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Focusing and amplification of electromagnetic waves by time reversal in an leaky reverberation chamber

Focalisation et amplification d'ondes électromagnétiques par retournement temporel dans une chambre semi-réverbérante

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ABSTRACT

In this article, time reversal is used to generate high power microwave pulses from a low power arbitrary wave generator. We use a reverberation chamber with an aperture on the front face and we take advantage of the pulse compression property of time reversal. High amplitude peaks are generated outside the chamber thanks to the long spreading time of the signals inside. We study the amplitude of this peak and the width of the focal spot with respect to the different experimental parameters. A gain of 18 dB compared to a directive antenna of the same aperture is obtained.

RÉSUMÉ

Dans cet article, le renversement du temps est utilisé pour engendrer des impulsions micro-ondes de forte amplitude à partir d'un générateur d'ondes arbitraires. Nous utilisons une cavité réverbérante ouverte sur sa face avant et profitons des propriétés de compression d'impulsion du renversement temporel. Des impulsions de fortes amplitudes sont générées à l'extérieur de la cavité grâce à l'étalement temporel des signaux à l'intérieur. L'amplitude ainsi que la largeur de la tache focale des impulsions sont étudiées en fonction des différents paramètres expérimentaux. Un gain de 18 dB par rapport à une antenne directive de même ouverture est obtenu.

1. Introduction

Since 1990, Time Reversal (TR) has been used to focus acoustic waves in space and time [1]. Basically, a TR experiment is divided in two steps. In the first step, a source emits a short pulse. After propagation, the time dependence of the wave field is recorded by an array of transducers, the so-called Time Reversal Mirror (TRM). In the second step, these signals are flipped in time and re-emitted by the TRM. Due to the reversibility of the wave in the propagation medium, the time reversed field naturally back-propagates toward the initial source position. Finally, a pulse as short as the initial emitted

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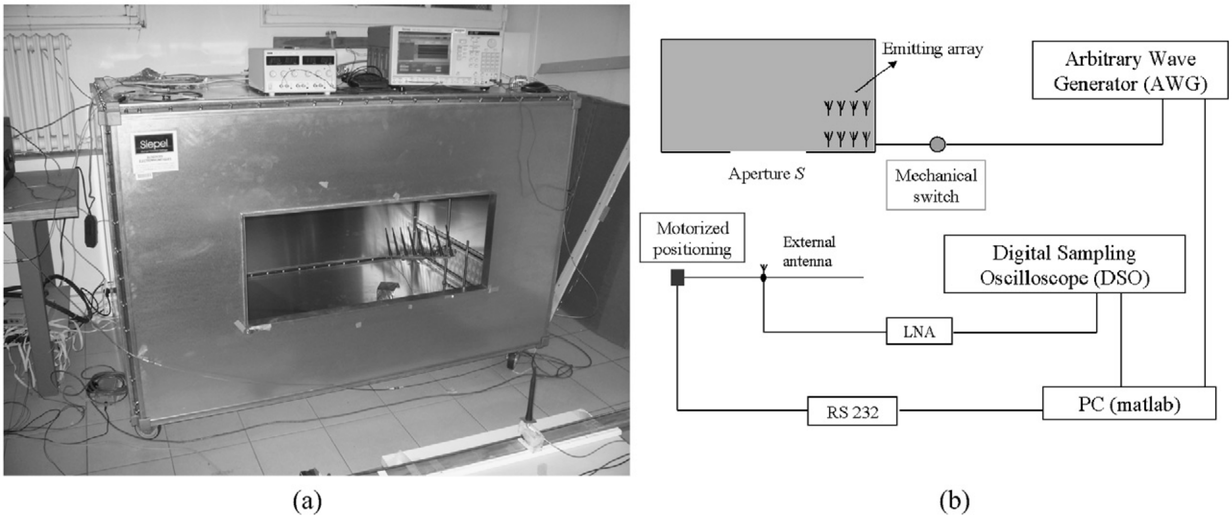

Fig. 1. (a) Picture of the reverberation cavity; (b) Schematic view of the experimental setup.

one is obtained at the focus. It has been shown that TR still works in a heterogeneous medium. The more the medium is complex, the more the TR is efficient. In a complex medium, the size of the focal spot is no more governed by the aperture of the TRM, but by the size of the complex medium. Indeed, time reversal takes advantage of the multiple scatterings in the medium. During the second step of TR, all the wave contributions back-propagate along the multiple paths and finally constructively interfere at the focus to give rise to a high amplitude pulse.

The first TR experiment in high-Q cavity was performed with a silicon wafer plate. A very good time and spatial focusing of elastic waves have been observed even if the TRM was composed of a single channel [2]. In 2004, Lerosey et al. performed the first TR experiment with microwaves in a reverberation chamber covered with aluminium [3]. In electromagnetism, reverberation chambers are commonly used for immunity tests or power radiation estimation [4]. As in acoustics, their principle asset lies in the presence of a diffuse field in the chamber. This diffuse field is obtained thanks to the multiple reflections on the chamber boundaries.

The first application of microwave time reversal concerns digital wireless communications [5,6]. Here, our goal is different; it consists of taking advantage of the reverberated field to generate high amplitude microwave pulses outside the chamber. Indeed, we will see that the time compression property of TR leads to generate high amplitude pulses. In acoustics, Montaldo et al. studied experimentally this effect [7]. They succeeded in generating shock waves in front of a waveguide made of aluminium. A pulse was emitted outside the waveguide and the time dependence of the field was recorded on an array of transducers glued at the end of the waveguide. After TR, a high amplitude acoustic pulse was recorded at the initial emission position. The trick to obtain a high amplitude pulse is to normalize the signals flipped in time before re-emission.

Similarly, in the present work, the electromagnetic waves are focused outside the reverberation chamber through a small aperture. We study the dependence of the amplitude and the width of the focal spot with respect to several configurations.

2. Experiments

The experimental setup is shown in Fig. 1. The reverberation chamber is a 1.8 m $\times$ 1.2 m $\times$ 1.1 m parallelepiped covered with aluminium (Fig. 1(a)). We consider that this chamber has reverberating properties from 700 MHz. Inside the chamber, the TR mirror consists of 8 half-wavelength omni-directional antennas. The inter-antenna distance is 10 cm. The antennas bandwidth lies between 2.2 GHz and 3.2 GHz. They are linked to an Arbitrary Wave Generator (AWG) by the way of an 8 channels electro-mechanical switch (Fig. 1(b)). The sampling rate of the AWG is 10 GS/s. Outside the chamber, a motorized positioning antenna is located at 90 cm in front of the chamber aperture. A Digital Sampling Oscilloscope (DSO), with a sampling rate of 20 GS/s, records the amplified signal of the antenna.

In the first step of the TR process, the initial short pulse would be generated at the external antenna and the field recorded at the TRM. However, due to the reciprocity theorem, the same signal is exactly obtained by emitting the short pulse at the TRM and recording the field at the external antenna. By this way, the AWG is always connected to the TRM and the DSO to the external antenna.

In Fig. 2(a) is plotted the transient response recorded at the external antenna for an aperture of 0.4 m^2 when 1 of the 8 antennas of the TRM emits a signal of carrier frequency of 2.7 GHz modulated by a 1 ns Gaussian envelope. The reflections give rise to a time spreading of 400 ns, which corresponds to a wave path of more than 100 m before the wave extinction. The field decay is exponential. The decay rate is well predicted by a diffuse field model. In such a model, the signal envelope $s(t)$ is expressed as $s(t) = \frac{AS}{\lambda D}\exp(-\alpha t)$. The coefficient α is the inverse of the Sabine's time (well known in cavity acoustics). For an aperture of size S in a cavity of volume V, $\alpha = cS/V$, where c is the speed of light. As for the

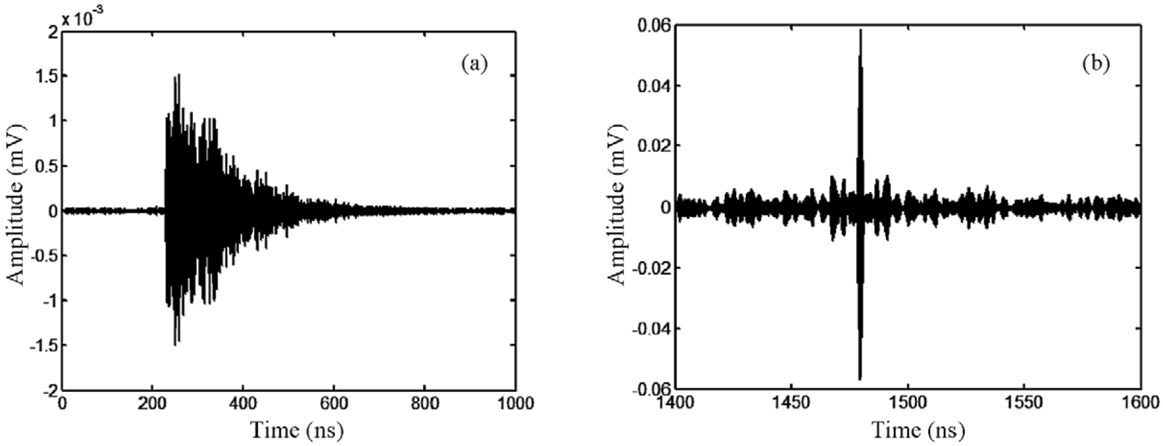

Fig. 2. (a) Transient response of the reverberation chamber for a 1 ns pulse @ 2.7 GHz; (b) TR pulse compression.

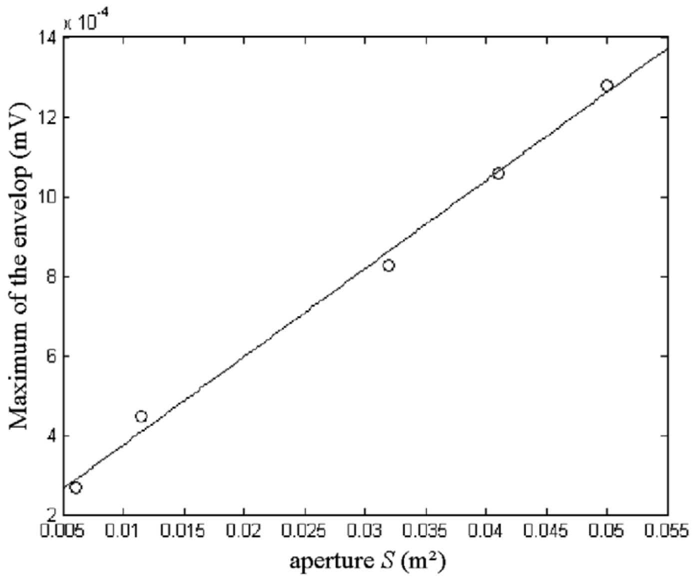

Fig. 3. Maximum of the envelope of the transient signal with respect to the aperture area. The wavelength λ equals 11 cm at 2.7 GHz and D equals 90 cm.

amplitude factor in front of $\exp(-\alpha t)$, A is the maximum of the diffuse field inside the cavity, λ stands for the wavelength and D is the distance between the external antenna and the aperture. This factor takes into account the diffraction by the aperture. The linearity of the maximum of the envelope with respect to S is displayed in Fig. 3.

The transient signal is then flipped in time, normalized, and then re-emitted. Due to the AWG characteristics, the normalized maximum peak-to-peak output voltage is 1 V. The TR field recorded at the external antenna, when only one element of the TRM is emitting, is plotted in Fig. 2(b). We observe a gain of 32 dB between the amplitude of the TR peak and the maximum of the transient response, for an aperture of $S \sim \lambda^2$.

3. Time reversal properties

First, we studied the dependence of the TR peak with respect to the number of antennas composing the TR mirror. Due to the linearity of the TR process, we find that the pulse amplitude increases linearly with the number of antennas (Fig. 4(a)).

We have also studied the TR peak amplitude according to the duration of the initial pulse or in other words with respect to the bandwidth. In a TR experiment, all the frequencies within the bandwidth are added in phase at the time where the waves focus. Consequently, the larger the bandwidth is, the higher the pulse becomes. A TR mirror is a generalization of the concept of phase conjugation mirror which does not only work at one frequency but on an overall bandwidth.

In Fig. 4(b), TR received signals are displayed for different initial length of the pulses. As expected, we observe that higher amplitudes are obtained for the shorter initial pulses. However, due to the finite bandwidth of the antennas, the TR

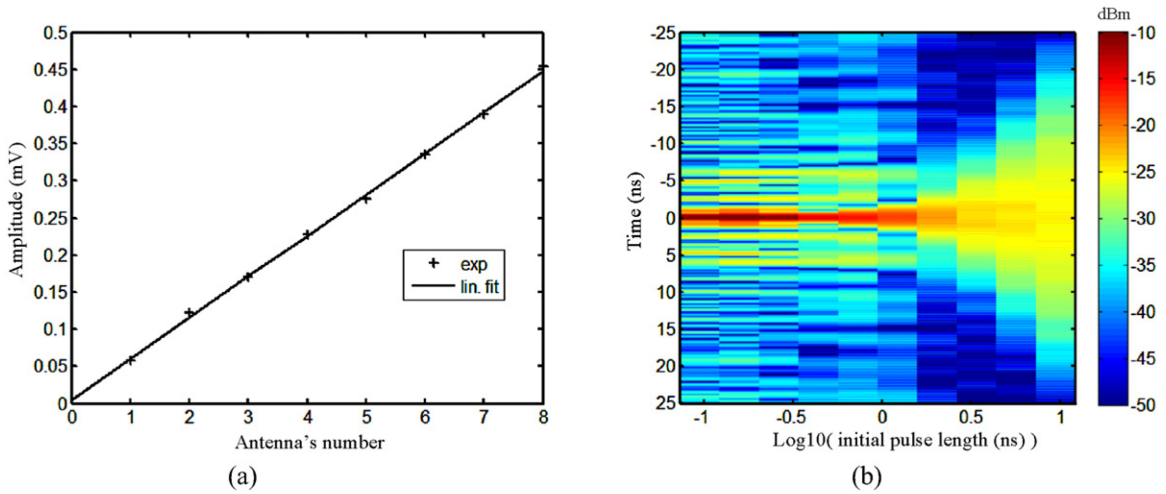

Fig. 4. (a) Amplitude of the TR peak with respect to the number of antennas composing the TR mirror; (b) Signals after TR for different initial pulses length.

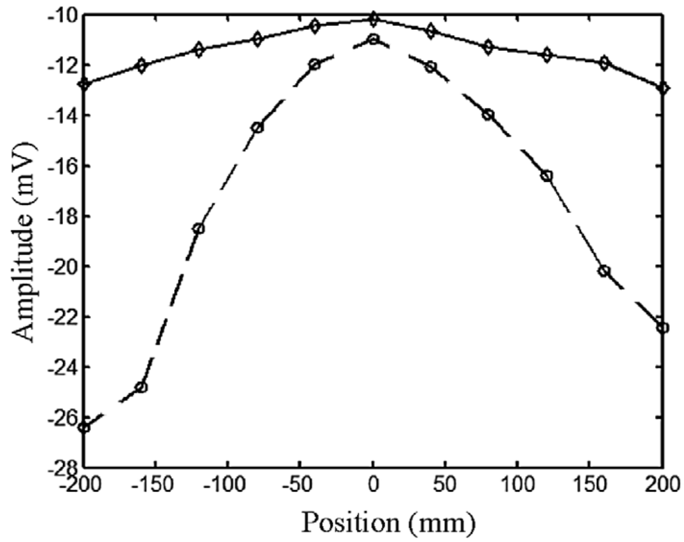

Fig. 5. Focal spot for horizontal apertures of 52 cm (dashed line) and 16 cm (bold line).

pulse duration is limited to 1 ns. Consequently, the amplitude of the TR peak reaches a plateau (at −10 dBm) for short initial pulses.

4. Size of the focal spot

The focal spot is measured thanks to the motor positioning system linked to the external antenna. In Fig. 5, the size of the lateral focal spot is plotted for two different sizes of the chamber apertures. The −3 dB focal spot width is 150 mm (respect. 400 mm) for an aperture with a horizontal dimension of 52 cm (respect. 16 cm). The vertical aperture is equal to 40 cm.

These results are in agreement with the diffraction theory, which predicts that the focal spot size is roughly equal to $\lambda D/L$, where L is the lateral size of the aperture. The wavelength λ is very close to the wavelength corresponding to the central frequency of the initial pulse.

We have studied the effect of the aperture size on the amplitude of the TR peak (see Fig. 6). The aperture area varies between 0.01 m^2 and 0.4 m^2. We observe an optimal aperture area, roughly equal to λ^2. Indeed, more the reverberation time of the room is large, more is the TR peak.

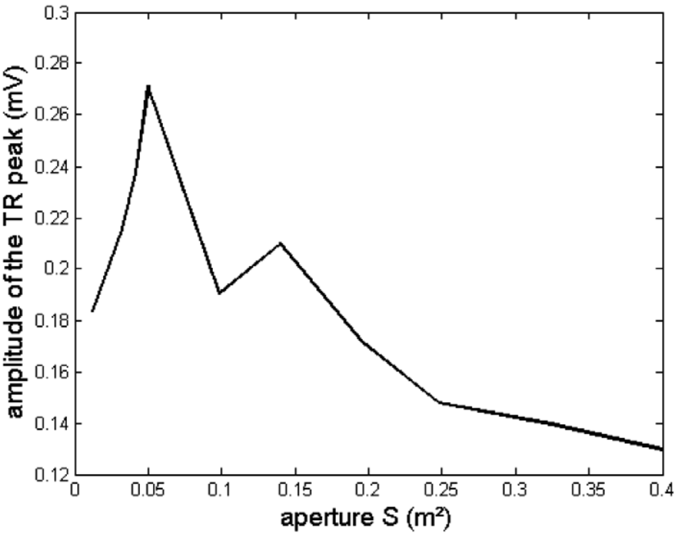

Fig. 6. Amplitude of the TR focusing peak with respect to the aperture size.

This point can be explained by considering that the transient signal can be predicted from a transient diffuse field model. In such a case, the transient signal can be considered as the superposition of pulses of length τ, which is the duration of the initial pulse:

$$s(t) = \frac{AS}{\lambda D} \operatorname{Re} \sum_{n=0}^{+\infty} \beta_n \exp(-\alpha \tau n) \delta(t - n\tau) \tag{1}$$

where β_n is random complex amplitude. Its mean value equals 0 and its variance 1.

Due to theory of linear systems, the TR signal is equal to $(s(t) \otimes s(-t))/s(t=0)$ where $\otimes$ represents the convolution operator. The coefficient $1/s(t=0)$ corresponds to the normalization of the flipped signal before the emission by the AWG. Because the length τ is very small compared to Sabine's time of the chamber $(1/\alpha)$, using Eq. (1), the TR peak is given by:

$$S_{\mathrm{TR}} = \left(\frac{A}{\lambda D}\right) \cdot \left(\frac{V}{c\tau}\right) \tag{2}$$

Eq. (2) is the product of two terms. The first one is linked to the diffraction by the aperture, whereas the second one is linked to the time compression effect of the time reversal. We observe that the TR peak S_{TR} does not depend on S. Hence, with this theoretical approach, the TR pulse does not depend on the aperture area. The mismatch between the theory and the experimental results comes from the diffuse field hypothesis. The diffuse field model is only valid from a certain mixing time. Before this time, the echoes from the boundaries arrive at distinct times. The overlapping of the echoes is a condition in order to approximate the wave field with Eq. (1). In such a case, the time compression is less efficient. This phenomenon is all the more important that the aperture is large. This effect is all the more predominant that the energy of the diffuse part of the field is weak compared to the energy of the signal before the mixing time. As a consequence, the smaller apertures give rise to the higher TR peaks.

As the transmission through a sub-wavelength aperture decreases exponentially, the optimum aperture size is given by $S \sim \lambda^2$, as shown experimentally. Fig. 6 confirms this approach. The envelope of the transient response decreases rapidly as soon as $S < \lambda^2$.

5. One-bit time reversal

One way to increase the amplitude of the TR pulse is to apply the one-bit time reversal method. Derode et al. were the firsts to investigate this method [8]. It consists, before the emission of the flipped transient response, in setting the amplitude of the re-emitted signal to ± 1, depending on the sign of the signal. Actually, the re-emitted signal $b(t)$ is defined as following:

$$b(t) = \begin{cases} +1 & \text{if } s(t) \geqslant 0 \\ -1 & \text{if } s(t) < 0 \end{cases} \tag{3}$$

Derode et al. showed that the spatial and temporal compression aspects keep almost the same whereas the amplitude of the pulse is larger for one-bit TR than for classic TR. Indeed, as we compensate the exponential decrease of the transient

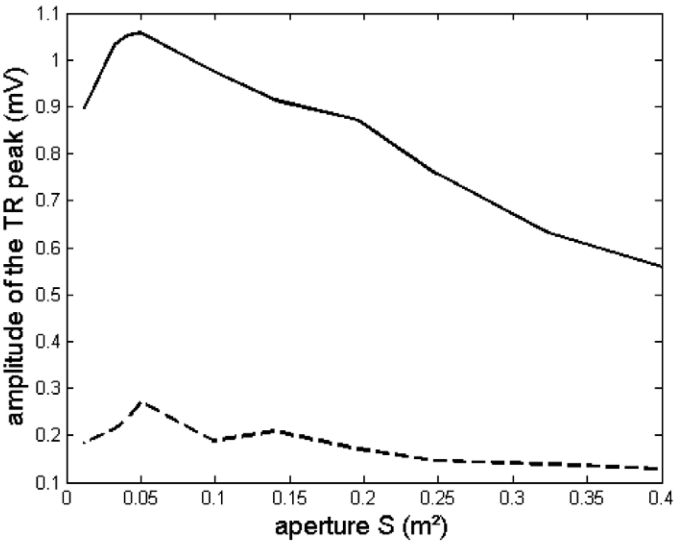

Fig. 7. Amplitude of the one-bit (bold line) and "classical" (dash line) TR focusing peak with respect to the aperture.

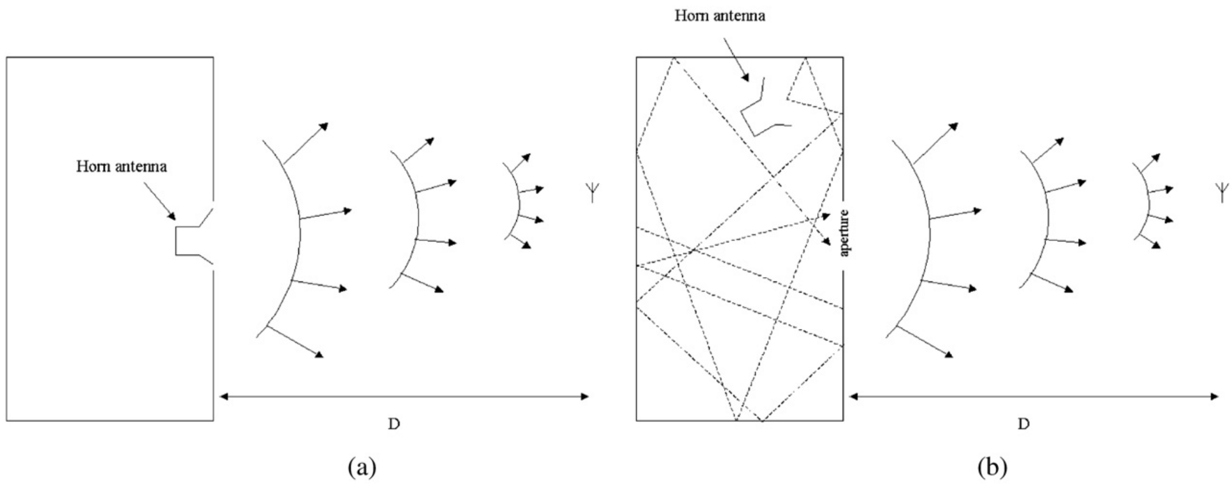

Fig. 8. Picture of the experimental setup with the horn antenna settled (a) outside the chamber and (b) inside the chamber.

signal with the one-bit TR, more energy is transmitted to the chamber. In Fig. 7 we observe that the one-bit TR is about 4 times higher than for classical TR whatever the chamber aperture size is. We retrieve the same profile and the optimized aperture remains still $S \sim \lambda^2$.

Hence, the optimal gain between the TR peak and the maximum transient signal reaches 46 dB with one-bit time reversal.

6. Comparison with an antenna of the same aperture

To compare our system with a directive antenna, we replace our time reversal mirror made of dipoles by a single horn antenna of aperture 0.4 m^2, working between 1 and 18 GHz and with a beamwidth of 35.94 deg at 3 GHz. To only measure the gain of the reverberation chamber, two time reversal experiments are performed. The first one is done without the reverberation chamber. The horn antenna is placed at a distance D of the focus. For the second one, the horn antenna is settled inside the chamber. The chamber aperture is the same as the one of the horn in order to obtain the same spatial compression.

A gain of 18 dB on the amplitude of the TR peak at a distance of 2.50 m has been measured between the two configurations.

Another advantage of the TR in the reverberation chamber is the electronic steering of the focal spot. A directive antenna should indeed take aim to the focusing point, whereas our system focuses on the initial source position even if the position is off-centred. Obviously the gain between the two methods is all the more important than the source is off-centred. Another key point concerns the polarization. Due to the multiple reflections inside the chamber, the three polarizations are statistically equivalent inside the reverberation cavity. Hence, TR pulse with arbitrary polarization can be obtained independently of the polarization of the antenna inside the chamber.

7. Conclusion

The combination of TR technique and reverberation chamber leads to generate high amplitude pulses from a low power arbitrary waveform generator. The potential application of this work could be the development of an "electromagnetic bazooka", a non-nuclear electromagnetic pulse (NNEMP) weapon.

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