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Intensity distribution of light emitted from a fiber tip mapped by short surface acoustic wave pulses

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Abstract

Laser generation of short surface acoustic wave (SAW) pulses with a fiber tip is demonstrated. In the experiments, a tapered optical fiber tip was used to guide the 532 nm radiation of a Nd : YAG laser with 180 ps pulse duration to the surface to be investigated. Due to the increasing spatial confinement of the laser radiation with decreasing tip–sample distance, SAW pulses with frequency components up to 1 GHz were excited in an aluminum film deposited on a quartz substrate. It is shown that thermoelastic excitation of elastic surface wave pulses provides a new tool for studying the spatial intensity distribution of the exciting laser light emanating from the aperture of a near-field optical device as a function of distance. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Surface acoustic wave (SAW) spectroscopy has found increasing interest as a nondestructive method for the evaluation of elastic film properties and for the investigation of the nonlinear and anisotropic behavior of crystals [1–4]. In these experiments the SAW pulse is excited by sharply focusing a short laser pulse (ns–ps) onto the surface, and detected by using an actively stabilized Michelson interferometer to measure the transient surface displacement. From the nonlinear dispersion of the coherent SAW pulse during propagation in a substrate covered with a film, the density, Young's modulus, and Poisson's ratio of the film materials can be extracted [2]. Since the nonlinearity of the dispersion curve depends on the ratio of the film thickness to the largest wave vector in the SAW pulse, more information can be obtained from SAW spectroscopy by increasing the frequency range. The frequency range of the experiment is limited at present by the width of the line focus [1–3] or the spot size of the point focus [4] at the

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surface if picosecond laser pulses are used. The excited surface pulse cannot be shorter than the laser pulse and the shortest wavelength in the pulse is at least twice the spatial width of the focus at the surface. The confinement effect with the smaller frequency range limits the spectral range and this was spatial confinement in the present experiment.

Recently, scanning near-field optical microscopy (SNOM) has attracted much attention in the scientific community due to its high spatial resolution. SNOM overcomes the Abbe diffraction limit in the optical regime by using tapered optical fibers or pipette tips with a nanometer-sized aperture. It has become a new tool for optical imaging, photoluminescence spectroscopy, surface modification, and optical lithography in the submicrometer regime [5–8].

In this paper, we report the first results obtained for the optical generation and detection of short SAW pulses by combining SAW spectroscopy and near-field optical devices. Since the excitation of broad-band SAWs with picosecond laser pulses in a strongly absorbing material is limited by the spatial resolution of the exciting optical field, SAW spectroscopy provides a new tool for monitoring the intensity distribution of the exciting radiation at the surface via the pulse shape of the elastic surface wave.

2. Experiment

In all experiments a frequency-doubled Nd : YAG laser with a wavelength of 532 nm and a pulse duration of 180 ps (FWHM) was used to excite the SAW pulses. The sample investigated was an aluminum film, which was evaporated onto a fused silica substrate. The thickness of the film was determined by a stylus-type profilometer to be 650 nm. Before the experiments, the surface of the aluminum film was slightly processed (roughened) to increase its light absorption.

As shown in Fig. 1, the laser pulses were coupled into the open end of the fiber with a single-mode fiber coupler (Newport Inc.), and were conducted to the sample surface via a coated fiber tip (Nanonics LTD). The tip–sample distance was controlled by a piezoelectric transducer. However, no

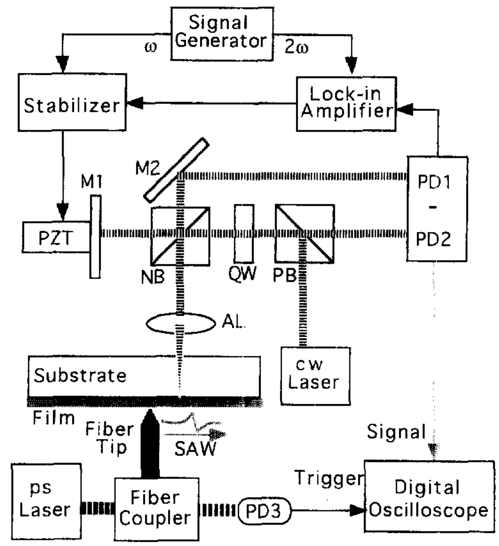

Fig. 1. Scheme of the experimental setup. The SAW pulse was generated by laser pulses transmitted from a fiber tip and detected with a Michelson interferometer. Achromatic lens (AL), photodiode (P), mirror (M), quarter-wave plate (QW), piezoelectric transducer (PZT), polarizing beam (PB) and nonpolarizing beam (NB) splitters.

absolute distance measurements could be performed with the present setup. The input energy of the laser pulse transferred to the fiber was less than 8 μJ in all experiments. No apparent signs of heat or mechanical damage to the fiber tip were found after the experiments.

The laser-generated SAW pulses were then monitored with an actively stabilized Michelson interferometer after they had propagated a distance of about 0.4 mm. By using a stabilized cw Nd : YAG laser (532 nm, 120 mW) as the light source of the interferometer and a photodiode–amplifier system (Hamamatsu S4753 PIN photodiode and Avantek INA-03184 amplifier) as the detector (1.5 GHz), we were able to measure transient surface displacements of the elastic pulses in the subangstrom range with frequency components up to 1.0 GHz. A very short distance of 0.4 mm between SAW excitation at the film surface and detection from the back side at the substrate–film interface was selected to monitor the undistorted pulse profile launched at the source (see Fig. 1).

3. Results and discussion

3.1. Laser pulse from the fiber tip

As mentioned before, the frequency range of laser-excited SAW pulses is determined by the confinement of the optical excitation in space and time. In order to characterize the temporal behavior of the laser pulses emerging from the fiber tip, the laser pulses emitted from the metal-coated tip end with an aperture size in the micrometer range were measured by the photodiode–amplifier system mentioned above. As shown in Fig. 2, the measured optical signal had a pulse width of about 550 ps, with frequency components in the measured Fourier-transform spectrum up to 2 GHz. This proves that the present experiments were limited by the spatial confinement of the laser radiation. The main frequency limitation was due to the oscilloscope (Tektronix TDS 680B) used in these measurements, which had an analog bandwidth of 1 GHz and a sampling rate of 5 GS/s. It has been shown before [9–11] that optical fiber or pipette tips can transmit fs–ps laser pulses without significant pulse broadening. Therefore, a bandwidth limitation of SAW pulses by the laser-pulse duration could be avoided by choosing a ps laser.

3.2. Laser-generated SAW pulses

The SAW pulses generated by the laser pulses emitted from the fiber tip were measured at different tip–sample distances. When the fiber tip was several micrometers away from the sample surface, the SAW signal is bipolar as shown in Fig. 3a. This profile is similar to the shape of SAW pulses usually observed with a focusing lens. No oscillations appeared in the signal shape indicating that the dispersion of the SAW pulse during propagation was very small for the small propagation distance of 0.4 mm and frequency range investigated. As shown in Fig. 4a the Fourier transform of this signal shows a frequency range of about 300 MHz, although we were able to detect very small

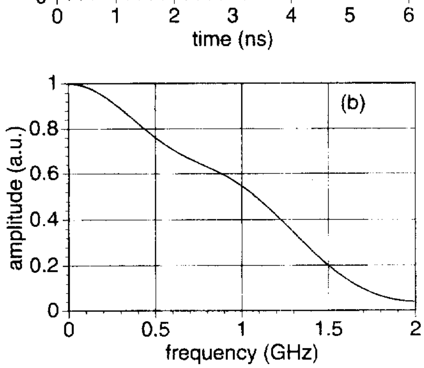

Fig. 2. Signal of a 180 ps laser pulse transmitted through an optical fiber tip measured by the fast photodiode system (a) and its Fourier transform (b).

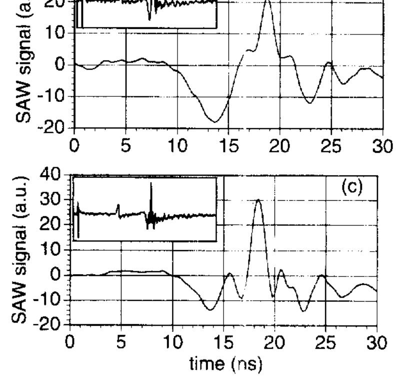

Fig. 3. Laser-generated SAW pulse after propagating 0.4 mm away from the fiber tip source in a 650 nm aluminum film on fused silica. The tip–sample distance varies between far-field (a) and near-field region (b) and (c).

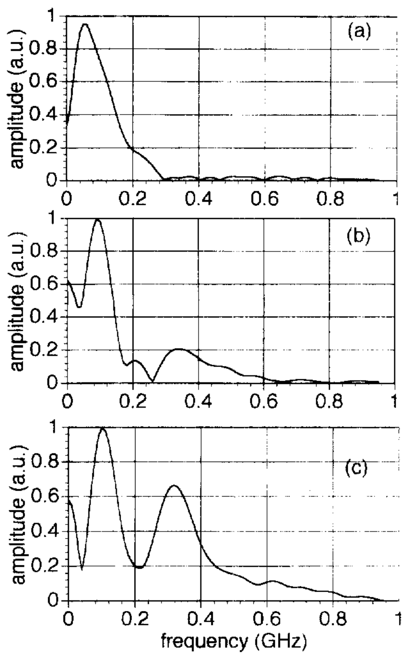

Fig. 4. The corresponding Fourier transforms of the SAW pulses shown in Fig. 3a–Fig. 3c.

contributions for frequencies up to 900 MHz. The inset in Fig. 3a shows the whole signal monitored by the Michelson interferometer. Three peaks appear in the measured signal, corresponding to the laser pulse, the shear bulk acoustic wave and the SAW pulse with the lowest phase velocity.

When the tip–sample distance decreased, the shape of the SAW pulse changed drastically as indicated in Fig. 3b and Fig. 3c. The width of the main peak decreased as the tip–sample distance was reduced, indicating an extension of the frequency spectrum of the SAW pulse. A further reduction of the tip–sample distance caused no obvious extension of the frequency spectrum of the measured SAW signal. Besides the central peak, additional small oscillations occurred in the pulse shape as shown in Fig. 3c. We think this behavior is due to diffraction of the light emitted from the fiber tip. Thus, the thermoelastic excitation of the elastic wave pulses provides a new tool for studying the spatial intensity distribution of the exciting laser light at the surface. Such an imaging of the spatial light distribution is indeed expected for the case where the spatial confinement limits SAW excitation. It is clear from Fig. 4b, Fig. 4c that the frequency range of SAW pulses was extended substantially up to nearly 1 GHz by decreasing the tip–sample distance.

As we can see from the experimental setup presented in Fig. 1, the probe beam was focused with a spherical lens through the substrate onto the film–substrate interface. The focus-spot size was about 2 μm, thus, the frequency components of the SAW signal above 1 GHz could not be detected effectively by the Michelson interferometer, since the probe spot size became comparable to the SAW wavelength.

Fiber tips with an aperture of 100 nm can, in principle, generate SAW pulses with frequencies up to 10 GHz. Recent developments in ultrafast scanning probe microscopy [12, 13] may help to detect such a short SAW pulse with high spatial resolution. The present experiments are far from reaching the 10 GHz frequency range. The reason is that the excitation and detection method used were limited to the 1 GHz range. Nevertheless, substantially higher frequency components were observed when the tip–sample distance was decreased.

4. Conclusions

In conclusion, we have shown for the first time that tapered fiber-optic tips or pipette tips can be applied for the optical generation of broad-band SAW pulses. Elastic surface pulses with frequency components up to 1 GHz have been excited and detected with a setup limited to this frequency range. It is demonstrated that near-field optical methods provide a new approach to generating high-frequency broad-band SAW pulses with the potential of extending the frequency range into the hypersound region. The varying intensity distribution of the radiation field coming from the tip was mapped in the profile of the excited elastic surface wave pulse for distances between far field and near field.

Despite the fact that optical resolution beyond the diffraction limit has not been achieved in the present experiments the observed extension of the frequency range and the imaging of the electromagnetic field distribution at the surface by the SAW pulse shape indicate the great potential of this technique in SAW spectroscopy and for investigating the field distribution of an aperture as a function of the tip–surface distance.

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