纳米光子学及其应用

第18讲：光子晶体光纤

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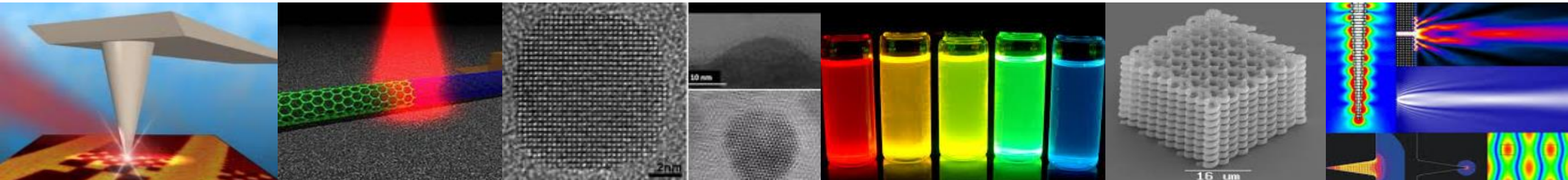
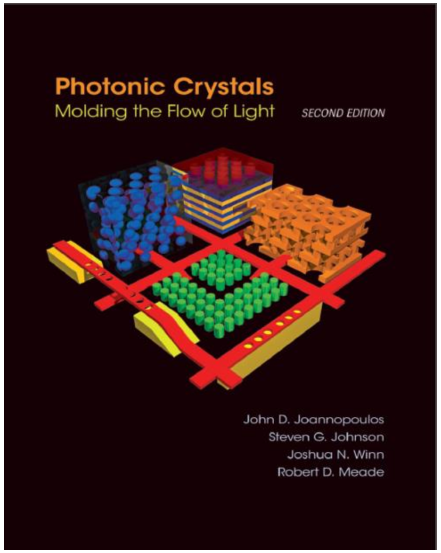
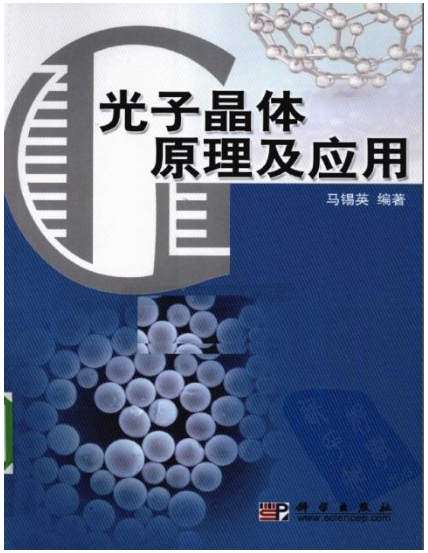


本讲内容

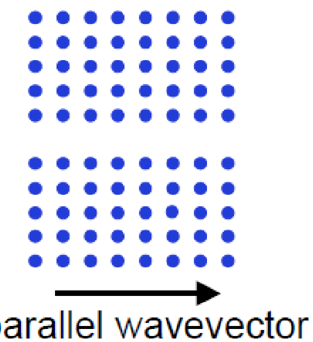
- 1、引言——为什么要研究光子晶体光纤？
- 2、**光子晶体**光纤简介
- 3、全内反射型光子晶体光纤
- 4、空气带隙型光纤
- 5、布拉格光栅
- 6、光子晶体光纤的制备
- 7、光子晶体光纤的应用

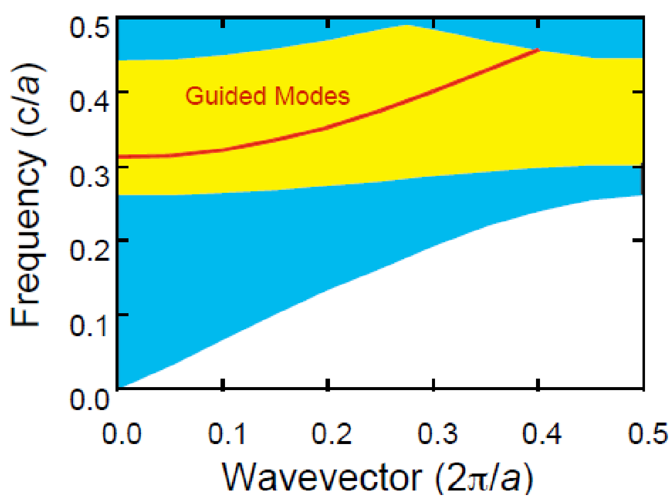


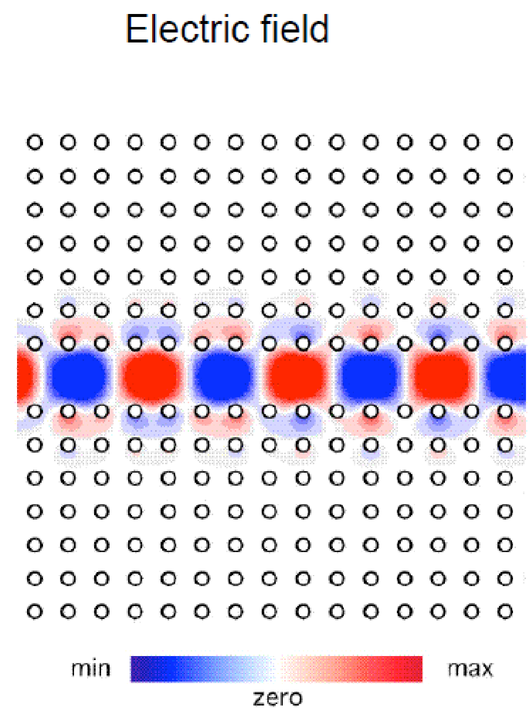


1、引言

光子晶体光波导—导模传播







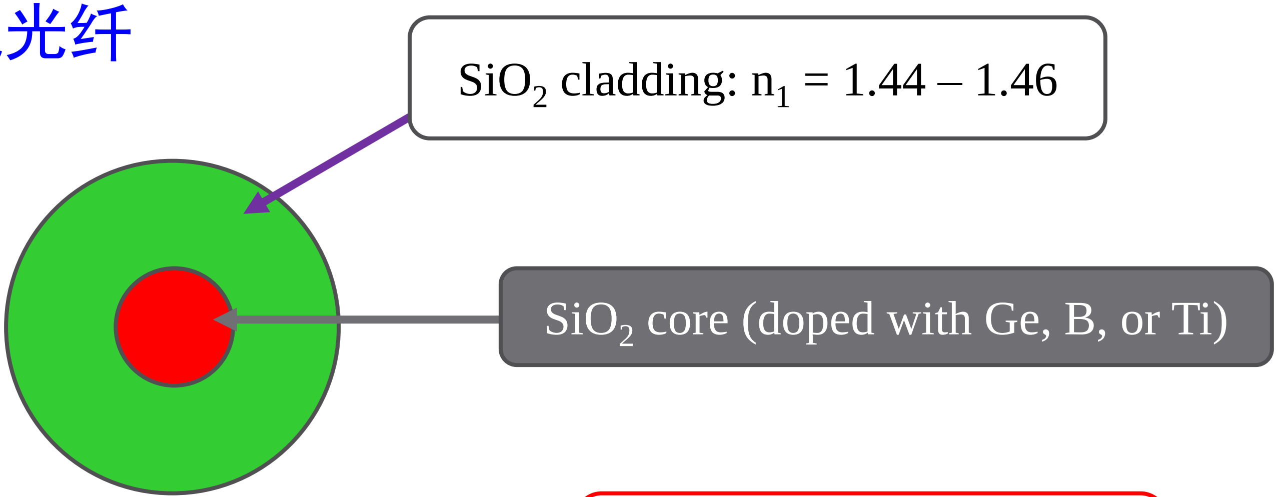
低损耗、无标度(波长可扩展)

1、引言

能否将光子晶体用于光纤中？
带来哪些新性质？

1、引言

传统光纤



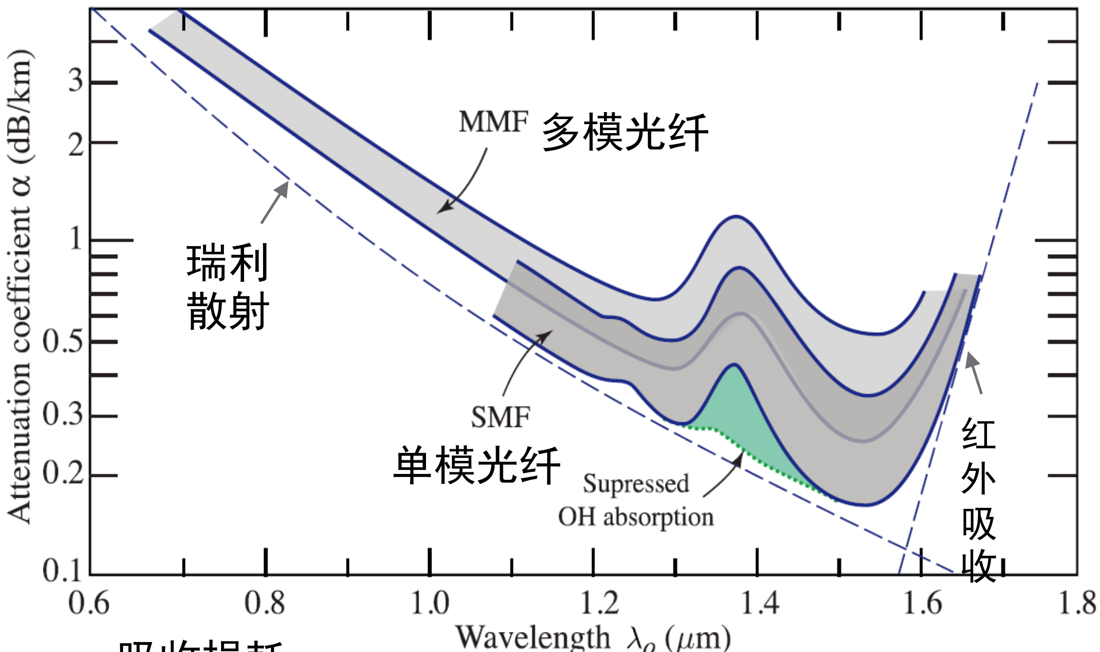
相对折射率差：$\boxed{\dfrac{n_2 - n_1}{n_2} = 0.001 \sim 0.02}$

纤芯对光场的限制能力弱，在包层中存在很大能量

为避免长距离传输时间延迟——单模光纤

1、引言

传统光纤中的损耗



损耗系数的数学表达式：

$$\alpha = -\frac{10\lg\left(\frac{P_{out}}{P_{in}}\right)}{L}$$

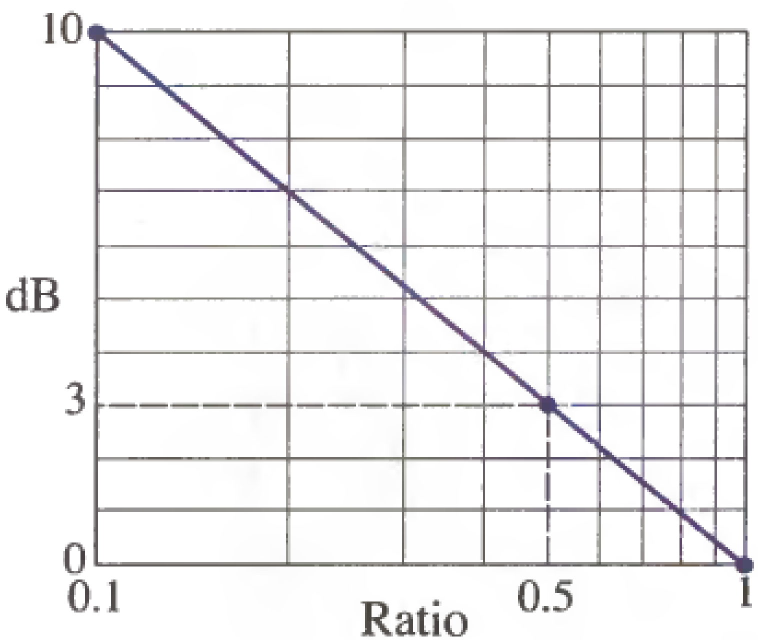
单位：dB/km

- 吸收损耗
  - 本征吸收：紫外本征吸收-能级跃迁、红外吸收-声子吸收带
  - 杂质吸收：材料不纯，含过渡金属离子和OH根离子
  - 原子缺陷吸收：缺陷能级对光的吸收
- 散射损耗
  - 瑞利散射：材料的不均匀性引起
- 弯曲损耗

1.55 μm 损耗0.16 dB/km
每公里损耗能量3.6%

1、引言

传统光纤中的损耗



The dB value of a ratio.

$$\alpha = -\frac{10\lg\left(\frac{P_{out}}{P_{in}}\right)}{L}$$

$$\frac{P(z)}{P(0)} = 10^{-\alpha z/10} \approx e^{-0.23\,\alpha z}, \qquad \alpha \text{ in dB/km.}$$

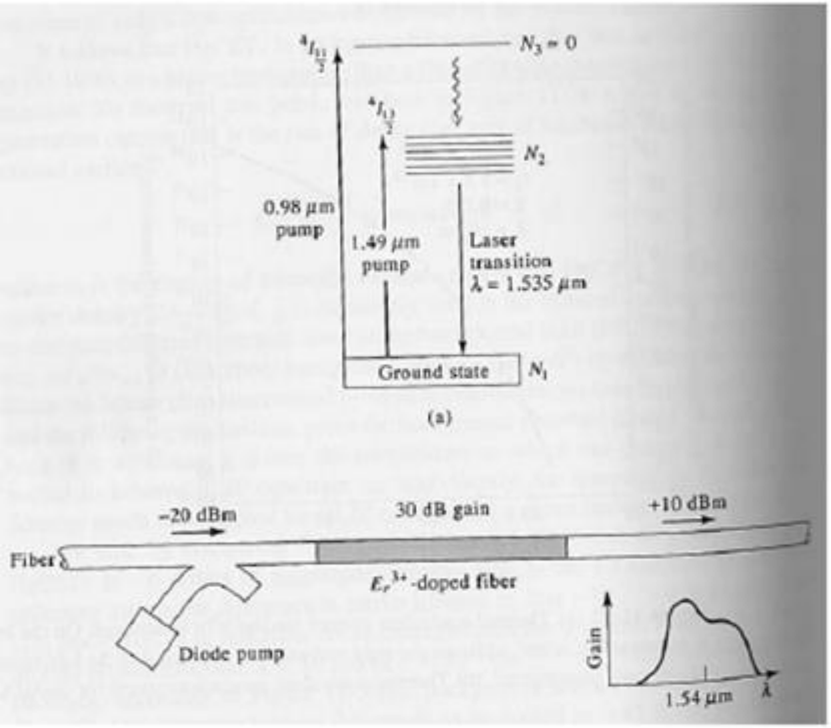
- 3 dB对应能量损失一半
- 10 dB对应能量剩余10%
- 20 dB对应能量剩余1%

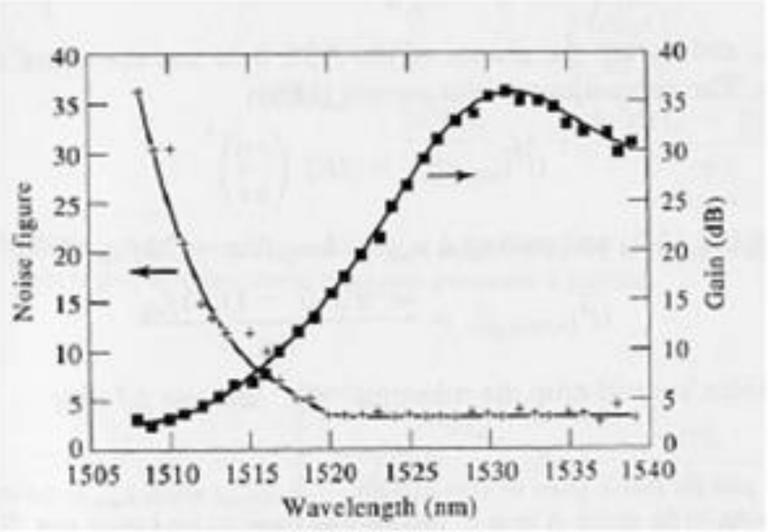
传统光纤：1.55 μm 的典型损耗0.16 dB/km

- 50 km后能量剩余15.9%
- 100 km后能量剩余2.5%
- 一般50 – 100 km放置一个光放大器

1、引言

远距离通信中光纤光学放大





Er, gain maximum close to 1.55 micron

Usable bandwidth limited by the amplifier bandwidth to be approximately 30nm

<u>Improving bandwidth by removing amplifiers, guiding in air?</u>

1、引言

传统光纤中的导模

在芯层中：

$$\beta^2 + k_\perp^2 = n_1^2 k_0^2$$

$$\Rightarrow \beta^2 = n_1^2 k_0^2 - k_\perp^2$$

$$\Rightarrow \beta < n_1 k_0$$

在包层中：

$$\beta^2 + k_\perp^2 = n_2^2 k_0^2$$

在包层中横向是倏逝波，满足：

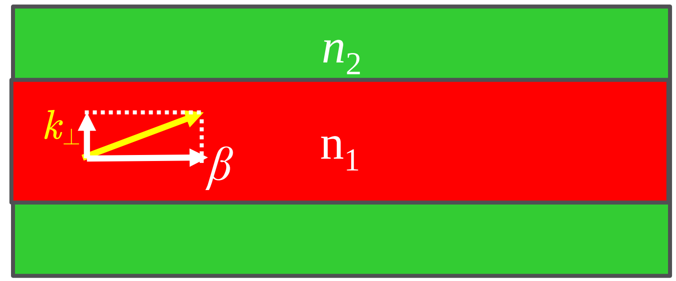
$$k_\perp^2 = n_2^2 k_0^2 - \beta^2 < 0$$

$$\Rightarrow n_2 k_0 < \beta$$

即：

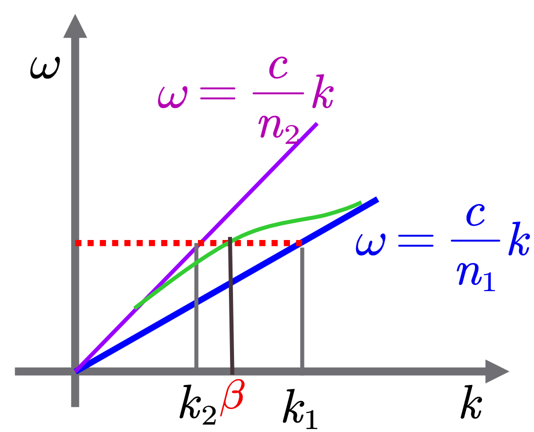
$$n_2 k_0 < \beta < n_1 k_0$$

同一频率



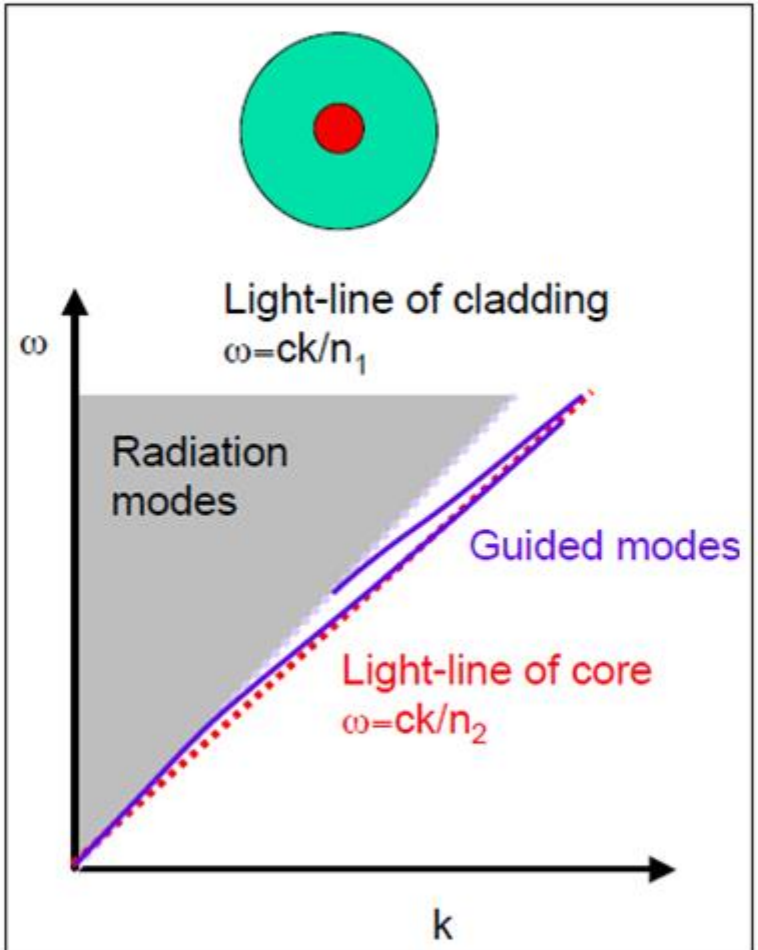
导模位于两个光锥之间

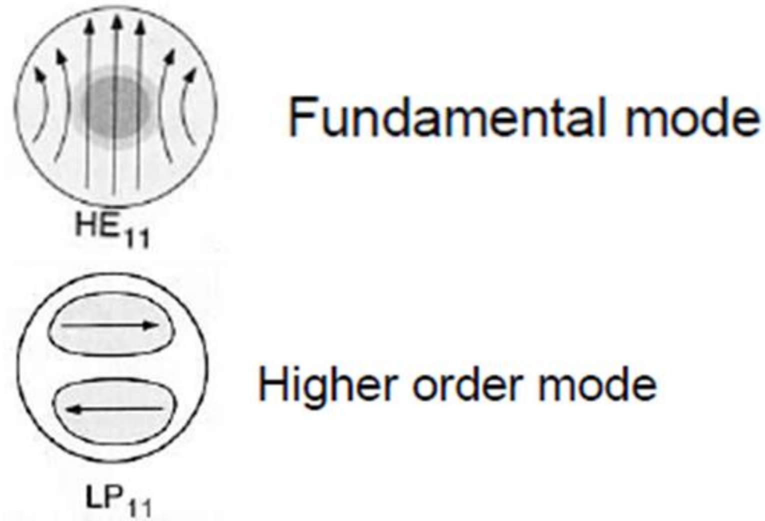
$$\omega = \frac{c}{n_2} k_2, \ \omega = \frac{c}{n_1} k_1$$



1、引言

传统光纤中的导模



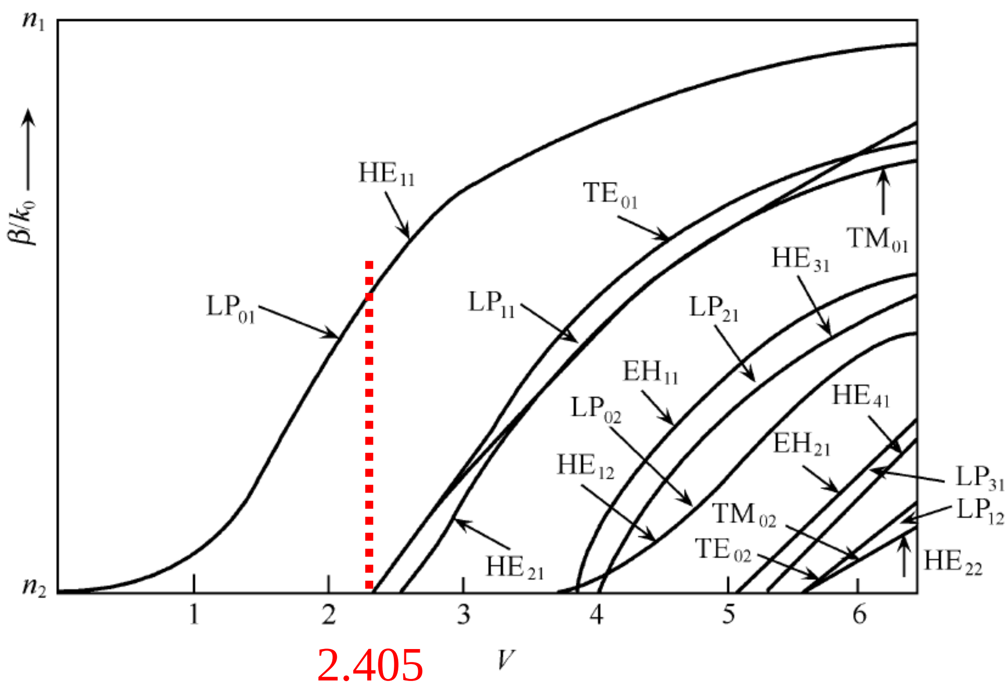


- 普通单模光纤截止波长一般大于 1 μm
- 短波呈现多模

1、引言

传统光纤中的导模

归一化频率：$V = \dfrac{2\pi a}{\lambda}\sqrt{n_{\rm core}^2 - n_{\rm clad}^2}$　　a 为圆形截面阶跃型波导半径



$V < V_0 = 2.405$ 单模传输

$$\lambda > \frac{2\pi a}{V_0}\sqrt{n_{\rm core}^2 - n_{\rm clad}^2}$$

$$\lambda > 2.6a\sqrt{n_{\rm core}^2 - n_{\rm clad}^2}$$

取典型值：$n_{\rm core} = 1.455$
$n_{\rm clad} = 1.45$
$a = 3\ \mu\text{m}$

$$\lambda > 0.94\ \mu\text{m}$$

典型的光纤，低于0.94 μm的波长的光不能实现单模。

单模传输与波长和光纤直径相关，短波长单模传输需要更小的芯径

1、引言

- 传统光纤：
  - 存在损耗，不可避免，长距离传输需要进行光放大
  - 光放大，受限于增益介质，带宽有限
  - 难以实现全光谱单模传输
- 光子晶体能否解决传统光纤面临的困境？
- 能不能带来新的性质？

2、光子晶体光纤简介

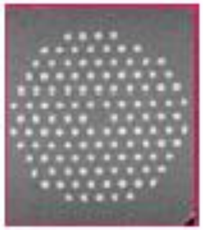
2、光子晶体光纤简介

光子晶体光纤

光子晶体光纤通常由纯石英或聚合物等材料为基底，在光纤的横截面上具有一、二维的周期性折射率分布(空气孔或高折射率柱)，而沿光纤长度方向不变。

全内反射型光子晶体光纤 (total internal reflection, TIR-PCF)

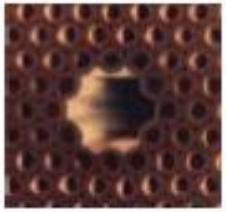
$n_{core} > n_{clad}$



空气包层有效折射率低于纤芯折射率

空气带隙型光纤 (photonic band gap, PBG-PCF)

$n_{core} < n_{clad}$

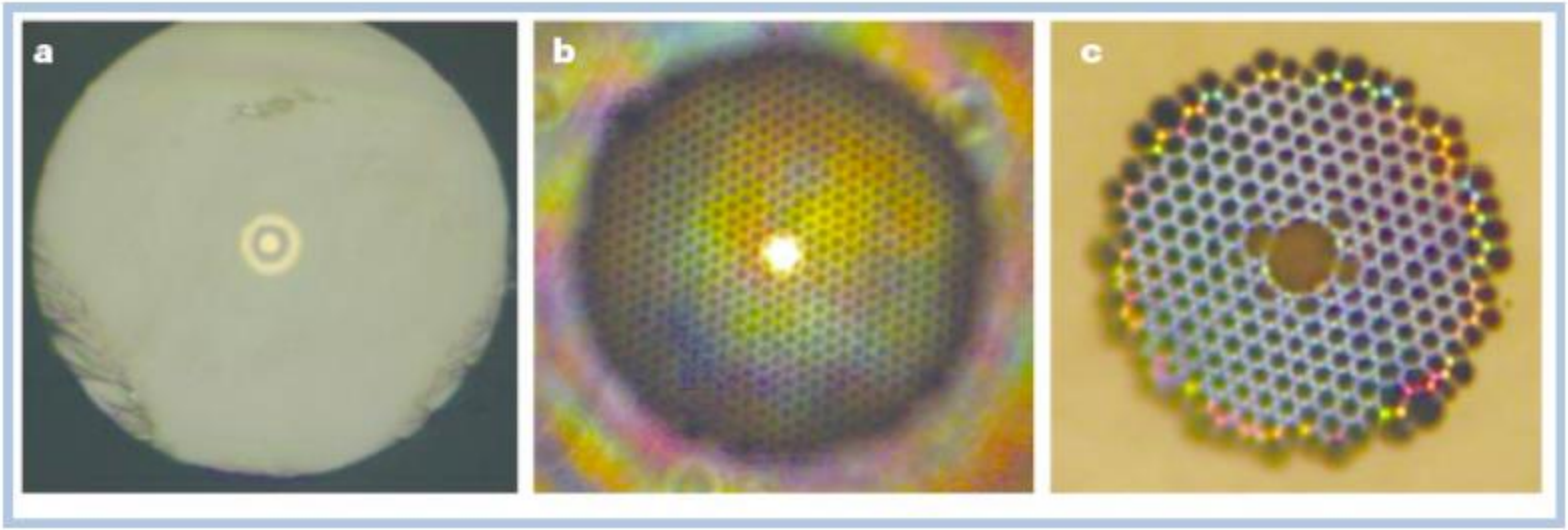


传导光波频率位于包层光子带隙频域内

2、光子晶体光纤简介

光子晶体光纤实物图

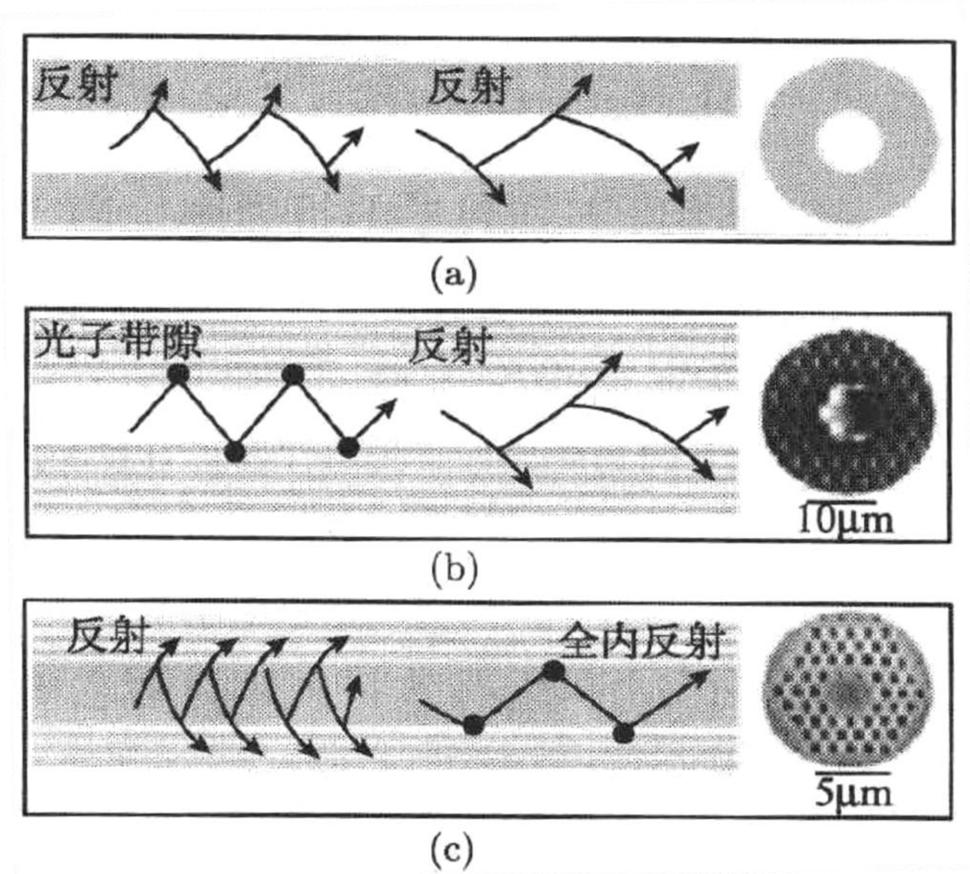
Photonic crystal fiber (PCF)



Conventional fiber Core diameter 9 micron	Dielectric-core PCF Core diameter 5 micron	Air-core PCF Core diameter 9 micron
传统光纤	介质核 全内反射型	空气核 光子带隙型

2、光子晶体光纤简介

光子晶体光纤导光原理



空心毛细管：不能导光

空心光子晶体光纤

实心光子晶体光纤
（全内反射型光子晶体光纤）

2、光子晶体光纤简介

发展简史

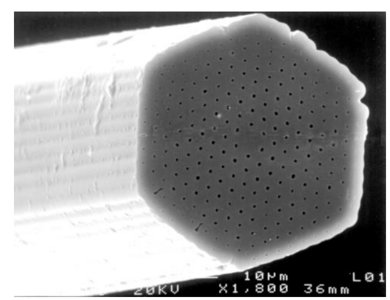
1970: Idea that a cylindrical Bragg waveguide can guide light

1991: Idea that light could be trapped inside a 2D PhC made of silica capillaries.

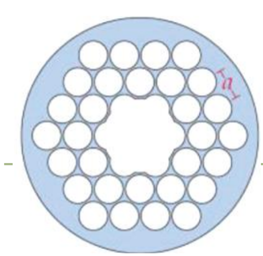
1995: Theoretical proof that bandgap guiding is possible

1996: First PCF prototype

- By stacking silica capillaries, then drawing to fiber
- Index guidance. d_{hole}/pitch=0.2



1999 : First HC PCF



Hollow Core

2、光子晶体光纤简介

发展简史

Philip Russell

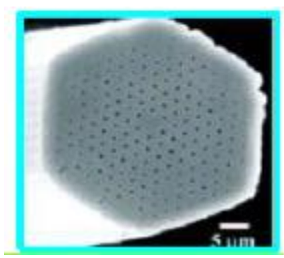
photonic crystal fiber

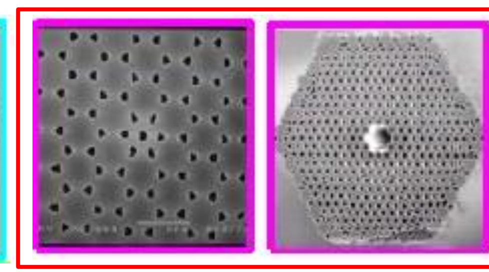
University of Bath, UK

Photonic crystal fiber
光子晶体光纤

Index guiding fiber
折射率引导型光纤

Photonic band gap fiber
光子带隙光纤





E.Yablonovitch, S. John
Idea of photonic crystal

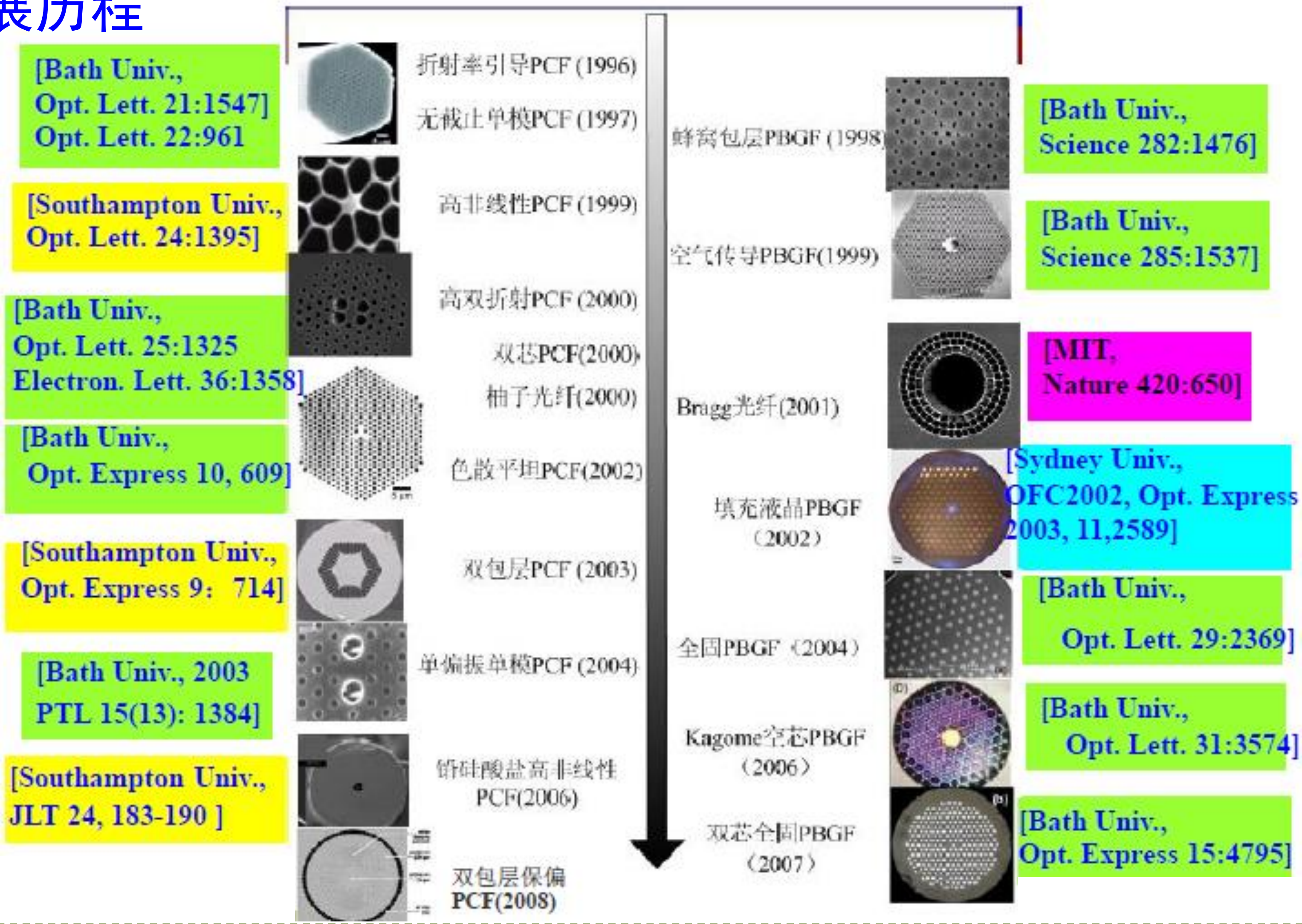
J. C. Knight

Holey fiber

1987 1991 1996 1998

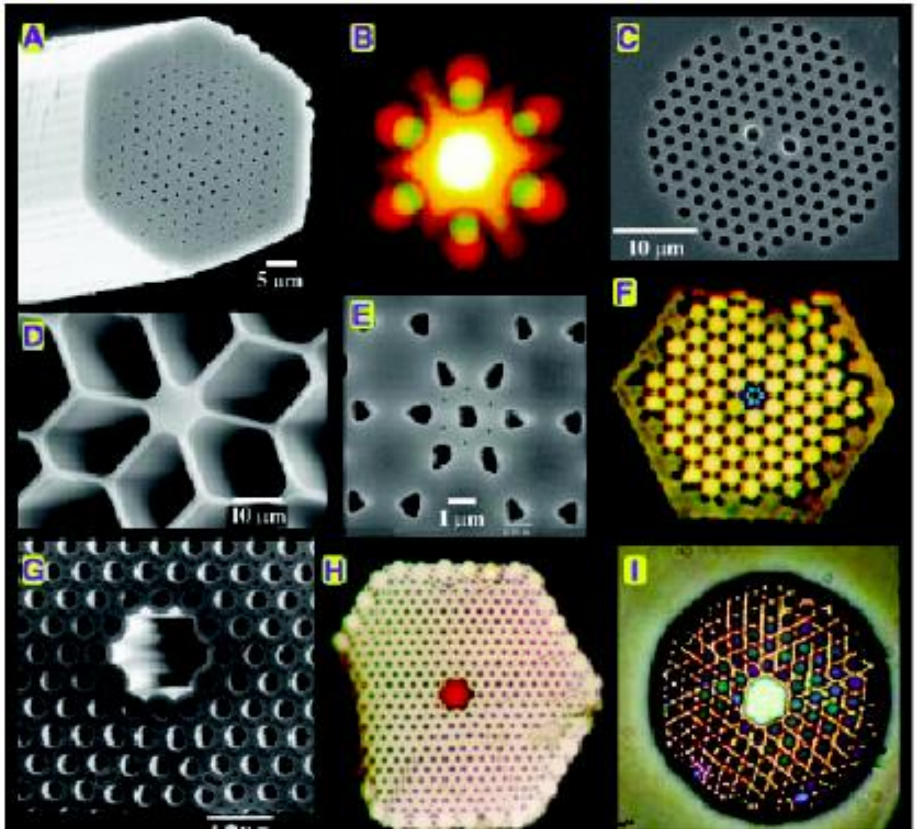
2、光子晶体光纤简介

发展历程



2、光子晶体光纤简介

各种类型的光子晶体光纤



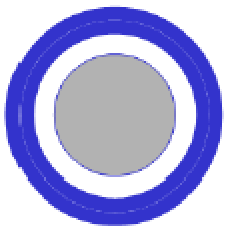
"Photonic crystal fibers guide light by corralling it within a periodic array of microscopic air holes that run along the entire fiber length…."

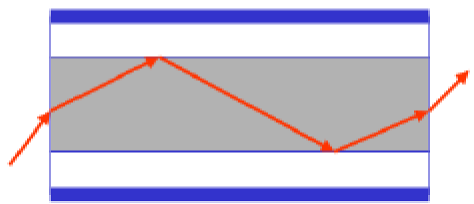
P. Russell, Science, 299, 358, 2003

2、光子晶体光纤简介

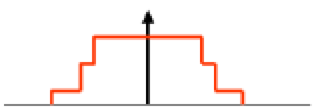
光子晶体导光机制与优势

普通光纤：



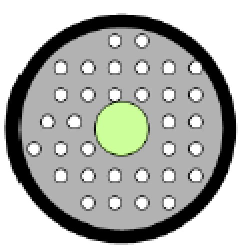


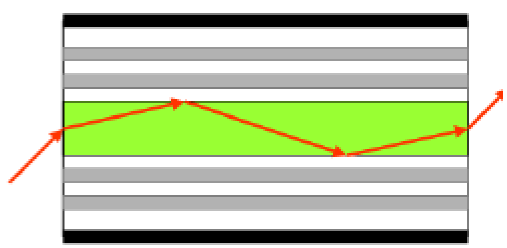
- 损耗、色散
- 单模光纤直径小
- 单模波长有限—特定的工作波长



折射率分布

光子晶体光纤：





- 低损耗，色散可设计
- 强烈的非线性光学效应
- 大直径单模光纤
- 所有波长能单模工作

带隙型PBG-PCF导光

2、光子晶体光纤简介

光子晶体光纤分类

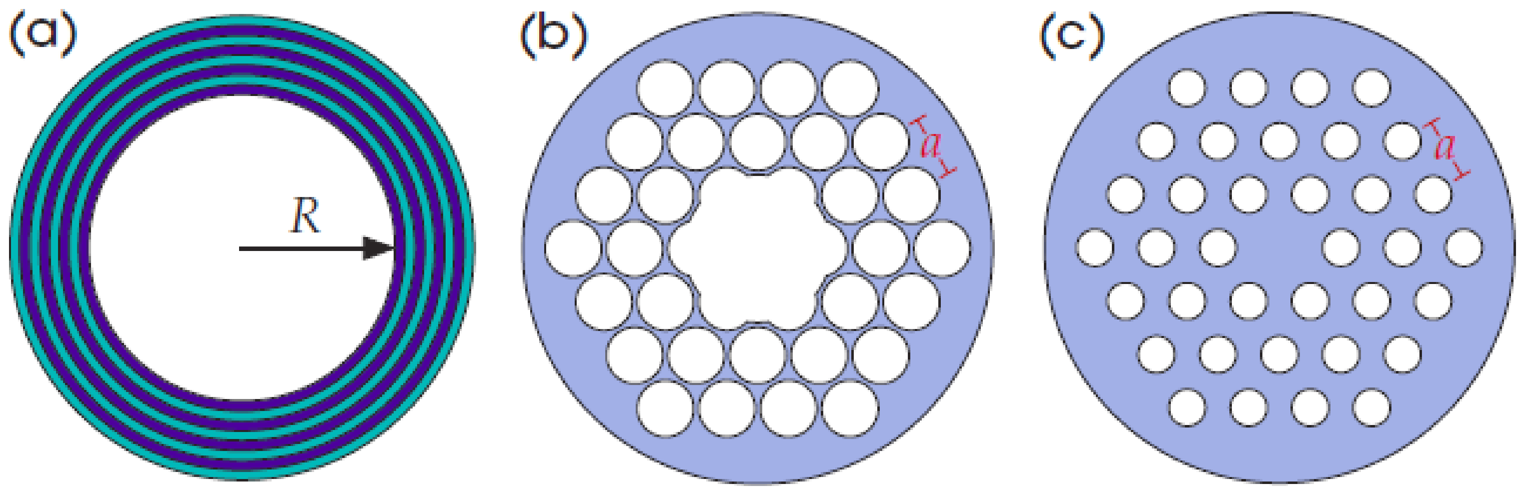


Figure 1: Three examples of photonic-crystal fibers. (a) Bragg fiber, with a one-dimensionally periodic cladding of concentric layers. (b) Two-dimensionally periodic structure (a triangular lattice of air holes, or "holey fiber"), confining light in a hollow core by a band gap. (c) Holey fiber that confines light in a solid core by index guiding.

2、光子晶体光纤简介

光子晶体光纤分类

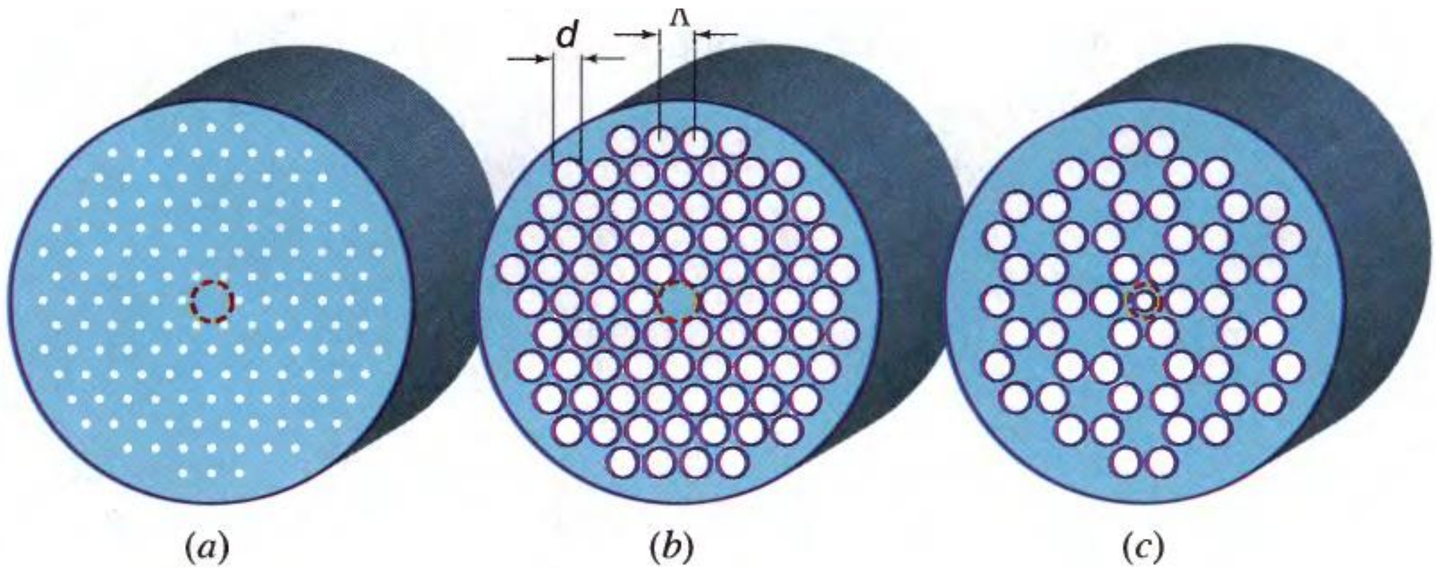
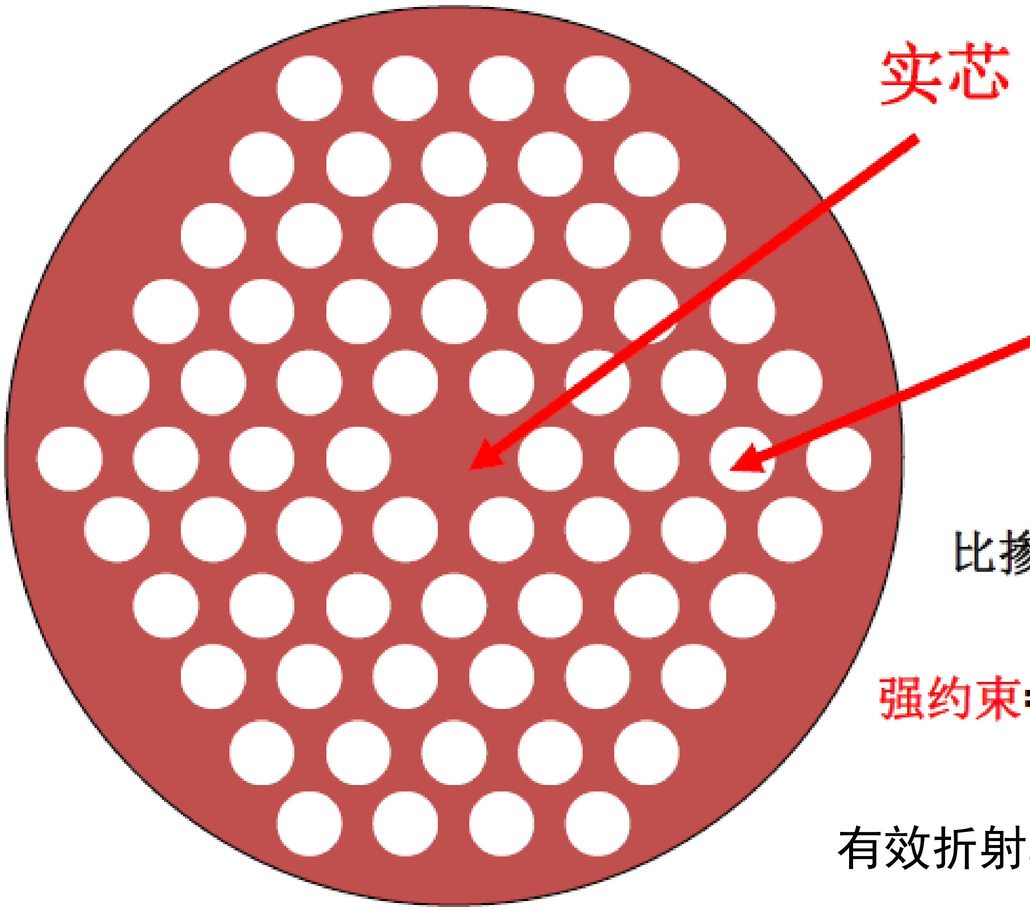


Figure 9.4-1 Various forms of holey fibers. (*a*) Solid core (dotted circle) surrounded by a cladding of the same material but suffused with a periodic array of cylindrical air holes whose diameters are much smaller than a wavelength. The average refractive index of the cladding is lower than that of the core. (*b*) Photonic-crystal holey fiber with cladding that contains a periodic array of large air holes and a solid core (dotted circle). (*c*) Photonic-crystal holey fiber with cladding that contains a periodic array of large air holes and a core that is an air hole of a different size (dotted circle).

3、全内反射型光子晶体光纤

3、全内反射型光子晶体光纤



比掺杂硅具有更高的折射率比…

强约束= 增强非线性、双折射 …

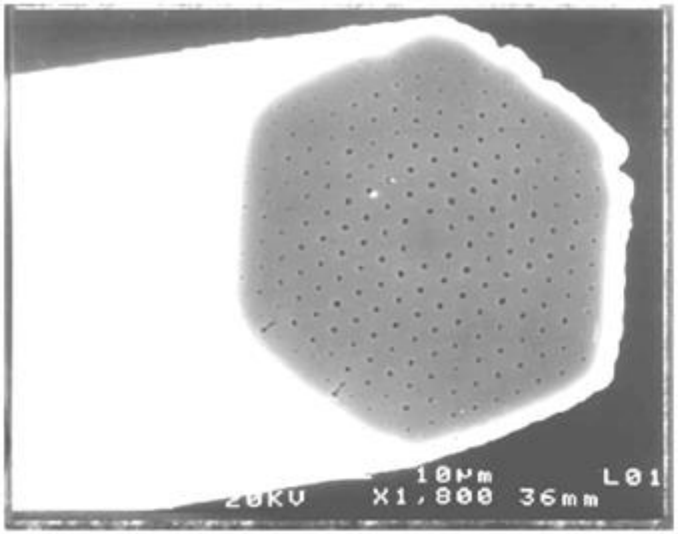
有效折射率与波长和孔的排列密切相关

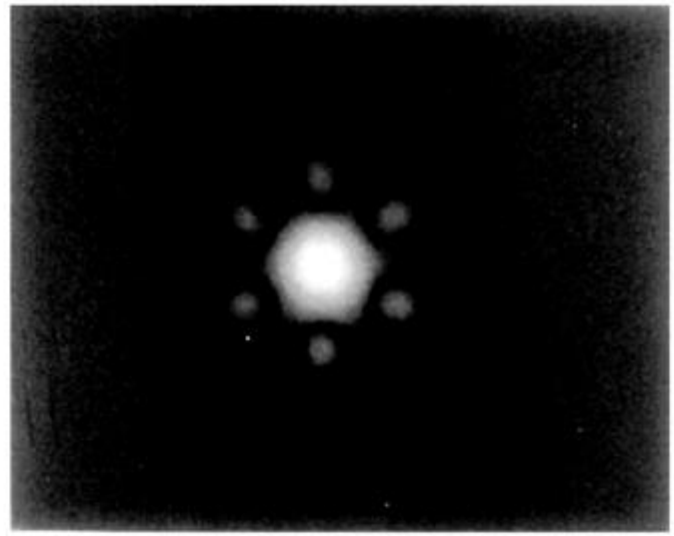
[J. C. Knight *et al.*, *Opt. Lett.* **21**, 1547 (1996)]

3、全内反射型光子晶体光纤

永久单模传输特性

Solid core photonic crystal fiber.





Solid core region nominally 4.6 μm wide

The fiber supports a single mode over the range of at least 458-1550nm

Knight et al, Opt. Lett. 21, 1547, 1996

$$V_{\mathrm{PCF}} = \frac{2\pi a}{\lambda}\sqrt{n_{\mathrm{c}}^2 - n_{\mathrm{clad}}^2}$$

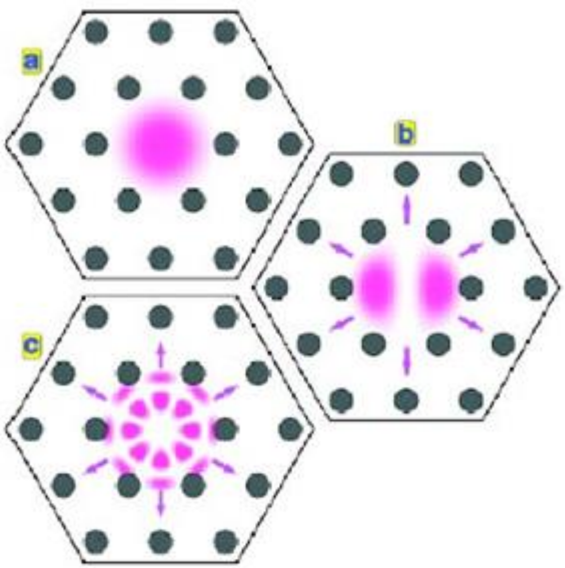
对TIF-PCF，只要空气孔直径 d 与孔间距 Λ 的比值小于0.45，所有波长均可单模传输

波长减小，折射率差也随着减小，使V_{PCF}变化小，从而实现无限单模传输

3、全内反射型光子晶体光纤

永久单模传输特性

单模特性物理解释：包层实现模式筛选



The lower modes can not escape as the wire mesh are too narrow.

The higher order modes can leak through the narrow strip.

Increasing the relative size of the diameters of holes (d) with respect to the pitch (Λ) leads to the trapping of higher modes

Single mode behavior occurs when $d/\Lambda < 0.45$

Knight et al, Opt. Lett. 21, 1547, 1996

3、全内反射型光子晶体光纤

永久单模传输特性

为什么要单模传输？

不同模式色散关系不一致，即：

$$\omega = \omega(\beta)$$

不一致

群速度： $v_{\mathrm{g}} = \dfrac{\mathrm{d}\omega}{\mathrm{d}\beta}$

不同模式不一致！

相同的时间，传播的距离不一致

导致信号波包展宽，影响信号的传输！

3、全内反射型光子晶体光纤

可调谐色散特性

群速度色散：不同频率以不同的群速度传播

材料色散——纤芯材料的折射率随波长变化而引起

波导色散——由模式的传播常数随波长变换引起

非色散介质中，电磁波的轴向传播常数为：

$$\beta = k_0 \cdot n = \frac{\omega}{c} \cdot n$$

n 有效折射率

电磁波的相速度 v_p 和群速度 v_g 的定义分别为：

$$v_{\mathrm{p}} = \frac{\omega}{\beta},\ v_{\mathrm{g}} = \frac{\mathrm{d}\omega}{\mathrm{d}\beta}$$

光信号在介质中传播单位距离的群时延定义为：

$$\tau = \frac{1}{v_g} = \frac{\mathrm{d}\beta}{\mathrm{d}\omega}$$

单模光纤的模内色散用**色散系数*D*(*λ*)**表示，单位ps/(nm.km)，即单位波长间隔(1 nm)的各频率成分在光纤中传输1 km时所产生的群延时差：

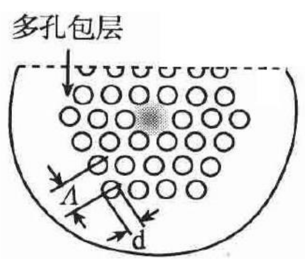
$$D(\lambda) = \frac{\mathrm{d}\tau}{\mathrm{d}\lambda} = \frac{\mathrm{d}}{\mathrm{d}\lambda}\left(\frac{\mathrm{d}\beta}{\mathrm{d}\omega}\right) = -\frac{1}{c\lambda}k_0\left(\frac{\mathrm{d}^2\beta}{\mathrm{d}{k_0}^2}\right)$$

λ：真空中波长

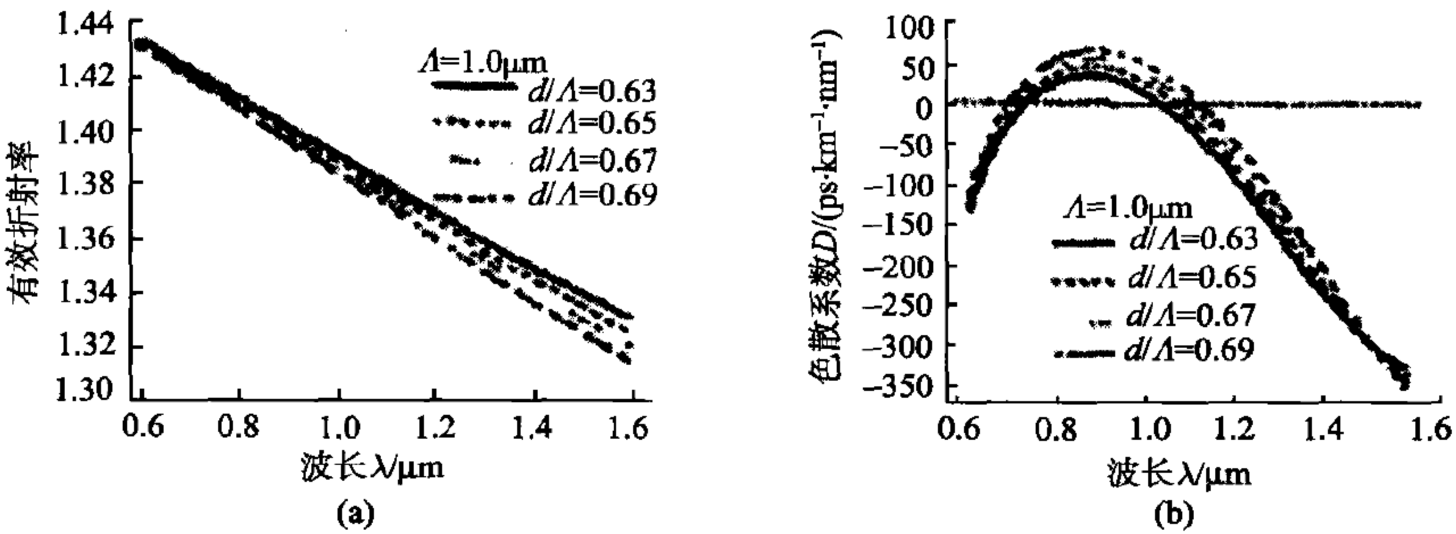
3、全内反射型光子晶体光纤

可调谐色散特性-仿真结果

希望色散系数$D(\lambda)$越小越好，最好为0，**不同波长成分**没有时延



Λ: 孔间距
d: 孔径



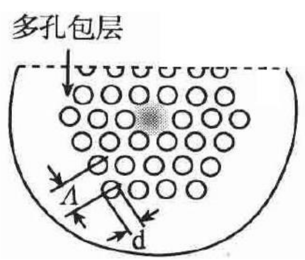
短波长零色散 PCF 参数随波长变化的模拟关系

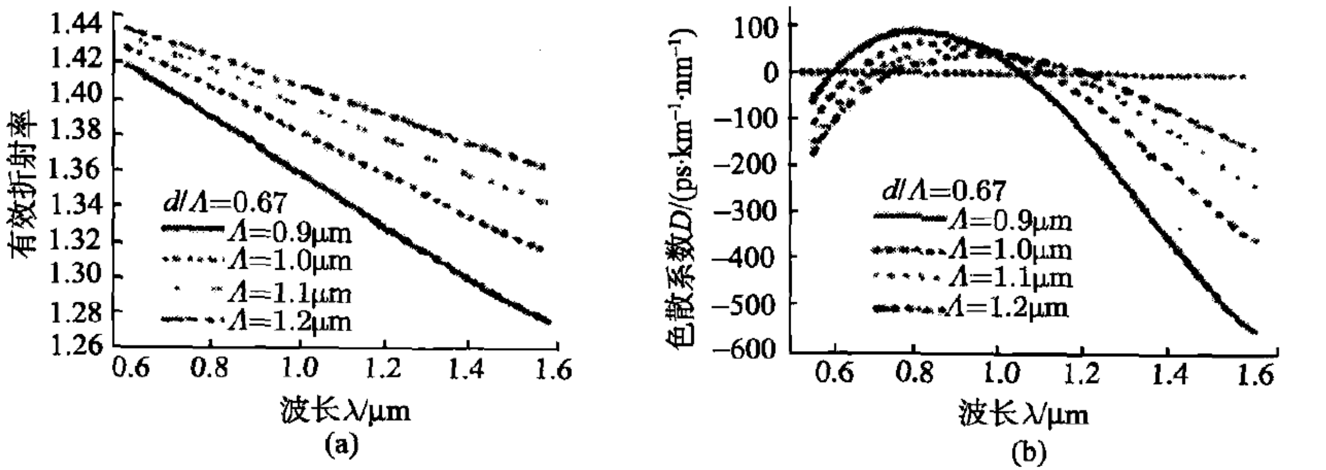
(a) 光纤包层有效折射率；(b) 色散系数 *D*

- 包层有效折射率与孔间距和孔距相关
- 孔间距Λ不变，改变d/Λ比值可以改变包层折射率，$\beta(\omega)$改变
- 色散系数$D(\lambda)$改变，零点位置随之改变

3、全内反射型光子晶体光纤

可调谐色散特性-仿真结果





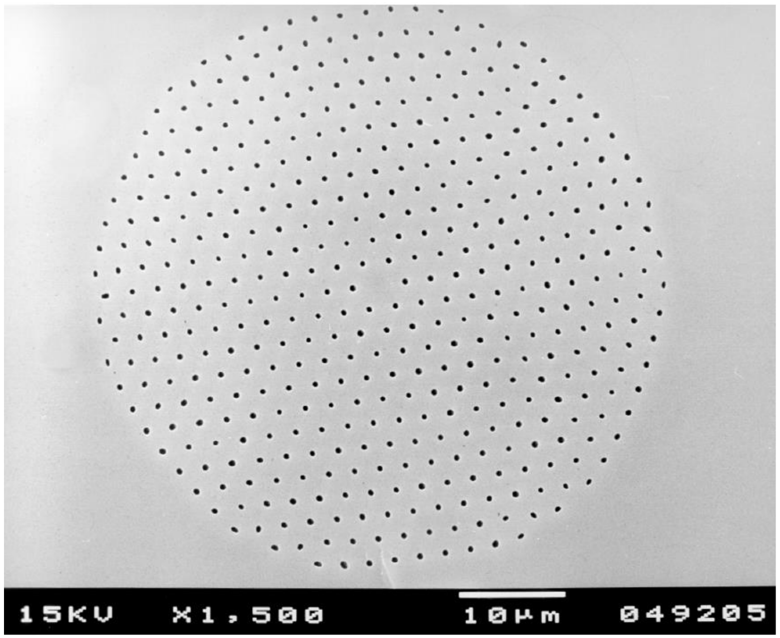
$d/\Lambda=0.67$，孔间距Λ分别为 0.9、1.0、1.1、1.2 时短波长零色散 PCF 参数随波长变化的模拟关系

(a) 光纤包层有效折射率；(b) 色散系数 D

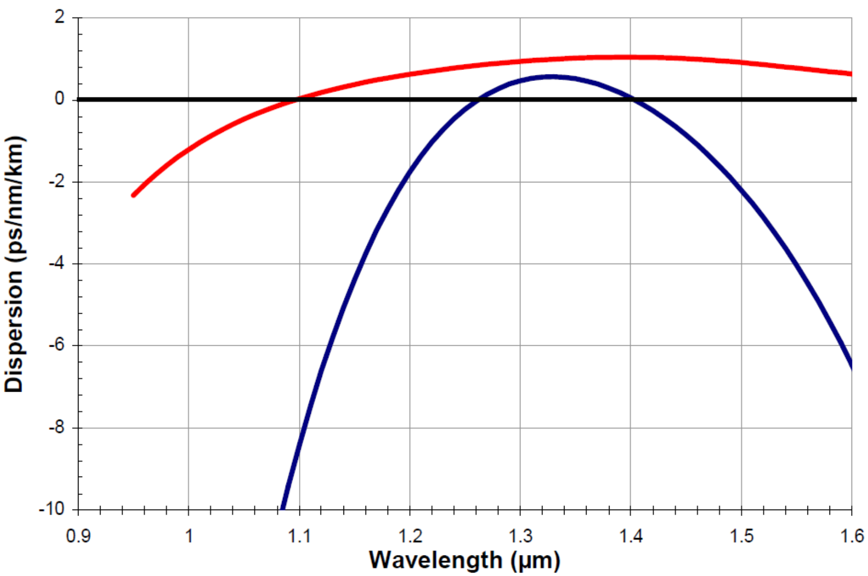
- d/Λ比值不变，改变孔间距Λ，也可以改变包层折射率
- 色散系数$D(\lambda)$改变，零点位置随之改变

3、全内反射型光子晶体光纤

可调谐色散特性-平坦和超低色散PCF



Λ = 2.47μm and an average d of 0.57μm



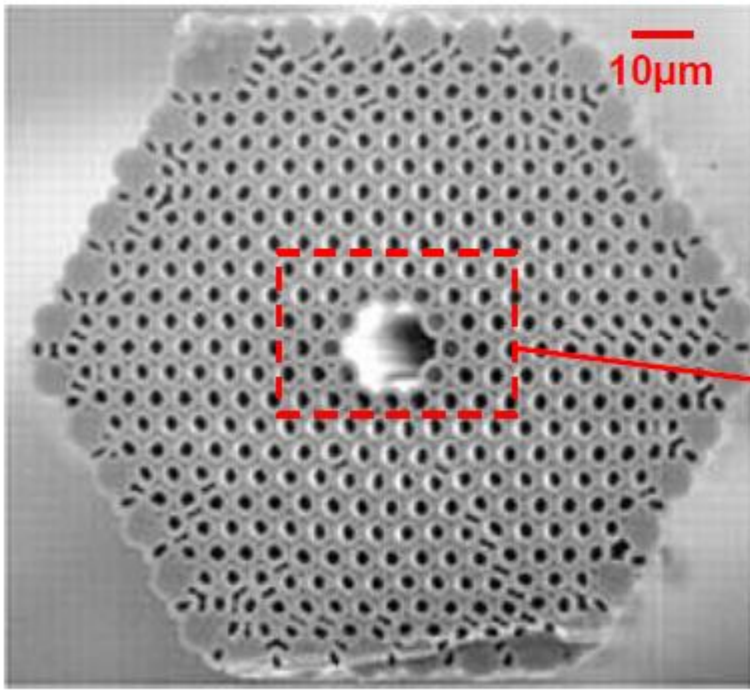
Red curve: d = 0.58, Λ = 2.59, dark blue curve: d= 0.57, Λ=2.47

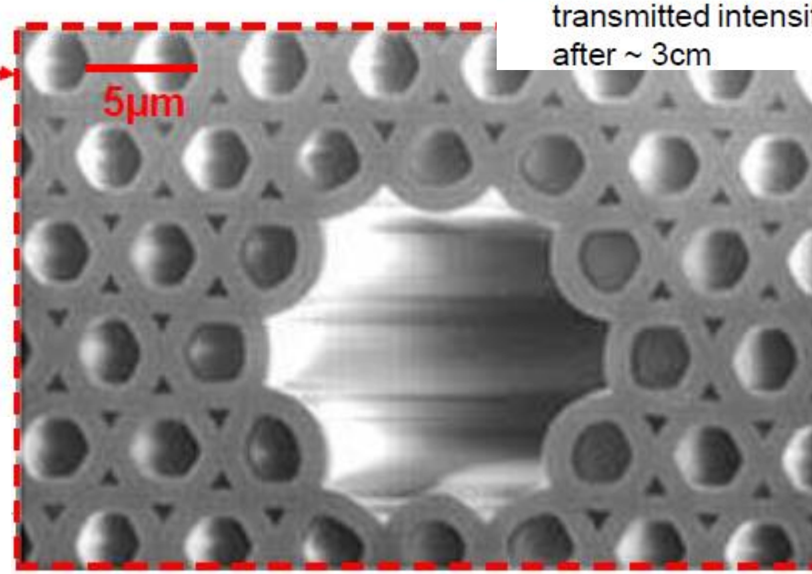
平坦和超低色散的PCF

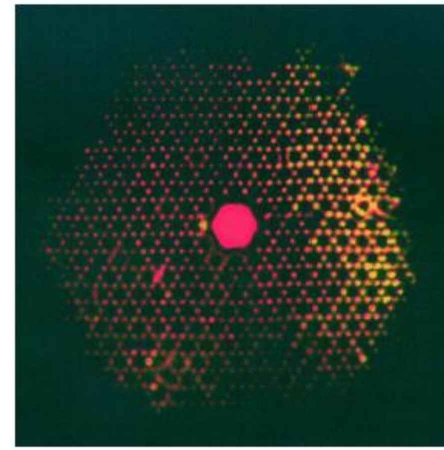
4、空气带隙型光纤

4、空气带隙型光纤

[R. F. Cregan *et al.*, *Science* **285**, 1537 (1999)]







transmitted intensity
after ~ 3cm

4、空气带隙型光纤

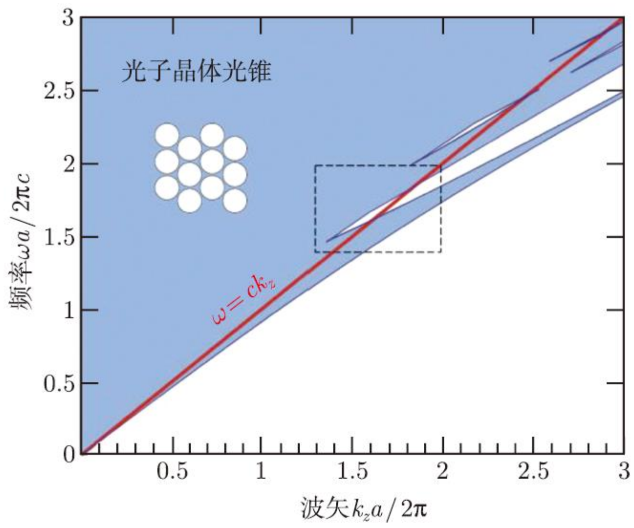
导光原理

二维光子晶体带隙？ 2D平面内的全向带隙可否？

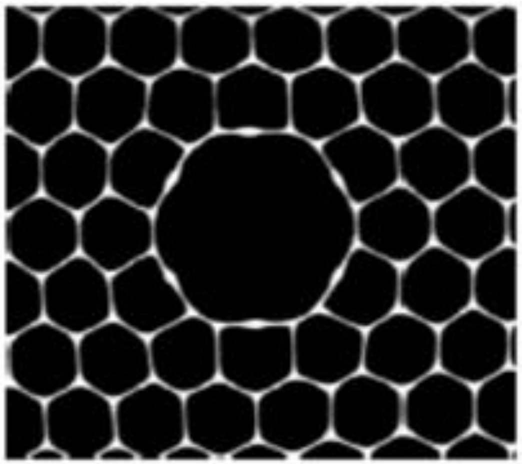
二维光子晶体：考虑的是$k_z = 0$，并没有考虑 $k_z \neq 0$ 的情况。

对于$k_z \neq 0$ 的情况，比较复杂。对于由SiO_2构成的空心光子晶体，有结论：

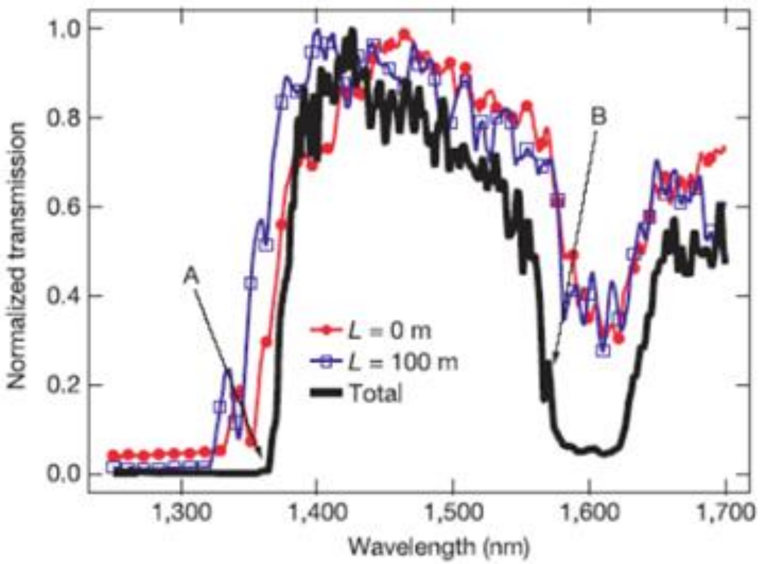
当孔的半径 $r = 0.47a$时 (a 为空气孔周期)，对有限的k_z存在带隙



4、空气带隙型光纤



Transmission through a 100m fiber

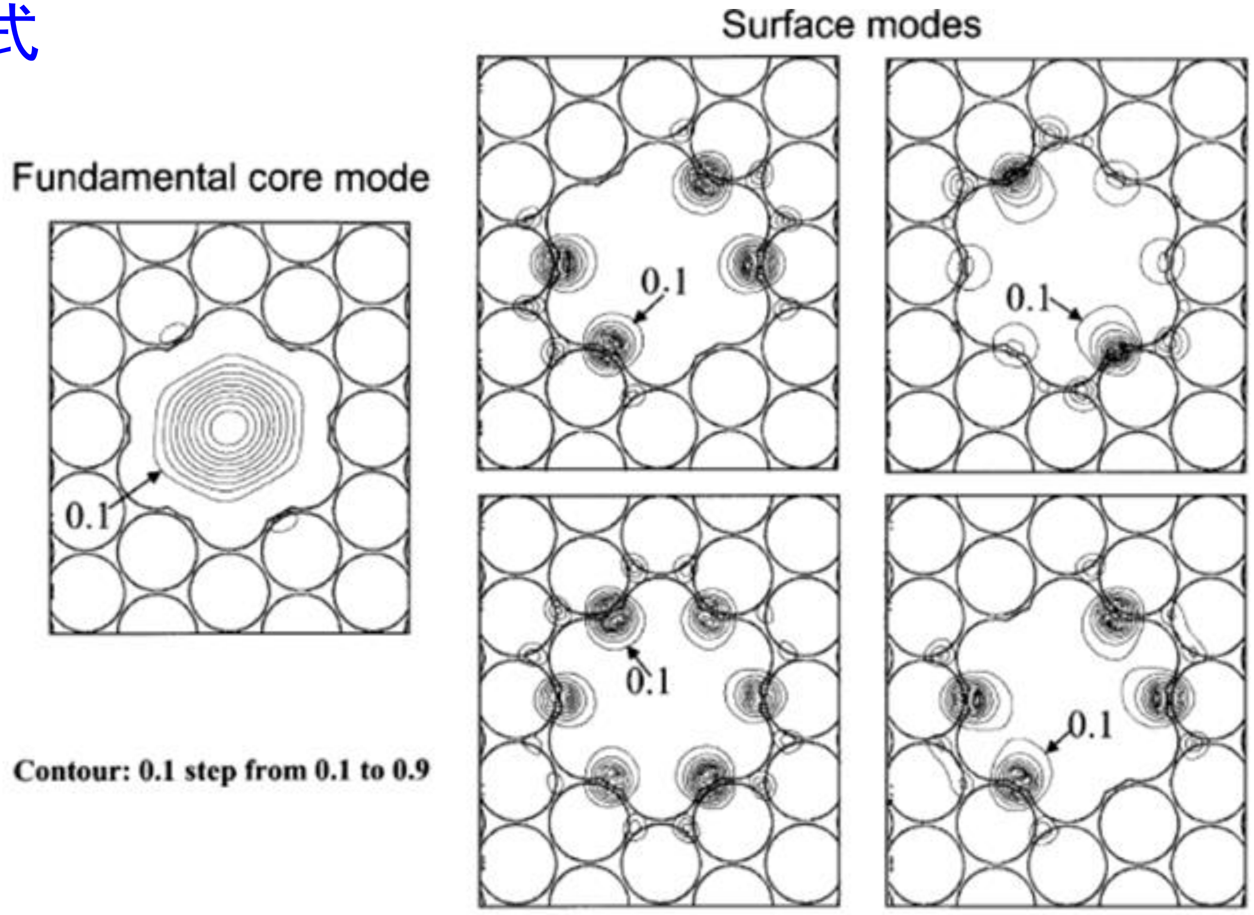


- The transmission spectra changes a little.
- 13 dB/km in propagation loss, comparable to early days of conventional optical fiber.
- Loss primarily due to the coupling of core modes to surface modes, and likely can be further reduced significantly in newer design.

Smith et al., Nature, 424, 657 (2003)

4、空气带隙型光纤

表面模式



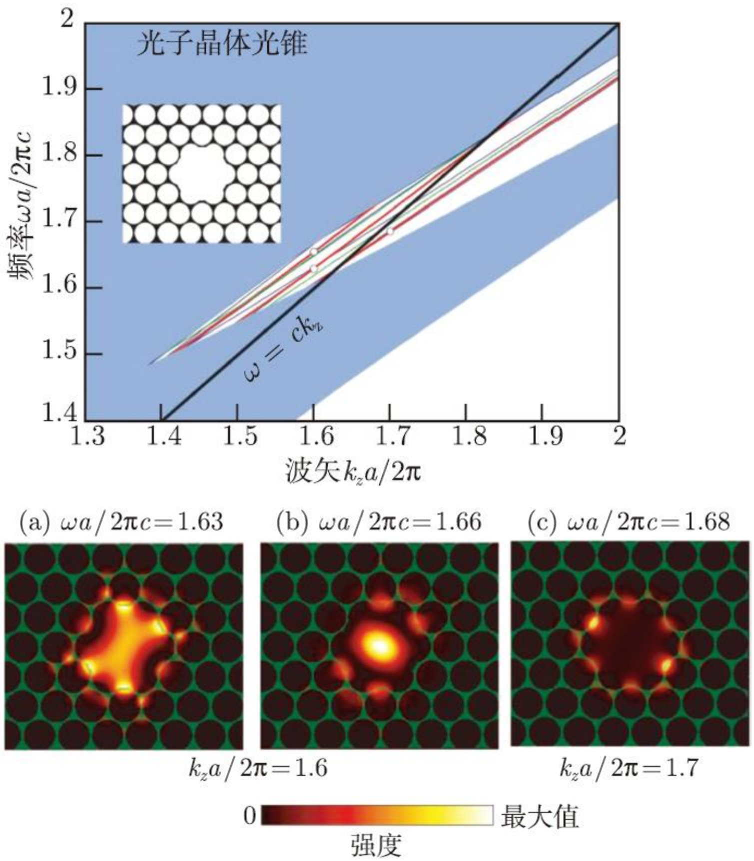
对于场集中在表面的模式，由于表面粗糙度而产生的散射比集中在芯层的模式要严重得多，造成极大的损耗！

H. Kim, J. Shin, S. Fan, M. Digonnet, G. S. Kino, IEEE J. Quantum Electronics, 40, 552 (2004)

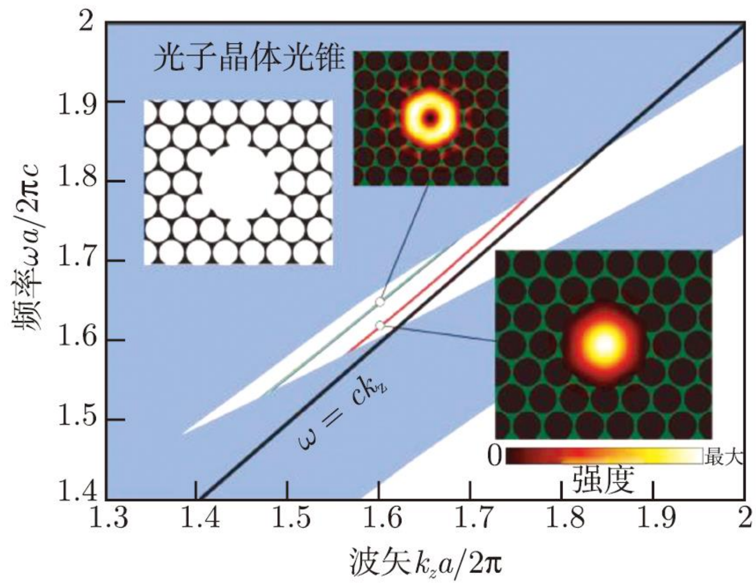
4、空气带隙型光纤

表面模式

一种减小损耗的方案：去掉产生表面态的位置。

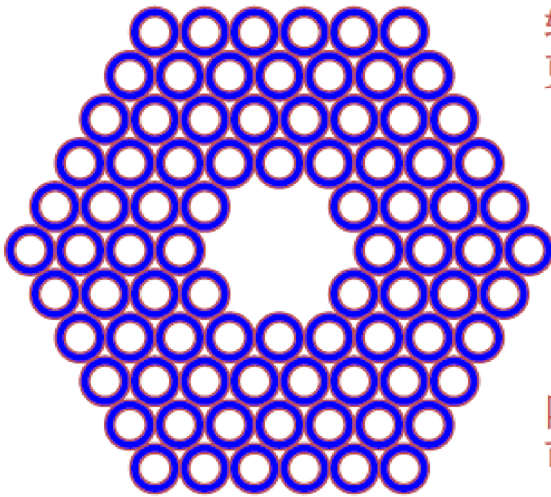


扩大孔



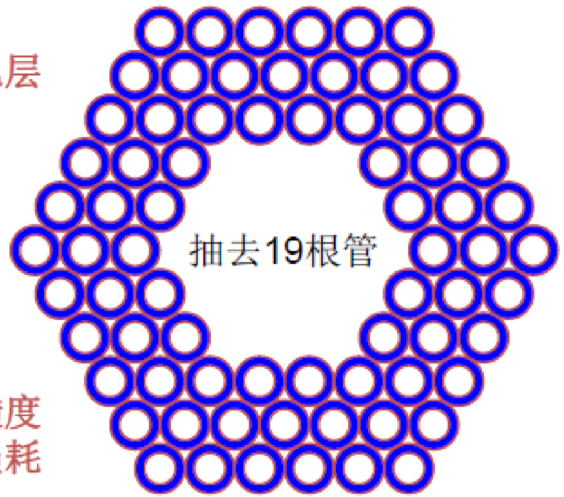
4、空气带隙型光纤

表面模式

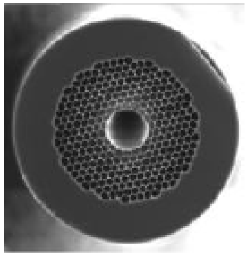


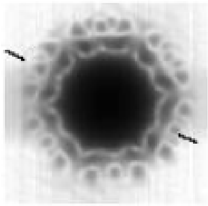
较大纤芯=
更少的场进入包层

降低毛细管粗糙度
可以减小光纤损耗



13dB/km
over ~ 100m @1.5μm
[Smith, *et al.*, *Nature* **424**, 657 (2003)]





1.7dB/km
over ~ 800m @1.57μm
[Mangan, *et al.*, *OFC 2004* PDP24]

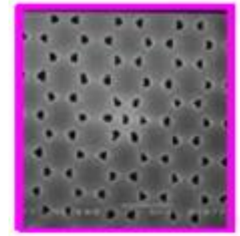
4、空气带隙型光纤

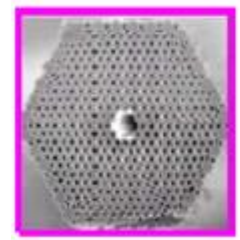
空气带隙型光纤的特点

➢低非线性、高损伤阈值

低损耗

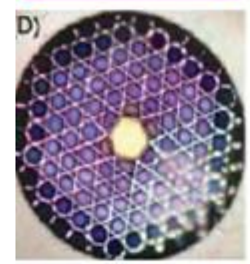
目前，通过降低毛细管粗糙度(散射↓)、增大纤芯空气孔直径、增大波长，最小损耗可达0.1dB/km





➢独特的色散特性

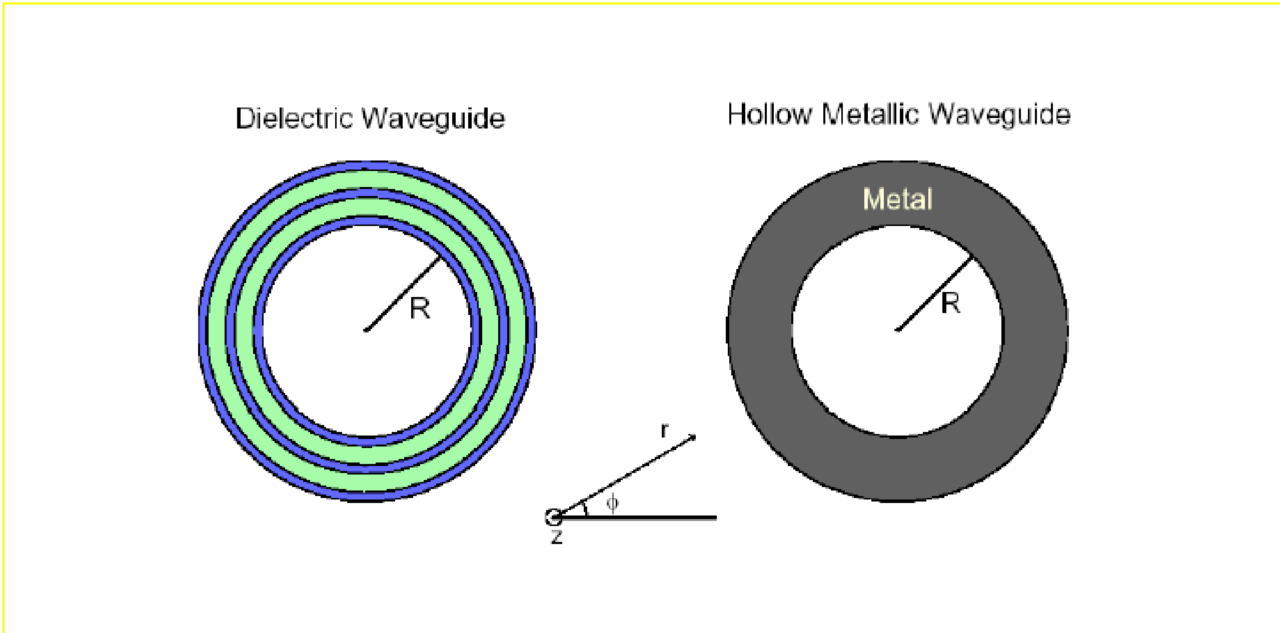
特殊应用：研究气体非线性、光与物质的相互作用、高功率激光传输、高峰值功率脉冲传输、锁模超短脉冲产生和放大等



➢缺点：制造工艺要求高

5、布拉格光纤

5、布拉格光纤

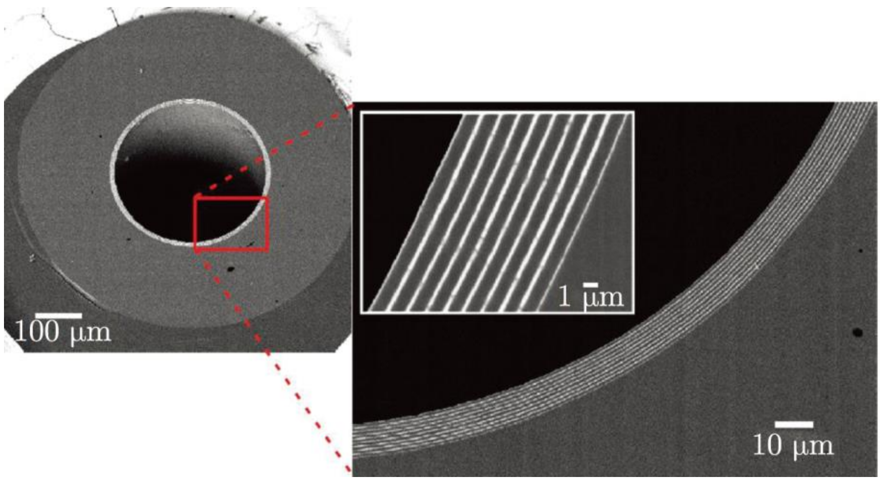


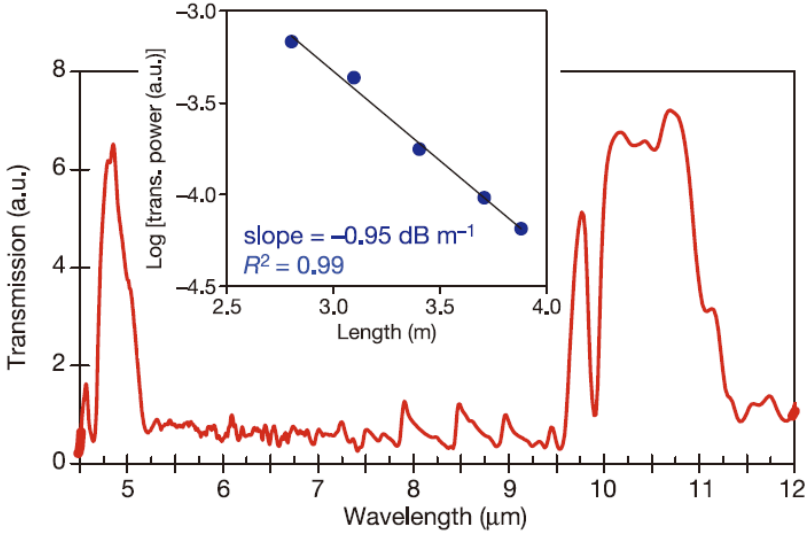
Using multilayer-film reflection to replace metal and create a light pipe.

The boundary condition for EM field at the boundary of core-film boundary can be designed to be rather similar to that at the metal boundary.

P. Yeh, A. Yariv and E. Marom, J. Opt. Soc. Am. 68, 1196 (1978).

5、布拉格光纤





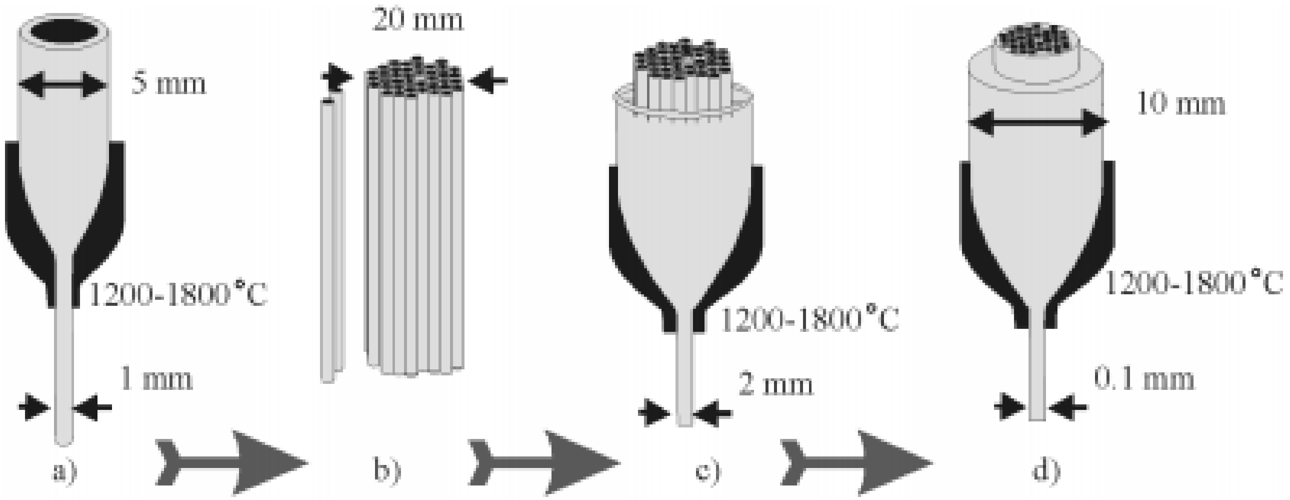
- Guiding of intense CO_2 laser light at 10.6 μm wavelength for high power applications.
- Loss: 0.95 dB/m, remain 80% power after 1 m transmission.

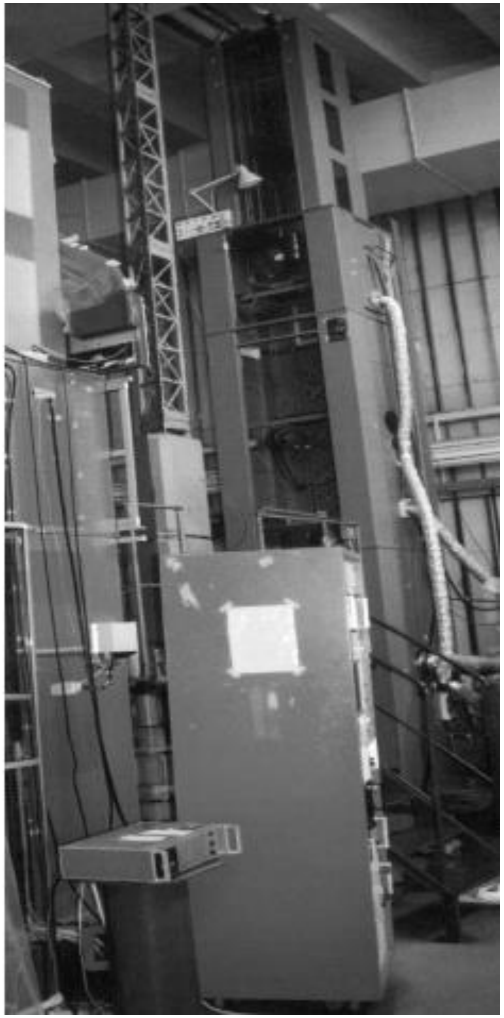
Temelkuran et al., Nature, 420, 650 (2002)

6、光子晶体光纤的制备

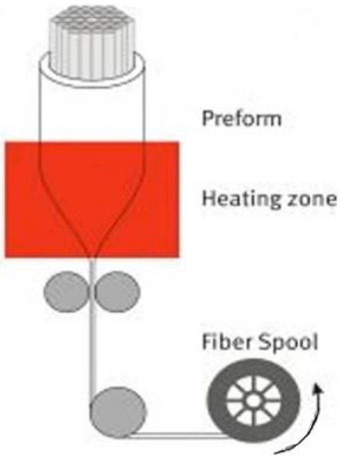
6、光子晶体光纤的制备

毛细管集束法

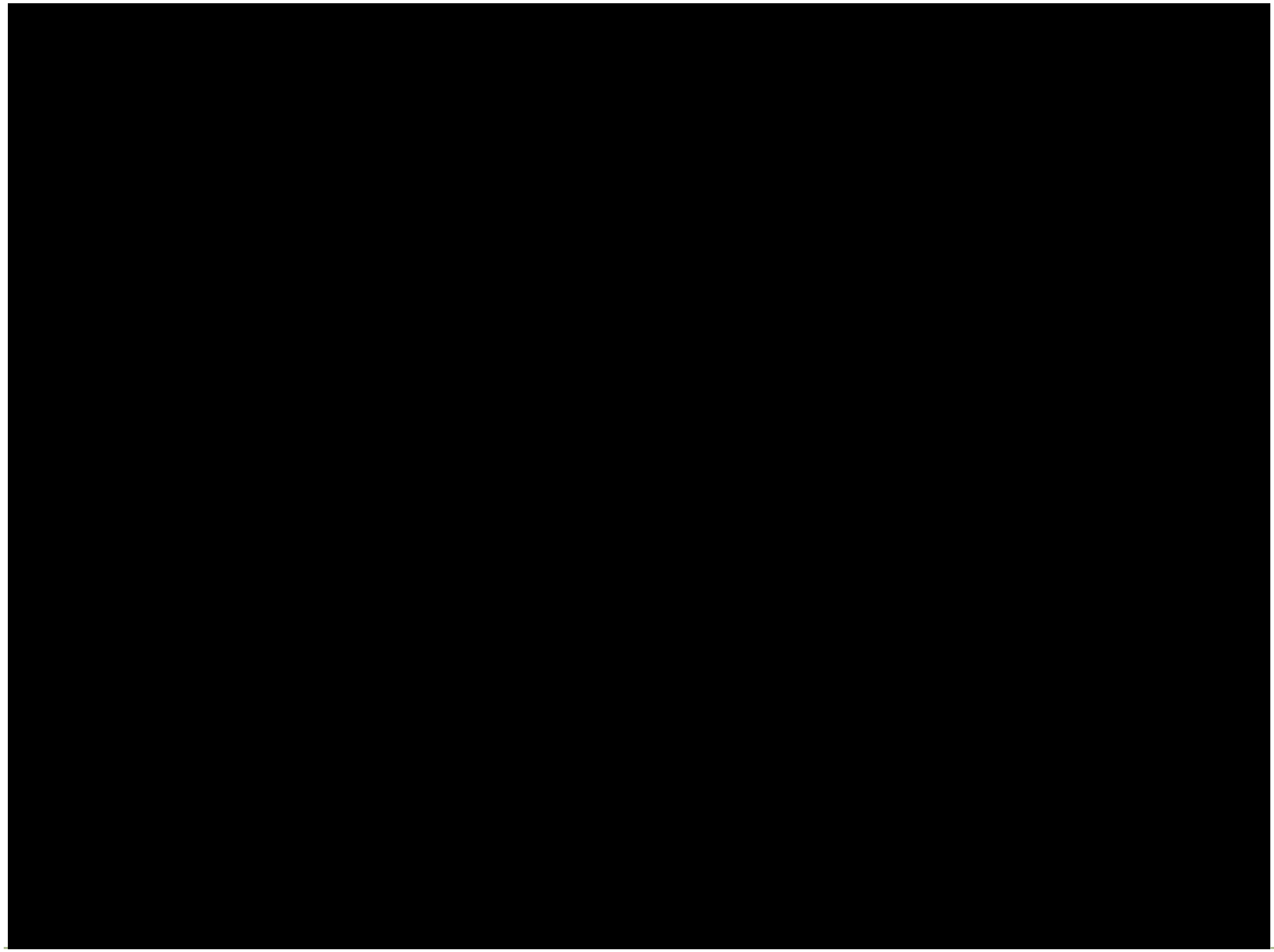




拉成毛细管



6、光子晶体光纤的制备



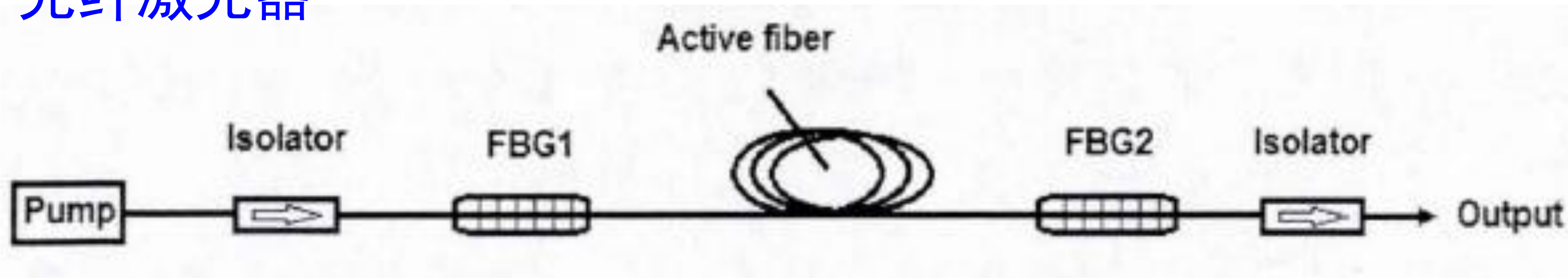
7、光子晶体光纤的应用

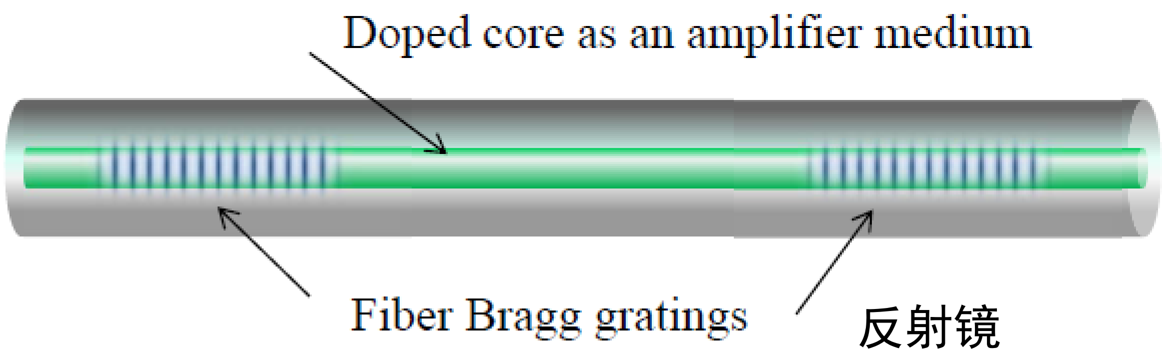
7、光子晶体光纤的应用

- 光纤激光器
- 光子晶体光纤带通滤波器
- 光子晶体光纤放大器
- 光子晶体光纤传感器
- 、、、、

7、光子晶体光纤的应用

光纤激光器





- High power laser
- Low-noise lasers
- Supercontinuum sources
- New mid-IR light sources

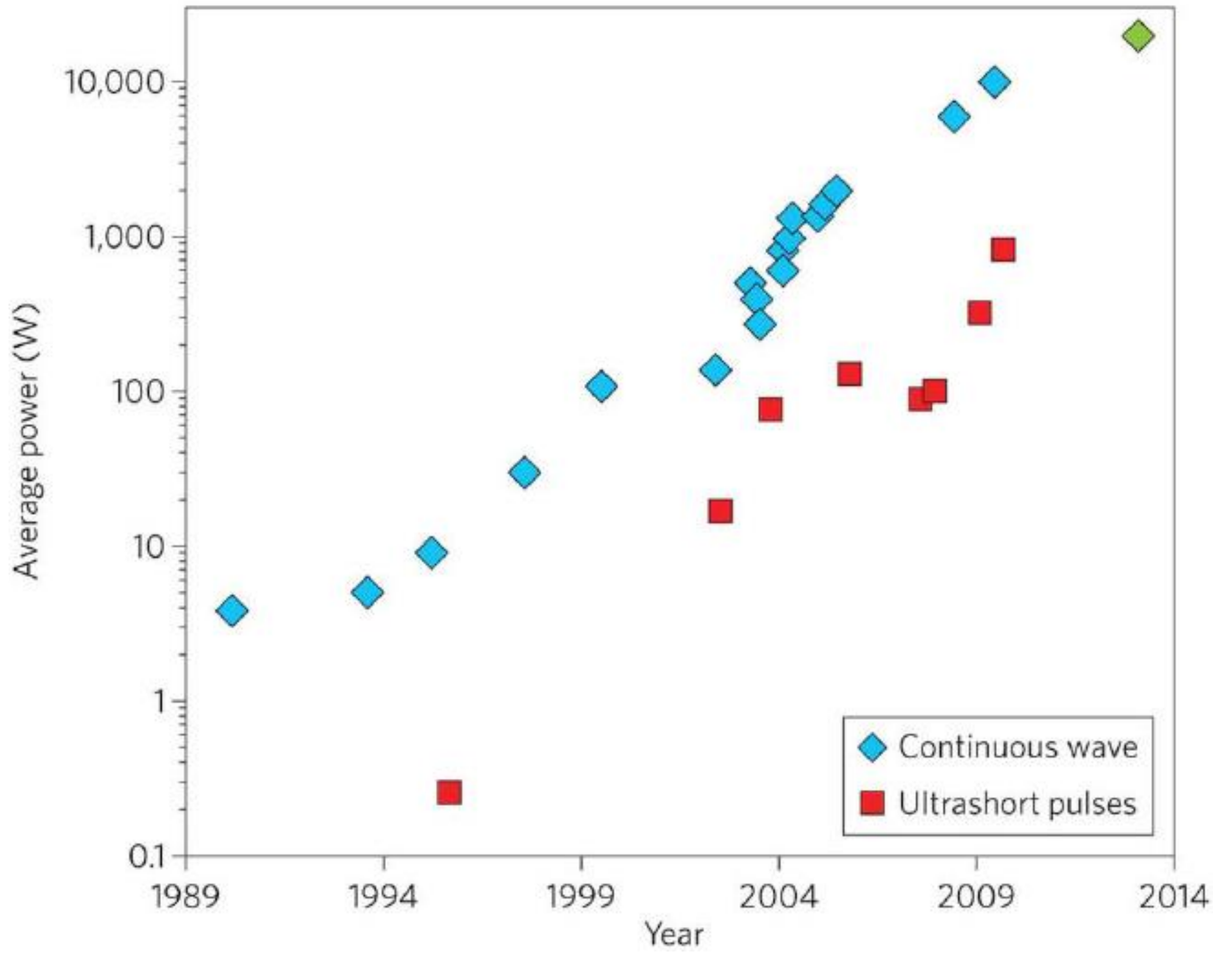
7、光子晶体光纤的应用

光纤激光器分类

按谐振腔结构分类	F-P 腔、环形腔、环路反射器光纤谐振腔以及“8”字型腔、DBR、DFB 光纤激光器
按光纤结构分类	单包层光纤激光器、双包层光纤激光器
按增益介质分类	稀土类掺杂光纤激光器、非线性效应光纤激光器、单晶光纤激光器、塑料光纤激光器
按工作机制分类	上转换光纤激光器、下转换光纤激光器
按掺杂元素分类	掺铒、钕、Pr^{3+}、铥、镱、钬等 15 种
按输出波长分类	S-波段(1280-1350nm)、C-波段(1528-1565nm)、L-波段(1561-1620nm)
按输出激光分类	脉冲激光器、连续激光器

7、光子晶体光纤的应用

光纤激光器功率增长



C. Jauregui, et al., Nat. Photon., 7, 861 (2013)

7、光子晶体光纤的应用

光纤激光器

4W超连续谱光纤激光光源

2kW连续波光纤激光切割机

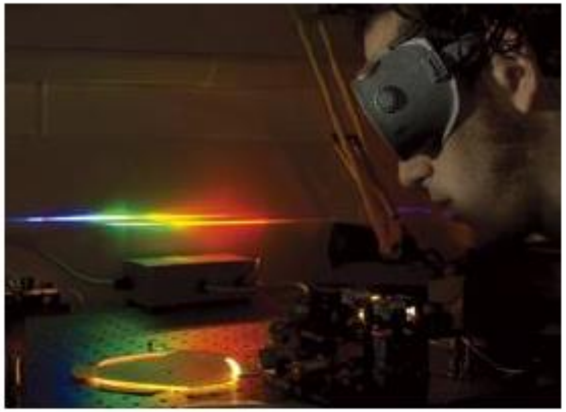
10000W光纤激光

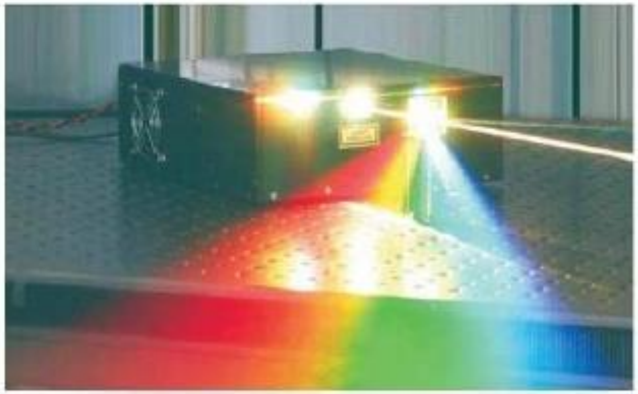
7、光子晶体光纤的应用

光子晶体光纤激光器

超连续谱产生通常是指窄带的入射光通过非线性作用光谱得到极大的展宽的现象。

在孔中可以装载气体或低折射率掺杂(如掺锗等材料)液体，或使用高非线性折射率材料，从而使光子晶体光纤具有可控制的非线性。

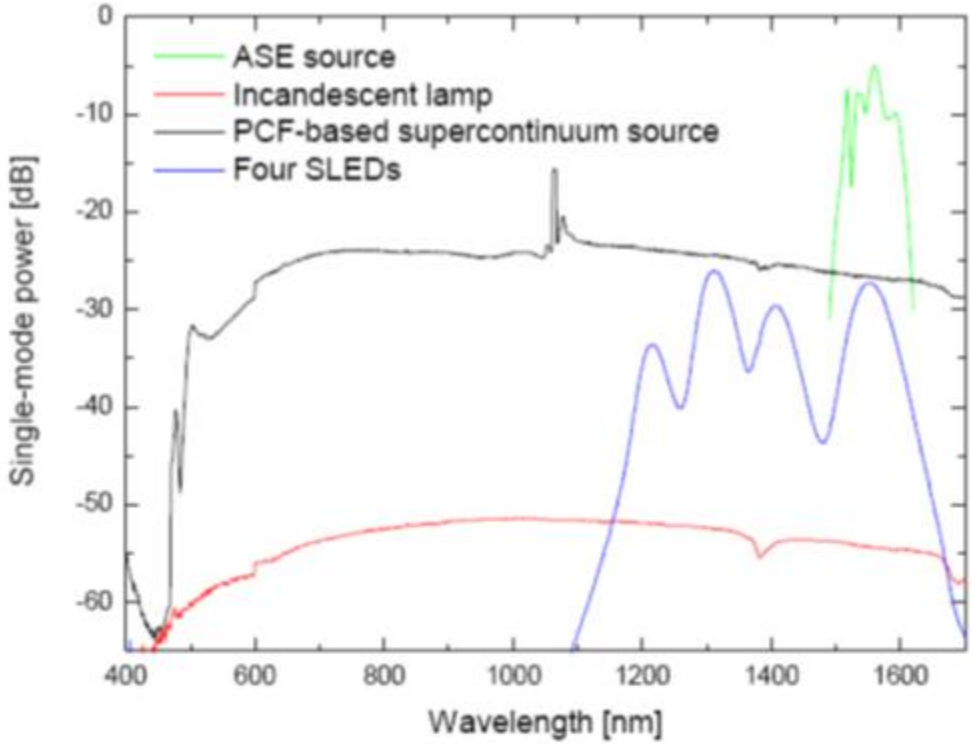




University of Bath的研究人员开发的非线性PCF可以弥补超连续光纤激光器中的蓝光缺陷，增强了蓝光波段的输出

7、光子晶体光纤的应用

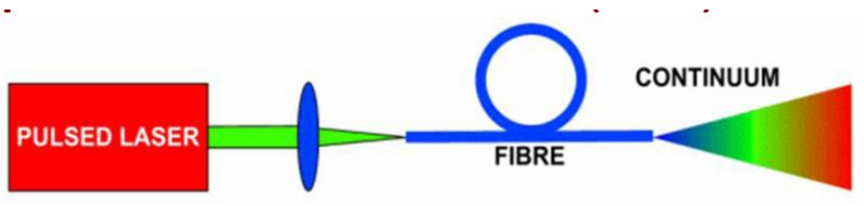
超连续谱光谱

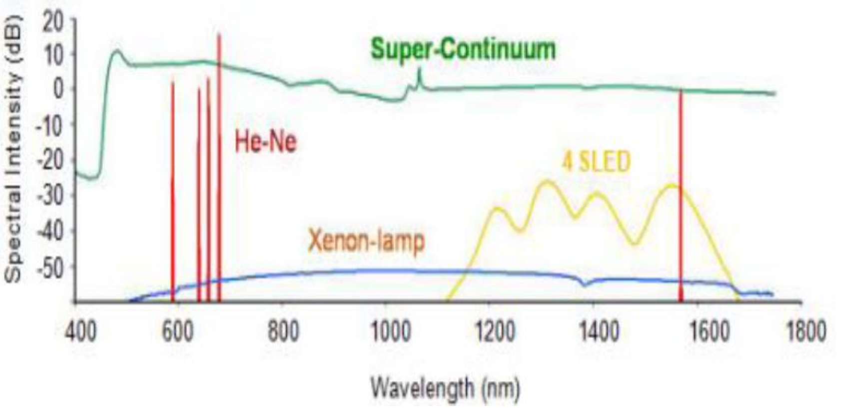


不同光源发光光谱的对比：
ASE：放大自发辐射
超连续光源频谱：蓝光 – 近红外

7、光子晶体光纤的应用

超连续谱的作用





A supercontinuum source provides:

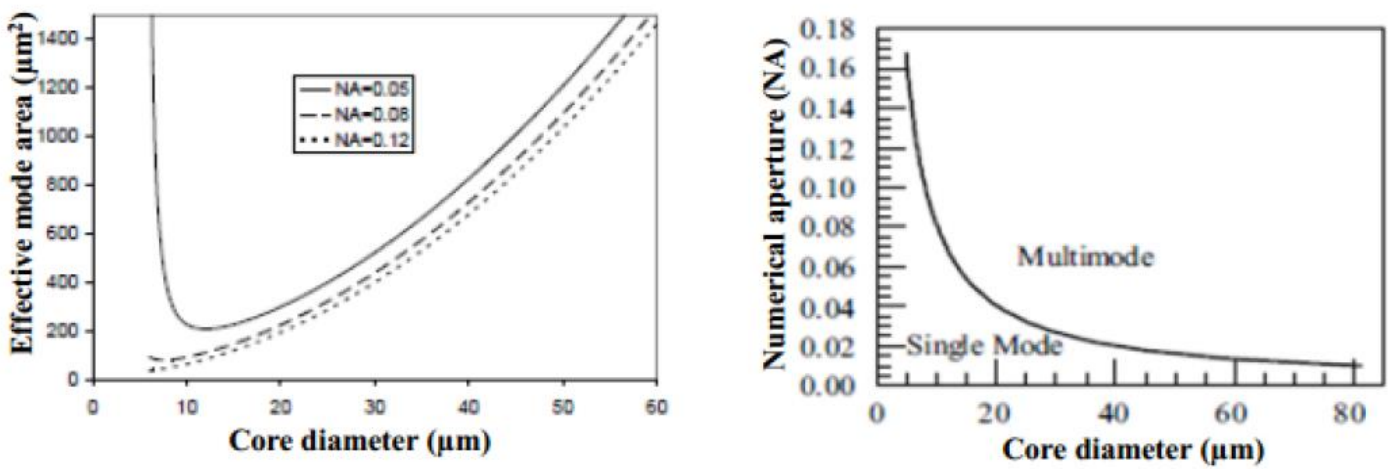
- Ultra broadband white-light spectrum
- Single-mode beam characteristics
- Excellent pointing stability
- High Brightness
- This type of source is required for High resolution imaging: Optical Coherence Tomography (OCT), and Early Cancer Detection
- Biophotonics: Flow cytometry
- Spectroscopy: Pump probe experiments, Time-resolved spectroscopy

7、光子晶体光纤的应用

高功率光纤激光器

Requirements: **Large Mode Area** with **Single-mode** Operation

Challenges:



•*Li et al.*, "*fiber design for higher power laser*", Proc. Of SPIE Vol. 6469, 64690H, (2007)

- **Core diameter increases** – Effective mode area increases
- **Too large core diameter** – Waveguide become multimode

So, there is a trade off between LMA and SM operation

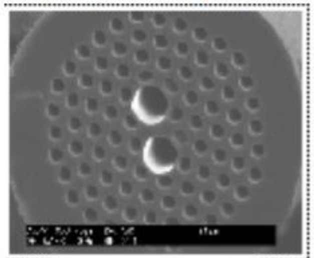
7、光子晶体光纤的应用

光子晶体光纤激光器

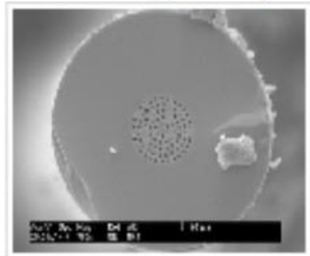
自主研发生产的光子晶体光纤、掺稀土光纤、无源匹配光纤可供选择

http://www.yslphotonics.com/pic.asp?classid=17&pid=2

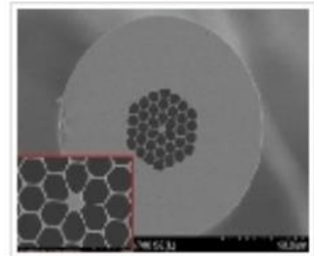
武汉 安扬激光



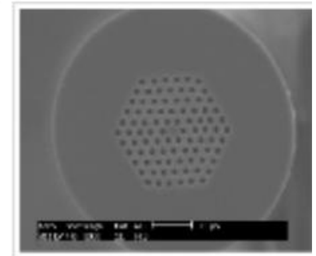
PM-125-01



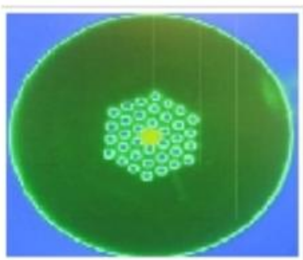
SC-PCF-01



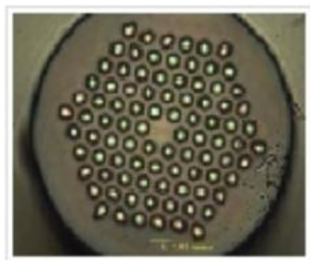
SC-PCF-02



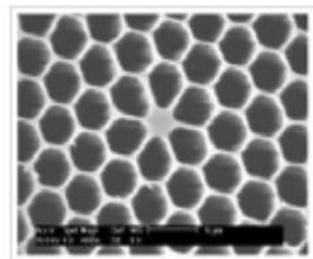
SM-7 PCF



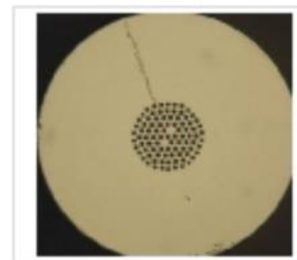
SM-10 PCF



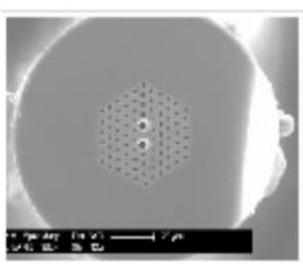
All solid PBG

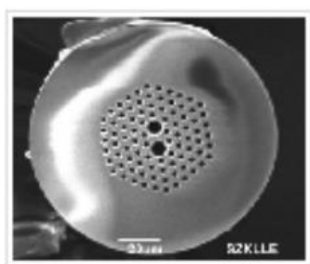


NL-2.3-850 PCF



DOUBLE CORE SM



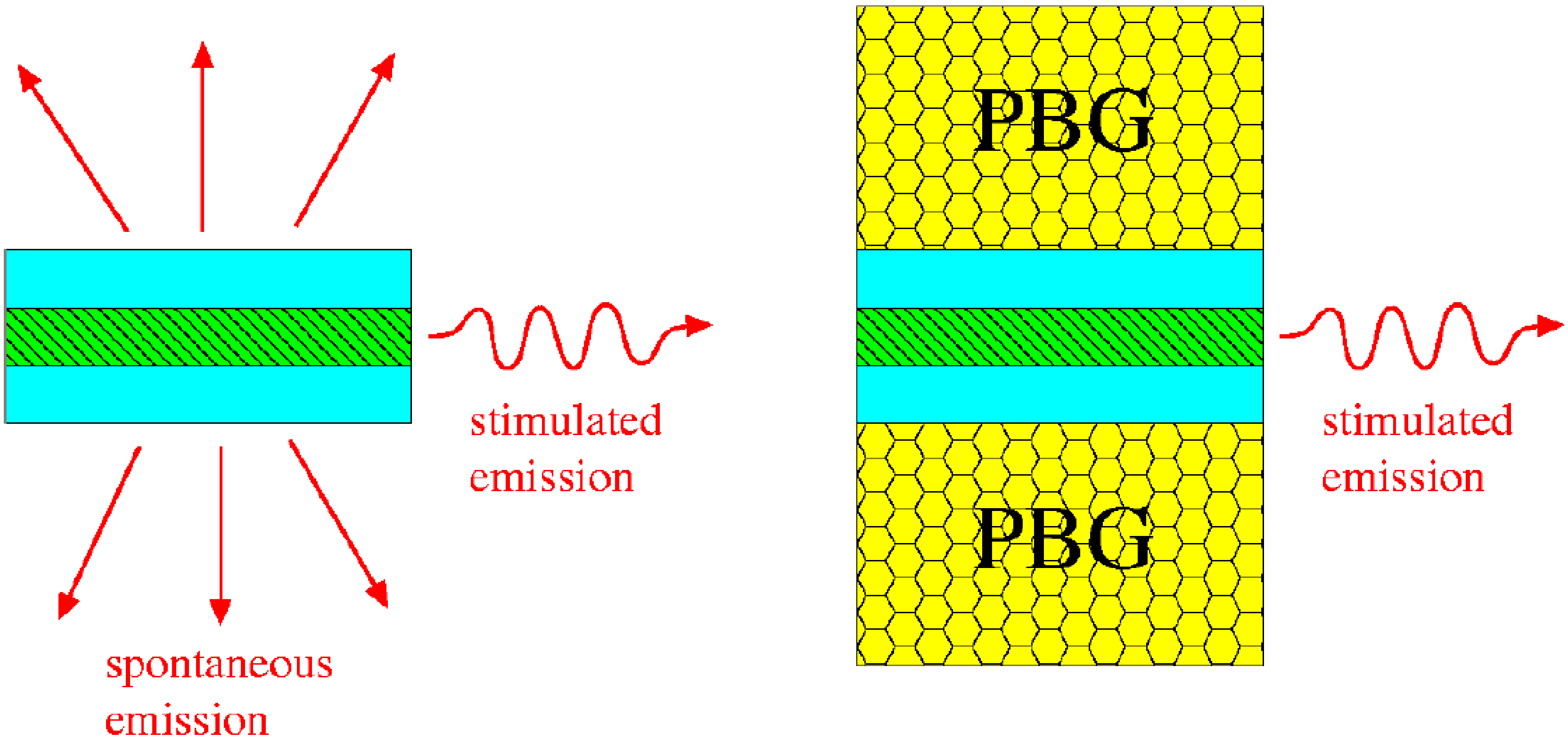


7、光子晶体光纤的应用

其他应用

7、光子晶体光纤的应用

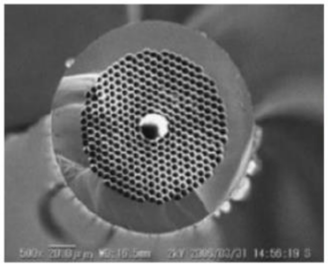
抑制自发辐射



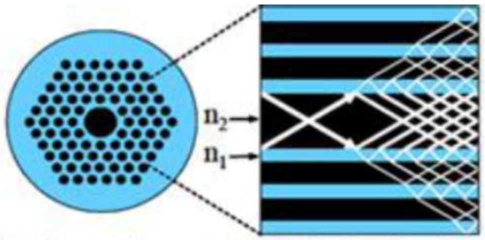
Low-threshold lasers, single-mode LEDs, mirrors, optical filters

7、光子晶体光纤的应用

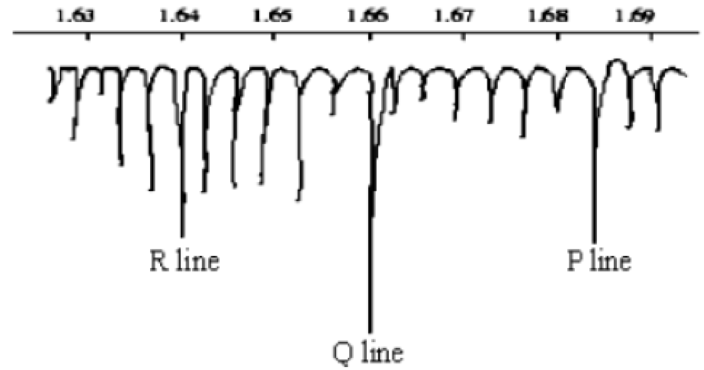
气体探测器



HC-PBG Fiber

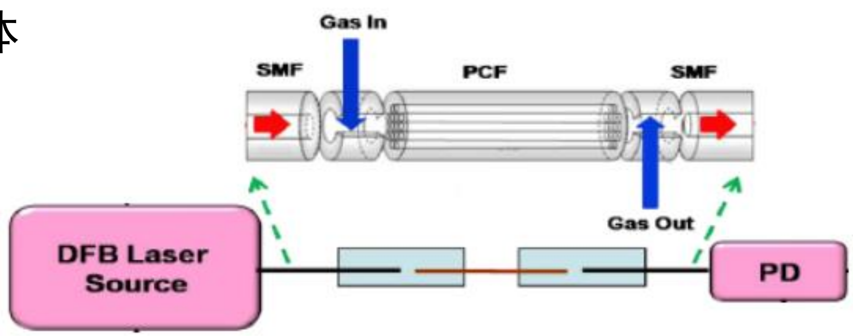


Bandgap-guidance, n_1=1.45 (silica) and n_2=1 (air).



Transmission Spectra of Methane

带隙引导型光纤：
多孔，利于气体
在其中传输



Methane gas detection at 1653.7nm with detection sensitivity of 500ppm.

不同浓度甲烷气体对光的吸收不同——检测透过光的强度

小结

- 优点
  - 在很大频率范围内支持光的单模传输
  - PCF允许改变纤芯面积，以削弱或加强光纤的非线性效应
  - 可灵活设计色散和色散斜率
  - 允许出现大于直角的光路转弯
  - PBG-PCF不受光波与纤芯材料之间的相互作用的限制，可大大限制光纤的非线性效应带来的影响并降低损耗
- 存在问题
  - 制备工艺不完善
  - PCF中非线性机制还需深入研究
  - 与传统光纤及器件的融合