

Flexible hollow fiber for pulse compressors

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A stretched flexible hollow fiber is proposed as a waveguide in high-energy pulse compressors. This approach leads to superior straightness virtually independent of the fiber length. It is particularly well suited for fibers with inner diameters much larger than the wavelength, where the main limitation for the fiber length is losses due to undesired fiber bending. The construction issues are discussed, and the quality of the waveguide is proved by comparing the experimental data with calculations showing that the transmission of the fiber reaches the theoretical limit and that the emerging beam is diffraction limited. © 2008 Optical Society of America

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1. Introduction

To generate ultrashort, few-cycle laser pulses, ultra-broadband radiation is necessary. Since no gain material has a sufficiently broad gain bandwidth, nonlinear spectral broadening methods have to be applied to the amplified pulses. This is especially important in the UV spectral range, because the gain materials available in this region do not support the amplification of pulses shorter than 100 fs. The spectral extension of high-energy laser pulses is usually achieved by self-phase modulation in noble gases filled into a hollow waveguide [1]. Applying this method, submillijoule pulses with durations under 10 fs have been generated in the near IR range [2]. The technique can also be applied to UV pulses [3]; however, because of the short wavelength, many issues have to be addressed for an optimized operation.

A crucial point of the technique is that the hollow fibers are multimode waveguides and the refractive index of the core material (noble gas) is smaller than that of the cladding (fused silica); therefore no total internal reflection occurs at the interface. As a result the wave guiding is not as strong as in conventional fibers, leading to larger propagation losses that limit the nonlinear interaction length. Furthermore the

losses depend very sensitively on the wavelength, the inner diameter (ID), and the straightness of the fiber [4] (see Fig. 1):

$$\alpha = \alpha_0 + \alpha_R, \quad \text{where } \alpha_0 \sim \frac{\lambda^2}{a^3} \quad \text{and} \quad \alpha_R \sim \frac{1}{R^2} \frac{a^3}{\lambda^2}. \quad (1)$$

In Eq. (1) α is the overall attenuation constant of a curved fiber, α_0 is the attenuation constant of the straight waveguide, α_R is the attenuation due to curvature of a radius of R , λ denotes the wavelength, and a is the inner radius of the waveguide. Consequently to minimize the losses, α should be minimized, but this imposes a strict criterion on the straightness of the waveguide (R_{\min} has to be large). Furthermore the losses of the fundamental mode are increasing more rapidly than those of the higher-order modes by bending the fiber. Therefore it is a key point to keep the hollow waveguide as straight as possible.

Figure 1(a) shows that by increasing the ID of the waveguide, the transmission increases. The dependence of the transmission on the wavelength is also significant; the shorter the wavelength, the higher the transmission of a straight hollow waveguide. On the other hand Fig. 1(b) shows that at short wavelengths, the transmission is much more sensitive to the curvature of the waveguide.

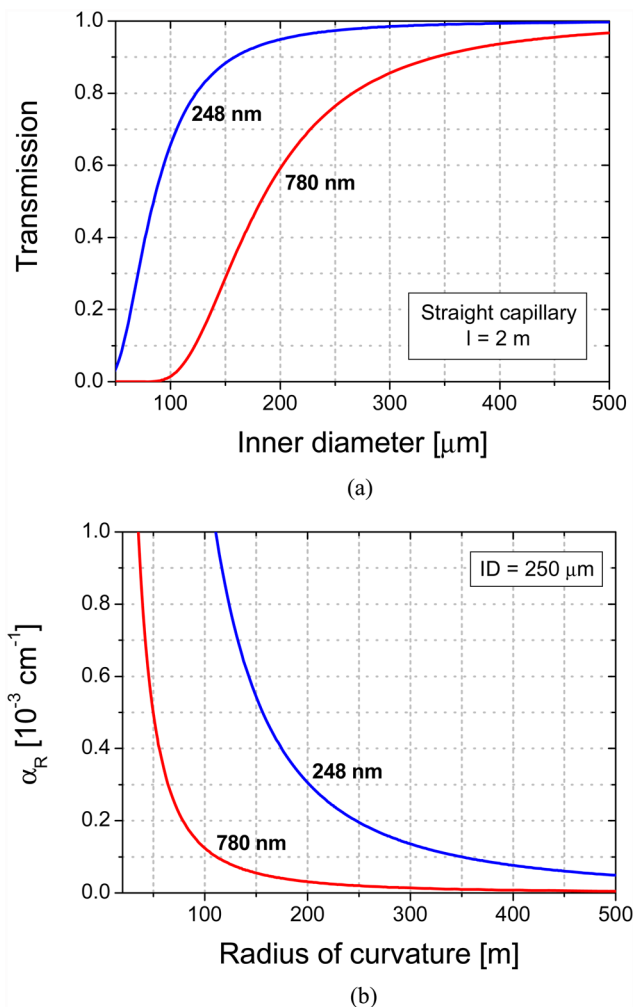


Fig. 1. (Color online) (a) Overall transmission of a 2-m-long straight hollow fiber as a function of the ID. (b) Losses due to the curvature of a fiber of 250 μm ID at 248 nm and 780 nm, respectively.

To use a hollow-fiber compressor optimally, some design criteria should be taken into account [5]: (i) to maintain single-mode propagation in the waveguide, the pulse peak power has to be lower than the critical power of self-focusing, which imposes limitation on the maximal gas pressure; (ii) the ionization limits the peak intensity, determining the minimal core radius; and (iii) the length of the fiber is limited by the propagation losses of the fundamental mode.

In current setups the input pulse energy in the near-IR range is usually not more than 1–2 mJ, while in the UV energies, only up to 10–20 μJ have been achieved due to technical difficulties arising in this wavelength range. In these cases the optimal fiber length is approximately 0.5–1 m. However, there is a demand for the compression of higher energy pulses. Taking the properties of the available noble gases into account, the compression of pulses of several millijoules in the UV and several tens of millijoules in the IR seems possible. In these cases

the cross section of the fiber has to be increased considerably due to the ionization issues, which leads to a rapid decrease of the propagation losses [see Fig. 1(a)], enabling the use of considerably longer fibers. Furthermore to prevent nonlinear effects in front of the waveguide, it is desirable to apply a pressure gradient along the capillary, which, by reducing the effective interaction length, also demands for longer fibers [6].

Even in the lower energy range, a long waveguide can provide benefits being an alternative to the more complex cascaded hollow-fiber arrangements [7] in the generation of supercontinua. We note, however, that the fiber cascading technique is clearly superior in terms of spectral broadening capability and remains the method of choice when the spectral broadening is the only figure of merit.

For the majority of present pulse compressors using a fiber that is 0.5–1 m in length, the commonly used rigid hollow fibers offer an optimal solution; however, the cases discussed above demand longer waveguides beyond the availability of rigid fibers. We propose an alternative approach using stretched flexible hollow fibers as waveguides, which allows using much longer fibers than in previous setups without introducing considerable bending losses.

2. Construction Guidelines

In a standard hollow-fiber compressor, a rigid fused silica capillary with a wall thickness of several hundreds of micrometers or even a few millimeters is used, which is typically mounted into a mechanical support over the full length (e.g., in a V-groove of a metal bar [1] or into a glass tube having an ID fitting exactly to the outer diameter (OD) of the waveguide [8]). In this case the straightness of the waveguide is mainly determined by the quality of the supporting mechanics and the wall uniformity of the fiber. According to the state-of-the-art manufacturing process, the variation of either the ID or the OD of the capillary can be minimized [9], which results in slight wall-thickness variations yielding local curvature of the core if the fiber is forced to be straight externally. Furthermore the precision manufacturing of the support becomes rapidly challenging with increasing length. These technical difficulties limit the fiber length to ~ 1 m in most of the practical cases [7], and because of the manufacturing process, much longer fibers of this sort are hardly available.

We introduce stretched flexible fibers with small wall thickness instead of rigid capillaries. Such fibers of arbitrary length are available with similar tolerances and quality to rigid fibers (see, for example, Ref. [10]).

To determine the magnitude of the force that has to be applied to properly stretch the fiber, let us suppose that the fiber is an infinitely flexible string whose ends are at the same height, and only the gravitational force described by the weight per unit length (W) and a horizontal stretching force pair (T) act on it. In this case the string forms a catenary,

which is described by the function $y = a \cosh(x/a)$, where x and y are the horizontal and vertical coordinates and $a = T/W$, respectively (the xy -coordinate system has its origin at the apex of the catenary). The catenary has the smallest radius of curvature in the middle: $R_{\min} = a$. As an example, when a force of 10 N is applied to a fiber having an ID of 320 μm , an OD of 440 μm , and a linear density of 0.1358 g/m, the resulting radius of curvature is ~ 7500 m, obviously imposing a negligible effect on the attenuation [see Fig. 1(b)]. It is interesting to note that the minimum radius of curvature depends only on the ratio of the forces and is independent of the length of the string. We also note that our assumption is rather pessimistic, because the fiber tends to stretch itself due to the manufacturing process.

Figure 2 shows the fiber unit. The support consists of a glass tube (an ID of 5 mm and an OD of 8 mm) that is pressed into a groove on the top of an aluminum profile with a cross section of 25 mm \times 50 mm. Aluminum plates are mounted at both ends of the profile, serving as an interface to an external vacuum system. The tube extends beyond the end plates and is sealed to them by O-rings. The construction allows the application of a pressure gradient between the two ends of the fiber, which is advantageous for the compression of high-energy pulses [6], because it allows us to evacuate the focal region in front of the fiber leading to an optimized beam launching by preventing defocusing effects due to ionization. In the course of manufacturing, the capillary is fed through the glass tube and pulled by a force of 10–15 N. The supporting glass tube assembly is oriented so it does not touch the stretched capillary over its entire length. The waveguide is then glued into the tube at both ends over a length of ~ 10 mm by epoxy glue. After curing, the fiber is cut within the glued regions by a diamond tool. Since the support only holds the fiber at the two ends, it is not necessary for the support to be straight; it is enough to maintain a constant shape during and after the gluing process.

3. Test of the Fiber Unit

A. Wave Guiding Properties

To demonstrate the feasibility of the proposed approach, a 3-m-long assembly has been built, and its wave guiding properties were tested. The beam of a He–Ne laser, after passing through a polarizer

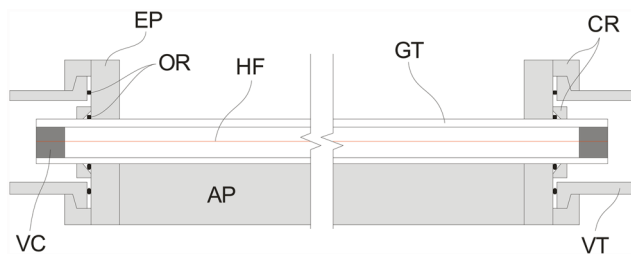


Fig. 2. (Color online) Fiber assembly. HF, hollow fiber; GT, glass tube; VC, vacuum-tight cement; AP, supporting aluminum profile; EP, end plate; OR, O-ring; CR, clamping ring; VT, vacuum tubing.

and a spatial filter, was launched into the capillary of a 320 μm ID. The mode matching ($w_0 = 0.6436a = 103 \mu\text{m}$) [11] was carefully optimized by monitoring the beam waist by a 12 bit CCD camera (Lumenera LU165M-IO). No considerable stray light was observed at the ends of the fiber. To measure the transmission of the fiber, the CW light of the laser was jagged by a chopper, and the input and output power was measured by a silicon photodiode and an oscilloscope. In this way the influence of the weak ambient light present during the experiments could be discriminated. The measured throughput of the fiber was found to be $85.2\% \pm 2.15\%$, which agrees well with the theoretical value of 86.4% (taking 98.1% launching efficiency and 88.1% transmission value for a straight fiber into account). The beam profile of the emerging beam was recorded at several distances behind the exit of the fiber by putting the 2/3 in. sensor of the camera directly into the laser beam. The frames were evaluated by commercially available beam profiler software (MrBeam). To provide optimal illumination of the CCD sensor for each beam profile of different diameters, the attenuation of the laser beam had to be varied by a factor of ~ 100 without influencing the beam launching. This was achieved by applying reflective neutral density filters placed directly in front of the fiber (coarse tuning) and by rotating a half-wave plate in front of the polarizer (fine tuning). In this way we could maintain optimal incoupling without the need of readjustment, and we were also able to measure the beam profiles very close to the fiber behind its exit. To determine the quality of the emerging beam, the measured beam profiles were compared with the calculated EH_{11} fiber mode propagating over different distances. By using the approximations that (i) the inner radius (a) is large compared with the wavelength and (ii) the mode has low losses, the electric field of the fundamental mode is linearly polarized, and its spatial distribution is cylindrically symmetrical [12]:

$$E(r) = J_0\left(\frac{u_{11}}{a}r\right) \exp i(\gamma z - \omega t), \quad (2)$$

where $u_{11} \approx 2.4048$ is the first root of $J_0(x)$, and γ is the propagation constant of the mode. The free-space propagation was calculated using the angular spectrum propagation method [13]:

$$E(r, z) = H^{-1}\left\{\exp\left(i\sqrt{k_0^2 - k^2}z\right)H\{E(r, 0)\}\right\}, \quad (3)$$

where H denotes the zeroth-order Hankel transform, and $k_0 = 2\pi/\lambda$. For the computation of the Hankel transform, Ferrari's algorithm [14] was implemented. The measured half-widths of the intensity profile at the $1/e^2$ level together with the calculated ones are plotted for a propagation range of 0.5 m as shown in Fig. 3. The cross sections of the measured and calculated beam profiles at a distance of

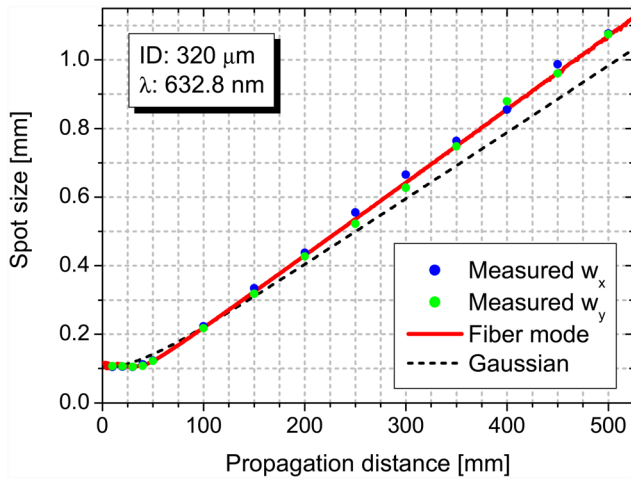


Fig. 3. (Color online) Spot size ($HW 1/e^2$) as a function of the propagation distance behind the fiber exit. The dots represent the measured values of the beam size in horizontal and vertical directions. The curves show the calculated beam sizes of the propagated fiber mode (solid) and a Gaussian beam (dashed).

0.5 m behind the fiber are shown in Fig. 4. It can be seen from the figures that both the beam size and the shape of the beam profile fit well with the calculated values, allowing us to conclude that the beam emerging from the fiber is diffraction limited. The calculation was carried out for different wavelengths and fiber radii, and it shows that the divergence and the focal region scale similarly to a Gaussian beam:

$$\Theta = \frac{\lambda}{c_a a}, \quad z_0 = \frac{c_a a^2}{\lambda}, \quad (4)$$

where Θ is the half angle of the divergence, z_0 is a characteristic length of the focal region (analog to the Rayleigh length of Gaussian beams), and

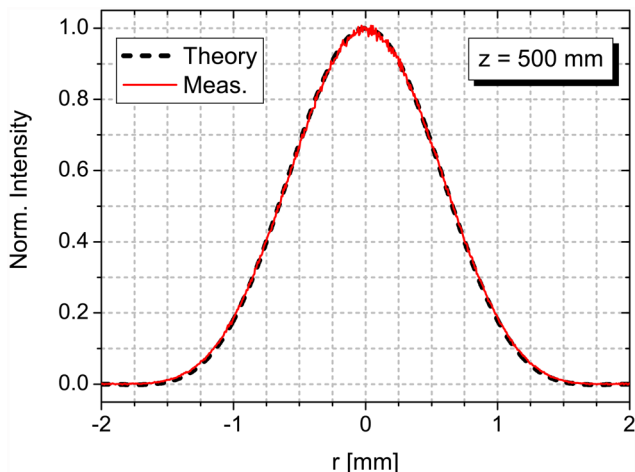


Fig. 4. (Color online) Radial distribution of the beam profile 500 mm behind the fiber exit. The solid curve is a section across the measured beam profile, and the dashed curve is the corresponding calculated curve.

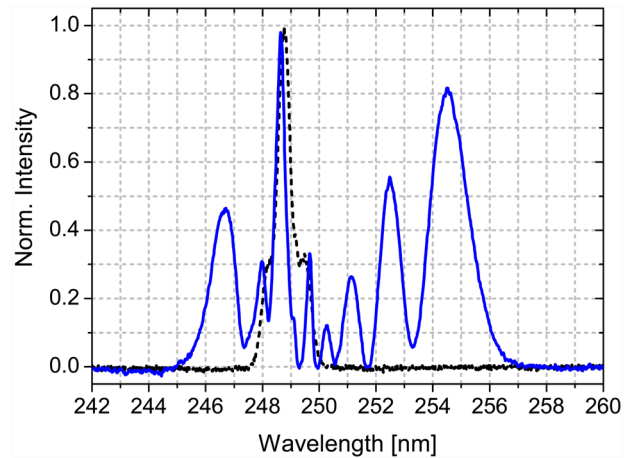


Fig. 5. (Color online) Spectral broadening in the new fiber assembly. The solid curve shows the output spectrum for an input pulse of $120 \mu\text{J}$, and the dashed curve was recorded at strong attenuation at the input (no broadening).

$c_a \approx 1.8413$ is a constant. For the case of $\text{ID} = 320 \mu\text{m}$ and $\lambda = 632.8 \text{ nm}$ (shown in Fig. 3), $\Theta = 2.14 \text{ mrad}$ and $z_0 \approx 75 \text{ mm}$.

B. Spectral Broadening

To demonstrate that the new waveguide can be successfully used in pulse compressors, a spectral broadening experiment was carried out. Optical pulses of our femtosecond excimer laser system that were 120 fs long and operating at 248.5 nm were coupled into a differentially pressurized hollow fiber of 320 μm ID. For optimal beam matching, a central portion of the flat-topped laser beam was cut by a 10 mm-diameter circular aperture and focused into the hollow fiber with an effective focal length of 5.5 m (the beam waist was monitored by a UV-sensitive CCD camera). Because of the short wavelength, the required f-number of the focusing is very large, thus necessitating a very long focusing geometry. To fit the experiment into our laboratory, a 2 m-long fiber was used. The beam launching setup in front of the fiber was evacuated, while the output side of the fiber was open, experiencing atmospheric air. The input energy was attenuated to $\sim 120 \mu\text{J}$ to get regular spectrum and clear beam profile behind the fiber. The resulting spectrum is shown in Fig. 5 (solid curve) having a bandwidth of 10 nm. For comparison a spectrum was recorded for a pulse with reduced input energy (dashed curve), where no spectral broadening was observed in the gas. Assuming a Gaussian pulse shape, one can estimate that the above pulse could be compressed to ~ 10 fs duration.

4. Conclusion

A stretched flexible capillary unit has been proposed for use in pulse compressor arrangements. The design enables us to scale up the fiber length freely, virtually canceling the bending losses. The feasibility of the approach was experimentally tested on a 3 m-long unit, and the results show that its transmission

reaches the theoretical limit and the beam emerging from the fiber is found to be diffraction limited. A further test confirmed that considerable spectral broadening can be achieved by the newly designed fiber assembly. The method we propose is also well-suited to the implementation of a pressure gradient in the hollow fiber. Because of its attributes and scalability, the stretched flexible capillary waveguide opens new perspectives for the compression of multi-millijoule laser pulses, especially in the UV spectral range where increasing the fiber lengths gives substantial advantages. Experiments on this subject are currently running in our laboratory.

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