Rapid communication

Electrical conductivity of long plasma channels in air generated by self-guided femtosecond laser pulses

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Abstract. By slightly focussing ~ 1 TW femtosecond laser pulses, we generated long self-stabilizing filaments in air. Free carriers generated by the pulse move in the electrical field of a bias voltage along these filaments. This is a direct measurement demonstrating the creation of a plasma \( n_e > 10^{12} \text{ cm}^{-3} \) in the filaments, which plays a crucial role in the interplay of diffraction and self-focussing, leading to the formation of long stable channels. These filaments may have applications for laser-triggered lightning.

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When femtosecond near infrared laser pulses with pulse energies exceeding ~ 1 mJ are propagated in gases such as air at approximately atmospheric pressure, bright self-guided light channels are formed [1]. It has been demonstrated that such filaments emit a white light continuum [2, 3], which can propagate in the atmosphere over distances exceeding 10 km in a collimated beam [3, 4], and are efficient waveguides for the generation of high harmonics of the laser fundamental [5]. The mechanism that leads to the formation and stabilization of these remarkable light filaments has been debated and two scenarios based on a moving focus model [6] or alternatively on a dynamic equilibrium between diffraction, self-focussing and ionization [7] have been discussed. First applications of this intriguing phenomenon which are presently being studied include a novel broad spectrum LIDAR technique [3, 4] and the use of such channels for the initiation of electric breakdowns in the atmosphere as a “laser lightning rod” [3, 8].

For both the clarification of the mechanism leading to the channel formation and the application of this phenomenon to lightning control, it is essential to know whether these filaments are electrically conductive and to determine their conductivity. In this short note we present an experiment that demonstrates the existence of a connected plasma column in self-guided light filaments over distances of meters.

1 Experimental set-up

Measurement of the electrical properties of self-guided light filaments is complicated by the experimental observation that the build-up of these channels is severely influenced by all, even small, obstacles that impact on the unhindered propagation of the light in the gas. The use of probes inside the filament is therefore difficult and consequently we decided on an experiment that determines the existence of free charges by a capacitive coupling to a pick-up capacitor. Our laser source was a terawatt-class CPA Ti:sapphire laser system with pulse energy up to 160 mJ during our experiments and a pulse repetition rate of 10 Hz. The pulse duration was about 100 fs, the output beam diameter was 70 mm with a beam parameter \( M^2 \approx 2.5 - 3 \).

These pulses were slightly focussed using an \( f = 8 \text{ m} \) glass lens. Depending on the laser energy, the spatial profile of these pulses starts to break up into many hot spots due to small scale self-focussing. Nearer to the focal region these hot spots evolve into many thin filaments. Nevertheless, these filaments do not unite in the focal position to form one plasma spark in air. There is instead a small area filled with all the individual filaments, strongly fluctuating in pattern with each laser shot. After passing the focal position by a few meters, these filaments appear as bright white spots with colorful rings when viewed on a screen (Fig. 1), a beautiful demonstration of white light generation in gases, first observed by Corkum and Rolland [9]. The diameter of a single filament is typically several 100 \( \mu \text{m} \), corresponding to guided laser intensities on the order of \( 10^{13} \text{ W cm}^{-2} \) [7]. For pulse energies exceeding ~ 20 mJ, a single channel breaks up into several filaments and for 200 mJ/100 fs Ti:sapphire laser pulses we observed typically 10–20 channels.

Figure 2 depicts the experimental set-up near the focal region of the lens. It consists of an optical rail parallel to the light path with a pick-up capacitor and a bias electrode mounted on it. The outer electrode of the pick-up capacitor is, in some of the experiments, a brass tube, length 120 mm, inner diameter 21 mm, wall thickness 2 mm, mounted on
Video capture of filaments in air as seen on a screen about 5 m behind focal position of an $f = 8\,\text{m}$ lens when irradiated with a 160 mJ, 100 fs pulse. The numerous bright white spots represent the light filaments emitting a white light continuum on an insulating post. In other experiments where better spatial resolution was needed a ring electrode of 2 mm length with an inner diameter of 11 mm was used. The electrode is soldered to the inner conductor of a 50 $\Omega$ coaxial cable. This cable is connected to a digital oscilloscope with a BNC connector so that the shield of the coaxial cable is grounded. The input impedance of the oscilloscope is 1 M$\Omega$ and the input capacitance 25 pF.

The bundle of laser filaments passes the axis of the brass tube or the ring, thus forming the inner electrode of the pick-up capacitor in the case in which free carriers are generated by the intense light. The bias electrode is a massive aluminum block mounted on insulating plastic. It is connected to the output of a voltage supply and could be set to either $-30 \rightarrow +30\,\text{V}$, or $+300 \rightarrow +1200\,\text{V}$ against common ground potential depending on the voltage source in use. The idea behind this set-up is easily explained by the help of the equivalent circuit depicted in Fig. 3b: If carriers are generated in the filaments, the pick-up capacitor is formed and carriers are extracted towards the bias electrode. Depending on the conductivity, the bias voltage, and the life-time of the carriers, a certain charge is extracted from the pick-up capacitor. The associated charge will appear as a voltage pulse on the oscilloscope.

Fig. 1. Video capture of filaments in air as seen on a screen about 5 m behind focal position of an $f = 8\,\text{m}$ lens when irradiated with a 160 mJ, 100 fs pulse. The numerous bright white spots represent the light filaments emitting a white light continuum.

Fig. 2. Schematic experimental set-up: laser pulses coming from the right are slightly focussed by the $f = 8\,\text{m}$ lens. The filaments are created due to self-focussing and are passing through a brass tube that is positioned parallel to the light path on an optical rail. The brass tube is connected to an oscilloscope by a 50 $\Omega$ cable. The scope is characterized by its input impedance $R_0 = 1\,\text{M} \Omega$ and its time constant $R_0 C_0$. The signal $S$ detected by the scope is due to the charge brought onto the pick-up capacitor $C_{\text{pu}}$ in the field of the bias voltage.

Fig. 3a,b. a Electrical pulse shape of the signal when a laser pulse passing the pick-up capacitor creates filaments. The fast oscillations are caused by the unmatched impedances on both sides of the 50 $\Omega$ cable (cable ringing). The signal $S$ decays with the much longer time constant $R_0 C_0$ of the scope. The rise time of the first fast oscillation is due to the time constant $R C_{\text{pu}}$. Laser energy: 30 mJ, $x = 25\,\text{cm}$, ring electrode. b Calculations of the expected signal using the SPICE program and the model circuit shown in the inset.