Monomode Guiding of 10^{16} W/cm^2 Laser Pulses over 100 Rayleigh Lengths in Hollow Capillary Dielectric Tubes

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Monomode guiding over 100 Rayleigh lengths (10 cm) of high intensity ultrashort laser pulses (10^{16} W/cm^2, 120 fs) has been demonstrated in hollow dielectric capillary tubes (45–70 μm internal diameter) without inner wall damage. Analytical predictions for coupling conditions and damping length are confirmed experimentally for tubes under vacuum. With 5 to 40 mbar of He gas in the tube, when laser ionization occurs the energy and duration of the transmitted pulse decrease while its spectrum is broadened. [S0031-9007(99)09293-5]

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Many applications based on the interaction of a short, intense laser pulse with a gas or a plasma, such as laser particle acceleration [1], x-ray laser [2,3], and harmonic generation [4], require an interaction length L well in excess of the Rayleigh length (z_R) of the laser beam. For example, the dephasing length of an ultrarelativistic electron injected in a plasma wave generated by the laser wakefield mechanism, as in Ref. [5], typically exceeds $1000z_R$. Guiding the same intensity over 1 m ($L = 1000z_R$) instead of 1 mm would increase the energy gain from a few MeV to a few GeV. In order to propagate high laser intensities over distances significantly longer than z_R, the laser beam has to be guided. Conventional guiding structures such as solid-core fiber optics cannot be used to guide laser beams at intensities exceeding the glass breakdown threshold. Moreover, the applications mentioned above rely on the interaction of the laser beam with gas or plasma inside the guiding structure.

Various mechanisms have been proposed to guide a high intensity laser pulse in a plasma. They are based on an appropriate modification of the transverse profile of the refractive index of the plasma. For sufficiently high laser powers, the refractive index can be modified by the laser pulse itself and lead to relativistic and/or ponderomotive self-channeling [6]. Alternatively, Durfee *et al.* [7] have demonstrated that a long laser pulse can create a plasma channel [7–9] in which a short laser pulse can be guided over more than $70z_R$. The guiding of an intense (10^{16} W/cm^2) laser pulse has also been demonstrated in a plasma channel created by a slow capillary discharge [10]. In all of these schemes, the guiding conditions fix the electron plasma density and its spatial profile. However, many applications need plasma parameters very different from those required by the laser guiding, and would benefit from a guiding structure existing independently of the plasma.

The use of hollow capillary tubes as a guiding structure is attractive for laser plasma interaction over long distances. In this case, the laser pulse is guided by the tube inner wall and the plasma can be provided by the ionization of a gas filling the tube. Guiding of high intensity laser pulses in hollow capillary tubes has been observed in a few experiments [11,12]. The guiding was multimode, leading to a complex transverse intensity profile and a low group velocity v_g. Inner wall breakdown has been observed at high intensities [11].

In opposition to multimode guiding, monomode guiding gives a smooth transverse profile, a high v_g of particular interest for laser-plasma acceleration [5], and a small attenuation. This last property also minimizes the energy transfer to the inner wall, reducing the risk of wall breakdown that could damage the tube. Moreover, because each mode has its own v_g, guiding an ultrashort pulse without temporal dispersion requires a monomode propagation. Monomode guiding in dielectric tubes filled with gas has been used for laser applications [13,14], but at intensities below the gas ionization threshold ($<10^{14}$ W/cm^2).

In this Letter, we report monomode guiding of a 120 fs laser pulse at an intensity up to 10^{16} W/cm^2 in hollow dielectric capillary tubes as long as 10 cm ($100z_R$) without apparent inner wall breakdown. The tube was under vacuum or filled with helium gas at pressures up to 40 mbar.

In order to understand our experimental results, we used an analytical model that describes the laser beam propagation in a hollow capillary tube. Assuming λ (laser wavelength) $\ll a$ (inner radius of the tube) and resolving the Maxwell equations, the propagation inside the tube can be calculated in term of modes with a perturbative treatment. The zero order (electromagnetic field equal to zero inside the wall) gives the different modes, while the first order gives their damping lengths [15]. In our conditions, the incident laser beam has a linear polarization and a cylindrical symmetry around the propagation axis z. It is possible to build a base of modes adapted to this incident field.

In this base, only a group of modes indexed by an integer n is excited. Their transverse intensity profiles $I_n(r)$ present a Bessel-like shape: $I_n(r) = J_0^2(\alpha_{n,0} r/a)$, where $\alpha_{n,0}$ is the nth zero of the Bessel function J_0. The corresponding dispersion equations are $\varepsilon\omega^2/c^2 = k_n^2 + k_{\perp n}^2$, where k_n is the wave number of the nth mode, ε is the dielectric constant of the medium inside the tube ($\varepsilon = 1$ in vacuum), and $k_{\perp n} = \alpha_{n,0}/a$ is the transverse component of the wave vector. The relativistic factor $\gamma_{g,n}$ associated with the group velocity $v_{g,n}$ of mode n is given by $\gamma_{g,n} = (2\pi/\alpha_{n,0})(a/\lambda)$. For a dielectric hollow capillary tube (dielectric constant ε_w), the damping length $L_{d,n}$ of the nth mode for the electric field is given by

$$\frac{1}{L_{d,n}} = \mathrm{Im}\left[\frac{\alpha_{n,0}^2}{2a^3}\left(\frac{\lambda}{2\pi}\right)^2 \frac{(\varepsilon + \varepsilon_w)}{\sqrt{\varepsilon - \varepsilon_w}}\right].$$

For solid-core fibers, $\varepsilon > \varepsilon_w$ and no damping occurs. With hollow capillary tubes ($\varepsilon \approx 1 < \varepsilon_w$), the electric field of the mode n is multiplied by the factor $\exp(-L/L_{d,n})$ after a propagation distance L. Associated with this damping, one can calculate the laser intensity contrast between the axis ($r = 0$) and the vicinity of the tube wall ($r = a$):

$$\frac{I_n(r = a)}{I_n(r = 0)} = \left[\frac{J_0'(\alpha_{n,0})}{4\pi}\right]^2 \left|\frac{\varepsilon + \varepsilon_w}{\sqrt{\varepsilon - \varepsilon_w}}\right|^2 \left(\frac{\lambda}{a}\right)^2.$$

As $\alpha_{n,0}$ increases with the mode order n, one can conclude that the fundamental mode ($n = 1$, also called EH_{11}) has the smallest transverse gradients and damping rate and the highest v_g. In addition, for a given intensity on the axis, it has the smallest intensity on the tube inner wall, decreasing the risk of wall breakdown. With $a = 25\ \mu$m, $\lambda = 0.8\ \mu$m, $\varepsilon_w = 2.25$ (glass), $\varepsilon = 1$ (vacuum), and $n = 1$ ($\alpha_{1,0} = 2.405$), one gets $\gamma_{g,1} \approx 81.6$, $L_{d,1} \approx 11.5$ cm, and $I_1(r = a)/I_1(r = 0) \approx 10^{-4}$.

For a beam guided in the fundamental mode, the angle of incidence on the wall surface is typically equal to $\pi/2 - k_{\perp 1}/k_1 \approx \pi/2 - 1.2 \times 10^{-2}$ with the above laser and tube parameters. Since the electric field transmitted into the wall is much lower at this grazing incidence, the wall breakdown threshold might be higher by a factor 10 to 100 than the value of 10^{13} to 10^{14} W/cm^2 obtained for glass at normal incidence [16]. So, with the above parameters, it seems possible to guide up to 10^{20} W/cm^2 on the laser axis, without ionizing the tube.

In the experiments, the incident beam is focused on the entrance plane of the tube. The on-axis ($r < a$) part of its energy is projected onto the different modes while the outer shell ($r > a$) is lost in the entrance wall of the tube. To couple the largest part of the incident laser energy into the fundamental mode EH_{11}, the radial size of the incident beam has to be adapted to the tube inner diameter. Assuming a Gaussian incident beam with an electric field $E(r) \propto \exp[-(r/w_0)^2]$, the best entrance coupling into the EH_{11} mode is obtained when $w_0/a = 0.6435$ [17]. More than 98% of the incident energy is then transferred into the fundamental mode, inducing a quasiperfect monomode guiding.

The experiment was performed at the Laboratoire d'Optique Appliquée with 10 Hz, 30 mJ, and $\tau = 120$ fs (FWHM) linearly polarized laser pulses of central wavelength $\lambda = 0.8\ \mu$m. The beam (diameter at $1/e^2$ in intensity equal to 25 mm) enters a vacuum chamber and is focused by a $f/8$ plano-convex M_gF_2 lens on the entrance plane of a collinear capillary tube. A small part ($<1\%$) of the beam is sent before focusing to a calibrated photodiode and to a second order single-shot autocorrelator. The capillary tube is mounted on a target support with 5 degrees of freedom (the x-y-z translations and the θ_x-θ_y rotations). A $f/4$ M_gF_2 lens images the output plane of the tube on the slit of an imaging spectrometer. The output beam is split into three parts: 96% of the output energy goes into a calorimeter, 2% to the autocorrelator, and the last 2% into the spectrometer coupled to a 16 bit CCD camera. The specular reflection of the spectrometer grating gives the image of the laser focal spot, while the first order gives its spectrum.

In a first part of the experiment we tested the guiding in tubes under vacuum. We tested tubes with radii $a = 20$ to 35 μm and $l = 1$ to 10 cm. By reducing the beam size (diaphragm) before focusing, the radius w_0 of the incident laser focal spot was varied from 14 to 46 μm. In this parameter range, only the mode EH_{11} was observed at the tube output plane. The laser pulse duration, frequency spectrum, and polarization at the input and output of the tube have been measured for several tubes and incident energies. No significant modification has been observed.

A typical transverse intensity profile at the output plane of a tube ($a = 30\ \mu$m; $L = 5.4$ cm) is shown in Fig. 1 for two incident focal spot radii. Independently of w_0 and in agreement with the theoretical value of 10^{-4}, the contrast ratio of the intensity measured between the tube axis and the vicinity of the inner wall is better than 10^{-3} (measurement limited by the scattered light emitted by the tube wall).

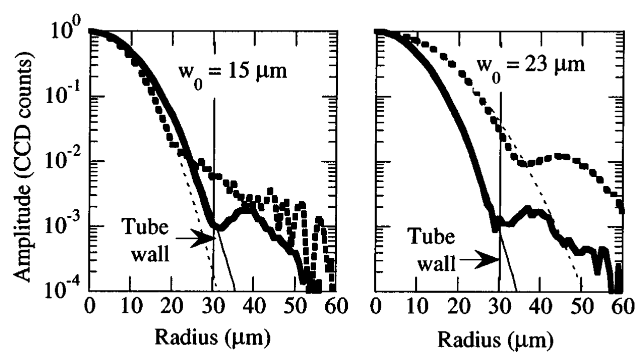

FIG. 1. Normalized radial profiles of the laser focal spot at the input (dashed line) and the output plane (full line) of a ($a = 30\ \mu$m; $L = 5.4$ cm) tube, for two incident beam waists. Bold line: measurement; thin line: Gaussian fit.

To study the beam coupling, we measured the transmission in energy versus the incident focal spot radius. A typical result is presented in Fig. 2 for three tube diameters. The theoretical transmission is also presented for these three tubes. As expected, the coupling of the incident beam into the mode EH_{11} is maximum when $w_0/a \approx 0.64$. For a perfect Gaussian beam, the analytical model predicts that the best coupling is $C_g = 98\%$. The energy transmission in the fundamental mode (i.e., the output energy measured in the mode EH_{11} divided by the total incident energy) should be $T_g = C_g \exp[-2(L/L_{d,1})]$. However, measurements of the incident focal spot show that it is not perfectly Gaussian and that the relative energy contained in the inner diameter of these three tubes is only $C_{\exp} \approx 97\%$, 87%, and 84%, respectively. For this reason, we replaced C_g by $C_{\exp}$ in the theoretical curves in Fig. 2. A good agreement is obtained, indicating also that the damping length is close to the theoretical value of the fundamental mode $L_{d,1}$. A small part of the incident energy could also go in higher order modes, but this contribution is smaller than the experimental error bars.

To study the damping length of a tube, we measured its transmission for different lengths. To avoid changes at its input, the tube was shortened by cutting its output side. The energy transmission T versus the tube length is presented in Fig. 3 for two tubes: $a = 35$ and 25 μm. The values of T at $L = 0$ (i.e., the coupling factor $C_{\exp}$) are, respectively, 84% and 78%, close to the energy ratio contained in a 35 (25) μm radius of the focal spot imaged without the tube. The experimental results are fitted by $T = C_{\exp} \exp[-2(z/L_d)]$. The best fit indicates damping lengths $L_d = 36 \pm 5$ (12 ± 1) cm for $a = 35$ (25) μm, close to the theoretical values for the fundamental mode $L_{d,1} = 31.5$ (11.5) cm. The energy transmission factor has been measured for different incident energies. It remained constant ($\approx$15%) for incident intensities from $I_{\text{in}} \approx 5 \times 10^{14}$ to 5×10^{16} W/cm^2 ($I_{\text{out}} \approx 10^{14}$ to 10^{16} W/cm^2). The beam waist adapted to the EH_{11} mode was w_0 ($= 0.6435a$) ≈ 16 μm. The associated Rayleigh length can then be estimated to z_R ($= \pi w_0^2/\lambda$) ≈ 1 mm, indicating that an intensity larger than 10^{16} W/cm^2 has been guided over $100 z_R$ (10.5 cm). In a guiding experiment made by Jackel *et al.* [11] with the same tube inner radius but in a multimode regime, inner wall breakdown was observed at $I > 10^{15}$ W/cm^2.

In the second part of the experiment, we studied the guiding in tubes filled with gas or plasma. The interaction chamber was filled with up to 40 mbar of He. The following results were obtained with tubes of $a = 25$ μm and $L = 1.2$ to 4 cm ($\approx$ 12 to $39 z_R$). The measured output intensity profile was always EH_{11}-like. The tube output was imaged at 90° on a spectrometer. At laser energies above 20 mJ and pressures below 20 mbar, the spectral line at 587.6 nm ($1s2p$-$1s3d$) of He I (atom) is always observed. Electrons on the upper level ($1s3d$) can come from a collisional recombination of He^+ or from multiphoton excitation of the ground state. Even in this last case, the gap between the energy of the upper level (23.07 eV) and the ionization energy (24.58 eV) is lower than the energy of a 0.8 μm photon (1.55 eV), so that multiphoton excitation will also lead to the atom ionization. Thus, observation of this line at the tube output indicates that a plasma is created all along the tube (1.2 to 4 cm).

Figure 4 shows the transmitted laser spectrum measured under vacuum and at 10 mbar, without and with tube ($L = 4$ cm $\approx 40 z_R$). The rapid ionization of the gas in the front of the laser pulse induces a spectral blueshift. Because each temporal slice of the pulse sees a different electron density variation, the blueshift effect also leads to a spectral broadening [18,19]. These effects are important only when the pulse is guided, confirming that ionization occurs over a length much larger than $2z_R$ and that $I_{\text{out}} \geq 10^{15}$ W/cm^2 (also confirmed by the T, τ, and w_0 measurements at the tube exit).

We observed that the transmission factor T decreases when the laser ionizes the gas. For example, for a tube with $L = 1.2$ cm, T decreases from 50% $\pm$ 5% under

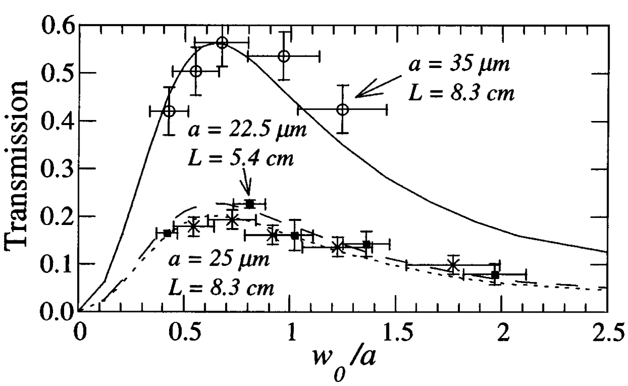

FIG. 2. Measured and theoretical transmission versus w_0/a for tubes with (a (μm); L (cm)) = (35; 8.3) (circles and solid line), (25; 8.3) (crosses and dotted line), and (22.5; 5.4) (squares and dashed line). The theoretical curves are obtained by replacing $C_g = 0.98$ by $C_{\exp} = 0.97-0.87$ and 0.84, respectively.

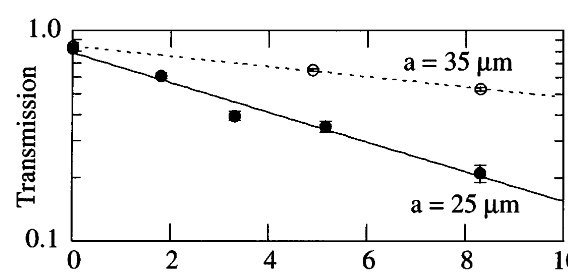

FIG. 3. Energy transmission measured as a function of the tube length, for two tube radii: $a = 35$ μm (empty circles) and $a = 25$ μm (filled circles). The curves are exponential fits: $T = C \exp(-2z/L_d)$.

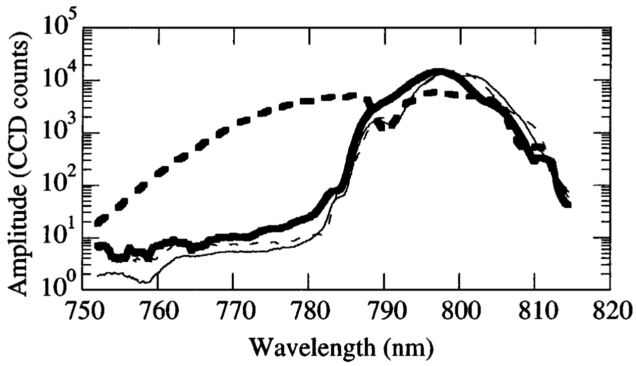

FIG. 4. Transmitted laser spectra without and with a ($a = 25\ \mu$m, $L = 4$ cm) tube. The spectra are normalized to the same integral.

vacuum to 30% ± 5% in 20 mbar of He, and to only 10% ± 5% in 40 mbar. In addition, when the tube length is increased to 4 cm, the transmission under vacuum is divided by 2.5 ($T = 20\% \pm 5\%$), while it is divided by 6 ($T = 5\% \pm 2\%$) at 20 mbar, indicating that not only the coupling factor but also the damping length L_d in the tube are affected by the gas ionization.

The input and output pulse durations were also measured for different helium gas pressures and tube lengths. Without tube, the pulse duration was 185 ± 30 fs under vacuum and 175 ± 50 fs at 20 mbar. At this same pressure, but after a tube of $L = 2.5$ cm, the duration was 110 ± 15 fs. With a longer tube ($L = 4$ cm), the duration was decreased from 160 ± 40 fs under vacuum to 65 ± 15 fs at 20 mbar.

The decreases of the energy and of the duration of the transmitted pulse have the same relative amplitudes and occur only when the laser ionizes the gas. The ionization-induced refraction of the laser beam [19] could explain these modifications. Refraction before the tube entrance tends to increase the size of the focal spot, and thus decrease the fraction of the energy injected inside the tube (coupling factor C_{exp}). We have demonstrated in a previous experiment [19] that refraction acts on the second temporal part of the pulse, after the ionization. The front part remains on the laser axis, whereas the rest of the pulse spreads at the periphery. In the presence of a tube, the front wall blocks a part of these refracted rays. The transmitted pulse is then shortened. Refraction inside the tube increases the contribution of higher order modes and thus increases the energy lost in the inner wall that is the damping in the tube. If the first temporal part of the transmitted pulse is not affected by ionization, the second part is more damped due to this refraction mechanism, inducing a duration decrease in the tube.

At high incident intensity ($>10^{15}$ W/cm^2) and a 10 Hz repetition rate, we observed a shot-to-shot decrease of the tube transmission. After a few tens of laser shots, the entrance of the tube was melted, leading to a zero transmission. This effect might be due to the poor radial intensity contrast of the incident focal spot (cf. Fig. 1): Because the laser absorption is higher at normal incidence, the energy contained in $r > a$ melts the front face of the tube. If this does not affect single-shot experiments, high repetition rates will require a specific study of the laser injection in the tube (for instance, using adapted cone-shaped input).

In conclusion, monomode guiding over $100 z_R$ (10 cm) of an ultrashort laser pulse at intensities up to 10^{16} W/cm^2 without any inner wall glass breakdown has been observed for the first time in hollow dielectric capillary tubes. The propagation in the tube has been studied under vacuum and in up to 40 mbar of helium gas. In vacuum, the best entrance coupling condition, the damping length, and the transverse intensity profile at the tube exit agree with the analytical theory. In He gas and with incident intensities of the order of 10^{16} W/cm^2, ionization occurs all along the tube ($40 z_R$). Ionization-induced refraction before and inside the tube could explain the observed decrease of the energy and duration of the transmitted pulse. In addition, we observed the broadening of the frequency spectrum required by the scheme proposed by Tempea and Brabec [18] for the generation of high-energy few-cycle optical pulses.

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