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Pulse Duration and Temporal Contrast as Critical Parameters for Internal Structuring of Silicon

Amlan Das¹, Andong Wang¹, Olivier Utéza¹, David Grojo¹
1. Aix-Marseille Université, CNRS, LP3, F-13288 Marseille, France

The advent of infrared laser technologies creates a new avenue for directly creating 3D microdevices inside silicon chips by laser writing. However, challenges persist due to material nonlinearities that prevent to reach writing conditions with the shortest femtosecond pulses [1]. When turning to longer pulses up to nanosecond duration, the situation progressively improves. Decreased power and nonlinear effects make bulk modification become usually achievable [2]. However, the literature remains very contradictory on the conditions for bulk Si modifications. Some report waveguide writing with ultrashort pulses [3] while others show very hardly achievable modifications with relatively long pulses [4]. This is the opposite of current understanding and provides a motivation to study laser-technology-dependent parameters. After studying the pulse duration dependence [2], we have found that by combining different pulse durations, the temporal contrast corresponding to the intensity ratio of the background or pre/post – pulses to the main peak pulse is another key parameter in these situations.

For illustration purpose, we have extracted the intensity autocorrelation trace of the 800-fs pulses from a fiber laser used in Ref. [5]. As shown in Fig. 1(a) with the red curve, we can experimentally mimic the exhibited contrast imperfection by combining a femtosecond pulses with 4-ps pulse of modest intensity. We developed an experiment where pulses can be synchronized for multi-timescale analysis of the problem.

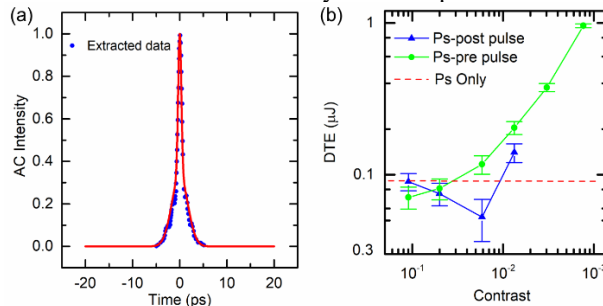


Fig. 1(a) Intensity autocorrelation trace from literature and fitting procedure by combining two components of 800 fs and 4 ps with gaussian approximation. **(b)** Damage threshold energy (DTE) measurement as function of picosecond contrast measured with double pulse sequences. 'ps-post' signifies the fs component (190 fs) arrives 20 ps ahead of ps component (11ps) whereas 'ps-pre pulse' is the exact opposite.

Concentrating on the picosecond contrast problem, we have measured the damage threshold energy (DTE) for different combinations with a 190-fs pulse and 11-ps pulse delayed by 20 ps [6]. The results are shown in Fig. 1(b). The 11-ps alone can easily create damage 300 μm inside silicon at focusing condition of $\text{NA}=0.85$. The required energy level is indicated by the dashed red line. By mimicking femtosecond interaction with a degraded picosecond contrast, the measurement significantly deviates from single picosecond pulse case. The picosecond pre-pulse is very illustrative as higher is the intensity contrast, higher is the damage threshold up to conditions for which permanent modification become inaccessible above 1.3×10^{-3} contrast ratio. Interestingly, looking at the ps-post pulse case, one can find that a femtosecond pre-pulse can advantageously or disadvantageously prepare a picosecond interaction (see blue curve going above and below red dashed line). A similar study has been repeated adding a 5 ns background to the interaction. Overall, this allows to discuss the key dynamical aspects for energy deposition in these configurations, including the plasma effects and the material thermal response [6]. The unusually high sensitivity to the contrast solves the discrepancies observed in most previous reports and suggest that an important degree of optimization exists in the temporal domain [7] for 3D laser writing inside silicon.

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