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Perspective on ultrashort pulse laser micromachining

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Abstract
Ultrashort pulse lasers have found widespread applications in precise micromachining. Here, we present our brief perspective on the development of this innovative technology from the 1990s until today.

Keywords Ultrashort pulse laser · Materials processing · Micromachining · Ablation

In the early 1990s, the pulse energy of ultrashort pulse lasers could be significantly increased. The development of the chirped pulse amplification technique by G. Mourou and D. Strickland was decisive for this [1] and finally awarded with the Nobel Prize in Physics 2018. Laser systems with pulse energies in the Joule range could be demonstrated for the first time, and commercial table-top systems with pulse energies in the mJ range became widely available. This opened up the possibility of studying laser-matter interactions on timescales in the picosecond and femtosecond range for many scientists worldwide. Especially at the labs of the Lawrence Livermore National Laboratory [2], University of Michigan [3] and also in our group at the Laser Zentrum Hannover [4], the potential of industrial applications in ultra precision machining was seen early on. It is interesting to note that one of the early papers resulting from this work [5], which demonstrates the fundamental advantages of ultrashort laser pulses in the processing of materials with high thermal conductivity, is among the most ever cited publications in Applied Physics A. These results were supported by a theoretical description based on a two-temperature model to describe the energy transfer in the laser-matter interaction on ultra-short time scales, which was originally developed in the 1950s to describe the energy relaxation between electrons and ion lattices [6] to explain deviations from Ohm's law at very high current strengths. Twenty years later, it was applied to describe the interaction of laser radiation with metals [7], providing the basis for optimizing the ablation efficiency [8, 9]. Based on these results, a new branch of ultra-precision machining quickly developed. With the increase in the average power of ultra-short pulse lasers through the use of new types of laser geometries such as discs and fibers [10], production systems for high-volume ultra-precision production were created in a timely manner. A prominent example was the introduction of ultra-short pulse laser-based processing in the production of engine components at Robert Bosch GmbH in close cooperation with TRUMPF Laser GmbH + Co. KG, which enabled a significant reduction in fuel consumption and thus the emission of climate-relevant gases. This development was awarded the Future Prize by the German Federal President due to the social and economic impacts for Germany [11]. Today, the ultra-short pulse laser is an essential part of modern industrial production. The energy-efficient green manufacture of products in the fields of medical technology (e.g. stent production [12]), energy technology, automotive technology, but also in consumer electronics is unthinkable without ultra short pulse laser-based manufacturing processes [13–19]. As a result, the market for ultra short pulse laser systems has grown disproportionately to US$ 1.6 Billion in 2021 and is

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projected to reach US$ 3.8 Billion by 2027, growing at a CAGR of more than 15% from 2021 to 2027 [20].

What will the future bring us? Currently, there is a trend on using higher repetition rates or bursts of pulses [21–23]. Furthermore, there is no doubt that new emission wavelengths from ultrashort pulse lasers, for example in the range of 2 μm [24], will open up new fields of applications especially in semiconductor industry [25]. However, new types of beam guidance systems based on microstructured glass fibers will also lead to the fact that the area of application of ultrashort pulse lasers will continue to grow, especially in industrial production. Ultrashort pulse lasers have the potential to develop into a universal machine tool.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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