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Nonreciprocal Acoustics

New nonreciprocal acoustic devices put sound on a one-way street.

Introduction

In conventional propagation media, wave motion obeys a fundamental property, reciprocity, that describes the symmetry in wave transmission between two points in space. Reciprocity guarantees that wave propagation always occurs in a symmetrical fashion. If waves can make their way from a source to an observer, the opposite propagation path, from the observer to the source, is equally possible and the transmission is symmetric. Reciprocity is a concept so natural that we implicitly assume its validity in our everyday lives. When we hear our neighbors through a common wall, we also know that they can hear us.

It is well known in the field of theoretical acoustics that reciprocity may not hold in specific situations, for instance, in the presence of fluid in motion (Morse and Ingard, 1968; Godin, 1997). Furthermore, recent work has shown engineered devices with strongly nonreciprocal responses (Liang et al., 2009, 2010; Boechler et al., 2011; Fleury et al., 2014, 2015; Popa and Cummer, 2014). These devices force the acoustic energy to flow only in one direction and thereby create a "one-way street" for sound. How can such extreme behavior, somewhat contrary to common sense, be achieved? What are the technological implications and potential applications of strongly nonreciprocal acoustic devices? In this article, we provide an overview of the relevant physical concepts and discuss the recent progress in the emerging field of nonreciprocal acoustics. This review highlights the challenges associated with breaking reciprocity and provides our vision on the future of this research area. We discuss promising applications of these devices and their potential to fundamentally alter the existing wave propagation paradigm in acoustics, offering unprecedented control over sound transmission. We envision that devices exploiting nonreciprocal wave phenomena may lead to new solutions to existing problems in a variety of acoustics-related fields, including energy concentration and harvesting, communications and imaging systems, signal processing, and even thermal management.

Rayleigh Reciprocity Theorem

To our knowledge, the first reciprocity relationship written specifically for acoustic waves appears in a work by Helmholtz (1860) on the theory of airborne noise in pipes with open ends. Although Lamb (1888) provided additional insight into acoustic reciprocity for more general scenarios, it was the work of Rayleigh (1873) that formulated the general reciprocity theorem for sound. Consider an acoustic medium at rest, as represented in **Figure 1a** (possibly inhomogeneous, as represented by the darker purple region). At any point A, acoustic waves may be excited. According to Rayleigh, "the resulting velocity potential at a second point B is the same both in magnitude and in phase, as it would have been at A, had B been the source of sound" (**Figure 1b**). This statement about the exact equality of the velocity potentials in both situations may be at first surprising because it holds even in the presence of absorption losses and in arbitrarily inhomogeneous media. The proof of this result is provided in volume II of Rayleigh's *The Theory of Sound* (1878), and it is typically discussed in most books on acoustics (e.g., Morse and Ingard, 1968; Pierce, 1981). Reciprocity is indeed an important property that is widely exploited in measurement techniques, for instance, in scattering and radiation patterns measurements and transducer calibration.

Reciprocity is not a property specific to the field of acoustics. In electromagnetism, for instance, the equivalent statement is known as the Lorentz reciprocity theorem (Landau and Lifshitz, 1960). Indeed, a reciprocity theorem can be formulated for many physical systems supporting wave propagation because it is simply related to time-reversal symmetry through the application of a fundamental result known as the Onsager-Casimir principle of microscopic reversibility (Casimir, 1945). This elementary physical result provides a clear picture into the conditions for which reciprocity holds.

Consider a linear time-invariant (LTI), possibly inhomogeneous, medium in which time-harmonic perturbations are excited at frequency ω. Waves can be excited at source points and detected at receive points, which we call ports (for instance, an acoustic source at point A and a sensor at point B in **Figure 1** constitute two ports). It is important to determine how the medium behaves under time reversal, i.e., whether it is invariant or not on reversing the time flow (changing the sign of the time parameter in all equations describing the state of the medium). In a linear time-invariant medium, there can be only two different sources of broken time-reversal symmetry. The first one is the presence of absorption losses, represented by the material loss factor η, which macroscopically describes microscopic absorption processes that take energy out of wave propagation. At the macroscopic level, an absorptive medium is not invariant under a time-reversal operation because a time-reversed wave absorption process is equivalent to wave amplification. The second source of broken time-reversal symmetry, which appears at both the microscopic and macroscopic levels, is the dependence of the properties of the medium on a parameter or set of parameters **B**, which is oddly symmetric on time reversal (i.e., its sign flips when a time-reversal operation is applied). A typical example of such a parameter is the static magnetic field bias. Because magnetic fields are the result of charges moving along circular paths, they flip their sign under time reversal as the circular motion of charges is reversed. In a general linear medium, both η and **B** may be nonzero. In such a case, the Onsager-Casimir principle tells us that $t_{AB}(\omega,\eta,\mathbf{B})=t_{BA}(\omega,\eta,-\mathbf{B})$ in general, where t_{AB} is the complex field transmission coefficient between points A and B (Casimir, 1945). This relationship between the transmission from A to B and from B to A indicates that, in the presence of an odd bias, $\mathbf{B} \neq 0$, the reciprocity statement $t_{AB}(\omega,\eta,\mathbf{B})=t_{BA}(\omega,\eta,\mathbf{B})$ does not hold unless $\mathbf{B} = 0$. Reciprocity is therefore related to microscopic reversibility, defined as $\mathbf{B} = 0$, and holds even if time-reversal symmetry is macroscopically broken ($\eta \neq 0$). This result shows how reciprocity, which is equivalent to microscopic reversibility, is intimately related to time-reversal symmetry.

From the above discussion, it is clear that it is possible to find situations in which reciprocity between two points in space may not hold. In a LTI medium, only the use of an external bias, i.e., $\mathbf{B} \neq 0$, odd with respect to time-reversal symmetry, allows one to break reciprocity. Magnetic fields can indeed break electromagnetic reciprocity in ferrites (Lax and Button, 1962) and acoustic reciprocity in magnetoelastic crystals (Kittel, 1958). Another possibility is to break some of the basic assumptions of the Onsager-Casimir principle, such as linearity or time invariance. Reciprocity is indeed broken in the presence of nonlinear processes (for instance, at large acoustic intensities) or time-dependent material properties (for instance, in a time-modulated medium or geometry).

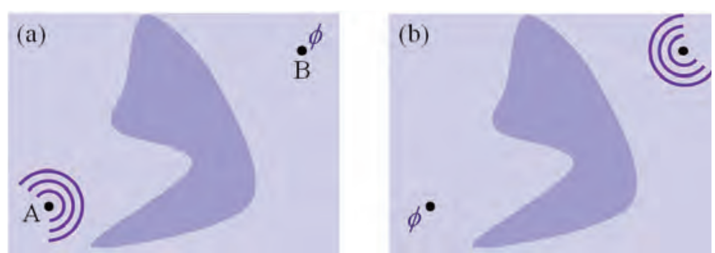

Figure 1. *Rayleigh reciprocity theorem states that the velocity potential (ϕ) induced at point B by a time-harmonic source placed at point A (a) is the same in both magnitude and phase as the one induced at point A if the same source is placed at point B (b).*

Nonreciprocal Electromagnetic Devices

Although it is known that reciprocity does not hold in every situation, it is not trivial to engineer compact and practical devices that are capable of strongly breaking reciprocity, thereby isolating two different points, A and B, with t_{AB}= 1 and t_{BA}= 0. Until recently, highly nonreciprocal devices have existed for electromagnetic waves based on an external magnetic bias, $\mathbf{B} \neq 0$, but their acoustic counterparts have been absent. To better grasp the functionality, applicability, and unique wave manipulation features of these devices, we briefly review basic examples of nonreciprocal electromagnetic devices, namely, isolators and circulators, which have long been used in the microwave and photonics industry (Pozar, 2005). Isolators are two-port devices that allow signal transmission in only one direction (**Figure 2a**). They are used to protect sources from unwanted reflections or to connect different circuits together in a modular way such that interference with reflected signals is minimized. Circulators combine three isolators into a three-port network that allows signal transmission in a unirotational fashion. **Figure 2b** shows a circulator that allows signal transmission in the right-handed direction: signals from ports 1, 2, and 3 can only be transmitted to ports 2, 3, and 1, respectively. Circulators allow a receiver and a transmitter to be connected to the same antenna. As such, they are essential parts of radar systems, and they are becoming crucial components to enable full duplex operation in the next generation of communication devices (**Figure 2c**).

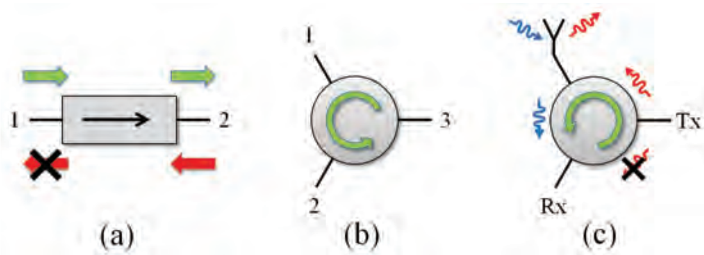

Figure 2. *Nonreciprocal devices. (a) Isolator, allowing transmission from port 1 to port 2 but not in the opposite direction. (b) Circulator, allowing transmission between ports in a unirotational fashion from port 1 to port 2, from port 2 to port 3, and from port 3 to port 1 but not in the opposite direction. (c) Operation of a circulator for full duplex operation, connecting a transmitter (Tx) and a receiver (Rx) to the same antenna. The circulator allows the signal from the Tx to reach the antenna and be routed to free space while a received signal can be received at the same time and on the same frequency channel and be routed to the Rx. The signal from the Tx, typically at a much larger intensity than the received one, is prevented from leaking into the Rx.*

Nonreciprocal Acoustic Devices Based on Nonlinearity

The functionality of isolators and circulators has been recently extended to acoustic waves. Given that magneto-acoustic effects are much weaker than their electromagnetic counterparts, alternative ways to break reciprocity than conventional magnetic bias have been explored. The first works that reported large nonreciprocal acoustic effects in compact devices all relied on nonlinear effects, breaking one of the fundamental assumptions behind Rayleigh reciprocity. Liang et al. (2009) showed that nonreciprocal isolation could be achieved by pairing a nonlinear acoustic medium and a frequency selective mirror, as represented in **Figure 3, left**. The frequency-selective acoustic mirror is created using a sonic crystal with a bandgap between the frequencies f_1 and f_2. Due to its structure, the mirror reflects any harmonic signal of frequency f_0 in the range $f_1 < f_0 < f_2$. The nonlinear medium is placed to the right of the frequency-selective mirror. When an acoustic wave with fundamental frequency f_0 is incident from the left (**Figure 3, right, red**), it is strongly reflected by the mirror and no signal is transmitted from left to right, i.e., $t_{L\to R} \approx 0$. However, when the same signal comes from the right (**Figure 3, right, green**), it enters the nonlinear medium first, which converts some of the incident energy from f_0 to $2f_0$ through second-harmonic generation (SHG). If the bandgap is designed such that $2f_0$ is not in the bandgap, some of the acoustic energy is transmitted through the mirror to the other side: $t_{R\to L} \neq 0$, breaking reciprocity. A relevant metric of the performance of these types of devices is the isolation, $IS = 20 \log(|t_{R\to L}/t_{L\to R}|)$ which quantifies the transmission contrast. For nonlinear devices like those introduced by Liang et al. (2009), the *IS* is extremely large due to the excellent reflection properties of sonic crystals operated in their bandgap. The large *IS* implies that reciprocity is strongly broken by this method. The insertion loss in transmit mode, however, is relatively large. It depends on the efficiency of the SHG in the nonlinear medium and the loss in both the medium and the frequency-selective mirror. The method was later experimentally tested (Liang et al., 2010) using layers of water and glass to realize a sonic crystal and an ultrasound contrast agent microbubble solution as the nonlinear medium. The experiment demonstrated isolation levels up to 80 dB obtained for incident acoustic waves of 5 kPa or larger. The same principle was used in a subsequent experimental work (Boechler et al., 2011) to obtain similar isolation levels by using bifurcation and chaos as the source of nonlinear frequency conversion in a granular sonic crystal. Later, Popa and Cummer (2014) proposed a different approach based on an electroacoustic transducer loaded with a nonlinear electronic circuit placed between two Fabry-Perot cavities tuned to different frequencies. They measured up to 10 dB of isolation in a system whose main advantage over the previous nonlinear methods was its subwavelength size, enabled by the use of active elements.

It should be mentioned that these nonlinear solutions to nonreciprocal acoustics do not break the Rayleigh theorem at the fundamental frequency. In these approaches, trans-

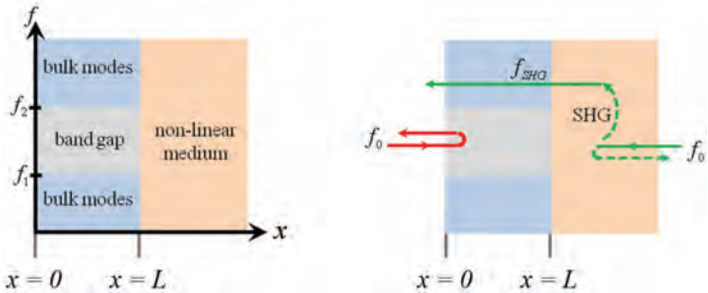

Figure 3. *Left: A nonlinear isolator can be constructed by pairing a frequency-selective mirror, which reflects any acoustic signal with frequency f_0 in the reject band, $f_1 < f_0 < f_2$ to a nonlinear medium capable of second-harmonic generation (SHG). Right: At frequency f_0, a signal incident from the left is reflected (red), whereas the same signal incident from the right makes it to the other side by SHG of a signal at frequency $f_{SHG} > f_2$ (green).*

mission at the fundamental frequency is small from both directions, but frequency conversion is largely asymmetric, allowing one to efficiently transmit power from only one side. In this sense, the definition of isolation introduced above refers to the total transmitted power, irrelevant of the specific frequency content of the signal.

Linear Nonreciprocal Acoustic Devices

Nonlinear acoustic isolators may have several undesirable features for practical applications: (1) they are typically bulky, especially when one wants large isolation ratios; (2) they only isolate for specific (high) levels of input acoustic power; and (3) they rely on frequency conversion, which significantly alters the incident acoustic signal. Linear nonreciprocity requires using an odd-vector bias, an important condition that early works on linear acoustic isolation failed to recognize (see Jalas et al., 2013; Maznev et al., 2013 for reviews of these works and detailed discussions on why they actually do not break reciprocity). Motivated by this fact, Fleury et al. (2014) presented a linear nonreciprocal acoustic device in the form of a subwavelength acoustic circulator for airborne acoustic waves based on a subwavelength acoustic ring cavity filled with a circulating fluid (**Figure 4a**). For design simplicity, air was selected as the fluid and circulation was achieved through the use of fans (**Figure 4b**). The cavity was symmetrically coupled to three acoustic waveguides, which formed the input and output channels of the device.

When the fluid in the cavity is not circulating, the structure operates as a reciprocal sound splitter, which equally divides the input power to the output ports as explained in the following. Consider the case where the structure is excited from port 1 with frequency ω. When the signal enters the cavity, it follows closed paths in opposite directions with a length equal to the average circumference of the cavity l. Every time the signal passes in front of an output hole, a small part leaks out to the corresponding waveguide. To achieve significant transmission at the output waveguides, the multiple circulations of the signal in the cavity should interfere constructively, which happens if $l\omega/c = 2m\pi$, where c is the speed of sound and m is an integer. This equation essentially provides the resonant frequencies of the cavity modes, which are pairs of counterrotating modes with azimuthal dependence $e^{\pm im\varphi}$, where "plus" and "minus" signs correspond to waves propagating in the right- and left-handed directions, respectively, and φ is the polar angle. The above condition leads to constructive interference for each of the modes individually, while different modes appear at the output ports with a phase difference of $2\pi/3$ or $4\pi/3$ with respect to each other for odd and even m, respectively. This phase mismatch results in a slight reflection at the input port equal to 1/9 of the incident power, which can be shown from power conservation and reciprocity to be the minimum reflection that can be achieved in any rotationally symmetric three-port system (Pozar, 2005).

If the fluid in the cavity starts rotating with velocity v in the right-handed direction, the frequencies of the signals propagating in the right- and left-handed directions are shifted by $-\omega v/c$ and $\omega v/c$ with respect to the input signal, respectively, due to the Doppler effect (Pierce, 1981). In this case, it is evident that both waves have a detuned resonance condition, with the right- and left-handed modes being up- and downshifted by $\omega_0 v/c$ with respect to the static cavity resonance ω_0. The fact that the resonance frequencies of the rotating modes are symmetrically located with respect to ω_0 allows one to completely cancel the phase mismatch between counterrotating modes at one of the output ports for a particular circulation velocity. This leads to unity transmission at one port and perfect isolation at the other. For rotation in the right-handed direction, unitary and zero transmission happen at ports 3 and 2, respectively. Under the same rotation condition but for excitation from waveguide 3, power is transmitted to port 2 instead of port 1, providing clear evidence of nonreciprocity. Likewise, power from port 2 is totally transmitted to port 1. It is interesting that power flows in the direction opposite to the cavity fluid bias, highlighting that the circulation is not a simple "dragging" of the acoustic wave by the moving fluid but rather a wave interference phenomenon. This is also evident when analyzing the problem using coupled mode theory. Coupled mode theory shows that maximum *IS* (now without frequency conversion), i.e., maximum difference in transmission between different output ports, occurs when $v = c/(2Q\sqrt{3})$, where Q is the quality factor of the cavity resonance, defined as the ratio between the resonance frequency and the transmission bandwidth (Fleury et al., 2014). This expression shows that ideal isolation can arise for moderate fluid velocities provided that the cavity is strongly resonant. F**igures 4c** and **d**, shows the amplitude of the transmission to ports 2 and 3 versus frequency under excitation from port 1, and the acoustic pressure distribution at the resonance frequency of the ring is shown without (**Figure 4e**) and with (**Figure 4f**) a circulating fluid at the optimum velocity. As expected, isolation becomes maximum (theoretically infinite) at the resonance frequency of the static cavity. Furthermore, the corresponding optimum velocity (0.5 m/s) is orders of magnitude smaller than the speed of sound (340 m/s) thanks to the large quality factor of the cavity (Q = 200). Since the typical decay time for an intracavity mode is approximately Q periods, the interaction between the wave and the moving fluid is significantly boosted in the resonant system, resulting in a very strong nonreciprocal effect in this subwavelength device. These results have been validated experimentally in the audible range (Fleury et al., 2014).

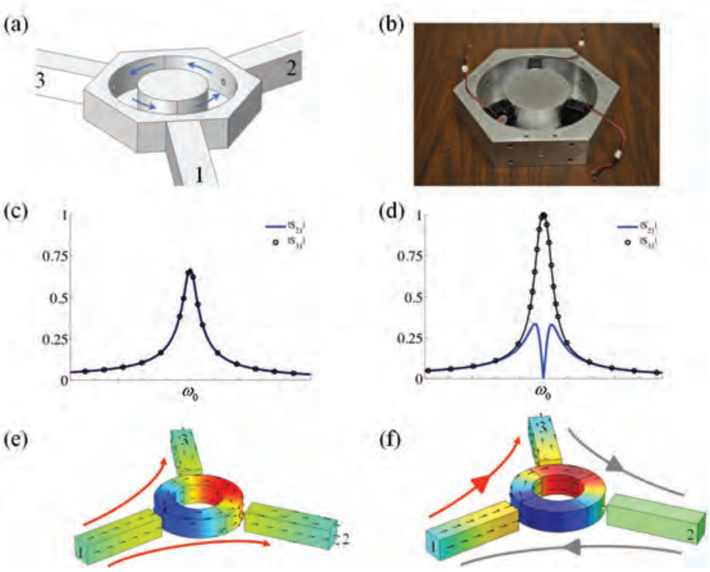

Figure 4. Acoustic circulator based on angular-momentum biasing through a circulating fluid. (a) Cavity filled with a circulating fluid and coupled to three waveguides. (b) Realization of the cavity shown in panel (a). The cavity is air-filled, circulation is achieved via three small fans. (c) Transmission without fluid circulation. Transmission at ports 2 and 3 for excitation from port 1 is indicated by $|S_{21}|$ and, $|S_{31}|$, respectively, and their amplitude is unity when the transmitted signal equals that of the incident signal. Without circulation, the structure operates as a reciprocal power splitter. (d) Transmission at ports 2 and 3 for excitation from port 1 with fluid circulation and at the circulator frequency ω_0. (e) Acoustic pressure in the system (surface color) and power flow (vector plot) at the cavity resonance without fluid circulation. Red arrows indicate the direction of sound transmission. (f) Same as panel (e) but fluid motion is applied. The red arrow indicates the one-way direction of sound transmission for excitation at port 1. The grey arrows indicate direction of one-way sound transmission if sound were incident from port 2 or 3. ©2014 AAAS. Adapted with permission (Fleury et al., 2014)

Ultrasonic waves with frequencies larger than 20 kHz and wavelengths in the submillimeter scale are important for several practical applications in engineering, medicine, and chemistry. Implementation of the circulator in **Figure 4a** at these frequencies may be a challenging task due to the small wavelengths and the consequently small cavity size required, although recent advances in the field of microfluidics may offer possible solutions. Another approach that completely avoids the problems associated with fluid motion (including noise) is the possibility of realizing effective angular momentum biasing via spatiotemporal modulation. A possible structure that employs this technique is shown in **Figure 5, top** (Fleury et al., 2015). The device consists of three identical cylindrical acoustic cavities that are symmetrically coupled to each other through small channels and to external waveguides. If the cavity volumes are modulated by a time-dependent amount ΔV with amplitude δV and frequency ω_m in a rotating fashion (with a phase difference of 120° between neighboring cavities), an effective angular momentum bias is imparted to the structure, making it possible to realize a circulator with ideally perfect isolation. By tailoring both the strength of the modulation δV and its frequency ω_m, it is possible to induce circulation of the acoustic signal as demonstrated by the simulations presented in **Figure 5, bottom.**

An advantage of this approach is that it employs a small modulation of the cavity volume at a frequency much lower than the signal frequency. Similar to the previous discussion on the limited fluid speed, the resonant behavior of the spatiotemporally modulated system enables isolation levels up to 50 dB, with insertion losses as low as 0.3 dB despite the weak modulation. Compared with the previous linear acoustic circulator design based on fluid motion, this system is noise free and its total size does not exceed $\lambda/6$. In addition, the volume modulation can be implemented using electromechanical actuators, leading to a design that can be fully implemented in an integrated component and may find direct applications in ultrasound imaging systems, acoustic transducers, and communication systems.

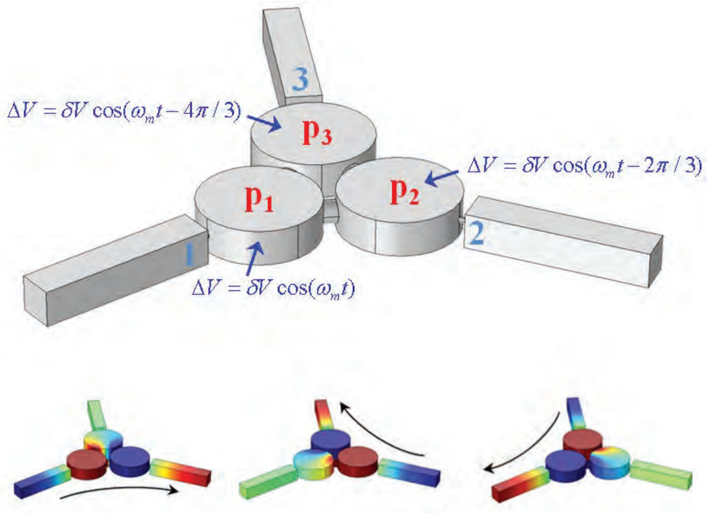

Figure 5. Acoustic circulator based on angular-momentum biasing through spatiotemporal modulation. Top: Three cylindrical cavities are coupled together through small channels. The cavities are also coupled to three external waveguides through small channels. The volume of the cavities is dynamically modulated with the same amplitude and frequency and with a phase difference of 120° between adjacent cavities. Bottom: By tailoring both the amplitude and frequency of the volume modulation, it is possible to obtain an acoustic circulator(full-wave simulations, complex pressure field). Adapted with permission from Fleury et al. (2015). © 2015 American Physical Society.

Outlook for Nonreciprocal Acoustic Devices

The realization of nonreciprocal acoustic systems based on existing theoretical foundations and experimental validation can undeniably extend our ability to manipulate acoustic signals. They therefore have a strong potential for broad industrial impact, as is the case for their electromagnetic counterparts. This section therefore provides a technological outlook for this nascent field based on a few possible applications for which nonreciprocal acoustical devices may offer unique capabilities.

Circulators are widely used in electromagnetics in radar and radiocommunication systems as a way to realize full duplex operation with a single antenna (**Figure 6, top**). Full duplex operation means that a given transducer is capable of emitting and receiving at the same time on the same frequency channel. If one does not have a circulator, the functionality can be realized using two distinct transducers (**Figure 6, middle**), one for the receiving circuit (Rx) and the other one for the transmitting circuit (Tx). This, however, requires the use of two well-isolated transducers, and suitable, quite convoluted signal-processing tricks to distinguish the two signal flows.

If one wants to use a single transducer, full duplex operation is no longer possible because the transducer cannot distinguish between incident and outgoing signals at the same frequency. A solution is to use time-multiplexing techniques and time gating in the form of a switch that connects the transducer to Rx or Tx depending on whether one is receiving or transmitting (**Figure 6, bottom**). Half duplex is typical in sonar, underwater acoustic communication systems, and ultrasound imaging devices. These systems send short pulses or use signal-processing techniques such as pulse compression to separate the incident wave from echoes. In these cases, the output power is limited by the duration of the pulse, which ultimately limits the sampling rate and the signal-to-noise ratio. In underwater acoustic communication systems, half duplex means that two communicating systems cannot talk at the same time and have to take turns sending information, which ultimately limits the communication speed. Using different frequency channels to transmit and receive is another option, but this also implies an inefficient use of the available spectrum. In other words, the absence of acoustic circulators inherently limits current acoustic imaging and communication systems. Interestingly, coupling an electro-

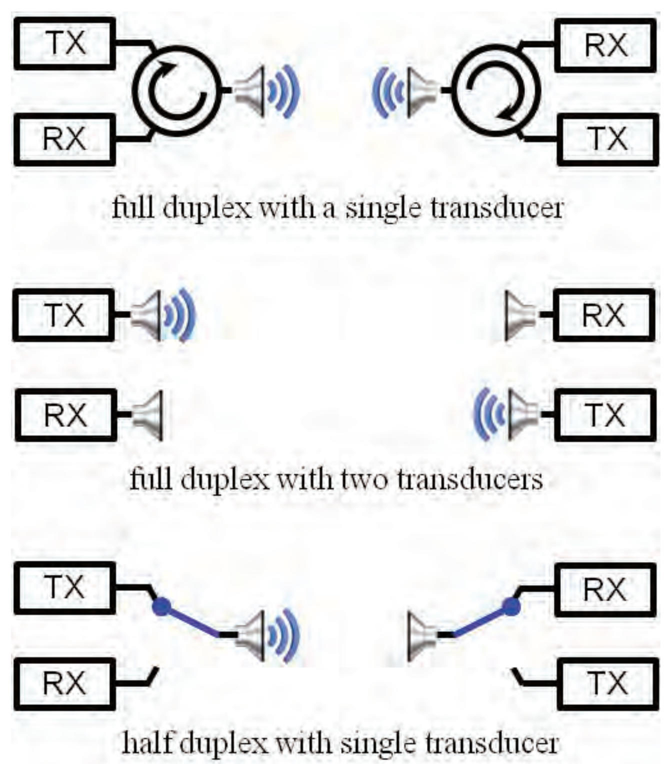

Figure 6. Nonreciprocal acoustic devices such as isolators may be used to enable full duplex operation in underwater acoustic communications or sonar systems.

magnetic circulator to an acoustic transducer is not a viable solution for full duplex acoustic operation because there are no efficient electromagnetic circulators that can handle the required levels of power at such low frequencies (circulators based on transistors would completely break down due to the nonlinear behavior of transistors at higher powers). For these reasons, acoustic circulators appear to be an ideal technology for underwater communications and imaging systems.

Another promising application field for nonreciprocal acoustics is the manipulation of vibrational energy for system protection or energy harvesting. Nonreciprocal devices completely redefine the common paradigm of wave propagation according to which waves have to travel in both directions and, as a result, according to which reflections always exist at device interfaces or in the presence of defects. Nonreciprocal materials may be used to force acoustic waves to go one way along a predefined path from one point to another. This could eliminate Fabry-Pérot resonances, matching problems, and sensitivity to defects or disorder. In this vein, nonreciprocal materials are promising in the development of the acoustic equivalent of topological insulators (Khanikaev et al. 2015), with application potentials in energy harvesting and vibrational energy isolation. Due to their large physical size, such artificial nonreciprocal materials may lead to broader bandwidths than the ones reported for subwavelength nonreciprocal devices and find applications in noise control and management. Finally, the concept of nonreciprocal phononic propagation may lead to several exciting possibilities in the field of heat management via the nonreciprocal control of thermal phonons. This application area has the potential to create a novel class of highly asymmetric thermal conductors that easily conduct heat in one direction but insulate in the other (Maldovan, 2013).

Summary

Nonreciprocal devices that break the symmetry of sound transmission between two points in space have been recently demonstrated using various approaches, thereby opening exciting new directions in acoustics research. Such systems let sound propagate in one direction and completely block any transmission in the reverse direction, violating one of the most basic principles of acoustics, Rayleigh reciprocity. They can be achieved by using either nonlinearities or a parameter that is odd-symmetric under time reversal for linear systems. The latter can be achieved by imparting angular momentum via a moving fluid. Nonlinear systems that achieve highly nonreciprocal response are relevant for high-power routing and manipulation of sound, such as the protection of systems from incident acoustic power beyond a given threshold. Linear systems that break nonreciprocity are relevant in different scenarios, such as signal manipulation and processing, and hold significant promise in underwater acoustic communication systems and sonic and ultrasonic imaging devices. Moreover, violation of Rayleigh reciprocity may lead to a novel class of artificial materials that overcome the fundamental limitations of conventional materials by completely modifying the common paradigm of wave propagation within the medium. These materials will not exhibit reflections at defects or impedance-matching issues arising from multiple reflections between interfaces. More futuristic applications for these nonreciprocal devices may also be envisioned, including defect and disorder-free, topologically protected sound propagation in sonic or phononic crystals as well as control of thermal heat transfer in nonreciprocal phononic systems. It is our opinion that nonreciprocal acoustics has a bright future as a new frontier in acoustical device engineering. It introduces a new degree of freedom in system design by relaxing the usual constraint of time-reversal symmetry in wave propagation and scattering and therefore considerably extends our ability to control acoustic waves.

Acknowledgments

This work was partially supported by the Air Force Office of Scientific Research and the National Science Foundation. MRH acknowledges the support from the Office of Naval Research.

Biosketches

Romain Fleury received a MS degree in micro- and nanotechnology from the University of Lille and the National Engineering Diploma from Ecole Centrale de Lille, France, in 2010. In 2015, he received a PhD degree in Electrical and Computer Engineering from the University of Texas at Austin. His research interests focus on novel interdisciplinary wave phenomena in acoustics, electromagnetics, and condensed matter physics. His PhD work on artificial acoustic materials with broken time-reversal symmetry has led to two patent applications, three best student papers award (including two from ASA), and several high-impact publications including the cover of *Science* in 2014.

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