Applications of Linear and Nonlinear Properties of Crystalline Whispering Gallery Mode Resonators

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Outline

- Introduction
- Fundamentals of crystalline WGM resonators
- Spectrum engineering
- Delay-slow light devices
- Filters
- Modulators and receivers
- Novel sources based on nonlinearities
- Conclusions

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What are WGM resonators

- Whispering Gallery Modes are electromagnetic resonances that occur in circularly symmetric dielectrics, and trap light in a circling orbit via total internal reflection
- They can be produced in a variety of shapes
- They can be produced in a variety of sizes (10's of mm to μm)
- They can be fabricated from a variety of materials
- They can be made with various fabrication processes

Features of WGM Resonators

- Ultra-high Q allows long optical delays (ns to ms range)
- Ultra-narrow spectral linewidth makes them ideal filters
  - Photonic microwave filters *with microwave signals carried as sidebands on an optical carrier* --- any microwave frequency can be supported
  - Multi-resonator structures with high rejection band (~ 100 dB)
  - Optical filters for signal processing, spectroscopy, laser stabilization, …
- Resonators made using materials with electooptic effect can lead to
  - Tunable filters (optical and microwave) with > 40 GHz tunablity
  - Highly efficient modulators
  - Optical memory using photorefractivity

Applications

- Linear regime
  - Cavity QED
  - “Artificial” atoms and molecules
  - Spectroscopy and materials studies
  - Filters (fixed and tunable; microwave and optical)
  - Modulators
  - Delays
  - Slow light (multi-resonator structures)
- Nonlinear regime
  - Lasers (including Raman lasers) and THz sources
  - OPO

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Whispering Gallery Modes for Spherical Resonators

Whispering Gallery Modes are electromagnetic resonances which occur in circularly symmetric dielectrics. These resonators trap light in a circling orbit via total internal reflection .
The WGM usually is characterized by mode Numbers n, l, and m

is the radial mode number
is the angular mode number
m ***is the azimuthal mode number***

$$\nabla \times (\nabla \times E) + \frac{\varepsilon}{c^2}\frac{\partial^2 E}{\partial t^2} = 0$$

$$(\nabla^2 + k^2)\cdot \vec{e} = 0$$

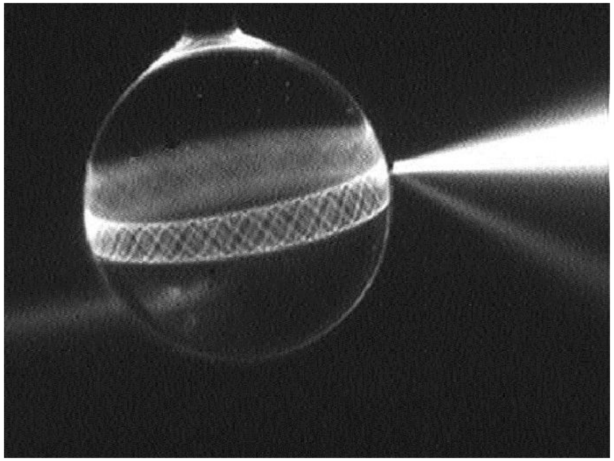
$$e = \sum_{l.m}[R_{TE}(r)Y_l^m(\theta,\phi) + \frac{1}{\varepsilon}\nabla \times (R_{TM}(r)Y_l^m(\theta,\phi))]$$

$$\frac{\partial^2 R}{\partial r^2} + [k^2\varepsilon - \frac{l(l+1)}{r^2}]R = 0$$

$J_{l+1/2}(kr)$ is the solution

$$k_{l,q} = \frac{1}{a\varepsilon_0}\left[l + \alpha_q\left(\frac{l}{2}\right)^{1/3} - \sqrt{\frac{\varepsilon_0}{\varepsilon_0 - 1}} + \frac{3\alpha_q^2}{20}\left(\frac{2}{l}\right)^{1/3} + \ldots\right]$$

$$H_\rho = n(n+1)\frac{\sqrt{k_p\rho}}{\rho^2}J_{n+\frac{1}{2}}(k_p\rho)P_n^m(\cos\theta)\sin(m\phi)$$

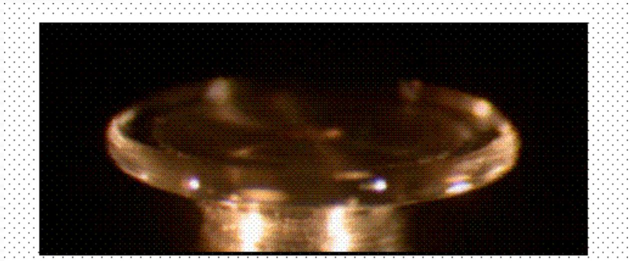


OEwaves

Crystalline WGM resonator

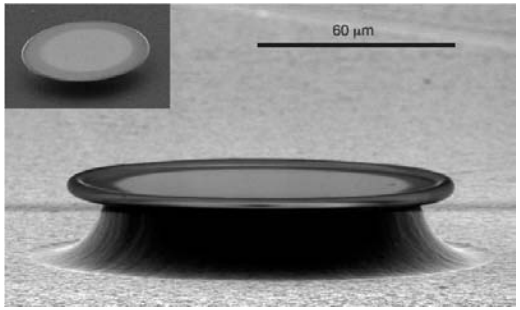
- Extremely high Q (> 10^{11} has been demonstrated at JPL, finesse>10^{7})
  - Long delays (micro seconds)
  - Narrow optical/phtonic filters
  - Reference resonator for laser stabilization
- Small mode volumes for exploring nonlinear effects
  - Second harmonic generation with great efficiency
  - Efficient parametric processes (four-wave mixing, up/down conversion)
  - Entangled photon source
- Crystalline material with electooptic effects
  - Frequency tunability
  - Highly efficient modulators
  - Optical memory using photorefractivity
- Support wide wavelength range (from THz to UV)
  - Unique feature, very different from FP cavity
- Small sizes: ranging from 10's of micron to a few mm
  - Compact
  - Easier for mechanical and thermal stabilization

Types of Whispering Gallery Mode Resonators

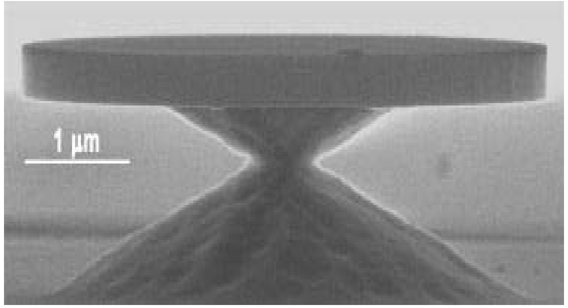


Calcium fluoride resonators that have $Q = 2 \times 10^{10}$.

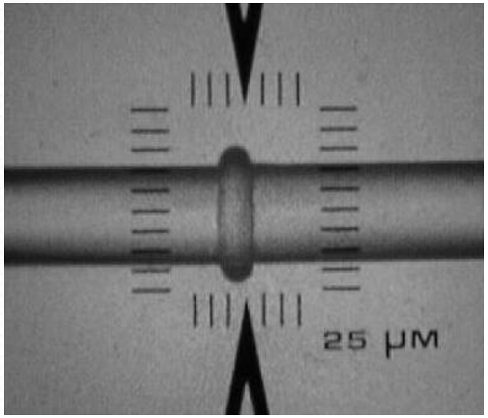
Crystalline disk $Q \sim 3ex10^{11}$
L. Maleki et al, Physical Review A 70, 051804(R) 2004.



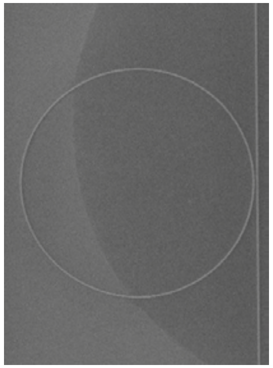
Fused silica microtoroid $q \sim 1 \times 10^{8}$
K. Vahala et al., Nature, vol 421, 27 February 2003 p. 925.



Silicon microdisk, $Q \sim 5 \times 10^{5}$
O.Painter et al. App. Phys.Let. Vol 85 No 17, 25 October 2004



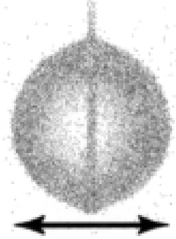
Toroidal resonator fabricated by placing a melting sphere between two fibers



Micro-ring resonators.

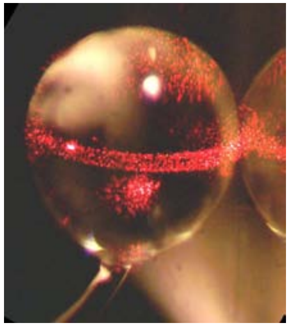
$Q \sim 10^{4}$ to 10^{7}.

R< 100 μm



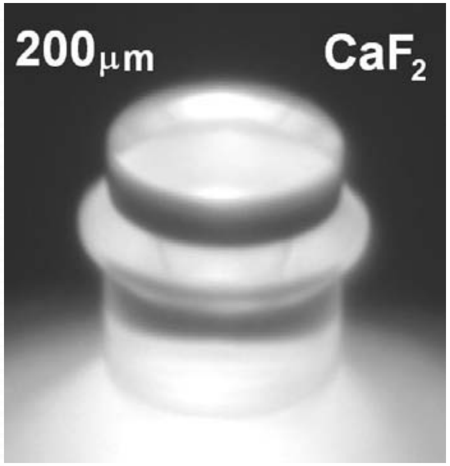
Solid H2, $Q > 10^{9}$

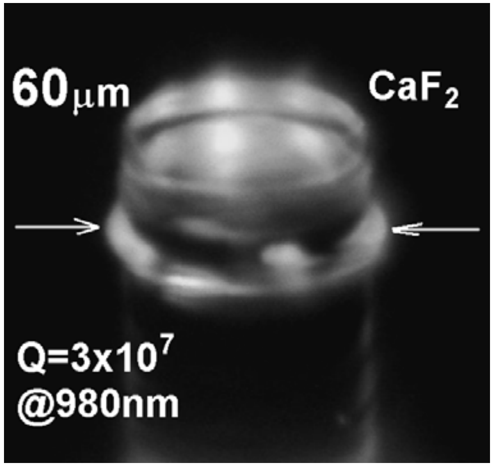
K.Hakuta et al. Opt.Lett.,27 No 6 March 15 2002

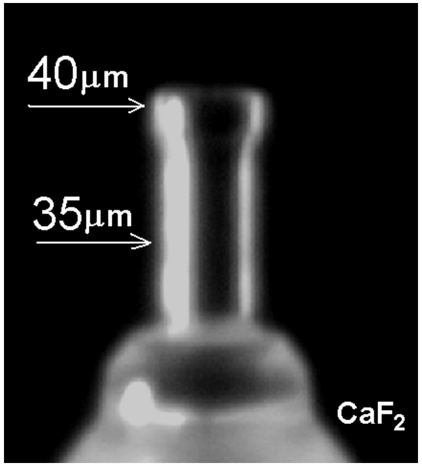


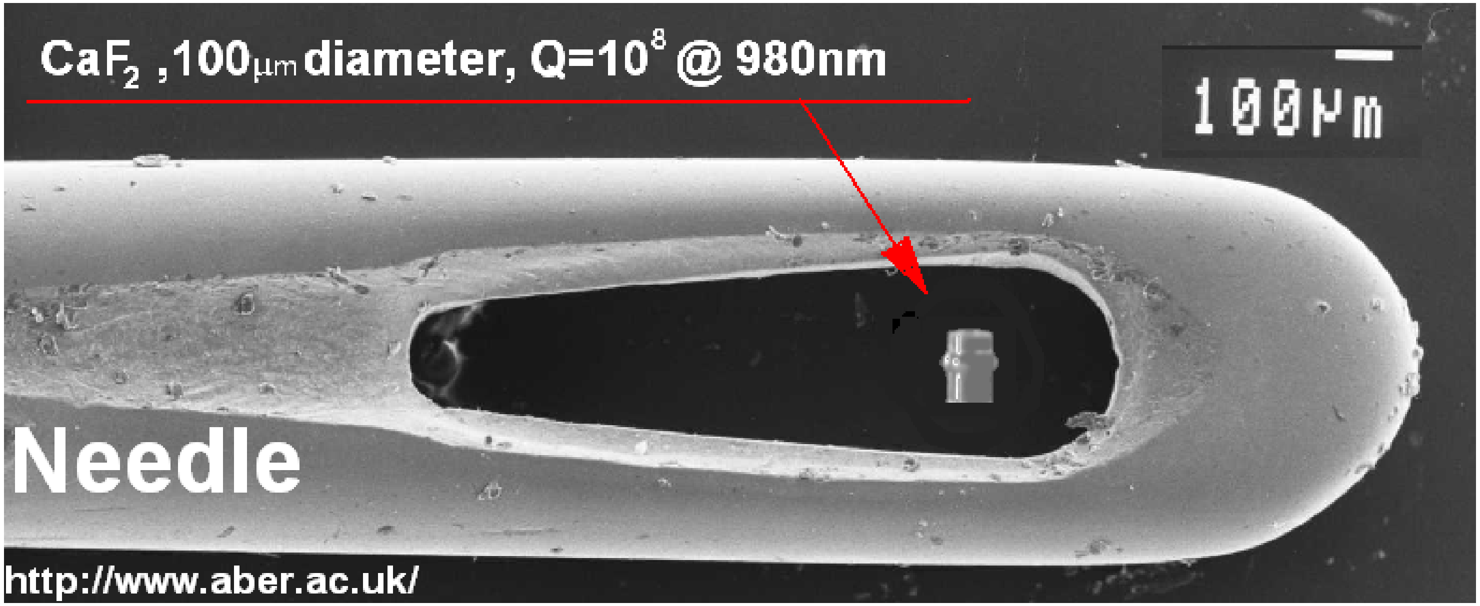
silica microsphere
$Q = 8x10^{9}$

New crystalline ultra-high Q microcavities

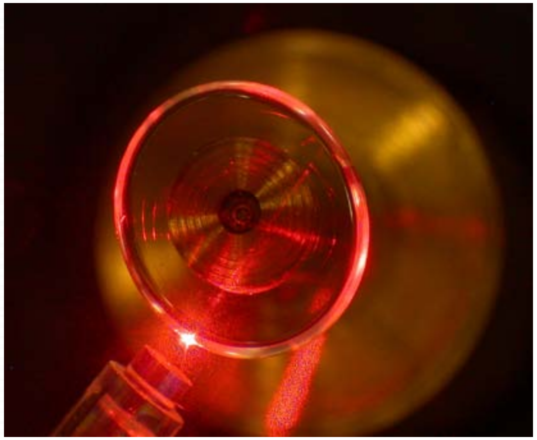




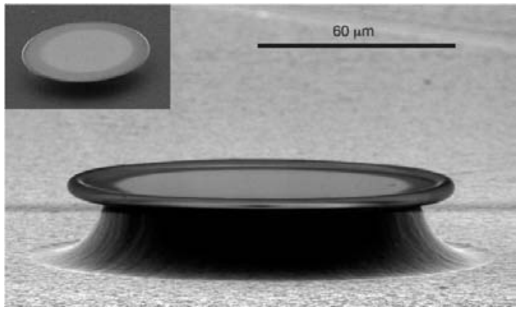




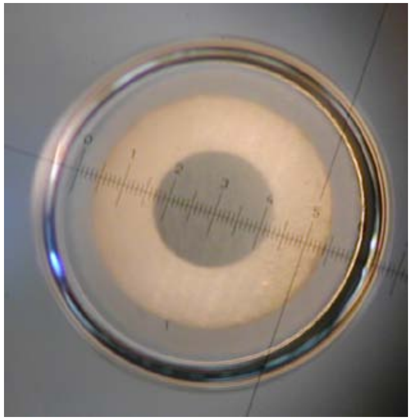
Non-spherical Structures



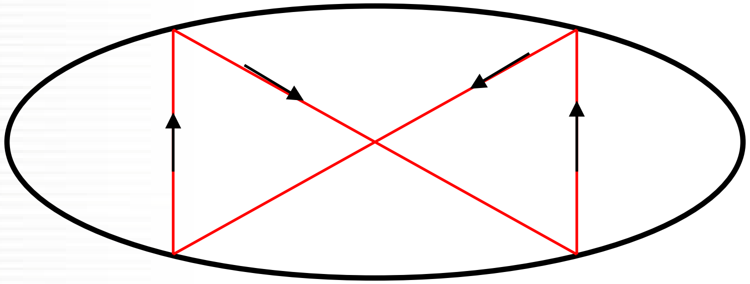
Elliptical Resonators

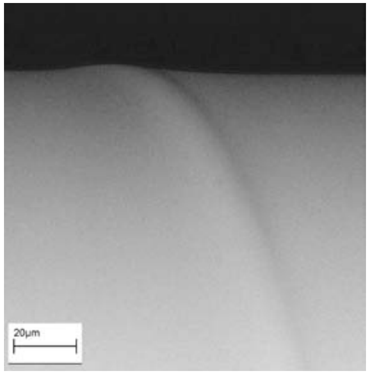


Toroidal Resonators

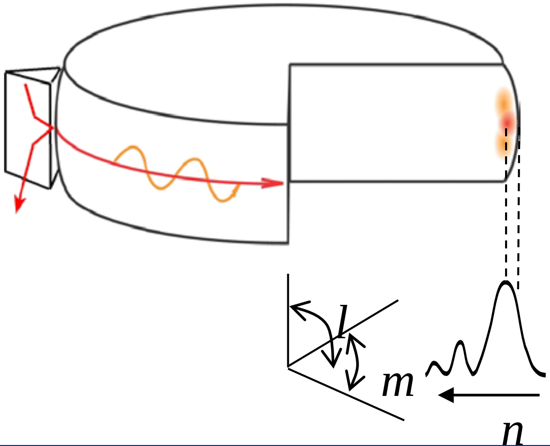


Disk Resonators





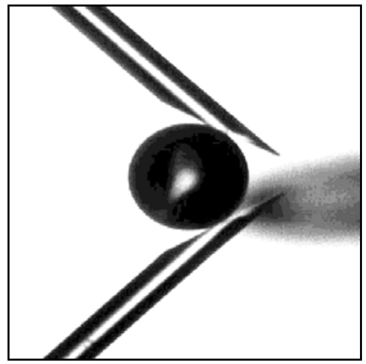
"Rim" Resonators



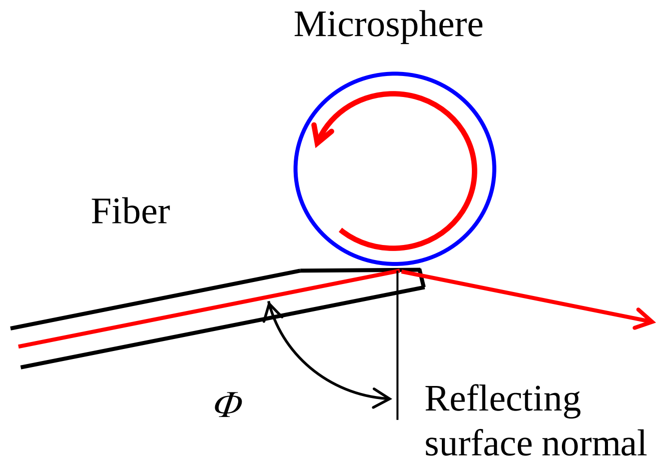
Coupling Schemes

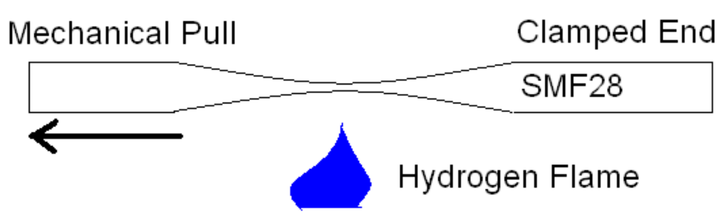
For a resonator with index n surrounded by air, the evanescent height, h, is:

$$h = \frac{1}{k\sqrt{n^2 - 1}}$$



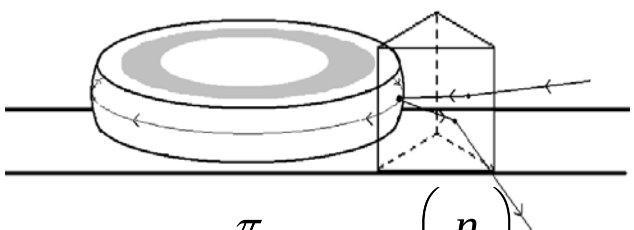
Angled Fiber





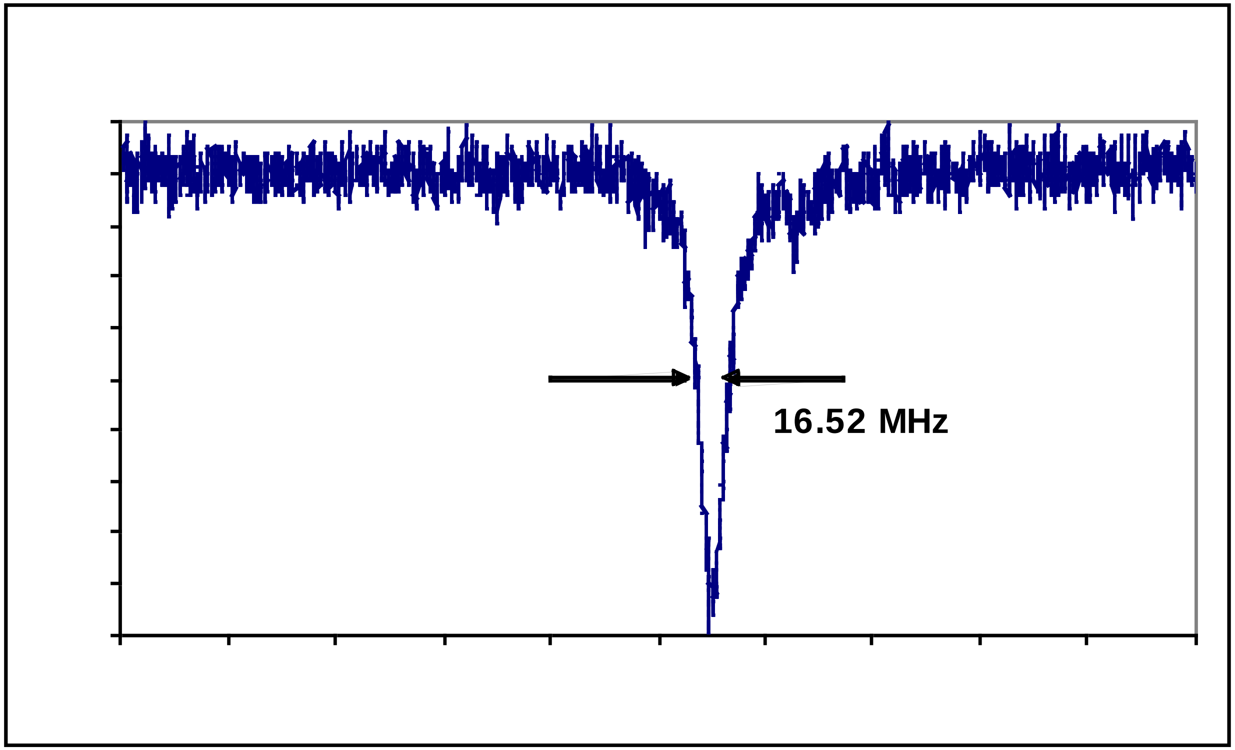
Fiber taper

Prism Coupling



$$\theta_{input} = \frac{\pi}{2} - \arcsin\left(\frac{n}{n_c}\right)$$

Coupling with Low Insertion Loss



With prism coupling and elliptical resonator

Optical Loss Mechanisms

- Linear Loss
  - Radiative : $\alpha_{radiative} = Ae^{-l}$
  - Intrinsic material loss: $Q_{material} = \dfrac{2\pi l}{\alpha_{mateial}\lambda}$
  - Surface loss: $Q_{surface} = \dfrac{\lambda^2 R}{\pi\sigma^2 B}$, σ and B are surface inhmogeneity parameters.

$$Q^{-1} = Q_{rad}^{-1} + Q_{surface}^{-1} + Q_{material}^{-1}$$

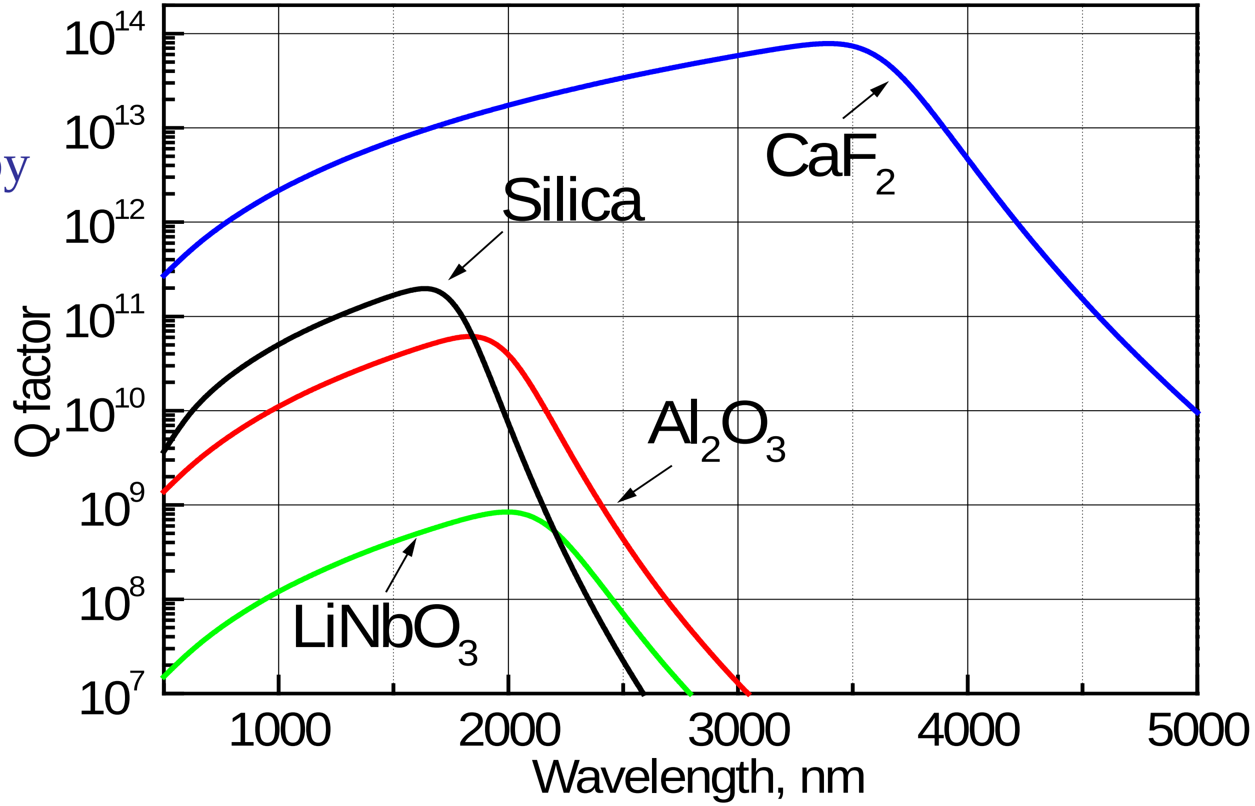
- Nonlinear Loss
  - SRS, FWM, Parametric processes

Calculated values for achievable Q's

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

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

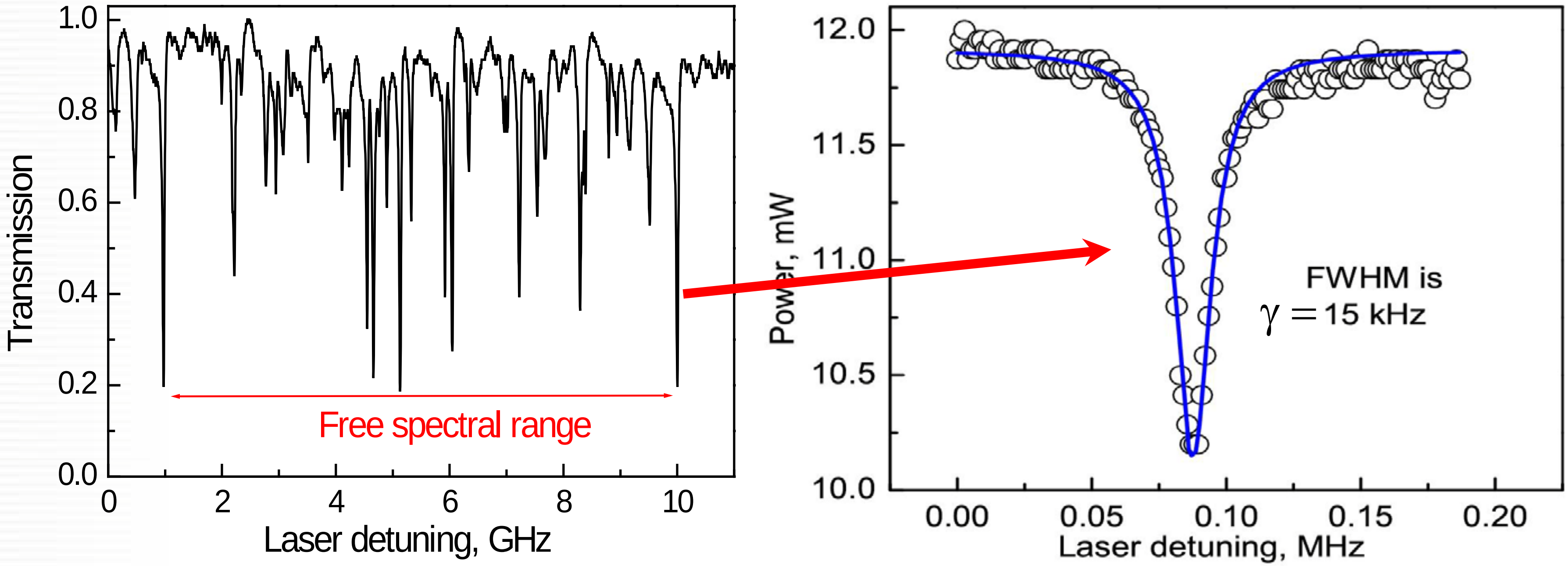
=> $$Q = \frac{2\pi n}{\alpha\lambda}$$



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

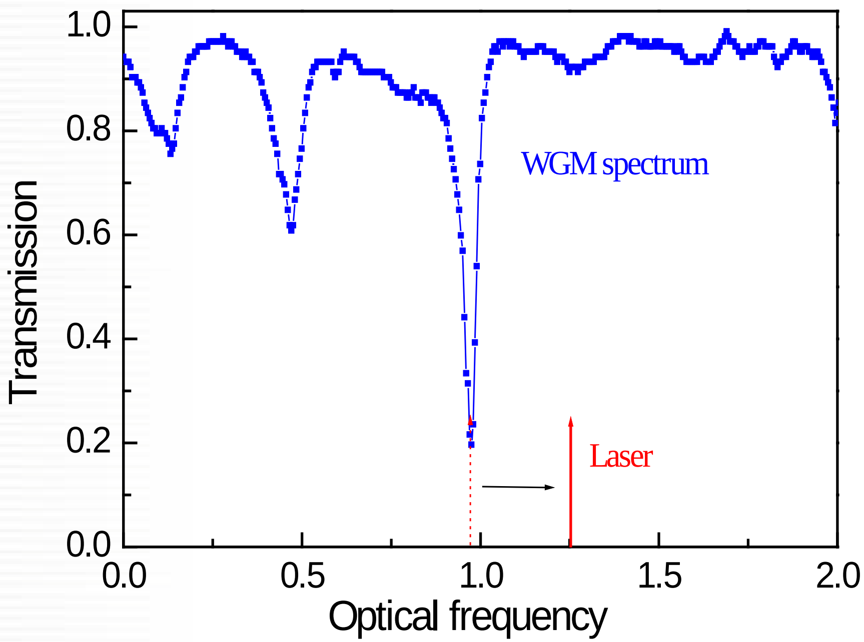
Typical WGM spectra

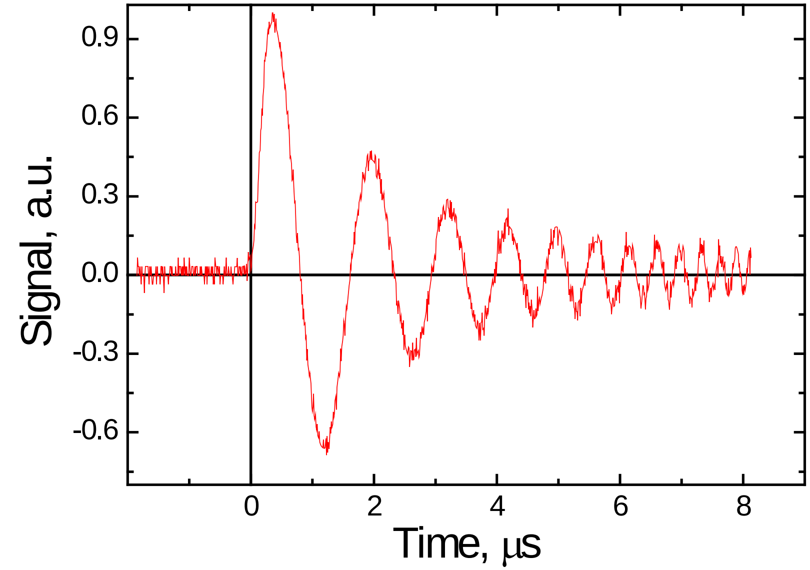


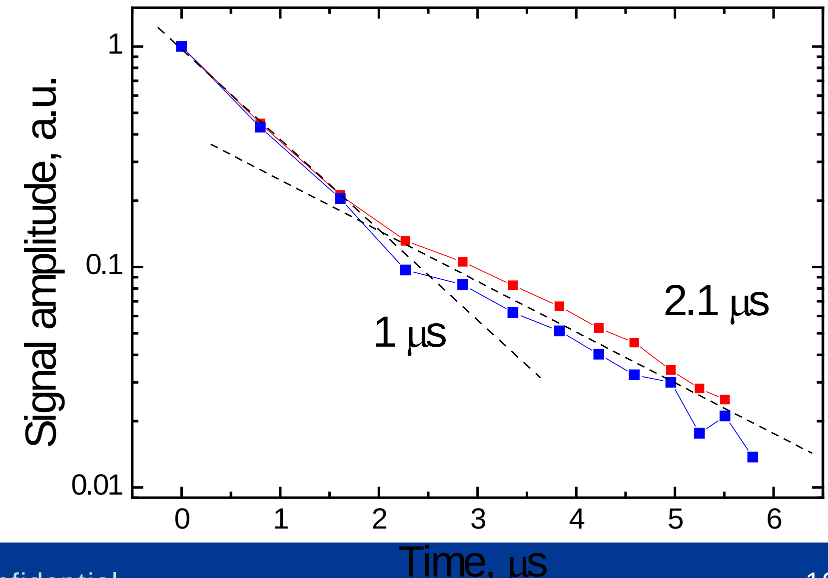
$Q = \omega/\gamma$ $> 2 \times 10^{10}$ Fluorite
$> 4 \times 10^{8}$ $LiNbO_3$

$F = \Omega_{FSR}/\gamma$ $\sim 6 \times 10^{5}$

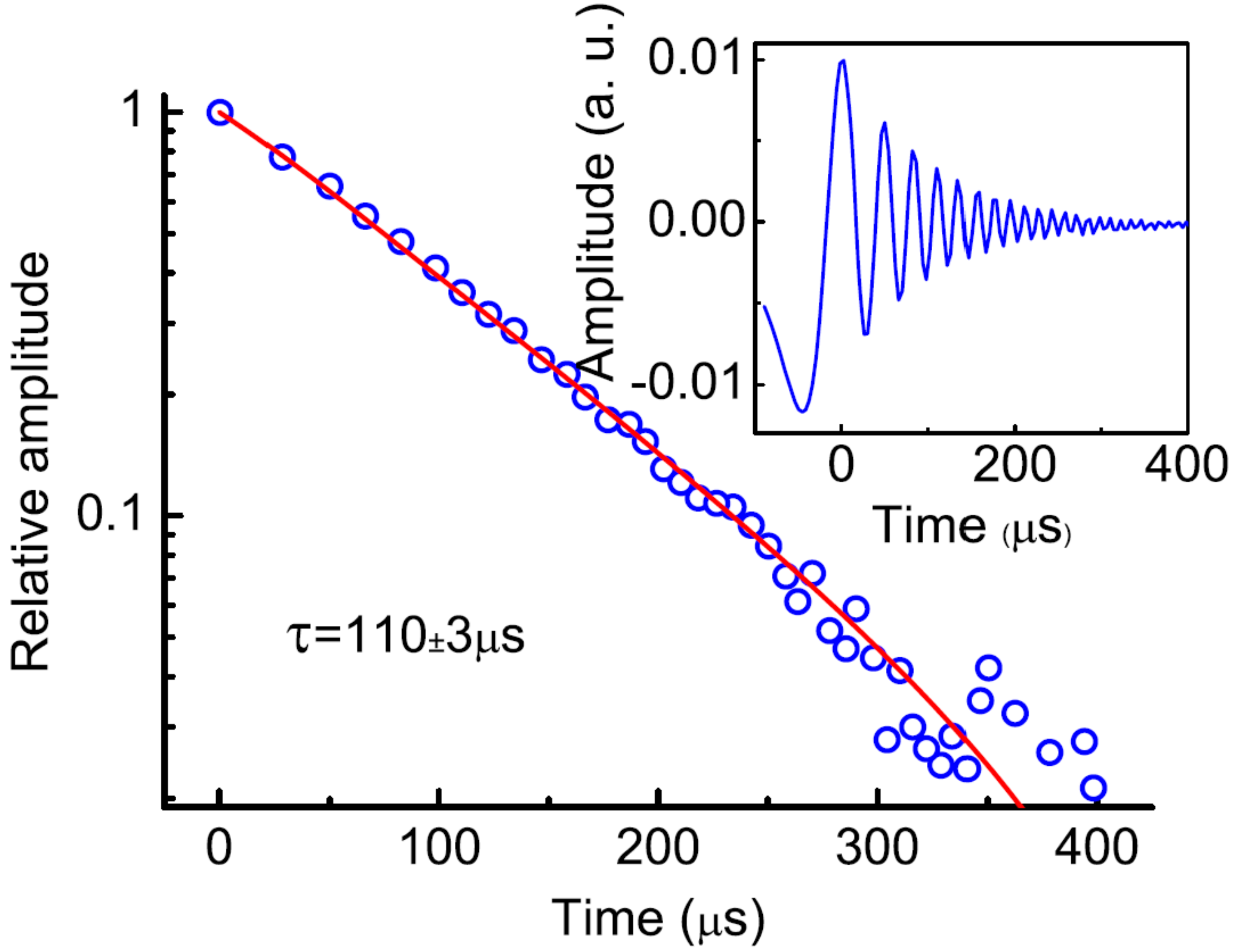
The ring-down measurement of a fluorite WGM resonator life time



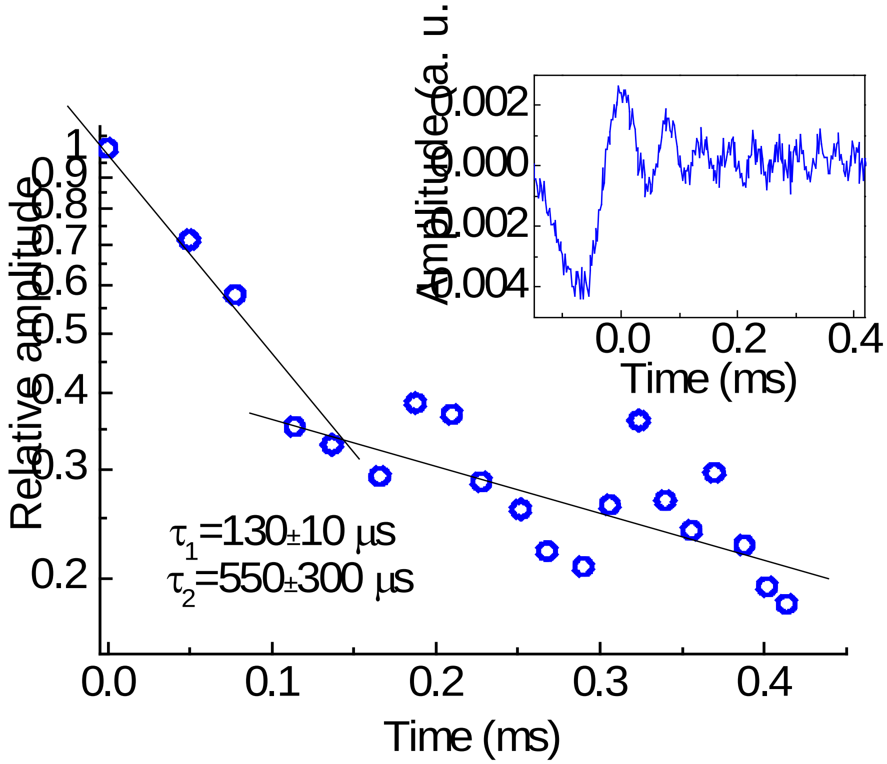




Response of the CaF2 resonator above the threshold



Record Q



Equivalent Q ~ 3 x 10^{11}; Δf = 660 Hz!

Measured Qs

	775nm	1064nm	1319nm	1550nm
α-Al_2O_3	$8x10^7$		$1.5x10^9$	
Quartz				$5x10^9$
SLN	$7x10^7$	$8x10^7$	$2x10^8$	$6x10^8$
SLT	$7x10^7$		$2x10^8$	$2x10^9$
Fused Silica	$8x10^9$			
MgF_2			$>10^{10}$	
CaF_2	$>6x10^{10}$	$>6x10^{10}$	$>4x10^{10}$	$3x10^{11}$

Important Resonator Parameters

Q

Cavity field build-up factor and linewidth

V

Small size and optical energy density

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

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

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)]

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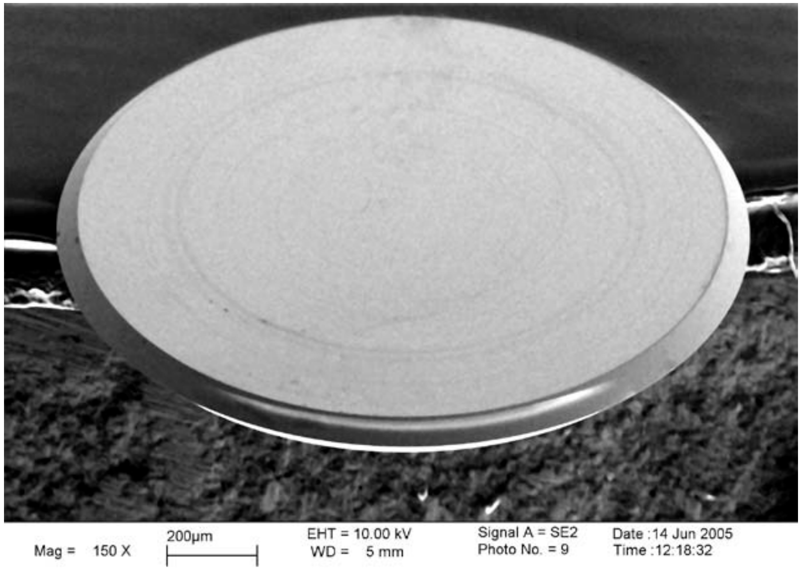
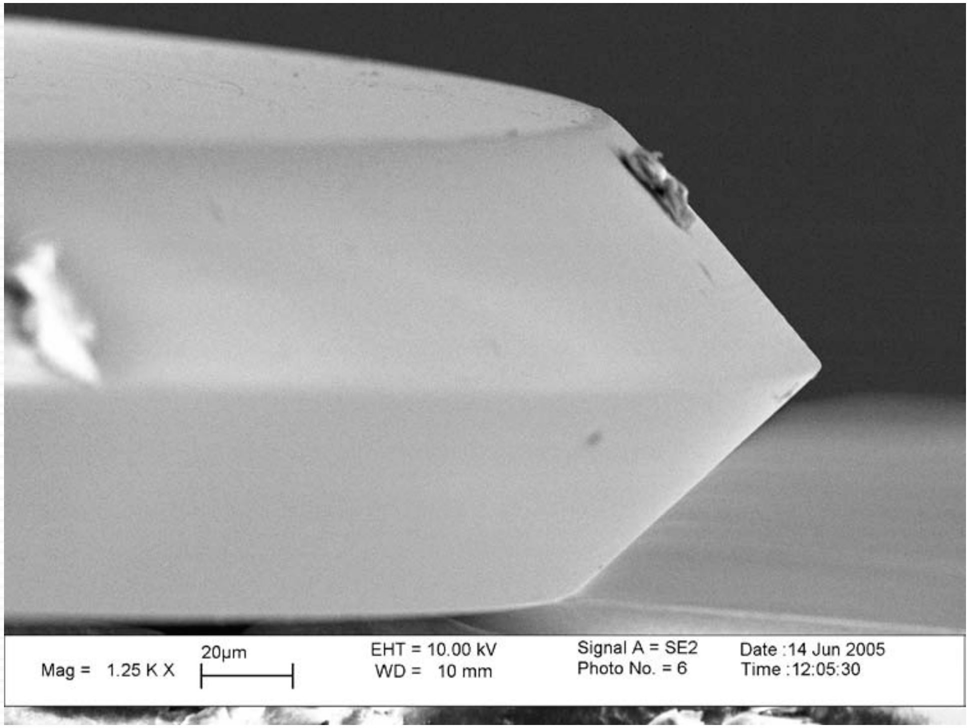
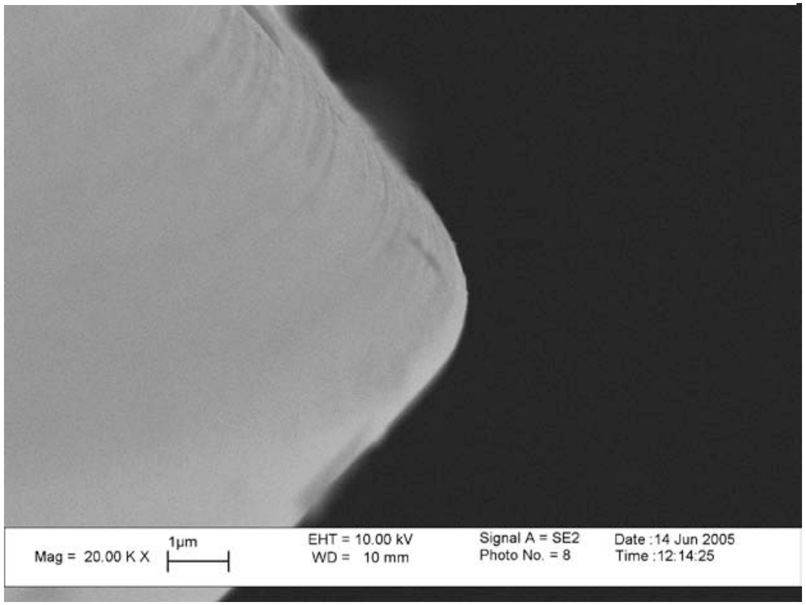
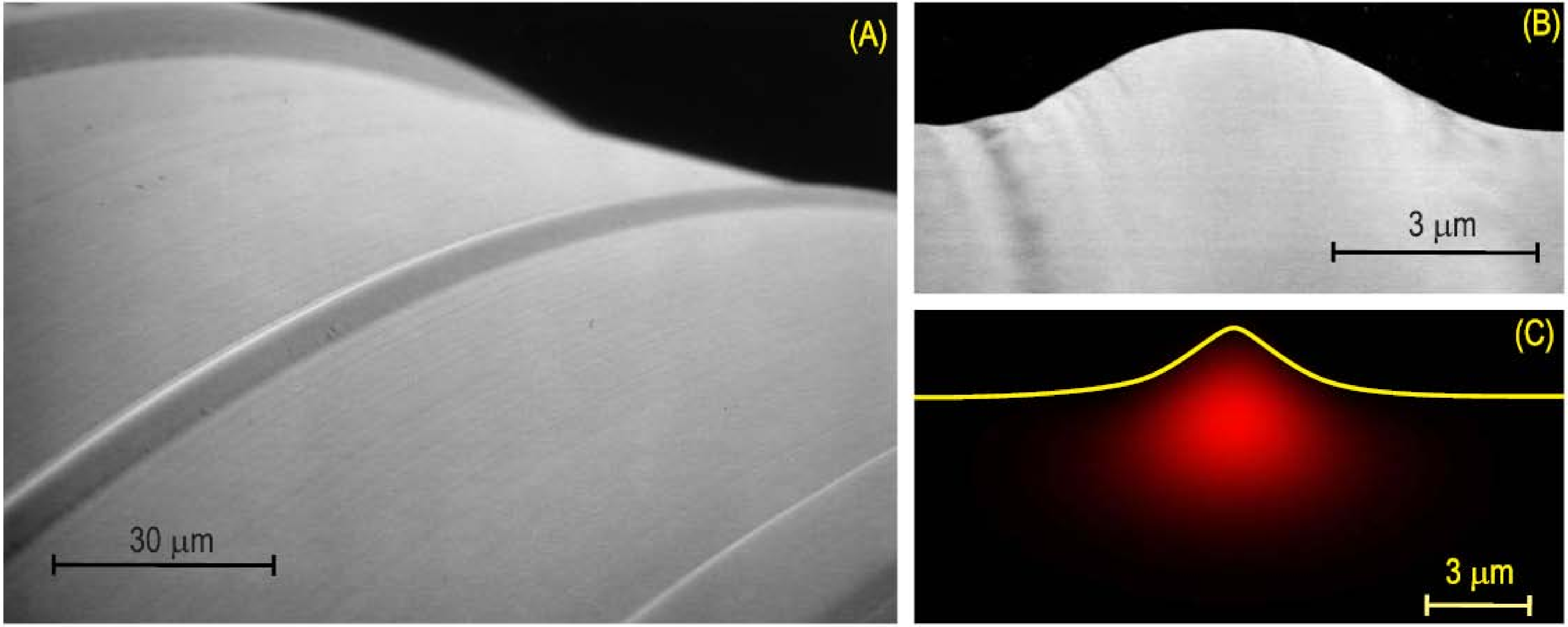
Frequency spectrum and mode volume can be engineered by design of the resonator profile



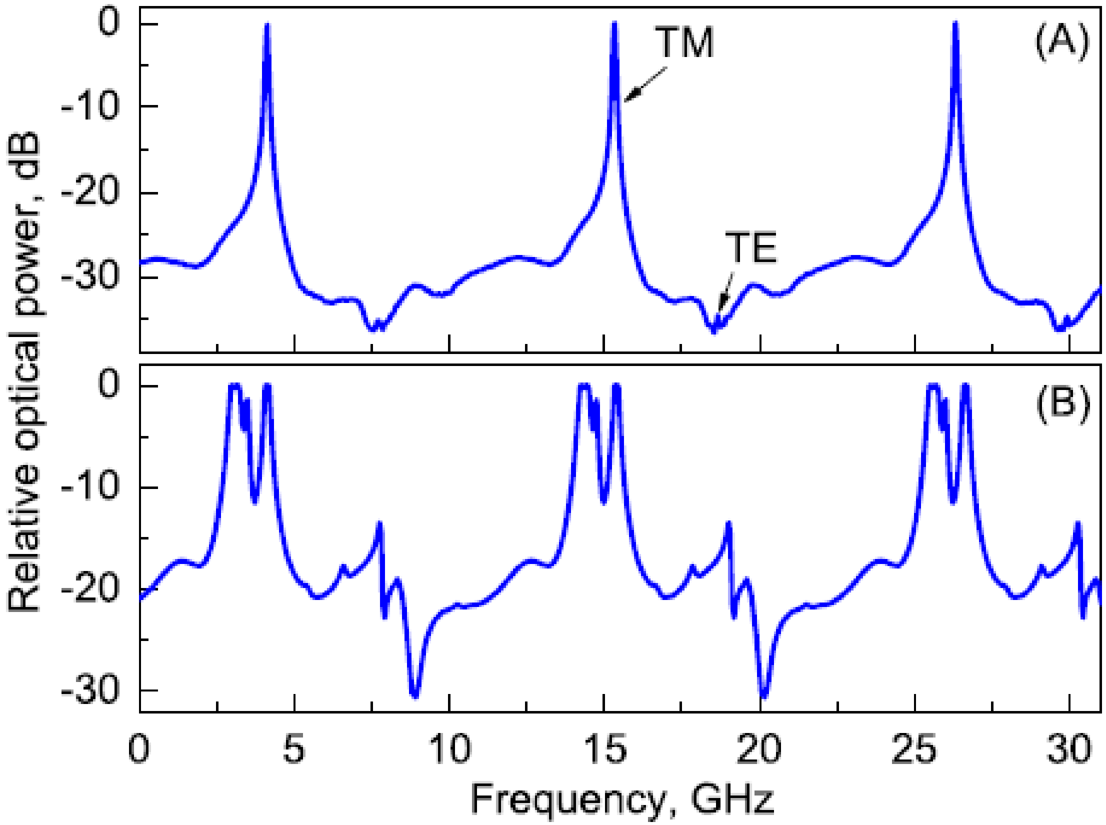




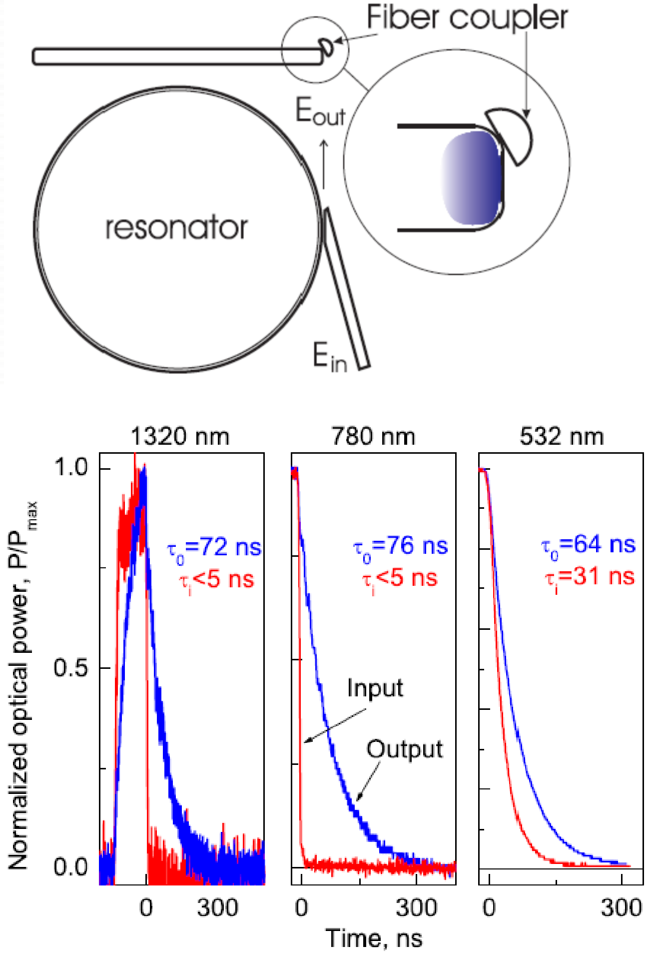
Single mode WGM resonators

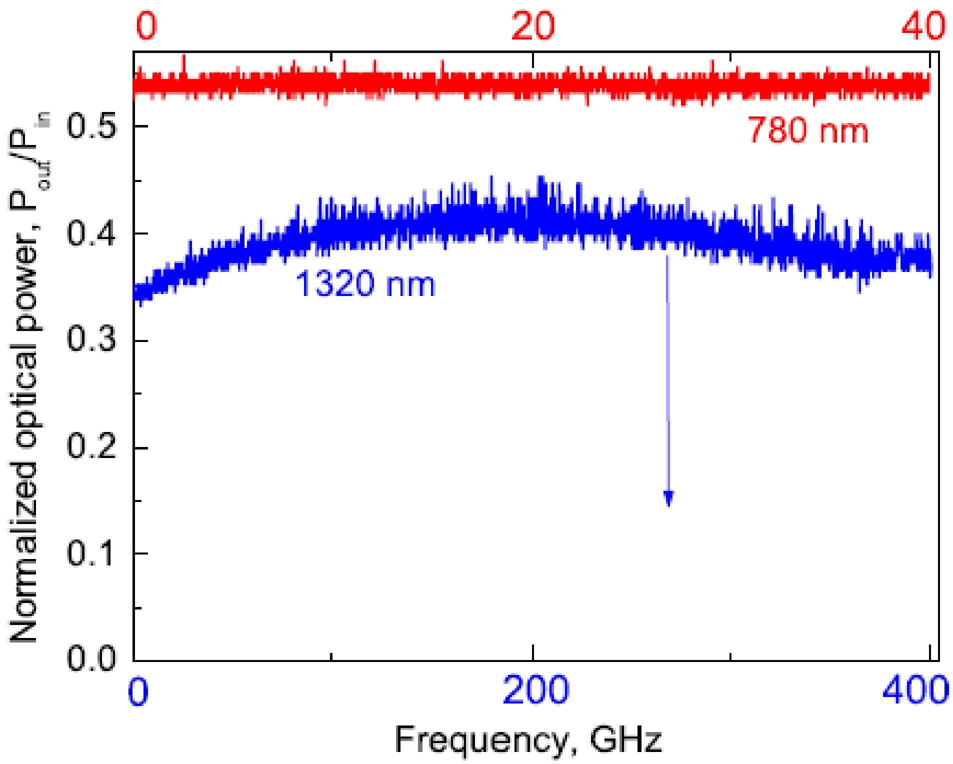


More on single mode WGM resonators: true single mode spectrum

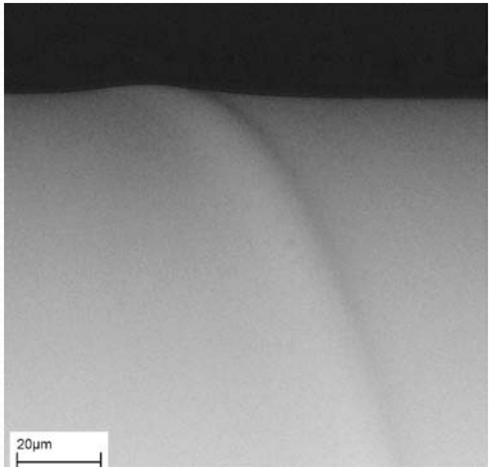


White light WGM resonators



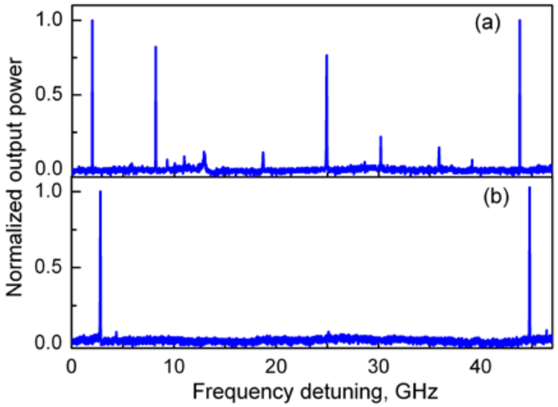


Novel configuration of whispering gallery mode resonators

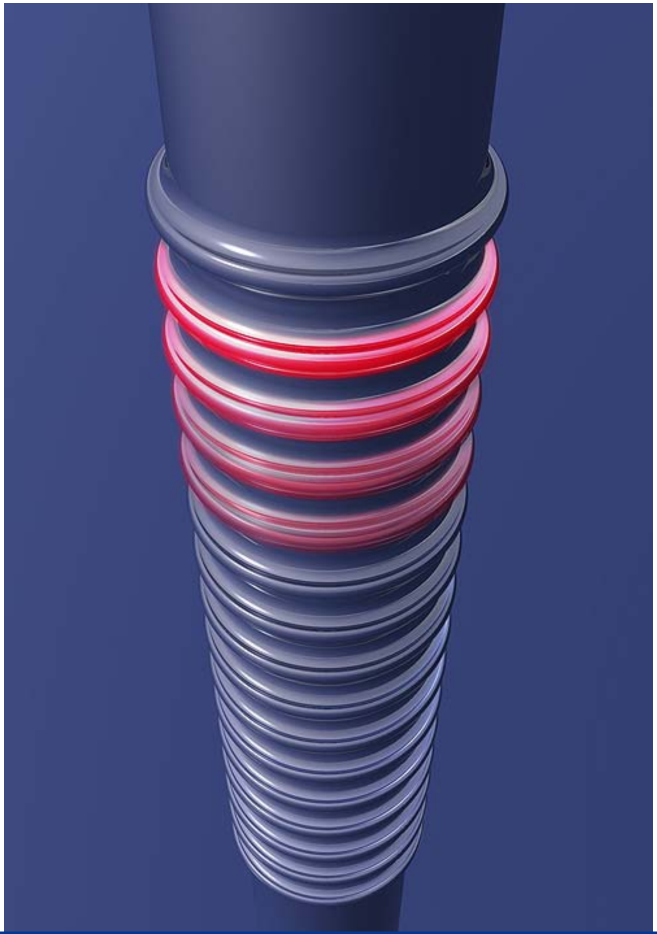


STM picture of a single mode resonator being a “rim” over a multimode wave guide

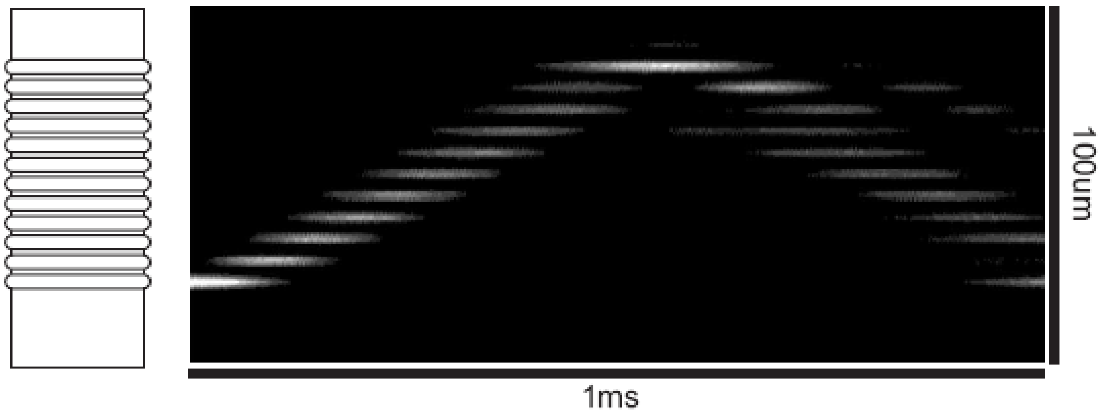
$$\varepsilon = \varepsilon_0 \left(1 + \frac{2L(z)}{R_0} \right)$$



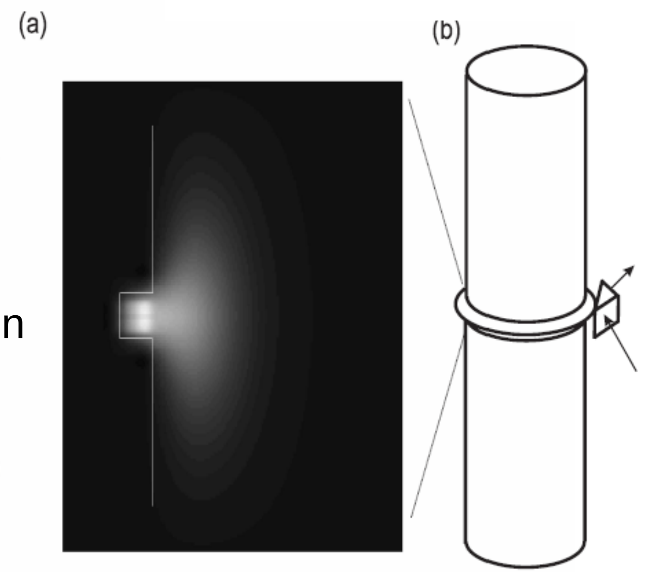
(a) After diamond turning
(b) After proper tune-up



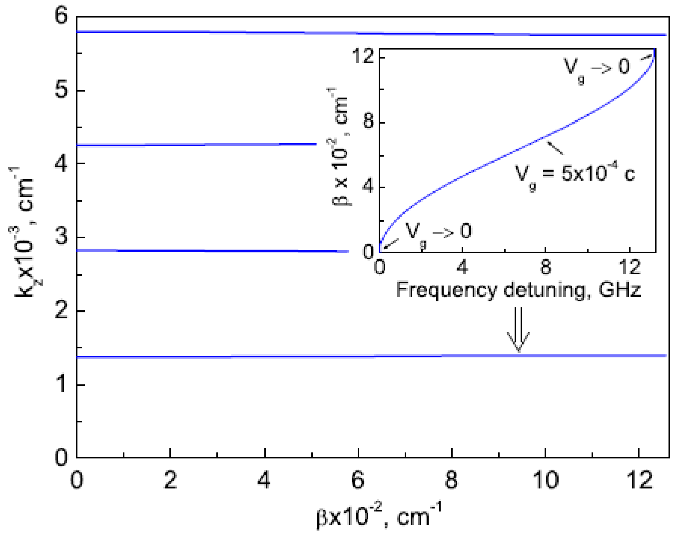
Delay line with coupled resonators



Field distribution



Band structure



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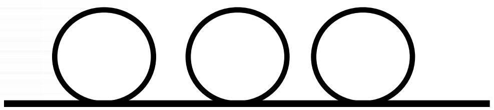
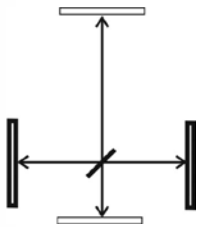
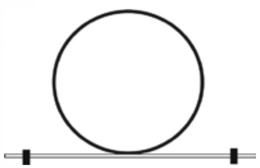
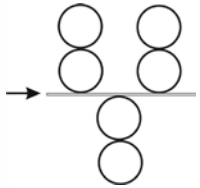
Coupled resonator systems









- “Slow light” and SCISSOR solitons

J. Heebner and R. Boyd, JOSA B 19, 722 (2002) and

J. Mod.Opt. 49, 2629 (2002).

- Coupled cavities for enhancing cross-phase modulation in EIT

T. Opatrny and D. Welch, Phys. Rev. A 64, 023805 (2001)

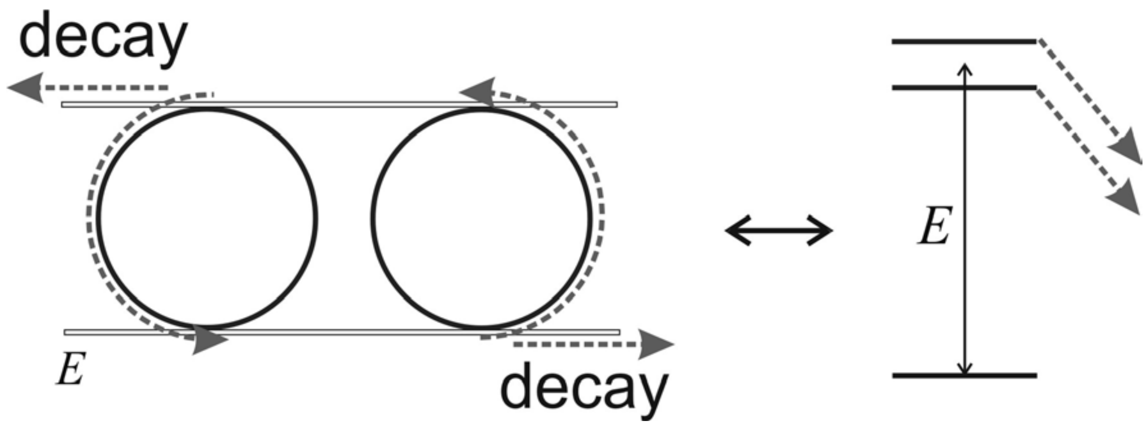
- Sharp asymmetric line shapes in side coupled waveguide-cavity systems

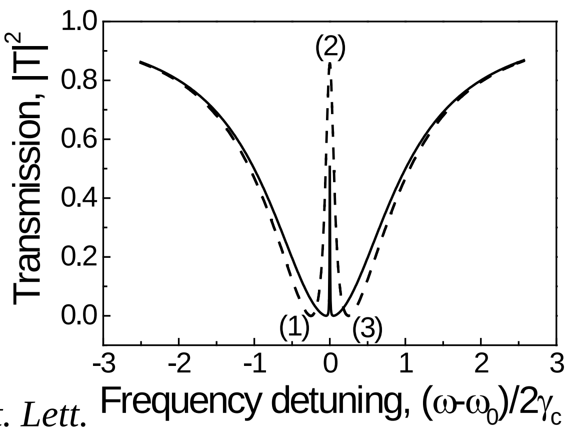
S. Fan, Appl. Phys. Lett. 80, 908 (2002).

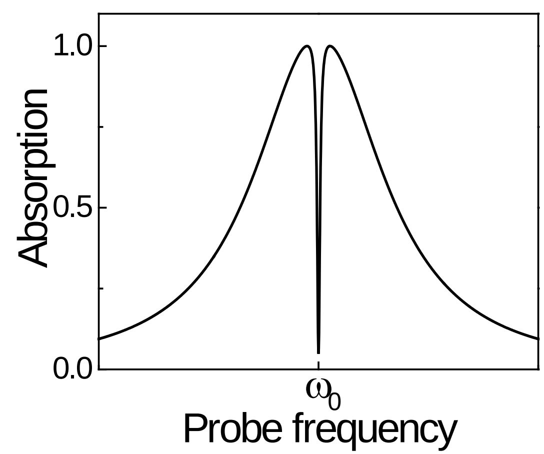
- Storing light all optically

M. Yanik and S. Fan, quant-ph/0312027 (2003).

An analogy with EIT in quantum systems: interference of decays

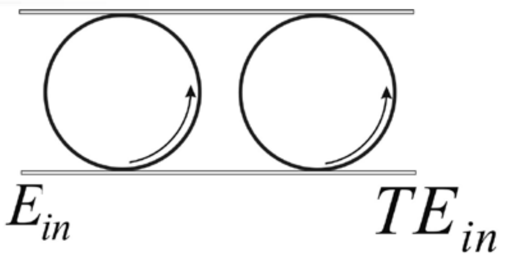


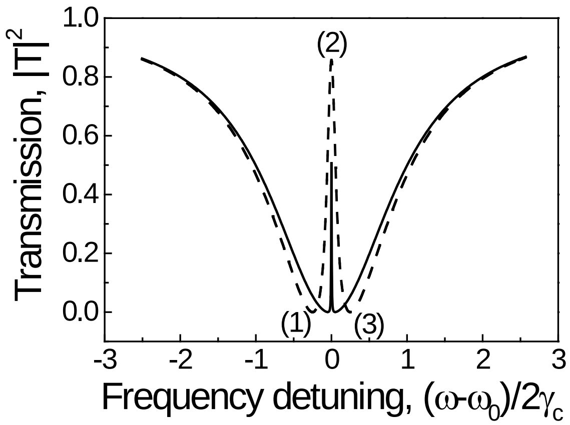




L.Maleki et al., Opt. Lett. 29, 626 (2004)

"EIT" in a system of two coupled resonators





The width of the transparency resonance (2) depends on the resonators' frequencies

$$\Gamma \approx \frac{\left[4\gamma\gamma_c + (\omega_1 - \omega_2)^2\right]^2}{4\gamma_c(\omega_1 - \omega_2)^2},$$

$$(\omega_1 - \omega_2)^2 \geq 4\gamma\gamma_c$$

$$T = \frac{[\gamma + i(\omega - \omega_1)][\gamma + i(\omega - \omega_2)]}{[2\gamma_c + \gamma + i(\omega - \omega_1)][2\gamma_c + \gamma + i(\omega - \omega_2)] - 4e^{i\psi}\gamma_c^2}$$

$$T_1 = T_3 = \frac{\gamma^2}{4\gamma_c^2}, \qquad T_2 = \frac{(\omega_1 - \omega_2)^4}{\left[4\gamma\gamma_c + (\omega_1 - \omega_2)^2\right]^2}$$

$$\omega_0 = \frac{\omega_1 + \omega_2}{2}$$

γ_c Is the linewidth due to loading of the resonators

γ Is the linewidth due to absorption of the material

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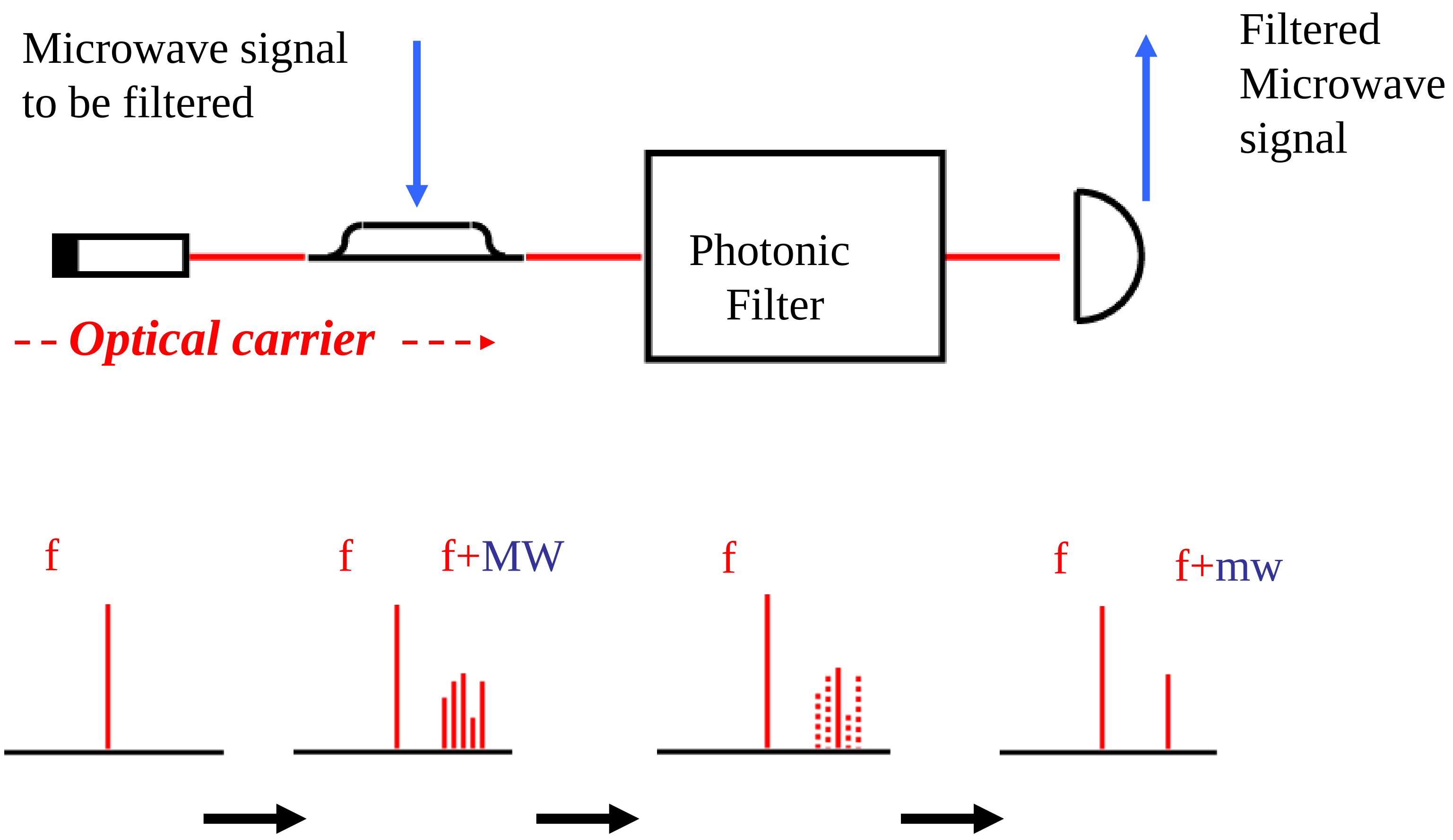
Outline

- Introduction
- Fundamentals of crystalline WGM resonators
- Spectrum engineering
- Filters
- Modulators and receivers
- Novel sources based on nonlinearities
- Conclusions

WGM Filters

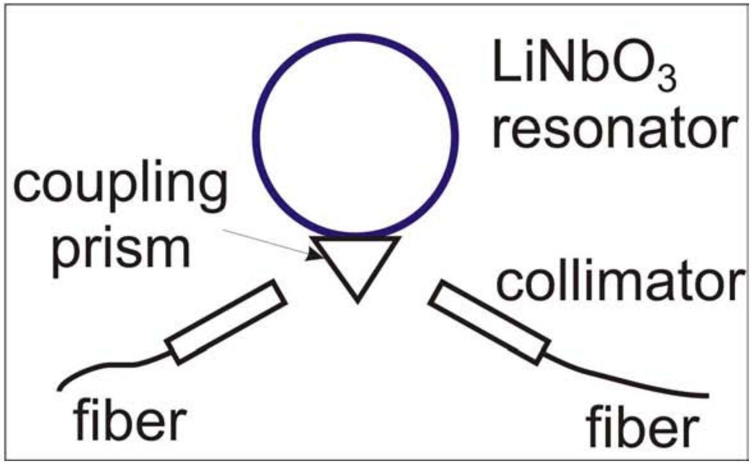
- WGM filters are a powerful new tool for photonic processing of RF signals and enable new capabilities
- WGM tunable filters offer wide tunability range with sub-microsecond tuning speed
- OEwaves has demonstrated single and multi-pole filters with tunability exceeding 12 GHz; fast tuning speed has been demonstrated with measurement of waveform

Photonic filters



Lithium Niobate Whispering Gallery Mode Resonators in optical frequency domain

Photograph of 1 mm size WGM resonator disk



Optical coupling scheme for the disk resonator

Features:

- Large quality factor → $Q = 8\times10^{8}\ at\ \lambda = 1550\,nm$
- Large electro-optical tuning range: 20 GHz per 150 V
- Insertion loss: 2-7 dB
- Small size: 0.1-12 mm

$$Q = 8\times10^{8}\ at\ \lambda = 1550\,nm$$

$$Q = 2\times10^{8}\ at\ \lambda = 1310\,nm$$

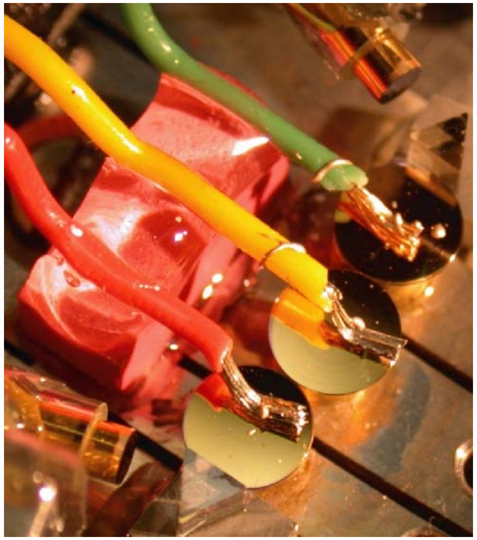
$$Q = 8\times10^{7}\ at\ \lambda = 1064\,nm$$

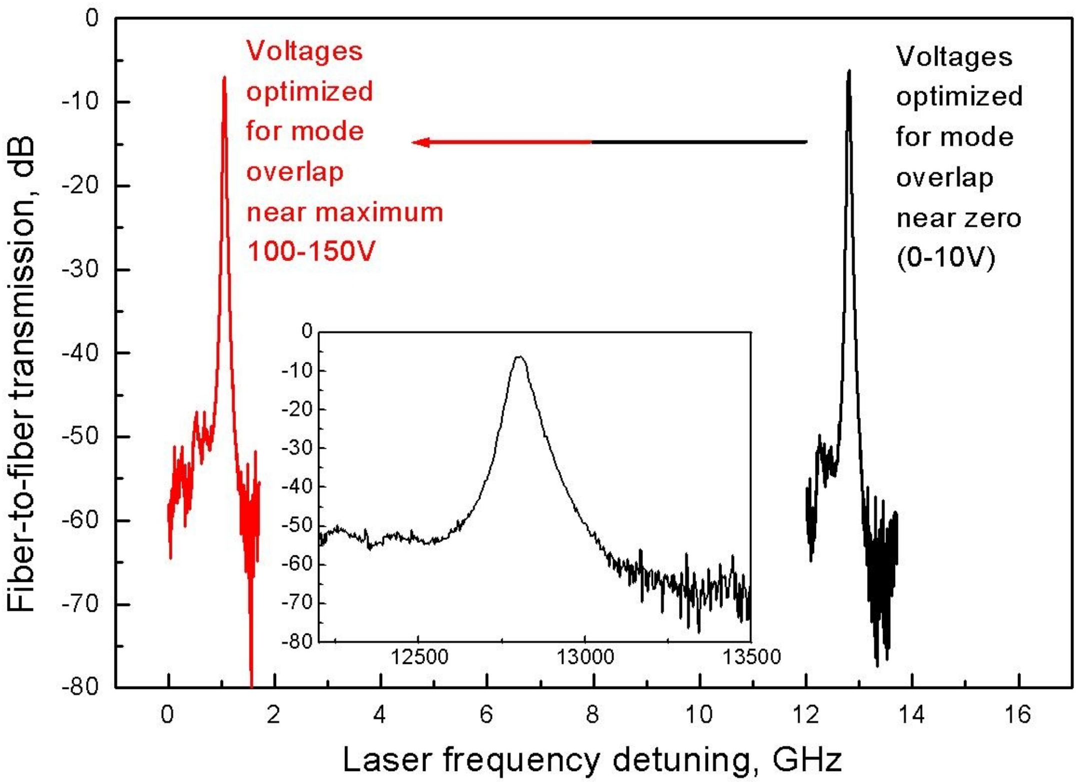
$$Q = 7\times10^{7}\ at\ \lambda = 780\,nm$$

Tri-pole tunable filter prototype

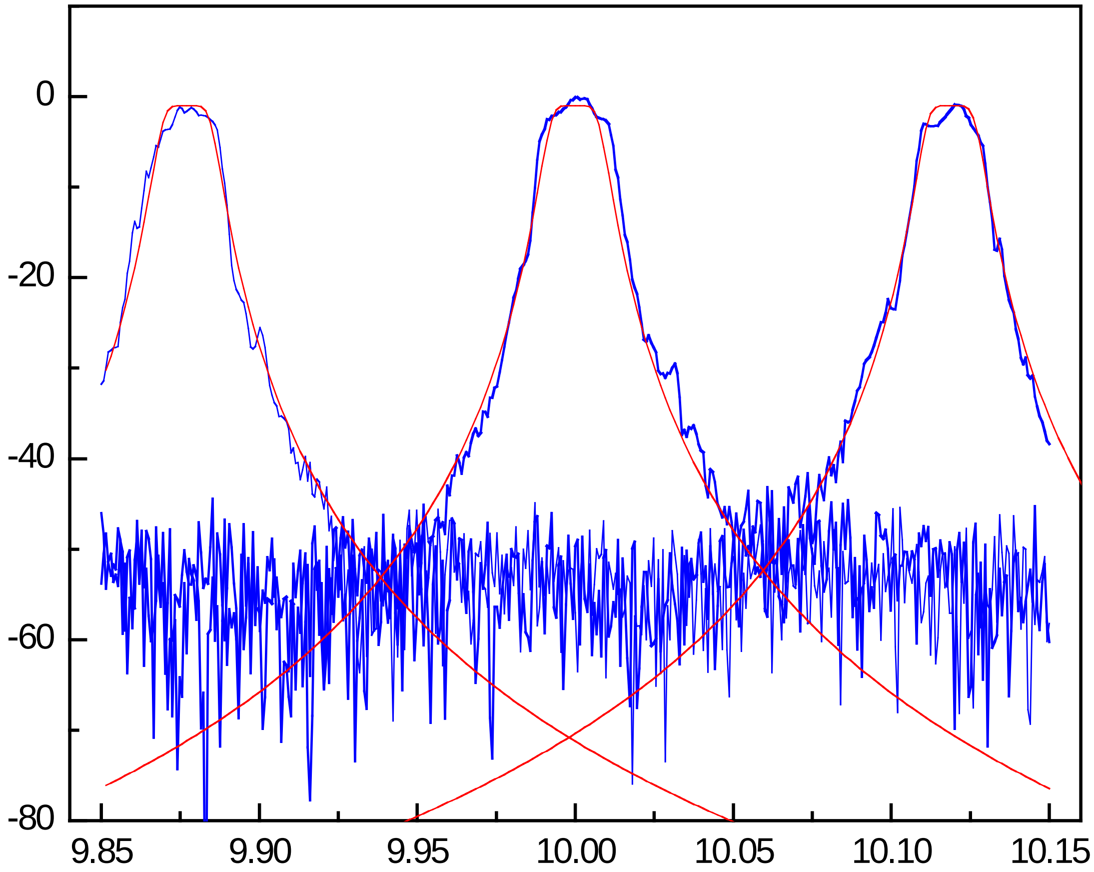
Characteristic third order filter function and 12 GHz tuning

3-pole tunable filter

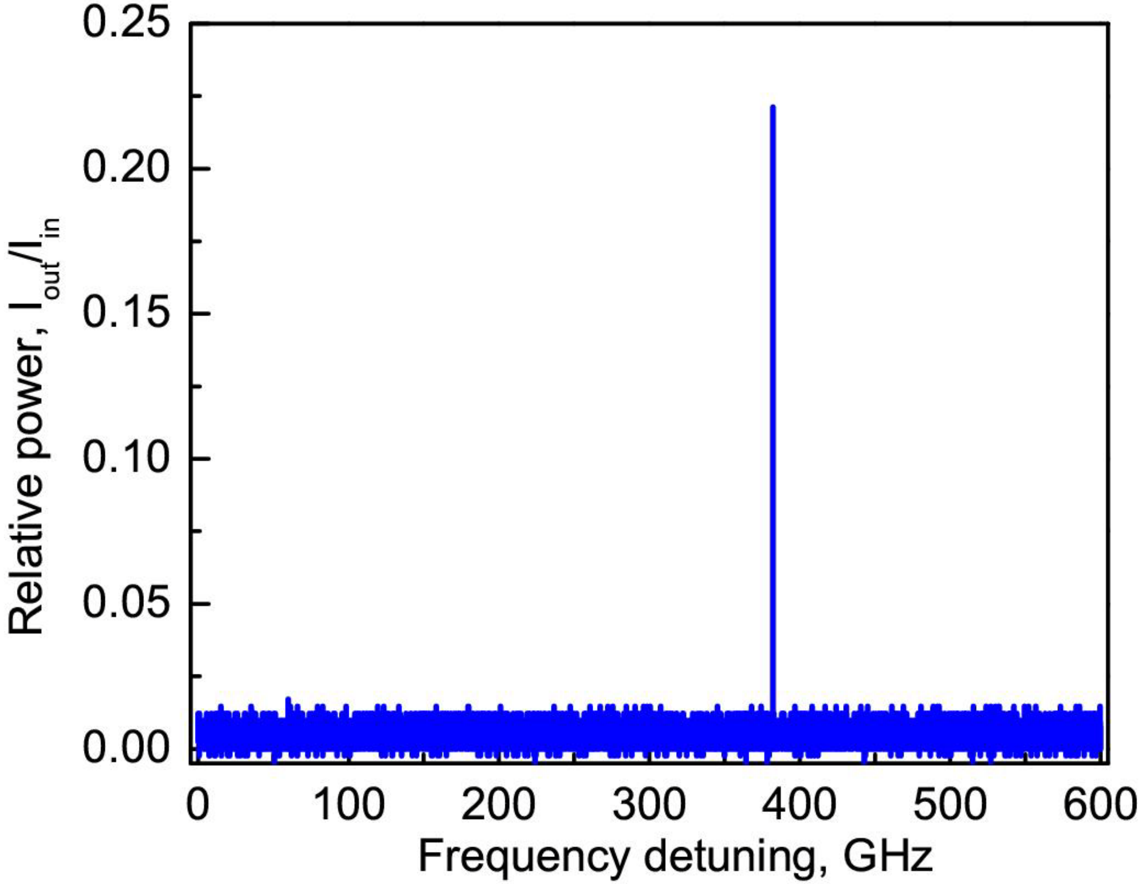




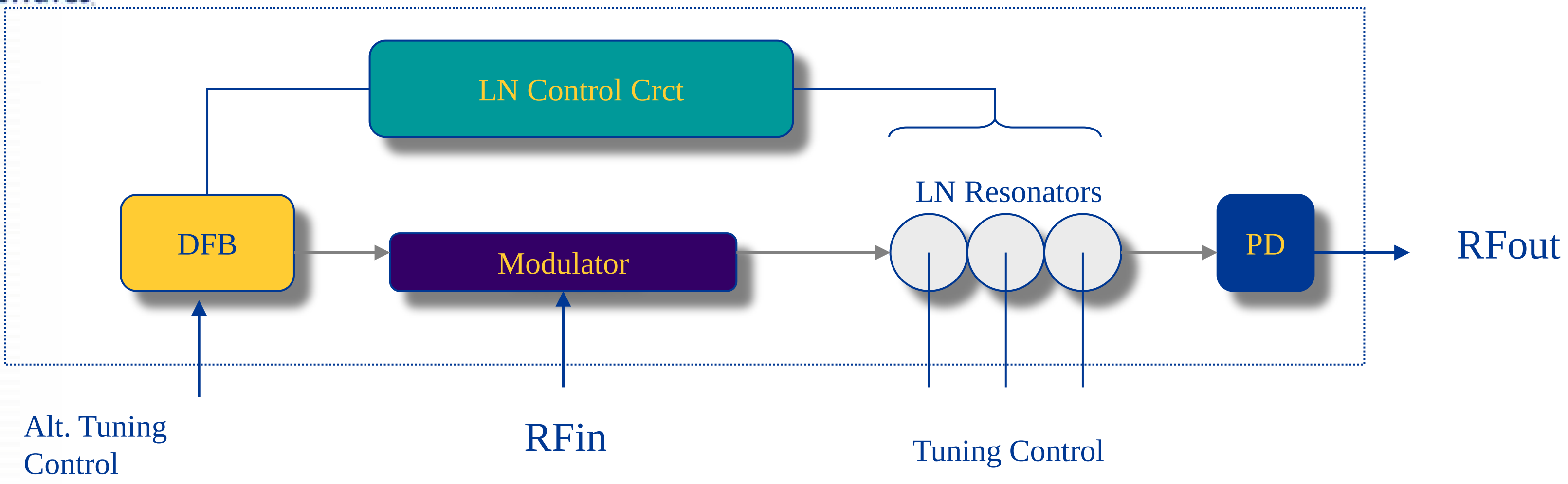
Tri-pole Filter Data (close-up)
Full X-band Tuning is Achieved (8-12GHz)

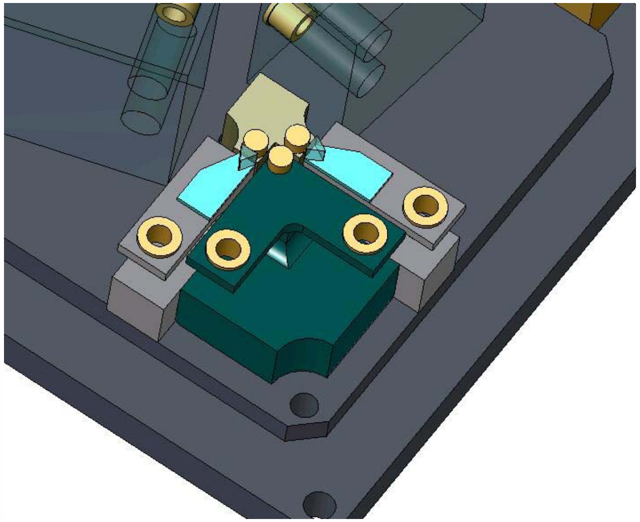


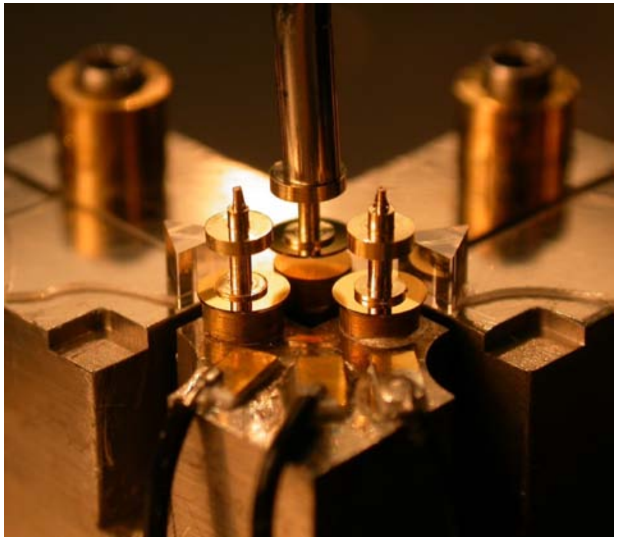
Single mode "Vernier"



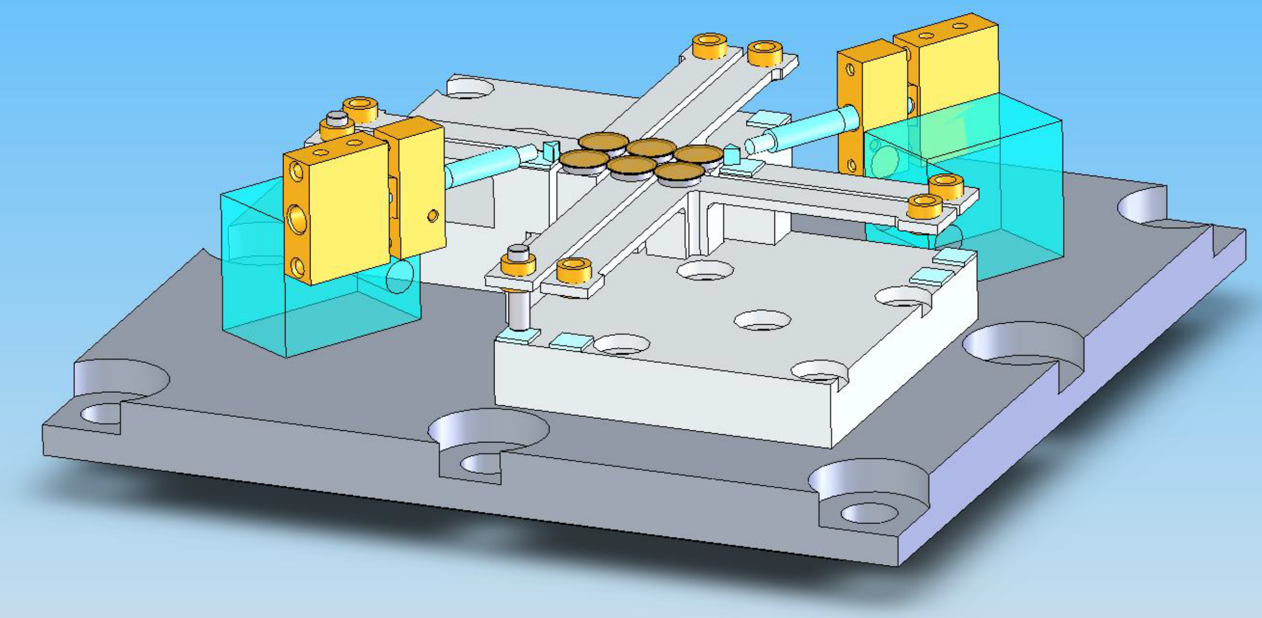
Tri-Pole Filter Architecture of AOSP Phase II







Orthogonal Flexture-based Mechanical Design of Six-pole Optical Filter (AOSP)



- *Independent mech. trimming of all couplings*
- *Improved linearity and stability*
- *Tap coupler/PD at third resonator for alignment*

Outline

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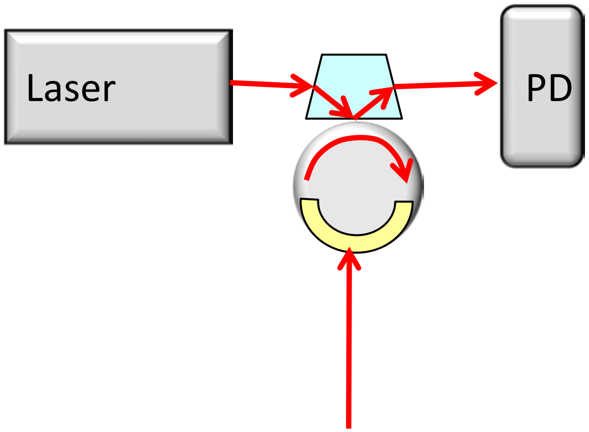
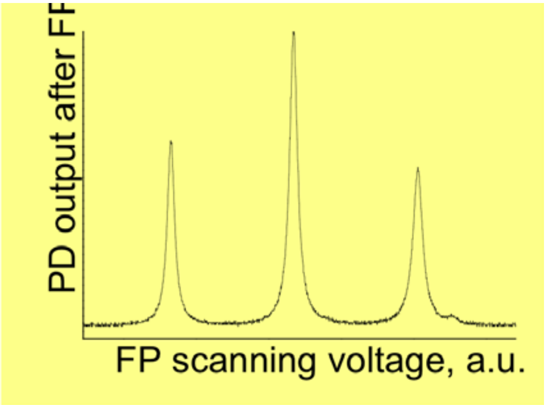
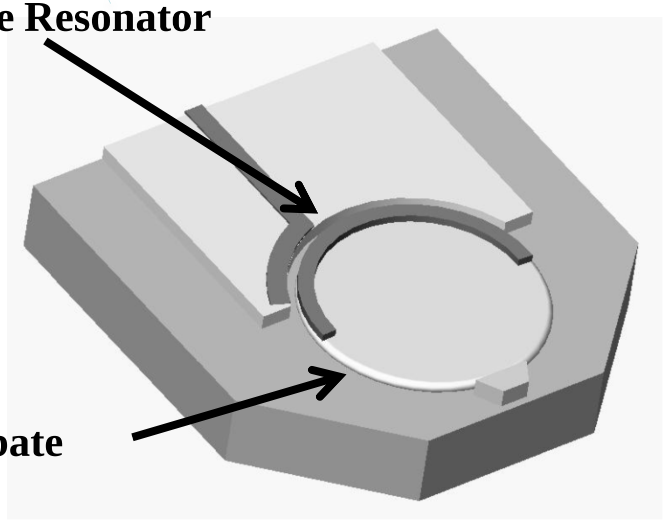
WGM based EOM

The carrier and sidebands have the same polarization





Microwave Resonator



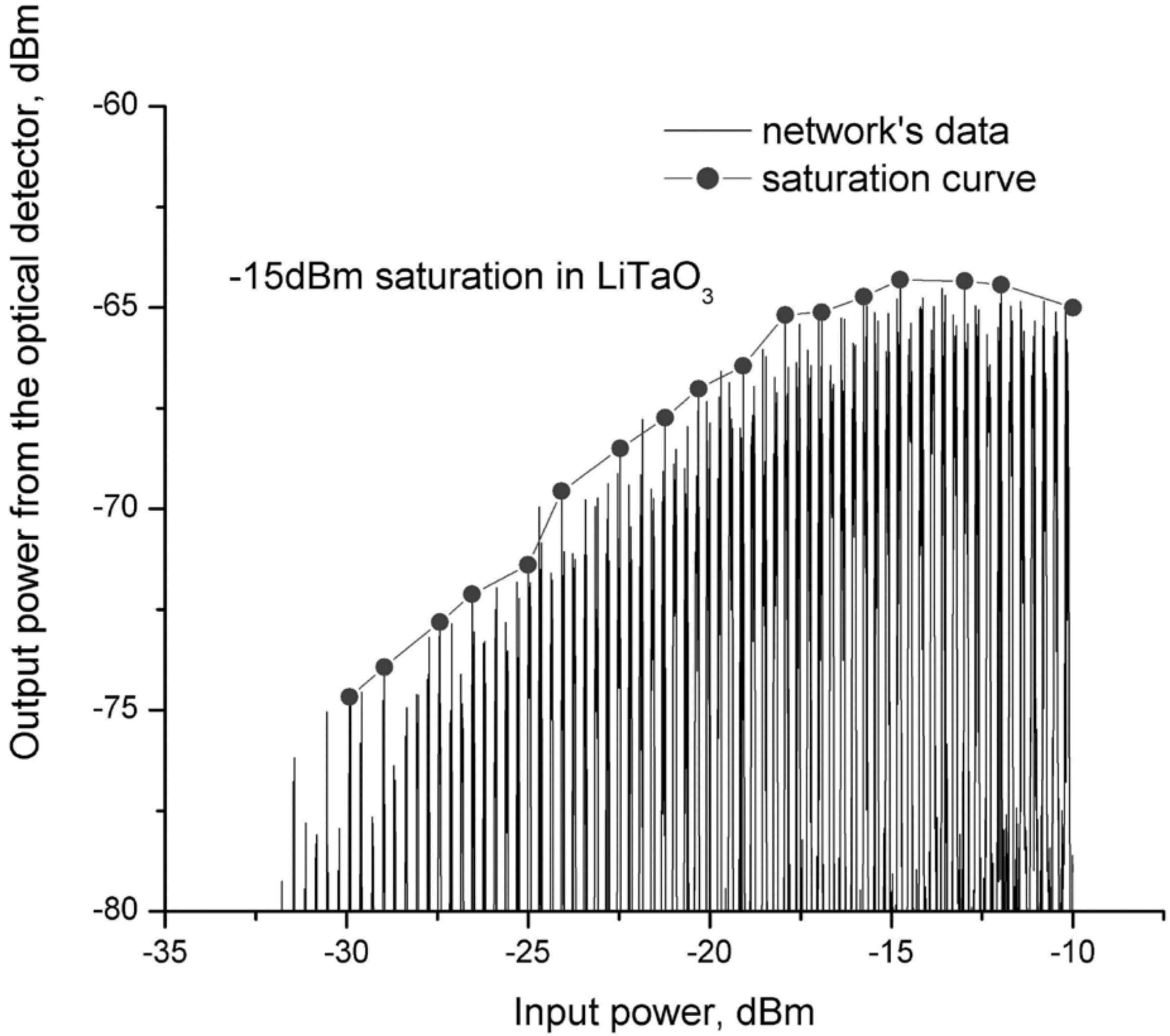
Lithium Niobate Resonator

First High Performance WGM Modulator Fabricated With Lithium Niobate

V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki, JOSA B, 20, 333 (2003).

Generates mostly phase modulated light so the RF return is relatively low.

Typical sensitivity achievable in linear modulator - saturation at -15dBm RF power



Characteristics of WGMR Modulators

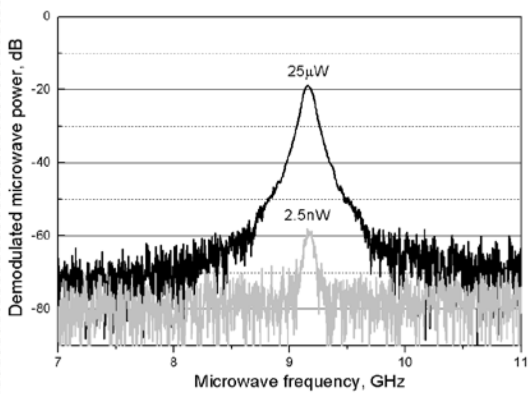
- Narrow Bandwidth (< 20) MHz
- Low RF Saturation power
- Low optical power handling capability

Ideal for applications such as in oscillators (OEO) and narrow-band receivers--- BUT

Limited for other applications

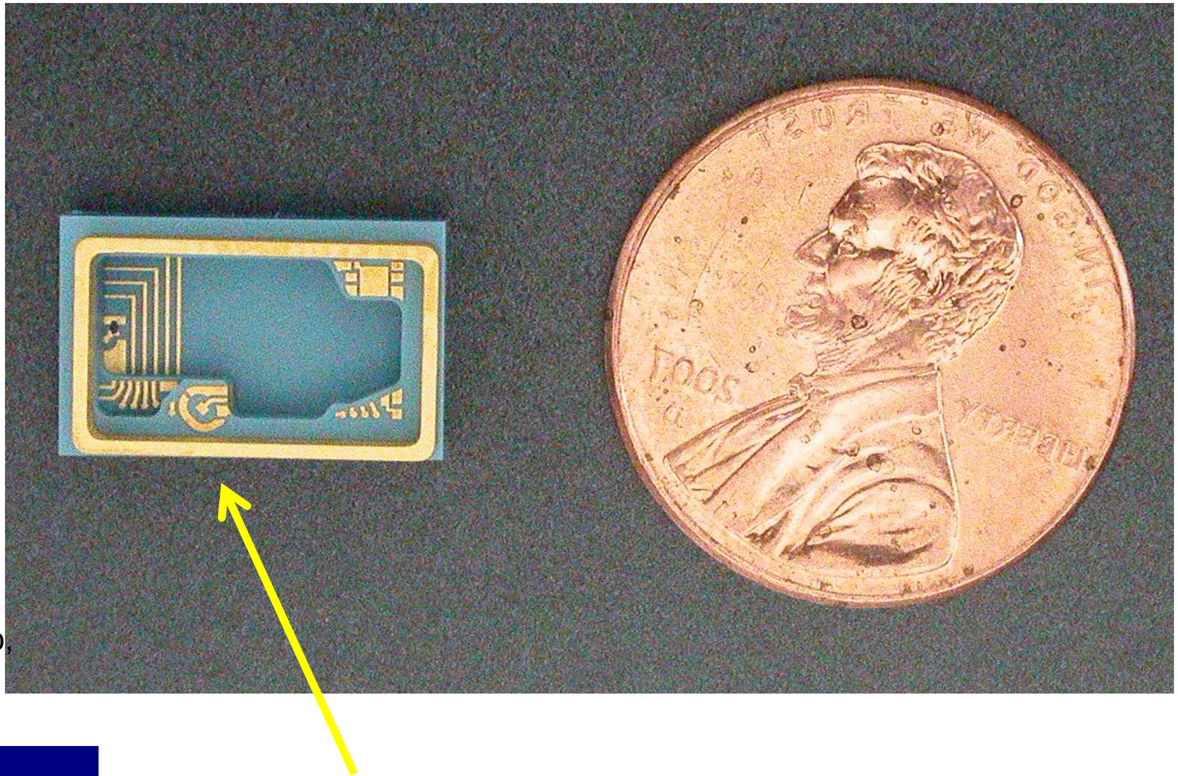
OEwaves

WGMR Modulator as a Receiver



First High Performance WGM Modulator Fabricated With Lithium Niobate

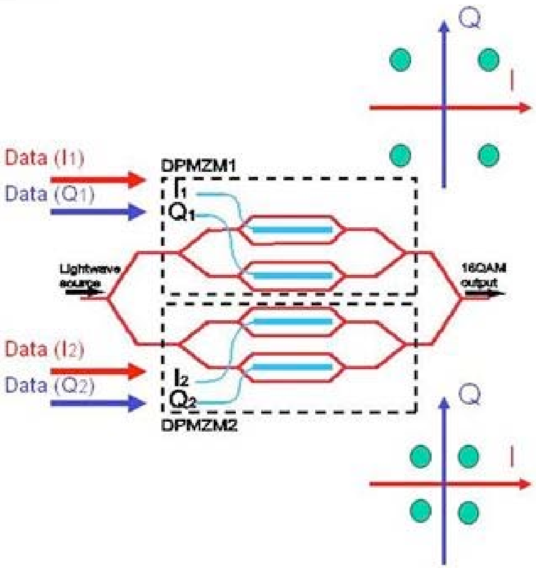
V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki, JOSA B, 20, 333 (2003).

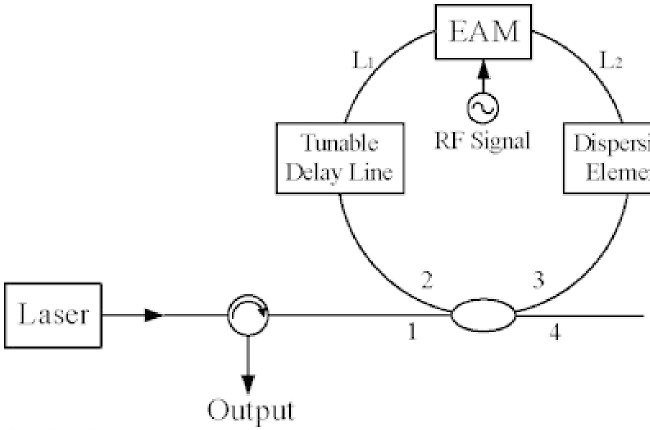


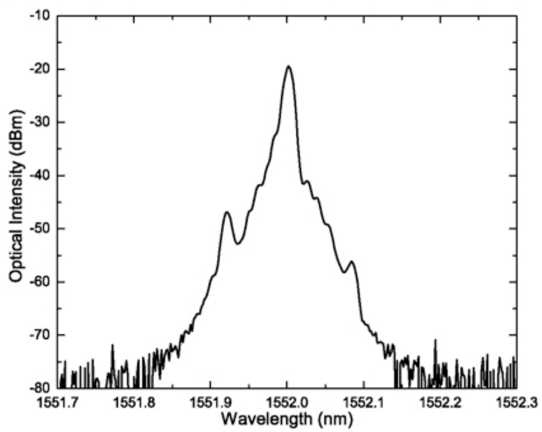
Empty Base

Highly Effective Modulation Using Electro-Optic Effect

SSB Modulator

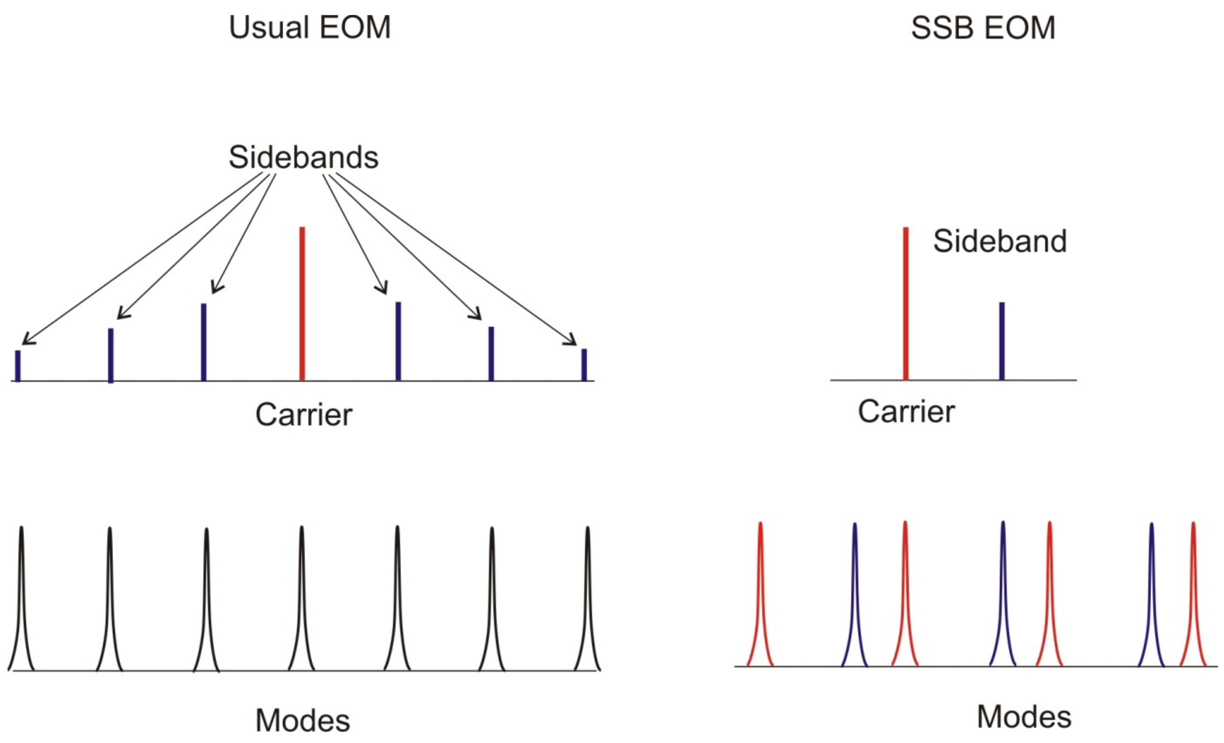




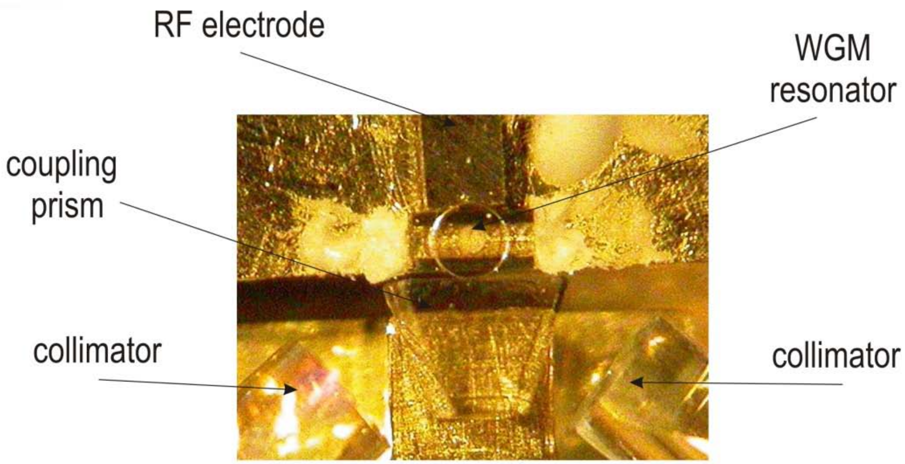


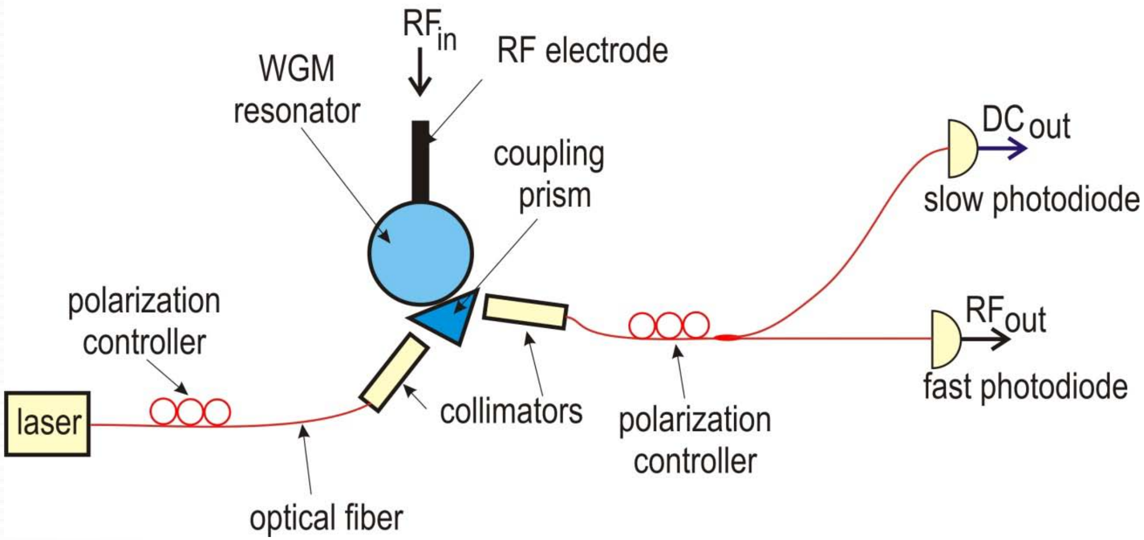
Typical suppression of the sidemode is ~ 30 dB

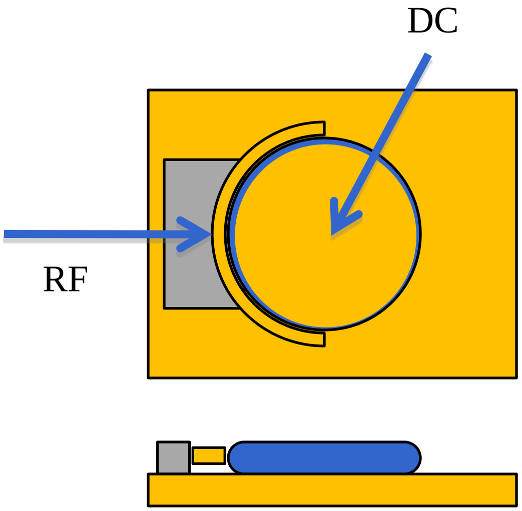
WGM SSB versus conventional WGM EOM



WGM Based SSB EOM

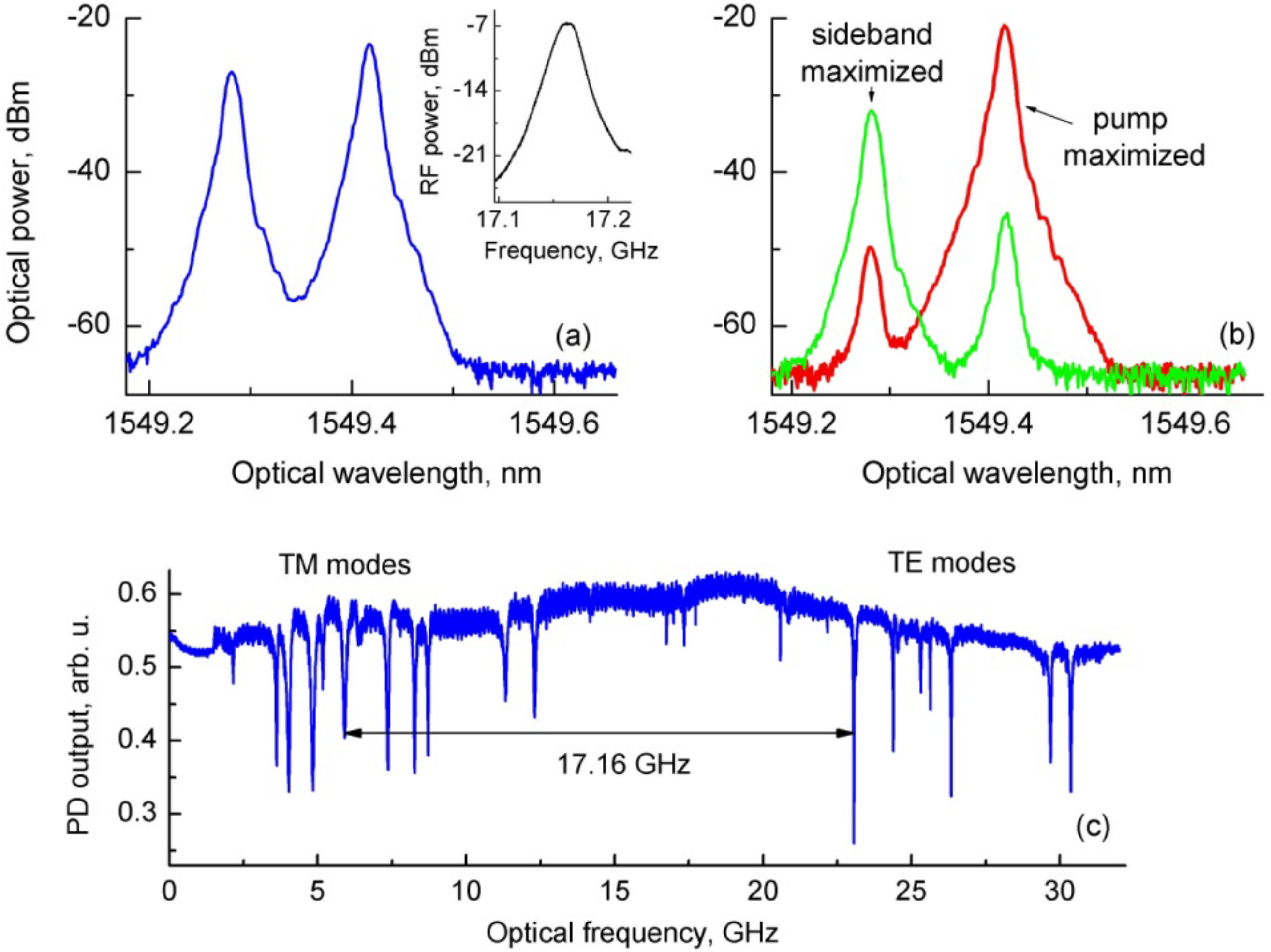






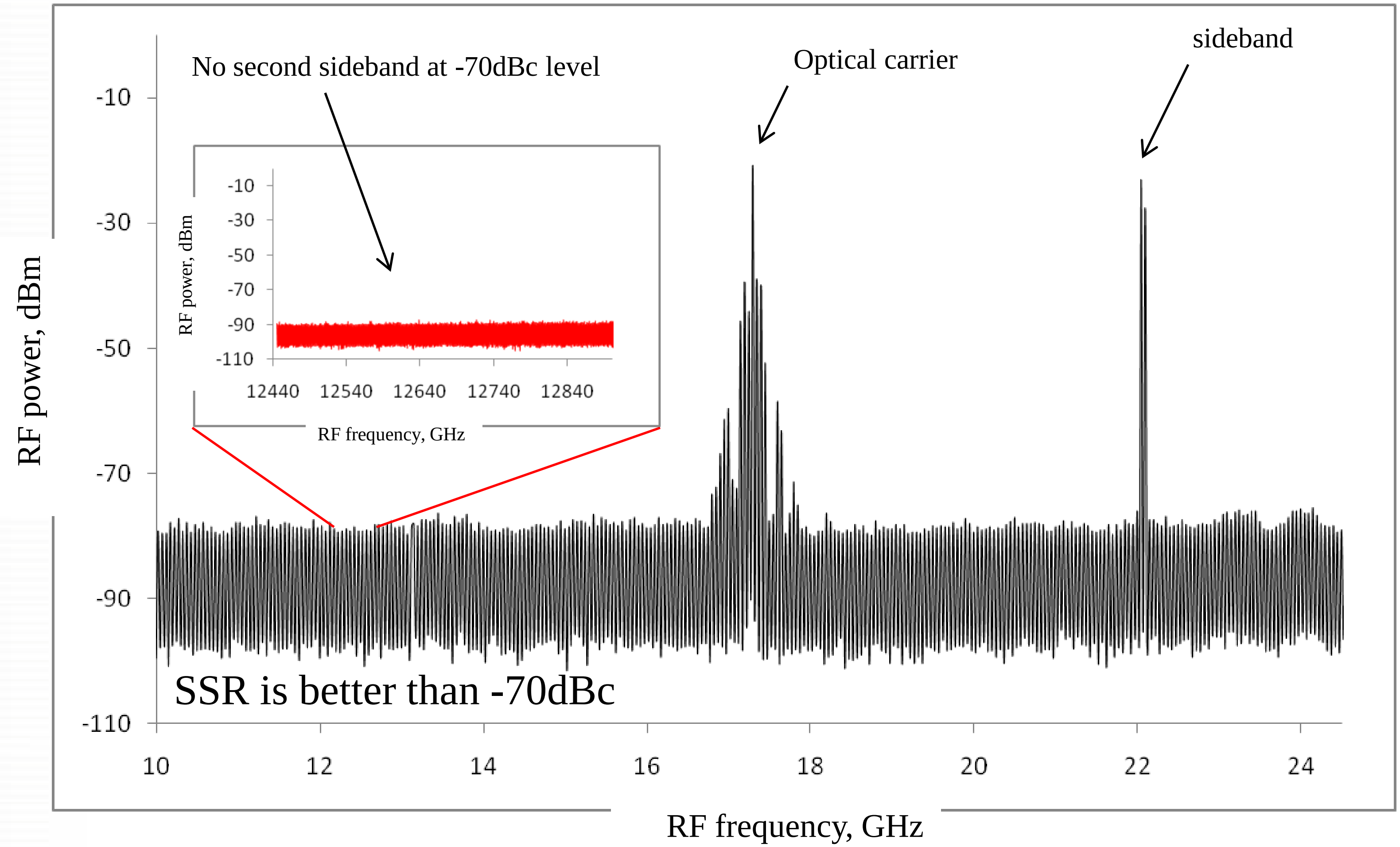
A. A. Savchenkov, W. Liang, A. B. Matsko, V. S. Ilchenko, D. Seidel, and L. Maleki, "Tunable optical single-sideband modulator with complete sideband suppression," Opt. Lett. 34, 1300-1302 (2009)

Coupling between TE and TM modes

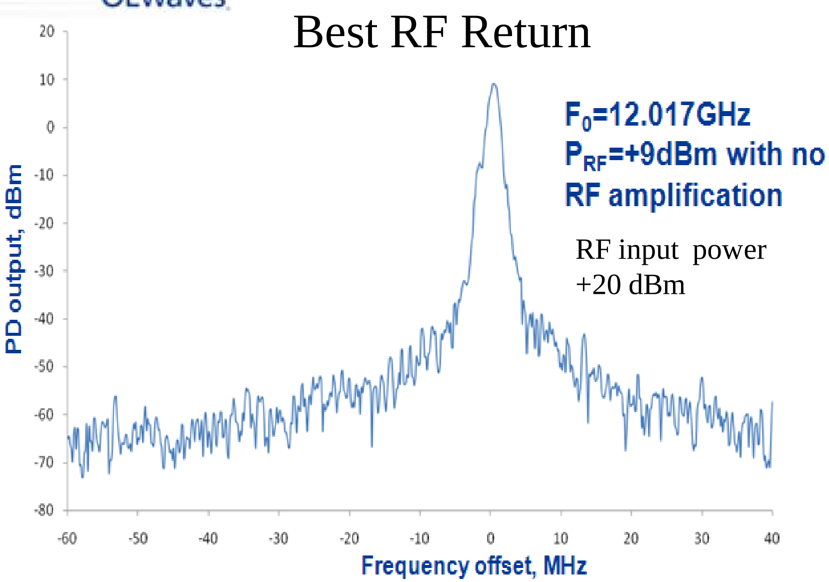


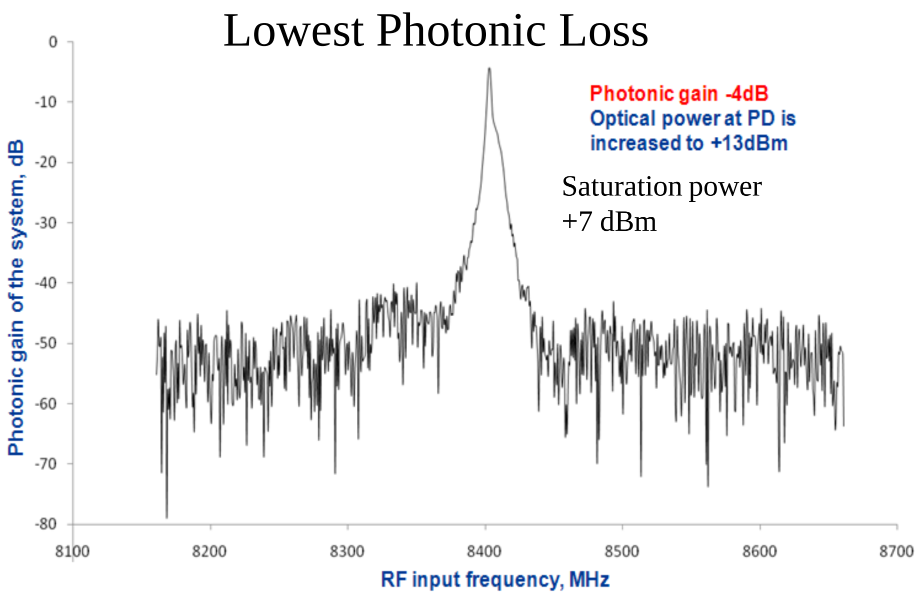
SSR measurements

Second sideband level determines crosstalk between frequency channels



SSB RF Return and Photonic Loss





Maximum RF return = +9dBm

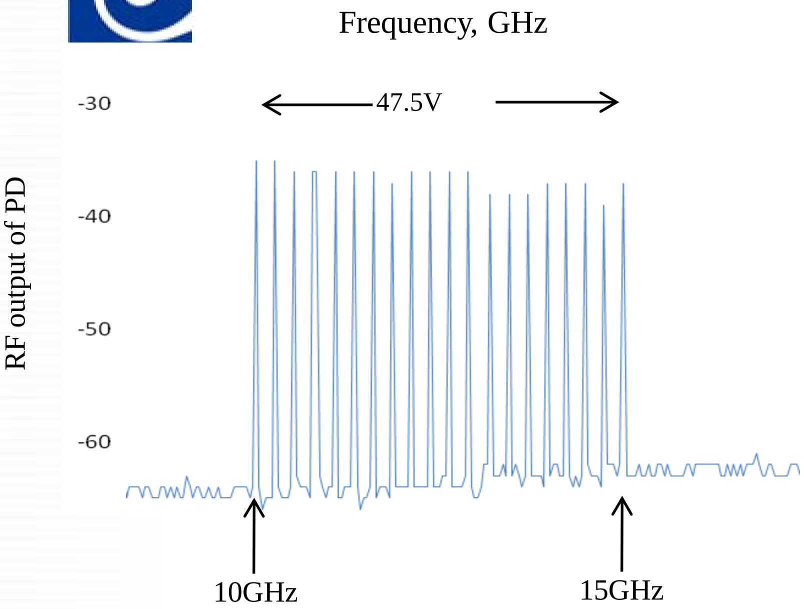
It exactly corresponds to SSB equation: $P_{RF}=P_{carrier}+P_{sideband}+G$,where

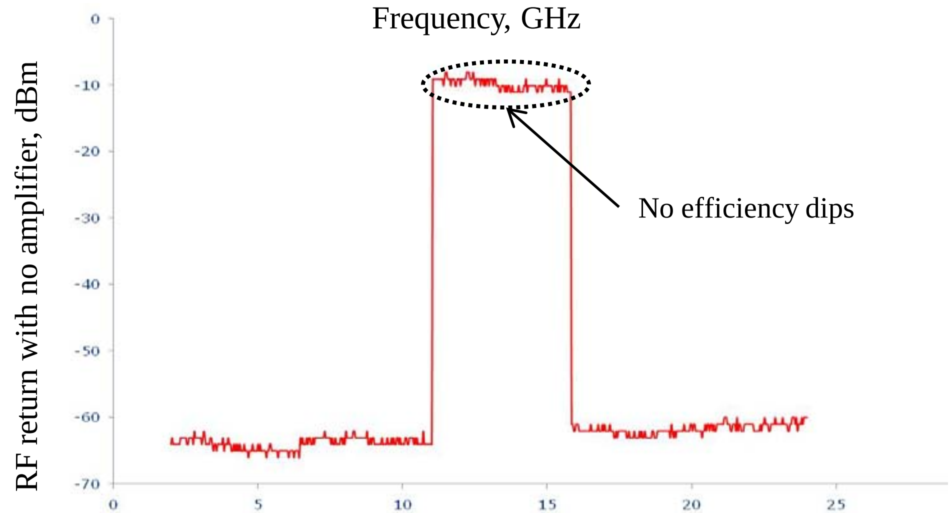
$P_{carrier}$=+13dBm, $P_{sideband}$=+13dBm

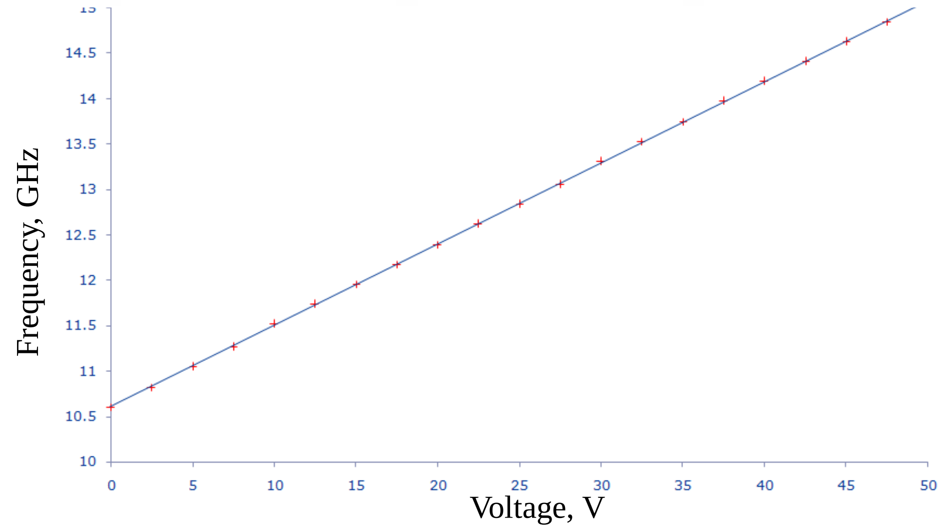
G=-17.4dB

$$G = 1\ \ l \quad \frac{R^2\rho}{2\ 00}; \quad R_0 = 0.8\ , \rho_0 = 55, G_0 = -10\ .4d$$

SSB Tunability







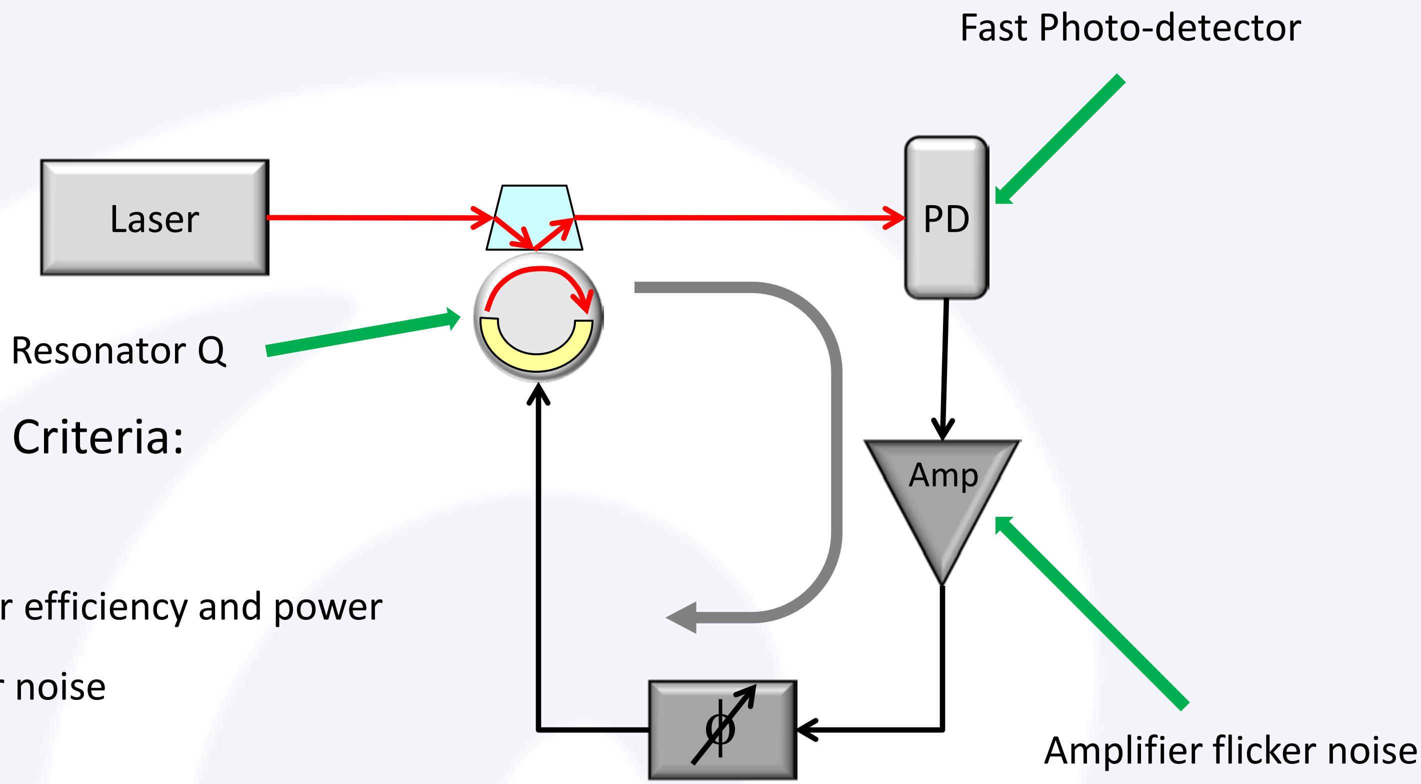
- Wide tunability from -90 to +90V (2-18GHz)
- Linear tuning
- Efficiency dips < 2dB

SSB Modulator Characteristics

- Higher RF saturation (but still lower than 10 mW)
- Larger bandwidth (100 MHz to 1 GHz possible)
- Very large RF return (nearly optimal power in sideband)
- Center frequency widely tunable (1-40 GHz possible)

A new class of optical modulator

WGM Based Tunable OEO



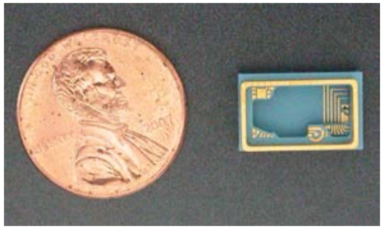
Performance Criteria:

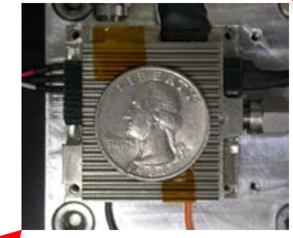
Resonator Q

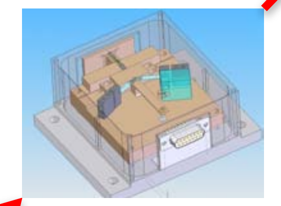
Photo-detector efficiency and power

Amplifier flicker noise

Transition to Products



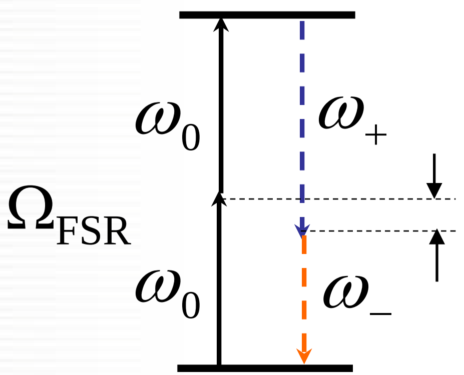


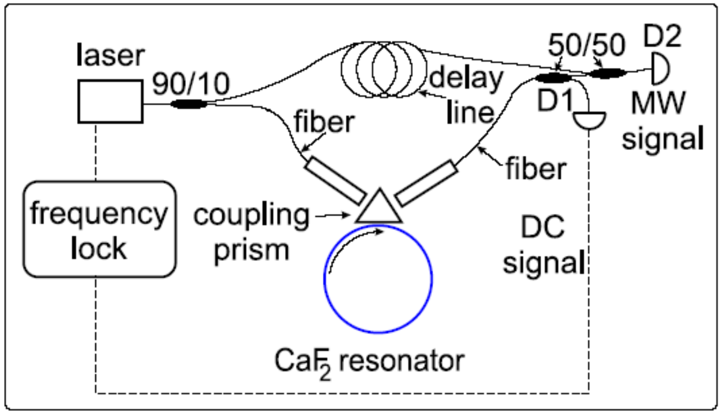


Calcium fluoride resonators that have $Q = 2 \times 10^{10}$.

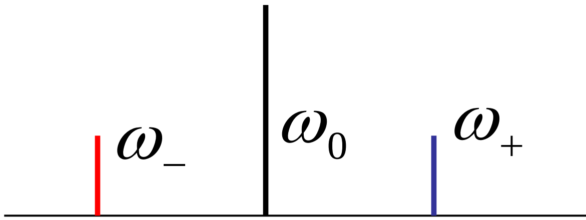
Hyper-parametric oscillations based on FWM in a fluorite resonator

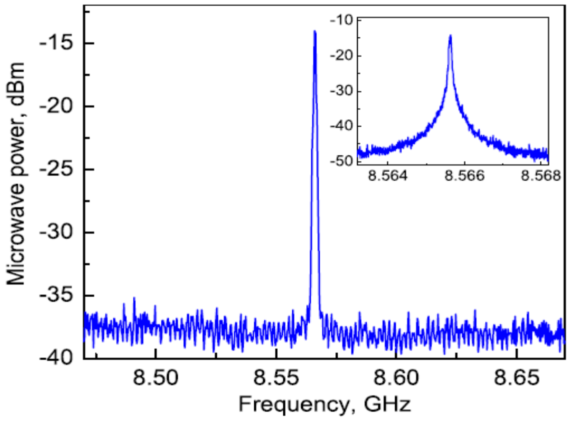
Transition diagram





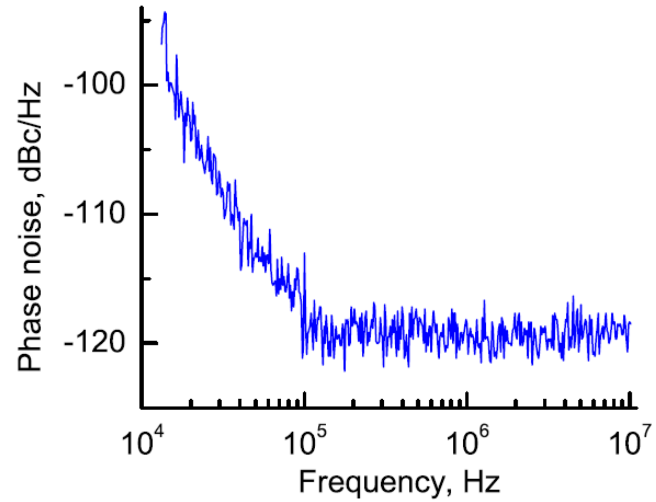
Optical spectrum





A.A. Savchenkov et al., PRL 93, 243905 (2004) & Optics Express 16, 4130 (2008)

Currently we have -125 dBc at 100 kHz and -135 dBc noise floor.



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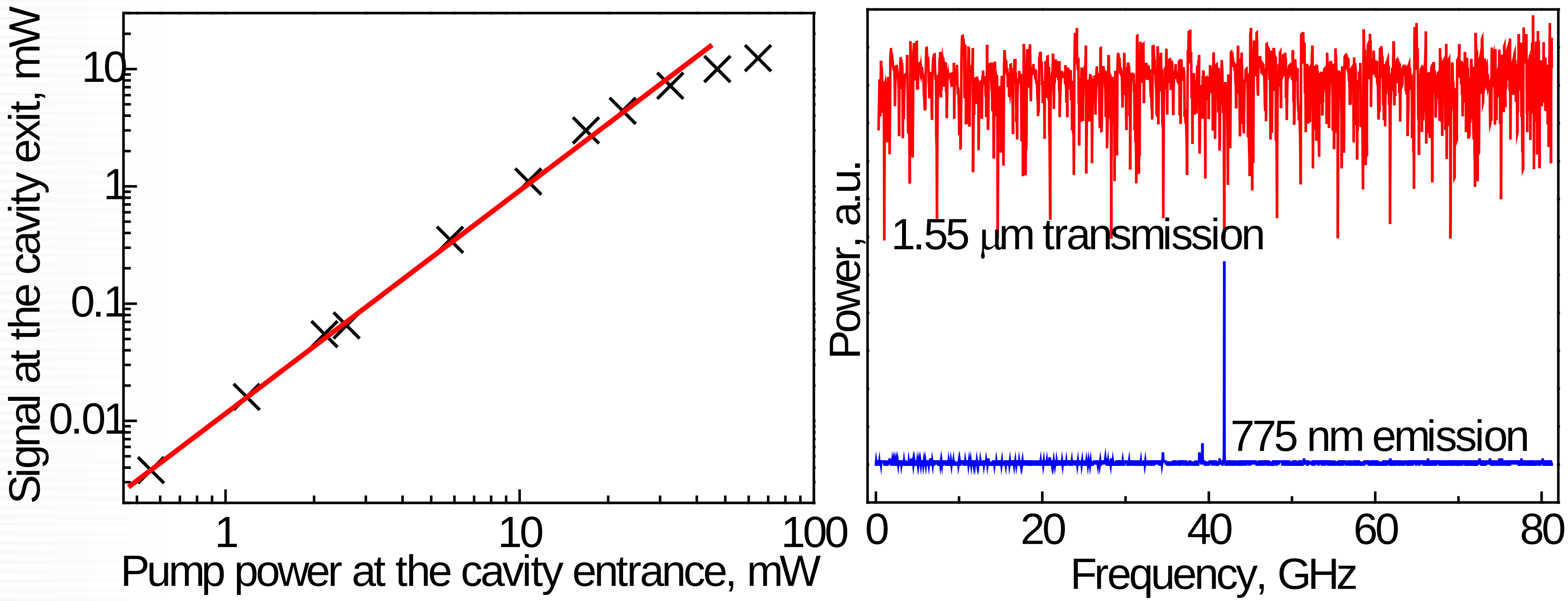
Efficiency of the frequency conversion with a WGM PPLN resonator and spectra of the pump and signal



V. S. Ilchenko et al., Phys. Rev. Lett. 92 (4): art. no. 043903 (2004)

Hyperparametric Oscillation

The reverse of the frequency doubling is parametric generation of photon pairs (sub-threshold) or of squeezed vacuum (above-threshold).

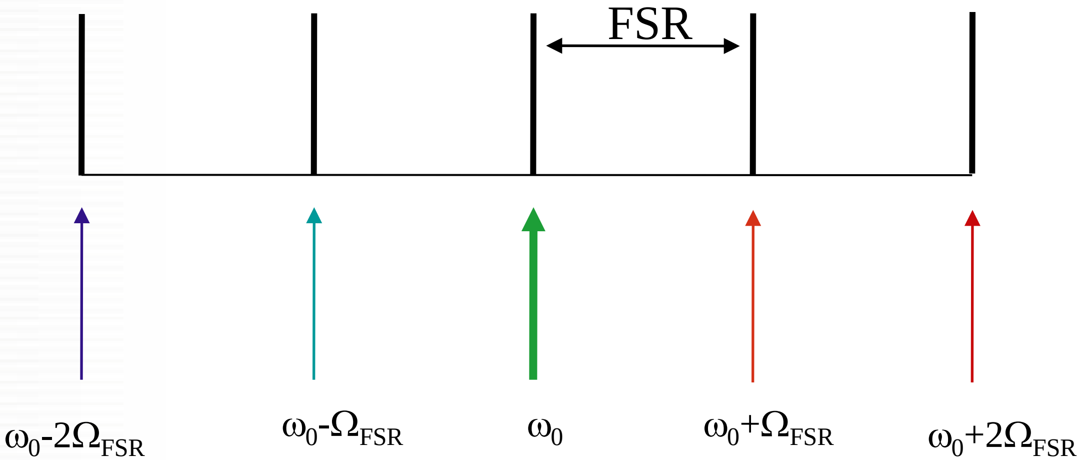
The OPO threshold in our case is

$$P_{th} = \frac{\varepsilon_p \varepsilon_s^2}{(8\pi)^3 (\chi^{(2)})^2} \left(\frac{V_s}{V_{pss}} \right)^2 \frac{\omega_p V_p}{Q_s^2 Q_p}$$

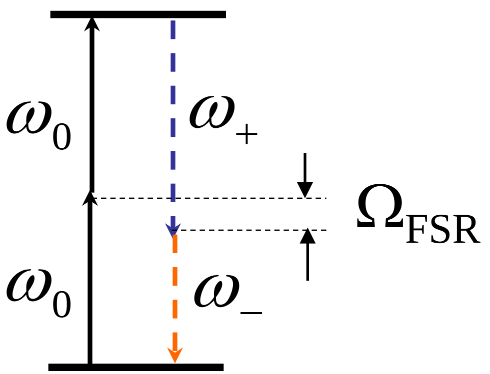
Which can be as low as 1.5 pW.
(The state of the art is 0.5 mW)

Applications of Nonlinear Processes

Hyper-parametric oscillations in fluorite resonators

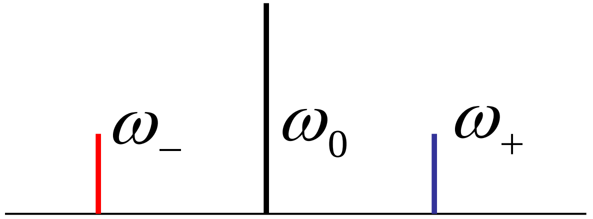


Transition diagram



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

Optical spectrum

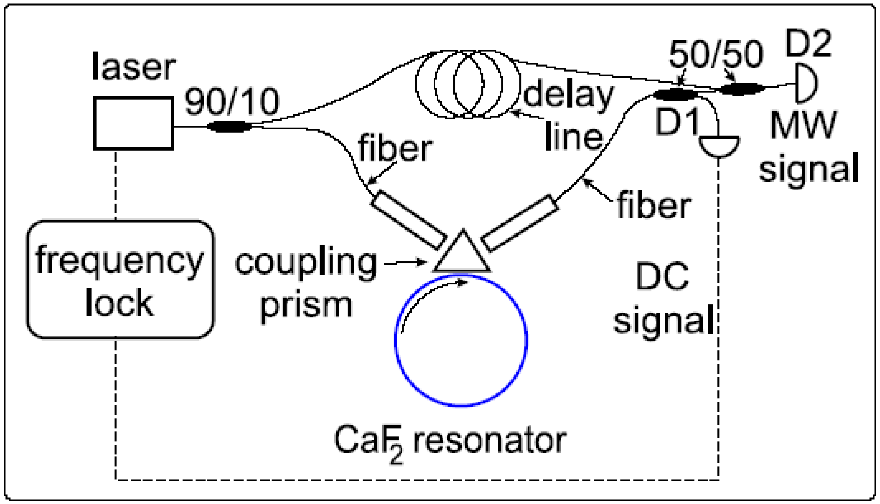


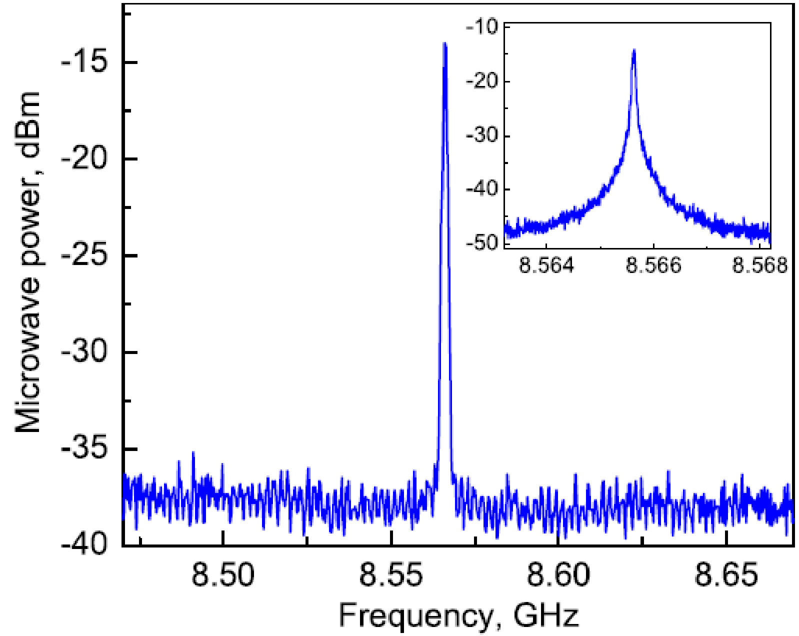
Selection rules

FWM: TE-TE

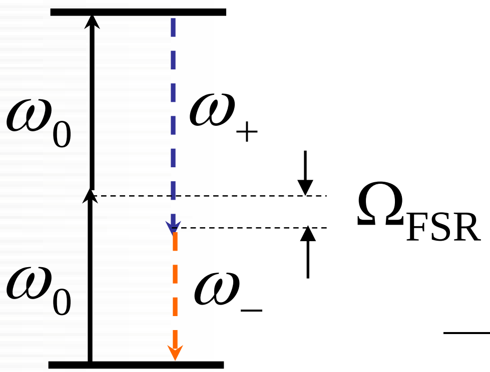
SRS: TE-TM

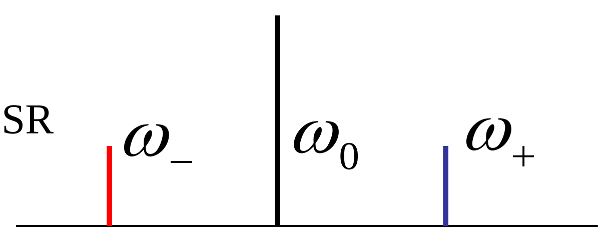
Hyper-parametric oscillations in fluorite resonators





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





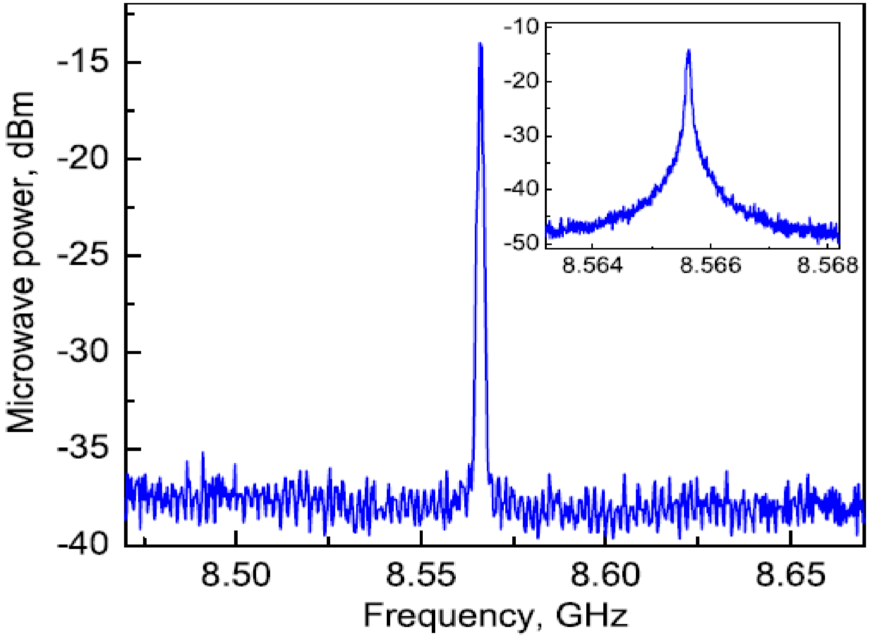
Hamiltonian:

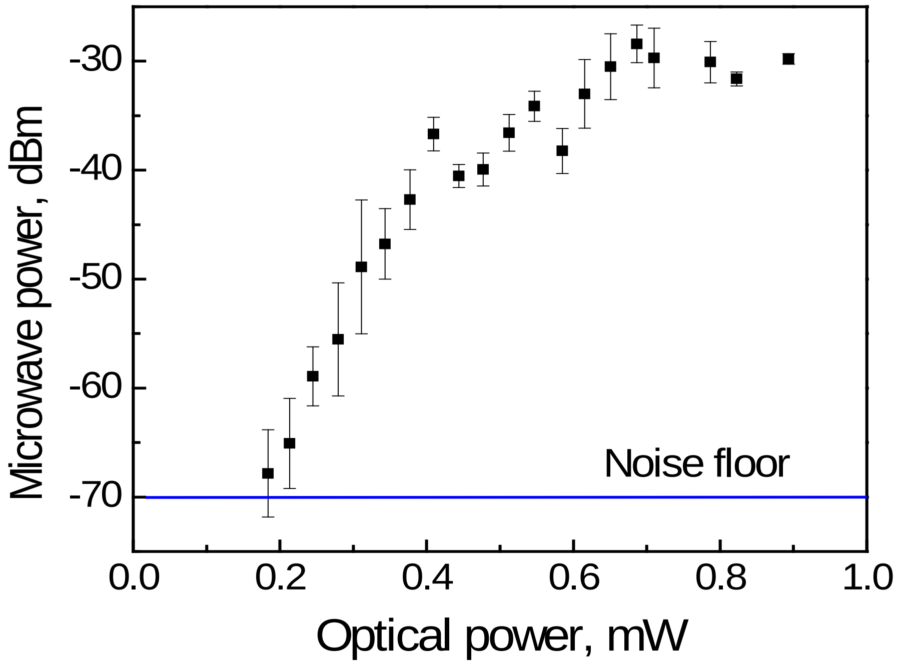
$$H = -\hbar g\left(b_-^+ b_+^+ aa + a^+ a^+ b_+ b_-\right),$$

$$g = \omega_0 \frac{n_2}{n_0} \frac{\hbar \omega_0 c}{V n_0}$$

A.A.Savchenkov et al., Phys. Rev. Lett. ***93****, art. no. 243905 (2004)*

Microwave beat note observed

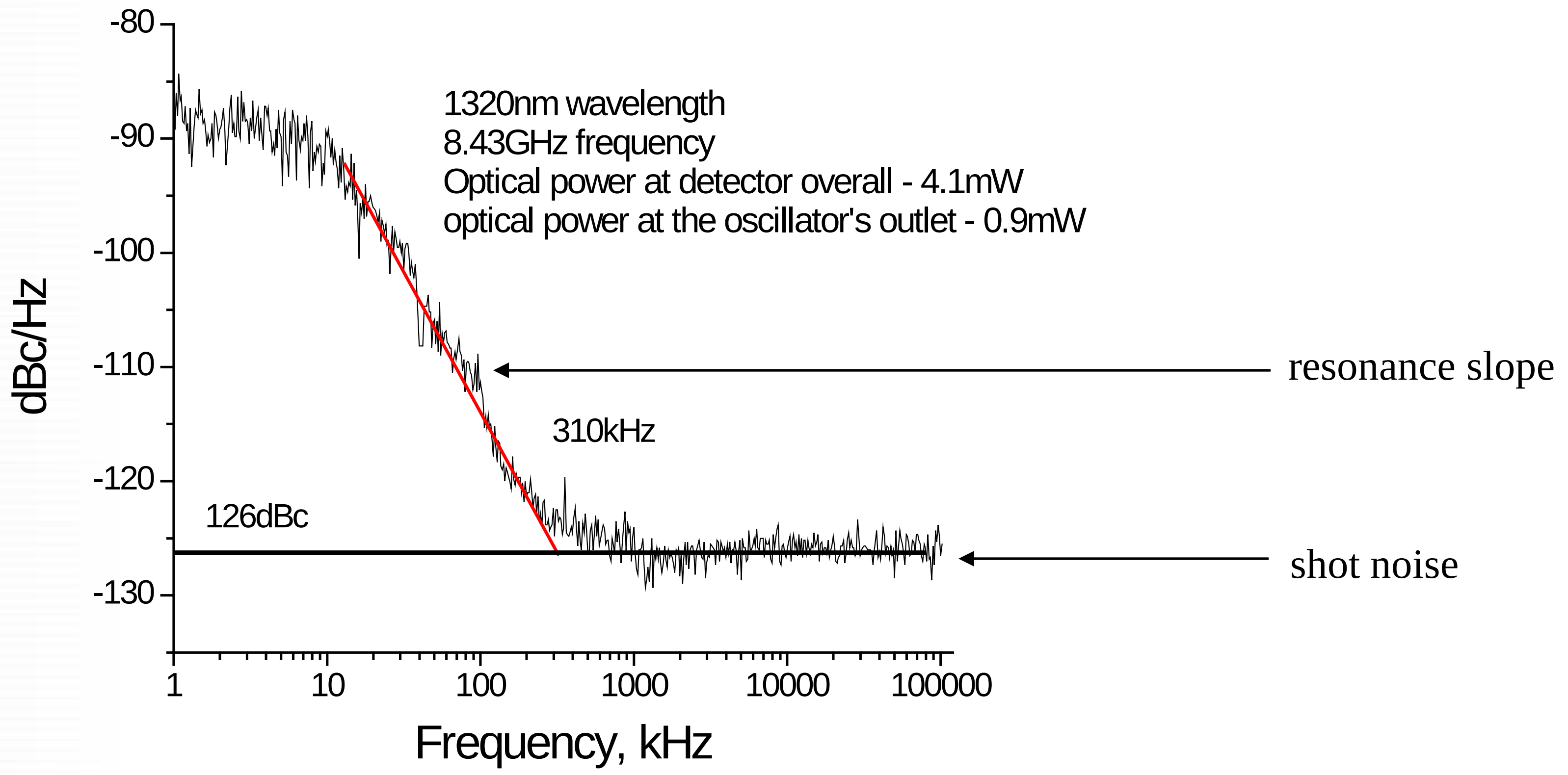




- Second-order ($2\Omega_{FSR}$) beat note is insignificant
- Raman scattering is not observed (expected at 322 cm^{-1})

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

Phase noise of oscillations



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

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

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

Self-phase modulation

Cross-phase modulation

Four-wave mixing

Equations of motion in an open system:

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

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

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

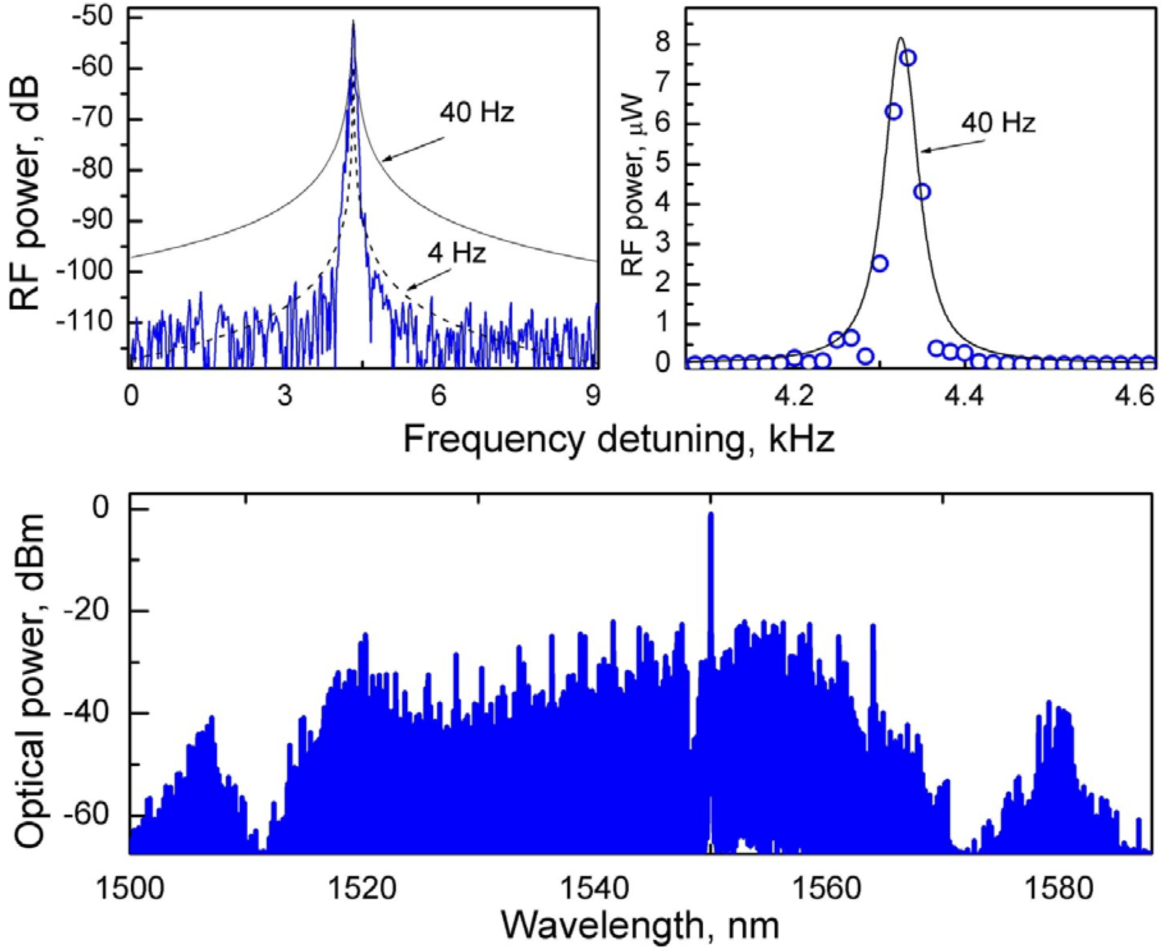
Temperature tuning

SPM and CPM

FWM

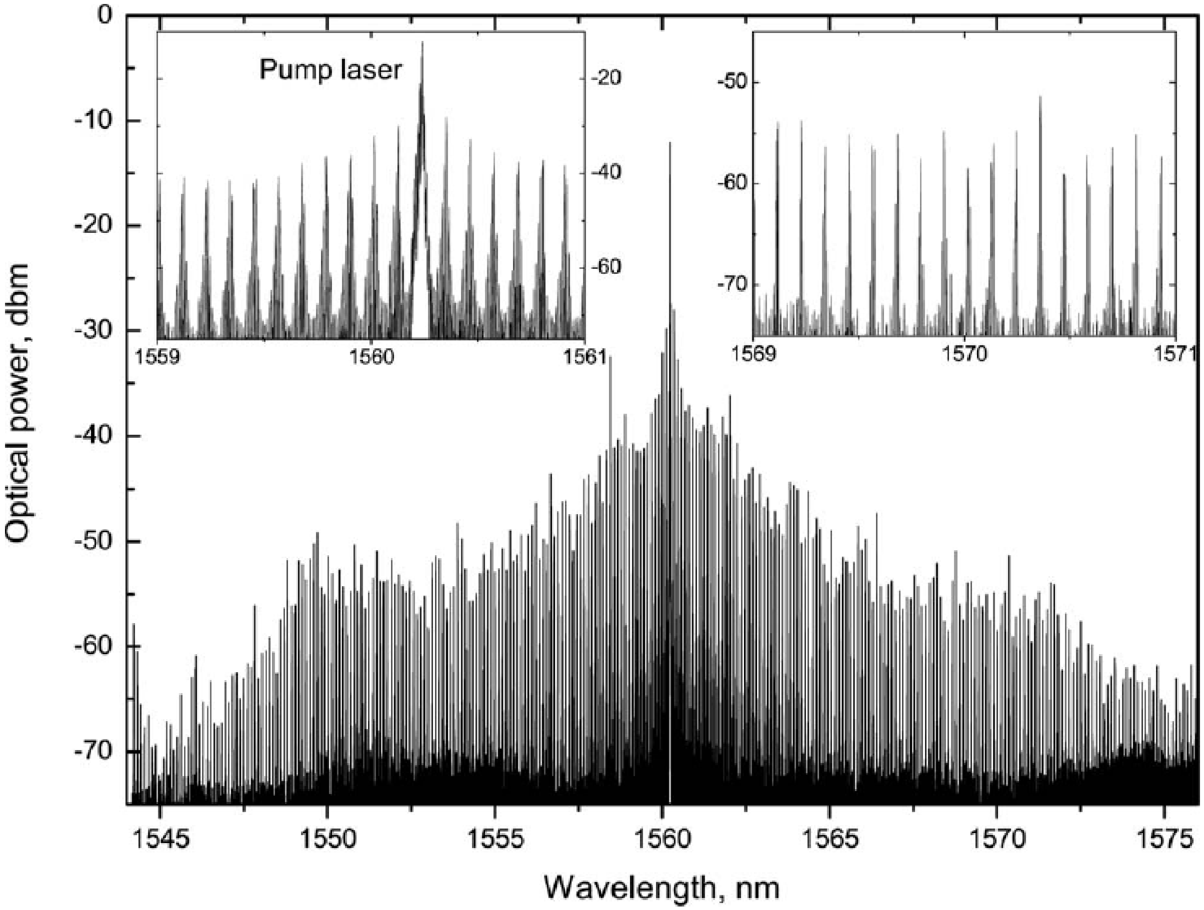
Where $\langle f_{c0}\rangle = \sqrt{\frac{2\gamma_{c0}P_0}{\hbar\omega_0}}\, e^{-i\omega t}$ and $g = \omega_0 \frac{n_2}{n_0}\frac{\hbar\omega_0 c}{\mathcal{V} n_0}$

Optical comb and 25 GHz RF generation



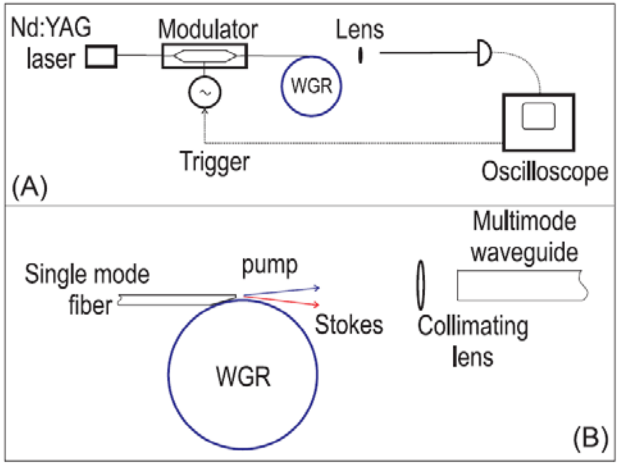
A. A. Savchenkov et al.,"Tunable Optical Frequency Comb with a Crystalline Whispering Gallery Mode Resonator," Phys. Rev. Lett. ***101****, 093902 (2008).*

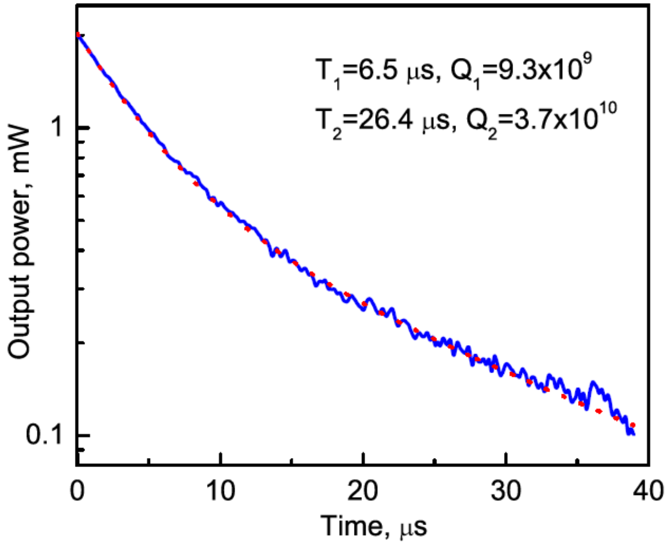
Optical comb at 13.8 GHz



I. S. Grudinin, N. Yu, and L. Maleki, Opt. Lett. ***34****, 878-880 (2009)*

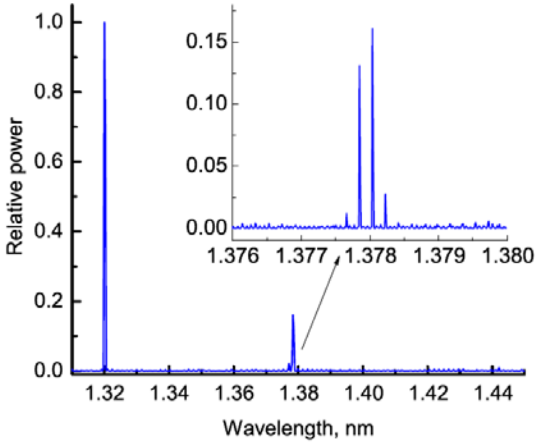
Stimulated Raman Scattering & nonlinear decay





Typical ringdown characteristics of the fluorite WGM resonator. The solid line corresponds to the experimental observation, and the dotted line – to the theoretical simulation.

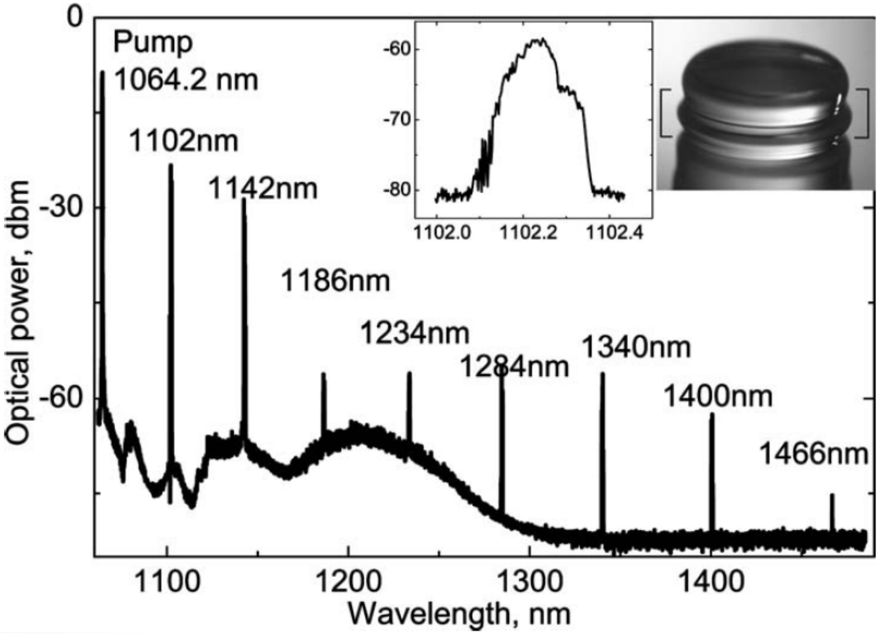
The scheme of the experimental setup. (A) The frequency of a continuous wave Nd:YAG laser was slowly swept across the free spectral range of the resonator. When coupling of the light to a whispering gallery mode exceeded 30 % the light was abruptly switched off with an electrooptic modulator triggered by an oscilloscope. In this configuration critical coupling (all light is entering the resonator) corresponds to zero signal on the photodiode, while zero coupling corresponds to the maximum signal on the photodiode. (B) The light exiting the resonator was collimated and geometrically separated from the Stokes light.

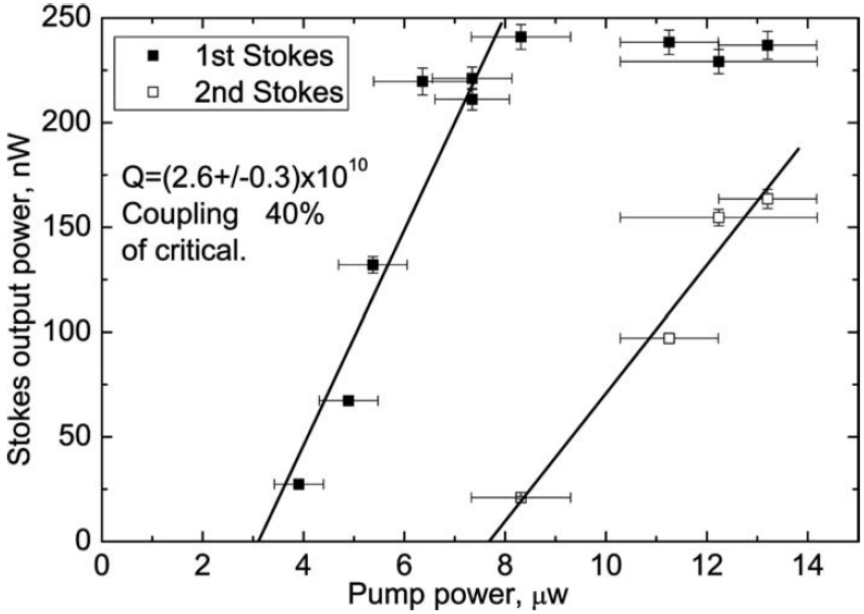


The spectrum of light exiting the Raman-active WGM resonator. The inset shows the structure of the Stokes line. The wavelength difference between the peaks shown in the inset corresponds to the free spectral range of the resonator.

A. A. Savchenkov, et al Opt. Lett. 32, 497-499 (2007).

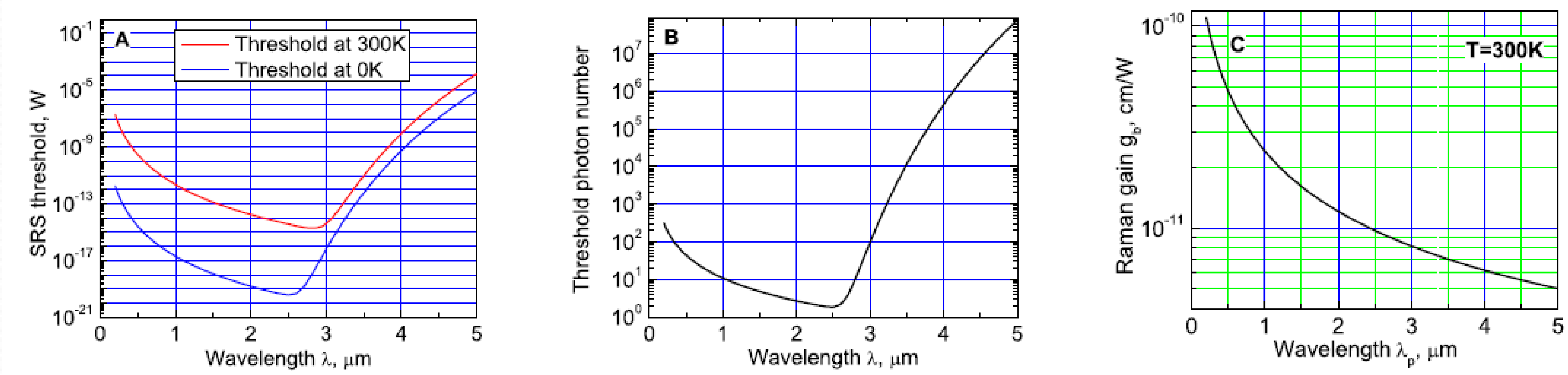
Ultra-low threshold multi-order SRS





I. S. Grudinin and L. Maleki, Opt. Lett. ***32****, 166-168 (2007)*

The lowest possible SRS threshold



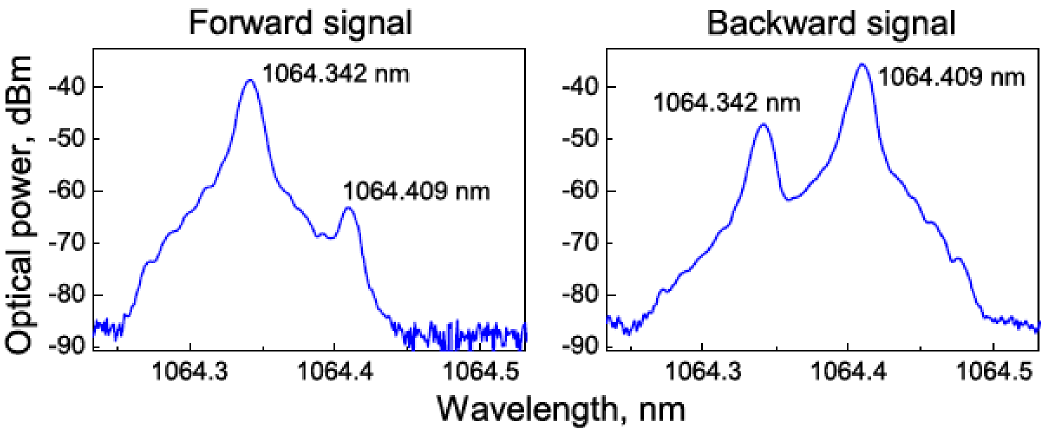
A) SRS threshold for a 1 mm ideal-surface cavity made with an ideal CaF_2.

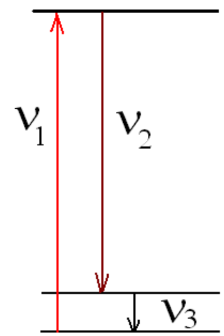
B) Low temperature SRS threshold for a 1 mm ideal cavity made with CaF_2 in terms of photon number.

C) Theoretically evaluated wavelength dependence of the Raman gain in CaF_2.

I. Grudinin, A. B. Matsko, and L. Maleki, Opt. Express 15, 3390 (2007).

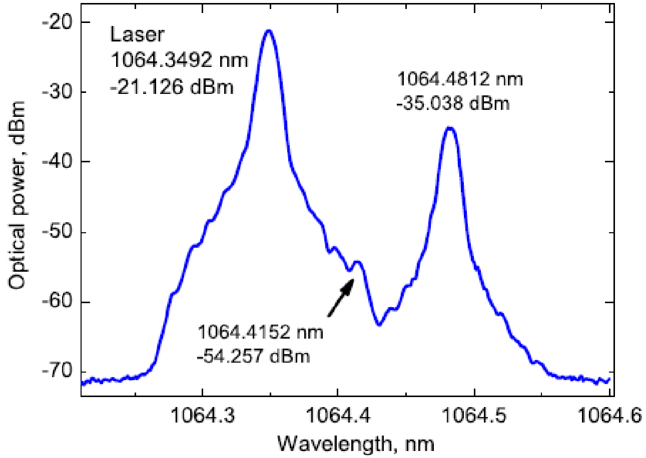
Stimulated Brillouin Scattering





ν_1 and ν_2 are resonant with cavity WG modes, ν_3 corresponds to 17.7GHz phonons.

Pump and SBS lines for fluorite cavity. The pump power was 50μW. The two Stokes lines have frequencies red-shifted by 17.7 GHz (weak backward Stokes is seen because of the residual Rayleigh scattering) and by ~35 GHz (strong Stokes line created by the backward Stokes). The width of each line is limited by the OSA resolution of 0.012 nm.



I. S. Grudinin et al., Phys. Rev. Lett. ***102****, 043902 (2009).*

Summary

Very high Q factor
+
Small mode volume

→ Low thresholds of nonlinear effects

Very high Q-factor and small volume significantly reduce the threshold for various nonlinear optical processes in crystalline WGM disk resonators using low power CW laser excitation. This helps the study of nonlinear phenomena in crystalline material and results in development of novel optical and microwave photonic devices.