

Laser Beam Shaping

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Laser beam shaping is the process of redistributing the irradiance and phase of a beam of optical radiation. This process of controlling optical beams is an enabling technology, which is used in a number of sectors of scientific, engineering, and industrial R&D. The shape of a laser beam generally refers to its irradiance profile, while the phase of a beam generally affects its propagation characteristics. Earlier work of Frieden¹ and Kreuzer² during the 1960s articulated well the goals of some contemporary laser beam shaping applications. Namely, geometrical optics was used to determine the configuration of a two-element optical system that would transform an input plane wave with a Gaussian irradiance profile into an output plane wave with uniform irradiance. For some contemporary applications, physical optics must be used for the optical design of the laser beam shapers. A general presentation of the theory and techniques of laser beam shaping is given in a book edited by Dickey and Holswade.³ Laser beam shaping has become an important component of many laser-based applications, such as materials processing, medical applications, lithography, optical data storage, laser printing, isotope separation, optical data processing, and laboratory research.

The first conference on laser beam shaping was held in 2000 at the Annual Meeting of the SPIE. This Laser Beam Shaping conference⁴ included a discussion of the fundamental limits of any beam shaping technique and the foundation for successful beam shaping design, including geometric techniques and optimization-based techniques. Applications included high-power laser fiber injection, UV and deep-UV homogenizers, micromachining in the electronics industry, and beam shaping techniques for laser printing.

The Laser Beam Shaping II conference⁵ continued to bring together both workers in the field and potential users of the technology. Theory and design was again addressed, but the papers were primarily in the area of de-

sign techniques and configurations. The applications included the important areas of optical data storage and laser material processing and machining. The optical data storage session and the two material processing and machining sessions are exemplary of the potential applications of laser beam shaping to technology and industrial processes.

The Laser Beam Shaping III conference⁶ continued the effort to integrate the various facets of beam shaping theory, design, and application. The first session emphasized applications with keynote papers on the important and established area of lithography and photoablation systems for microelectronics and optoelectronics, and the potential of laser beam shaping for the complex problem of stable isotope separation. Papers on methods and design included adaptive systems, sensitivity to figure error, ultra-short-pulse systems, intercavity methods, and three-dimensional beam shaping.

The interest in laser beam shaping continues to grow; old techniques are finding new applications and new techniques are being developed. This year, the Laser Beam Shaping IV conference⁷ continued the effort to document ongoing work on the various facets of beam shaping theory, design, and application. The conference included papers on achromatic beam shaping, new beam integration techniques, picosecond techniques for the Stanford Linear Accelerator, laser diode array techniques, application of vector diffraction theory, and many other interesting papers. Summaries of five papers from this conference are included as *Optical Engineering Letters* appearing in this section.

The Laser Beam Shaping conference continues to attract interesting speakers and an interested audience. New ideas and techniques continue to be developed in the laser beam shaping field. The Laser Beam Shaping V conference is scheduled to be part of the SPIE 2004 Annual Meeting and will continue the effort to bring together en-

gineers, scientists, and system designers interested in the application and development of the laser beam shaping technology.

First in this special section, there are five *Optical Engineering Letters* based on innovative and significant results presented at this year's Laser Beam Shaping IV conference. The first two letters are from the theory and design section. Zhao and Li describe the use of a vector angular spectrum approach to self-iterative algorithms diffraction theory of beam shaping systems, which should provide rigorous results for subwavelength feature sizes. Zhang describes a lossless method and apparatus to transform a collimated straight-line beam into a collimated spherical arc beam using coaxial axicons. This method can be used to transform a collimated rectangular beam into a collimated meniscus-shaped beam. The next two letters are from the integrators section. Sales describes structured microlens arrays for beam shaping, diffusion, and homogenization and for providing the ability to perform complex beam shaping with low-loss irradiance control. Possible applications of these structured microlens arrays include excimer laser beam shaping, display screens, light-control films, and illumination. Brown describes an innovative method of optically combining the light from laser diodes bars using a multiaperture beam integrator approach. Possible applications include efficient optical pumps for solid-state lasers used in machining and product marking. The final letter is from the applications section. Wilson, Massoumian, and Juškaitis describe generation and focusing of radially polarized electric fields that have been coupled into a high-numerical-aperture microscope objective so as to produce an axially polarized focal spot. Applications of the capability to create spatially varying polarization range from studies of singularities in optical fields to single molecule studies.

The next part of the section includes five full-length papers based on recent developments in the field: a refractive laser beam shaper with a broad bandwidth from deep UV to IR (Hoffnagle and Jefferson); description of a refractive-diffractive hybrid beam shaper that allows for reduction in the phase depth of the diffractive element (Tan, Yan, and Jin); analysis and optimization on a single zone binary flattop beam shaper (Yang and Wang); demonstration of using holographic gratings as diffractive shapers for transformation of Gaussian beams to super-Gaussian beams (Miler, Aubrecht, and Pala); and using geometrical optics-based methods to design a two-mirror shaper with no central obscuration for transforming an elliptical Gaussian input beam into an output beam with a Fermi-Dirac output beam profile (Shealy and Chao).

Hoffnagle and Jefferson have used the design method of Kreuzer² with convex aspherics to ease fabrication and introduced a continuous roll-off of the output beam profile for more control of the far-field diffraction pattern. A fused silica lens pair has been demonstrated to operate from 250 to 1550 nm to transform a Gaussian beam into a flattop beam. The authors present measurements of both the irradiance profile and phase of the output beam and compare results to their design. Seventy-eight percent of the total input power is transformed into a uniform output beam to better than 5% rms. The output wavefront is pla-

nar to within a quarter wave at 514 nm, which allows the beam to propagate approximately 0.5 m without significant change in profile. The graphics on the cover of this issue of *Optical Engineering*, contributed by authors Hoffnagle and Jefferson, represent the transformation of an input Gaussian beam profile to an output Fermi-Dirac form in the refractive Keplerian beam shaper system described in this article.

Tan, Yan, and Jin show that using a lens with a diffractive optical element as part of a beam shaping system offers promise for beam shaping as a result of high light efficiency, increased flexibility in phase design, and broad selectivity of materials to use in fabrication as a result of reduced phase requirements of the diffractive optical element. After optimization, their results show the phase depth of the diffractive surface is less than 1.1π with phase steps of 0.1π .

Yang and Wang present analysis and optimization of single zone binary phase plates to achieve excellent flattop beam shaping. The authors show that degradation of flattop beam shaping quality due to etching depth errors, deviation of illuminating wavelength, and variation of input beam size can be compensated for by adjusting axial location of the output plane. Experimental results are given in support of the theoretical analysis.

Miler, Aubrecht, and Pala describe recording and development of Gaussian gratings for beam shaping of input Gaussian to super-Gaussian of the fourth order. The holographic beam shapers were fabricated by interference of natural size laser beams.

Shealy and Chao review the general geometrical-optics-based methods for design of beam shapers when diffraction effects are not important, and apply these methods to the design of a two-mirror system with no central obscuration for shaping an elliptical Gaussian input beam into a Fermi-Dirac output beam profile. Optical analysis of the two-mirror systems suggests that current technologies can fabricate these aspheric mirror surfaces.

We hope that this collection of papers and letters will introduce readers to the state of the art of laser beam shaping and that this special section will serve as a stimulus for the exchange of ideas among research and application workers in the field.

Finally, we would like to thank all the participants in the recent Laser Beam Shaping conferences at the Annual Meeting of the SPIE, the authors of the letters and full-length papers in this special section, and the reviewers of these manuscripts for their valuable efforts and contributions to ensure the high quality of the publication. We also want to thank the editor Dr. O'Shea, managing editor Ms. Labes, and the SPIE editorial staff for providing the opportunity and technical support for presenting this special section to the readers.

References

1. B. R. Frieden, "Lossless conversion of a plane laser wave to a plane wave of uniform irradiance," *Appl. Opt.* **4**(11), 1400-1403 (1965).
2. J. L. Kreuzer, "Coherent light optical system yielding an output beam of desired intensity distribution at a desired equiphase surface," U.S. Patent No. 3,476,463 (Nov. 1969).
3. F. M. Dickey and S. C. Holswade, *Laser Beam Shaping: Theory and Techniques*, Marcel Dekker, New York (2000).
4. F. M. Dickey and S. C. Holswade, Eds., *Laser Beam Shaping, Proc. SPIE* **4095**, 1-216 (2000).

5. F. M. Dickey, S. C. Holswade, and D. L. Shealy, Eds., *Laser Beam Shaping II, Proc. SPIE 4443*, 1–198 (2001).
6. F. M. Dickey, S. C. Holswade, and D. L. Shealy, Eds., *Laser Beam Shaping III, Proc. SPIE 4770*, 1–158 (2002).
7. F. M. Dickey and D. L. Shealy, Eds., *Laser Beam Shaping IV, Proc. SPIE 5175* (in press).



David L. Shealy earned a BS in physics, outstanding major and Phi Kappa Phi, in 1966 and a PhD in physics, Phi Beta Kappa, in 1973, both from the University of Georgia. He joined the faculty at the University of Alabama at Birmingham (UAB) in 1973 as an assistant professor of physics, and is now a professor and chair of the Department of Physics. While on leave from UAB, he worked during 1980-84 as staff scientist and principal

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tial equation methods for designing laser beam shaping systems using geometrical optics. Dr. Shealy has published more than 130 journal and proceedings articles, book chapters, and reports and presented more than 140 invited and contributed papers. He is a member of SPIE and a fellow of OSA.



Fred M. Dickey is a distinguished member of the technical staff at Sandia National Laboratories, Albuquerque, New Mexico. He is the author of more than 75 papers and book chapters and holds nine patents. He is coeditor and coauthor of the book *Laser Beam Shaping: Theory and Techniques* published by Marcel Dekker (2000). His current research interests include laser beam shaping, Fourier optics, synthetic aperture radar systems

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