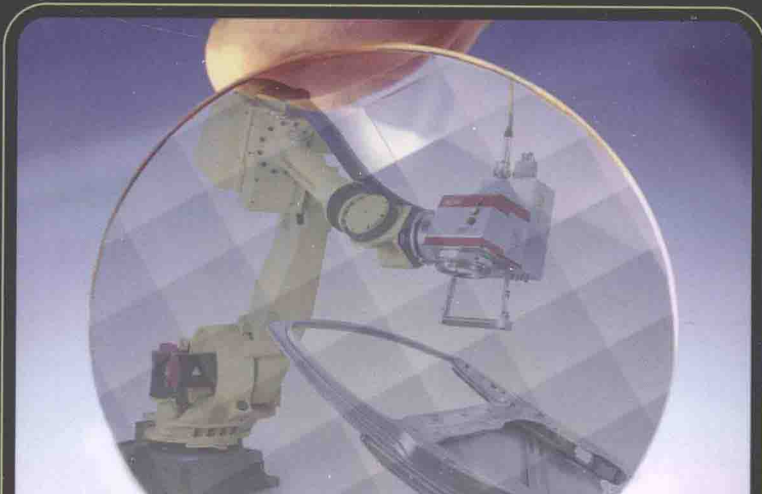
Second Edition

Laser Beam Shaping Applications



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Laser Beam Shaping Applications

Second Edition

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Cover artwork is a combination of a faceted beam integrator and a fiber optic laser beam delivery system each used within the laser processing industry. Both images were supplied by II-VI Corporation, Saxonburg, PA. The authors would like to thank Steve Rummel and John Ryan for supplying those images on behalf of II-VI Corporation.

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We dedicate this book to our children:
Stephen and Alan
Brent and Andrew

Preface

Since the advent of the laser, many applications have required shaping the laser beam irradiance profile. A few of the primary applications include material processing, such as welding, cutting, and drilling; and medical procedures, such as corneal surgery and cosmetic skin treatments. Other applications include laser–material interaction studies, lithography, semiconductor manufacture, graphic arts, optical data processing, and military uses. Over the past 30 years, laser beam shaping technology has matured in theory, design, fabrication techniques, and applications. A good illustration of this is that flattop beams are used in lithography and material processing, but they are also used in the LIGO system that recently detected gravity waves. In the LIGO system, flattop beams are used to increase signal-to-noise in the interferometric system.

This revised edition of *Laser Beam Shaping Applications* (first edition 2005) treats the applications and related technology of laser beam shaping. It is a companion volume to *Laser Beam Shaping: Theory and Techniques* (second edition 2014). The application of beam shaping goes beyond the physical and geometrical optics theory needed to develop beam shaping techniques; it inherently includes the physics of the beam–material interaction. The subtleties of the theory and techniques are best appreciated through the experience of application and design. The chapter authors are highly recognized leaders in the field of laser beam shaping applications. In addition to revising the chapters in the first edition, four new chapters have been added. The subject of the chapters is outlined in the introduction chapter.

This book is intended primarily for optical engineers, scientists, and students who have a need to apply laser beam shaping techniques to improve laser processes. It should be a valuable asset to someone researching, designing, procuring, or assessing the need for beam shaping with respect to a given application. Because of the broad treatment of theory and practice in the book, we think it should also appeal to scientists and engineers in other disciplines.

Although "all" applications of a technology can never be treated in a single volume, this book should provide the potential user of beam shaping techniques with the major insights, knowledge, and experience that can only be derived from applied systems development. In addition, this book provides extensive references to the literature.

The editors express their gratitude to the contributing authors; it is their efforts that made the book possible. It was a pleasure working with the staff of Taylor & Francis Group. Finally, we express our appreciation to the very helpful Ashley Gasque.

Fred M. Dickey

Todd E. Lizotte

Editors

Fred M. Dickey received his BS (1964) and MS (1965) degrees from Missouri University of Science and Technology, Rolla, Missouri, and his PhD degree (1975) from the University of Kansas, Lawrence, Kansas. A fellow of the International Optical Engineering Society (SPIE) and the Optical Society of America and a senior member of Institute of Electrical and Electronic Engineers (IEEE), he heads FMD Consulting, LLC, Springfield, Missouri. He is the author of more than 100 papers and book chapters, holds nine patents, and started and chaired the SPIE Laser Beam Shaping conference, for the first 8 years, and now which is in its eighteenth year, and is currently a committee member.

Todd E. Lizotte is an entrepreneur, inventor, technologist, and author who continues to seek technological and business opportunities through the application of laser beam shaping technology. As a cofounder of several high-tech startups over the past 26 years, Lizotte has demonstrated the critical impact that laser beam shaping has had within the industrial marketplace, by improving the quality and throughput of precision laser processes. Lizotte's laser beam shaping innovations have been applied directly to the microelectronics packaging, semiconductor, and automotive industries to name a few and lead to the acquisition of NanoVia LP a company cofounded by Lizotte, by Hitachi Ltd. Japan in 2003. For more than 10 years, Lizotte worked for Hitachi holding the executive position as Director of Emerging Technology in the United States and was fortunate enough to jointly work on various laser beam shaping projects with colleagues worldwide, developing 24+ patents covering technology that continues to be used today. Since leaving Hitachi in 2014, Lizotte has focused on business development projects at Pivotal Development Co., LLC in the United States, Europe, Africa, and China.

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Contents

1 Introduction

Todd E. Lizotte

The goal of technical publishing in its most basic form is to transfer knowledge. In terms of applications, it is to provide examples of how new technology can be applied within a particular industry to inspire and motivate its further use by others. As the reader goes through this book, there comes a moment where the abstract focuses to a point where ideas merge and one might ask, "Could that work for my application?" The editor's goals for this book, *Laser Beam Shaping Applications* (second edition), is threefold: (1) update the information originating in the first edition, (2) explore new applications that have come about during the time period between the two publications, and (3) inspire creativity to drive further innovation within the field.

As engineers and technologists tasked with the implementation of laser technology, we continue to seek optical solutions employing coherent monochromatic beams of light generated by lasers, delivering energy to the work surface with the goal of increasing quality, reliability, and repeatability of processes. Instead of crudely compressing the laser beam into a concentrated spot, laser beam shaping offers techniques capable of finessing and tailoring a process to specific material properties. This ability to fine-tune the process using optical techniques enables a host of material processing tasks to be achieved or improved, including milling, cutting, drilling, welding, and heat treating.

The newer, updated information contained in the second edition has emerged over the past 12 years. It should also be mentioned that the real genesis with laser beam shaping applications within the industry over the past 20 years coincides with and is reinforced by the introduction of the definitive book, *Laser Beam Shaping Theory and Techniques* (2000, first edition), written by *Fred M. Dickey and Scott C. Holswade.* It can be said with confidence that the introduction to laser beam shaping theory brought forward the adoption of the technology into the mainstream laser industry and enabled the creation of a host of laser material processes that spurred the further development of products, such as high-density electronics, handheld personal electronic devices, computer miniaturization, and flat panel displays. Most people, if not all, have a large screen flat panel TV, shifted over from flip phones to smartphones, and have acquired a tablet-sized computer. The fact is laser beam shaping has made significant contributions to the quality and capability of these technologies on the factory production line, opening the door to the visualization of and access to data by individuals to a level not seen since the introduction of the first personal computers. It is clear to many of us within the industry that laser beam shaping is no longer new and strange as it was 20–30 years ago. More people throughout the industry are now aware of its potential and familiar with the terms used to describe beam shaping. The second edition of *Laser Beam Shaping Applications* represents a continuation of the transfer of knowhow to the industry, reiterating its prominence as a means to push the boundaries of laser processing technology.

It will become apparent while reading that topics are discussed within the context of their applications in order to familiarize the reader with the solutions derived for each purpose and in some cases omit many other discussions about the specific details of the theory of laser beam shaping. Such an approach keeps the focus on the potential of the application of laser beam shaping technology and its successful implementation. If a reader wants to delve into a more complete and integrated book on theory, the book, *Beam Shaping Theory and Techniques*, which is the predecessor to the *Laser Beam Shaping Applications* is an excellent choice.

In this edition, new and additional chapters will demonstrate clearly that the field of laser beam shaping is an enabler for increasing the stability, quality, and speed of laser-based processes. What becomes evident is that, although the application may change, the concepts described and much of the discussions on the specific approaches continue to stay current and demonstrate the longevity, adaptability, and transferability of laser beam shaping. The editors are pleased to acknowledge that Chapters 2, 3, and 7 have been revised by their respective authors to include updates and further work realized since the last printing. Chapters 4, 10, 11, and 12 are included without revisions and although they do not contain updated material, each still provides a unique perspective on technologies and applications that are still relevant today. Chapter 4 addresses beam shaping for excimer lasers, covering varying integrator and prismatic-based homogenizer beam shaper designs of interest to the industry for bulk material removal, using ablation techniques and precision micromachining. Chapters 5, 8, and 9 cover entirely new areas as well as new applications, which include beam shaping using micro-optical elements for illumination in lithography work, through the use of shaped fiber optics, and the use of beam shaping for optical tweezers. Chapter 10 treats the application of deformable mirrors and explains their method of actively shaping higher powered laser beams due to the segmentation of actuators under a deformable substrate. Chapter 11 is an example of the application of spectral control in dispersive lasers. Each of these chapters provides the reader with ample opportunities to compare and contrast applications.

A great comparative example is included in the updated Chapter 2, "Illuminators in Microlithography," written by Paul Michaloski, and Chapter 3, "Laser Beam Shaping in Array-Type Laser Printing Systems," written by Andrew Kurtz, Daniel Haas, and Nissim Pilossof. Each chapter reveals that two applications that occupy either end of a product spectrum can benefit from similar laser beam shaping technology. Both chapters offer insights into the use of fly's eye uniformizers, also known as fly's eye homogenizers, or refractive integrators as well as the use of kaleidoscope or light pipe design for homogenization of laser beams. Each application describes the clear benefits from the two styles of integrator designs in relation to their respective technology areas and provides the reader the opportunity to recognize how the technology can be leveraged within the two such diverse cases.

Chapter 12, "Beam Shaping: A Review," written by Fred M. Dickey and Scott C. Holswade, continues to provide an excellent base foundation for the readers who are new to the field of laser beam shaping. What makes Chapter 12 useful to a novice and to those actually engaged in the technology is that it provides foundational material in a manner that clarifies and assures the reader that as he or she reads other chapters, he or she will have the basics to clearly and concisely understand the opportunities as well as the difficulties that are associated with beam shaping.

New to this edition, Chapter 5, "Micro-Optics Is Key Enabling Technology for Illumination Light Shaping in Photolithography," written by Reinhardt Voelkel, expands on a similar theme as Chapter 2; however, it introduces the use of monolithic wafer-based refractive micro-optics and vividly describes their use in a host of lithographic illumination techniques. Chapter 5 further expands on the natural evolution of established lens array integrators over the past years and demonstrates the importance of hybridization of established techniques and the evolution of integrators as they began to take the form of monolithic wafer-based micro-optical elements. Section 5.2.3 with the introduction of Kohler integrators that were utilized for early lithographic tools in the 1970s provides a splendid historical perspective on why the need for continued development of illumination in some cases drove the development of micro-optical fabrication techniques that transformed today's lithography industry. Chapter 8, "Applications of Diffractive Optics Elements in Optical Trapping," written by Ruben Ramos-Garcia, Victor Arrizon, and Ulises Ruiz, provides a primer for the broader role of spatial light modulators within this field and the use of diffractive optical elements. Chapter 8 serves as a basic building block for the value of laser beam shaping within the field of optical tweezers or trapping while recognizing the different degrees of technical sophistication of the intended reader. Chapter 9, "Laser Beam Shaping through Fiber Optic Beam Delivery," written by Todd Lizotte and Orest Ohar, demonstrates that light pipes adapted into smaller form factors, such as drawn square fibers, can open doors to new laser materials processing applications for precision material removal and offer laser beam shaping opportunities for more traditional robotic based fiber optic based processes. Chapter 9 provides the reader with an existing robotic example on a production floor to emphasize the concepts governing the application and to demonstrate the true nature of a product that incorporates laser beam shaping technology.

Considering these new and revised chapters, it becomes apparent that solutions in each individual industry continue to evolve as beam shaping technology and fabrication techniques improve, and/or newer technologies emerge. From the chapters added to this new edition, the reader can ponder the evolution of beam integrators over time and witness the shift from the basics of light pipes and the early days of refractive integrators to the modern versions that leverage micro-optical technology.

The theory of laser beam shaping is bound within the constraints of physics and calculations, whereas applications provide a tangible point in time to gauge the progress of a technology, within real terms of its proven limitations at that moment in time, including in some cases, the lack of computing power, access to the most efficient optical materials, and the basic state of fabrication techniques used to realize the final application. Each chapter could be considered a historical marker. As an example, take optical integrators back in the late 1970s and early 1980s, at that time cylindrical and spherical refractive lens and reflective mirror integrators began to find traction within the burgeoning laser industry. Made by stacking individual lenses (spherical or cylindrical) or faceted mirror segments, the lens array integrators were expensive and somewhat clumsy to use and replicate (Figures 1.1 and 1.2).

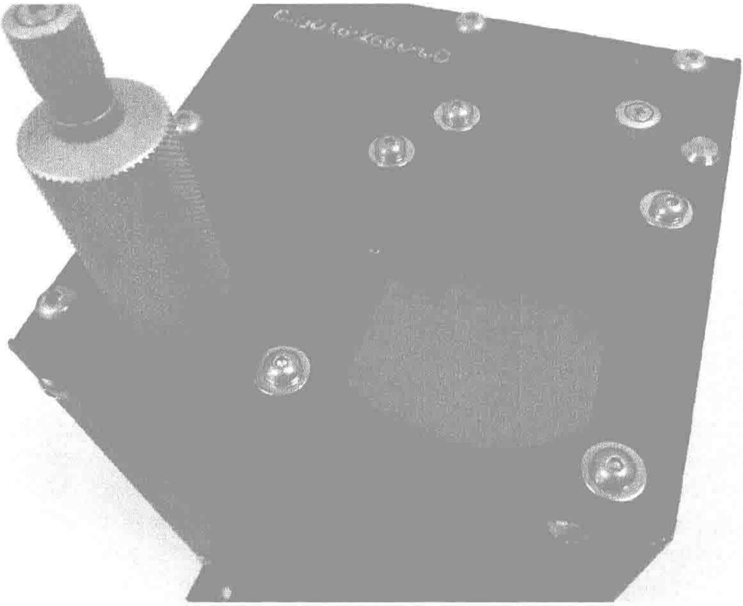

FIGURE 1.1 Refractive lens array homogenizer, circa 1985.

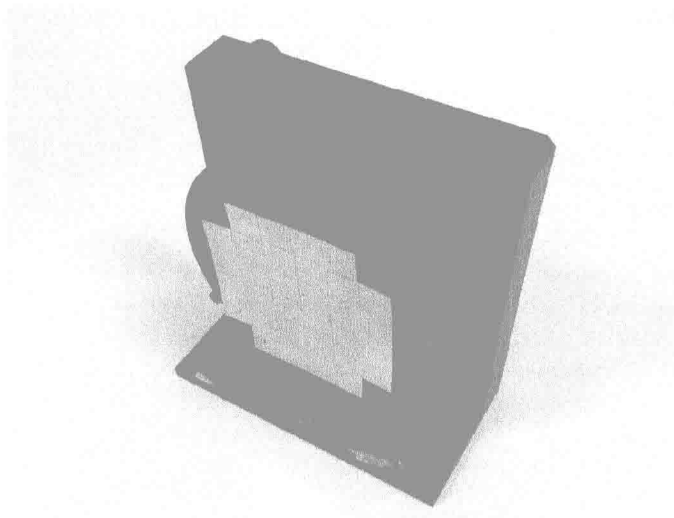

FIGURE 1.2 Reflective segmented mirror array homogenizer, circa 1990.

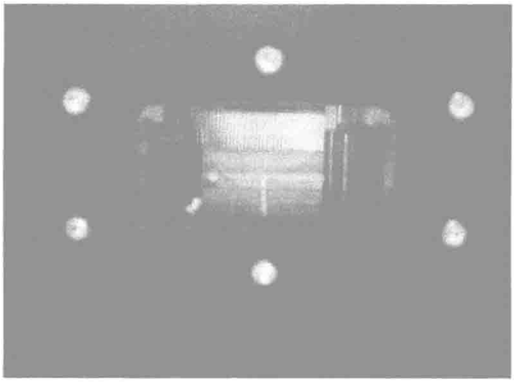

FIGURE 1.3 Refractive monolithic lens array homogenizer, circa 2008.

Approximately 15 years ago, such devices began to take the form of reactively ion-etched monolithic refractive lens arrays (Figure 1.3), which also came with their own limitations, including part-to-part reproducibility and alignment. Ultimately, through continued fabrication development, these monolithic micro-optical arrays reduced the cost of the beam shaper designs and allowed the technology to leap into other markets, such as printing, telecom, and laser-material processing. Each chapter provides the reader a clear vantage point to evaluate the evolution of beam shaping technology and weigh its progress. There are times, however, where even the older designs become more relevant to today's needs or industrial demands on a true production floor. Even stacked lens array integrators continue to find relevance within the latest generation of laser processing systems for large panel displays as they continue producing cutting edge products that consumers purchase every day.

It is evident in the growth of laser beam shaping that even though the solutions are specific within this book, they may be applied in different ways to other applications in the future. Even though these chapters represent some of the most understood techniques within the industry, each of them can be enhanced, modified, or combined to tackle the next challenge faced within an industry that continues to leverage laser technology.

The editors thank the authors who submitted new and revised chapters to this edition and add that as with most books, no editor or author can ever be completely right, although they all strive for that level of perfection. The editors shall be grateful for any comments, corrections, or criticisms that readers may find relevant and bring to their attention.