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# Material Processing by fs Laser Pulse Trains: Experiments vs. Simulations

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The use of femtosecond (fs) trains of pulse is now well established as an efficient technique to modify dielectric materials. Through numerous experimental parameters, it is possible to adjust the amount of deposited energy into the material with a great accuracy.

When an intense fs laser pulse is focused inside a dielectric material, here soda-lime glass, electrons get promoted from the valence band (VB) to the conduction band (CB) by photo-ionization processes. After the fs pulse interaction, electrons in the CB transfer their energy to the lattice through collisional processes, and heat diffusion towards the surrounding cold matter of the focal point sets in. Due to the low heat diffusion coefficient (a few microseconds for micron-size volume), and by using a few hundreds kilohertz repetition rate (RR), one can achieve pulse-to-pulse accumulation of temperature. For sufficiently large number of pulses, it is possible to exceed the annealing temperature, and the dielectric material gets modified permanently.

Our approach to simulate this phenomenon is based on the separation of the different timescales of the key physical processes. To this end, the laser pulse propagation is simulated by a paraxial Forward Maxwell code taking into account key nonlinear effects [1], in order to compute the single pulse energy deposition in the material. Thermal diffusion is taken into account by the heat equation [2], where we use the (repeated) single pulse energy deposition as heat source. Finally, reaching the annealing temperature is used as a threshold to get the dimensions of the permanent modification of the matter.

Simulations and experiments were performed in soda-lime glass for a train of 300 fs pulses with an incident energy of  $1.3 \mu\text{J}$  per pulse. The laser beam, with a wavelength centered around 1030 nm, was focused into the glass bulk by a  $10\times$  objective. The theoretically predicted dimensions of the glass transition temperature zone presented in Fig. 1(a) are confronted with the dimensions of the experimental modifications of the glass [c.f. Fig. 1(b)]. We note a threshold-like behavior for the onset of measurable modifications between 100 and 200 kHz, in the experiments as well as in the simulation results. The experimental dimensions are well reproduced by our model, despite a slight deviation in the predicted

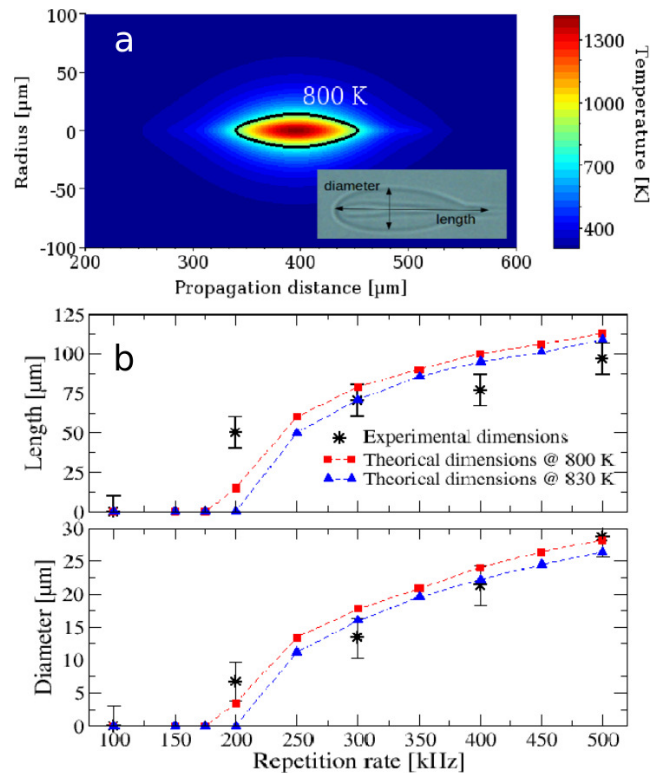


Figure 1: (a) Theoretically predicted thermal map and experimental structure induced by a train of 500 laser pulses at 500 kHz repetition rate (RR) and with an incident energy of  $1.3 \mu\text{J}$  per pulse. (b) Experimental (stars) and theoretical (squares and triangles) dimensions as a function of the RR. The laser pulses were propagating from left to right

length for 200 and 300 kHz. We attribute this discrepancy to changes in the propagation dynamics due to successive material modification [3] which is not (yet) taken account in this work.

## References

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