Hyper-parametric oscillations in a whispering gallery mode fluorite resonator

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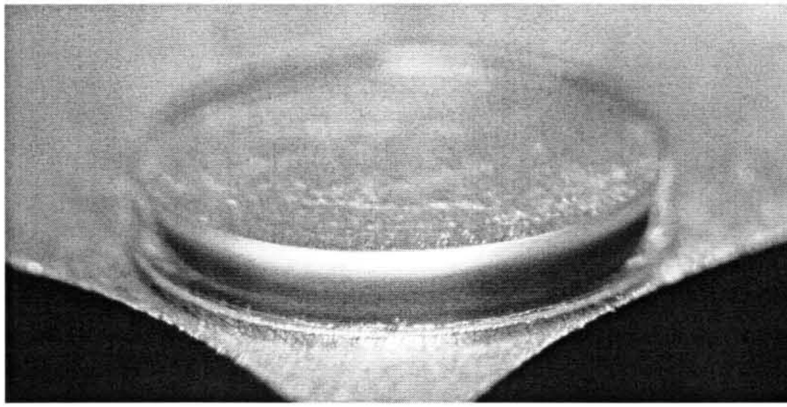
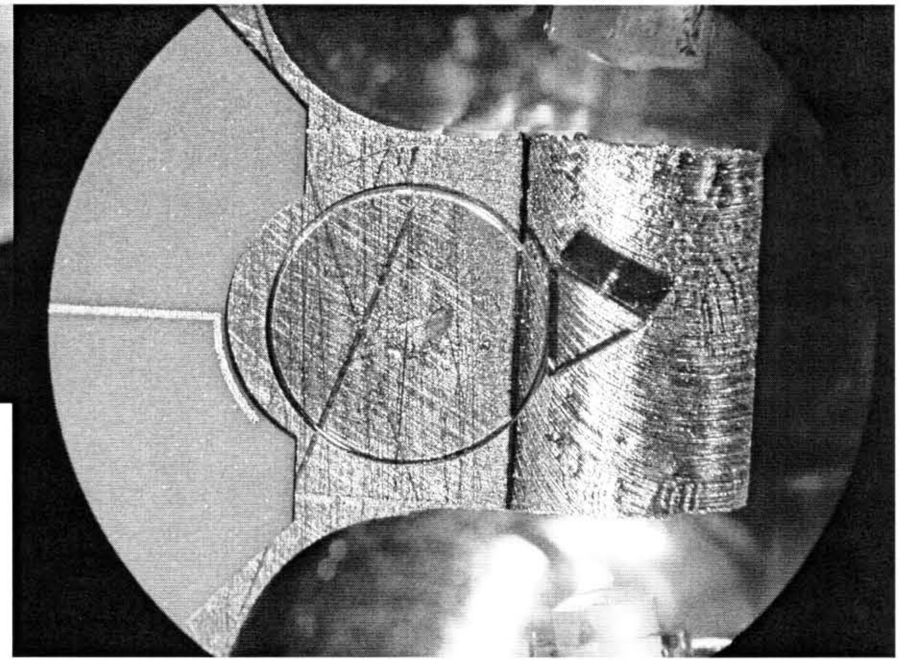
Frontiers in optics 2004,
the 88th annual OSA meeting,
Rochester, October 10-14

Thank$: NASA, DARPA

Whispering Gallery Mode resonators





… Come in various shapes and sizes.

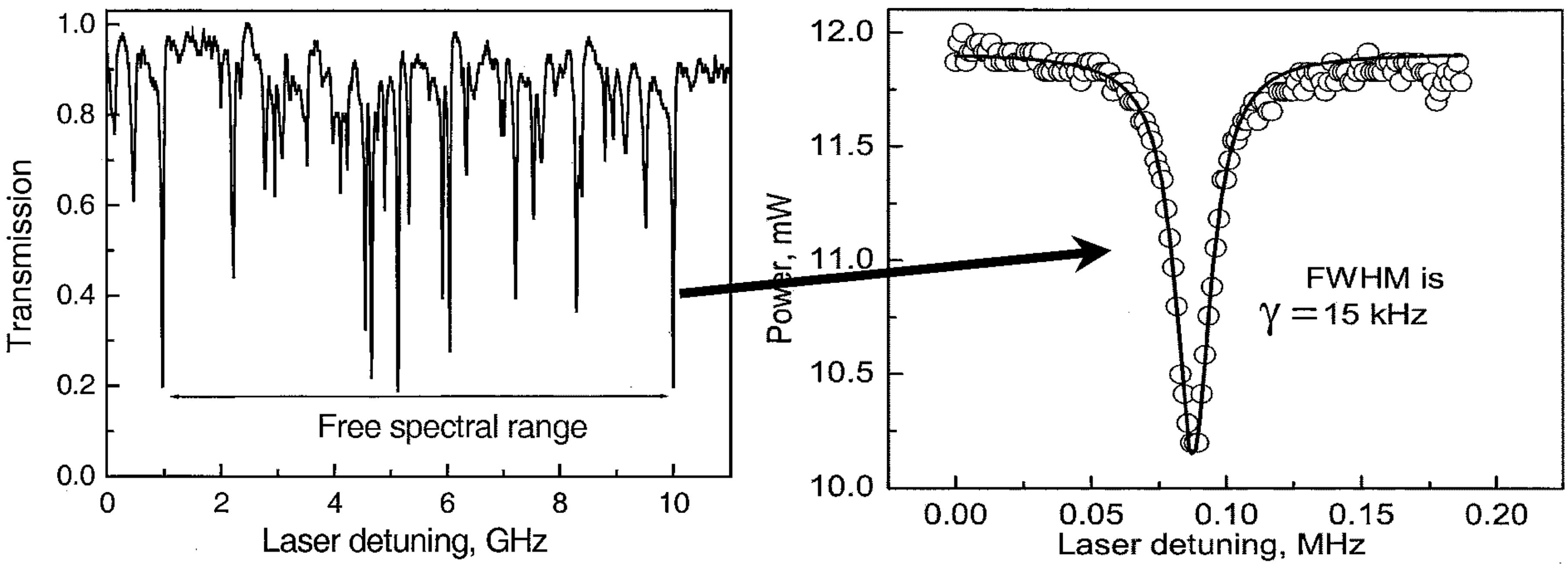
We are mostly interested in the disk resonators. They:
- have cleaner spectrum;
- are ideal for electro-optical applications;
- may have very small mode volume (good for nonlinear optics).

→ Low microwave power EO modulators

→ Continuously tunable, narrow-band pass and stop optical filter

[References available]

Typical WGM spectrum



$$Q = \omega/\gamma > 2 \times 10^{10}$$

Important parameters

Q

V

Cavity field build-up factor and linewidth

$$\frac{Q^n}{V}$$

Small size and optical energy density

E.g. $V = \pi \times 1\ \text{mm} \times 100\ \mu\text{m} \times 10\ \mu\text{m}$

Figure of merit for nonlinear processes:

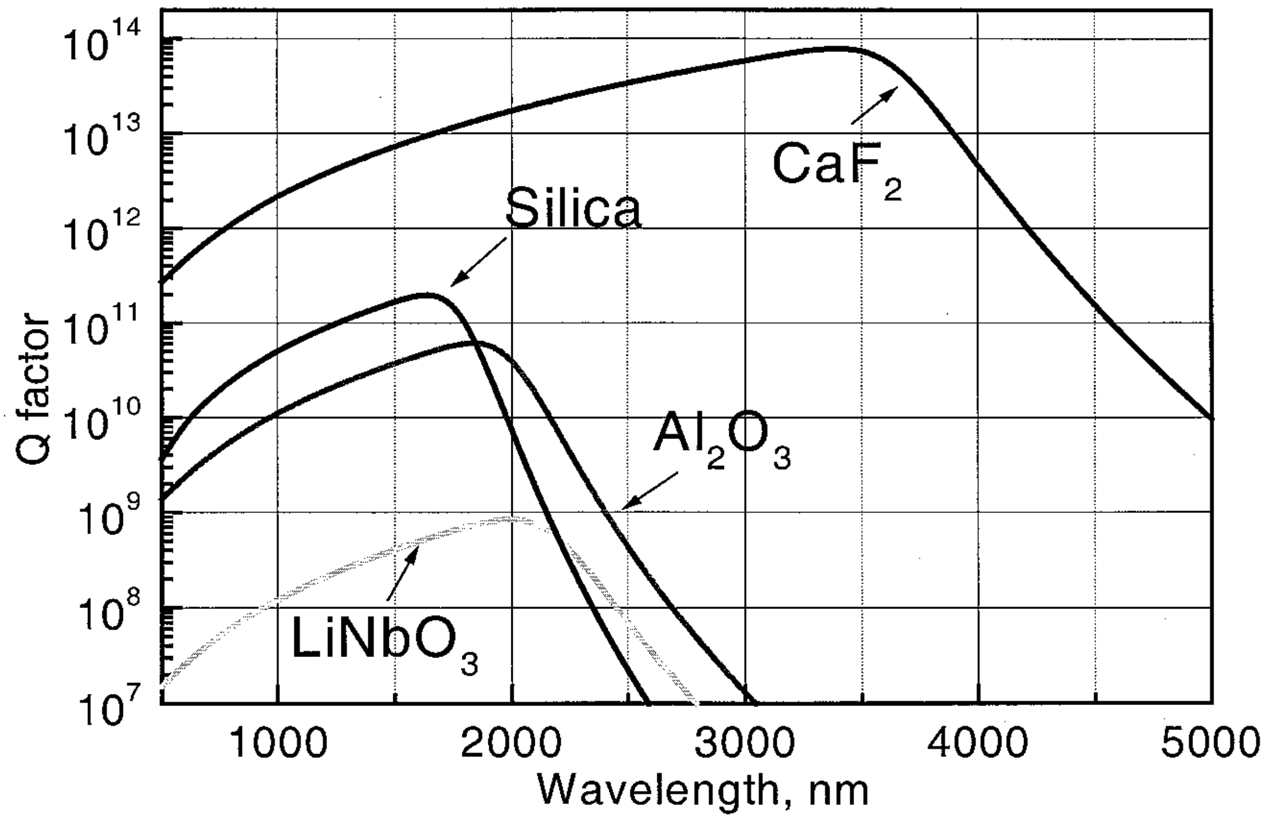
Purcell's factor: n=1 SRS and FWM: n=2 Frequency doubling: n=3

[V.S. Ilchenko et al., JOSA B 20, 1304 (2003)]

For crystalline resonators, linewidth is ultimately determined by the material absorption α:

$$2\gamma^{-1} = n_0(\alpha c)^{-1}$$

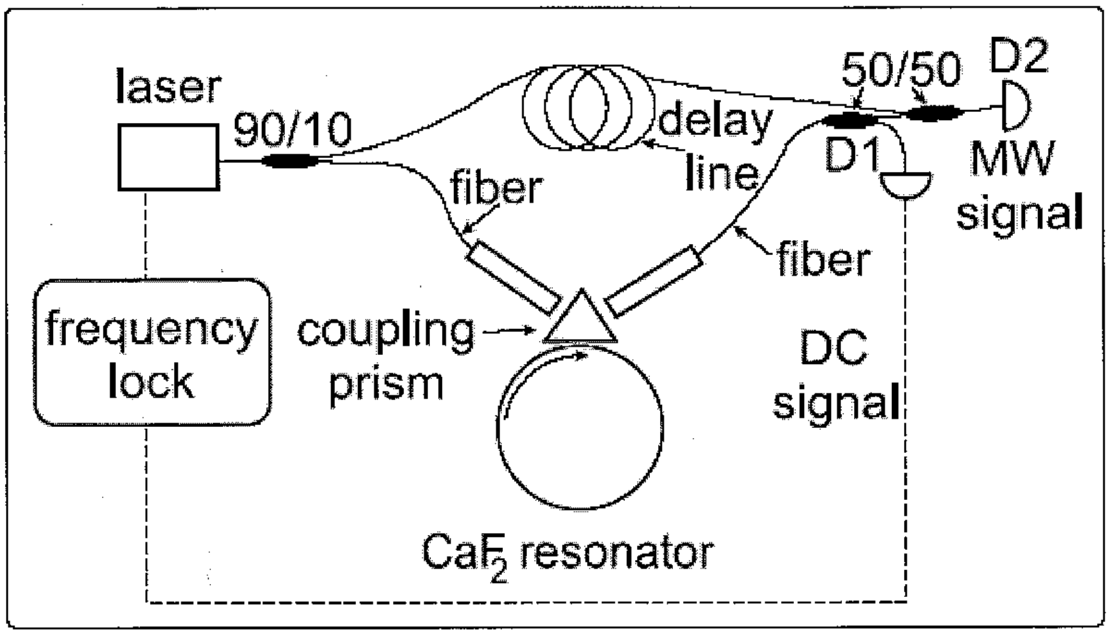
$$\Rightarrow \quad Q = \frac{2\pi n}{\alpha\lambda}$$



For $\alpha \simeq \alpha_{UV}\, e^{\lambda_{UV}/\lambda} + \alpha_R\, \lambda^{-4} + \alpha_{IR}\, e^{-\lambda_{IR}/\lambda}$

E.D.Palik, "Handbook on optical constants of solids", Academic, NY, 1998

Hyper-parametric oscillations in fluorite resonators



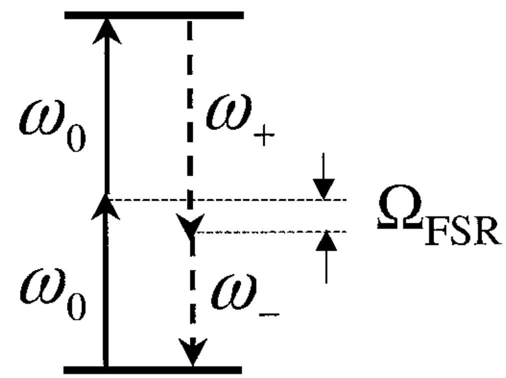
$$Q = 2\times10^{10} \; at \; \lambda = 1310\,nm$$

Selection rules

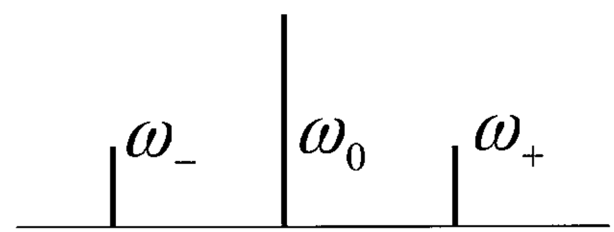
FWM: TE-TE

SRS: TE-TM

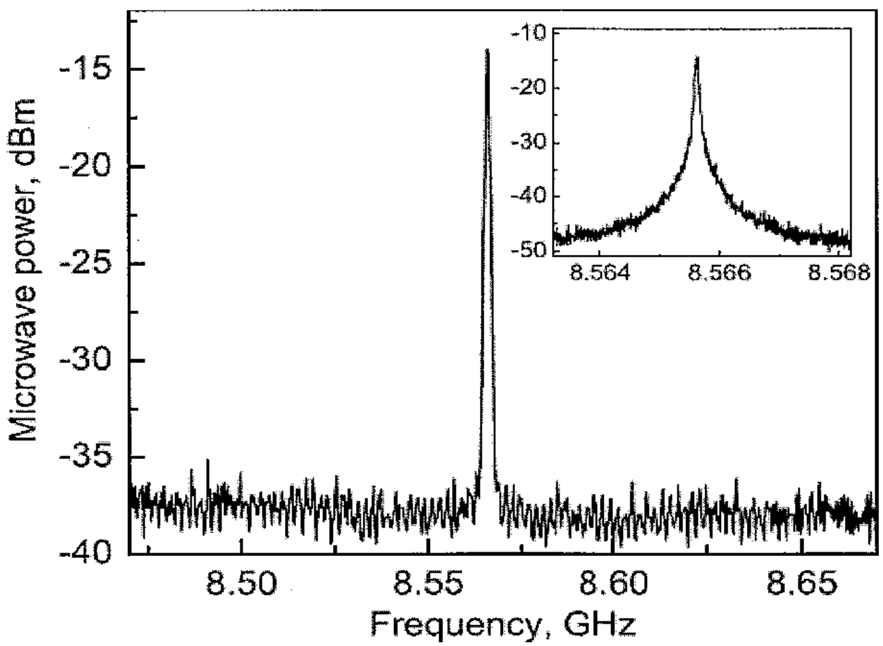
Transition diagram

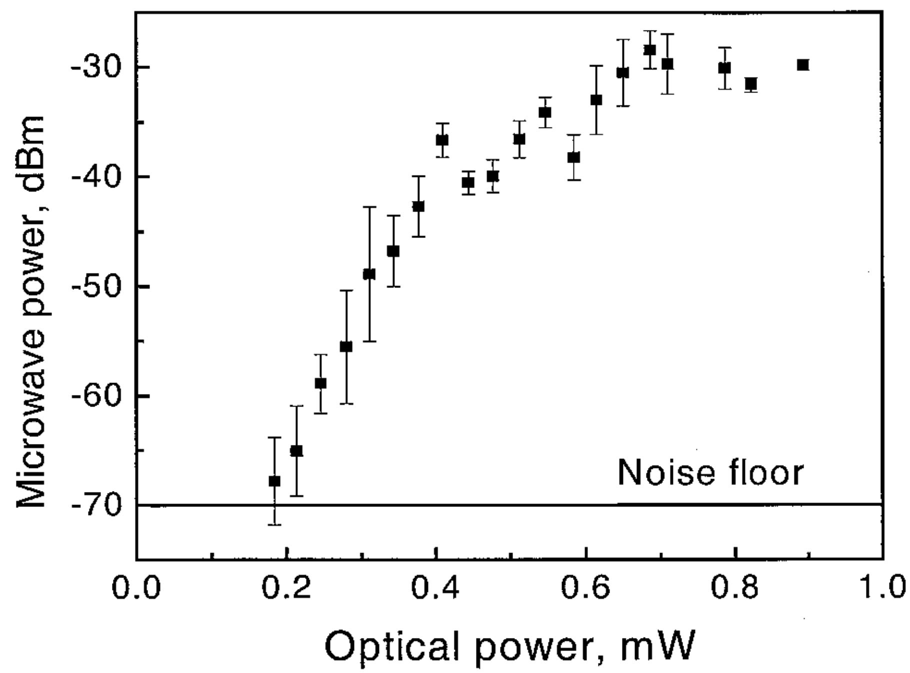


Optical spectrum



Microwave beat note observed





- Second-order ($2\Omega_{FSR}$) beat note is insignificant
- Raman scattering is not observed (expected at 322 cm^{-1})

A.A.Savchenkov et al.,
Submitted to PRL (2004)

Analysis

Kerr Hamiltonian: $H = H_0 + V, \quad H_0 = \hbar\omega_0 a^\dagger a + \hbar\omega_+ b_+^\dagger b_+ + \hbar\omega_- b_-^\dagger b_-,$ where

$$V = -\hbar\frac{g}{2}\left(a^\dagger a^\dagger aa + b_+^\dagger b_+^\dagger b_+ b_+ + b_-^\dagger b_-^\dagger b_- b_-\right) - 2\hbar g\left(b_-^\dagger b_+^\dagger b_+ b_- + a^\dagger b_+^\dagger b_+ a + a^\dagger b_-^\dagger b_- a\right)$$

$$- \hbar g\left(b_-^\dagger b_+^\dagger aa + a^\dagger a^\dagger b_+ b_-\right)$$

Self-phase modulation — Cross-phase modulation — Four-wave mixing

Equations of motion in an open system:

$$\dot{a} = -(i\omega_0 + i\kappa(T) + \gamma_0 + \gamma_{c0})a + ig\left[a^\dagger a + 2b_+^\dagger b_+ + 2b_-^\dagger b_-\right]a + 2iga^\dagger b_+ b_- + f_0 + f_{c0},$$

$$\dot{b}_+ = -(i\omega_+ + i\kappa(T) + \gamma_+ + \gamma_{c+})b_+ + ig\left[2a^\dagger a + b_+^\dagger b_+ + 2b_-^\dagger b_-\right]b_+ + igb_-^\dagger aa + f_+ + f_{c+}$$

$$\dot{b}_- = -(i\omega_- + i\kappa(T) + \gamma_- + \gamma_{c-})b_- + ig\left[2a^\dagger a + 2b_+^\dagger b_+ + b_-^\dagger b_-\right]b_- + igb_+^\dagger aa + f_- + f_{c-}$$

Temperature tuning — SPM and CPM — FWM

Where $\langle f_{c0}\rangle = \sqrt{\dfrac{2\gamma_{c0}P_0}{\hbar\omega_0}}\, e^{-i\omega t}$ and $g = \omega_0 \dfrac{n_2}{n_0}\dfrac{\hbar\omega_0 c}{\mathcal{V} n_0}$

Results of analysis

Experiment

1. Complex dynamics of the system (laser lock helps) ✓

2. Threshold power: $P_{th} \simeq 1.54 \frac{\pi}{2} \frac{\gamma_0 + \gamma_{c0}}{2\gamma_{c0}} \frac{n_0^2 \mathcal{V}}{n_2 \lambda Q^2}$, ✓

3. Phase modulation (when critically coupled) ✓

4. Beat note frequency $\omega - \tilde{\omega}_- = \tilde{\omega}_+ - \omega = \frac{1}{2}(\omega_+ - \omega_-)$, is independent on the nonlinear dynamics of the system ✓

5. Phase diffusion is very low: $D_{min} = \frac{(\gamma_{c0} + \gamma_0)^2}{2} \frac{\hbar \omega}{P_{B\ opt}} = \omega_0^2 \frac{\gamma_0 + \gamma_{c0}}{2\gamma_{c0}} \frac{\hbar \omega_0 n_2 \lambda}{4\pi \mathcal{V} n_0^2}$. ***To be tested***

Summary and conclusions

☞ Very high Q-factor and small volume allow us to reach the oscillation threshold for the four-wave mixing process in WGM disk resonators with low power DC optical fields.

☞ The generated fields can be represented as the sidebands of the phase-modulated carrier (the pump). The sidebands frequency is very stable in spite of complex mode dynamics of the system, which suggests the possibility of its application as a secondary frequency standard.

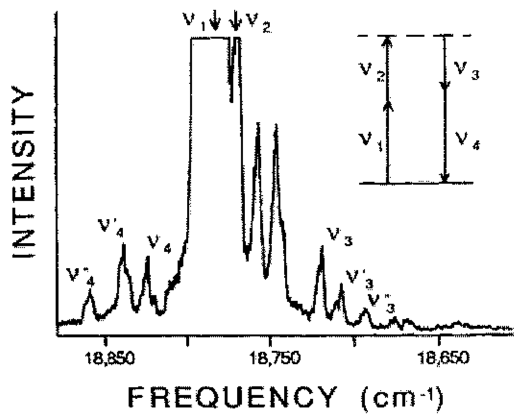
☞ The absence of the SRS in the pump polarization (TE) is a consequence of the selection rules; however its absence in the TM polarization is surprising and is in contradiction with the results for amorphous materials [*S.M. Spillane, T.J. Kippenberg, K.J. Vahala, Nature 415, 621 (2002)*]. This may be due to asymmetry of the Brillouin zone in crystals. Further research is needed.

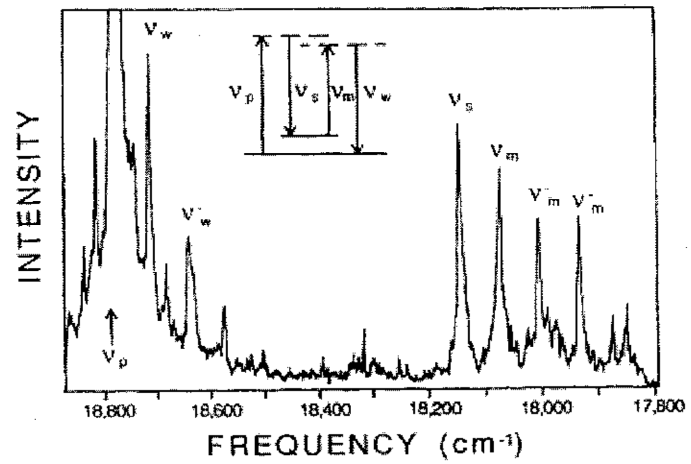
☞ Just like parametric down conversion, hyper-parametric conversion can produce nonclassical (e.g. entangled or squeezed) light. We plan on carrying out the research of quantum optical properties of our system.

Earlier results on CW four wave mixing in amorphous materials

H.-B. Lin and A.J. Campillo, Phys. Rev. Lett. 73, 2440 (1994).

CS_2 droplets





S.M. Spillane, T.J. Kippenberg, K.J. Vahala, Nature 415, 621 (2002).

Fused silica microspheres