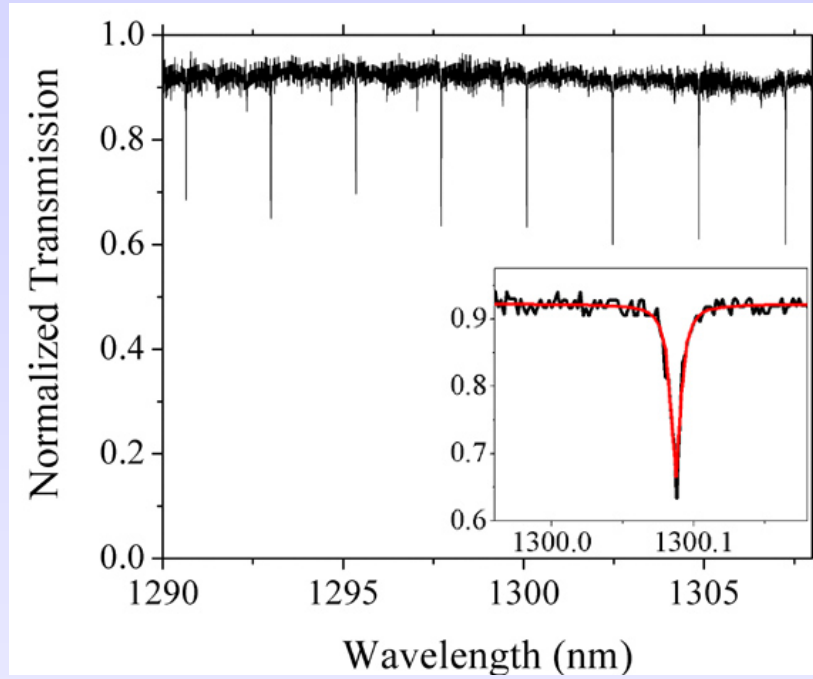
$$Q_{\text{water}} < Q_{\text{heavy water}}$$



Testing set-up in water



Mode spectra – toroids in liquid



Mode spectrum of resonator immersed in water. The regular free spectral range is preserved, even in the reduced index contrast.

Quality factor at 1300nm



Quality Factor:

$$Q_o^{-1} = Q_{rad}^{-1} + Q_{abs}^{-1}$$

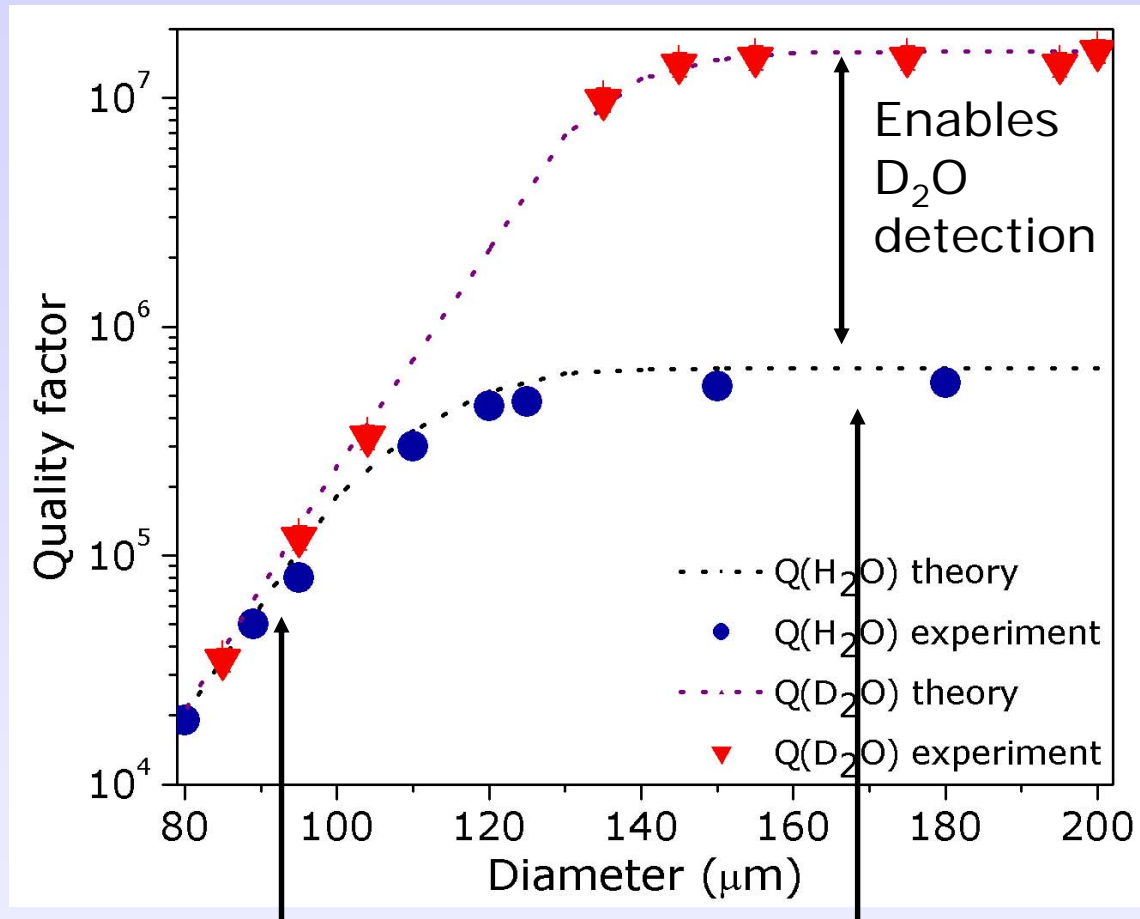
Q_{rad} = radiation loss

Q_{abs} = absorption loss

1300nm

- $Q > 10^7$ achieved
in D_2O and
 $Q \sim 10^6$ in H_2O

- Q_{abs} limited



Q_{rad} limited

Q_{abs} limited

To perform D_2O detection:

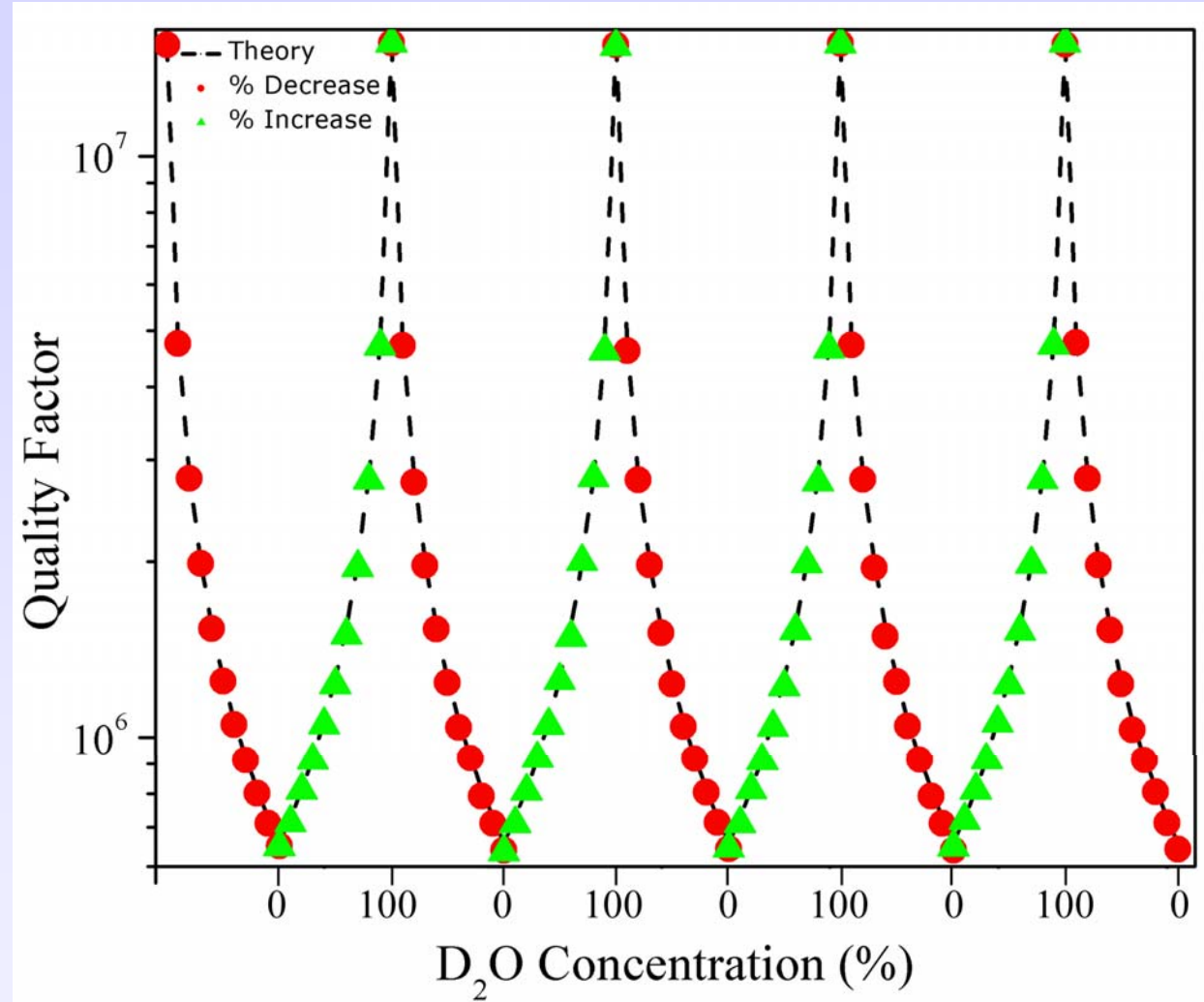
must use a toroid with a diameter > 150 mm

Reversible detection of D₂O



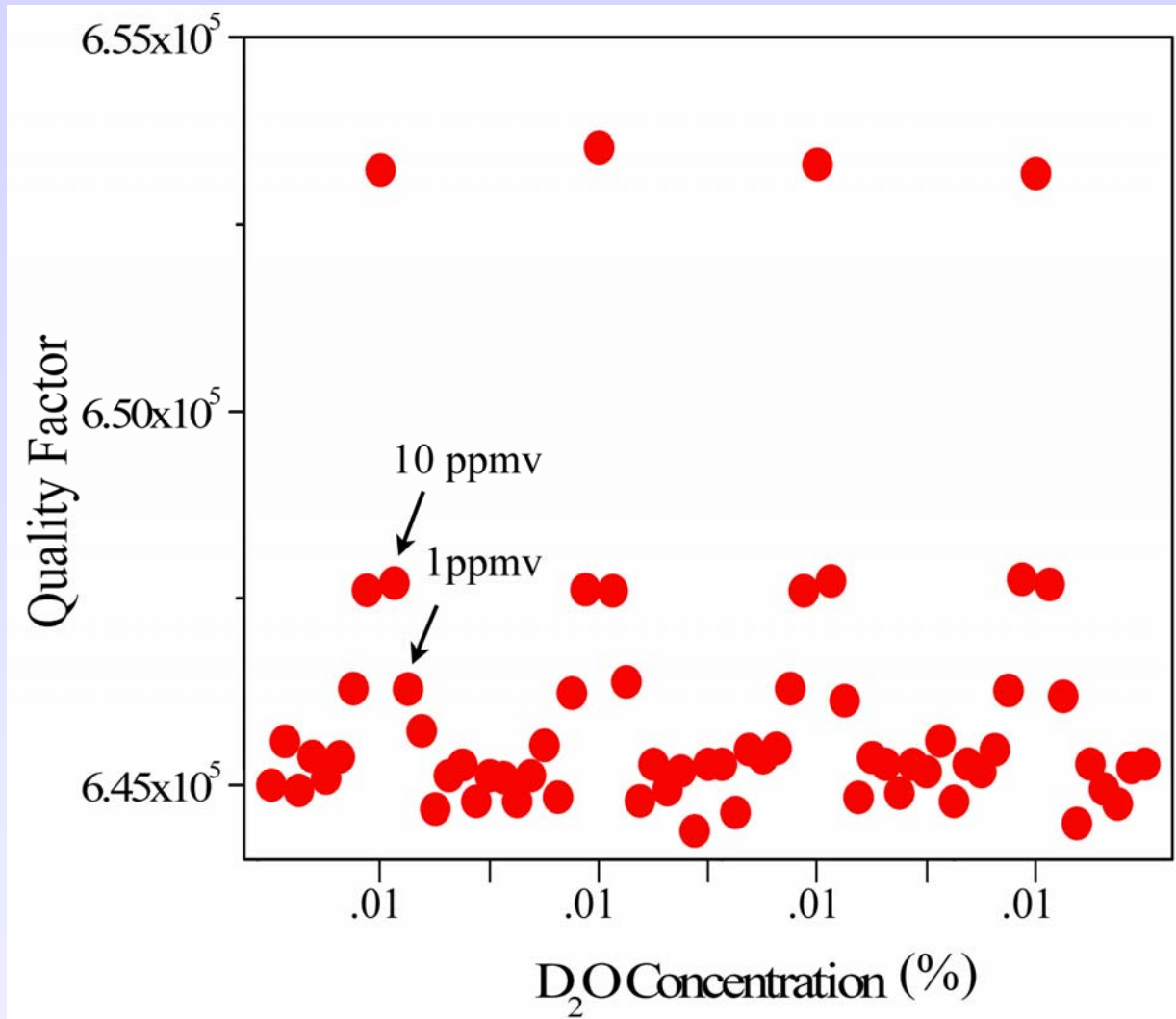
Initially, 100% D₂O, decrease concentration in 10% increments, until 100% H₂O.

$$Q_{mat} = \frac{2\pi n_{eff}}{\lambda \alpha}$$



- Good agreement with theory
- Able to perform cyclic detection

Low concentration detection of D₂O



- 1ppmv minimum concentration

—————→ **30x improvement over previous methods**

In Summary



- Demonstrated 1ppmv detection of D₂O which is 30x lower than previous method
- Demonstrated ability to flush the system, therefore allowing cyclic detection
- Good agreement between experiment and theory



**DARPA Center for
Optofluidics Integration**

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<http://www.vahala.caltech.edu>