

Review

Yao Lu, Yibo Huang, Junkai Cheng, Ruobin Ma, Xitan Xu, Yijia Zang, Qiang Wu* and Jingjun Xu*

Nonlinear optical physics at terahertz frequency

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Abstract: Terahertz (THz) waves have exhibited promising prospects in 6G/7G communications, sensing, nondestructive detection, material modulation, and biomedical applications. With the development of high-power THz sources, more and more nonlinear optical effects at THz frequency and THz-induced nonlinear optical phenomena are investigated. These studies not only show a clear physics picture of electrons, ions, and molecules but also provide many novel applications in sensing, imaging, communications, and aerospace. Here, we review recent developments in THz nonlinear physics and THz-induced nonlinear optical phenomena. This review provides an overview and illustrates examples of how to achieve strong THz nonlinear phenomena and how to use THz waves to achieve nonlinear material modulation.

Keywords: terahertz; nonlinear optics; light-matter interaction

1 Introduction

Light-matter interaction (LMI) has been a long-discussed topic in optics and condensed-matter physics [1]. In the early studies, LMI at visible and infrared frequencies were mainly discussed since lasers at such frequencies are highly developed. LMI indicates how light can polarize, heat, melt, and ablate the electrons, ions, or molecules within most materials. However, the significant difference in mass of

these microparticles causes an individual energy scale. By considering the resonant frequencies of these different particles, we find that each particle can easily interact with light at a similar frequency but is minimally affected by light far away from the resonant frequency. The Lorentz oscillator equation and energy band theory provide the fundamental basis for investigating traditional LMI that involves high frequency light.

For LMIs between high frequency light and crystal solids, the heavy ions are less possibly to contribute to such fast oscillations. Therefore, the traditional approaches assume that the ions are fixed in the crystal, only electrons can respond to such fast electromagnetic oscillations. The motion of the ions is usually taken as a perturbation to the electronic polarizations, which is known as Born-Oppenheimer approximation [2], [3]. Nevertheless, when the pump beam becomes low-frequency light such as terahertz (THz) or microwave, the ionic polarization would dominate the whole LMI process. In this case, Born-Oppenheimer approximation is not valid anymore. Especially, for the THz pump light (about 0.1 ~ 10 THz), at which the optical phonon frequency for majority crystal materials is located, strong coupling between the input THz waves and the optical phonons forms a new quasiparticle, stimulated phonon polaritons, which plays unneglected role in LMI at the THz frequency and also causes large THz nonlinearity in polar crystal solids [4]. In Figure 1, we show the dominated LMI mechanisms through various wavelengths. Notably, some physical processes, including Raman/Brillouin scattering, although the pump light could be at visible or infrared, are beyond Born-Oppenheimer approximations.

Besides, many low-dimensional materials, such as graphene, are also found to behave very large THz nonlinearity due to its Dirac electrons at the special band structures. Metamaterials/metasurfaces, plasmons, and superconductors have also been options to achieve THz nonlinearity.

In this review, we report some states of the art of the nonlinear LMI process at THz frequency. A series of nonlinear phenomena at THz frequency or induced by THz waves in recent years are displayed, including frequency conversion, Kerr effect, nonlinear absorptions, as well as THz modulating ions, molecules, and electrons in materials to realize

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Nonlinear Physics Research Reports In Physics

**Andrei V. Gaponov-Grekhov, Mikhail I.
Rabinovich, Jüri Engelbrecht**

Nonlinear Physics Research Reports In Physics:

Research Reports in Physics ,19?? **Dynamics of Heterogeneous Materials** Vitali Nesterenko,2013-03-09 This monograph deals with the behavior of essentially nonlinear heterogeneous materials in processes occurring under intense dynamic loading where microstructural effects play the main role This book is not an introduction to the dynamic behavior of materials and general information available in other books is not included The material herein is presented in a form I hope will make it useful not only for researchers working in related areas but also for graduate students I used it successfully to teach a course on the dynamic behavior of materials at the University of California San Diego Another course well suited to the topic may be nonlinear wave dynamics in solids especially the part on strongly nonlinear waves About 100 problems presented in the book at the end of each chapter will help the reader to develop a deeper understanding of the subject I tried to follow a few rules in writing this book 1 To focus on strongly nonlinear phenomena where there is no small parameter with respect to the amplitude of disturbance including solitons shock waves and localized shear 2 To take into account phenomena sensitive to materials structure where typical space scale of material parameters particle size cell size are presented in the models or are variable in experimental research *U.S. Government Research Reports* ,1964 **Partial Differential**

Equations in China Chaohao Gu,Xiaxi Ding,Chung-Chun Yang,2012-12-06 In the past few years there has been a fruitful exchange of expertise on the subject of partial differential equations PDEs between mathematicians from the People s Republic of China and the rest of the world The goal of this collection of papers is to summarize and introduce the historical progress of the development of PDEs in China from the 1950s to the 1980s The results presented here were mainly published before the 1980s but having been printed in the Chinese language have not reached the wider audience they deserve Topics covered include among others nonlinear hyperbolic equations nonlinear elliptic equations nonlinear parabolic equations mixed equations free boundary problems minimal surfaces in Riemannian manifolds microlocal analysis and solitons For mathematicians and physicists interested in the historical development of PDEs in the People s Republic of China

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Energy Research Abstracts ,1990 *The Granular State: Volume 627* Surajit Sen,Melany L. Hunt,2001-04-09 These 38

papers from the April 2000 symposium study granular structure granular flows nonlinear waves in granular media vibrated and rotated granular media and stress distributions Topics include jamming in liquids and granular materials nuclear magnetic resonance studies of granular flows the blueprint of a concept for a nozzle free inkjet printer mixing and segregation processes in a Turbula blender persistence of granular structure during die compaction of ceramic powders and humidity induced cohesion effects in granular media c Book News Inc *Nonlinear Waves 1* Andrei V. Gaponov-Grekhov, Mikhail I. Rabinovich, Jüri Engelbrecht, 2012-12-06 Since 1972 the Schools on Nonlinear Physics in Gorky have been a meeting place for Soviet scientists working in this field Instead of producing for the first time English proceedings it has been decided to present a good cross section of nonlinear physics in the USSR Thus the participants at the last School were invited to provide English reviews and research papers for these two volumes which in the years to come will be followed by the proceedings of forthcoming schools The first volume starts with a historical overview of nonlinear dynamics from Poincaré to the present day and touches topics like attractors nonlinear oscillators and waves turbulence pattern formation and dynamics of structures in nonequilibrium dissipative media It then deals with structures bistabilities instabilities chaos dynamics of defects in 1d systems self organizations solitons spatio temporal structures and wave collapse in optical systems lasers plasmas reaction diffusion systems and solids *Government-wide Index to Federal Research & Development Reports*, 1967 *U.S. Government Research & Development Reports*, 1970 *Soviet Science and Technology*, 1987 **Soviet Science and Technology 1987**, 1988 *High-Tc Superconductivity* Aleksandr S. Davydov, Vadim M. Loktev, 2012-12-06 High Tc Superconductivity is based on a meeting held in Kiev and contains contributions discussing the most recent achievements in this field The book includes reviews and original papers covering theoretical and experimental aspects of the subject Keywords electronic and magnetic properties metallization processes emission and optic spectra lavitation pinning frustration and fluctuations thin films *Forthcoming Books* Rose Arny, 1992 **Annals of Differential Equations**, 2000 **Nuovo Cimento**, 1999 **Quark—Gluon Plasma** Bikash Sinha, Santanu Pal, Sibaji Raha, 2012-12-06 Quark Gluon Plasma QGP is a state of matter predicted by the theory of strong interactions Quantum Chromodynamics QCD The area of QGP lies at the interface of particle physics field theory nuclear physics and many body theory statistical physics cosmology and astrophysics In its brief history about a decade QGP has seen a rapid convergence of ideas from these previously diverging disciplines This volume includes the lectures delivered by eminent specialists to students without prior experience in QGP Each course thus starts from the basics and takes the students by steps to the current problems The chapters are self contained and pedagogic in style The book may therefore serve as an introduction for advanced graduate students intending to enter this field or for physicists working in other areas Experts in QGP may also find this volume a handy reference Specific examples used to elucidate how theoretical predictions and experimentally accessible quantities may not always correspond to one another make this book ideal for self study for beginners This feature will also make the

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web turner exhibited four paintings of whaling at the royal academy two in 1845 and two in 1846 his patron elhanan bicknell was a partner in a whaling firm bicknell bought one of the 1845 paintings but disliked its finish and returned it

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