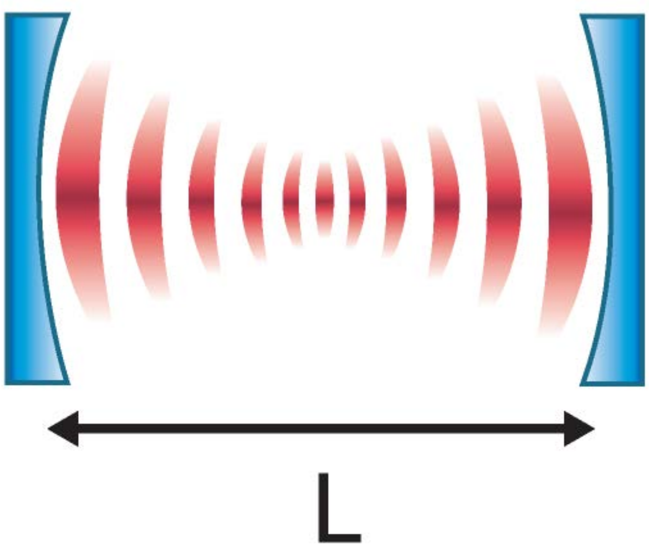
微纳光子学

- 现代工程与应用科学学院
- 2020-4-1

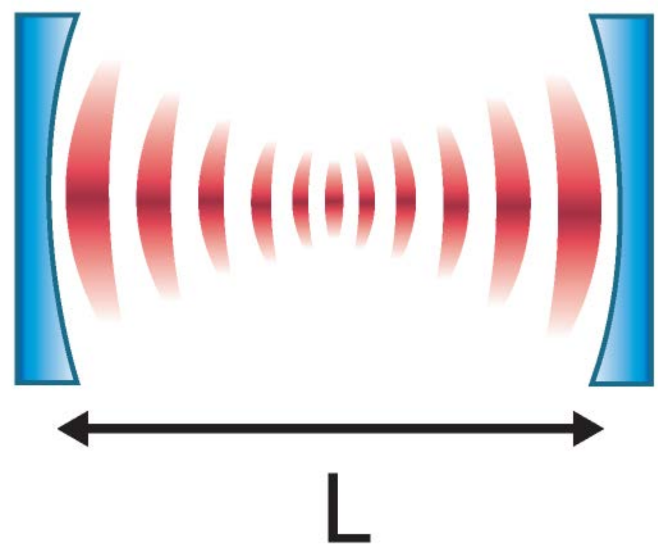
光学微腔

Optical cavity



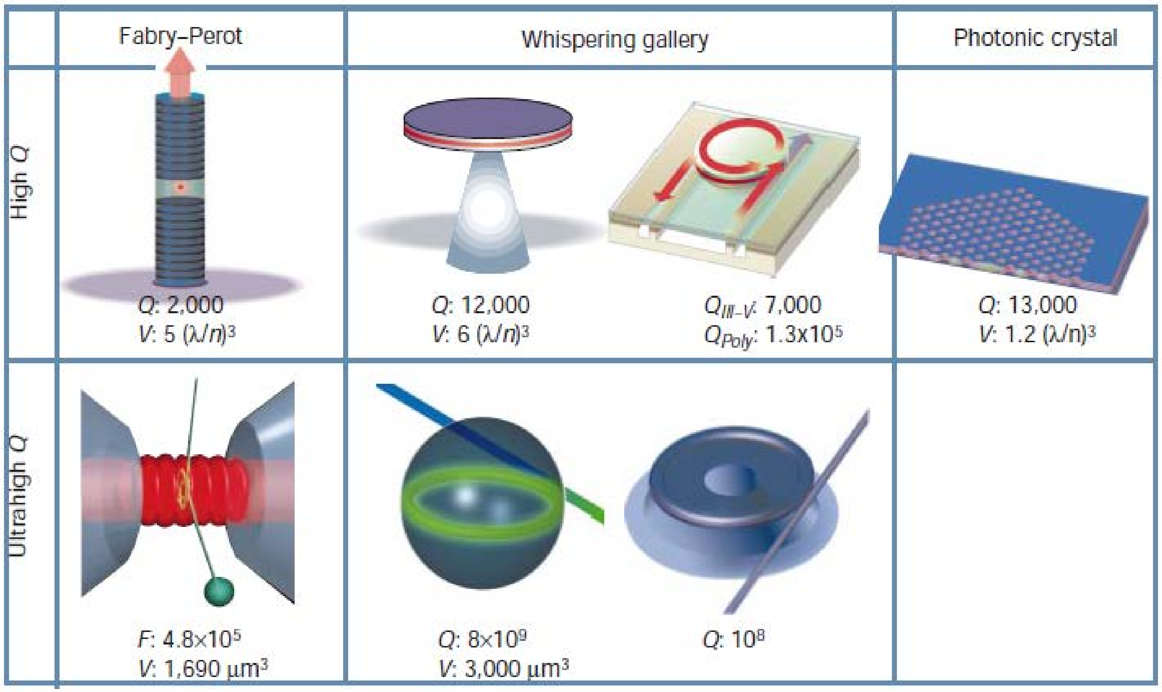
$\omega = \pi m c/(nL)$

Optical microcavity



光学微腔

光学微腔分类

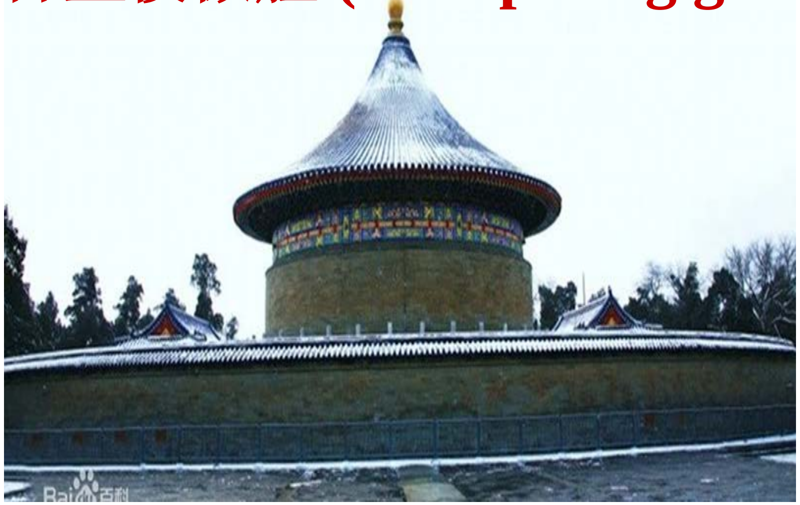


FP腔　　　　回音壁腔　　　　光子晶体微腔

K.J. Vahala, Nature **424**, 839 (2003).

光学微腔

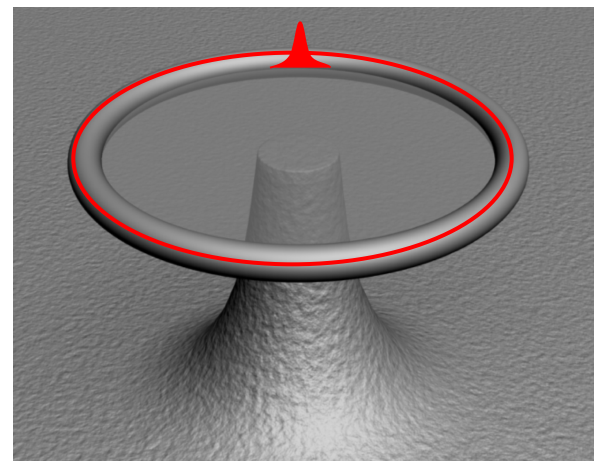
回音壁模微腔 (Whispering gallery mode)



特征:

高品质因子

小模式体积



$Q=10^8$

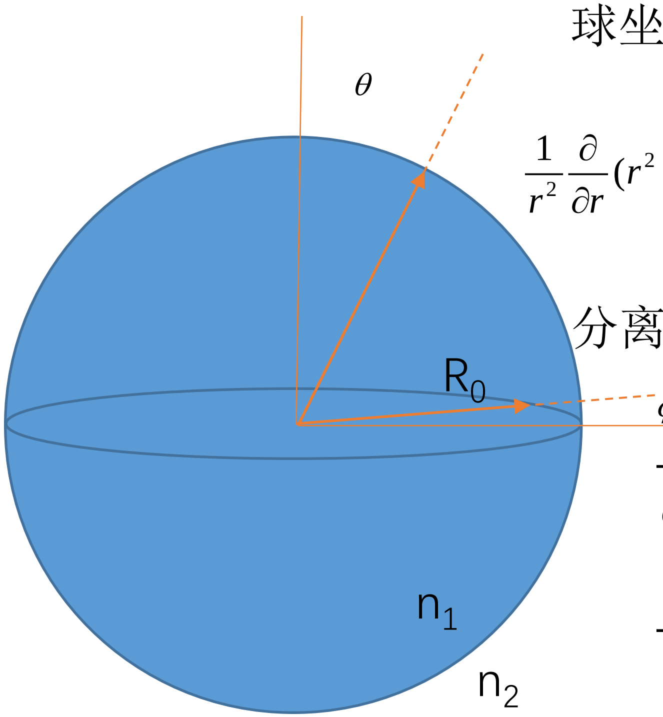
$D=10\ \mu m$

$N=5 \times 10^6$

$L_{eff} \approx 16$ m

$$\nabla^2 E + k_{1,2}^2 E = 0$$

球坐标下为



$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial}{\partial r})E(r,\theta,\varphi)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\frac{\partial}{\partial\theta})E(r,\theta,\varphi)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2}{\partial\varphi^2}E(r,\theta,\varphi)+k_{1,2}^2E=0$$

分离变量 $E(r,\theta,\varphi)=E(r)E(\theta)E(\varphi)$

$$\frac{\partial}{\partial\varphi^2}E(\varphi)=-m^2E(\varphi)$$

$$\frac{d}{dr}(r^2\frac{dE(r)}{dr})+[k_{1,2}^2r^2-l(l+1)]E(r)=0$$

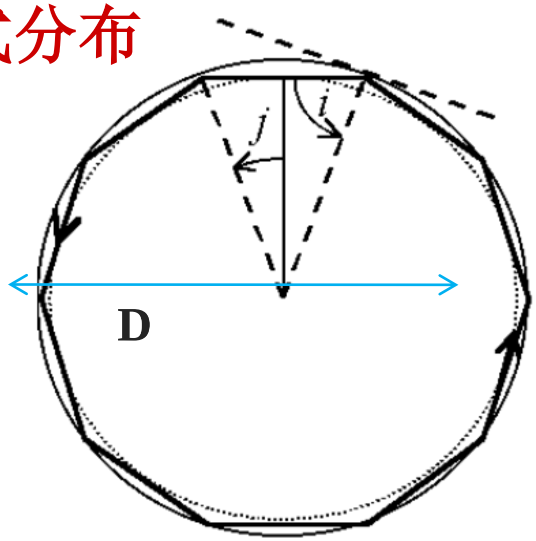
$$(1-x^2)\frac{d^2E(x)}{dx}-2x\frac{dE(x)}{dx}+[l(l+1)-\frac{m^2}{1-x^2}]E(x)=0$$

其中$x=\cos\theta$

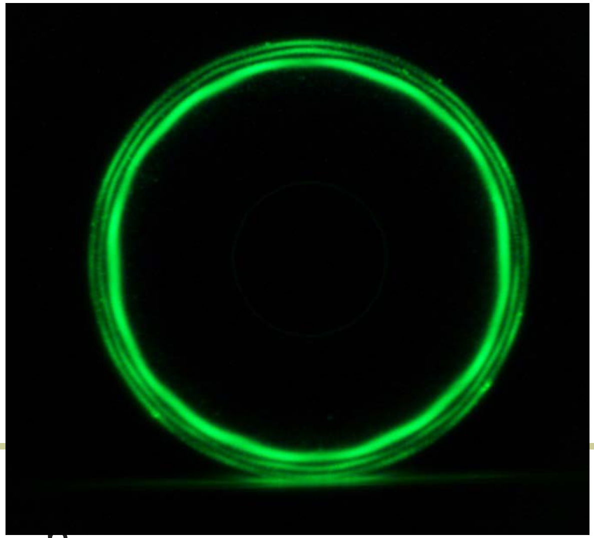
A. N. Oraevsky, "Whispering-gallery waves," Quantum Electronics 32, 377 (2002).

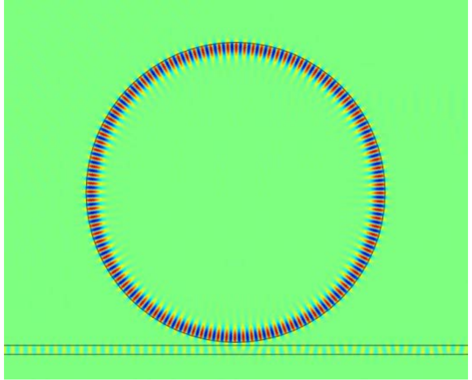
光学微腔

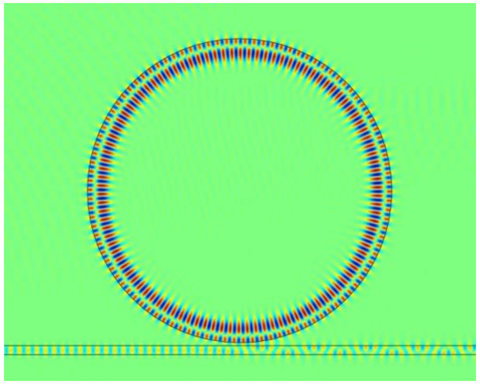
模式分布

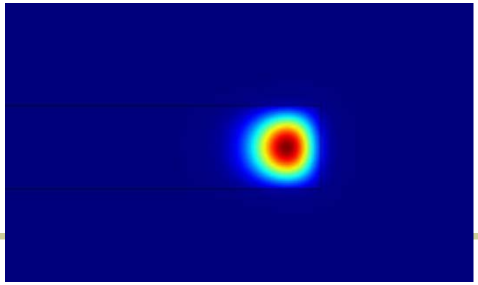


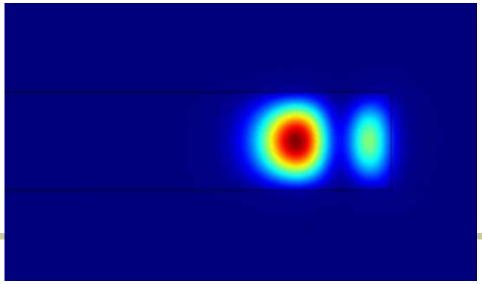
$$n\pi D = m\lambda = m\frac{2\pi c}{\omega} \rightarrow \omega = \frac{2mc}{nD}$$



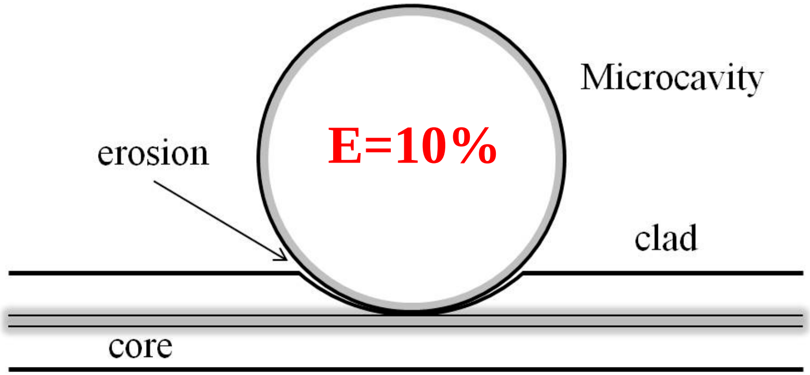




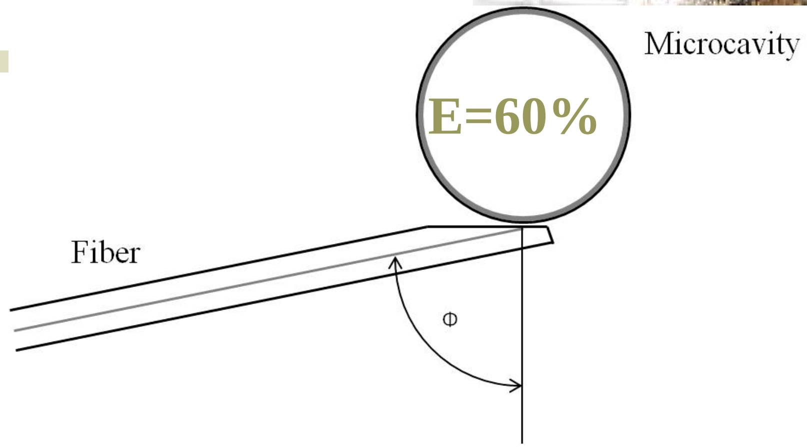




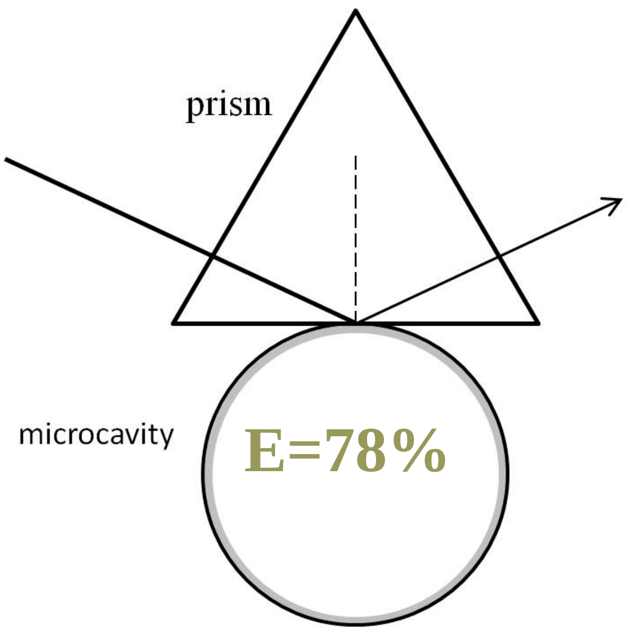
耦合方式比较



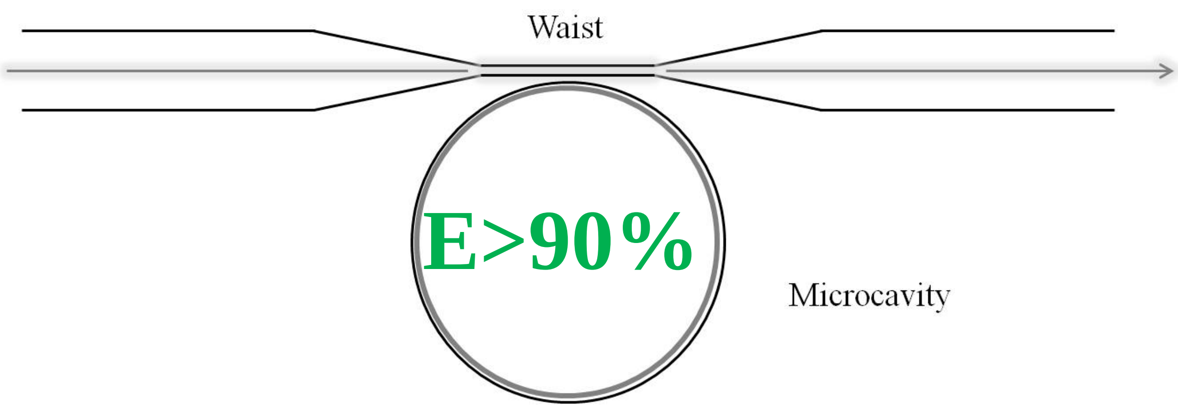
N. Dubreuil et al., *Opt. Lett.* ***20***, 813-815 (1995).



V. S. Ilchenko et al., *Opt. Lett.* ***24***, 723-725 (1999).



L. Collot et al., *Europhys. Lett.* ***23***, 327-334 (1993).



J. C. Knight et al., *Opt. Lett.* ***22***, 1129-1131 (1997).

光学微腔应用

- 光通信器件(滤波器、路由器、光开关…)
- 非线性光学[拉曼、布里渊、四波混频、(二、三次) 谐波]
- 超灵敏传感器(单分子探测）
- 精密测量

  超窄线宽激光器

  微型光频梳
- 腔-光力学
- 腔-量子电动力学
- ……

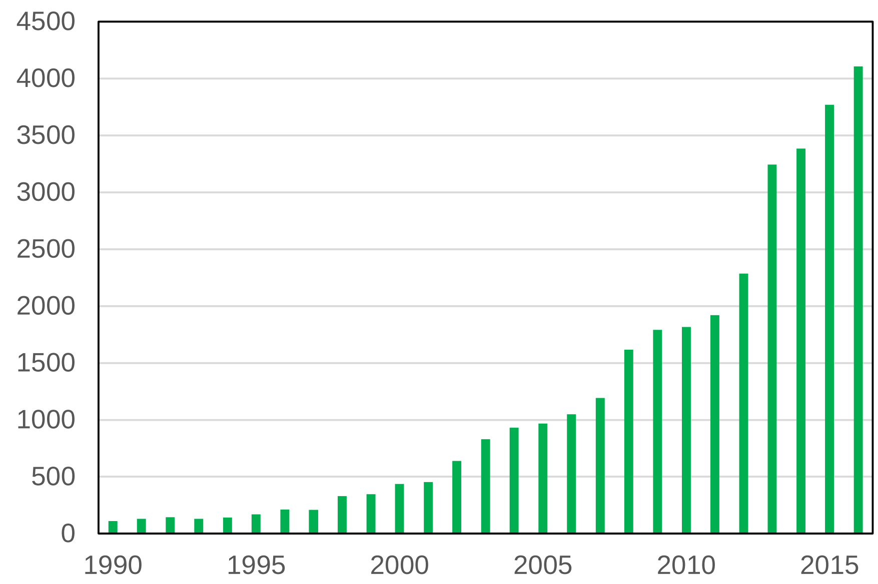
光学微腔应用

- 光通信器件（滤波器、路由器、光开关、隔离器 ...）
- 非线性光学[拉曼、布里渊、四波混频、(二、三次) 谐波]
- 超灵敏传感器(单分子探测）
- 精密测量

  超窄线宽激光器、

  微型光频梳
- 腔-光力学
- 腔-量子电动力学
- ……

每年出版的文献数



关键词：microcavity (ISI Web of Knowledge)

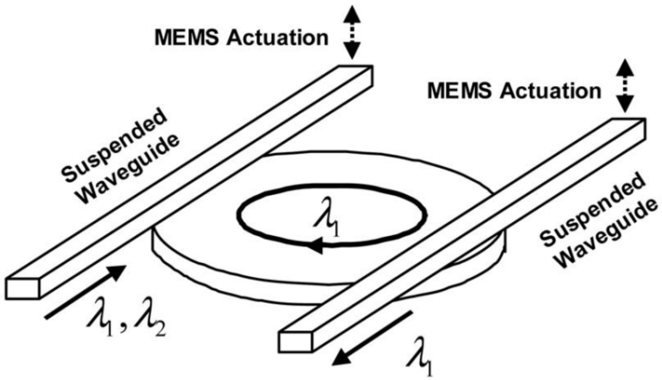
光学微腔应用

参考文献

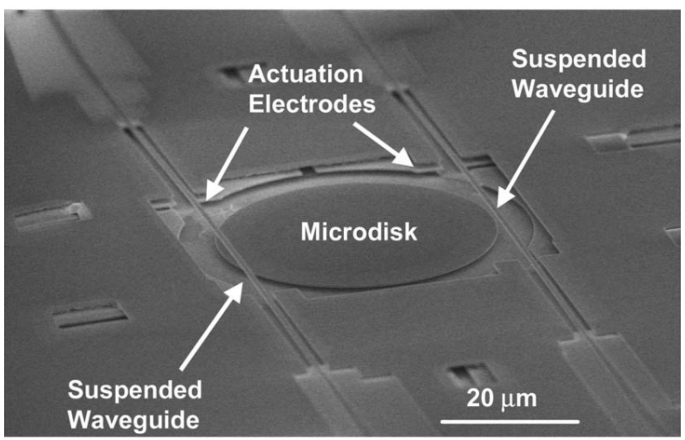
1. K. J. Vahala, Optical microcavities (World Scientific Publishing, Singapore, 2004).
2. K. J. Vahala, “Optical microcavities,” Nature **424**, 839-846 (2003).
3. A. B. Matsko and V. S. Ilchenko, “Optical resonators with whispering-gallery modes-part I: Basics,” IEEE J. Sel. Top. Quantum Electron. **12**, 3-14 (2006).
4. V. S. Ilchenko and A. B. Matsko, “Optical resonators with whispering-gallery modes-part II: Applications,” IEEE J. Sel. Top. Quantum Electron. **12**, 15-32 (2006).
5. H. Cao and J. Wiersig, “Dielectric microcavities: Model systems for wave chaos and non-Hermitian physics,” Rev. Mod. Phys. **87**, 61 (2015).

光学微腔应用举例

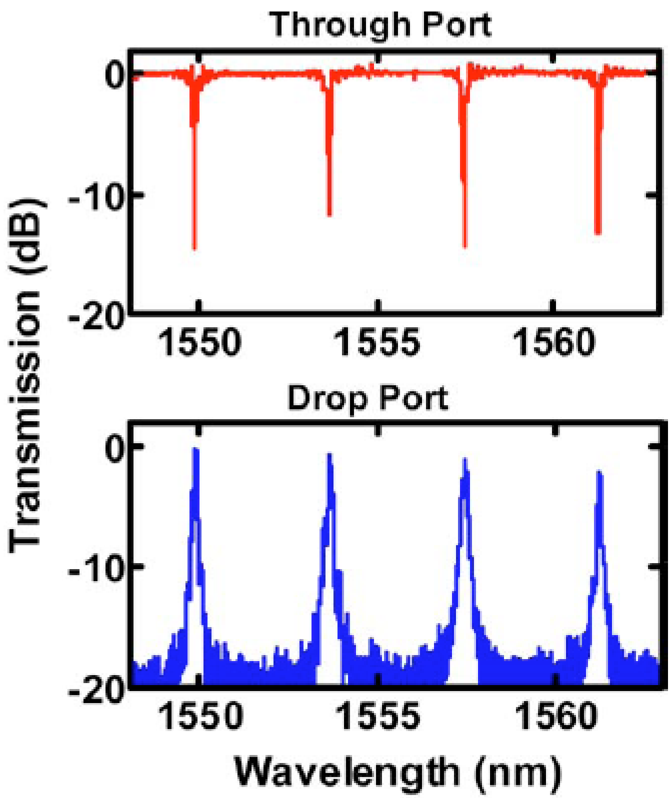
光通信器件-上下话路滤波器(add-drop filter)



(a)



(b)



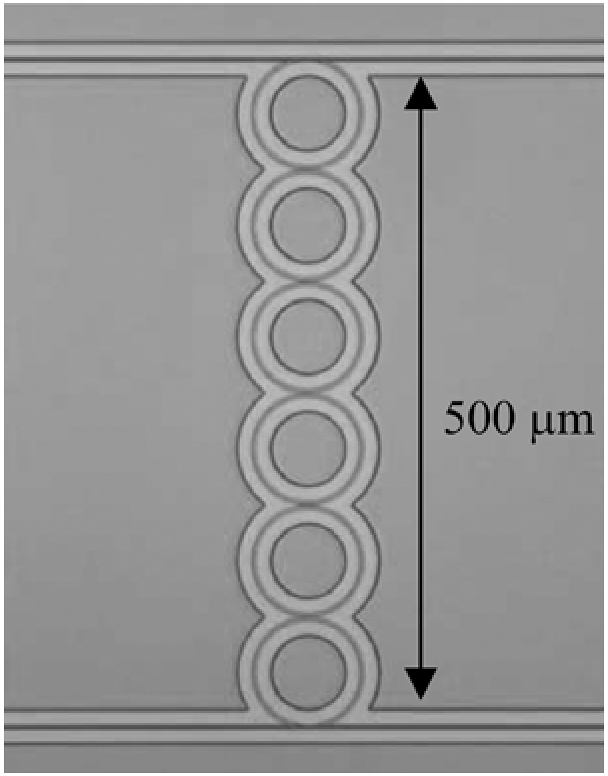
(b)

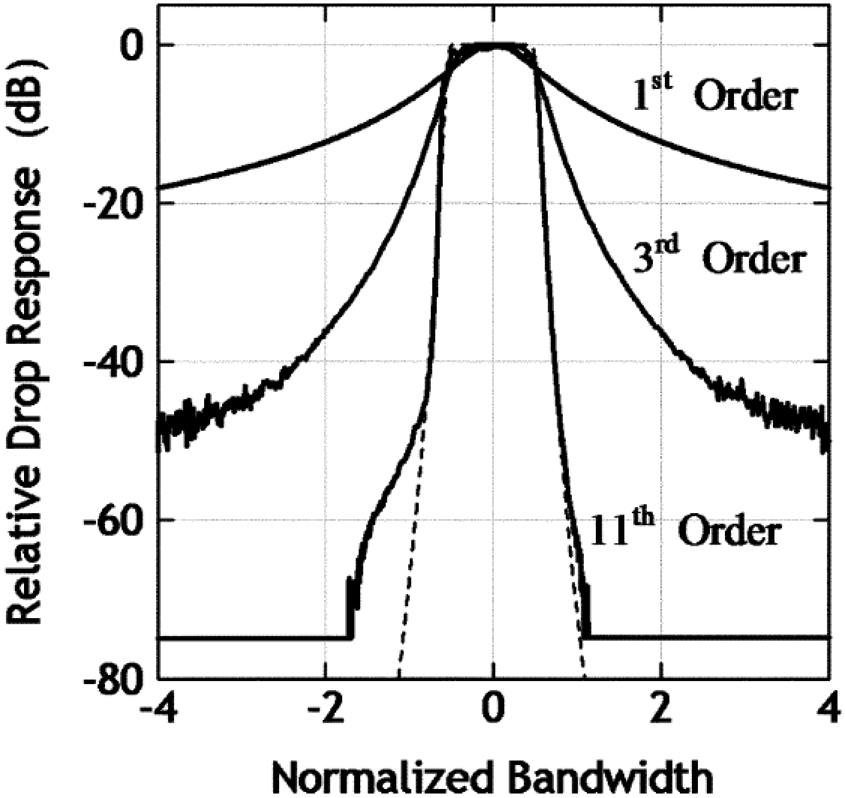
M. C. M. Lee et al., Opt. Lett. **31**, 2444 (2006).

光学微腔应用举例

光通信器件-高阶滤波器

6th Order Filter

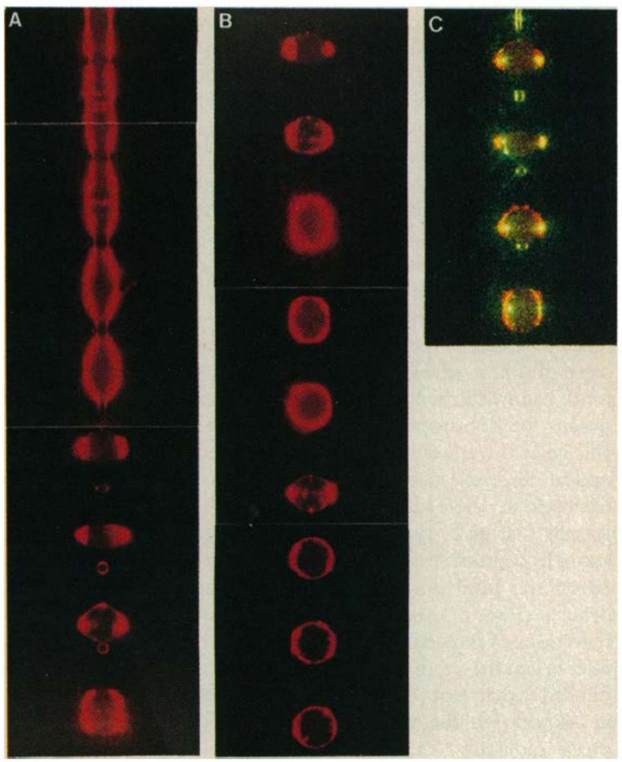


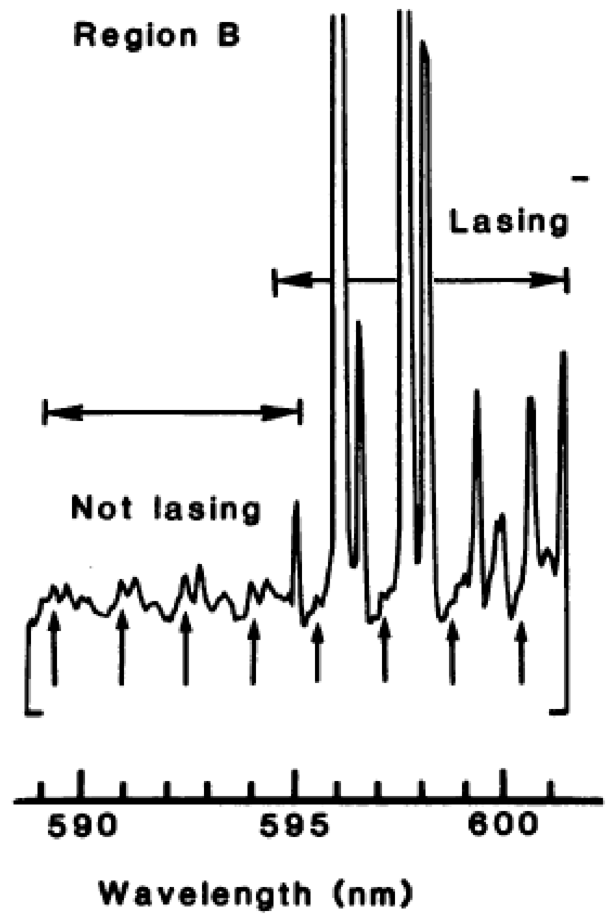


B. E. Little et al., IEEE Photon. Technol. Lett. **16**, 2263 (2004).

光学微腔应用举例

小液滴激光器 (Droplets)

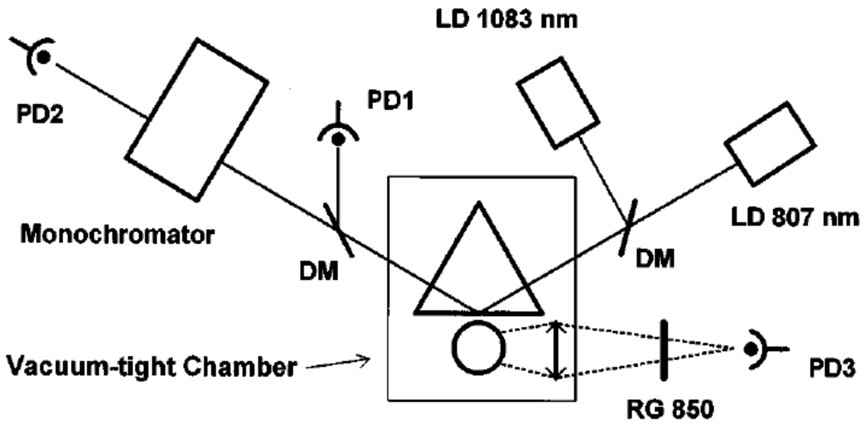


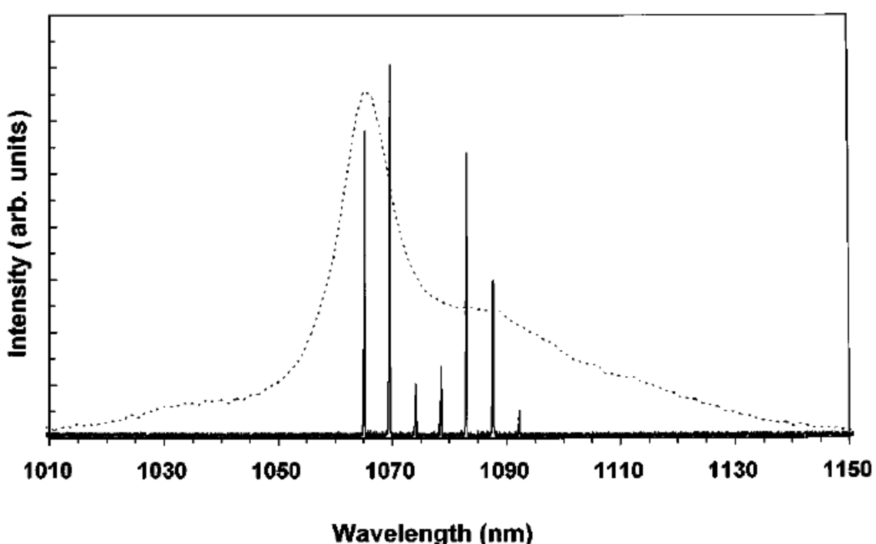


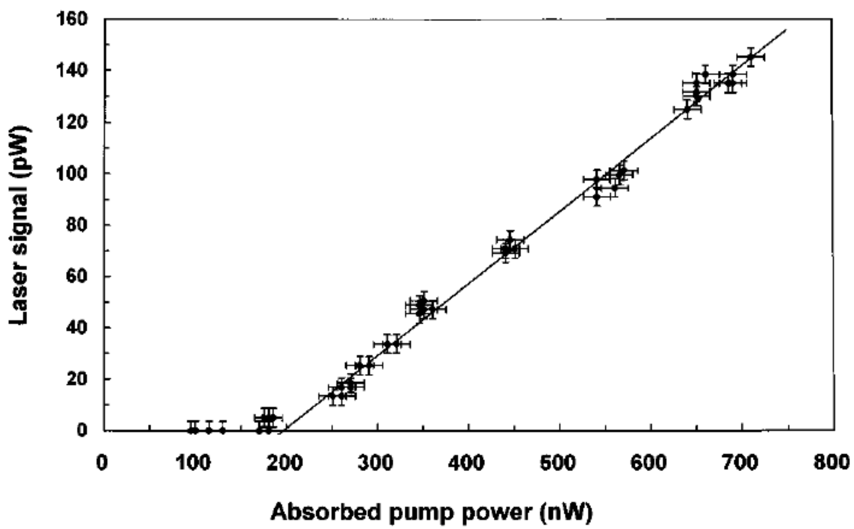
S. X. Qian et al., Science. **231**, 486 (1986).

光学微腔应用举例

微球激光器





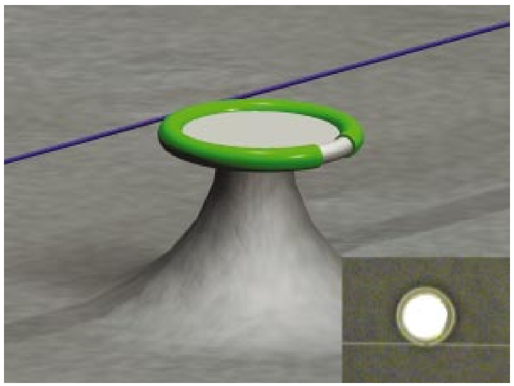


阈值：200 nW

V. Sandoghdar, F. Treussart, J. Hare, V. Lefèvre-Seguin, J. -M. Raimond, and S. Haroche, Phys. Rev. A **54**, R1777 (1996).

光学微腔应用举例

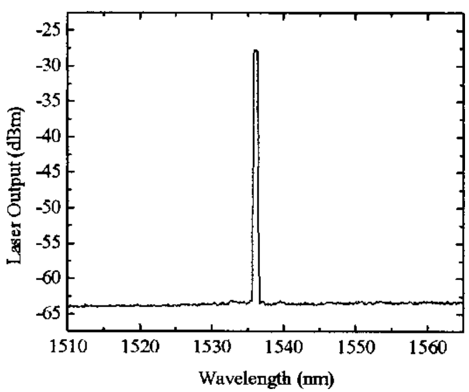
超窄线宽激光器

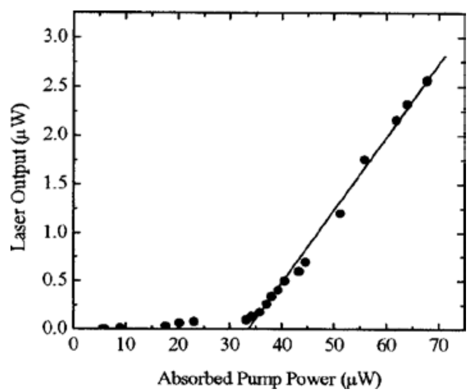


低阈值: 34 微瓦

Schawlow-Townes formula

$$\Delta\upsilon = \frac{h\upsilon^3 n_{sp}}{4\pi}\cdot\frac{1}{P}\cdot\frac{1}{Q^2}$$





超窄线宽: Hz 量级

Y. Lan et al., Appl. Phys. Lett. 83, 825 (2003).

光学微腔应用举例

最小的纳米激光器 （44 nm）

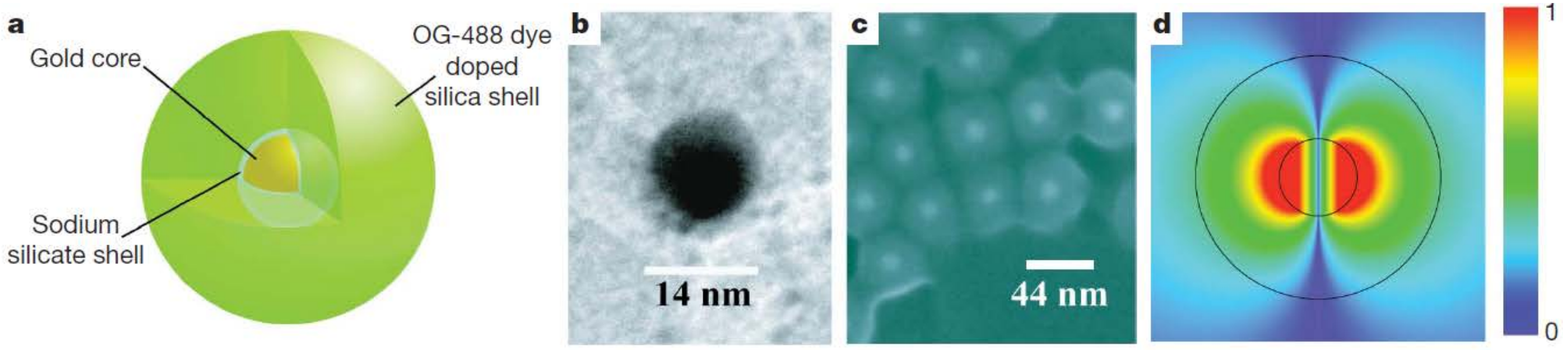
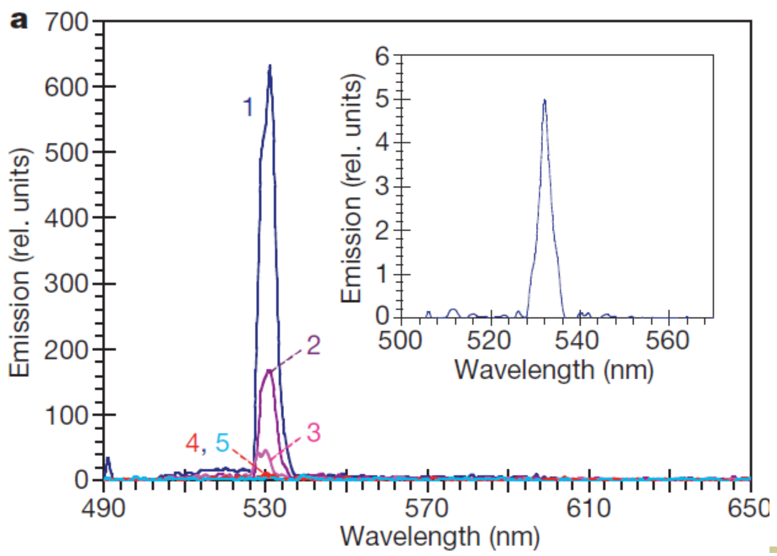


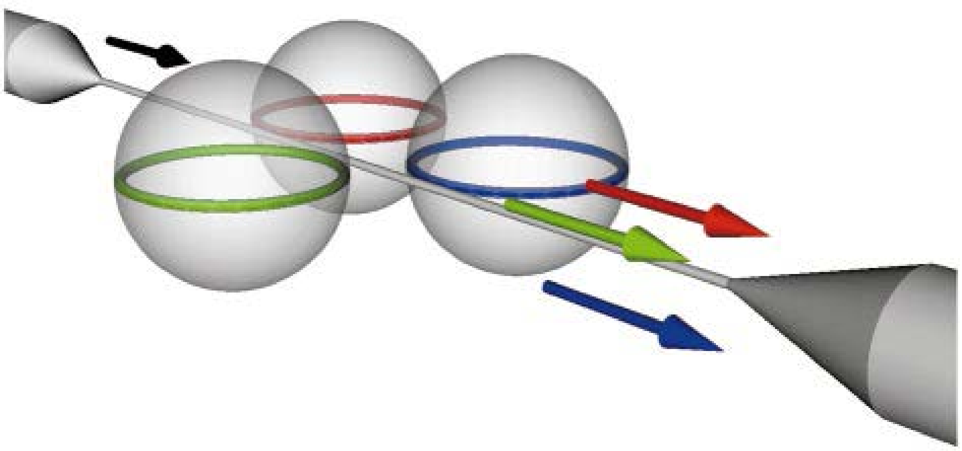
Figure 1 | Spaser design.

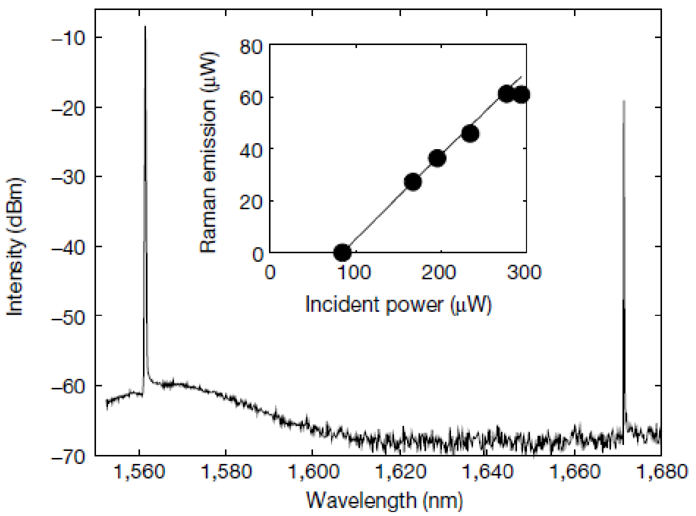


M. A. Noginov et al., Nature **460**, 1110 (2009).

光学微腔应用举例

低阈值拉曼激光





Ultrolow threshold: 86 μW

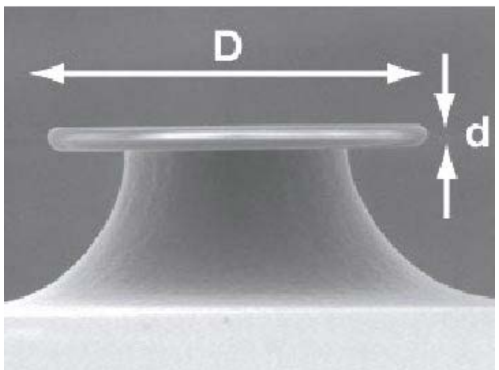
$$P_t = C(\Gamma)\frac{\pi^2 n^2}{g_R \lambda_p \lambda_R} V_{\text{eff}} \cdot \left(\frac{1}{Q_0}\right)^2 \cdot \frac{(1+K)^3}{K}.$$

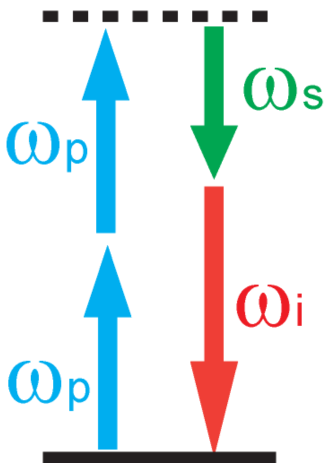
S. M. Spillane et al., Nature **415**, 621 (2002).

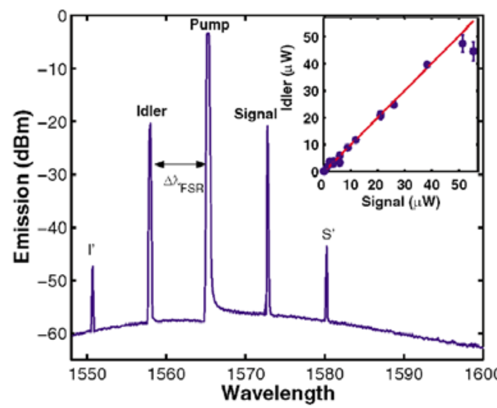
光学微腔应用举例

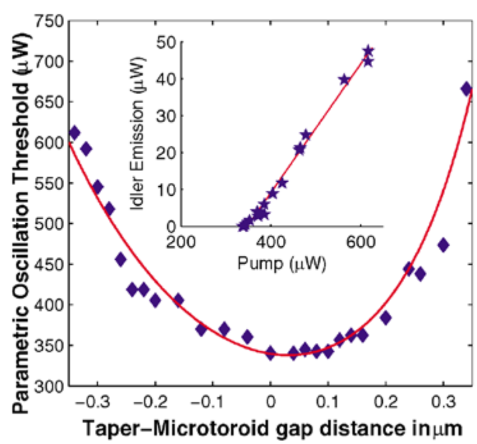
微型光频梳

参量振荡器









阈值: 339 μW

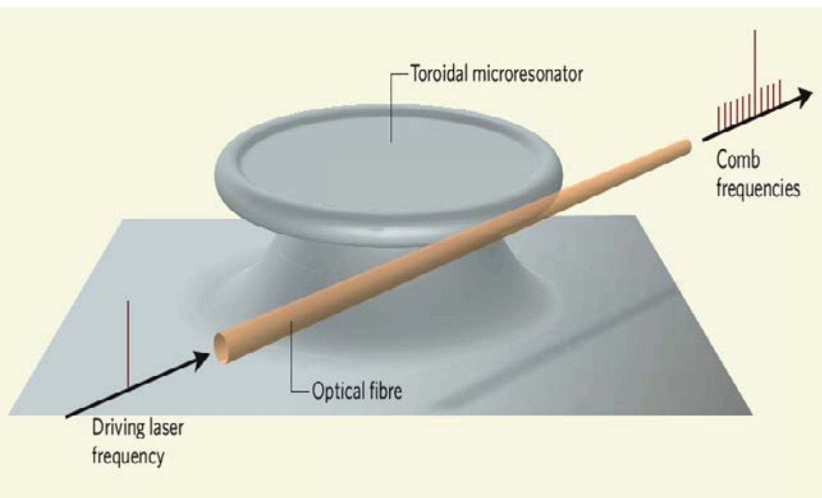
转换效率: 36%

T.J. Kippenberg et al., Phys. Rev. Lett. **93**, 083904 (2004).

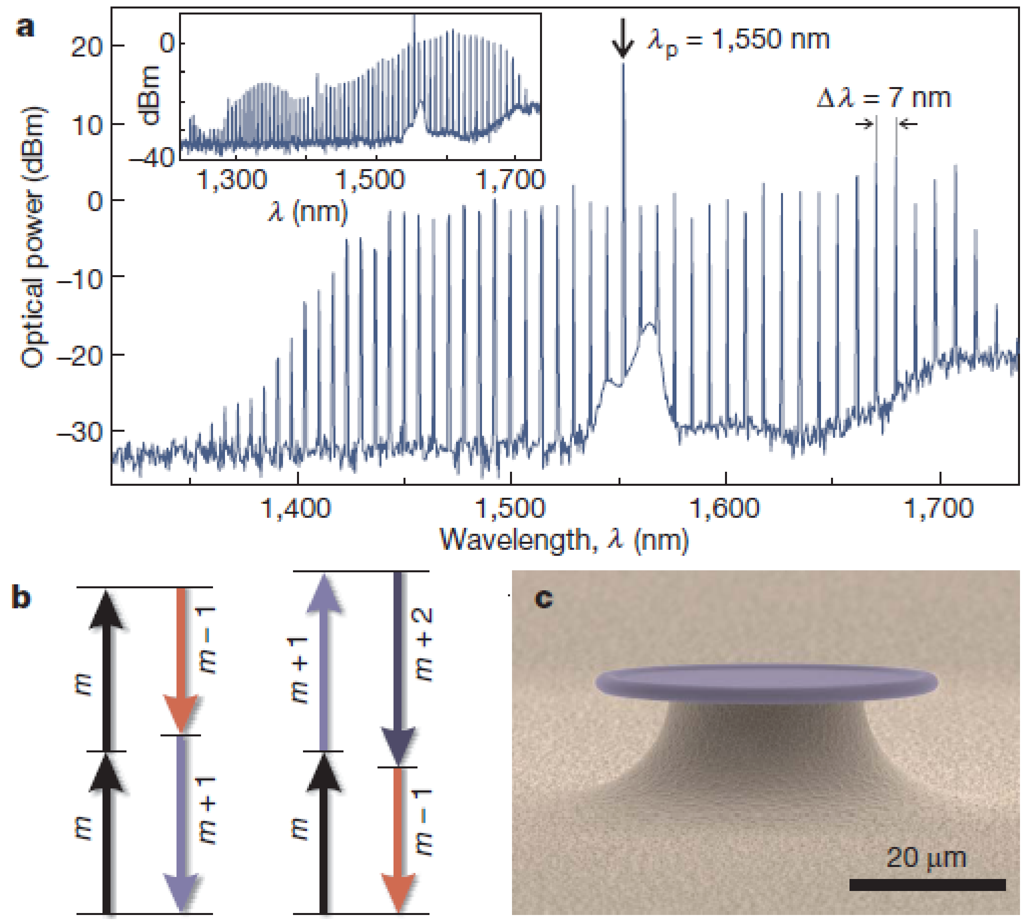
光学微腔应用举例

微型光频梳

级联的参量振荡 ➡ 光频梳



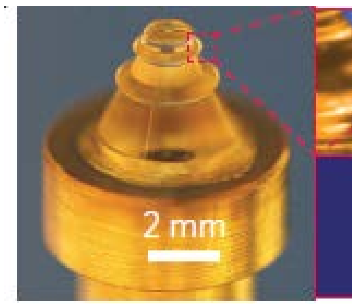
示意图

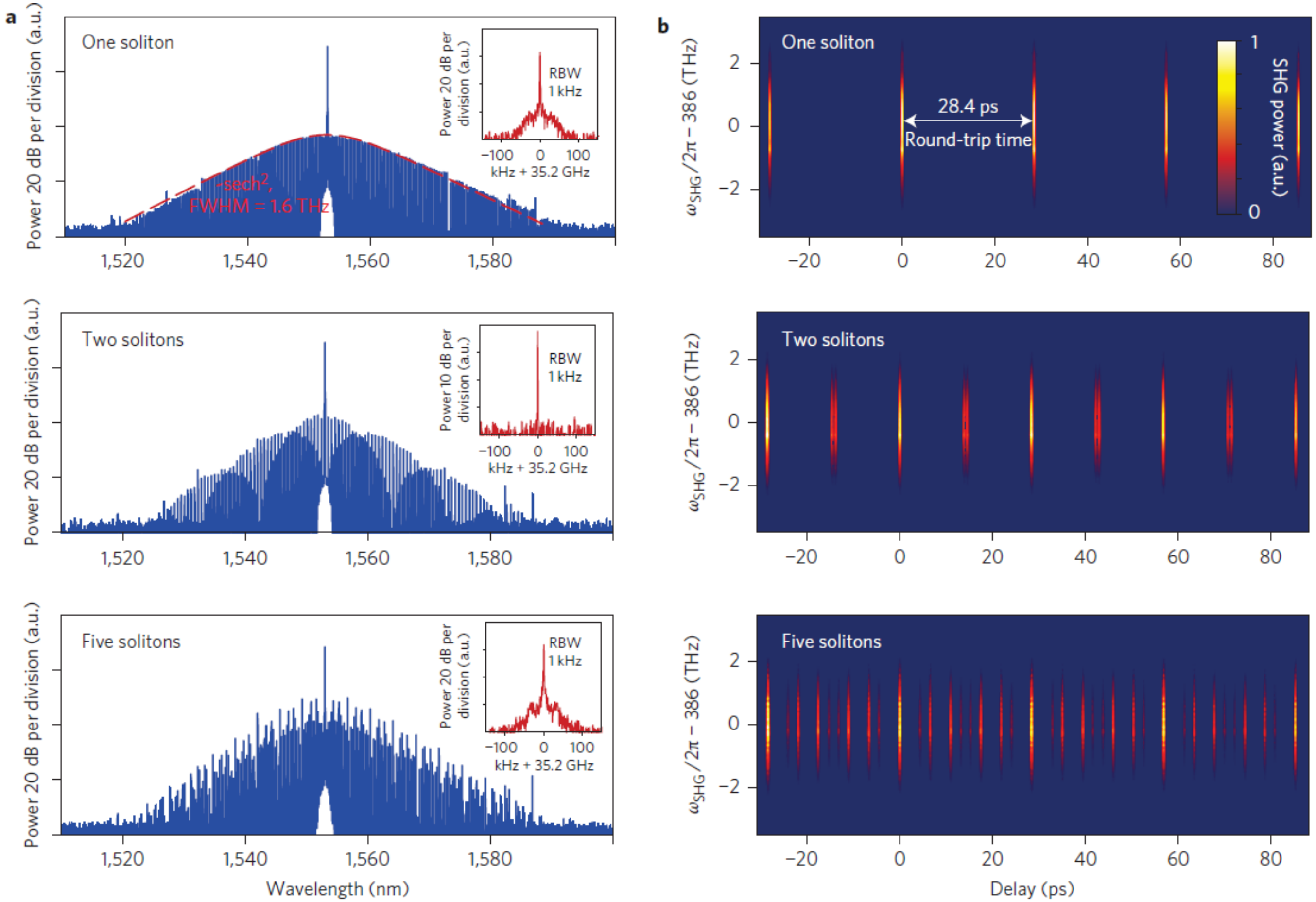


P. Del Haye, et al., Nature. **450**, 1214 (2007).

光学微腔应用举例

微型光频梳(时间孤子)





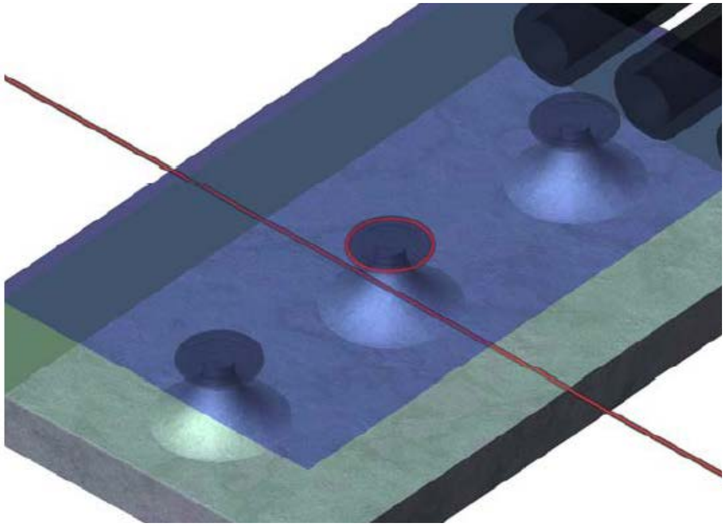
T. Herr et al., *Nat. Photonics* 8, 145 (2014).

光学微腔应用举例

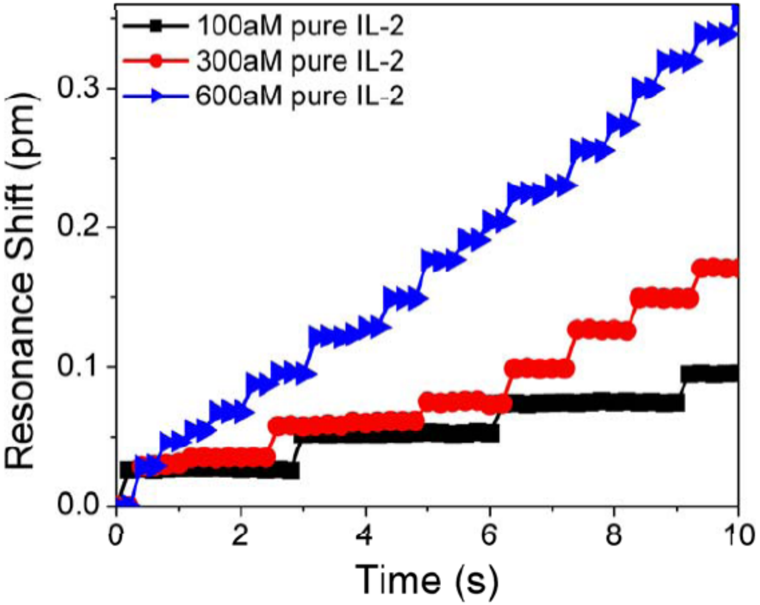
微型传感器

Label-Free, **Single-Molecule Detection** with Optical Microcavities

Base on the shift of the resonant wavelength



Detection setup



The position of the resonance wavelength as a function of time at three different IL-2 concentrations.

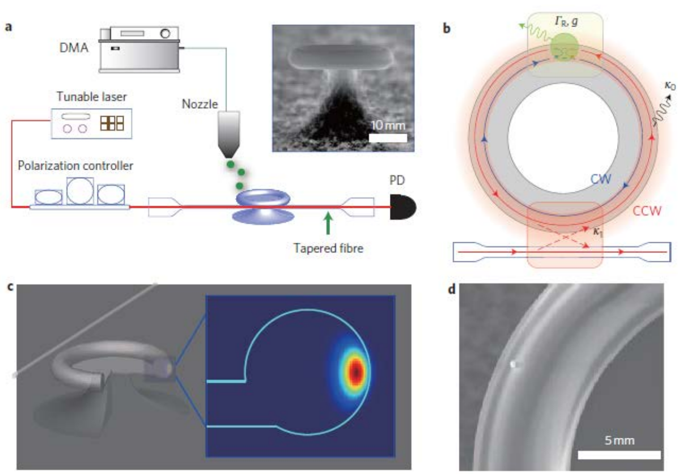
A. M. Armani et al., Science. **317**, 783 (2007).

光学微腔应用举例

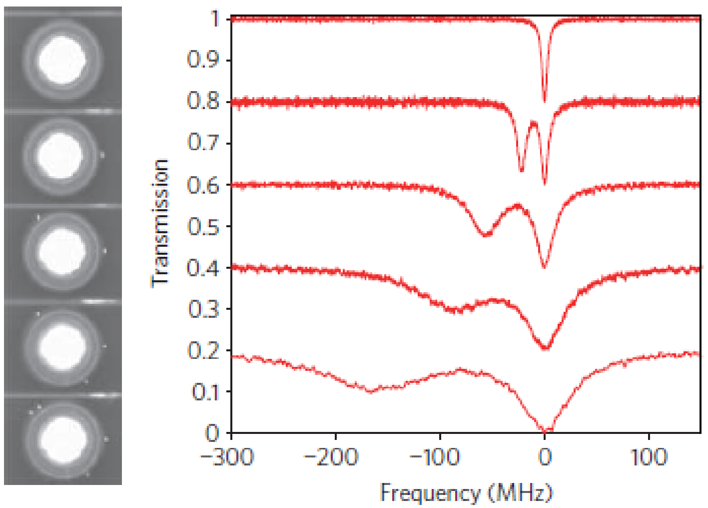
微型传感器

Single nanoparticle detection and sizing On-chip

Base on the mode splitting induced by scattering



Detection setup



Transmission spectra and the amount of splitting versus number of deposited particles.

J. Zhu et al. Nat. Photon. **4**, 46 (2010).

作业

用Comsol软件仿真直径为100微米的微球腔（材料为氧化硅）在1550 nm波长附件的TE和TM模式分布，并分别计算其基模式的模式体积。

备注：球为轴对称图形，可简化为二维模型。

选作：由于微球结构有解析解，大家可以考虑解析解与Comsol仿真结果的比较。