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Sonographic probing of laser filaments in air

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The acoustic wave emitted from the plasma channel associated with a filament induced by a femtosecond laser pulse in air was detected with a microphone. This sonographic detection provides a new method to determine the length and the spatial profile of the free-electron density of a filament. The acoustic wave is emitted owing to the expansion of the gas in the filament, which is heated through collisions with high-energy photoelectrons generated by multiphoton ionization. Compared with other methods, the acoustic detection is simpler, more sensitive, and with higher spatial resolution, making it suitable for field measurements over kilometer-range distances or laboratory-scale studies on the fine structure of a filament. © 2003 Optical Society of America

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1. Introduction

Fn1 High-energy femtosecond laser pulses propagating in air form long filaments, owing to an equilibrium between Kerr focusing and defocusing on laser-induced plasma.[1] The properties of the filaments open exciting perspectives for applications, such as white-light lidar[2] and laser lightning control.[3,4] These applications in turn stimulate the need for better characterization of the filamentation propagation, especially the need of the precise determination of the length and the spatial profile of the free-electron density of a filament. Not only is the laser triggering and guiding of high voltage discharge based on the plasma channel associated to a filament, but also the backscattering enhancement of the white light, interesting for lidar applications, is considered to be due to the refractive-index gradient induced by free-electron distribution.[5] Some methods have been used to measure the free-electron density in a filament. An electric field induced by free electrons has been detected by an antenna.[6,7] Fluorescence from excited N_2 molecules and N_2^+ ions has been measured with a spectrometer along a filament[8] and more recently in the backscattering direction.[9] A diffraction interferometer has been used to determine the decay of the free electrons.[10] More recently, subterahertz radiation from a filament has been detected with a heterodyne detector.[11] The application of these current methods, however, is mainly limited to laboratory-scale experiments. On the atmospheric scale,[12] a slightly focused or a collimated beam lead to long filaments (length exceeding 10 m). A more sensitive and simpler operational method is therefore needed.

In this paper, we demonstrate that the acoustic wave emitted from a long plasma channel associated to a filament can be detected with a microphone with high sensitivity, low noise, and high spatial resolution. Furthermore, the acoustic detection presents a large dynamic range, exceeding 3 orders of magnitude.

2. Experimental Setup and Results

In our experiments (Fig. 1), a chirped pulse amplification (CPA) laser delivered pulses of 120 fs in duration and 8 mJ in energy with a 20-Hz repetition rate at 810 nm. The output beam was focused by a spherical mirror with a focal length of 5 m to initiate a filament in the laboratory. The beam diameter was ~7 mm (1/e level) on the spherical mirror. A microphone (bandwidth, ~15 kHz together with its amplifier) was installed inside a shielding tube oriented perpendicularly toward the filament at a distance of 10 cm from it. The tube had a length of 7 cm and an inner diameter of 0.6 cm, restricting the directly measured filament to a length of 1.1 cm. F1

A pulsed acoustic signal was detected by the microphone and recorded by a digital oscilloscope syn-

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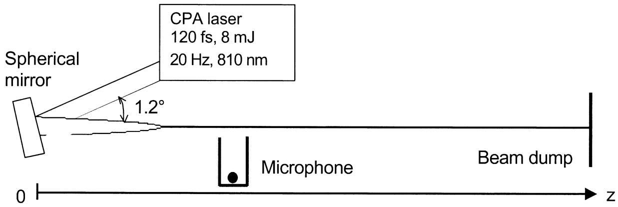

Fig. 1. Experimental setup. The spherical mirror (with 5-m focal length) was used with a small incident angle (1.2°) to reduce the astigmatism. The laser beam had a diameter of 7 mm (e^{-1} level) at the spherical mirror. The origin of the Oz axis corresponds to the location of the spherical mirror. The beam dump was located 14 m from the spherical mirror.

chronized to a laser pulse by use of a photodiode that detected scattered light from the spherical mirror. F2 In Fig. 2 a typical acoustic signal is shown with an average over 256 laser pulses. The acoustic signal exhibits an overpressure followed by a underpressure, typical for a shock wave due to an explosion. After the initial shock wave some secondary peaks are also detected owing to echo from the surrounding natural reflectors near the setup. The voltage of the first peak as a function of the propagation distance z F3 is shown in Fig. 3. One first notices the slope changes and signal jumps on the curve at 2.5 and 7 m, as indicated by the arrows. The beam profile was checked with impacts on a black paper. The highest intensity spots in the filament drilled holes in the paper, while the surrounding intensity whitewashed the paper. The impacts showed that three small filaments started around 2.5 m and that beyond 7 m, the beam intensity was not powerful enough to drill the black paper. The profile checks also showed the fusion[13] of the three initial filaments into a single filament around 4.2 m. The jump on the signal around 2.5 m thus indicates the starting of the plasma channel (the Kerr focusing collapse point), and the rapid decrease of the signal around 7 m the ending of it. That allows us to determine the length of the plasma channel of 4.5 m. Before and after the

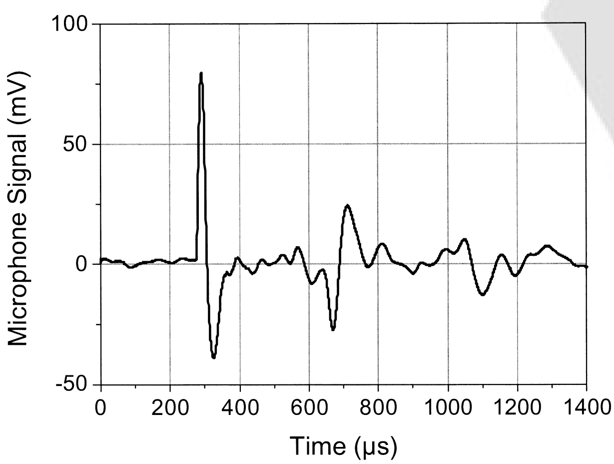

Fig. 2. Acoustic signal recorded by a digital oscilloscope synchronized on laser pulses with an average over 256 shots. The origin of the time axis is the laser pulse.

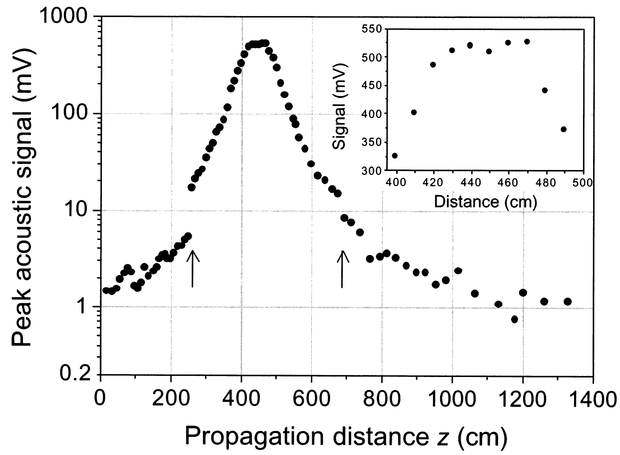

Fig. 3. Peak acoustic signal as a function of the propagation distance z. The arrows show the starting and the ending points of the plasma channel. The insert presents a detail of the signals between 400 and 500 cm from the spherical mirror.

plasma channel, a pulsed acoustic signal was still detected over the background acoustic noise, which was estimated to 0.2 mV in our laboratory. This noise level is 3 orders of magnitude under the maximal acoustic signal (~500 mV) that we detected at the center of the filament, corresponding to a plasma density 3 orders of magnitude lower than that measured in the center part of the filament, as we will see in Section 3. We interpret the signals detected outside the filament as being due to the ionization of dust particles in air. In a dust-free, clean laboratory we observed a much lower background and, as a consequence, much larger jumps of the acoustic signal in the starting and the ending points of the filament. Once the filaments start, the signal increases exponentially [$S(z) \sim \exp(0.021z)$] and reaches a plateau at 4.2 m, before the geometrical focal point (see the insert in Fig. 3), where the three initial filaments collapse into a single filament. After the plateau, the decrease of the signal is quite similar to the increase [$S(z) \sim \exp(-0.022z)$]. A check of the black paper showed a minimal filament diameter in the range of 100–150 μm in the plateau, where the acoustic signal reached its maximal value. An energy in the filament of ~0.8 mJ (~10% of the total energy) was determined by use of a power meter and a diaphragm that allowed only the filament through.

3. Discussions

It is well known that in a filament with a femtosecond laser pulse, air molecules (nitrogen and oxygen) are partially ionized through the multiphoton ionization (MPI). The photoionization dynamics in an intense laser field has been extensively studied.[14] It has been shown that photoelectrons are ejected from molecules with an initial kinetic energy of a few electron volts,[15] which corresponds to an initial free-electron temperature in the order of 10^4–10^5 °K. An energy transfer occurs between the free electrons and the background gas (ions and neutral molecules) owing to elastic and inelastic collisions. The gas in the filament is then heated to a high temperature when thermal equilibrium is reached in the filament. The heated gas expands, leading to a shock wave emission.

Detailed theoretical analysis of the energy transfer between free electrons and heavy species (ions and neutral molecules) in a femtosecond pulse-induced plasma has been given by V. E. Gusev[16] for solid-state targets and by F. Vidal *et al*. for the air.[17] The authors estimated the time of the energy transfer from electrons to heavy species in the order of 10^{-11} s for typical solid-state targets and in the range of 10^{-9}–10^{-8} s in the air. Especially a final equilibrium temperature of approximately 0.1 eV (corresponding to a temperature of 1200 °K) is reached in a filament in air 10^{-6}–10^{-5} s after the exciting laser pulse.[17]

The relationship between the acoustic signal and the initial free-electron density has been studied by some authors. For example, when the acoustic technique was used to measure the multiphoton absorption by polyatomic molecules, it has been demonstrated that the first peak in the acoustic waveform is proportional to the optical energy absorbed by the gas.[18] For a given gas and a given excitation wavelength, the absorbed energy is in turn proportional to the initial free-electron density generated by the MPI. Therefore in our experiments, the microphone signal shown in Fig. 3 provides a direct measurement on the free-electron density profile in the plasma channel. If we define the beginning and the end of a filament as the points where the acoustic signal jumps and where the slope of the electron density profile changes (i.e., where the signal due to the plasma generated in the filament overrides the noise from the background aerosols), the simple and reproducible sonometric experiments yield a clear measurement of the filament length.

In Fig. 3, we remark that the free-electron density varies over nearly 2 orders of magnitude along the channel (actually, ~50 times). This large dynamic range is due to the high-order nonlinearity of the MPI process: A small variation of the light intensity in the filaments leads to a large variation in the free electron density. By use of an effective power-law dependence of I^{α} for the ionization rate on the light intensity I, and taking a value of 7.5 for α,[19] the measured variation for the free-electron density corresponds to a variation of a factor 1.7 only in light intensity, which is consistent with the expected intensity clamping in a filament.[20]

To determine the absolute free-electron density, a calibration with cross-check measurements is needed. The calibration can be provided in laboratory experiments, for example by the fluorescence[8] of N_2 or N_2^+, or the electric conductivity measurements.[21] However the cross-check calibration might not be always necessary, because of the self-organized nature of the filaments, in which the maximum free-electron density is determined by the equilibrium between Kerr self-focusing and defocusing on the plasma. An universal value, or at least a universal order of magnitude, is found for the maximal value of the free-electron density, independently of the input laser pulse parameters. This maximal value for the free-electron density can also be considered as a consequence of the intensity clamping in the filaments, which limits the free-electron density to a typical value of 3×10^{16} cm^{-3} (Ref. 21). In most experiments, when the input laser pulse parameters (energy, duration, chirp, or focusing) are changed, the resulting filaments can have different locations (starting and ending positions), lengths, and free-electron density profiles. The sonographic detection provides a precise and simple method to determine these filament parameters.

The particular spatial plasma profile observed in our experiment is due to our experimental configuration. In particular, the use of a focusing mirror, which was needed to observe filaments in a short propagation distance inside of our laboratory, made the filament diverge rapidly after the geometrical focus point. That corresponds to the quick decay of the observed acoustic signal. Even though refocusing[8] after the geometrical focus can be observed, a filament formed with the use of a focusing lens is in general shorter than a filament formed by a pure self-focusing in a collimated beam. Before the geometric focus, the filament starts owing to the Kerr focusing, as described by the moving focus model.[22]

4. Conclusion

We have demonstrated that the acoustic wave emitted by a filament is a suitable observable for a nondestructive determination of the presence of the plasma channel, its length, and its free-electron density profile. The advantages of the sonographic method are the simplicity, the sensitivity, and the high spatial resolution, thanks to the low speed of the sound. In a field experiment one could take advantages of this simple and sensitive detection method to perform long-distance propagation measurements, while in a laboratory-scale experiment one could benefit from the high spatial resolution (within one centimeter) to study the fine structure in a filament. However, the propagation of the acoustic wave is essentially transverse to the axis of the filament, owing to the cylindrical form of a filament. This limits the use of the acoustic detection in the backwards remote-sensing configuration. AQ: B

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