Temporally shaped femtosecond pulses for high resolution materials processing

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The modification of materials with femtosecond laser pulses is becoming a mainstream processing technique for selected applications due to the high lateral resolution modifications that are possible to achieve. This is possible mainly thanks to the nonlinear absorption mechanisms that are triggered when the characteristic high-power peaks interact with the subject material. Traditional direct-write laser systems employ nominal bandwidth-limited pulses which typically display Gaussian temporal profiles, resulting most of the time in crater shaped modifications at the surface level in dielectric, semiconductor and metallic materials. Advancements in temporal pulse shaping techniques [1-3] have demonstrated significant improvements with regards to the final size and depth increasing the overall ablation efficiency and final lateral resolution. In this work, we present a survey that includes the formation micro- and nanometric size modifications in dielectrics, semiconductors and metals induced by temporally shaped femtosecond laser pulses coming from an amplified Ti:Sapphire femtosecond laser system operating at 1 kHz, nominal wavelength of 790 nm and pulse duration of 30 fs. Five types of femtosecond pulses were used [1-3] as shown in Figure 1A; (i) regular Gaussian bandwidth-limited pulses (BWL, Fig. 1Aa) employed to compare against (ii) positive and negative group delay dispersion pulses (GDD, only showed "+" in Fig. 1Ab), and (iii) positively and negatively dispersed temporal Airy pulses (TAP, Fig. 1Ac and 1Ad respectively).

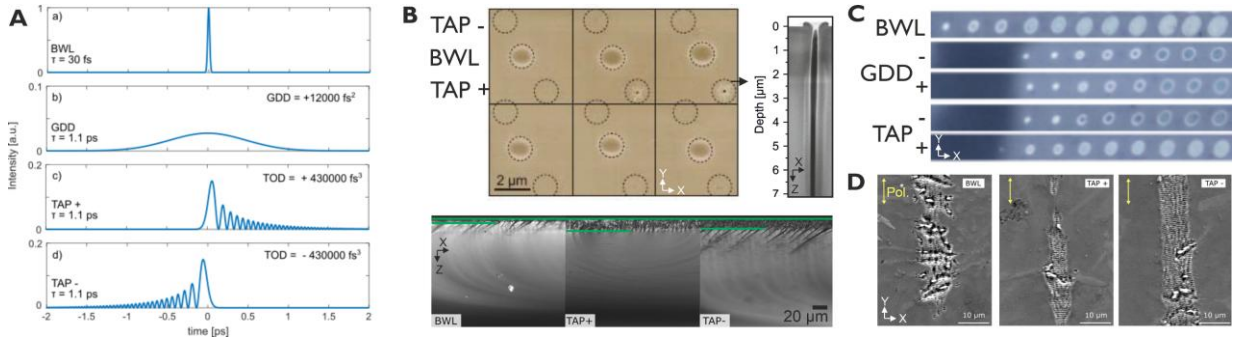

Figure 1 (A) Intensity profiles of the temporally shaped laser pulses implemented for the irradiation of (B) fused silica (top [2]) and soda lime glass (bottom [3]), (C) crystalline silicon <111>, and (D) AlSi10Mg alloy.

Examples and applications are presented for different material types. *In dielectrics*, we demonstrate that it is possible to control the energy deposition extent and its penetration depth, enabling deeper modifications compared to BWL Gaussian pulses. Asymmetrically structured TAP enabled efficient creation of high aspect ratio nanochannels (Fig. 1B), achieving depths of several micrometers and diameters around 250 nm in a single laser shot on fused silica [1,2] (Fig. 1B, top) without relying on self-focusing or filamentation, which can also be used for glass dicing applications [3] (Fig. 1B, bottom). *For semiconductors*, preliminary findings demonstrate that the asymmetric nature of the temporally shaped pulses leads to the formation of amorphous thin films with different depths when these pulses interact with substrates of crystalline silicon with orientation <111> (Fig. 1C). The formation of laser-induced periodic surface structures *on metallic materials*, in particular Al-based alloys, benefit from the different temporal shapes, since the effective surface plasmon lengths induced allow forming homogeneous LIPSS at the lowest fluences (Fig. 1D). Optical microscopy, atomic force microscopy and scanning electron microscopy were employed to assess the morphological quality of the produced surface markings and in selected cases lateral cross-sections obtained via focus ion beam milling. These results highlight the critical role of temporal pulse shaping in controlling laser-material interactions and open new pathways for high-precision material processing across various disciplines and fields of application.

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