Study on pulse compression in tapered holey fibres*

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This paper proposes three kinds of tapered holey fibres with a multi-layer of holes whose pitch of air holes at the end of untapered and tapered are 5.8 μm and 1.8 μm. The central wavelength which locates in the anomalous dispersion region is 1.55 μm. An adaptive split-step Fourier method is numerically used to study the pulse propagation in tapered holey fibres. For the considered convex tapered holey fibre, at a wavelength of 1.55 μm, a compression factor of 136.7 can be achieved by initial width of 800 fs propagation through a length of 0.8 m. It demonstrates that in anomalous dispersion region, pulse can be compressed with the increase of nonlinearity coefficient and the decrease of dispersion coefficient.

Keywords: tapered holey fibre, pulse compression, anomalous dispersion

PACC: 4280M, 4281D

1. Introduction

Holey fibre,[1,2] which is also named as microstructure optical fibre or photonic crystal fibre (PCF), has attracted wide attention recently. Holey fibre is commonly single-material-based optical fibre with air-filled holes which surround the core along the entire length, which can provide strong mode confinement to the light field, long interaction lengths and customizable wavelength dispersion. The propagation of short pulses in monomode optical fibres is affected by a number of linear and nonlinear effects.[3−13] The interplay of these effects leads to a rich variety of phenomena. The influence of different effects on pulse propagation depends on the pulse power and width and the fibre properties (such as dispersion, nonlinear properties). Therefore, the study of optical pulses, especially single ultra-short pulses propagation in PCF has generated intense interest recently.[14−18]

Tapering is a powerful post processing technique to regulate the properties of a given section of holey fibre.[19] The tapering process enhances the nonlinearity by reducing the core size. Tapered holey fibres have been used over the past few years in a variety of applications, used to couple mode,[20] to convert spot-size and numerical aperture,[21] to convert multi-to-single mode,[22] to generate a supercontinuum,[23] and soliton self-frequency shift.[24] With the rapid development of fibre-optic technology, high-quality ultra-short pulses will play a very important role in modern communication. Recently, their potential for compression of femtosecond pulse has been pointed out.[25−27]

In this paper, the tapered holey fibres are designed with regular triangular around the core and a length of 0.8 m which have a multi-layer air holes with regular triangular around the core. Here we choose 1.55 μm as the central wavelength because this region is the third window of optical communication and a very important gain window for optical fibre lasers and amplifiers.[28] The pulsed fibre-lasers have been demonstrated in this region, therefore a high quality pulse compression scheme in this spectral range is very desirable. Along with the initial Gaussian pulses of 800-fs propagation in the three kinds of tapered holey fibres with η of 0.9, 1.0, 1.1, the central wavelength of 1.55 μm locates in the anomalous dispersion region. We theoretically obtained pulse durations of 5.85 fs, 11.7 fs and 11.8 fs, respectively. We achieved a high efficient compression in a convex tapered holey fibre, and the compression factor is up to 136.7.

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2. Simulation results and discussion

The shape of tapered holey fibre is shown in Fig. 1. The parameters of tapered holey fibre can be expressed as:[29]

$$\Lambda(Z) = \Lambda(0) + [\Lambda(0) - \Lambda(L)]\left[\left(1 - \frac{z}{L}\right)^{\eta} - 1\right], \quad (1)$$

where $\Lambda(z)$ is the pitch of air holes of the tapered holey fibre at distance z, $\Lambda(0)$ and $\Lambda(L)$ are the pitch of air holes at the end of untapered and tapered holey fibres, respectively, z is the distance of the end of untapered holey fibre in the Cartesian coordinate system. L is the total length of the fibre. Based on Eq. (1), the designs of the nonuniform taper curve depends on the parameter η. When $\eta = 1$, the taper is a linear taper structure. When other values of η are substituted, nonuniform-shape tapers are obtained. When $\eta > 1$, the taper is concave as the slope decreases toward the end of the taper. Otherwise, a convex taper is obtained as the slope increases toward the end of the taper. In this paper $\Lambda(0)$ is 5.5 μm, $\Lambda(L)$ is 1.8 μm, L is 0.8 m and η are 0.9, 1.0, 1.1 respectively. The ratio of the core diameter to the pitch is $d/\Lambda = 0.5$.

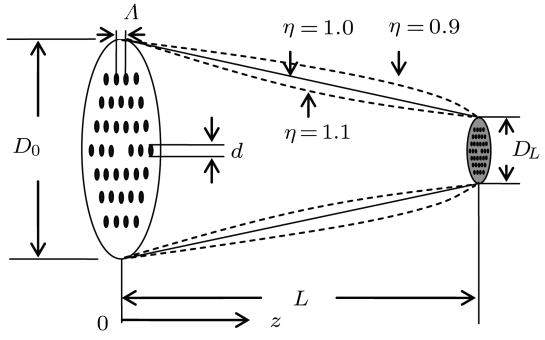


Fig. 1. The shape of tapered holey fibre.

The GVD (group-velocity dispersion) and SPM (self-phase modulation) play an important role in pulse propagation. The dispersion length $L_{\rm D} = T_0^2/|\beta_2|$ and the nonlinear length $L_{\rm NL} = 1/\gamma P_0$ provide the length scales over which dispersion or nonlinear effects become important for pulse evolution. If the pulse evolution is governed by GVD, the nonlinear effects play a relatively minor role. The pulse temporal will broaden. Pulse evolution in the fibre is governed by SPM which induced spectral broadening. Therefore, the pulse can be compressed with the increase of nonlinear coefficient and the decrease of dispersion coefficient.

In the numerical simulation, the initial laser pulse is an unchirped Gaussion pulse. The initial pulse is written as:

$$A(0,T) = \sqrt{P_0}\exp\left(-\frac{T^2}{2T_0^2}\right), \quad (2)$$

where P_0 is the peak power of pulse, and T_0 is the input pulse width (at $1/e$-intensity point). In practice, it is customary to use the full width at half maximum (FWHM) $T_{\rm FWHM}$ in place of T_0. For a Gaussian pulse, the two are related as $T_{\rm FWHM} = 2(\ln 2)^{1/2}T_0 \approx 1.665T_0$.

The tapered holey fibre is different from the uniform holey fibre, the dispersion of tapered holey fibre not only relates to wavelength but also to the diameter of core. In this paper, all of the tapered holey fibres are divided into M segments in numerical simulation. The length of each segment is expressed as l_i $(i = 1-M)$ for which the end of the untapered and tapered holey fibres is so small that it is approximately uniform ($l_i = 5$ μm).

The propagation of pulses in an optical fibre with variable dispersion and effective mode area can be described by the nonlinear Schrödinger (NLS) equation:

$$\frac{\partial U}{\partial Z} + \frac{\alpha(\omega)}{2}U + \left[\sum_{n=2}^{15}\beta_n(\omega)\frac{{\rm i}^{n-1}}{n!}\frac{\partial^n}{\partial T^n}\right]U = {\rm i}\,\gamma(\omega)\left[|U|^2U + \frac{\rm i}{\omega_0}\frac{\partial(|U|^2U)}{\partial T} - T_{\rm R}U\frac{\partial|U|^2}{\partial T}\right], \quad (3)$$

where U is the slowly varying amplitude of the pulse envelope, z is the distance of propagation, ω is the angular frequency, α is the confinement loss, $\beta_n(\omega)$ is the higher-order dispersion coefficient, $\gamma(\omega) = 2\pi n_2/\lambda S_{\rm eff}$ is the nonlinear coefficient, n_2 is the nonlinear index of silica, $S_{\rm eff}$ is the efficient core area, $T = t - \beta_1 z$ is the time parameter of the frame which is moving with the pulse at the group velocity $\nu_{\rm g}$. In order to improve the precision, we consider the coefficients $\beta_2 - \beta_{15}$ in the process of simulation. The left part of the equa-

tion shows the linear effects and the right part shows the nonlinear effects. The three terms on the right-hand side of Eq. (3) govern, respectively, the effects of SPM, self-steepening and self-frequency shift on pulse propagation inside optical fibres. The $T_{\rm R}$ is the coefficient of intrapulse Raman scattering and associated with the slope of Raman gain.

The dispersion profiles of the tapered holey fibre used in the simulations are calculated by using a fully analytical vector effective-index method. The propagation of the pulse through the optical fibre is calculated from the generalized NLS equation (3) which we solve by using an adaptive, symmetrized split-step Fourier method.[30] The variations of fibre parameters corresponding to the pulse spectrum peak with the transmission distance can be taken into account adequately in this method.

Figure 2 shows the nonlinear coefficients and the dispersion at the central wavelength of 1.55 μm as a function of distance z. Along with the pulse propagation in the fibre, the pulse at the central wavelength is in the anomalous dispersion region, and the dispersion coefficients peak at 0.64 m, 0.6 m, and 0.584 m, then decrease sharply corresponding to convex, linear and concave tapered holey fibres. The nonlinear coefficients increase from 0.00194 $\mathrm{W^{-1}\cdot m^{-1}}$ to 0.01468 $\mathrm{W^{-1}\cdot m^{-1}}$. For the convex tapered holey fibre, from 0 to 0.64 m, dispersion increases from 42.28 ps/(km·nm) to 66.21 ps/(km·nm), then it decreases rapidly to 25.90 ps/(km·nm) at the output end of the fibre.

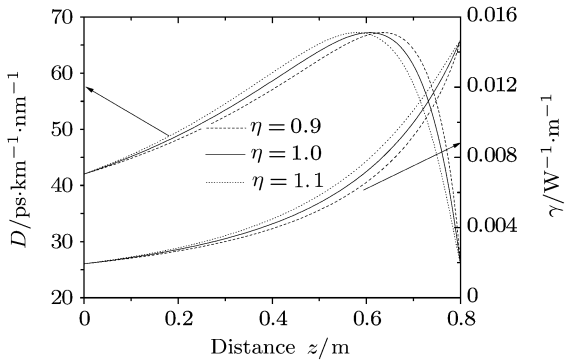


Fig. 2. The nonlinear coefficients and the dispersion coefficients at the central wavelength of 1.55 μm as functions of distance z.

Figure 3 shows the evolvement of temporal profile in the tapered holey fibres. In this paper, the initial pump laser is an unchirp Gaussian pulse and wavelength is 1.55 μm with an initial FWHM of 800 fs. The single pulse energy is 70.3 nJ and peak power is 1255 W. Along with the pulse propagation in the fibres, the peak power increases and the pedestal energy decreases. Meanwhile temporal merely changes until it propagates to 0.56 m. It demonstrated that pulse has been compressed in these three tapered holey fibres. According to Fig. 2, where the rapid increase of peak power exactly corresponds to the dispersion decreasing regime. The results fully indicate that pulse can be highly efficiently compressed with the increase of nonlinear coefficient and the decrease of dispersion coefficient. However, the efficiencies of compression are different. It is about two times bigger in convex tapered holey fibre than in the other two kinds of tapered holey fibres. In Fig. 3(d), we obtain that at the end of the three kinds of tapered holey fibres, the peak powers of pulses are up to 43681 W, 28273 W, 25608 W, respectively.

To understand the pulse shape of evolution in the convex tapered holey fibre, it is helpful to look at changes in the pulse temporal. Figure 4 shows the evolution of pulse shape when a single pulse energy of 70.3 nJ is launched at the fibre. In this figure, the x axis represents the normalized time, which ranges from -2 to 2. The y axis shows the pulse power, the peak power varies from 1.25 kW to 45.00 kW. The z axis represents distance. The temporal changes result from an interplay between the SPM and GVD effects. The SPM generates a frequency chirp such that the leading edge of the pulse is red-shifted, while its trailing-edge is blue-shifted from the central frequency. Figure 4 shows that SPM dominates the pulse evolution and produces changes in the pulse temporal. From 0 to 0.64 m, GVD and SPM nearly balance each other in such a way that pulse shape has no obvious changes along with the fibre length. From 0.64 m to the output, SPM plays a significant role during pulse propagation, the temporal changes significantly as shown in Fig. 4 for $z = 0.64$ m. It is this mutual interaction between the GVD and SPM effects that is responsible for the temporal evolution pattern. However, affected by high order dispersion, self-steepening and Raman scattering, pulse shape distortion and time delay have been observed at the end of fibre.

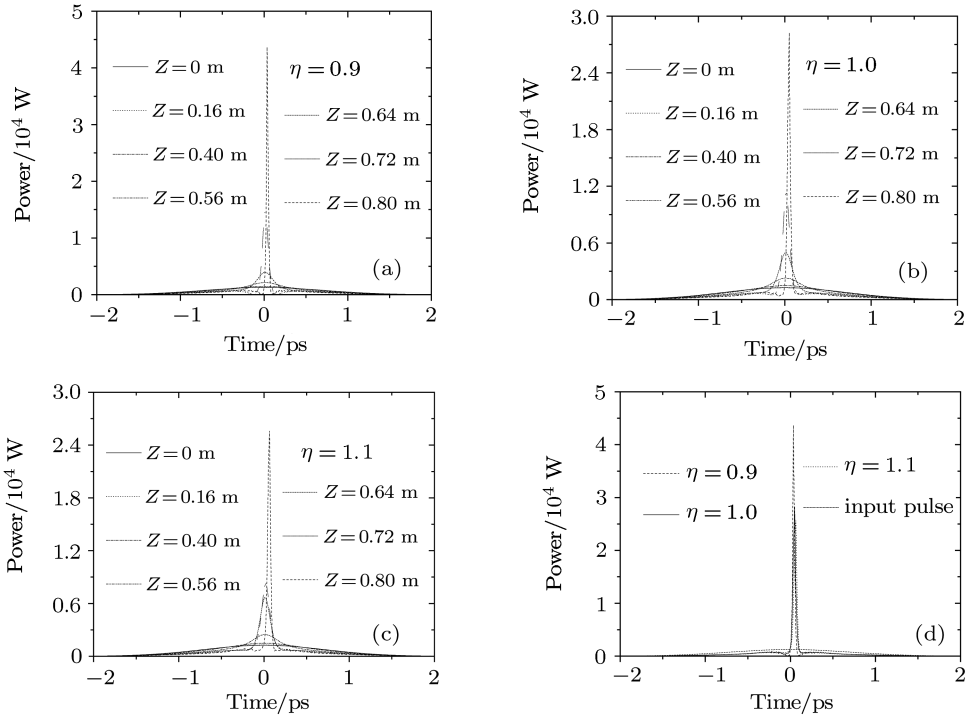


Fig. 3. Temporal profile as a function of propagation distance z for η of (a) 0.9, (b) 1.0, (c) 1.1, and the output pulses from tapered holey fibres in (d).

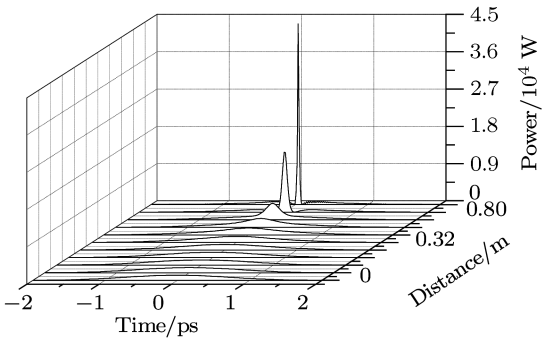


Fig. 4. Pulse shape evolution as a function of distance z.

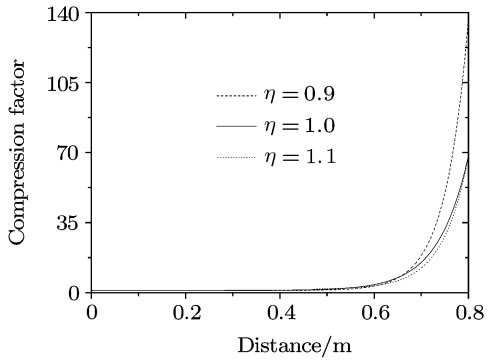


Fig. 5. Compression factor as a function of distance z.

Figure 5 shows the compression factor as a function of distance z. For all the three kinds of tapered holey fibres, from 0 m to 0.6 m, the compression factor changed very slowly, varies from 1 to 15.2, but it changes obviously from 0.6 m to the end of the fibre, it rapidly increases to 136.70, 68.37, 67.80 corresponding to the convex, linear and concave tapered holey fibres respectively which we have considered in this paper. As a result, we obtained a pulse width of 5.85 fs in a convex tapered holey fibre.

From the results, we can see that pulse has been highly efficiently compressed through these three kinds of tapered holey fibres. Even in dispersion increasing regime, the increase of the nonlinear coefficient plays a major role in pulse evolution. As a result, the compression factor varies very little, from 1 to 15.2. In dispersion decreasing regime, dispersion coefficient rapidly decreases and nonlinear coefficient increases, this effect leads to the rapid increase of compression factor, especially in the convex tapered holey fibre. For the pulse and the tapered holey fibres we have considered in this paper, convex tapered holey fibre is better for optical pulse compression, because

dispersion decreases faster in convex holey fibre than that in the other two, and the nonlinear effect increases rapidly, both effects contribute to the sharp raise of compression factor to 136.7.

3. Conclusion

We have presented a theoretical study of unchirped femtosecond Gasssian pulse propagation in three kinds of tapered holey fibres. Our analysis shows that in the anomalous dispersion regime the pulse can be highly efficiently compressed based on dispersion decrease and nonlinear increase. For the convex tapered holey fibre that we considered, pulse as short as 5.85 fs has been produced with an initial FWHM duration of 800 fs. These three tapered holey fibres will play an important role in femtosecond lasers which can be used to produce ultra-short pulse.

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