Filamentation of femtosecond nondiffracting beams

*Applications to laser ablation*


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Femtosecond laser ablation is not a direct process.


I \sim 10^{12} to 10^{14} \text{W/cm}^2
Motivations

Femtosecond lasers have enabled significant progresses for precision micro and nanofabrication with ablation accuracy down to \( \sim 10-100 \) nm.

But the extent of laser ablation with high accuracy is limited to surface nanocraters or spherical nanovoids in the bulk of transparent materials.

Motivations

We aim at fabricating much deeper structures.

The control of the longitudinal profile of ablation structures during drilling and dicing is a key technological issue.
Motivations - drilling in transparent materials

Need to control the beam propagation and energy deposition

Need to deal with the nonlinear propagation.
Deep drilling with Gaussian beams

Weakly focused Gaussian beams yield pulse spatio-temporal distortions (filamentation, splitting…).

Main Objective: we show that the use of stationary regimes of filamentation allows a higher degree of control of the energy deposition process.

Non diffracting Bessel beams for high aspect ratio drilling

Accelerating beams for laser machining of curved profiles

Conical structure

Caustic structure
Beam shaping toolbox

- Bessel beams
- Accelerating beams

Fourier filtering

SLM image

800 nm
5 KHz
100 fs

High-quality beams
1-2 µm spot size
High angles (up to 50°)
Non diffracting Bessel beams for high aspect ratio drilling

Conical structure
Diffraction-free Bessel beams

Longitudinally extended Bessel beams are an invariant solution to the wave equation
Generated from a superposition of plane waves by an axicon
What matters is not the intensity distribution

The conical structure can be a stationary solution of the nonlinear propagation AND an attractor of the filamentation regime.

2 filamentation regimes at high intensity

Non-stationary (periodic peaks) Stationary (absence of pulse dynamics)

What matters is not the intensity distribution

The conical structure can be a stationary solution of the nonlinear propagation AND an attractor.

Water assisted drilling in glass with fs Bessel beams

Non-stationary (periodic peaks) Stationary (absence of pulse dynamics)


Experimental setup

High conical angles allow us to maintain a stationary regime


Single shot machining of glass (Corning 0211)

Result

200 nm  →  0.65 µJ

200 nm  ←  0.85 µJ

330 nm  →
Through-channel with a single laser shot

3 µJ single pulse


Unexpectedly deep material extraction. Origin?
Numerical simulations (NLSE+plasma equation)

We accurately reproduce our experimental results with 2 numerical models (NLSE or UPPE)

Zhang *et al*, in preparation
Dense plasma formation

Plasma densities are close to those observed during fs laser induced micro-explosions.

This time on much longer propagation distances.

F. Courvoisier, FEMTO-ST, FRGLS 2013
Potential practical applications

Nanofluidics

Nanophotonics

Accelerating beams for laser machining of curved profiles

Caustic structure
Accelerating beams

Airy beams are (nondiffracting) solutions of the paraxial wave equation. Airy beams follow a parabolic trajectory: they are one example of accelerating beam.

Accelerating beams

Airy beams sustain curved & stationary filaments.

**Curved Plasma Channel Generation Using Ultraintense Airy Beams**

Pavel Polynkin, Miroslav Kolesik, Jerome V. Moloney, Georgios A. Siviloglou, Demetrios N. Christodoulides

BUT: paraxial trajectories, parabolic only

Polynkin et al, Science 324, 229 (2009)

Accelerating beams are caustics

Accelerating beams can be viewed as caustics – the boundary of an envelope of rays that forms a curve of concentrated light.

The amplitude distribution is accurately described with catastrophe theory and allows us to calculate the phase mask.

L. Froehly et al, Opt. Express **19** 16455 (2011)
Setup

Beams are generated from the Fourier space
Arbitrary accelerating beams-nonparaxial regime

Bending over more than 95 degrees

Numeric

Experiment

Arbitrary accelerating beams-nonparaxial regime

The caustic approach allows us to design the phase mask to generate an accelerating beam with an arbitrary trajectory.

Spherical light

Half-sphere with 50 µm radius
Setup

Experimental result

- Propagation distance (µm)
- Transverse distance (µm)
- Beam cross section
- 3D View

@ 5%
@ 50%
1 µm

F. Courvoisier, FEMTO-ST, FRGLS 2013
Edge profiling – 3D processing concept
Edge profiling – 3D processing concept
Results on silicon

100 µm thick silicon slide
initially cut squared

Results on silicon – quartic profile

It also works for transparent materials – diamond

Direct trench machining in silicon

Debris distribution is highly asymmetric.

Analysis in terms of light propagation direction

Surface trench opening determines the depth of the trench along the caustic trajectory.

Analysis in terms of light propagation direction

Surface trench opening determines the depth of the trench
This is performed by the SIDE lobes, that are more intense on surface

Conclusion

Shaping light direction and addressing stationary filamentation regimes provides a novel degree of control for ultrafast laser micro and nanomachining.

We have reported high aspect ratio drilling and curved edge profiling.

Perspectives:
- novel tool to create and manipulate plasmas
- Curved nanochannels?