微纳光纤(波导)及应用

- 现代工程与应用科学学院
- 2020-3-4

微纳光纤及应用

参考文献：

1. L. Tong and M. Sumetsky, Subwavelength and nanometer diameter optical fibers (Zhejiang University Press, Springer, 2009).
2. G. Brambilla, F. Xu, P. Horak, Y. Jung, F. Koizumi, N. P. Sessions, E. Koukharenko, X. Feng, G. S. Murugan, J. S. Wilkinson, and D. J. Richardson, “Optical fiber nanowires and microwires: Fabrication and applications,” Adv. Opt. Photon. 1, 107-161 (2009).
3. M. Summetsky, “Nanophotonics of optical fibers” Nanophotonics **2**, 393-406 (2013).
4. X. Q. Wu and L. M. Tong “Optical microfibers and nanofibers,” Nanophotonics **2**, 407-428 (2013).
5. 童利民等“微纳光子学研究前沿”（上海交通大学出版社，2014）。

主要内容

- 简介
- 制备
- 理论基础
- 微纳光纤器件及应用
- 总结

简介

光纤

Godfather of Broadband
Father of Fiber Optics
Father of Fiber Optic Communications

高　锟　Charles K. Kao

出生日期　1933年11月4日上海

学历
英国伦敦大学理学士(1957)
英国伦敦大学哲学博士(1965)

经历
英国国际电话电报公司(1957)
英国国际电话电报公司附属标准通讯实验室(1960)
香港中文大学电子学系教授及讲座教授(1970-1974)
英国国际电话电报公司:
首席科学家(1974);
工程总裁、行政科学家(1982);
研究事务总裁(1986)
香港中文大学校长(1987-1996)
美国国家工程院院士(1990)
台湾中央研究院院士(1992)
香港高科桥有限公司主席兼行政总裁(1996-)

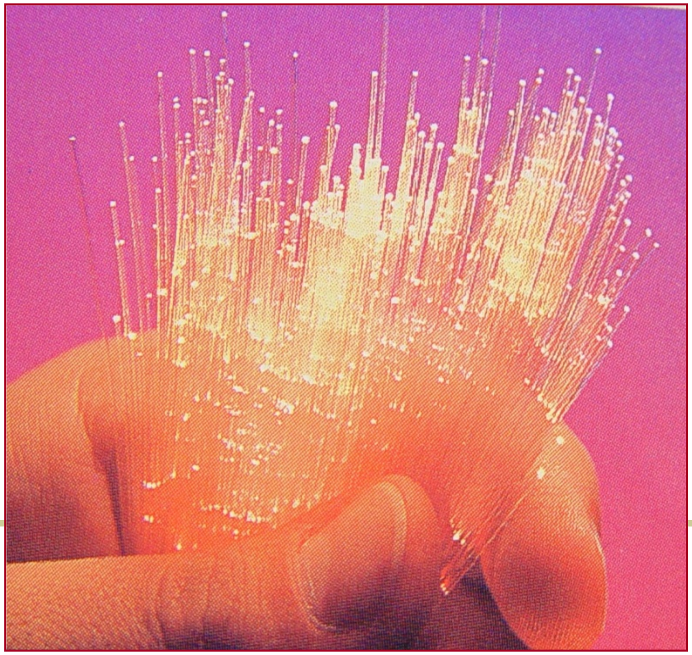
K. C. Kao and G. A. Hockham, *Proc. IEE* **113**, 1151-1158 (1966).

简介

光纤

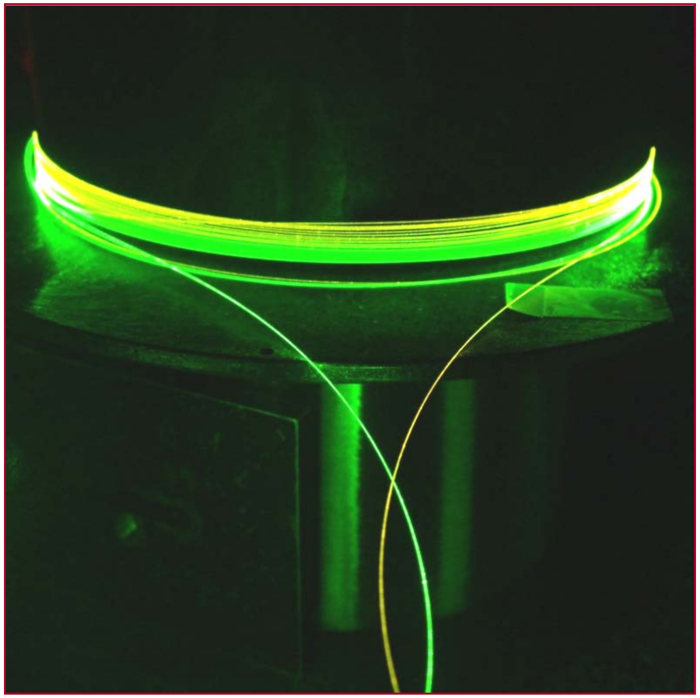
Optical fibers have been very successful in handling light both linearly and nonlinearly for a variety of applications

Linear



When the light is strong enough

Nonlinear



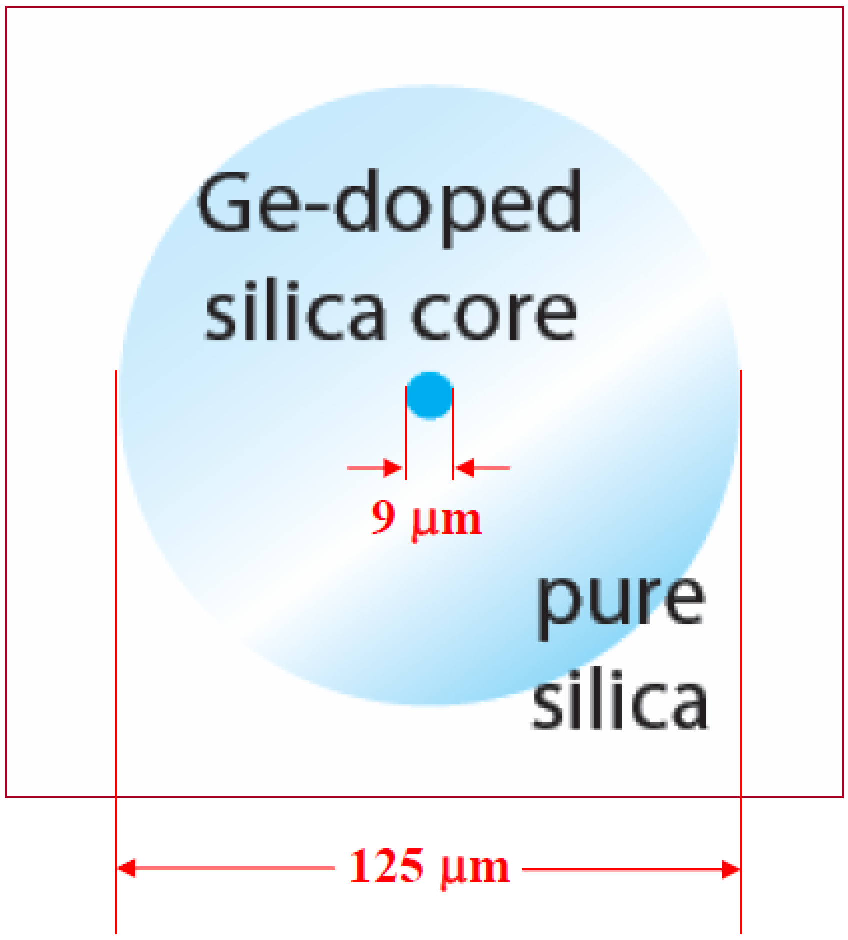
- Optical communications
- Optical sensors
- Power delivery

…

简介

光纤

标准单模光纤



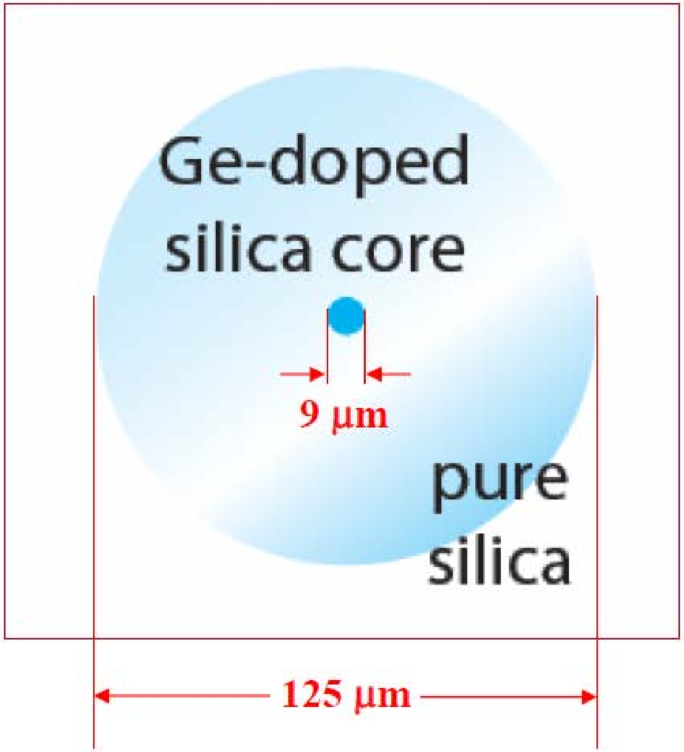
简介

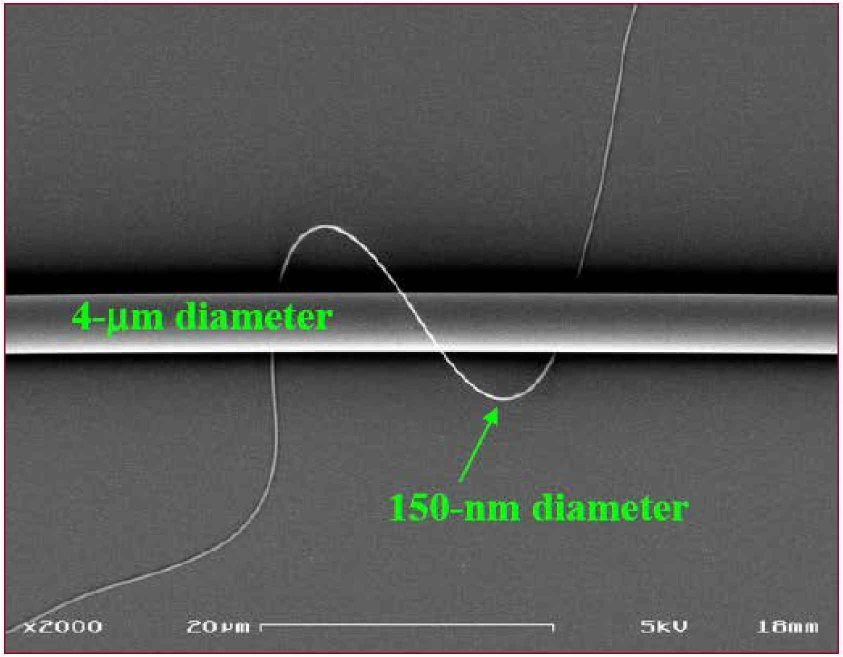
光纤

Microfiber, nanowire, nanofiber, nanotaper, sub-wavelength-diameter

标准单模光纤

微纳光纤

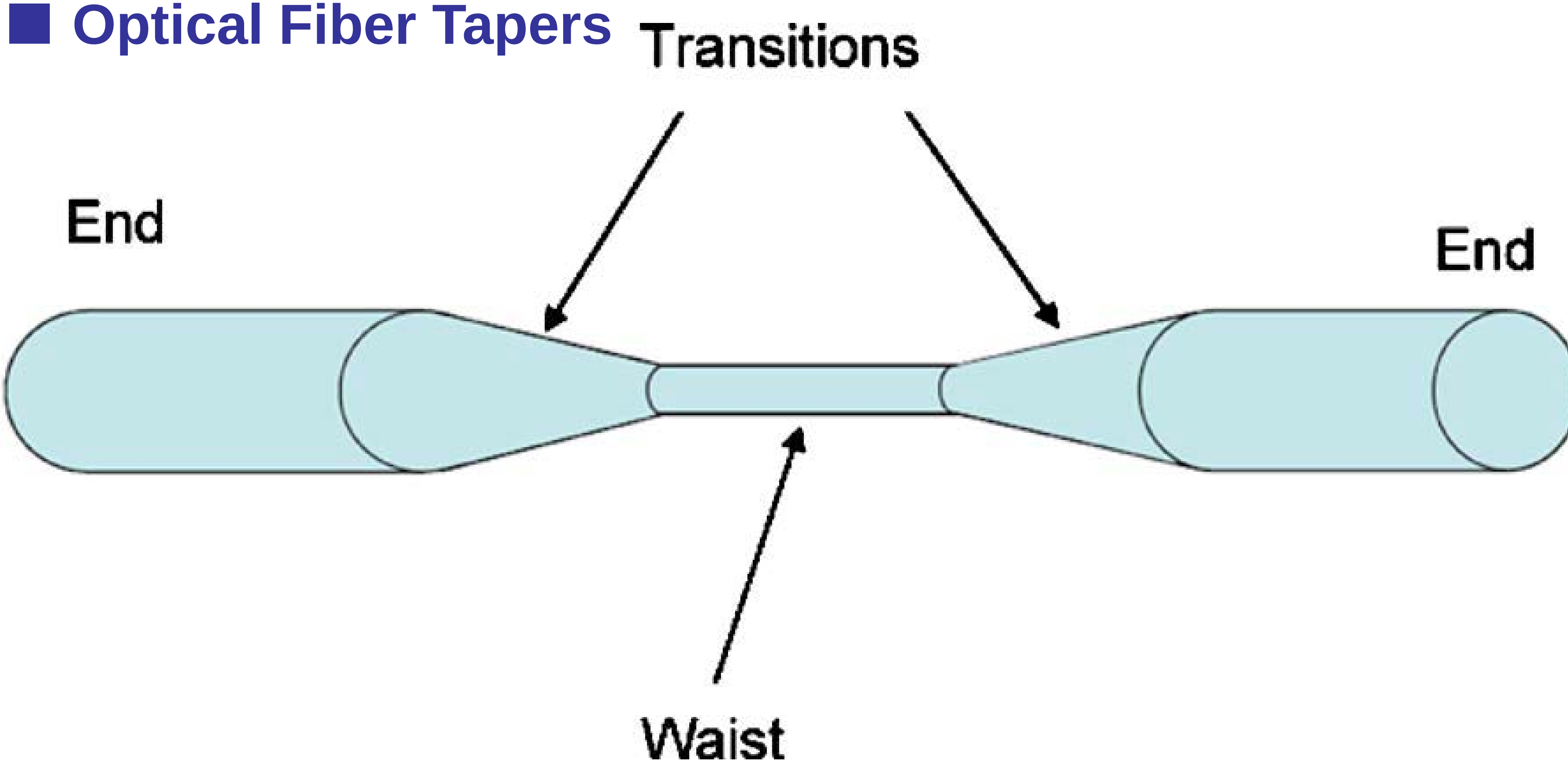




简介

微纳光纤

- **Optical Fiber Tapers**



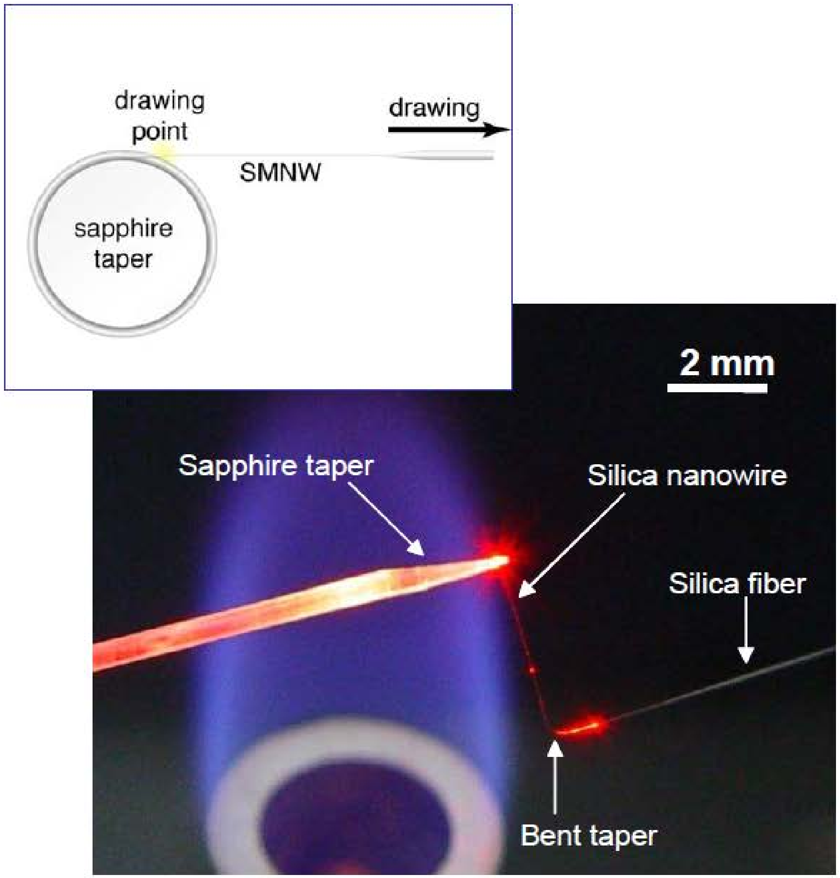
简介

典型光学特性

- 光场约束能力强　　传输光束等效直径可以 <λ
- 传输损耗低　　单模损耗 <0.01 dB/mm
- 大比例倏逝波传输　　倏逝波能量比例可大于 98%
- 亚波长直径长距离相干传输　　传输距离可大于10 cm
- 大波导色散　　波导和总色散可达到标准单模光纤的10^3倍以上
- 高表面能量密度　　10 mW的可见光输入可在表面产生高于1 MW/cm^2的能量密度

制备

玻璃光纤二步高温拉伸



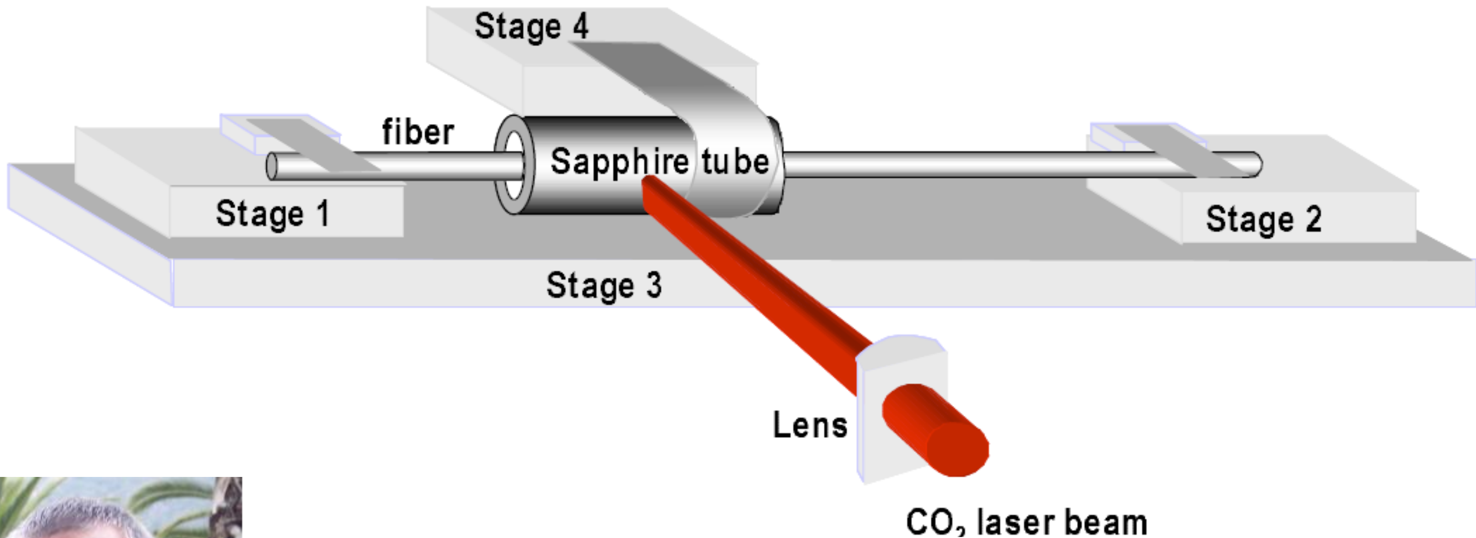
Limin Tong

≥ 20 nm 直径光纤

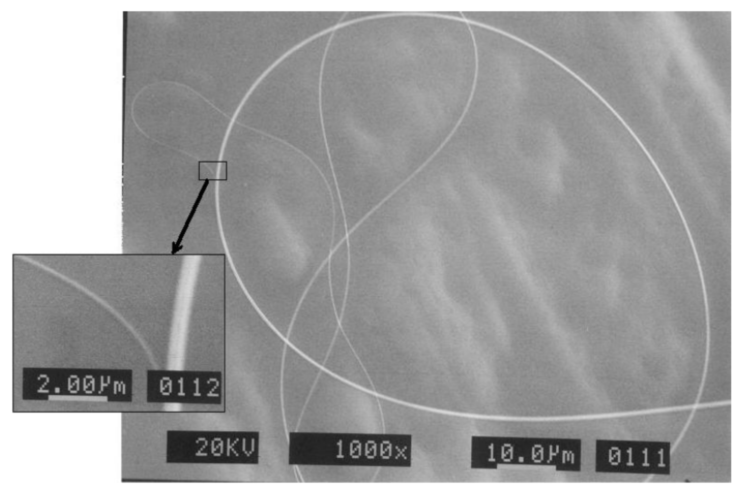
Eric Mazur

L. Tong et al., Nature **426**, 816 (2003).
L. Tong et al., Nanotechnology **16,** 1445 (2005).

制备



OFS Misha Sumetsky



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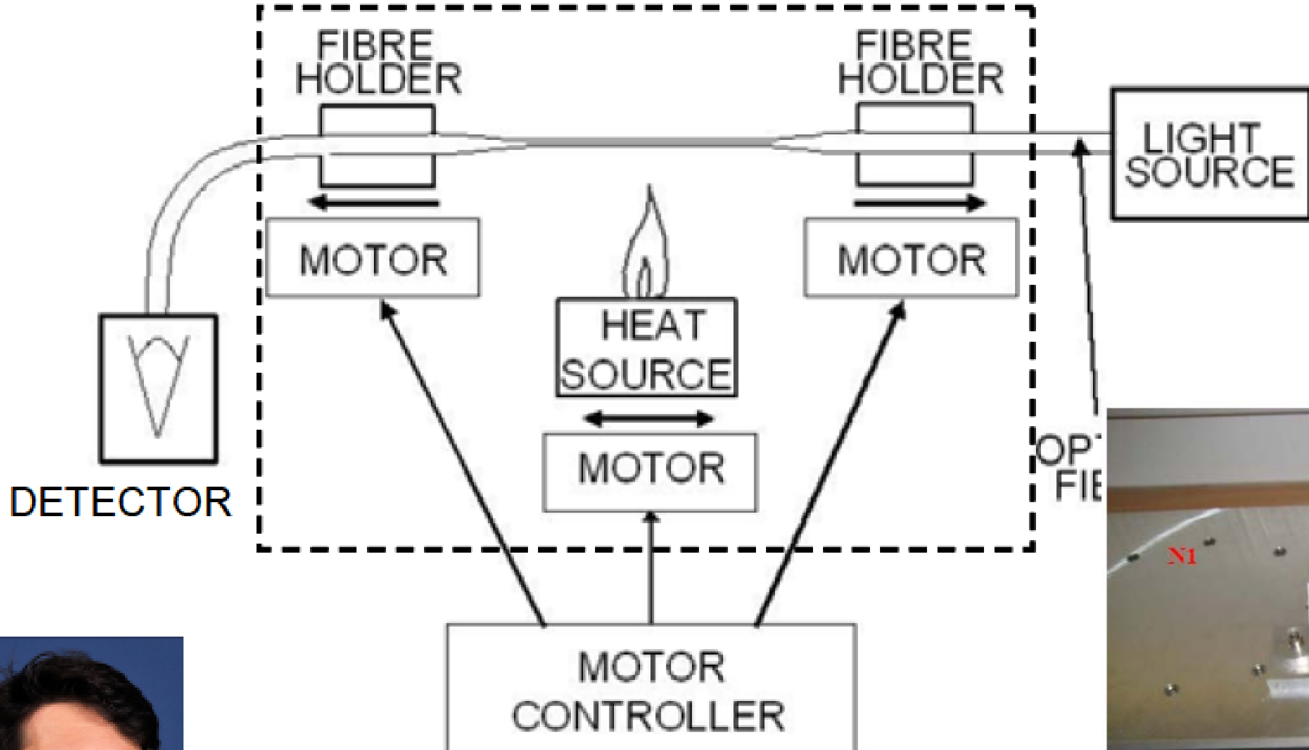
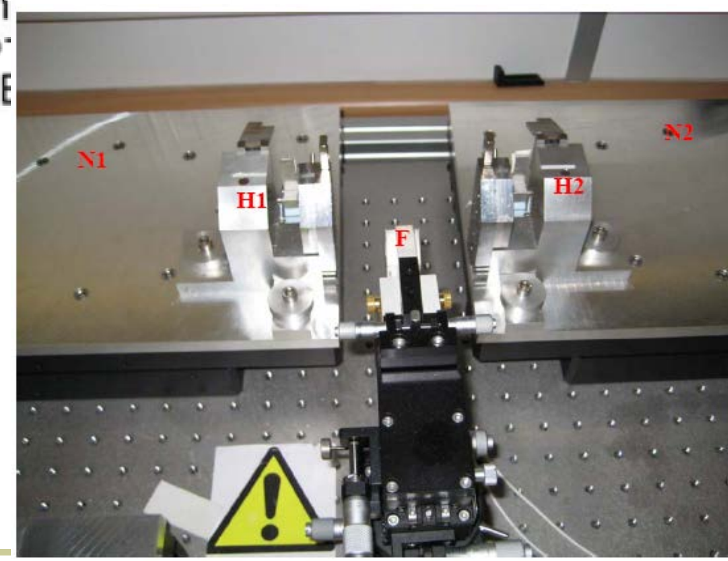




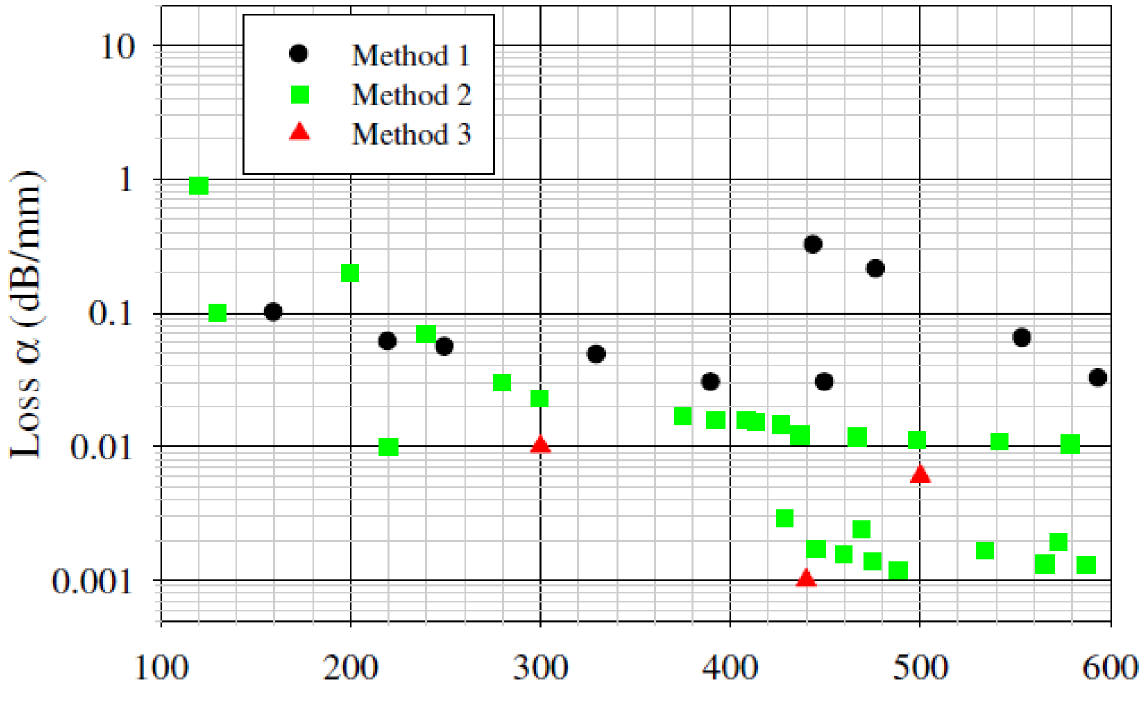
University of Southampton

Gilberto Brambilla

Brambilla, G; Finazzi, V; Richardson, DJ. Ultra-low-loss optical fiber nanotapers. *Opt. Express*, 2004 12, 2258-2263.

制备

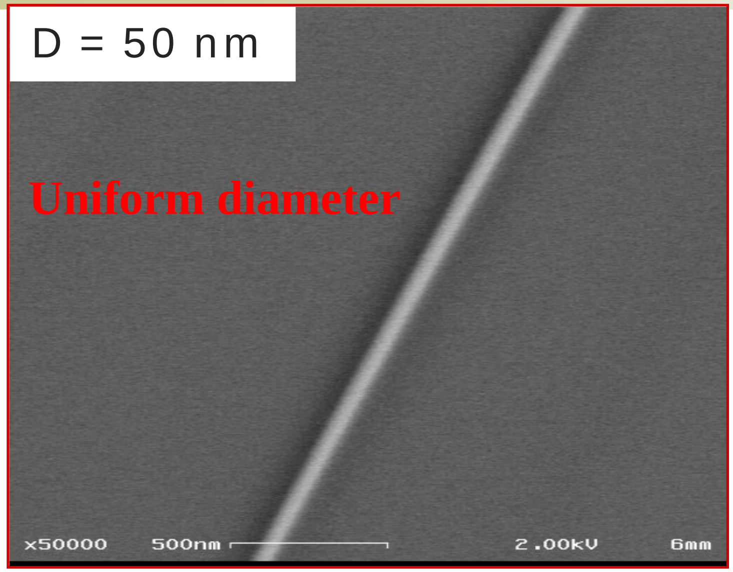
损耗

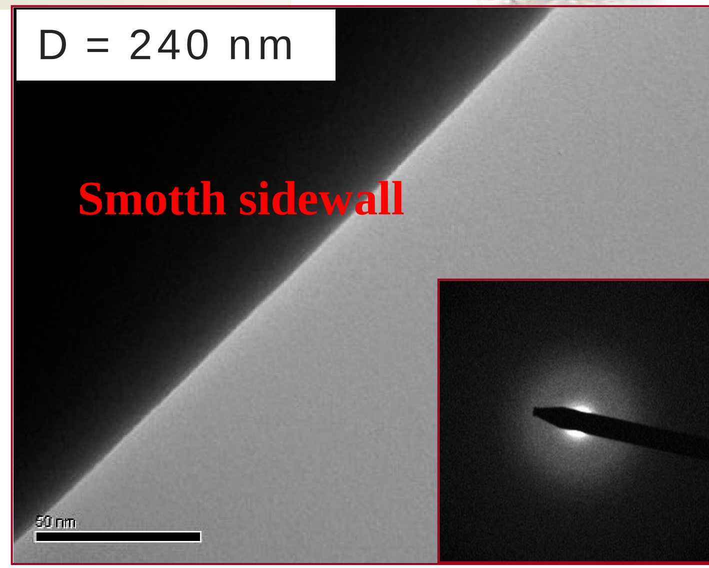


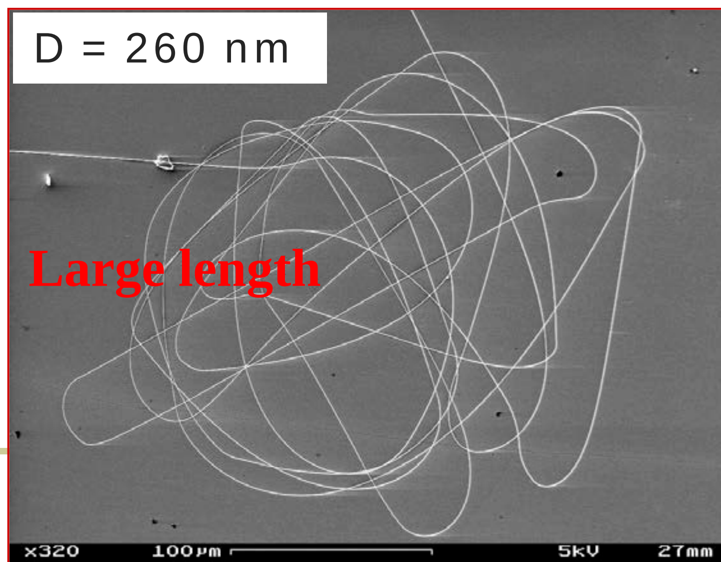
G. Brambilla et al., *Adv. Opt. Photon.* **1**, 107-161 (2009).

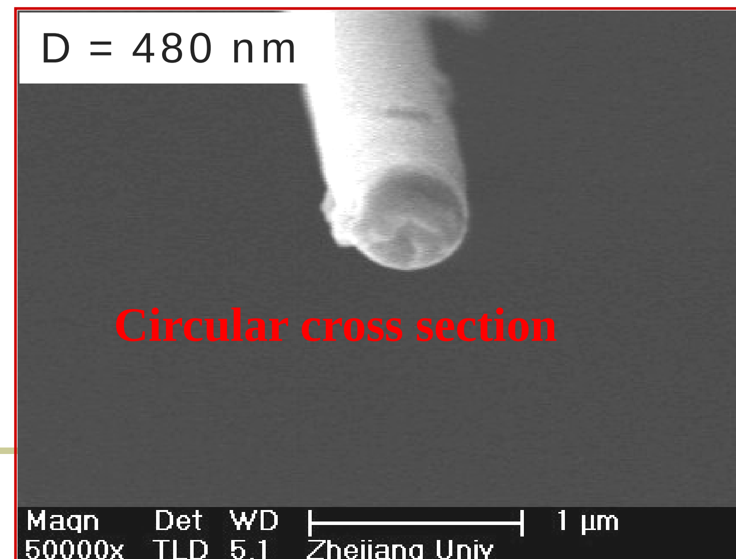
制备

扫描电镜照片





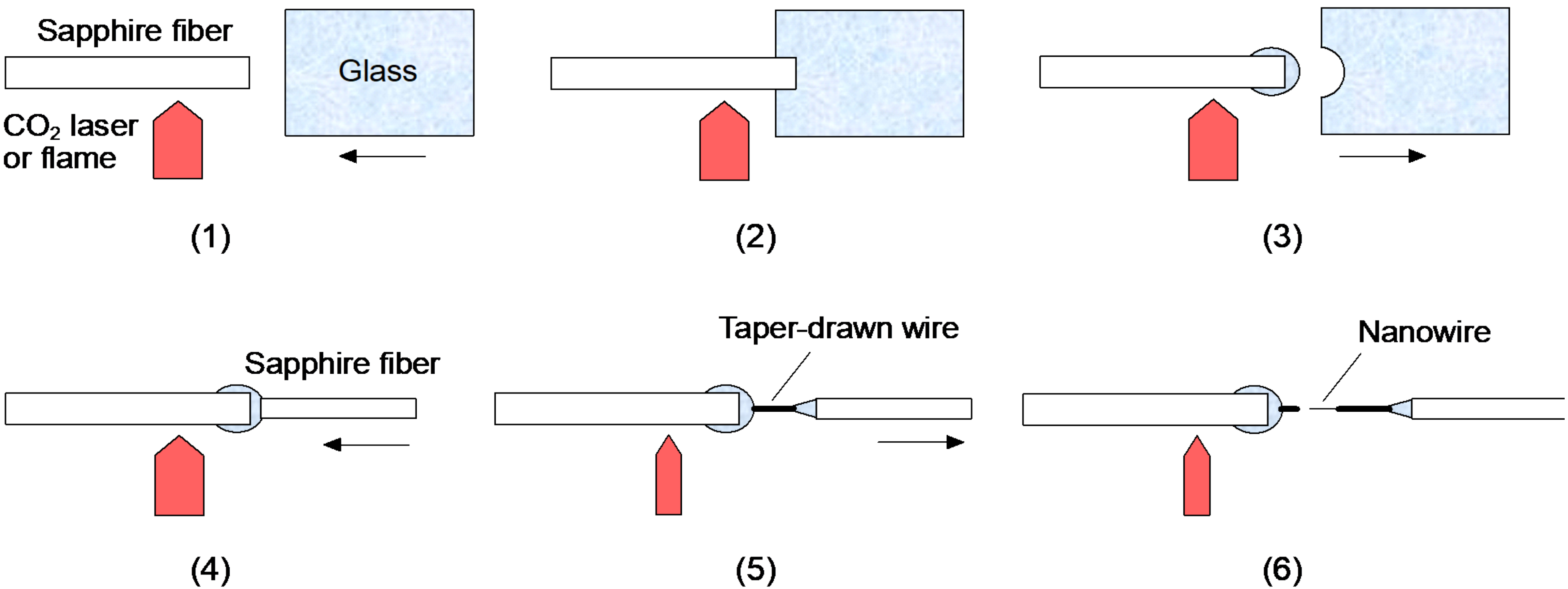




L. Tong et al., Nature **426**, 816 (2003).

制备

玻璃高温拉伸→ 多组分玻璃微纳光纤

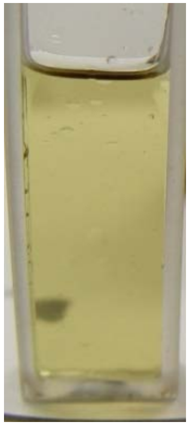


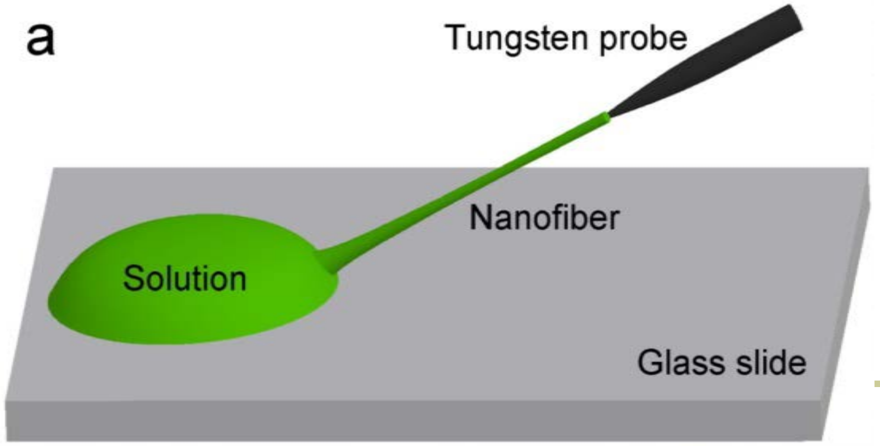
光纤直径 → 50 nm

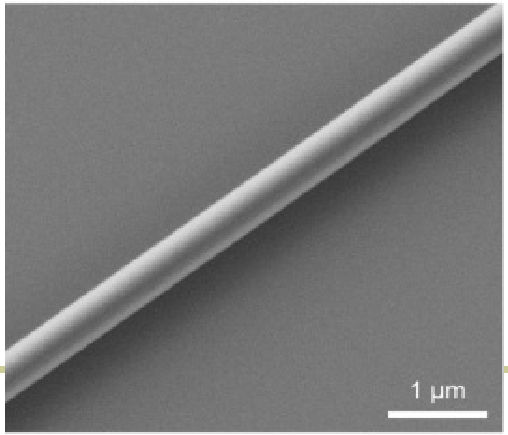
L. Tong et al., Opt. Express **14**, 82 (2006).

制备

聚合物光纤
溶液拉伸



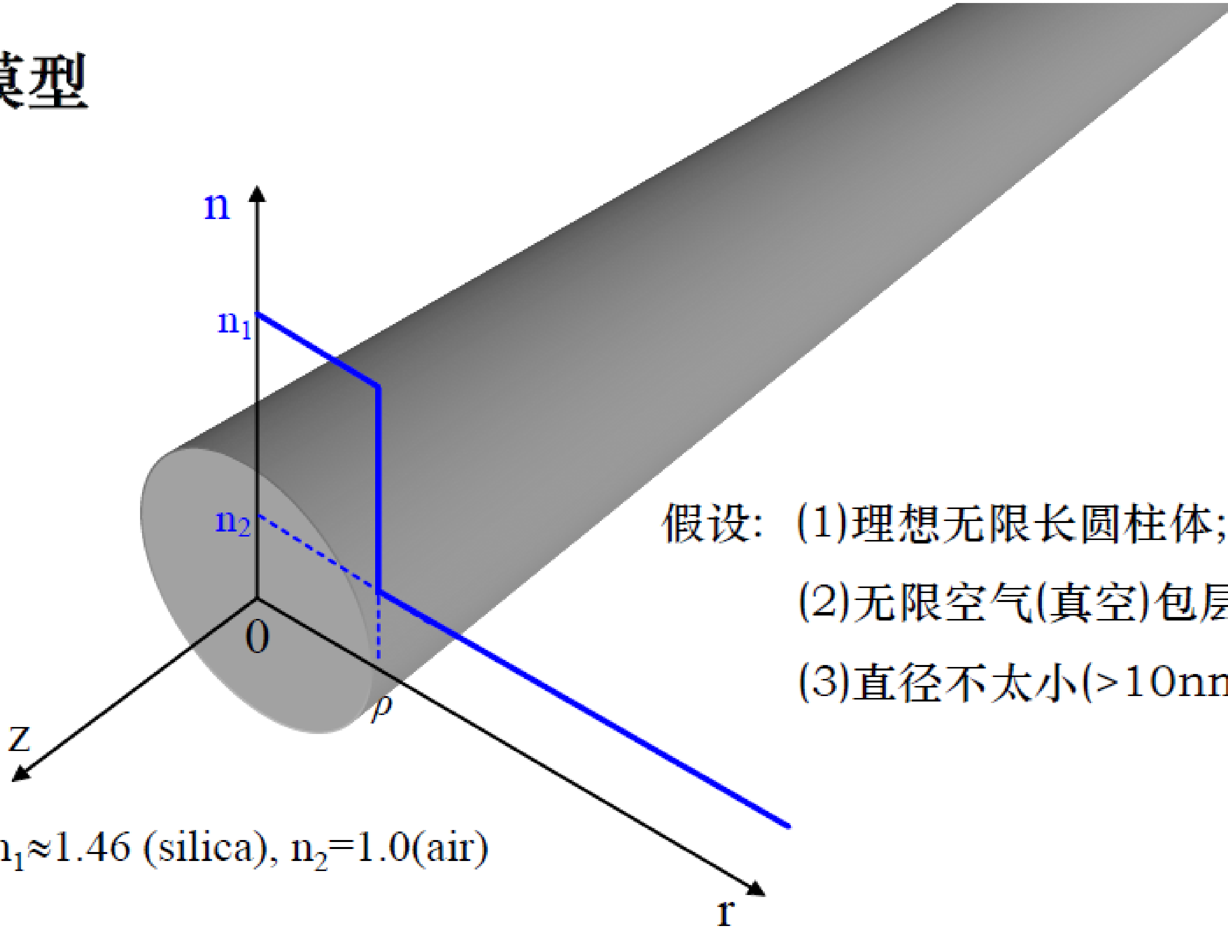




F. X. Gu et al., *Nano Lett.* 8, 2757 (2008)

理论基础

数学模型



$n_1 \approx 1.46$ (silica), $n_2 = 1.0$(air)

假设：(1)理想无限长圆柱体;

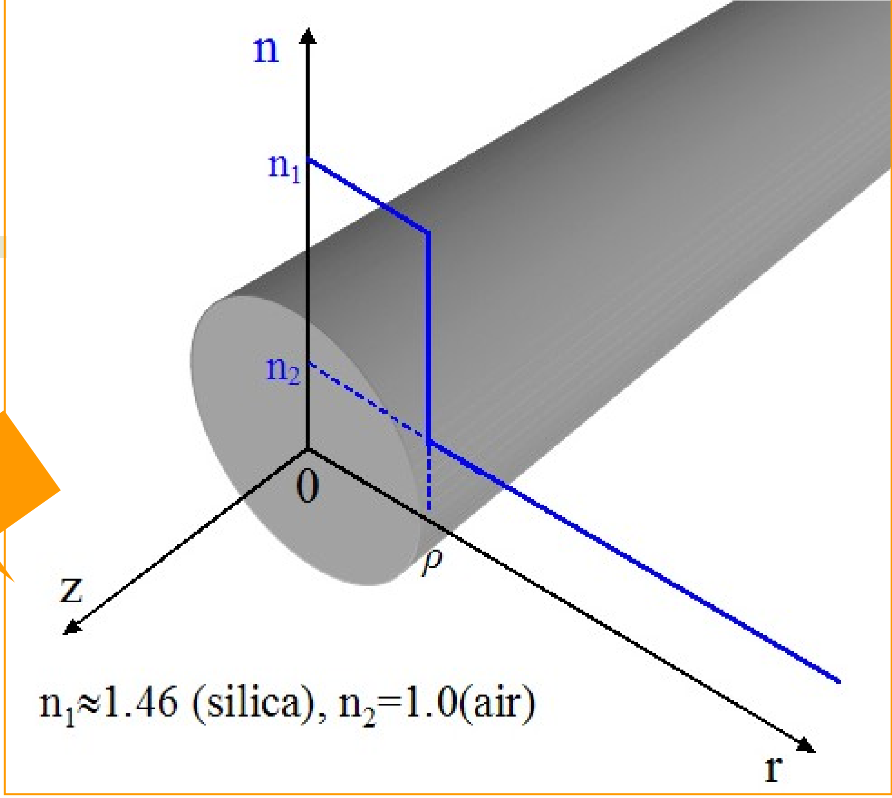
(2)无限空气(真空)包层;

(3)直径不太小(>10nm)。

理论基础

- **Basic model**

Perfect cylindrical symmetry



Helmholtz Equations

$$(\nabla^2 + n^2k^2 - \beta^2)\vec{e} = 0,$$
$$(\nabla^2 + n^2k^2 - \beta^2)\vec{h} = 0.$$

+

Boundary conditions

$$n(r) = \begin{cases} n_1, & 0 \le r < \rho \\ n_2, & \rho \le r < \infty \end{cases}$$

Analytical solutions of guided modes supported by the fiber [1]

A. W. Snyder and J. D. Love, *Optical waveguide theory*, Chapman and Hall, New York, 1983.

理论基础

圆柱对称结构 → 解析解

波导的折射率分布:

$$n(r)=\begin{cases} n_1, & 0\le r<\rho \\ n_2, & \rho\le r<\infty \end{cases}$$

非吸收和无源介质的Helmholtz方程:

$$(\nabla^2+n^2k^2-\beta^2)\vec{e}=0,$$
$$(\nabla^2+n^2k^2-\beta^2)\vec{h}=0.$$

方程的解析解 [3-1] :

其中: $k=2\pi/\lambda_0$,

β 为传播常数,

$R=r/\rho$ 为归一化半径,

$U=\rho(k_0^2n_1^2-\beta^2)^{1/2}$,

$W=\rho(\beta^2-k_0^2n_2^2)^{1/2}$,

$V=k_0\rho(n_1^2-n_2^2)^{1/2}$,

J_v为第一类贝塞尔函数,

K_v为第二类修正贝塞尔函数。

A. W. Snyder and J. D. Love, *Optical waveguide theory*, Chapman and Hall, New York, 1983.

解析解

$HE_{\nu m}, EH_{\nu m}$	$0 \le r < \rho$	$\rho \le r < \infty$
e_r	$-\frac{a_1 J_{\nu-1}(UR)+a_2 J_{\nu+1}(UR)}{J_\nu(U)} f_\nu(\phi)$	$-\frac{U}{W}\frac{a_1 K_{\nu-1}(WR)-a_2 K_{\nu+1}(WR)}{K_\nu(W)} f_\nu(\phi)$
e_ϕ	$-\frac{a_1 J_{\nu-1}(UR)-a_2 J_{\nu+1}(UR)}{J_\nu(U)} g_\nu(\phi)$	$-\frac{U}{W}\frac{a_1 K_{\nu-1}(WR)+a_2 K_{\nu+1}(WR)}{K_\nu(W)} g_\nu(\phi)$
e_z	$\frac{-iU}{\rho\beta}\frac{J_\nu(UR)}{J_\nu(U)} f_\nu(\phi)$	$\frac{-iU}{\rho\beta}\frac{K_\nu(WR)}{K_\nu(W)} f_\nu(\phi)$
h_r	$\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}\frac{kn_1^2}{\beta}\frac{a_3 J_{\nu-1}(UR)-a_4 J_{\nu+1}(UR)}{J_\nu(U)} g_\nu(\phi)$	$\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}\frac{kn_1^2}{\beta}\frac{U}{W}\frac{a_5 K_{\nu-1}(WR)+a_6 K_{\nu+1}(WR)}{K_\nu(W)} g_\nu(\phi)$
h_ϕ	$-\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}\frac{kn_1^2}{\beta}\frac{a_3 J_{\nu-1}(UR)+a_4 J_{\nu+1}(UR)}{J_\nu(U)} f_\nu(\phi)$	$-\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}\frac{kn_1^2}{\beta}\frac{U}{W}\frac{a_5 K_{\nu-1}(WR)-a_6 K_{\nu+1}(WR)}{K_\nu(W)} f_\nu(\phi)$
h_z	$-i\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}\frac{UF_2}{k\rho}\frac{J_\nu(UR)}{J_\nu(U)} g_\nu(\phi)$	$-i\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2}\frac{UF_2}{k\rho}\frac{K_\nu(WR)}{K_\nu(W)} g_\nu(\phi)$

$$f_\nu(\phi)=\begin{cases}\cos(\nu\phi)\\ \sin(\nu\phi)\end{cases}; \qquad g_\nu(\phi)=\begin{cases}-\sin(\nu\phi) & even\\ \cos(\nu\phi) & odd\end{cases}$$

$$a_1=\frac{(F_2-1)}{2};\quad a_3=\frac{(F_1-1)}{2};\quad a_5=\frac{(F_1-1+2\Delta)}{2}$$

$$a_2=\frac{(F_2+1)}{2};\quad a_4=\frac{(F_1+1)}{2};\quad a_6=\frac{(F_1+1-2\Delta)}{2}$$

$$F_1=\left(\frac{UW}{V}\right)^2\frac{b_1+(1-2\Delta)b_2}{\nu};\ F_2=\left(\frac{V}{UW}\right)^2\frac{\nu}{b_1+b_2}$$

$$b_1=\frac{1}{2U}\left\{\frac{J_{\nu-1}(U)}{J_\nu(U)}-\frac{J_{\nu+1}(U)}{J_\nu(U)}\right\}$$

$$b_2=-\frac{1}{2W}\left\{\frac{K_{\nu-1}(W)}{K_\nu(W)}+\frac{K_{\nu+1}(W)}{K_\nu(W)}\right\}$$

解析解

TE_{0m}		$0 \le r < \rho$	$\rho \le r < \infty$
	e_ϕ	$-\dfrac{J_1(UR)}{J_1(U)}$	$-\dfrac{K_1(WR)}{K_1(W)}$
	h_r	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{\beta}{k} \dfrac{J_1(UR)}{J_1(U)}$	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{\beta}{k} \dfrac{K_1(WR)}{K_1(W)}$
	h_z	$i\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{U}{k\rho} \dfrac{J_0(UR)}{J_1(U)}$	$-i\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{W}{k\rho} \dfrac{K_0(WR)}{K_1(W)}$
		$e_r = e_z = h_\phi = 0$	
TM_{0m}	e_r	$\dfrac{J_1(UR)}{J_1(U)}$	$\dfrac{n_1^{\ 2}}{n_2^{\ 2}} \dfrac{K_1(WR)}{K_1(W)}$
	e_z	$\dfrac{iU}{\rho\beta} \dfrac{J_0(UR)}{J_1(U)}$	$\dfrac{-in_1^{\ 2}}{n_2^{\ 2}} \dfrac{W}{\rho\beta} \dfrac{K_0(WR)}{K_1(W)}$
	h_ϕ	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{kn_1^{\ 2}}{\beta} \dfrac{J_1(UR)}{J_1(U)}$	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{kn_1^{\ 2}}{\beta} \dfrac{K_1(WR)}{K_1(W)}$
		$e_\phi = h_r = h_z = 0$	

理论基础

试探解（解析解）+ 圆柱对称边界条件

本征方程

HE_{vm}

EH_{vm}

$$\left\{\frac{J_v'(U)}{UJ_v(U)}+\frac{K_v'(W)}{WK_v(W)}\right\}\left\{\frac{J_v'(U)}{UJ_v(U)}+\frac{n_2^2K_v'(W)}{n_1^2WK_v(W)}\right\}=\left(\frac{v\beta}{kn_1}\right)^2\left(\frac{V}{UW}\right)^4$$

TE_{0m}

$$\frac{J_1(U)}{UJ_0(U)}+\frac{K_1(W)}{WK_0(W)}=0$$

TM_{0m}

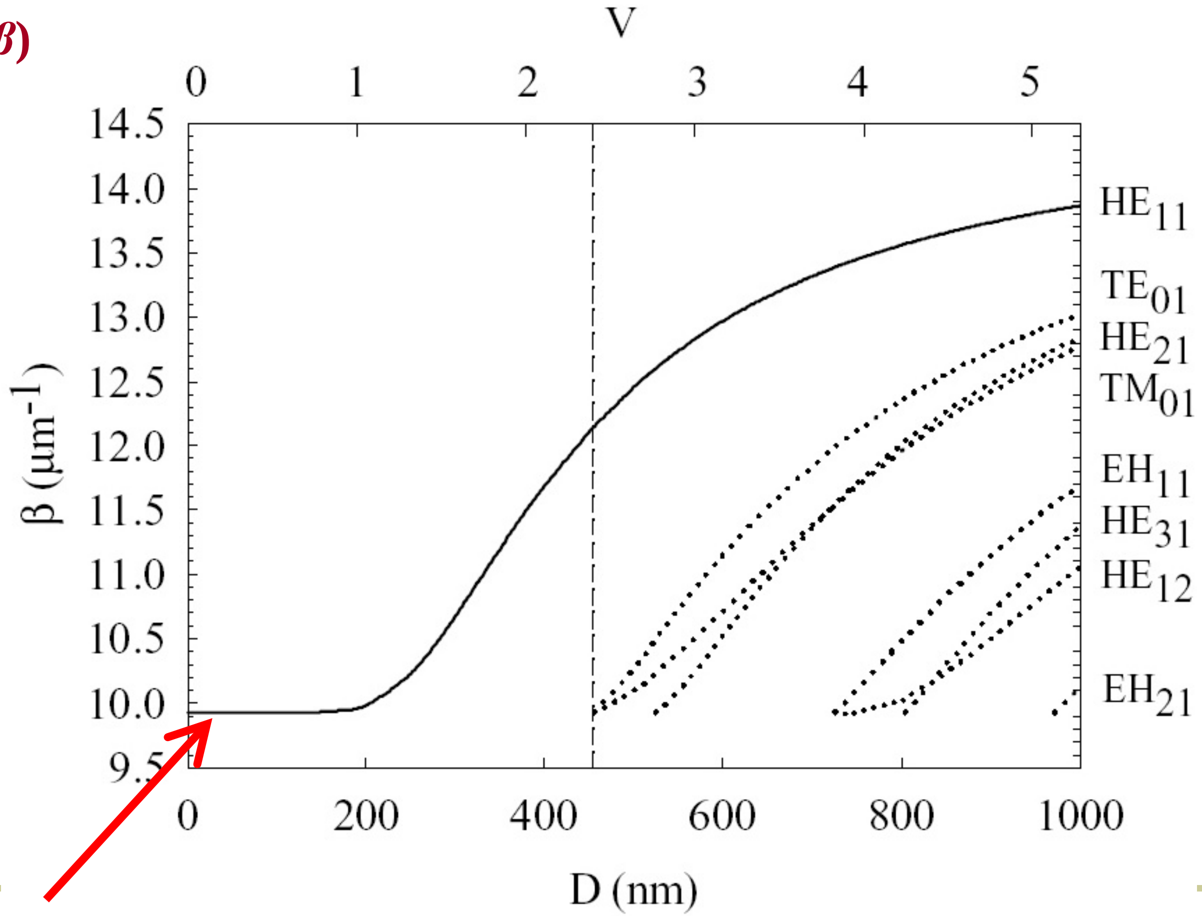
$$\frac{n_1^2J_1(U)}{UJ_0(U)}+\frac{n_2^2K_1(W)}{WK_0(W)}=0$$

理论基础

- **Basic model**

Propagation constants (*β*)

Air-clad silica microfibers
Wavelength: 633 nm



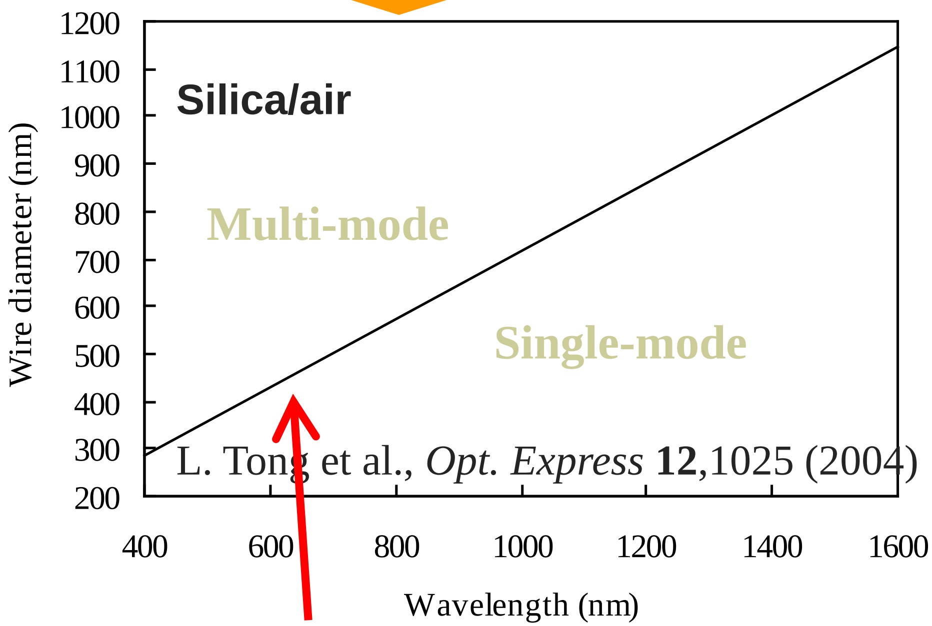
no cutoff of the fundamental modes

L. Tong et al., *Opt. Express* **12**,1025 (2004)

理论基础

- **Single-mode condition**

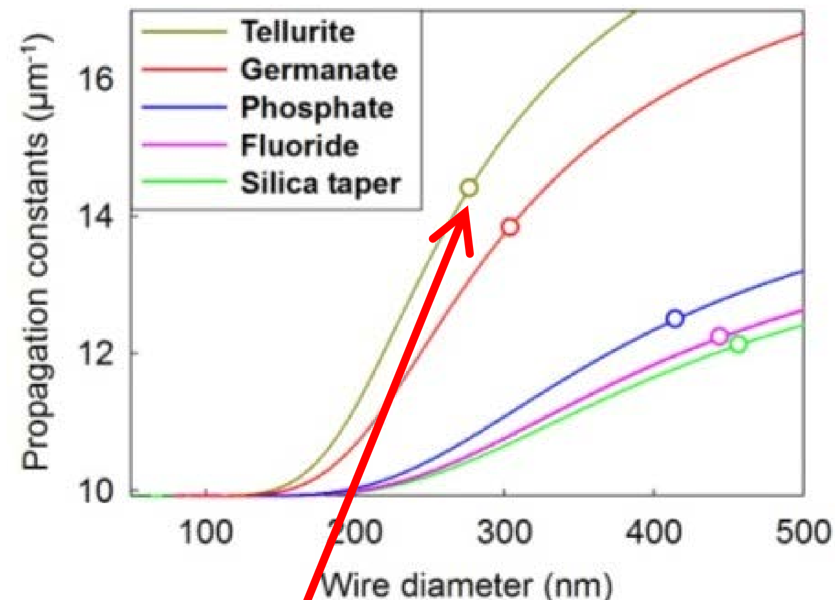
$$V = \pi \cdot \frac{D}{\lambda_0} \cdot \left(n_1^{\ 2} - n_2^{\ 2}\right)^{1/2} \approx 2.405$$



L. Tong et al., *Opt. Express* **12**,1025 (2004)

β for HE_{11} mode of several glass nanofibers

L. Tong et al., *Opt. Express* **14**, 82 (2006)



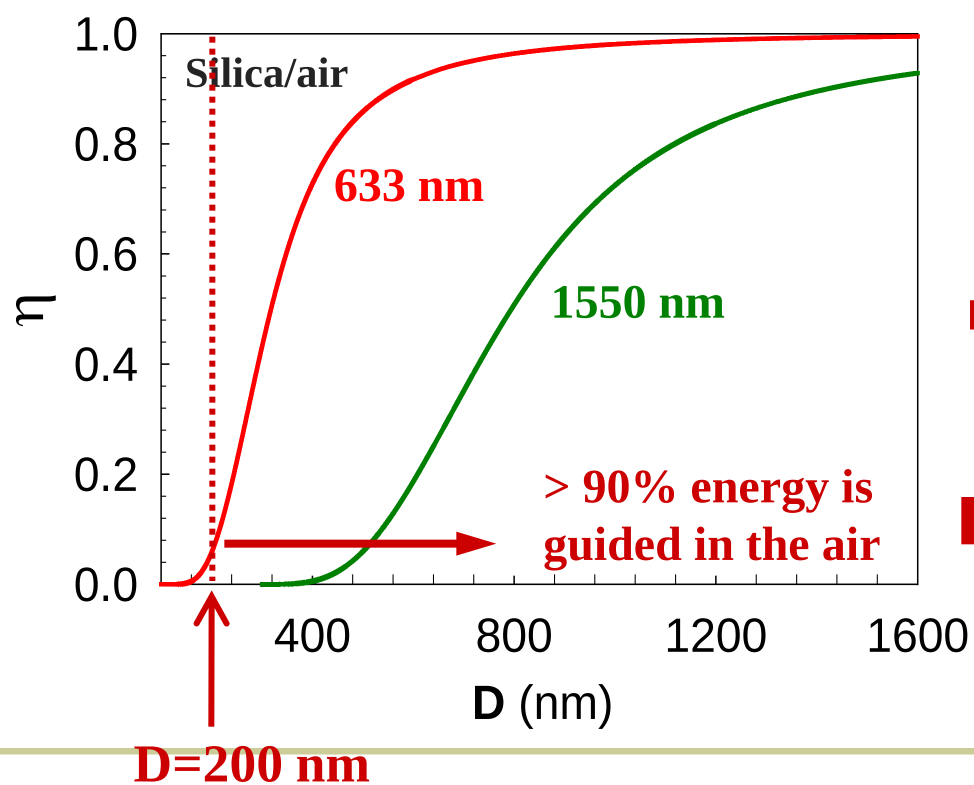
The shorter the wavelength **the higher the refractive index**

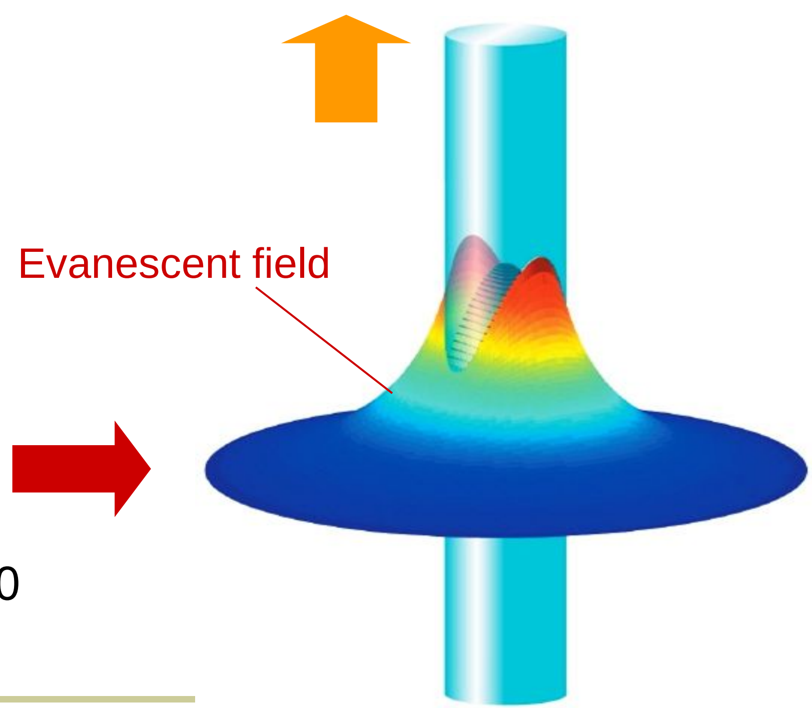
the smaller the single-mode cutoff diameter

理论基础

- **Evanescent field of HE$_{11}$ mode**

Fractional power inside the core

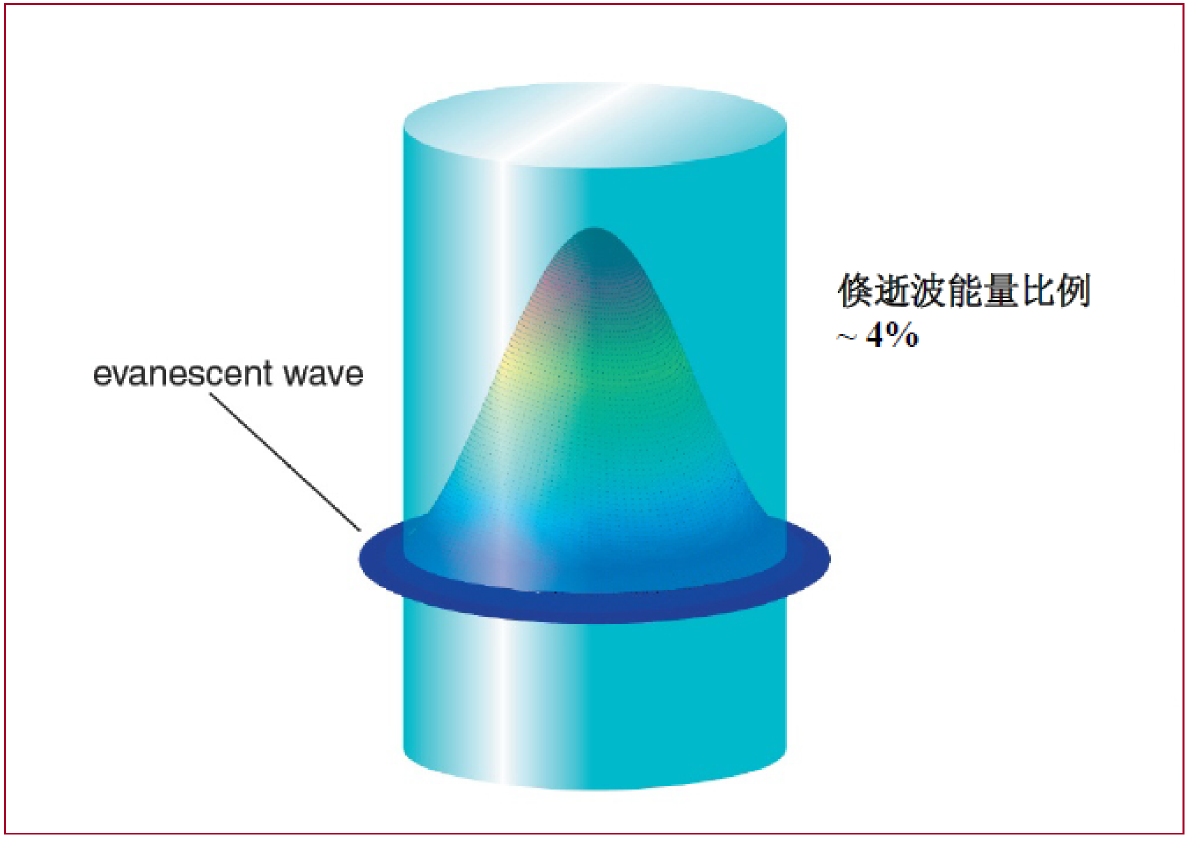




L. Tong et al., *Opt. Express* **12**,1025 (2004)

理论基础

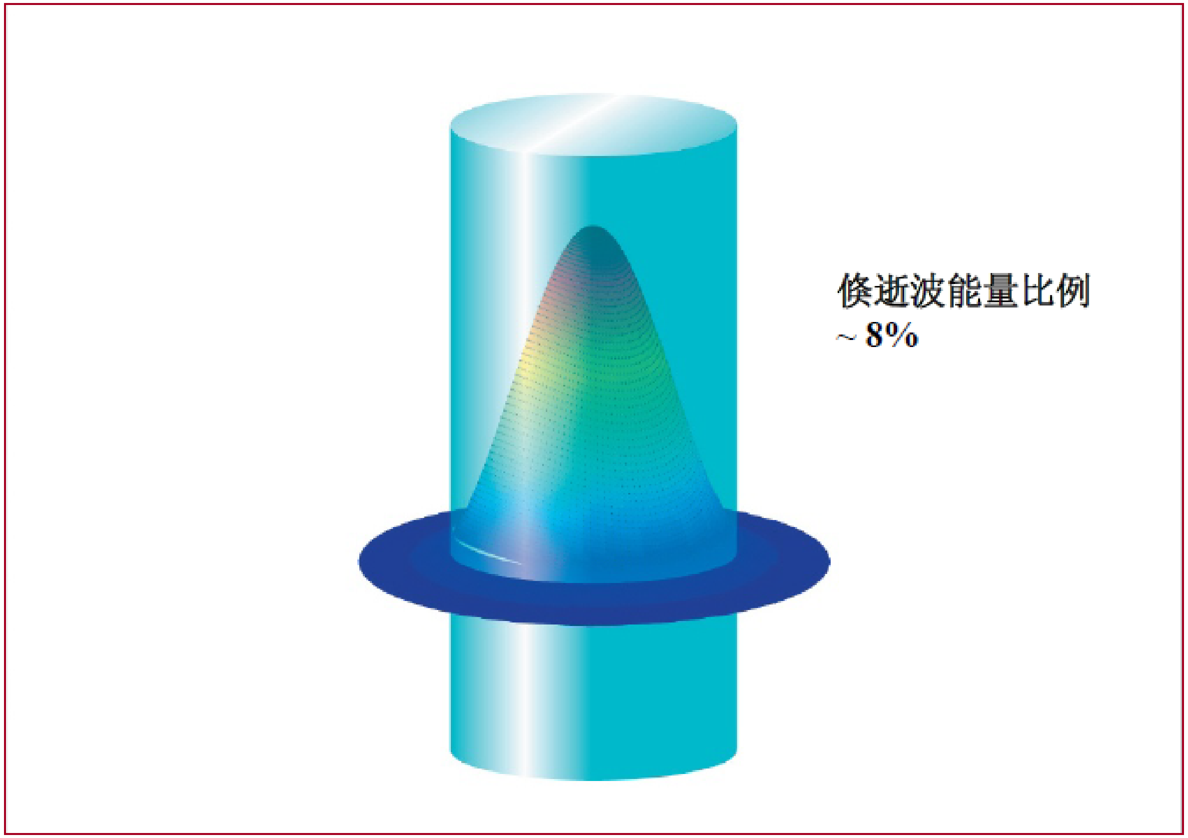
Poynting矢量 (基模能量分布, λ =633 nm)



D=800 nm

理论基础

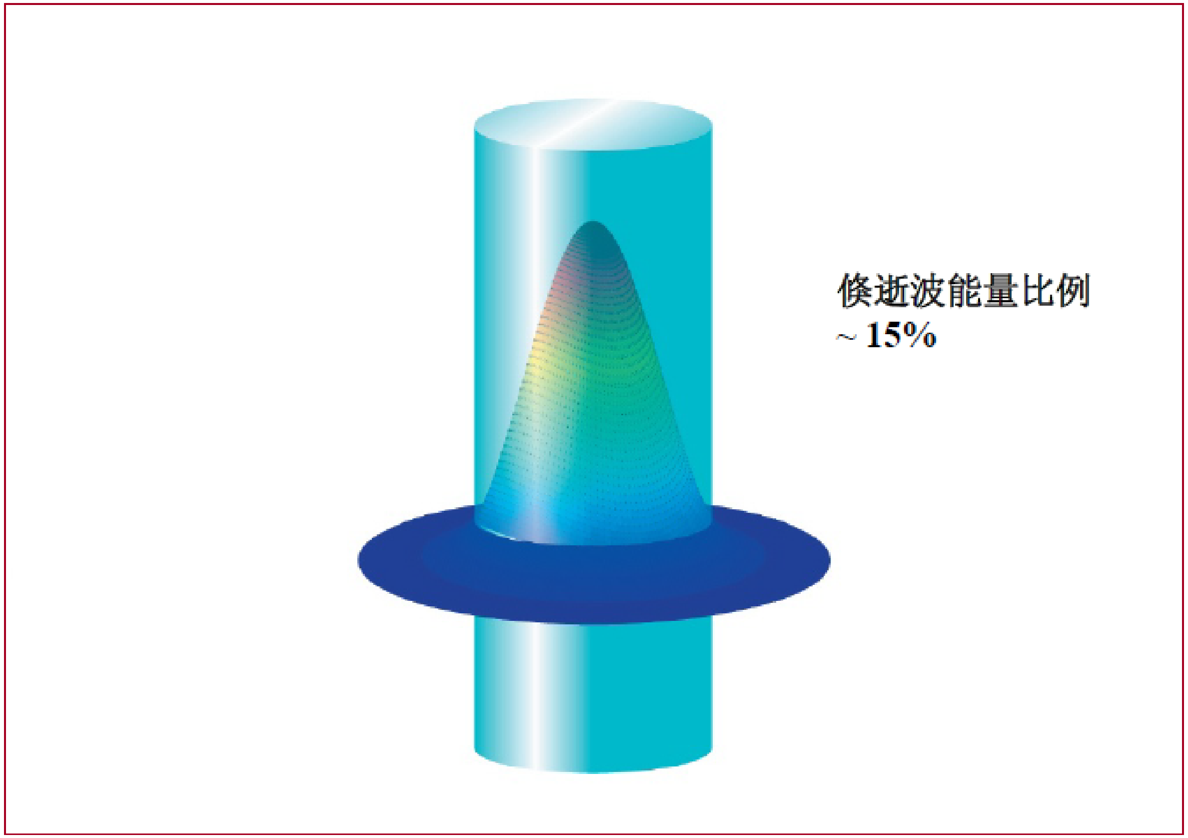
Poynting矢量 (基模能量分布, λ =633 nm)



D=600 nm

理论基础

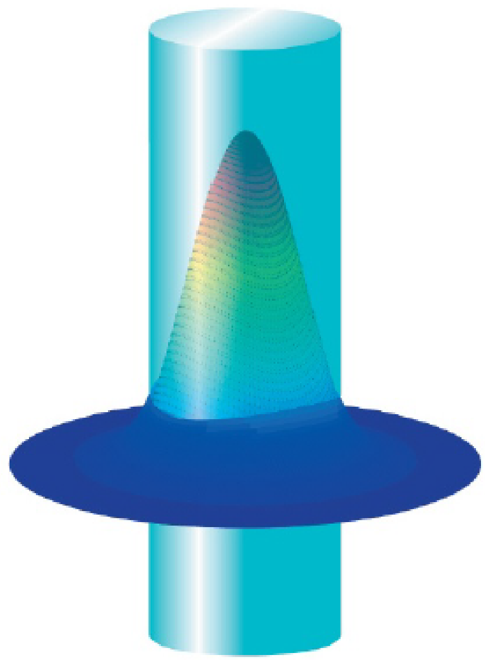
Poynting矢量 (基模能量分布, λ =633 nm)



D=500 nm

理论基础

Poynting矢量 (基模能量分布, λ =633 nm)

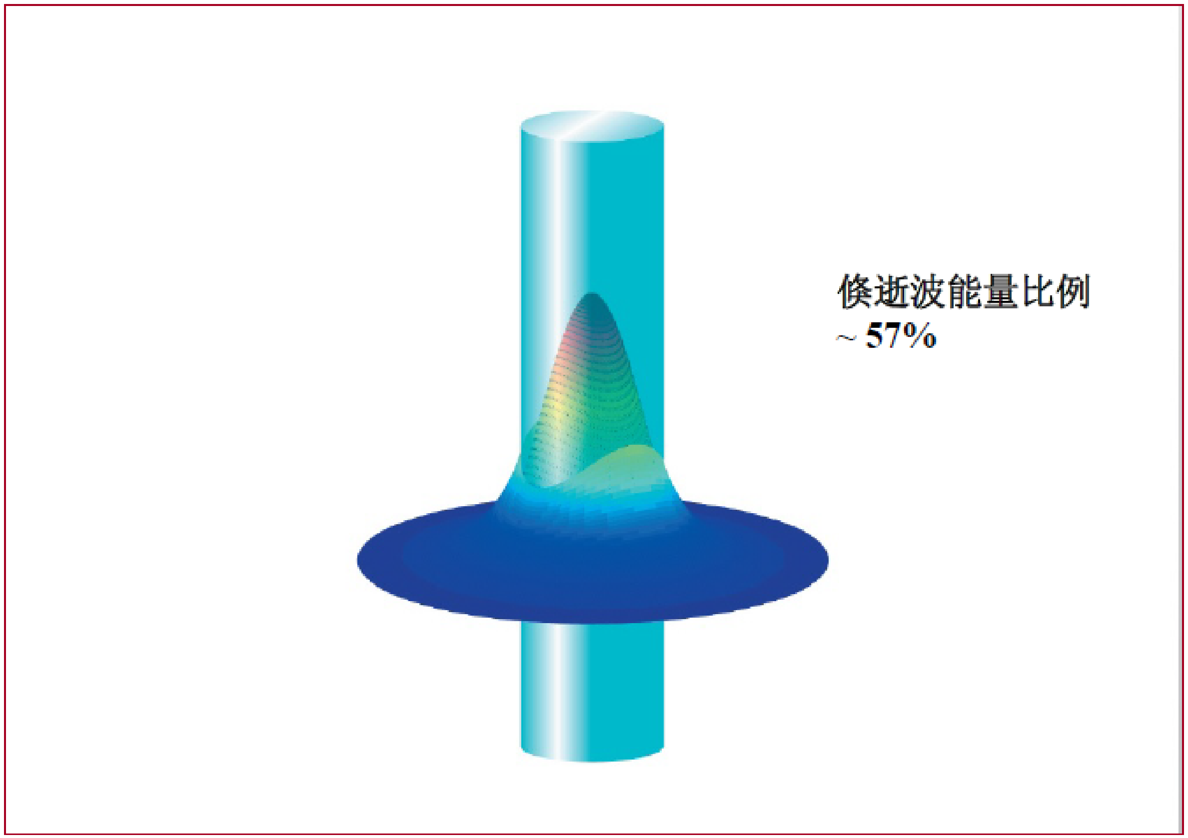


倏逝波能量比例
~ 28%

D=400 nm

理论基础

Poynting矢量 (基模能量分布, λ =633 nm)



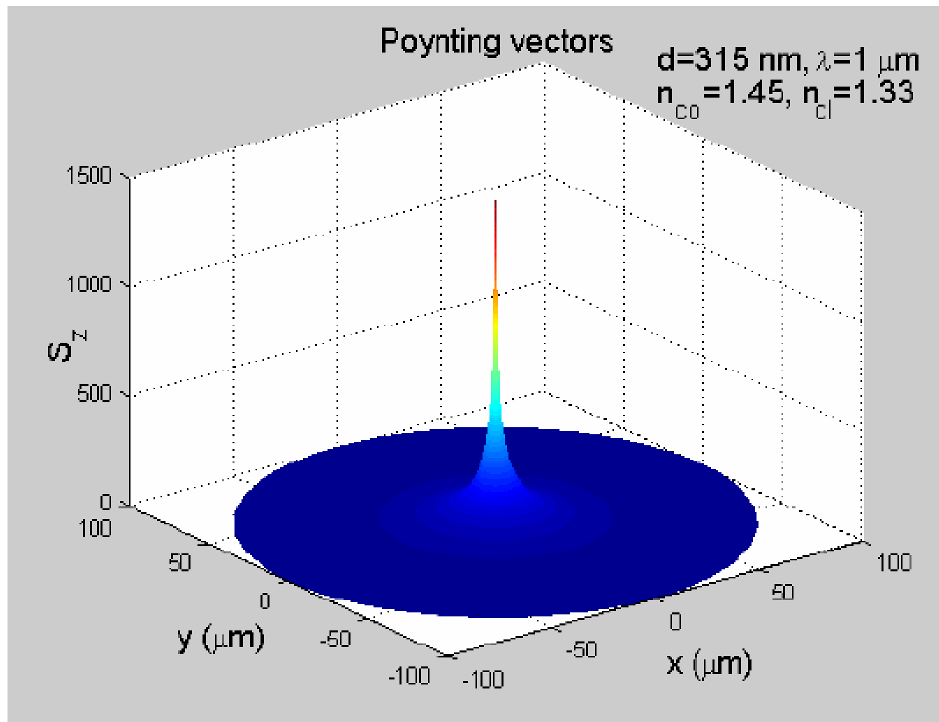
D=300 nm

理论基础

液体包层光纤的**Poynting**矢量 (基模能量分布, **λ =1 μm**)

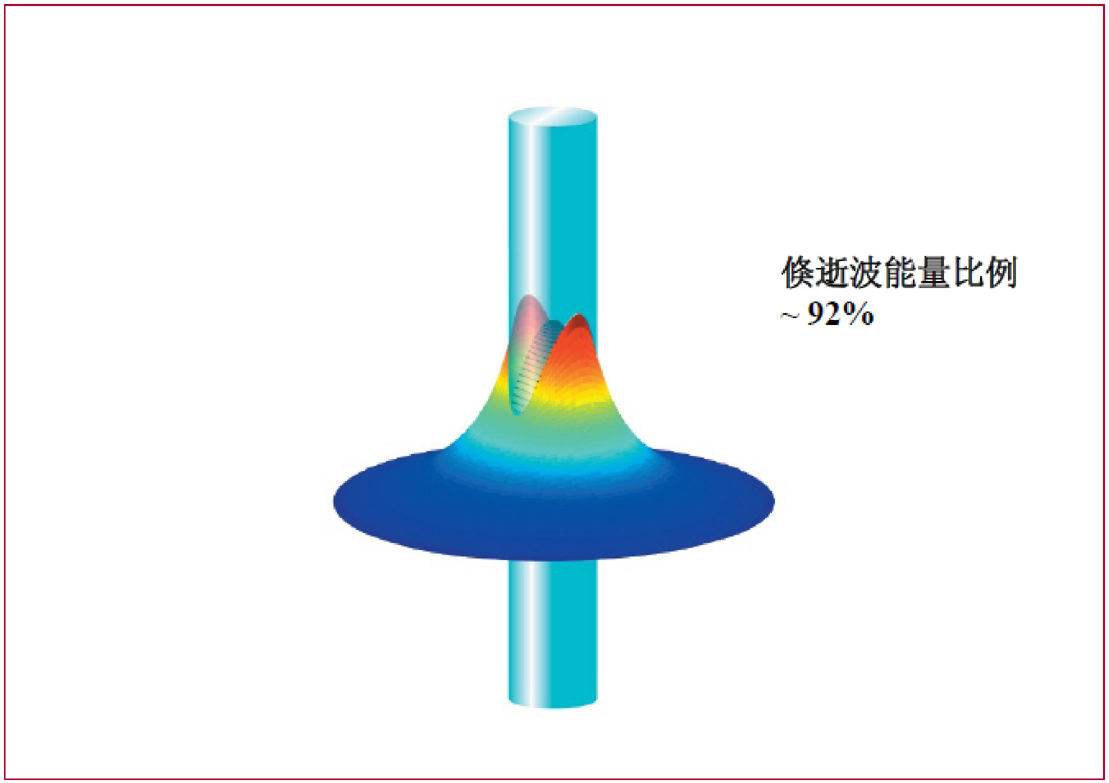
D=315 nm
液体: 水

倏逝波能量比例
~ **86%**



理论基础

Poynting矢量 (基模能量分布, λ =633 nm)



D=200 nm

作业:

利用有限元分析模拟（例如Comsol）的方法计算微纳光纤的模式分布，给出不同直径的光纤外的倏逝场的能量占总能量的比例（波长为1550 nm）。