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Solitary surface acoustic waves and bulk solitons in nanosecond and picosecond laser ultrasonics

Peter Hess *, Alexey M. Lomonosov

Institute of Physical Chemistry, University of Heidelberg, Im Neuenheimer Feld 253, D-69120 Heidelberg, Germany

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ABSTRACT

Recent achievements of nonlinear acoustics concerning the realization of solitons and solitary waves in crystals and their surfaces attained by nanosecond and picosecond laser ultrasonics are discussed and compared. The corresponding pump–probe setups are described, which allow an all-optical contact-free excitation and detection of short strain pulses in the broad frequency range between 10 MHz and about 300 GHz. The formation of solitons in the propagating longitudinal strain pulses is investigated for nonlinear media with intrinsic lattice-based dispersion. The excitation of solitary surface acoustic waves is realized by a geometric film-based dispersion effect. Future developments and potential applications of nonlinear nanosecond and picosecond ultrasonics are discussed.

1. Introduction

The invention of lasers in 1960 had and is still having a strong impact on the fast development of nonlinear sciences. This is true not only for the field of nonlinear optics but also for continued progress in nonlinear acoustics with its long tradition. In fact, nonlinear effects seem to be even more pronounced in acoustics than in optics [1].

Laser techniques allow the efficient contact-free excitation and detection of coherent pulses of longitudinal acoustic bulk waves and surface acoustic waves (SAWs) with shocks in nonlinear media. After a strain pulse with finite amplitude is launched with a short pump-laser pulse, the developing shock front becomes steeper and steeper with propagation distance due to the elastic nonlinearity of the material, caused by the anharmonicity of the interatomic potential. This process can be described as a resonant coupling of higher harmonics with the fundamental wave, yielding an increasingly nonlinear pulse profile.

If the effects of nonlinearity are balanced by intrinsic or deliberately introduced geometric dispersion, solitons or solitary pulses can be formed. In this situation the dispersion effect limits the growth of higher harmonics, generating a localized stable wavepacket that keeps its shape while traveling. This is remarkable since a constant shape is usually observed only in systems that are both linear and non-dispersive. The strain pulses are detected at the surface by applying an optical probe, which measures the change in optical reflectivity or the transient surface displacement or its velocity.

Here two laser-based approaches to nonlinear acoustics will be discussed, the generation of nonlinear longitudinal bulk waves using picosecond ultrasonics, and studies of nonlinear SAW pulses employing nanosecond lasers. Note that the different time scales involved (nanosecond versus picosecond) and types of acoustic waves excited (bulk versus surface wave) provide complementary insight into the nature of moderate and strongly nonlinear elastic wavepackets. Only longitudinal pulses propagating in crystals and Rayleigh waves launched on the plane surface of an elastic half space will be considered.

2. Experimental

2.1. Excitation and detection of longitudinal acoustic strain pulses

In the last few years laser-based picosecond ultrasonics has made tremendous progress in the excitation of nonlinear ultrashort strain pulses and their optical detection by the changes

* Corresponding author. Tel.: +49 6221 545205; fax: +49 6221 544255.
E-mail address: peter.hess@urz.uni-heidelberg.de (P. Hess).

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induced in the reflectivity of the laser probe [2,3] or by using Brillouin scattering [4]. The so-called 'low' and 'high' power laser sources employed were a mode-locked Ti:sapphire laser radiating at 800 nm with nanojoule pulse energy and 200 fs pulse duration at ~80 MHz [2] and an amplified Ti:sapphire laser system radiating at 800 nm with millijoule pulse energy and 100 fs pulse duration at 1 kHz [4].

The scheme of a typical picosecond pump–probe setup is presented in Fig. 1. The optical pump pulses are strongly absorbed in a 15–50 nm thick metal film (e.g. Al, Ti, Cr) within a depth of tens of nanometers and launch two counterpropagating strain pulses by thermoelastic emission. The absorbed photons excite conduction electrons, which diffuse through the thin metal film and equilibrate later with the phonon system, heating the lattice by a few degrees.

With the sample configuration of Fig. 1a bipolar strain pulse profile is launched. The elastic nonlinearity, caused by the anharmonicity of the intermolecular potential, decreases in the order MgO, sapphire, α-quartz, and silicon for the materials investigated in the first detection of bulk solitons [2]. The intrinsic phonon dispersion, separating higher and lower frequencies, is caused by the discrete spacing of the lattice atoms in the crystal. The shape of an emitted bipolar pulse changes during propagation in a nonlinear and dispersive medium, forming a coherent train of solitons and an oscillating tail, as a result of the compensation of phonon dispersion and elastic nonlinearity. The modified strain pulse hits the detector, consisting of a 15–80 nm thick metal film (e.g. Al) on the opposite side of the sample. The resulting change in reflectivity is monitored as a function of time by shifting the probe pulse with respect to the pump pulse by a suitable delay line. Calculation of the strain from the measured optical reflectivity change yields the shape of the strain pulse [5].

2.2. Excitation and detection of nonlinear surface acoustic wave pulses

SAWs are guided waves, which penetrate approximately one wavelength deep into the solid. It is important to note that the main part of the pulse energy stays within this depth during wave propagation along the surface. This particular property reduces diffraction losses as compared with acoustic bulk waves.

To launch strongly nonlinear SAW pulses no sophisticated laser system is required. Typically, Nd:YAG lasers radiating at 1.064 μm with 30–160 mJ pulse energy and 1–8 ns pulse duration are used in single-pulse experiments [6]. As depicted in Fig. 2, the explosive evaporation of a thin layer of a highly absorbing carbon suspension, deposited in the source region, is employed to excite SAWs with finite amplitude. By sharply focusing the pump-laser pulse with a cylindrical lens into a line a plane surface wave propagating

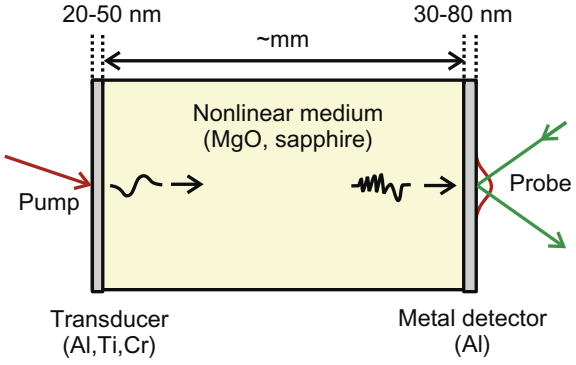

Fig. 1. Schematic diagram of a typical picosecond laser pump–probe setup for generating longitudinal strain pulses in a thin metal film propagating in the sample to the metal detector.

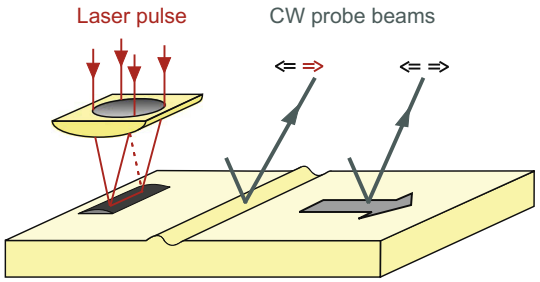

Fig. 2. Schematic diagram of a nanosecond pump–probe setup for generating SAW pulses with a pulsed laser and two-point laser probe-beam deflection detected with a position-sensitive detector.

in a well-defined direction is obtained [7,8]. During propagation the shape of the elastic pulse changes due to nonlinear elasticity, which in the frequency domain is visible as both frequency-up and frequency-down conversion that steepens the shocks and changes the pulse length.

Since Rayleigh waves are non-dispersive in homogeneous media, a layer needs to be added to introduce geometric dispersion caused by the finite width of the layer. The transient surface displacement can be detected at a distance of several millimeters from the source with a stabilized Michelson interferometer [6]. Frequently, however, another method is applied that uses transient deflection of a cw probe-laser beam monitored by a position-sensitive detector. This delivers the vertical surface velocity or shear displacement gradient. This detection method is substantially simpler to use. In the two-point-probe method SAWs are registered at 1–2 mm and 15–20 mm from the line source, which enables one to evaluate the nonlinear evolution. The pulse shape of the first probe spot is inserted as initial condition in the nonlinear evolution equation to simulate the nonlinear pulse development. The profile measured at the second probe spot allows a comparison between theory and experiment [6].

3. Result

3.1. Bulk solitons and formation of shocks in picosecond ultrasonics

Longitudinal bulk solitons have been excited and detected at low temperatures around 32–35 K in the crystalline materials silicon, α-quartz, sapphire, and MgO, with strongly increasing nonlinear parameters (C_3) from silicon to MgO, using the mode-locked low-power Ti:sapphire laser [2]. Fig. 3 illustrates the typical shape of an excited linear strain pulse, the development of nonlinear profiles, and of solitons if intrinsic dispersion is included. In the latter case the leading compressive part of the bipolar pulse transforms into a soliton, whereas the trailing rarefaction part forms an oscillating radiative tail [9]. Note that the compressive part, consisting of one or several half-cycle strain pulses, is traveling slightly faster and the rarefaction part slightly slower than the linear sound velocity.

While for silicon ($C_3 = -3.73 \times 10^{12}$ g cm^{-1} s^{-2}) only one soliton has been separated from the compressive phase (see Fig. 4), for MgO ($C_3 = -18.3 \times 10^{12}$ g cm^{-1} s^{-2}) the development of four solitons could be observed at a laser-pulse energy of 1–2 nJ [2,10]. As expected from theory, the velocity of solitons increased with their magnitude. At higher temperatures, e.g., 300 K, the strain pulse is not able to travel far enough to form a soliton due to strong attenuation that is mainly caused by the interaction with thermal phonons. At very low temperatures, however, attenuation and diffraction of the strain pulse may be negligible. In fact, simulations of soliton pulse shapes by a one-dimensional (1D) treatment, based