Quantum Electronics **41** (11) 989–992 (2011)

PACS numbers: 42.65.Re; 42.65.Jx
DOI: 10.1070/QE2011v041n11ABEH014700

Degree of compression and energy efficiency of a capillary compressor of femtosecond laser pulses

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Abstract. **A relation between the degree of pulse compression and energy efficiency is derived for femtosecond laser pulse compressors that utilise spectral broadening of pulses in a gas-filled capillary. We show that the degree of compression has a maximum at an energy efficiency from 15% to 30%. A 15-fold compression of a 290-fs pulse with an energy efficiency of 24% is demonstrated.**

Keywords: *femtosecond pulses, capillary, pulse compression.*

1. Introduction

The temporal compression of femtosecond laser pulses through nonlinear spectral broadening in a gas-filled capillary tube is currently widely used at pulse energies of up to ~10 mJ [1–7]. Capillary pulse compressors, which comprise a chamber, a capillary tube placed in it and a temporal compressor proper, enable a decrease in pulse duration by up to a factor of 15. The maximum degree of compression (the ratio of the pulse duration at the compressor input to the compressed pulse duration) can be achieved at pulse durations of at least 50 fs. For shorter laser pulses, the degree of compression is lower. In particular, ~20-fs pulses are compressed to ~5 fs [8]. Along with the degree of compression, an important parameter of compressors is their energy efficiency: the ratio of the compressed pulse energy to the pulse energy at the compressor input. The energy efficiency of a compressor is determined primarily by the propagation loss in its capillary tube, which is typically made of silica glass. The measured energy efficiency of capillary compressors ranges from 20% to 70%.

The degree of compression (or spectral broadening) and efficiency of a capillary compressor depend on the capillary dimensions (length and inner diameter) and the gas composition and pressure in the capillary. To evaluate the shape and width of the output spectrum, use is typically made of numerical solutions to equations that describe nonlinear femtosecond pulse propagation in a gas-filled capillary. Numerical simulation results agree rather well with experimental data [5, 6]. However, optimising the operation of a capillary compressor so as to maximise its energy efficiency at a given degree of compression and assessing the effect of the parameters of compressors on their output characteristics require lengthy numerical calculations and cannot be performed in every case. It is thus necessary to derive sufficiently simple analytical expressions which could be used to evaluate and optimise the performance of a capillary compressor. One example is the formula derived by Vozzi et al. [9], which relates spectral broadening to the inner diameter of the capillary.

The objective of this work was to develop a method for analytically evaluating the characteristics of capillary compressors and to obtain experimental evidence in support of analytical results.

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Received 2 August 2011
Kvantovaya Elektronika **41** (11) 989–992 (2011)
Translated by O.M. Tsarev

2. Analytical evaluation of a capillary compressor

This paper examines capillary compressors in which the spectral broadening of laser pulses is only due to self-phase modulation, caused by the fact that the refractive index of the inert gas in the capillary is a nonlinear function of laser beam intensity. The spectral broadening due to gas ionisation by a femtosecond laser pulse is here left out of consideration. Moreover, we ignore the influence of the dispersion in the active medium on the pulse duration in the capillary. For this reason, the results below are applicable to pulse durations of at least 50 fs at beam intensities in the capillary within 10^{14} W cm^{-2} and a wavelength of ~1 μm.

In practice, the capillary length in a compressor is usually set by the dimensions of the cell in which the capillary is placed. For this reason, the capillary length often cannot be varied widely. The performance of a compressor can be optimised by varying the transmission of a capillary of a particular length (via changes in its inner diameter) and the gas pressure and composition in the capillary.

The spectral broadening of a pulse [the ratio of the width of its spectrum at the output of the capillary, $\Delta\omega$, to the width of the input spectrum, $(\Delta\omega)_0$] due to its self-phase modulation in the capillary is given by [10]

$$F = \frac{\Delta\omega}{(\Delta\omega)_0} = (1 + 0.77\varphi^2)^{1/2}. \quad (1)$$

Here, φ is the nonlinear phase shift given by

$$\varphi = n_2 \frac{2\pi}{\lambda} I \frac{1 - \exp(-\alpha L)}{\alpha} = n_2 \frac{2\pi}{\lambda} I \frac{(1-T)L}{-\ln T}, \quad (2)$$

where n_2 is the nonlinear refractive index of the gas; λ is the centre wavelength; I is the peak intensity in the capillary; α is the attenuation coefficient in the capillary; T is the transmittance of the capillary (the ratio of the pulse energy at the output of the capillary to the input pulse energy); and L is its length.

The maximum intensity in the capillary and, hence, the maximum spectral broadening are limited by the excitation of higher order spatial modes, which experience higher propagation losses in the capillary in comparison with the fundamental mode. Because of this, in practical applications use is commonly made of capillary compressors with a nearly Gaussian intensity distribution of the fundamental mode. Higher order modes emerge at sufficiently high beam intensities in the capillary owing to the influence of the nonlinear refractive index. The maximum intensity of the EH_{11} fundamental mode at which no higher order modes emerge in the capillary is [2]

$$I_{\max} \approx \frac{0.07\lambda^2}{n_2 a^2}, \qquad (3)$$

where a is the inner radius of the capillary. Note that the maximum power of the fundamental mode in the capillary, proportional to $I_{\max} a^2$, is independent of the capillary diameter.

At a given laser pulse power, the value of n_2 at which the spectral broadening of the pulse reaches the maximum level and relation (3) is satisfied can be found by varying the gas pressure in the capillary, because $n_2(p) \approx n_2(1\ \text{атм})p$, where $n_2(1\ \text{atm})$ is the nonlinear refractive index at a gas pressure $p = 1$ atm.

It follows from (2) and (3) that, at the maximum intensity of the fundamental mode in the capillary, the corresponding maximum spectral broadening is independent of the nonlinear refractive index of the medium and, hence, of the nature of the gas in the capillary.

The attenuation coefficient of the pulses in the dielectric capillary is [11]

$$\alpha = k\frac{\lambda^2}{a^3} = \frac{-\ln T}{L}, \qquad (4)$$

where k depends on the mode number and the refractive indices of the gas and capillary material.

Substituting the maximum intensity from (3) into (2) and expressing the inner radius of the capillary, a, through its transmittance T and length L from (4), we obtain the following expression for the maximum nonlinear phase advance:

$$\varphi_{\max} \approx \frac{0.4}{k^{2/3}}\left(\frac{L}{\lambda}\right)^{1/3}\frac{1-T}{(-\ln T)^{1/3}}. \qquad (5)$$

At a considerable spectral broadening ($F \geqslant 2$), (1) can be written in the form

$$F_{\max} \approx 0.88\varphi_{\max}. \qquad (6)$$

Let

$$K = F_{\max}\left(\frac{\lambda}{L}\right)^{1/3} \approx c\frac{1-T}{(-\ln T)^{1/3}}. \qquad (7)$$

This function depends only on the transmittance of the capillary.

Figure 1 shows the function $K(T)$. It has a maximum at $T \approx 0.16$. Also presented in Fig. 1 are experimental data from various reports. For each experimentally determined K value, we calculated the transmittance of the capillary from its length and inner diameter and the laser wavelength. Spectral broadening was evaluated from the experimental data. They agree rather well with the calculation results. In our calculations, the constant c in (7) was taken in the form $c = 0.4s/k^{2/3}$, where s is an adjustable parameter for improving the fit to the experimental data. For silica capillaries and the fundamental mode, we have $k = 0.42$. The best fit to the experimental data was obtained with $c = 0.44$ and, accordingly, $s = 0.62$.

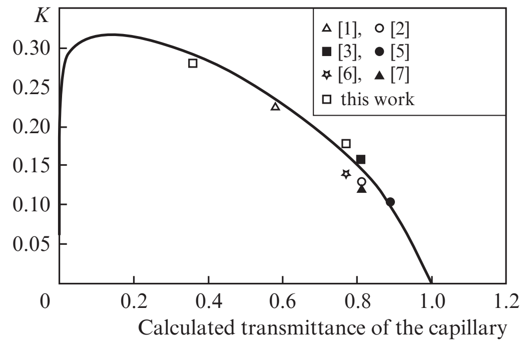

Figure 1. Calculated (solid curve) and measured (data points) K as a function of the calculated transmittance of the capillary. The data points were taken from works indicated at the symbols.

The experimental data presented in Fig. 1 were taken from studies where spectral broadening was only due to self-phase modulation and light propagated through a silica capillary in the EH_{11} fundamental mode, but the capillary length and diameter were varied widely. For example, Nagy and Simon [7] used a 3-m-long hollow fibre, whereas in this study the capillary length was 20 cm. The laser wavelength ranged from 0.5 to 1 μm.

Using relation (7) between the transmittance of a capillary (or the energy efficiency of a compressor) and spectral broadening, we can easily estimate the maximum possible spectral broadening of pulses at the output of the capillary. It follows from our calculations that, at a given capillary length, the spectral broadening has a maximum at a transmittance of 0.16. The length and inner diameter of silica capillaries are then related by

$$L \approx 4.4\frac{a^2}{\lambda^2}, \qquad (8)$$

which was obtained by putting $T = 0.16$ into (4).

The degree of compression, defined as the ratio of the pulse duration at the compressor input, τ_0, to the compressed pulse duration, τ, is determined by the spectral broadening in the gas-filled capillary and can reach a maximum equal to the spectral broadening, but usually it is slightly lower. The reason for this is that, because of the irregular form of the spectrum broadened as a result of self-phase modulation, the compressed pulse duration exceeds the duration of a pulse that has a spectrum of the same width but smooth in shape.

As follows from the above calculations, the highest degree of compression can be reached when the capillary has a transmittance from 15% to 30%. This transmittance range is rather wide because K has a flat maximum (Fig. 1). Accordingly, the energy efficiency of the capillary compressor at the maximum degree of compression will be 15% to 30%. At a given capillary length, an increase in the energy efficiency of the compressor to 70%–90% will be accompanied by about a factor of 2 drop in the degree of compression. It is in such mode (high energy efficiency and nonoptimal compression) that most compressors operate [2–7]. Note also that, at a given degree of compression, the energy efficiency of a compressor can be raised by increasing the capillary length. Since F varies as $L^{1/3}$, increasing the capillary length we can reach a particular degree of compression at a higher transmittance of the capillary. Clearly, the capillary diameter then also increases.

In what follows, we describe an experimental study of a capillary compressor, which was aimed at providing further evidence in support of the above calculation results.

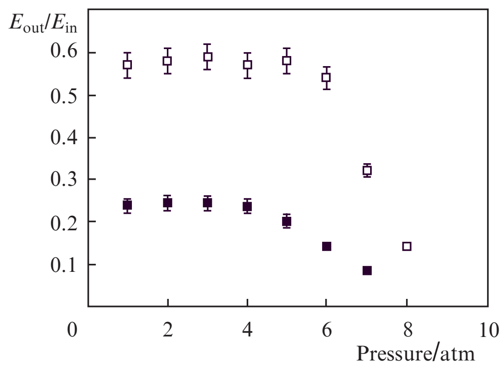

Figure 2. Ratio of the pulse energy at the capillary output to the input pulse energy as a function of xenon pressure for the capillaries with an inner diameter of 90 (■) and 140 μm (□).

3. Experimental results

In our experiments, we used a TETA-3 femtosecond ytterbium laser (Avesta Project), which generated 290-fs pulses at 1028 nm with a pulse energy of up to 150 μJ and a repetition rate of 3 kHz. The laser beam had a Gaussian profile, $1/e^2$ diameter of 4 mm and divergence of 1.05 diffraction limits.

The beam was focused onto the input end of a silica capillary placed in a 30-cm-long chamber. We used two capillaries 20 cm in length, with inner diameters of 90 and 140 μm. The focusing lens had a focal length $f = 17$ and 30 cm, respectively. The active gas used was xenon. The output beam was collimated by a lens and sent to a prism compressor. The compressed pulse duration was measured by an ASF-20 autocorrelator (Avesta Project).

Figure 2 shows the ratio of the pulse energy at the capillary output, E_{out}, to the input pulse energy, E_{in}, as a function of xenon pressure at a constant input pulse energy of 125 μJ. The ratio is seen to decrease starting at a xenon pressure of ~5 atm in the two capillaries. The drop in output pulse energy may be due to the excitation of higher order modes with increasing gas pressure. In accordance with the above, the gas pressure at which this process begins is independent of the inner diameter of the capillary. The calculated critical power in the capillary [2], $P_{cr} \approx 0.1\lambda^2/n_2$, is ~0.4 GW at a xenon pressure of 4 atm (the n_2 of xenon is 8.1×10^{-19} cm^2 W^{-1} atm^{-1} [1]), which is comparable to the laser pulse power in our experiments: ~0.4 GW. Note also that the laser beam had the highest intensity, ~1.3×10^{13} W cm^{-2}, at the input of the capillary with an inner diameter of 90 μm. At this intensity, gas ionisa-

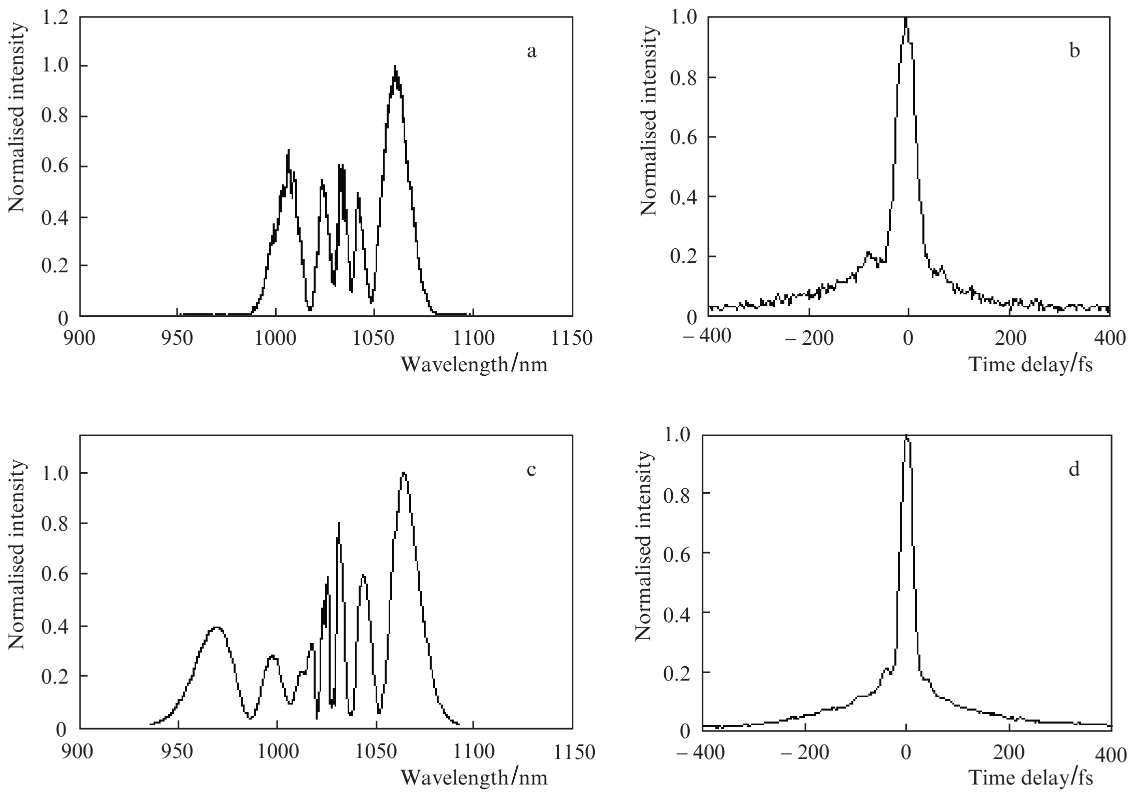

Figure 3. (a, c) Spectra of output pulses and (b, d) autocorrelation functions of the compressed pulses for the capillaries with an inner diameter of (a, b) 140 and (c, d) 90 μm.

tion is insignificant [8], as is its contribution to spectral broadening and laser light absorption.

The measured pulse energy ratio is equal to the product of the transmittance of the capillary, T, and the input energy coupling coefficient, b: $E_{out}/E_{in} = bT$. Under the conditions of our experiments, b was ~0.8. (The value of b was determined by measuring the transmittance of capillaries having the same diameter and differing in length.) The transmittance of the capillaries was ~0.7 and ~0.3 at inner diameters of 140 and 90 μm, respectively. The calculated transmittances of these capillaries are 0.77 and 0.36, respectively.

Figures 3a and 3c show the spectra of output pulses. At a xenon pressure of 4 atm, the width of the spectrum was ~70 nm for the capillary with an inner diameter of 140 μm and ~110 nm for the 90-μm-diameter capillary. The width of the spectrum at the input of the capillary was ~7 nm. Thus, the spectrum was expanded by ~10 times in the 140-μm-diameter capillary and by ~15 times in the 90-μm-diameter capillary. These results correlate with the widths of the spectrum calculated for capillaries with the transmittances in question (Fig. 1).

Figures 3b and 3d show the measured autocorrelation functions of compressed pulses. It follows from these data that the pulse duration after the compression was 31 fs for the capillary with an inner diameter of 140 μm and 20 fs for the 90-μm-diameter capillary.

4. Conclusions

We have analysed the effect of the parameters of capillary compressors on their energy efficiency and the degree of pulse compression. The results indicate that, at a given capillary length, the maximum degree of temporal pulse compression can be achieved at a 15% to 30% transmittance (and, accordingly, energy efficiency) of the compressor. The maximum degree of compression increases with capillary length, L, in proportion to $L^{1/3}$.

Based on the analysis results, 15-fold pulse compression was achieved: a 290-fs ytterbium laser pulse was compressed to 20 fs with an energy efficiency of 24% using a 20-cm-long capillary with an inner diameter of 90 μm. The experimental data obtained agree with calculation results.

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