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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 $M^2 \simeq 2.5-3$.

These pulses were slightly focussed using an $f = 8$ 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 μm, 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

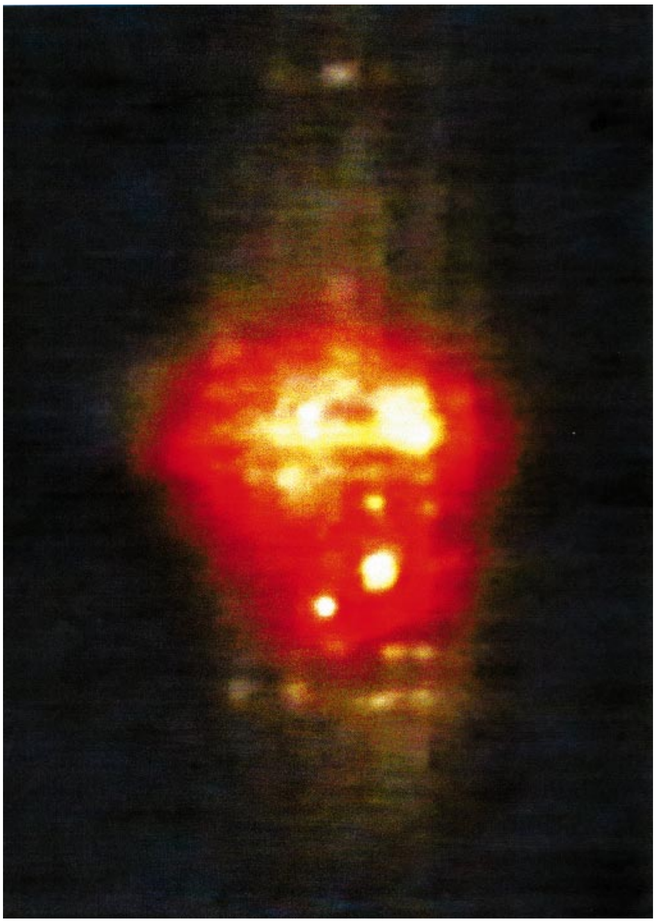

Fig. 1. Video capture of filaments in air as seen on a screen about 5 m behind focal position of an $f = 8$ m lens when irradiated with a 160 mJ, 100 fs pulse. The numerous *bright white spots* represent the light filaments emitting a white light continuum

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 Ω 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 MΩ 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 $-30 - +30$ V, or $+300 - +1200$ 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.

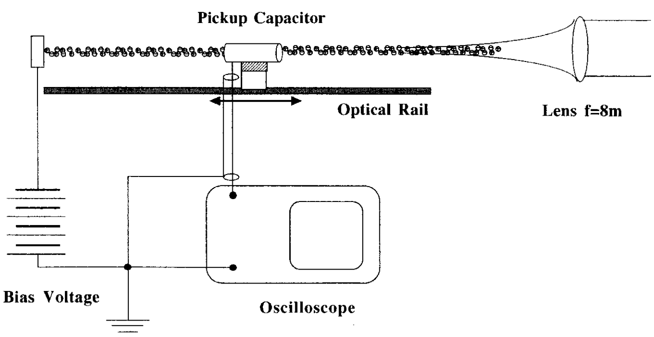

Fig. 2. Schematic experimental set-up: laser pulses coming from the right are slightly focussed by the $f = 8$ m lens. The filaments are created due to self-focussing and are passing through a brass tube that is positioned parallel to the light path on an optical rail. The brass tube is connected to an oscilloscope by a 50 Ω cable. The scope is characterized by its input impedance $R_0 = 1$ MΩ and its time constant R_0C_0. The signal S detected by the scope is due to the charge brought onto the pick-up capacitor C_{pu} in the field of the bias voltage

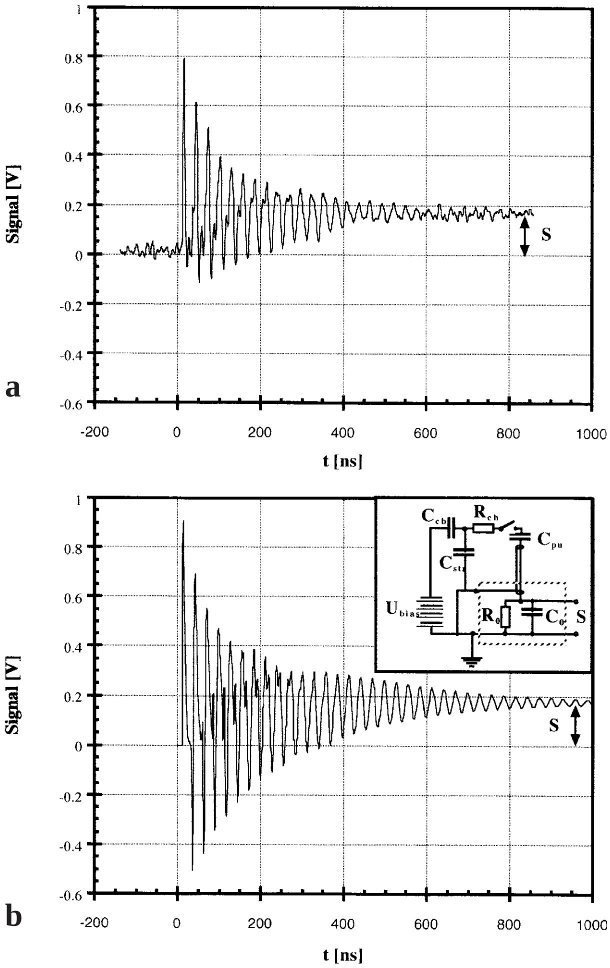

Fig. 3a,b. a Electrical pulse shape of the signal when a laser pulse passing the pick-up capacitor creates filaments. The fast oscillations are caused by the unmatched impedances on both sides of the 50 Ω cable (cable ringing). The signal S decays with the much longer time constant R_0C_0 of the scope. The rise time of the first fast oscillation is due to the time constant RC_{pu}. Laser energy: 30 mJ, $x = 25$ cm, ring electrode. **b** Calculations of the expected signal using the SPICE program and the model circuit shown in the *inset*

2 Experimental results and discussion

When the light filament was initiated by a laser pulse between the rod and the bias electrode a signal was measured with the oscilloscope as is shown in Fig. 3a. A rapidly oscillating component with a frequency of 35 MHz and a decay time of about 200 ns is observed. This damped oscillation is superimposed on a quasi DC-signal level indicated as S. On a much larger time scale of 30 μs this signal level S decays back to zero. This signal is now discussed on the basis of the model circuit shown in the inset of Fig. 3b. The switch represents the initiation of the filament. Before the switch is closed, i.e. the filament is initiated, the capacitance C_{pu} representing the cylindrical rod or the ring electrode is uncharged. The electrostatic potential has the value U_{bias} at the bias electrode and ground potential ($U = 0$) at the rod. The potential of any point A between the bias electrode and the rod is given by the stray capacitances C_{cb} and C_{str}, where C_{str} indicates the capacitance between the initiated filament and the grounded rail (Fig. 2).

Once the channel is formed it represents an ohmic resistor R. The channel passing through the center of the rod also forms the inner conductor of a cylindrical capacitor C_{pu}. From the geometry of the set-up, this capacitance C_{pu} may be estimated as $C_{\text{pu}} = (2 \pm 1)$pF for the rod electrode and $C_{\text{pu}} \approx 0.1$ pF for the ring. It is thus much smaller than the capacitance of the oscilloscope $C_0 = 25$ pF, and the oscilloscope may thus be regarded as a passive current monitor. If we also assume $C_{\text{str}} \gg C_{\text{cb}}$, which is justified as long as the distance x between pick-up capacitor and bias electrode is not too small ($x \gtrsim 10$ cm), the signal measured by the oscilloscope may be calculated using the well-known simulation program SPICE. The signal may also be calculated analytically and has the general form:

$$U_{\text{S}} = A\,\text{e}^{-t/\tau} + S\,, \tag{1}$$

with

$$A = \text{const.} \times U_{\text{bias}};$$
$$S \simeq \frac{C_{\text{cb}}}{C_{\text{str}} + C_{\text{pu}}} \frac{C_{\text{pu}}}{C_0} U_{\text{bias}} \quad \text{and} \quad \tau \simeq RC_{\text{pu}}\,. \tag{2}$$

In the analytical solution the multiple reflections from the cable shown in Fig. 3 and reproduced by the SPICE program have been neglected.

The result of the SPICE calculation is shown in Fig. 3b and resembles closely to the measured signal. The slow decay with the time constant of $R_0C_0 \approx 25$ μs is observed for longer time scales, but not shown in Fig. 3a. The signal represents the charging of capacitor C_{pu} by the charges that are present between point A and the capacitor and were initiated by the light channel. In fact S is proportional to the charge on capacitor C_{pu}. The appearance of this signal S therefore demonstrates unambigiously the presence of free charges in the light filament. In order to test this model further, the signal S was measured as a function of the bias voltage U_{bias} for different distances between the rod and the center electrode. For each distance a linear increase of the signal with bias voltage was observed (Fig. 4) in agreement with (2). The signal increases with decreasing distance, which is also expected since C_{str} increases with increasing distance. When the light filament is interrupted by a dielectric plastic plate between pick-up capacitor C_{pu} and bias electrode the observed signal S remains almost unchanged, which is expected due to the small change this causes in the capacitance C_{cb}.

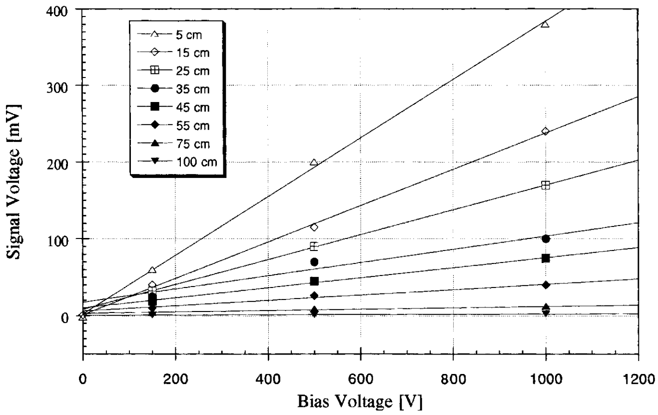

Fig. 4. The linear dependencies of the signal S on bias voltage at each distance x between pick-up capacitor (120 mm tube) and bias electrode – as an indicated in the inset picture – corroborates the model in which the free charges of a thin plasma are moving in the electrical field of the bias voltage, thus influencing a displacement current towards the scope input. Laser energy: 30 mJ

The duration of the rapid oscillations depends on the pick-up capacity C_{pu} and the channel resistivity R. In fact we observed that the pulse duration decreased for higher laser energies indicating a decreased resistivity in the channel, since the pick-up capacitance is nearly independent of shape and number of channels. Also for increased distances x between pick-up capacitor and bias electrode the pulse duration increased due to an increased resistivity. For the conditions of Fig. 3 with $E_{\text{L}} = 30$ mJ, $x = 25$ cm, we measure a time constant of $\tau = RC_{\text{pu}} = 1 \times 10^{-8}$ s which yields $R = 1 \times 10^5\,\Omega$ for the resistivity of the channel. With a total channel area of $A < 10^{-2}$ cm^2 (Fig. 1) and a collision time for electrons in air of 1.1×10^{-12} s [8] we estimate a lower limit for the electron density in the channel of $n_{\text{e}} \gtrsim 6 \times 10^{11}$ cm^{-3}. This value for n_{e} exceeds the minimum electron density required for lightning initiation of 5×10^{11} cm^{-3} [8].

In conclusion, our results demonstrate the existence of free charges in the channel. Since free charges will affect the propagation characteristics of the femtosecond laser pulse, this finding strongly supports a model of the channel formation that relies on a dynamic equilibrium between self-focussing, diffraction and ionization [1, 5]. This result is also encouraging for the further investigation of the use of femtosecond laser-induced light filaments for lightning control.

Note added in proof

After submission of this paper we became aware of the results of a similar experiment conducted by the group of Prof. A. Mysyrowicz at ENSTA/Palaiseau [S. Tsortzakis et al. "Evidence for a conducting channel in air by self-guided femtosecond laser pulses", submitted to Phys. Rev. Lett.]. In agreement with the present experiment these authors measure a substantial charge in the channel. Their absolute values for the electron density of $n_{\text{e}} = 10^{16}$ cm^{-3} are, however, substantially higher than the lower limit of $n_{\text{e}} = 10^{12}$ cm^{-3} measured in the present experiment. This difference may be attributed mainly to the more stringent estimate of the filament diameter in the ENSTA experiment as opposed to the present experiment, which averages over 10–20 channels.

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