Sculptured ultrashort laser beams for materials engineering and energy harvesting

Stelios Tzortzakis

Science Program, Texas A&M University at Qatar
Institute of Electronic Structure and Laser, FORTH
& University of Crete, Greece

Outline

Introduction

- Intense laser beams – Solitons – Filaments and Complex spatio-temporal wave packets
- Sculpted Exotic beams for tamed waves

Advanced materials engineering

- Large volume high resolution photo-polymerization

Silicon Photonics

- Direct laser writing of photonic circuits in the bulk of silicon – merging optics and electronics under the same platform

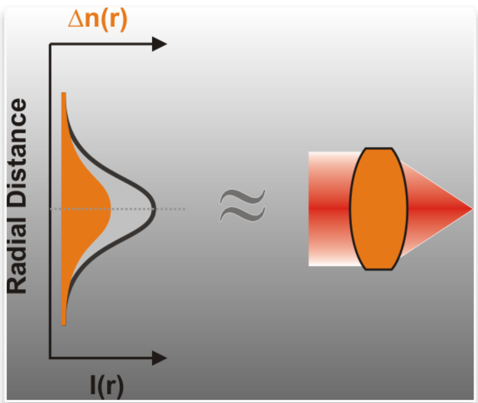
Teaser: Passive radiative cooling

- Improving the performance of photovoltaics

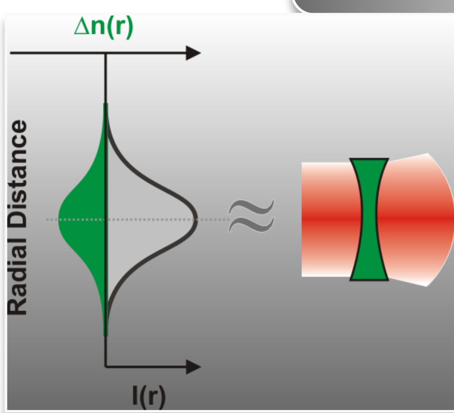
Intense nonlinear laser propagation: Filamentation

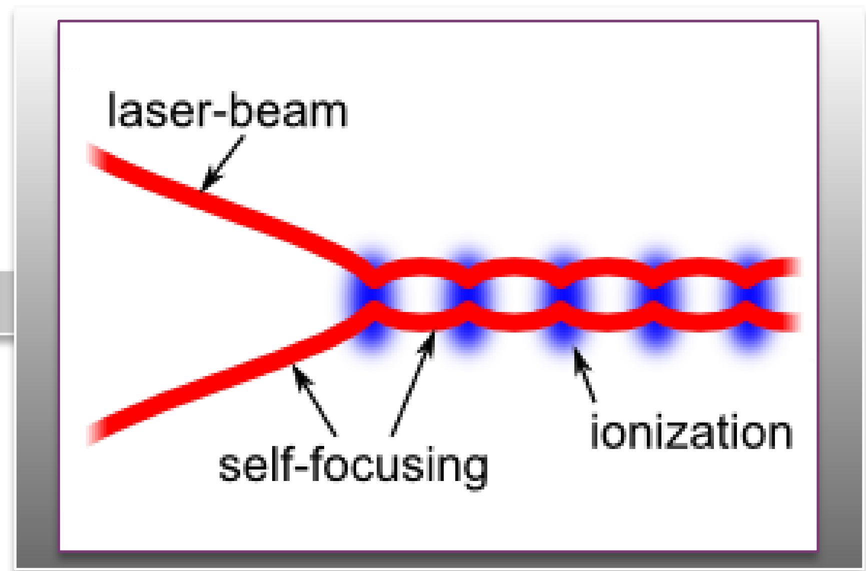
Dynamic equilibrium in space and time between
Kerr effect and ionization

Kerr effect



ionization





Modeling the propagation of intense fs pulses

$$\frac{\partial E}{\partial z} = \frac{i}{2k}\Delta_{\perp} E - i\frac{k''}{2}\frac{\partial^2 E}{\partial t^2} + N\left(E^2,\rho\right)\cdot \mathrm{E}$$

Unidirectional Pulse Propagation Equation (UPPE)

$$where: \quad N\left(E^2,\rho\right) = T^2 N_{Kerr}\left(|E|^2\right) + N_{Plasma}(\rho) + T N_{MPA}\left(|E|^2\right)$$

$$N_{Kerr}\left(|E|^2\right) = ik_0 n_2 (1-a)|E|^2 + ik_0 n_0 a \int_{-\infty}^{t} R(t-\tau)|E|^2 \, d\tau$$

$$N_{Plasma}(\rho) = -\frac{\sigma}{2}(1 + \imath\omega_0\tau_C)\rho$$

$$N_{MPA}\left(|E|^2\right) = -\frac{\beta_K}{2}|E|^{2K-2}\left[1 - \frac{\rho}{\rho_{at}}\right]$$

$$T = 1 + i\omega_0 \frac{\partial}{\partial t}$$

$\beta_K = K\hbar\omega_0\rho_{at}\sigma_K$

σ_K : *Cross Section for Multi Photon Ionization*

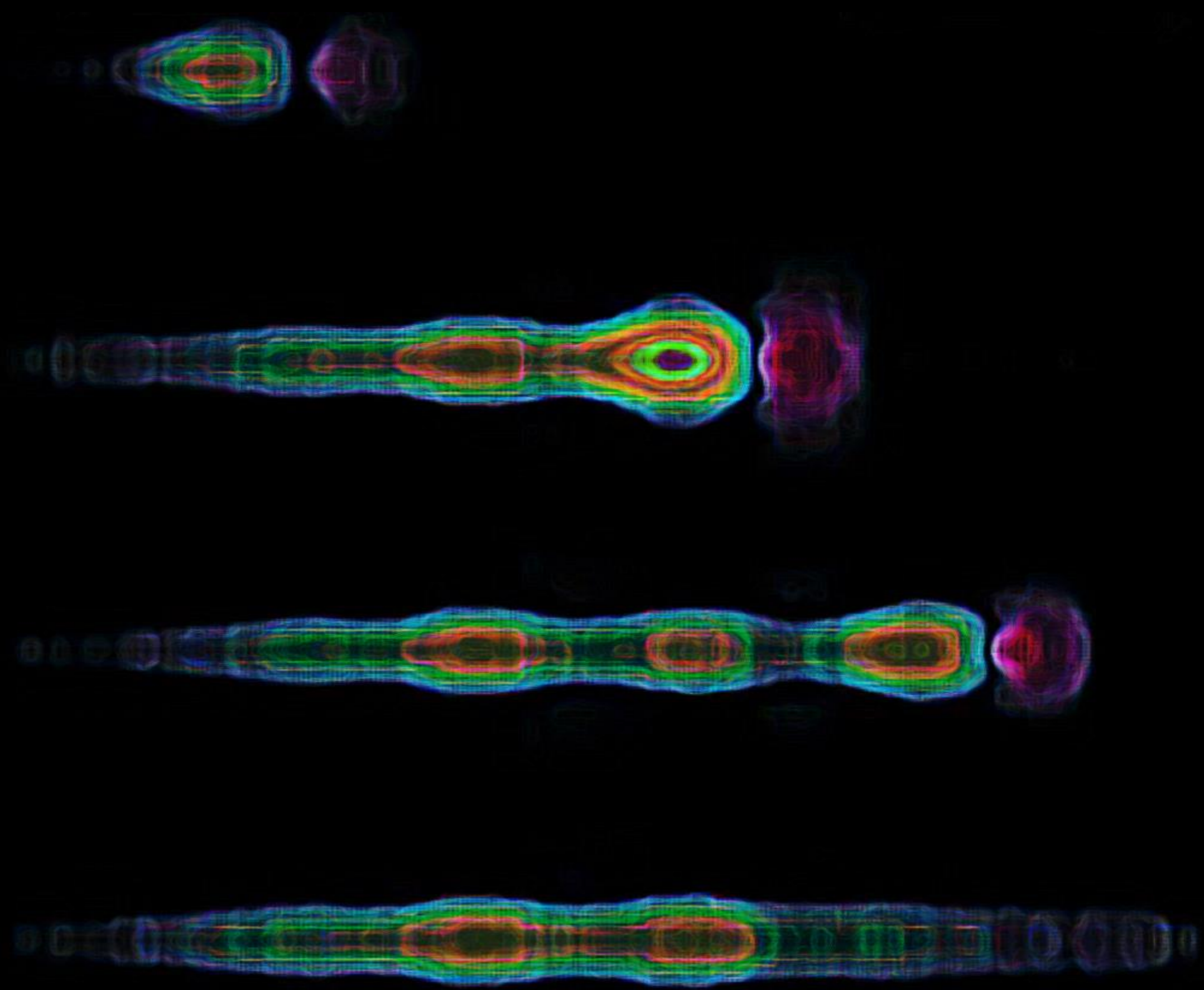
with rate $W_{MPI} = \sigma_K I^K$

for $K = \dfrac{U_i}{\hbar\omega_0 + 1}$ *photons*

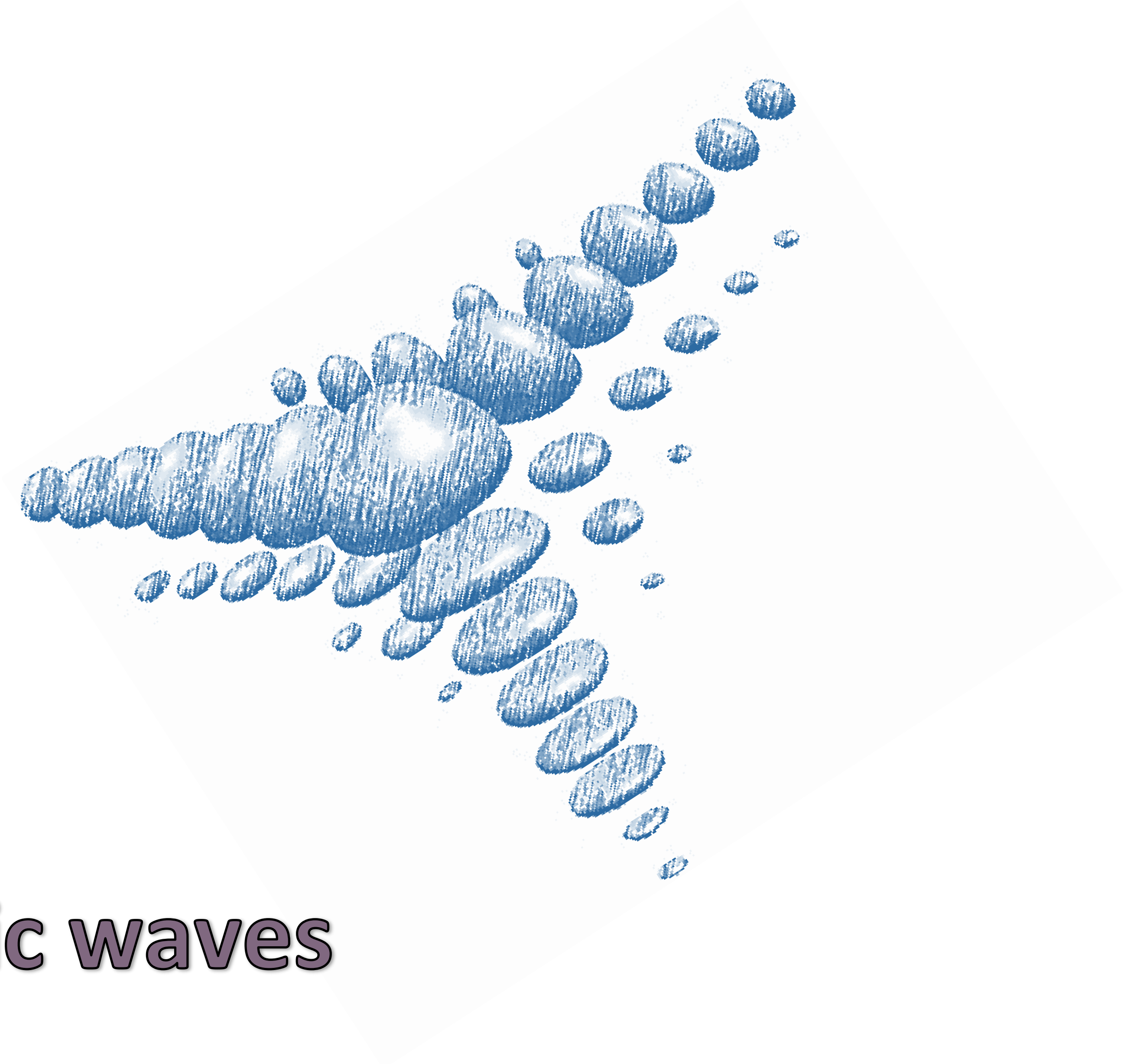
$\sigma = \dfrac{k_0}{n_0\rho_C}\cdot\dfrac{\omega_0\tau_C}{\left(1+\omega_0^2\tau_C^2\right)}$: *Cross Section for Inverse Bremsstrahlung*

$$\frac{\partial \rho}{\partial t} = \sigma_K |\mathrm{E}|^{2K}\left(\rho_{at} - \rho\right) + \frac{\sigma}{U_i}\rho|\mathrm{E}|^2 - a\rho^2$$

Filamentation holography

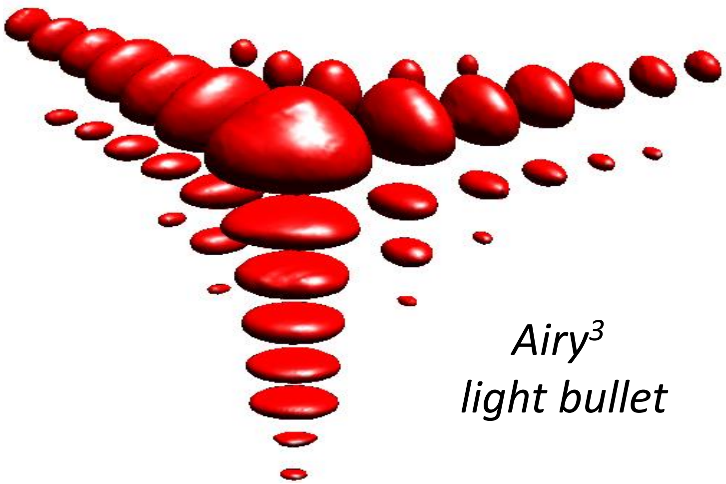


APL **93**, 041120 (2008); PRA **84**, 053809 (2011)

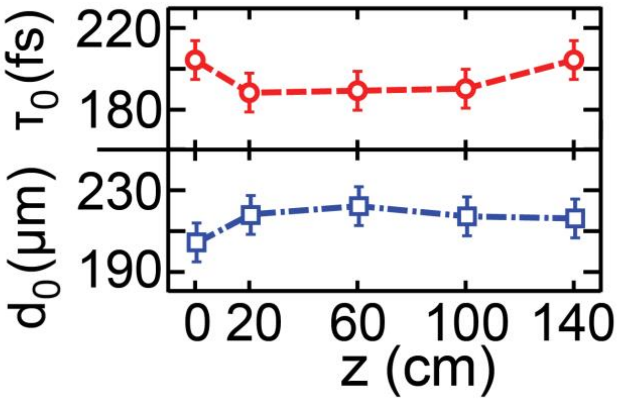


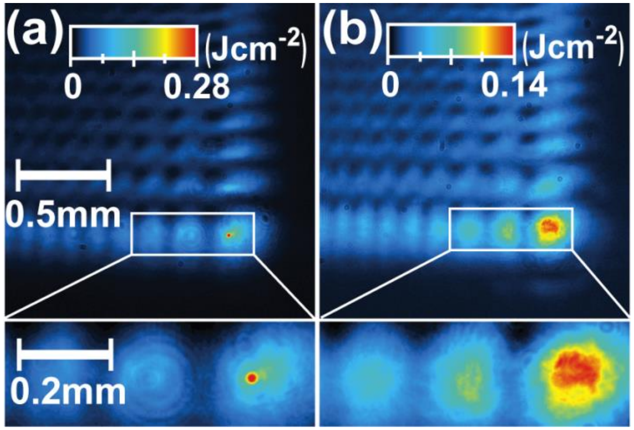
Exotic waves

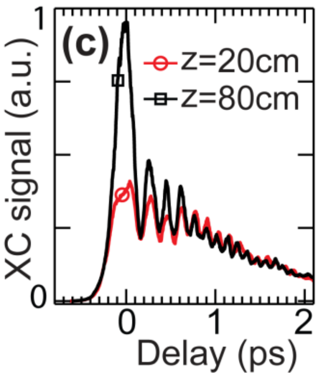
Self-healing Airy cube light bullets



Airy³
light bullet



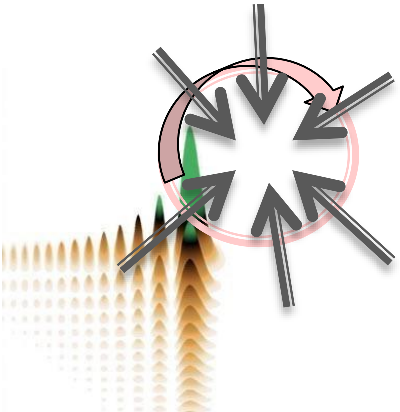


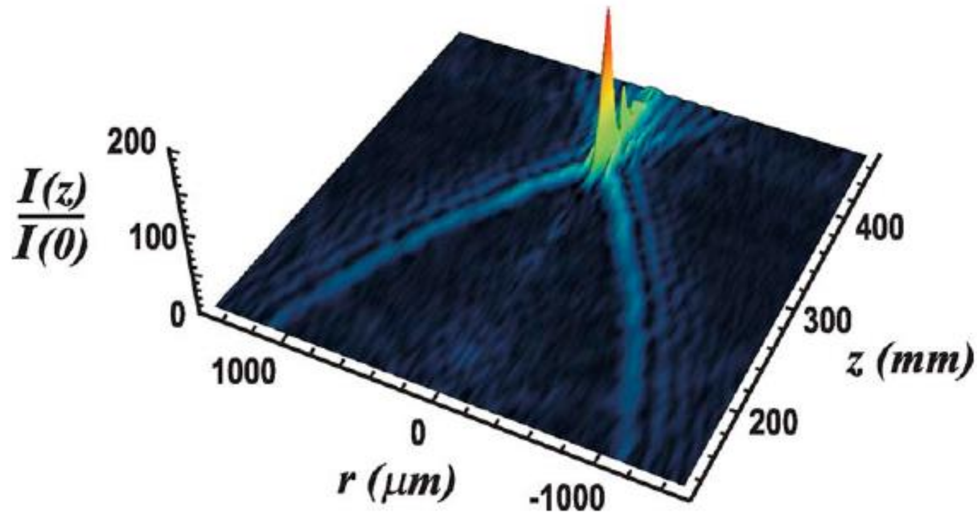


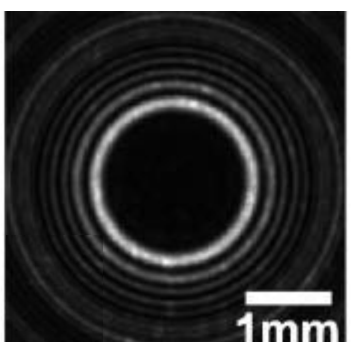
Self-healing in space and time

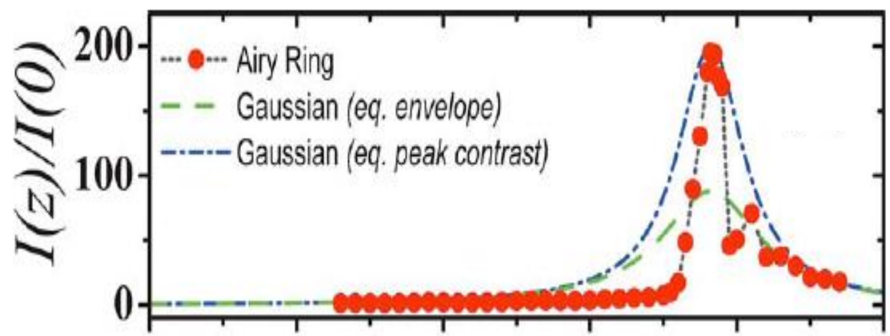
Phys. Rev. Lett. **105**, 253901 (2010)

Airy Ring Sharply Autofocusing Beams



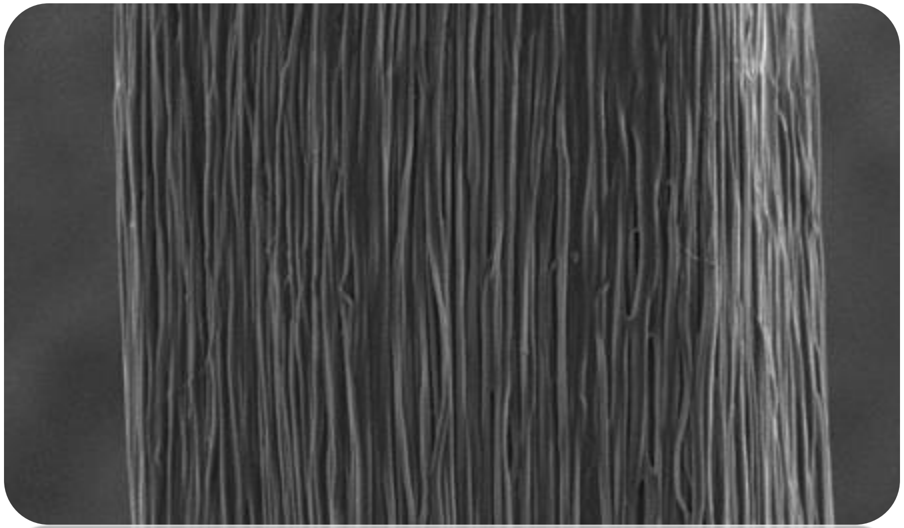






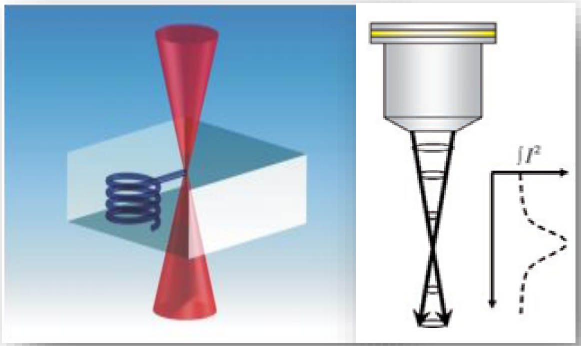
Exciting candidates for a variety of applications, as in bio-medicine, laser nanosurgery and optical lithography (e.g. photopolymerization)

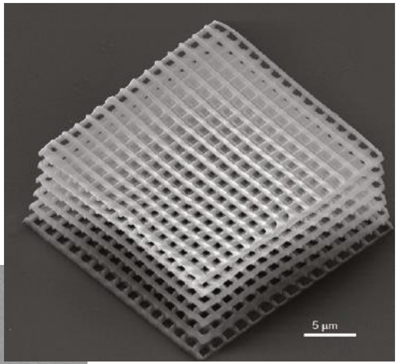
Opt. Lett. 36, 1842 (2011)



Advanced materials engineering

Direct laser writing by Multi-photon polymerization



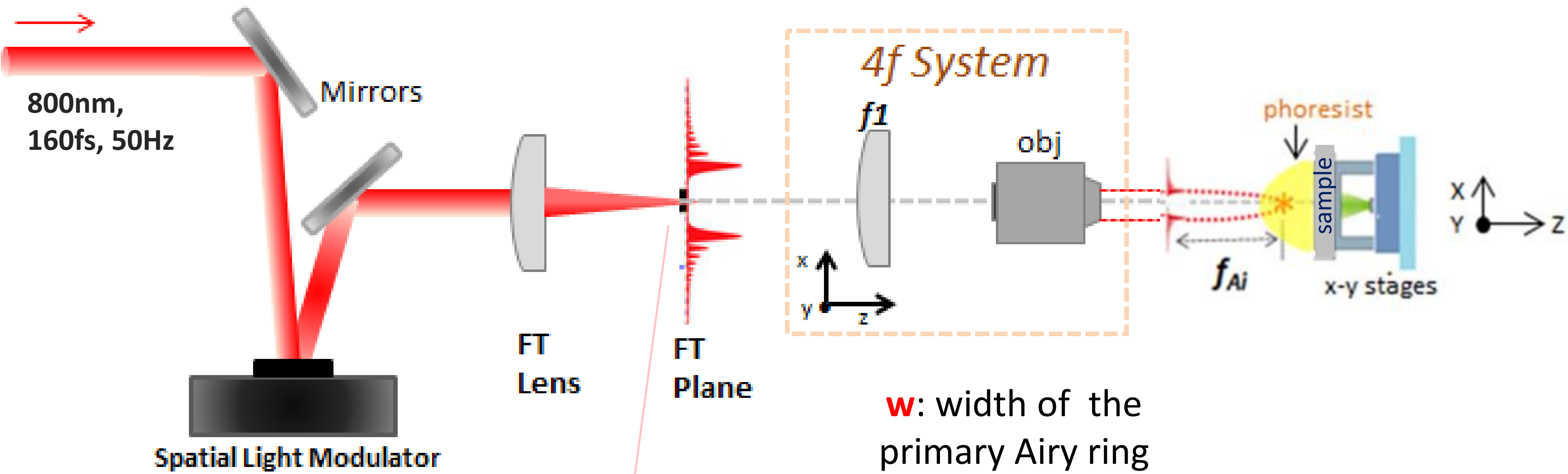


[*]

- *3D Writing of complex Micro- & Nano-structures but limited in volume, typically 100 µm - height*

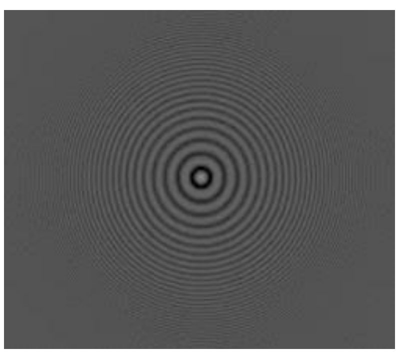
I. Sakellari et. al, ACSNano, 6, 3, 2302–2311 , 2012

Using ring-Airy beams

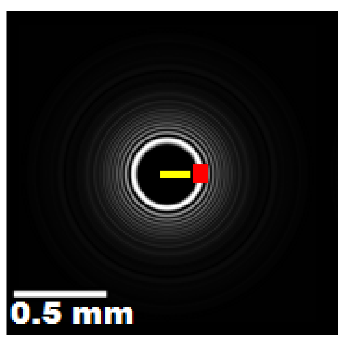


w: width of the primary Airy ring

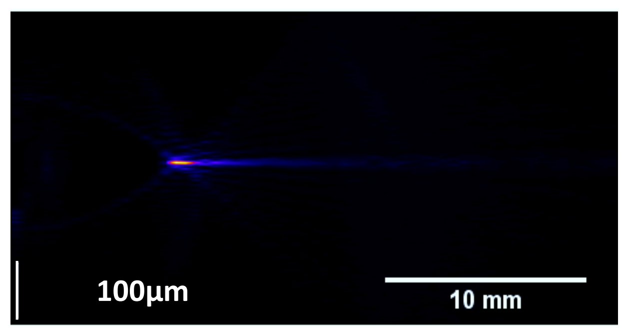
r_0: radius of the primary Airy ring



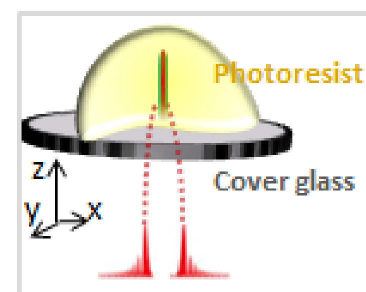
Typical phase mask



Intensity profile at the FT plane

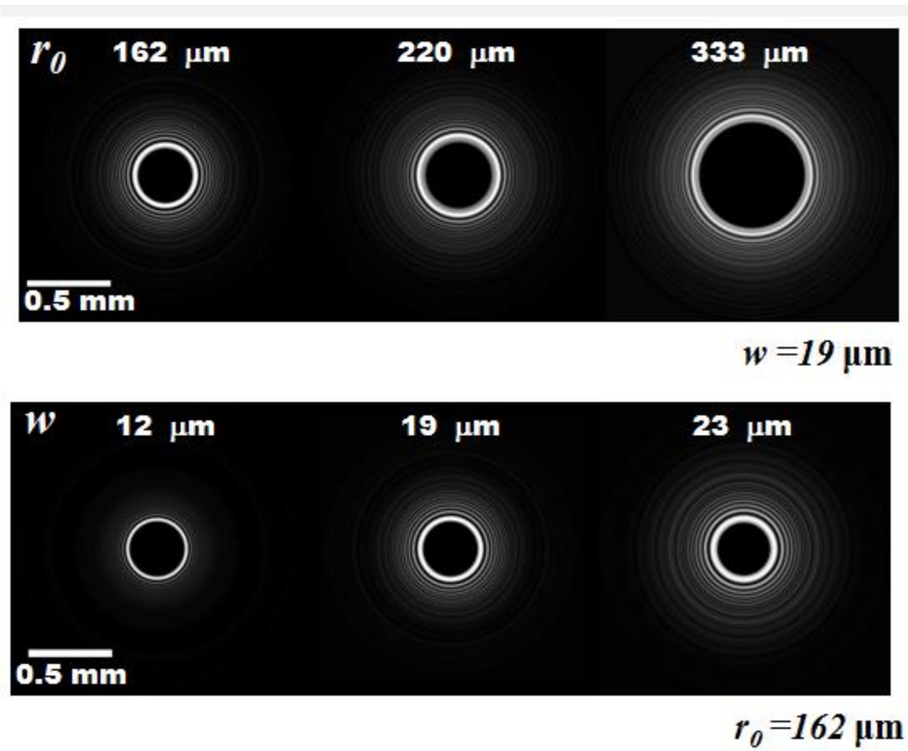


Ring-Airy propagation dynamics

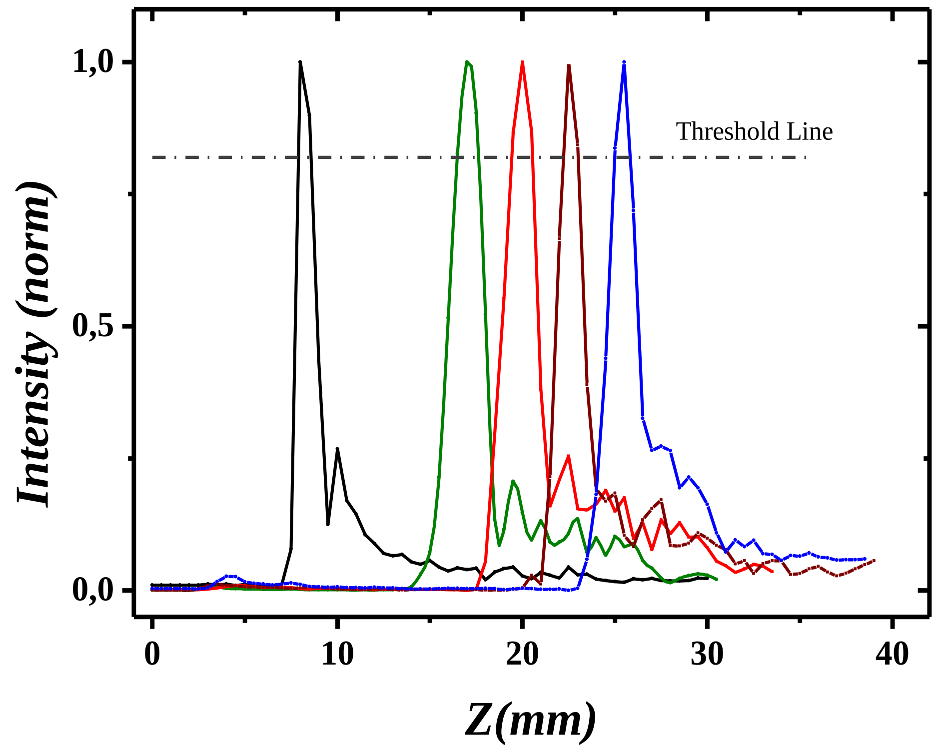


Working-distance control

By adjusting the w and/or r_0 parameters of the primary ring, using the appropriate phase mask, the focus position can be manipulated in real time with the SLM.



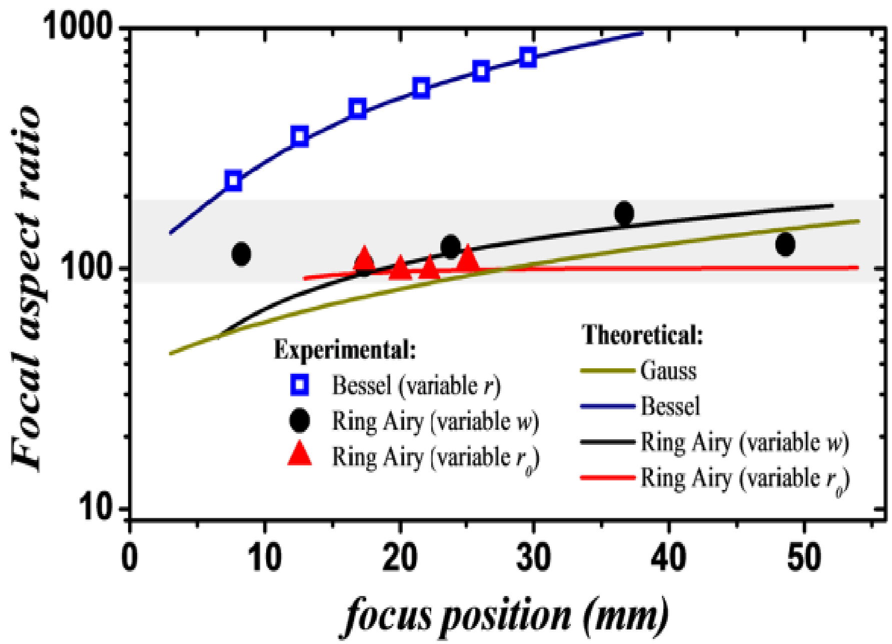
Intensity profiles of ring-Airy beams as captured by the CCD at the FT plane



Experimental intensity distributions (normalized values) of the ring-Airy beams along the propagation axis

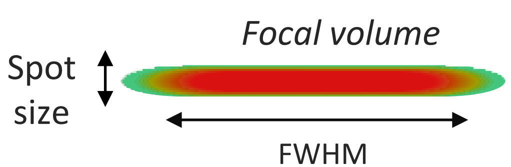
Bessel beams vs. ring-Airy beams

Focal voxel aspect Ratio comparative curves



- In an MPP application the polymerization takes place only at areas where the intensity is high enough.
- We used the 80% of the peak intensity distribution as a threshold.

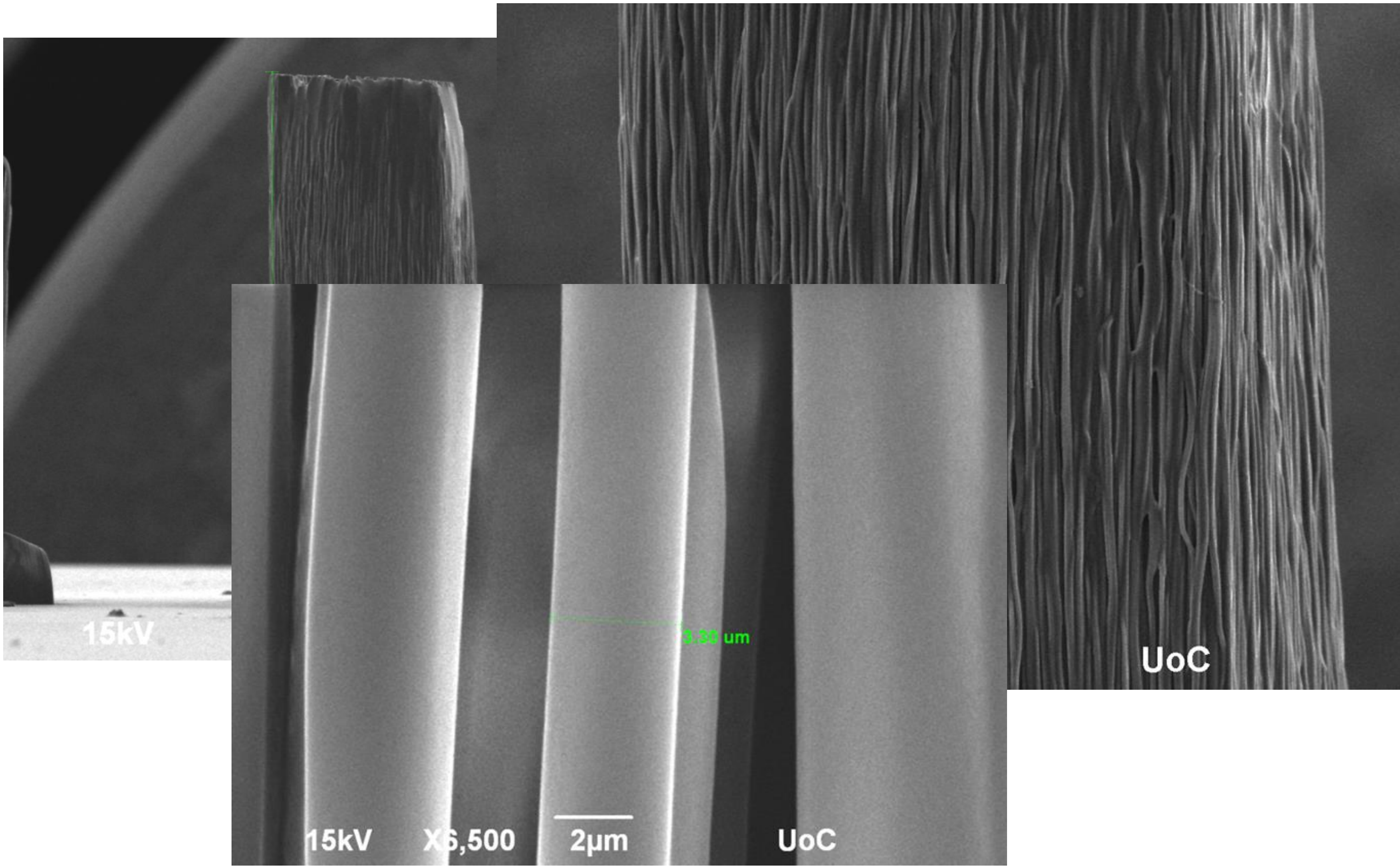
- The ring Airy beams keep the voxel aspect ratio almost invariant !
- The voxel aspect ratio for Bessel beams is increasing as the beam focus is pushed further away.



Focus Aspect Ratio: $\frac{Longitudinal\ size\ of\ Focus}{Focus\ Diameter}$

optica Optica 3, 525-530 (2016)

3D structures using ring-Airy beams

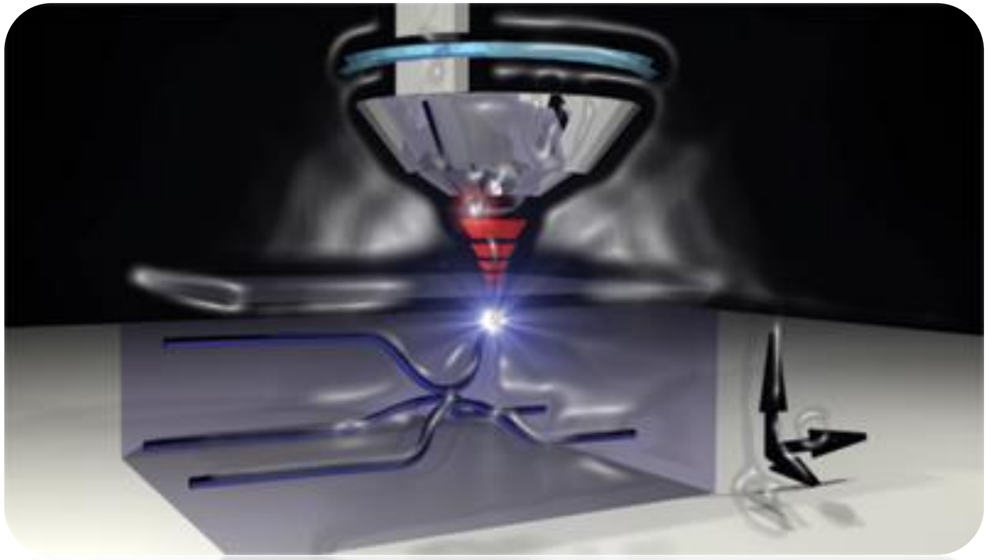


Optica **3**, 525-530 (2016)

3D structures using ring-Airy beams

Aspect ratio ~ $\frac{20000\mu m}{4\mu m}$

BurjKhalifa, Dubai



Silicon photonics

"MINOS" Greek-French CNRS associated lab

MINOS LAB

INSTITUTE OF FORTH ELECTRONIC STRUCTURE & LASER

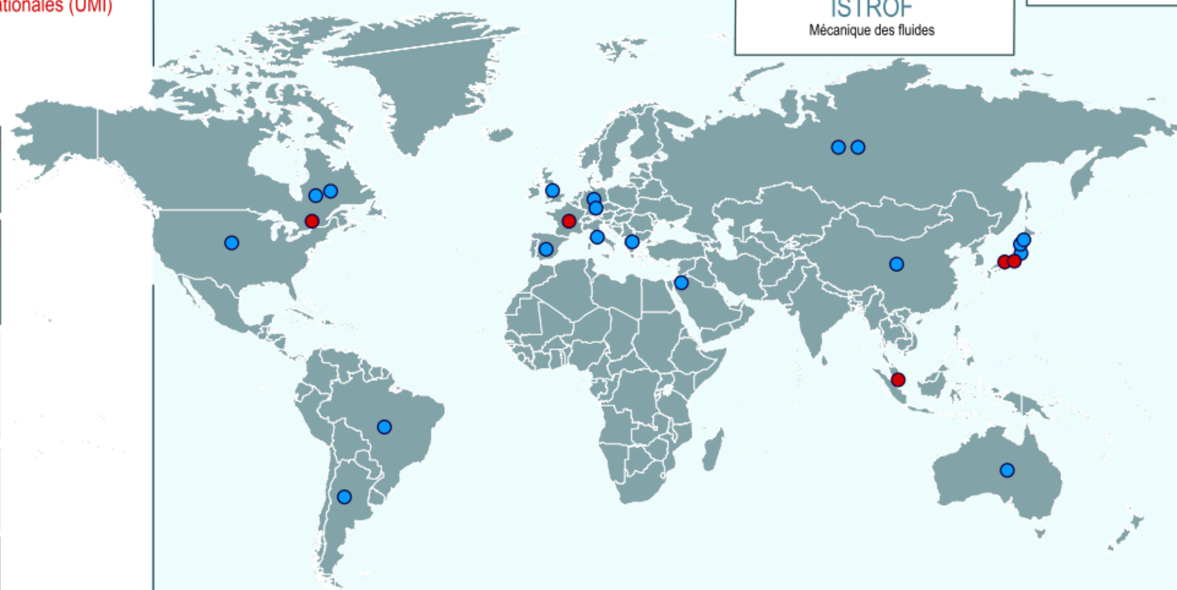
cnrs

LP3

Aix*Marseille université

Les UMI et LIA

- 19 laboratoires internationaux associés (LIA)
- 5 unités mixtes internationales (UMI)



Canada — LN2: Micro/nanotechnologies

France / USA — GeorgiaTech: Réseaux sécurisés, matériaux intelligents

Singapour — CINTRA: Micro/nano électronique, photonique

Japon — JRL: Robotique

Japon — LIMMS: Micro/nanotechnologie, MEMS

Espagne — WIDE: Intégration de puissance

Royaume-Uni — SFGEN: Bioingénierie

Allemagne — Branlant: Approche expérimentale intégrée de la structure des splicéosomes et régulation de l'épissage alternatif; ISTROF: Mécanique des fluides

Italie — COSS & VITA: Mécanique milieux continus / applications matériaux et structures industrielles

Grèce — MINOS: Interaction Laser/ Matière

Russie — KaPPA: Cinétique et physique plasmas pulsés et post-luminescence; LICS: Magnétoacoustique

Japon — FJ-MFL: Fusion magnétique; ElyT Lab: Ingénierie; NextPV: Photovoltaïque

Chine — Metislab: Ingénierie pour la santé et théorie de l'image et du signal

Australie — ALPhFA: Photonique

USA — ATLAB: Nano ingénierie des matériaux et procédés

Canada (Québec) — STEP: Technologies et applications des plasmas

Canada — BSIP: Biomécanique et Modélisation colonne vertébrale

Brésil — JC.Maxwell: Modélisation et conception en électromagnétisme

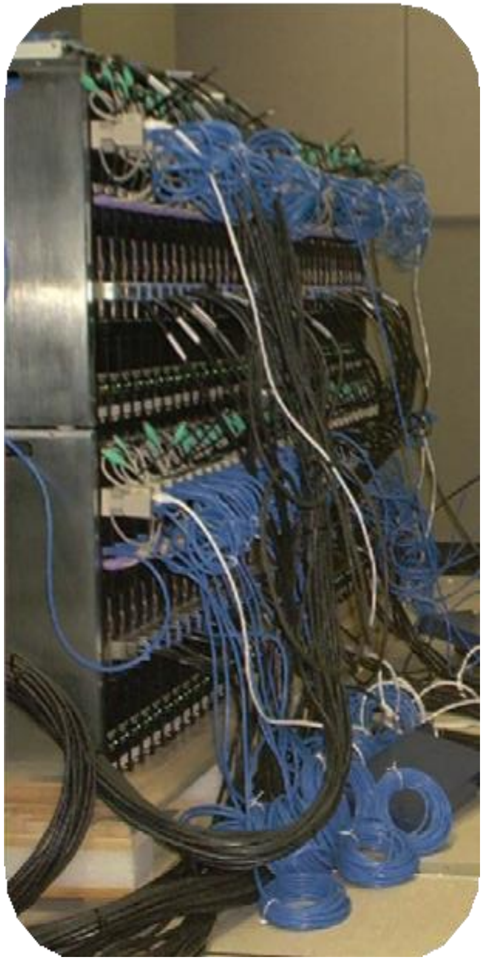
Argentine — PMF: Mécanique des fluides

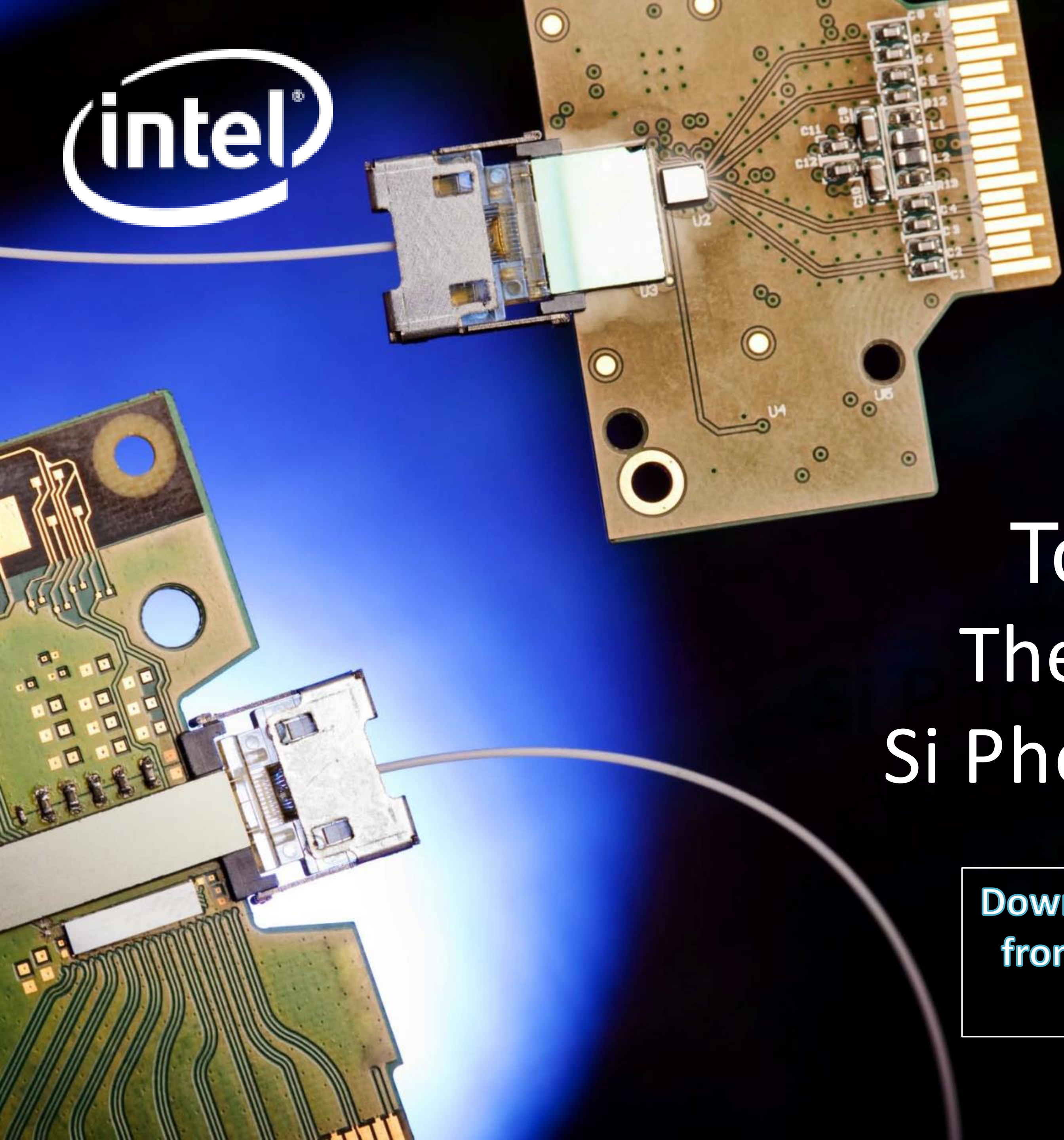
Israël — NaBi: Nanobiosciences, biophotonique

Coordinators: Mark Sentis (LP3) & Stelios Tzortzakis (IESL)

The Optical-Electronics Telecommunications Interface

The road from this…



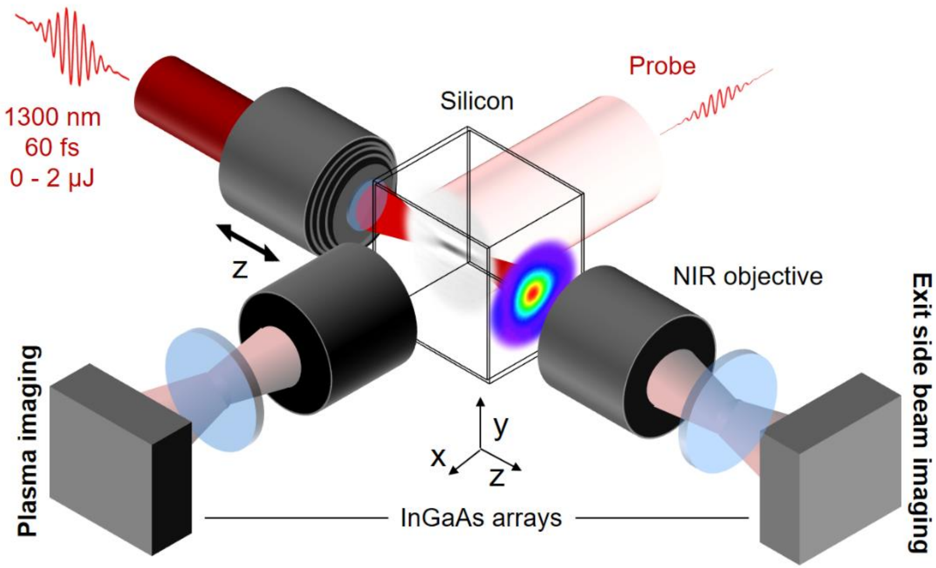


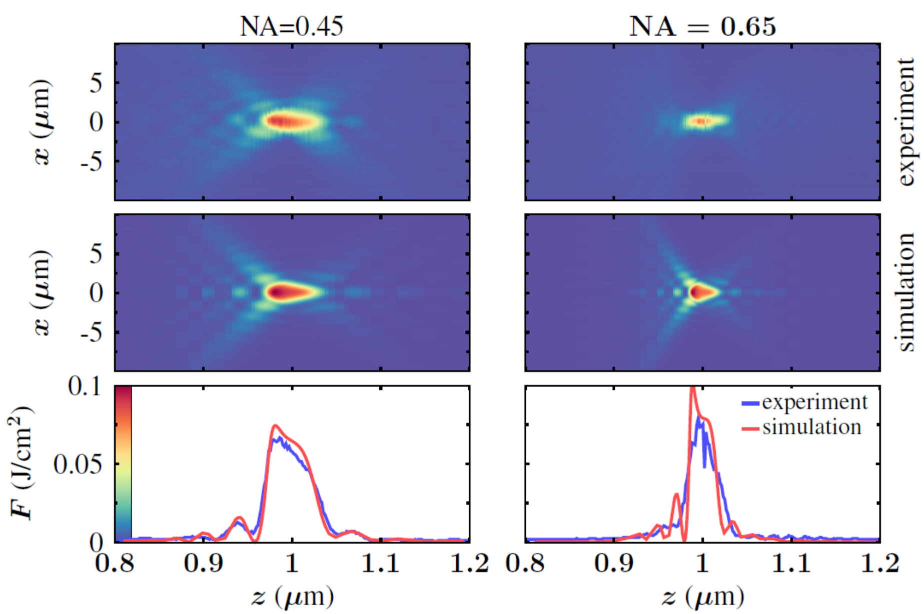
To this…
The 50 Gbps Si Photonics Link

Download a full HD movie from iTunes in less than a second!

Imaging laser propagation in Si

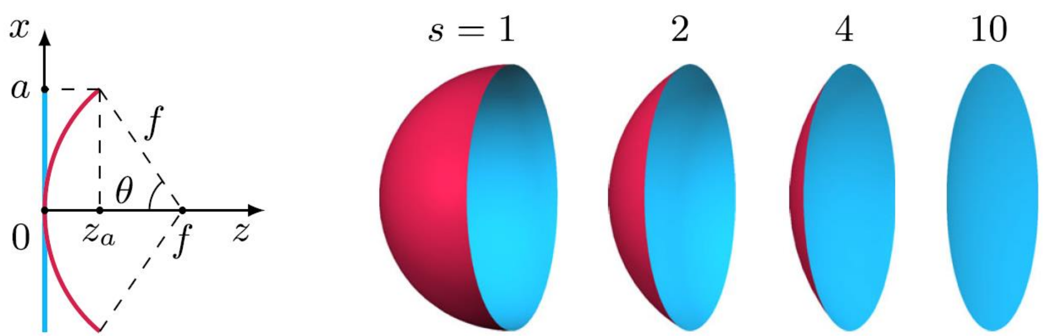
Experimental holographic setup



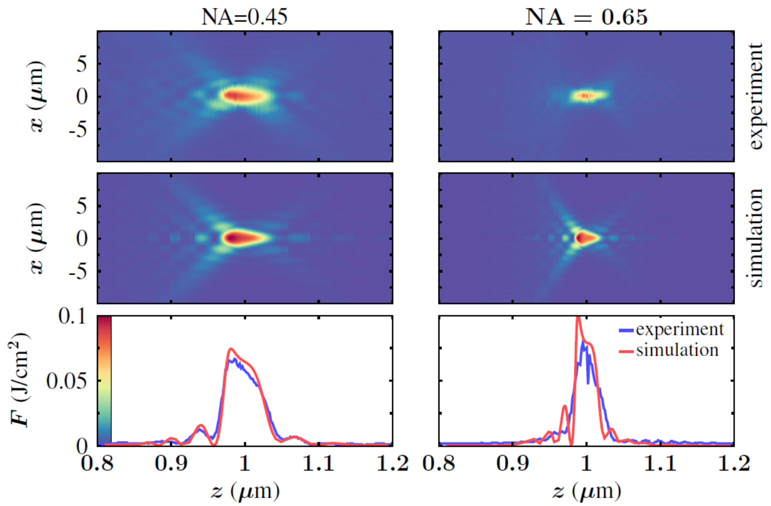


Excellent agreement between our simulations and experimental results

A Transformation Optics Solution to nonparaxial propagation problems



The problem is projected to a stretched space-time one such that it becomes paraxial!

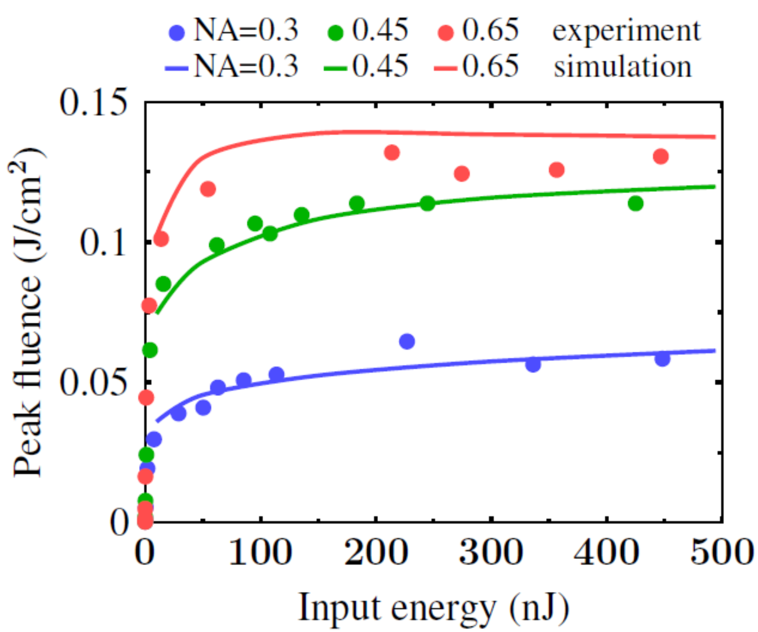


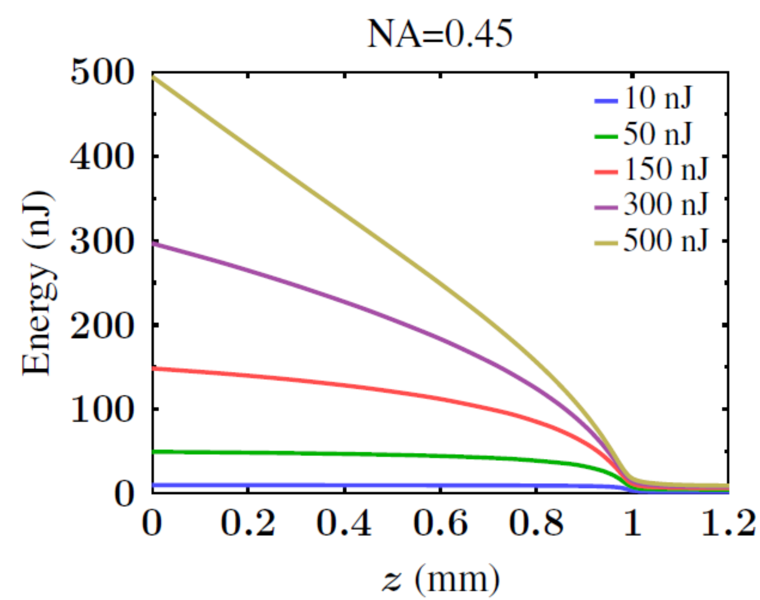
Excellent agreement between our simulations and experimental results

PRL **117,** 043902 (2016) PHYSICAL REVIEW LETTERS

Identifying the problem

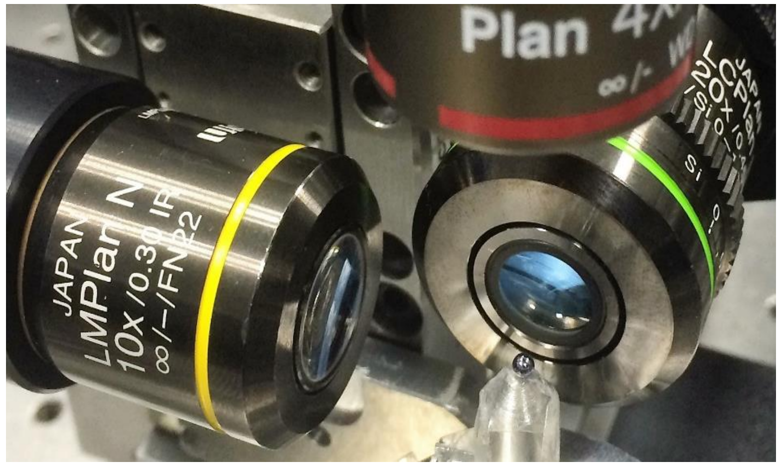
<u>To date all attempts to modify the bulk of Si using femtosecond pulses have failed! Why?</u>

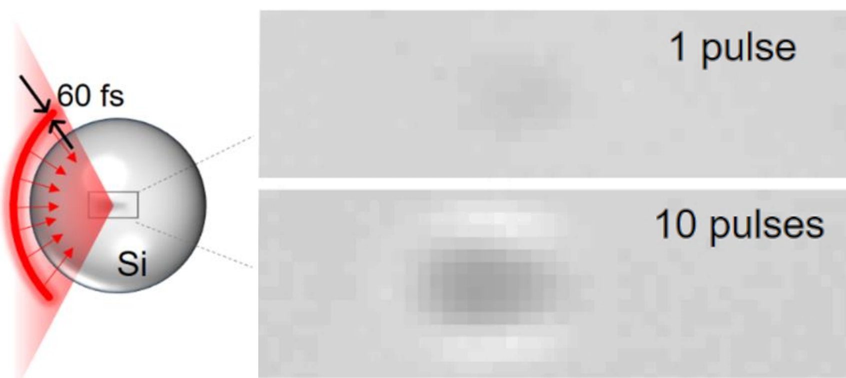




Two-photon absorption and defocusing in plasma lead to the depletion of the pulse energy on the way to focus.

Achieving ultrafast laser writing in bulk Si – opening the horizon for 3D silicon photonics





Induce permanent index modification in the bulk of Si using extreme localization of light in space and time.

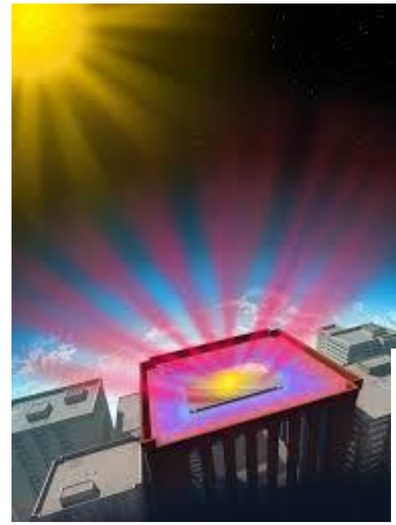
Took <u>20 years</u> to reach this milestone from the time of the first demonstration in the bulk of glasses!

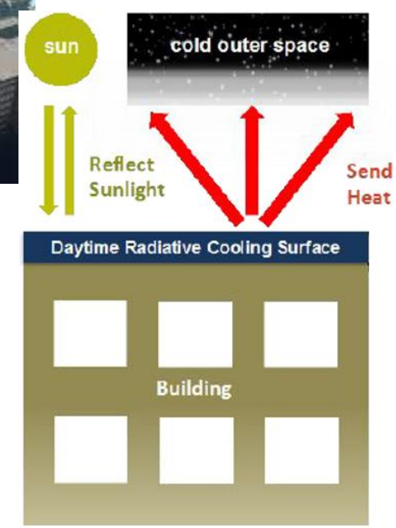
nature COMMUNICATIONS Nat. Commun. **8**, 773 (2017)

Teaser: Passive radiative cooling

Passive Radiative Cooling

- **Radiative cooling**: Dissipate excess heat into remote heat sinks via thermal radiation.
- **Materials**: Combination of natural and artificial materials, like metamaterials.
- Application in **photovoltaic cells**: reduced temperature of operation, resulting in **higher performance and longer lifetimes**.
- **A joint research project between FORTH and Texas A&M University, funded by Qatar Foundation.**





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FORTH

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Qatar National Research Fund
Member of Qatar Foundation

Acknowledgments

UNIS group:

V. Fedorov

T. Koulouklidis

M. Manousidaki

D. Mansour

Ch. Daskalaki

M. Loulakis

D. Papazoglou

INSTITUTE OF FORTH ELECTRONIC STRUCTURE & LASER

University of Crete

TEXAS A&M UNIVERSITY

Collaborators:

Farsari / Manousidaki, FORTH

Kafesaki / Perrakis, FORTH

Grojo / Chanal, Univ. of Marseille

Zacharakis / Di Batista, FORTH

A. Couairon, Ecole Polytechnique

D. Christodoulides, CREOL

Moloney / Kolesik, Arizona

X.-C. Zhang, Rochester

Funding

LaserlabEurope

The "**Integrated Initiative**" of European Laser Infrastructures in the 7th Framework Programme of the European Union

SEVENTH FRAMEWORK PROGRAMME

European Commission HORIZON 2020

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