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Plasma generation using time reversal of microwaves

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ABSTRACT

We report the experimental demonstration of plasma generation by time-reversal focusing. After a learning phase, the amplified time reversed signal built at a central frequency of 2.45 GHz injected in a low loss metallic cavity allows us to ignite and maintain a localized centimeter-sized plasma in argon at 133 Pa. The plasma spatial position is totally controlled by the signal waveform.

Time reversal (TR) has been extensively studied as a method to focus acoustic[1] and electromagnetic[2] waves. In a TR experiment, a source first sends a short pulse that propagates through a complex medium, and the radiated field is recorded using an array of transducers located all around the source, the so-called time reversal mirror (TRM). The recorded waveforms are then time-reversed and re-emitted by the TRM such that the resulting wave converges back to its initial source. TRM has found a lot of applications in the fields of medicine,[3] communications,[4,5] and smart objects.[6] In a large reverberant or ergodic cavity, a simpler one-channel TR can be achieved using only one point source and one point receiver,[7] which leads to a low complex system when dealing for example with microwaves.[2] In this letter, we propose to use TR of microwaves inside a cavity to control in both space and time the generation of plasmas as illustrated in Fig. 1.

Plasmas excited by microwaves in reverberant cavities are commonly used for many industrial applications such as material surface processing in microelectronics[8] or diamond growth applications.[9] The use of microwave fields actually leads to electrodeless configurations preventing from plasma contamination while providing isotropic plasmas of rather high electron densities. Their generation generally requires an antenna located outside a pressure controlled chamber with metallic boundaries to prevent microwave radiation. The plasma can then be excited either in the whole chamber or in a spatially localized volume.[10] In the last case, the cavity is designed to excite a specific microwave mode for an accurate control of the position of the plasma discharge. In both cases, the final plasma location remains definitely imposed by the design of the whole system (source and cavity). TR can theoretically overcome this problem by allowing a dynamic and external control of the plasma location in a metallic cavity. This letter demonstrates that the microwave focusing and amplification[11] capabilities of TR make it a good candidate for developing an interesting kind of plasma source, allowing, in particular, the control of the plasma location in time and space inside a reverberant cavity. The basic concept of TR plasma ignition aims to focus electromagnetic waves on a short time scale and in a small space high enough to reach the plasma breakdown condition.

The experimental setups implemented during the two steps of the TR procedure are presented in Fig. 2. Our TR experiment takes place in a reverberant metallic cavity with dimensions of 0.6 m × 0.6 m × 0.3 m, that is to say, $5\lambda_0 \times 5\lambda_0 \times 2.5\lambda_0$ at the microwave carrier frequency of $f_0 = 2.45$ GHz. Four electrically small coaxial probes that act as monopoles are located inside the cavity. One is used as a source and the three others as receivers during the TR operation. The emitting monopole is located in an appendix of the cavity in which the initial air remains at atmospheric pressure to prevent gas breakdown in its vicinity during the high power re-emission of the time-reversed waveforms. This appendix is connected to the main cavity through a glass window. The three receivers are located in the main cavity in which the composition and the pressure of the gas can be controlled (here, the main cavity is pumped with a turbomolecular pump down to approximately 1.33 Pa and argon is subjected to a working pressure of 133 Pa). As shown in Figs. 2(a) and 2(b), these monopoles are separated by 6 cm which is supposed to be the spatial resolution of our TR experiment at 2.45 GHz.[5] In order to increase the ergodicity of the cavity, the geometrical effects due to the high symmetry of the parallelepiped cavity are reduced by using a metallic hemisphere on the

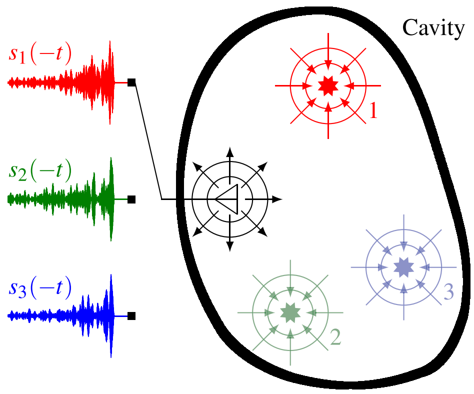

FIG. 1. Principle of plasma ignition by TR. The position of the plasma (denoted by a colored star) inside the cavity is controlled by the waveform of the signal transmitted to the cavity.

horizontal surface.[12] Finally, this vacuum chamber also includes a faradized window to observe inside the cavity as well as electrical feedthroughs for the transfer of the different signals to the monopoles.

The first step of our TR experiment consists in recording the pulse responses between one of the three monopoles (positions 1, 2, and 3) situated inside the cavity and the monopole located in the appendix of the cavity. Figure 2(a) shows the associated experimental setup that is based on those developed for TR of electromagnetic waves.[2] It deals with a waveform generator that delivers a short pulse to the in-phase (thereafter referred to I) analog input of an I/Q modulator, while the quadrature (thereafter referred to Q) analog input remains equal to 0. The bandwidth of the pulse signal is 250 MHz, that is to say, the maximum value for our waveform generator and I/Q modulator. The corresponding minimum duration for a generated pulse is 8 ns. This value is used in the whole study. These baseband signals are up-converted by the I/Q modulator to obtain a signal $e(t) = m_I(t)\cos(2\pi f_0 t)$, where $f_0 = 2.45$ GHz represents the microwave carrier frequency. Next, this waveform $e(t)$ feeds one of the three coaxial probes inside the main cavity, denoted as the j probe. The radiated waves are then reflected by the walls of the cavity, thus remaining inside for a much longer time than the duration of the initial pulse. Usually,[2] the absorption time t_a is used to characterize the time during which the energy is stored in the cavity. It is estimated experimentally at about $t_a = 100$ ns in our case. The signal $s_j(t)$ received by the monopole in the appendix of the cavity, which can be expressed as $s_j(t) = m'_{I_j}(t)\cos(2\pi f_0 t) + m'_{Q_j}(t)\sin(2\pi f_0 t)$, is recorded and down-converted using an I/Q demodulation. This operation is repeated for each of the three monopoles, and all the received baseband signals are recorded in the computer.

Once all the signals have been stored, the experimental setup shown in Fig. 2(b) is implemented to perform the second step of the TR operation. We first select the received monopole j. The associated baseband waveforms that have been recorded during the first step are then time-reversed on the computer and combined with the carrier frequency to obtain the time-reversed impulse response $s_j(-t) = m'_{I_j}(-t)\cos(2\pi f_0 t) - m'_{Q_j}(-t)\sin(2\pi f_0 t)$. Next, the resulting RF signal is amplified using a 2 kW traveling wave tube (TWT) pulsed power amplifier (TMD PTC7353). The pulse repetition period of the amplifier is set at $T_{ampli} = 166$ μs. The amplified signal is finally supplied to the source antenna and radiated inside the cavity. The result of the TR operation is evaluated by measuring the signals received on the three coaxial probes using an oscilloscope and by visually detecting the plasma discharges.

The measured results during our TR experiments are shown in Fig. 3. The experimental conditions (133 Pa in argon) have been chosen so as to minimize the breakdown threshold associated with our pulse width of 8 ns and operating frequency of $f_0 = 2.45$ GHz.[13] Figures 3(b)–3(d) show the results when sending $s_1(-t)$, $s_2(-t)$, or $s_3(-t)$, respectively. For each case, we present the signals measured on the three coaxial probes as well as a picture taken inside the cavity;

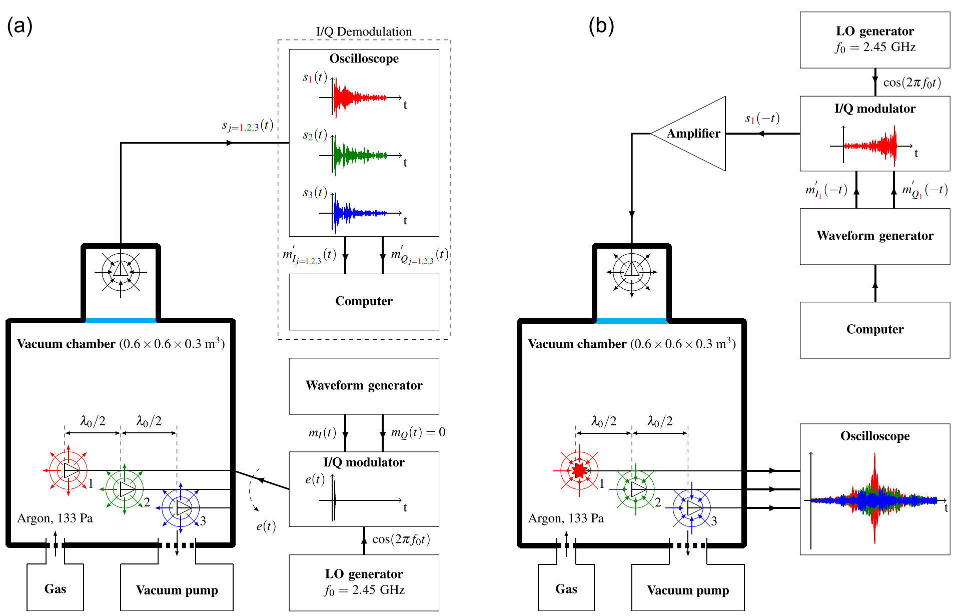

FIG. 2. (a) Sketch of a transmit experiment. A modulated pulse $e(t) = m_I(t)\cos(2\pi f_0 t)$ is transmitted to one of the monopoles 1, 2, or 3, which act here as transmitters. The pulse responses $s_j(t)$ between one of the monopoles 1, 2, and 3 and the monopole located in the appendix of the cavity, which acts here as a receiver, are demodulated, and the corresponding baseband signals $m'_{I_j}(t)$ and $m'_{Q_j}(t)$ are recorded. (b) Sketch of a receive experiment. The baseband signals recorded during the transmit experiment can then be time reversed and transmitted to the monopole in the appendix, which now acts as a transmitter. Depending on the signals transmitted $s_1(-t)$, $s_2(-t)$, or $s_3(-t)$, the focusing occurs on monopoles 1, 2, or 3 respectively, which now act as receivers. For example, $s_1(-t)$ allows us to obtain a plasma breakdown only near monopole 1 (denoted by the red star) and the other monopoles receive a lower microwave power.

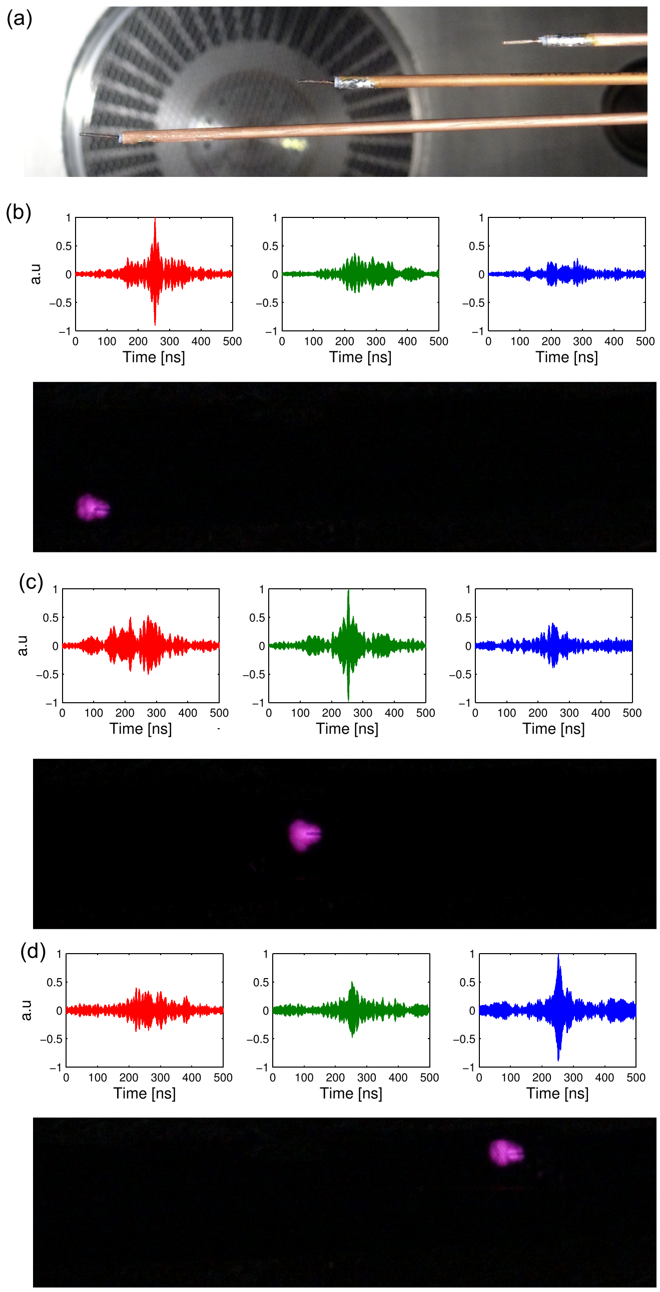

FIG. 3. (a) Pictures of the three receiving monopoles. (b)–(d) For each TR experiment (on receiver 1, 2, and 3 respectively): signals measured on the three receivers (in red, green, and blue for receivers 1, 2, and 3 respectively) with the picture of the corresponding ignited plasmas. For each TR experiment, the measured signals are normalized to the value of the corresponding refocused pulse.

these pictures have the same viewing angle as the picture of the three probes in Fig. 3(a). The exposure time of these pictures is 40 ms. We first notice that the TR operation allows us to generate localized plasma discharges (approximately 1 cm in diameter, with this dimension being related to the working pressure of 133 Pa, and the energy sent in the cavity) and that their position depends on the selected waveform as expected. More precisely, for a given signal $s_j(-t)$ applied to the emitting monopole, the reconstructed pulse is only measured on the signal recorded at probe *j* and a discharge is also only observed in front of probe *j*.

The results presented in this paper were obtained with a refocused pulse generated periodically with a period T_{ampli}. Preliminary measurements showed that the repetition of the TR refocused pulses ensures the reproducibility of the plasma ignition process. It is probably due to the presence of free electrons generated during the previous pulse that remains in the gas and lowers the breakdown field threshold.[14] A similar behavior has been reported in the literature for pulsed microwave plasmas, with the breakdown being a function of the off-time between two successive pulses.[15] Consequently, the power amplification required for plasma ignition is lowered which decreases the overall electric field level in the cavity and prevents parasitic breakdown at other unexpected locations.

Note that the coaxial probes involved in the first step of the TR experiment, namely, the signal acquisition step, have to remain during the second step in order to preserve the cavity response. Consequently, the pin of the wire probably participates in the electric field enhancement at the edge of the metallic probes. However, the plasma breakdown is only obtained with the appropriate signal, suggesting that the local increase in the electric field leading to the breakdown is mainly due to the TR focusing rather than the geometrical effect induced by the wire.

The duration of the refocused pulses presented in Fig. 3 is about 8 ns which is similar to the one of the initial pulse. They are surrounded by side lobes as reported in the literature.[2] The corresponding peak-to-noise ratio can be estimated to be between 4 and 5. It has been shown to vary as $\sqrt{\Delta\nu/\delta\nu}$, with $\Delta\nu = 250$ MHz being the frequency bandwidth and $\delta\nu$ the correlation frequency of the reverberated field.[16] The latter corresponds to the inverse of the shortest time between the characteristic absorption time of the cavity t_a and its Heisenberg time t_H. t_H can be seen as a threshold above which it is not possible to get more uncorrelated information on the bandwidth. Thus, if $t_a < t_H$, the available information is limited by t_a, whereas if $t_a > t_H$, it is limited by t_H. Using our experimental setup, we estimated $t_a = 100$ ns and $t_H = 600$ ns.[2,17] Consequently, the peak-to-noise ratio in the time domain is given by $\sqrt{\Delta\nu * t_a} = 5$, in good agreement with the experimental results presented in Fig. 3. To control the location of the plasma ignition, one also has to take into account the "spatial peak-to-noise ratio." One can see in Fig. 3 that the ratio between the magnitudes of the refocusing peak and the lobes measured on the neighboring probes is on the same order as the peak to noise ratio in the time domain. This is linked to the ergodicity of the cavity.[17–19]

Our experimental results demonstrate that time reversal of microwaves can be used to generate local plasmas inside metallic cavities. The discharge is controlled in both space and time by only changing the microwave waveform. In reactive gases, it paves the way for interesting plasma assisted processing and toll manufacturing. This so-called "plasma brush" can directly impact applied research on surface treatments, etching, or thin film deposition. The control of energy deposition in time and space also offers new opportunities to study microwave plasma breakdown.[20,21] Finally, since the plasma absorbs a part of the incident microwave energy, it could behave as a nonlinear microwave sink.[22]

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