Scientists demonstrate time reflection of electromagnetic waves

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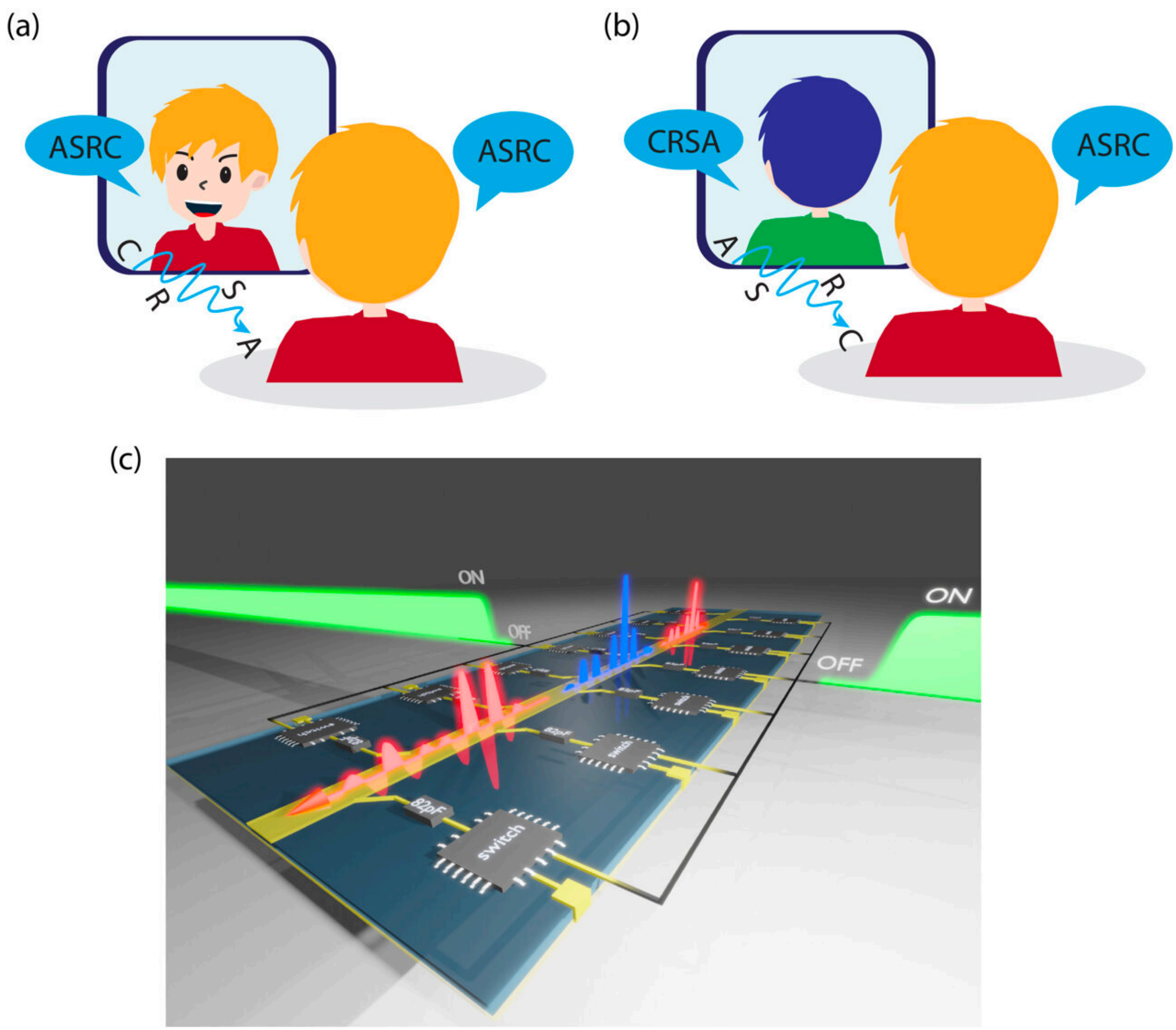

(a) Conventional spatial reflections: A person sees their face when they look into a mirror, or when they speak the echo comes back in the same order. (b) Time reflections: The person sees their back when they look into a mirror, and they see themselves in different colors. They hear their echoes in a reversed order, similar to a rewound tape. (c) Illustration of the experimental platform used to realize time reflections. A control signal (in green) is used to uniformly activate a set of switches distributed along a metal stripline. Upon closing/opening the switches, the electromagnetic impedance of this tailored metamaterial is abruptly decreased/increased, causing a broadband forward-propagating signal (in blue) to be partially time-reflected, (in red) with all its frequencies converted. (Adapted from *Nature Physics*). Credit: Andrea Alu

When we look in a mirror, we are used to seeing our faces looking back at us. The reflected images are produced by electromagnetic light waves bouncing off of the mirrored surface, creating the common phenomenon called spatial reflection. Similarly, spatial reflections of sound waves form echoes that carry our words back to us in the same order we spoke them.

Scientists have hypothesized for more than six decades the possibility of observing a different form of wave reflections, known as temporal, or time, reflections. In contrast to spatial reflections, which arise when light or sound waves hit a boundary such as a mirror or a wall at a specific location in space, time reflections arise when the entire medium in which the wave is traveling suddenly and abruptly changes its properties across all of space. At such an event, a portion of the wave is time reversed, and its frequency is converted to a new frequency.

To date, this phenomenon had never been observed for electromagnetic waves. The fundamental reason for this lack of evidence is that the optical properties of a material cannot be easily changed at a speed and magnitude that induces time reflections. Now, however, in a newly published paper in *Nature Physics*, researchers at the Advanced Science Research Center at the CUNY Graduate Center (CUNY ASRC) detail a breakthrough experiment in which they were able to observe time reflections of electromagnetic signals in a tailored metamaterial.

"This has been really exciting to see, because of how long ago this counterintuitive phenomenon was predicted, and how different time-reflected waves behave compared to space-reflected ones," said the paper's corresponding author Andrea Alù, Distinguished Professor of Physics at The City University of New York Graduate Center and founding director of the CUNY ASRC Photonics Initiative. "Using a sophisticated metamaterial design, we were able to realize the conditions to change the material's properties in time both abruptly and with a large contrast."

This feat caused a significant portion of the broadband signals traveling in the metamaterial to be instantaneously time reversed and frequency converted. The effect forms a strange echo in which the last part of the signal is reflected first. As a result, if you were to look into a time mirror, your reflection would be flipped, and you would see your back instead of your face. In the acoustic version of this observation, you would hear sound similar to what is emitted during the rewinding of a tape.

The researchers also demonstrated that the duration of the time-reflected signals was stretched in time due to broadband frequency conversion. As a result, if the light signals were visible to our eyes, all their colors would be abruptly transformed, such that red would become green, orange would turn to blue, and yellow would appear violet.

To achieve their breakthrough, the researchers used engineered metamaterials. They injected broadband signals into a meandered strip of metal that was about 6 meters long, printed on a board and loaded with a dense array of electronic switches connected to reservoir capacitors. All the switches were then triggered at the same time, suddenly and uniformly doubling the impedance along the line. This quick and large change in electromagnetic properties produced a temporal interface, and the measured signals faithfully carried a time-reversed copy of the incoming signals.

The experiment demonstrated that it is possible to realize a time interface, producing efficient time reversal and frequency transformation of broadband electromagnetic waves. Both these operations offer new degrees of freedom for extreme wave control. The achievement can pave the way for exciting applications in wireless communications and for the development of small, low-energy, wave-based computers.

"The key roadblock that prevented time reflections in previous studies was the belief that it would require large amounts of energy to create a temporal interface," said Gengyu Xu, the paper's co-first author and a postdoctoral researcher at CUNY ASRC. "It is very difficult to change the properties of a medium quick enough, uniformly, and with enough contrast to time reflect electromagnetic signals because they oscillate very fast. Our idea was to avoid changing the properties of the host material, and instead create a metamaterial in which additional elements can be abruptly added or subtracted through fast switches."

"The exotic electromagnetic properties of metamaterials have so far been engineered by combining in smart ways many spatial interfaces," added co-first author Shixiong Yin, a graduate student at CUNY ASRC and at The City College of New York. "Our experiment shows that it is possible to add time interfaces into the mix, extending the degrees of freedom to manipulate waves. We also have been able to create a time version of a resonant cavity, which can be used to realize a new form of filtering technology for electromagnetic signals."

The introduced metamaterial platform can powerfully combine multiple time interfaces, enabling electromagnetic time crystals and time metamaterials. Combined with tailored spatial interfaces, the discovery offers the potential to open new directions for photonic technologies, and new ways to enhance and manipulate wave-matter interactions.

More information: Andrea Alù, Observation of temporal reflection and broadband frequency translation at photonic time interfaces, *Nature Physics* (2023). DOI: 10.1038/s41567-023-01975-y. www.nature.com/articles/s41567-023-01975-y

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