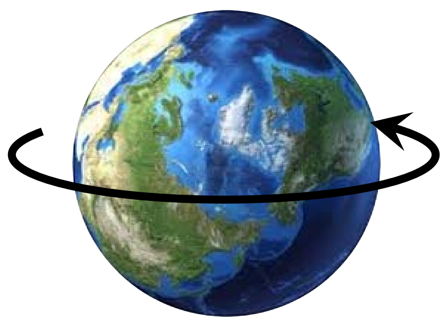
提纲

1. **飞秒激光微纳加工简介**
2. 芯片实验室器件
3. 电光集成器件
4. 工业应用
5. 总结和展望

The properties of ultrafast laser pulses

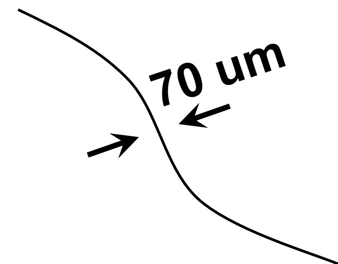
飞秒脉冲激光的特点：脉冲宽度极短

1秒



光绕地球行走7.5圈的时间

100飞秒



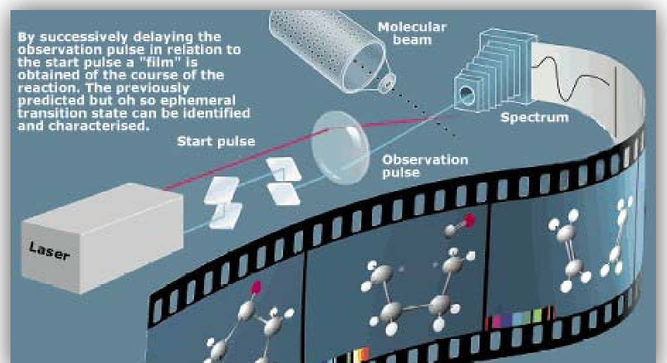
光穿越半根头发丝的时间

1飞秒=10^{-15}秒

Why ultrafast laser?

The Nobel Prize in Chemistry 1999
飞秒化学

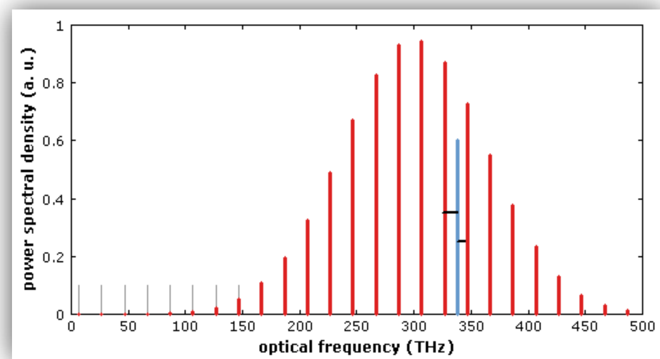
Ahmed H. Zewail



http://www.nobelprize.org

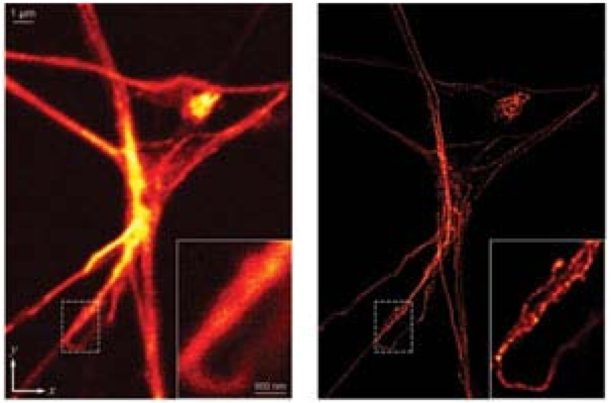
The Nobel Prize in Physics 2005
飞秒光梳

John L. Hall **Theodor W. Hänsch**



http://www.nobelprize.org

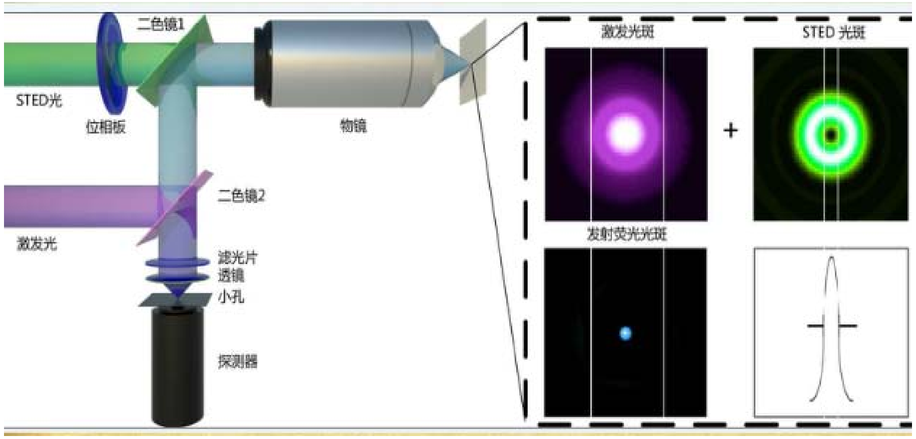
Why ultrafast laser?



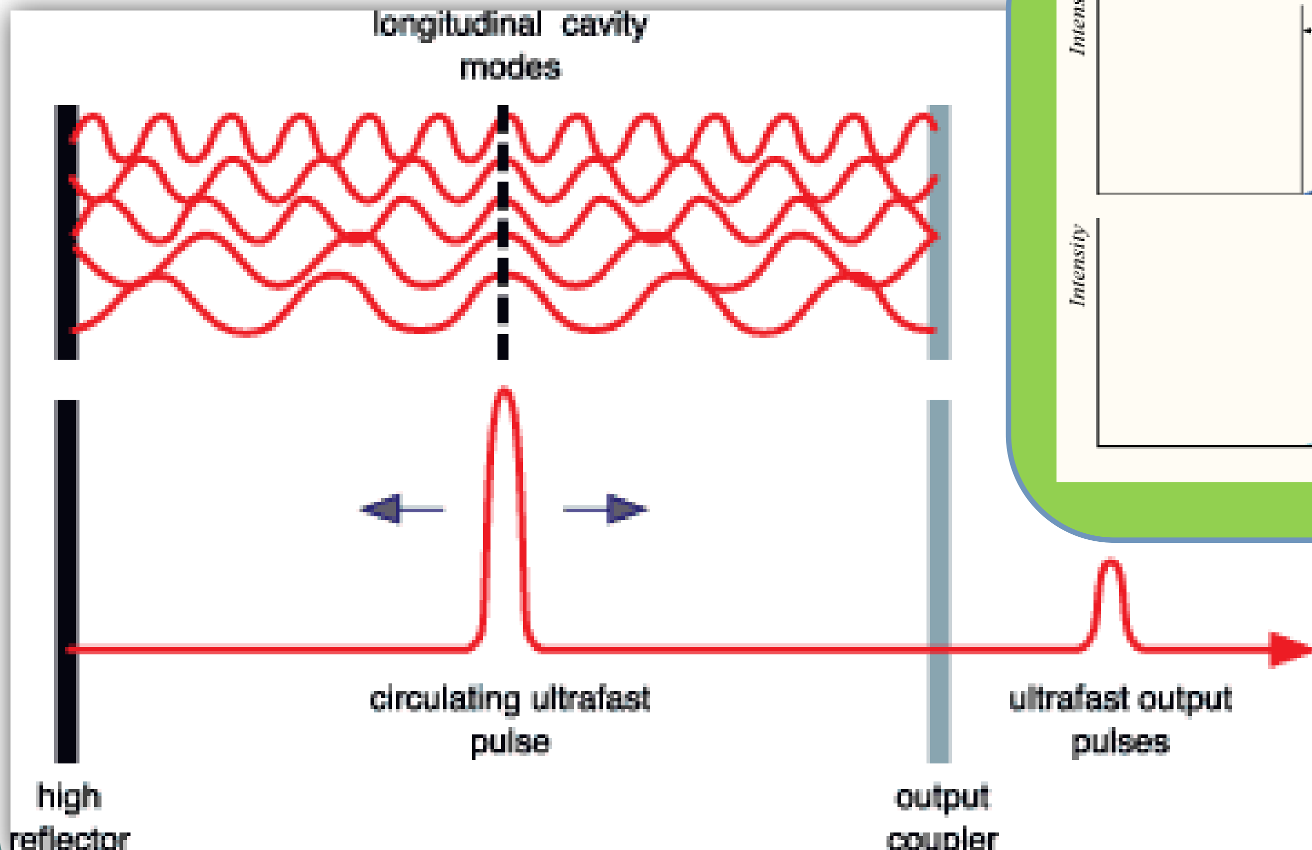
由共聚焦显微镜(左图)和STED(右图)成像的一个神经元

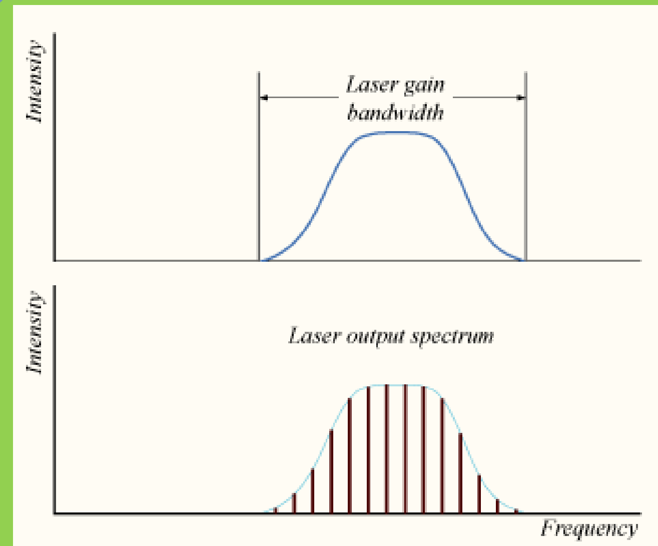
Stimulated emission depletion (STED) microscopy

S. W. Hell, J. Wichmann, *Opt. Lett.* 19, 780 (1994)



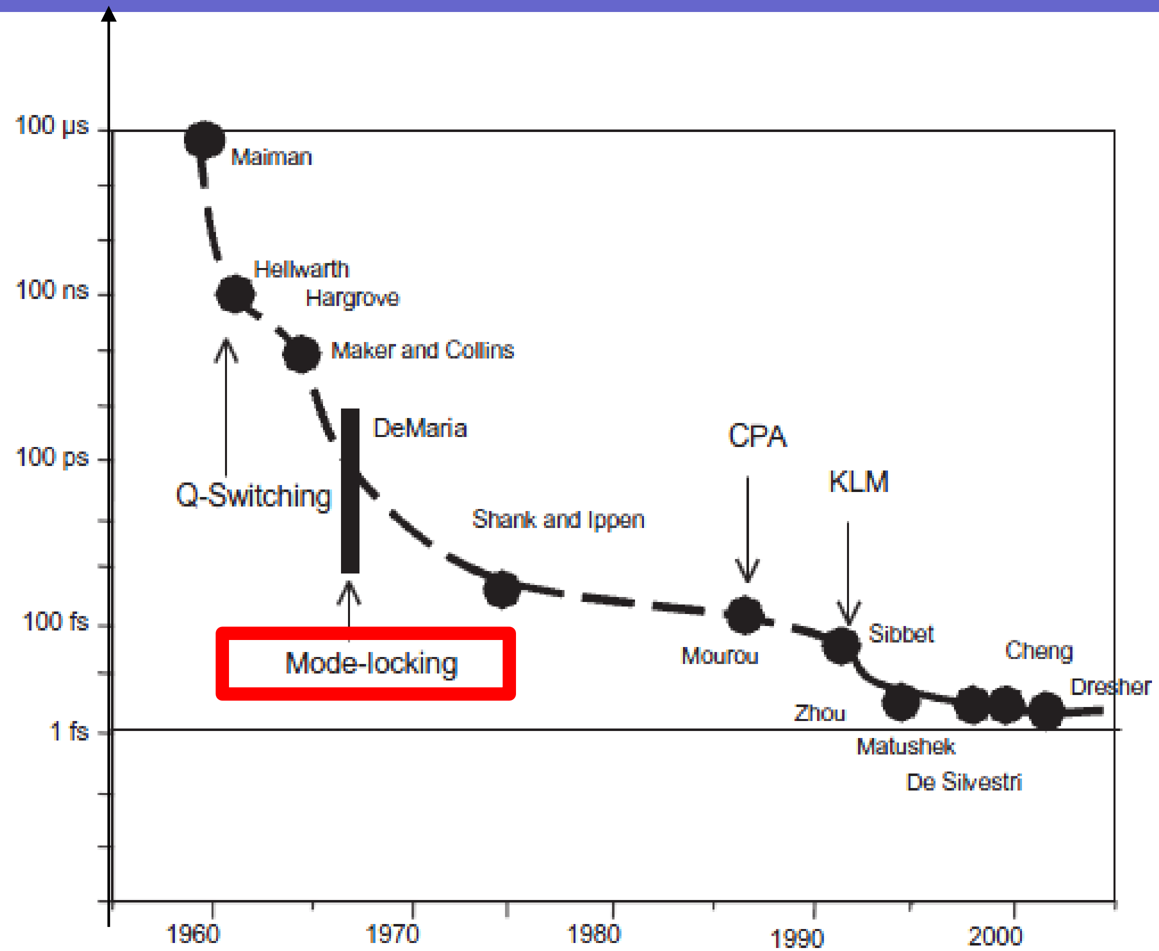
The key ideas – mode locking and CPA





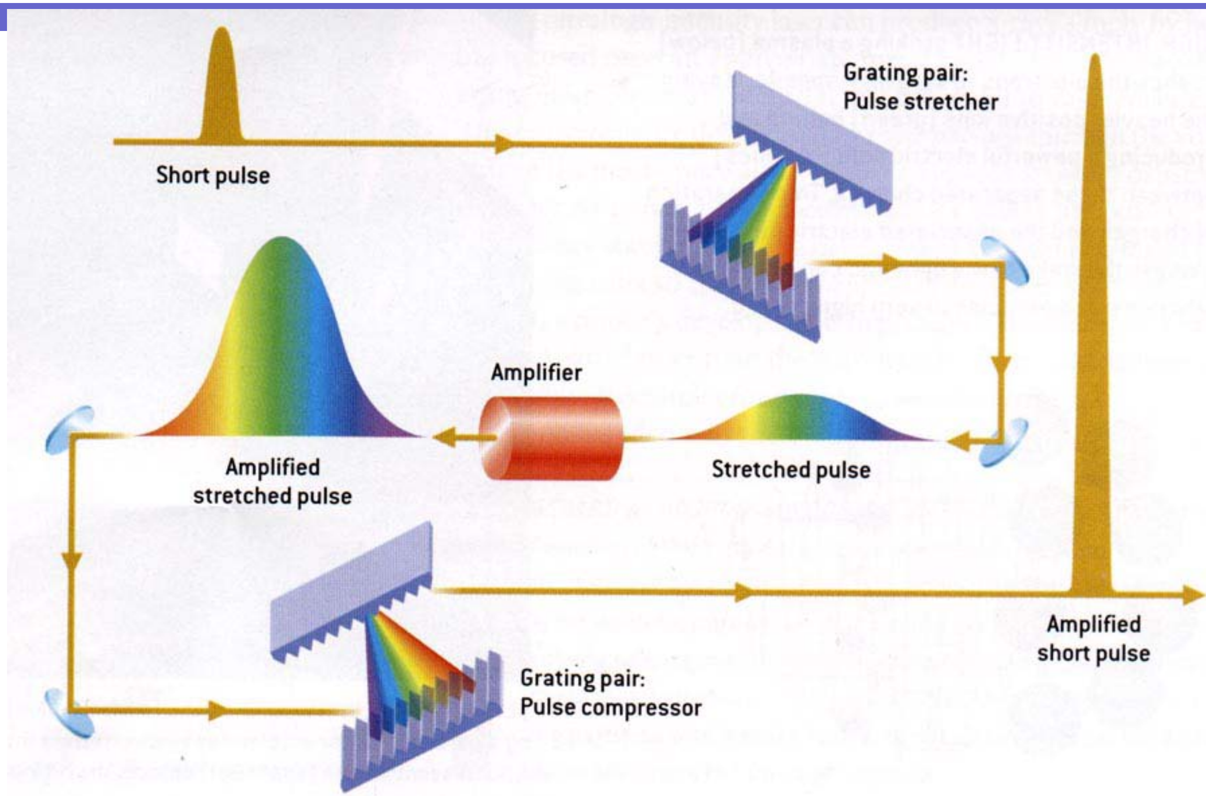
http://spie.org

Passion for short laser pulses



Rep. Prog. Phys. 67, 813 (2004)

The key ideas – mode locking and CPA

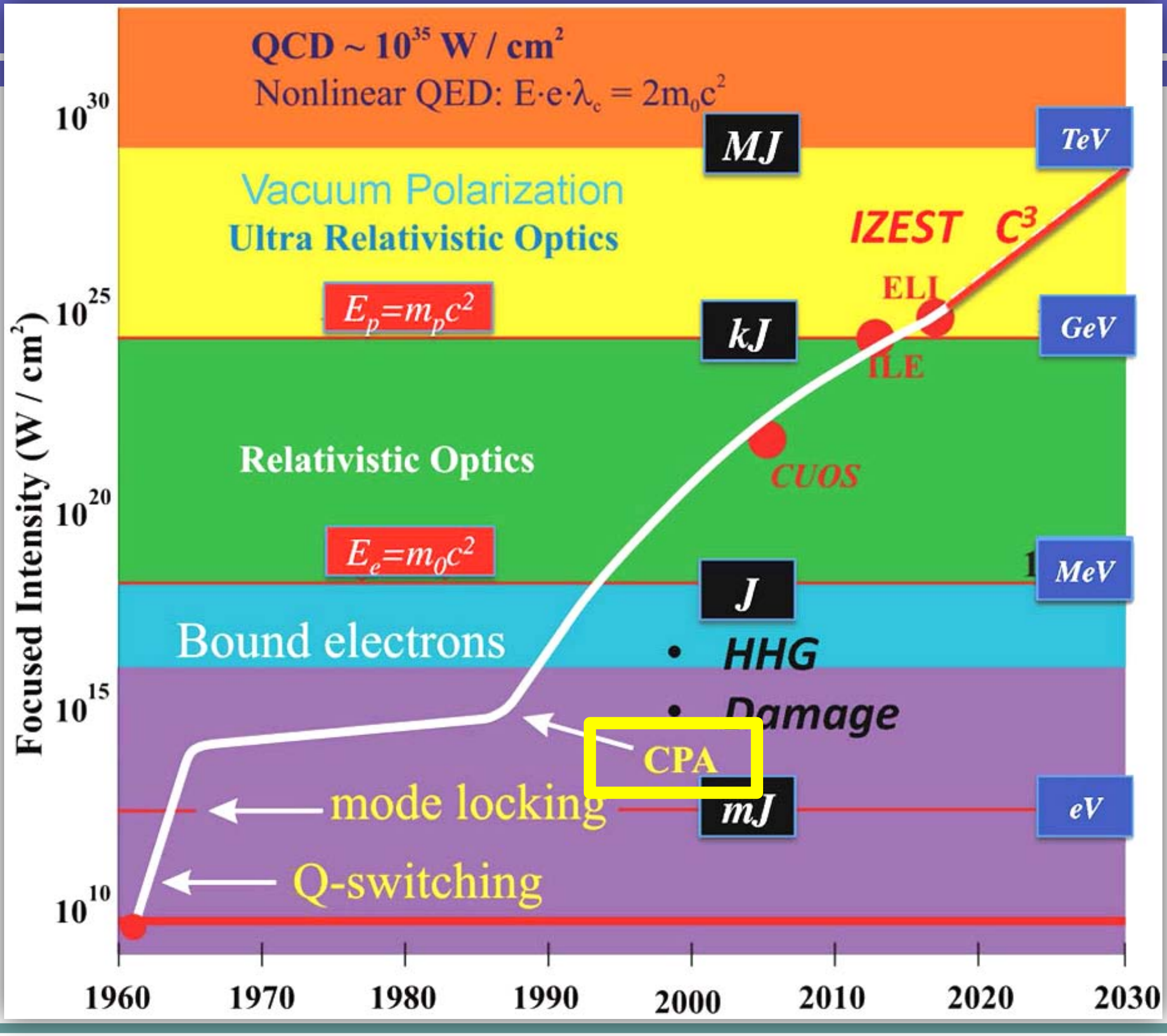


Chirped Pulse Amplification(CPA): 啁啾脉冲光放大技术

短脉冲激光振荡器 ⇨ 脉冲展宽 ⇨ 能量放大 ⇨ 脉冲压缩 ⇨ 高能短脉冲输出

D. rickland and G. Mourou, Opt. Commun. 56, 219 (1985)

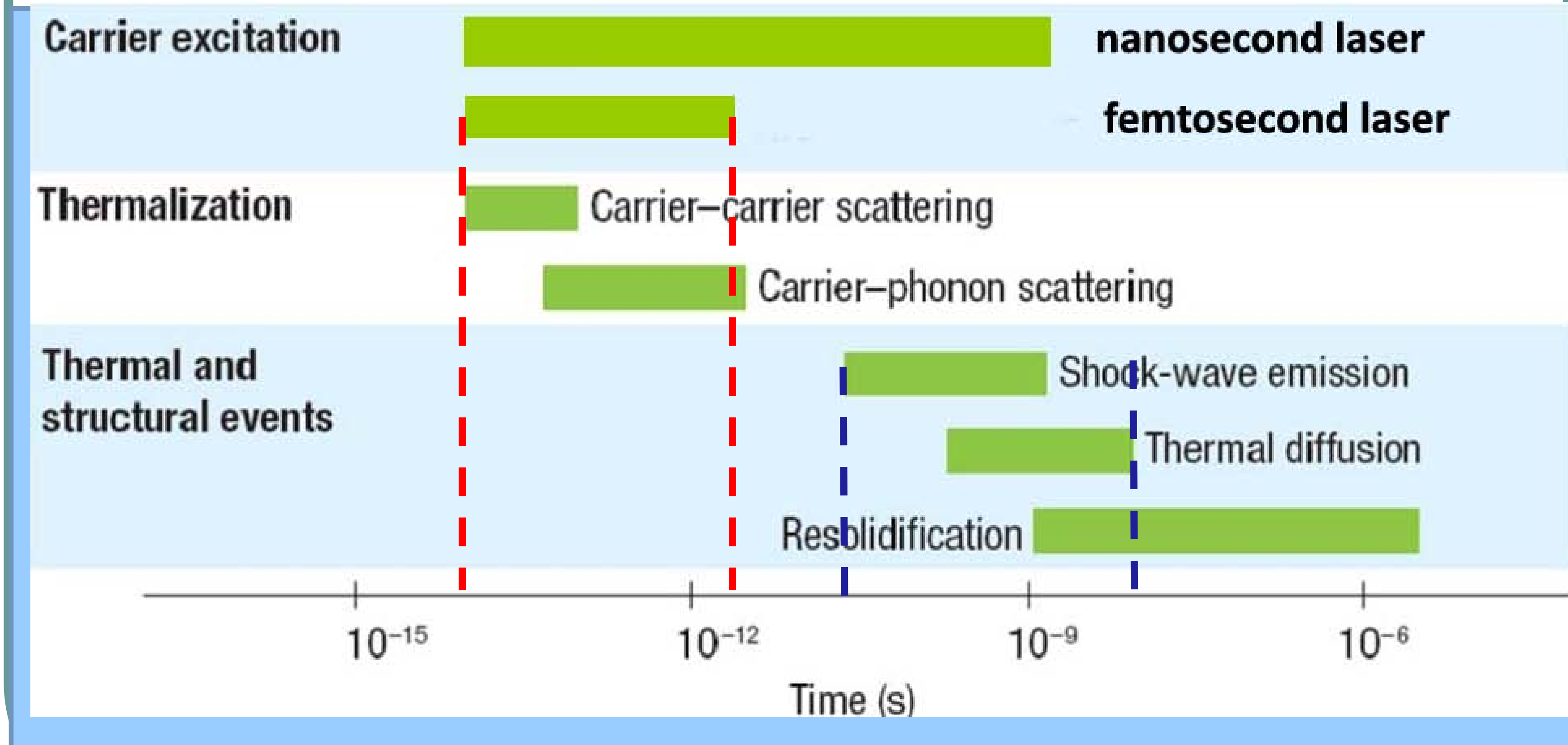
Passion for intense laser pulses



http://spie.org (G. Mourou)

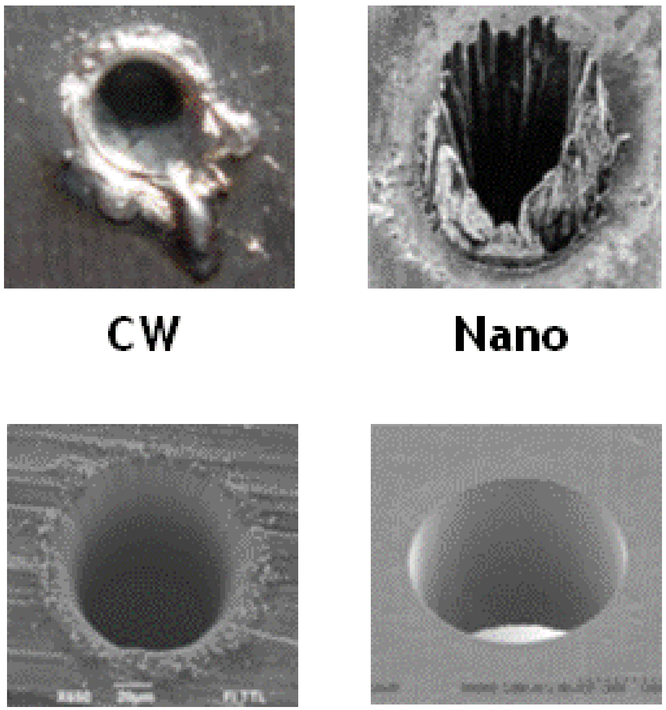
超快激光加工的优势----对热效应的几乎完全的抑制

飞秒激光与透明材料相互作用的时间尺度



Nature Photonics 2, 219 - 225 (2008)

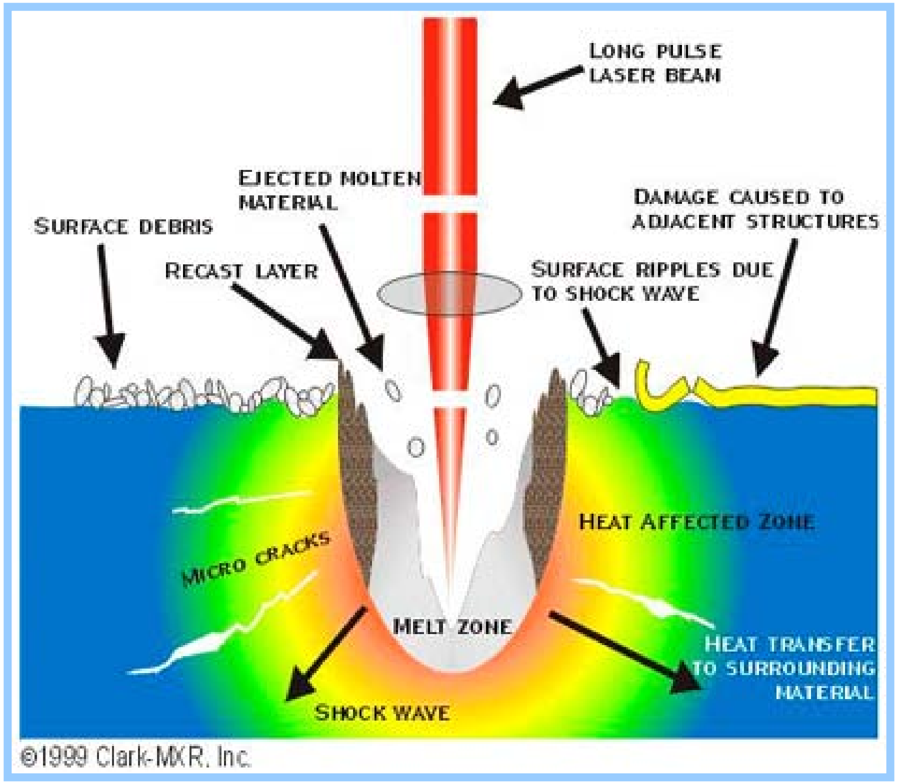
超快激光加工的优势之一 ---- 对热效应的几乎完全的抑制



CW　　Nano

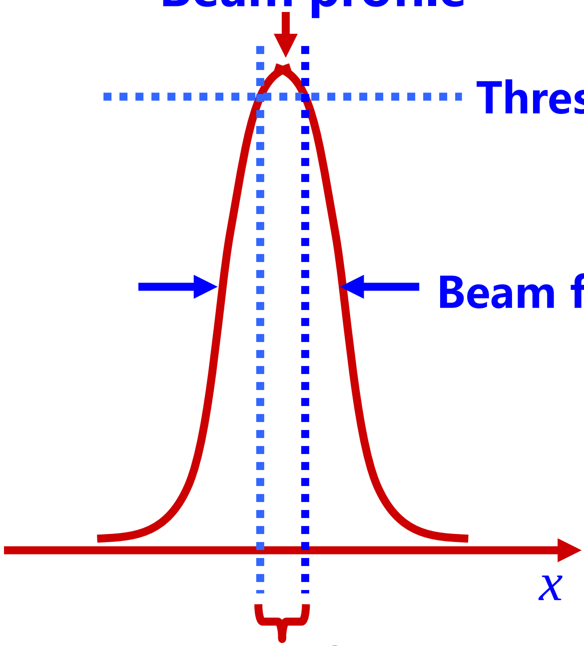
Pico　　Femto

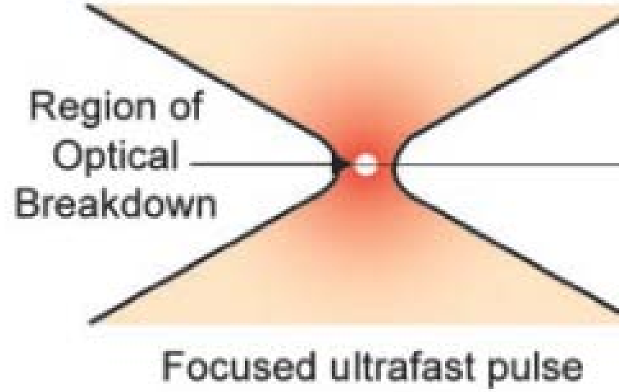
B. N. Chichkov, et al., Appl. Phys. A 63, 109 (1996)

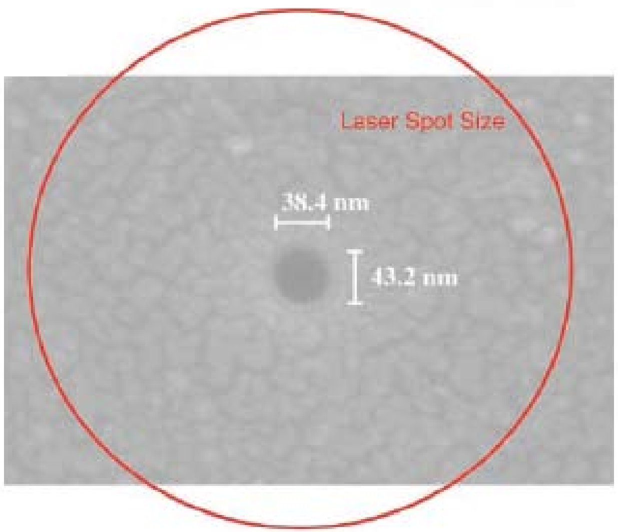


超快激光加工的优势之二----可实现超越衍射极限的纳米加工

超越衍射极限的限制

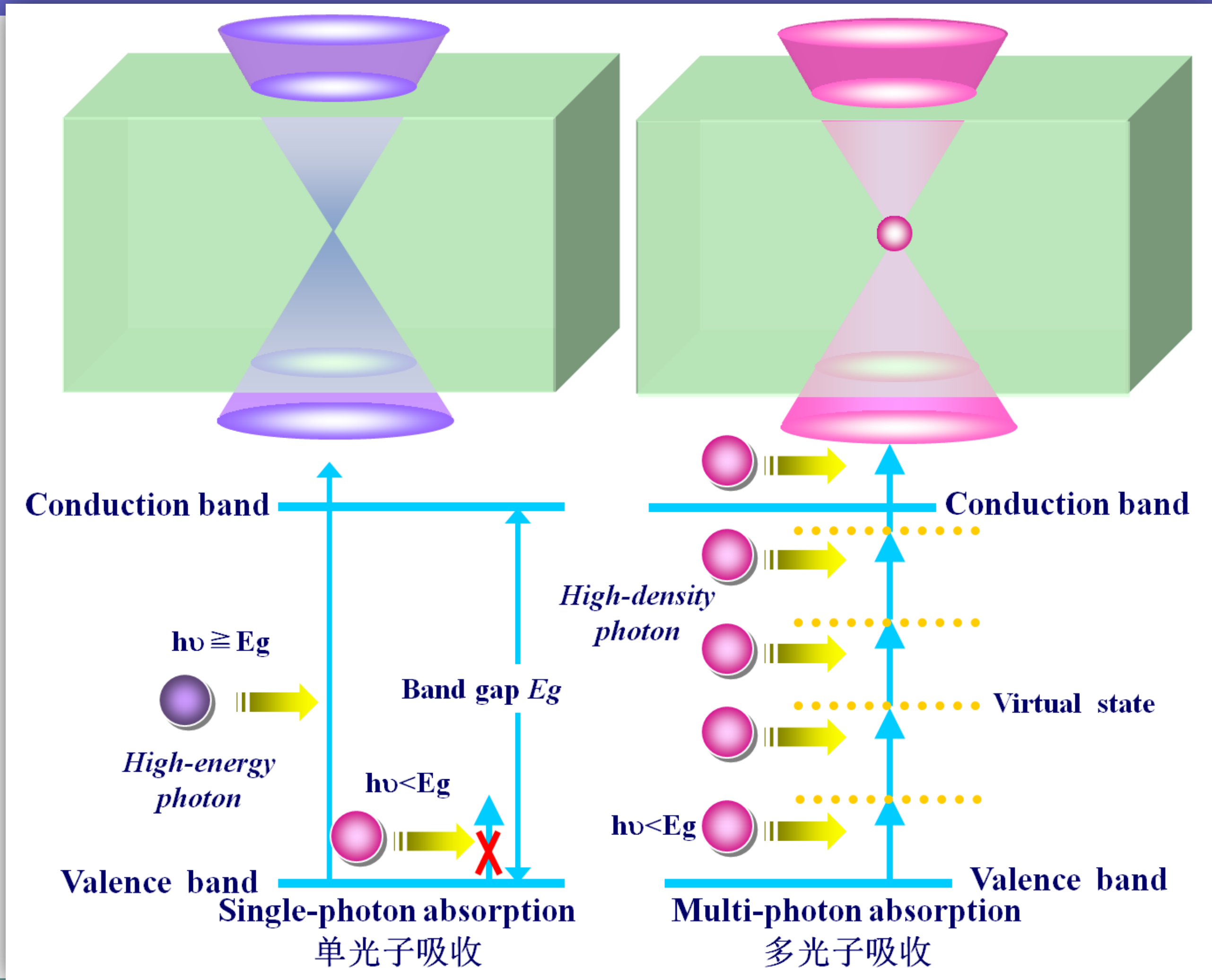






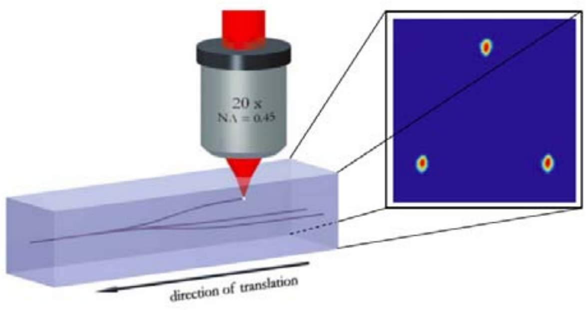
A. P. Joglekar, et al. PNAS 101, 5856(2004)

超快激光加工的优势之三 ---- 针对透明材料的三维加工能力

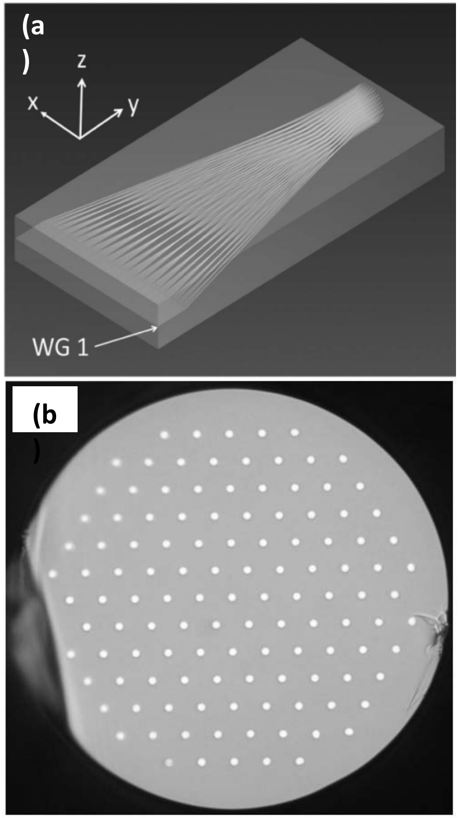


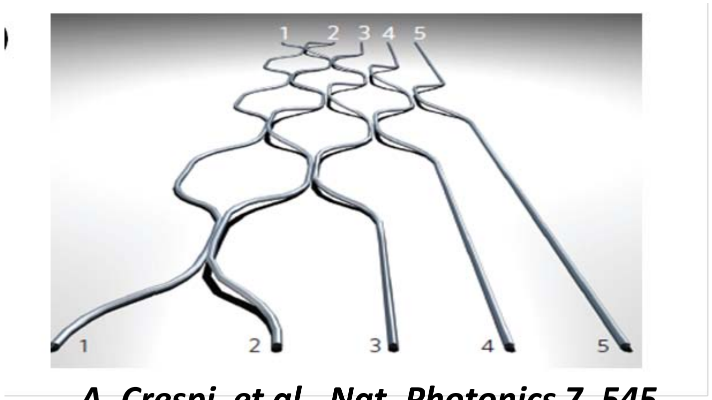
超快激光加工的优势之三 ---- 针对透明材料的三维加工能力

集成光子回路 (Photonic integrated circuit)



K. M. Davis et al., Opt Lett 21, 1729 (1996)
S. Nolte, et al., Appl. Phys. A, 77, 109 (2003)



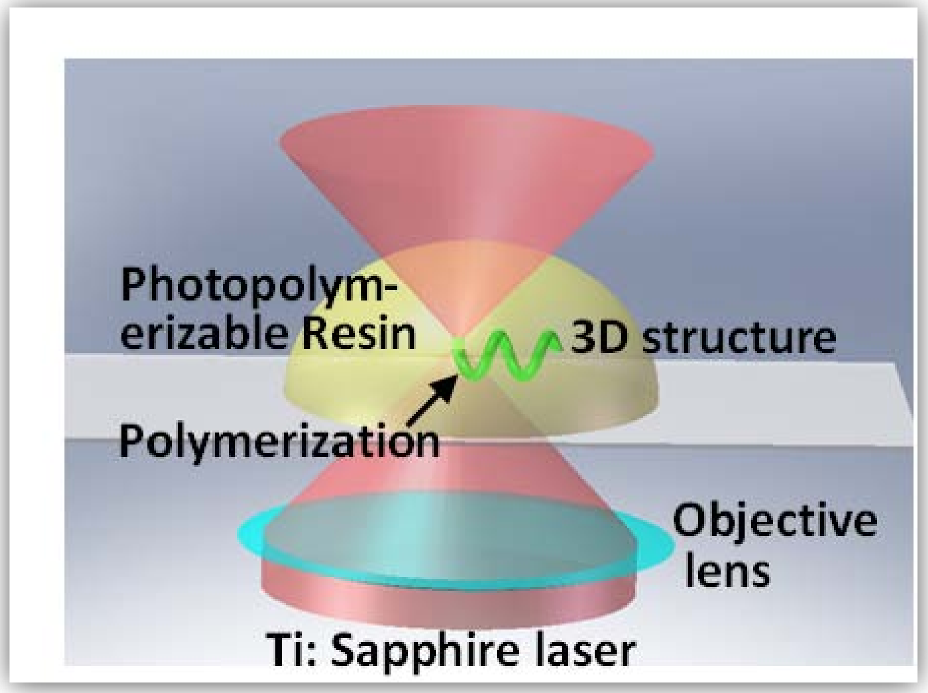


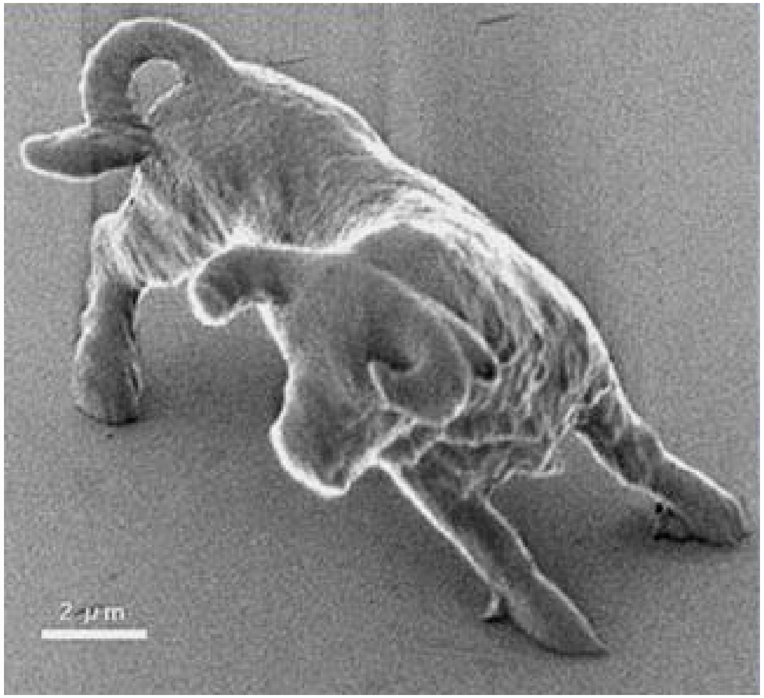
A. Crespi, et al., Nat. Photonics 7, 545 (2013)

R. R. Thomson, et al., Opt. Lett. 37, 2331 (2012)

超快激光加工的优势之三 ---- 针对透明材料的三维加工能力

双光子聚合 (Two-photon polymerization)

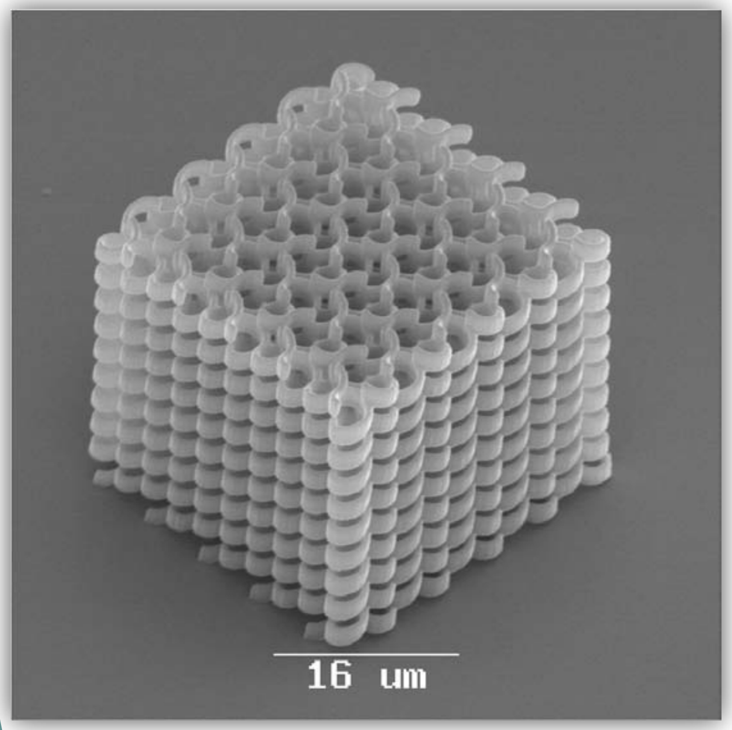




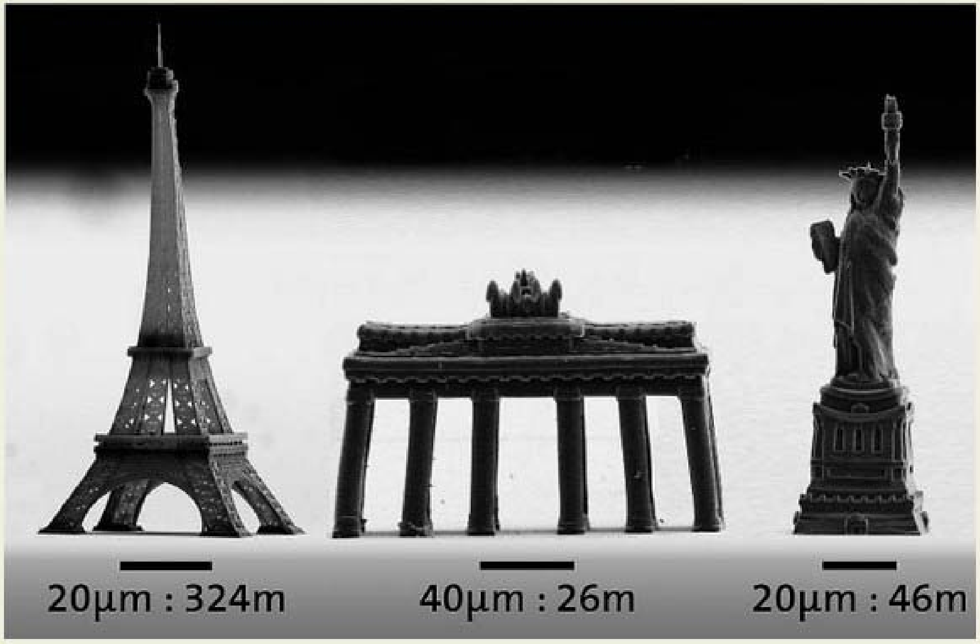
S. Kawata, et al., Nature 412, 697, 2001

超快激光加工的优势之三 ---- 针对透明材料的三维加工能力

双光子聚合 (Two-photon polymerization)



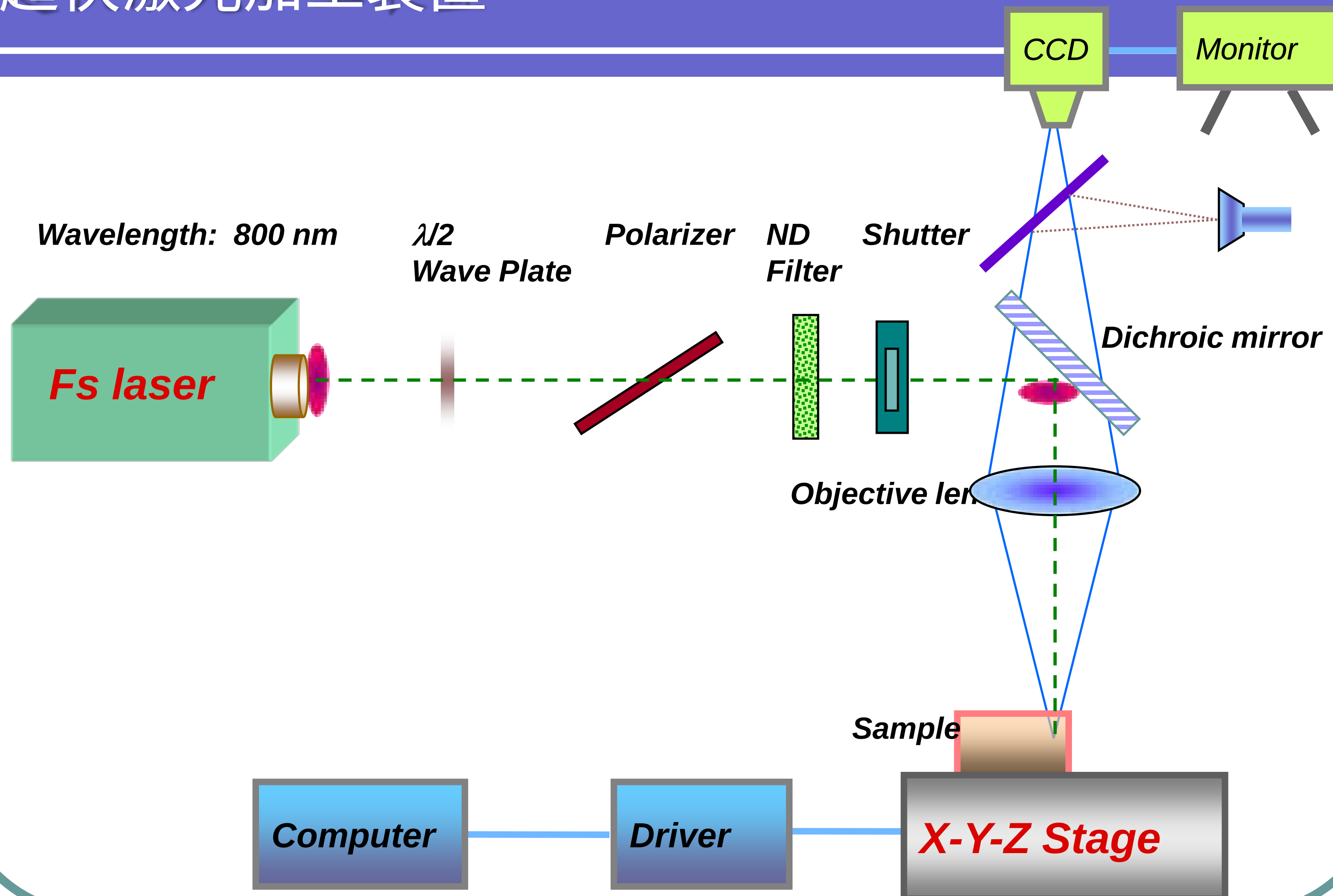
M. Farsari, et al., Nat. Photonics 3, 450 (2009)



Micro models of the Eiffel Tower, Brandenburg Gate and Statue of Liberty, made via TPP. Photo courtesy of Nanoscribe.

http://www.micromanufacturing.com

超快激光加工装置



CCD
Monitor
Wavelength: 800 nm
λ/2
Wave Plate
Polarizer
ND
Filter
Shutter
Dichroic mirror
Fs laser
Objective len
Sample
Computer
Driver
X-Y-Z Stage

提纲

1. 飞秒激光微纳加工简介
2. **芯片实验室器件**
3. 电光集成器件
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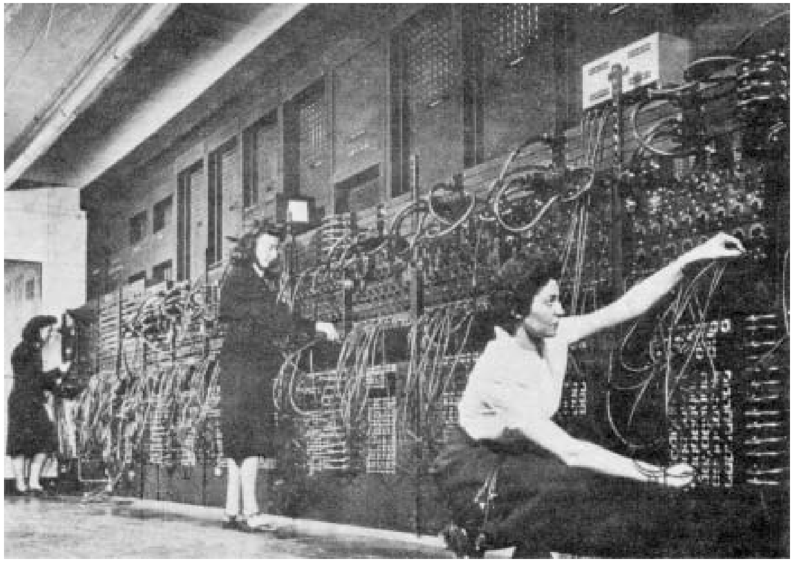
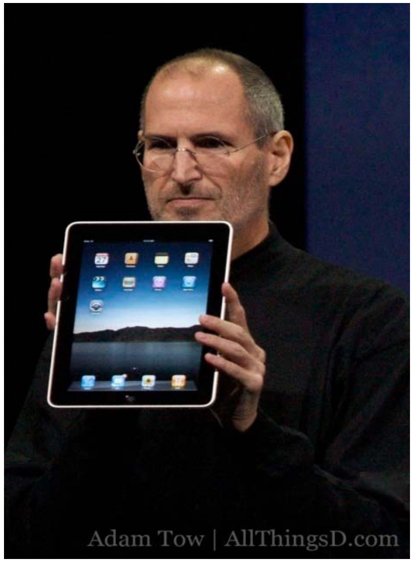
5. 总结和展望

研究背景——小型化和集成



第一台计算机 ENIAC, 1946年

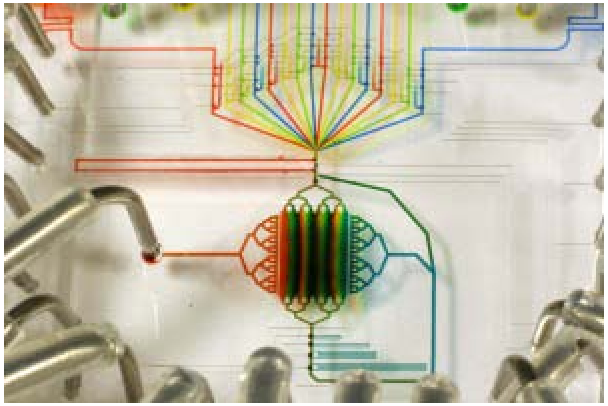


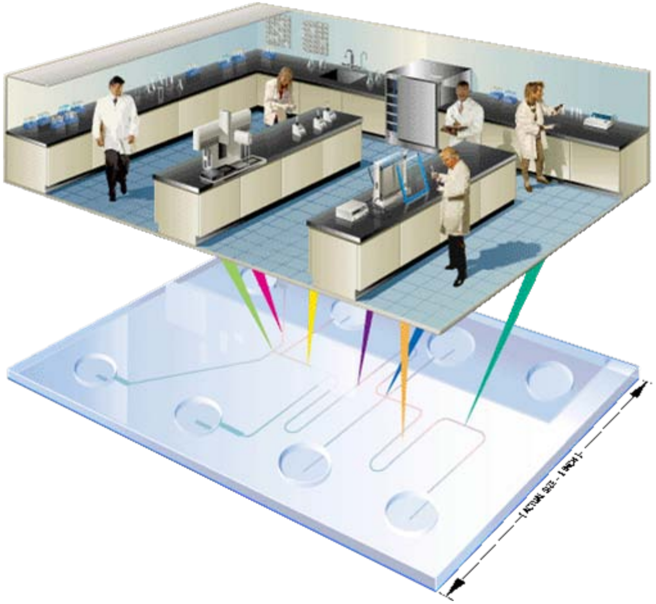
苹果iPad，2010年

电子领域的小型化和集成已经极大的改变了我们的生活方式

研究背景——下一代小型化和集成

微流体 (microfluidics)技术 **芯片实验室(Lab-on-a-chip)技术**





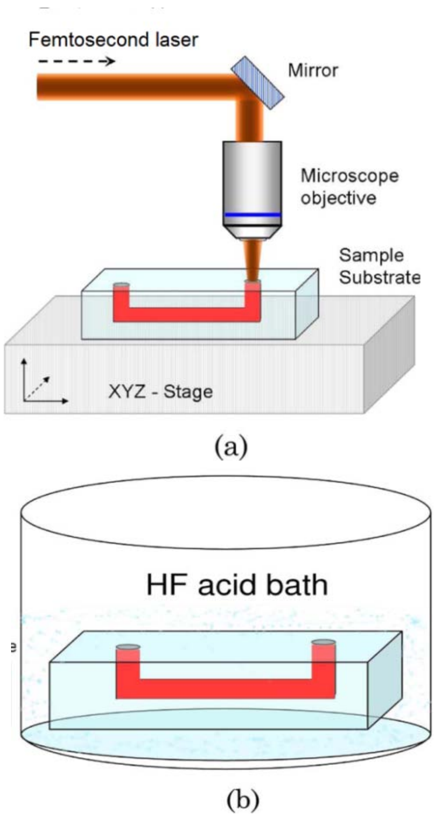
Small Channels, Big Ideas

All-in-One Integration

随着人们对健康关注度的提高，生物、医疗领域的小型化和集成技术吸引了广泛的研究兴趣。而这对现有的加工技术提出了新的挑战。

飞秒激光加工三维微流通道 ------ 传统方法

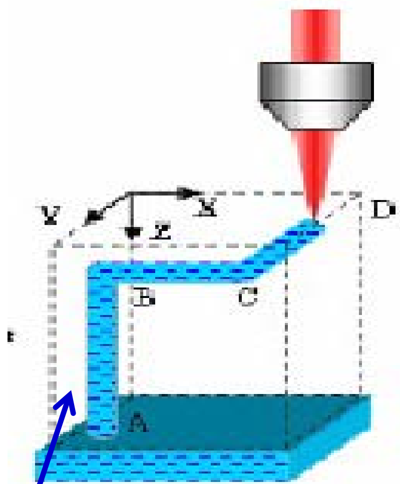
1. 飞秒激光直写+化学刻蚀



Marcinkevicius et al., Opt. Lett., 26, 277, 2001

Vishnubhatla et al., Appl. Opt., 48,114, 2009

2. 水辅助飞秒激光直写



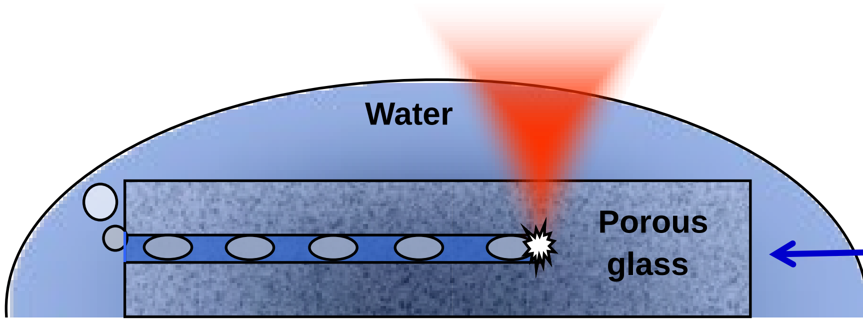
Li et al., Opt. Lett., 26, 1912, 2001

Hwang et al., Appl. Phys. A 79, 605, 2004

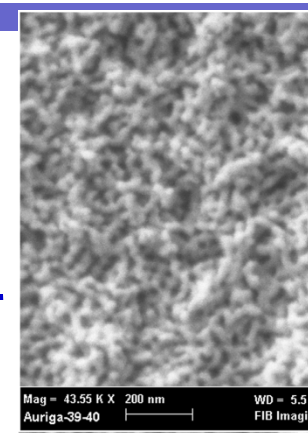
总长度小于10 mm

随通道长度的增加，通道内的传质过程越来越困难

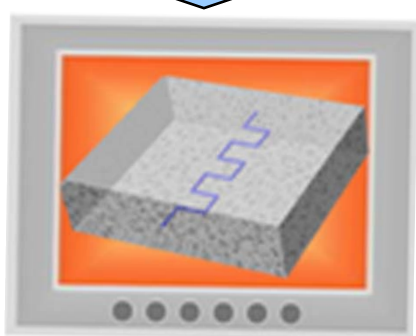
飞秒激光加工三维微流通道 ------ 新策略



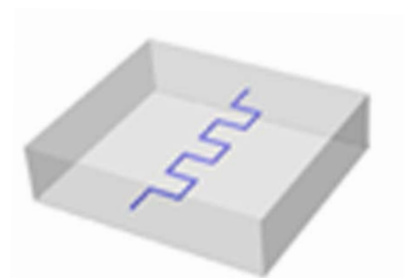
多孔玻璃内部水辅助飞秒
激光三维直写



3D 连通的多孔网络



退火处理



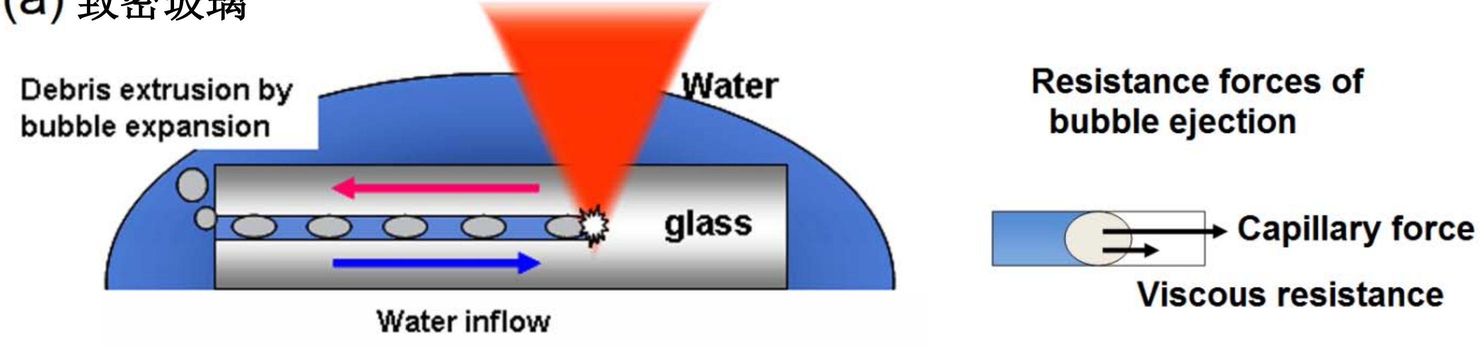
纳米孔闭合，微通道留在致密的
玻璃中

Y. Liao, Y. Ju, et al, *Opt. Lett.*, 35, 3225 (2010)

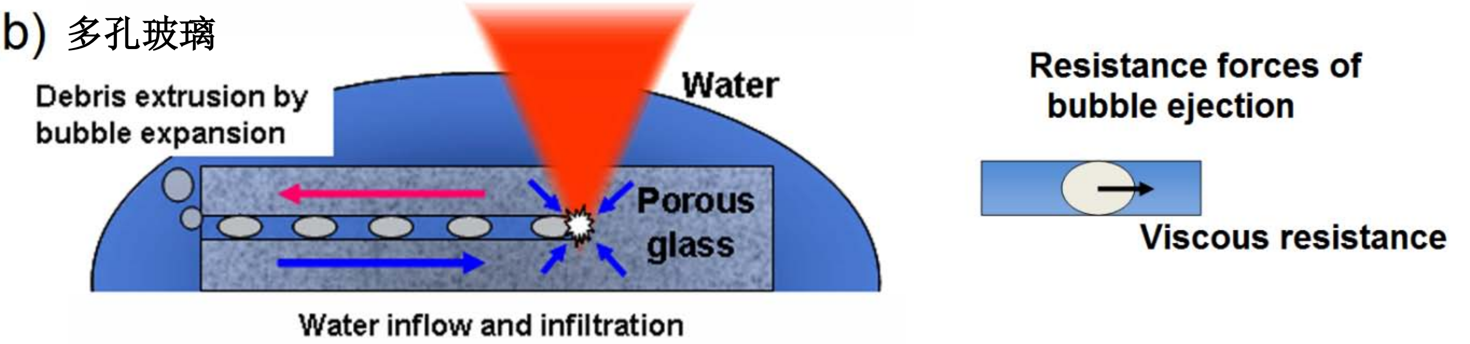
获得任意长度和任意构型的三维微通道

飞秒激光加工三维微流通道 ------ 新策略

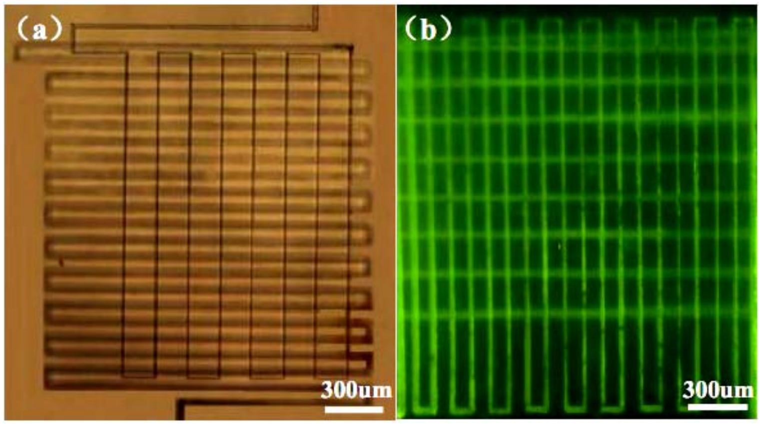
(a) 致密玻璃

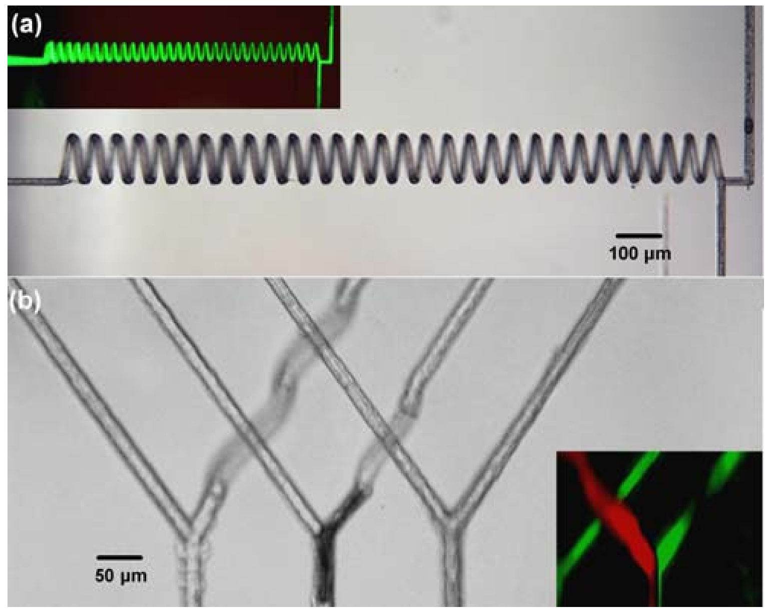


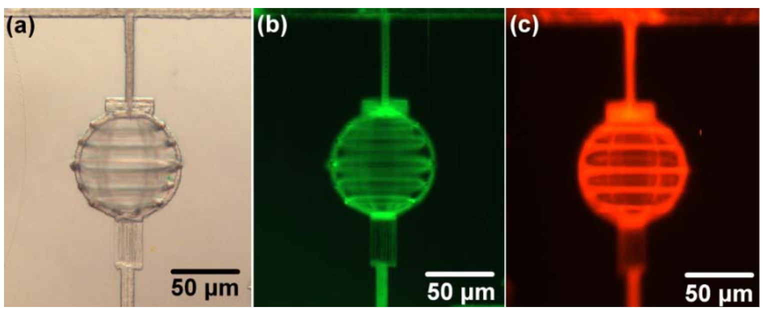
(b) 多孔玻璃



高长径比的三维微流通道





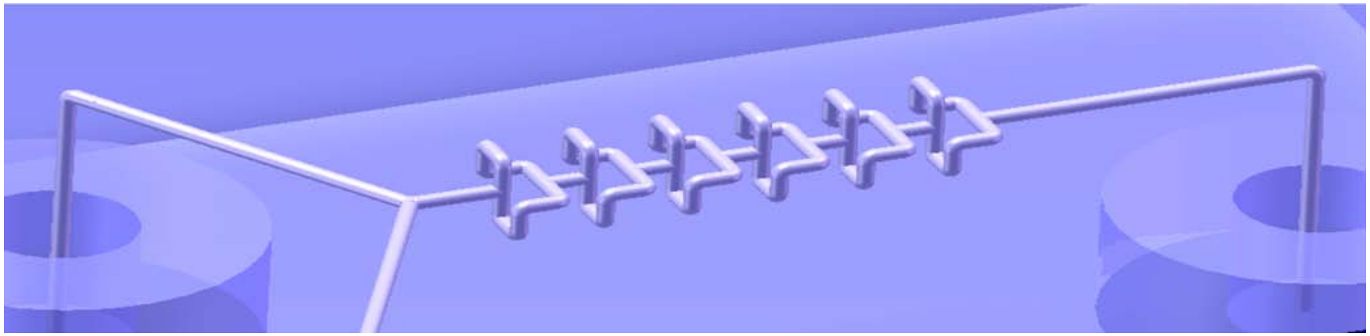


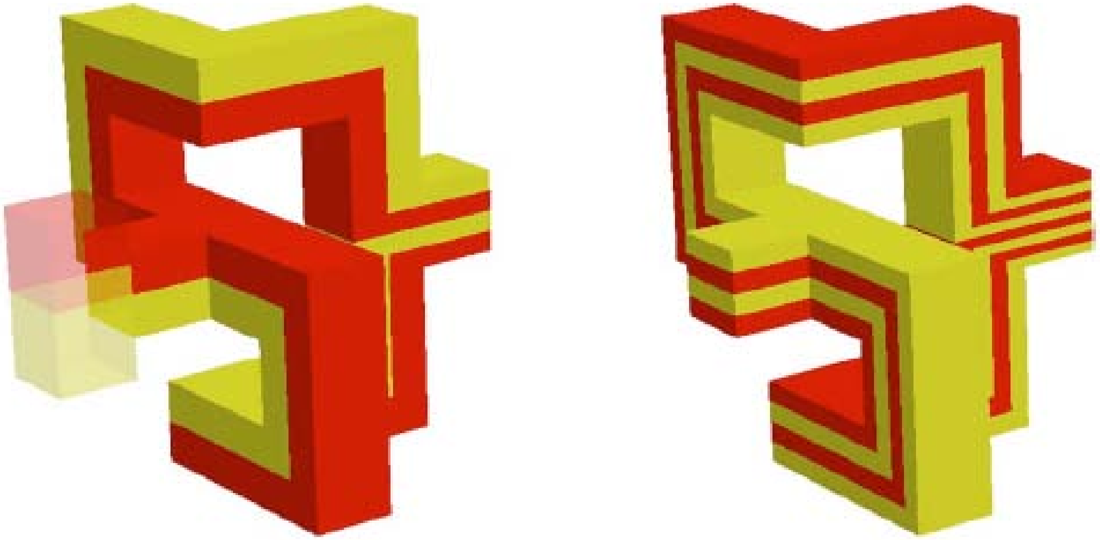
不同几何构型的三维微流通道

Y. Liao, et al, Lab Chip, 12 ,746 (2012)

C. Liu, Y. Liao, et al, *J. Laser Micro/Nanoeng. 8*, 170 (2013)

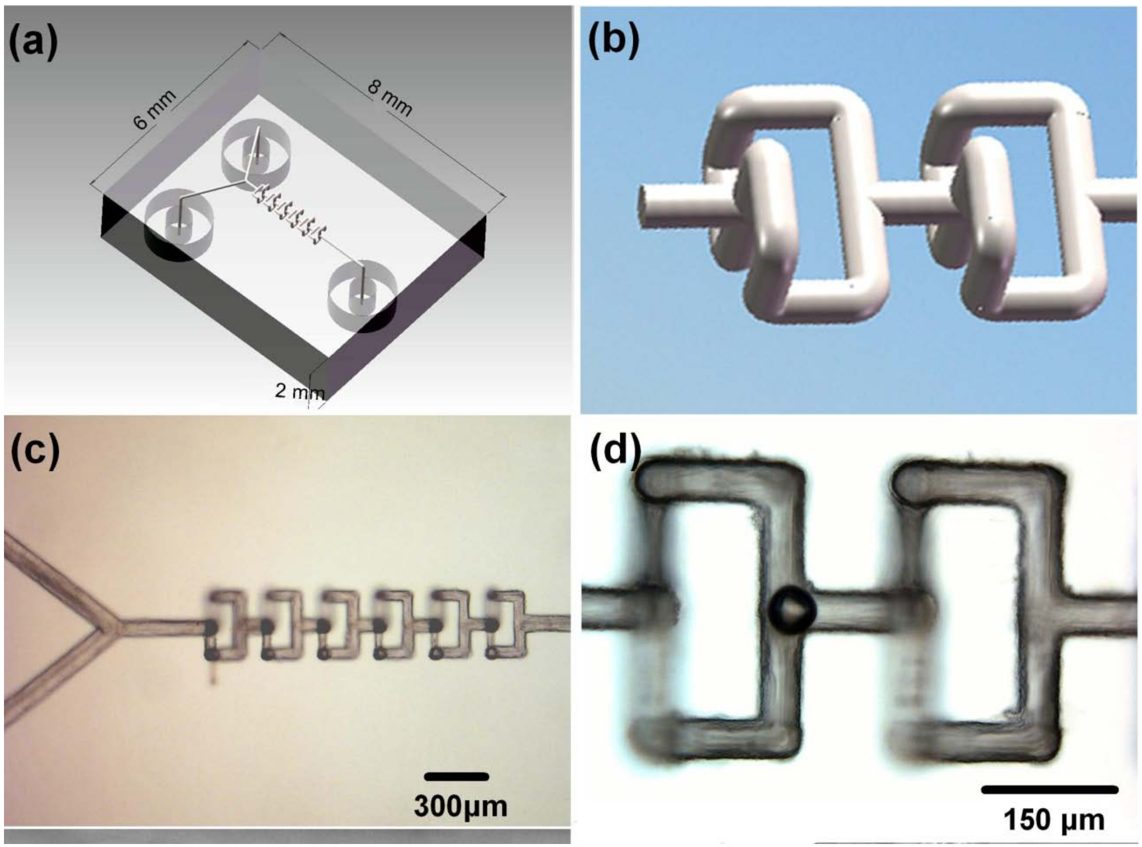
基于baker变换的三维微流混合器





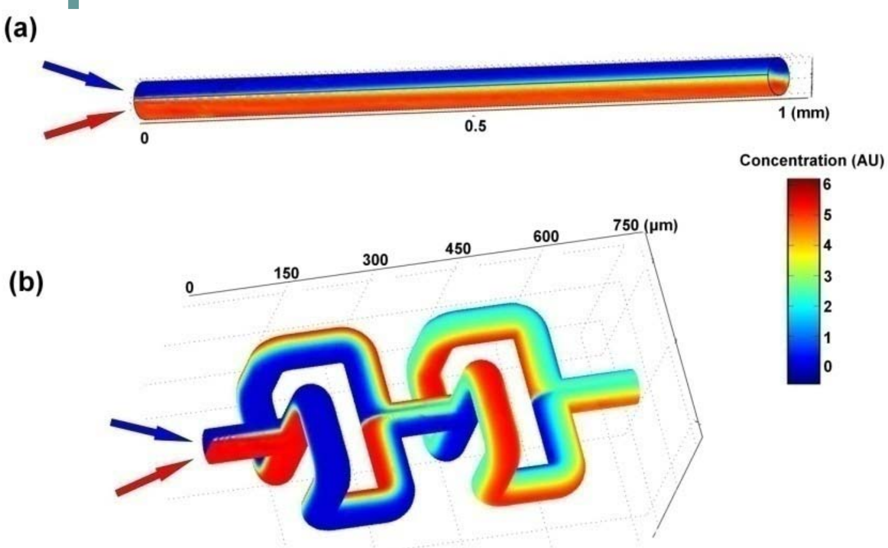
P. Carriere, Phys. Fluid. 19, 118110 2007

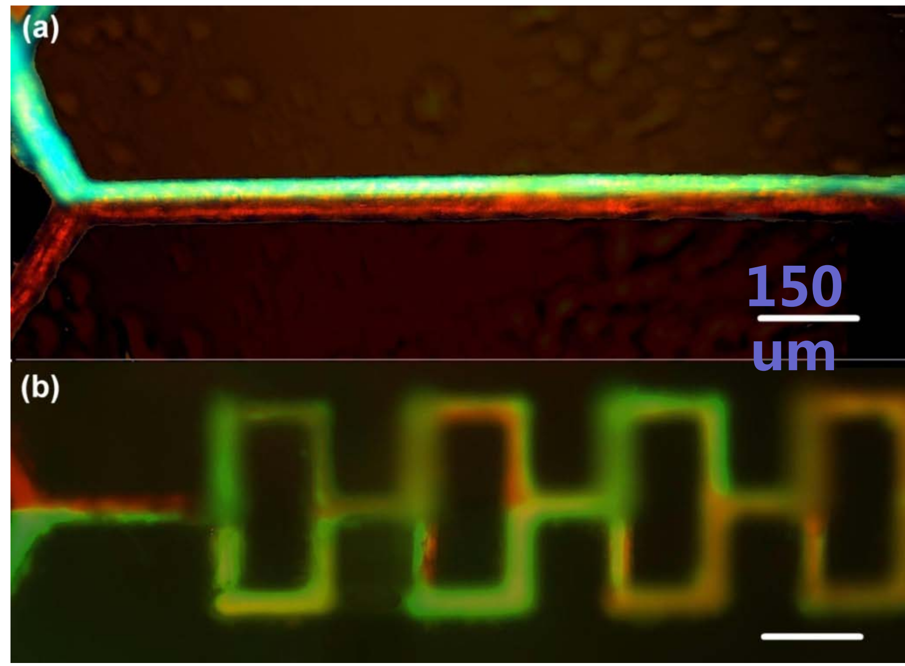
基于baker变换的三维微流混合器



Y. Liao, et al, Lab Chip, 12 ,746 (2012)

基于baker变换的三维微流混合器





数值模拟

实验结果

Y. Liao, et al, Lab Chip, 12 ,746 (2012)

相关报道----- *SPIE Newsroom，Laser Institute of America，Institute of Nanotechnology*

SPIE Newsroom

10.1117/2.1201202.004150

How to make a 3D micromixer

Ya Cheng, Yang Liao, Zhizhan Xu, Koji Sugioka, and Katsumi Midorikawa

A femtosecond laser can make microchannels in fused silica to combine tiny volumes of liquids.

Microfluidics is a rapidly emerging technology that enables miniaturization and integration for biological, chemical, and medical applications. By integrating fluidic functions such as valving, metering, mixing, transport, and separation on a single substrate, microfluidic systems can be used to control and manipulate tiny volumes of liquids with high precision, enabling downsizing of both chemical and biological analyses.[1] Fluid mixing is an essential function required by most

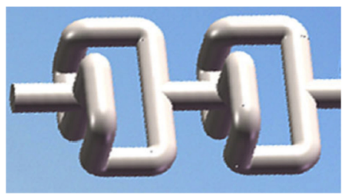


Figure 1. Close-up schematic diagram of the 3D passive microfluidic mixer

INSTITUTE OF nanoTECHNOLOGY

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04 April 2012 Shanghai Institute of Optics and Fine Mechanics

3D Microfluidic mixer by Femtosecond Laser Direct Writing

Microfluidics is a rapidly emerging technology that enables miniaturization and integration for biological, chemical, and medical applications. The fluid mixing is an essential function required by most microfluidic systems, however, fast and efficient fluid mixing inside microchannels is usually difficult to achieve due to the laminar nature of microflows characterized by low Reynolds numbers. Recently, various passive mixers have been developed to achieve efficient mixing by utilizing three-dimensional (3D) geometric structures to induce disturbance in the fluids. Nevertheless, the fabrication of 3D microfluidic structures with arbitrary geometries is still challenging if not impossible, because today's

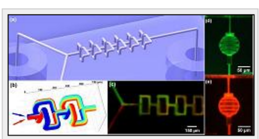

Figure (a) Schematic 3D diagram of the passive microfluidic mixer, (b) Numerical simulation of mixing result, (c) Fluorescence microscopy image of mixing experiment, (d) and (e) Fluorescence microscopy images of the Chinese lantern filled with green and red fluorescent dyes, respectively. Image Credit: SIOM.

Laser Institute of America

Laser Applications and Safety

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Femtosecond Laser Micro/Nanomachining of Glass Materials for Optofluidic Applications and Beyond

AUGUST 28, 2012

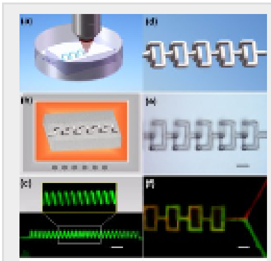
LASER EDITORIALS

By Ya Cheng

Nowadays, microfluidic systems for controlling and manipulating tiny volumes of liquids with high precision have attracted significant attention due to their capability of downsizing both chemistry and biology. In addition, it is often desirable to incorporate micro-optical structures into the microfluidic chips, which leads to not only compact chemical and biological sensors, but also tunable and reconfigurable laser devices. For both microfluidic and micro-optical applications, fused silica can be an ideal substrate material due to its excellent physical and chemical properties, such as chemical inertness, low thermal expansion coefficient, low autofluorescence, exceptional transmittance over a wide spectral range, and so on. On the other hand, fabrication of three-dimensional (3D) microstructures with fused silica, including embedded microfluidic channels and microspherical optical lenses, has long been a challenge because traditional approaches based on photolithography inherently produce planar structures. Here, we show that these difficulties can be overcome by means of femtosecond laser micromachining.

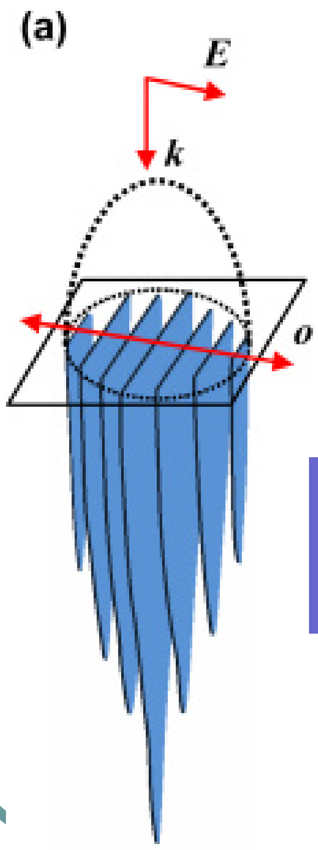
FEMTOSECOND FLEXIBILITY

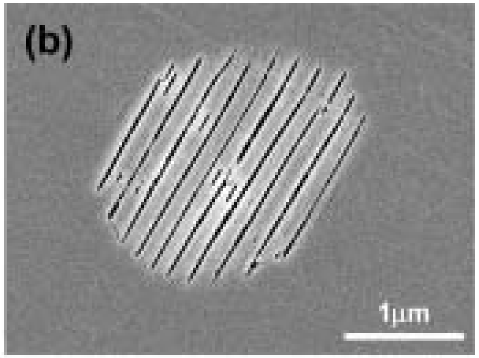
The 3D nature of the femtosecond laser direct writing offers flexibility for constructing complex microfluidic networks in glass. The main fabrication process includes two steps: (1) direct formation of hollow microchannels in a porous glass substrate immersed in water by femtosecond laser ablation (Fig. 1(a)); and (2) postannealing of the glass sample at ~ 1150 °C by which the porous glass can be consolidated due to collapse of the nanopores (Fig. 1(b)). The consolidated glass sample can then be used to confine liquids in the fabricated 3D microfluidic channel without any leakage, as evidenced by Fig. 1(c). Because



从微流到纳流------超越衍射极限

研究背景-----纳米光栅（nanogratings）效应





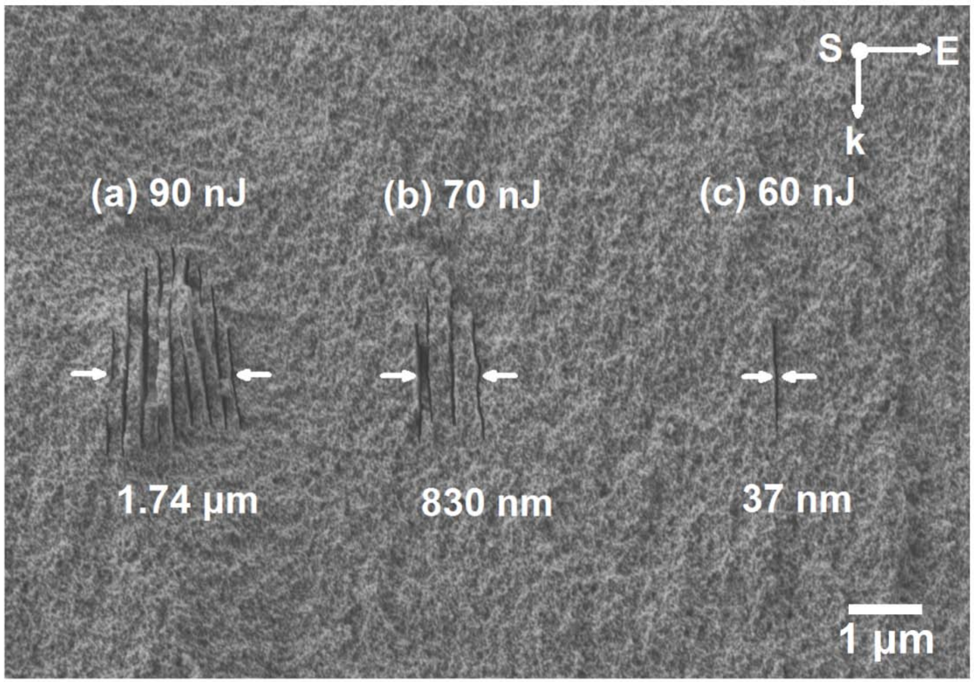
石英玻璃中的纳米光栅结构，一般由有折射率改变的周期性的纳米面构成

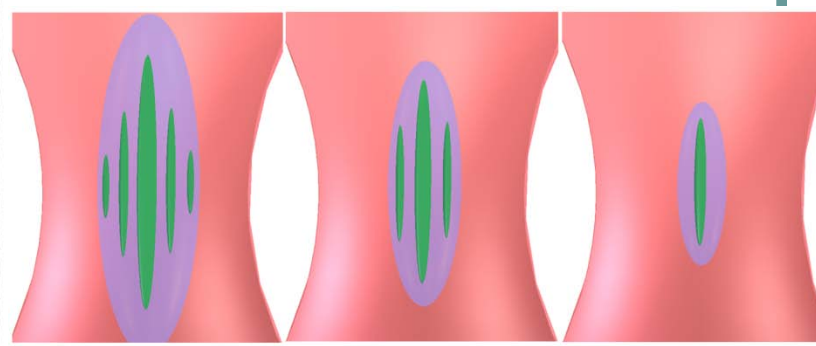
Y. Shimotsuma, et al, PRL (2003)
R. S. Taylor, et al, OL (2007)

高损伤阈值的偏振元件，
可获得径向偏振和环向偏振光束

从微流到纳流------超越衍射极限

超越衍射极限的机理------纳米光栅效应和阈值效应的结合



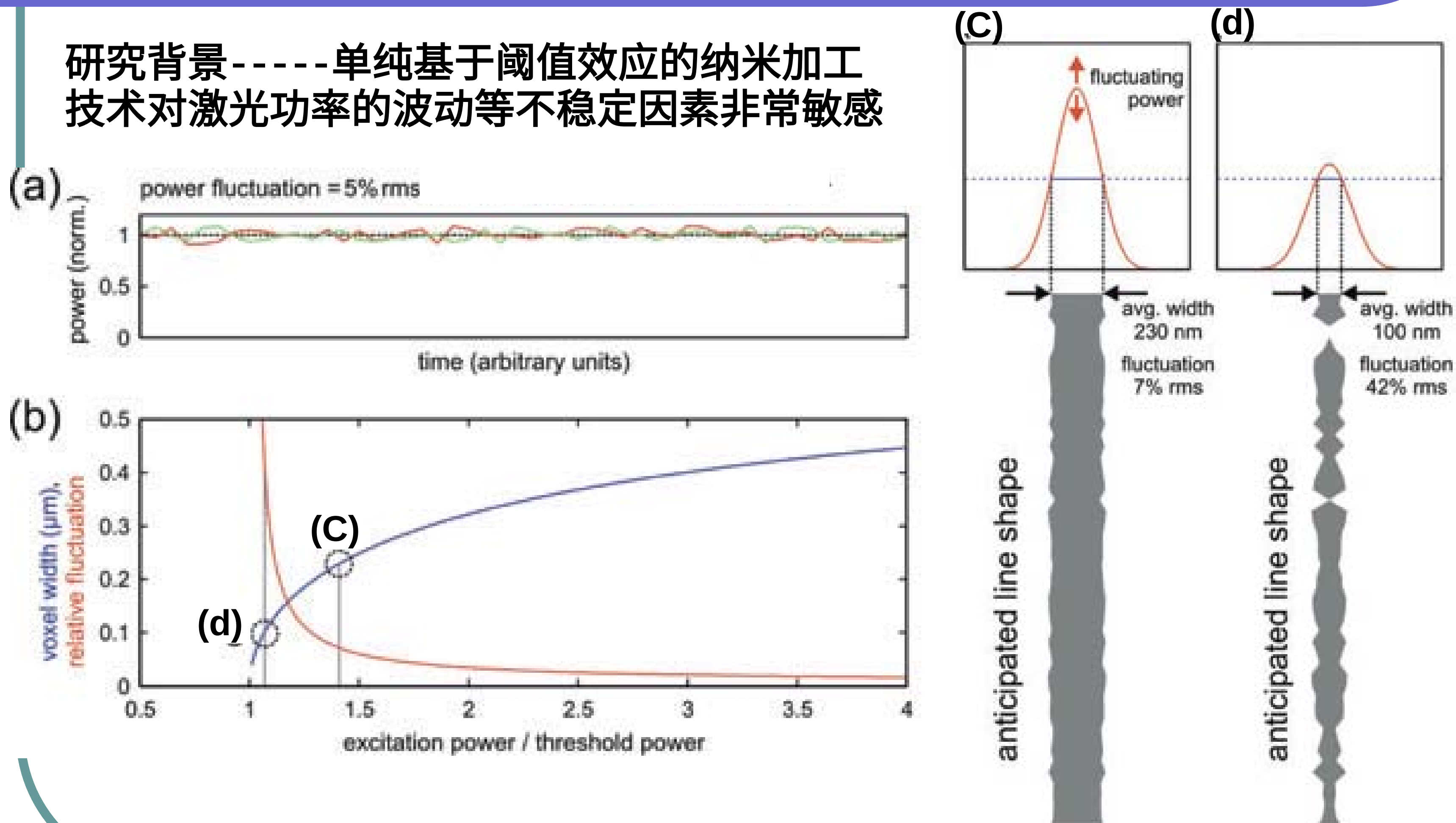


Y. Liao et al, Opt. Lett. 38, 187 (2013)

加工线宽小于~λ/20，可用于玻璃材料的纳米隐形划切

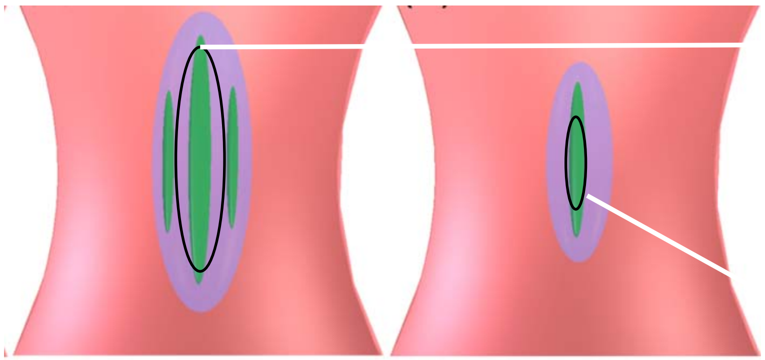
从微流到纳流----超越衍射极限的三维纳米加工技术

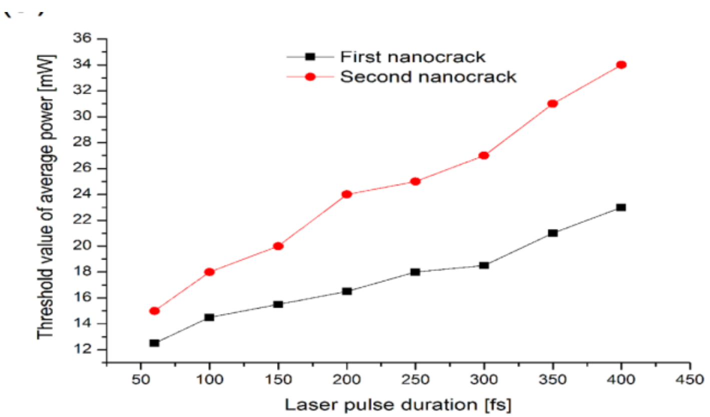
研究背景-----单纯基于阈值效应的纳米加工技术对激光功率的波动等不稳定因素非常敏感

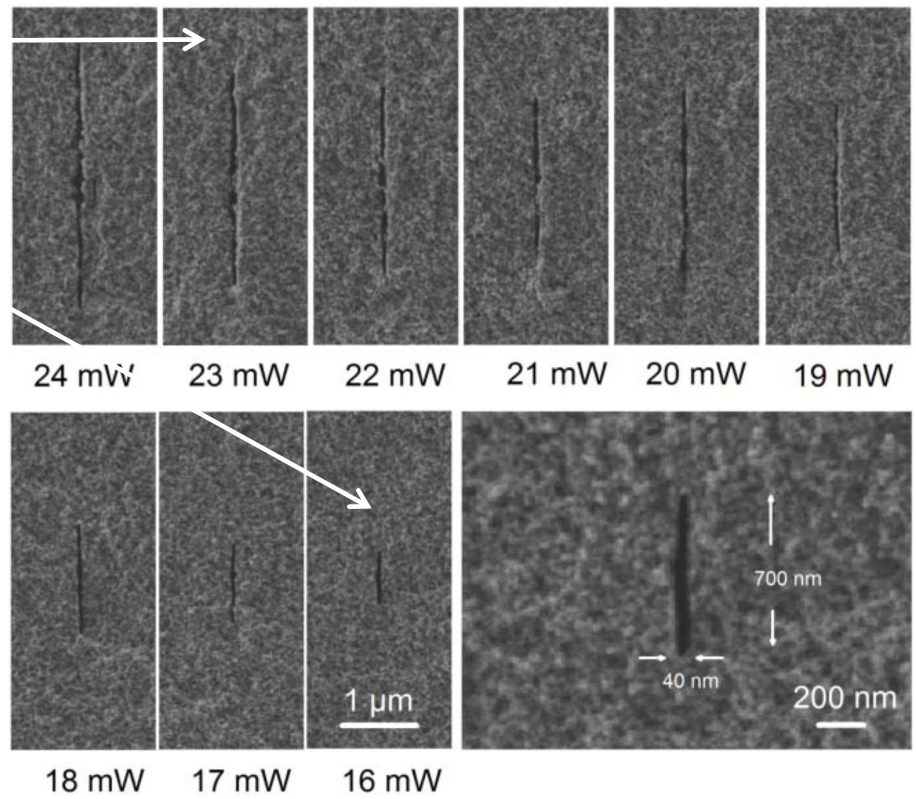


J. Fischer et al., Laser Photon. Rev. 7, 22 (2013)

从微流到纳流----超越衍射极限的三维纳米加工技术





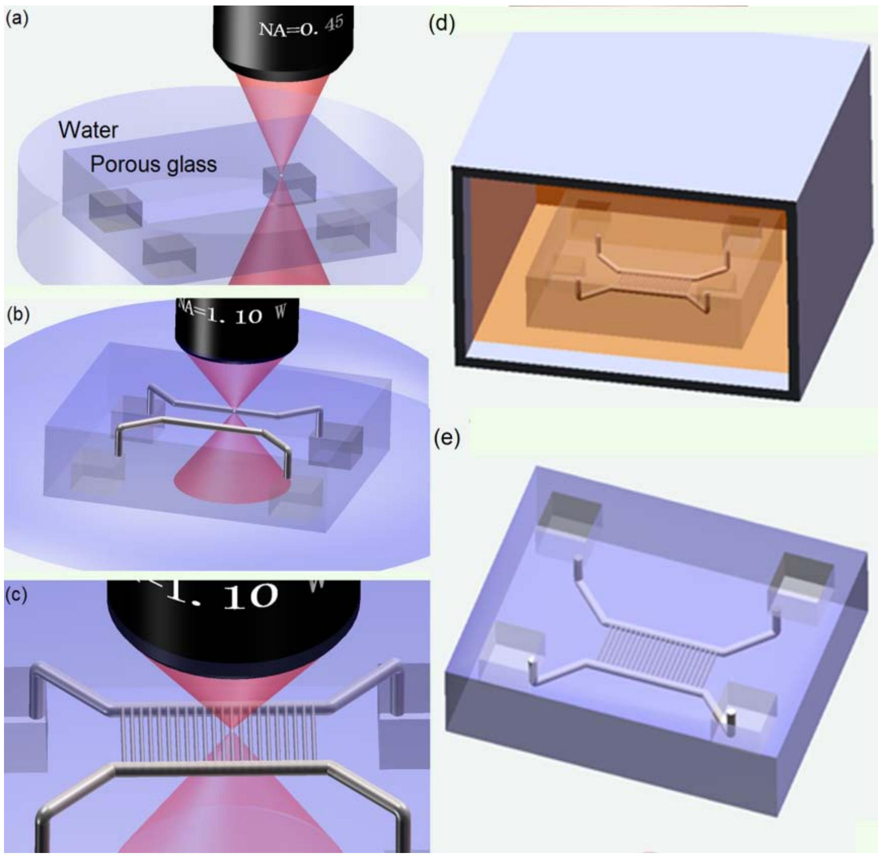


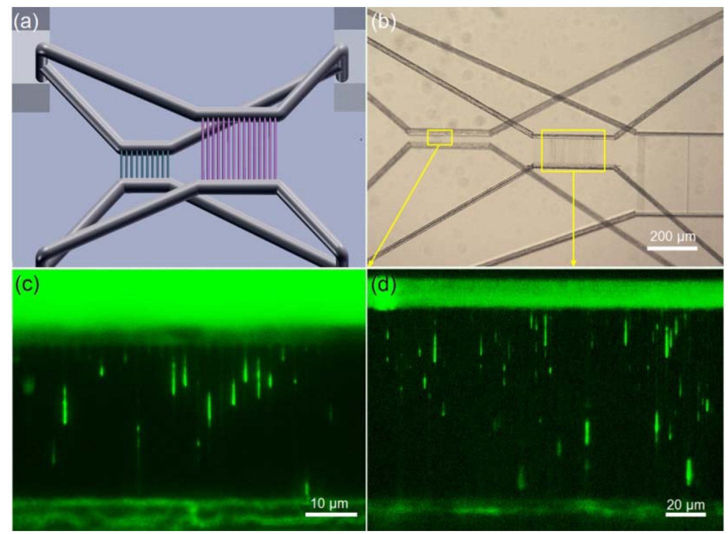
对应形成单根纳米的功率窗口约为加工阈值的~ 45%

Y. Liao, et al, Appl. Phys. A 114, 223 (2013) (Invited)

从微流到纳流---微纳流体通道的三维集成

用于单分子研究的三维纳流体器件



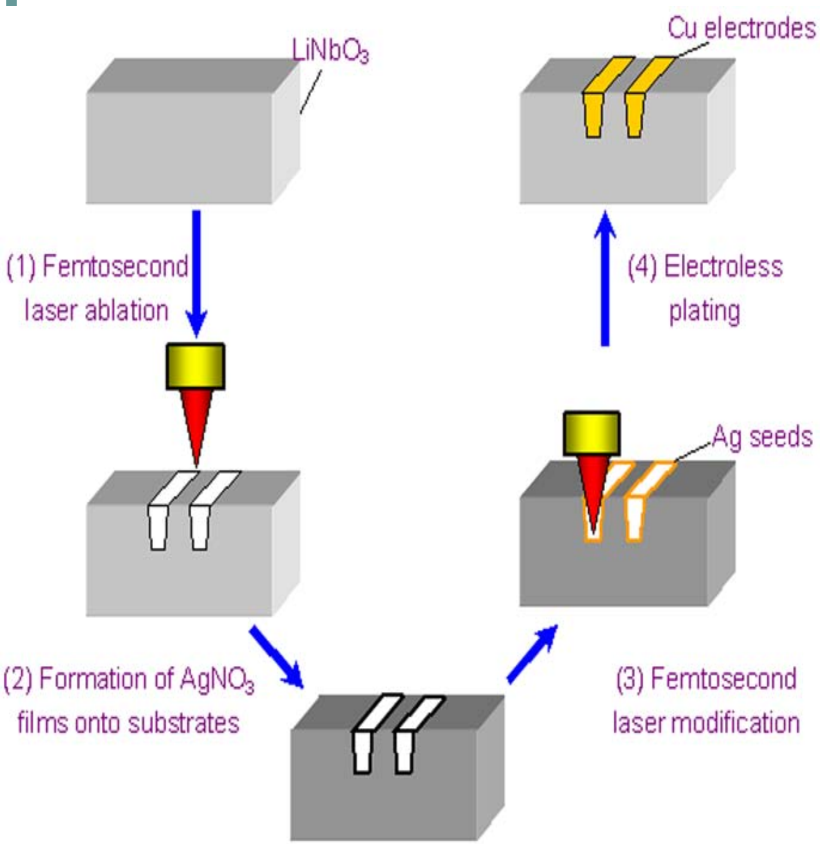


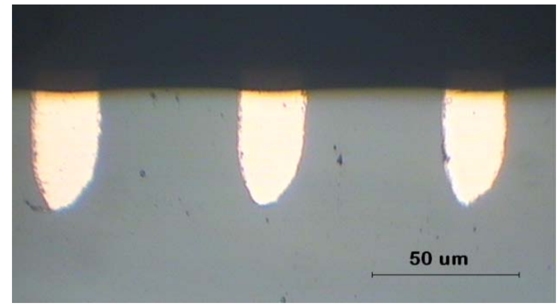
Y. Liao, et al, Lab Chip, 13, 1626 (2013)

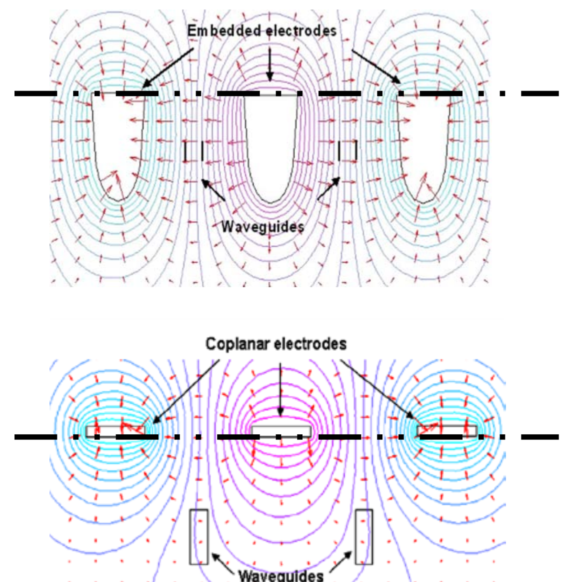
提纲

1. 飞秒激光微纳加工简介
2. 芯片实验室器件
3. **电光集成器件**
4. 工业应用
5. 总结和展望

三维微电极



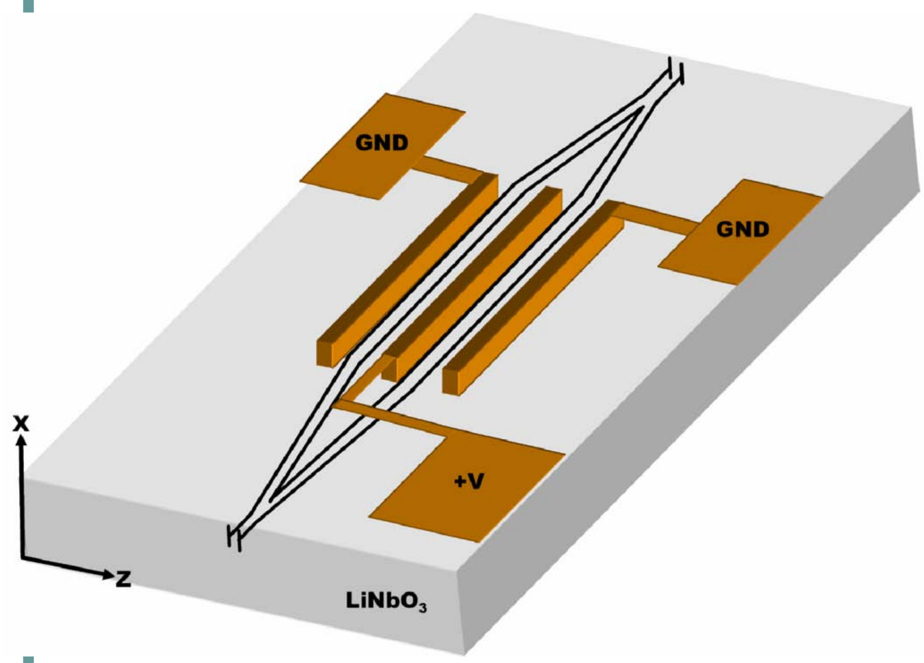




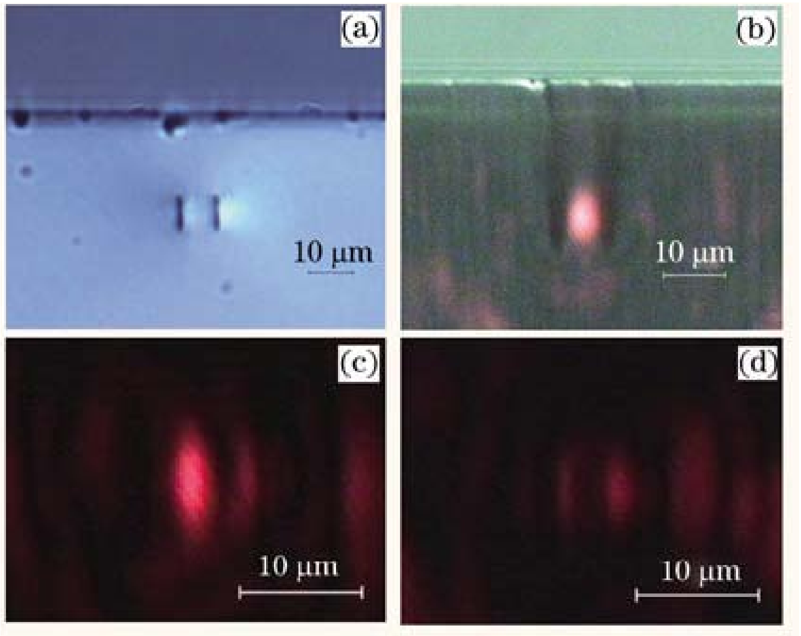
嵌入的微电极和表面微电极产生电场的数值模拟（截面）

Y. Liao, et al, *Opt. Lett.* 33, 2281 (2008)
Y. Liao, et al, *Appl. Surf. Sci.*, 254, 7018 (2008)

铌酸锂晶体内部光波导和微电极的集成



Mach-zehnder电光调制器的布局示意图

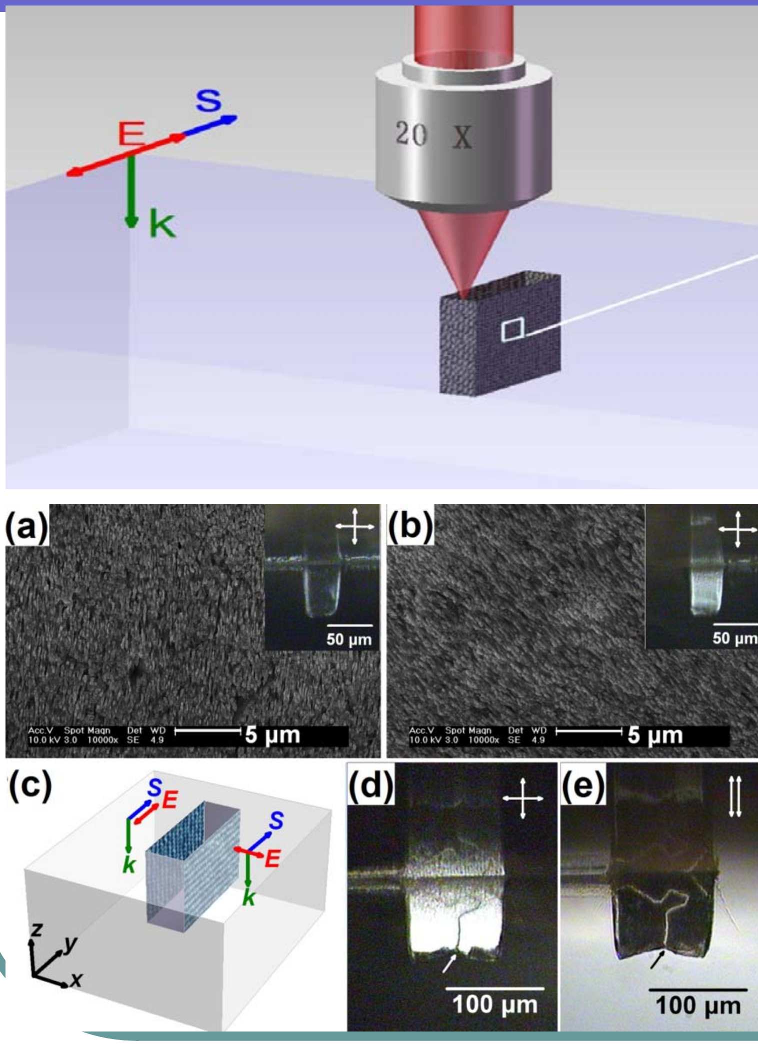


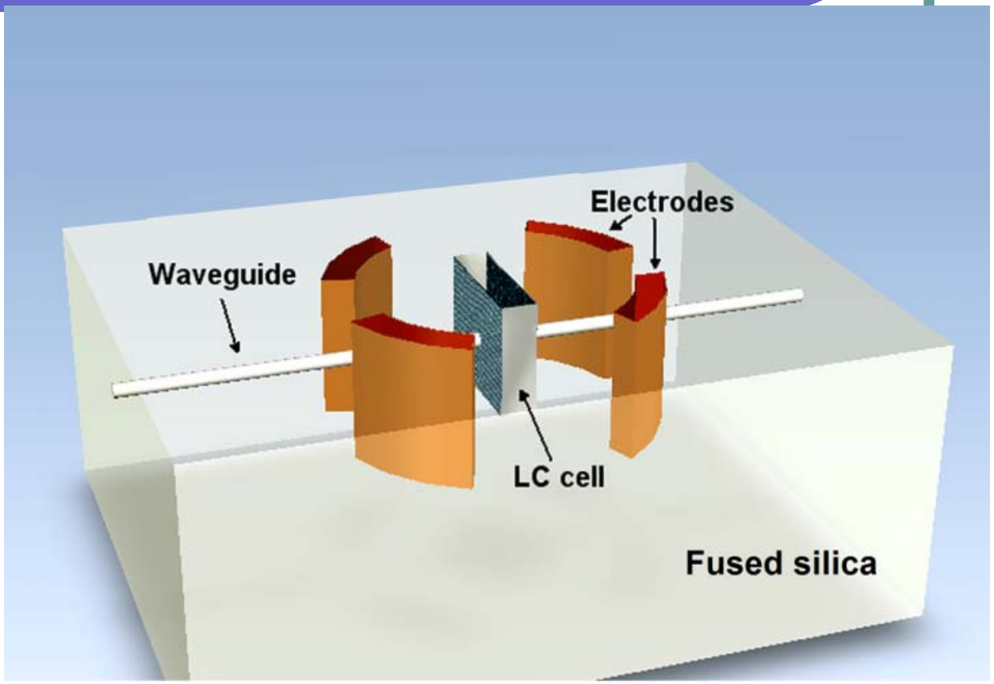
(a)光波导端面的光学显微图和(b) 亮场光强分布, (c)和(d)分别为加0 V和19 V的直流电压时输出端的近场光强分布

波导传播损耗 ~1.2 dB/cm

消光比 ~9.2 dB

基于飞秒激光诱导纳米结构的集成液晶电光调制器





Y. Liao, et al, Chem. Phys. Lett., 498, 188 (2010)

Y. Liao, et al, Opt. Mater. Express, 3, 1698 (2013）

提纲

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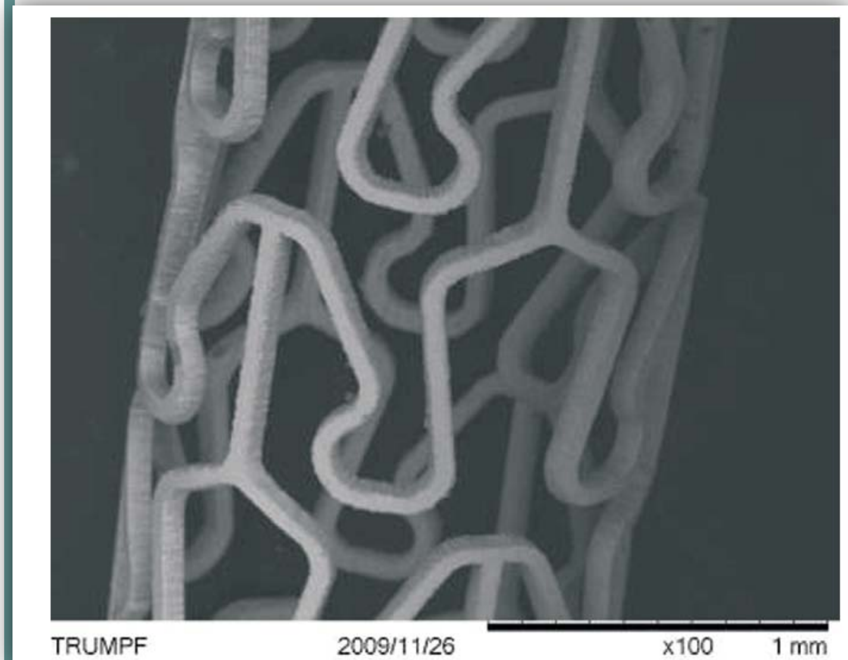
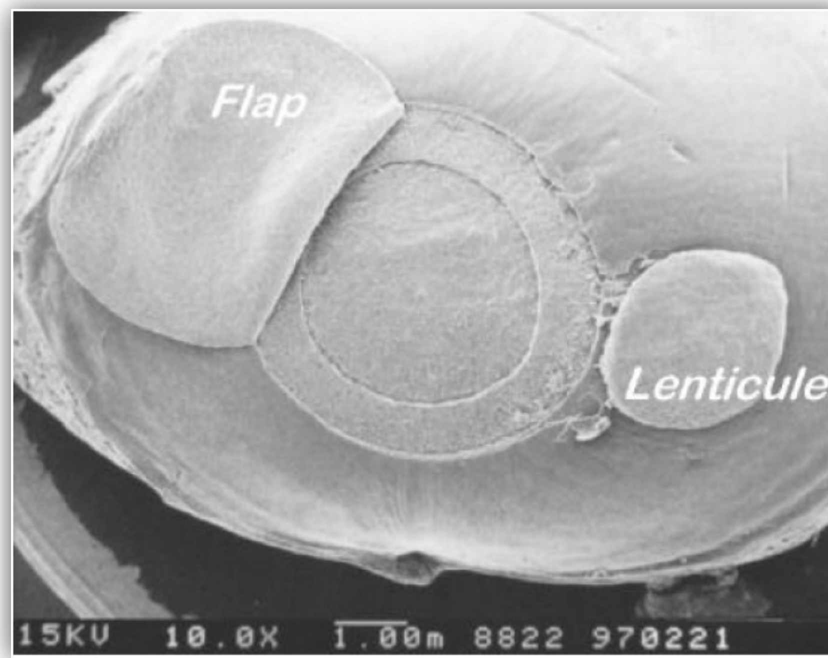
工业应用----生物医疗



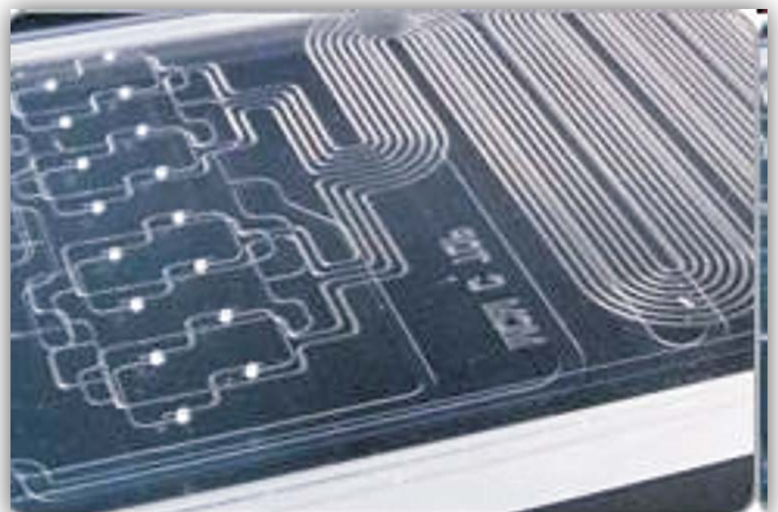
生物支架加工

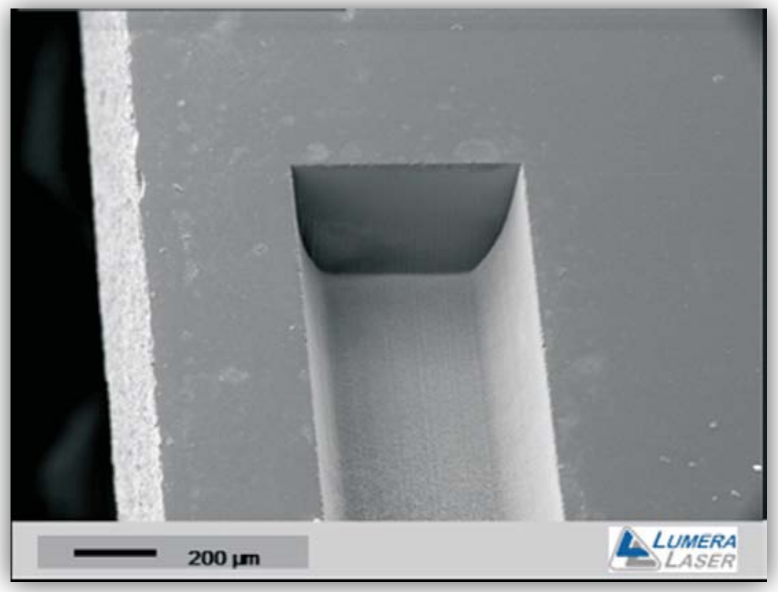


眼科手术

F. Dausinger and S. Sommer, "Ultrafast Laser Processing: From Micro- to Nanoscale Industrial Applications", in "Ultrafast Laser Processing: From Micro- to Nanoscale" , Edited by K. Sugioka and Y. Cheng, Pan Stanford Publishing Pte. Ltd. , 2013

工业应用----生物医疗

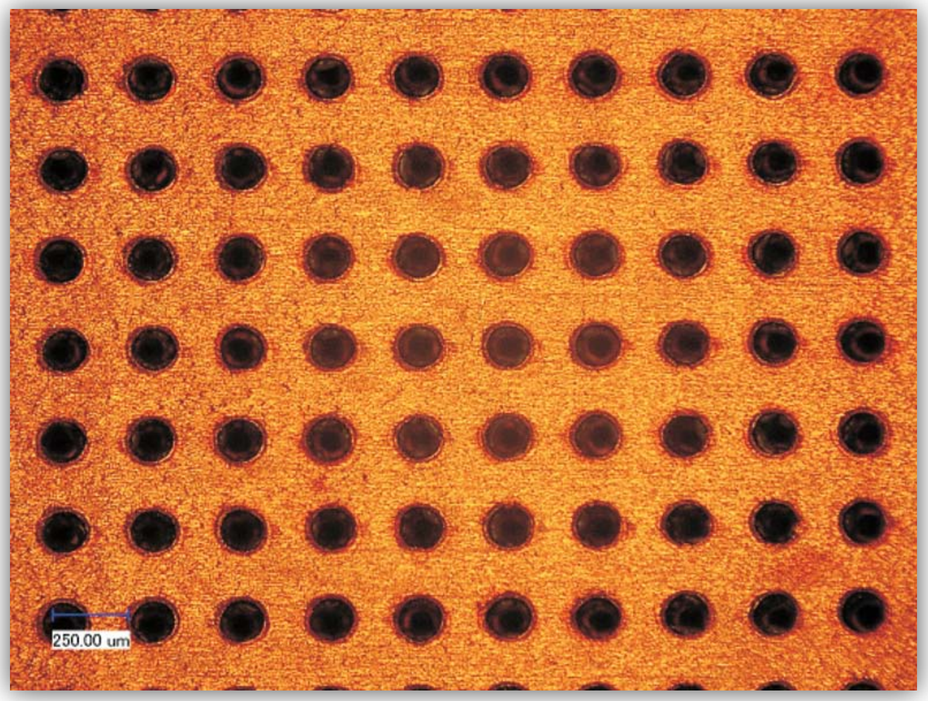




微流芯片加工

F. Dausinger and S. Sommer, "Ultrafast Laser Processing: From Micro- to Nanoscale Industrial Applications", in "Ultrafast Laser Processing: From Micro- to Nanoscale" , Edited by K. Sugioka and Y. Cheng, Pan Stanford Publishing Pte. Ltd. , 2013

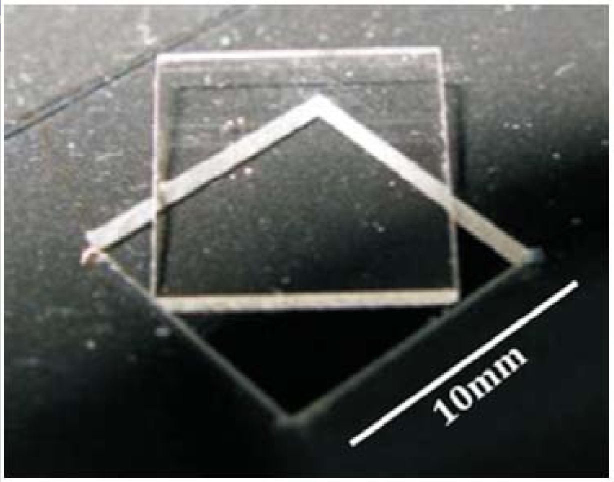
工业应用----半导体IC行业



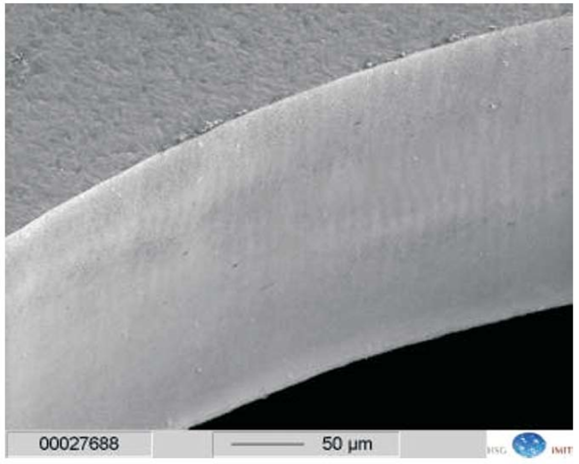
High-precision drilling-PCB

F. Dausinger and S. Sommer, "Ultrafast Laser Processing: From Micro- to Nanoscale Industrial Applications", in "Ultrafast Laser Processing: From Micro- to Nanoscale" , Edited by K. Sugioka and Y. Cheng, Pan Stanford Publishing Pte. Ltd. , 2013

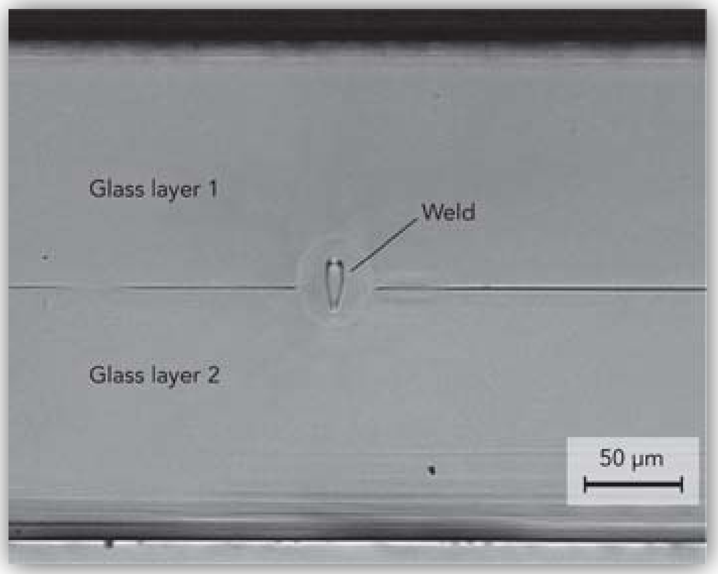
工业应用----半导体IC行业



Glass cutting



Silicon cutting



Glass welding

http://www.industrial-lasers.com/

工业应用----半导体IC行业

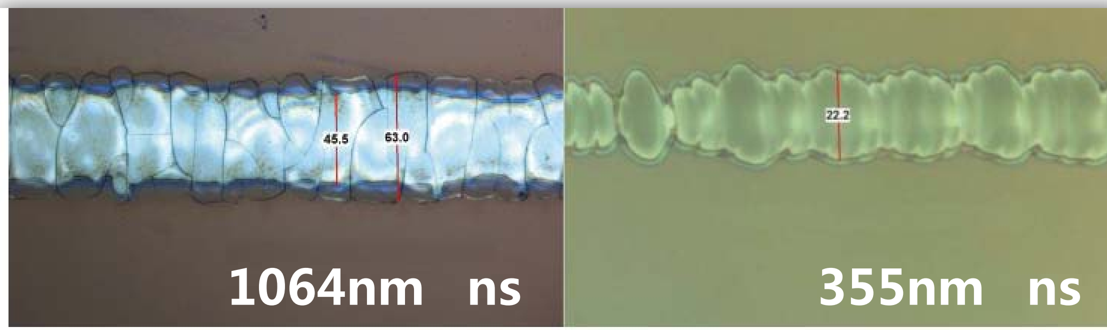


FIGURE 5: ITO on glass substrates (top view). Nanosecond laser at 1064 nm (left), nanosecond laser at 355 nm (right).

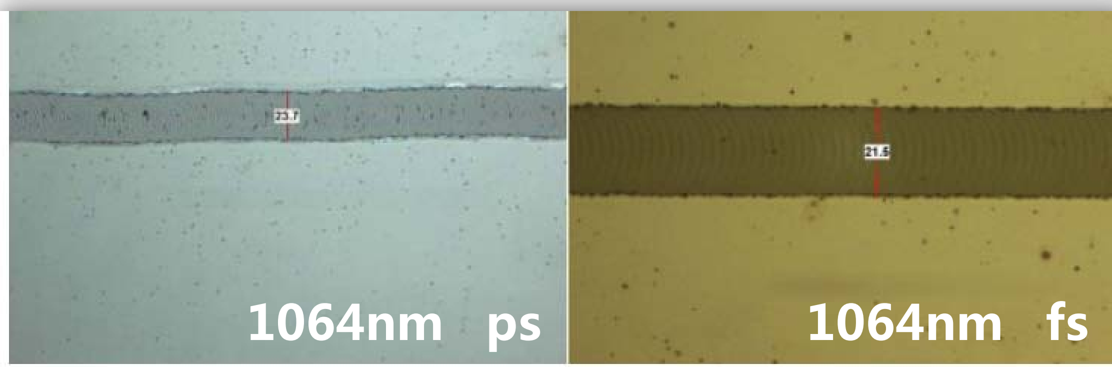
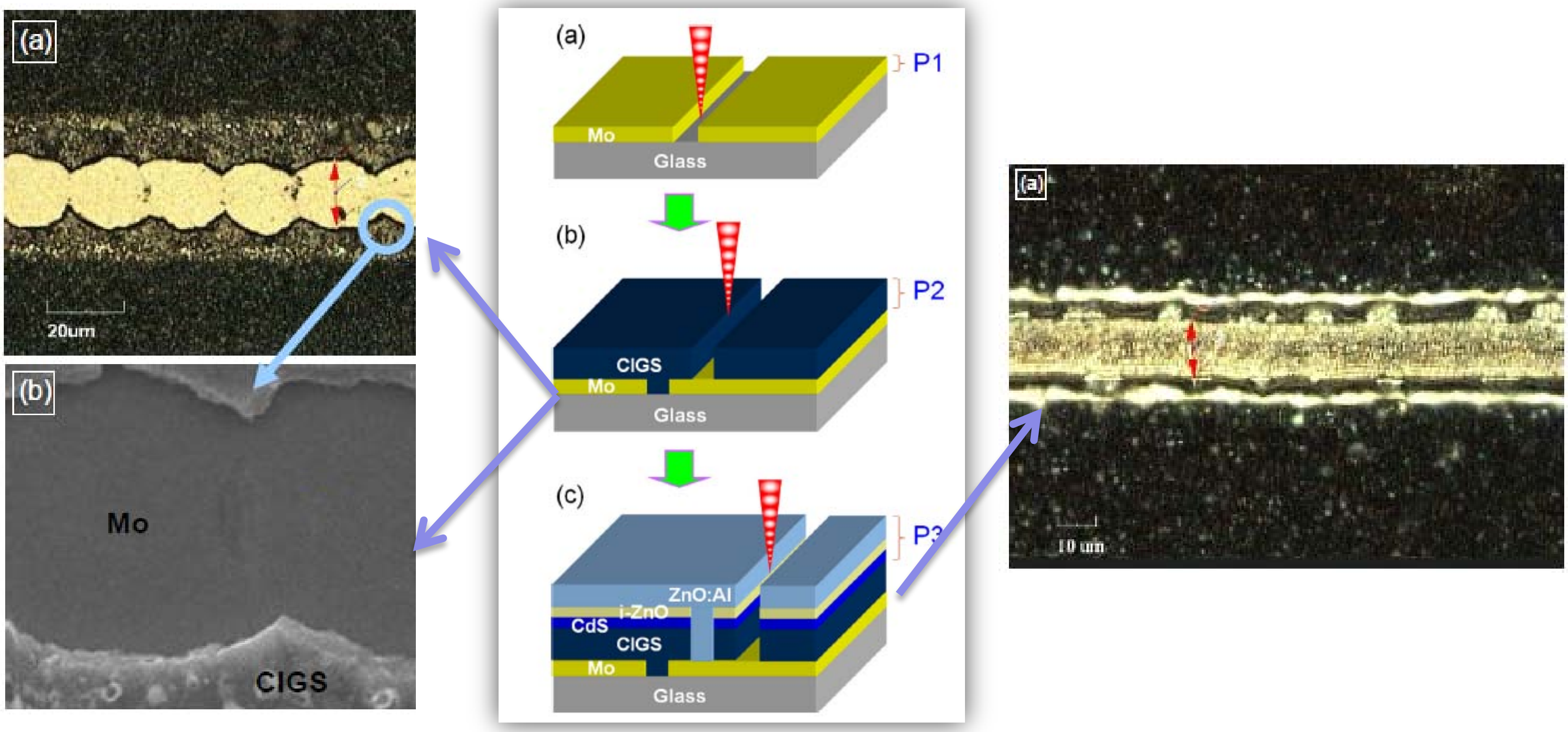


FIGURE 7: ITO on PET foil substrates (top view). Picosecond laser at 1064 nm (left), femtosecond laser at 1024 nm (right).

Patterning of ITO layers

M. Gebhardt, et al., Laser Technik J. 8, 29 (2011)

工业应用----半导体IC行业



CIGS（铜铟镓硒）薄膜太阳能电池加工

T. L. Chang, et al., Microelectron. Eng 110, 381385 (2013)

工业应用----汽车行业

汽车引擎气缸内部微结构

Th. Bauer, et al., Technical Digest of LPM 2010 (JLPS), pp.127

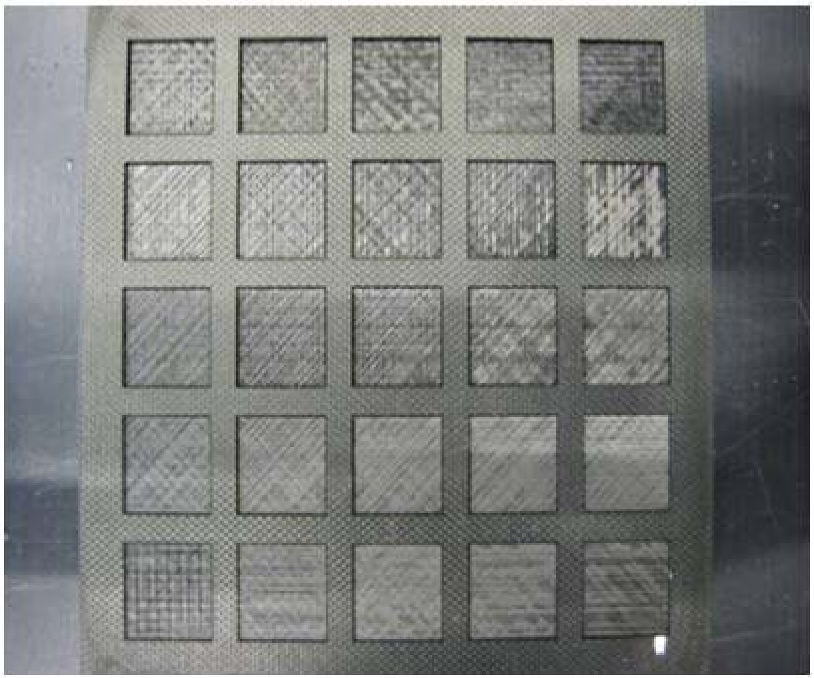
工业应用----其他

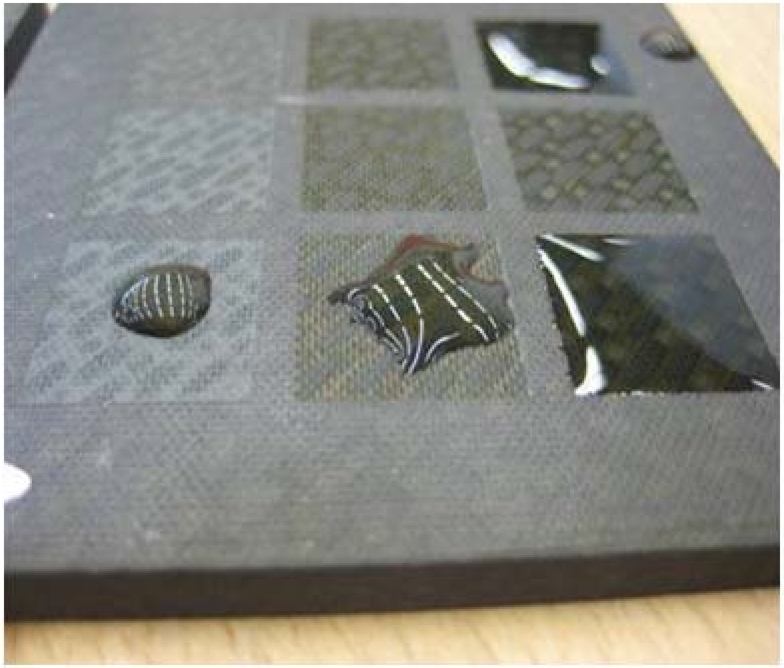
Laser cleaning

B. Becker, et al., Proceedings of LAMP 2013

工业应用----其他

Laser surface pretreatment

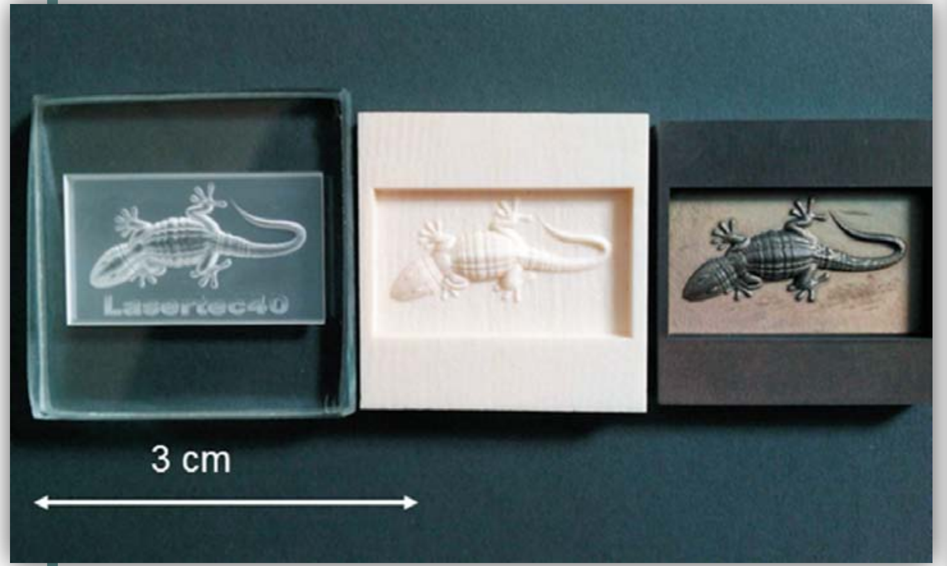




B. Becker, et al., Proceedings of LAMP 2013

工业应用----其他

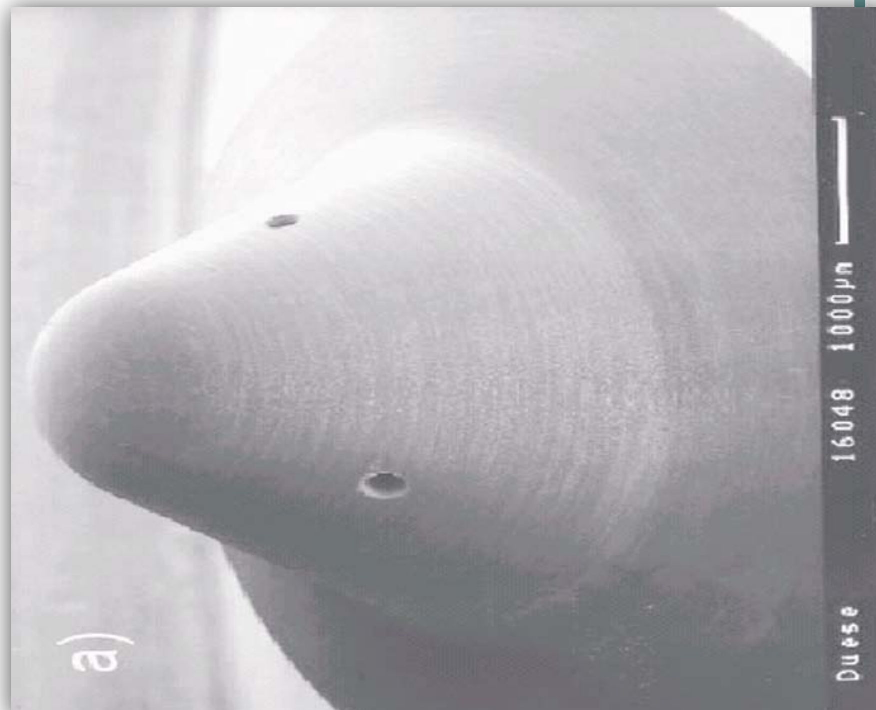
浮雕和铸模成型 (Embossing and moulding)



F. Dausinger and S. Sommer, "Ultrafast Laser Processing: From Micro- to Nanoscale Industrial Applications", in "Ultrafast Laser Processing: From Micro- to Nanoscale" , Edited by K. Sugioka and Y. Cheng, Pan Stanford Publishing Pte. Ltd. , 2013

工业应用----其他

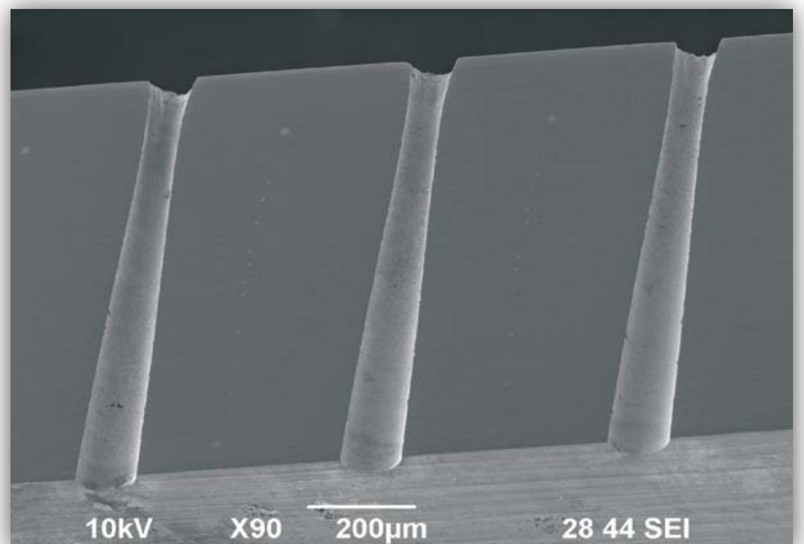
High-precision drilling-injection nozzles

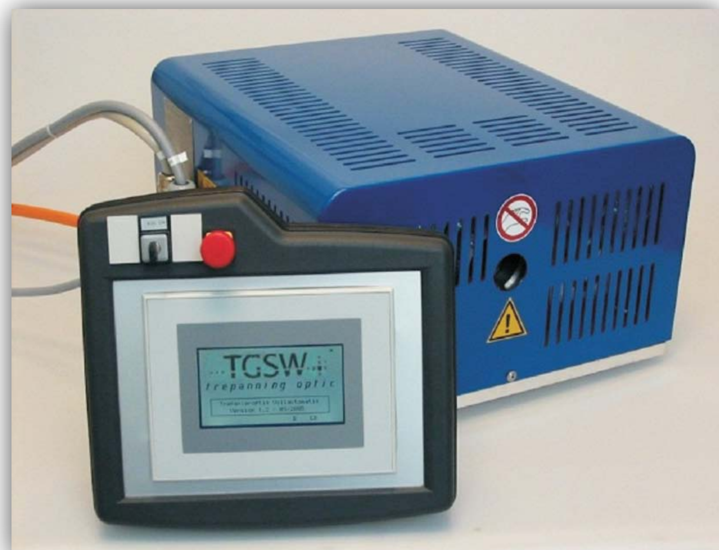


F. Dausinger and S. Sommer, "Ultrafast Laser Processing: From Micro- to Nanoscale Industrial Applications", in "Ultrafast Laser Processing: From Micro- to Nanoscale" , Edited by K. Sugioka and Y. Cheng, Pan Stanford Publishing Pte. Ltd. , 2013

工业应用----其他

High-precision drilling- negative conical holes





F. Dausinger and S. Sommer, "Ultrafast Laser Processing: From Micro- to Nanoscale Industrial Applications", in "Ultrafast Laser Processing: From Micro- to Nanoscale" , Edited by K. Sugioka and Y. Cheng, Pan Stanford Publishing Pte. Ltd. , 2013

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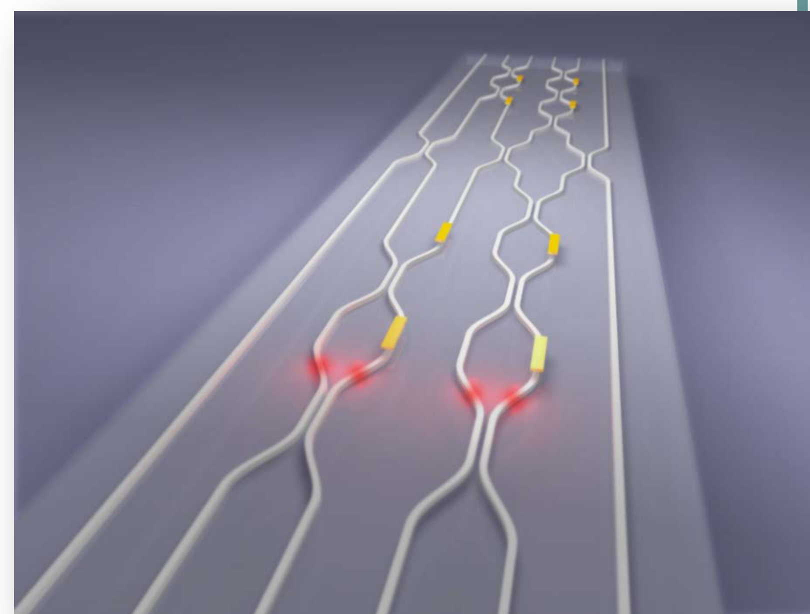
总结和展望

Lab on a chip

http://www.gene-quantification.de/lab-on-chip.html

Advanced photonic circuit



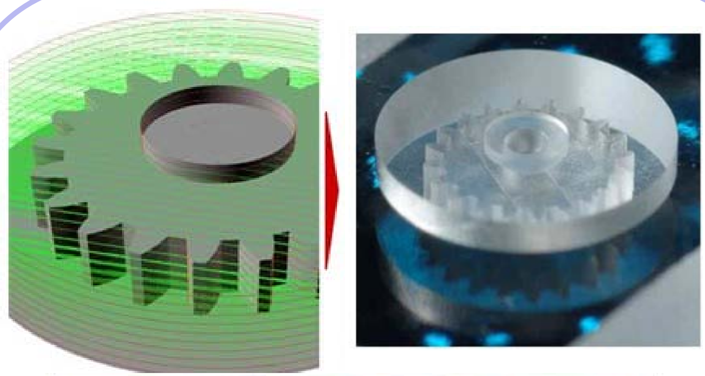
http://physics. org

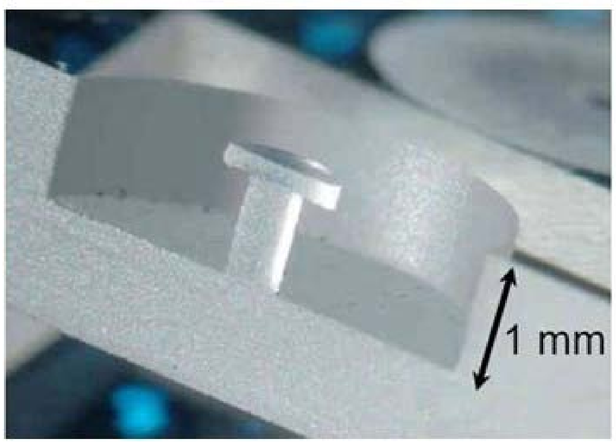
SIOM

State Key Laboratory of High Field Laser Physics, SIOM

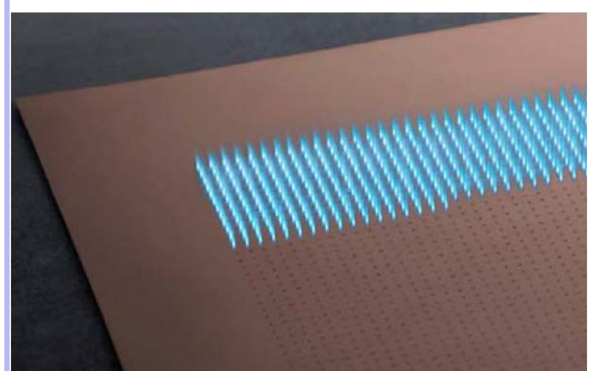
总结和展望

3D substractive printing (激光三维减材打印)





High-throughput, high-precision micro- and nanomachining



Laser drilling, laser cutting, micro milling, marking, engraving, scribing and dicing

J. Gottmann, et al., J. Laser Micro Nanoeng.8, 15 (2013)   B. Becker, Proceedings of LAMP 2013

谢谢！

Thank you for your attention!

SIOM

State Key Laboratory of High Field Laser Physics, SIOM

Ideal industrial ultrafast lasers

1. Ease of maintenance (reliability & stability) and operation [使用、维护方便]
2. High average power (hundreds to a few thousands watts) [高平均功率]
3. High repetition rate (100 kHz ~ 10 MHz) [高重复频率]
4. Conservative pulse duration (less than ~500 fs, or ideally < 300 fs) [脉宽短于500 飞秒]
5. Conservative pulse energy (> 10 μJ) [脉冲能量大于10 微焦]
6. High beam quality ($M^2 < 1.5$) [高光束品质]
7. Wavelength tunability (UV to IR, e. g., ~400 nm ~2 μm) [波长在紫外到红外波段内可调谐]
8. Reasonable photon cost (a few times of that of the nanosecond lasers) [容易承受的价格]…