微腔光子学
Microcavity photonics

--Organic/Inorganic hybrid materials based optical microcavities and applications

Lei Xu

Department of Optical Science and Engineering
Fudan University, Shanghai 200433, China

Outlines

- Background
- Important works in the field
- Our works
- Conclusion

Researches on:

Microcavity optics

Materials and devices for integrated optics

Novel optical properties driven by ultrafast laser pulses irradiation

Photonics development =

New materials +

New device structures

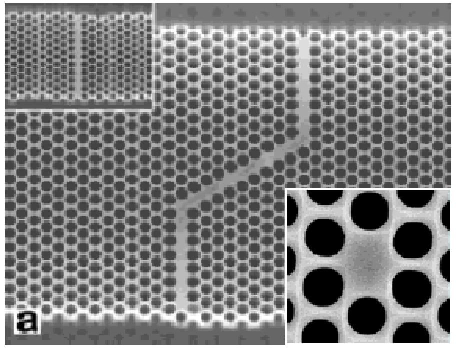
- Electronics
- Micro-electronics
- Integrated Circuit
- VLSI circuit
- Nano-electronics

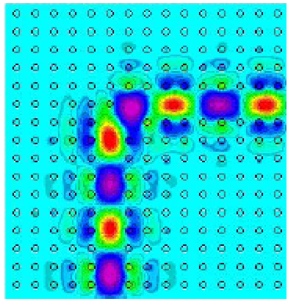
- Photonics
- Micro-photonics
- Integrated optics
- Large scale integration
- Nano-photonics

Pushing the Size Limits of Photonics

- Controlling the flow of light in small volumes – optical memory, logic, switching, etc.

Photonic Crystals (>1 μm)

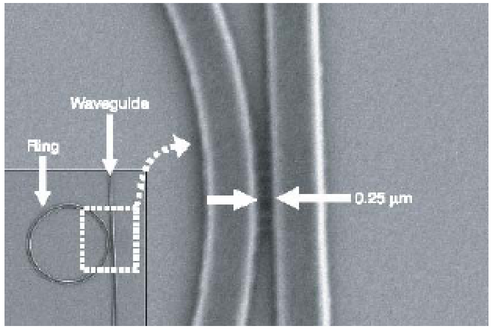


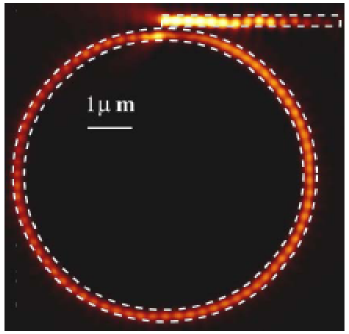


S.Y. Lin *et.al. Science* **282**, 274 (1998).

A. Birner *et. al. Adv. Mat.* **13**, 377 (2001).

Slab/Slot Waveguides (<1 μm)

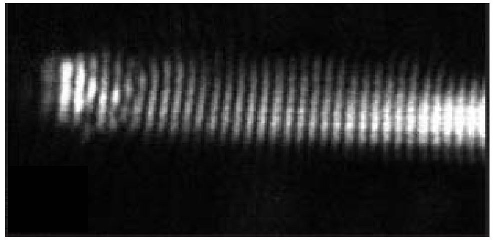


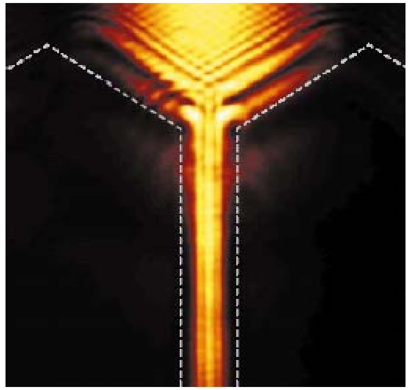


V.L. Almeida *et. al. Nature* **431**, 1081 (2004).

R. Quidant *et. al. Phys. Rev. B* **69**, 81402R (2004).

Plasmonics (< 100 nm)





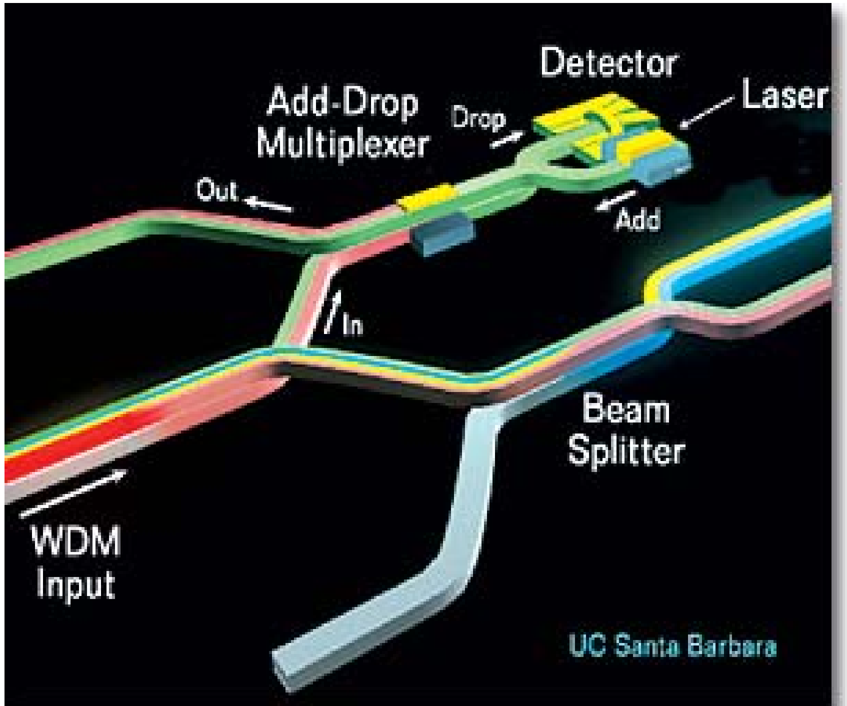
J.C. Krenn *et. al. Phil. Trans. R. Soc. Lond.* A ***362**, 739 (2004)*

Barnes *et. al. Nature* **424**, 824 (2003).

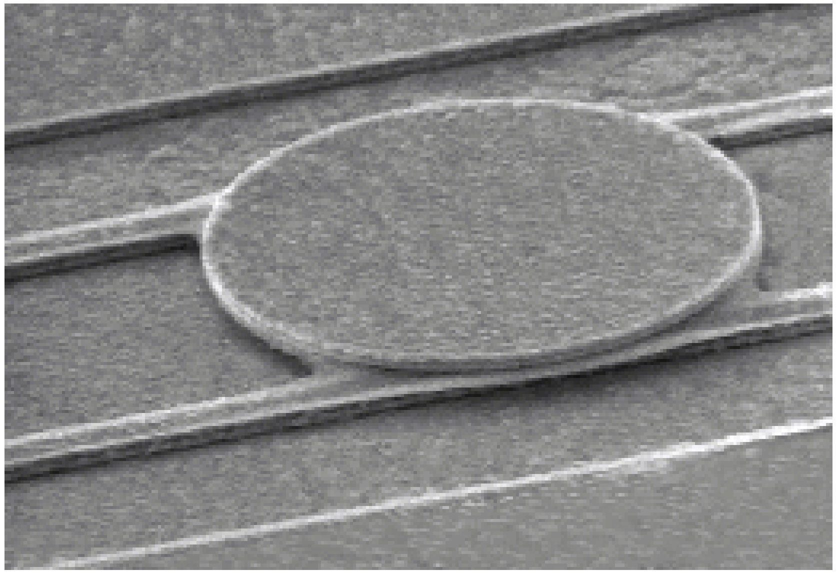
College of Chemistry

University of California, Berkeley

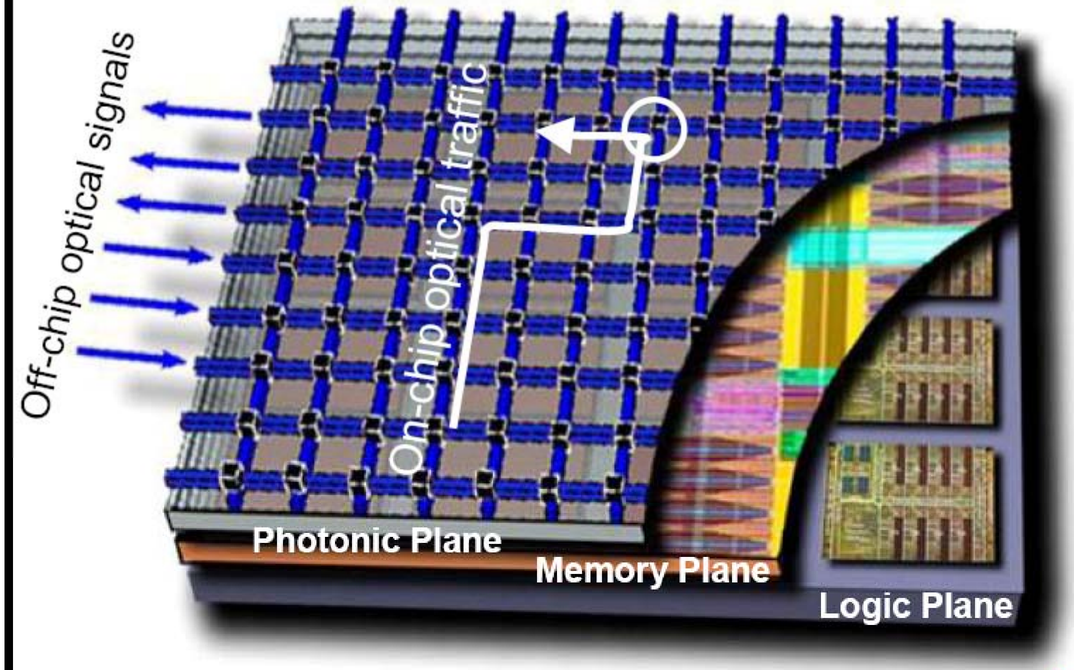
光子芯片 Photonic chip



Vertical integration



Optical interconnects



36 "Cell" chip (~300 cores)

Optoelectronic system on chip

Logic plane	~300 cores
Memory plane	~30GB eDRAM
Photonic plane	On-Chip Optical Network
	>70Tbps optical on-chip
	>70Tbps optical off-chip

Photonic layer is not only connecting various cores, but also routes the traffic

All future dates and specifications are estimations only. Subject to change without notice.

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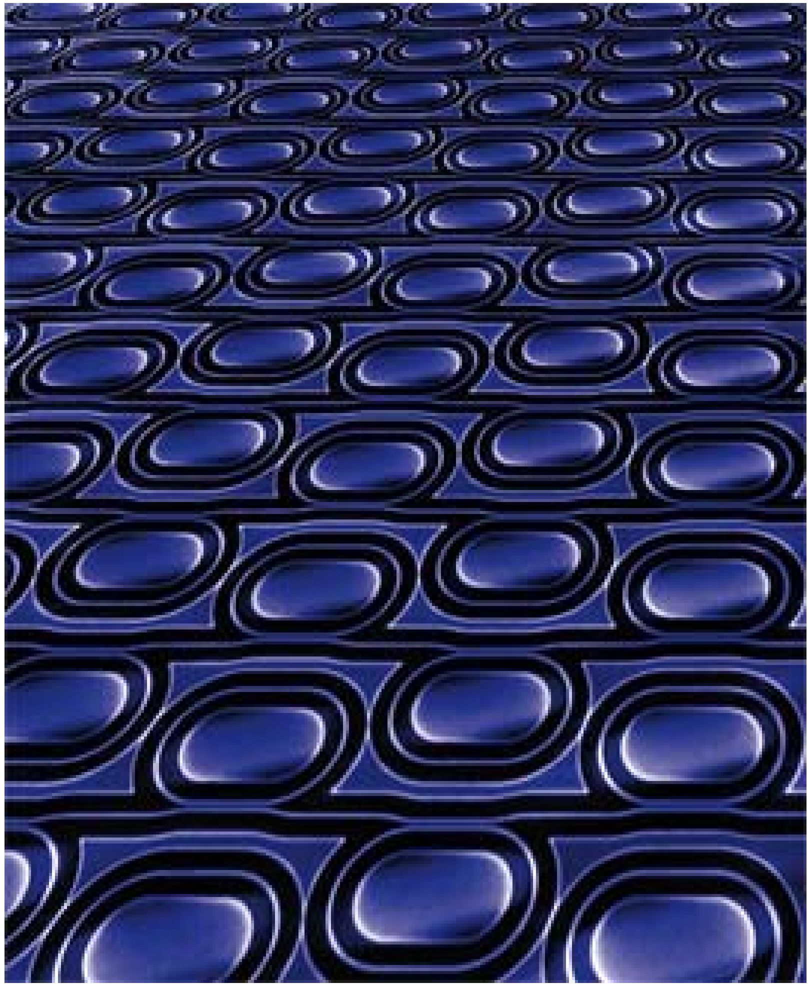
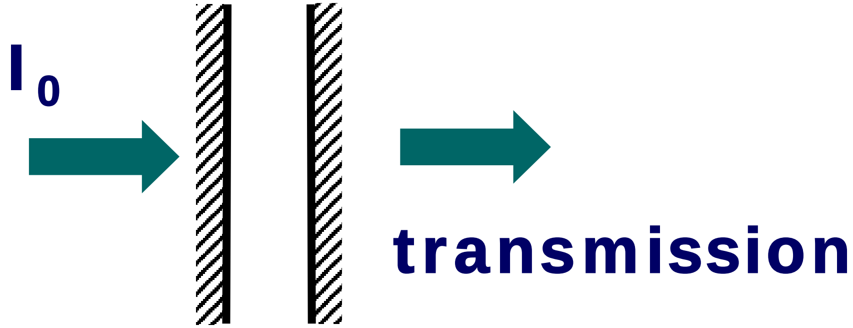
Optical microcavity are important element in photonic integrated circuit



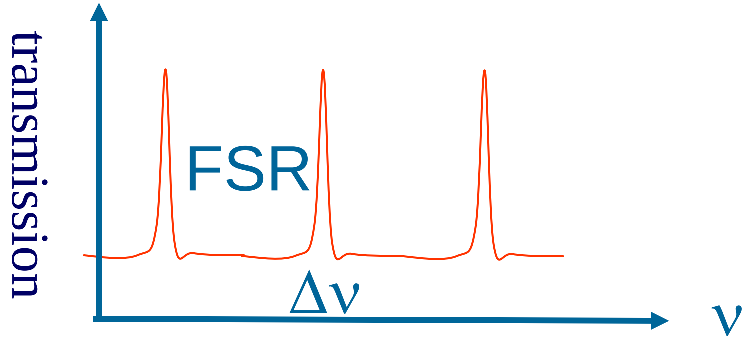
www.research.ibm.com/photonics/

A Fabry-Perot cavity



Mode formation requirement

$$2nd = m\lambda$$



Q = ν/Δν

FSR = c/2nL

Light intensity in a cavity:

Cavity enhancement

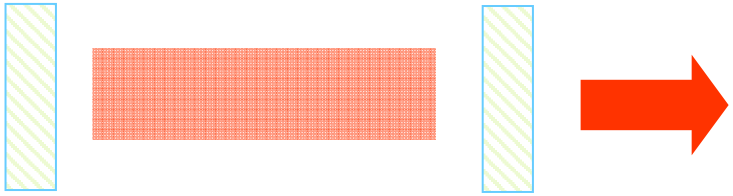
Purcell effect

$$I = \frac{I_0/(1-R)}{1+(2F/\pi)^2\sin^2(\varphi/2)} >> I_0$$

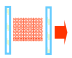
$$F = \pi\sqrt{R}/(1-R)$$

Applications of optical cavities

- Light generation
  - Laser & cavity-enhanced LED
- Light routing and manipulation
  - Optical filters for WDM
  - Modulators and switches
  - Slow light: CROW
- Light interaction with matter
  - Cavity-enhanced photodetector
  - Spectroscopy and sensing
  - Non-linear optics
  - Optical tweezers & MOEMS
  - Cavity QED



Conventional cavity

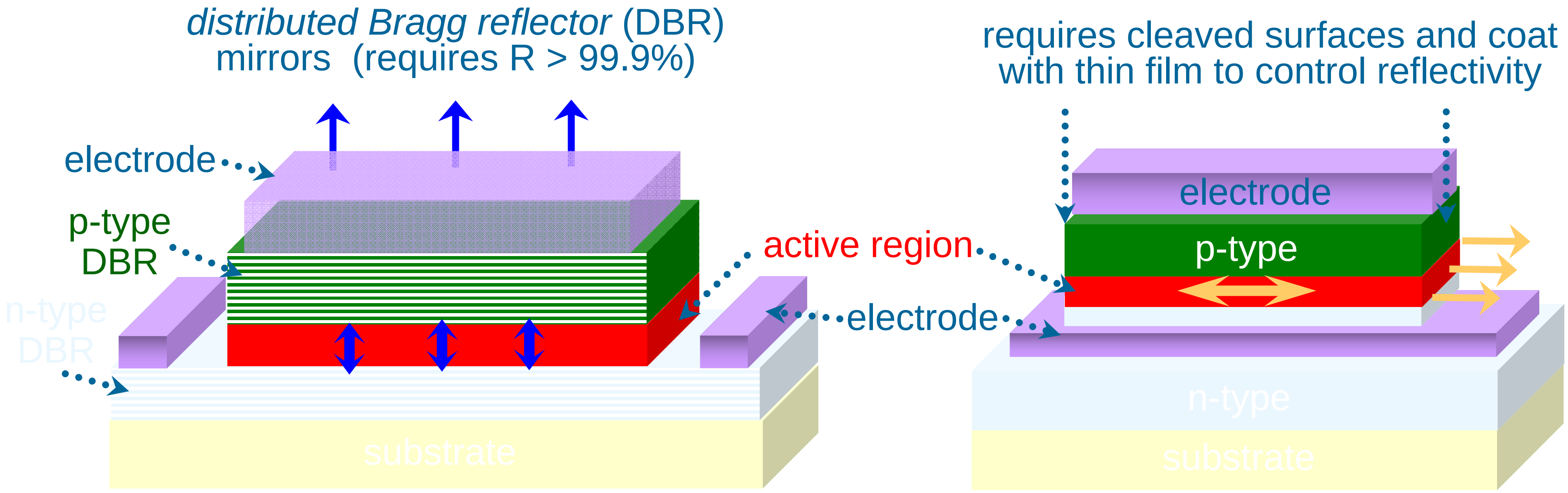


Micro-cavity

Conventional lasers

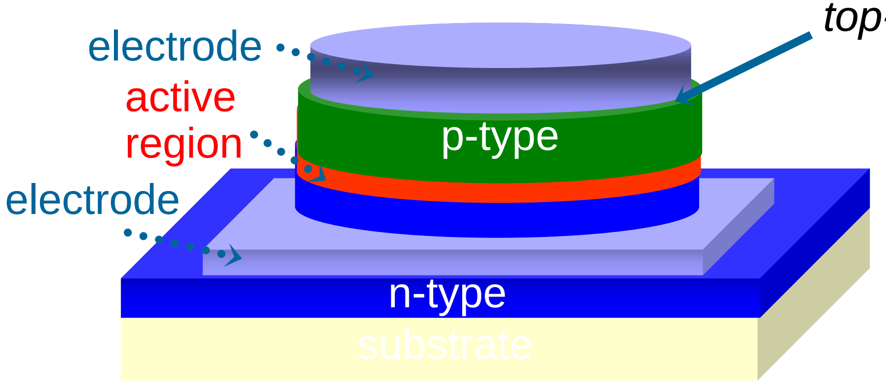
VCSELs - *vertical cavity surface emitting lasers*

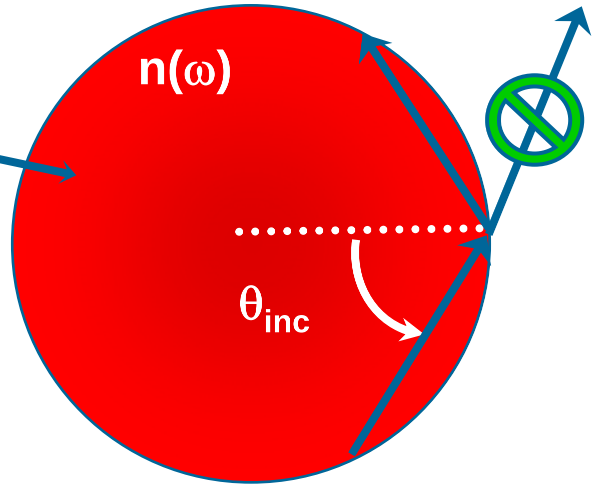
Edge emitters



- ➢ material difficulties: optical and electrical confinement
- ➢ electrodes must be *transparent*

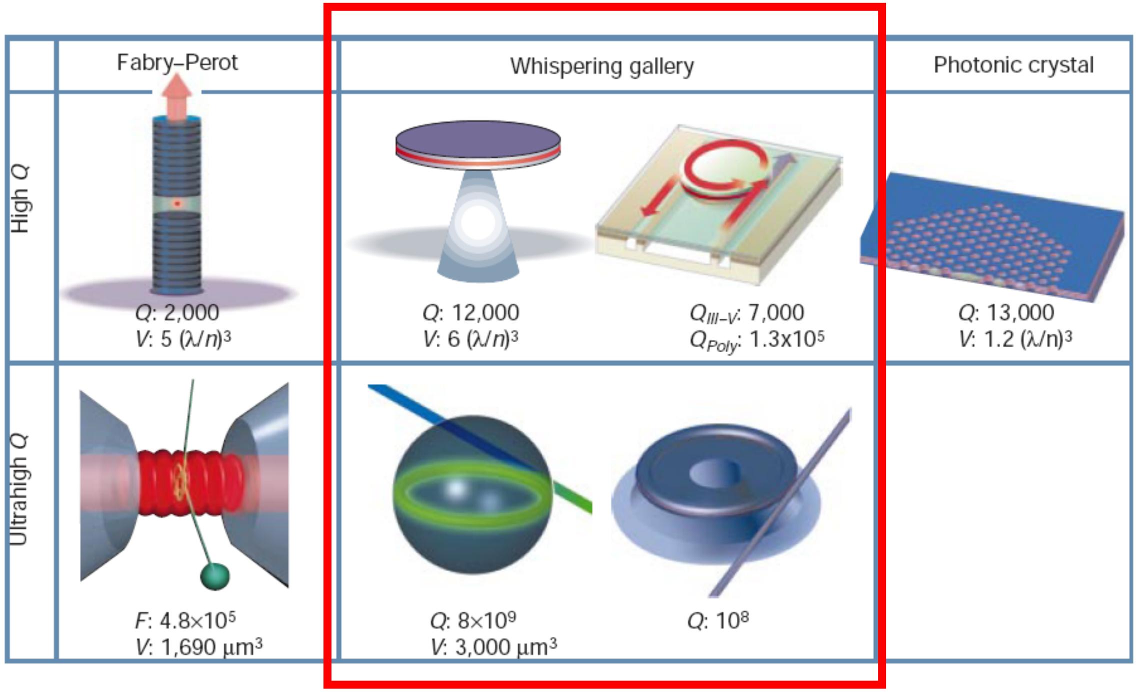
Whispering gallery modes: Total internal reflection (TIR)





- ~~electrodes must be *transparent*~~
- ~~mirrors~~
- 100% reflectivity from sidewalls

Optical microcavities



Vahala, Nature, 2003

High Q cavities: very low threshold laser
Universal cavity structure: UV laser

圣保罗教堂回音壁 瑞利

History of micro-cavity

1939 Dielectric Resonators

(Propose WGM to create high-Q optical resonators)

R. D. Richtmyer

1961 Stimulated emission into optical whispering modes of spheres

(First experimental observation of WGM millimeter-sized dielectric spheres of CaF2:Sm++)

C. G. B. Garret, W. Kaiser and W. L. Bond

1980 Observation of resonances in the radiation pressure on dielectric spheres

(Liquid droplets of micrometer-sized cavities)

A. Ashkin and J. M. Dziedzic

1986 Lasing droplets

S. X. Qian, RK Chang

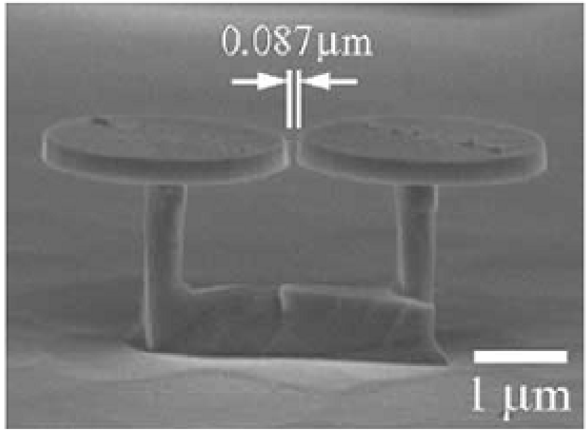
1992 Whispering-gallery mode micro-disk lasers **(Two-dimensional semiconductor circular micro-disks)**

S. L. McCall, A. F.J.Levi, R. E. Slusher

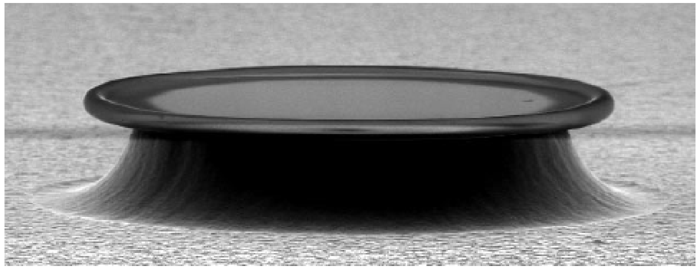
Topics (2010 ICTON)

- **Microcavity lasers and LEDs**
- **Microresonator-based bio(chemical) sensors**
- **Single-molecule sensors**
- **Coupling and transport phenomena**
- **Slow-light structures**
- **Cavity opto-mechanics**
- **Tunable cavities**
- **Tuning optical properties of single emitters with microcavities**
- **Optical bistability in microcavity structures**
- **Quantum information processing with microresonators**
- **Localized and quasi-localized photonic states in aperiodic structures**
- **Cavity polaritons and plasmons**

Materials for optical microcavities

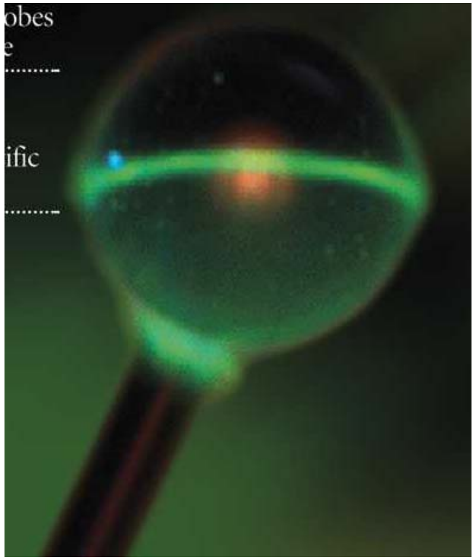


Semiconductors (Si, III-V, nano-materials)

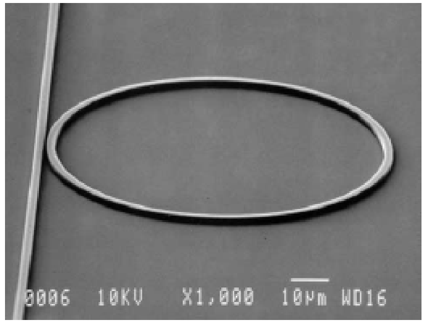


SiO_2

Crystals ($LiNbO_3$)



RE-doped glasses



Polymers

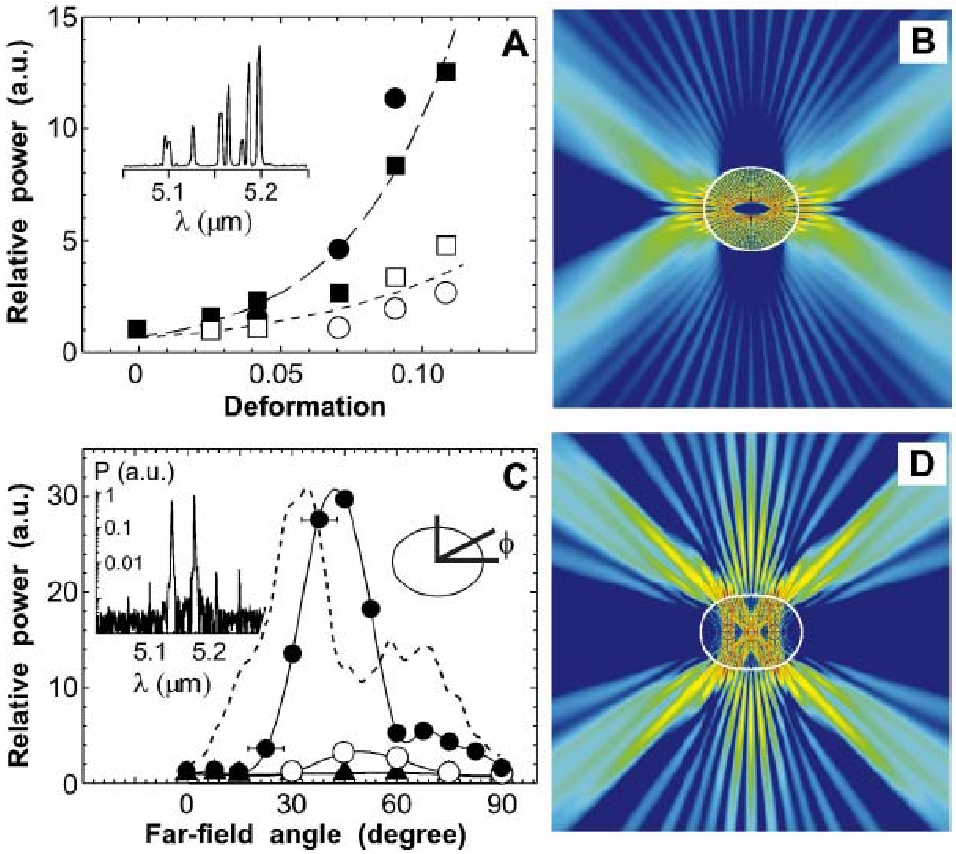
Important Works

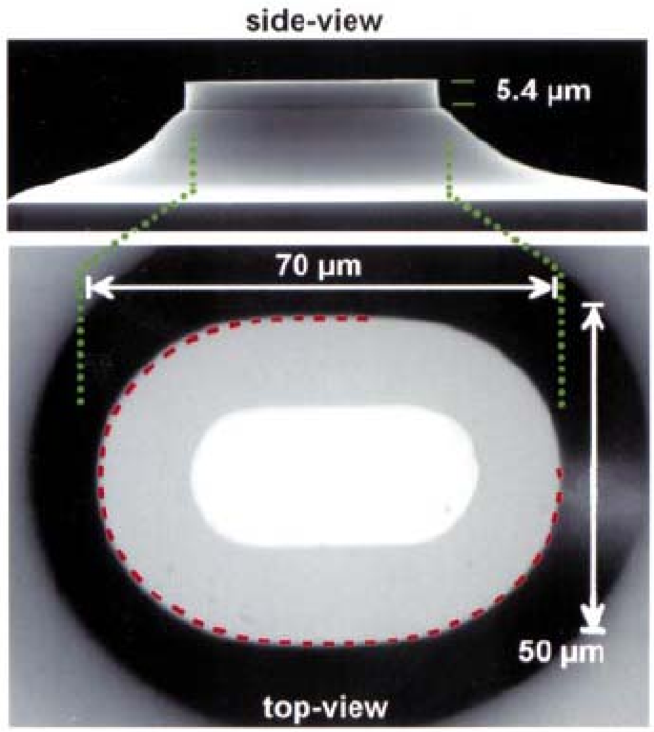
High-Power Directional Emission from Microlasers with Chaotic Resonators

Claire Gmachl, Federico Capasso,* E. E. Narimanov,
Jens U. Nöckel, A. Douglas Stone, Jérôme Faist,†
Deborah L. Sivco, Alfred Y. Cho

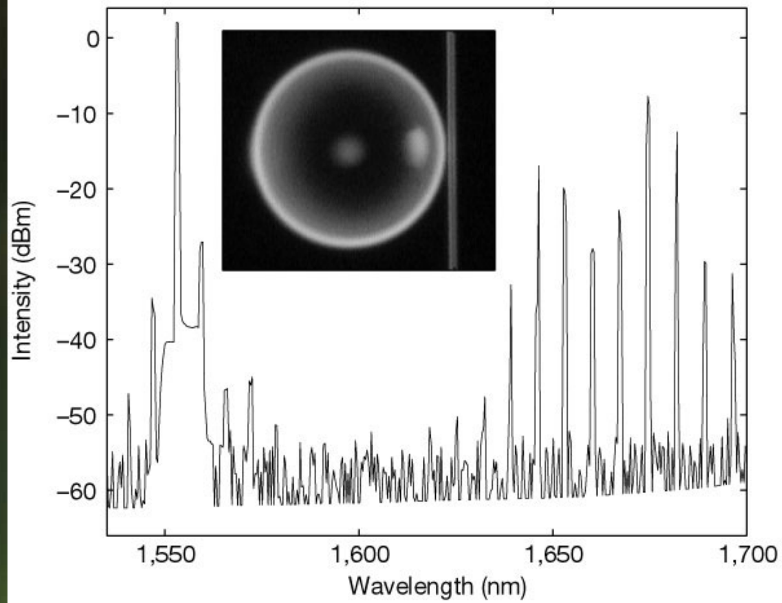
Science 280,1557 (1998)

标志性工作1





标志性工作II



Er doped silica sphere

Ultra-high-Q toroid microcavity on a chip

标志性工作！！！

Nature 421,925 (2003)

D. K. Armani, T. J. Kippenberg, S. M. Spillane & K. J. Vahala

Department of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA

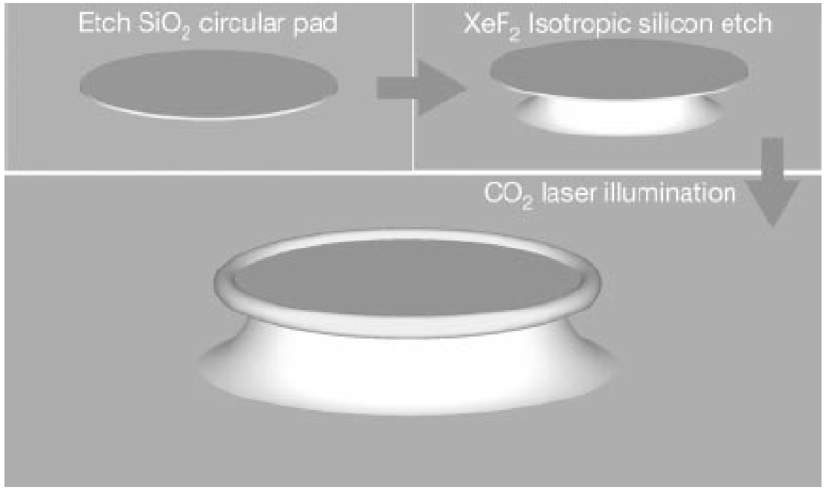


Figure 1 Flow diagram illustrating the process used to fabricate ultra-high-Q planar microcavities.

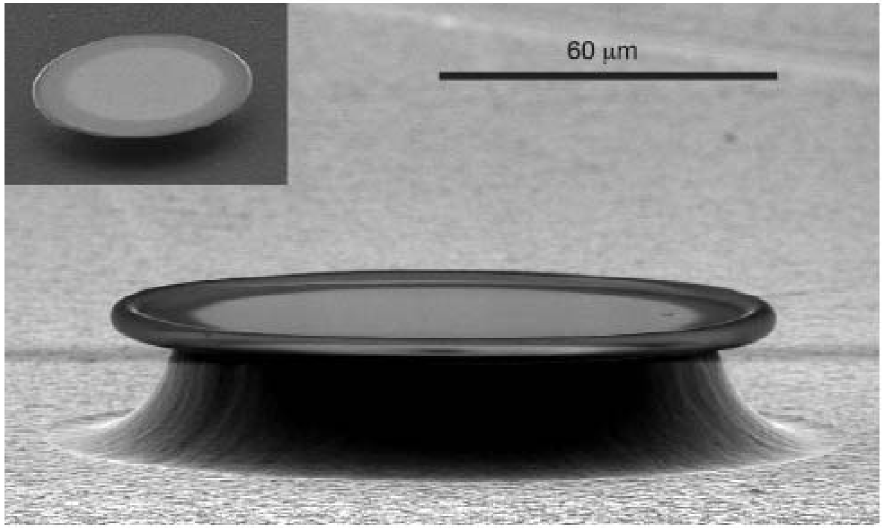


Figure 2 Scanning electron micrograph of a silica microdisk after selective reflow treatment with a CO_2 laser. The inset shows the microdisk prior to laser treatment. This toroidal microresonator had an intrinsic cavity Q of 1.00×10^8.

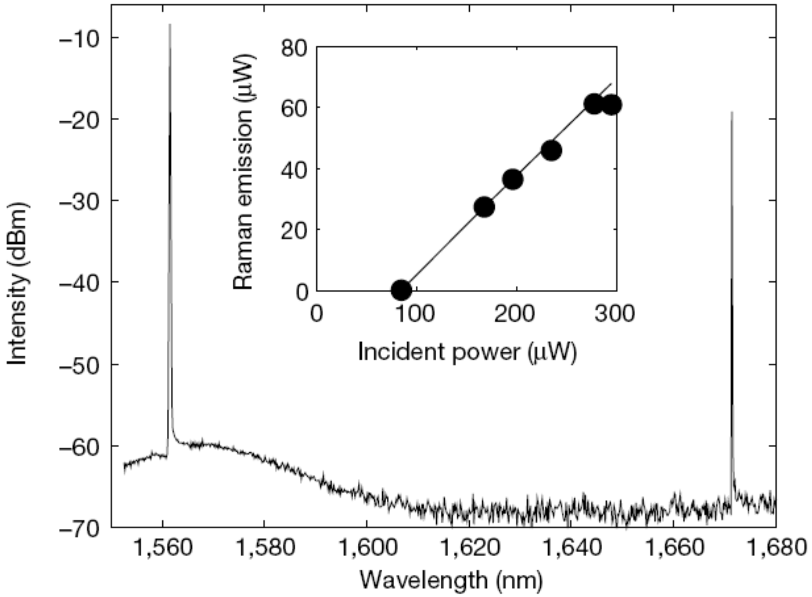


Figure 4 Single longitudinal mode Raman lasing. Raman spectrum for a 40-μm-diameter microsphere, exhibiting a unidirectional conversion efficiency of 16% (pump is at 1,555 nm). Inset, Raman power output (sum of forward and backward emission) versus incident pump power. Differential quantum efficiency is 36%.

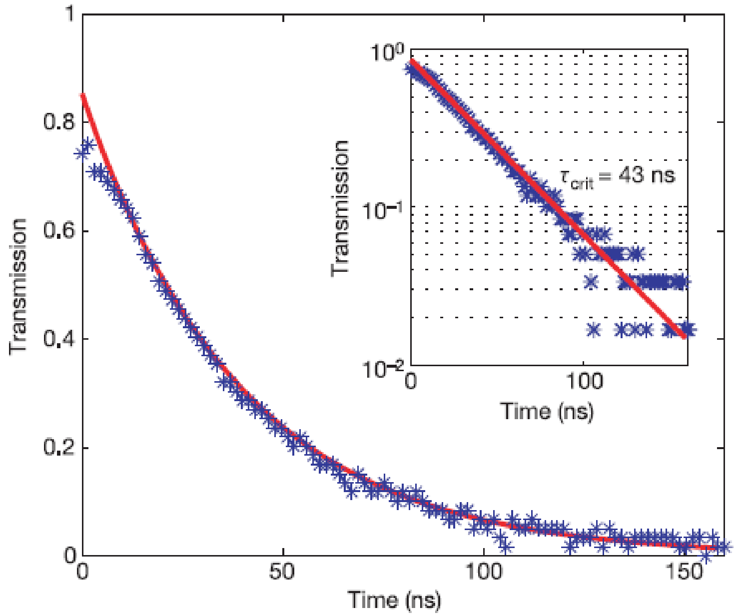


Figure 4 Ringdown measurement of a 90-μm-diameter toroid microcavity at the critical-coupling point. The measured lifetime of $\tau_{crit} = 43$ ns corresponds to an intrinsic quality factor of $Q = 1.25 \times 10^8$.

Cavity mode photon lifetime

τ=43ns,

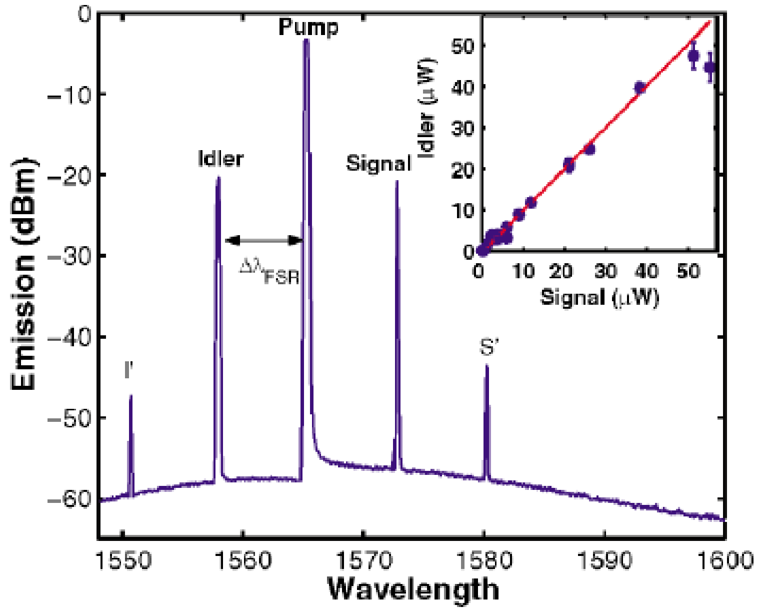
$Q = 3 \times 10^8$

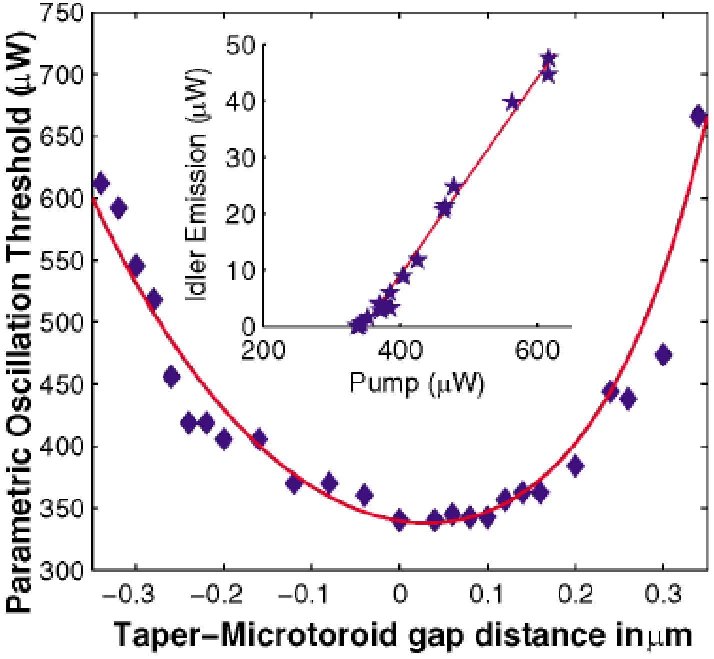
Kerr-Nonlinearity Optical Parametric Oscillation in an Ultrahigh-Q Toroid Microcavity

T. J. Kippenberg, S. M. Spillane, and K. J. Vahala*

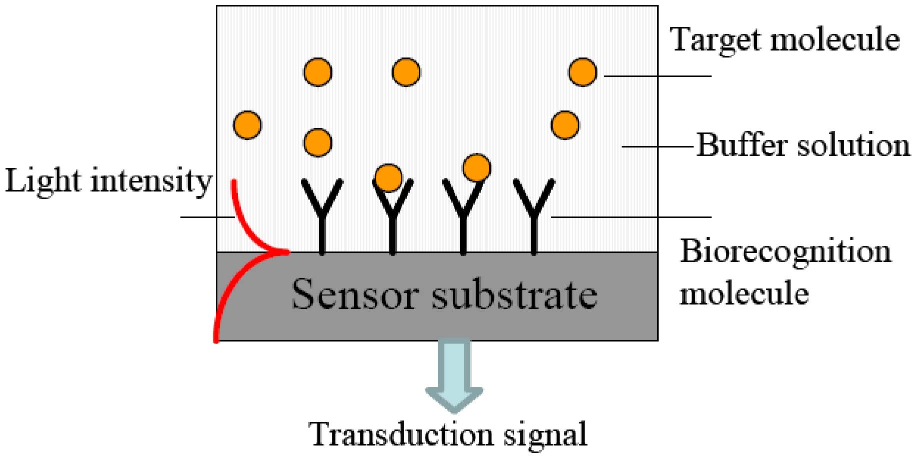
$$P_t^{\mathrm{Kerr}} = \frac{\omega_0^2 Q_0^{-2}(1+K)^2 + (\Delta\omega/2)^2}{\gamma \Delta\omega \frac{c}{n_{\mathrm{eff}}}} \frac{C(\Gamma)\pi^2 R n_{\mathrm{eff}}}{2\lambda_0} \times \frac{(K+1)^2}{Q_0 K}.$$

Ultralow level optical nonlinearity generation

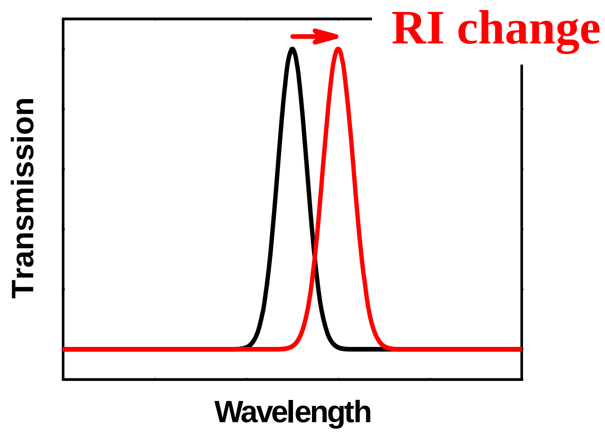


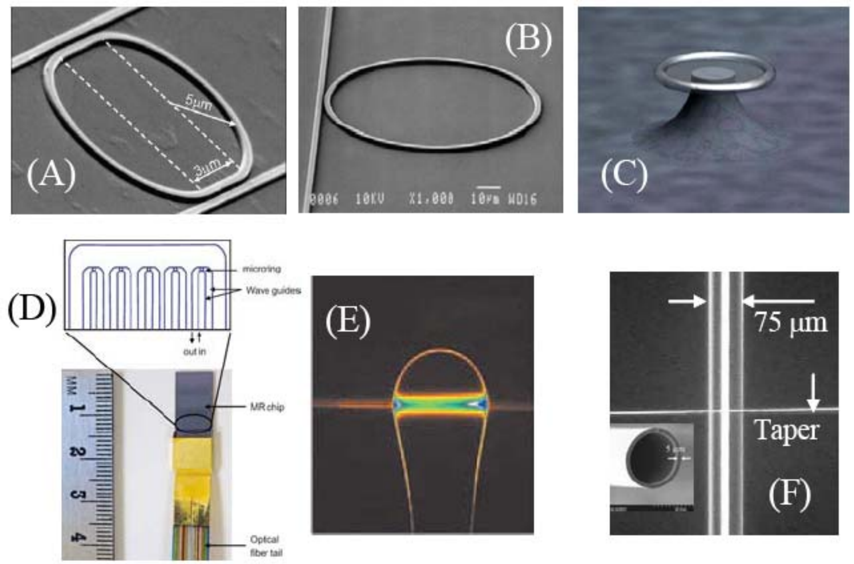


Bio-sensing using optical microcavities



Label-free optical bio-sensor detects environmental RI change

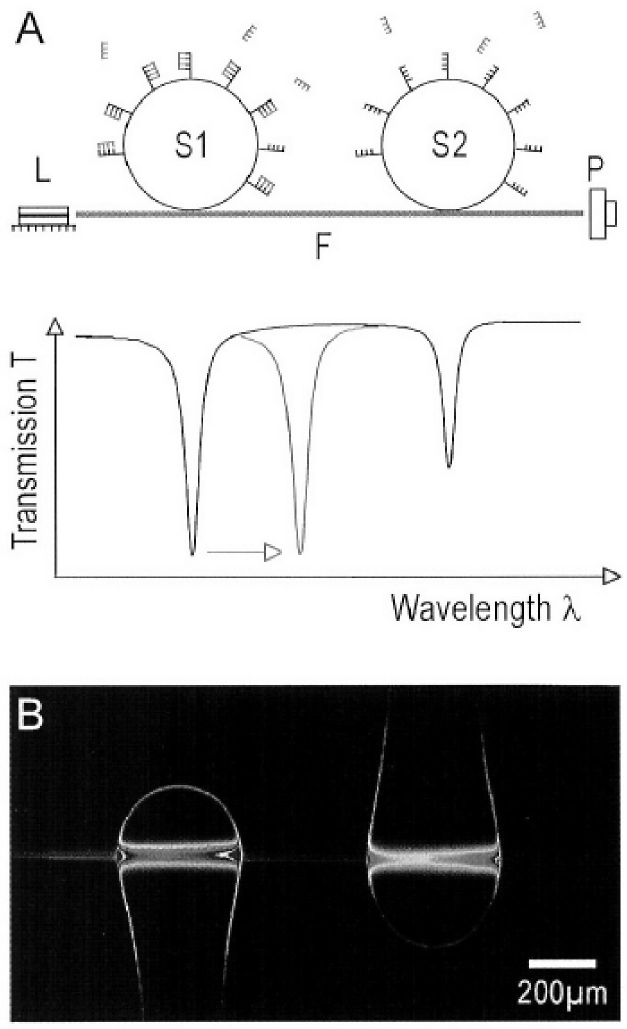




ANALYTICA CHIMICA ACTA 620, 8, 2008

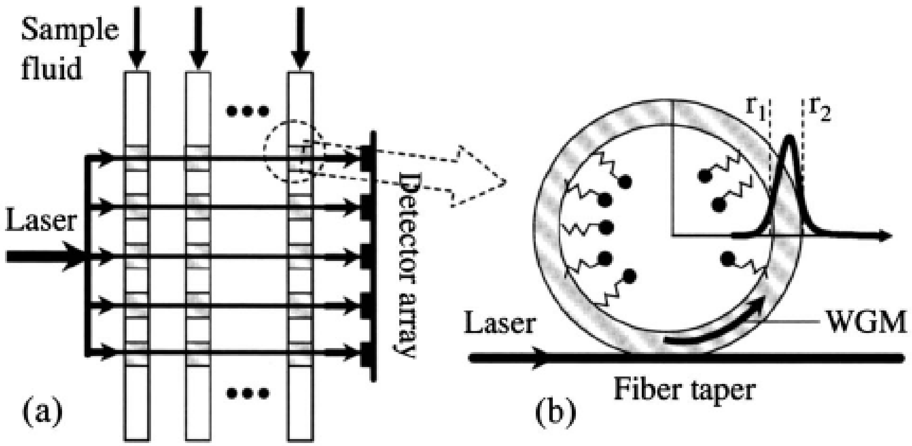
Using two microcavities with different chemical surface modification to detect DNA

Sensitivity: 6 pg/mm^2



Biophysical Journal 85, 1974 (2003)

Opto-fluidic sensor



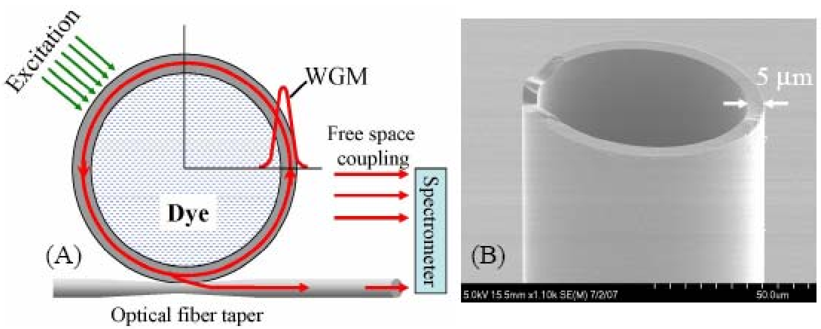
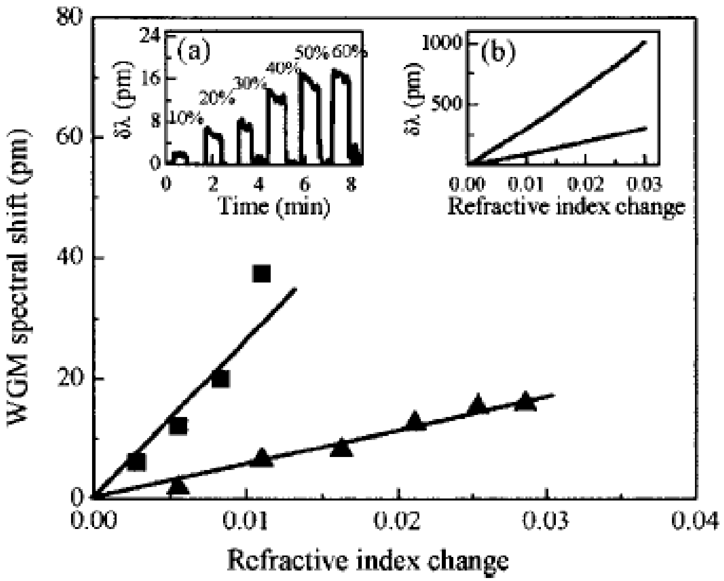


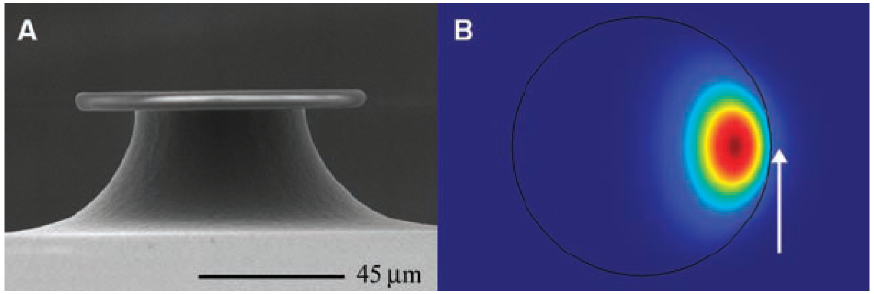
Fig. 1. (A) Concept of OFRR dye lasers. (B) SEM image of the OFRR. OD = 75 µm.

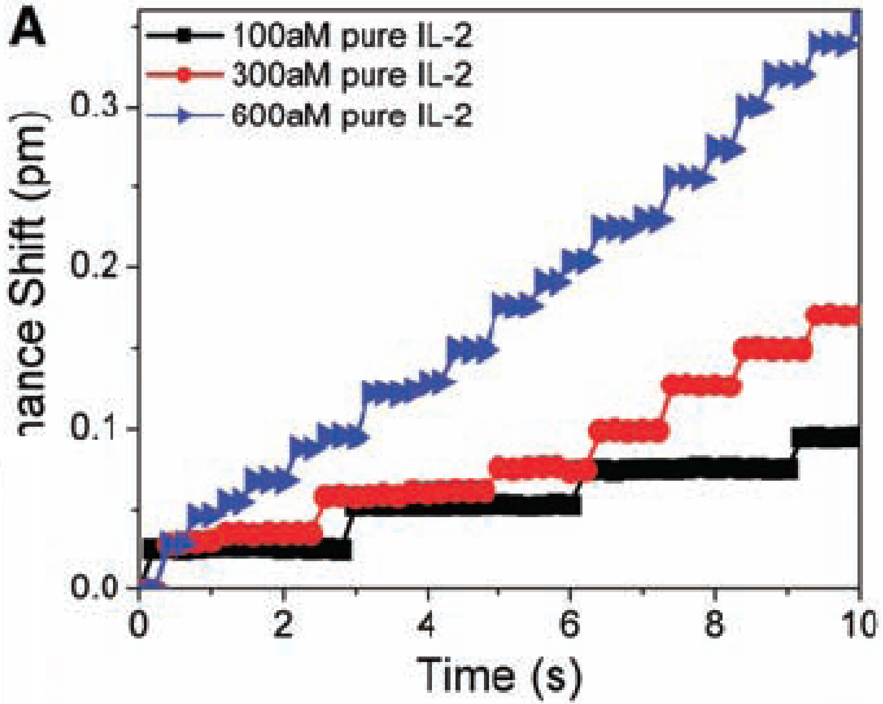


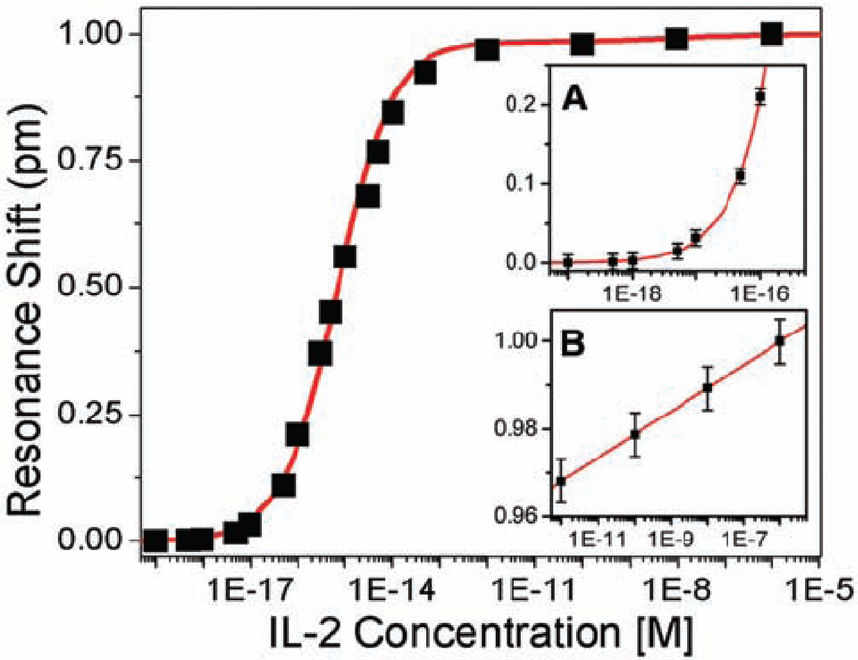
Optics Express 15, 15523 (2007)

Optics Letters 31, 1319 (2006)

Single molecule detection with ultra-high Q cavity

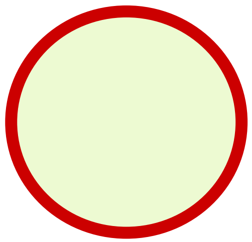






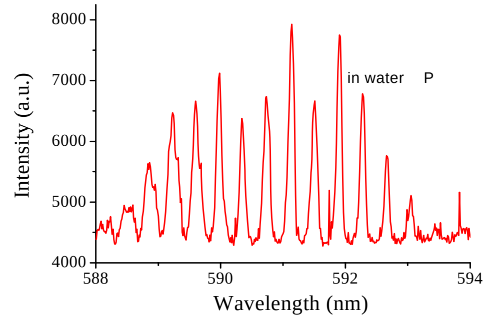
Science 317, 783 (2007)

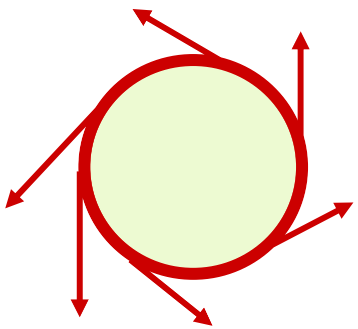
Directional emission



$2\pi Rn = m\lambda$

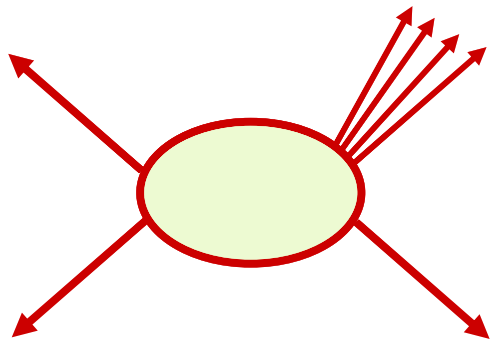
whispering gallery modes (WGM)





Stable WGM:
Tunneling leakage
Weak output
poor directionality

Chaotic WGM:
Refractive leakage
Intense output possible



Unidirectional lasing from a microcavity with a rounded isosceles triangle shape

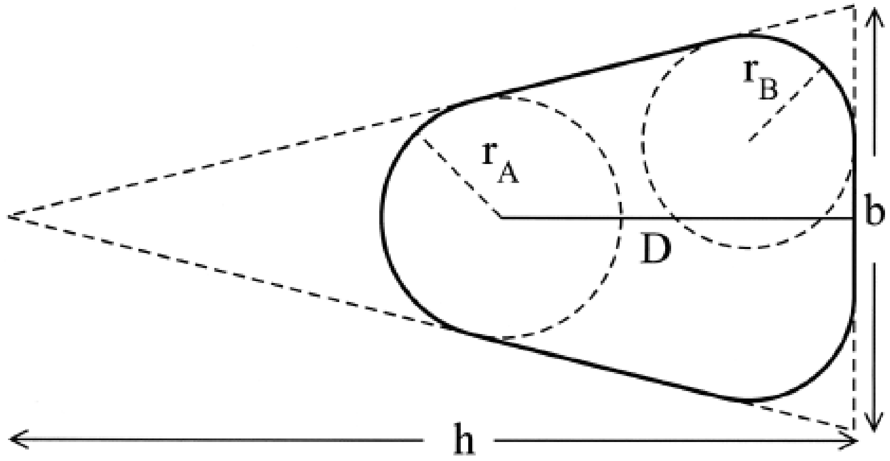
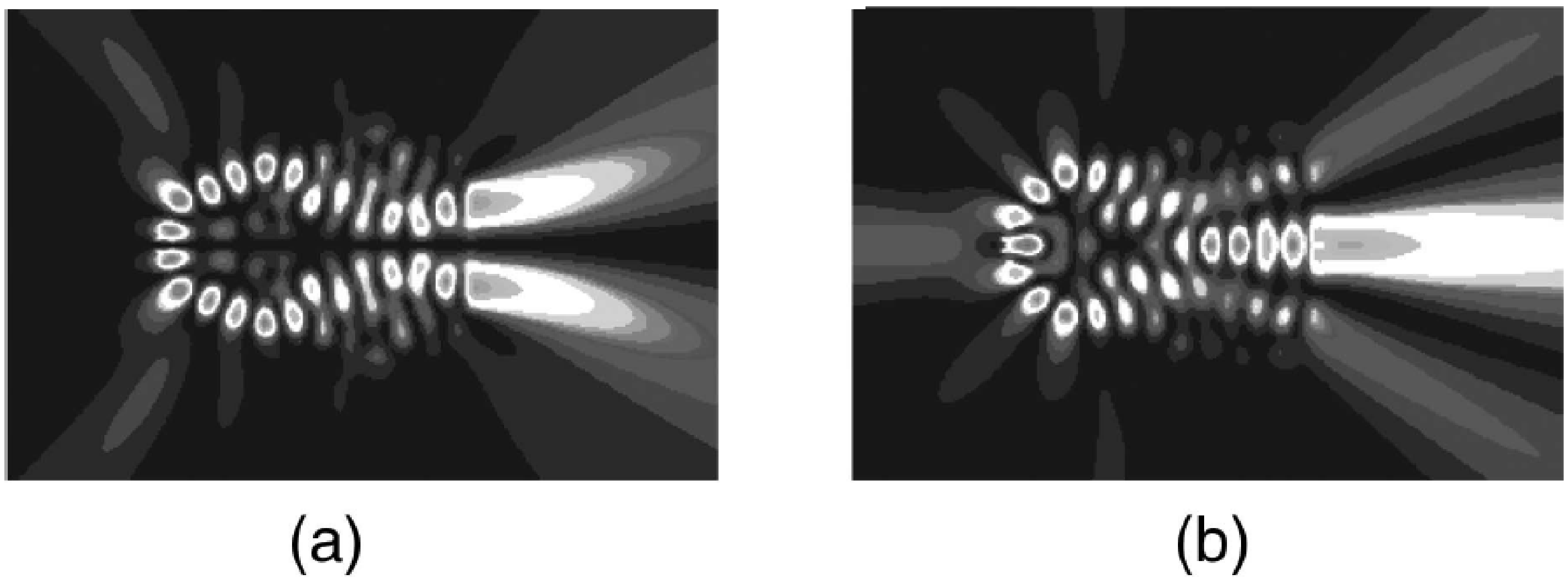


Fig. 1. Rounded-isosceles-triangle-shaped microcavity.



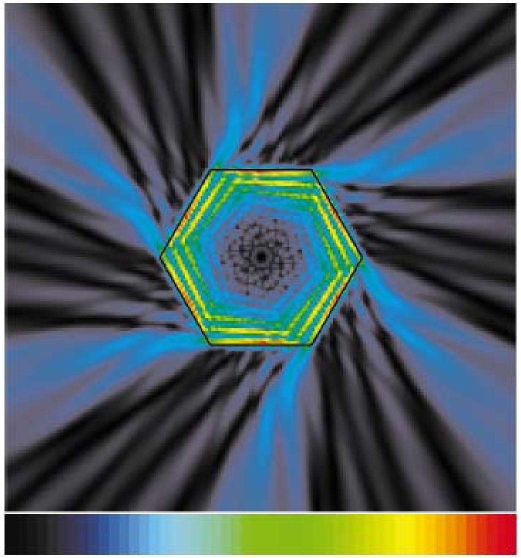
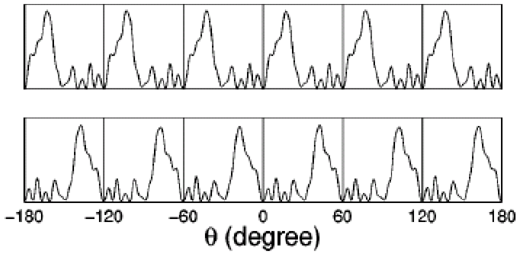


FIG. 8. (Color) Chiral resonance 50−. $kR=42.6318-i0.06766$, $s=200$, $2N=4000$.



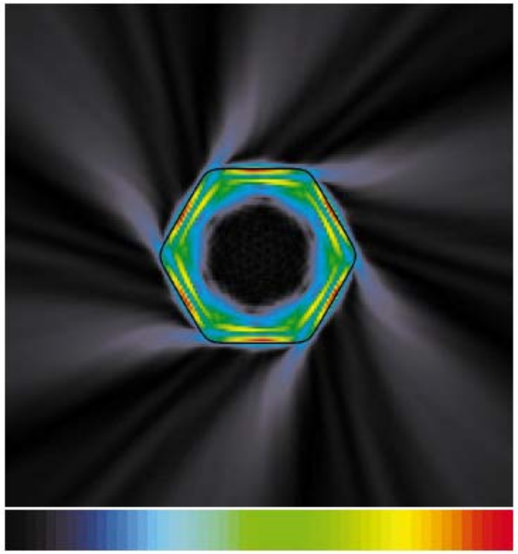
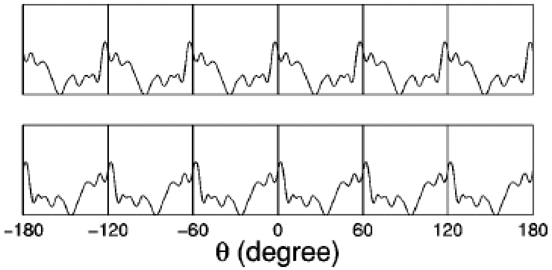
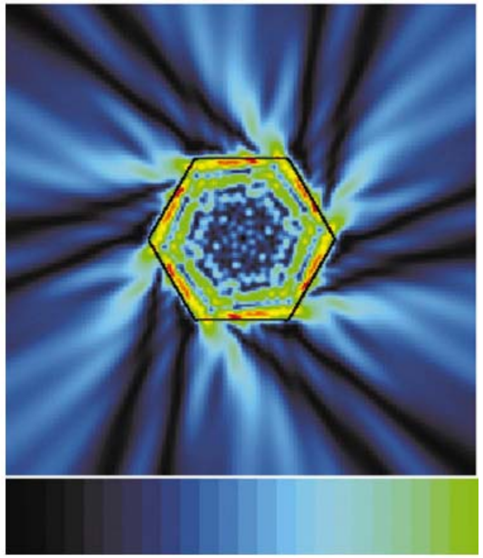
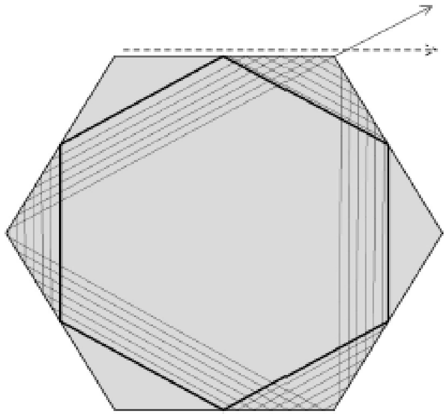


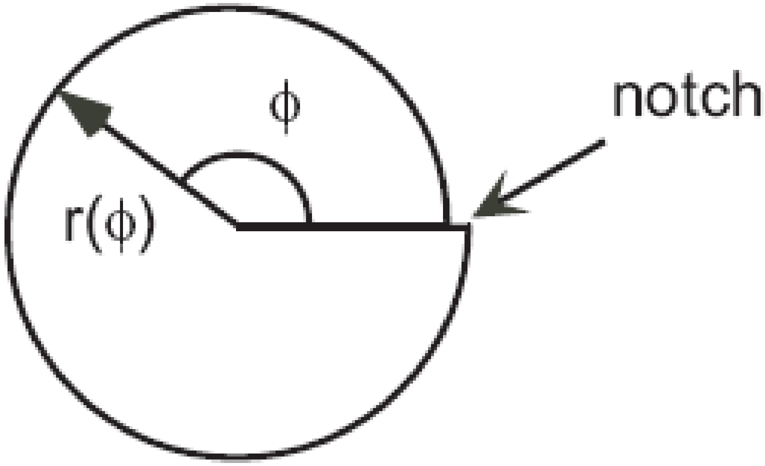
FIG. 10. (Color) Resonance 50− in a rounded hexagon with $s=20$, cf. Fig. 8. $kR=42.7099-i0.01836$, $2N=4000$.





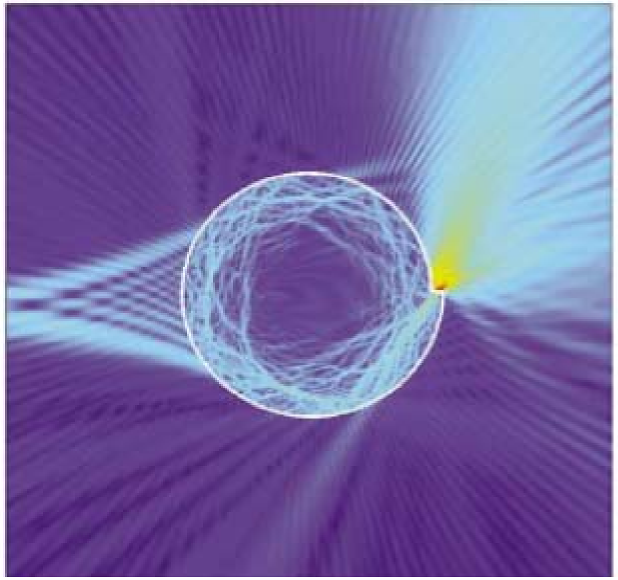


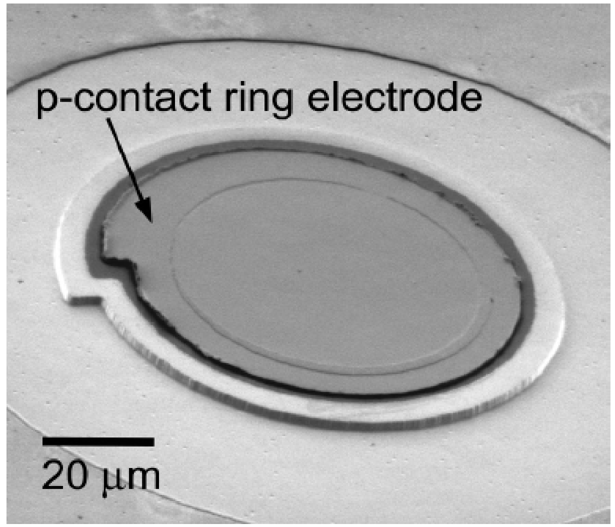
Spiral-shaped cavity



$$r(\phi) = r_o(1+\varepsilon\phi/2\pi)$$

(a)



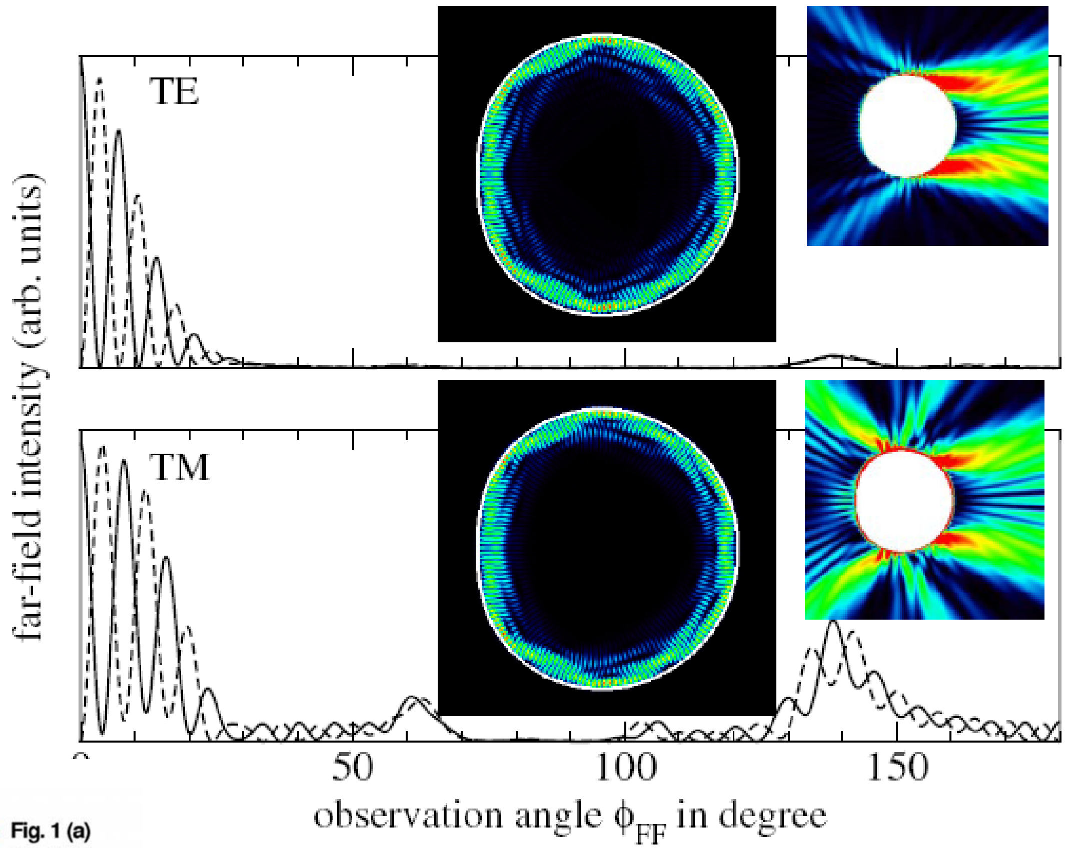


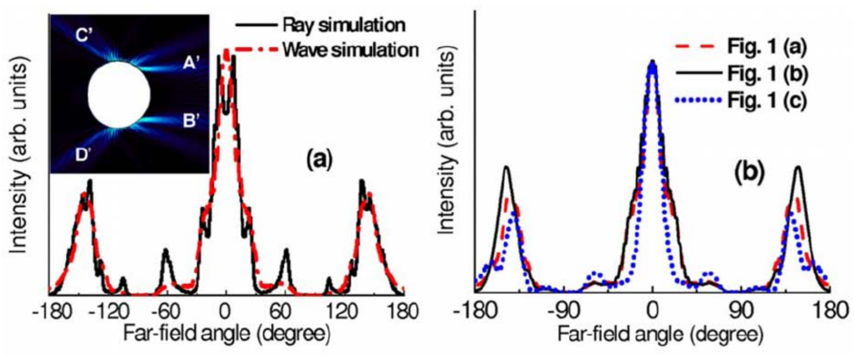
Appl.Phys.Lett. 84(14) 2004

Combining high Q and directional emission

$$R(\varphi) = R_0(1+\varepsilon\cos(\varphi))$$

Limacon type cavity

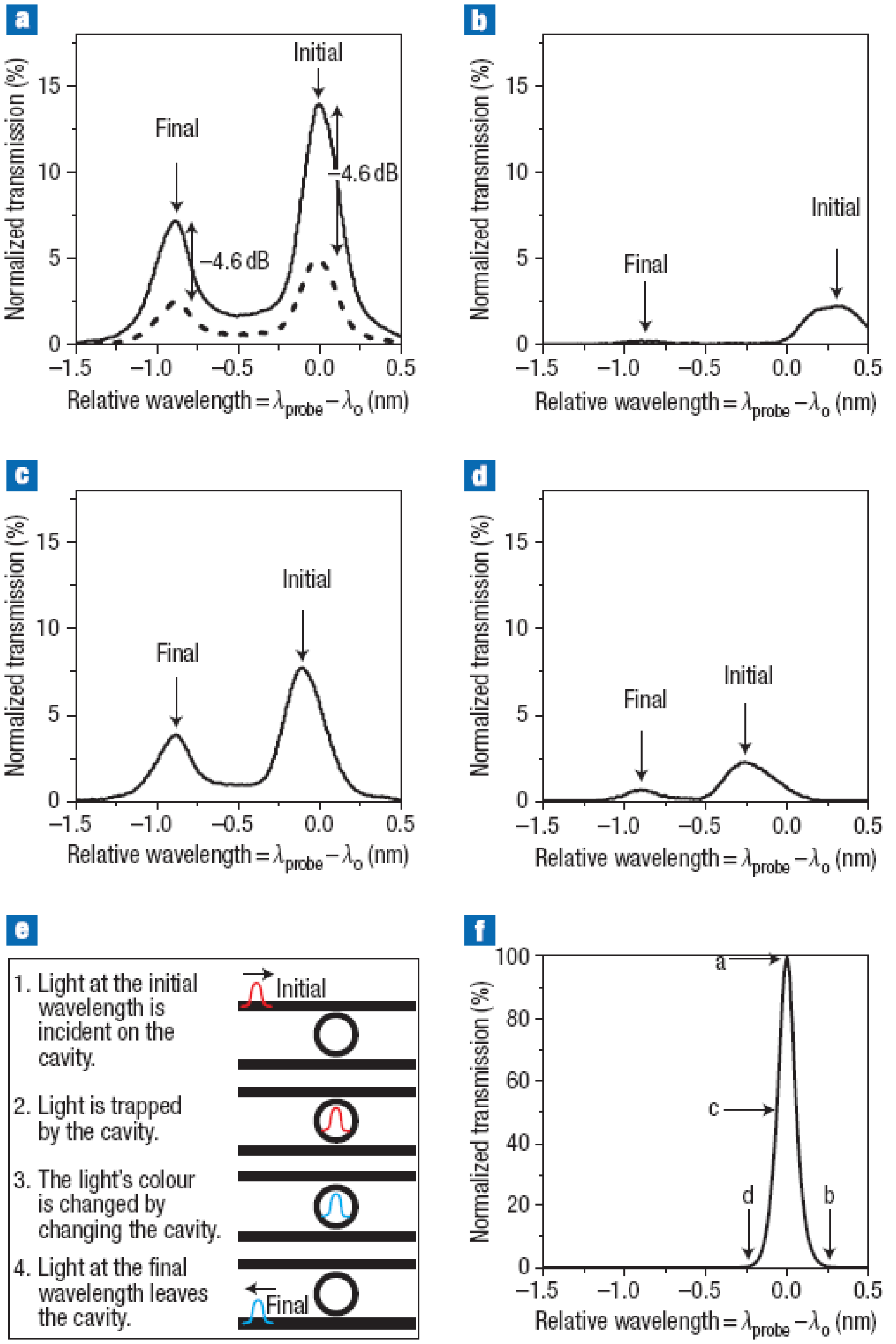




Physical Review Letters 100, 033901 (2008)
Applied Physics Letters 94, 251101 (2009)

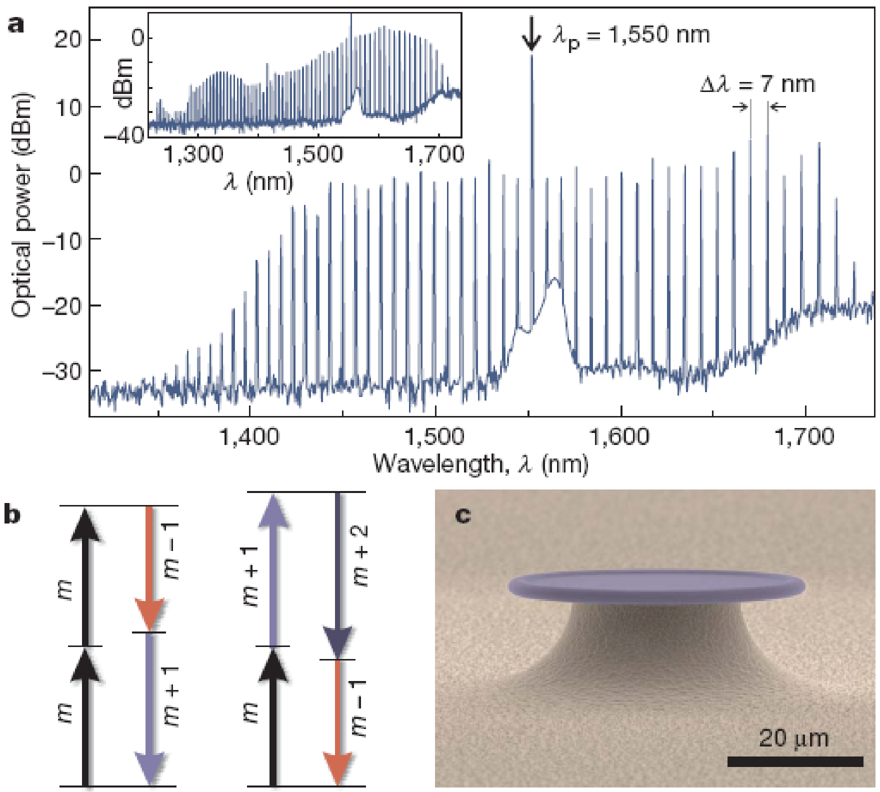
Wavelength conversion by changing the optical length of a cavity

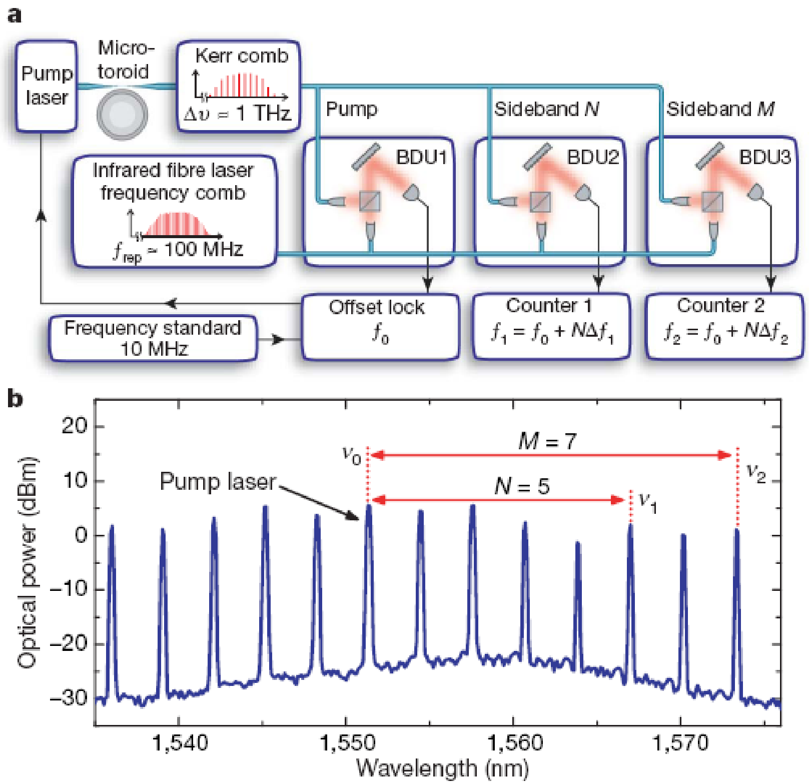
Requirement for microcavity:
High Q to allow long photon lifetime in the cavity



Nature Photonics 1, 293 (2007)

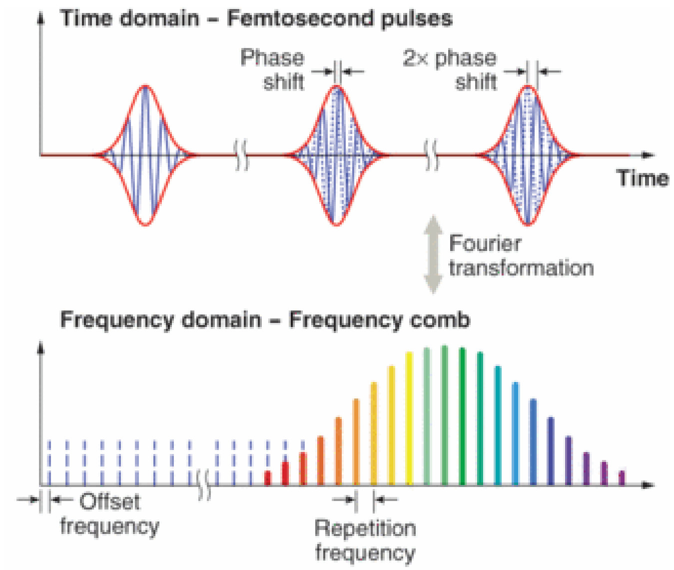
Optical frequency comb generation

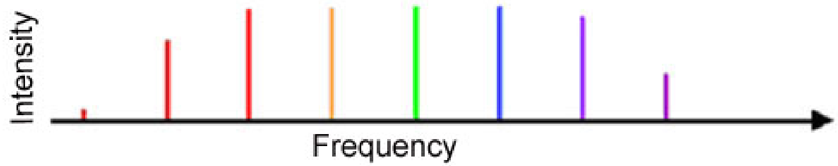




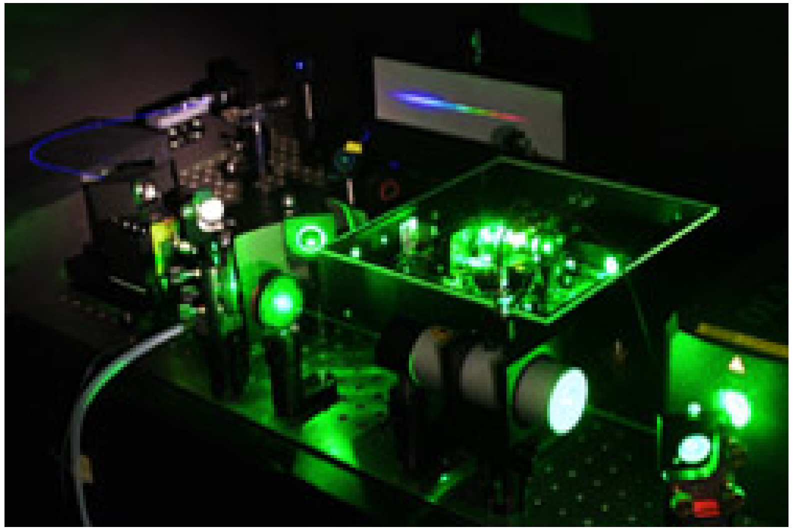
Nature Photonics 450, 1214 (2007)

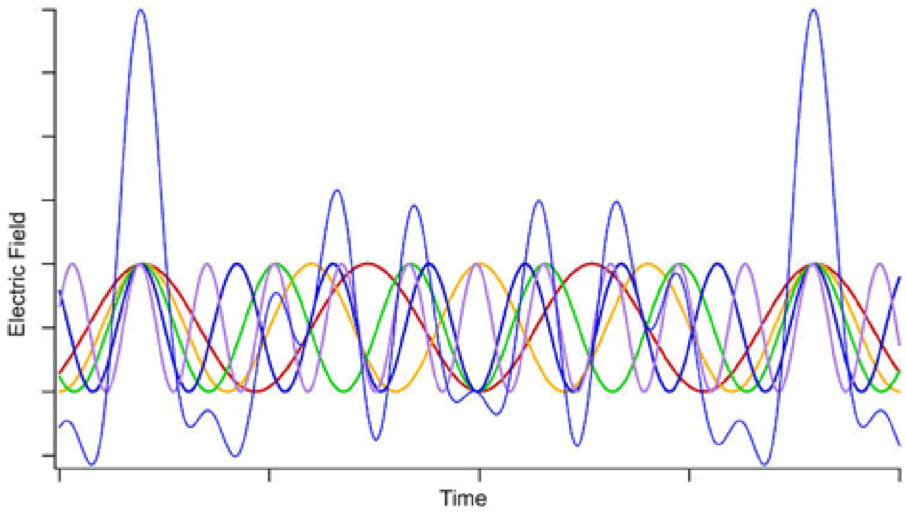
Frequency comb: 频率梳 Nobel prize 2007
bring together ultrafast and ultra-precision



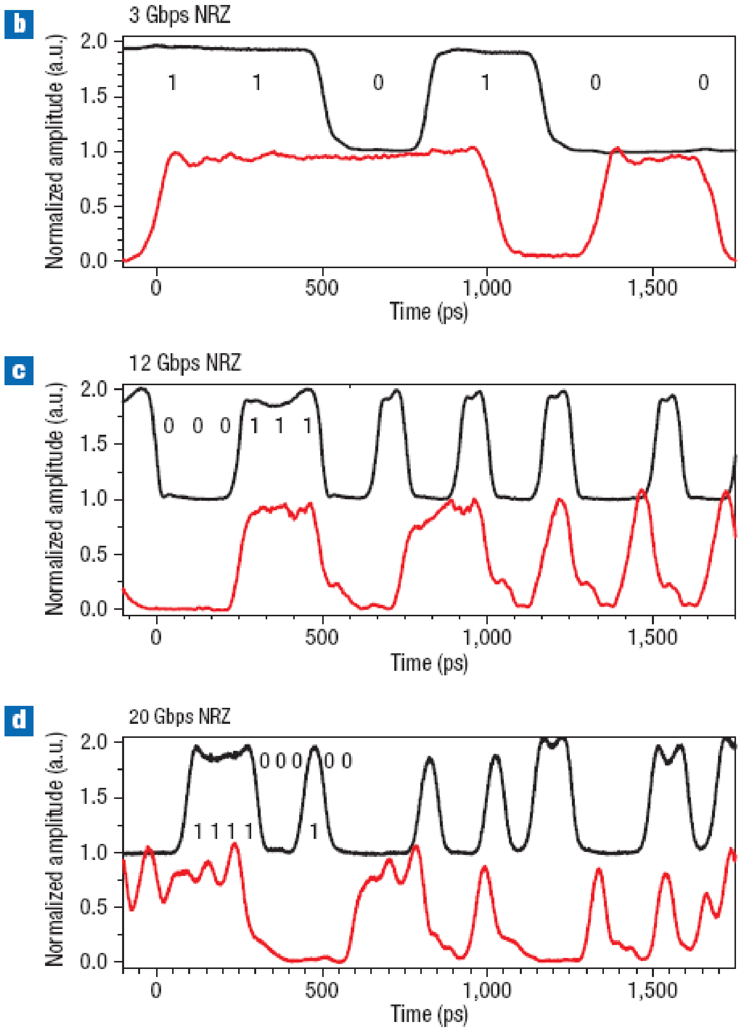


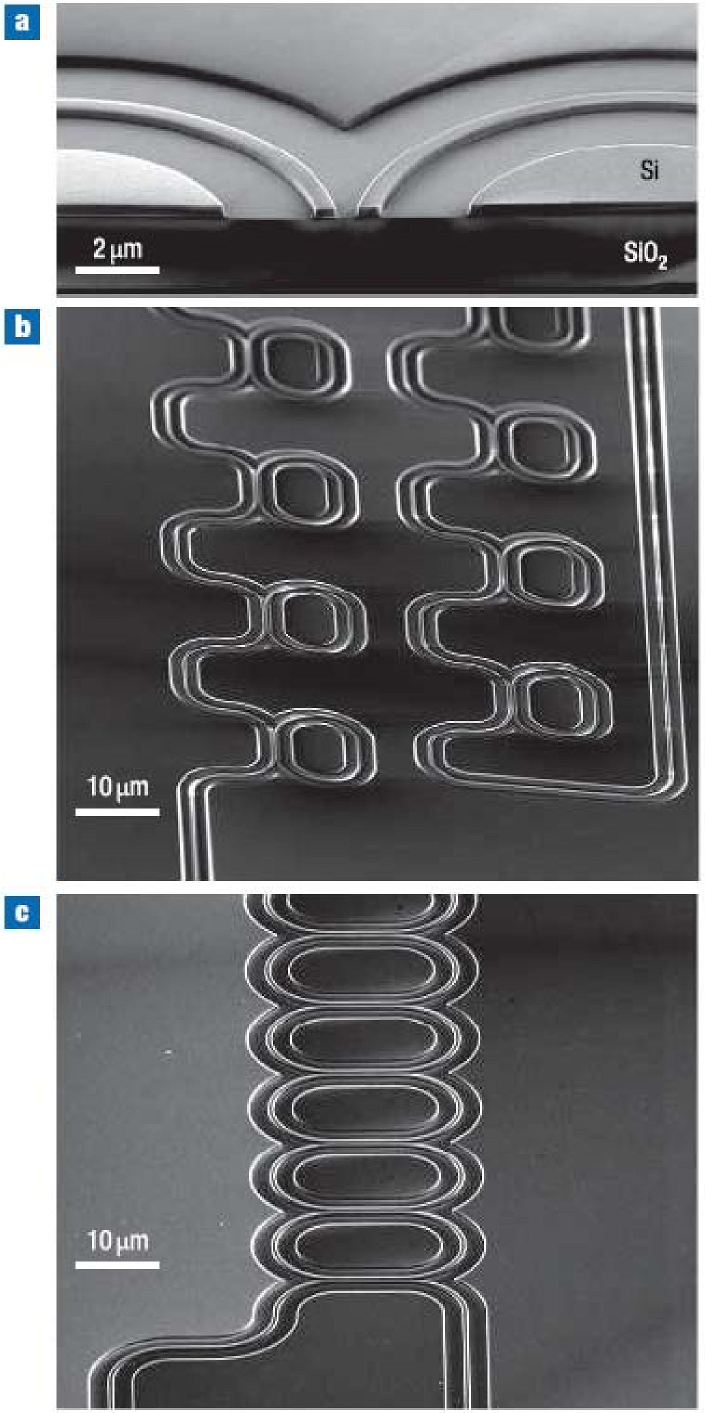
$$f = mf_0 + f_{offset}$$





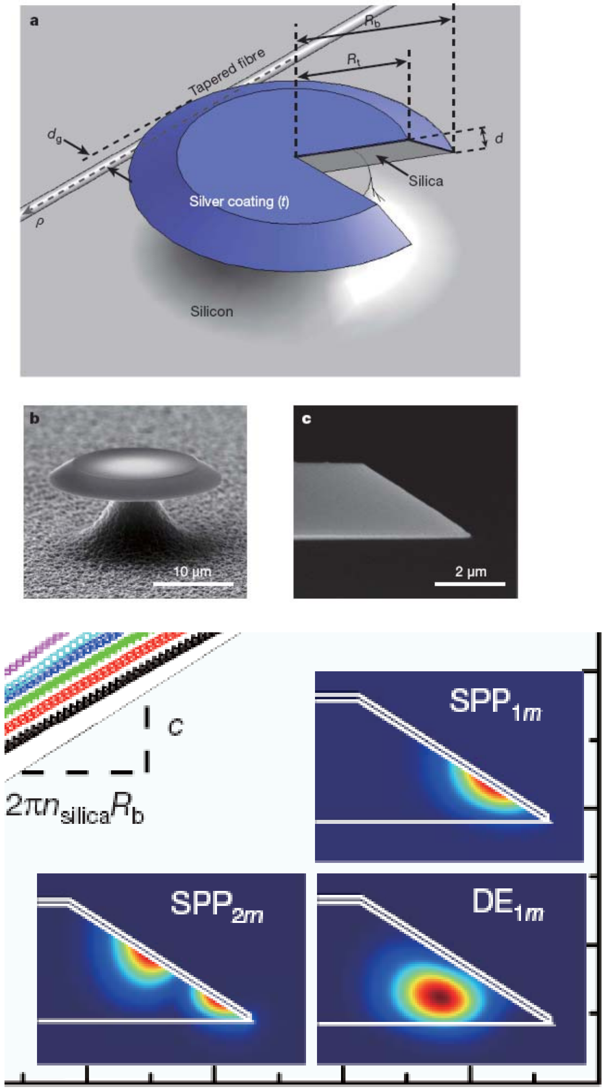
Optical buffer with coupled microcavities

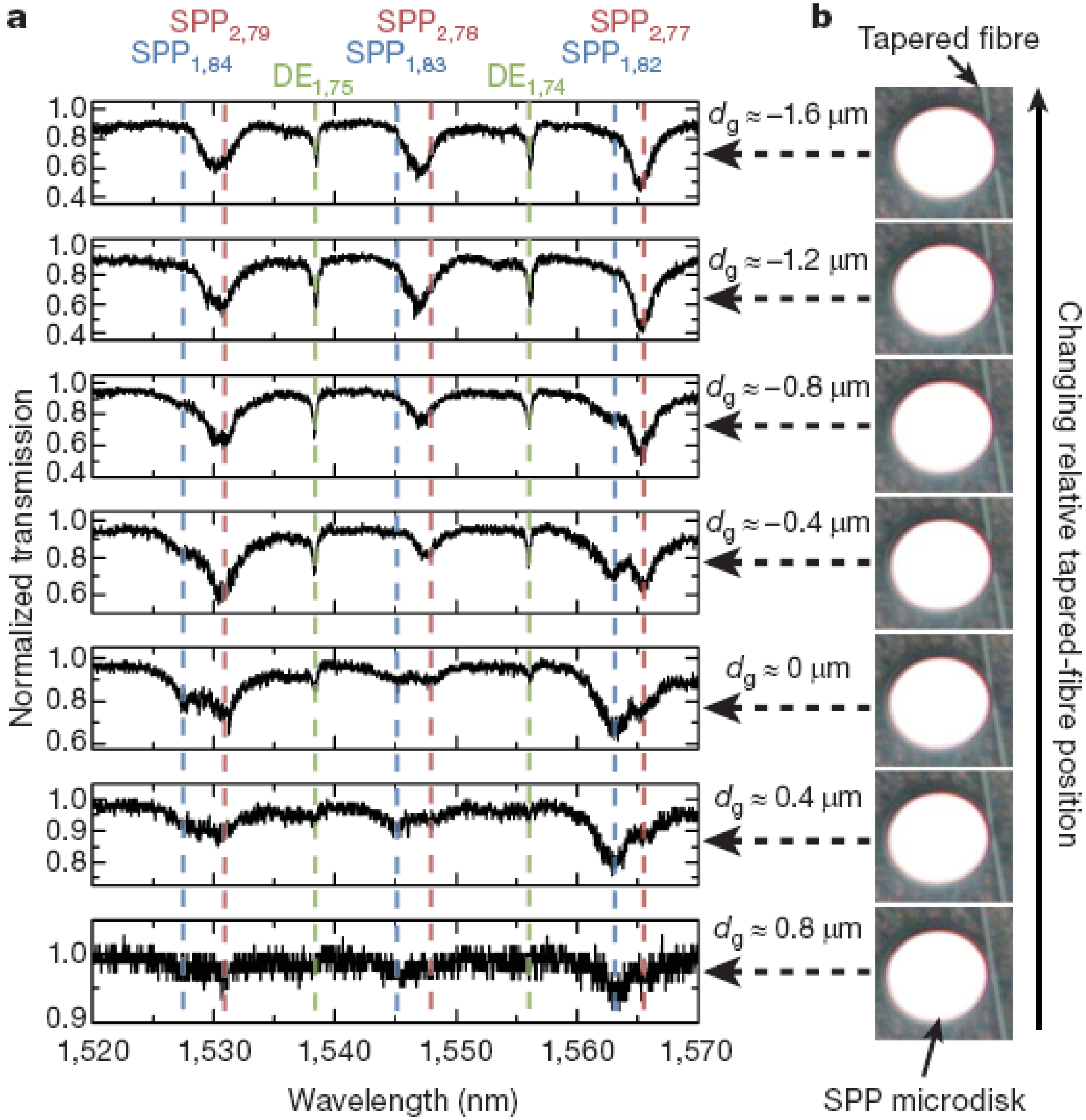




Nature Photonics 1, 65 (2007)

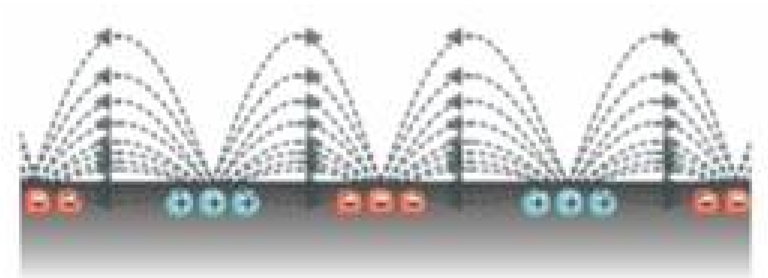
High Q surface plasmon polariton whispering gallery modes

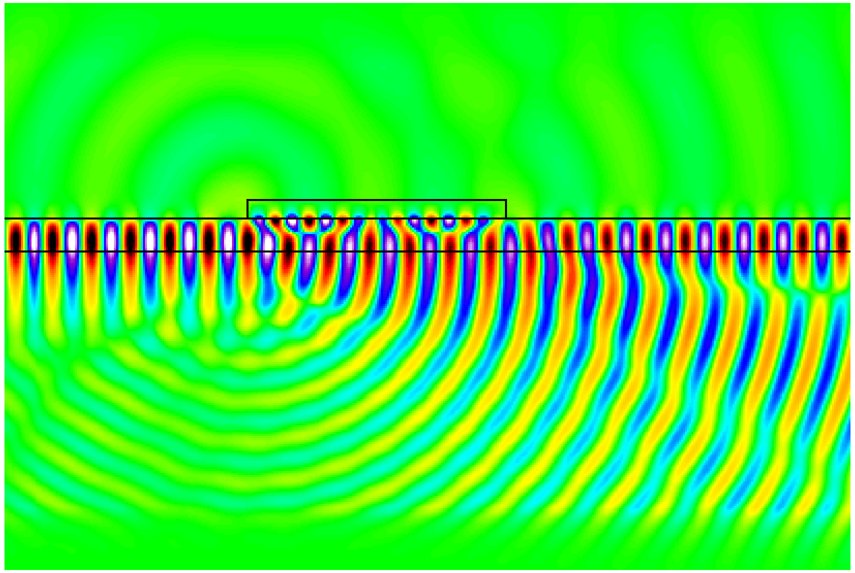


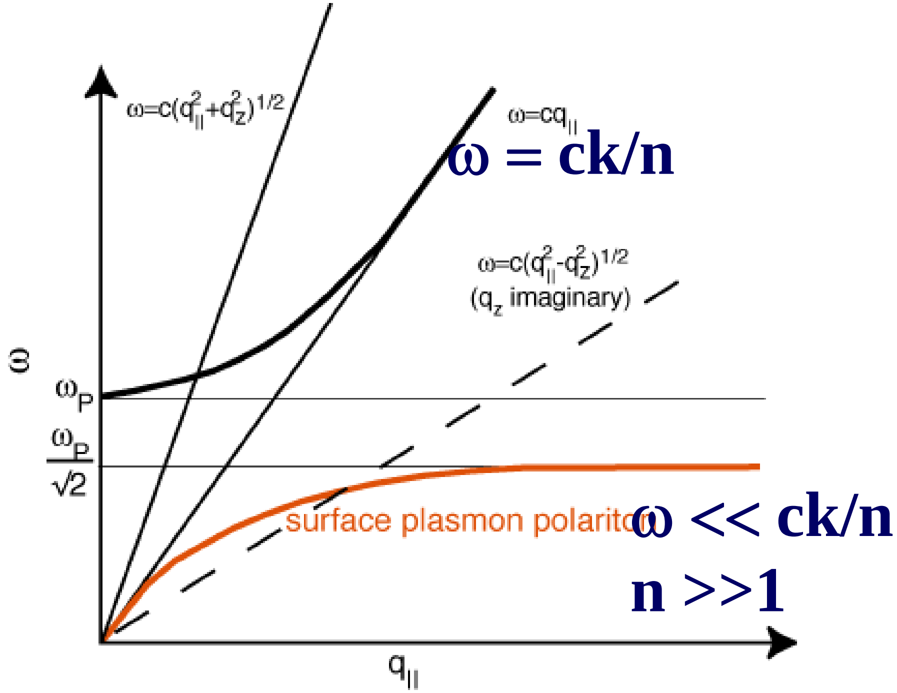


Nature 457, 455 (2009)

Surface plasmon polariton
表面等离子极化子







Opto-mechanics

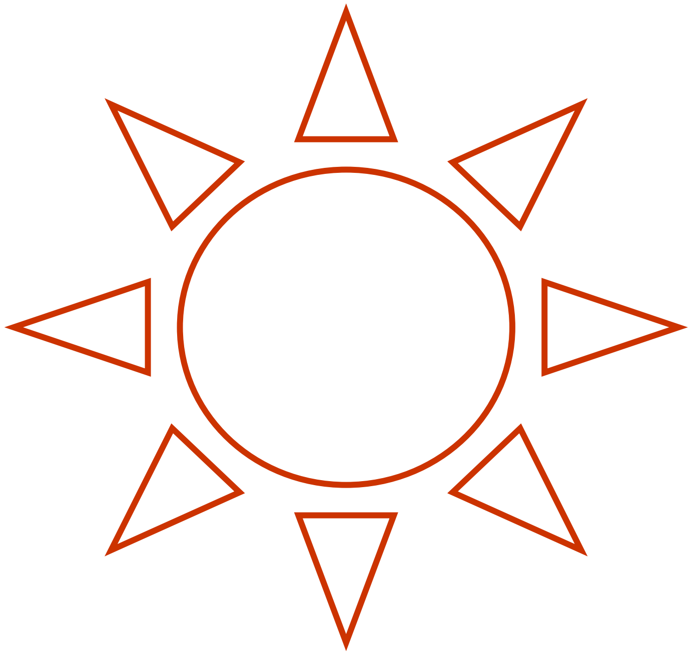


Photo-energy/

Mechanical energy

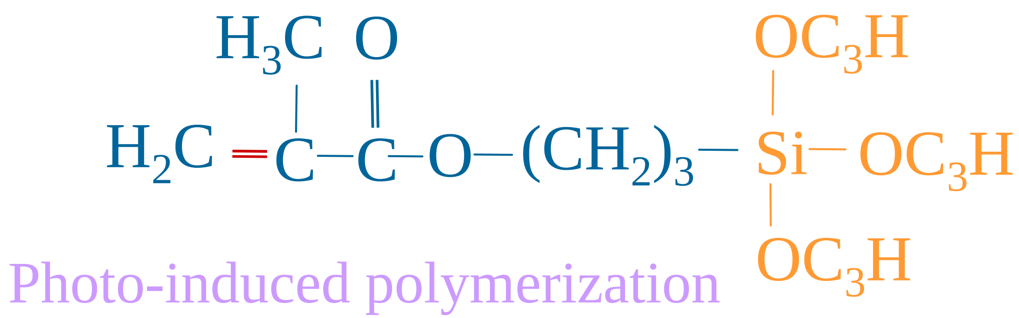
conversion

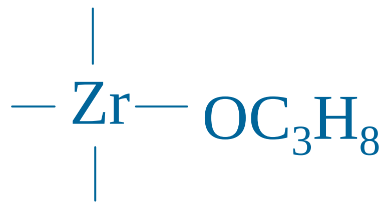
Cool the microcavity to μK

(ground state of mechanical vibration)

Our works

Our approach: Organic-inorganic Materials





PMMA SiO_2 ZrO_2

MAPTMS ZPO

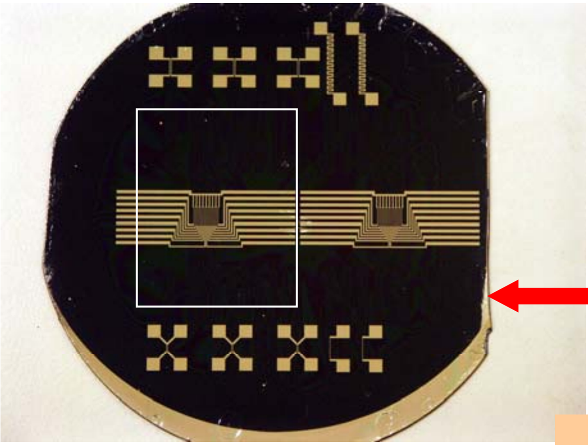
Easy to prepare thin films of excellent optical quality

Easy control of refractive index

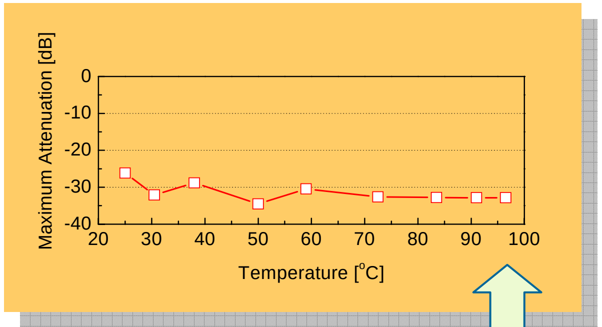
Versatile doping to obtain photonic materials (active, nonlinear optical, …

Integrated optical devices based on pattern-able organic/inorganic hybrid materials

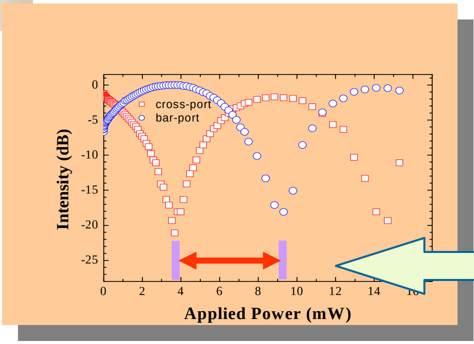
采用可光学加工的复合材料，获得光学功能突出,兼备有机和无机材料优异性能的集成光子器件



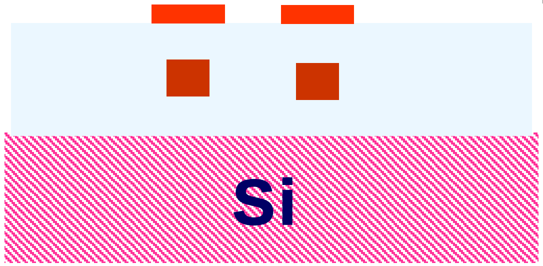
3英寸硅片上的集成光子器件



Thermal stability > 100 ^{o}C

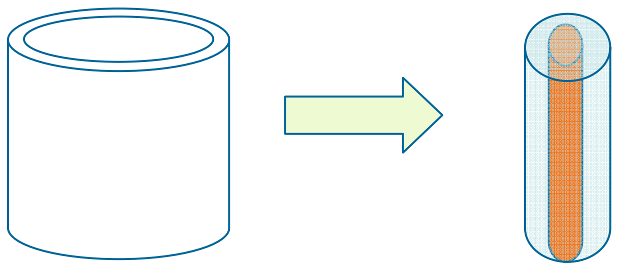


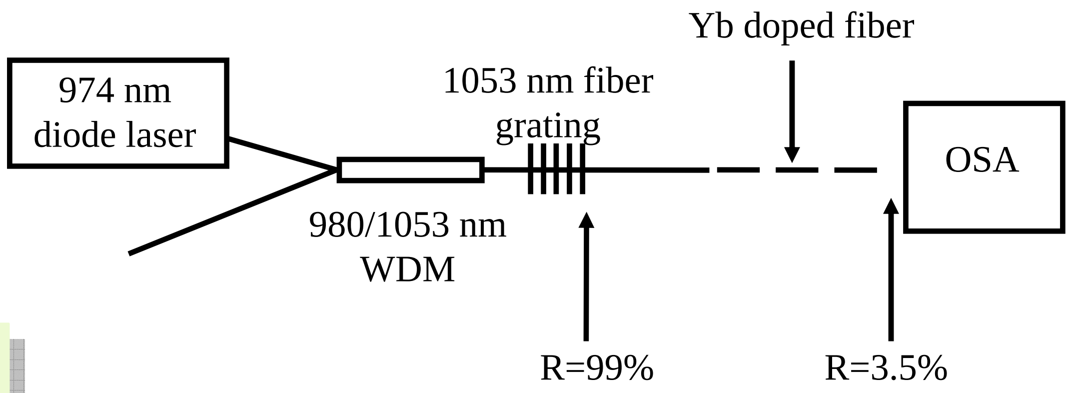
Switching power 5mW

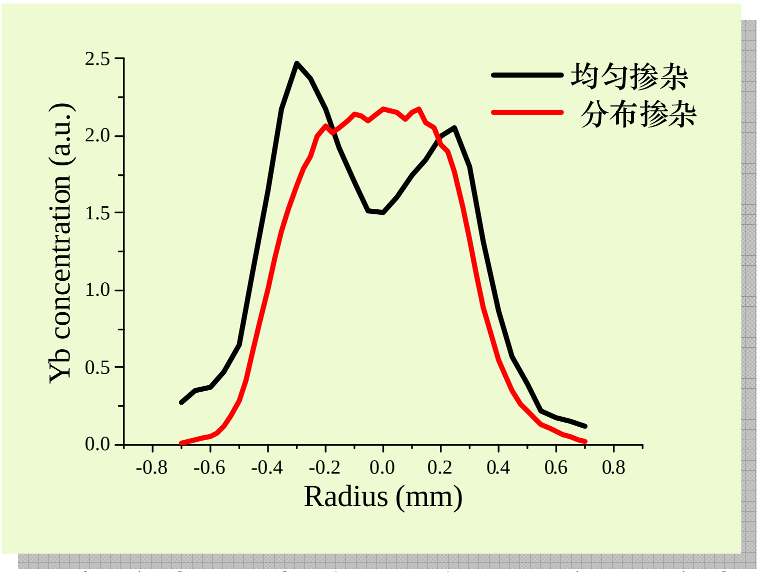


Optics Express 14, 6029 (2006)
Optics Express 16, 3172, (2008)
Optics Express 16, 9844, (2008)
J. Appl. Phys. 94, 4228 (2003)
Invited talk: OECC, APOC

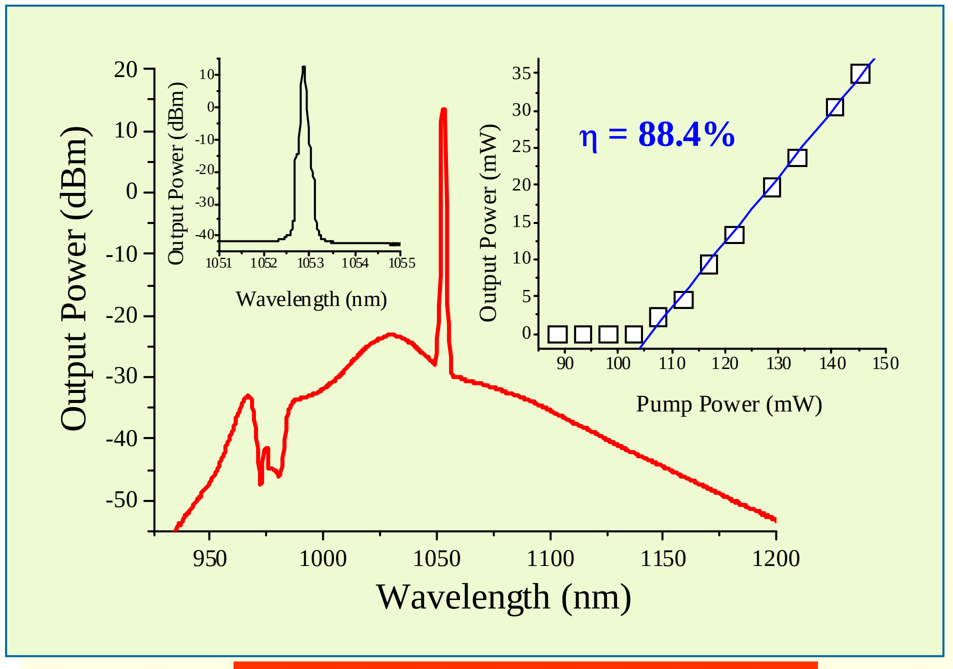
Heavy Yb doping optical fiber and fiber laser







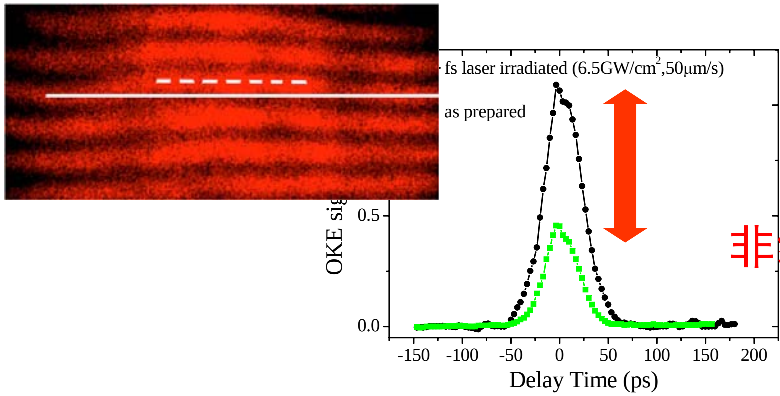
分布掺杂的溶胶-凝胶法制备重掺杂Yb光纤预制棒, Yb浓度均匀分布, 保证拉制的光纤高质量。



Slope efficiency 88%

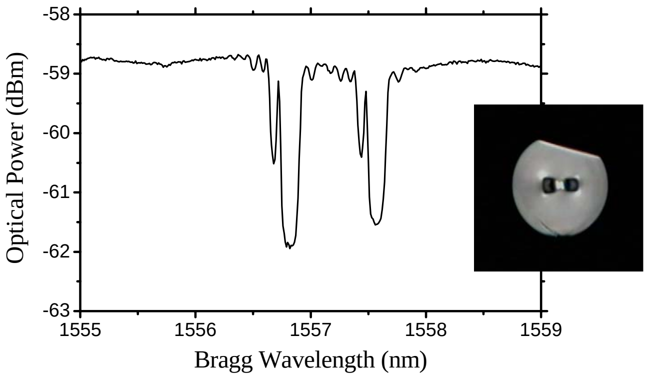
IEEE J.Lightwave Technology 26 3256 (2008)

Materials modification by laser light irradiation-To generate novel or enhanced optical functions



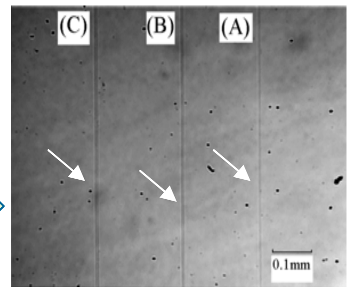
非线性增强

飞秒激光辐照使硫系玻璃的三阶光学非线性系数增强50%, 可用与波导光开关，缩短器件尺寸



双折射产生两个谐振峰，可用一根光纤同时传感温度和应力，可用于高灵敏度传感

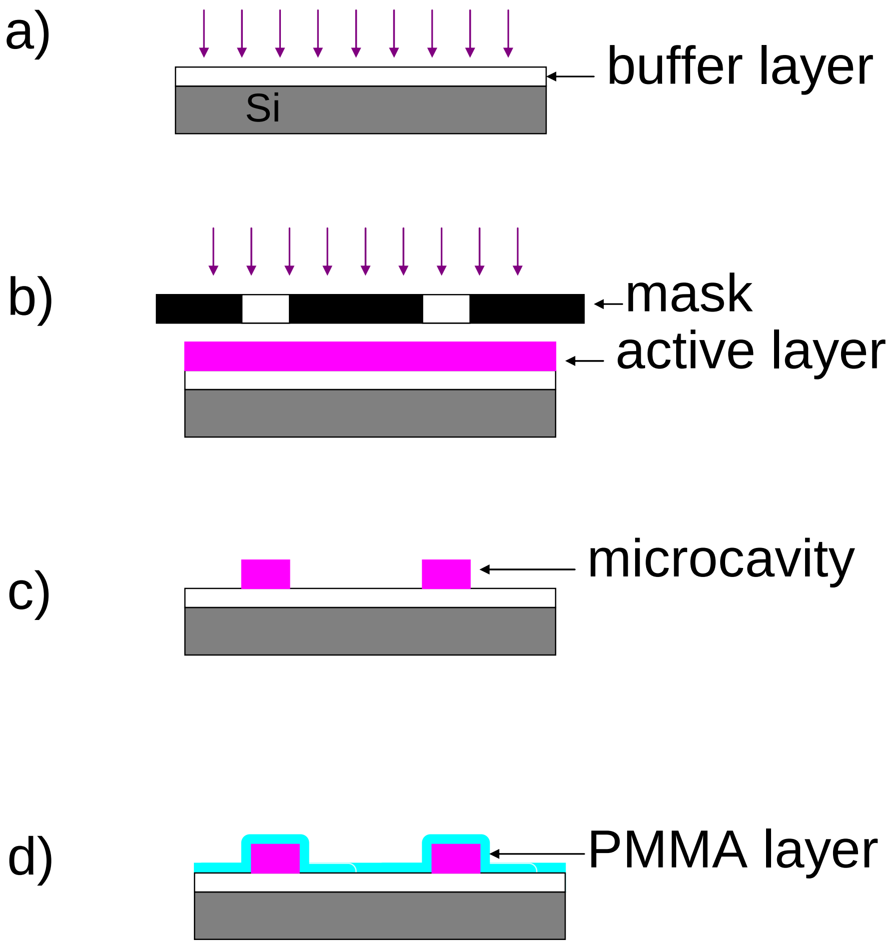
飞秒激光直写的波导光放大器

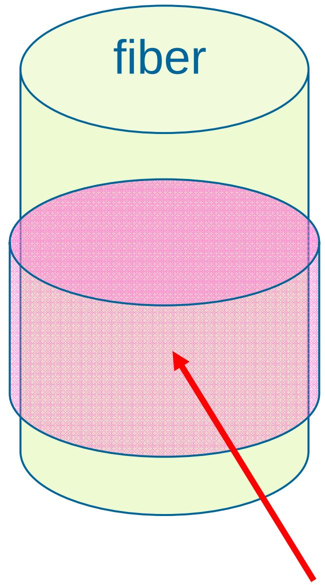


Optics Letters 2009
Chemical Physics 2009
J.Chem.Phys. 2008
Appl.Phys.Lett., 2007

Directional Lasing From Extremely Deformed Micro-cavity

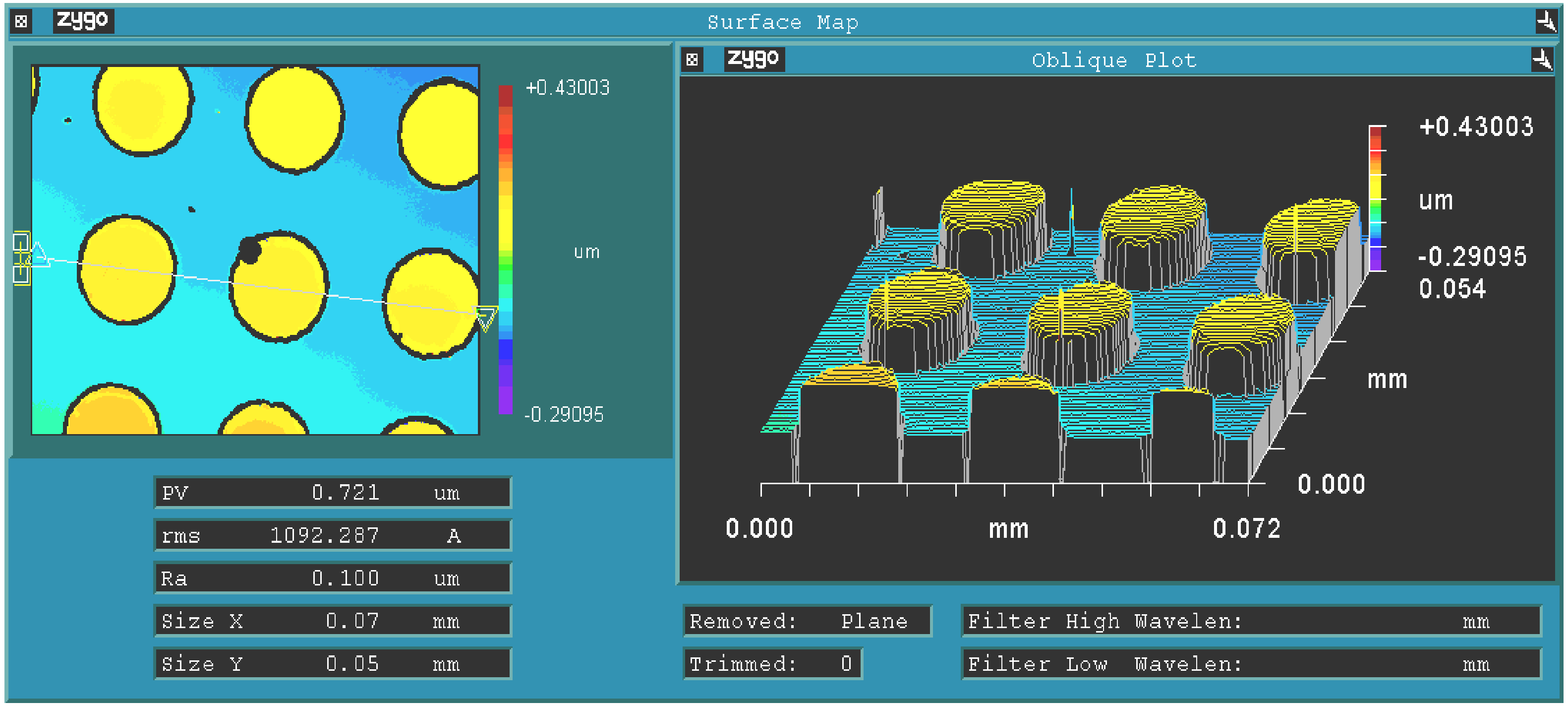
Fabrication Process





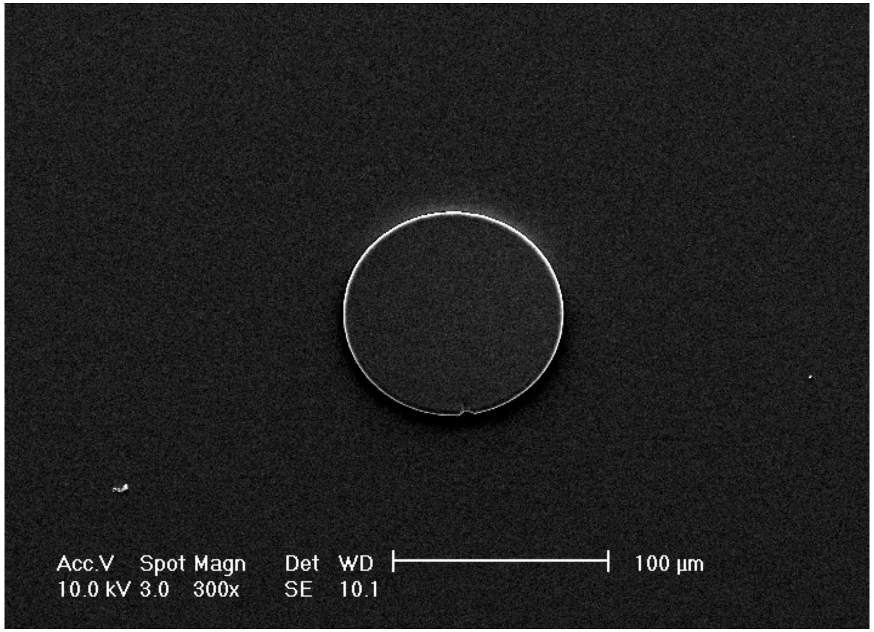
RhB doped organic/inorganic hybrid coatings

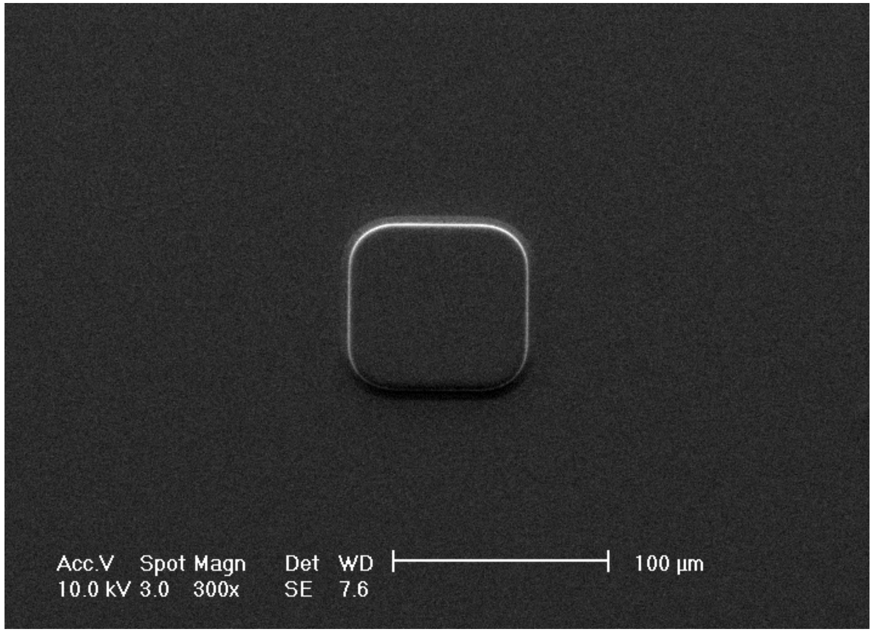
RhB doped photo-patternable organic/inorganic material



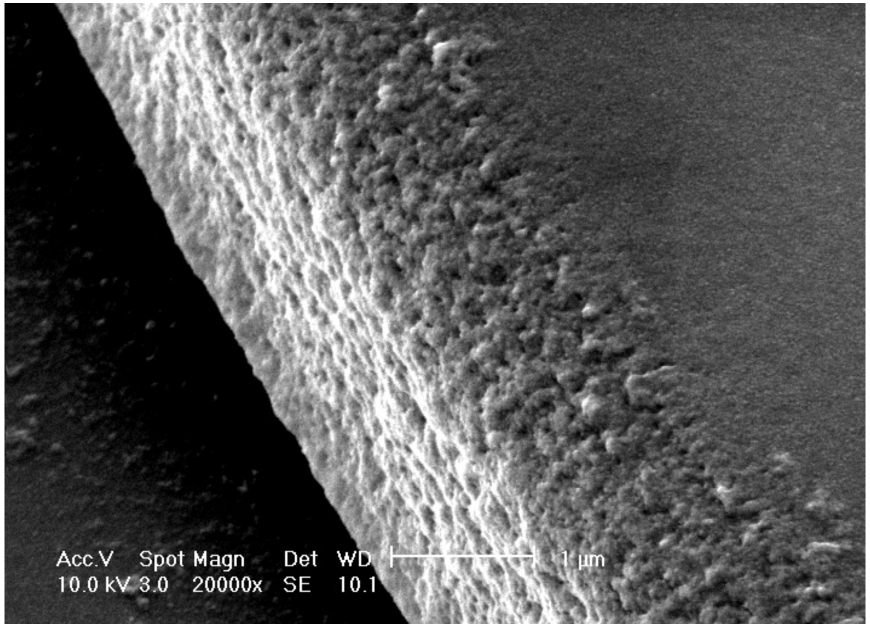
Direct UV patterning using organic/inorganic hybrid materials

Circular Disks and Square Disks

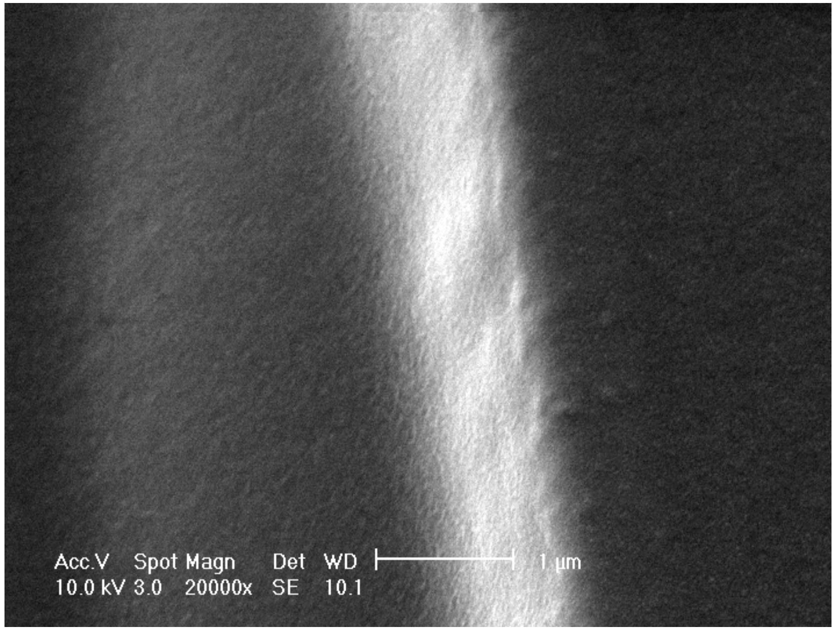




Improvement of Boundary Roughness after PMMA Coating

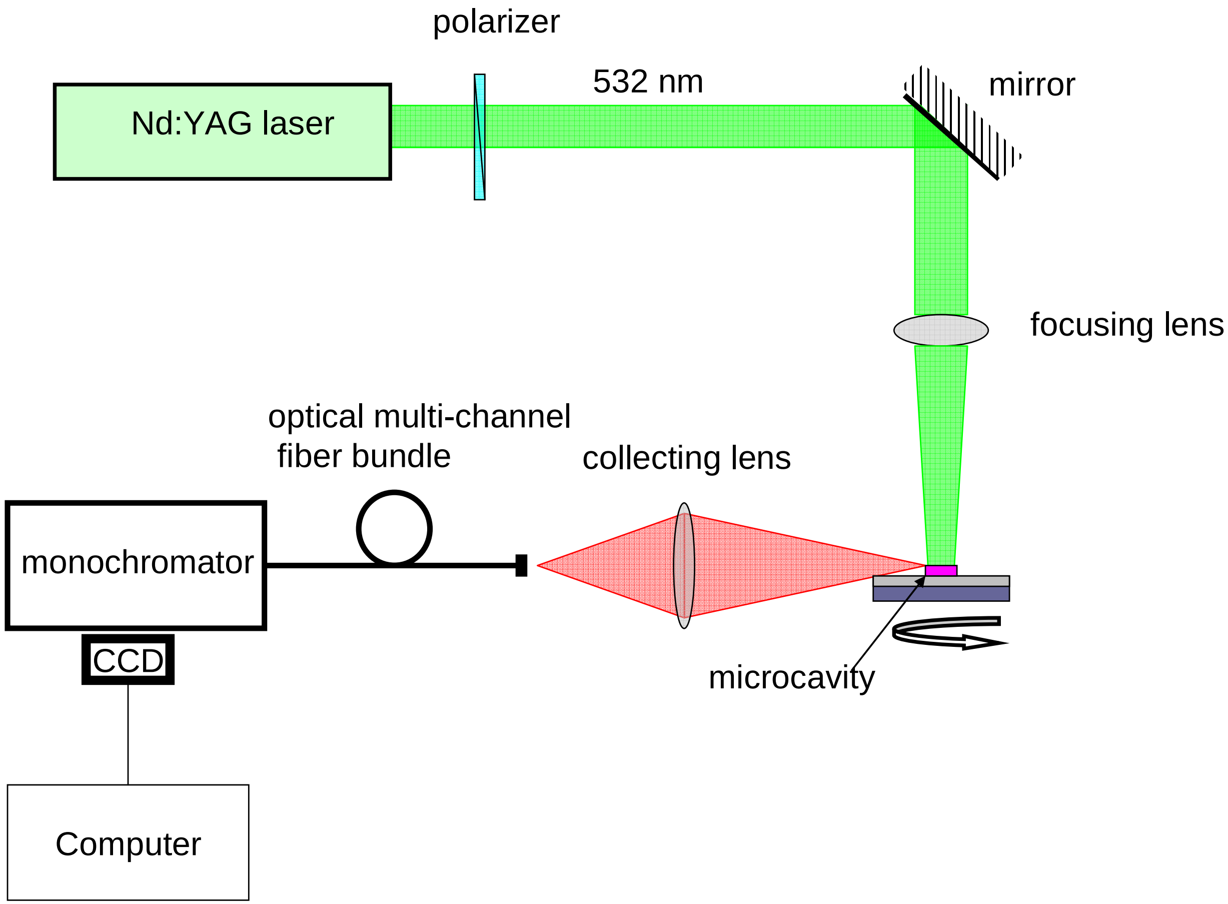


Bare disk

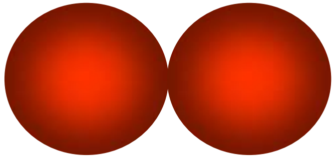


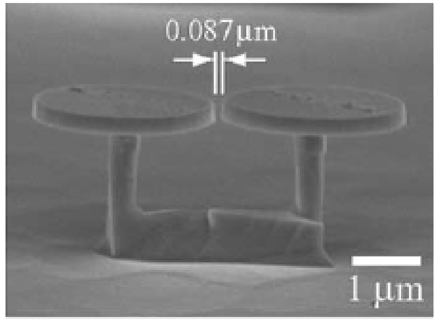
Cladded disk

Experimental Setup

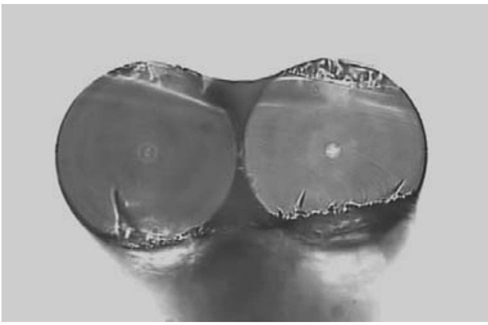


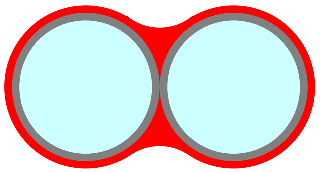
耦合微腔 coupled microcavities

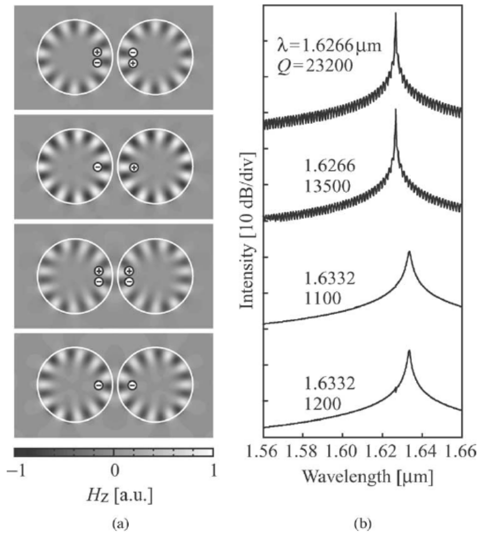




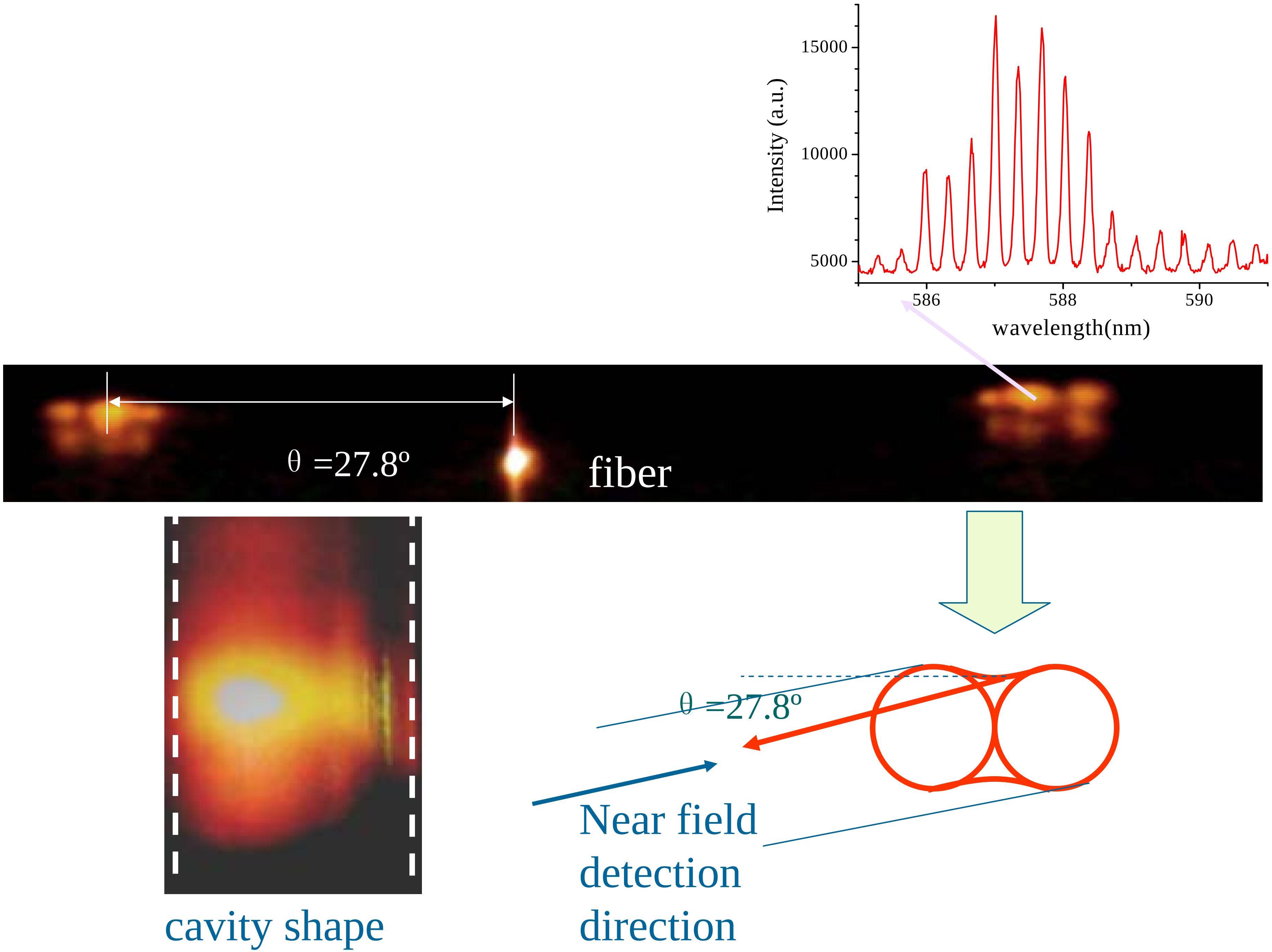
耦合微腔可以产生新颖的光学现象
photonic molecule (PM)
asymmetric-photonic molecule (AM)



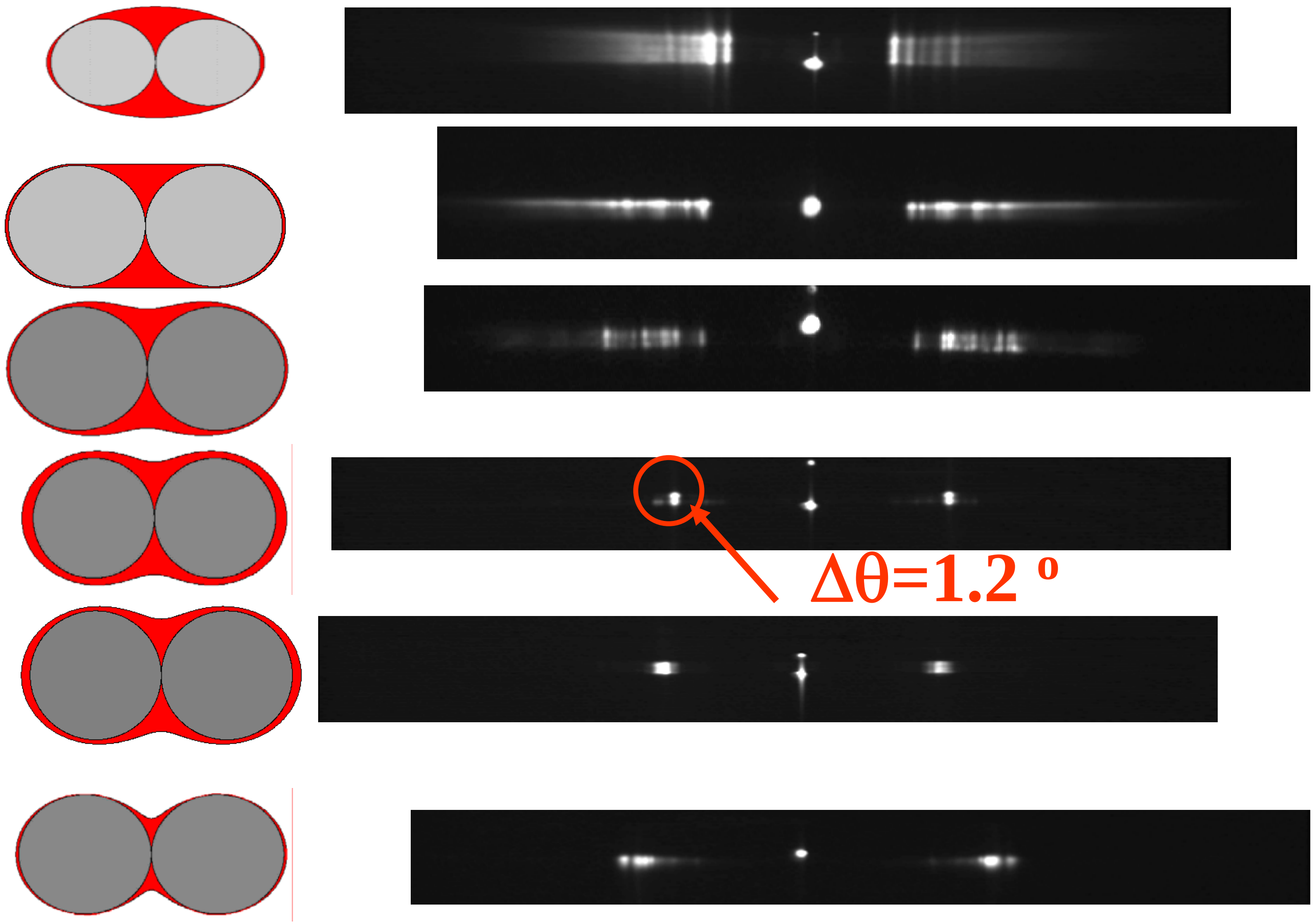




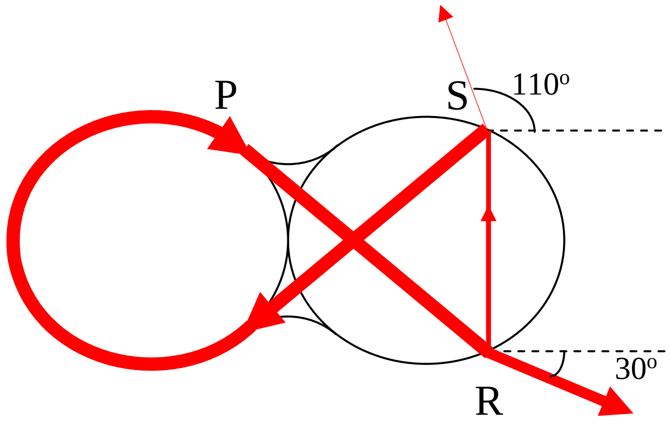
IEEE JSTQE 12, 71 (2006)

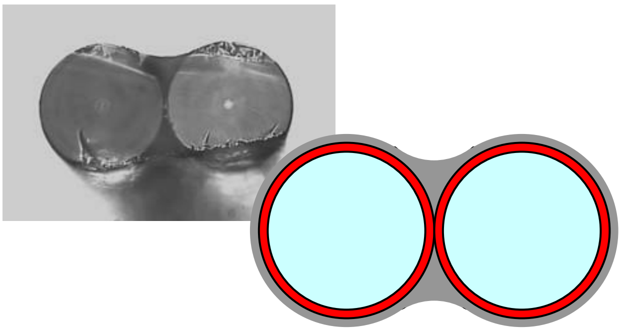

Intensity (a.u.)
15000
10000
5000
586
588
590
wavelength(nm)
θ =27.8°
fiber
cavity shape
θ =27.8°
Near field detection direction

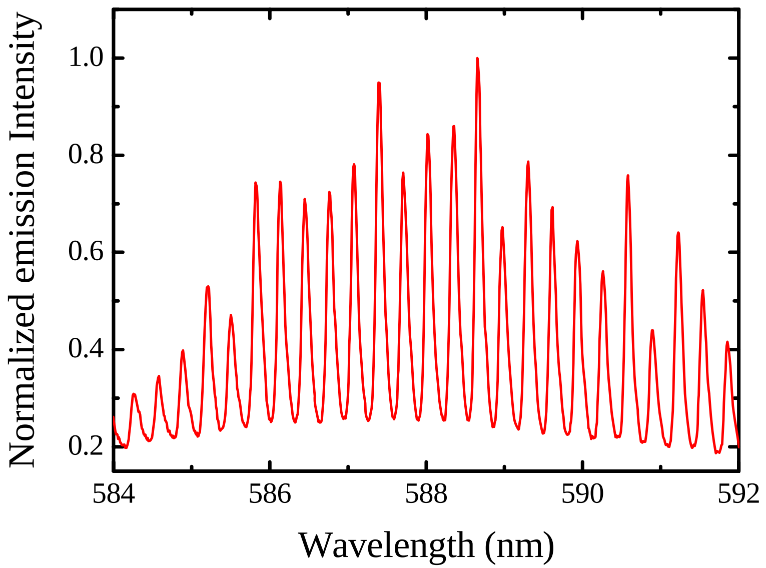
Directional laser emission

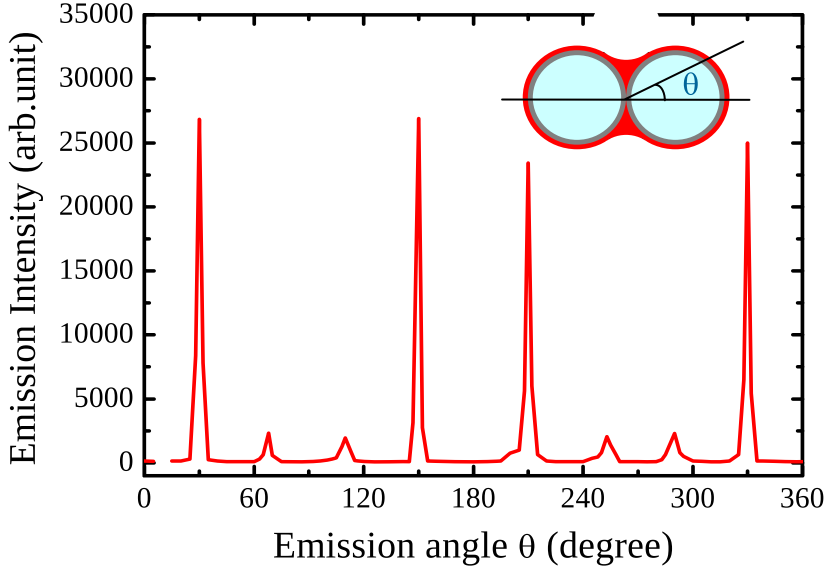


extremely deformed microcavity





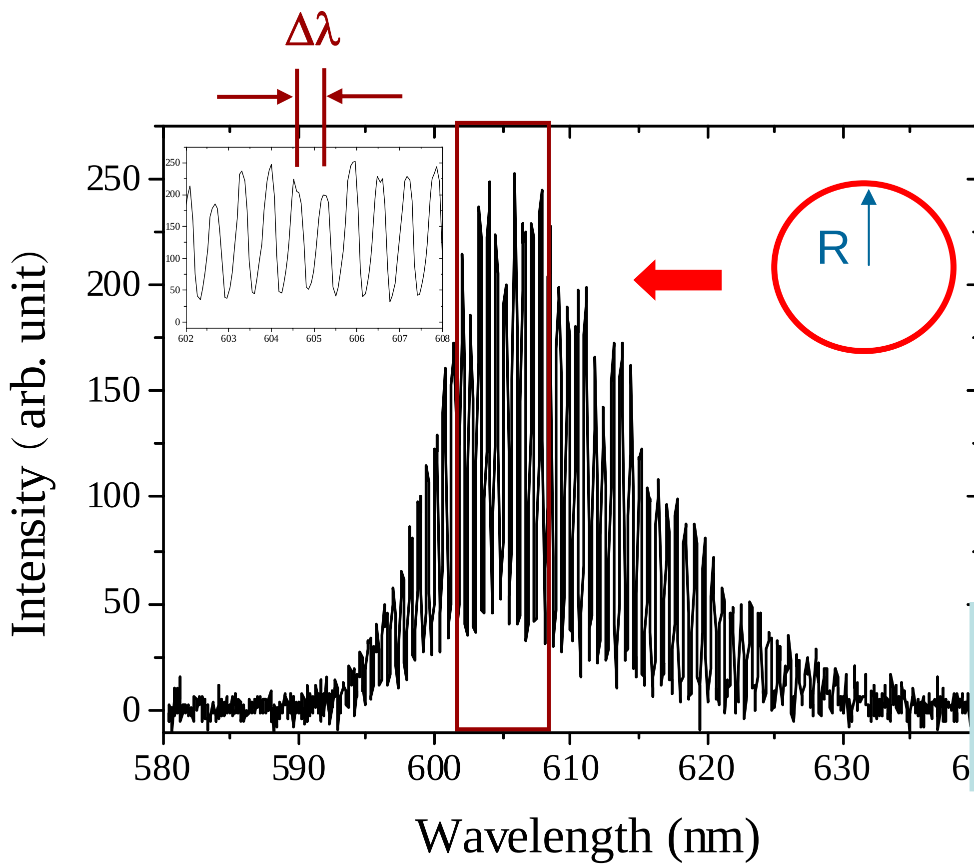




L.Shang, et al., Appl.Phys.Lett., 92,071111 (2008)

Single frequency whispering gallery mode laser

Whispering gallery mode micro-ring laser



$$2\pi n_{eff} R = m\lambda$$

$$\Delta\lambda = \frac{\lambda^2}{2\pi R n_{eff}}$$

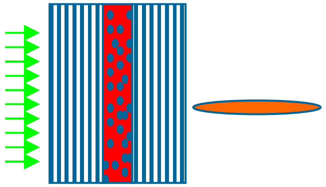
$$R = 50\,\mu m$$

$$\Delta\lambda = 0.4nm \quad @\,\lambda = 600nm$$

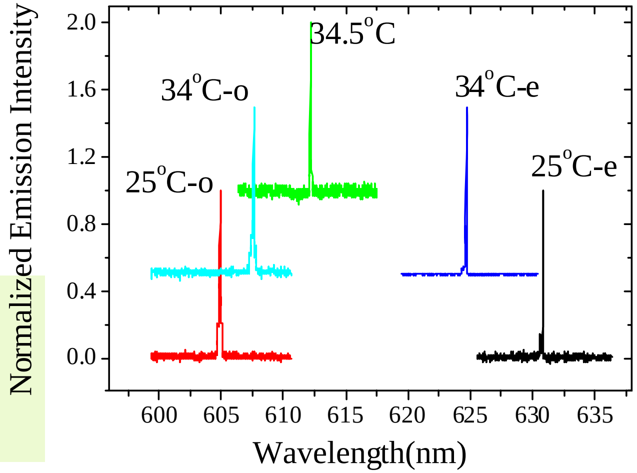
Much smaller than gain spectra

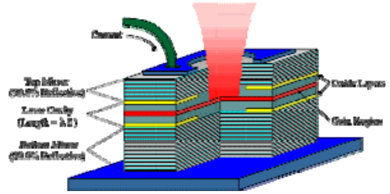
Smaller cavity → **Lower Q fabrication difficulties, electric & optical coupling**

Conventional single frequency (mode) selection techniques



Planar random cavity laser
Q. Song & L Xu, ***Phys.Rev.Lett.***, 96, 033902 (2006), ***Opt.Lett.*** 32, 373 (2007)

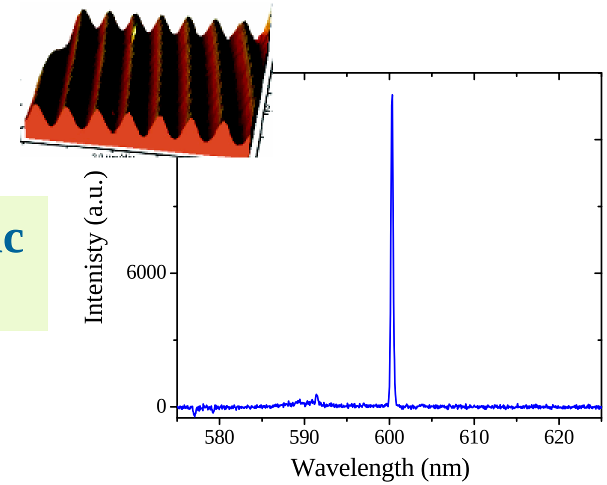




VCSEL

$$2nd = m\lambda$$

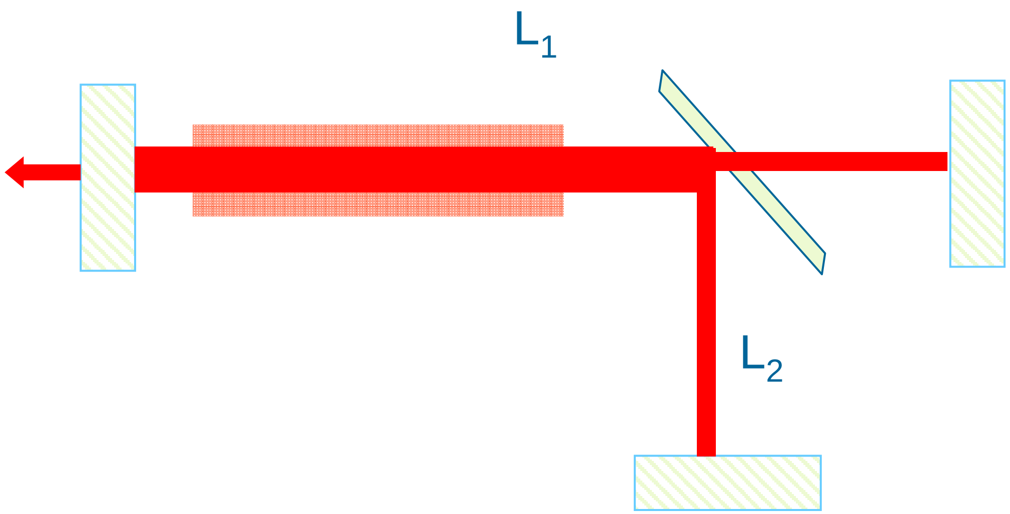
Dye doped organic/inorganic hybrid DFB laser



$$\lambda_B = 2\Lambda n_{eff}$$

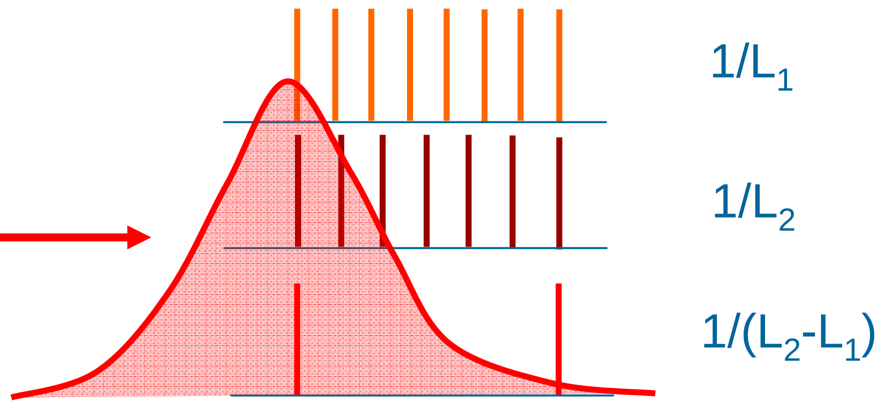
DFB

Composite cavity laser

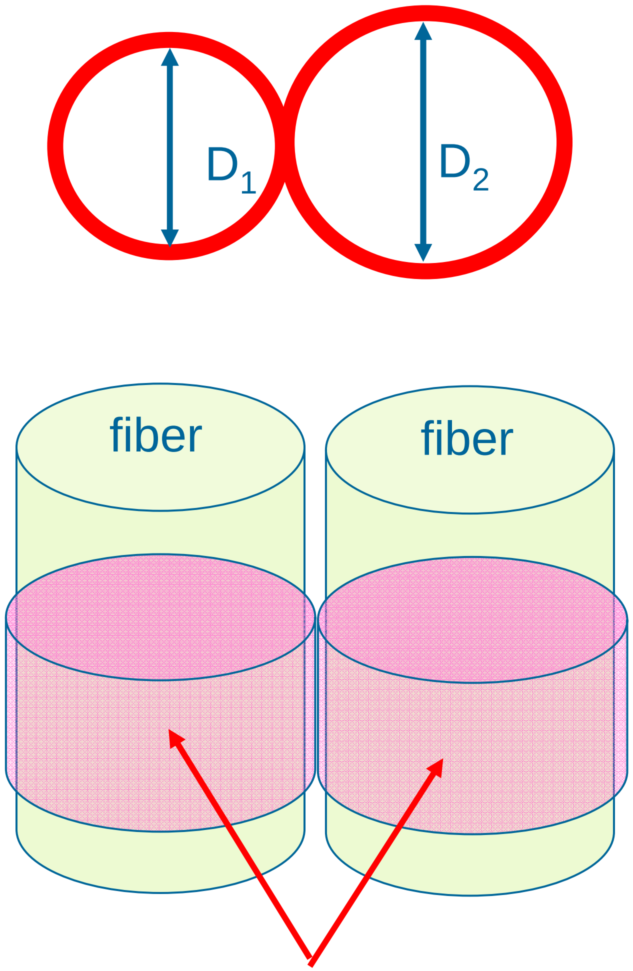


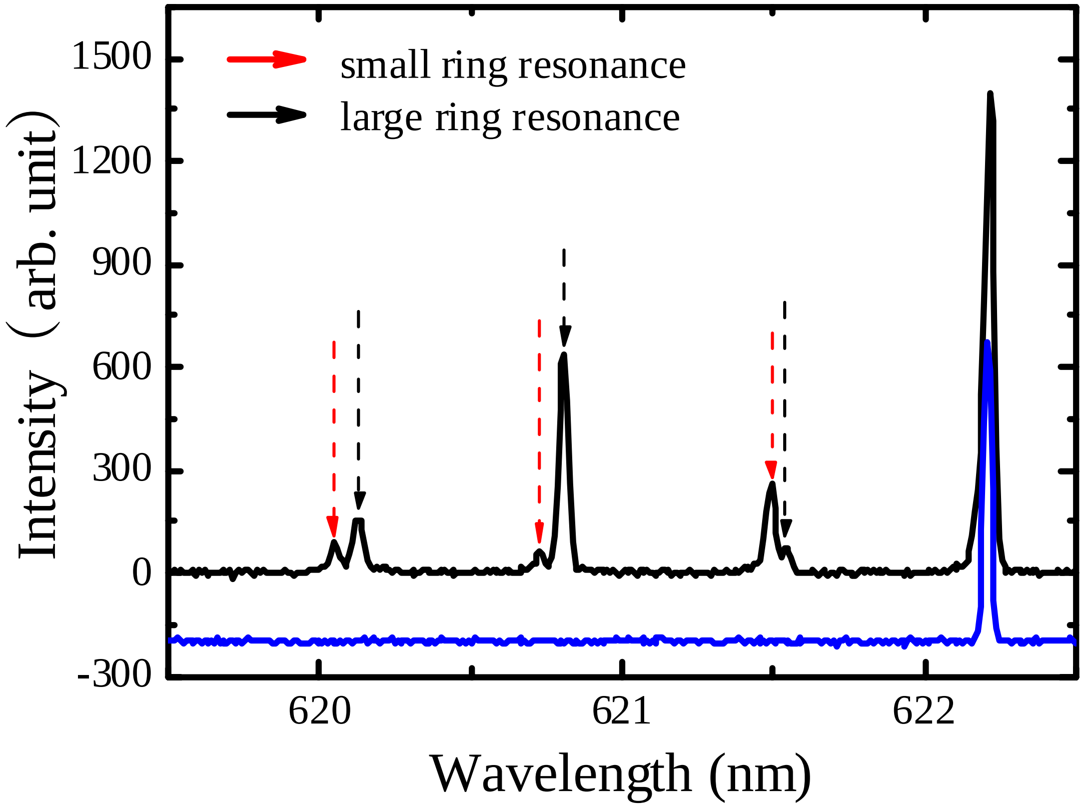
$L_1 = L_2 + \delta$

游标效应 Vernier effect:

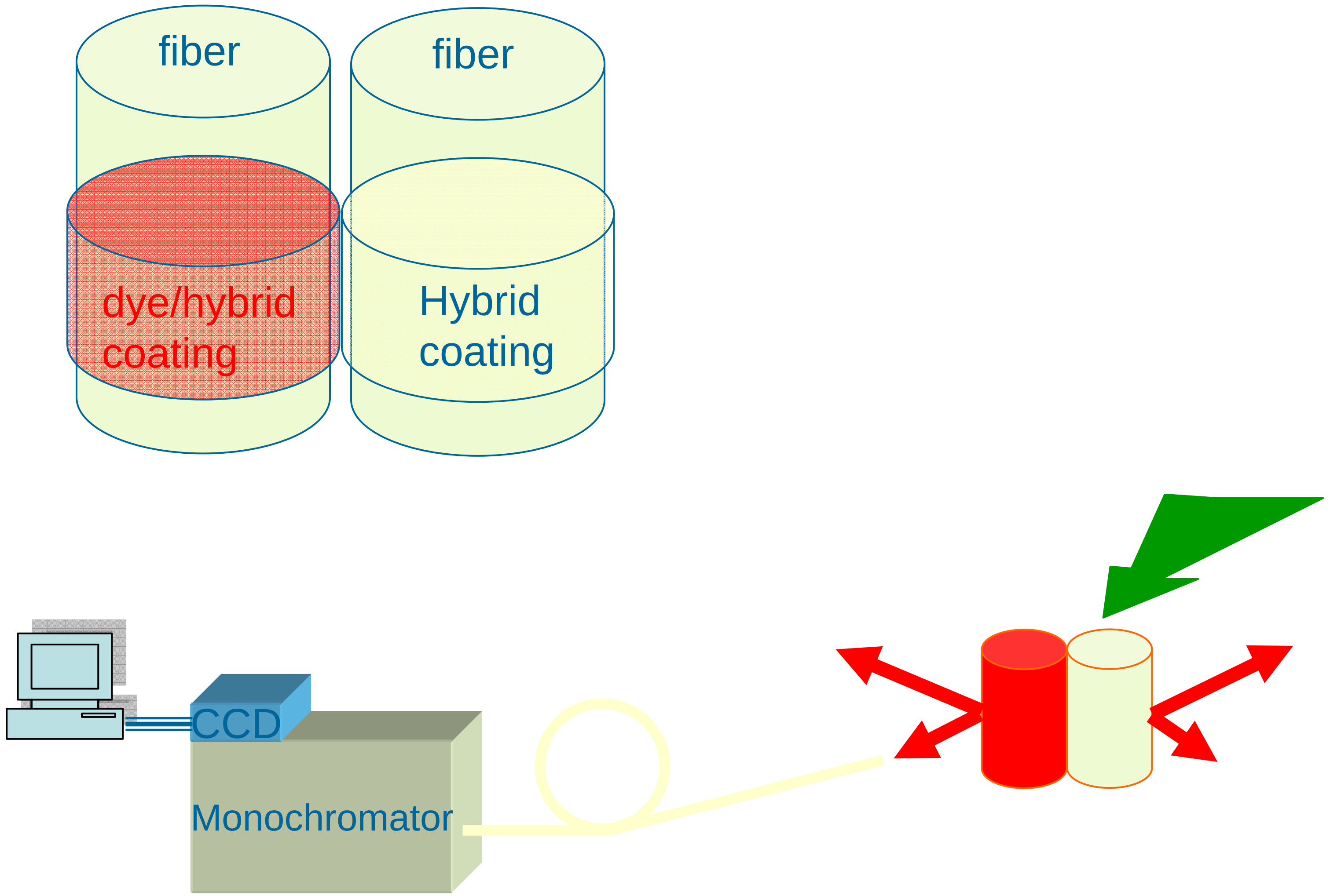


Mode selection in asymmetric coupled microcavity laser

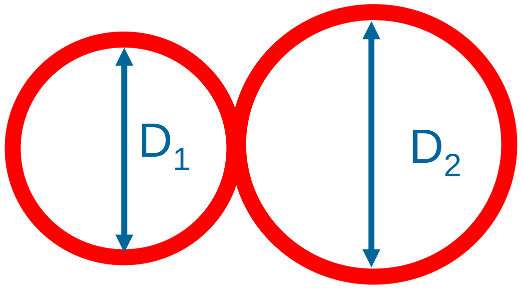




RhB doped organic/inorganic hybrid coatings


fiber
fiber
dye/hybrid coating
Hybrid coating
CCD
Monochromator

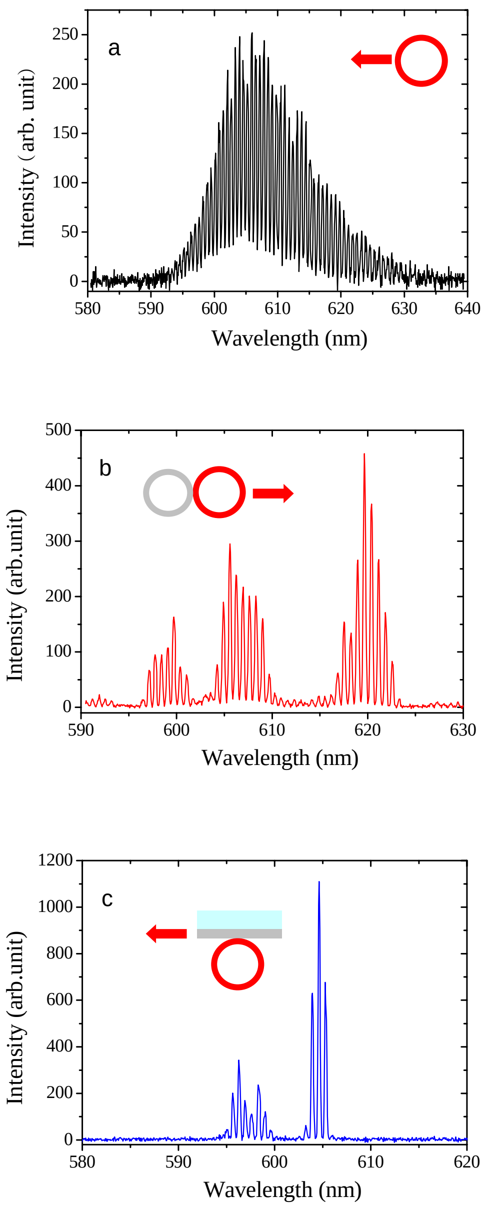
Modulated emission spectrum from coupled cavities



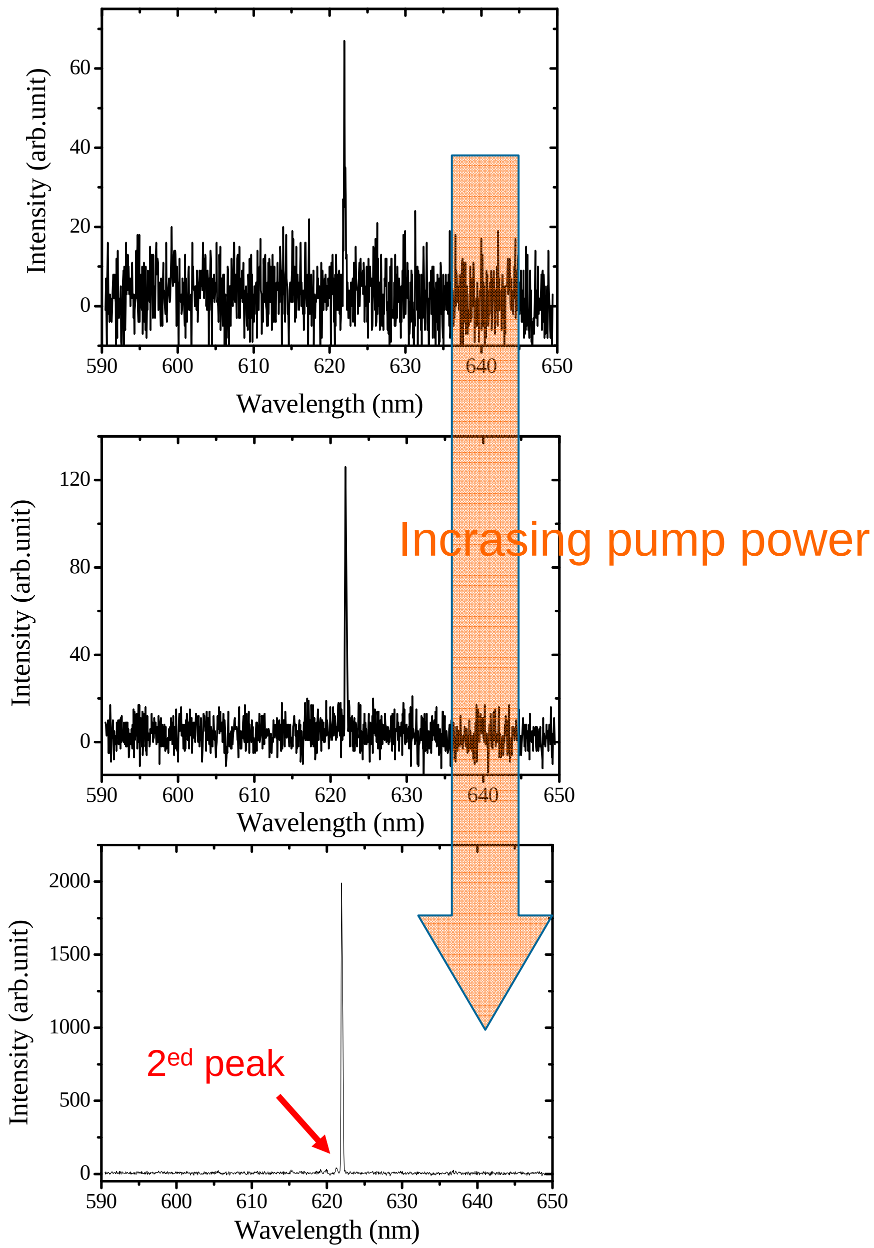
Modulation width

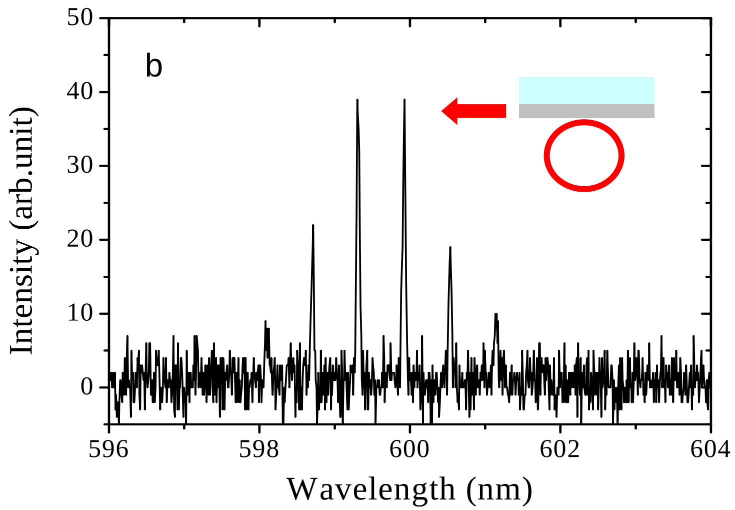
$$\Delta\lambda \approx \frac{\lambda^2}{\pi n_{eff}\,(D_1 - D_2)}$$

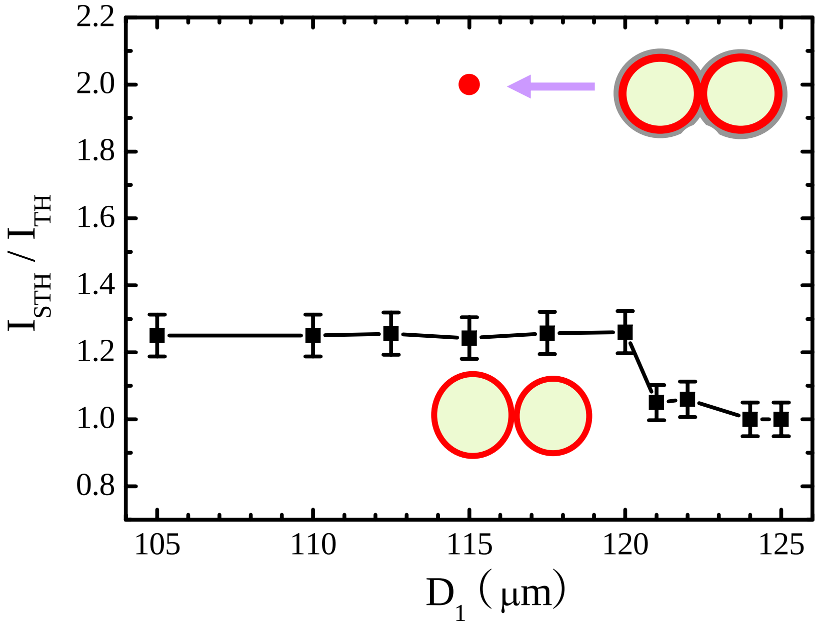
N_{eff}=1.5, D=125μm, ΔD=6μm
Δλ=10 nm



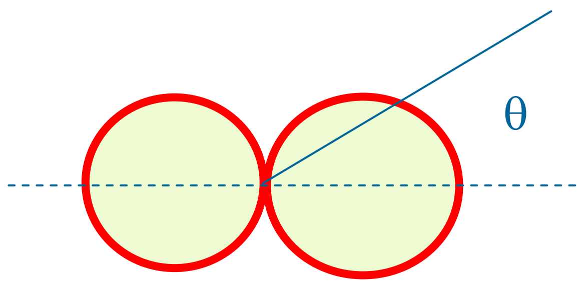
Multi-mode suppression

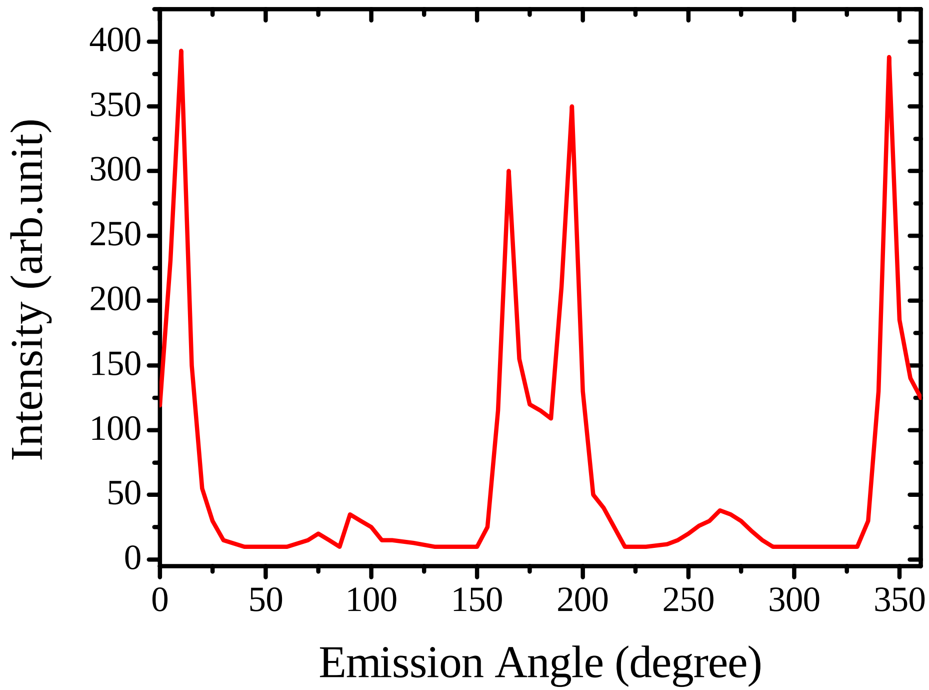




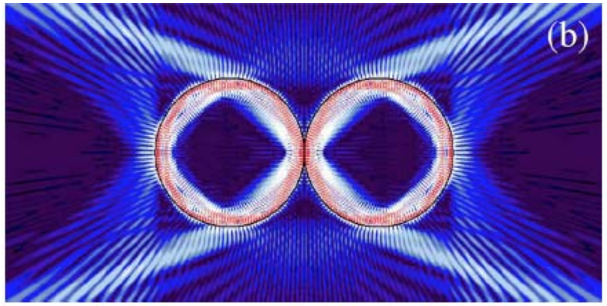


Angular emission

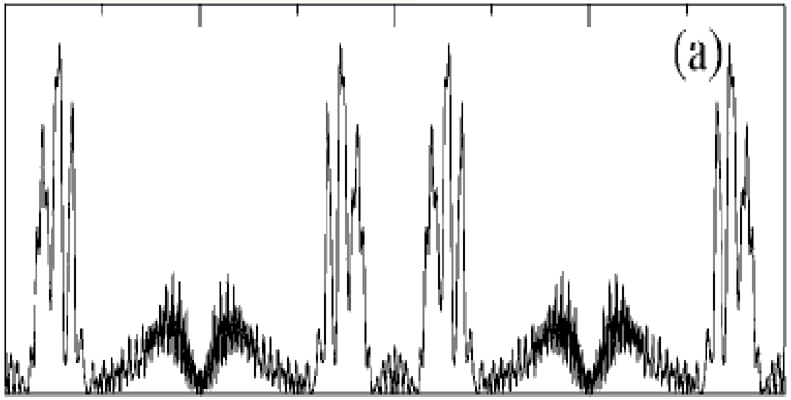




Near field pattern

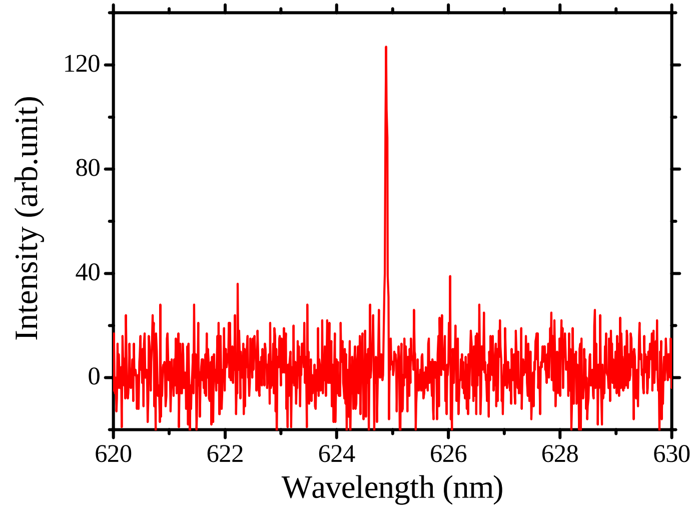


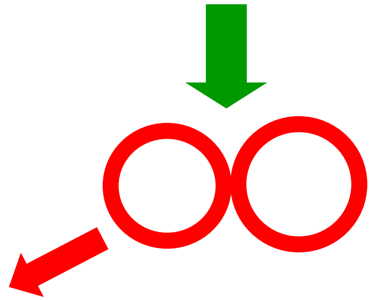
Far-field pattern

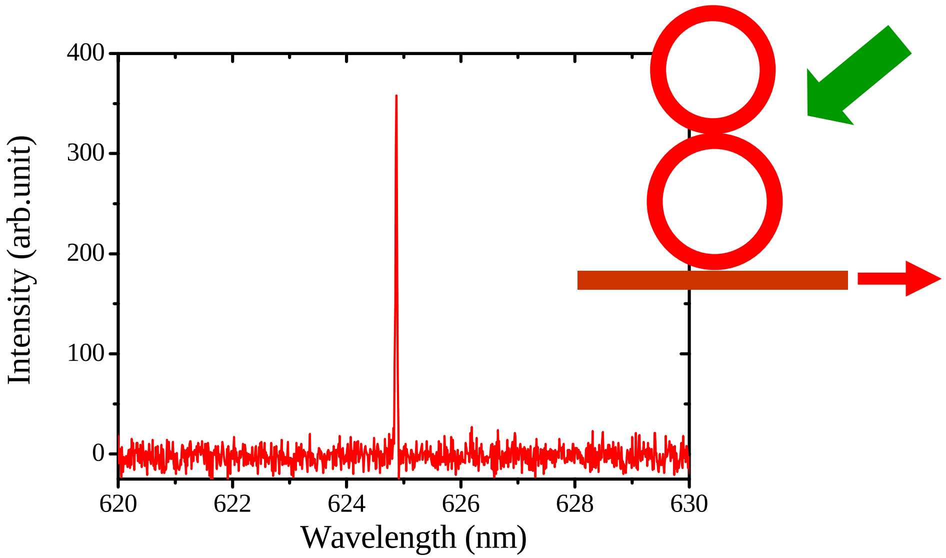


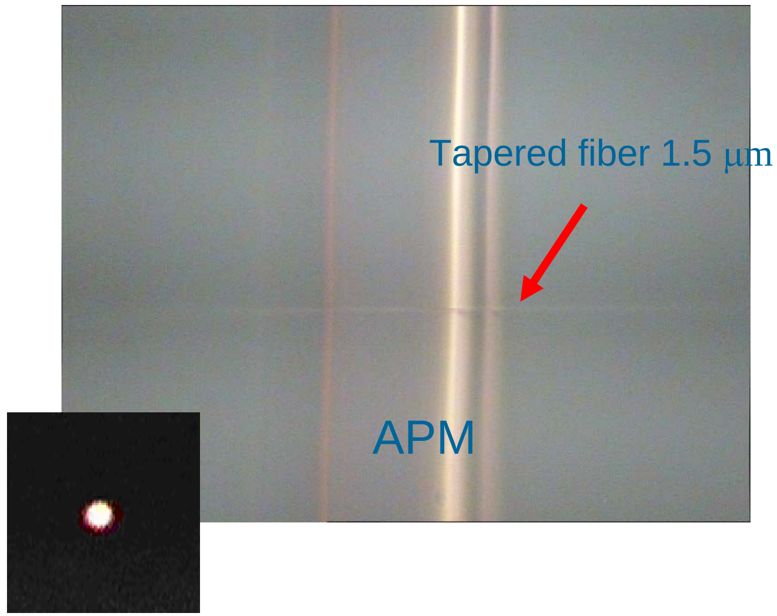
J.Ryu, PRA 74, 013804 (2006)

Tapered fiber coupled single frequency coupled microcavity laser

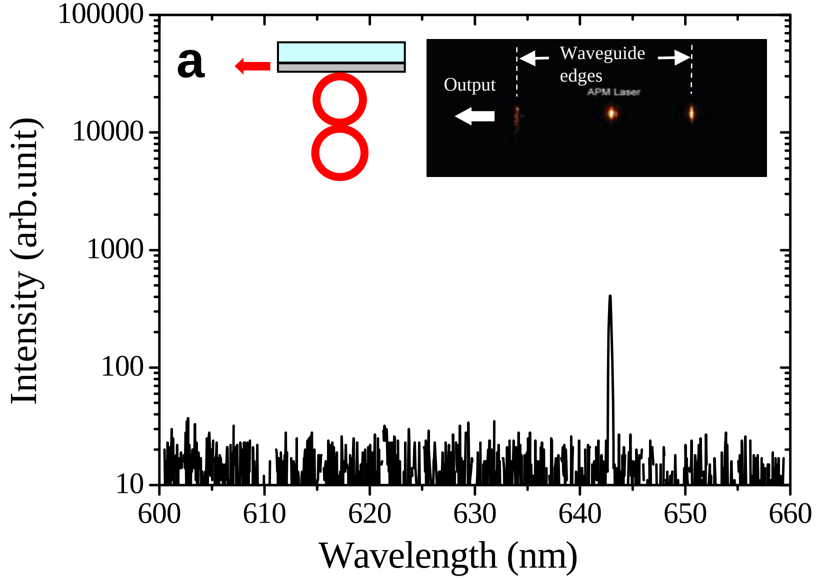


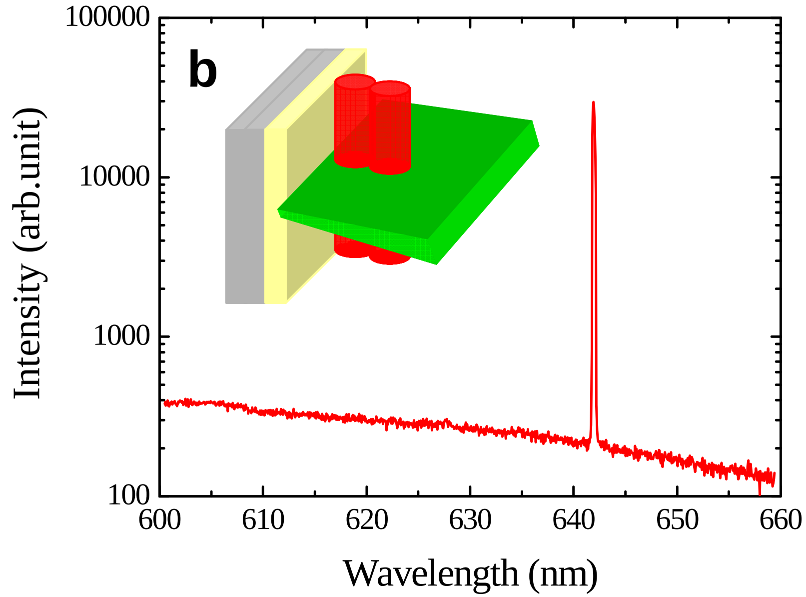


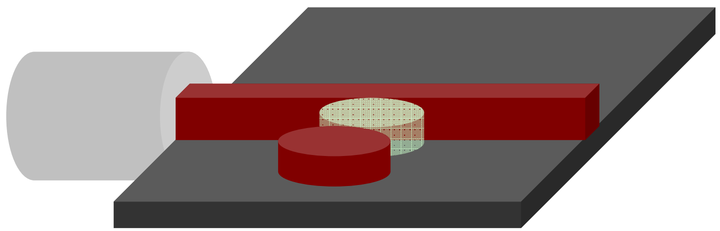




Single frequency oscillator + pre-amplifier



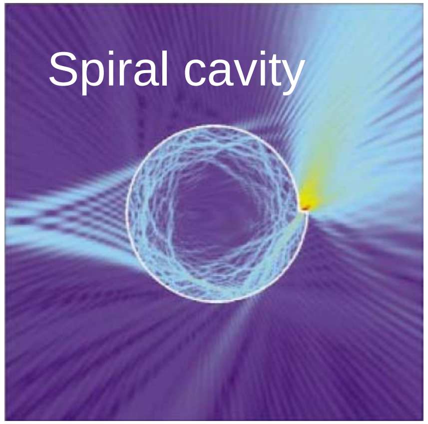


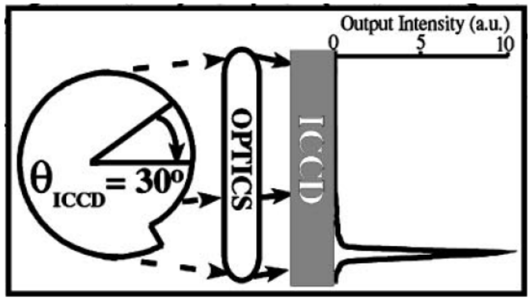


Integrated single mode
micro-laser on chip

L.Shang & L.Xu, Optics Letters, 33,1150 (2008)

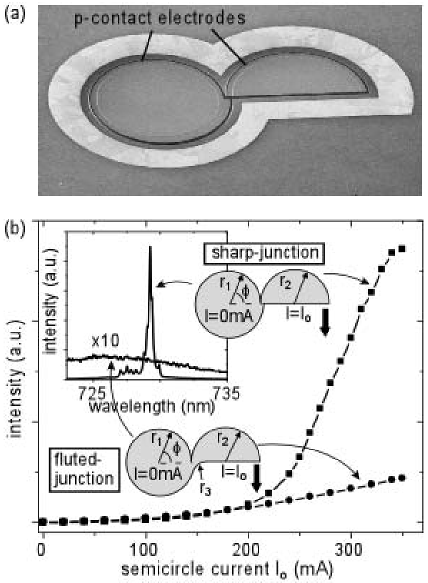
Toward a unidirectional single frequency laser on chip





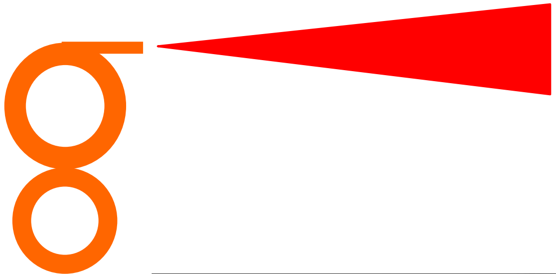
$$R(\phi) = R_0(1 + \varepsilon\phi / 2\pi)$$

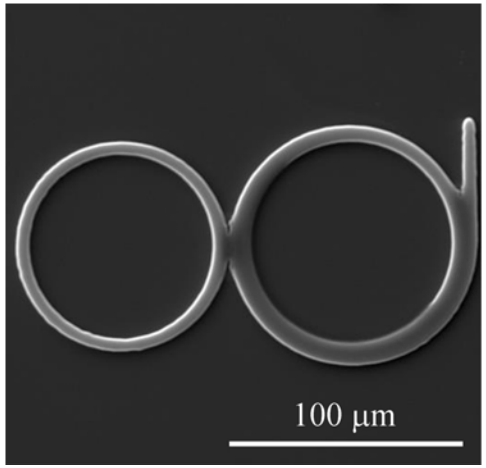
G.D.Chern et al,, APL 83,1710 (2003)



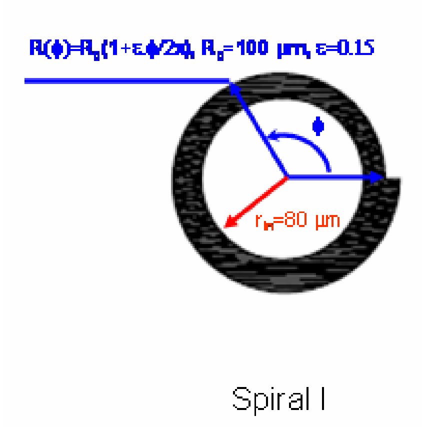
G.D.Chern, et al., Opt. Lett. 32, 1093 (2007)

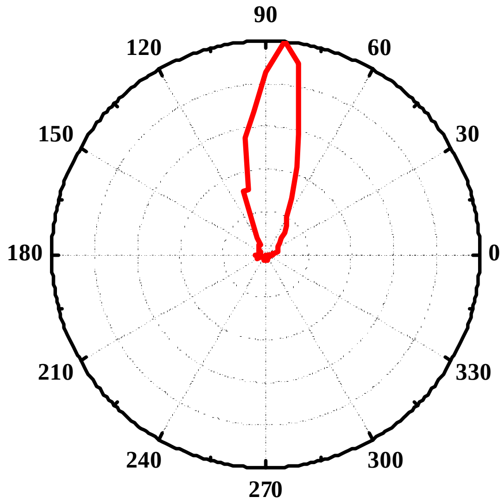
A coupled spiral cavity

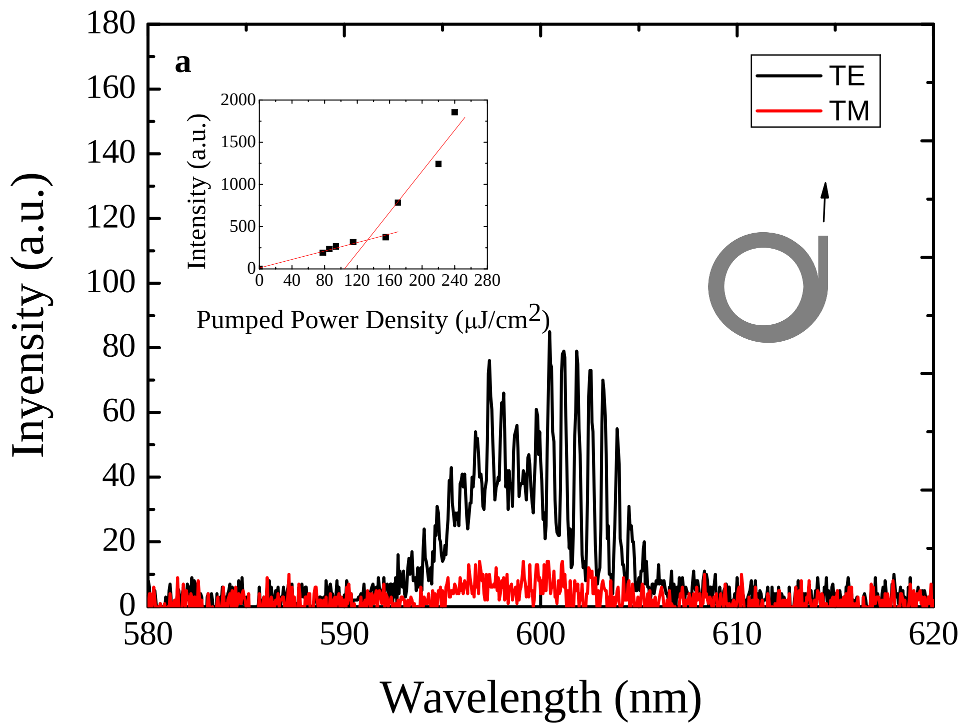




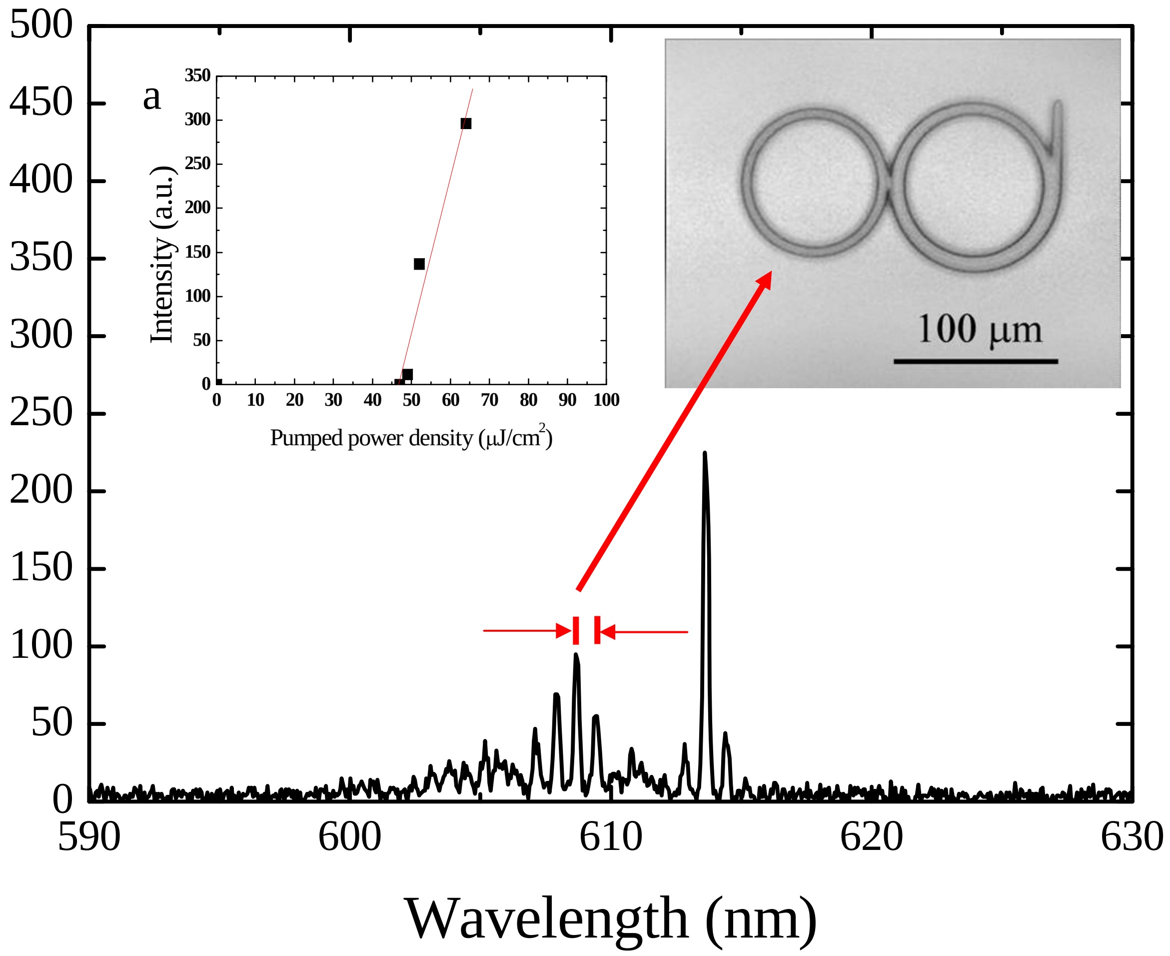
Unidirectioanl emission from Spiral microcavities







Ring-spiral coupled microcavity resonance



Pump threshold=45 μJ/cm^2

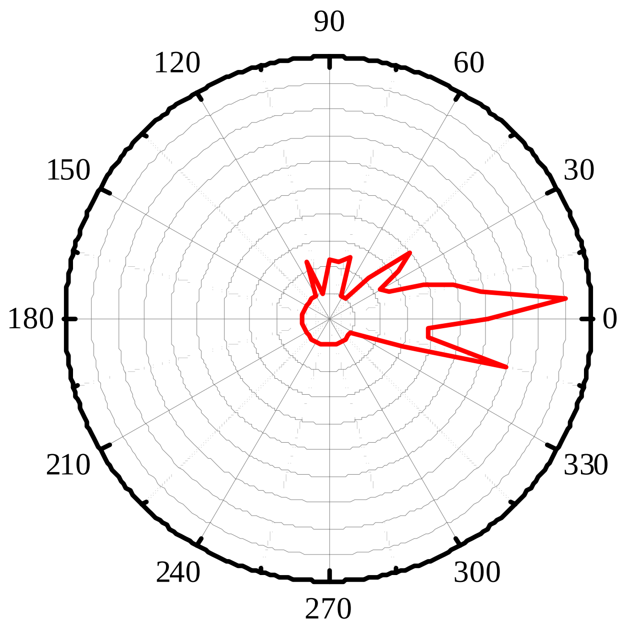
Spiral

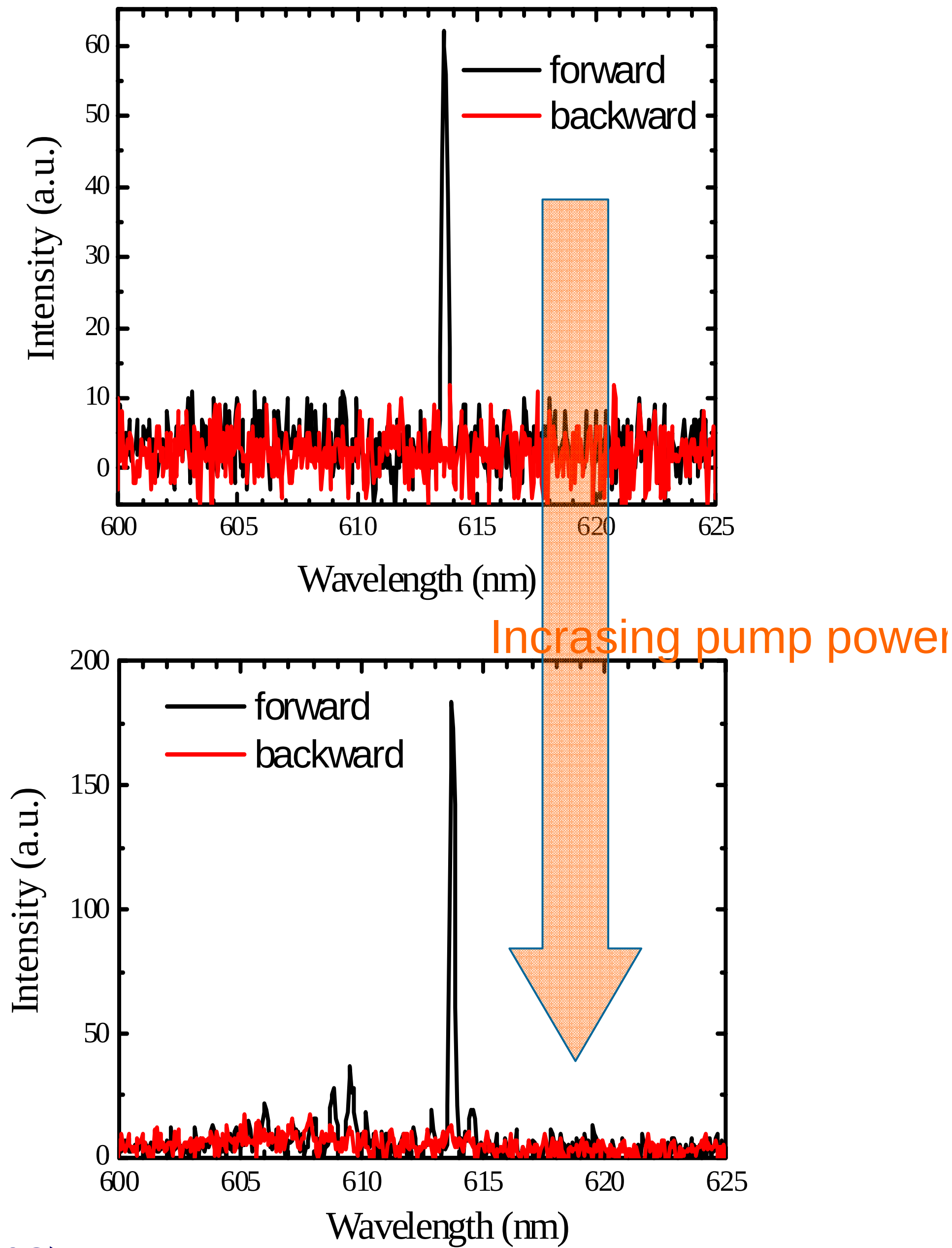
Pump threshold=130 μJ/cm^2

Ring: resonator

Spiral: resonance filter

Uni-directional single mode lasing





X.Wu & L.Xu, Appl.Phys.Lett. 93, 081105 (2008)

Single mode microcavity laser: possible applications

UV single mode laser: difficulty in conventioanl cavity fabrication (DBR)

Optical sensing

Passive sensing *vs* Active sensing

light propagation | *light emission*

Passive sensing (*light propagation*)

High Q, high sensitivity

Precisely controlled experiment, (critical coupling)

Single channel detection

Single frequency tunable input laser (<< 0.1 pm)

Active sensing (*light emission*)

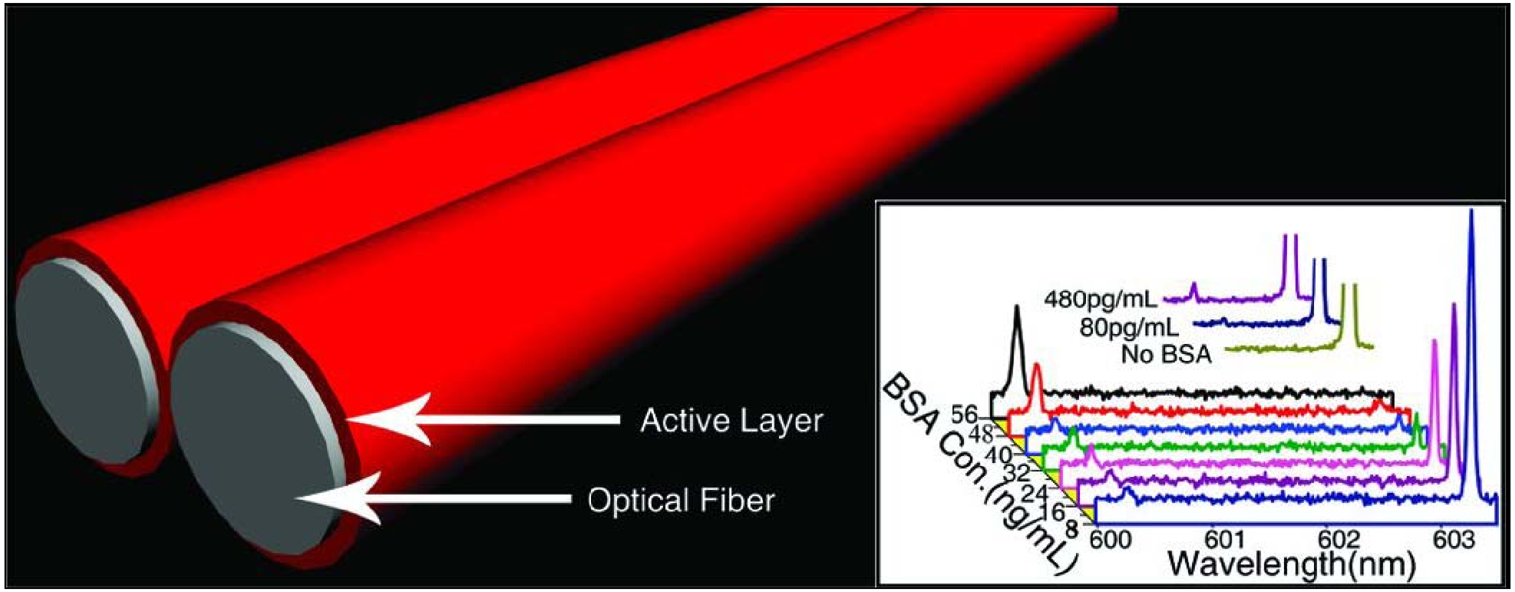
Parallel (2D) fast detection

Simple experimental setup

need high resolution spectrometer (> 10 pm)

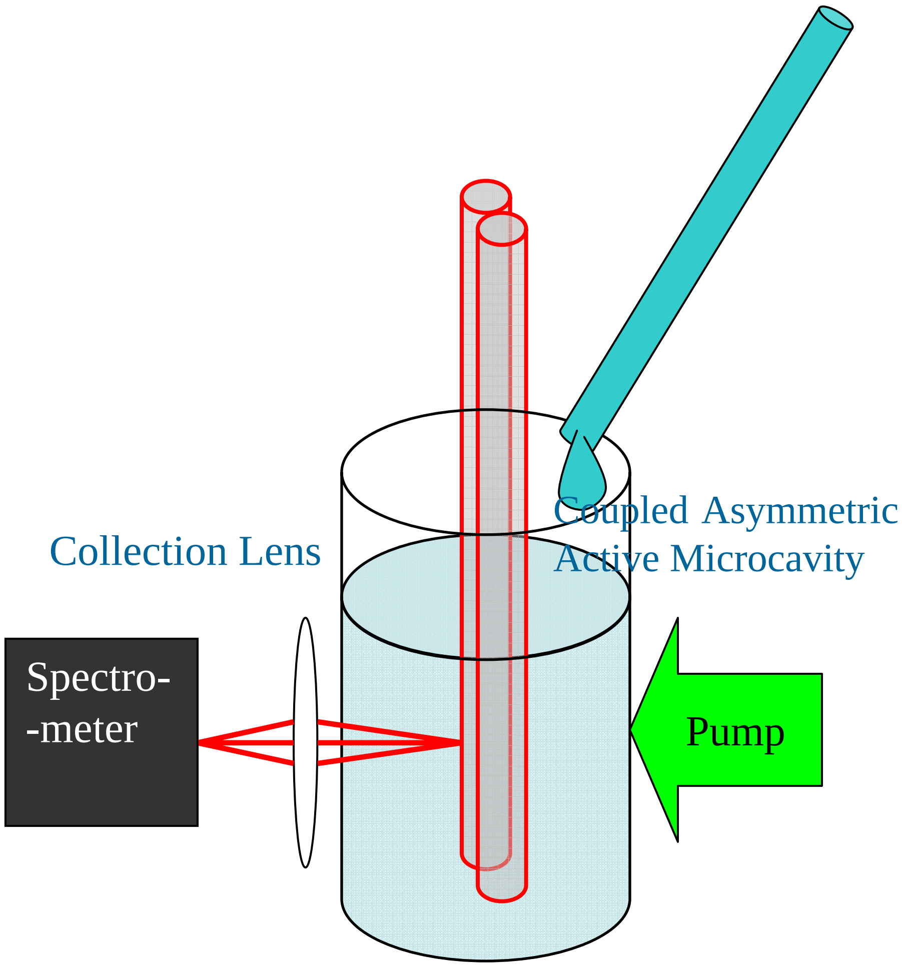
Special mechanism to reduce spectral resolution requirement

Coupling variation induced ultrahigh sensitive label free bio-sensor by using single mode coupled microcavity laser

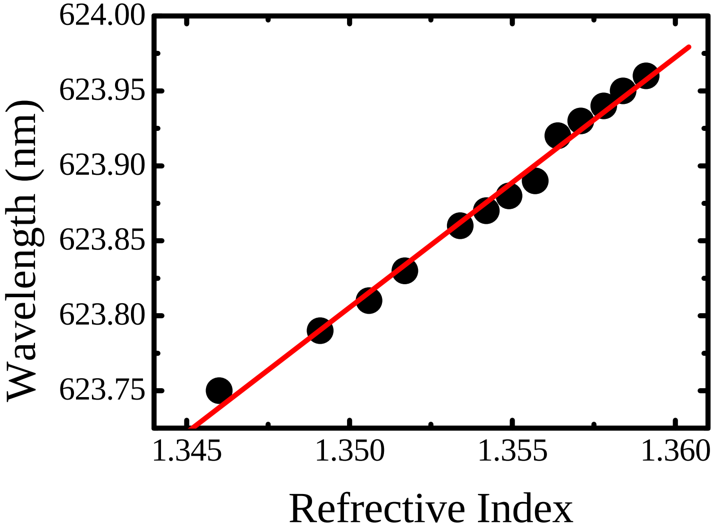


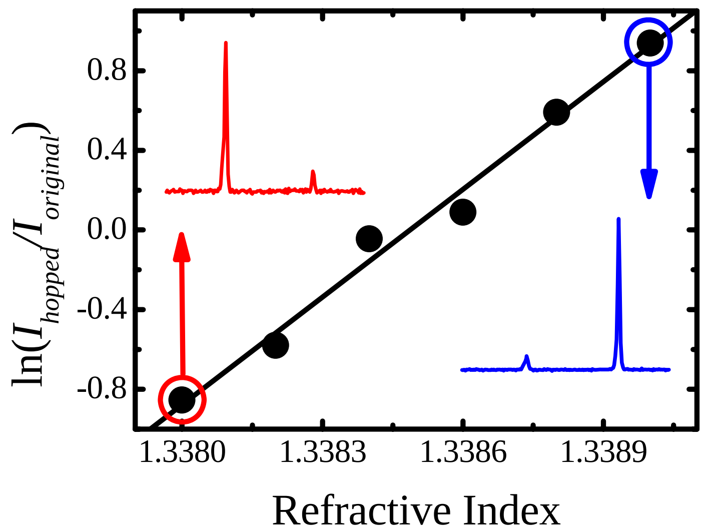
H Li & L. Xu, JACS 131,16612 (2009)

Setup

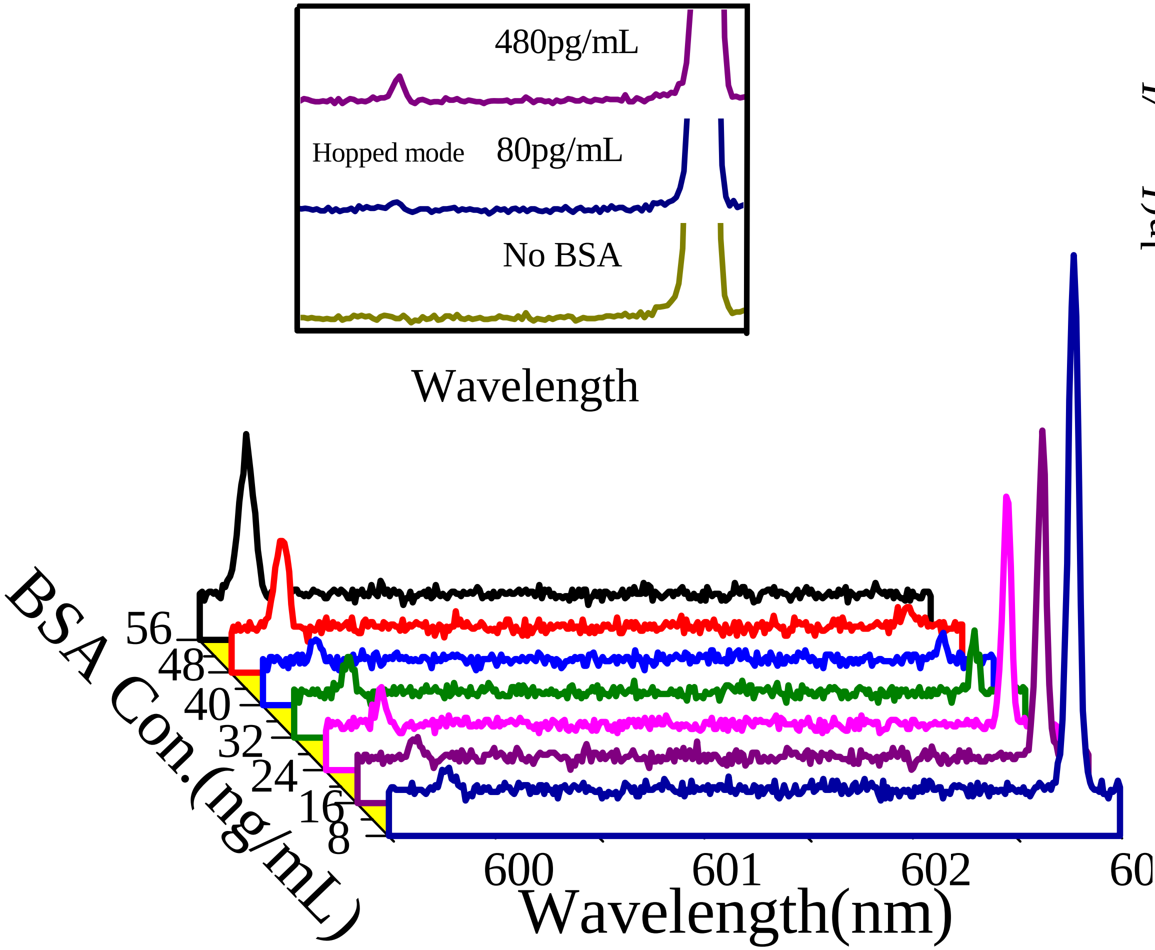

Collection Lens
Coupled Asymmetric
Active Microcavity
Spectro-
-meter
Pump

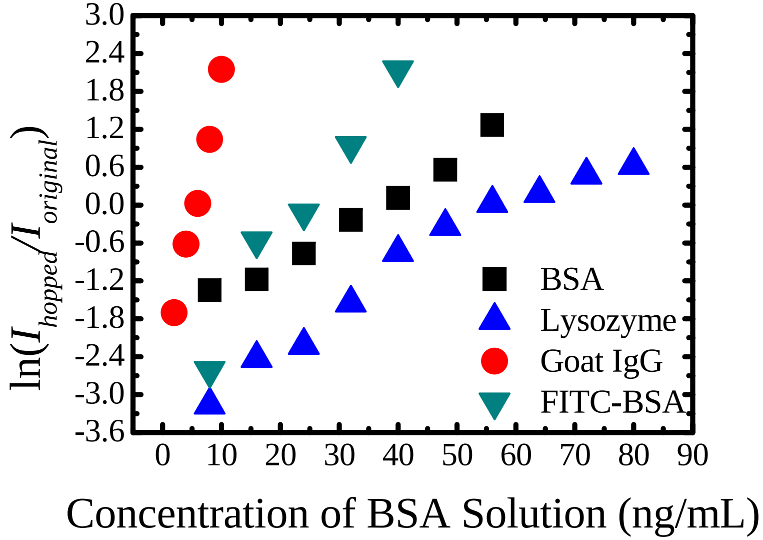
- **Resonance shift vs hopping**





Bio-sensing result

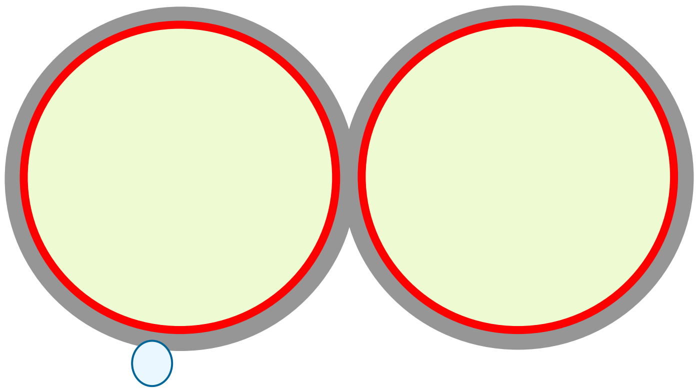




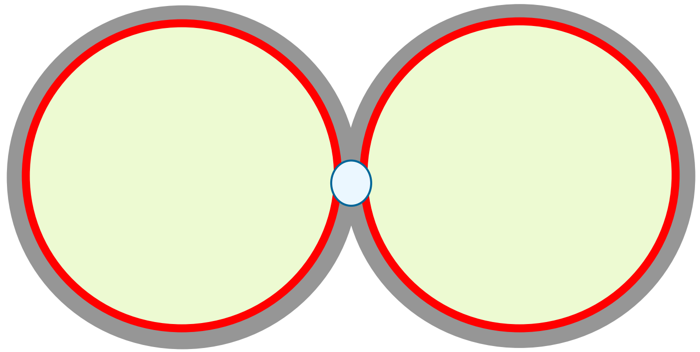
Minimum observable BSA concentration
80 pg/ml

RI change sensing vs coupling variation sensing

Conventional sensing

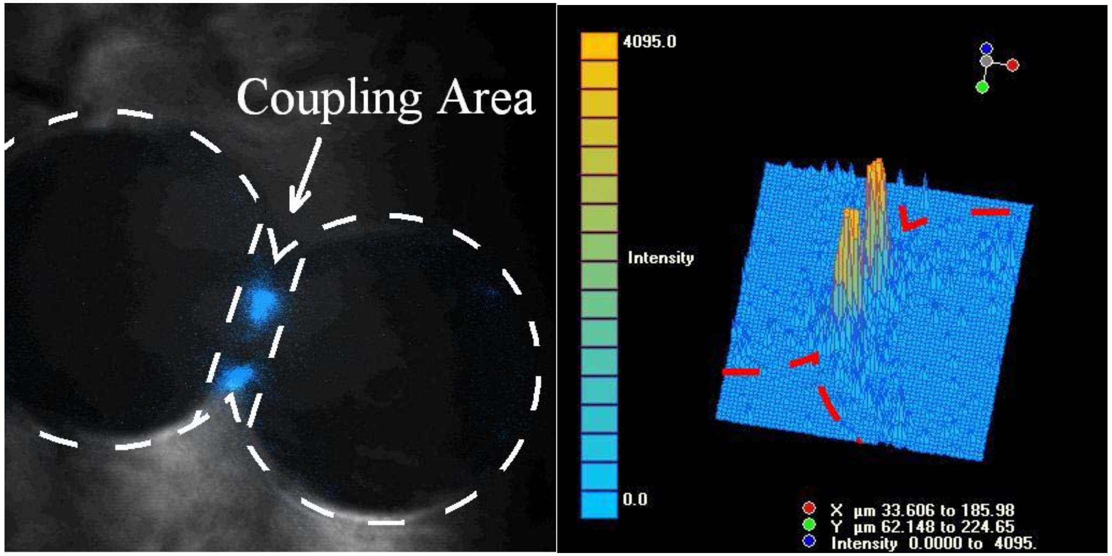


Coupling sensing



High RI agent

Imaging of fluorescent protein (cypet, FIRC-BSA)

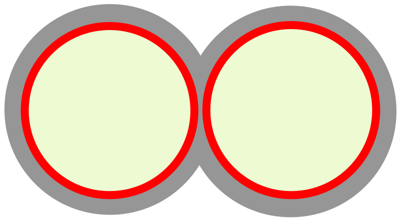


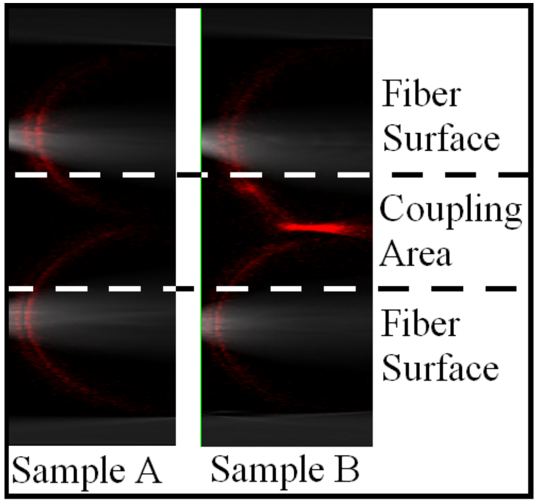
Reason of mode hopping

Sticking of bio sample in the coupling region changes coupling coefficient

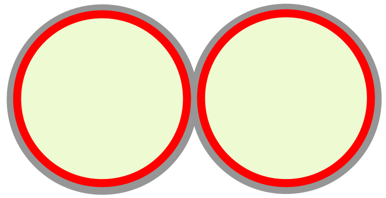
Further proof of coupling variation induced ultrahigh sensitivity

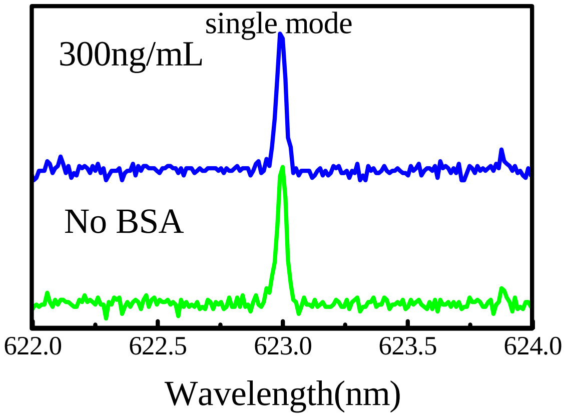
Thick polymer coating blocks coupling region

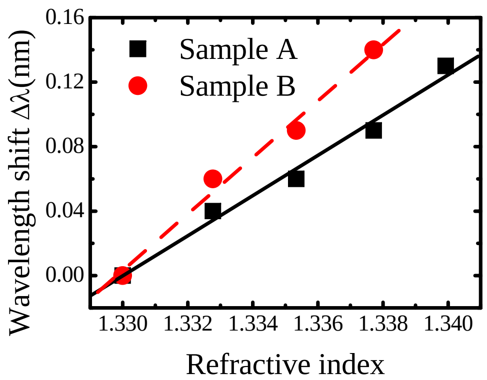




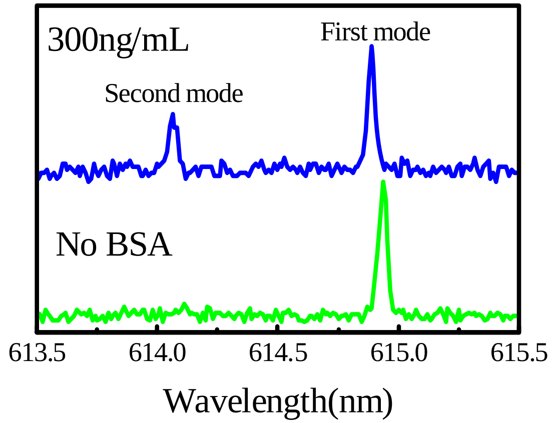
Thin polymer coating leaves coupling region partly open







Conventional RI sensing



Future directions

We have reviewed four broad application areas of optical microcavities and highlighted several microcavity designs for each (see Table 1). Impressive results have been achieved in all areas. Substantial, additional gains are possible in quantum optical applications with continued improvement in microfabrication techniques and with implementation of new low-loss designs. Triggered, single photon sources will benefit from higher Purcell factors for improved fibre coupling, and miniaturization to the submicrometre scale of cavity QED devices (using either strong or weak coupling) is feasible. Also, the emergence of new ultrahigh-*Q*, wafer-based geometries should provide a platform for strong-coupling studies that combine both laboratory-on-chip functions and efficient coupling to optical fibres. Technological applications such as the dynamic add/drop device will provide better control and reproducibility of filter characteristics in designs that are increasingly complex.

One other area that deserves special note is that of biological and chemical sensing. Optical sensors that use evanescent field coupling have been developed[116,117]; however, high-*Q* optical microcavities, as a sensor transducer, offer the potential to greatly enhance detection sensitivity[39]. Recently, sensors based on both monolithic[118] and microsphere[119] whispering gallery transducers have been demonstrated. It seems likely that this will become an important application area for these devices. Likewise, the broad technological impact that resonant devices have had at acoustic, radio and microwave frequencies suggests that many other applications for these devices will emerge in the optical domain. □