Novel Optical Pulse Stretcher using Tapered Photonic Crystal Fibers

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Abstract

Objective: The main objective of this work is to generate the stretched pulses in the time domain at 1550 nm wavelength by using novel Tapered Photonic Crystal Fibers (TPCFs). Methods/Statistical Analysis: In this paper, a new analytical technique known as self-similar scaling analysis is used to obtain exponentially varying Group Velocity Dispersion (GVD) and nonlinear profiles. Results: The outcome of the simulation shows that the sequential stretching factor is strongly reliant on the input pulse width and the propagation distance. We demonstrate the highly stretched distortion less pulses. Applications: The proposed TPCF based stretchers may find attractive applications in ultrafast optical communication and intense power fiber based systems.

Keywords: Group Velocity Dispersion, Photonic Crystal Fiber; Self-similar Analysis, Stretched Optical Pulses

1. Introduction

In recent times, optical fiber stretcher has played a vital position in the chirped pulse fiber amplifier (CPFA) system and it is the major component in rapid fiber optic systems. It is also used in material processing, optical microlithography, ultrafast fiber optic communication systems and in military. In the Chirped Pulse Amplification (CPA)12. In the recent decade, with the help of single mode fibers, we achieved pulse stretchers with advantages such as compact size, improved reliability and longer duration13,4. However, in the current optical fiber stretching units, the value of normal dispersion is considerably less; Hence a long fiber is required to attain high temporal stretching factors. As a result, the nonlinear higher order dispersion come into play, leading to pulse distortion thereby the quality of optical pulse is affected due to chromatic dispersion5.

As the PCFs exhibit unique properties, they can be used as stretcher, compressor, amplifier etc. that can find wide applications in spectroscopy, material processing, optical microlithography, medical applications and holography9–11. It is known that in the pulsed lasers sources, by means of the duration of effective pumping and the energy extraction rate of effective pumping we can determine the value of optical pulse duration. However, in certain applications, it is often essential to broaden the optical light pulses without dropping their energy. The extent of optical light pulses is enlarged by means of optical pulse stretches that temporally stretch the light pulses. Usually, an ideal optical pulse stretcher augments the duration of the laser pulses without bring in losses. Hence, the peak power of the laser may be reduced without dropping its average power12. In common, prism or grating pairs are familiar with construct a pulse stretcher. On the other hand, it has been demonstrated that the above discussed setups are not suitable in the free space optics for achieving high stretching factors as linear and nonlinear effects come into play13. Thus, it is very challenging to control
the desired dispersion profiles in the free space optics by using grating/prism pairs.

Thanks to the invention of PCFs, tailoring the optical properties by carefully tuning the structure of PCFs has become relatively easier.\textsuperscript{14,15} Especially, the GVD and nonlinear coefficient of PCFs are able to tuned by altering the pitch ($\Lambda$), the hole diameter ($d$). As a result, PCFs turn out to be precious devices for control the spectral and sequential characteristics of short pulses. Recently, by using Photonic Quasi-crystal Fibers (PQFs) pulse stretcher has been numerically demonstrated\textsuperscript{16}.

In this paper, we intend designing pulse stretchers by exploiting the optical properties of the TPCFs. The paper is planned as follows. Sec 2 presents theoretical modeling of laser pulse propagation in the TPCFs. Sec 3 discusses the prominence of design parameter pitch and diameter of hole for designing efficient pulse stretcher. In Sec 4, we present a study of pulse stretching through self similar analysis. The Figures 1a and 1b represents the geometrical structure and mode field diameter of the proposed TPCF.

\textbf{Figure 1.} (a) Geometrical structure of the proposed single mode hexagonal PCF with $d/\Lambda=0.3$ and $\Lambda=3.804\ \mu m$ (b) Mode field distribution of the proposed TPCF.

\section{2. Theoretical Model}

The optical pulse propagation in a TPCF is governed by the following modified Nonlinear Schrödinger (NLS) equation\textsuperscript{17-19}.

\[ \frac{\partial U}{\partial z} + i\frac{\beta_2(z)}{2}\frac{\partial^2U}{\partial t^2} + ig(z)|U|^2U + \frac{\gamma(z)}{2}U = 0. \]  \hspace{1cm} (1)

Here, $U$ is the envelope of the input wave, $z$ is the fiber length, and $t$ is the time in the moving reference frame. The parameters $\beta_2(z)$ and $\gamma(z)$ are the group velocity dispersion and nonlinear coefficient, respectively. $g(z)$ is the distributed gain/loss. We assume that the self similar solution of above equation is defined as,

\[ U(z, t) = \frac{1}{\sqrt{1 - \alpha_{20} |\partial U/\partial z|}} R e^{i t - \frac{t - T_c}{\tau} - i(\alpha_0(z) + i \frac{\gamma_0(z)}{2\beta_0(z)} \exp\left[\frac{G(z)}{2}\right])} \]  \hspace{1cm} (2)

Here, $G(z)$, $D(z)$, and $T_c$ are the collective gain/loss, cumulative dispersion, and the center of the pulse, respectively. The parameters $\alpha_0$ and $\alpha_2$ are the constant phase and chirp, respectively. Finally, the chirped bright solitary wave in a TPCF is given by

\[ U(z, t) = \sqrt{\frac{e^{i \alpha_{20} |\partial U/\partial z|}}{\eta e^{i\alpha_{20} |\partial U/\partial z|}}} \exp\left[i \left(\frac{t - T_c}{\tau} - i \frac{\gamma_0 |U|^2}{2\beta_0(z)} (t - T_c) - \frac{\beta_0 |U|^2}{2\beta_0(z)} (t - T_c)^2\right)\right] \]  \hspace{1cm} (3)

Here, $T_c$, $\alpha_{20}$ are the initial pulse width in ps and initial chirp $Thz^2$, respectively. Equation (3) represents the bright soliton for varying profiles of the medium, namely, $\beta_2(z)$, $\gamma(z)$, and $g(z)$. It should be pointed that there is a restriction that says that we cannot vary all the three parameters at the same time. However, we can vary any two of them by maintaining the third one a constant. So, we consider a most physically appropriate system having the gain/loss as a constant and the GVD and nonlinear coefficient vary along the propagation direction. On this point, the GVD and nonlinear coefficient vary in the following way:

\[ \beta_2(z) = \beta_{20} \exp(-\sigma z) \]  \hspace{1cm} (4)

\[ \sigma = 2\alpha_{20} \beta_{20} \]  \hspace{1cm} (5)

\[ \gamma(z) = \gamma_0 \exp(\rho z) \]  \hspace{1cm} (6)

where, $\beta_{20}$, $\gamma_0$ are the initial GVD, nonlinear coefficient, $\sigma$ is decay rate and $\rho$ is the growth rate. Thus these self similar conditions are help to design a self similar TPCF to get efficient stretched pulses.

\section{3. Self Similar Conditions: Designing TPCF Stretcher}

In this section, we explore if there are any other chances to generate the chirped solitary waves for various choices of positive and negative exponentially varying GVD and nonlinear coefficient. It is known that while the dispersion decreasing profile facilitates the compression of the laser pulses, the dispersion increasing profile supports the pulse stretching. Thus, in this section, we focus on the dispersion increasing profiles to design the pulse stretcher. It
has been shown that the chirped solitary wave does exist even for the following two cases.

i) Increasing GVD and decreasing nonlinear coefficient
\[ \beta_2(z) = \beta_{20} \exp(\sigma z) \] (7)
\[ \gamma(z) = \gamma_0 \exp(-\rho z) \] (8)

ii) Both GVD and nonlinear coefficient increase
\[ \beta_2(z) = \beta_{20} \exp(\sigma z) \] (9)
\[ \gamma(z) = \gamma_0 \exp(\rho z) \] (10)

In what follows, we examine the progresses of these chirped solitary waves by appropriately designing various TPCFs. The following two possibilities are described for designing the tapered PCF through self similar conditions to get stretched pulses.

### 3.1 Increasing GVD and decreasing nonlinear coefficient

From the analytical results of equations (7) and (8), we start the analysis to design the TPCF of increasing GVD and decreasing nonlinear coefficient profiles at 1550 nm. We obtain the required profiles by randomly varying the design parameters such as diameter of air hole and pitch. In the proposed TPCF, we decrease the diameter of air hole and keep the pitch as constant. We choose the PCF of length \( L = 1.49 \) km which is four times the dispersion length \( \left( L = 4L_D \right) \) where \( L_D = 373.41 \) m. Here, the relative air hole diameter \( d/\Lambda \) varies exponentially from 0.3 to 0.2804, the diameter of the air hole \( d \) varies from 1.141 \( \mu m \) to 0.953 \( \mu m \) and \( \Lambda \) varies exponentially from 3.804 \( \mu m \) to 4 \( \mu m \).

To study the self similar pulse stretching at 1550 nm, we design the PCF in such a way that it provides a maximum possible GVD, which leads to low dispersion length \( L_D = T_0^2/\beta_2 \) within single mode regime. Here \( T_0 \) and \( \beta_2 \) are the pulse width and GVD, respectively. For this case, the initial medium’s parameters are given as follows: \( D_0 = 0.6760 \) ps/nm.km, \( \beta_{20} = -0.8616 \) ps\(^2\)/km, \( \gamma_0 = 2.714 \) (Wkm\(^{-1}\)), \( L_D = 373.4 \) m, input FWHM (Full Width at Half Maximum) = 1 ps, \( T_0 = 0.56721 \) ps.

### 3.2 Both GVD and Nonlinear Coefficient Increase

From the Eqns. (9) and (10), we design the PCF for both increasing in dispersion and nonlinearity parameters at 1550 nm. In this case, the design parameters, namely, pitch and relative air hole diameter, \( d/\Lambda \), are varied arbitrarily. While tapering the PCF, we decrease the diameter of the air hole and keep the pitch as constant. For this case, the initial parameters are given as follows: \( D_0 = 5.404 \) ps/nm.km, \( \beta_{20} = -6.8877 \) ps\(^2\)/km, \( \gamma_0 = 3.30851 \) W\(^{-1}\).km\(^{-1}\), \( L_D = 46.745 \) m, FWHM= 1 ps, \( T_0 = 0.56721 \) ps.

We choose the PCF of length \( L = 187 \) m which is four times the dispersion length \( L_D = 46.74 \) m. Here, the relative air hole diameter \( d/\Lambda \) varies exponentially from 0.2653 to 0.2838, the pitch \( \Lambda \) varies from 2.45 \( \mu m \) to 2.29 \( \mu m \) with the diameter of the air hole being a constant \( d = 2.45 \mu m \).

### 4. Result and Analysis

#### 1.1 Increasing GVD and Decreasing Nonlinear Coefficient

Having computed the required optical properties by designing the tapered PCFs, in this section, we perform the pulse stretching by solving the modified NLS equation numerically. The following Table 1 shows the important pulse parameters, namely, pulse width and energy before and after stretching the laser pulses.

| S. No | Parameter | Initial value | Final Value |
|------|-----------|--------------|-------------|
| 1    | Width     | 0.56721 ps   | 4.5249 ps   |
| 2    | Energy    | 1.1194 J     | 0.2514 J    |

In Figure 2, the blue and green curves represent input and output pulses, respectively. At this juncture, it is essential to analyze an important factor known as Pulse
Novel Optical Pulse Stretchers using Tapered Photonic Crystal Fibers

Stretching Factor (PBF) which is defined as the ratio of the (FWHM) of the input and output pulses. Figure 3 represents the variation of PBF against pulse width for various lengths of the fiber.

From Figure 3, it is clear that the PBF is highly dependent on the length of the fiber and pulse duration. For the total length of the fiber $Z=4L_D$, we get the PBF as 2.1 that is gradually decreases when we increase the pulse duration. Thus, it is very clear that the proposed stretcher generates highly distortion less stretched pulses.

4.2 Both GVD and Nonlinear Coefficient Increase

Next, we carry out the stretching analysis for the other case. The following Table 2 shows the important pulse parameters, namely, pulse width and energy before and after stretching the laser pulses.

| S. No. | Parameter | Initial value | Final Value |
|-------|-----------|---------------|-------------|
| 1     | Width     | 0.56721ps     | 5.4740ps    |
| 2     | Energy    | 7.3405 J      | 1.1331 J    |

As has been discussed in the above case, using the computed physical parameter values, we once again solve the NLS type equation numerically Figure 4 depicts input pulse as well as output pulse which is highly broadened in time domain. The pulse stretching ratio is clearly presented in Figure 5 for various values of fiber length. We get the PBF as 4.6 when length of the fiber $Z=4L_D$.

5. Conclusion

We have designed two novel fiber stretchers, one, based on GVD increasing and nonlinear coefficient decreasing profiles and the other, based on both GVD and nonlinear coefficient increasing profiles, using TPCFs. We have
demonstrated numerical simulation on the propagation of chirped hyperbolic secant pulses in these fibers. We have been able to generate highly stretched distortion less pulses. We envisage that the proposed pulse stretchers may be useful for stretching the low energy optical pulses in the chirped pulse fiber amplifier system.

6. References

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