Time Reversal of Wideband Microwaves

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ABSTRACT:
In this paper, time reversal is applied to wideband electromagnetic waves in a reverberant room. To that end a multi-antenna time-reversal mirror (TRM) has been built. A 150-MHz bandwidth pulse at a central frequency of 2.45 GHz is radiated by a monopolar antenna, spread in time due to reverberation, recorded at the TRM, time-reversed and retransmitted. The time-reversed wave converges back to its source and focus in both time and space. The time compression is studied versus the number of antennas in the TRM and its bandwidth. The focal spot is also measured thanks to a 8-channel receiving array.

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Time reversal (TR) has been studied for quite a long time as a method to focus an ultrasonic wave in both time and space [1]. Basically, the field radiated by an acoustic source is initially recorded at a transducer array. Then it is time-reversed and retransmitted through the medium by the same array acting as a Time Reversal Mirror (TRM). The resulting wave travels back and refocuses at the initial source position (spatial focusing). Even when the medium is highly dispersive due to reverberation or scattering, the time-reversed signals are compressed into a a pulse as short as the transmitted one (time compression). Spatial focusing and time compression have been deeply studied both theoretically [2] and experimentally [3] in the past.

The main difficulty to transpose the concept to high-frequency electromagnetic waves lies in the much higher sampling frequencies that are needed to digitize them compared to the ultrasonic case. Nevertheless in a recent paper [4] it has been shown that it is possible to time-reverse microwaves without the need to fully digitize them as it is classically done with ultrasound. In fact the interesting part of a radio frequency modulated signal is its complex envelop. Thus time reverse such a modulated wave consists in digitizing and time reversing the modulation and phase conjugating the carrier. This principle allowed us to study TR for high-frequency electromagnetic waves using nowadays electronic components. Especially when the medium is highly reverberating we showed that the wave could be focused very precisely in space even with a TRM limited to a single antenna. However this basic experiment was carried out with a narrow bandwidth (2 MHz)and thus it was not far from a phase conjugation technique. Concurrently other authors also showed [5] that phase conjugation arrays in a cluttered environment could achieve much better spatial resolution than in free space. This can be explained by the fact that multipathing is taken advantage of in such techniques. Parallel to these experimental studies, a lot of theoretical works has been done [6, 7, 8], especially on time reversal applied to electromagnetic communications and medical imaging [9].

We present here a setup with a much higher bandwidth (150 MHz at -6 dB) that we have developed to study systematically the temporal and spatial focusing property of TRMs in highly reverberant media. Experimentally a one-channel time reversal experiment consists in recording an impulse response from a source antenna to a receiving one, time reversing it, and sending it back. As we decided to use a 2.45-GHz carrier frequency and a bandwidth of 150 MHz, a solution would have consisted in using an arbitrary waveform generator (AWG) with a 3 GHz bandwidth to create the initial radio pulse and a scope with the same bandwidth to record it. This is unfeasible with nowadays AWGs which are limited to a 2-GHz bandwidth. Thus the technique we introduced in [4] has been adapted to the current setup using a 2-channel 300-MHz bandwidth AWG (Tektronix AWG520). The setup is summarized in figure 1.The 2-channel generator feeds a wideband IQ modulator (RFMD2480 - 250 MHz bandwidth) to produce the 2.45 GHz RF signal. As to the receive side, a very high bandwidth scope (Tektronix TDS6604 - 20 GS/s) has been used to record directly the RF signal which is then numerically demodulated. In addition to this setup which stands for a single-channel TRM, a pair of 8-channel switches is used; one to emulate a 8-channel TRM, the other one to emulate a 8-channel receiver. Finally we used two kinds of antennas: commercial half-wavelength antennas are used on the TRM side whereas on the receiving one the field is scanned with a homemade antenna array. This latter consists of 8 quarter-wavelength thin wires on a ground plane which avoids parasitic radiations from cables. The spacing between antenna is 1.56cm, i.e., $\lambda/8$ with λ the

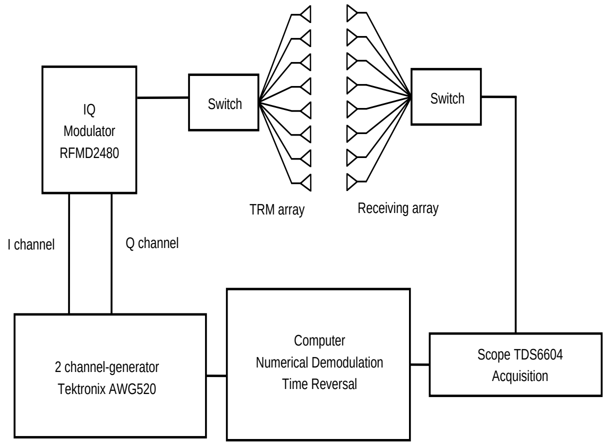

Figure 1: Experimental Setup.

dominant wavelength . Using such an "ideal" array allows to measure the spatial focusing with a satisfying precision. In order to maximize the time spread of the signals and consequently to fully take advantage of TR, all the experiments have been conducted in a reverberant chamber consisting of a $1m^3$-aluminum-walled cavity.

To record the impulse response between the "target" antenna where one intends to refocus and the time-reversal mirror, we use the following procedure. Usually, the "target antenna" emits a short pulse, and the impulse responses are recorded at each antenna of the TRM. Here on the contrary each antenna of the TRM emits successively a $10ns$-long pulse and the corresponding impulse responses are recorded at the "target " antenna and digitized by the scope. Due to reciprocity of the medium, these two sets of impulse responses are actually strictly identical. Fig.2-a shows a typical impulse response between two antennas within the cavity.

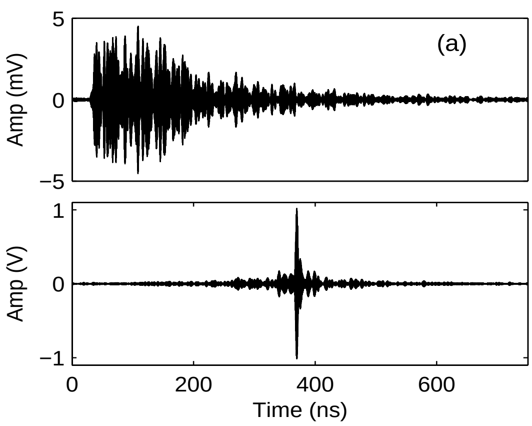

Figure 2: Up: a typical impulse response in the cavity. Down: the TR compression obtained with a 8-channel TRM.

We see here that the reverberation time of the cavity is about a few hundreds ns which means a huge time spread. The time spread actually depends on the chosen antenna pair. Thus we estimate the reverberation time as the rms-delay spread averaged over the set of 64 possible responses recorded between the 8 elements of the emitting array (TRM), and the 8 elements of the receiving one. We finally found a reverberation time of $\tau_R = 160ns$ which is much larger than both the mean period and the pulse length. Therefore the typical impulse response in Fig.2-a shows a coda-like waveform similar to those observed with ultrasound [3].

The 8 responses are then time-reversed, normalized by their maximum amplitude and successively transmitted by each TRM antenna. In Fig.2-b is plotted the resulting time compression obtained in summing the contributions produced by each antenna of the TRM. A pulse of $10ns$ is recovered which is the time-reversed replica of the initial 10ns-long pulse. Note that its amplitude is about 200 times higher than the maximum amplitude of the impulse response itself. This is due to the fact that the time-reversed signals are normalized before reemission. Thus as shown by [3], the amplitude increases not only as the number of antennas (i.e. 8) but also as the ratio "reverberation time over pulse length". This principle is of great interest for example in ultrasound medical therapy where one intends to create high amplitudes at a given location to burn tissues or destroy kidney stones.

The refocused pulse is surrounded by sidelobes because TR is not perfect here. Indeed as explained in [1], one must have a medium without absorption and an infinite number of antenna in order to perform a perfect TR experiment without sidelobes. The squared amplitude of the TR peak over the variance of the sidelobes is thus an estimate of the quality of TR focusing. In the following it is referred to as the Signal-to-Noise Ratio (SNR). We have experimentally studied the SNR as a function of the bandwidth. As suggested in previous papers [3, 4] the shape of the time-reversed signal recorded at the source can be explained in the following way: at the focusing time and at the target antenna all the frequency components of the time reversed signals add up coherently, whereas they add up incoherently at other times or other places. As a consequence, the SNR is expected to vary as the number of independent frequencies within the bandwidth. This is also given by the ratio reverberation time over pulse length which is confirmed in figure 3. Experimentally, the slope of the curve is 190ns which is consistent with the reverberation time of the cavity.

Note that the theoretical modal density of the cavity which is given by $n(f) = 8\pi V f^2/c^3$ equals 5.6μs. Hence the modes are not resolved since this value is much larger than the experimental reverberation time due to dissipation. If they were resolved the SNR would asymptotically reach the modal density times the bandwidth[10, 11].

We have also studied the SNR versus the number of antennas and the spacing between them. Fig.4 shows 3 different curves of the SNR versus the number of antennas

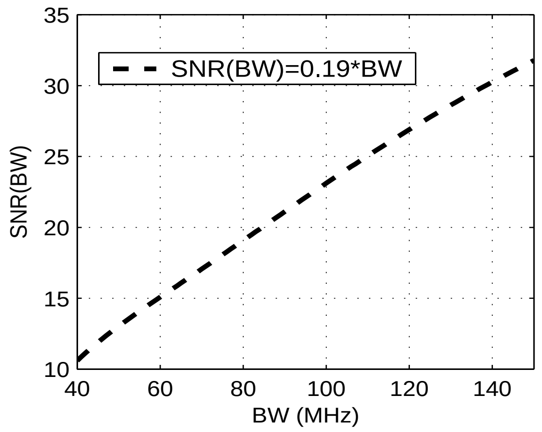

Figure 3: Squared amplitude of the TR peak over the variance of the sidelobes with respect to the bandwidth of the initial pulse.

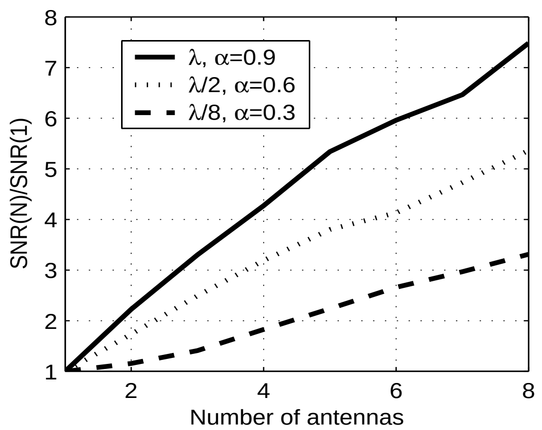

Figure 4: Signal to Noise Ratio as a function of the number of antenna in the TRM for different antenna spacing.

with a spacing of respectively λ, $\lambda/2$ and $\lambda/8$. We can see that the slopes (here noted α) of the curves are decreasing with the antenna spacing. This is related to the increase in spatial correlations of the measured impulse responses when the receiving antenna are brought closer. We now come to the study of spatial focusing. Spatial focusing of TR in disordered media has been studied both experimentally and theoretically with ultrasound in [3, 10, 11], theoretically for random TR electromagnetic fields in [6] and applied in the communication context [5, 7]. However no TR focal spot measurements have been reported for wideband electromagnetic waves. To measure the focal spot, we have built an antenna array instead of using a single receiver that would be moved in the focal plane. Indeed since a radiator is also a scatterer, it modifies the electromagnetic field it measures. Our array consists of thin wire monopoles on a ground plane. This latter eliminates the parasitic radiations that possibly come from the cables. The spacing between antennas on the array is $\lambda/8$. In fig.5 is plotted the maximum of the absolute value of the TR amplitude with respect to the distance from the "target " antenna. As already shown in scattering media or cavities for scalar waves, the focal spot gives a statistical estimator of the spatial field correlation function [3].

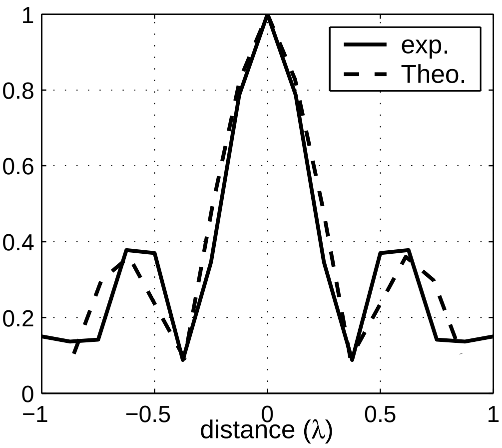

Figure 5: Focal spot created by TR.

Our antennas being vertically polarized, we are sensitive to the z component of the electric field. The direction of scanning is perpendicular to z. The focal spot is thus related to $\langle\, E_z(x=0)E_z(x=d)\rangle$ with E_z the z component of the electric field in the cavity. This quantity has been calculated analytically in [12] and writes:

$$\frac{\langle E_z(0)E_z(d)\rangle}{\langle\, E_z^2\rangle} = \frac{3}{2}\frac{sin(kd)}{kd}\left(1-\frac{1}{(kd)^2}\right)+\frac{3}{2}\frac{cos(kd)}{(kd)^2}$$

It must be pointed out that we actually do not directly record E_z but the current that this field induces in the measuring antenna. Hence the TR focal spot is an estimation of the correlation function of the currents circulating in the receiving antennas. This current correlation function is obviously related to the E_z correlation function written above but its measurement also depends on the mutual coupling between measuring antennas. To take this into account, we built a model which will be presented elsewhere since its full development is out of the scope of this paper. We see in fig.5 that the experimental focal spot obtained with the 8-channel TRM is in good agreement with the solution calculated from this model.

We have performed TR experiments for wideband microwaves. Especially, we have shown that TR focusing provides a gain in amplitude proportional to the reverberation time of cavity. We have also underlined that the SNR of the TR focused pulse grows as both the bandwidth and the number of antennas. Finally we have demonstrated that the focal spot actually fits the theoretical prediction based on the study of the field correlation function in the cavity and which takes into account the mutual coupling between measuring antennas. The different aspects studied in this letter are of great interest for issues in medical imaging and therapy, UWB (Ultra Wide Band) and MIMO communications and security of transmission.

[1] M. Fink. Time reversed acoustics. *Physics Today*, 50:34, 1997.

[2] P. Blomgren, G. Papanicolaou, and H. Zhao. Super-resolution in time-reversal acoustics. *J. Acoust. Soc. Am.*, 11:203–248, 2002.

[3] A. Derode, A. Tourin, and M. Fink. Random multiple scattering of ultrasound ii. is time reversal a self-averaging process? *Phys. Rev. E.*, 64:036606–1,036606–13, 2001.

[4] G. Lerosey, J. de Rosny, A. Tourin, A. Derode, G. Montaldo, and M. Fink. Time reversal of electromagnetic waves. *Phys. Rev. Lett.*, 92-19:193904, 2004.

[5] B.E. Henty and D.D. Stancil. Multipath-enabled super-resolution for rf and microwave communication using phase-conjugate arrays. *Phys. Rev. Lett.*, 93:243904–1,243904–4, 2004.

[6] C. Oestges, A.D. Kim, G. Papanicolaou, and A.J. Paulraj. Characterization of space-time focusing in time reversed random fields. *IEEE Trans. Ant. and Prop.*, 53:283–293, 2005.

[7] G. Lerosey, J. de Rosny, G. Montaldo, A. Tourin, A. Derode, and M. Fink. Time reversal of electromagnetic waves and telecommunication. *Radio Science*, 40-5:29–39, 2005.

[8] T. Strohmer, M. Emami, J. Hansen, G. Papanicolaou, and A. Paulraj. Application of time-reversal with mmse equalizer to uwb communications. *in Proc. IEEE Global Telecommunications Conference*, 5:3123–3127, 2004.

[9] P. Kosmas and C.M. Rappaport. Time reversal with the fdtd method for microwave breast cancer detection. *IEEE trans. micro. theory and techniques*, 53-7:2317–2323, 2005.

[10] C. Draeger and M. Fink. One-channel time reversal of elastic waves in a chaotic 2d-silicon cavity. *Phys. Rev. Lett.*, 79:407, 1997.

[11] N. Quieffin, S. Catheline, R.K. Ing, and M. Fink. Real-time focusing using an ultrasonic one channel time-reversal mirror coupled to a solid cavity. *J. acoust. soc. am.*, 115-5:1955, 2004.

[12] Ph. de Doncker. Spatial correlation functions for fields in three-dimensionnl rayleigh channels. *PIER*, 40:55–69, 2003.