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Femtosecond Laser Micromachining

Photonic and Microfluidic Devices
in Transparent Materials

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Femtosecond Laser Micromachining

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in Transparent Materials

With 305 Figures

 Springer

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Preface

In 1996, a seminal paper by Hirao and coworkers demonstrated that tightly focused femtosecond laser pulses could modify in a permanent way the optical properties of a small volume inside the bulk of a transparent substrate. By a suitable choice of the irradiation conditions, one can induce a refractive index increase localized in the focal volume, thus enabling direct optical waveguide writing by simple translation of the substrate. This discovery has developed, in little over a decade, into a burgeoning research field with many groups working on the understanding and optimization of the process and even more researchers interested in exploiting its unique capabilities for microfabrication.

Femtosecond laser waveguide writing has some clear advantages over competing techniques, such as silica-on-silicon, ion exchange, or sol-gel:

- (1) It is a direct, maskless fabrication technique, i.e., in a single step one can create optical waveguides or more complicated photonic devices (splitters, interferometers, etc.) by simply moving the sample with respect to the laser focus, avoiding complex clean room facilities; this is particularly important for rapid prototyping or on-demand production of a small number of devices, since it does not require the fabrication of dedicated photolithographic masks.
- (2) In contrast with other techniques, which are optimized for specific substrates, it is highly flexible; with a suitable choice of irradiation parameters (wavelength, pulse energy, repetition rate, focusing conditions, translation speed, etc.) one can inscribe waveguides in almost any type of glass. In addition, the technique has been extended to crystalline materials (silicon, lithium niobate) and to polymers.
- (3) It is a truly three-dimensional technique, since it allows one to define waveguides at arbitrary depths inside the substrate, according to geometries that would be impossible with standard fabrication techniques. This added degree of freedom is important because it allows developing innovative and unique device architectures.

Initial interest in femtosecond waveguide writing was mainly focused on the fabrication of devices for optical communications (splitters, interleavers, directional

couplers, fiber and waveguide Bragg gratings, waveguide amplifiers and lasers, etc.). The field was considerably extended when, in another seminal paper in 2001, Marcinkevicius et al. demonstrated that femtosecond laser irradiation followed by etching in hydrofluoric acid solution enables the fabrication of directly buried microfluidic channels in fused silica. The etching rate in the laser irradiated regions is in fact enhanced by up to two orders of magnitude with respect to the pristine material, thus enabling the manufacturing of microchannels with high aspect ratio. This added capability broadens the scope of femtosecond micromachining to microfluidics, and microsystems in general. In particular, the possibility of combining optical waveguides with microchannels, both fabricated by femtosecond laser micromachining, opens exciting perspectives for optofluidics, a novel research field exploiting the synergy of optics and fluidics for the realization of completely new functionalities. With this addition, the arsenal of tools provided by femtosecond laser microstructuring becomes of interest not only for optics and photonics, but also for a wide range of disciplines, from biology to analytical chemistry.

The interest in femtosecond laser microfabrication has been boosted by the parallel developments in laser technology that have occurred in the first decade of the third millennium. Ultrafast lasers were initially very sophisticated devices that could only be operated by highly trained users in a research laboratory environment. Progress in laser media, optical pumping schemes, and mode-locking techniques has resulted in a new generation of compact, rugged, and reliable ultrafast laser systems, which guarantee turn-key operation. This makes the technique of femtosecond laser microfabrication amenable to real-world applications in an industrial environment.

This book, featuring contributions from the most renowned experts, has the ambition of providing a comprehensive introduction to the field of femtosecond laser micromachining of glass, starting from the basic concepts and progressing to the more advanced applications. The book will be of interest for experienced researchers working on femtosecond microstructuring, who will find advanced technical discussions and detailed descriptions of the various applications. It will also serve as an introductory textbook for graduate students or researchers approaching the field for the first time, since it also provides an entry-level coverage of the basic principles and techniques. Finally, and most importantly, it will be an invaluable reference for those researchers working in other disciplines and who will be the final users of the femtosecond laser microfabricated devices, making them aware of the new technological opportunities offered by the technique.

The book is structured in four parts. Part I deals with the fundamentals of femtosecond laser micromachining of transparent materials, describing the underlying physical mechanisms and the technical details of the fabrication process. Part II reviews the properties of waveguides and optical devices, both passive and active, fabricated in glass. Part III deals with refractive index modifications in materials different from glass, such as crystals and polymers. Finally, Part IV describes the more advanced applications to microsystems, including micro- and optofluidic devices.

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Milano
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Roberto Osellame
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and Optimization Strategies**

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