# Nonlinear Optics with Relativistic Electrons

FOR THE last thirty years, scientists have studied nonlinear optics of electrons that are bound to atoms and molecules, many of the important advances having been published in the pages of this journal. Nonlinear effects arise in this case due to anharmonic oscillatory motion of electrons in the combined fields of atom and laser. The study of nonlinear optics was enabled by the invention of $Q$-switched lasers, which resulted in an orders-of-magnitude increase in the peak power of lasers. The rate of advancement in our understanding of nonlinear optics has been quite staggering. For instance, harmonic generation (e.g., frequency doubling) went from being barely detectable to almost unity efficiency in just a few short years. Now the field is quite mature, having spawned numerous subfields and commercial products.

In the last decade, table-top lasers have undergone a similar orders-of-magnitude jump in peak power, with the invention of the technique of chirped pulse amplification. They now have multiterawatt peak power and, when focused, produce electromagnetic intensities exceeding $10^{20}$ W/cm$^2$, which is high enough to cause nonlinearity in even unbound (ionized) electrons. Thus, a new field of nonlinear optics, that of relativistic electrons, has been launched. In this case, the nonlinearity arises because the electrons oscillate in these enourmous laser fields at relativistic velocities, resulting in relativistic mass changes exceeding the electron rest mass and highly nonlinear motion. As can be seen from the following reviews, effects analogous to those studied with conventional nonlinear optics—self-focusing, self-modulation, harmonic generation, and so on—are all found, but based on this entirely different physical mechanism. It is also obvious that rapid advancement is underway and that new subfields and commerical products are on the horizon, i.e., compact and ultrashort pulse duration laser-based electron accelerators and X-ray sources.

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High field interactions can be studied with either single electrons, beams, gases, solids, or plasmas. Each is reviewed in this special issue. The exhaustive review by Esarey *et al.* discusses analytical methods to solve for the propagation of intense lasers through gases undergoing ionization and gaseous-density plasmas, with particular emphasis on self-focusing. The results of recent experiments in which self-guiding is observed over many Rayleigh lengths, and which may soon permit laser-based accelerators to reach GeV energies, are also presented. Gibbon reviews harmonic generation from single electrons, gases, plasmas, and solid surfaces. This mechanism promises to become the basis for a new generation of coherent radiation sources, with femtosecond durations and sub-10-nm wavelengths. Leemans *et al.* discuss scattering of ultrashort-pulse duration lasers with relativistic electron beams. Proof-of-principle experiments demonstrate the generation of coherent radiation, again with femtosecond duration, but in this case with angstrom-scale wavelength. Meyerhofer also discusses theory and recent experiments on the the scattering of laser light with electrons at rest and in relativistic beams, but in this case in the nonlinear regime, where multiphoton Compton scattering and harmonic generation occur. Mori reviews the nonlinear optics of plasmas at near-relativistic intensities, presenting a single simple analysis that gives physical insight into several diverse nonlinear phenomena, including Raman forward scattering, self-modulation, and self-focusing.

We hope this collection of reviews will summarize the dramatic advances made in this rapidly developing field and set the stage for further exciting achievements.

DONALD UMSTADTER, *Guest Editor*
University of Michigan
Ann Arbor, MI 48109–2099

THEODORE B. NORRIS, *Guest Editor*
University of Michigan
Ann Arbor, MI 48109–2099

**Donald Umstadter** received the Ph.D. degree in physics from the University of California at Los Angeles. His doctoral research was on the subject of nonlinear plasma waves generated by stimulated Raman scattering and optical mixing.

He is now an Associate Professor in the Departments of Nuclear Engineering and Radiological Sciences and Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor. He also coordinates the high-field physics program at the Center for Ultrafast Optical Science. Prior to coming to Michigan, he completed a two-year postdoctoral fellowship at AT&T Bell Laboratories, Murray Hill, NJ, in the area of high-intensity laser-plasma interactions. His current research interests include nonlinear optics in relativistic plasmas and the development and applications of compact and ultrashort-pulse duration laser-based particle accelerators and short-wavelength radiation sources. For more information, see http://www.eecs.umich.edu/˜dpu/.

Dr. Umstadter was the recipient of the Outstanding Research Scientist Award at the University of Michigan in 1997.

**Theodore B. Norris** received the B.A. degree in physics (with Highest Honors) from Oberlin College, Oberlin, OH, in 1982, and the Ph.D. degree in physics from the University of Rochester, Rochester, NY, in 1989, with a dissertation on time-resolved tunneling in semiconductor heterostructures.

He continued his investigations of time-resolved optical studies of semiconductors at Thomson-CSF, France from 1989 to 1990. During 1990–1992, he was an Assistant Research Scientist at the Ultrafast Science Laboratory, University of Michigan, Ann Arbor, and from 1992 to 1996 an Assistant Professor in the Electrical Engineering and Computer Science Department (EECS) at the University of Michigan, where he recently received the EECS Department Research Excellence Award. He is currently an Associate Professor in the EECS Department at the University of Michigan. His research interests include application of femtosecond optical techniques to the physics of semiconductor structures, in developing new ultrafast optical and electronic probes with high spatial resolution for applications to semiconductor nanostructures and biological imaging, and in developing new laser sources for applications in femtosecond spectroscopy and the generation of terahertz radiation. His work has appeared in over 60 journal and 80 conference publications. His research is performed at the National Science Foundation Center for Ultrafast Optical Science and the Electrical Engineering and Computer Science Department at the University of Michigan. He is presently serving as an Associate Editor of the IEEE JOURNAL OF QUANTUM ELECTRONICS.

Dr. Norris is a member of the Optical Society of America and the American Physical Society.