

2443-15

**Winter College on Optics: Trends in Laser Development and Multidisciplinary  
Applications to Science and Industry**

*4 - 15 February 2013*

**Femtosecond laser micromachining - introduction  
(part 1)**

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 POLITECNICO DI MILANO



# Femtosecond laser micromachining

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## Outline of the presentation

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- Nonlinear light-matter interaction, photoinduced material modifications
- Femtosecond laser optical waveguide writing
- Fabrication of integrated photonic devices
  - passive devices
  - active devices
  - polarisation control

## What will come next

- Fabrication of microchannels and fully integrated microoptofluidic devices
- Surface structuring and texturing
- Two-photon polymerisation

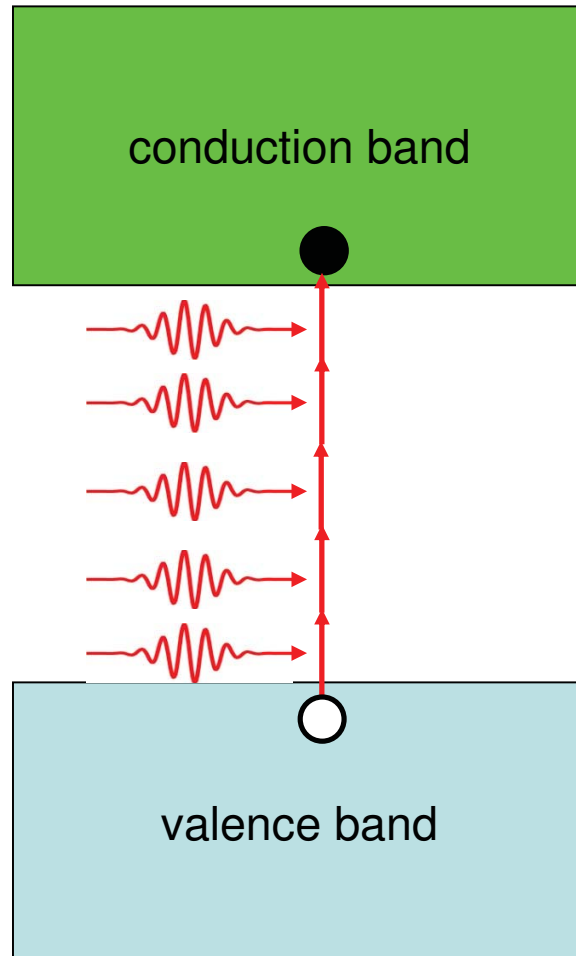


## **Material modification following nonlinear light absorption**



# Multiphoton ionization

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- Simultaneous absorption of  $k$  photons brings electron from valence to conduction band

$$\frac{dn}{dt} = \sigma_k I^k(t)$$

$n(t)$  electron density

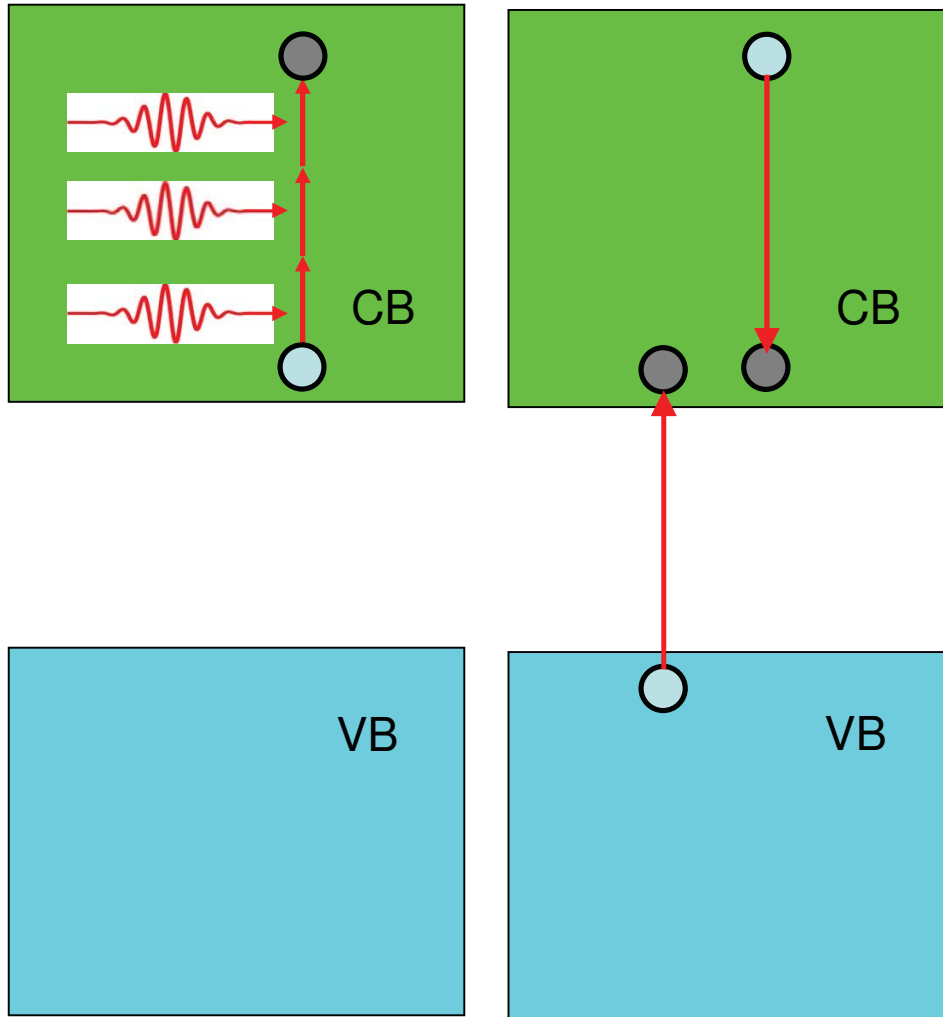
$I(t)$  laser intensity

$\sigma_k$   $k$ -photon absorption cross section



## Avalanche ionization

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- Free electrons in the conduction band are accelerated by the laser field until they have enough kinetic energy to kick another electron into the conduction band

$$\frac{dn}{dt} = \alpha I(t) n(t)$$

$\alpha$  avalanche ionization coefficient



### Femtosecond absorption

- The peak power is sufficient to trigger, in the focus, **multiphoton ionization** which provides a **seed of electrons** in the conduction band
- The electrons are accelerated by the laser and **multiplied by avalanche ionization**  $\Rightarrow$  **deterministic** and highly reproducible process

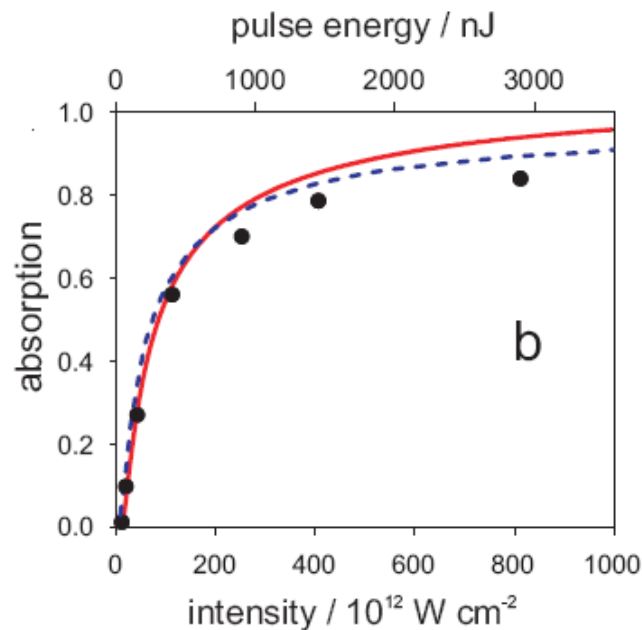
### Long pulse absorption

- The peak power is too low for **multiphoton ionization**
- Avalanche ionization initiated by spurious free electrons in the conduction band from defects or impurities  $\Rightarrow$  **poorly reproducible** process



## Femtosecond absorption

- The peak power is sufficient to trigger, in the focus, **multiphoton ionization** which provides a **seed of electrons** in the conduction band
- The electrons are accelerated by the laser and **multiplied by avalanche ionization**  $\Rightarrow$  **deterministic** and highly reproducible process



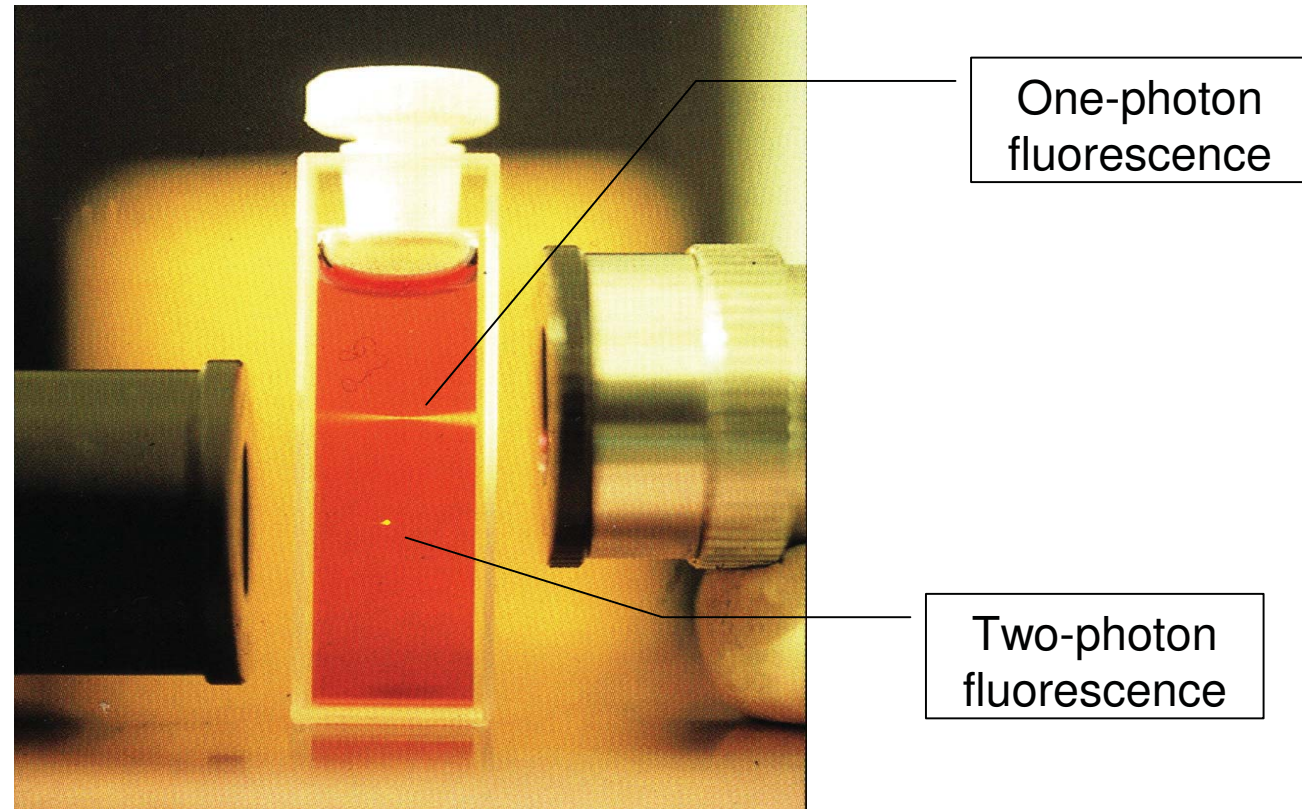
Femtosecond pulse absorption as a function of peak intensity (Rayner *et al.*, Opt. Express **13**, 3208 (2005))

**Highly localized and reproducible deposition of energy in the focus of the laser beam**



## One photon vs multiphoton absorption

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Light is absorbed only in the focus, where the intensity is sufficient

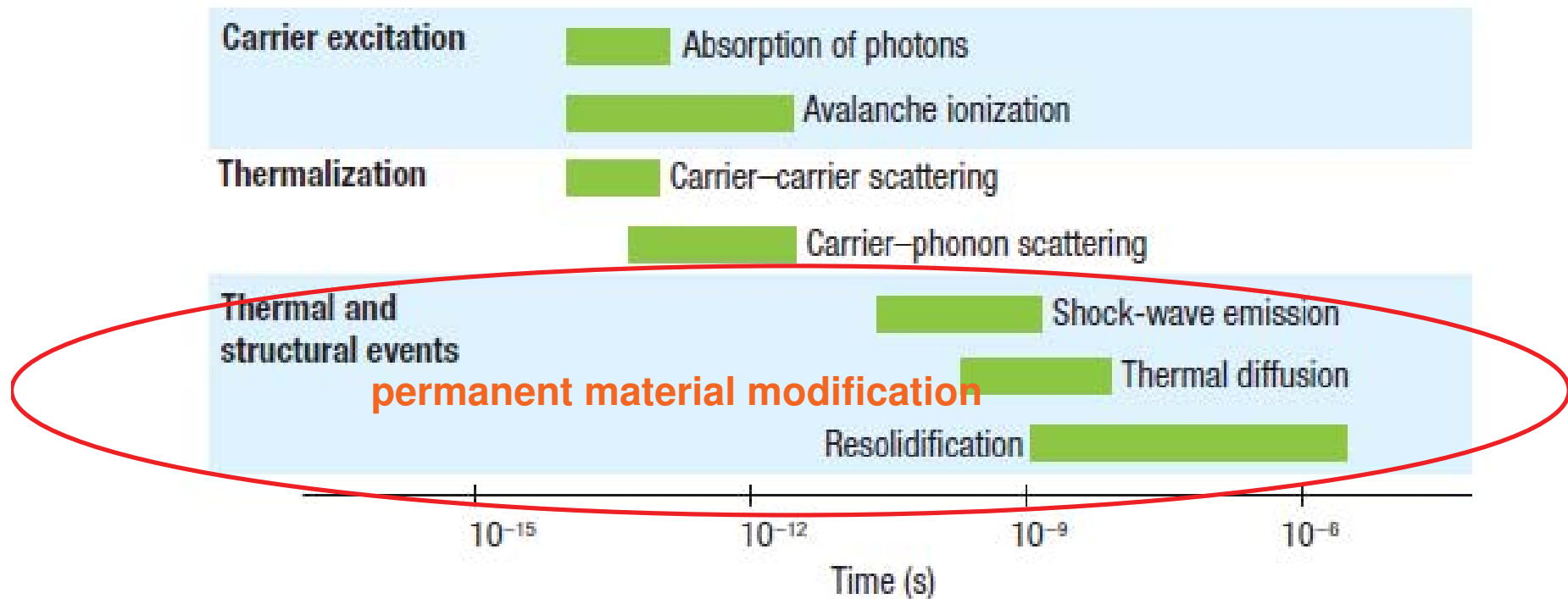
W. Denk et al., Science **248**, 73 (1990)



# What happens following nonlinear light absorption?

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Timescales of light-matter interaction in transparent materials

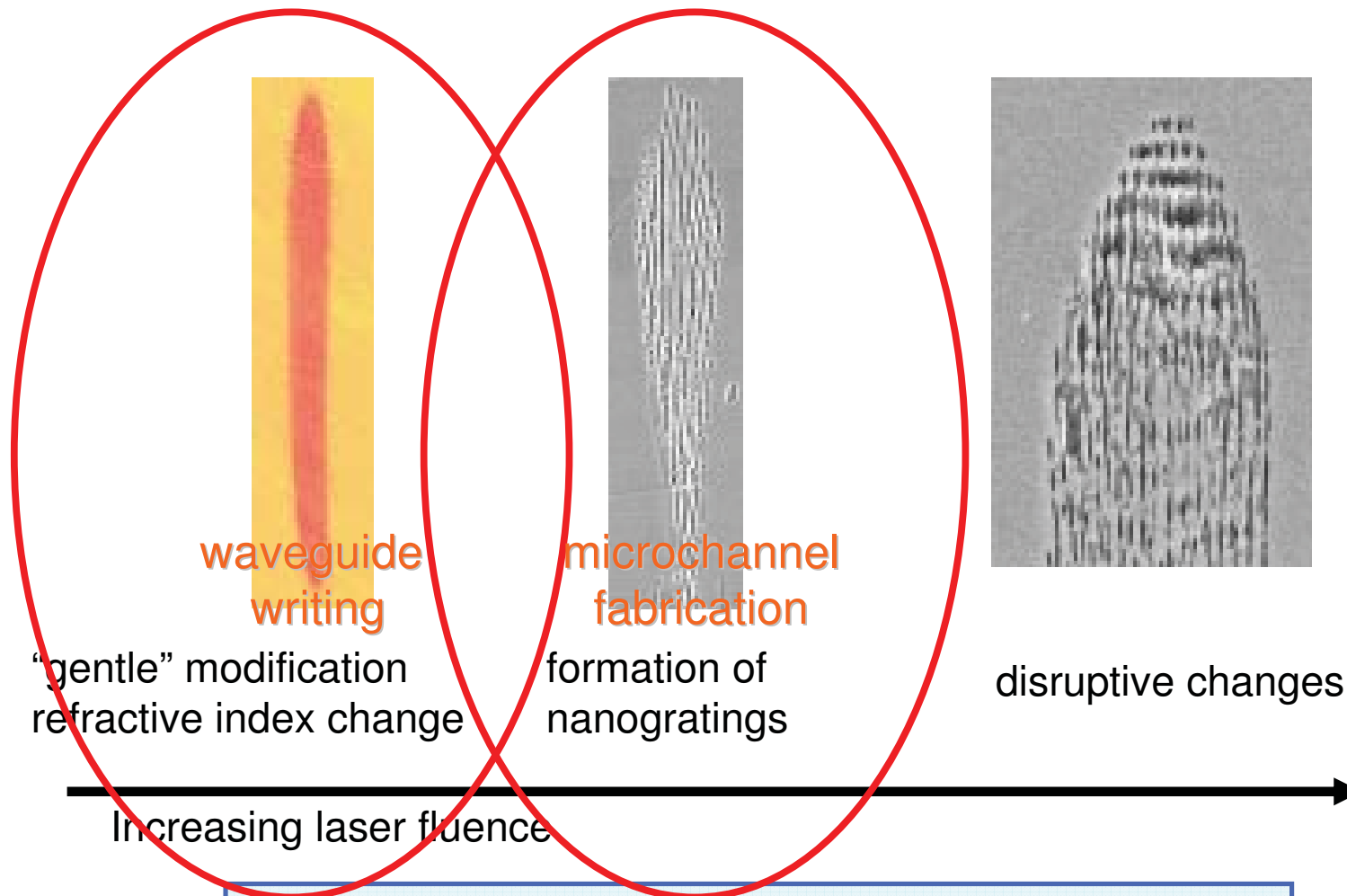


R. Gatass and E. Mazur, Nature Photonics **2**, 219 (2008)



## Regimes of material modification

10



R. Taylor et al., Laser Photonics Reviews 2, 26 (2008)



## **Femtosecond laser optical waveguide writing**

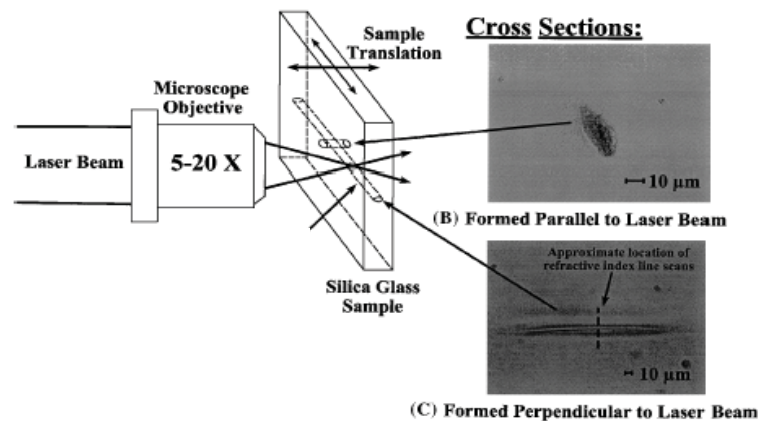


November 1, 1996 / Vol. 21, No. 21 / OPTICS LETTERS 1729

## Writing waveguides in glass with a femtosecond laser

K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao

*Hirao Active Glass Project, Exploratory Research for Advanced Technology, Research Development Corporation of Japan,  
15 Mori Moto-Cho, Shimogamo, Sakyo-Ku, Kyoto G06, Japan*



Seminal paper by Hirao et al., demonstrating permanent positive refractive index changes

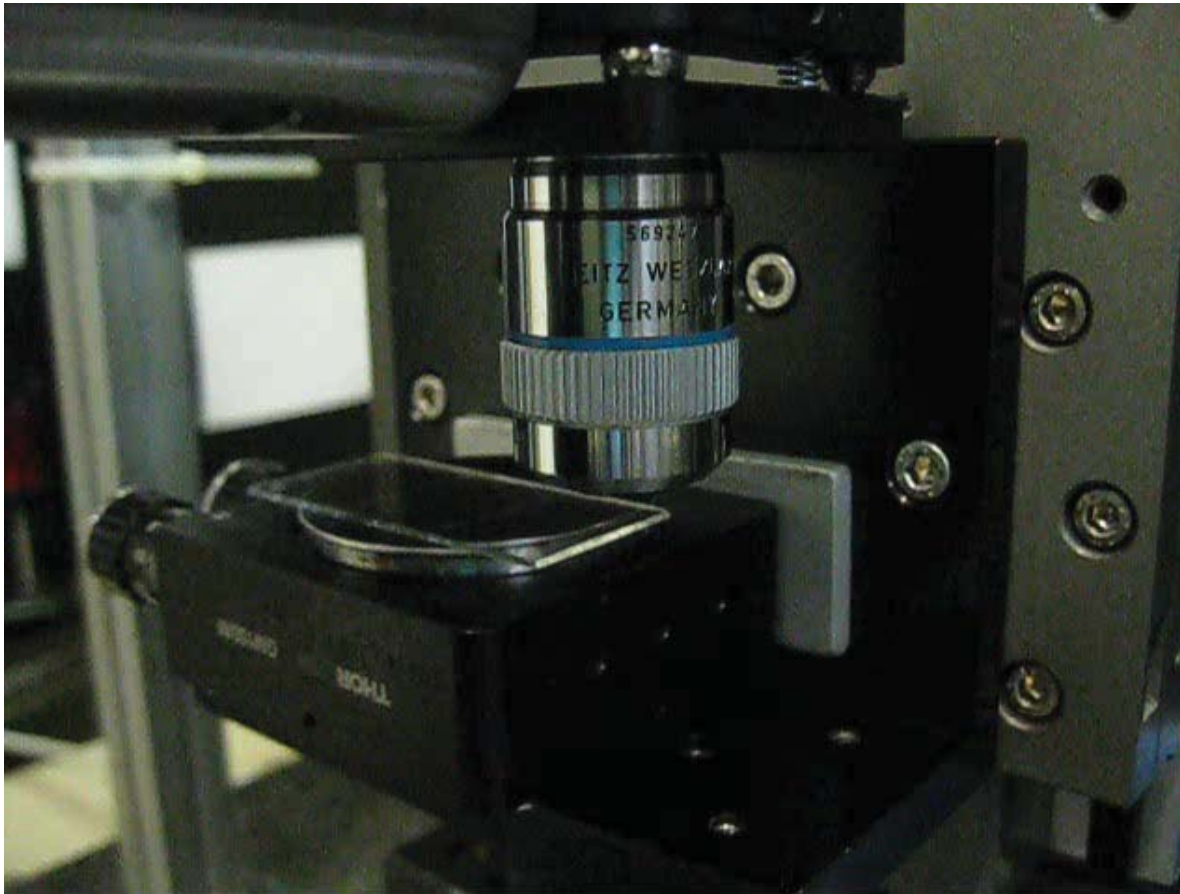


Not yet fully understood, several mechanisms have been proposed such as:

- **Structural modifications**, i.e. changes in the structure of the glass network
- **Color center formation**, with UV absorption causing a refractive index change through Kramers-Krönig
- **Melting and rapid resolidification (quenching)**, causing regions of material densification

These mechanisms may act simultaneously.

A.M. Streltsov et al., J. Opt. Soc. Am. B **19**, 2496 (2002)



## ADVANTAGES

Single step, no need for photolithography

Three-dimensional photonic circuits

Fast and cheap prototyping

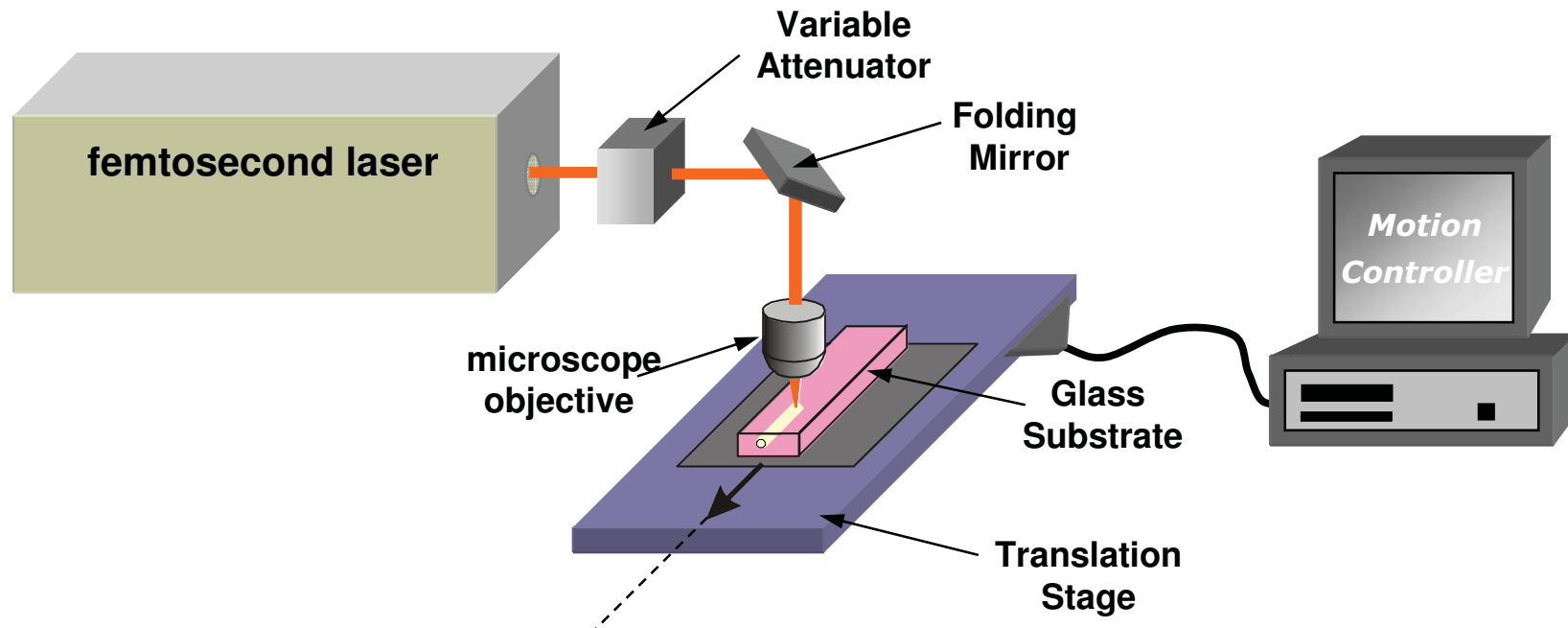
Applicable to a wide variety of substrates

Waveguides are fabricated by **translation** of the sample.



## Waveguide fabrication setup

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- The basic setup is remarkably simple: laser, focusing optics, computer-controlled translation stage



- **Amplified Ti:Sapphire systems:** 100-200 fs long pulses at 800nm, few  $\mu\text{J}$  energies per pulse, 1-200 kHz repetition rate

### single-pulse regime

- **Diode-pumped fiber or bulk Yb lasers:** 300-400 fs long pulses at 1040nm,  $< 1 \mu\text{J}$  energies per pulse, 200 kHz-2 MHz repetition rate

### cumulative regime

- **Long-cavity Ti:Sapphire oscillators:** 10-50 fs long pulses at 800nm, tens of nJ energy per pulse, 4-25 MHz repetition rate

**Cumulative regime:** pulse period much shorter than heat diffusion time out of the focal volume

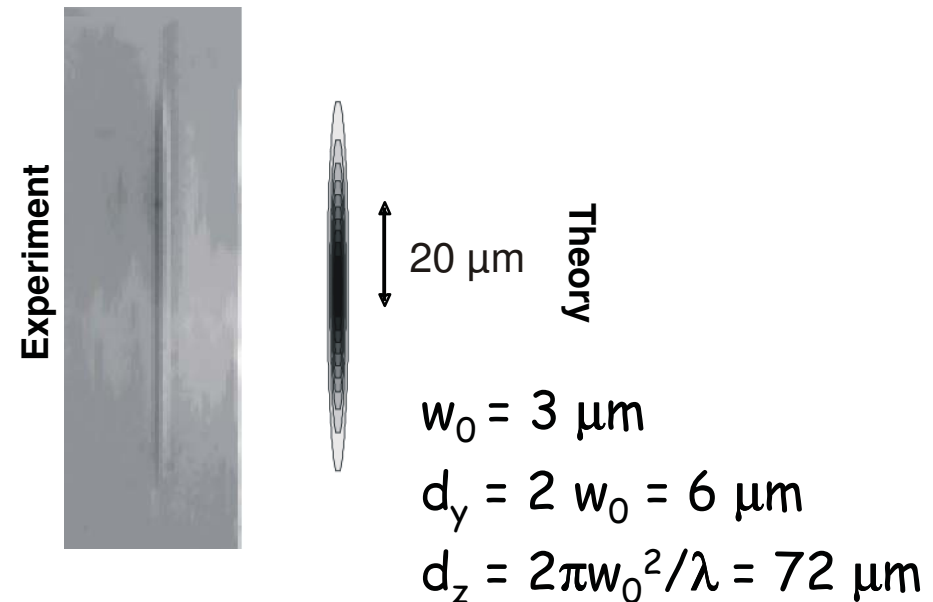
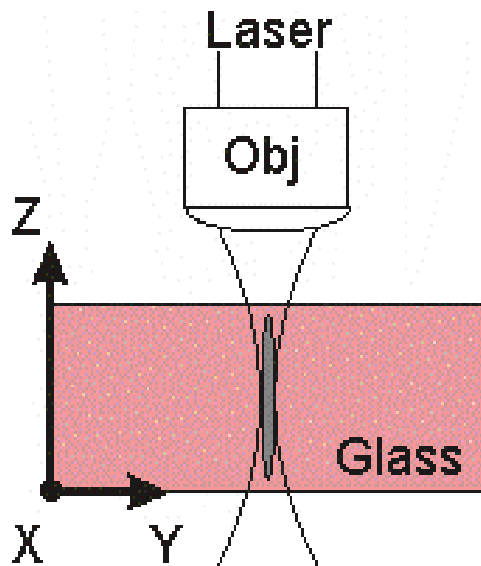
repetition rate



## Single-pulse regime: the asymmetry problem

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- In transverse geometry, writing with low repetition rate systems provides waveguides with an intrinsically asymmetric cross section → very poor coupling with standard fibers

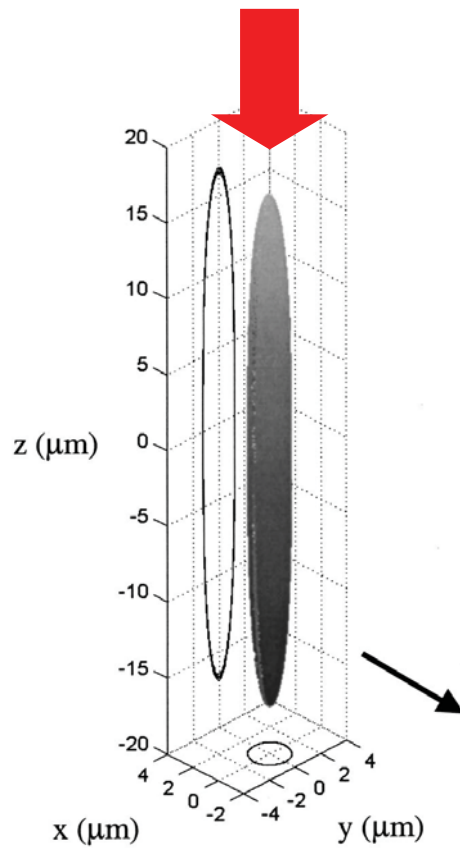


- The confocal parameter is much larger than the focal diameter

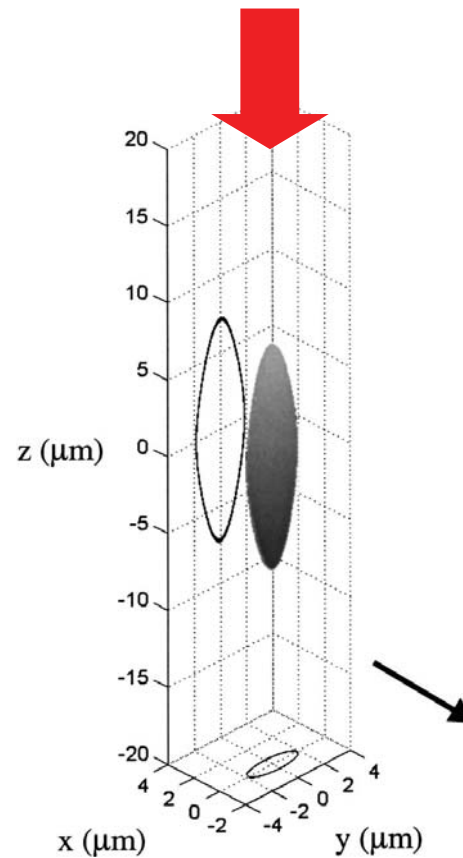


## Solution: astigmatic beam shaping

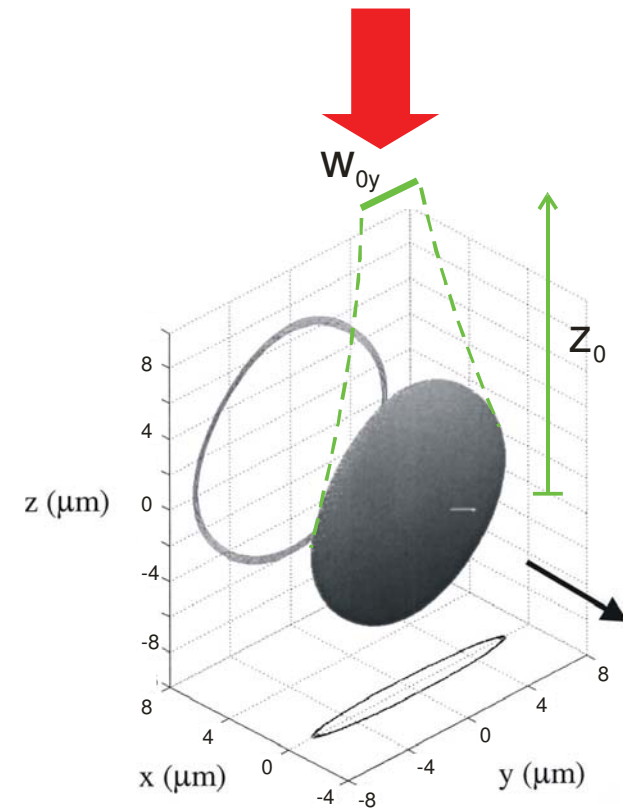
18



Standard beam  
with  $w_0 = 2\mu\text{m}$



Astigmatic beam with  
 $w_{0x} = 1\mu\text{m}$  and  $w_{0y} = 3\mu\text{m}$



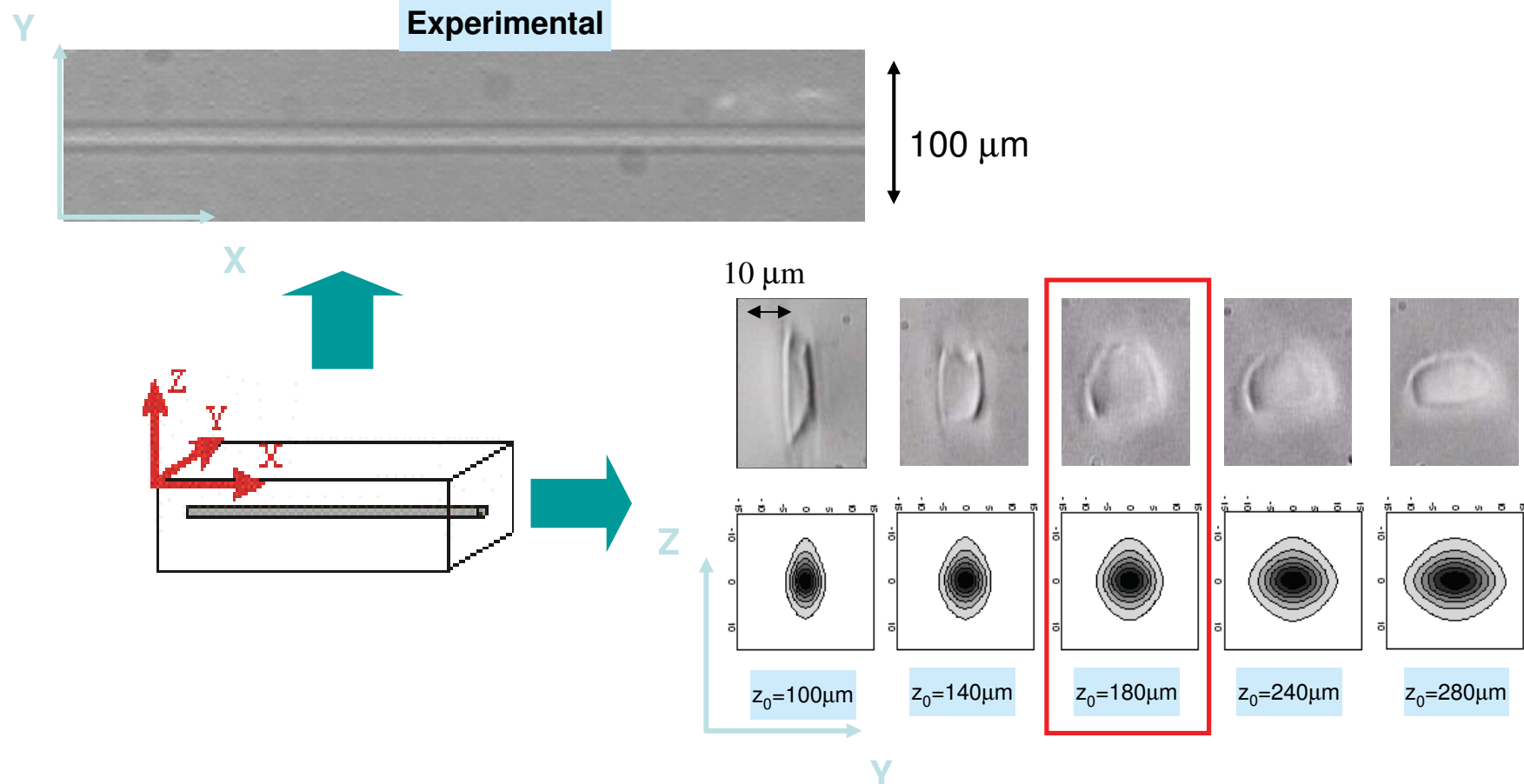
Astigmatic beam with  $w_{0x} = 1\mu\text{m}$   
and  $w_{0y} = 3\mu\text{m}$ , but with an  
offset of  $z_0 = 180\mu\text{m}$

G. Cerullo *et al.*, Optics Letters **27**, 1938 (2002)



# Astigmatic beam shaping: experimental results

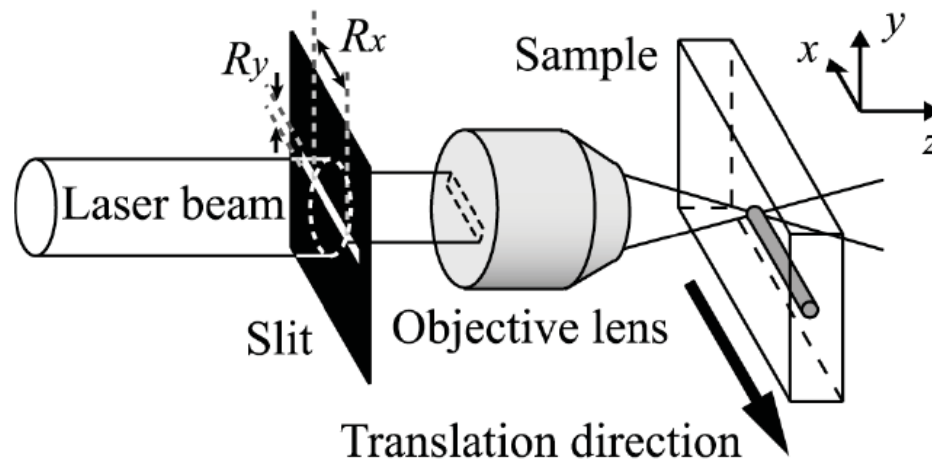
19



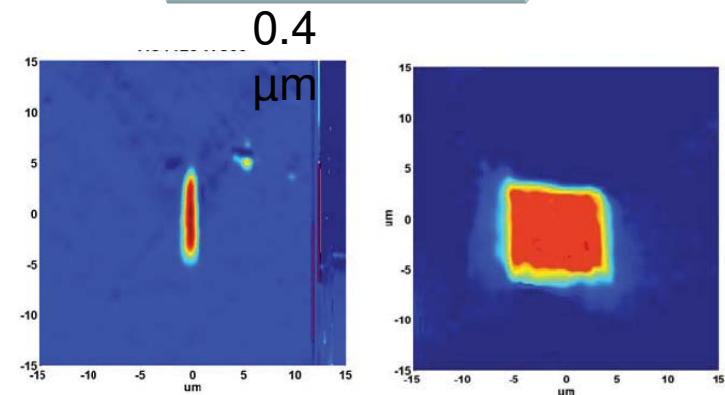
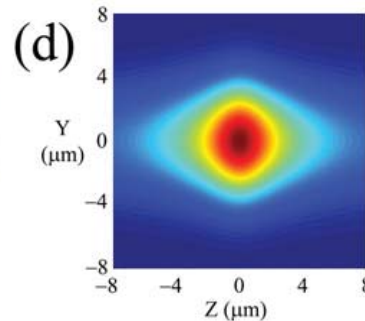
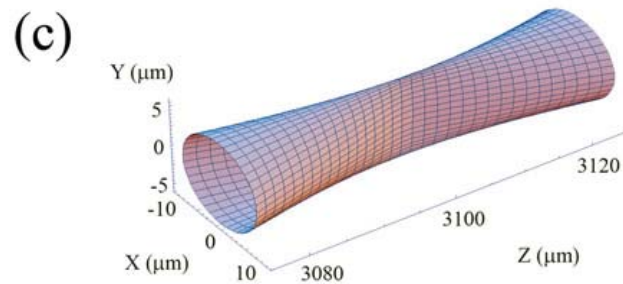
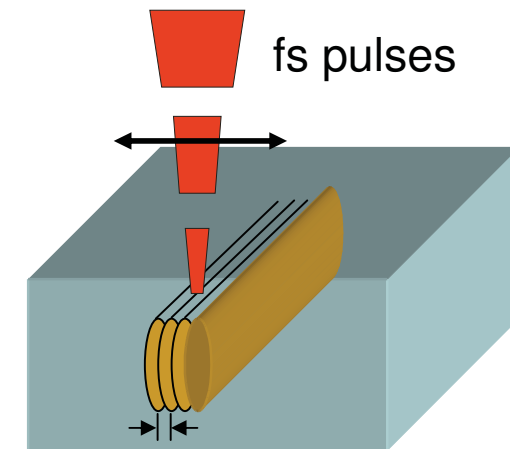
R. Osellame *et al.*, J. Opt. Soc. Am. B **20**, 1559 (2003)



- Slit Beam shaping

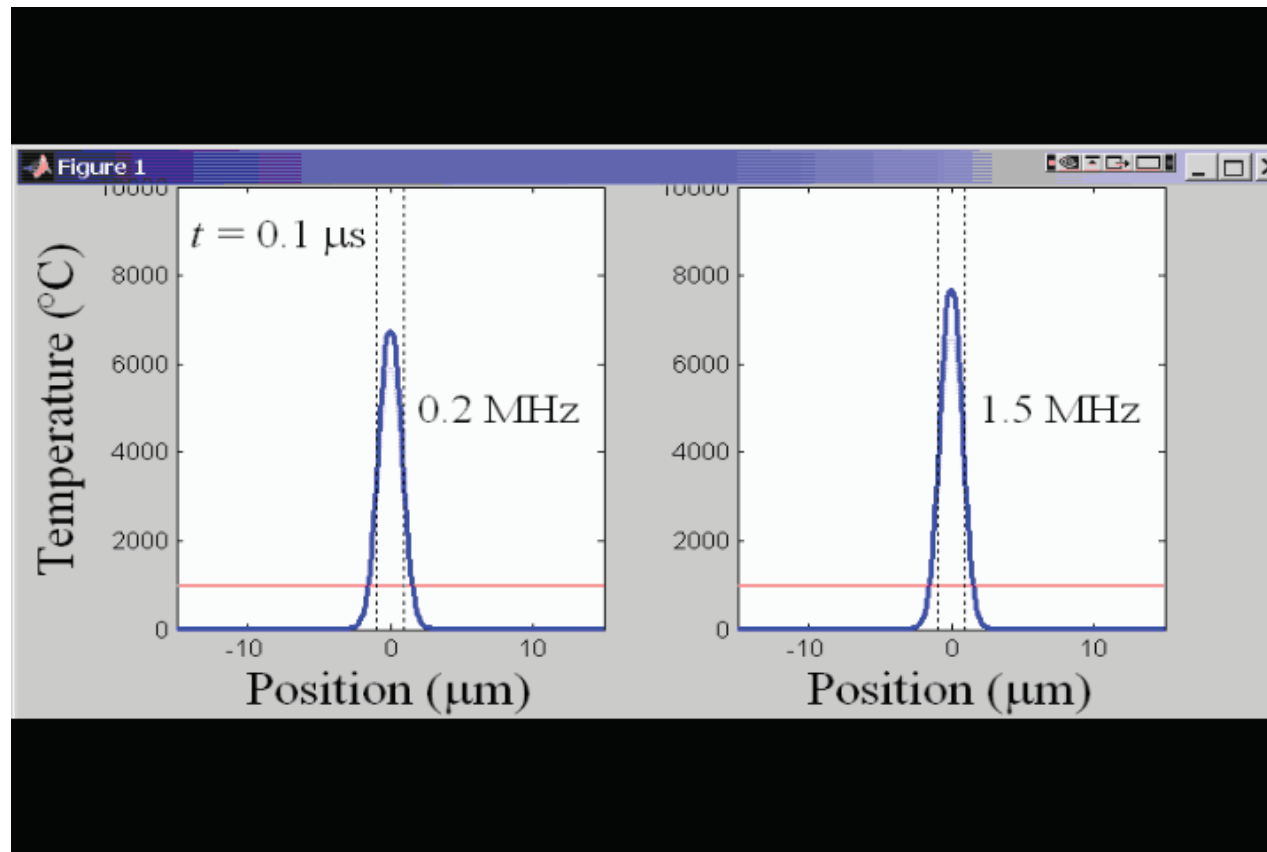


- Multiscan approach



S. Sowa *et al.*, Opt. Expr. **14**, 291 (2006)

Y. Nasu *et al.*, Opt. Lett. **30**, 723 (2005)



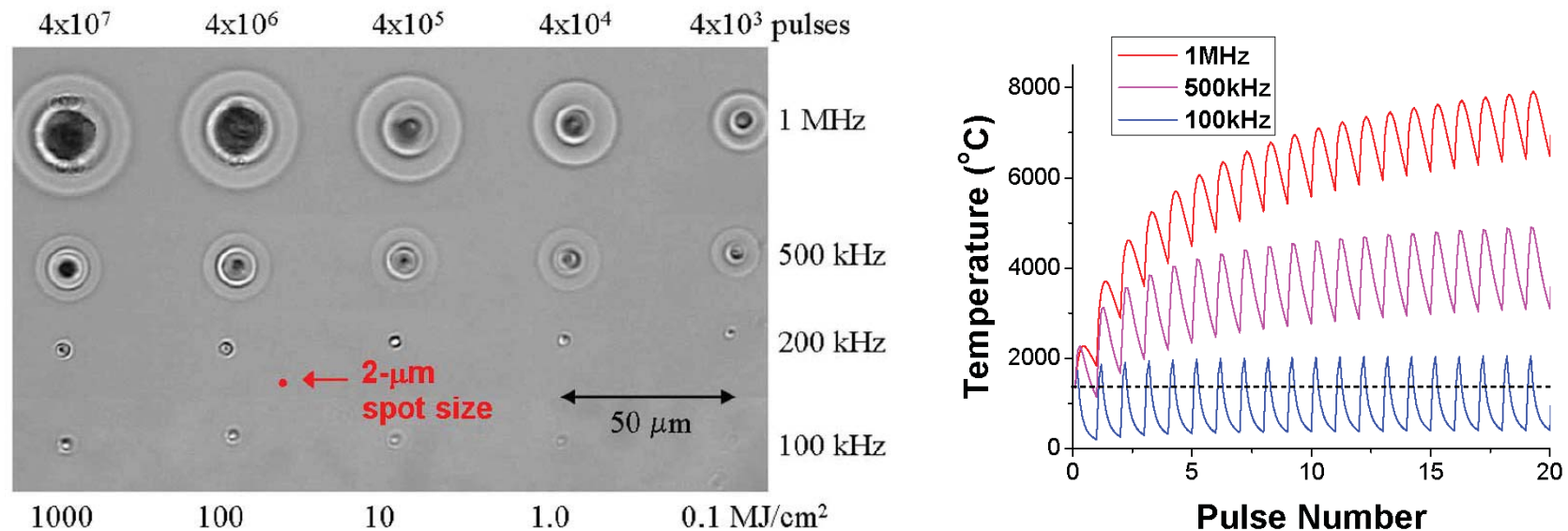
- Borosilicate glass. Heat diffusion time out of focal volume  $\sim 1 \mu\text{s}$

S. Eaton et al., Opt. Express **16**, 9443 (2008)



## Waveguide writing in the cumulative regime

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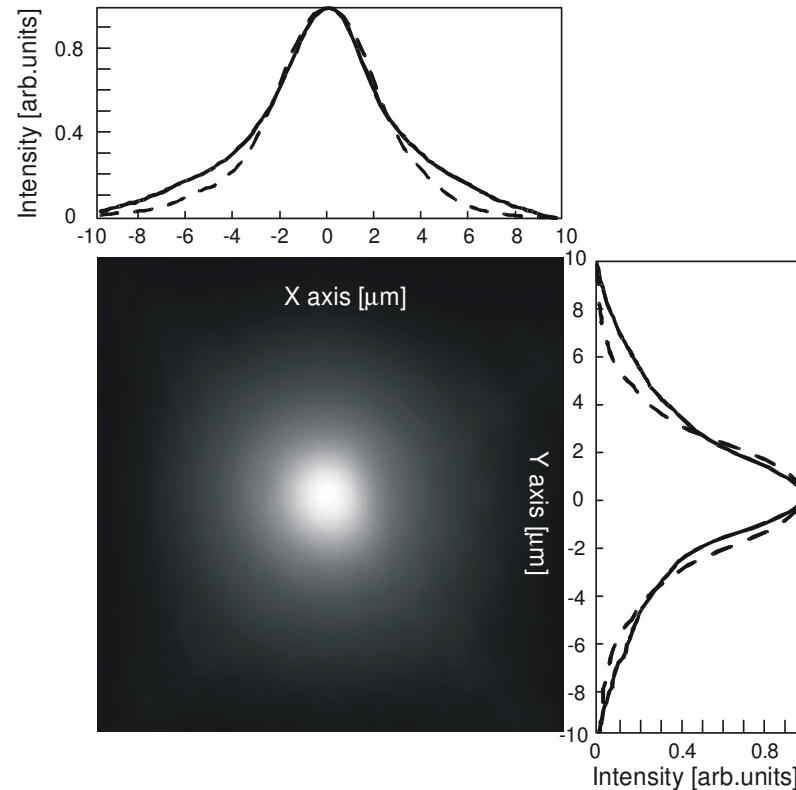
- Due to isotropic heat diffusion, waveguide cross section becomes symmetric
- Waveguide cross-section can be controlled by average power and translation speed

S. Eaton et al., Opt. Express **13**, 4708 (2005)

C. Schaffer et al., Appl. Phys. A **76**, 351 (2003)



## **Passive photonic devices by femtosecond writing**



- Single transverse mode waveguides with high circular symmetry at  $1.5 \mu\text{m}$ .
- Mode matching with standard telecom fibers: 0.2 dB coupling losses (propagation losses  $< 0.2 \text{ dB/cm}$ )



- Output mode characterization (2D intensity profile)

- Losses measurements:  $IL = 10 \log_{10} \left( \frac{P_{out}}{P_{in}} \right)$

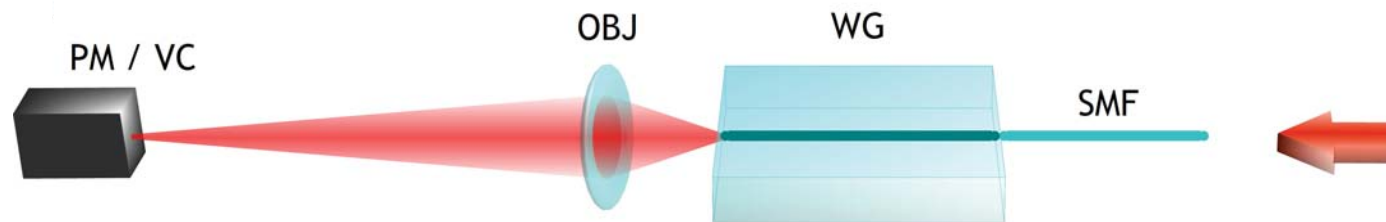
for straight waveguides (length  $l$ ):  $IL = CL + FL + PL \cdot l$

- Polarization behaviour characterization

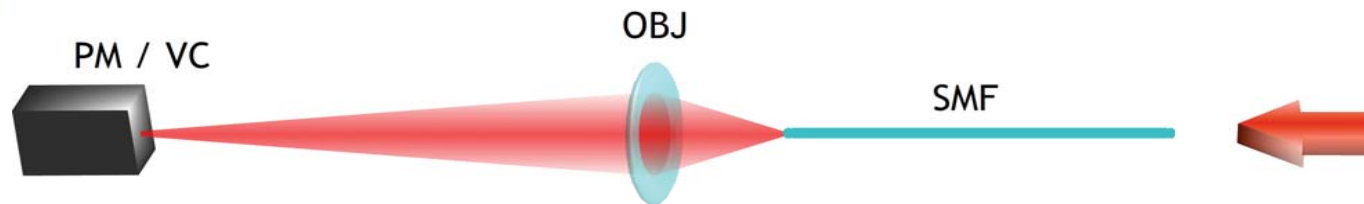


## Output mode profile and losses

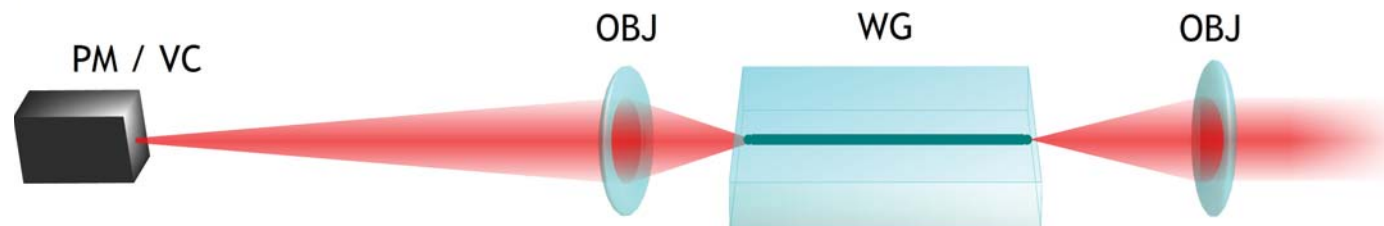
26



Laser light from a single mode fiber (SMF) is coupled to the waveguide (WG). An objective (OBJ) images the output facet of the waveguide onto a power meter head (PM), or onto a videocamera (VC), for measuring the transmitted power, or onto a videocamera (VC), for measuring the intensity profile of the guided mode.



The waveguide is removed and the collection setup is used for measuring the power or the mode profile of a SMF.

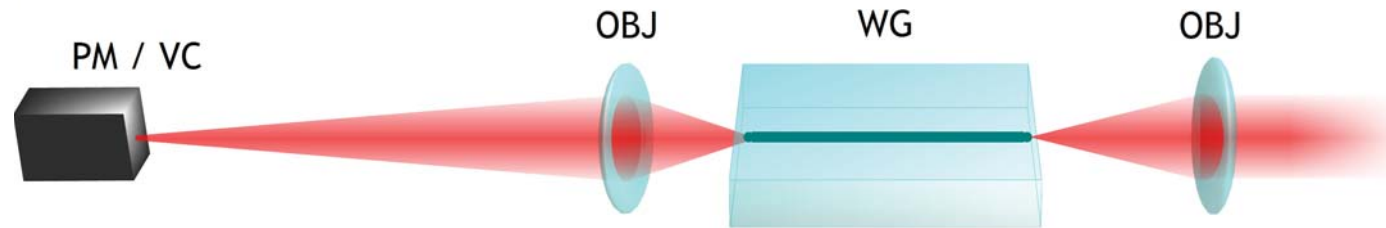


A free-space laser beam is coupled to the waveguide through an objective; the collection setup is analogous to the previous case.

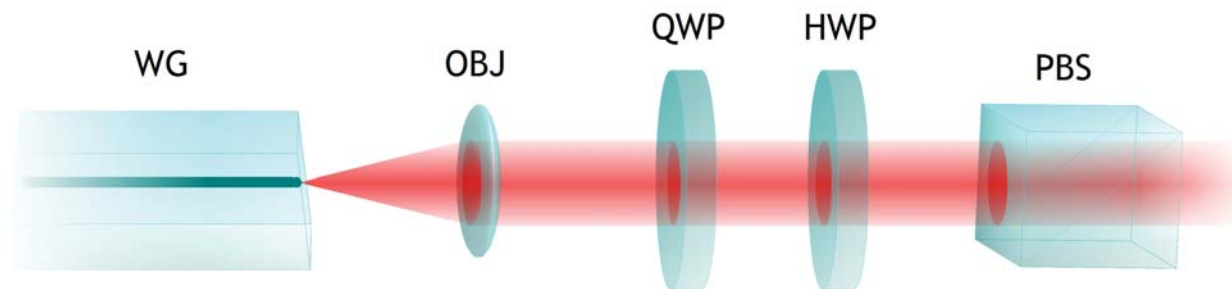


## Polarization behaviour

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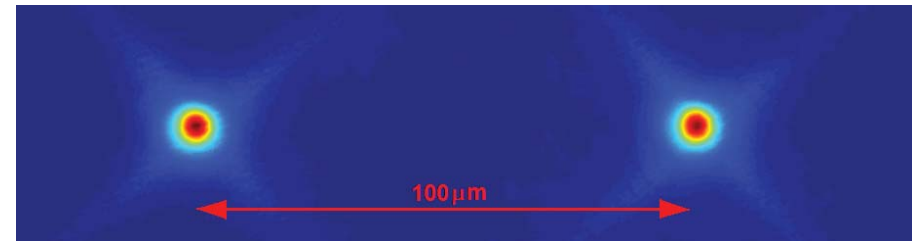
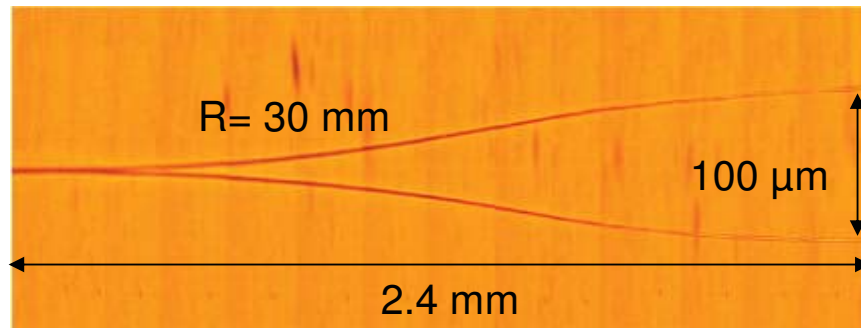
No optical fibers are used for light coupling to preserve polarization of the input light



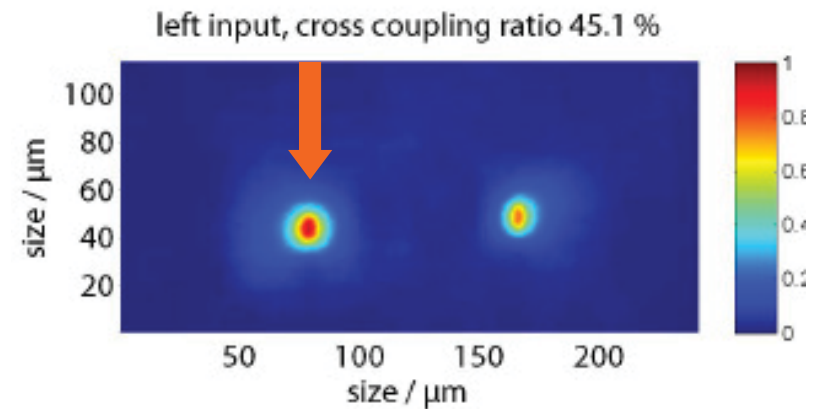
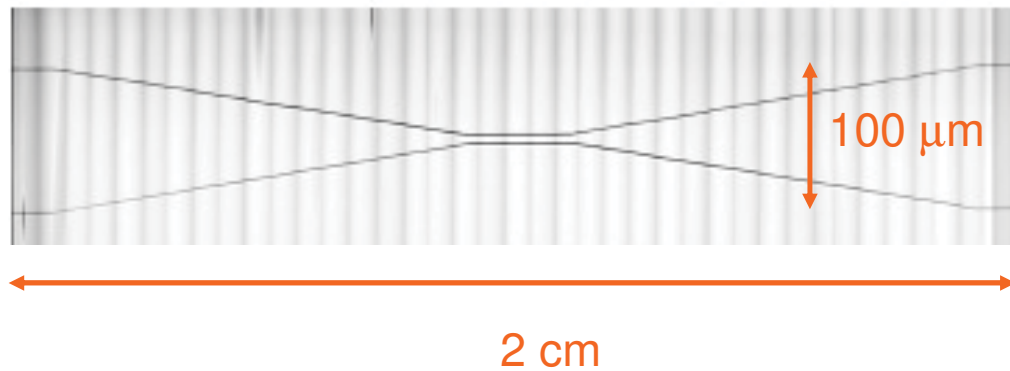
A polarizing beam splitter (PBS), a half-wave plate (HWP) and a quarter-wave plate (QWP) are used to manipulate the polarization of the input light, in order to perform measurements of the polarization behaviour of the device.



## ● Splitter



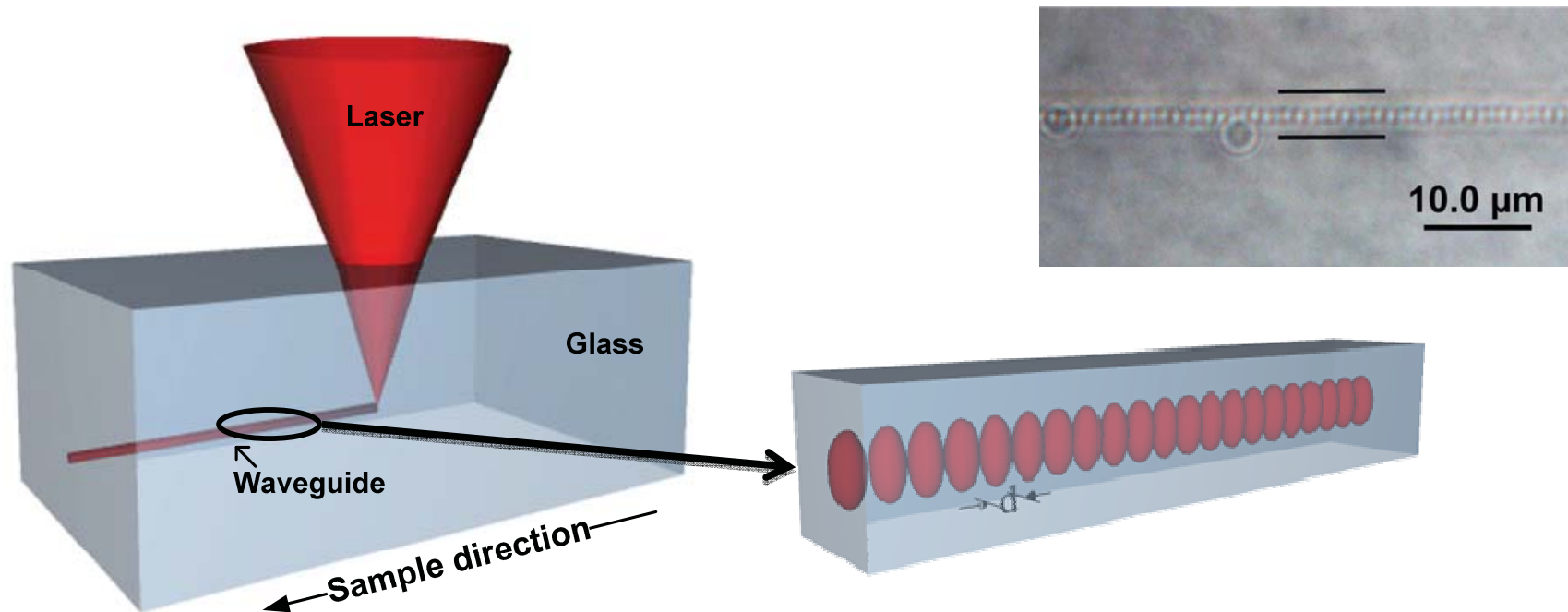
## ● Directional coupler





# Bragg grating waveguide fabrication: single pulse method

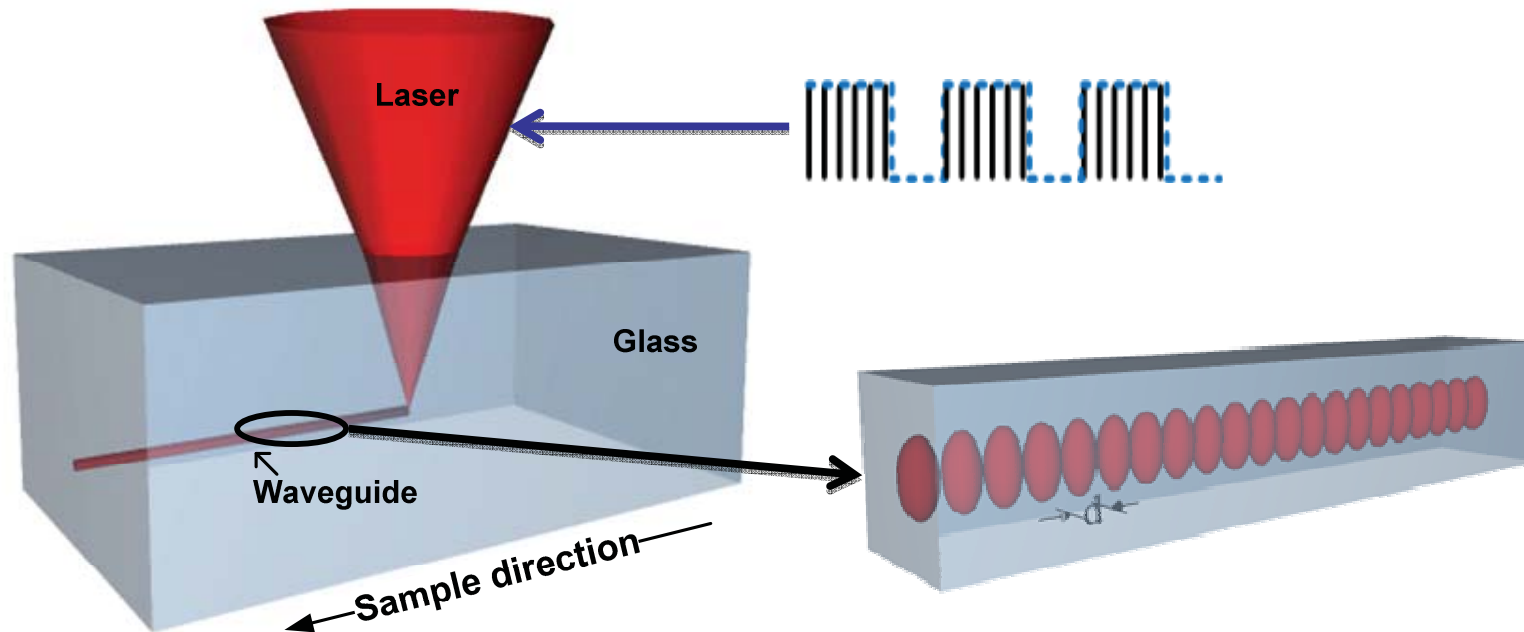
29



- Laser is scanned rapidly, so individual shots create periodic index modulation

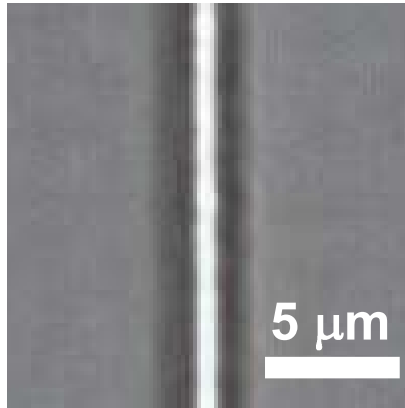
G.D Marshall et al., Opt. Lett. **31**, 2690 (2006)

H. Zhang et al., Opt. Lett. **31**, 3495 (2006)

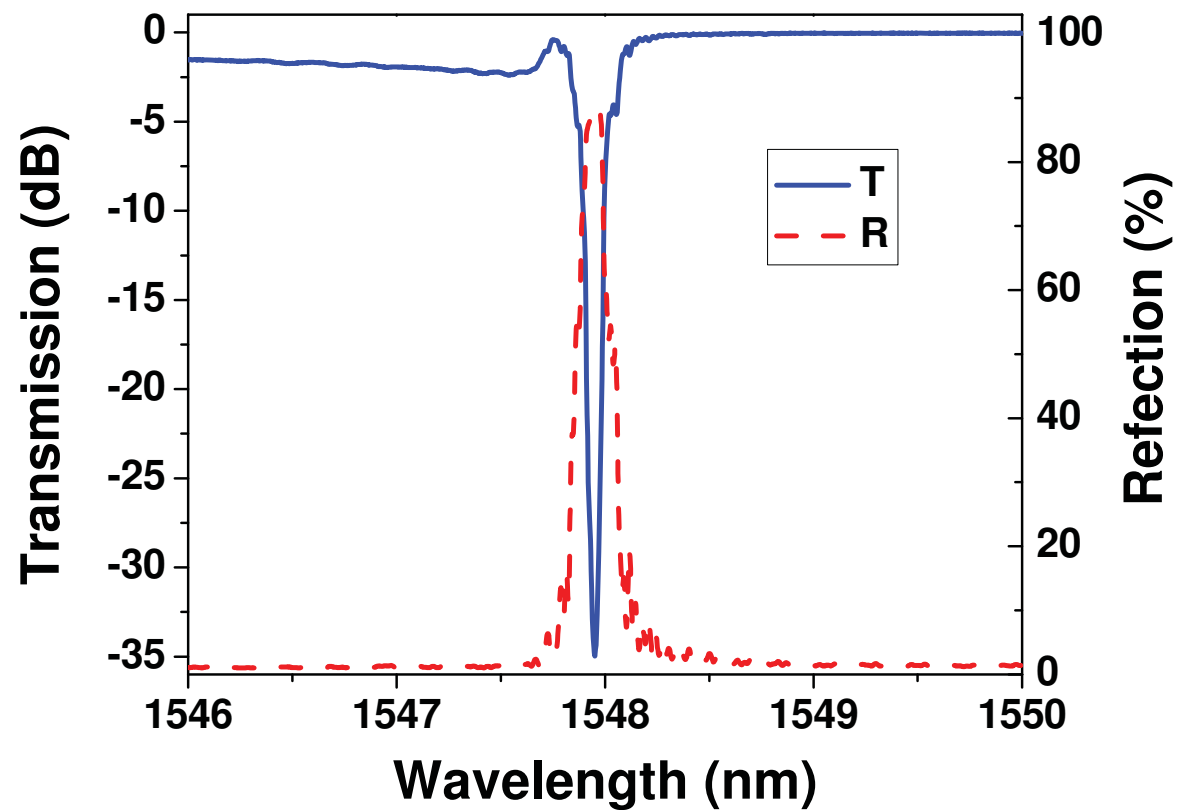
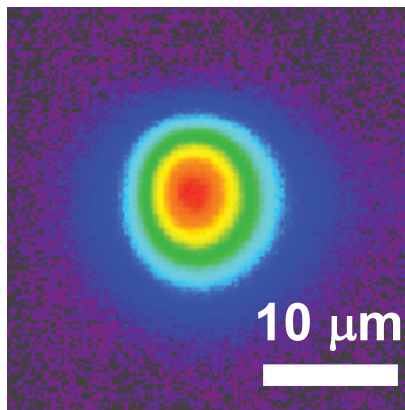


- Writing beam intensity periodically modulated by acousto-optic modulator

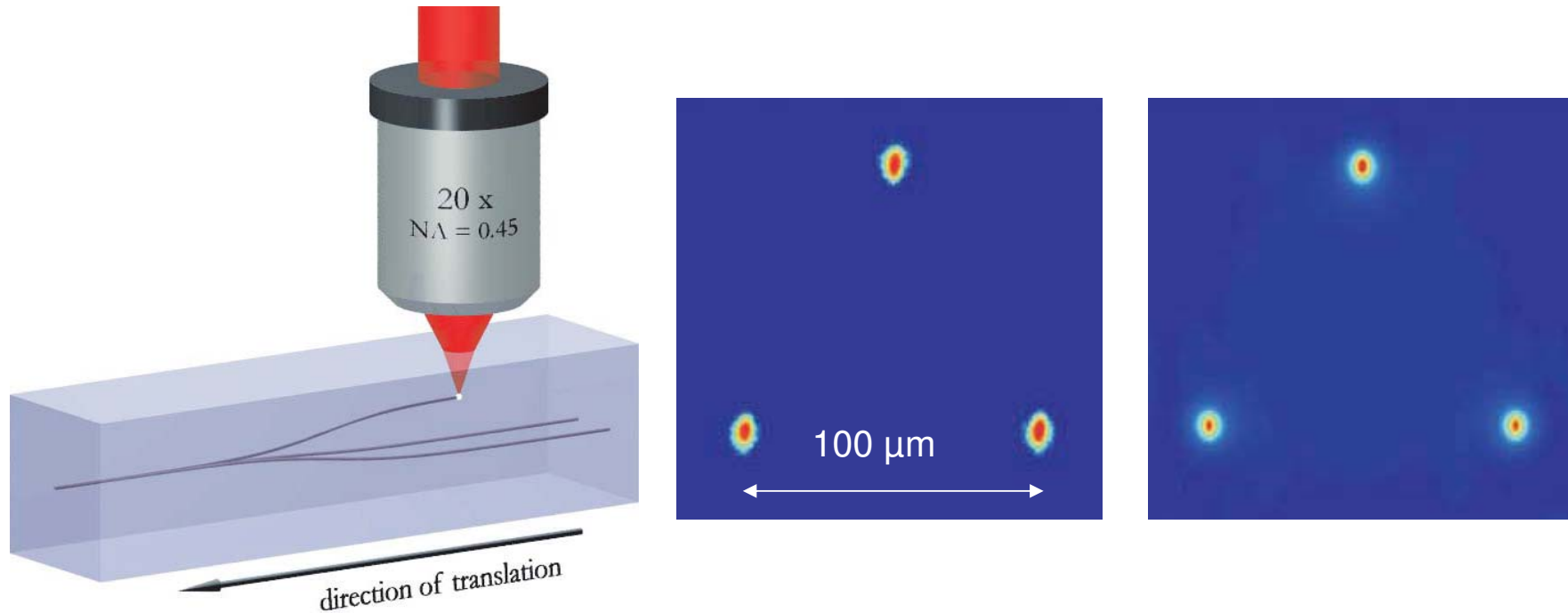
H. Zhang *et al.*, Opt. Lett. **32**, 2559 (2007)



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H. Zhang *et al.*, Opt. Lett. **32**, 2559 (2007)

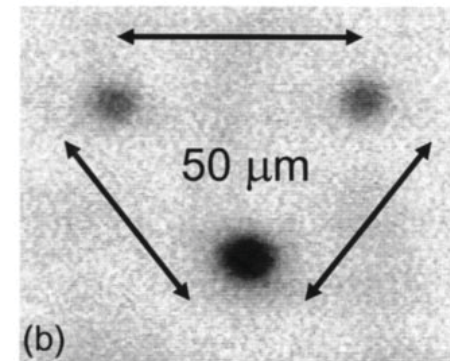
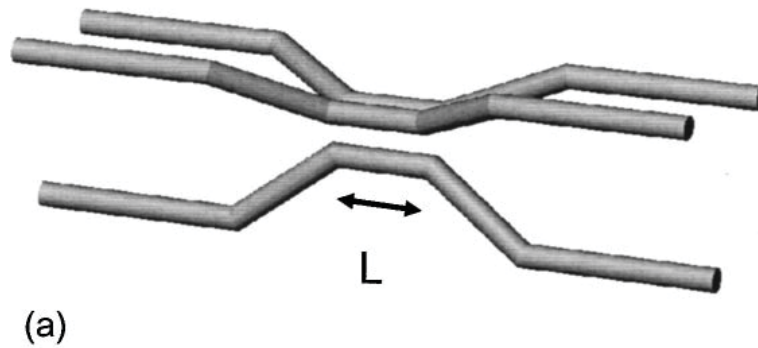


- Three-dimensional splitter written in fused silica

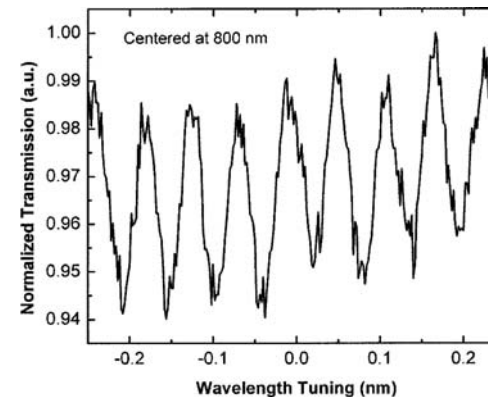
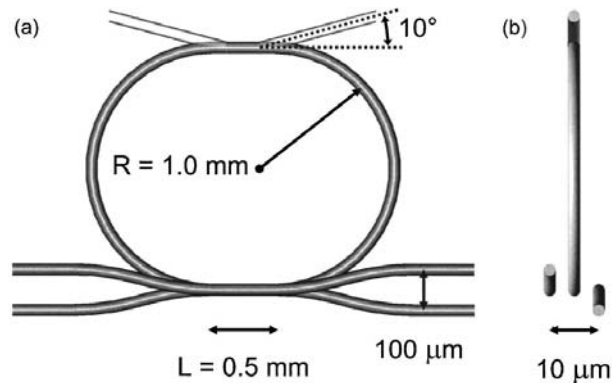
S. Nolte et al., Appl. Phys. A **77**, 109 (2003)



- Three-waveguide directional coupler



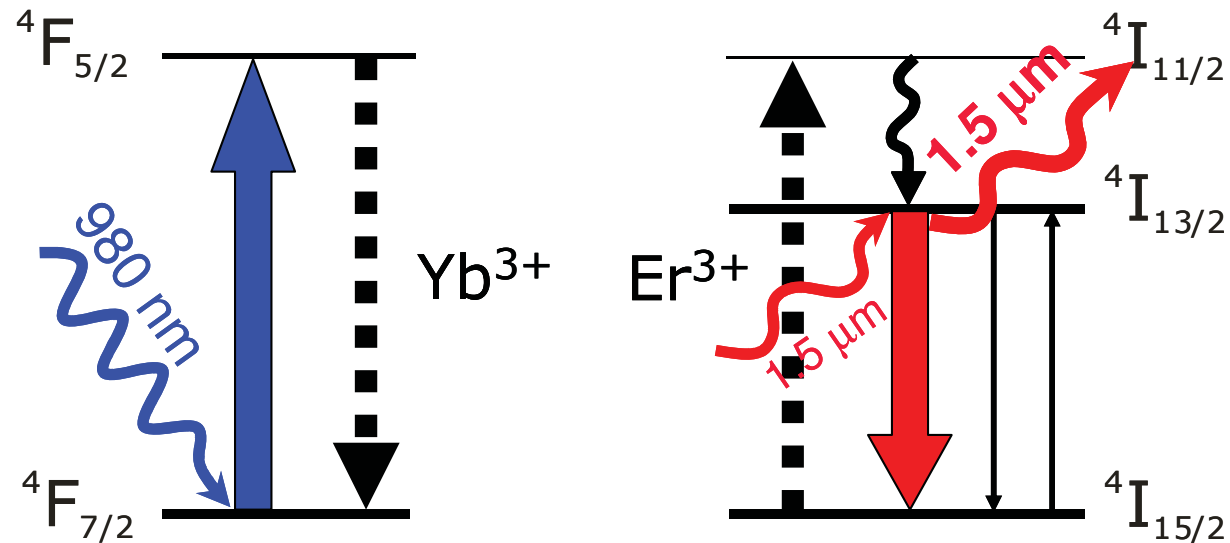
- 3D microring resonator



A. M. Kowalevich *et al.*, Opt. Lett. **30**, 1060 (2005)



## **Active photonic devices by femtosecond writing**

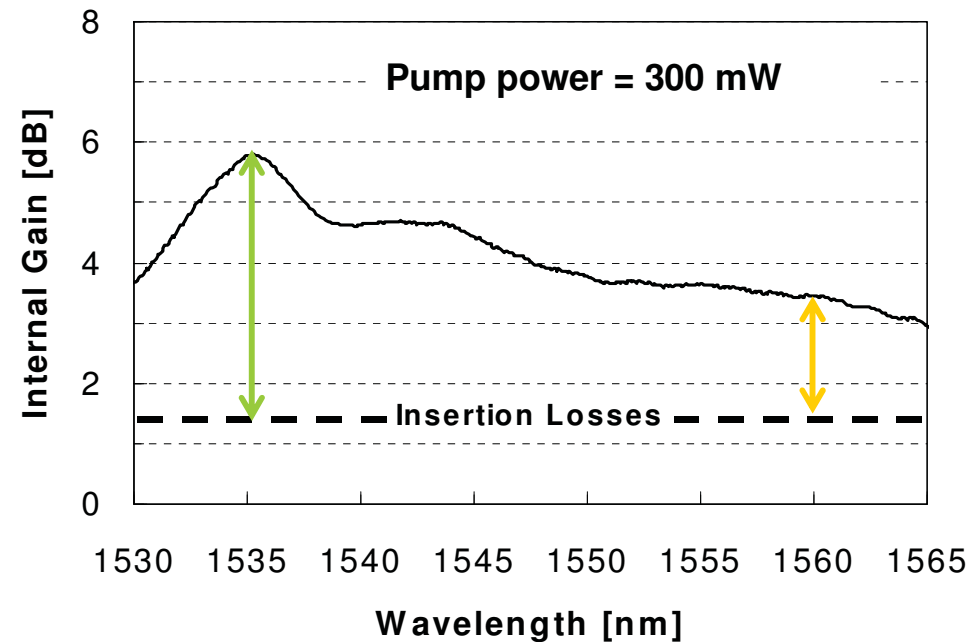
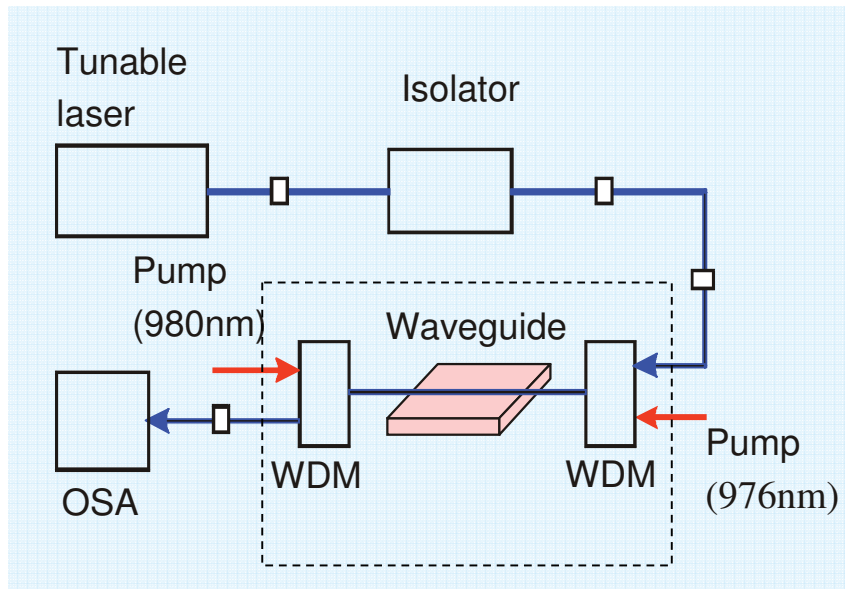


- Glass base suitable for compact active devices (high-gain per unit length)
- Allows for high doping concentration: 1-10 % weight  $\text{Er}_2\text{O}_3$  or  $\text{Yb}_2\text{O}_3$
- Three-level system, pumped at 980 nm and lasing at 1.5  $\mu\text{m}$  in the telecom band



## Active waveguides with net gain in the whole telecom C-band

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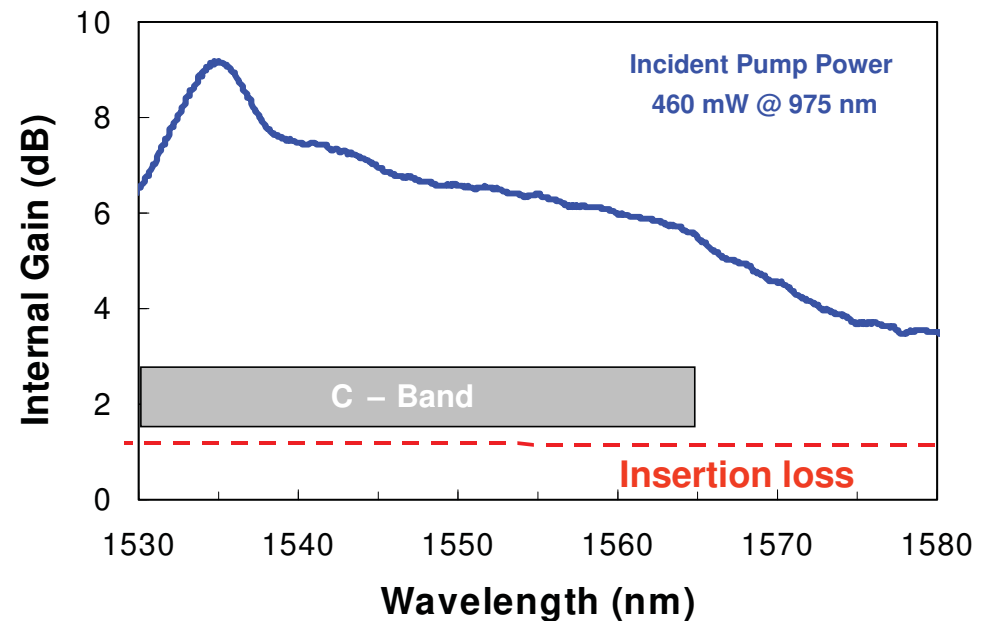
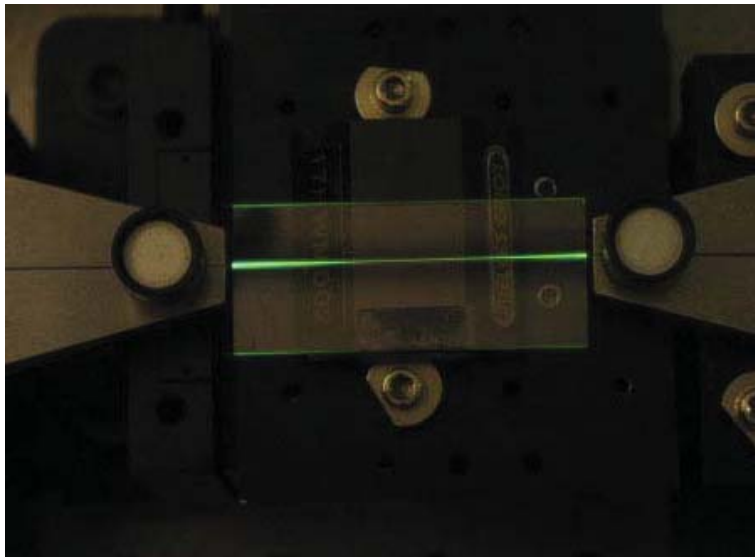
- Internal gain (6 dB) overcomes insertion losses (1.4 dB) over the whole C band
- Possibility of active devices such as waveguide amplifiers or lasers

R. Osellame *et al.*, Opt. Lett. **29**, 1902 (2004)



# Femtosecond laser written Erbium-Doped Waveguide Amplifier

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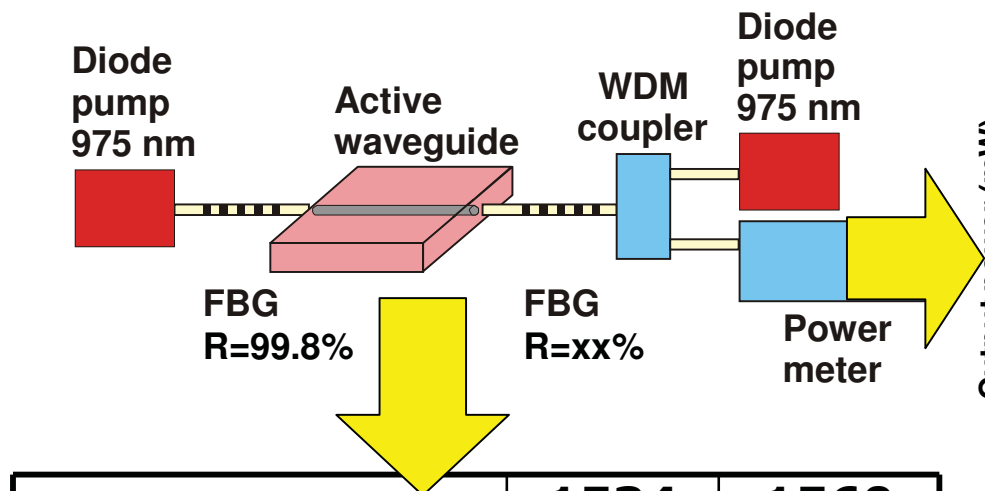
- Improved insertion losses (1.9 dB for  $L=37$  mm  $\rightarrow$  propagation loss  $< 0.4$  dB/cm)
- Gain over the whole C-band: 7.4 dB peak at 1535 nm, 3.7 dB at 1565 nm

G. Della Valle et al., Opt. Express **13**, 5976 (2005)

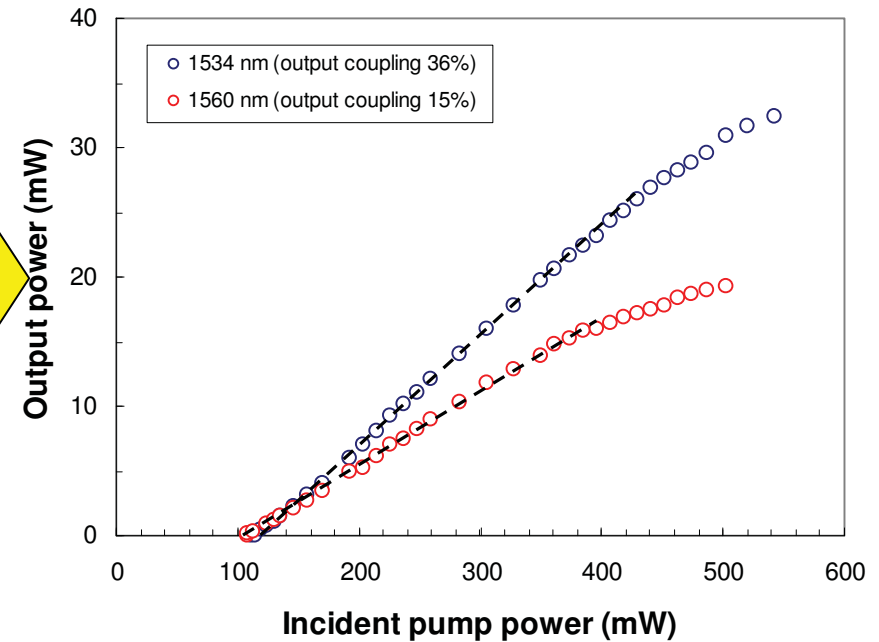


## Femtosecond laser written waveguide laser

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Performance	1534 nm	1560 nm
Pump Power Threshold (mW)	112	102
Maximum Output Power (mW)	32.3	19.2
Slope Efficiency	8.4 %	5.8 %



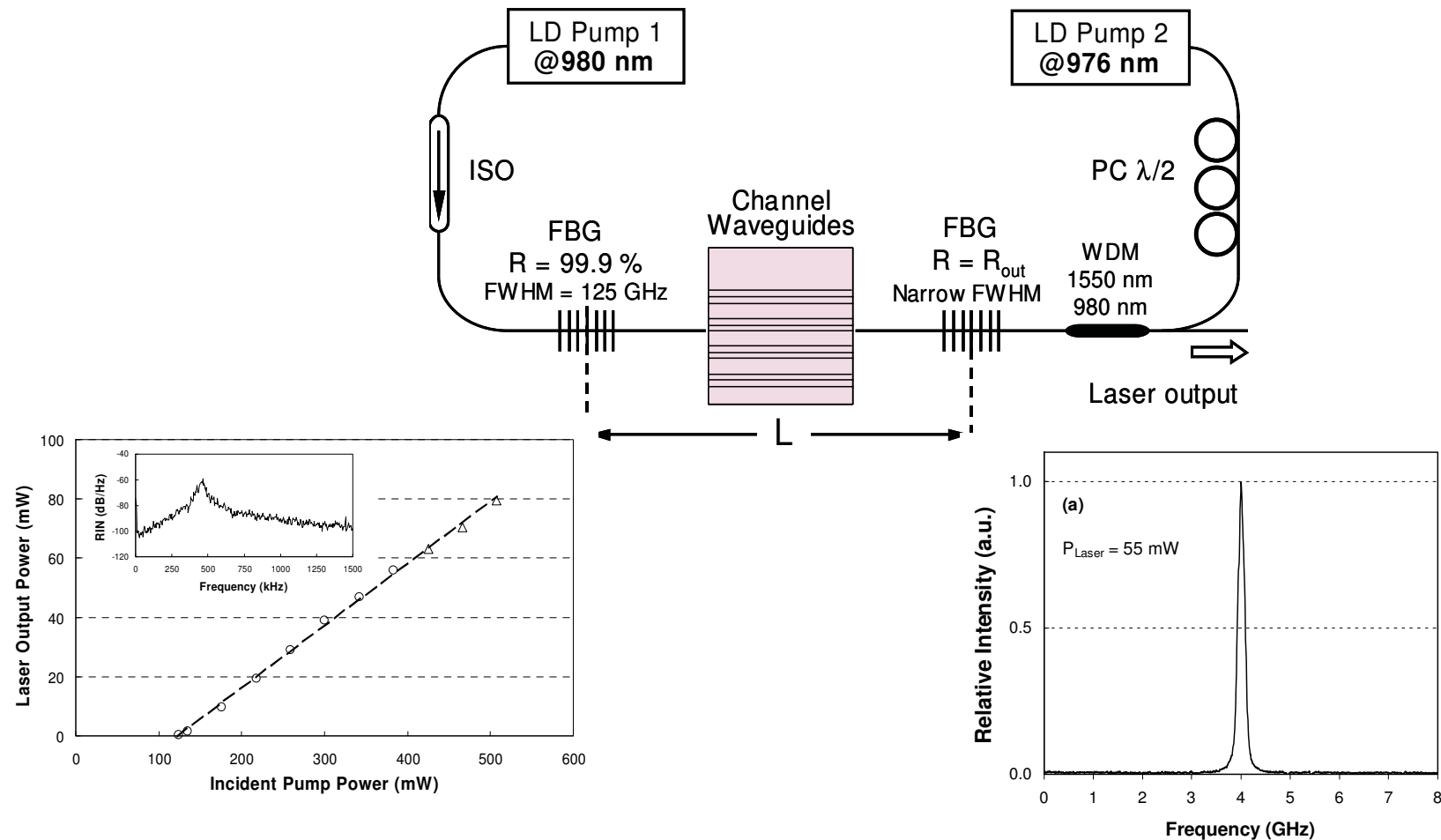
Waveguide laser array  
on the ITU grid

S. Taccheo *et al.*, Opt. Lett. **29**, 2626 (2004)



# Single longitudinal mode waveguide laser

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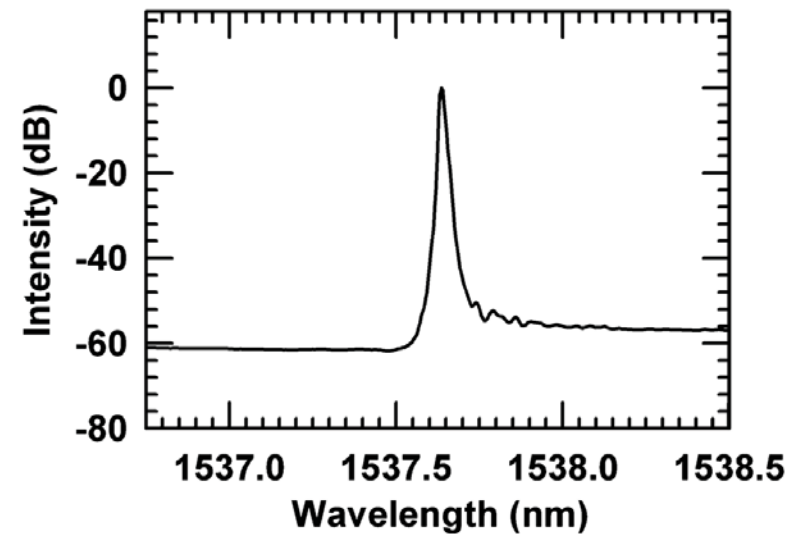
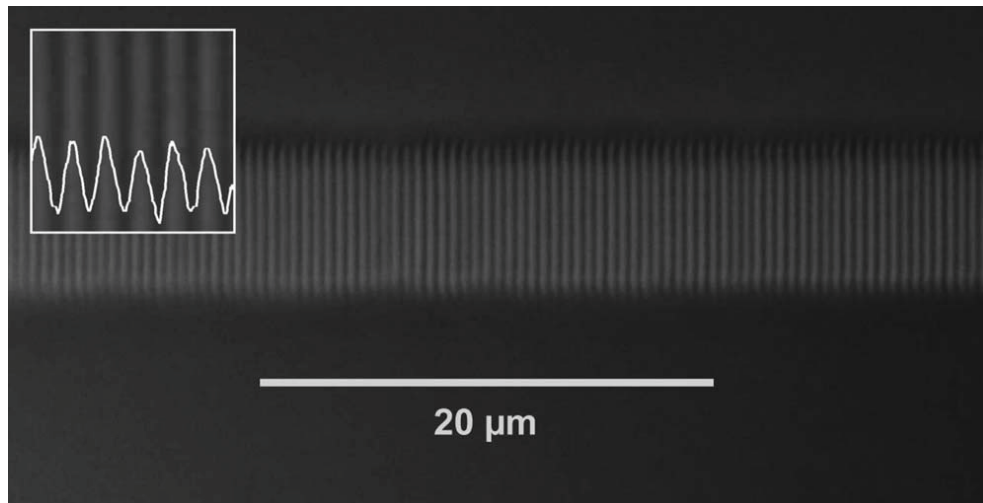


G. Della Valle *et al.*, Opt. Express **15**, 3190 (2007)



## Waveguide laser with distributed feedback Bragg grating

40



- Femtosecond laser written Bragg gratings integrated into the waveguide

G.D. Marshall *et al.*, Opt. Lett. **33**, 956 (2008)



## **Femtosecond laser microfabrication of waveguides for polarization encoded qubits**



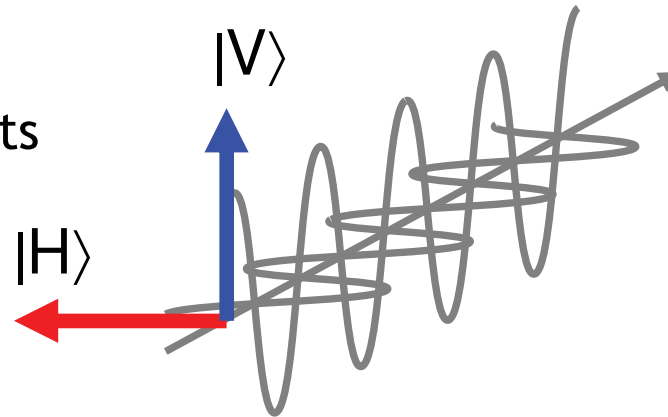
By properly tailoring the fabrication parameters, waveguides obtained by femtosecond laser irradiation are ideal candidates for the realization of integrated photonic quantum circuits

*What do we need to change or optimize to meet the requirements of quantum circuits?*

Photons entanglement must be preserved  
during the propagation



Polarization-  
encoded qubits



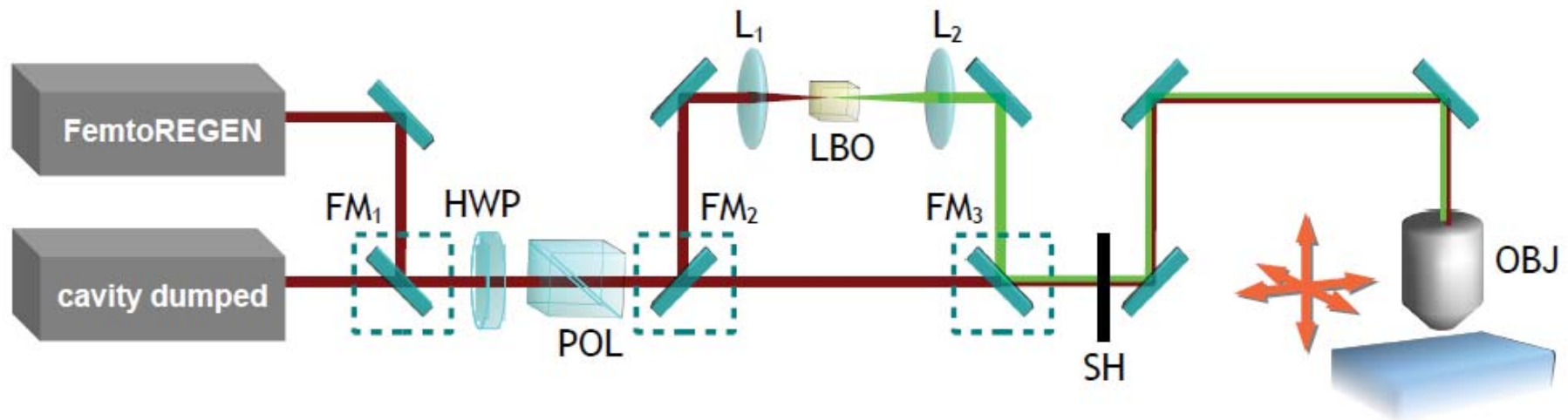
## POLARIZATION ENCODING APPROACH

- most commonly adopted
- no need for path duplication (compactness)
- sources of entangled states



## Waveguide writing set-up

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- Femtosecond laser systems: cavity dumped oscillator or HighQLaser FemtoREGEN
- SHG stage can be inserted in line (LBO, lithium triborate crystal)
- Attenuation is performed by a half-wave plate (HWP) and a Glan-Thomson polarizer (POL)
- SH, mechanical shutter to block or enable the beam in the machining area
- The beam is focused into the substrate by a microscope objective (OBJ)
- 3D translation of the sample by computer-controlled high-precision stages

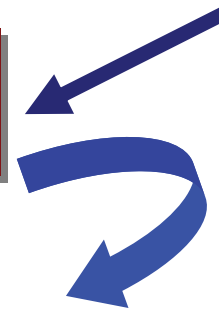


Waveguide birefringence



Decoherence, polarization mode dispersion

Deleterious effects on polarization encoded qubits

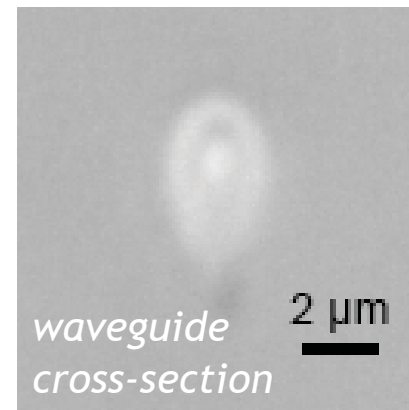


### OPTIMIZATION OF THE WAVEGUIDE BIREFRINGENCE

#### SUBSTRATE CHOICE

- EAGLE2000 borosilicate glass
- fs-laser irradiation does not create birefringent nanostructures
- thermal effects (high repetition rates) circularize the waveguide

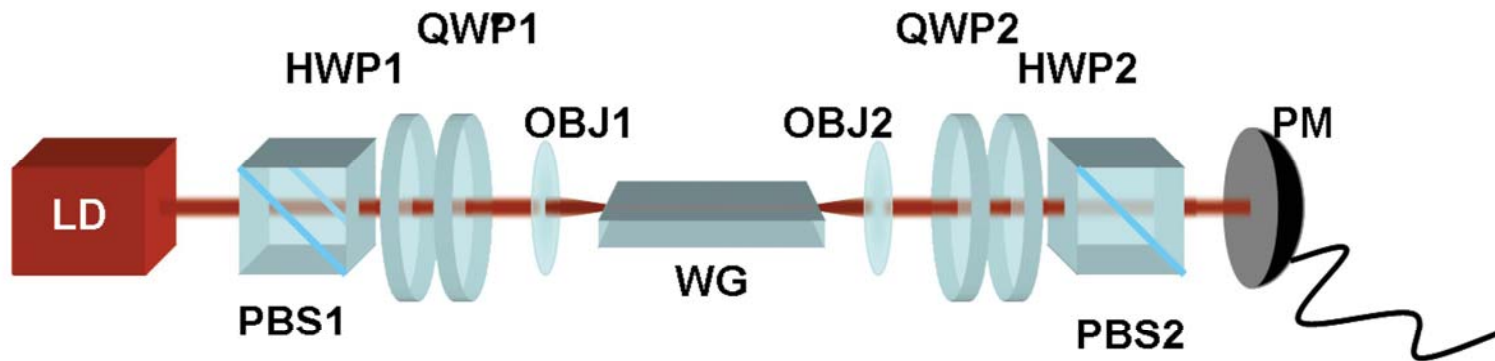
#### PARAMETERS OPTIMIZATION



Single mode guiding  
@806 nm

$f_{\text{rep}} = 1\text{MHz}$     $\lambda = 1030\text{nm}$   
 $E_{\text{pulse}} = 220\text{ nJ}$   
 $\text{N.A.} = 0.6$     $v = 40\text{ mm/s}$

$$\Delta n_{\text{eff}} = 7 \times 10^{-5}$$



LD: laser diode @ 806 nm,  $\Delta\lambda = 2$  nm. PBS1 and PBS2: polarizing beam splitters.  
HWP1 and HWP2: half-wave plates. QWP1 and QWP2: quarter-wave plates.  
OBJ1 and OBJ2: objectives. PM: power meter.

Light with six different polarization states is injected into the waveguide. For each input state, the output state is projected on the same six polarization states. Normalized Stokes vector.



## POLARIZATION INDEPENDENT DIRECTIONAL COUPLER

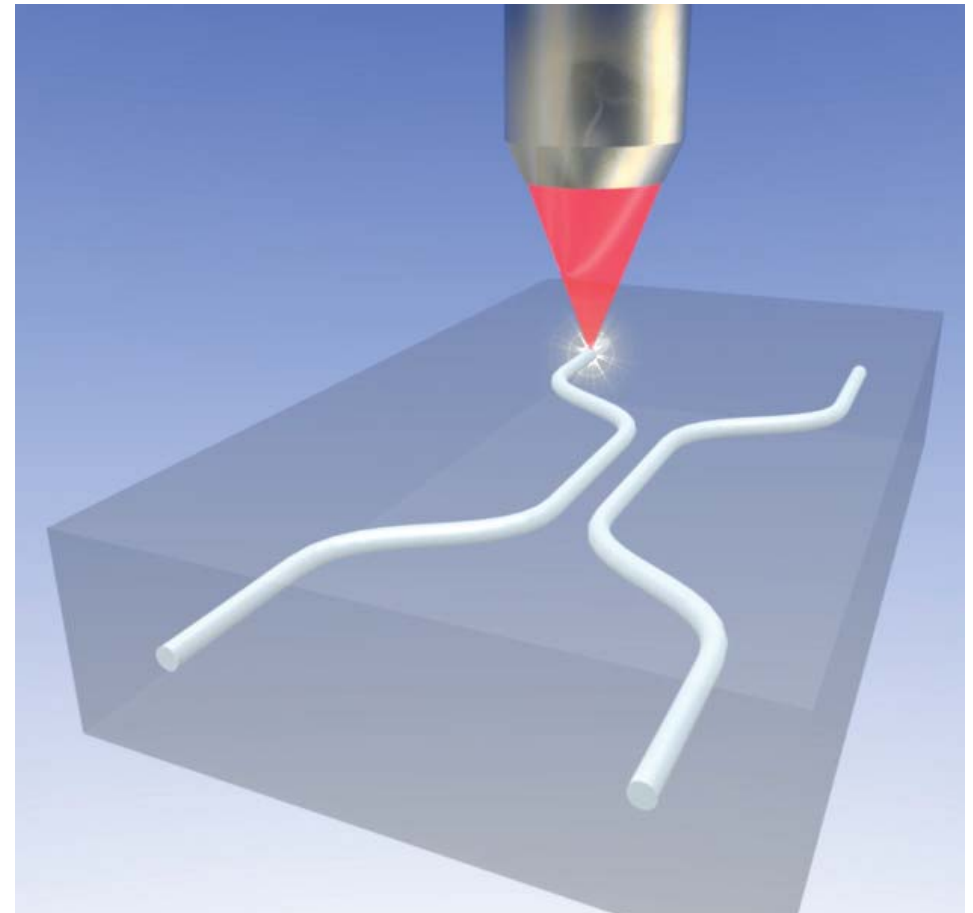
- Integrated analogous of bulk beam splitter cube



basic component to exploit  
**quantum interference**

- Two modes are coupled by evanescent field
- Stable fiber coupling provided by pigtailed.

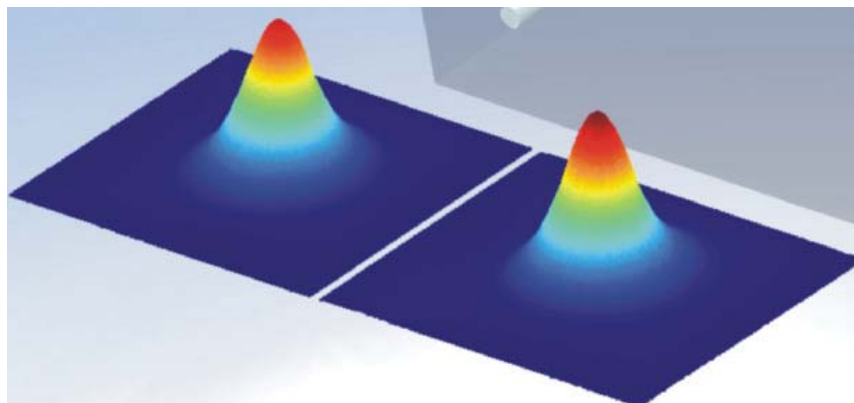
$$R_H = 49\%$$
$$R_V = 58\%$$



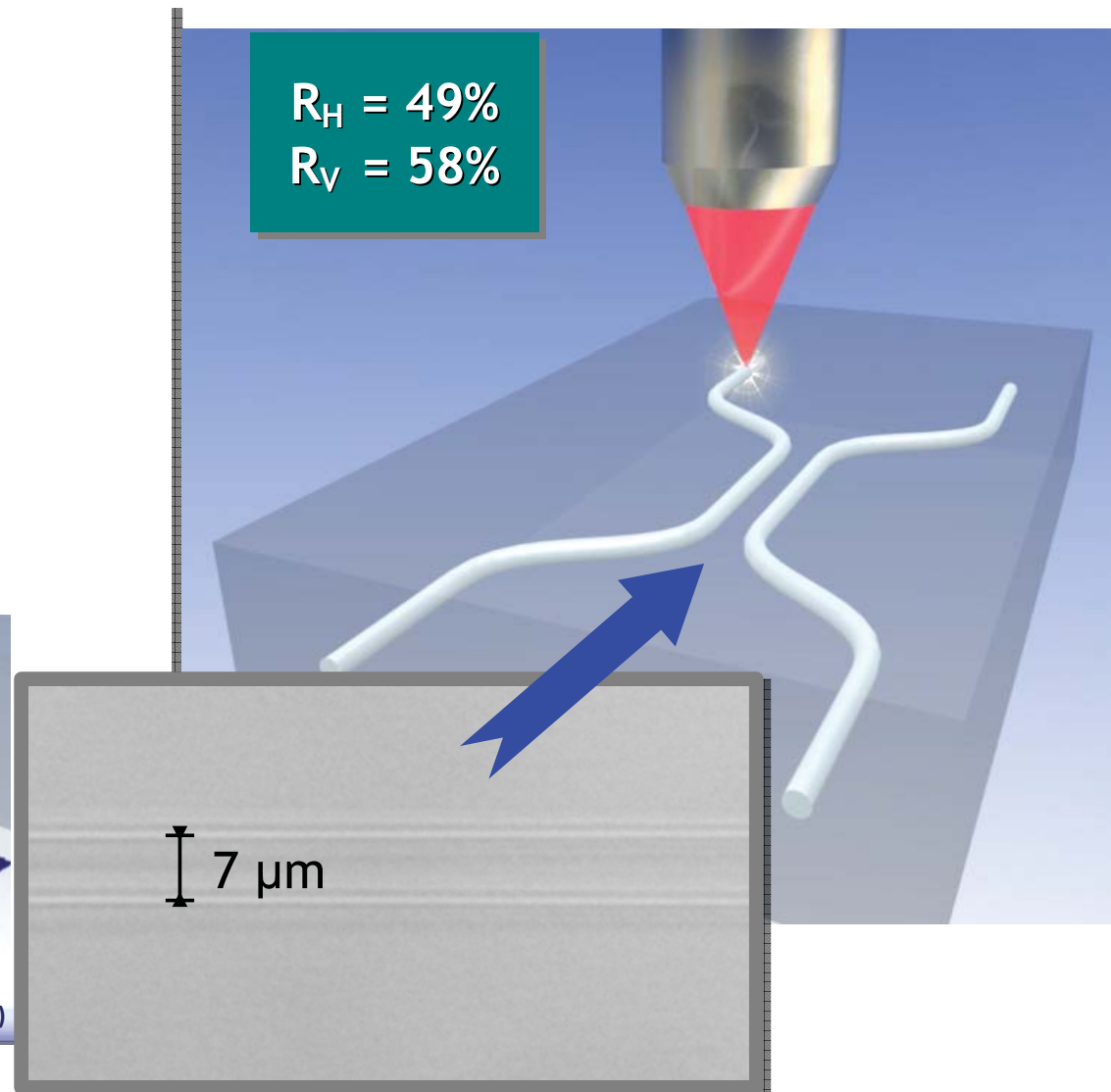


# Polarization independent directional couplers

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L. Sansoni et al., Phys. Rev. Lett. 105, 200503 (2010)





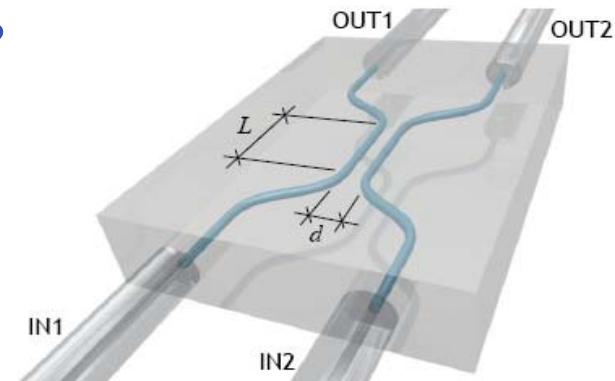
## Partially polarizing directional couplers

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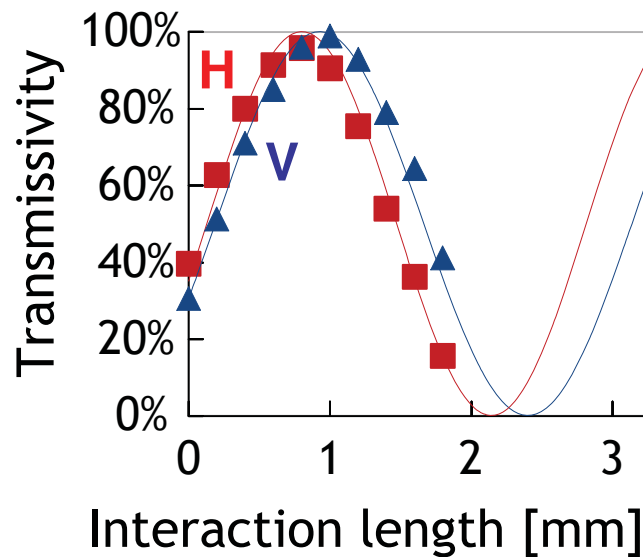
Integrating polarization-encoded quantum gates: how to build partially polarizing directional couplers?

*Directional coupler transmission as a function of the interaction length*

$$T = \sin^2 \kappa L$$



The coupling coefficient is polarization dependent! (birefringence)

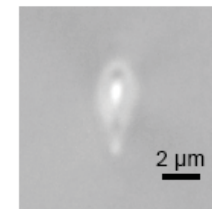


A. Crespi et al., Nature Comm., (2011)

Short interaction lengths:  
practical polarization insensitivity

### Fabrication parameters

Substrate	EAGLE2000
Laser system	FemtoREGEN
Wavelength	1040 nm
Repetition rate	960 kHz
Pulse energy	240 nJ
Translation speed	20 mm/s
Objective	0.45 NA



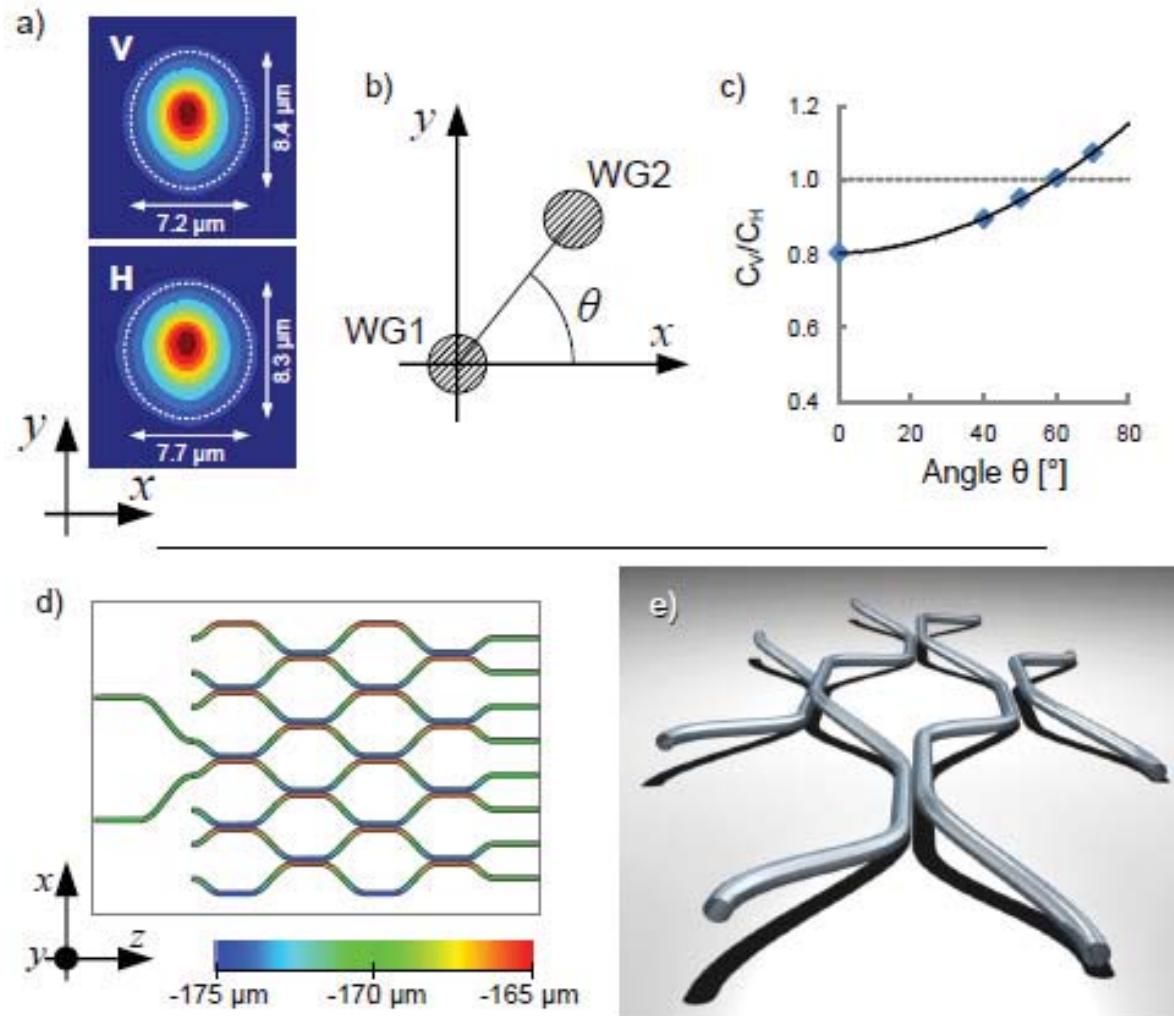
@ L=7.4 mm  
 $T_H = 0$   
 $T_V = 2/3$

Enhanced and tailored polarization sensitive behaviour with greater interaction lengths





What to do when polarization insensitive directional couplers are needed?



L. Sansoni et al., PRL 108, 010502 (2012)





- Femtosecond laser micromachining can produce low loss optical waveguides with excellent prototyping and 3D capabilities
- Depending on the substrate material both passive and active devices can be integrated
- Polarization behaviour of integrated waveguide directional couplers can be tailored
- Several applications fields can benefit from this powerful microfabrication technique, including quantum optics



**Thank you for your attention**