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Micro-Optics 3D Printed via Multi-Photon Laser Lithography

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The field of 3D micro-optics is rapidly expanding, and essential advances in femtosecond laser direct-write 3D multi-photon lithography (MPL, also known as two-photon or multi-photon polymerization) are being made. Micro-optics realized via MPL emerged a decade ago and the field has exploded during the last five years. Impressive findings have revealed its potential for beam shaping, advanced imaging, optical sensing, integrated photonic circuits, and much more. This is supported by a game-changing and increasing industrial interest from key established companies in this field. In this review, the origin and the advancement of micro-optics fabrication with MPL are detailed by describing the chronology, distinguishing discrete application groups, providing generalized technical data on the processes and available materials, and discussing the foreseen near-future advances.

1. Introduction

The rapid growth of laser applications has stimulated the demand and supply for new optical components. At the same time, devices are becoming miniaturized and highly integrated to maximize functionality. Here, the field of laser technology and industrial trends meet to create synergy.

While the first use of ultrafast lasers for 3D structuring was proposed in 1991 for optical data storage,[1] their use to create 3D printed objects was first presented by Maruo in a technology-opening article in 1997,[2] where the use of this technology to fabricate micro-optics was also envisaged. The serial writing method of this technique offered flexibility for free-form fabrication, but was limited by its throughput.[3] It took some years for the technology to mature from proof-of-principle level to additive manufacturing as a tool for efficient and reliable fabrication in the modern lab.[4–6] Though the first micro-optical elements were demonstrated as early as 2006,[7] the major efforts and results only started to emerge in 2010,[8,9] together with the development of hybrid organic–inorganic materials,[10,11] and rapidly accelerated with the implementation of commercial 3D lithography systems.[12–14] By 2020, ultrafast laser 3D printing, also known as two-photon polymerization (TPP or 2PP), multi-photon lithography (MPL),[15–17] or simply laser direct writing (LDW), also in literature referenced as direct laser writing (DLW),[18]) was already an established technique for routine fabrication of diverse micro-optical single elements, stacked components, and integrated devices.[19–21] The latest advances in the 3D printing of free-form micro-optics are enhanced by optical grade materials of high refractive index (n) polymers,[22] high-performance hybrids,[23] and optically active[24] or pure inorganic glasses.[25] **Figure 1** shows the development of the technique in terms of published papers and citations, defining an "innovator stage" of the technology followed from 2015 by the "early adopters stage." Examples of micro-optical elements fabricated using MPL and the growth in the complexity of the structures that can be achieved by this technique are also shown in Figure 1.

The advances in this scientific field attracted the attention of the related laser-assisted precision additive manufacturing industry. First, in 2007 Nanoscribe GmbH and in 2008 Workshop of Photonics established companies oriented toward commercialization of this technology aimed at general wide angle application fields. While in 2013, Multiphoton Optics GmbH and Femtika UAB were established and made micro-optics a significant part of their targeted applications. Finally, in 2017, Vanguard Photonics GmbH manufactured dedicated MPL equipment for micro-lenses and wire bond production. Other companies targeting more diverse applications have continued to emerge, such as UpNano established in 2018, and focusing mostly on biomedical applications yet also offering solutions

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