Design of an Efficient and a Compact Optical Pulse Compressor Using a Tapered Photonic Crystal Fiber

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Abstract— Ultrashort pulses (USPs) at wavelengths down to the communication window with a high repetition frequency range (GHz-THz) have found wide applications, especially, in bio-photonic sensors, optical coherence tomography, materials processing, etc.. There are some desirable features that USPs need to satisfy such as being pedestal-free and transform-limited for their suitability in communication as well as non-communication based applications. However, it is very difficult to meet out these desirable characteristicseven with carefully configured laser system. Hence, pulse-compression techniques have been the ultimate solution for generating USPs, in recent times.

Having realized the importance of generating USPs through pulse compression, we aim at designing a novel practicable pulse compressor using a tapered photonic crystal fiber (PCF) operating down to ultraviolet regime. The pulse propagation in a tapered PCF is governed by the nonlinear Schrdinger (NLS) type equation. We adopt the self-similar scaling analysis for generating USPs. Based on the analytical results, we model a tapered PCF such that the dispersion decreases exponentially while the nonlinearity increases exponentially along the propagation direction. Here, the required tapering is achieved by exponentially decreasing the diameter of the air hole as well as its pitch. We envisage that the proposed pulse compressor would turn out to be an excellent tool for generating high quality USPs down to ultraviolet regime, which, in turn, might be very much useful in bio-photonic related applications.

1. INTRODUCTION

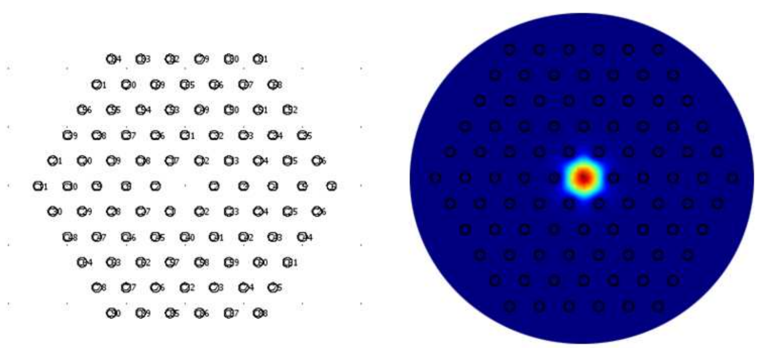
There has been remarkable progress over the past two decades in the generation of USPs using photonic crystal fibers because of their wide applications in the fields of medicine, science, engineering and technology. Although there are several techniques in vogue for generating USPs, pulse compression technique stands unique for several reasons [1]. Pulse compression in fiber was first investigated by Mollenauer et al. [2]. Generally, optical pulse compression is categorized into two types, namely, linear compression and nonlinear compression. Using a dispersive fiber delay line or grating pairs, linear compression of chirped pulses has been demonstrated [1, 3]. Recently, several nonlinear pulse compression techniques, namely, adiabatic pulse compression, soliton pulse compression and self-similar techniques have evolved and these techniques generally rely on the interplay between the self-phase modulation (SPM) and group velocity dispersion (GVD) [1].

Photonic crystal fibers are ideal media for generation of USPs owing to the design flexibility in controlling the mode propagation properties [4]. PCF consists of a central defect region surrounded by periodic air holes. Controlling the dispersion becomes an important issue in the case of practical optical communication systems [5]. It is obvious that, in PCFs, one can easily control the dispersion by appropriately choosing the designing parameters such as the air hole spacing Λ and the air hole diameter d [6]. By varying the arrangement and size of the air holes, the fiber dispersion can be tailored in broad ranges. Recently, Travers et al. have demonstrated the adiabatic pulse compression at 1.06 µm in a dispersion and nonlinearity varying PCF [10]. It has been demonstrated that the dispersion and nonlinear profiles could be engineered through the tapering process which has been achieved by simultaneously stretching and heating to post-process the fiber [8, 9]. In general, the tapering is done by reducing the pitch and diameter. Fiber tapering provides a convenient way to reduce the mode-field diameter (MFD) of fibers, thereby allowing for a better pulse compression [10–12]. We, thus, emphasize that the tapered PCFs are very much suitable for effective pulse compression studies when compared to conventional PCFs.

In this paper, we investigate the variations in optical properties, namely, the group velocity dispersion (GVD) and non-linearity along the propagation direction. Recently, the efficient pedestal-free pulse compression has been demonstrated using a PCF with an exponentially decreasing dispersion and increasing non-linearity profiles [10, 11].

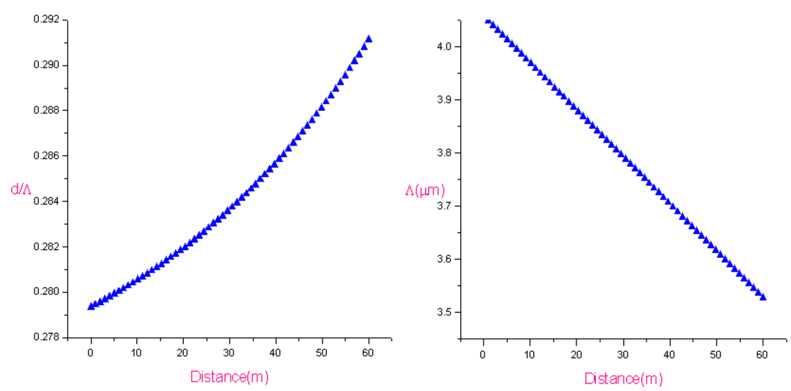
2. DESIGNING TAPERED PCF

In the proposed geometric tapered structure,there are 4 sections containing 5 rings of air holes. Tapered PCF can be designed by simultaneous reduction of its geometrical parameters, namely, diameter d, and pitch (Λ). In this work, the physical parameter $d/(\Lambda)$ (air filling fraction) is varied exponentially from 0.2796 to 0.2910 and pitch is varied from 4 to 3.5 µm. While tapering the PCF, we decrease the diameter of air hole as well as the pitch. Fig. 1 illustrates the schematic view of the tapered PCF that is designed using finite element method (FEM) [12]. Fig. 2 shows the exponentially decreasing $d/(\Lambda)$ and (Λ) along the fiber length.



(a) (b)

Figure 1: (a) Geometrical structure and (b) mode field distribution of the proposed tapered PCF with $d/(\Lambda)0.2796$ and $(\Lambda)4$ µm.



(a) (b)

Figure 2: (a) The variation of PCF parameter d/Λ along the propagation distance and (b) the physical parameter profile for tapered PCF with Λ along the propagation distance.

3. STUDY OF OPTICAL PROPERTIES

3.1. Dispersion

In this section, we delineate the important linear effect called group velocity dispersion. It is known that the dispersion does depend on both operating wavelength and the physical parameters such as core diameter and pitch. The dispersion parameter, D is determined from the second derivative of the computed n_{eff} value using finite element method. Fig. 3 depicts the variation of calculated dispersion with respect to distance. From Fig. 3, it is clear that the proposed tapered PCF exhibits anomalous dispersion which decreases exponentially from 75.3 to 5.9 ps/nmkm. The values of core diameter and pitch affect the GVD [13]. The dispersion value of the tapered fiber is calculated by using equation $D = \frac{\lambda}{c}\frac{d^2n}{d\lambda^2}$. Fig. 3 depicts the variation of calculated dispersion with respect to distance.

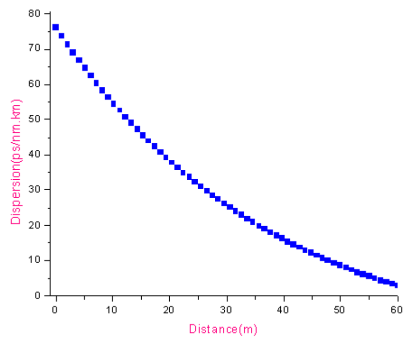


Figure 3: Variation of dispersion with respect to propagation distance.

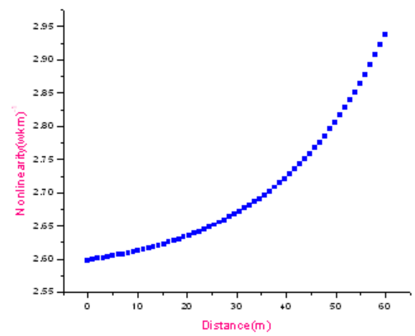


Figure 4: Variation of effective nonlinearity of the tapered PCF.

3.2. Nonlinear Property

By utilizing the A_{eff} value through FEM for different four PCF structures, the nonlinearity coefficient of the tapered fiber is computed using eqn $\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$ where n_2 value is $2.3 \times 10^{-20}\,\mathrm{m}^2/\mathrm{W}$, which can be calculated using various nonlinear method [1]. The effective mode area of the fundamental mode is calculated using finite element method and the initial value of A_{eff} is found to be $0.3602\,\mu\mathrm{m}^2$ and its final value is $0.3169\,\mu\mathrm{m}^2$. The decrease in effective area leads to significant enhancement in the nonlinear effect and consequently the intensity of the compressed pulses goes high. In Fig. 4, it is very clear that the non-linearity increases exponentially along the propagation distance. Increasing nonlinearity does result in high intensity of pulses. Nonlinearity is increased exponentially from 2.587 to $2.940\,\mathrm{W}^{-1}\mathrm{m}^{-1}$).

4. DESIGNING TAPERED PCF THROUGH SELF SIMILAR ANALYSIS

The nonlinear pulse propagation in a tapered PCF is described by the following modified NLS equation with the varying dispersion and the nonlinearity [14, 15].

$$\frac{\partial U}{\partial z} + i\frac{\beta_2(z)}{2}\frac{\partial^2 U}{\partial t^2} - i\gamma(z)|U|^2U = 0, \tag{1}$$

where U is the slowly varying envelope of the wave, z is the longitudinal coordinate, and t is the time in the moving reference frame. The parameters β_2 and γ are the second order dispersion coefficient and Kerr nonlinearity, respectively. We assume that the self-similar solution of above equation is given by

$$U(z,t) = \frac{1}{\sqrt{1-\alpha_{20}D(z)}}R\left[\frac{t-T_c}{1-\alpha_{20}D(z)}\right]\exp\left[i\alpha_1(z) + i\frac{\alpha_2(z)}{2}(t-T_c)^2\right] \tag{2}$$

The self-similar solution is possible if and only if the following conditions are satisfied [16]:

$$\beta_2(z) = \beta_{20}\exp(-\sigma z) \tag{3}$$
$$\sigma = \alpha_{20}\beta_{20} \tag{4}$$
$$\gamma(z) = \gamma_0\exp(\rho z) \tag{5}$$

where β_{20}, γ_0, σ and ρ are the initial dispersion, nonlinearity, decay rate and growth rate, respectively. Based on the analytical results, we model a tapered PCF such that the dispersion decreases exponentially while the nonlinearity increases exponentially along the propagation direction. Here, the required tapering is achieved by exponentially decreasing the diameter of the air hole as well as its pitch. We point out that the results pertaining to the generation of USPs will be published elsewhere.

5. CONCLUSION

In conclusion, we have successfully designed a tapered PCF at 1550 nm by increasing the air filling fraction $d/(\Lambda)$ and decreasing pitch (Λ) along propagation direction. In this tapering, dispersion is exponentially decreased and nonlinearity is exponentially increased along the fiber length. The generation of ultrashort pulses at 1550 nm can be used in telecommunications applications, ultrahigh optical data rate systems and used in bio-photonic related applications.

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