Ultra short Pulse Generation at 1550 nm using a Tapered Photonic Crystal Fiber (PCF)

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ABSTRACT
This dissertation aims at generating extremely short laser pulses, popularly referred to as UltraShort Pulses (USPs) whose pulse duration ranges from Pico second to a few Femto seconds. In this work, we attempt at a novel design of a class of fiber called photonic crystal fiber (PCF) new wherein the optical properties, namely, dispersion and nonlinearity decrease exponentially along the propagation direction.

General Terms
Finite Element Method, Nonlinear Schrödinger Equation.

Keywords
Photonic Crystal Fiber, Pulse compression, Split Step Fourier Method.

1. INTRODUCTION
ULTRASHORT pulse laser is a very important light source in the fields of optoelectronics, ultrafast optical measurements, optical chemistry, and ultrafast spectroscopy. Pulse compression process is found to be one of the best techniques to obtain Ultrashort pulses by means of optical fibers [1], [2]. Pulse compression in fiber was discovered by Mollenauer *et al*. [2] to generate ultrashort pulses. The recent work widespread research work on pulse compression in PCF is mainly motivated by nonlinear applications in telecommunication, Optical metrology, Optical coherence tomography (OCT) and sensor. Among these applications, the pulse compression at 1.55μm wavelength has many applications in telecommunications, ultra-broadband SC generation and biotelemetry.

PCFs also called holey fibers or microstructured fibers commonly consist of a fused silica core surrounded by a regular array of air holes running along the fiber length[3][4].They have the advantage of design flexibility in controlling the mode propagation properties. By varying the arrangement and size of the air holes, the fiber dispersion can be tailored in broad ranges [3][4]. Therefore, PCF is very much suitable for pulse compression in telecommunication window. In order to generate ultrashort pulses in PCFs requires a much high pump power and a short input pulse width.

In general, Tapering can be done by reducing the pitch and radius very much suitable for pulse compression applications. Fiber tapering provides a convenient way to reduce the mode-field diameter (MFD) of fibers, thereby allowing for a better pulse compression [5].

Optical Solitons formed as a result of the interplay between the dispersive and nonlinear effects. The word soliton refers to special kinds of wave packets that can propagate undistorted over long distances. In the case of fundamental Solitons (N=1) both dispersion and nonlinear balance each other and pulse shape doest change along the fiber[1].Soliton pulses can have bit rate upto160Gbit/s and beyond in telecommunication window. Moore's suggested that chirped solitary waves can be compressed more efficiently if the dispersion decreases approximately exponentially [7]. So we decrease both dispersion and nonlinearity exponentially for our requirements.

In this paper, we investigate the optical properties, such as dispersion and non-linearity in tapered PCF for various conditions of geometric parameters .we mainly utilize [6] and [7] which state that efficient pedestal-free Solitons pulse compression is possible using PCF with an exponentially decreasing dispersion and increasing non-linearity profiles. But in this paper, we proposed a new design where optical properties like dispersion and nonlinearity both decreases exponentially in order to study pulse compression applications .In general, tapering the dispersion and nonlinearity in optical fibers are challenging tasks. But in PCF it possible to tailor the dispersion and nonlinear properties by choosing proper air hole size and pitch.

2. DESIGN OF TAPERED PCF
A micro structured fiber consists of a periodic array of air holes with central defect acting as the core with the optical parameters of the fiber being completely determined by the pitch Λ and the ratio of diameter to pitch d/Λ. Finite Element Method (FEM) was used to solve the dispersion and non-linearity.

The geometric structure of hexagonal lattice with 5 rings of air holes was used. Tapered PCF can be designed by simultaneous reduction of its geometrical parameter (pitch) and d/Λ. Significant short pulses were obtained through experimentally and numerical simulation using pulse compression techniques at various wavelength by dispersion decreasing and nonlinearity increasing PCF [5].Our aim to study pulse compression at 1550nm and obtaining maximum dispersion to reduce dispersion length L_D in order to maximize compression factor. By choosing a proper air hole size and pitch, one can achieve maximum dispersion in PCF.

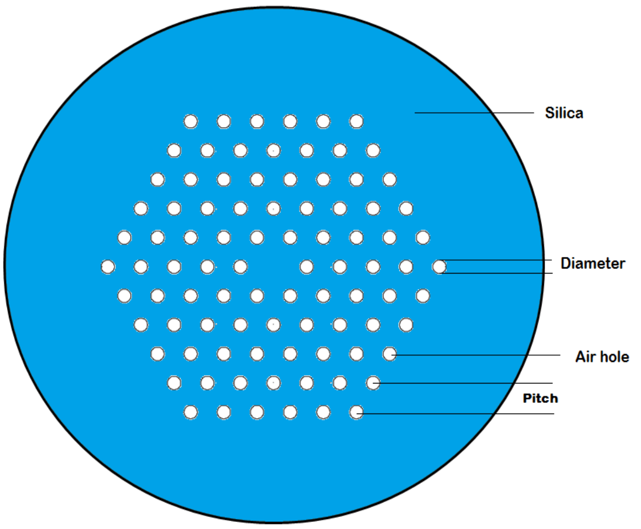

Fig 1. Schematic view of Tapered PCF.

In these work, silica core PCF has been used, where the core is filled with silica surrounded by numerous air hole cladding. Fig (1) illustrates the schematic view of Tapered PCF whose parameters are d/Λ=0.4μm and Λ=2.9μm.Both parameter varied exponentially along propagation distance in the tapered PCF where d/Λ varies from 0.4 to 0.2 shown in Fig 2 and Λ varies from 2.3μm to 4μm.The dispersion and nonlinearity profile fully depend on d/Λ and Λ profile. Moore's law states that efficient compression can be achieved if dispersion decreases exponentially. In order to decrease the dispersion exponentially both geometric parameter have varied exponentially

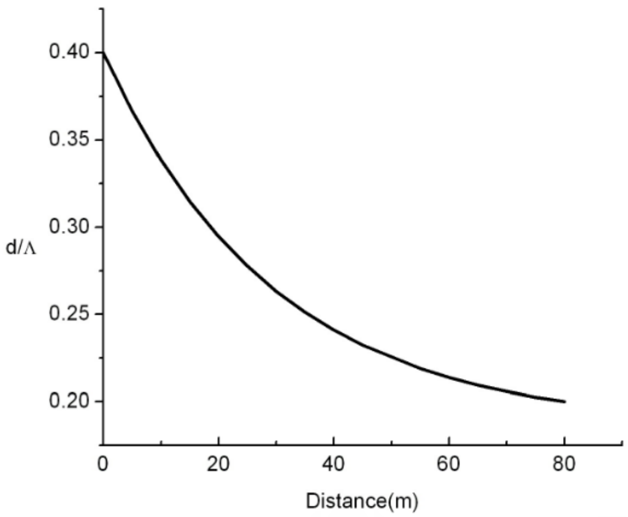

Fig 2. Variation of PCF parameter d/Λ along the propagation distance

If d/Λ ≤ 0.4 PCF will act as endless single mode [1].The value of d/Λ used in this design less than 0.4 therefore it acts endlessly single mode over wider wavelength ranges.

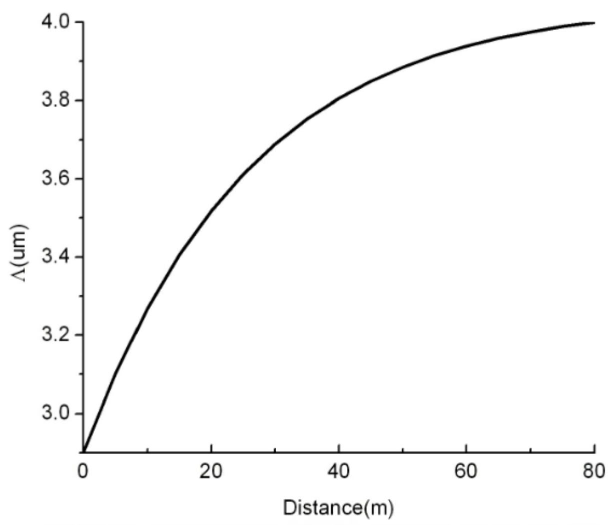

Fig 3.Variation of PCF parameter pitch (Λ) along the propagation distance

3. CHROMATIC DISPERSION AND NONLINEARITY

The dispersion characteristics of PCF are investigated by taking into account the refractive index of pure silica by means of the Sellemier formula, while the index of air is assumed constant. The dispersion *D* is given as

$$D = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} \quad (1)$$

Where λ is operating wavelength, n is effective refractive index, and c is the velocity of light in a vacuum.

$$\beta_2 = -\frac{\lambda^2}{2\pi c} D \quad (2)$$

β_2 is second dispersion coefficient. This equation shows relation between dispersion and Group Velocity Dispersion (GVD) parameter. If β_2 is negative, then it is anomalous GVD .From this design, maximum dispersion of 29.308(ps/nm-km) and minimum dispersion of 3.5(ps/nm-km) was obtained and its profile is decreased exponentially. From (2) calculated initial value of β_{20}= -0.037411ps^2/m.The anamalous dispersion support optical solitons pulses[1].According to [4] if the end point of the close to zero dispersion compression factor of 20 and higher is possible in theory.

Nonlinearity of tapered PCF γ given by,

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (3)$$

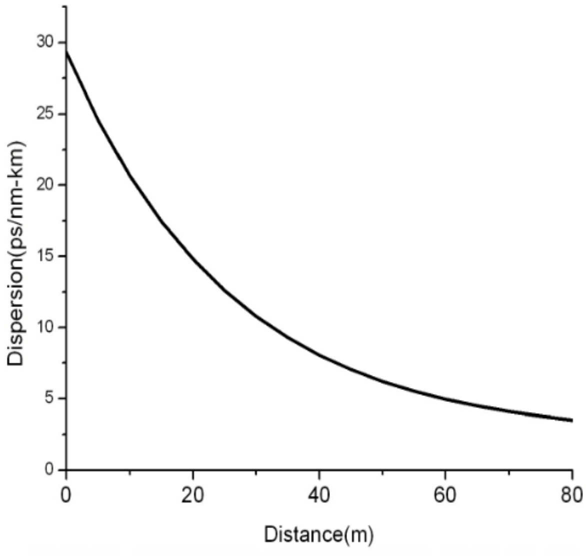

Fig 4. Dispersion profile along distance

Where n_2=2.3*$10^{-20}$$m^2$/W (non-linear co-efficient for silica).A_{eff} is effective core area..Fig.5 shows non-linearity decreases exponentially along a distance. High nonlinearity will results in high intensity of pulse. Nonlinearity have decreased exponentially from (0.006383934 to 0.001319635) wm^{-1}.

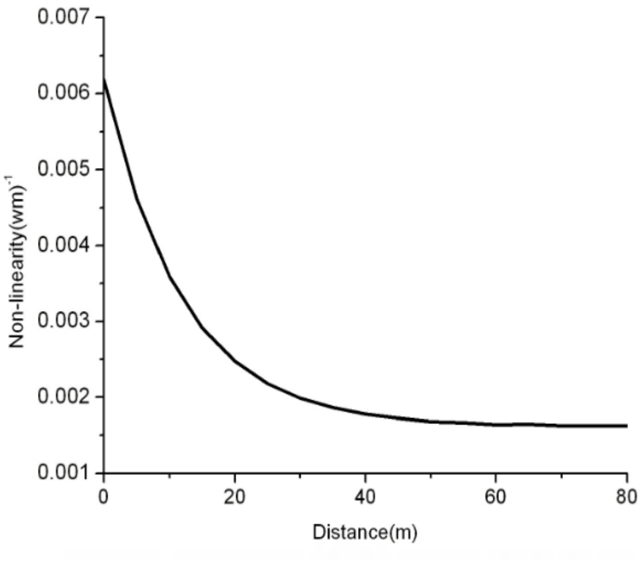

Fig 5. Nonlineartiy profile along distance

4. ANALYSIS OF PCF

Soliton is a term used to refer to a wave that propagates with constant shape over time and space, which may not sound unusual since most waves traveling in a linear, non-dispersive medium, exhibit that property. What makes soliton different is that they propagate with a constant shape in a nonlinear dispersive medium in a way that can be described by the Nonlinear Schrödinger equation,

$$\frac{\partial U}{\partial Z}+i\frac{\beta_2(Z)}{2}\frac{\partial^2 U}{\partial t^2}-i\gamma(Z)\,|U|^2\,U=0 \qquad (4)$$

Where U is the slowly varying envelope of the wave 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. To investigate the compression in PCF, we numerically solve (4) using Split Step Fourier Method with initial envelope of the soliton for the peak power $P0$ at z= 0.

$$U(Z,t)=\sqrt{Po}\,\sec h(\frac{t}{To})\exp(-\frac{iCt^2}{2To^2}) \qquad (5)$$

The hyperbolic-secant pulse shape that occurs naturally in the context of optical solitons and pulses emitted from some mode-locked lasers which equation (5) is going to be input pulse, where C is chirp parameter to controls initial chirp. The Full Width Half Maximum (FWHM) is related by

$$T_{FWHM}=2\ln(1+\sqrt{2})To \qquad (6)$$

Where T_0 is initial pulse width. It depends on fiber length and β_2. Decrease in β_2 will reduces the twice amount of output pulse width. To study the pulse propagation in PCF in the telecommunication window the optical properties, both dispersion and nonlinearity are equally important.

5. PULSE COMPRESSION

When a fiber is operated in the anomalous dispersion regime, it is possible to excite optical solitons that propagate without distortion by canceling the effect of group-velocity dispersion (GVD) through SPM. Soliton formation in optical fiber with anomalous dispersion is well understood [2]. Soliton compression is used to compress the pulses where the linear chip can be compensated by negative GVD Parameter and produces shortest pulses. But in the case of fiber with positive GVD, generally broadens pulse spectrum[9].The two important parameters for determining evolution of pulses in PCF are nonlinear length $L_{NL}$and dispersion length L_D.

$$L_D=\frac{To^2}{|\beta_2|} \qquad (7)$$

$$L_{NL}=\frac{1}{\gamma Po} \qquad (8)$$

where P_0 is the input peak power. When the input peak power is calculated from equation (7) and (8).For the fundamental soliton $L_D = L_{NL}$.The temporal pulse compression is based on soliton propagation in optical fiber may be realized through the interplay of the SPM and anomalous-GVD effects, by which a lot of pulse compression techniques have been developed. When P_o is sufficiently low, the soliton dynamics may be insignificant.

The hyperbolic secant pulse propagates in the anomalous-GVD regime of the fiber and is compressed through interplay between SPM and GVD. Compression factor is defined as ratio of FWHM of input pulse (T_{FWHM}) and the FWHM of output compressed pulse (T_{comp}) [8].
The pulse compression factor is approximately given by,

$$F_c = 1 + 0.6\frac{N^2 L}{L_D} \tag{9}$$

The study of temporal compression factor is used to invesitigate the pulse compresion in the anamalous dispersion regime.

6. CONCLUSION

In conclusion, we have been successfully designed a tapered PCF at 1550nm by decreasing the geometric parameter d/Λ and increasing pitch (Λ) along distance. In this tapering, both dispersion and nonlinearity exponentially decreased along a distance which is very much suitable for pulse compression applications. The Generation of ultrashort pulses at 1550nm can be used in telecommunications applications, ultrahigh optical data rate systems and used in OCT for imaging purpose.

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