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Optical Pulse Compression and its Effects Using Fiber Bragg Grating

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***Abstract*— The optical pulse compression is analyzed by NLSE using Fiber Bragg Grating (FBG) with the help of second order dispersion. A comprehensive study on the effect of frequency detune, coupling coefficient, figure of merit, and compression factor is done. The variation of frequency detuning and coupling coefficient with respect to the length of the grating is also studied. The compression and distortion of the optical pulses is studied with the concept of Full width at half maximum (FWHM) is also done. FWHM plays an important role in determining the compression of optical pulses. From the FWHM results we can able to obtain the rate at which the pulse is compressed.**

***Index terms*—compression, dispersion, FBG, FWHM, optical pulse**

I. Introduction

In the areas of telecommunications, photonics, ultrafast spectroscopy ultrashort pulses plays a significant role. The two commonly used optical pulse compression schemes are the higher order soliton compression and the adiabatic soliton compression. Higher order soliton compression suffers from significant pedestal generation in optics which causes intersymbol interference in telecommunication systems. Adiabatic soliton compression needs slowly varying dispersion and the maximum compression factor (CF) is typically limited to about 20 [1]. Recently, self-similar optical pulses have attracted much attention since the linear chirp facilitates efficient pulse compression for the linearly chirped self-similar solitary waves in optical fiber amplifiers [2], [3]. The generation of linearly chirped parabolic pulses which achieves efficient pulse compression by using a photonic bandgap (PBG) fiber [4]. However, because of small group-velocity dispersion (GVD) of optical fibers, this scheme requires of fibers of long lengths. A more attractive solution to achieve pulse compression is to use a highly dispersive nonlinear medium such as a fiber Bragg grating (FBG). Nonlinear Schrodinger Equation which models the optical pulse propagation in Nonlinear FBG.

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Higher order dispersion effects are neglected in the NLSE approximation, only second order dispersion $\beta_2^g = \partial^2\beta / \partial\omega^2$ is included [5]. The pulse width $T(z)$ and second order dispersion β_2^g decreases exponentially at the same rate as the second-order dispersion length L_{D2} which also decreases in the similar manner.

II. Effects Related to Pulse Compression

A. Ratio of Frequency Detune to Coupling Coefficient

The ratio b of frequency detune $\delta(z)$ and the coupling coefficient $\kappa(z)$ is normally discussed in this section. It plays an important role in determining the compression of a soliton pulse. The range of b value should be in the range of $1.5 \leq b \leq 3$ effective compression. For both the hyperbolic secant and Gaussian-shaped pulses, the compressed pulses experience severe distortions at large values of, such as $b > 4.5$. In mathematical representation it can be given as

$$b = \frac{\delta(z)}{\kappa(z)} \tag{1}$$

The ratio of the frequency detune to the coupling coefficient must be a constant for the nonlinear coefficient to be a constant. In the following, it shows that there is an optimum range of for quality optical pulse compression. First, since the proposed optical pulse compressor operates in the transmission region, it is necessary to ensure that the pulse spectrum does not overlap significantly with the reflection spectrum of the grating.

B. Figure of Merit

The figure of merit M is useful in the design and analysis of the proposed optical compressor namely Fiber bragg grating (FBG). Since the effect of PBG is not included in the NLSE approximation, the optical pulse can continue to compress as long as the second-order dispersion decreases exponentially. However, in optical pulse compression, the pulse bandwidth will broaden significantly. In real FBGs, the spectrum of the self-similar pulse will eventually extend into the Photonic bandgap (PBG) of the FBG during compression. The frequency components that fall into the PBG will then be reflected rather than transmitted by the NFBG. The figure of merit M which is the ratio of the second-order and third-order dispersions to measure the impact of higher order dispersion.

The figure of merit is expressed as

$$M = \frac{L_{D2}}{L_{D3}} = \frac{T(z^2)/|\beta_2^g|}{T(z^2)/|\beta_3^g|} = \frac{3|\beta_{20}|b\sqrt{b^2-1}}{T_0\beta_1} \quad (2)$$

Obviously for optimum pulse compression, *M* should be as small as possible. Note that the value of *M* is proportional to β_{20} (second order dispersion coefficient) and *b*, but is inversely proportional to the initial pulse width parameter T_0.

C. Compression Factor(CF)

The Compression Factor that can be obtained from the FBG can be determined by the following equation:

$$CF = exp(\sigma L) = \frac{\eta \Delta n \pi}{2\Delta n} \frac{(b^2-1)^{3/2}|\beta_{20}|}{\beta_1^2} \leq \frac{\eta 0.01\pi}{2\Delta n} \frac{(b^2-1)^{3/2}|\beta_{20}|}{\beta_1^2} \quad (3)$$

where it is used constraint $\Delta n \leq 0.01$ to obtain the inequality. Equation (3) shows that the maximum *CF* is determined by Δn, the value of *b* and β_{20}. For large *CF*, the parameters of *b* and β_{20} should be chosen as large as possible. However from (2), the figure of merit also increases with of *b* and β_{20}. Thus, the quality of compressed pulses will decrease if we increase the *CF* by increasing of *b* and β_{20} . However, if the higher order dispersion effect is important such as the cases when and are chosen to maximize the *CF*.

To achieve the exponentially decreasing second-order dispersion, one or more of the grating parameters, such as the average refractive index, index modulation depth and grating period, must vary exponentially along the grating length. We have also approximated the exponential decreasing dispersion profile by a number of gratings with constant dispersions. Then, we carried out a comprehensive study of the effect of the ratio of frequency detune to coupling coefficient, grating length, initial chirp, initial second-order dispersion, and initial pulsewidth on the compression of input chirped pulse, respectively.

D. Full width at half maximum(FWHM)

The Full width at half maximum *(FWHM)* is used to measure the width of the pulse when the pulse does not sharp edges in the half maximum value or power of the pulse. In pulse compression *FWHM* plays an important role in determining whether the pulse is compressed or not. Here, the *FWHM* of the input pulse is taken into account and noted as well, after the effective compression of the optical pulse at the output the *FWHM* is noted again for the compressed output pulse. If the *FWHM* of the compressed output pulse is lesser than the input pulse's *FWHM*, then it is said to be compressed.

III. PROPOSED METHODOLOGY

The nonlinear Schrodinger equation (NLSE) is a nonlinear variation of the Schrodinger equation in mathematics. It is a classical theory field equation with applications to optics and water waves. Unlike the Schrodinger equation, it never describes the physical state of the time evolution which is called as quantum state. In quantum mechanics, the equation is a special case of the nonlinear Schrodinger field, and when canonically quantized, it describes point particles known as bosonic particles with delta-function interactions the particles either repel or attract when they are at the same point in the physical state. The nonlinear Schrodinger equation is integrable when the particles move in one dimension of space. In the limit of infinite strength repulsion, the nonlinear Schrodinger equation bosons are equivalent to one dimensional free fermions. One of the simplest method used for solving nonlinear Schrodinger equation is Split Step Fourier Method [6].

The Nonlinear Schrodinger equation for *A(z,t)* in the presence of Group Velocity Dispersion and Self-Phase Modulation is given by

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\gamma |A|^2 A - \frac{\alpha}{2}A \quad (4)$$

where

- A - Amplitude
- z - propagating distance
- β_2 - GVD parameter
- γ - Nonlinear parameter
- α - Fiber loss

The above NLSE can be solved using many methods, but the most efficient method of solving NLSE is by Split Step Fourier Method which is explained below as follows.

A. Split Step Fourier Method

In numerical analysis, the Split-step Fourier method is a pseudo-spectral numerical method used to solve nonlinear partial differential equations like the nonlinear Schrodinger equation. The name comes into account for two reasons. First, the method does the computing of the solution in small steps, and treating the linear and the nonlinear steps separately. Second, it is necessary to Fourier transform again and again because the linear step is made in the frequency domain while the nonlinear step is made in the time domain. An example of usage of this method in optical fiber communication is in the field of light pulse propagation in optical fibers, where the interaction of linear and nonlinear mechanisms makes it difficult to find general analytical solutions. However, the split-step method provides a numerical solution to the problem [7].

Dispersion and nonlinear effects act simultaneously on propagating pulses during nonlinear pulse propagation in optical fibers. However, analytic solution cannot be employed to solve the NLSE with both dispersive and nonlinear terms present. Hence the numerical split step Fourier method is utilized, which breaks the entire length of the fiber into small step sizes of length "h" and then solves the nonlinear Schrodinger equation by splitting it into two halves, the linear part (dispersive part) and the nonlinear part over z to z + h.

Each part is solved individually and then combined together afterwards to obtain the aggregate output of the traversed pulse. It solves the linear dispersive part first, in the Fourier domain using the fast Fourier transforms and then inverse Fourier transforms to the time domain where it solves the equation for the nonlinear term before combining them. The process is repeated over the entire span of the fiber to approximate nonlinear pulse propagation[8].

In analyzing the NLSE we can rewrite the equation (4) in a different format as follows

$$\frac{\partial A}{\partial z} = \left[\frac{i\beta_2}{2}\frac{\partial^2}{\partial t^2} + i\gamma|A|^2 - \frac{\alpha}{2}\right]A \qquad (5)$$

B. Flow diagram for pulse compression

The flow diagram of optical pulse compression is given below with the help of flow graphs. The below mentioned methodology is used in compressing the pulse to a reasonable extent which is as follows

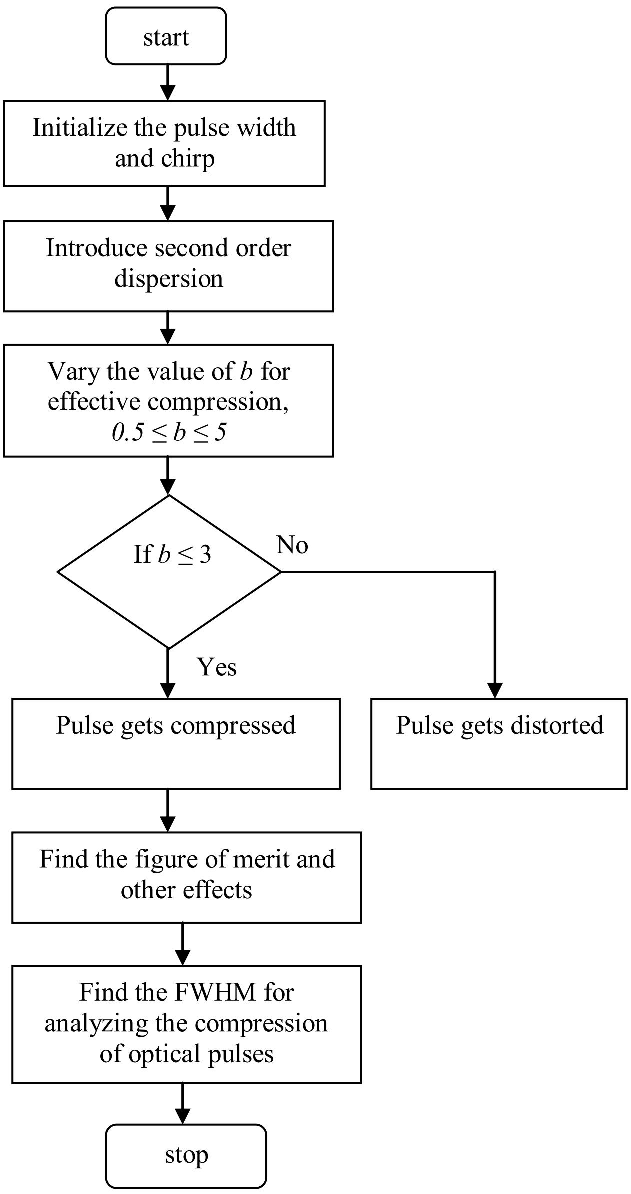

Fig:1 Flow diagram of optical pulse compression

IV. Simulations Results

The compression of initially chirped optical soliton pulses is discussed with the help of second order dispersion coefficient β_{20} and b ratio of frequency detune to coupling coefficient. In the first case for the minimum value of b, the optical pulse is more compressed. In the final case for maximum value of b the pulse is said to be least compressed or in other words distorted. For the effective compression the value of b should be in the range of $0.5 \le b \le 3.0$

A. Case 1

For higher compression of optical pulse set the parameters are as follows:

b=1.0, T_0=10.586 ps, C= - 0.5,

b- ratio of frequency detune to coupling coefficient

T_0- Pulse width, C- initial chirp

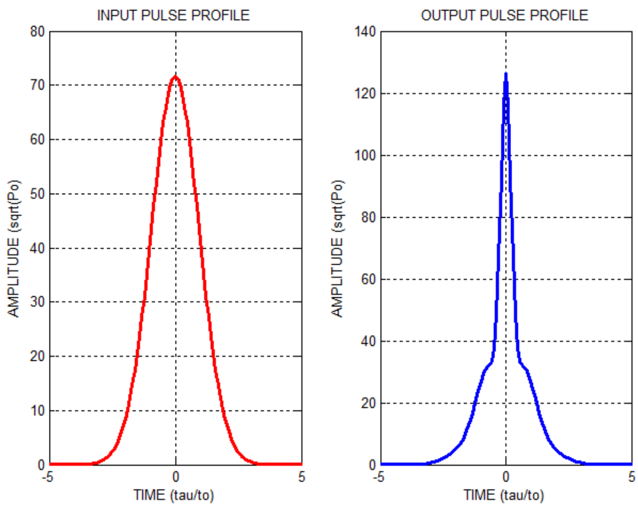

Fig:2 Comparison of input pulse and compressed output pulse

From the Case 1 results we can see that the pulse is said to be compressed for minimum value of b which is an important design parameter of the proposed optical pulse compressor. In the output pulse form the width of the pulse is reduced when compared to the input pulse, similarly the amplitude or power level of the pulse is increased which tells us the above pulse is compressed.

B. Case 2

For compression of optical pulse set the parameters are as follows:

b=2.0, T_0=10.586 ps, C= - 0.5,

b- ratio of frequency detune to coupling coefficient

T_0- Pulse width, C- initial chirp

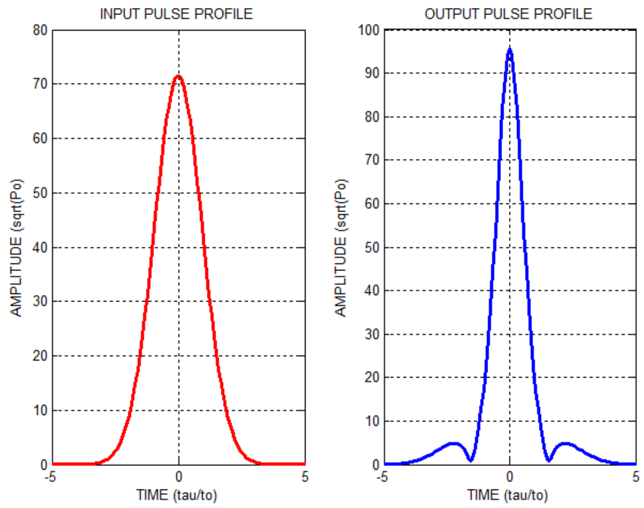

Fig:3 Comparison of input pulse and compressed output pulse

From the Case 2 results we can see that the pulse is said to be compressed for intermediate value of *b* which is an important design parameter of the proposed optical pulse compressor. In the output pulse form the width of the pulse is reduced when compared to the input pulse, similarly the amplitude or power level of the pulse is increased which tells us the above pulse is compressed but does not achieve higher compression. So as the value of *b* increases the compression of the pulse decreases.

C. *Case 3*

For compression of optical pulse set the parameters are as follows:

b=4.0, T_0=10.586 ps, *C*= - 0.5,

b- ratio of frequency detune to coupling coefficient

T_0- Pulse width, *C*- initial chirp

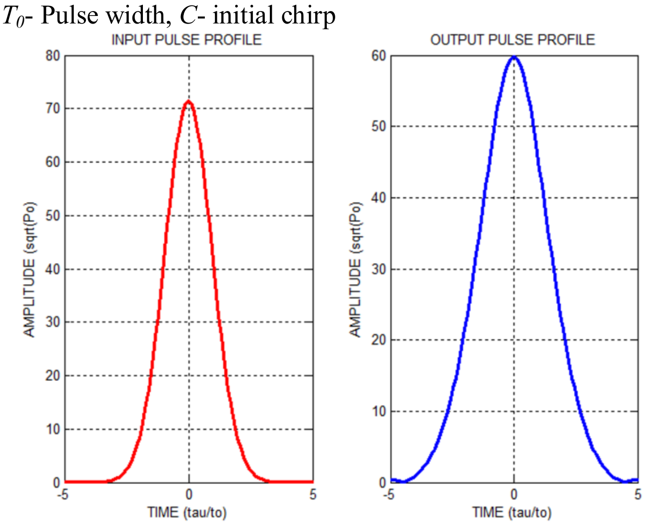

Fig:4 Comparison of input pulse and compressed output pulse

From the Case 3 results we can see that the pulse is said to be uncompressed for almost maximum value of *b*. In the output pulse form the width of the pulse is not reduced when compared to the input pulse, similarly the amplitude or power level of the pulse is decreased which tells us the above pulse is not compressed. So as the value of *b* increases the compression of the pulse decreases.

D. *Effect of Figure of Merit*

The effect of figure of merit (M) plays an important role in determining the compression of the optical pulse[9]. The graph of figure of merit is shown below as follows:

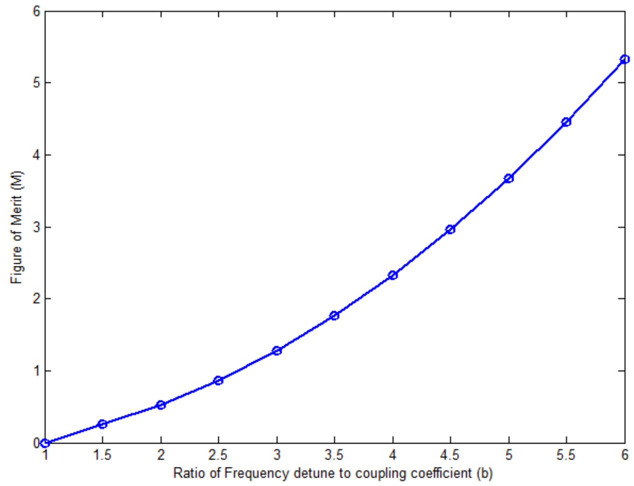

Fig 5: Figure of merit*(M)* vs Ratio of frequency detune to coupling coefficient *(b)*

From the above graph we can see the figure of merit *(M)* linearly increases as *b* increases which tells us that compression is inversely proportional to the figure of merit *(M)*. Obviously for optimum pulse compression, *M* should be as small as possible. We note that the value of *M* is proportional to $|\beta_{20}|$ and *b*, but is inversely proportional to the initial pulsewidth parameter T_0.

E. *Tabulation Results of FWHM*

The compression of optical pulse can be found by comparing the width of the input pulse as well as the output pulse with the parameter called *FWHM* which measures the width of the pulse at its half maximum value. From the tabulation results we can able to find out whether the pulse is compressed or not. If the *FWHM* of the output pulse is lesser than the *FWHM* of the input pulse then it is said to be compressed, if it is not then it is said to be uncompressed or distorted.

TABLE I. Compression of chirped pulse

(b) vs FWHM (ps)

S. No	Chirp	Value of b	FWHM(ps)
1	-0.5	0.5	1
2	-0.5	1	4
3	-0.5	1.5	7
4	-0.5	2	13
5	-0.5	2.5	19
6	-0.5	3	25
7	-0.5	3.5	31
8	-0.5	4	35
9	-0.5	4.5	37
10	-0.5	5	41

Note: FWHM of input pulse = 25 ps

V. Conclusion

The optical pulse compression using FBGs with exponentially decreasing second-order dispersion allows nearly pedestal-free pulse compression in a short length, leading to a novel all-fiber compression device. The figure of merit , which is the ratio of the second-order dispersion length to third-order dispersion length, to measure the effect of higher order dispersions is important for the compression because it determines the maximum and minimum compression of the optical pulses. For optimum pulse compression, figure of merit should be as small as possible. For the PBG, we found that the ratio of frequency detune of the pulse's center frequency from the Bragg frequency of the FBG to coupling coefficient of the FBG is an important design parameter for the proposed optical pulse compressor. These two parameters determines the compression as well as distortion of the pulse. FWHM is also used to figure out the compressed and distorted pulse using width of the optical pulse in the half maximum.

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