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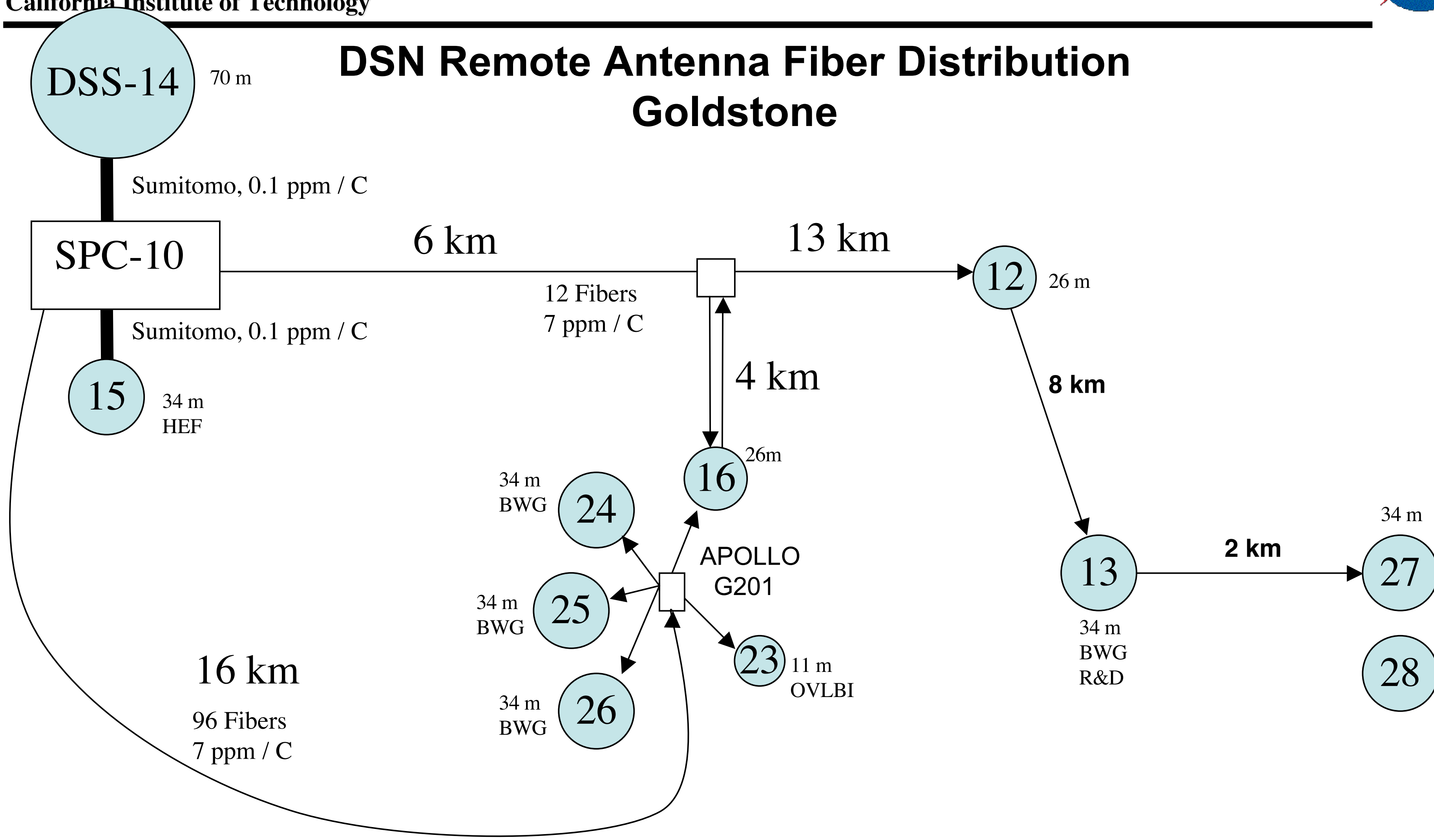
New Directions in Photonics Techniques for Communications and Radar

Lute Maleki

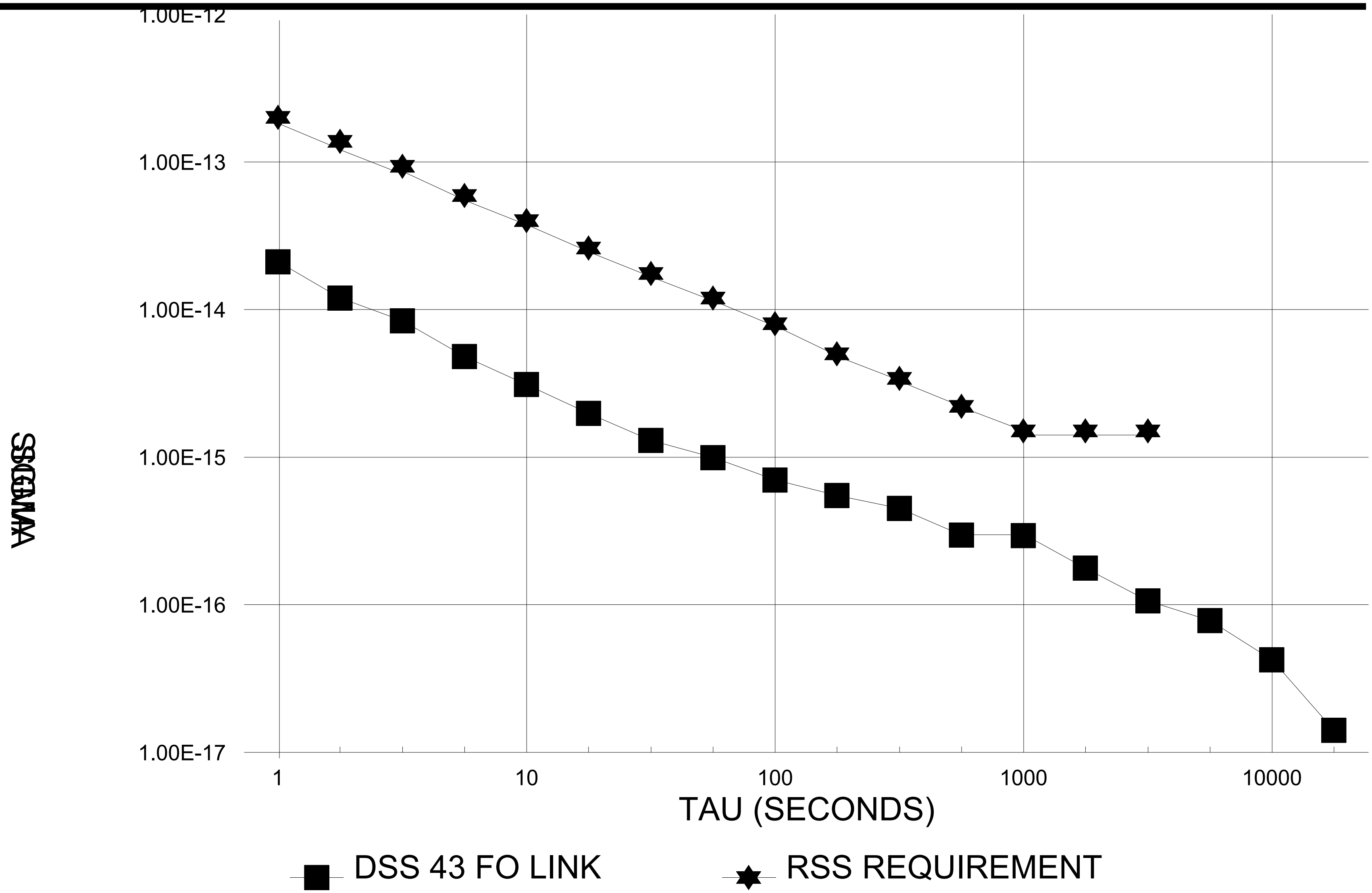
Quantum Sciences and Technology group

- History and Background
- Overview of RF Photonics
- Work at JPL
- Whispering Gallery Mode (WGM) resonators
- Devices and architectures
- Summary

DSN Remote Antenna Fiber Distribution Goldstone

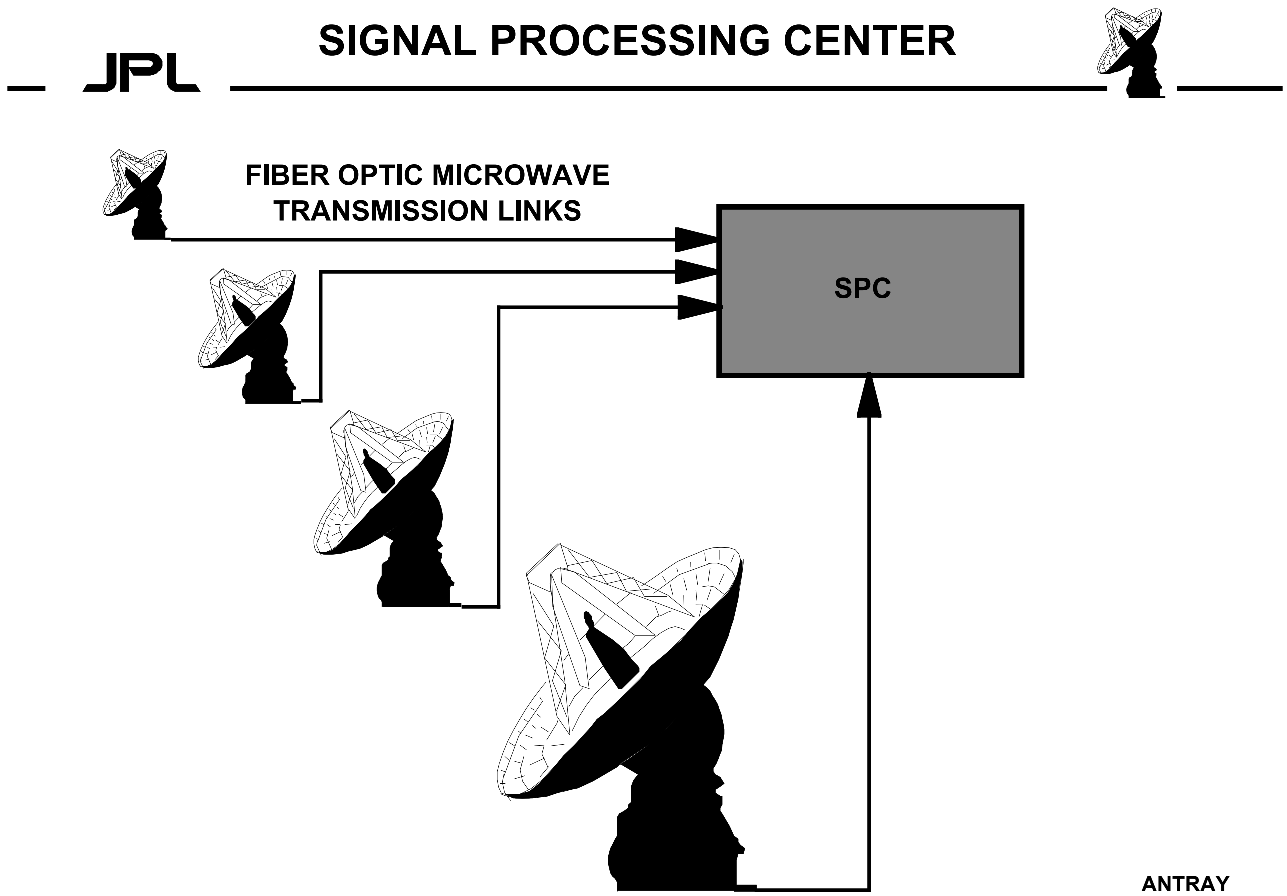


DSS 43 ALLAN DEVIATION



M. CALHOUN
SEC 331 8/5/93

CENTRALIZED
SIGNAL PROCESSING CENTER



ANTRAY

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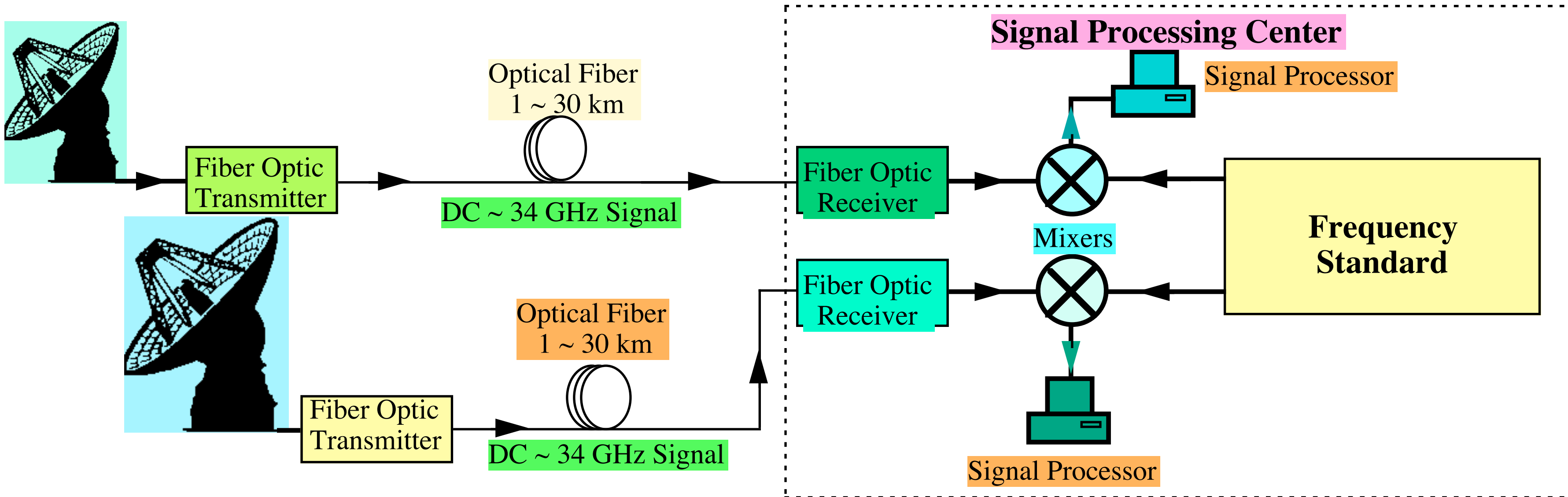
Antenna Remoting in DSN



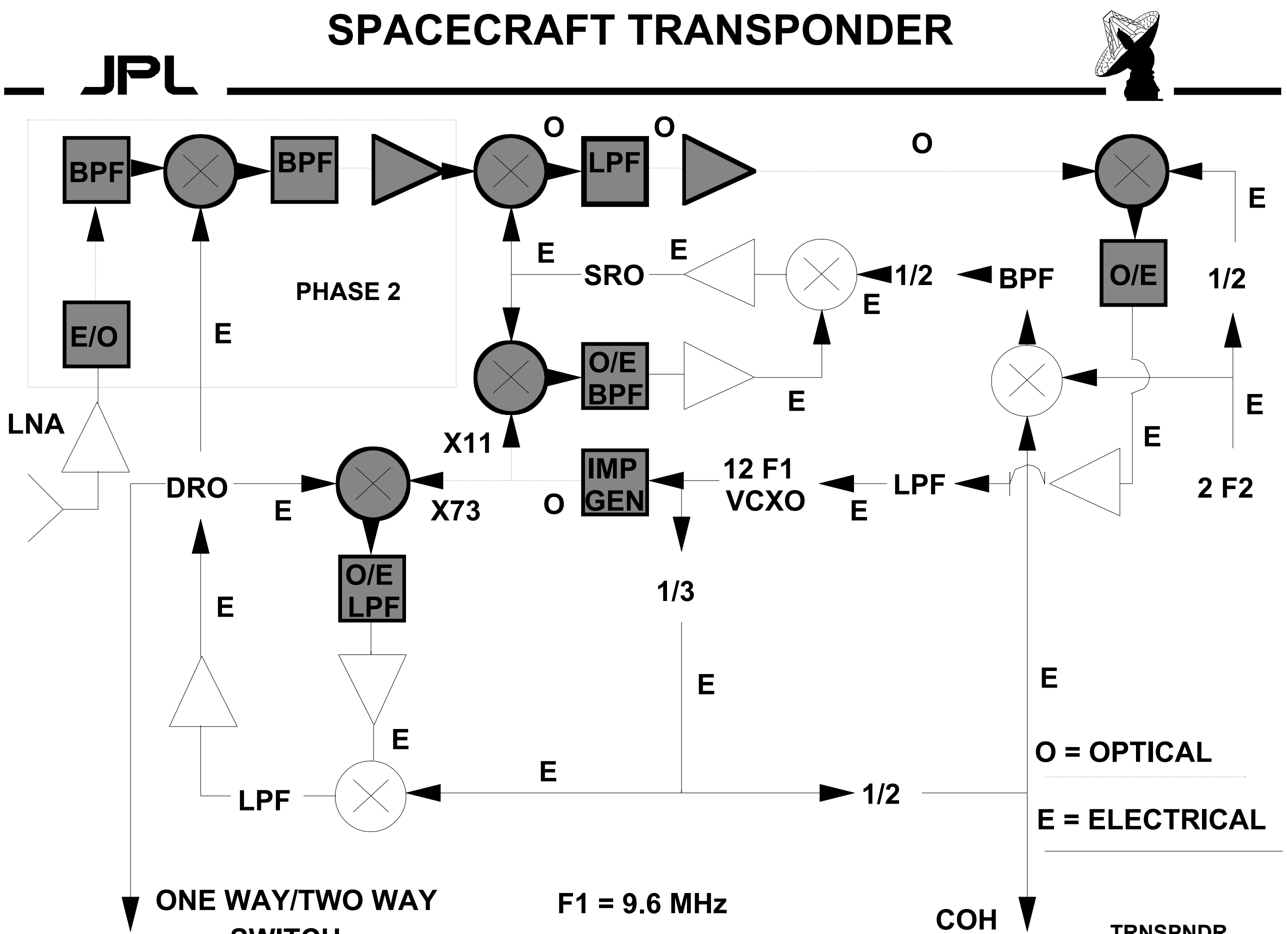
* Reduce the amount of equipment at the antenna.

* Share redundant hardware, lower hardware cost.

* Share signal processing and maintenance personnel, lower operation cost.

* Coherently array widely separated antennas to increase receiving sensitivity.

SPACECRAFT TRANSPONDER



F1 = 9.6 MHz

F2 = 12.25 MHz

Why Photonics

- The bandwidth is essentially ‘unlimited’
- Components and devices are have small size, low mass, and competitive power efficiency
- Waveguides are extremely low loss (0.2 dB/km for optical fibers)
- Photon detection at optical wavelength is very efficient
- EMI absent, (or significantly mitigated)
- Cost is becoming competitive (due to communications industry push)

Examples of Photonics Functions for Microwave and Millimeter Wave Systems

- Signal generation
- Up/down conversion
- Filtering
- Phase shifting
- Switching
- True-time delays
- A/D conversion

Examples of Photonics Functions for Microwave and Millimeter Wave Systems

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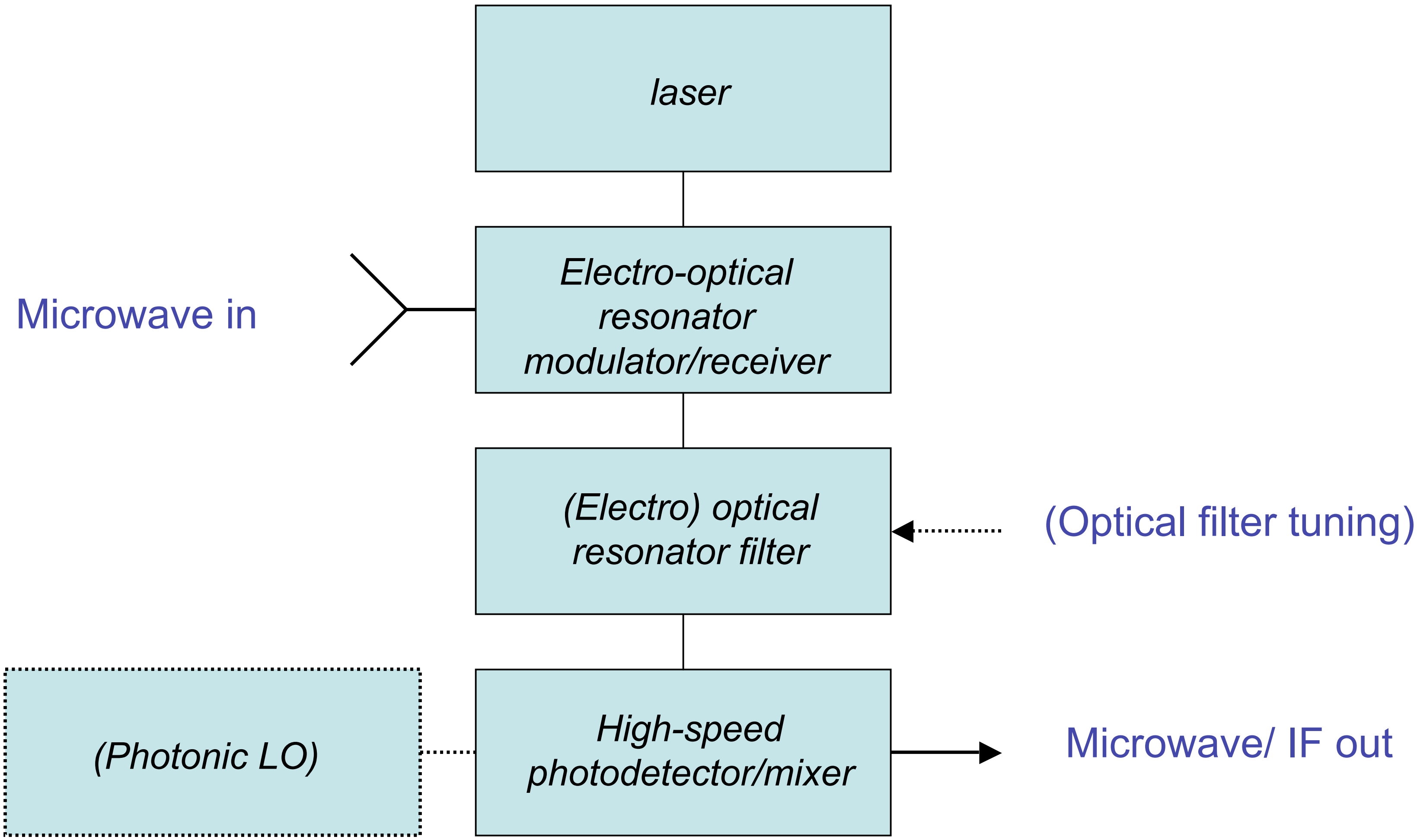
Manipulation of spectral properties and tunability is important for applications

Examples of RF photonics applications: *filtering, modulation, reception*



OEO as a Generic Frequency Control Device

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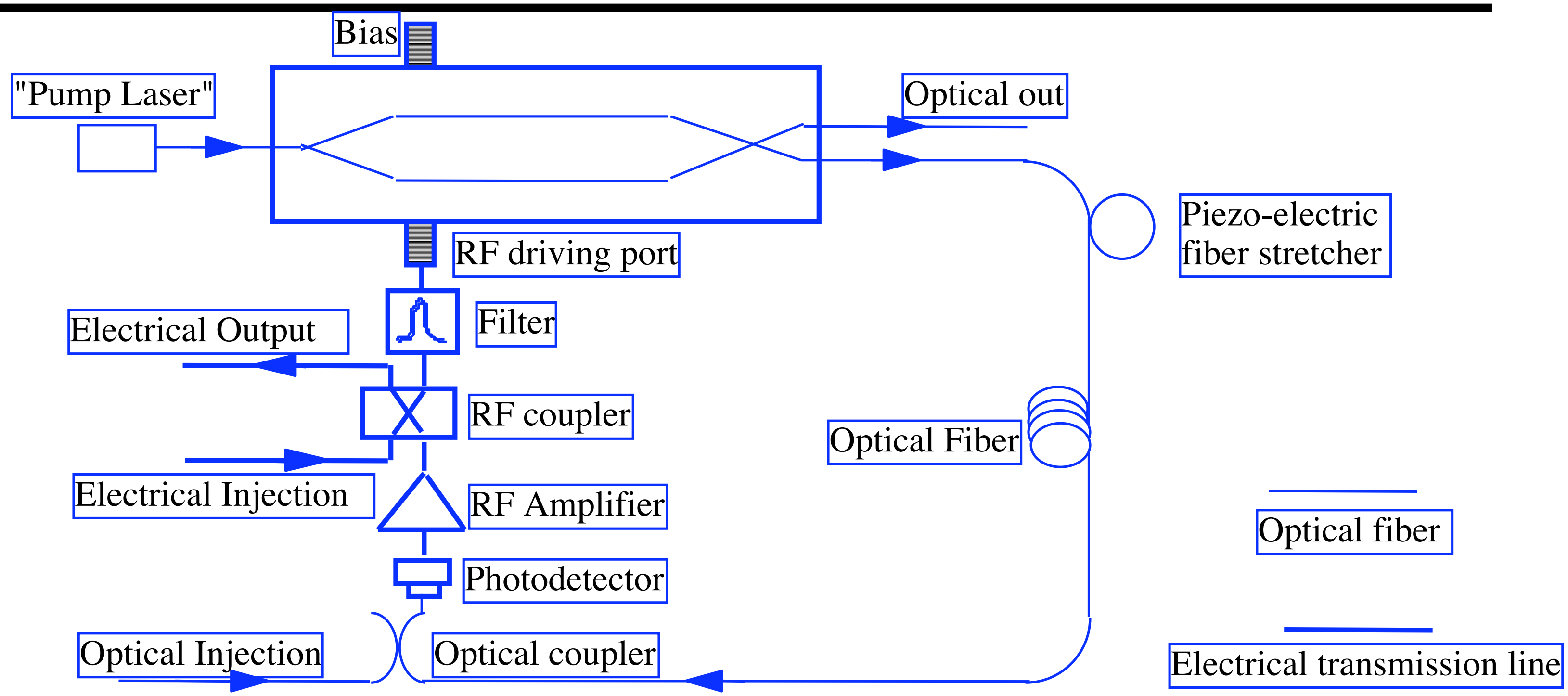

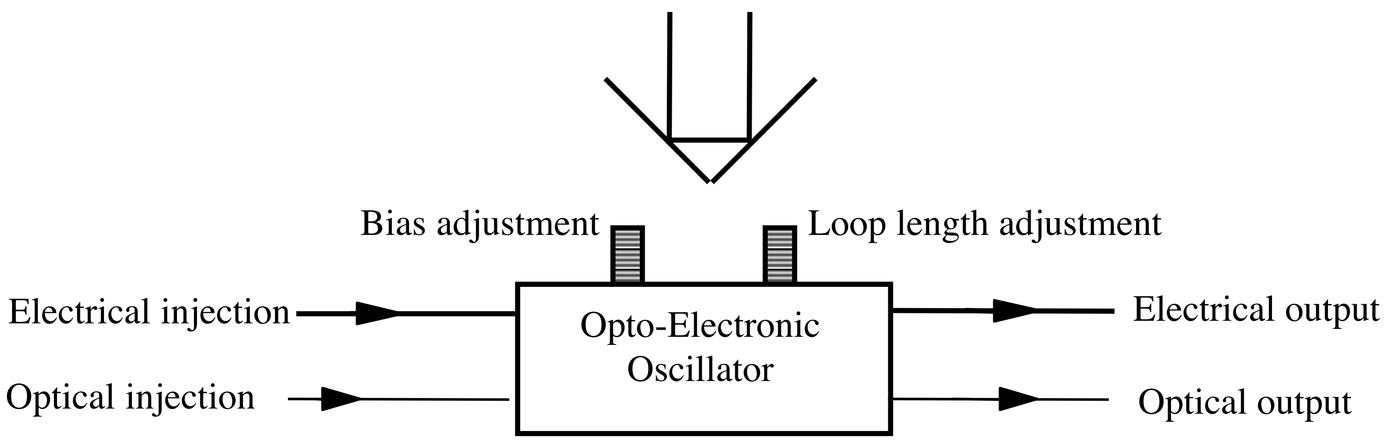

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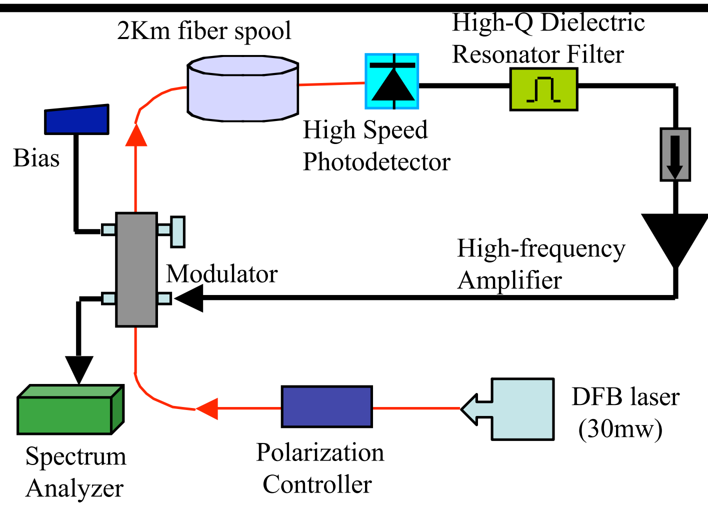
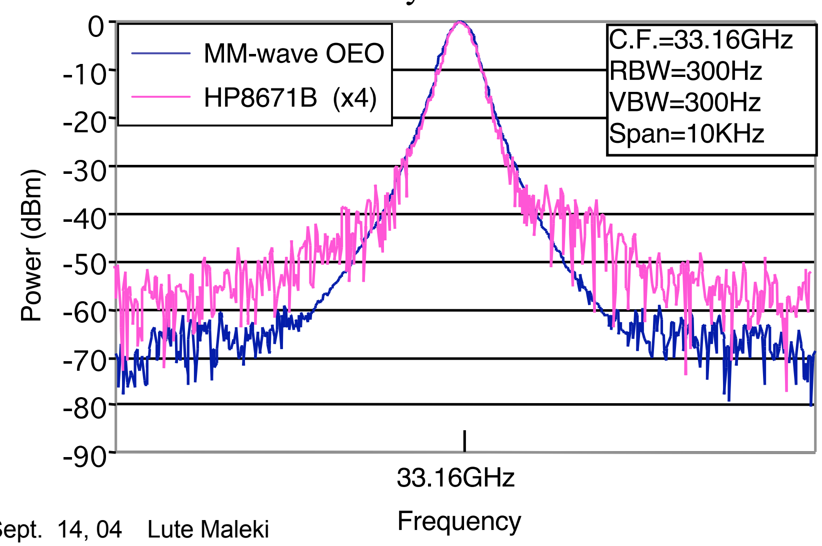
Ka-Band / Millimeter-wave OEO

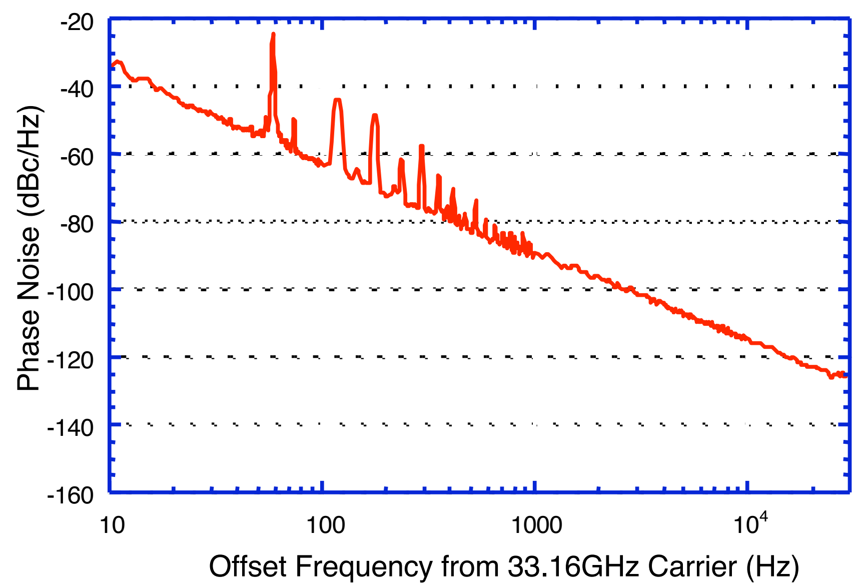


- Oscillating up to 33 GHz.
- Phase noise less than -30dBc/Hz at 10Hz and -120dBc/Hz at 10 KHz from both 28.29GHz and 33.16GHz carriers.
- Phase noise of mm-wave OEO is 20dB lower than that of the HP synthesizer with a 4□ multiplier.

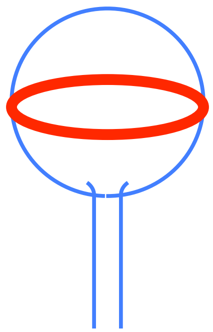
Comparison of Millimeter-wave OEO and HP Synthesizer



Phase Noise of 33.16GHz OEO



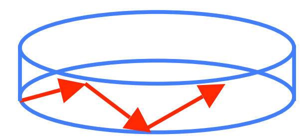
Whispering-gallery modes: ultra-high Q in optical resonators



CURVATURE CONFINEMENT

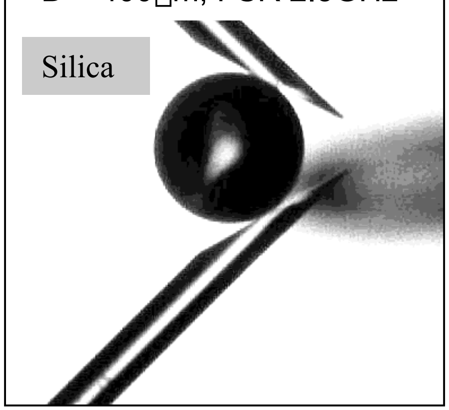
ALLOWS **Q** approaching LIMIT BY

MATERIAL ATTENUATION:

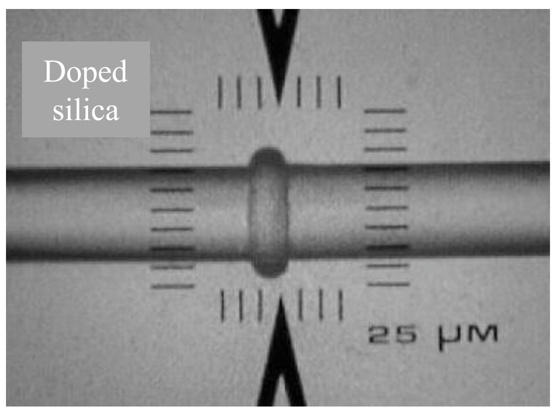


$Q=10^7$-10^9 in spheres and toroids vs. 10^3 - 10^5 in microrings

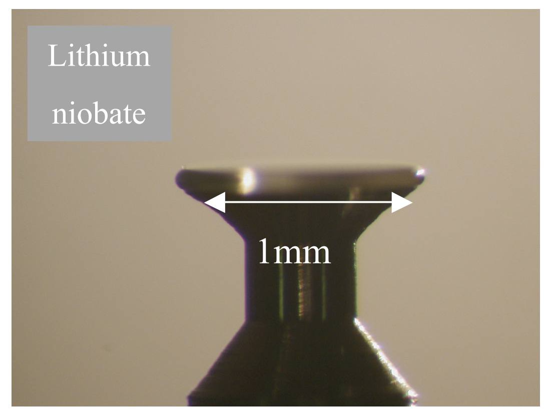
Low eccentricity spheroid
D = 400µm; FSR 2.5GHz



Oblate spheroid
D = 160µm; FSR ~400GHz



Oblate spheroid
D = 1.3mm; FSR 33GHz



Whispering Gallery Mode resonances are electromagnetic resonances which occur in circularly symmetric dielectric by the mean of the light is trapped in a circling orbit by continuously totally internally reflected from the surface of the resonator. The WGM usually is characterized by the mode number n, l and m

- n is the radial mode numbers
- l is the angular mode numbers
- m is azimuthal mode numbers

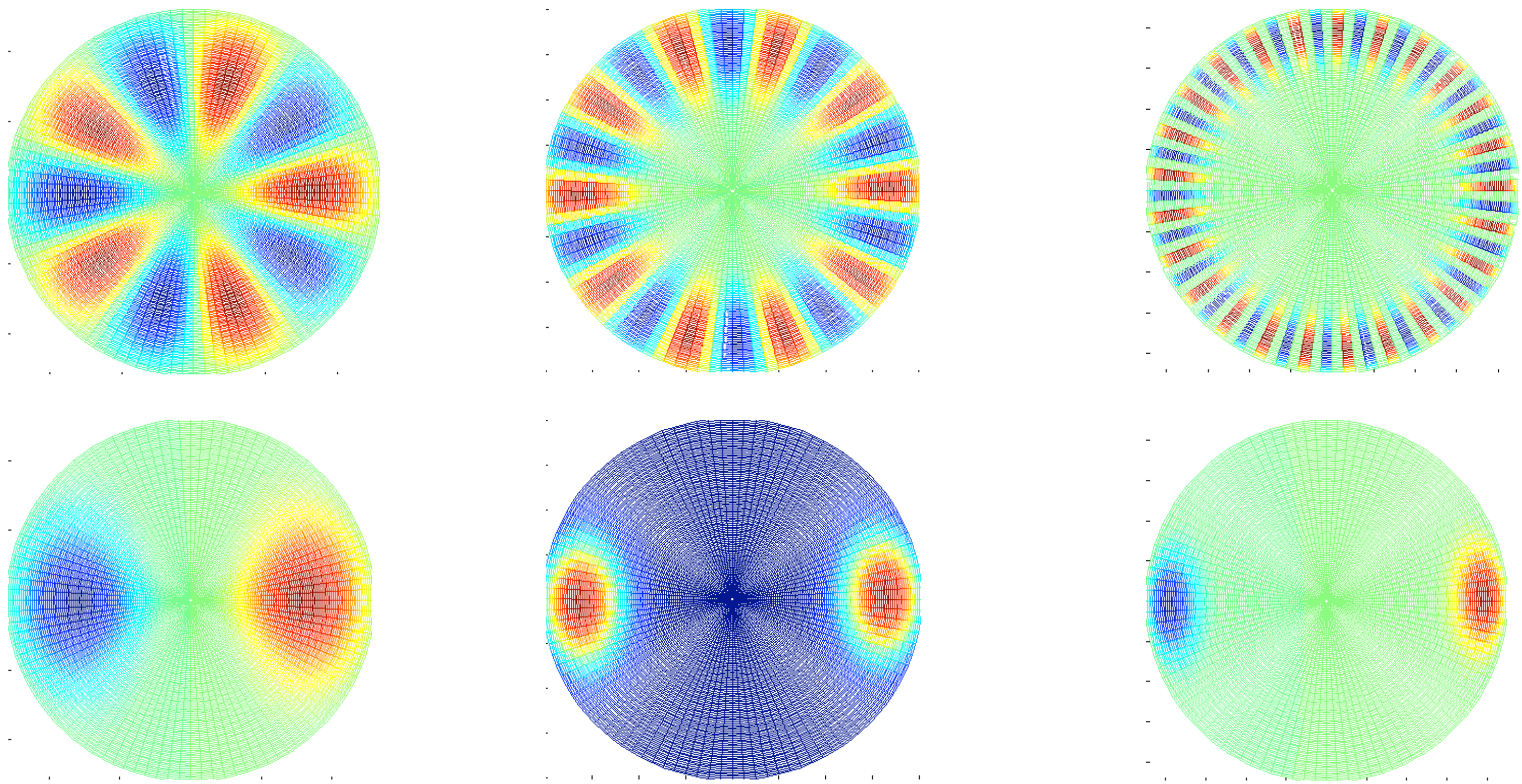
We would like to excite the modes that are confined close to equator of a sphere or the edge of the toroidal disk resonator, therefore we interested in exciting the modes with low n and m = l

Nature Feb 2002

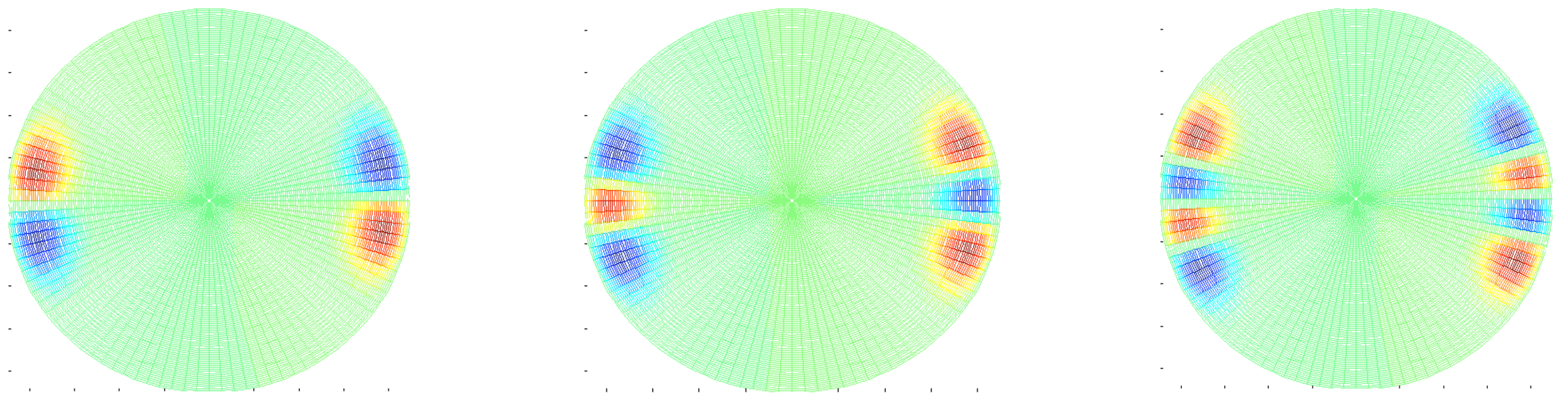
$$H_{\square} = n(n+1)\frac{\sqrt{k_p \square}}{\square^2} J_{n+\frac{1}{2}}(k_p \square) P_n^m(\cos\square)\sin(m\square)$$

M.E.Tobar,J.D.Anstie and J.G.Hartnett
IEEETransactionon Ultrasonics, Ferroelectronics and Freq. Control
Nov 2003

Whispering Gallery Modes

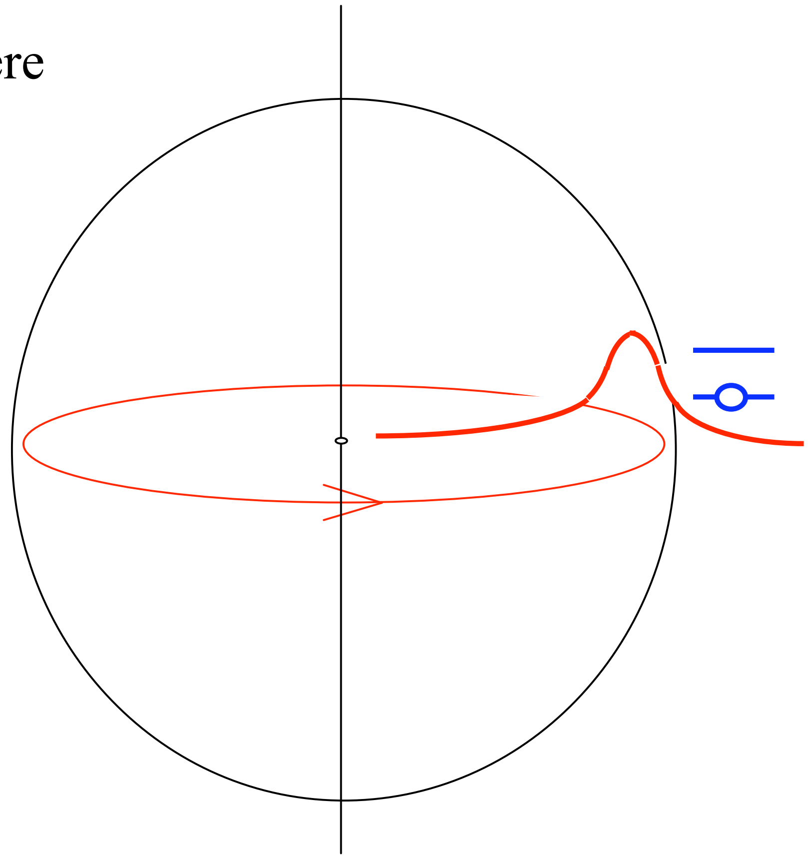


$l = m = 5$ $l = m = 10$ $l = m = 25$



Normalized modal distributions for *l* = 25, and *m* = 24, 23, and 22. At $l - m = 0$, the mode is Gaussian and centered about the equator. As $l - m$ increases, the energy distribution spreads further from the equator. Longitudinal cross section (*x*-*z* plane) showing WGM for (*l*,*m*) =(25,24), (25,23), and (25,22). The trend shows the concentration of field expands away from the equator as is increased.

Microsphere cavity

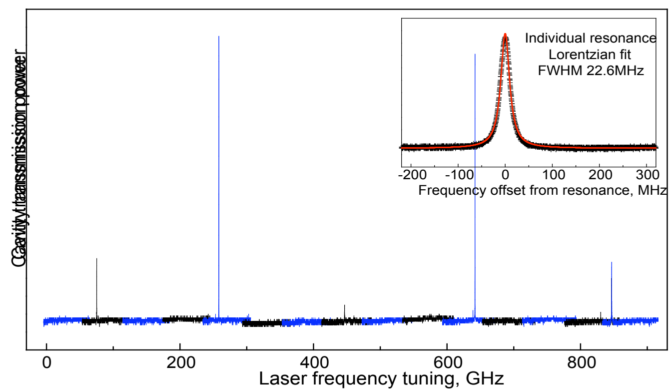


Two-level system in the evanescent field of WG mode

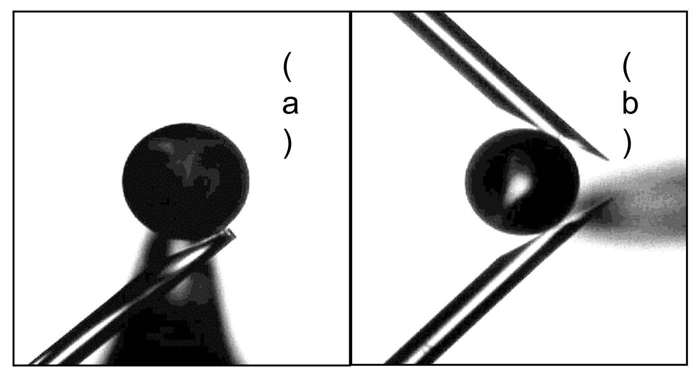
High-Q Photonic Filters

- JPL has previously demonstrated micro-resonators with Q> 10^9
  - Diameter 50-500 μm
  - Capable of supporting any optical carrier
  - RF frequency 5 GHz to 400 GHz obtained

- Efficient fiber coupling to micro-resonators achieved
  - Low insertion loss, simple approach to implement
  - Amenable to "mass production"
  - Critical coupling for highest efficiency possible



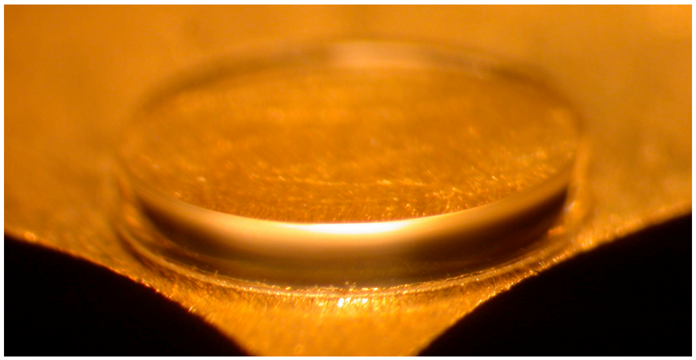
Spectrum of whispering-gallery modes in spheroidal dielectric microcavity (D = 160□m).



Fiber pigtailed microspherical resonator with 250 μm Diameter.

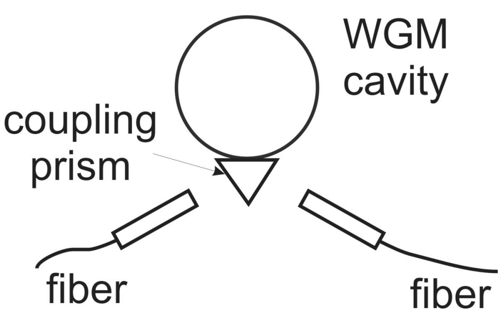
Filters

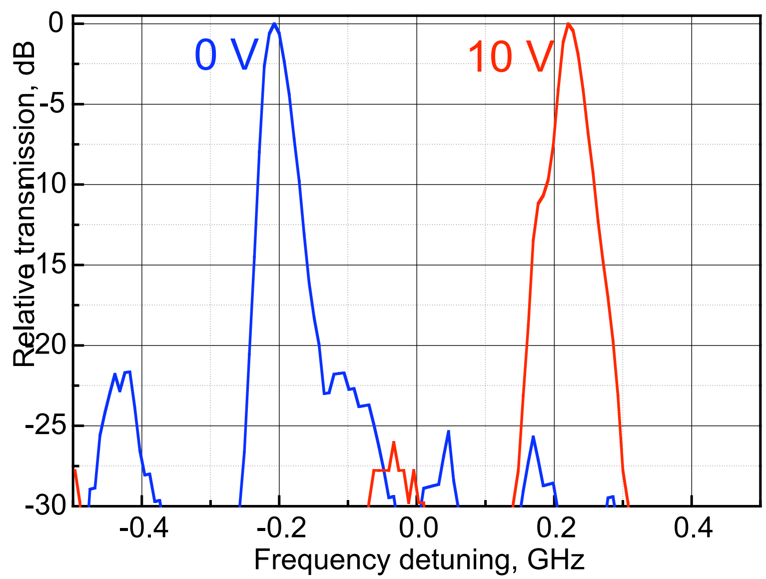
Tunable Lithium Niobate Filters



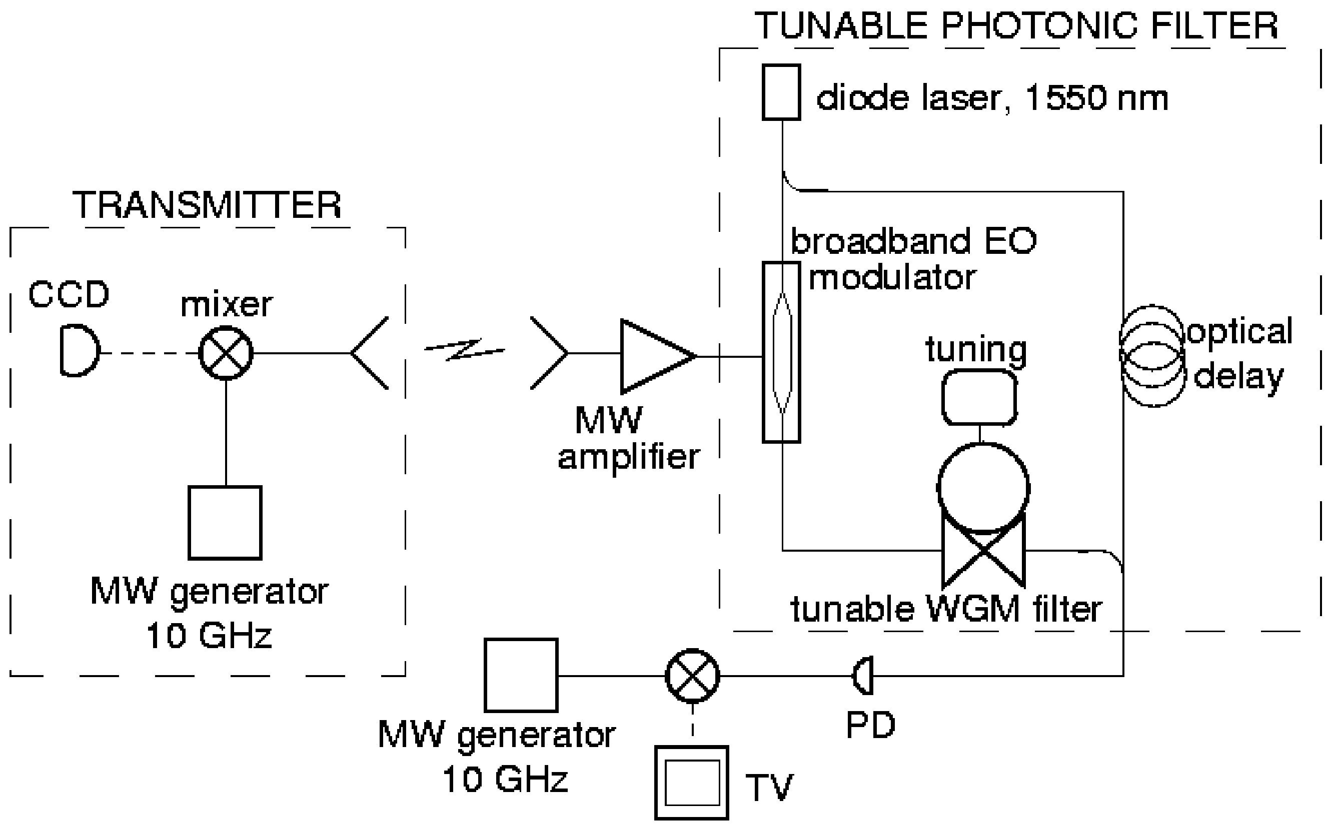
- Large quality factor:

  $Q = 2 \times 10^{8}$ *at* $\lambda = 1310\,nm$
- Large tuning range: 20 GHz per 150 V
- Insertion loss: 4-7 dB
- Small size: 1-12 mm
- High order filter realized

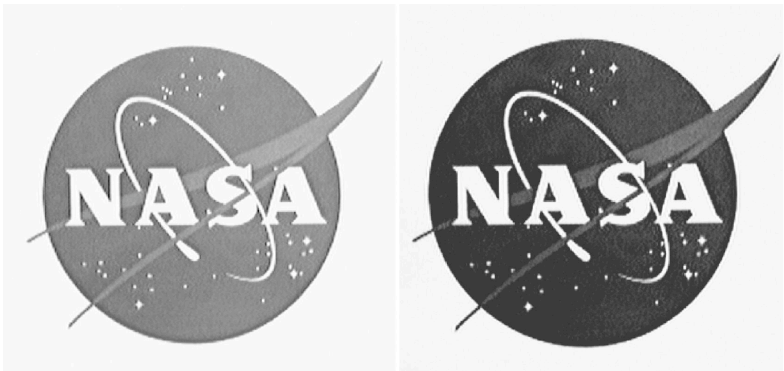




Photonic application: video transmission experiment



(A.A.Savchenkov et al., Electron. Lett. 39, 389 (2003))


NASA
NASA

Preliminary Results with Coupled Microspheres

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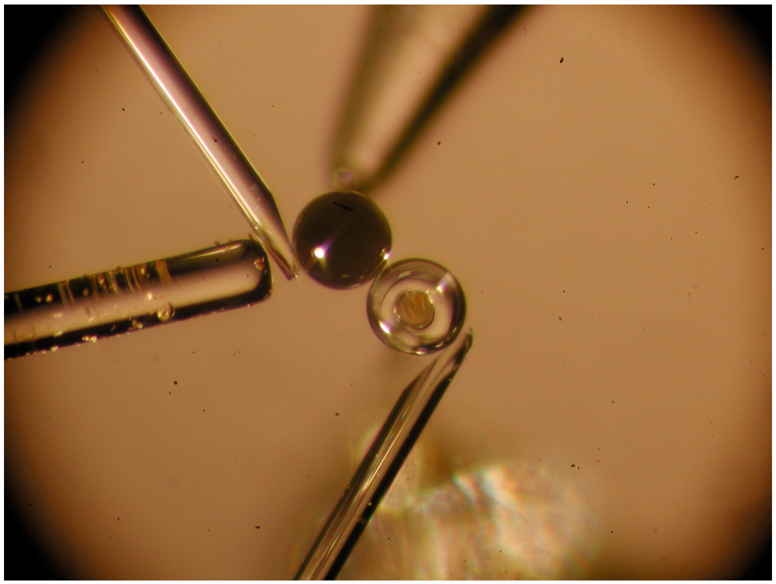
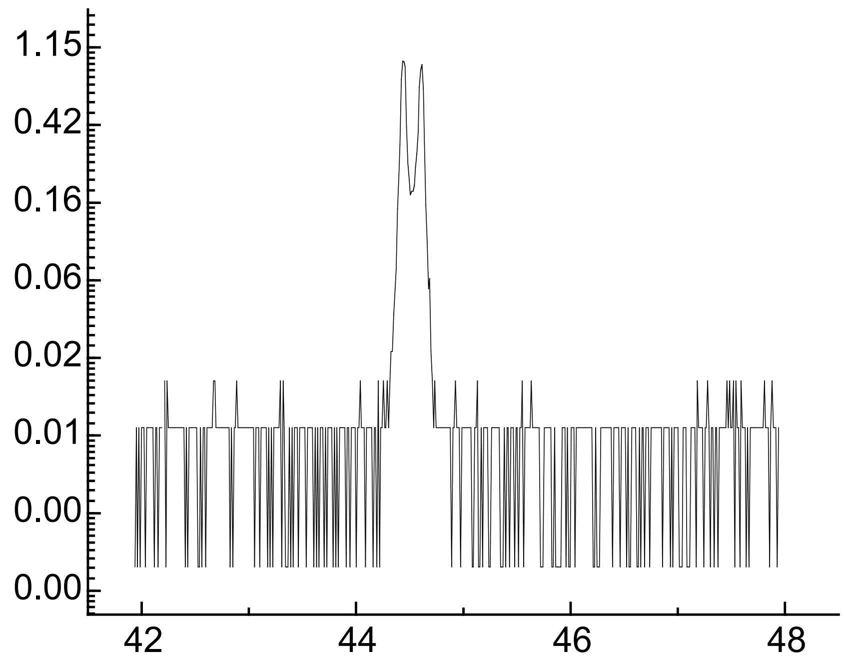
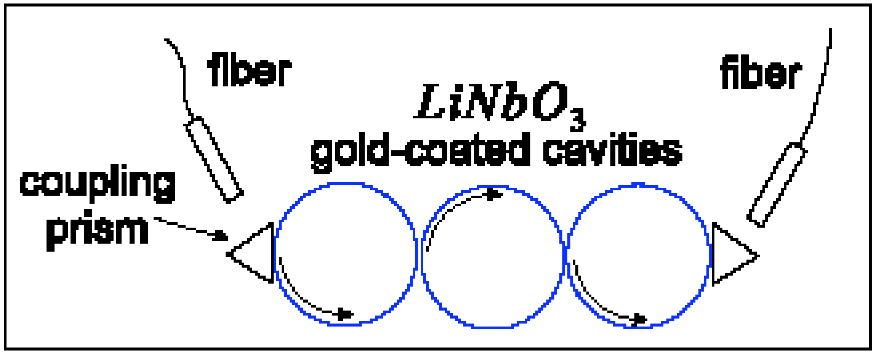




Third Order Filter



$$T = \frac{T_1 T_2 T_3}{(1 - R_1 R_2 \exp[i\psi_{12}])(1 - R_2 R_3 \exp[i\psi_{23}]) - R_1 R_3 |T_2|^2 \exp[i(\psi_{12} + \psi_{23})]},$$

Tunable filter based on three lithium niobate resonators

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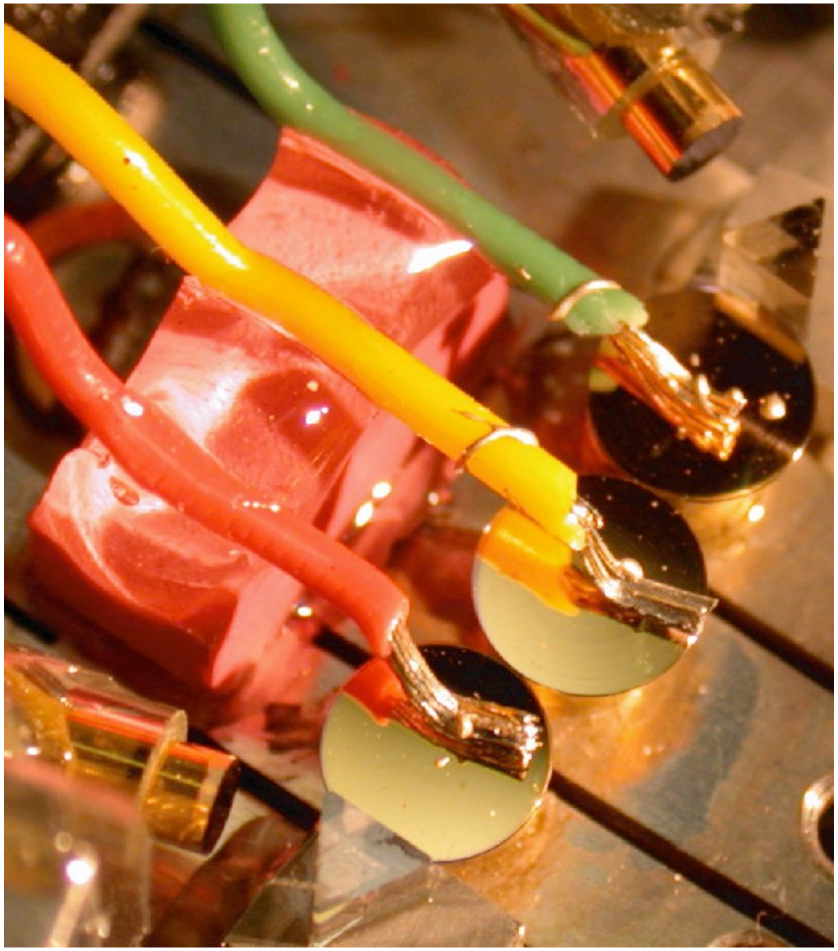
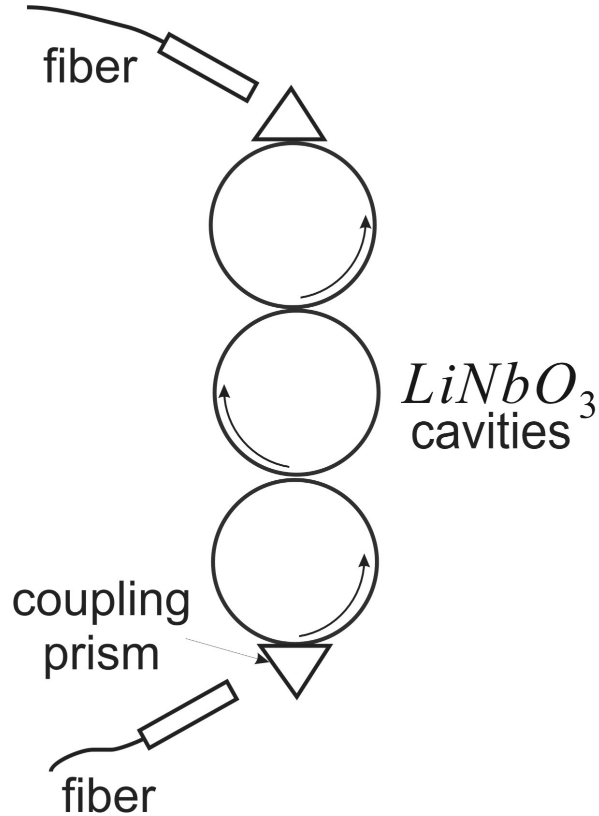
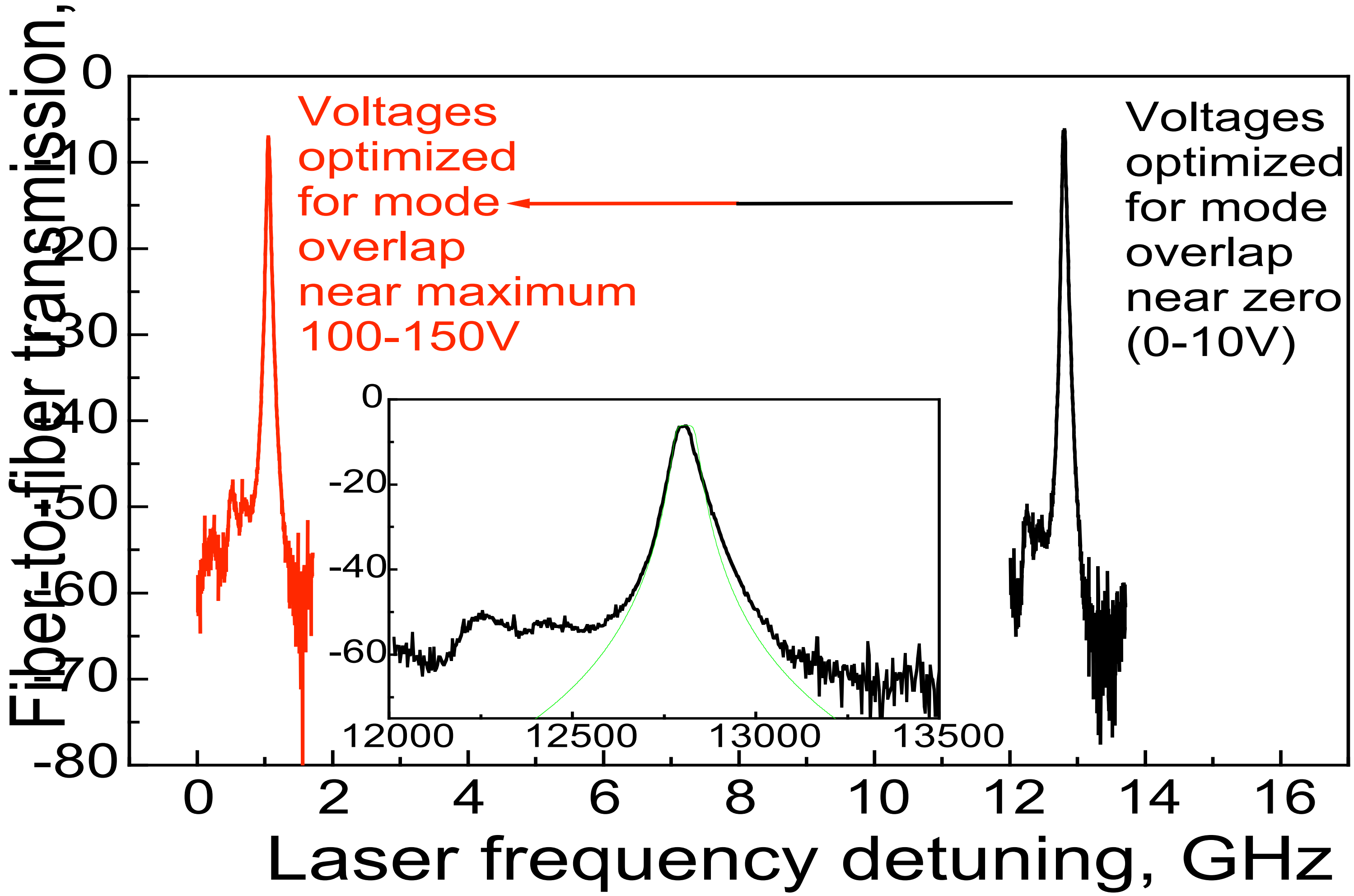




Filter function and tunability



Green line is the theoretical Butterworth filter curve, $\frac{\Gamma^6}{(\omega-\omega_0)^6+\Gamma^6}$ where $\Gamma = 29\ MHz$

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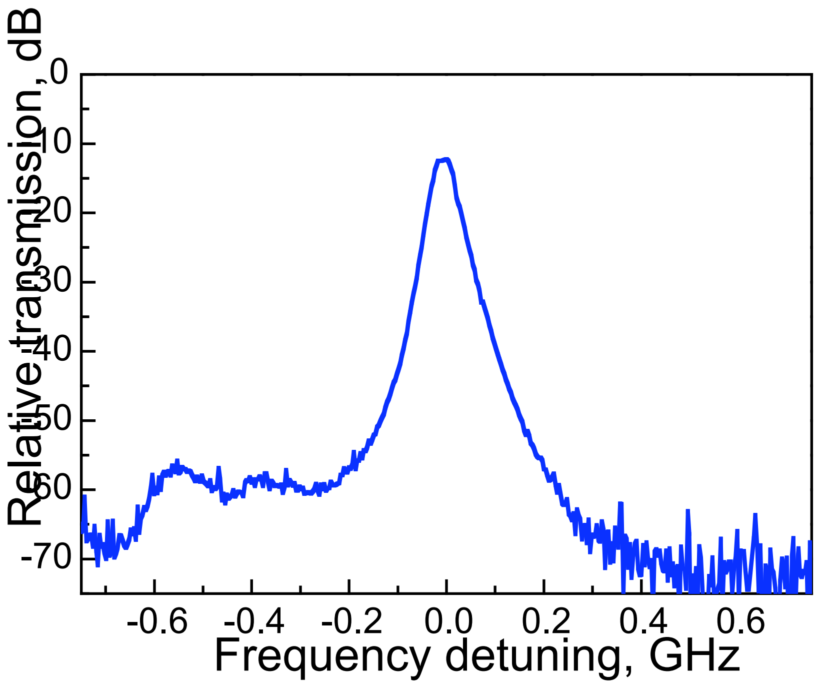
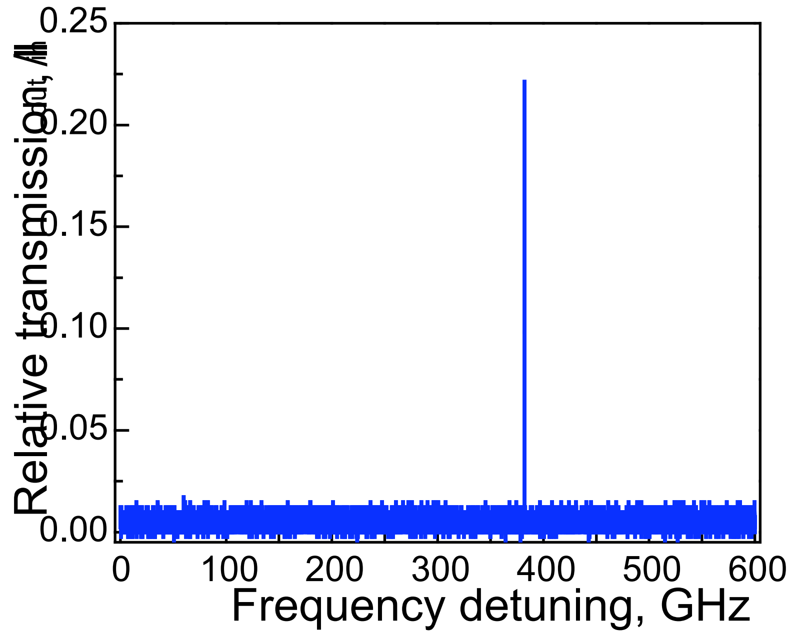
Third order filter based on three coupled WGM resonators





Modulators

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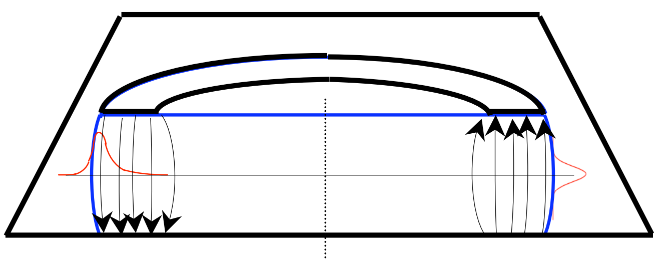
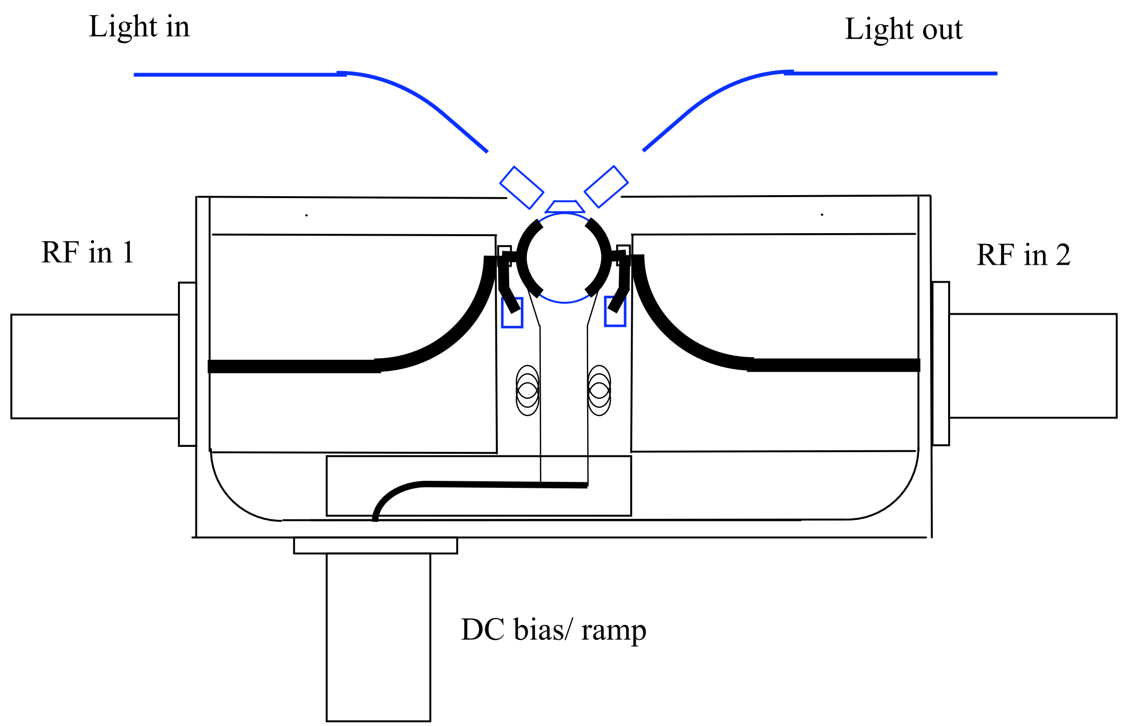
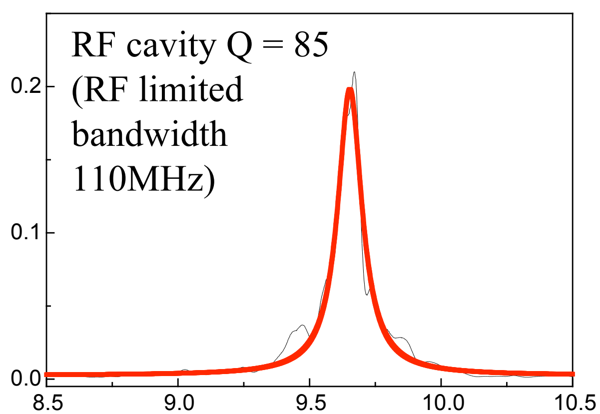
Schematic of optical and microwave mode overlap, microwave resonance, and example of embodiment

Operation of WG resonance modulator: high-Q optical whispering-gallery modes superimposed with mm-wave microstrip cavity

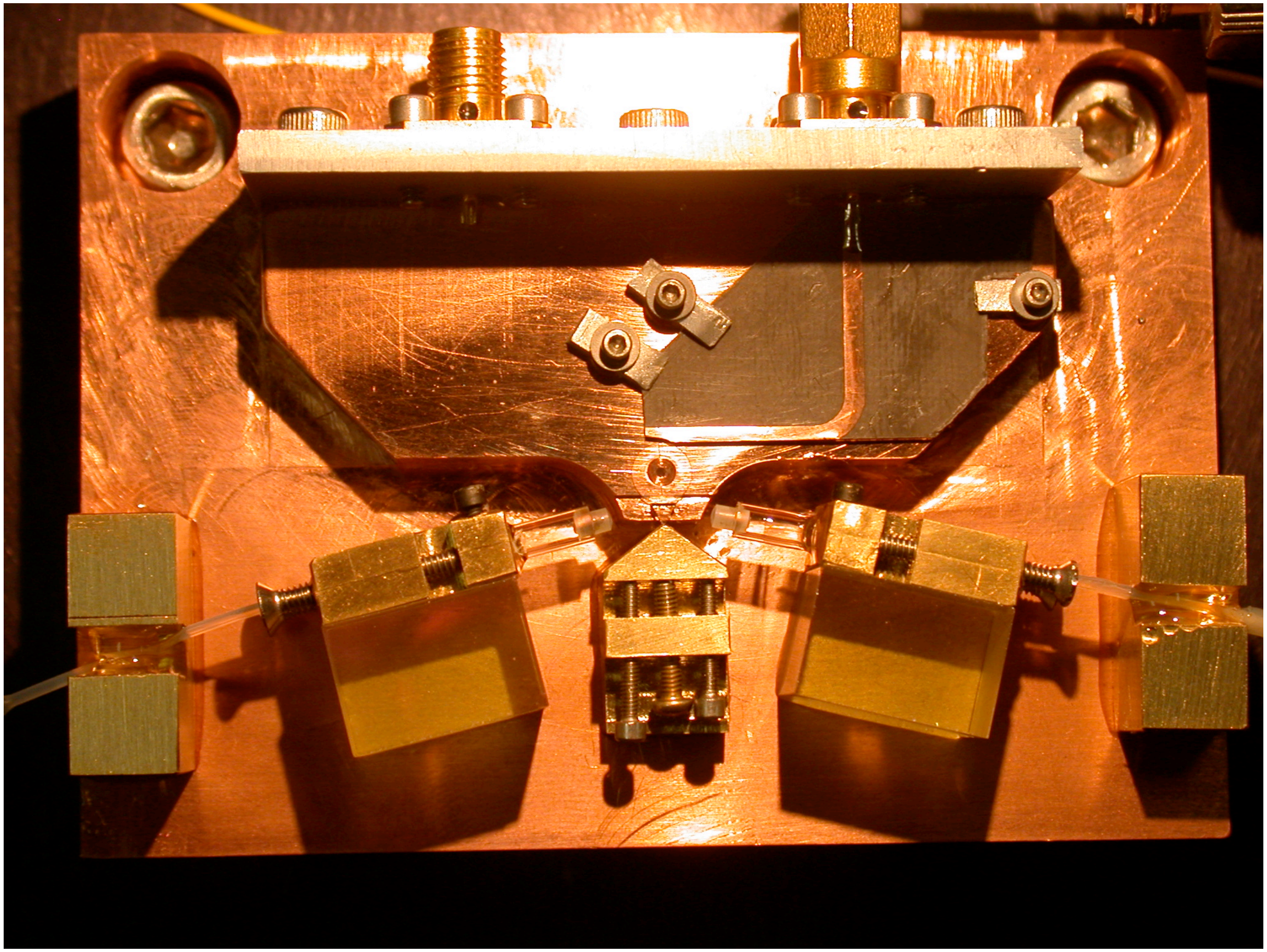


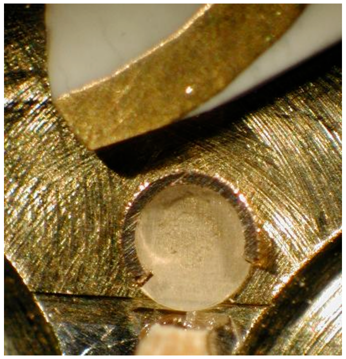


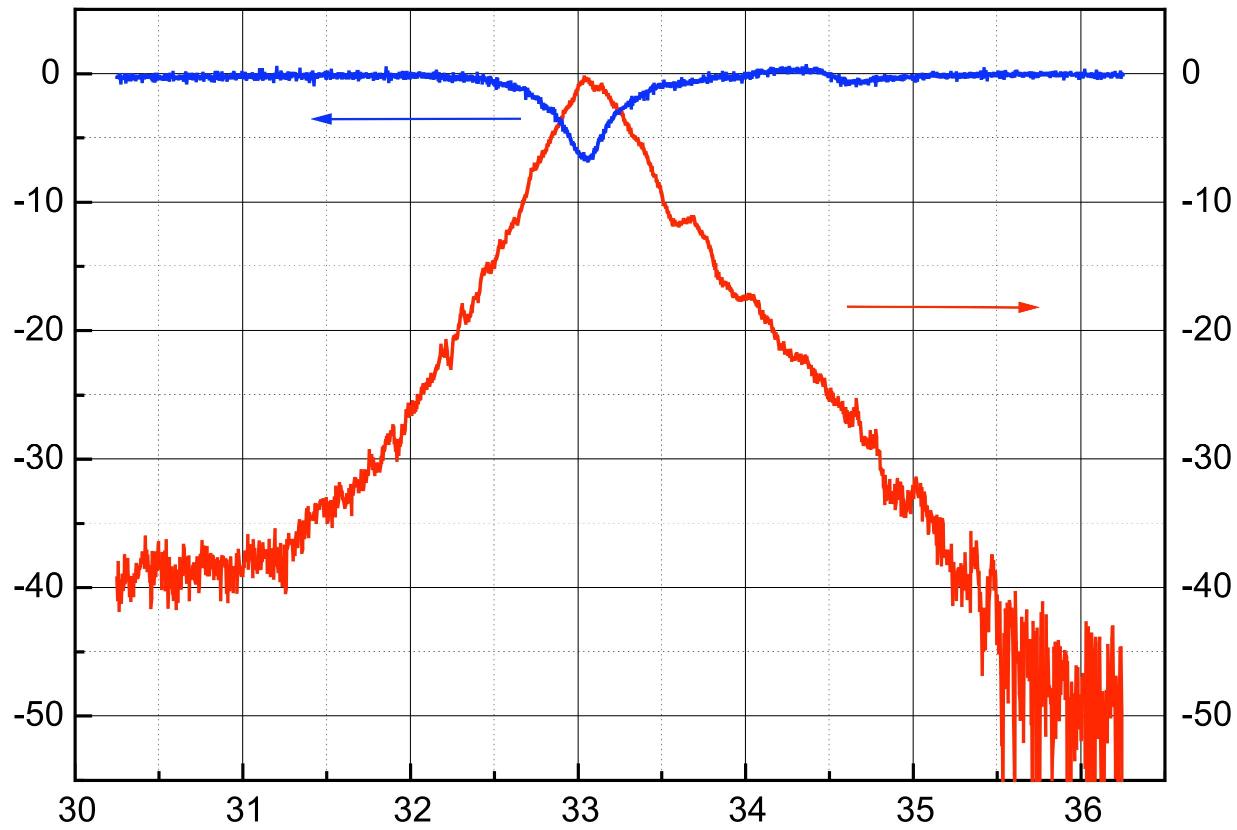


Integration

(Savchenkov, et al Electronic Letters 2003)






0
-10
-20
-30
-40
-50
30
31
32
33
34
35
36
0
-10
-20
-30
-40
-50

Ultra-High Efficency Modulator/Reciever

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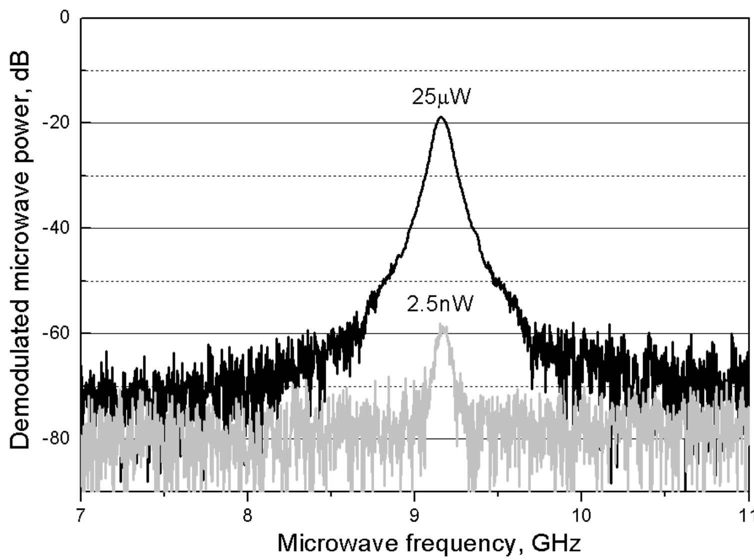

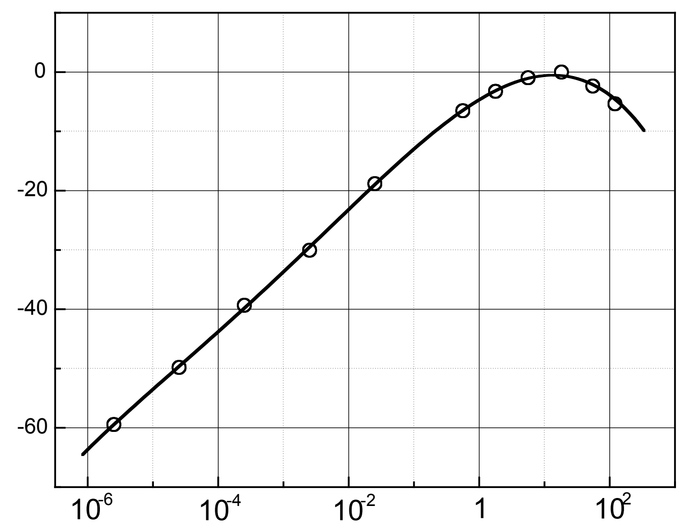

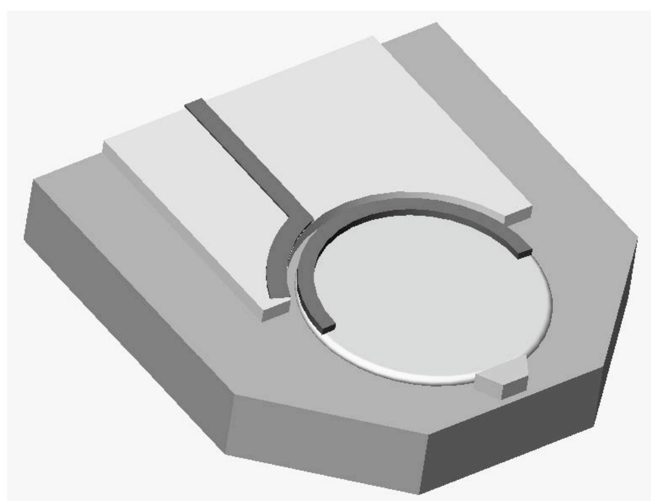

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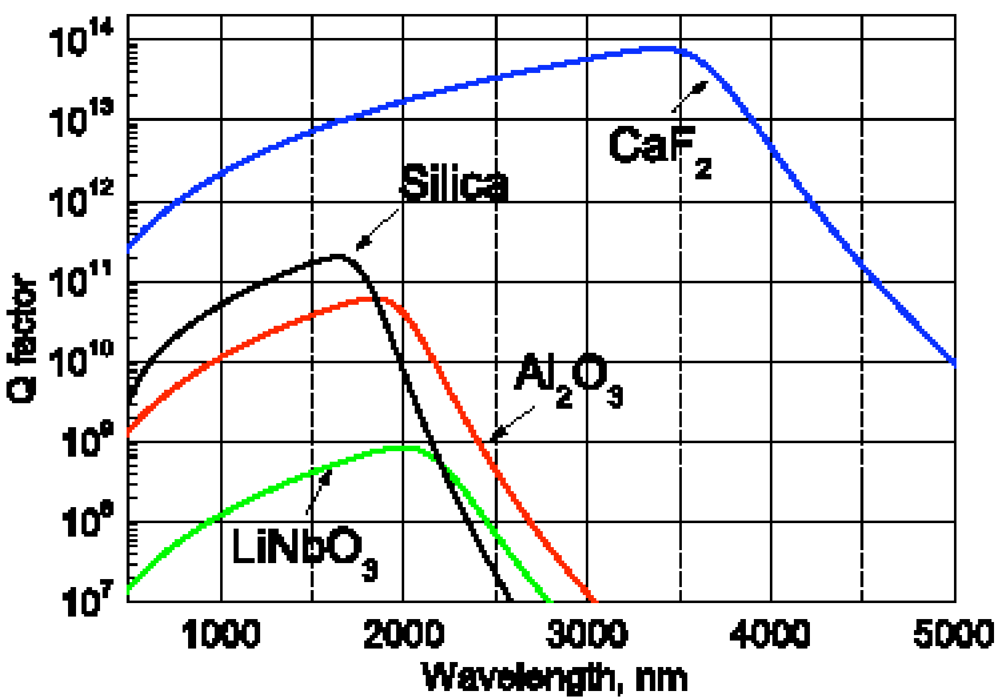
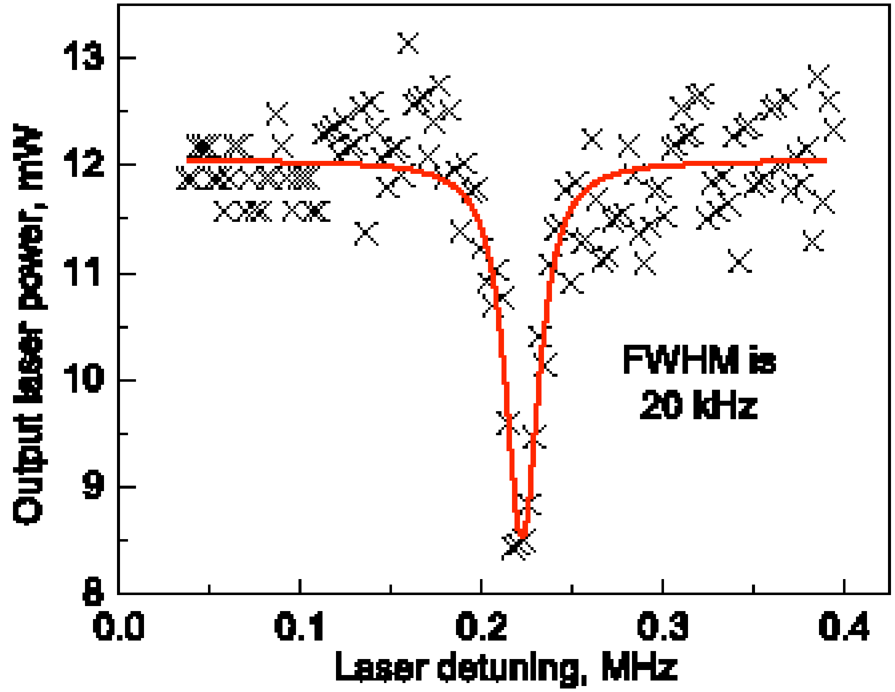
Theoretical Q Values



New Q Record



$Q = 2 \times 10^{10}$

Tunable Delays

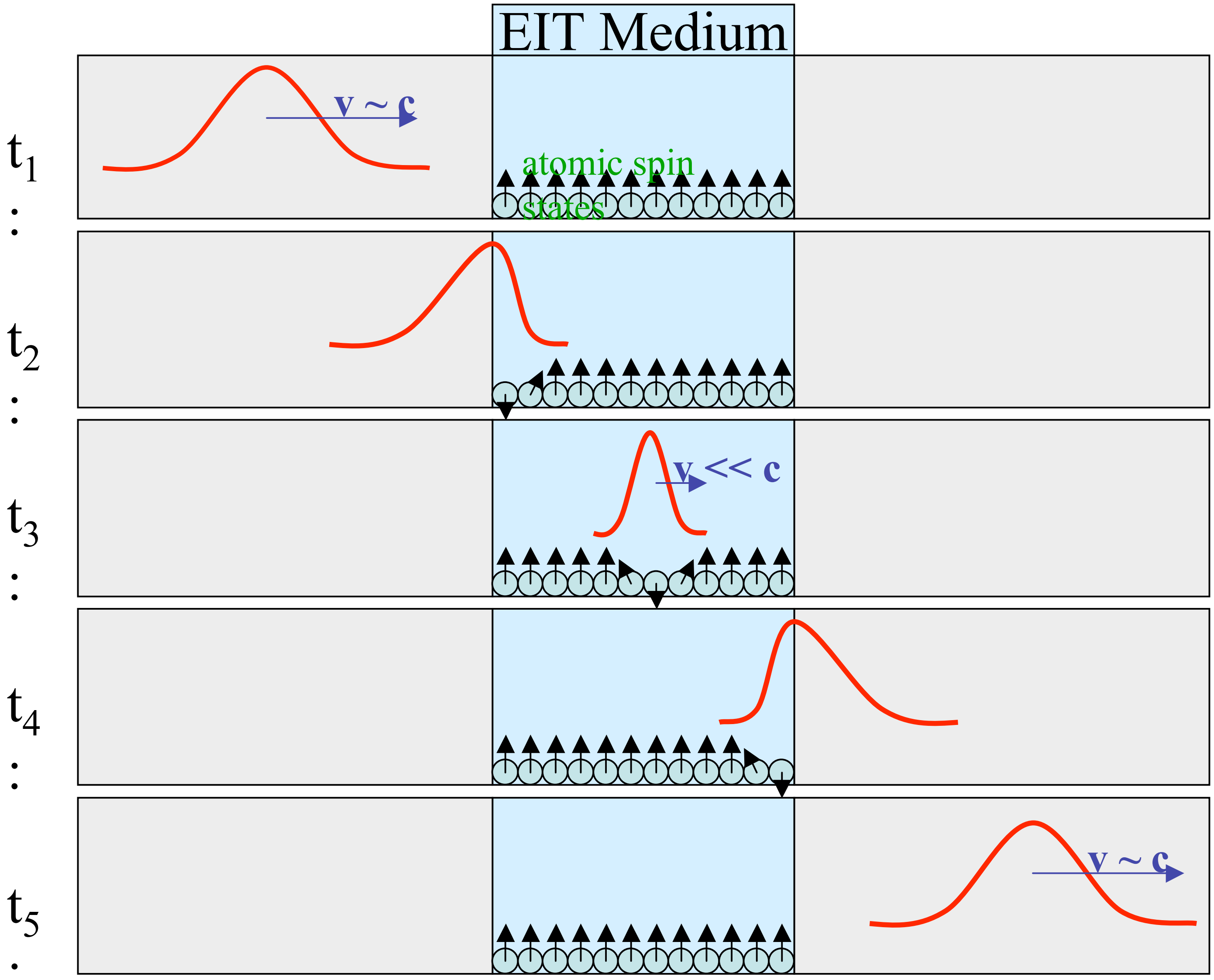
Phase Velocity: $$\mathrm{v}_p = \frac{\omega}{k}$$

Group Velocity: $$\mathrm{v}_g = \frac{\partial \omega}{\partial k} = \frac{d\omega}{dk}$$

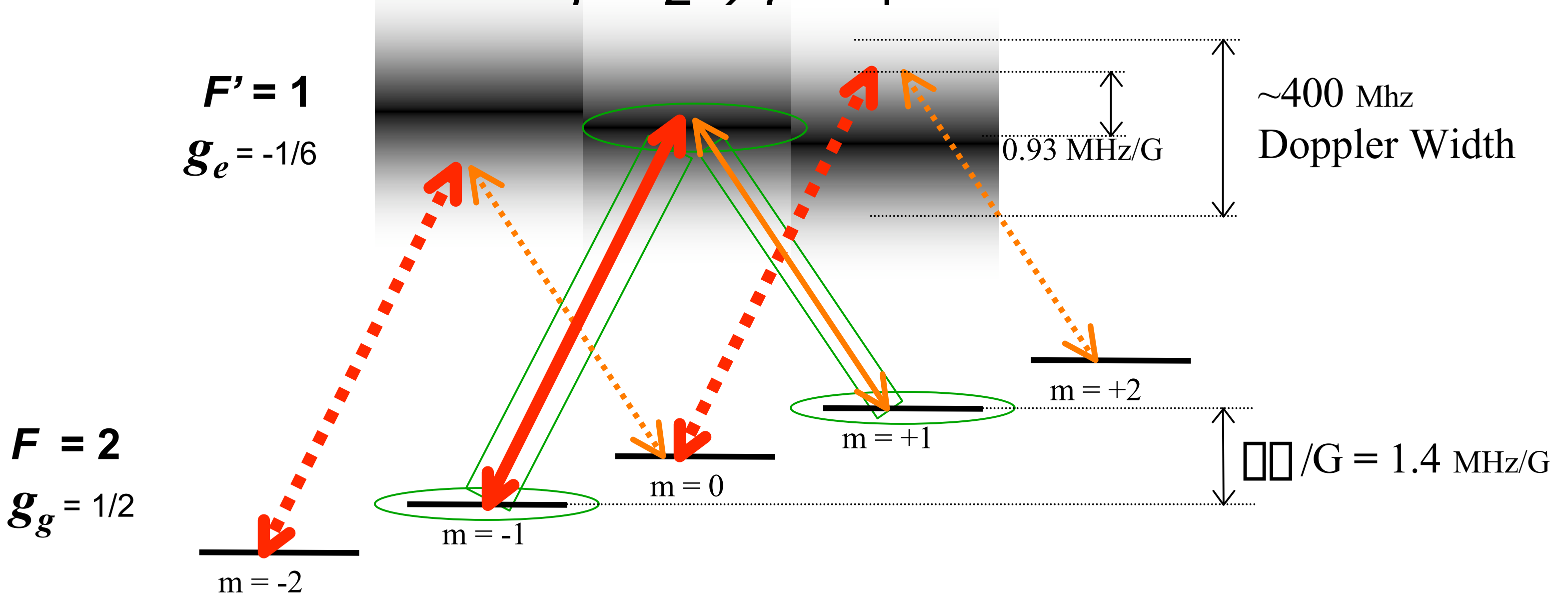
Differentiating the dispersion equation yields…

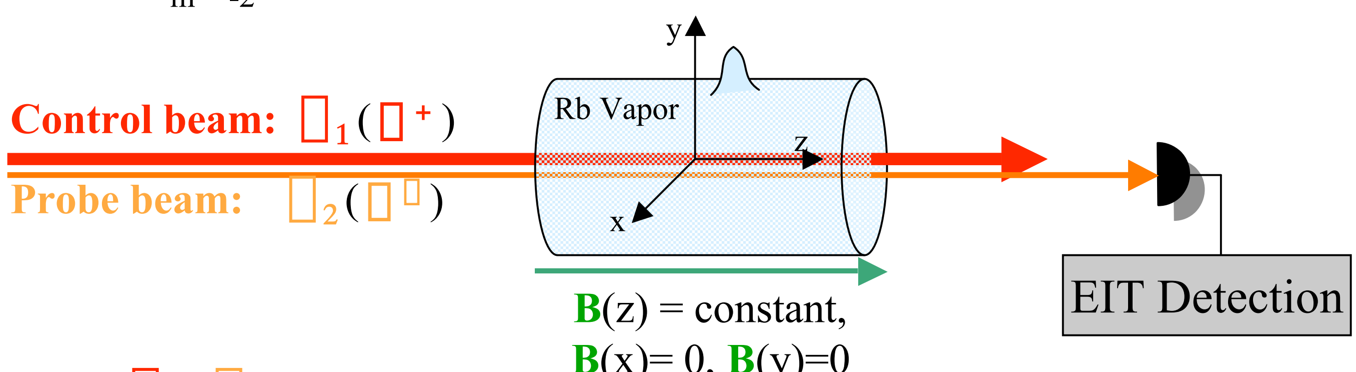
$$\frac{d}{dk}\left[kc = \omega n(\omega, k)\right] \Rightarrow \quad c = \frac{d\omega}{dk}\left(n + \omega \frac{\partial n}{\partial \omega}\right)$$

$$\mathrm{v}_g \equiv \frac{c}{n + \omega\left(\frac{\partial n}{\partial \omega}\right)}$$


EIT Medium
t1
v ~ c
atomic spin
states
t2
t3
v << c
t4
t5
v ~ c

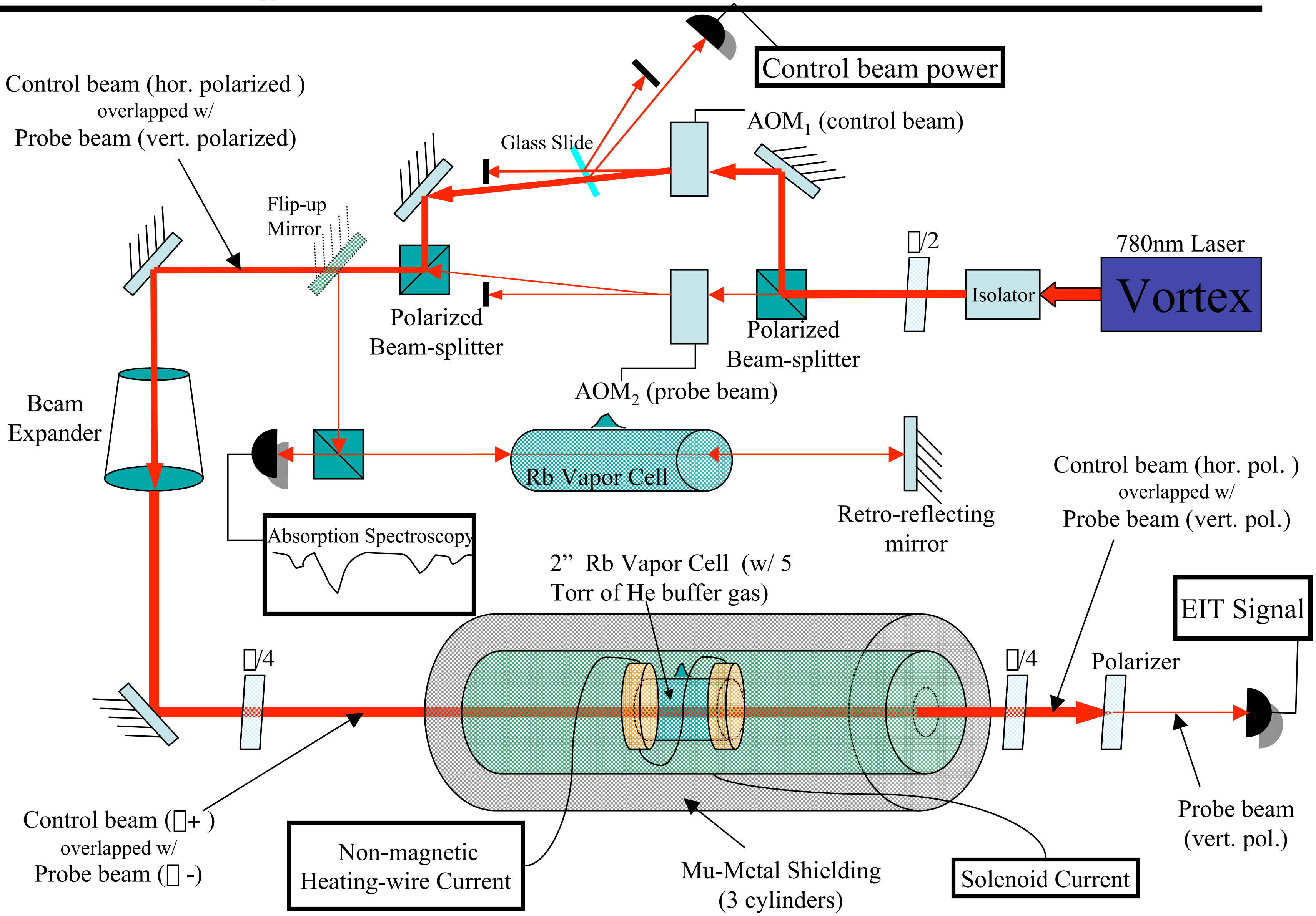
^{87}Rb D_1-line ($5^2S_{1/2} \rightarrow 5^2P_{1/2}$), $F = 2 \rightarrow F' = 1$

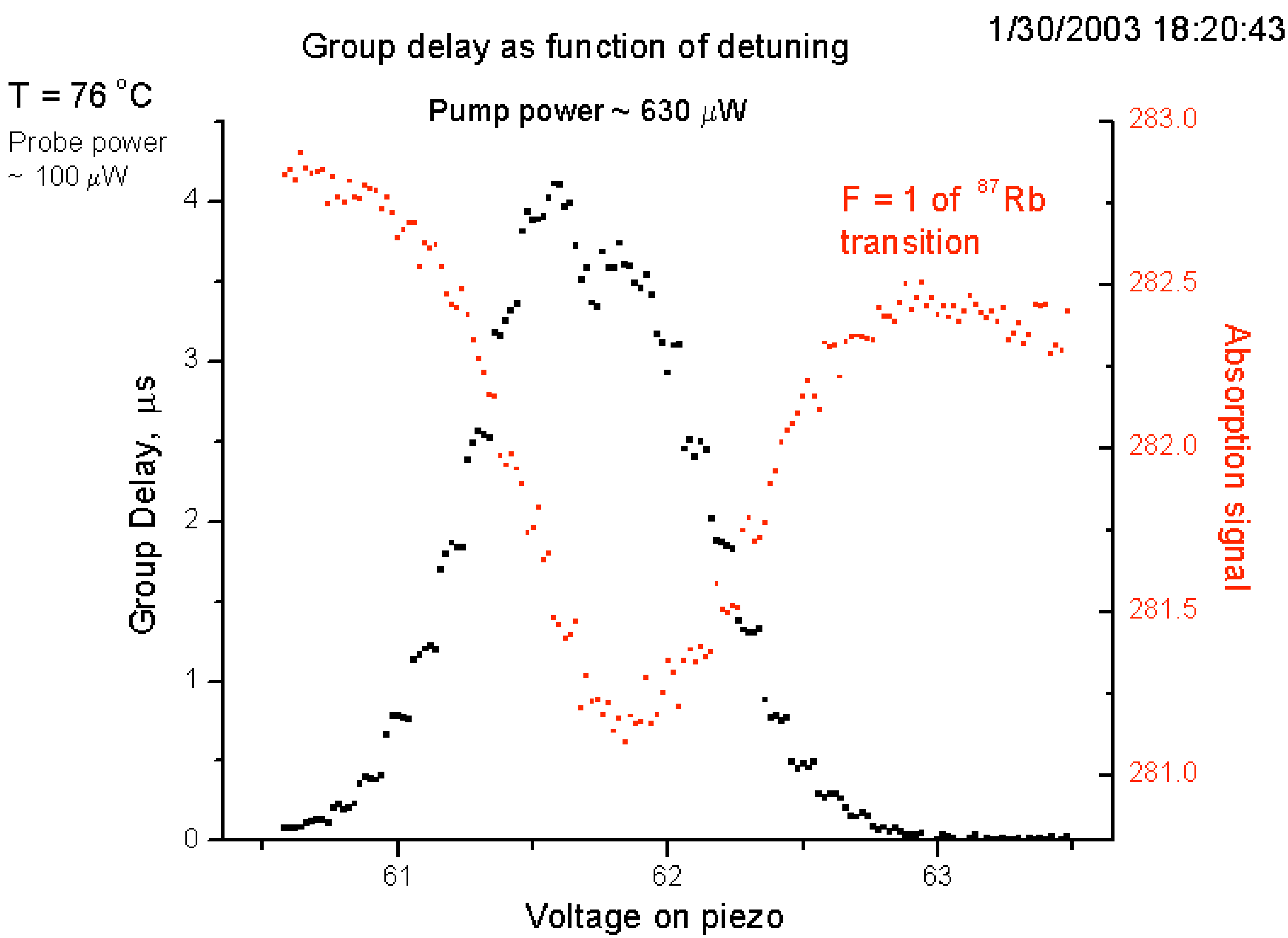


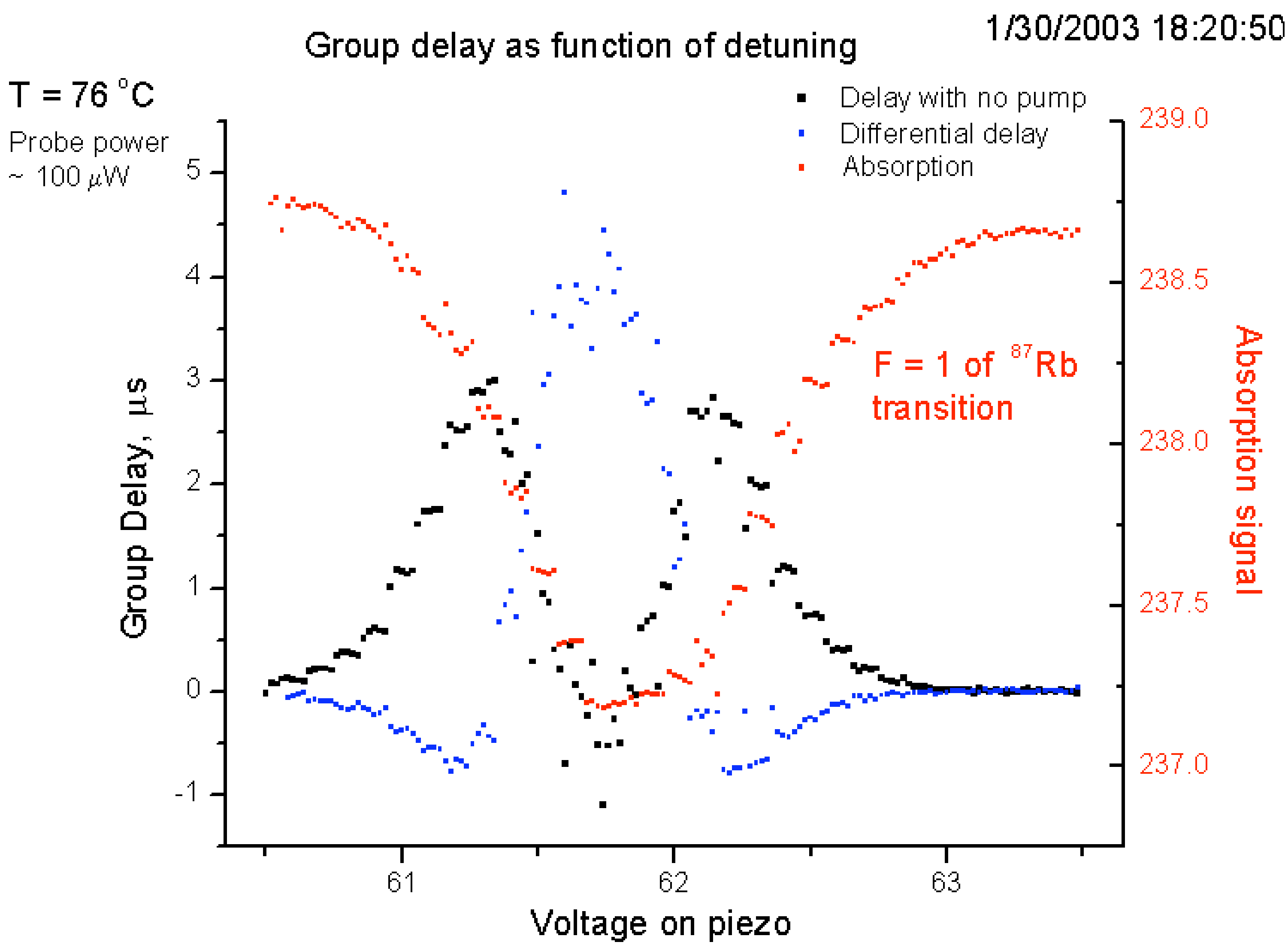


□□ = □$_1$ - □$_2$ = 2 □g_g **B**

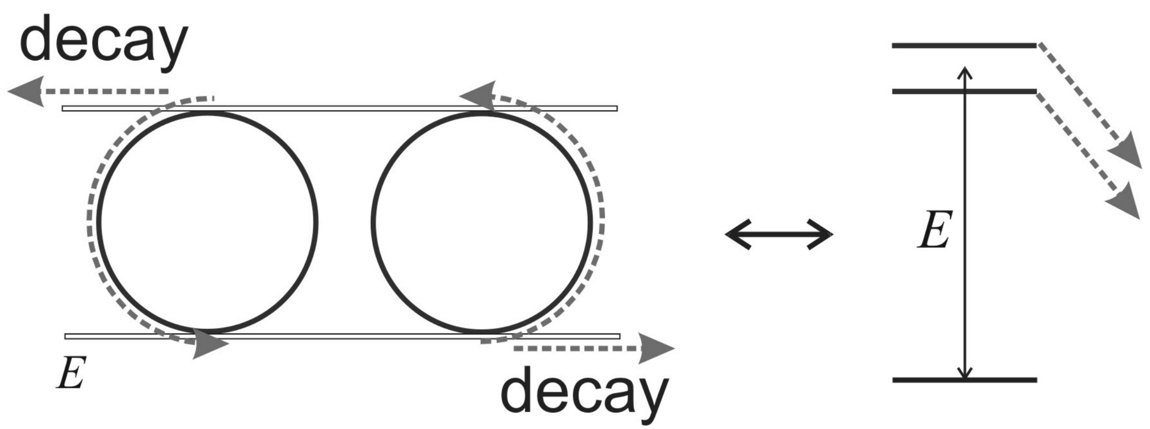
(where □ = 1.4 MHz/G, and g_g is the ground state Lande-factor)

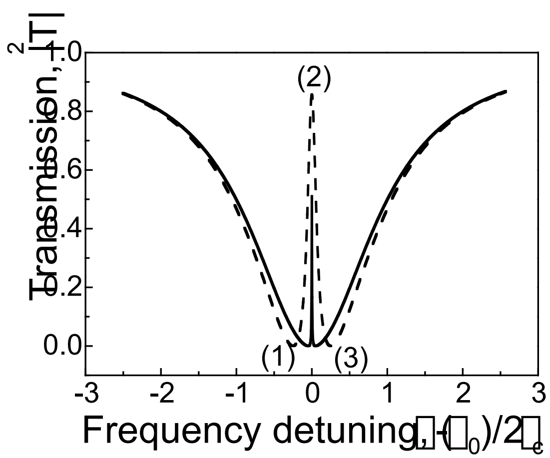

Control beam power
AOM$_1$ (control beam)
Glass Slide
Control beam (hor. polarized)
overlapped w/
Probe beam (vert. polarized)
Flip-up Mirror
□/2
780nm Laser
Vortex
Isolator
Polarized Beam-splitter
Polarized Beam-splitter
AOM$_2$ (probe beam)
Beam Expander
Rb Vapor Cell
Retro-reflecting mirror
Absorption Spectroscopy
Control beam (hor. pol.)
overlapped w/
Probe beam (vert. pol.)
2" Rb Vapor Cell (w/ 5 Torr of He buffer gas)
EIT Signal
□/4
□/4
Polarizer
Control beam (□+)
overlapped w/
Probe beam (□ -)
Non-magnetic Heating-wire Current
Mu-Metal Shielding (3 cylinders)
Solenoid Current
Probe beam (vert. pol.)

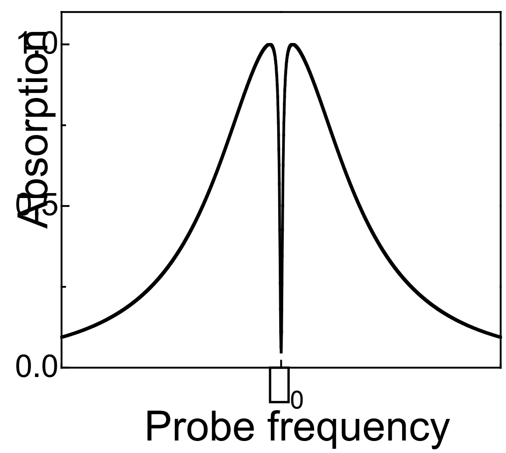

Group delay as function of detuning
1/30/2003 18:20:43
T = 76 °C
Probe power
~ 100 μW
Pump power ~ 630 μW
F = 1 of 87Rb
transition
Group Delay, μs
Absorption signal
Voltage on piezo
0
1
2
3
4
61
62
63
281.0
281.5
282.0
282.5
283.0

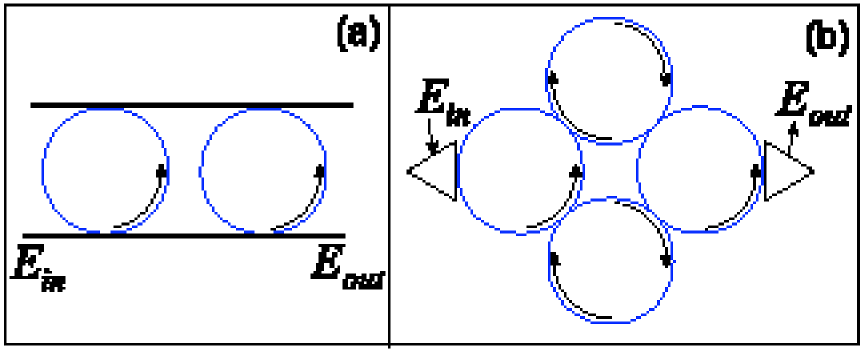

Group delay as function of detuning
1/30/2003 18:20:50
T = 76 °C
Probe power
~ 100 μW
Delay with no pump
Differential delay
Absorption
F = 1 of 87Rb
transition
Group Delay, μs
Absorption signal
Voltage on piezo
5
4
3
2
1
0
-1
61
62
63
239.0
238.5
238.0
237.5
237.0

An analogy with EIT in quantum systems: interference of decays









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

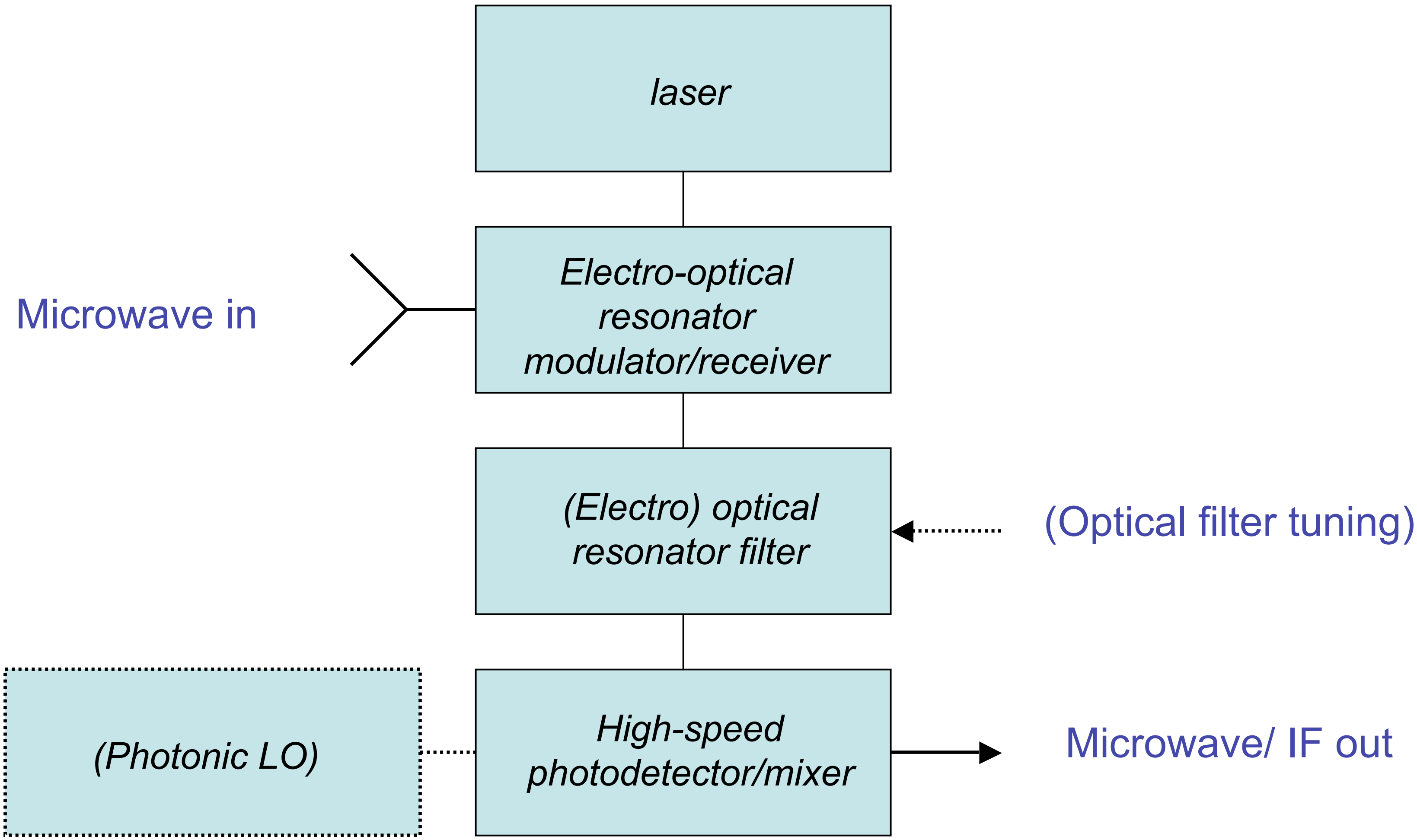
$$\tau_g \simeq \frac{16\gamma_c(\omega_1 - \omega_2)^2}{[16\gamma\gamma_c + (\omega_1 - \omega_2)^2]^2} \gg \gamma_c^{-1}.$$

WGM PPLN resonator

California Institute of Technology

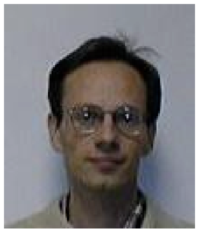
Manipulation of spectral properties and tunability is important for applications

Examples of RF photonics applications: *filtering, modulation, reception*



Potential Applications

- Multi-spectral radar receiver
- Wide-band receivers for planetary communication networks
- RF antenna remoting for the DSN
- Large arrays
- Photonic signal processing



Andrey Matsko

Anatoliy Savchenkov

Vladimir Ilchenko

Dmitry Strekalov

Nan Yu

Shouhua Huang

Makan Mohageg and Ivan Grudinin
David aveline