

A nonreciprocal antenna speaks without listening

Freed from the textbook symmetry between transmission and reception, the device could be a boon to communications.

Antennas are everywhere: on radios, televisions, cell phones, computers, and wireless internet routers. Each is optimized for a specific frequency range—for example, cellular frequency bands are around 800 MHz and 1.9 GHz. Normally, the time-reversal symmetry of Maxwell's equations dictates that if an antenna can transmit efficiently at a particular frequency and in a particular direction, it must be an equally good receiver at the same frequency and in the same direction.

That reciprocity comes in handy when measuring the reception pattern of an antenna; one need only measure the transmission pattern, which is easier. But reciprocity becomes a problem—and can slow down communications—when antennas are forced to listen to the reflections of their own signal or to other transmitted signals at the same frequency.

Now Andrea Alù and postdocs Yakir Hadad and Jason Soric of the University of Texas at Austin have designed and built an antenna that breaks time-reversal symmetry.¹ By passing a weak alternating electric signal through the device, they altered the way it interacts with transmitted and received signals. Under certain conditions, the antenna transmitted 50 times more strongly than it received.

Guided waves

Reciprocity-breaking devices are not new.² A common approach is to pass electromagnetic signals through a magnetic material that's been biased with an external magnetic field. Electrons in the material orbit with a particular handedness, thereby breaking time-reversal symmetry, and allow signals to pass in one direction but not the other. Such so-called magnetic isolators are deployed in some RF communications applications. But they're expensive and bulky, so there's active interest in developing alternatives.

For the past several years, Alù and his group have been working on breaking reciprocity in new and different contexts.

They first built a nonreciprocal device, called a circulator, for guided acoustic waves.³ It works by circulating a continuous flow of air through a ring-shaped acoustic cavity so that sound waves propagating clockwise and counterclockwise around the ring are endowed with different resonant frequencies. Three ports equally spaced around the ring coupled acoustic waveguides to the cavity, and the waves passing through them behaved in a nonreciprocal way: Sound waves entering the first port exited only the second, those entering the second exited only the third, and those entering the third exited only the first.

The acoustic device was inspired by the physics of magnetic materials. The circulation of air played the role of the circulation of electrons in a magnetic field, and the splitting of acoustic resonances was analogous to the Zeeman splitting of electronic energy levels. The next step was to translate the concept back into the electromagnetic realm while keeping the scale macroscopic.⁴ The acoustic waveguides were replaced by microwave ones, and the ring-shaped cavity was replaced by a ring of coupled LC circuits. In place of the air flow, the researchers circulated an electric signal that, in turn, caused the circuits' resonant frequencies to oscillate.

Key to the device's operation was the variable capacitor built into each of the coupled circuits. Its capacitance varies with the applied voltage—or, put another way, the voltage across it is not linearly related to the stored charge. The capacitor is similar to a standard semiconductor diode, with a reverse bias applied to create a region depleted of charge carriers. The depletion region serves as the capacitor's dielectric layer. The greater the reverse-bias voltage, the thicker the depletion region and the lower the capacitance. The variable capacitances resulted in variable resonant frequencies for the coupled circuits and led to the nonreciprocal behavior of elec-

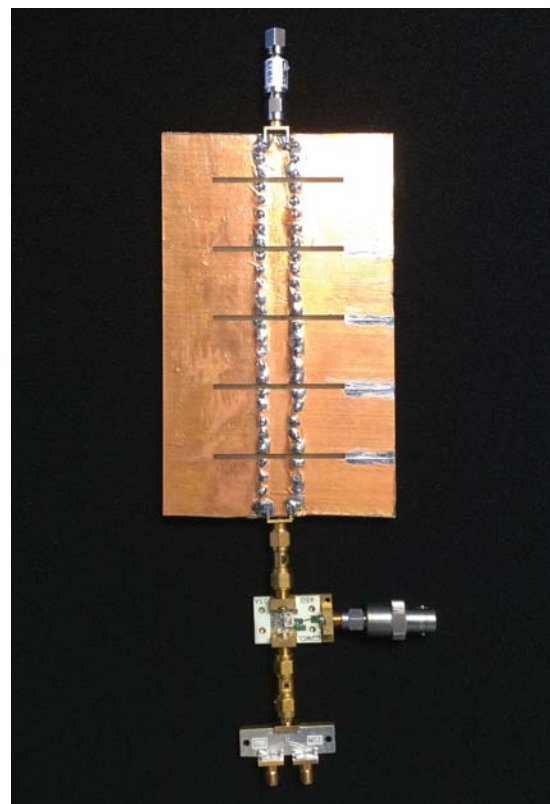


FIGURE 1. A HANDMADE ANTENNA that can break time-reversal symmetry. The antenna itself is the copper sheet with two soldered stripes and five narrow apertures spaced 2.6 cm apart. The electronics at the bottom of the image are used to combine the RF signal for transmission, a 600 MHz modulation signal, and a DC bias voltage. (Adapted from ref. 1.)

tromagnetic waves, with no magnetic fields required.

Free radiation

Until now, Alù and colleagues had dealt only with guided waves in closed systems. Extending the concepts to create a nonreciprocal antenna presented new challenges because of the many more degrees of freedom of waves propagating in free space. The researchers used two tricks to get their antenna to work.

First, they designed it with dimensions larger than the wavelengths it transmits and receives, so it doesn't behave like a point-like source. The emission or ab-

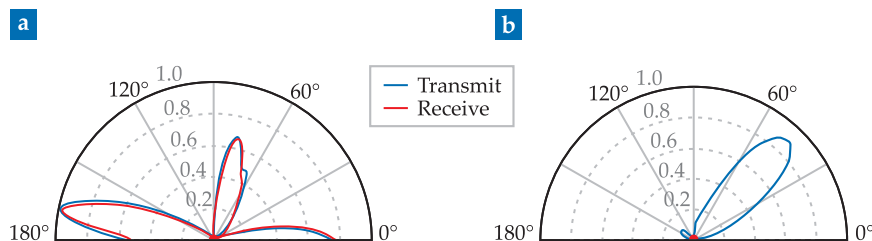


FIGURE 2. TRANSMISSION AND RECEPTION patterns, as a function of direction, for (a) the unmodulated antenna and (b) the antenna with the 600 MHz modulation applied. Both plots are normalized to the same scale—the maximum transmission intensity for the modulated antenna is almost 90% of the maximum intensity for the unmodulated antenna. (Adapted from ref. 1.)

sorption of a wave is contingent on spatially separated regions of the antenna acting in concert, and as a result, the antenna's transmission and reception patterns are highly dependent on direction.

Second, the team made use of a natural filtering property of free space: Radiating waves must travel at the speed of light. Signals can propagate along the antenna at various frequencies and velocities. But they can't be transmitted to or received from a certain direction unless their speed is just right to couple to a light-speed wave traveling in that direction: The radiated wave, projected onto the antenna plane, must match the speed of the antenna signal.

The device, shown in figure 1, consists of a copper sheet on which the researchers constructed a transmission line designed to carry RF signals. The transmission line is cut by slot-shaped apertures spaced 2.6 cm apart, and underneath each aperture is a variable capacitor (not visible) of the same kind as the researchers used in their work on guided electromagnetic waves. The antenna can transmit and receive—with equal efficiency—at frequencies between 3.6 GHz and 4.2 GHz (free-space wavelengths of 7.1–8.3 cm). The transmission and reception patterns, shown in figure 2a, are nearly identical, as dictated by reciprocity, and have a strong direction dependence.

To break time-reversal symmetry, the researchers injected a 600 MHz electric signal into the device. At that frequency, the signal propagated too slowly along the antenna to couple to radiating waves, but it still caused the capacitances to oscillate and influence the antenna's interaction with waves at other frequencies.

The most striking nonreciprocity was observed when the device was operated in an upconversion–downconversion mode that coupled a 3.5 GHz electric sig-

nal with a 4.1 GHz electromagnetic radiated wave, with the 600 MHz modulation supplying the required energy difference. The upconversion transmission pattern, shown in blue in figure 2b, is sharply peaked at one angle, where the transmission is almost as strong as it was for the static device. The downconversion reception pattern, on the other hand, shown in red but barely visible, is weaker by 17 dB, or a factor of 50. "For a signal going out, the 600 MHz modulation propagates in the same direction as the signal," Alù explains, "whereas a signal coming in flows in the opposite direction." Time-reversal symmetry is thus broken.

The researchers are working toward a much greater imbalance between transmission and reception. In their work on guided electromagnetic waves, the output of signals propagating in opposite directions differed by a factor of a million. Alù stresses that their proof-of-concept antenna was handmade, so there should be plenty of room for improvement as they optimize the design.

They also plan to explore whether similar devices could be designed for other regions of the electromagnetic spectrum. Photovoltaic and thermophotovoltaic cells, which harvest energy in the visible and IR parts of the spectrum, suffer the same symmetry that antennas do: A good absorber must also be a good emitter, so much of the energy that's harvested is immediately lost. Nonreciprocal cells could yield higher-efficiency solar-energy conversion.

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References

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