I. INTRODUCTION

There is growing interest in the development of novel materials for the control and manipulation of electromagnetic and acoustic waves. Materials that exhibit backward wave propagation, also referred to as negative-index materials, have received considerable attention owing in part to the fact that these materials display negative refraction and a variety of other nonintuitive physical effects.1–4 Backward wave motion is broadly defined as wave motion in which the energy flux direction, as given by the Poynting vector, is antiparallel to the phase velocity direction or direction of motion of the individual wave fronts. The possibility of such motion was first discussed in the early 20th century by Lamb in reference to vibration of mechanical systems.5 Since this time, backward wave propagation has been reported in a variety of structures such as optical and acoustic metamaterials,6–10 photonic and phononic crystals,11–13 and optical and acoustic waveguides14–16.

It has long been known that guided elastic waves, or Lamb waves, in a homogeneous plate can display backward wave propagation.16 In addition, interference effects between forward- and backward-propagating waves can lead to plate resonances in which Lamb waves have a finite phase velocity along the plate but vanishing group velocity. Such zero group velocity resonances have seen renewed interest recently and potentially can be used for accurate determination of the elastic properties of plates or dimensional changes.17–19 Guided elastic waves in other structures such as rods and cylindrical shells,15,20 and multilayer thin films and coatings21 can also exhibit backward wave motion and associated zero group velocity resonances. While the existence of backward wave modes in acoustic waveguides is well established, the behavior of such modes at the interface between two media, one supporting backward waves and the other only forward waves at a particular frequency, has not been reported. In this article, we study the refraction of backward-propagating Lamb waves at an interface between a plate that supports a backward-propagating mode at a given propagation frequency \( \omega_1 \) and wave number \( k_1 \) and a plate that supports a forward-propagating mode at the same \( \omega_1 \) and \( k_1 \). A focused and intensity-modulated continuous-wave laser source, serving as an ultrasonic point source, is used to excite backward-propagating Lamb waves on one side of the step, and the displacement field is probed using an optical interferometer. Conversion between forward- and backward-propagating modes at the interface leads to negative refraction, and we demonstrate for the first time the operation of a flat lens, similar to that predicted by Veselago in negative-index media, for guided elastic waves in isotropic media. We propose that guided elastic waves provide a convenient and powerful experimental test bed for the study of negative-index physics.

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II. VESELAGO LENS FOR LAMB WAVES

Lamb wave propagation in a free, isotropic, and infinite plate is described by the Rayleigh-Lamb dispersion equation, which provides a relationship between the wave number and frequency of waves propagating along the plate with displacement components both in the direction of propagation and perpendicular to the plate surface.22,23 For a fixed excitation frequency, there exist a finite number of real wave numbers, corresponding to propagating waves, and an infinite number of imaginary or complex wave numbers corresponding to exponentially decaying or evanescent waves. The dispersion relation for the first few modes in an aluminum plate, with a longitudinal wave velocity of \( c_L = 6.42 \text{ mm/\mu s} \) and a transverse wave velocity of \( c_T = 3.04 \text{ mm/\mu s} \), is shown in Fig. 1(a), where only the propagating modes are considered. The phase velocity is found through \( v_p = \omega/k \), while the group velocity is given by \( v_g = d\omega/dk \). The modes are labeled as symmetric (S) or antisymmetric (A) depending on the material displacement with respect to the midplane of the plate. With the exception of the lowest-order antisymmetric
FIG. 1. (Color online) (a) Lamb wave dispersion curves in an aluminum plate of infinite extent and thickness $h$, with longitudinal and shear wave velocities of 6420 and 3040 m/s, respectively. (b) A schematic of the plate with a step change in thickness. (c) Symmetric modes on each side of the thickness step and (d) a zoomed-in theoretical (solid lines) and experimental plot of the dispersion curve in the vicinity of the crossing point between the $S_2$ and $S_{2b}$ modes on the thick and thin sides of the plate.

$(A_0)$ and symmetric $(S_0)$ modes, each supported mode sees a cutoff frequency at $k = 0$ corresponding to longitudinal or shear thickness modes. For this material, and over the range of $\omega(k)$ space shown, backward wave propagation is seen in the mode labeled $S_{2b}$, where, for small values of wave number, a negative slope is observed. In this nomenclature, the modes are labeled with a numerical subscript giving the mode number and the subscript $b$ indicates backward propagation. The $S_{2b}$ branch, which extends from $k = 0$ to the point at which the slope of the curve goes to zero ($v_g = 0$), is classified as part of the $S_2$ mode and is indeed connected to this mode through a small imaginary loop in $\omega(k)$ space.\(^{15}\) The existence of backward waves in a particular mode depends on the Poisson’s ratio ($\nu$) and all propagating modes, with the exception of the three lowest modes ($A_0$, $S_0$, and $A_1$), exhibit backward wave propagation over some range of $\nu$.\(^{24,25}\) Backward waves themselves stem from repulsion of adjacent, closely spaced modes of the same family ($S$ or $A$) in the vicinity of $k = 0$.\(^{14,25}\)

In order to study mode conversion between forward- and backward-propagating modes, an aluminum plate with a step change in thickness was fabricated by masking one side of the sample and wet etching the other, resulting in the profile depicted in Fig. 1(b). When Lamb waves associated with a given mode encounter an interface between two media, mode conversion can occur in the reflected and transmitted waves such that the elastic boundary conditions between media, continuity of stress and displacement, are satisfied. Mode conversion across the interface is expected to be strong when the spatial overlap between the displacement fields associated with modes on each side of the interface are similar.

When a backward-propagating wave is converted into a forward-propagating wave upon refraction at an interface, the phenomenon of negative refraction occurs.\(^{1–3}\) Moreover, when the wave numbers on both sides of the interface are equal, the angle of refraction is equal in magnitude but opposite in sign to the incidence angle. As a result, rays originating from a point source on one side of the interface will converge in the symmetrically situated point on the other side, thus resulting in a geometrically perfect image. This “Veselago lens” effect was originally proposed for electromagnetic waves in the context of negative-index materials;\(^{1}\) however, the same concept\(^{1,1}\) is equally applicable to waves of any nature, as long as the conversion between backward- and forward-propagating modes takes place and the wave-number magnitude is preserved.

Here we seek to achieve mode conversion between the backward-propagating $S_{2b}$ branch in the thin side of the plate.
and the forward-propagating $S_2$ mode in the thick side, and the thickness step was chosen such that dispersion curves of these two modes intersect at a particular frequency. The mode conversion takes place near the interface, and over a length scale on the order of the wavelengths of the associated modes. Outside of this zone, the Rayleigh-Lamb dispersion equation may be used to predict the modes supported by the plate on each side of the interface. The dispersion curves (only symmetric modes are shown) calculated for each side of a sample with thicknesses of $h_1 = 131.7 \mu \text{m}$ and $h_2 = 102.5 \mu \text{m}$ are shown in Fig. 1(c) and a zoomed-in version of the overlap region is shown in Fig. 1(d), where the solid and dotted lines correspond to the regions of the plate with thickness $h_1$ and $h_2$, respectively. The modes are seen to intersect at a frequency of $28.0 \text{ MHz}$.

III. EXPERIMENTAL DETAILS

The experimental setup is depicted in Fig. 2. Lamb waves were generated through the thermoelastic mechanism using an intensity-modulated, continuous-wave diode laser with an integrated electroabsorption modulator, and operating at a wavelength of 1550 nm. The modulator was driven by a sinusoidal wave form from a signal generator. The fiber-coupled output was sent to an erbium-doped fiber amplifier where the modulated beam was amplified to 3.5 W. The amplified output was then collimated and focused using a lens with a spot size of 25 $\mu \text{m}$ (full width at half maximum) at the surface of the plate. The position of the excitation point on the plate surface was adjusted using a two-axis computer-controlled translation stage. The normal displacement of the plate surface was detected using a path-stabilized Michelson interferometer incorporating a 200-mW frequency-doubled Nd:yttrium aluminum garnet (YAG) laser. The signal beam of the interferometer was directed through a long working interferometer incorporating a 200-mW frequency-doubled Nd:YAG (λ = 532 nm) and the forward-propagating $S_2$ mode in the thick side, and the thickness step was chosen such that dispersion curves of these two modes intersect at a particular frequency. The mode conversion takes place near the interface, and over a length scale on the order of the wavelengths of the associated modes. Outside of this zone, the Rayleigh-Lamb dispersion equation may be used to predict the modes supported by the plate on each side of the interface. The dispersion curves (only symmetric modes are shown) calculated for each side of a sample with thicknesses of $h_1 = 131.7 \mu \text{m}$ and $h_2 = 102.5 \mu \text{m}$ are shown in Fig. 1(c) and a zoomed-in version of the overlap region is shown in Fig. 1(d), where the solid and dotted lines correspond to the regions of the plate with thickness $h_1$ and $h_2$, respectively. The modes are seen to intersect at a frequency of $28.0 \text{ MHz}$.

The experimental results for the $S_2$ mode in $p\text{th}_1$ and $S_{2b}$ mode in $p\text{th}_2$ are shown in Fig. 1(d) (squares) alongside the theoretical dispersion curves calculated for the best-fit plate.
thicknesses of $h_1 = 131.7 \, \mu m$ and $h_2 = 102.5 \, \mu m$. The experimental results confirm the intersection of the modes, and the dispersion curves show general agreement with theory for these thicknesses.

Two-dimensional scans of the displacement field were performed to evaluate the mode conversion at the interface. The detection laser was positioned 2.0 mm from the interface on $p_{th1}$. The excitation laser modulation frequency was fixed at 28.0 MHz. Taking the detection point as the origin (0,0) and referring to the coordinate system in Fig. 2, the generation laser was scanned from $-2.5$ to $2.5$ mm in the $x$ direction (parallel to the interface) and from $1.25$ to $7.5$ mm in the $y$ direction (perpendicular to the interface), both with a step size of $50 \, \mu m$. The in-phase and quadrature displacement components were measured at each step. The excitation source was scanned rather than the detection point to ensure constant light collection, and hence detection sensitivity, over the scan. However, through the reciprocity principle, this is equivalent to keeping the source at position (0,0) and scanning the detection point on the grid described above. Ten scans were performed and the displacement fields averaged to reduce the measurement noise. The raw (averaged) data corresponding to the in-phase and quadrature components of the displacement field are shown in Figs. 4(a) and 4(b), respectively. In the raw data, the displacement is dominated by the lower-order, high spatial frequency modes: primarily the lowest-order antisymmetric ($A_0$) and symmetric ($S_0$) modes. For these modes, the wave fronts appear to emanate from the detection point (0,0) on $p_{th1}$ and continue to diverge past the interface in $p_{th2}$. As expected, there is no evidence of backward wave propagation or associated negative refraction.

The $S_2$ ($p_{th1}$) and $S_{2b}$ ($p_{th2}$) modes can be isolated from the other modes based on wave number. The raw data was low-pass filtered as follows: We performed a two-dimensional spatial Fourier transform on the image, multiplied this by a Gaussian image with a half-maximum intensity point of $k_c = 16 \, mm^{-1}$, and performed an inverse Fourier transform. This procedure leaves only the $S_2$ and $S_{2b}$ modes whose wave numbers lie below the filter cutoff (see Fig. 3). The filtered images are shown in Fig. 5. The in-phase and quadrature components of the displacement field are shown in Figs. 5(a) and 5(b), while the magnitude and phase are given in Figs. 5(c) and 5(d), respectively. The interface, located at $y = 2.0 \, mm$, is marked by arrows.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig4}
\caption{(Color online) (a) In-phase and (b) quadrature components of the normal surface displacement measured with the detector fixed at $x = 0$ and $y = 0$, and the source scanned. The interface, located at $y = 2.0 \, mm$, is marked by arrows.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig5}
\caption{(Color online) Images of only the low spatial frequency modes resulting from applying a low-pass filter with a cutoff wave number of $16 \, mm^{-1}$ to the data shown in Fig. 4. The in-phase and quadrature components of the normal surface displacement are shown in (a) and (b), while the magnitude and phase are given in (c) and (d), respectively. The interface, located at $y = 2.0 \, mm$, is marked by arrows.}
\end{figure}

\section*{V. DISCUSSION AND CONCLUSIONS}

The characteristics of the lens require further discussion. First, the aperture of the lens appears to be limited to
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∼3.5 mm, and there appears to be little $S_2$-to-$S_{2b}$ mode conversion beyond a half angle of ∼40°. It is believed that this is a result of the redistribution of the Lamb wave energy into different modes to satisfy the continuity conditions at the interface. The interaction of Lamb waves with an interface is a complex process, and it is possible that the numerical aperture could be increased using different types of interfaces or alternate material systems. The wavelengths of the $S_2$ and $S_{2b}$ modes were nearly matched at 28.0 MHz, indicating that for an ideal Veselago lens the detection point and focal point should occur at equidistant points from the interface or, in the coordinate system shown in Fig. 5, the focal point should be at $y = 4.0$ mm. In the experimental result, the focal point appears to be shifted back from the interface. Spatial averaging Fig. 5(c) over 0.5-mm increments along the $y$ axis, we find a minimum central lobe between $y = 4.5$ and 5.0 mm with a full width at half maximum of 0.6 mm, close to the wavelength of the $S_{2b}$ mode (612 μm). We note that there are significant spatial fluctuations observed in the magnitude plot. While the origin of the signal distortion and extended focus are not clear, we propose that the former could stem from small imperfections at the interface and nonuniformity in the amplitude of the $S_2$-to-$S_{2b}$ mode converted wave, while the latter may result from variations in the thickness of $p_{th1}$ or $p_{th2}$ over the imaged region. Nevertheless, it is somewhat remarkable that a Lamb wave lens can be created by a simple thickness step in a homogeneous, isotropic plate.

While the existence of backward waves in acoustic waveguides has been known for quite some time, there has been little work in the design of guided wave structures and sources that take advantage of this intriguing phenomenon. Here we have demonstrated that Lamb wave energy can be focused through mode conversion between forward- and backward-propagating waves at an interface. A modulated point source has been used for excitation, thereby exciting numerous modes in the system and exciting the mode of interest with low efficiency. Selective excitation of a single propagating mode can be achieved potentially, for example, through patterning the source function to match the periodicity of the desired mode at a particular frequency. Using this approach, and optimizing the interface for mode conversion between forward- and backward-propagating modes, it may be possible to fabricate an efficient high numerical aperture surface acoustic wave or Lamb wave lens. Ultimately, one could envision utilizing backward waves, negative refraction, and focusing effects in plates or thin films to manipulate the flow of acoustic energy in novel ways, with potential applications in acoustic wave devices or sensors, or in the nondestructive characterization of materials.

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