

Energy deposition in femtosecond laser inscription

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Outline

What is femtosecond microfabrication

Fs inscription of waveguides

Models

Modelling in the framework of NLSE-Drude model

Analytical results

Role of the pulse shape in energy deposition

So what?

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Our own brass



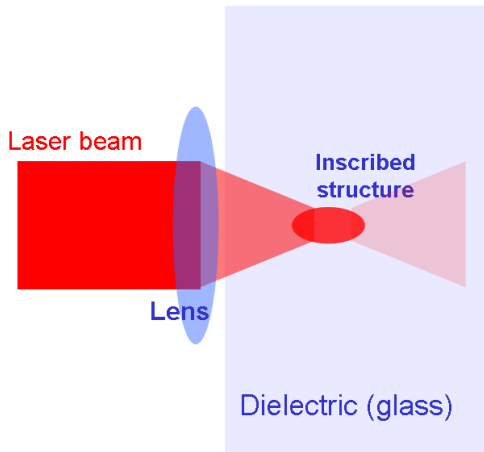
Why people shoot femtosecond lasers at something

Indeed, why? A few reasons are

1. Healthy curiosity.
2. Hitting something far away.
3. Laser surgery.
4. Laser modification of solid materials (surface and **bulk**).

Principle of femtosecond (fs) microfabrication

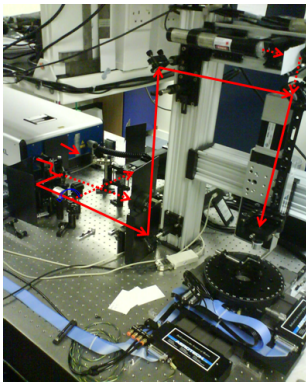
femtosecond microfabrication for dummies(=theoreticians)



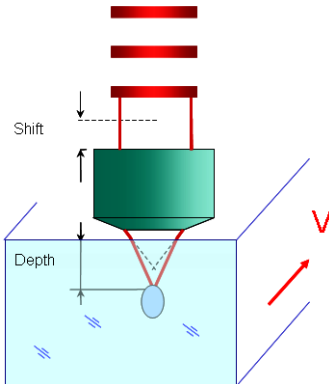
Laser pulse enters left to right

Femtosecond micro-fabrication/machining

Experimental implementation



Experimental setup



Schematic of fs inscription

Femtosecond micro-fabrication/machining

3D examples



Fig. 1. (a) Schematic of the symmetric three-waveguide directional coupler. Waveguides are initially separated by $50\text{ }\mu\text{m}$ and by $5\text{ }\mu\text{m}$ in interaction region L . (b) Inverse gray-scale CCD image of the waveguide outputs shows a 43:28:29 power-splitting ratio between the guides.

Microfabrication of 3D couplers. Kowalevitz et al, 2005

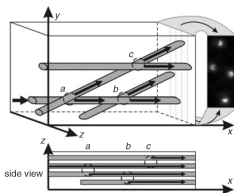


Fig. 3 Schematic of 1×4 splitter (top and side view) with experimental near-field of output face at 1550 nm

3D splitter. Osellame et al, 2005

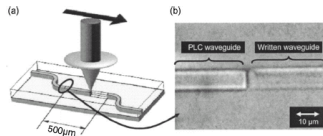


Fig. 5. (a) Schematic diagram of the waveguide connection in this experiment. (b) Image at the junction point of waveguide connection.

Lightwave Circuits. Nasu et al, 2005

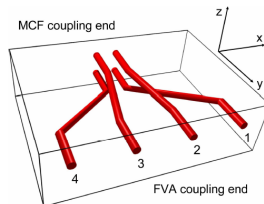


Fig. 1. Graphical representation of the fabricated fan-out device.

Fan out coupler. Thomson et al, 2007

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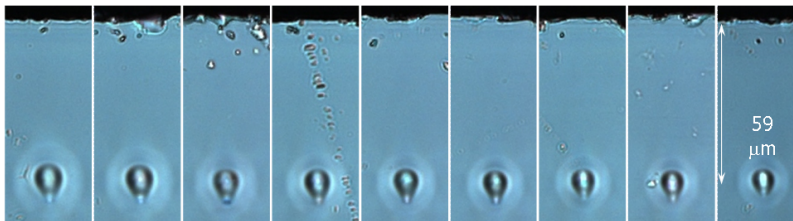
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Our own example: waveguide inscription

[Alsop, Dubov, Mezentsev, Bennion, Appl. Opt., 2010]

Shown: microphotographs of the waveguide cross-sections for translation speeds 20 to 60 mm/s increasing left to right



All the waveguides were inscribed with pulse energy of 30.7 nJ.

Waveguide inscription

Optimisation parameter space

Optimisation Target: lowest possible total losses of waveguide

| | | |
|-------------------------|-------|---|
| Pulse Energy, nJ | x5 | 17, 19.2, ..., 31 |
| Translation speed: mm/s | x9 | 20, 25, ..., 55, 60 |
| Inscription depth, mm | x3 | 68, 83 and 100 |
| Polarizations: | x2(3) | X – \perp and Y – \parallel to scan direction) |
| Translation direction | x2 | Forward and Backward |

Total: 540 tracks (**haystack of regimes**)

Task: **find one needle.**

Motivation for this work

- ▶ Establish thresholds for energy deposition (=absorption)
- ▶ Study energy absorption at different wavelengths
- ▶ Show the role of pulse shape

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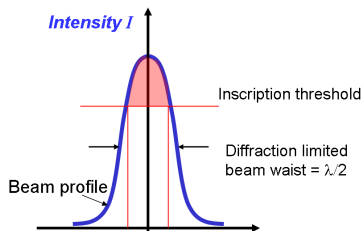
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Inscription threshold

Naive observation: Inscription is an irreversible change of refractive index when the light intensity exceeds certain threshold: $\delta n \sim I - I_{th}$



Careful control of pulse intensity can result in a very small structure, e.g., holes as small as 5 – 50 nm have been created. Experimentally determined inscription threshold for fused silica

$$I_{th} = 10 \div 30 \text{ TW/cm}^2$$

Why femtosecond?

H. Guo et al, J. Opt. A, (2004)

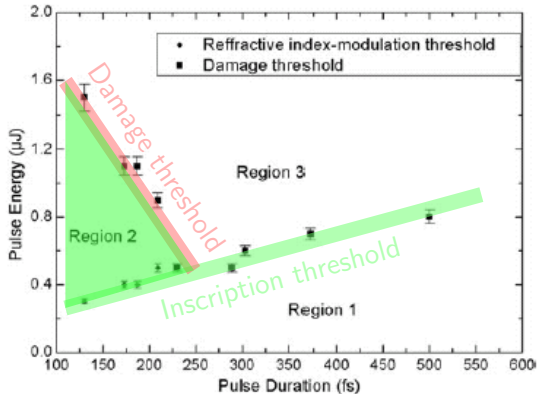


Figure 3. The dependence of the refractive index modulation threshold (♦) and damage threshold (■) on pulse duration with scan velocity of $10 \mu\text{m s}^{-1}$.

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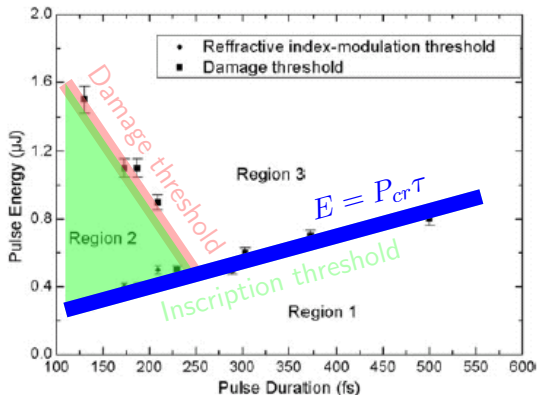


Figure 3. The dependence of the refractive index modulation threshold (♦) and damage threshold (■) on pulse duration with scan velocity of $10 \mu\text{m s}^{-1}$.

Energy deposition

Absorption of modest energy may produce a lot of damage

Let's consider a fs pulse with energy $E = 1 \mu\text{J}$.

What temperature can be achieved if all this energy is absorbed at focal volume $V = 1 \mu\text{m}^3$?

$$E = C_V \rho_m V \Delta T$$

$$C_V = 0.75 \times 10^3 \text{ J/kg/K}$$

$$\rho_m = 2.2 \times 10^3 \text{ kg/m}^3$$

- Temperature rise is then estimated as **1,000,000°K**

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- ▶ Typically, inscription operates at smaller energies **1,000°K**
- ▶ **Still a lot!!!**

Electromagnetic wave is described by a set of Maxwell equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

$$\mathbf{D} = \varepsilon \varepsilon_0 \mathbf{E} ; \quad \mathbf{B} = \mu_0 \mathbf{H} ,$$

where \mathbf{J} is an electron current density.

Description of plasma is based on relaxation dynamics of the electrons driven by the electromagnetic wave. The major source of plasma in strong electromagnetic field is multi-photon and avalanche ionisation to be included in the continuity equation.

$$\frac{d\mathbf{v}_e}{dt} = -\tau_c^{-1}\mathbf{v}_e - \frac{e}{m_e}e\mathbf{E}$$

$$\mathbf{J} = -e\rho\mathbf{v}_e$$

$$\frac{d\rho}{dt} = \text{ionisation sources} ,$$

\mathbf{v}_e is an electron velocity

τ_c is the shortest electron collision time

Simplifications and specific models

- ▶ Envelope approximation can be used to describe quasi-monochromatic paraxial evolution

$$\mathbf{E}(\mathbf{r}_\perp, z, t) = \hat{\mathbf{y}} \mathcal{E}(\mathbf{r}_\perp, z, t) \exp[i(kz - \omega t)]$$
$$\frac{\partial}{\partial z} = ik + \frac{\partial}{\partial z} ; \quad \frac{\partial}{\partial t} = -i\omega + \frac{\partial}{\partial t}$$

- ▶ Moving frame of coordinates:

$$t \rightarrow t - z/v_g ; \quad v_g = \frac{\partial \omega}{\partial k(\omega)}$$

- ▶ Kerr nonlinearity must be taken into account for strong laser field

$$n = \sqrt{\varepsilon} = n_0 + n_2 |\mathcal{E}|^2$$

- ▶ Multi-photon and avalanche ionization

Truncated model

[M. D. Feit and J. A. Fleck, Appl. Phys. Lett., 1974]

[L. Bergé et al, Rep. Prog. Phys., 2007]

Extended Non-Linear Schrödinger Equation (NLSE)
for envelope amplitude of electric field

$$i\mathcal{E}_z + \frac{1}{2k}\Delta_{\perp}\mathcal{E} - \frac{k''}{2}\frac{\partial^2\mathcal{E}}{\partial t^2} + k_0 n_2 |\mathcal{E}|^2 \mathcal{E} = \\ - \frac{i\sigma}{2}(1 + i\omega\tau)\rho\mathcal{E} - i\frac{\beta^{(K)}}{2}|\mathcal{E}|^{2(K-1)}\mathcal{E}$$

Electron balance equation for electron concentration:

$$\frac{\partial\rho}{\partial t} = \frac{1}{n_b^2}\frac{\sigma_{bs}}{E_g}\rho|\mathcal{E}|^2 + \frac{\beta^{(K)}}{K\hbar\omega}|\mathcal{E}|^{2K}$$

$K = E_g/\hbar\omega$, $K = 5, 6$ for $\lambda = 800$ nm in fused silica;
 $K = 2$ for $\lambda = 267$ nm = $800/3$ nm.

Estimation of the inscription threshold

Electron balance equation

$$\frac{\partial \rho}{\partial t} = \frac{1}{n_b^2} \frac{\sigma_{bs}}{E_g} \rho |\mathcal{E}|^2 + \frac{\beta^{(K)}}{K \hbar \omega} |\mathcal{E}|^{2K}$$

can be presented in normalised form by introducing scales ρ_{BD} for ρ and t_p for t :

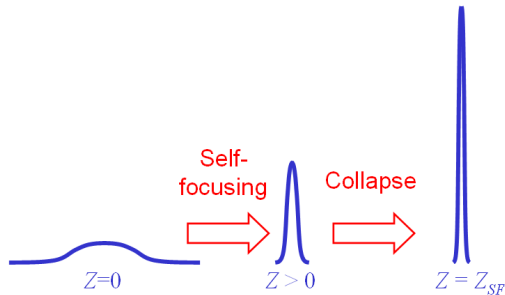
$$\frac{\partial \rho}{\partial t} = \frac{1}{n_b^2} \frac{\sigma_{bs}}{E_g} \rho |\mathcal{E}|^2 + \frac{\rho_{BD}}{t_p} \left(\frac{I}{I_{MPA}} \right)^K$$

where $I_{MPA} = \left(\frac{K \hbar \omega \rho_{BD}}{t_p \beta_K} \right)^{1/K} \sim 25 \times 10^{12} \text{ W/cm}^2$!!!

– naturally introduced intensity threshold for ionisation.
It is seen that ionisation kicks off when intensity exceeds the threshold I_{MPA}

Reduction to the pure 2D NLSE

$$\begin{aligned} i\mathcal{E}_z + \frac{1}{2k}\Delta_{\perp}\mathcal{E} + k_0 n_2 |\mathcal{E}|^2 \mathcal{E} = \\ = \frac{k''}{2} \frac{\partial^2 \mathcal{E}}{\partial t^2} - \frac{i\sigma}{2} (1 + i\omega\tau) \rho \mathcal{E} - i \frac{\beta^{(K)}}{2} |\mathcal{E}|^{2(K-1)} \mathcal{E} \end{aligned}$$

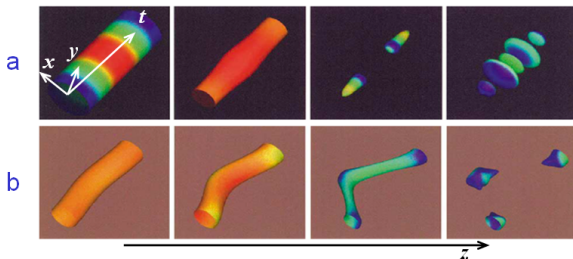


The beam collapses to singular (infinite) intensity at finite distance Z_{SF} if its power exceeds a critical value P_{cr}

Reduction to the 2D NLSE+normal dispersion

[Germaschewski, Bergé, Rasmussen, Grauer, Mezentsev, Physica D, 2001]

$$i\mathcal{E}_z + \frac{1}{2k}\Delta_{\perp}\mathcal{E} - \frac{k''}{2}\frac{\partial^2\mathcal{E}}{\partial t^2} + k_0n_2|\mathcal{E}|^2\mathcal{E} =$$
$$= -\frac{i\sigma}{2}(1+i\omega\tau)\rho\mathcal{E} - i\frac{\beta^{(K)}}{2}|\mathcal{E}|^{2(K-1)}\mathcal{E}$$



The collapse is arrested but dynamics is extremely complex
Eventual absorption MPA+PA also arrests collapse also known as
intensity clamping

[Braun et al, 1995; Kasparian et al, 2000]

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Initial conditions

Typically, the Gaussian initial condition is being used:

$$\mathcal{E}(z = 0, r, t) = \sqrt{\frac{2P_{in}}{\pi r_0^2}} \exp\left(-\frac{r^2}{r_0^2} - \frac{ikr^2}{2f} - \frac{t^2}{t_p^2}\right),$$

r_0 is the waist of the incident beam

t_p defines the conventionally defined pulsewidth

$t_{FWHM} = \sqrt{2 \ln 2} t_p \approx 1.177 t_p$

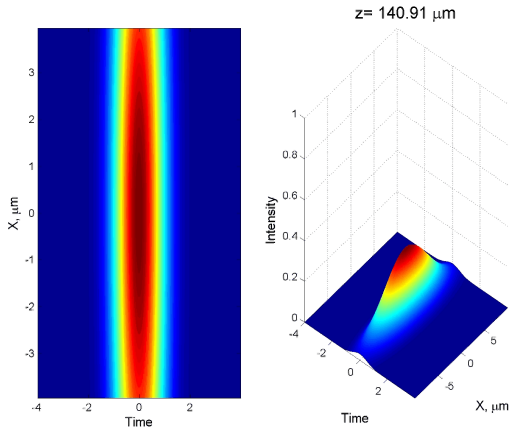
f is a focal length of the objective lens.

$P_{cr} = \lambda^2 / (2\pi n n_2) \sim 2.3 \text{ MW}$ critical power for self-focusing

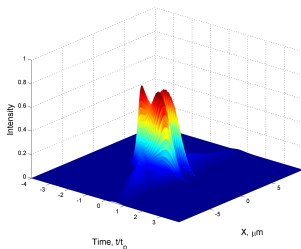
Light bullet laser pulse limited in space and time

Spatio-temporal dynamics of the light bullet

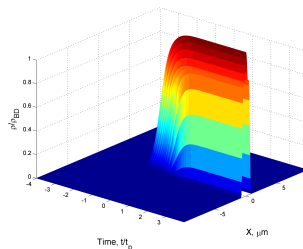
[Mezentsev et al. SPIE Proc. 2006, 2007]



What is left behind the laser pulse



Light intensity pattern



Plasma pattern

Laser pulse leaves behind a stationary cloud of plasma described by asymptotic distribution of plasma concentration:

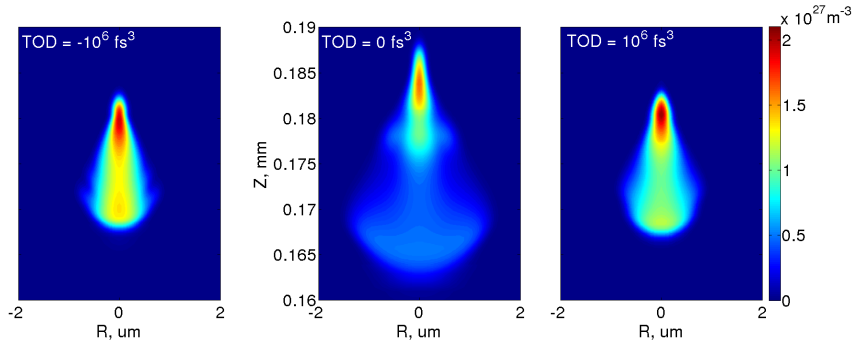
$$\rho(\mathbf{r}, z) = \int_{-\infty}^{\infty} \left[\frac{1}{n_b^2} \frac{\sigma}{E_g} \rho |\mathcal{E}(\mathbf{r}, z, t)|^2 + \frac{\beta^{(K)}}{K \hbar \omega} |\mathcal{E}(\mathbf{r}, z, t)|^{2K} \right] dt .$$

Manifestations of energy deposition

- ▶ Absorbed energy
- ▶ Distribution of plasma density leading to the material heating

Typical plasma distributions

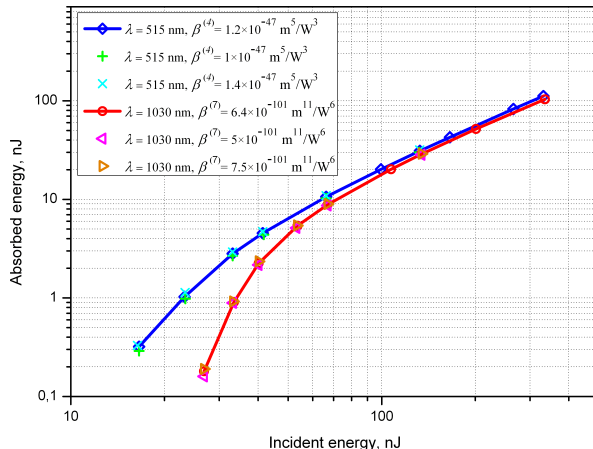
in this case – for different pulse shapes



Absorbed energy vs incident energy

$\lambda = 1030\text{nm}$ and $\lambda = 515\text{nm}$

[Dostovalov, Babin, Dubov, Baregheh, Mezentsev, Laser Physics, 2012]



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Fundamental identity for energy evolution

For the pulse energy

$$E(z) = \int_0^{\infty} 2\pi r dr \int_{-\infty}^{\infty} I(z, r, t) dt ; \quad I = |\mathcal{E}|^2$$

the wave equation holds the identity

$$\frac{dE(z)}{dz} = - \int_0^{\infty} 2\pi r dr \int_{-\infty}^{\infty} dt \left(\sigma \rho I + \beta^{(K)} I^K \right)$$

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A big question:

How to determine evolution of intensity $I(z, r, t)$?

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A big question:

How to determine evolution of intensity $I(z, r, t)$?

We use an analysis based on **exact** identity above using adiabatic approximation.

Quasi-conservative propagation

$$\begin{aligned} i\mathcal{E}_z + \frac{1}{2k}\Delta_{\perp}\mathcal{E} + k_0 n_2 |\mathcal{E}|^2 \mathcal{E} - \frac{k''}{2} \frac{\partial^2 \mathcal{E}}{\partial t^2} = \\ = -\frac{i\sigma}{2}(1 + i\omega\tau)\rho\mathcal{E} - i\frac{\beta^{(K)}}{2}|\mathcal{E}|^{2(K-1)}\mathcal{E} \end{aligned}$$

It is known that for subcritical powers ($P < P_{cr}$) the Gaussian pulses behave self-similarly (adiabatically)

[S.Turitsyn, V. Mezentsev, M. Dubov, A. Rubenchik, M. Fedoruk, and E. Podivilov, Optics Express, 2007]

Self-similar evolution can be treated as

$$|\mathcal{E}(z, r, t)| = \sqrt{\frac{2P_{in}}{\pi R^2(z)}} \exp\left(-\frac{r^2}{R^2(z)} - \frac{t^2}{t_p^2}\right)$$

where peak power and pulse radius now depend on propagation distance z and the right hand side of the reduced wave equation above can be treated as perturbation.

Evolution of energy

We now have an ordinary differential equation describing energy evolution

$$\frac{dE(z)}{dz} = \left[1 + M(E, z) \frac{\sigma}{R^2(z)} \frac{E}{E_g} \right] \left(\frac{2}{\pi} \right)^{\frac{3}{2}(K-1)} \frac{\beta^{(K)}}{K^{3/2} t_p^{K-1}} \frac{E^K}{R^{2(K-1)}}$$

blue and red terms are the contributions of MPA and plasma absorption respectively.

$M(E, z) \approx 1 \div 10$ is a dimensionless shape factor and is a smooth function of energy E

Qualitative results

- It is seen that plasma absorption responsible for substantial energy deposition kicks off when the pulse fluence E/R^2 exceeds a critical fluence

$$F_{cr} = \frac{1}{M} \frac{E_g}{\sigma}$$

defined by the gap energy over inverse Bremsstrahlung cross-section (!!!)

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- Another important for applications result is that the radius of the plasma cloud formed by the electron avalanche scales as square root of energy

$$R_{avalanche} = \sqrt{M\sigma E/E_g}$$

Low energy limit

In the low energy limit $E_{in}/w_0^2 \ll E_g/\sigma$ (w_0 is a beam waist) the absorbed energy can be found analytically:

$$\Delta E = \left(\frac{2}{\pi}\right)^{\frac{3}{2}(K-1)} \frac{\beta^{(K)} \mu(K) z_R}{K^{3/2} t_p^{K-1} w_0^{2(K-1)}} E_{in}^K$$

$$\mu(K = 4, 5, 6) = \left\{ \frac{3\pi}{8}, \frac{5\pi}{16}, \frac{35\pi}{128} \right\}$$

Power law $\Delta E \propto E_{in}^K$ is obtained analytically (!!!).

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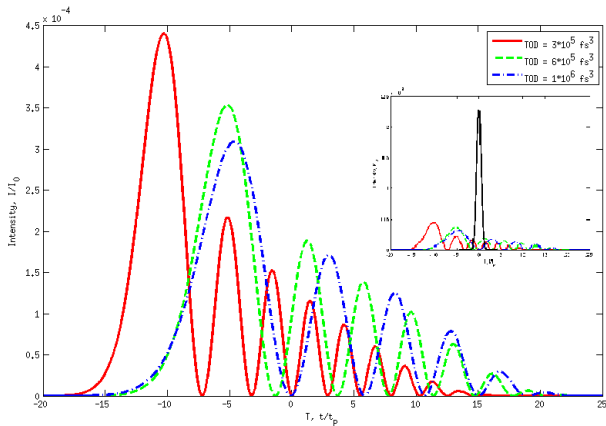
Modified initial pulse

The Gaussian initial condition is now modified in a way like the pulse travelled through the medium with third order dispersion:

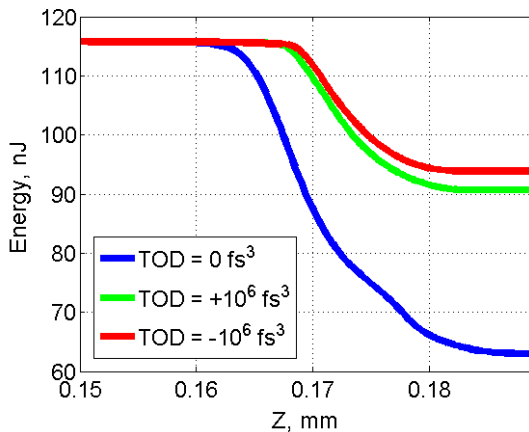
$$\mathcal{E}(z = 0, r, \omega) = \mathcal{E}_0(r) \exp(-i\varphi_3\omega^3) ,$$

φ_3 is the "Third Order Dispersion" (TOD) parameter.

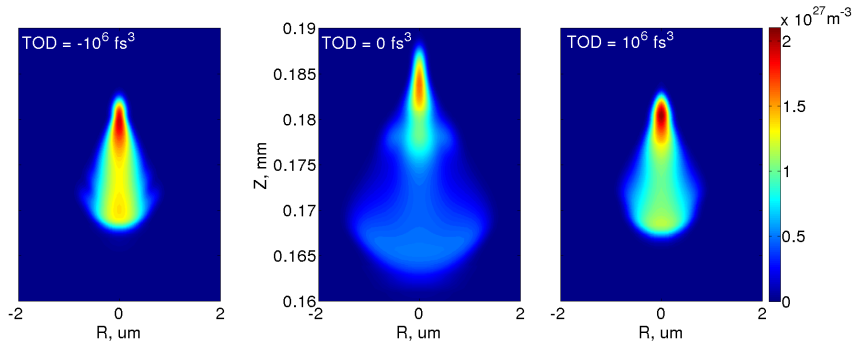
Pulse shapes



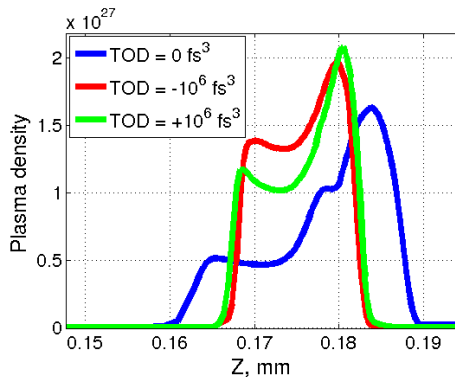
Evolution of the pulse energy



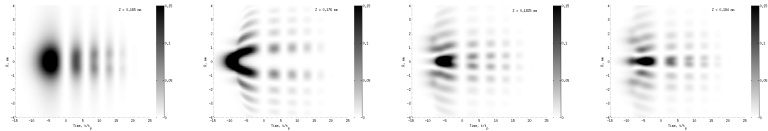
Plasma profiles for different pulse shapes



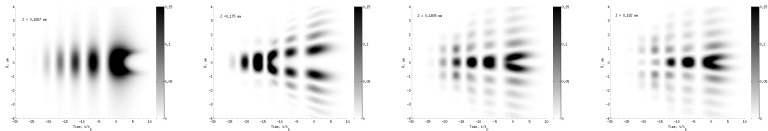
Plasma density on the beam axis



Light patterns at different propagation distances



Positive TOD



Negative TOD

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Conclusions (so what?)

- ▶ Energy deposition in femtosecond laser inscription is analysed in terms of absorbed energy and also a spatial distribution of electron-hole plasma.
- ▶ Analytic formulae for the inscription thresholds are established.
- ▶ Role of the laser pulse shape on the distribution of the deposited energy is analysed.