

Time Reversal of Electromagnetic Waves

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We report the first experimental demonstration of time-reversal focusing with electromagnetic waves. An antenna transmits a 1- μ s electromagnetic pulse at a central frequency of 2.45 GHz in a high- Q cavity. Another antenna records the strongly reverberated signal. The time-reversed wave is built and transmitted back by the same antenna acting now as a time-reversal mirror. The wave is found to converge to its initial source and is compressed in time. The quality of focusing is determined by the frequency bandwidth and the spectral correlations of the field within the cavity.

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In acoustics, time-reversal experiments can be carried out with broadband wave forms [1]. In such experiments, a source sends a short pulse that propagates through a more or less complex (but ideally nondissipative) medium and is captured by a transducer array, termed a time-reversal mirror (TRM). The recorded signals are digitized, stored in electronic memories, time reversed, reanalogized, and finally transmitted back by the TRM. The time-reversed wave is found to converge back to its source all the more accurately when the medium is complex and the frequency bandwidth is larger [2]. This is very appealing for applications such as subsurface detection [3], scatterer analysis [4], and telecommunications. Indeed, it was recently shown with ultrasonic waves that it is possible to take advantage of the complexity of a medium to convey more information through it by means of a TRM [5]. From a practical point of view, a TRM was used to focus a random series of bits simultaneously to different receivers which were only a few wavelengths apart. In the language of communication, it corresponds to a MIMO-MU (multiple input, multiple output–multiple users) configuration. While the transmission was free of error when strong multiple scattering occurred in the propagation medium, the error rate was huge in the homogeneous medium (free space) due to cross talk between receivers. Indeed, the spatial resolution of a TRM can be much thinner in a multiple scattering medium than in free space. It is the well-known “super-resolution” that has been experimentally highlighted [2,6] and theoretically discussed [2,7] in the past.

Is it possible to transpose this idea to the electromagnetic case? It is a challenging question because in many real environments (buildings or cities), microwaves with wavelengths between 10 and 30 cm are scattered by objects such as walls, desks, cars, etc., which produces a multitude of paths from the transmitter to the receiver. In such situations, a time-reversal antenna should be able not only to compensate for these multipaths, but also increase the information transfer rate thanks to the many reflections or reverberations, as it was already shown with ultrasound [5]. However, the first step is to

prove the feasibility of a time-reversal experiment with electromagnetic waves in the GHz range. This is the aim of this Letter. To that goal, we present the first one-channel electromagnetic time-reversal mirror working around 2.45 GHz.

From a practical point of view, the main difficulty to transpose the time-reversal technique developed for ultrasound directly to the electromagnetic case lies in the much higher sampling frequencies that are needed to digitize radio frequency signals. One way to overcome this limitation is to work only with quasimonochromatic signals and to do a phase conjugation using the so-called three-wave or four-wave mixing in a nonlinear material in order to naturally produce the analogic phase-conjugated wave [8]. Here, we want to perform a truly broadband time reversal experiment for an electromagnetic signal $m(t) \cos(2\pi\nu_0 t + \varphi(t))$, or equivalently $m_I(t) \cos(2\pi\nu_0 t) + m_Q(t) \sin(2\pi\nu_0 t)$. The carrier frequency is ν_0 , $m_I(t)$ and $m_Q(t)$ are the “baseband” signals. All the time-reversal operations are performed on the baseband signals. The advantage is that the sampling frequency can be much lower than $2\nu_0$.

The experimental setup is the following (Fig. 1). We use two omnidirectional antennas working around $\nu_0 = 2.45$ GHz and two transceiver circuit boards. On the transmit side, they permit one to encode the in-phase (cos) and quadrature (sin) components of a baseband signal (labeled I and Q , respectively) onto a 2.45 GHz wave carrier that can be radiated by the transmit antenna. On the receive side, the circuit boards demodulate the radio frequency signal back to the baseband.

The experiment takes place in a strongly reverberant cavity with dimensions 3.08 m \times 1.84 m \times 2.44 m. Using an arbitrary waveform generator, we deliver a short pulse $m_I(t)$ (central frequency 3 MHz, -6 dB bandwidth 2 MHz) to the I analog input [cf. Fig. 2(a)] of the transmit board. No signal is delivered to the Q analog input [Fig. 2(a')]. A mixer up converts this signal to the GHz band and delivers $e(t) = m_I(t) \cos(2\pi\nu_0 t)$. Then the waveform $e(t)$ is transmitted by antenna A. After

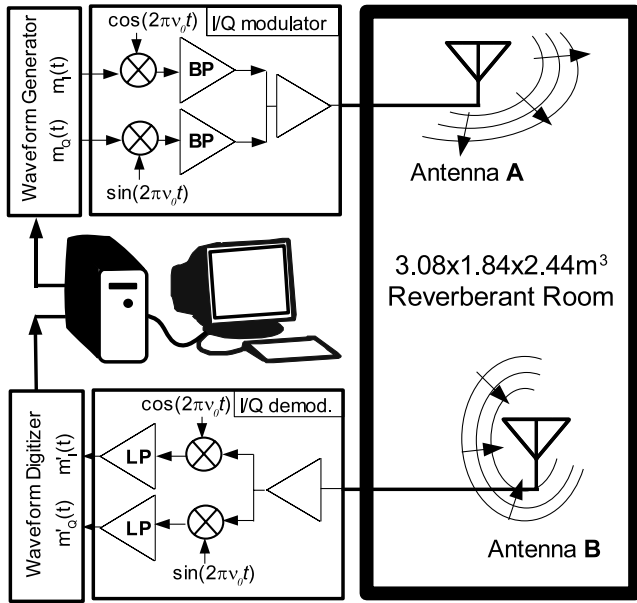


FIG. 1. Sketch of a transmit or receive experiment. The baseband signal $m_I(t)$ [$m_Q(t)$] is fed into a mixer that multiplies it by $\cos(2\pi\nu_0 t)$ [$\sin(2\pi\nu_0 t)$], with $\nu_0 = 2.45$ GHz. After amplification, the output rf signal is sent by antenna A, which is located in the reverberating room. The reverberated field is recorded by antenna B. Its spectrum is down-shifted to the baseband by a multiplier and a low-pass filter. The resulting signals $m'_I(t)$ and $m'_Q(t)$ are sampled and stored in the computer memory. Then they can be time reversed, reanalogized, and, following the same principle, sent back by antenna B while antenna A acts now as a receiver.

propagation, the signal $s(t) = m'_I(t)\cos(2\pi\nu_0 t) + m'_Q(t)\sin(2\pi\nu_0 t)$ is recorded by antenna B and down-converted to produce the I and Q components of the output signal $m'_I(t)$ and $m'_Q(t)$ that can be observed at the oscilloscope [Figs. 2(b) and 2(b')]. The received signals last more than $8 \mu\text{s}$, i.e., 8 times longer than the initial baseband pulse, or $\sim 19\,600$ periods of the rf wave. The rf wave has travelled more than 2 km in the 14-m^3 cavity, i.e., undergone ~ 6000 reflections.

Next, our goal is to time reverse the received radio signal $s(t)$. To that end, the baseband I and Q signals m'_I and m'_Q are digitized by the oscilloscope at a 40-MHz sampling rate, sent to a computer, and time reversed. The wave carrier has to be conjugated, too. The following step consists in reanalogizing the time-reversed I and Q signals and encoding them on the phase-conjugated wave carrier: the resulting rf signal writes $m'_I(-t)\cos(2\pi\nu_0 t) - m'_Q(-t)\sin(2\pi\nu_0 t) = s(-t)$. It is then transmitted back by antenna B. After propagation, the rf signal received on antenna A is down-converted to baseband. As can be seen in Fig. 3(a), the received signal on channel I is compressed in time and recovers its initial duration. It should be noticed that the acquisition window has been arbitrarily chosen in order to center the focused pulse within the figure.

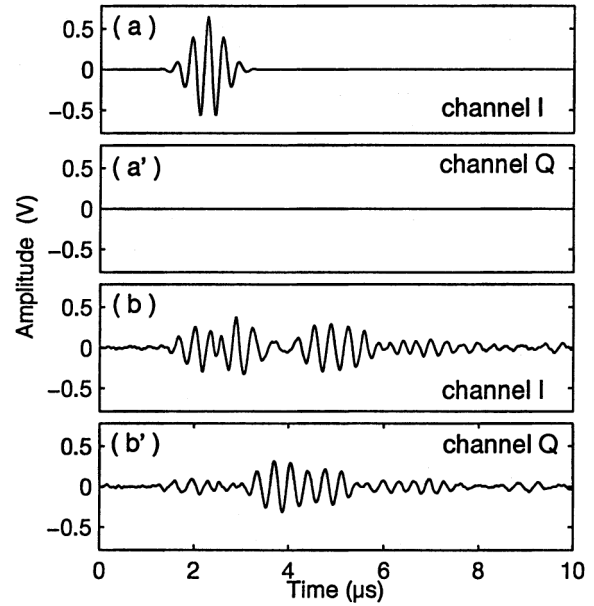


FIG. 2. (a),(a') Baseband representation [$m_I(t)$ and $m_Q(t)$] of the signal transmitted by antenna A. (b),(b') Baseband representation [i.e., $m'_I(t)$ and $m'_Q(t)$] of the signal reverberated inside the cavity and received by antenna B.

Actually, since the reverberated wave field has been captured by a single antenna, the time-reversal operation is not perfect. The waveform that is recreated is not the exact replica of the initial pulse: there are sidelobes around the peak on channel I , and a signal is measured on channel Q [Fig. 3(a')] even though nothing was sent on that channel. Similar effects have been observed for time

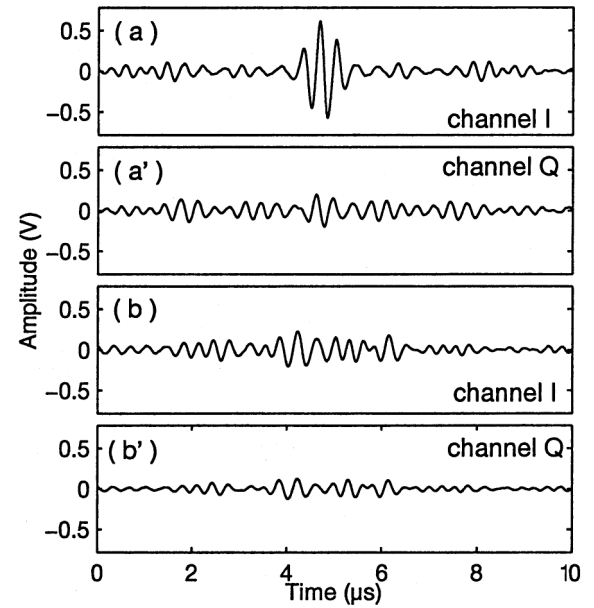


FIG. 3. (a),(a') Baseband representation of the signal received by antenna A after time reversal. (b),(b') Baseband representation of the signal received several wavelengths away from antenna A after time reversal.

reversal of ultrasonic waves: it can be shown that the peak-to-noise ratio in a one-channel time-reversal experiment varies as $\sqrt{\Delta\nu/\delta\nu}$, where $\Delta\nu$ is the available bandwidth and $\delta\nu$ defines the correlation frequency of the reverberated field [2]. $\delta\nu$ is the characteristic width of the field-field correlation function $\int \langle \psi(\nu') \psi^*(\nu' + \nu) \rangle d\nu'$, with ψ the scattered electromagnetic field. Therefore, one could expect an even stronger pulse compression if the bandwidth was larger, or the correlation frequency smaller. Given the dimensions of the cavity, the Heisenberg time (i.e., the inverse of the mean distance between eigenmodes) is $t_H \sim 80 \mu\text{s}$. But the characteristic absorption time is $t_a = 3.6 \mu\text{s}$ because of the attenuation due to the skin effect on the walls; therefore, the modes are not resolved and the correlation frequency $\delta\nu$ is determined by t_a rather than t_H . Taking $\Delta\nu = 2 \text{ MHz}$ and $\delta\nu = 1/t_a \approx 280 \text{ kHz}$ leads to a predicted peak-to-noise ratio roughly equal to 3, comparable to our experimental results.

The experiment shows that time reversal is able to compensate for multiple reverberation and recreate a short electromagnetic pulse at the source. But there is more to it: we have also verified that the amplitude of the recreated signal is stronger at antenna *A* than anywhere else in the cavity [Figs. 3(b) and 3(b')]; i.e., the time-reversed wave is spatially focused. This is consistent with past experiments using ultrasound in reverberant or strongly scattering media that proved that even with a one-channel time-reversal device, the pulse is sharply focused at the source and only at the source, the noise level surrounding the source being, once again, controlled by $\sqrt{\Delta\nu/\delta\nu}$ [2]. Here, the role of reverberation as well as the large frequency band must be emphasized. Since we have only a one-channel time reversal, no focusing would occur in free space no matter how large the bandwidth; in a reverberating medium, no focusing would occur either if the bandwidth was too narrow, as is the case in classical phase-conjugation techniques. Indeed, imagine a single time-reversal antenna trying to focus a pure monochromatic wave on some receiver; the phase-conjugated wave has no reason at all to be focused on this point since the antenna sends back only a sinusoidal spherical wave through the medium. But if the frequency bandwidth $\Delta\nu$ is much larger than the correlation frequency $\delta\nu$, the spectral components of the reverberated field ψ at two frequencies apart by more than $\delta\nu$ are decorrelated: there are roughly $\Delta\nu/\delta\nu$ decorrelated components in the spectrum of the reverberated signals. When we time reverse (i.e., phase conjugate coherently all along the bandwidth, and not just at one frequency) all these components, they add up in phase at $t = 0$ at the receiver position, because all the phases have been set back to zero all along the bandwidth. Thus, the amplitude at this position and at this time increases as $\Delta\nu/\delta\nu$, whereas outside the receiver position (and outside $t = 0$) the vari-

ous frequency components add up incoherently and their sum rises as $\sqrt{\Delta\nu/\delta\nu}$. On the whole, the peak-to-noise ratio increases as $\sqrt{\Delta\nu/\delta\nu}$ as the bandwidth is enlarged. It explains why a time-reversal experiment is possible even with one single time-reversal channel [2,7,9], as long as the frequency bandwidth is sufficiently larger than the correlation frequency of the propagation medium.

We have presented the first time-reversal experiment for electromagnetic waves in the GHz domain. The experiments were carried out in a reverberating cavity. To avoid digitizing the radio signals at GHz frequencies, we have time reversed the baseband signals and phase conjugated the wave carrier. Thanks to reverberation, the resulting signal at the source is compressed in time and in space with a signal-to-noise ratio depending on the ratio of the bandwidth to the frequency correlation of the medium. In the future, a larger bandwidth has to be used to improve both spatial and temporal focusing. This seems to be possible with the emergence of ultrawideband electromagnetics components. Thus time-reversal focusing could have promising applications in the field of wideband wireless communications in complex reverberant environments.

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