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Gradient Index Optics

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In the past century, every component of an optical system has become lighter and smaller, except the lenses. Typical lenses have too few degrees of freedom—just the refractive index, and the front and back surface shapes—to meet the demands of the vast array of modern optical systems which collect, project, or otherwise manipulate light. (Even in imaging systems, where computational power has the potential to eliminate the tight coupling between lenses and performance, more capable lenses would increase the trade space that optical designers have available to them).

Unlike a classic, homogenous lens, a gradient index (GRIN) lens has different refractive indices at different spatial locations within it, introducing new degrees of freedom, and opening up optical design space. Until recently, however, most GRIN lenses were fabricated by immersing a homogenous material in a molten salt bath allowing ions from the solute to diffuse inside the material to modify its refractive index locally. This is a sufficiently slow process that practical manufacture of GRIN lenses was limited to tiny (2–3 mm) diameters. So while GRIN lenses could be conceived of to solve optical design challenges, the lenses that were designed were often impossible to make.

What has changed? New materials and fabrication techniques in polymer, glass, and ceramics offer unprecedented control over both the extent of refractive index change within a lens, and the spatial location of that change. The possibility of creating arbitrary refractive index profiles opens the trade space between field of view, focal length, dispersion, lens speed, and lens size and weight. These new techniques then beget new design rules and tools, which are themselves enabled by the type of computational power that is now inexpensive and commonplace. And finally, new approaches to metrology allow evaluations of whether the lens that was designed is actually the one that was made.

In this *Optical Engineering* special section, twelve papers explore the current state of the art in materials and fabrication technology, design concepts, metrology, and applications of GRIN lenses. The first two papers explore fabrication advances in polymer and glass GRIN lenses. Ji et al. provide an overview of the types of lenses and GRIN profiles enabled by nanolayered polymers—a new approach to lens construction. Classic techniques have also been advanced, however, as demonstrated by Visconti and Bentley's discussion of glasses with shorter diffusion times, enabling large-diameter lenses through ion exchange.

Fully half of the papers focus on the design and use of the new GRIN materials. Visconti and Bentley describe GRIN-enabled dual-band imaging systems, while Visconti et al. address different eyepiece designs. McCarthy and Moore step through the design and tolerencing of a laser collimator, and Cakmakci presents the design of a lightweight surgical loupe. Less application specific, two papers by Corsetti et al. describe design rules and tools related to athermalization and color correction.

Without accurate metrology, the new GRIN materials and refractive index profiles are likely to remain impractical. Three papers thus describe advances in metrology in step with the kinds of lenses and designs described by the other papers in the special section. Yao et al. summarize recent advances in optical coherence tomography, translated from the biomedical world to imaging the internal structure of nanolayered lenses. Lin et al. and Teichman both advance laser deflection techniques to support a range of GRIN profiles.

This collection of papers, though a small sample of the work in progress related to GRIN optics, manages to touch on a wide range of recent advances. The materials, algorithms, and measurements described here are, we hope, just the vanguard of the movement to bring lenses out of the 19th century and into the 21st.

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Predrag Milojkovic received his PhD in 2001 from George Mason University for his work on novel free space optical interconnects for multiprocessor systems. He joined Army Research Lab in January 2010 after working at Northrop Grumman on new electro-optical and infrared imaging concepts, systems, and devices. His research at ARL is focused on computational imaging, optical super-resolution with active illumination, gradient-index optics, and optical analysis and modeling of high-resolution, wide-field-of-view imagers. He has published over 30 publications in peer reviewed journals and conferences, and he holds one patent. He currently serves as program co-chair for OSA's Computational Optical Sensing and Imaging conference and serves on the program committee for the Military Sensing Symposia Passive Sensors conference.

Stefanie Tompkins was the deputy director of the Strategic Technology Office until October 2013. In this position, she led DARPA program managers in the development of promising and potentially disruptive technologies related to command, control, communications, intelligence, surveillance, and reconnaissance. She also served as a DARPA program manager from 2007 to 2012, where her program portfolios focused on navigation systems and the design and manufacture of optical systems. She is currently the DARPA chief of staff. Prior to joining DARPA, she spent 10 years in industry, most recently at Science Applications International Corporation, where she managed a portfolio of technology development programs primarily related to remote sensing. As a NASA principal investigator, she conducted research in solar system spectroscopy. She has also served as a military intelligence officer in the U.S. Army. She received a BA in geology and geophysics from Princeton University and a MSc and PhD from Brown University. She holds patents for imaging spectrometer data analysis algorithms and has published numerous papers related to this topic.

Ravindra Athale received his BS in 1972 from the University of Bombay and MS in 1974 from the Indian Institute of Technology, Kanpur, both in physics. He received his PhD in electrical engineering in 1980 from the University of California, San Diego. From 1981 to 1985 he worked as a research physicist in the Optical Signal Processing section of Naval Research Laboratory. From 1985 to 1990 he was a senior principal staff member at BDM Corporation in McLean, Virginia, where he headed a group in optical computing and supported the DARPA program in strategic computing. From 1990 to 2001 he was a faculty member in the Electrical and Computer Engineering Department at George Mason University. From 2001 to 2005 he was on assignment to Defense Advanced Research Projects Agency as a program manager in photonics. At DARPA, he initiated programs in chip-to-chip optical interconnects, computational imaging systems, and university centers in nanophotonics. From 2005 to 2012 he was principal scientist in the Emerging Technology Office at MITRE Corp. where he managed an IR&D portfolio in emerging technologies and led a group in computational imaging. He is currently a program officer in charge of the electro-optic/infrared imaging sensor portfolio at the Office of Naval Research. He was elected Fellow of the Optical Society of America in 1989. He has published over 50 journal papers including two invited papers in *Proceedings of IEEE* and holds several patents in the area of optical processing. He received Optical Society of America's Leadership Award, New Focus/Bookham Prize for 2005 and was awarded Secretary of Defense Medal for Exceptional Public Service.