Scanning phononic lattices with ultrasound

R. E. Vines
Shell E&P Technology Company, 3737 Bellaire Boulevard, Houston, Texas 77025

J. P. Wolfe
Physics Department and Materials Research Laboratory, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801

A. V. Every
Department of Physics, University of the Witwatersrand, PO WITS 2050, Johannesburg, South Africa
(Received 4 June 1999)

A method for probing the elastic properties of newly developed periodic structures using acoustic waves is introduced. Highly anisotropic transmission of surface acoustic waves is observed by continuously scanning the wave vector angle. Preliminary models of wave propagation through multilayers and two-dimensional lattices explain some of the experimental features, while other features can be attributed to the resonant excitation of interface waves. [S0163-1829(99)04834-1]

Electromagnetic wave propagation in periodic structures has similarities to the propagation of electrons through a crystal lattice. Light scattering from periodic dielectric structures—so-called photonic lattices—exhibits forbidden energy gaps and has potential for modifying the radiative strength of optical transitions and for manipulating microwaves and light beams.[1,2] Analogous to these photonic structures are *phononic* lattices–media with periodically modulated elastic properties.[3–5] Acoustic waves propagating in such structures should exhibit a variety of interesting properties such as forbidden frequency gaps and wide variations in wave velocities. Band-gap engineering of this sort may yield vibrationless structures for the study of localized vibrations and the guiding of ultrasound.

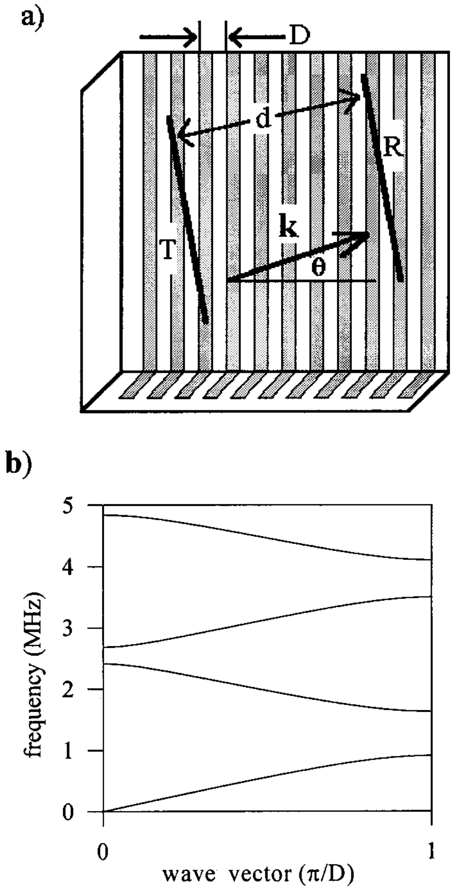
In this study we have constructed and examined the vibrational properties of two types of phononic structures–multilayers and two-dimensional (2D) hexagonal lattices. Surface acoustic waves are employed to probe the band structure of these media. In the light of preliminary model calculations, the experiments reveal frequency gaps (ranges of forbidden frequencies) and channeling of acoustic waves due to total internal reflections. Unexpected wave structures are discovered and are tentatively accounted for on the basis of the resonant excitation of Scholte-like waves. Such oscillations exist at the interface of the periodic solid and the surrounding liquid medium.

The experimental technique is conceptually simple: One observes the transmission of megahertz surface acoustic waves across a solid surface that has periodically modulated elastic properties. The sample is immersed in a water bath which serves as a transmission medium for the ultrasound. An ultrasonic transducer produces a pressure wave that is cylindrically focused to a line on the surface of the sample, labeled T in Fig. 1(a). This excitation creates a surface wave that, after propagating a distance d, is detected by a second transducer focused to the line labeled R in the figure. The velocity and attenuation of the wave will depend on the direction of the wave vector $\mathbf{k}$ with respect to the multilayer planes. To measure the angular dependence of the amplitude of the transmitted wave, the sample is rotated about an axis normal to the excitation surface. A similar angle-scanning technique (primarily using point source and point detection) was used to study the anisotropy of surface waves on crystals and composite materials.[6–8]

Consider first the multilayer structure depicted in Fig. 1(a). Slots cut in an aluminum substrate are filled with a polymer,[9] and the surface is polished flat. The slot width is 0.5 mm and the period D is 1.0 mm. The published density ρ, measured surface-wave velocity v, and acoustic impedance $Z=\rho v$ for each material are listed in the table. Alone, each medium exhibits elastic isotropy, but the composite structure is anisotropic.

A useful theoretical approach was developed earlier for high-frequency phonon propagation through semiconductor superlattices.[10] In the present experiments the line excitation indicated in Fig. 1(a) launches a superposition of plane waves directly into the bounded periodic structure. A detailed treatment of the evolution of this disturbance by linear response theory is beyond the scope of the present paper.[11] It is known, however, that for isotropic media a surface wave (or Rayleigh wave) has polarization and velocity close to that of the bulk transverse mode.[12,13] Therefore, the experimental results are compared to the propagation of transverse bulk waves across a bulk periodic structure. The predicted dispersion curves, assuming propagation normal to the planes, is plotted in the reduced-zone scheme in Fig. 1(b). Frequency gaps occur for wave vectors $\mathbf{k}=n\pi/D$, with $n=0,1,2,3,\ldots$.

Experimentally a short input pulse with bandwidth extending between approximately 1 and 6 MHz is applied, and the transmitted signal for a series of propagation angles is recorded. Figure 2(a) is the resulting angle-time image, where the light and dark regions correspond to positive and negative amplitudes. The source-to-detector distance [d in Fig. 1(a)] is 5 mm. It is immediately apparent that both the time of flight and the transmittance of various frequency components vary strongly with propagation angle. Although



Material	ρ (g/cm^2)	v (cm/μs)	Z (g/cm^{2}μs)
Al	2.7	0.29	0.783
polymer	1.35	0.226	0.305

FIG. 1. (a) Sketch of a multilayer structure consisting of alternating layers of aluminum and polymer (9) composite. Slot depth is 5 mm. The lines marked ''I'' and ''R'' represent the focal regions of the transmitting and receiving transducers. (b) The calculated dispersion curves for ultrasound propagating perpendicular to the layer interfaces, assuming $D=1.0$ mm and the parameters given in the table.

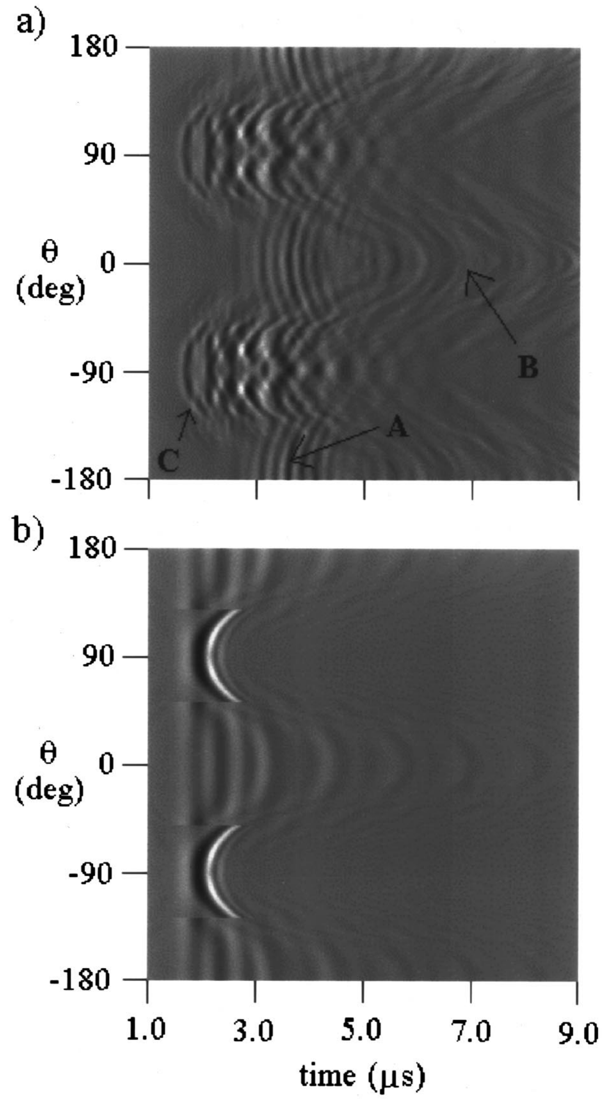


FIG. 2. (a) Experimental angle-time image showing the transmitted signal for a source-to-detector distance $d=5.0$ mm. (b) The calculated image for the multilayer sample and $d=5.0$ mm. The bright wave fronts near $\pm 90°$ correspond to channeled waves that undergo total internal reflection in the polymer layers.

the broadband incident pulse is relatively short—roughly two oscillations extending over a 0.5 μs pulse length—the transmitted wave forms last for several microseconds. These data show that ultrasonic waves in this periodic structure have a pronounced dispersion and frequency-dependent attenuation. The possible origins of three prominent features—labeled A, B, and C in the image—are discussed below.

Figure 2(b) is a theoretical simulation of the transverse wave propagation through the multilayer structure for a transverse mode polarized in the plane of the layers. The wave amplitude for a propagation distance d is determined from

$$u(d,t)=\sum A(d,\omega)e^{i(k(\omega)d-\omega t)}, \tag{1}$$

where the wave number $\mathbf{k}(\omega)$ is obtained from the calculated dispersion relation for this lattice, Fig. 1(b). The sum is computed for a uniform distribution of angular frequencies ω. The assumed form of the frequency spectrum is $A(d,\omega)=A(\omega)\exp(-\alpha\omega d)\exp(d/v\tau)$, where $\alpha=9.9\times10^{-2}$ μs/mm is calculated for fluid loading of an averaged Al/polymer surface,[14] and $A(\omega)$ is the frequency distribution when source and detector are overlapped $(d=0)$. The time τ accounts for attenuation of the wave due to various mechanisms. A Fourier transform of the experimental time traces shows a rapid decrease in transmission with frequency, so we empirically adopt the formula for Rayleigh scattering from defects, $\tau^{-1}=A\omega^4$, with A/v chosen to approximate the observed attenuation at high frequency.

Our elementary calculation separately treats line-wave segments introduced into the Al and polymer layers. Waves introduced at any incident angle into the Al layer refract into the adjoining polymer, etc., and eventually propagate to the detector. An example of this case is the low-frequency wave between $-45°$ and $+45°$, corresponding to the experimental feature labeled B. In contrast, waves introduced into the *polymer* at an incident angle between about 45° and 135° are predicted to undergo total internal reflection at the Al interfaces. This effect results in a channeling of acoustic energy along the polymer layers and corresponds to the bright arcs in the simulation. The shape of these wave fronts is given by the time of flight, $t = d/(v \sin\theta)$, where v is the surface-wave velocity in the polymer and $d/\sin\theta$ represents the total path length of the channeling wave.

This channeling effect appears to explain the feature labeled C in the experimental image, although the observed wave exhibits a much longer train of oscillations and also has additional structure near ±90°. Our elementary calculation of the channeling effect assumes that the wavelength of the wave is much smaller than the period of the lattice and neglects coupling to acoustic waves in nearby layers, which are gross approximations. A quantitative explanation of the data awaits a comprehensive theory of the surface waves in the bounded periodic medium.

The prominent feature labeled A in Fig. 2(a) has a quite different origin. The average velocity of this wave is about 1.5 mm/μs, which is close to that of water ($v = 1.48\,\mathrm{mm}/\mu\mathrm{s}$), and it seems to be associated with a distinct resonance of the system at a frequency $f_0 = \omega_0/2\pi \approx 4$ MHz. The velocity, minimal dispersion, and low attenuation of this wave suggest that its energy flux is located mainly in the water, but its anisotropy implies that the mode of excitation resides in the periodic solid. A sharply peaked frequency response of the lattice is expected at frequencies corresponding to certain critical points (turning values) in the dispersion relation of the superlattice. At the critical points there is a concentration of mode frequencies and vanishingly small group velocities, precluding a rapid migration of acoustic energy from the surface. Furthermore, the variation of elasticity associated with the lattice relaxes phase-matching constraints governing mode conversion at the interface.

We are able to account well for feature A and its variation with θ and d by assuming resonant scattering of the incident pulse into a wave located mainly in the liquid and traveling along the surface of the solid. This is the characteristic of Scholte interface waves.[11,15] The proposed model invokes an umklapp process that changes the surface component of the wave vector of each incident bulk partial wave from $\mathbf{k}_\parallel$ to $\mathbf{k}_\parallel + g$, where $g = 2\pi/D$, thereby allowing coupling between bulk and surface waves. For small angles, the model predicts an angular variation in the phase-velocity time delay,

$$\Delta t_A = \alpha\theta^2 \tag{2}$$

with $\alpha = (gd/2\omega_0)(1 - gv/\omega_0)$, which accounts well for the mean arrival time of feature A for various θ and d. A fuller description of this model will be presented elsewhere.

Now consider a two-dimensional hexagonal lattice of holes drilled in an Al substrate and filled with the same polymer, as shown in Fig. 3(a). The lattice parameter a is 1.0 mm. Our calculation follows earlier work[3] for transverse bulk waves propagating in a plane normal to the polymer cylinders. Constant-frequency curves in wave vector space for a polymer filling fraction of 26% are plotted in Fig. 3(b). Using these dispersion curves and a broad distribution of waves $A(d,\omega) = A(\omega)$ peaked at 2.25 MHz, we calculate the transmitted intensity as a function of angle. A Fourier transform of the transmitted amplitude is plotted in Fig. 3(c). The dark region between 1.4 and 1.7 MHz corresponds to the frequency gap between the first and second Brillouin zone. The gaps between higher zones are also seen. No complete gap for all frequencies is predicted for this lattice, although the inverse lattice does show a complete gap.[16]

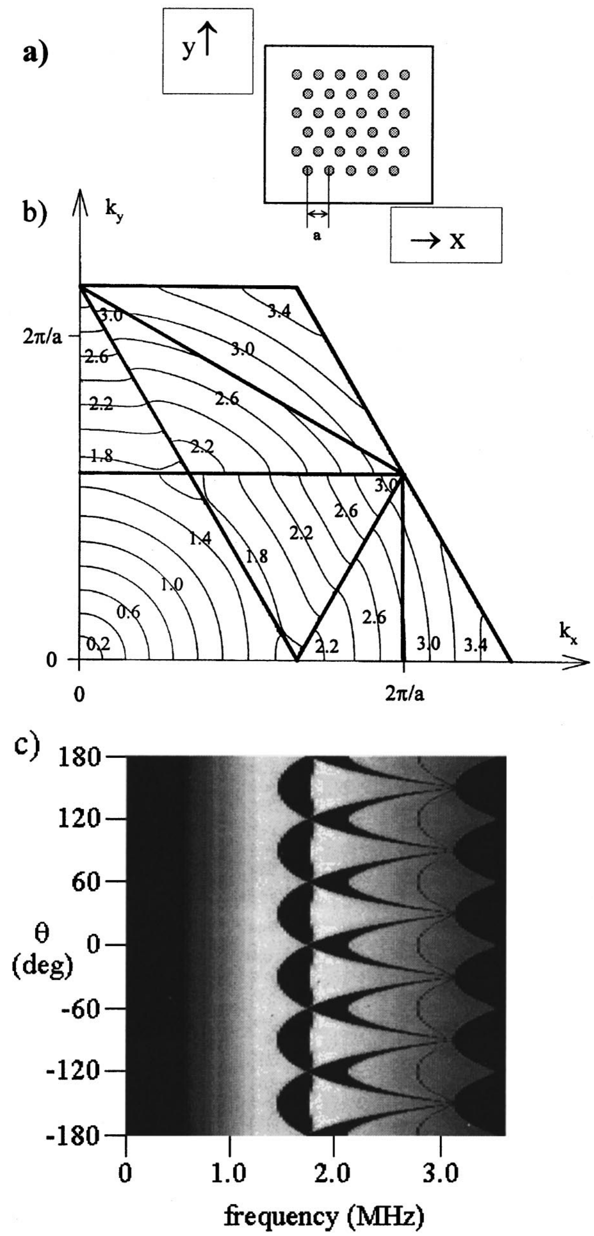


FIG. 3. (a) Sketch of the two-dimensional hexagonal lattice. (b) The dispersion surface for the first three Brillouin zones calculated for a lattice parameter $a = 1.0$ mm and a filling fraction of 26%. (c) The transmitted signal, indicated by brightness, as a function of frequency and angle of propagation with respect to the x axis.

The experimental angle-time image for this lattice is shown in Fig. 4(a), and its Fourier transform is given in Fig. 4(b). The latter images display obvious similarities to the simulation, but striking differences are also observed. A sharp cutoff in the experimental intensity is seen at about 1.5 MHz, and the angular variation of this cutoff has the same symmetry as the lowest band edge in Fig. 3(b). On the other hand, the data show no significant increase in amplitude in

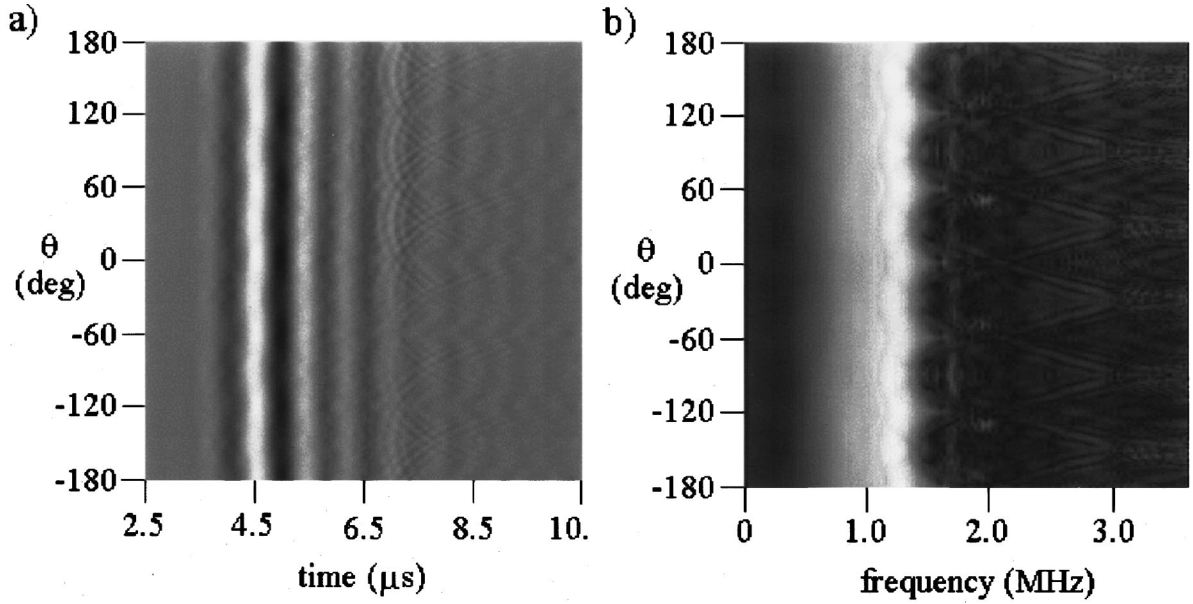


FIG. 4. (a) Experimental angle-time image for the hexagonal lattice and $d=10.0$ mm. (b) Fourier transform of part (a), showing the frequency dependence of the transmitted surface-wave intensity.

the higher Brillouin zones [bright regions above 1.7 MHz in Fig. 3(b)]. Instead, a pattern of dim lines is observed which nearly coincide with the predicted frequency gaps between the second and third zones.

The angle-time image of Fig. 4(a) contains high-frequency components between 6.5 and 8.5 MHz which are similar to the A waves in the multilayer sample. They have an average velocity approximately equal to the sound velocity in water and reveal a resonance in the response of the solid at $f_0 \approx 4.5$ MHz. Here again Eq. (2) for Scholte-like interface waves accounts accurately for the angular variation of this feature, the reciprocal lattice spacing in this case being $g=4\pi/\sqrt{3}a$.

In conclusion, our experiments have introduced new configurations of acoustically modulated materials and a powerful technique for examining their anisotropy and spectroscopic properties. The ease with which waves generated by line excitation can be scanned on a surface (compared to plane waves in bulk matter) suggests that this approach may yield broad insights into phononic and photonic lattices. Theoretical challenges remain in modeling actual surface acoustic waves on these periodic media, taking fluid loading into account. The observation of strong wave-channeling effects and excitation of Schlolte-like modes provide impetus for future studies.

This work was supported in part by the Department of Energy Grant No. DEFG02-96ER45439 in the Frederick Seitz Materials Research Laboratory. We wish to specifically thank Spencer Schultz and Cliff Gulyash who patiently fabricated the samples.

[1] E. Yablanovich, J. Phys.: Condens. Matter **5**, 2443 (1993).

[2] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton University, Princeton, 1995).

[3] M. S. Kushwaha *et al.*, Phys. Rev. B **49**, 2313 (1994); M. S. Kushwaha and P. Halevi, Appl. Phys. Lett. **64**, 1085 (1994).

[4] T. Aono and S. Tamura, Phys. Rev. B **58**, 4838 (1998); Y. Tanaka and S. Tamura, *ibid.* **58**, 7958 (1998).

[5] M. Siglas and E. N. Economou, Solid State Commun. **86**, 141 (1993); J. V. Sanchez-Perez, D. Caballero, R. Martinez-Sala, C. Rubio, J. Sanchez-Dehesa, F. Meseguer, J. Llinares, and F. Galvez, Phys. Rev. Lett. **80**, 5325 (1998).

[6] R. E. Vines, S. Tamura, and J. P. Wolfe, Phys. Rev. Lett. **74**, 2729 (1995).

[7] R. E. Vines, M. R. Hauser, and J. P. Wolfe, Z. Phys. B **98**, 255 (1995).

[8] J. P. Wolfe and R. E. Vines, Proc. - IEEE Ultrason. Symp. **96**, 607 (1996).

[9] Crystalbond™ 509 from Aremco Products, P.O. Box 429, Ossining, NY 10562. This material is a brittle solid at room temperature and melts at 40 °C.

[10] S. Tamura, D. C. Hurley, and J. P. Wolfe, Phys. Rev. B **38**, 1427 (1988).

[11] A. G. Every and G. A. D. Briggs, Phys. Rev. B **58**, 1601 (1998).

[12] T. C. Lim and G. W. Farnell, J. Appl. Phys. **39**, 4319 (1968).

[13] B. A. Auld, *Acoustic Fields and Waves in Solids* (Krieger Publishing, Malabar, FL, 1990), Vol. 2.

[14] K. Dransfeld and E. Salzmann, in *Physical Acoustics VII*, edited by W. P. Mason and R. N. Thurston (Academic Press, New York, 1970).

[15] A. H. Nayfeh, *Wave Propagation in Layered Anisotropic Media* (Elsevier, Amsterdam, 1995).

[16] R. E. Vines, Ph.D. thesis, University of Illinois at Urbana-Champaign, 1998.