Focal transformation and the Gouy phase shift of converging one-cycle surface acoustic waves excited by femtosecond laser pulses

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We studied the changes of the pulse shape and the phase of the spectral components in converging-surface acoustic wave pulses. These pulses were excited with a femtosecond laser by a thermoelastic mechanism. To produce converging acoustic pulses, the laser beam was focused with an axicon in a circle on the surface of an aluminum sample. During propagation through the focus, the shape of the pulses of the normal surface velocity changed from two to three polar. The absolute value of the phase of the spectral components experienced a change close to $\pi/2$ rad (Gouy phase shift) after passage of the focal region. These observations were confirmed by analytical and numerical calculations based on the two-dimensional wave equation for surface acoustic waves. © 2005 Optical Society of America

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A change in phase of a wave experiencing diffraction is a phenomenon that recently has received renewed interest in view of its importance for focused few-cycle optical pulses. This effect was discovered by Gouy[1] and studied for different types of wave: acoustic,[2] optic,[3] and electromagnetic waves in the terahertz region.[4] The phase changes are related to diffraction and changes in the topology and dimensionality of the wave front. In a recent theoretical study[5] it was shown that the appearance of the Gouy phase shift of finite beams originates from transverse spatial confinement. The change in the wave phase in the focal region also results in a small variation of the propagation velocity during this transition, such that superluminal propagation takes place.[6] For a focused spherical wave, the absolute value of the phase changes by π after propagation through the focal region with a change in focus of $\pi/2$.[7] The inversion of a spherical wave after focus owing to the Gouy phase shift leads to the fact that only odd harmonics are efficiently generated in focused optical beams.[8] This effect results also in a change of the polarity of pulses passing through the focus. In acoustics, a direct observation of the inversion of the polarity of a spherically converging pulse was also made.[9] This phase anomaly plays an important role in determining the resonance frequencies in optical cavities with plane and curved mirrors.[10] Recently, with this effect superresolution in a focused optical beam was demonstrated.[11]

It should be noted that diffraction of the initially plane wave and its transition to spherical divergence in the far field are also accompanied by a $\pi/2$ change in phase, as was observed with laser-generated picosecond acoustic pulses.[2] This additional phase shift results in a pulse shape that is a derivative of the initial pulse. This relationship is well known in laser photoacoustics (Ref. 9, p. 27), for which generation of acoustic pulses with pulsed lasers was extensively studied. For cylindrically converging waves the Gouy phase effect was studied less. With terahertz pulses the phase shift was observed for scattering from cylindrical and spherical targets.[12] The phase variation in cylindrically focused bulk phonon polaritons was also observed recently.[13,14]

The general character of this phenomenon allows it to be studied with different types of wave. In this Letter we investigate phase dependences and corresponding shape changes with one-cycle focused surface acoustic wave (SAW) pulses. The convergent SAW pulses were generated with a technique that employs laser pulses focused in a circle with an axicon.[15]

For generation of convergent SAW pulses we used the output of a femtosecond laser (Spectra-Physics Spitfire) with 1 mJ output energy and 50 fs pulse duration that was directed onto an axicon and then focused by a lens into a circle on the surface of a polished aluminum sample. The lens, with a focal length of 4 cm, provided a circle on the surface with a 2.96 mm diameter and a width of ~20 μm. A femtosecond laser source was selected because it produced more-efficient generation of surface acoustic pulses and caused less surface damage than a nanosecond laser source. For the excitation we used the full circle or we could place a mask and block a portion of the circle. The detection was performed with a probe-beam-deflection setup at different distances from the focus. We could vary the distance by moving the spot of the probe beam relative to the excitation circle, using a translation stage with micrometer precision. The measured signal was proportional to the normal surface velocity. Because of the small size of the probe spot (~5 μm) the shape of the SAW pulse could be resolved.

The excitation of SAWs by a short laser pulse by means of a thermoelastic mechanism can be described in the wave zone by the wave equation[16]

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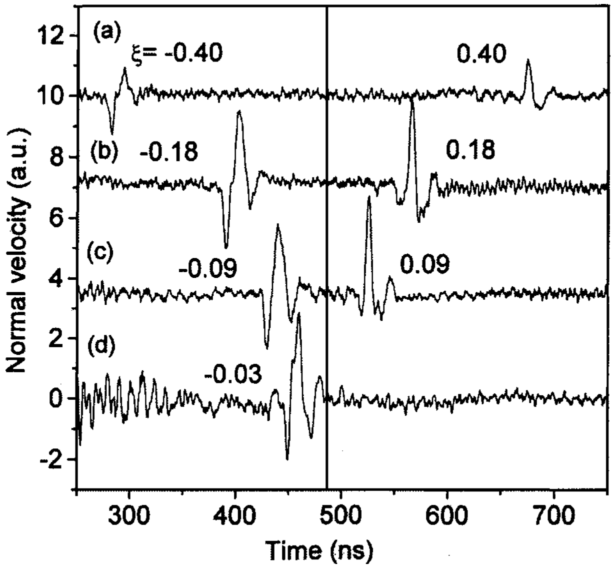

Fig. 1. Pulse shapes observed at several relative distances $\xi=(x-R_0)/R_0$ from the focus. Pulses (a)–(c) were detected with the excitation in a full circle. Pulse (d) was registered with the excitation in a semicircle, $x<R_0$.

$$\frac{1}{c_R^{\,2}}\frac{\partial^2 u}{\partial t^2}-\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=\frac{G}{c_R^{\,2}}\frac{\partial I_m(\mathbf{r},t)}{\partial t}, \qquad (1)$$

where u is the normal surface displacement, c_R is the propagation velocity of Rayleigh SAWs, and G is a constant for a given solid and depends on the solid's optical, thermophysical, and elastic properties. We assume that the absorption in the sample is strong and the laser intensity distribution along the arc is Gaussian. Then for a short pulse the temporal dependence can be described by a delta function:

$$I_m(\mathbf{r},t)\approx I(\mathbf{r},t)=F_0\exp\left(-\frac{y^2}{b^2}\right)f\left(x-\frac{y^2}{2R}\right)\delta(t), \quad (2)$$

where F_0 is the maximum laser fluence, normalized function $f(x)$ describes the fluence distribution perpendicular to the arc, and the focus position corresponds to $\{x=R, y=0\}$. Considering only the wave that propagates in the direction of positive x values and converges to the focus, in the far field, $x \gg b, a$, one can use an asymptotic expression for the normal surface displacement:

$$u(x,t)=\frac{1}{2\pi}\int\tilde{u}(\omega)\exp(-i\omega t)\mathrm{d}\omega, \qquad (3)$$

where

$$\tilde{u}(\omega)=\tilde{u}_0(\omega)\left[\left(1-\frac{x}{R}\right)+\frac{2ixc_R}{\omega b^2}\right]^{-1/2},$$

$\tilde{u}_0(\omega)=(GF_0/2)\exp(i\omega x/c_R)\tilde{f}(-\omega/c_R)$, and $\tilde{f}(\omega)=\int f(t)\exp(i\omega t)\mathrm{d}t$.

For normal surface velocity v, which can be found as the time derivative of the displacement, a similar relation between the spectral components in the near and the far wave fields takes place. We rewrite this relationship in the following form:

$$\tilde{v}(\omega)=\tilde{v}_0(\omega)\left[\left(1-\frac{x}{R}\right)^2+\left(\frac{2ixc_R}{\omega b^2}\right)^2\right]^{-1/2}\exp(i\varphi),$$

$$\varphi=\frac{\pi}{4}+\frac{1}{2}\tan^{-1}\left[\left(1-\frac{x}{R}\right)\frac{\omega b^2}{2xc_R}\right], \qquad (4)$$

with $\tilde{v}_0(\omega)=-i\omega\tilde{u}_0(\omega)$ and the explicit expression for phase change φ. For a Gaussian distribution, $f(x)=\exp(-x^2/a^2)$, we obtain $\tilde{v}_0(x,t)=-i\pi^{1/2}\omega a(GF_0/2)\exp(i\omega x/c_R-\omega^2a^2/4c_R^2)$.

Initially the SAW pulses were observed for excitation in a full circle (see Fig. 1). We normalized the distance from the focus to the radius of the excitation circle by introducing the dimensionless parameter $\xi=(x-R_0)/R_0$. The excitation was produced mostly as a result of a thermoelastic mechanism, as was confirmed by the shape of the observed pulse at large distances from the focus: The pulse of the normal surface velocity in Fig. 1(a) has a shape with positive and negative portions similar to that calculated for a thermoelastic mechanism.[16] In oscillograms (a)–(c) in Fig. 1 the first pulse corresponds to the first arrival of the pulse before the focus; the second pulse, to the arrival of the pulse before the focus; the second pulse, to the arrival of the pulse that propagated through the focus. As the observation point approached the focus, the time interval between these two arrivals decreased. In the focal region the probe-beam-deflection setup does not measure the SAW pulse accurately because waves arriving from the opposite directions form a standing wave. Therefore the pulse near the focus [curve (d) of Fig. 1] was measured when half of the circle was blocked, so the excitation took place in a semicircle. Relatively far from the focus, the pulses excited with irradiation of a semicircle had amplitudes and shapes similar to those observed with the excitation in a full circle. Exactly in focus, the contributions of the two semicircles overlap; therefore for

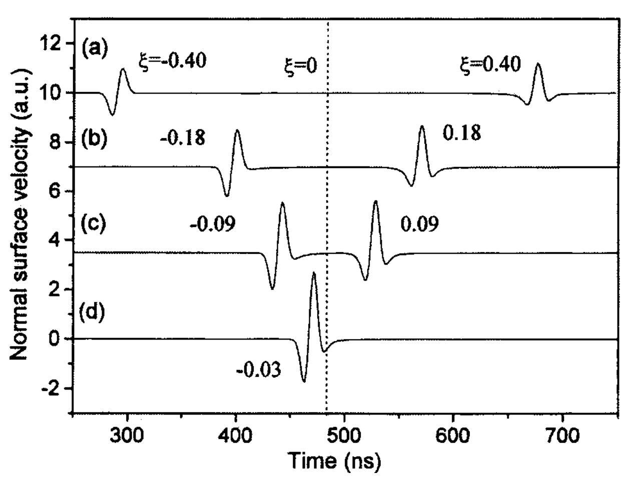

Fig. 2. SAW pulses calculated with the inverse Fourier transform of $\tilde{v}(\omega)$ from Eqs. (4) for the same relative distances as in Fig. 1. The dotted line shows the arrival time for $\xi=0$

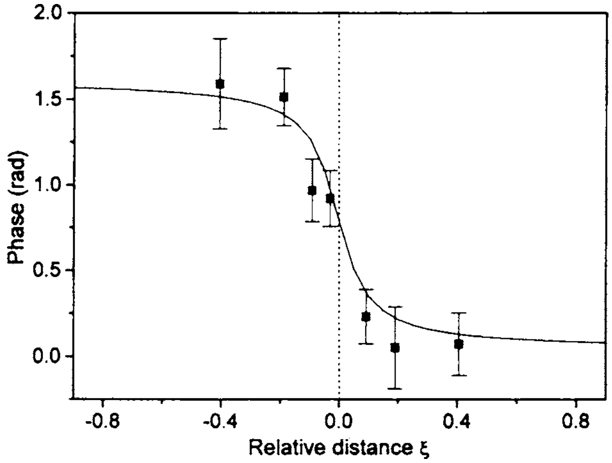

Fig. 3. Dependence of the average phase of the spectral components on relative distance ξ from the focus. Experimental data are shown by filled squares; the calculated dependence is shown by the solid curve. The vertical dotted line indicates the position of the focus.

Gaussian distribution $f(x)$ the amplitude of the pulse of the normal surface velocity from a semicircle [as in curve (d) of Fig. 1] is half of the amplitude of the pulse obtained with the excitation in the full circle. In Fig. 2 the calculated waveforms are presented for comparison. In the calculations the following parameters were used: $a=20\ \mu$m, $b=R_0/2$, $R_0=1.48$ mm, and $c_R=3064$ m/s.

From the measured pulse shapes we calculated phase shifts of spectral components at various distances from the focus (Fig. 3). For this, we performed a discrete Fourier transform of pulse shapes from Fig. 1, using the retarded time $(t-x/c)$. The spectrum of the pulses has a maximum near 60 MHz and decreases significantly at smaller and higher frequencies. We calculated an average phase of the spectral components in the frequency interval from 25.0 to 62.5 MHz, which is represented in Fig. 3 by filled squares. The solid curve shows the phase change calculated from Eqs. (4) for the same frequency interval.

The initial shape of the pulse [curve (a), Fig. 1] corresponds to the thermoelastic mechanism of the laser excitation. When the observation point approaches the focal region, the amplitude of the pulse increases according to cylindrical convergence of the wave. As was shown,[8] the phase change during passage of the wave through the focus depends also on the spatial dimensionality of the wave-front geometry. For a two-dimensional (2D) wave front, as in our experiments, the total expected phase change is $\pi/2$, and in the focus itself it is $\pi/4$. These values were confirmed by measurements with optic phonon polaritons.[13,14] The same regularity can be expected for 2D waves of a different nature. Indeed, in our experiments with SAW pulses we see that the changes of the phase closely follow the dependence calculated with the 2D wave diffraction model of Eqs. (4) for a Gaussian beam resulting in a total change of (-1.5 ± 0.25) rad after passage of the focal region, which is close to the theoretical prediction $(-\pi/2\approx-1.57$ rad). The absolute sign of the change depends on the sign in the exponential term $\exp(-i\omega t)$ in the Fourier transform [Eq. (3)]. For a positive sign the change is positive (as was obtained in Refs. 13 and 14), and for a negative sign (as was chosen in our consideration) it is negative.

In conclusion, we have studied convergent surface acoustic wave pulses generated by a femtosecond laser. The changes in the phase were close to predictions of the theory for a two-dimensional focused Gaussian beam. The total change of the phase absolute value of spectral components in the pulse after the passage of the focal region was close to $\pi/2$. The shape of a SAW pulse propagating through the focus changed from two polar, with negative and positive portions of the pulse, to three polar, with two negative portions and a positive portion in the middle. We have developed a model based on a 2D wave equation, and our calculations confirmed the observed evolution of the phase and the pulse shape during propagation through the focal region.

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