Chapter 2
Theoretical Models of Dispersion Compensation and soliton compression in Fibers

2.1 Introduction

Ultra-short optical pulse generation from semiconductor lasers is of great importance for future high bit rate optical communication and soliton transmission systems. There are two major techniques for generating short optical pulses from semiconductor lasers. One is active mode locking which can produce very short optical pulses, and requires an extended cavity formed by an external mirror and hence is more sensitive to mechanical disturbances. An alternative and straightforward approach is to directly modulate a Distributed Feedback Bragg (DFB) laser diode, and to excite only the first peak of the relaxation oscillation. This technique, which is called gain switching, can produce pulse trains up to the gigahertz (GHz) range and thus is practically more feasible for data transmission. Typically the gain-switched pulses are in the range 20-30ps and are accompanied by an inherent frequency chirping [1-5]. These chirped pulses could be temporally compressed by compensating for the undesired chirp with a dispersive fiber or a grating pair. Among them, the fiber compression method is the most practical method for communications because of its simplicity. It is called Linearly pulse compression.

After linearly pulses compression, the pulse nearly Fourier-transform-limited. The transform limit is due to the presence of nonlinear chirp that remains uncompensated for linear compression technique. Then nonlinear pulse compression is used. The optical pulses at wavelengths exceeding 1.3 μm generally experience both SPM (Self-Phase Modulation) and anomalous GVD (Group Velocity Dispersion) during their propagation in silica fiber [6]. Such a fiber can act as a compressor by itself without the need of an external grating pair. These solitons follow a periodic evolution pattern such that they go through an initial narrowing phase at the beginning of each period. By an appropriate choice of the fiber length, the input pulse can be compressor is referred to as the soliton-effect compressor to emphasize the role of soliton.

2.2 Theoretical Model of Dispersion Compensation

2.2.1 Brief Introduction

The linear optical pulse compression, it uses the dispersion compensation. In our experimental, the Dispersion-Compensated-Fiber (DCF) satisfies the compression rule. As a rule, semiconductor optical amplifier ring laser (SOAFL) emits chirped pulse. Because refractive index has some changes during pulse generated. The frequency chirp of SOAFL mode-locked pulses are negative and frequency decreases toward the trailing edge. It means the chirp parameter $C < 0$ and the instantaneous frequency increases linearly from the trailing edge to the leading edge. The DCF has large negative dispersion (dispersion parameter D) at 1.5 μm wavelength. It is in the normal-dispersion regime and $\beta_2 > 0$. The higher frequency (blue-shifted) components of an optical pulses travel slower than the lower frequency (red-shitted) components. This rule can be used linear pulse compression.

2.2.2 Chromatic Dispersion

When an electromagnetic wave interacts with bound electrons of a dielectric, the medium response in general depends on the optical frequency ω. This property, referred to as chromatic dispersion, manifests through the frequency dependence of the refractive index $n(\omega)$. On a fundamental level, the origin of chromatic dispersion is related to the characteristic resonance frequencies at which the medium absorbs the electromagnetic radiation through oscillations of bound electrons. Far from the medium resonance, the refractive index is well approximated by the Sellmeier equation

$$n^2(\omega) = 1 + \sum_{j=1}^{m} \frac{B_j \omega_j^{\,2}}{\omega_j^{\,2} - \omega^2} \qquad (2.2.2\text{-}1)$$

where ω_j is the resonance frequency and B_j is the strength of *jth* resonance. The sum in Equation (2.2.2-1) extends over all material resonance that contributes to the frequency range of interest.

Fiber dispersion plays a critical role in propagation of short optical pulses since different spectral components associated with the pulse travel at different speeds given by $C / n(\omega)$. Even when the nonlinear effects are not important, dispersion-induced pulse broadening can be detrimental for optical communication systems. Mathematically, the effects of fiber dispersion are accounted for by expanding the mode propagation constant β in a Taylor series about the center frequency ω_0:

$$\beta(\omega) = n(\omega)\frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \cdots \qquad (2.2.2\text{-}2)$$

Where

$$\beta_m = \left[\frac{d^m \beta}{d\omega^m}\right]_{\omega=\omega_0} \qquad (m=0,1,2,\ldots\ldots) \qquad (2.2.2\text{-}3)$$

The pulse envelop moves at the group velocity ($v_g = \beta_1^{-1}$) while the parameter β_2 is responsible for pulse broadening. The parameter β_1 and β_2 are related to the refractive index n and its derivatives through the relations

$$\beta_1 = \frac{1}{c}\left[n + \omega\frac{dn}{d\omega}\right] = \frac{n_g}{c} = \frac{1}{v_g} \qquad (2.2.2\text{-}4)$$

$$\beta_2 = \frac{1}{c}\left[2\frac{dn}{d\omega} + \omega\frac{d^2n}{d\omega^2}\right] \qquad (2.2.2\text{-}5)$$

where n_g is the group index.

Figure (2.2.2.1) and (2.2.2.2) show the variation of n, n_g, and β_2 with wavelength λ, for fused silica by using Equation (2.2.2-1),(2.2.2-4), and (2.2.2-5). The most notable feature is that β_2 vanishes at a wavelength of about 1.27μm and becomes negative for longer wavelengths. The wavelength at which β_2 = 0 is often referred to as the zero-dispersion wavelength λ_D. However, it should be noted that dispersion does not vanish at $\lambda = \lambda_D$. Pulse propagation near $\lambda = \lambda_D$ requires the inclusion of the cubic term in Equation (2.2.2-2). Such higher-order dispersive effects can distort ultra-short optical pulse both in the linear and nonlinear regimes. Their inclusion is however necessary only when the pulse wavelength A approaches λ_D to within a few nanometers.[7] [8]

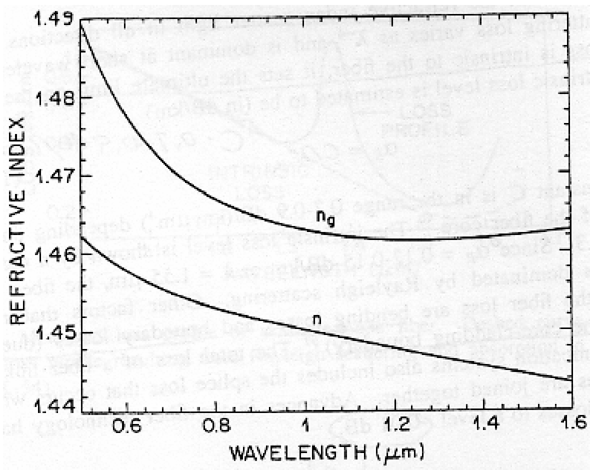

Figure 2.2.2.1 Variation of refractive index n and group index n_g with wavelength for fused silica. *From: G. P. Agrawal,* ***Nonlinear Fiber Optics.*** *(Academic New York, 1989)*

The curves shown in Figure (2.2.2.1) and (2.2.2.2) are for bulk fused silica. The dispersion behavior of actual glass fibers generally deviates from that shown in these figures for the following two reasons. First, the fiber core may have small amounts of dopants such as GeO_2 and P_2O_5. Equation (2.2.2-1) in that case should be used with parameters appropriate to the amount of doping levels. Second, because of dielectric wave guiding, the effective mode index is slightly lower than the material index $n(\omega)$, with reduction itself being ω dependent. This results in a waveguide contribution that must be added to the material contribution to obtain the total dispersion. Generally, the waveguide contribution to β_2 is negligible except near the zero-dispersion wavelength λ_D where the two become comparable. The main effect of the waveguide contribution is to shift λ_D slightly toward longer wavelengths; $\lambda_D \sim 1.31\ \mu m$ for typical fibers. Figure (2.2.2.3) shows the measured total dispersion of a single-mode fiber. The quantity plotted is the dispersion parameter D that is commonly used in the fiber-optics literature in place of β_2. It is related to β_2 by the relation

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 \approx -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} \qquad (2.2.2\text{-}6)$$

An interesting feature of the waveguide dispersion is that its contribution to D (or β_2) depends on the fiber-design parameters such as the core radius a and the core-cladding index difference Δ. This feature can be used to shift the zero-dispersion wavelength λ_D in the vicinity of 1.55 μm where the fiber loss is minimum. Such dispersion-shift fibers have potential applications in optical communication systems. It is possible to design dispersion-flattened optical fibers having low dispersion over a relatively large wavelength range 1.3 - 1.6 μm. This is achieved by the use of multiple cladding layers.

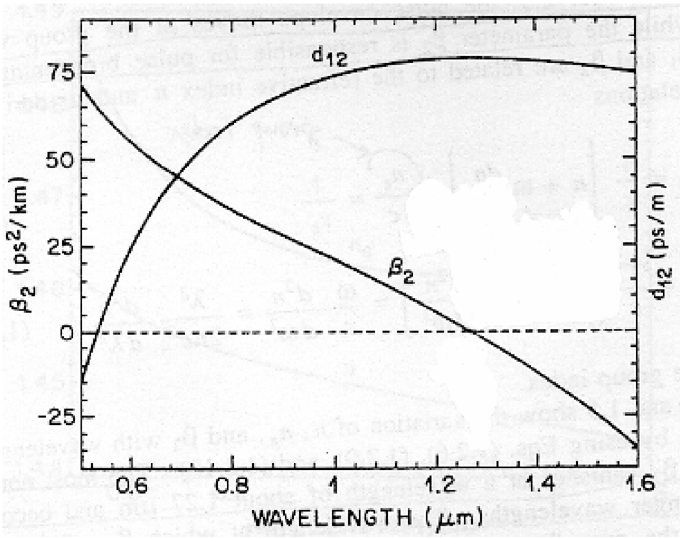

Figure 2.2.2.2 Variation of β_2 and d_{12} with wavelength for fused silica.

From: G. P. Agrawal, ***Nonlinear Fiber Optics.*** *(Academic New York, 1989)*

The non-linear effects in optical fibers can manifest a qualitatively different behavior depending on the sign of the dispersion parameter β_2 or D . Since

$$\beta_2 = \frac{d\beta_1}{d\omega} = \frac{d}{d\omega}\left[\frac{1}{v_g}\right] = -\frac{1}{{v_g}^2}\frac{dv_g}{d\omega} \qquad (2.2.2\text{-}7)$$

β_2 is generally referred to as the group-velocity dispersion (GVD) parameter. For wavelengths such that $\lambda < \lambda_D$, $\beta_2 > 0$, and the fiber is said to exhibit normal dispersion. In the normal-dispersion regime, the higher frequency (blue-shifted) components of an optical pulse travel slower than the lower frequency (red-shifted) components. By contrast, the opposite occurs in the so-called anomalous-dispersion regime in which $\beta_2 < 0$. As seem in Figure (2.2.2.2), silica fibers exhibit anomalous dispersion when the light wavelength exceeds the zero-dispersion wavelength ($\lambda > \lambda_D$). The anomalous-dispersion regime is of considerable interest for the study of nonlinear effects because it is in this regime that optical fibers can support solitons through a balance between the dispersive and nonlinear effects.

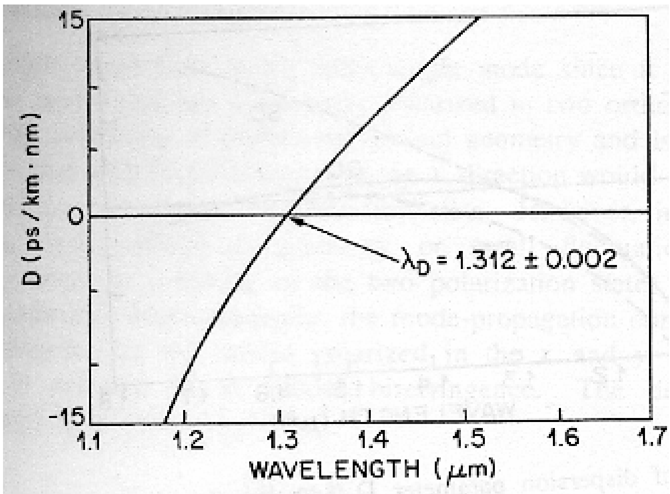

Figure 2.2.2.3 Measured variation of dispersion parameter D with wavelength for a single-mode fiber. *From: G. P. Agrawal,* ***Nonlinear Fiber Optics.*** *(Academic New York, 1989)*

An important feature of chromatic dispersion is that pulses at different wavelength propagate at different speeds inside the fiber because of the group-velocity mismatch. This feature leads to a walk-off effect that plays an important role in the description of the nonlinear phenomena involving more overlapping optical pulses. More specifically, the nonlinear interaction between two optical pulses ceases to occur when the faster moving pulse has completely walked through the slower moving pulse. The separation between the two pulses is governed by the walk-off parameter d_{12} defined

$$d_{12} = \beta_1(\lambda_1) - \beta_1(\lambda_2) = v_g^{-1}(\lambda_1) - v_g^{-1}(\lambda_2) \quad (2.2.2\text{-}8)$$

Where λ_1 and λ_2 are the center wavelengths of two pulses and β_1 at these wavelengths is evaluated using Equation (2.2.2-4). For pulses of width T_0, one can define the walk-off length L_w by the relation

$$L_w = \frac{T_0}{|d_{12}|} \quad (2.2.2\text{-}9)$$

2.2.3 Chirp Gaussian Pulse

For an initially unchirped Gaussian pulse, it shows that dispersion-induced broadening of the pulse does not depend on the sign of the GVD parameter β_2. Thus, for a given value of the dispersion length L_D, the pulse broadens by the same amount in the normal-dispersion and anomalous-dispersion regimes of the fiber. This behavior changes if the Gaussian pulse has an initial frequency chirp. For the case of linearly chirped Gaussian pulses, the incident field is given by

$$U(0,T)=\exp\left[-\frac{(1+iC)}{2}\frac{T^2}{T_0^{\ 2}}\right] \qquad (2.2.3\text{-}1)$$

where C is a chirp parameter. It can be finds that the instantaneous frequency increases linearly from the leading the trailing edge (uP-chirp) for C > 0 while the opposite occurs (down-chirp) for C < 0 by the Equation.

$$U(z,T)=|U(z,T)|\exp[i\phi(z,T)] \qquad (2.2.3\text{-}2)$$

It is commons refer to the chirp, as positive or negative depending on whether C is positive or negative., The numerical value of C can be estimated from the spectral width of the Gaussian pulse. By substituting Equation (2.4.7-1) in Equation (2.2.3-3)

$$U(0,\omega)=\int_{-\infty}^{\infty}U(0,T)\exp(i\omega T) \qquad (2.2.3\text{-}3)$$

$\tilde{U}(0,\omega)$ is given by

$$U(0,\omega)=\left[\frac{2\pi T_0^{\ 2}}{1+iC}\right]^{1/2}\exp\left[-\frac{\omega^2 T_0^{\ 2}}{2(1+iC)}\right] \qquad (2.2.3\text{-}4)$$

The spectral half-width (at $1/e$ -intensity point) from Equation (2.2.2-4) is given by

$$\Delta\omega\times T_0=\left(1+C^2\right)^{1/2} \qquad (2.2.3\text{-}5)$$

In the absence of frequency chirp (C=0), the spectral width is Fourier-transform-limited and satisfies the relation $\Delta\omega T=1$. The spectral width is enhanced by a factor of $(1+C^2)^{1/2}$ in the presence of linear chirp. Equation (2.2.3-6) can be used to estimate $|C|$ from measurements of $\Delta\nu$ and T_0.

Even a chirped Gaussian pulse maintains its Gaussian shape on propagation. The width T, after propagating a distance z is related to the initial width T_0 by the relation

$$\frac{T_1}{T_0} = \left[\left(1 + \frac{C\beta_2 z}{T_0^{\,2}}\right)^2 + \left(\frac{\beta_2 z}{T_0^{\,2}}\right)^2 \right]^{1/2} \tag{2.2.3-6}$$

This equation shows that broadening depends on the relative signs of the GVD parameter β_2 and the chirp parameter C [9]. Whereas a Gaussian pulse broadens monotonically with z if $\beta_2 C > 0$, it goes through an initial narrowing stage when $\beta_2 C < 0$. Figure (2.2.3.1) shows this behavior by plotting the broadening factor T_1/T_0 as a function of z/L_D. In the case $\beta_2 C < 0$, the pulse width becomes minimum at

$$Z_{\min} = \frac{C}{1+C^2} L_D \tag{2.2.3-7}$$

The minimum value of the pulse width at $z = z_{min}$ is given by

$$T_1^{\min} = \frac{T_0}{\left(1+C^2\right)^{1/2}} \tag{2.2.3-8}$$

It can be fined the length $z = z_{min}$, the pulse width is Fourier-transform-limited since $\Delta\nu T_1^{\min} = 1$.

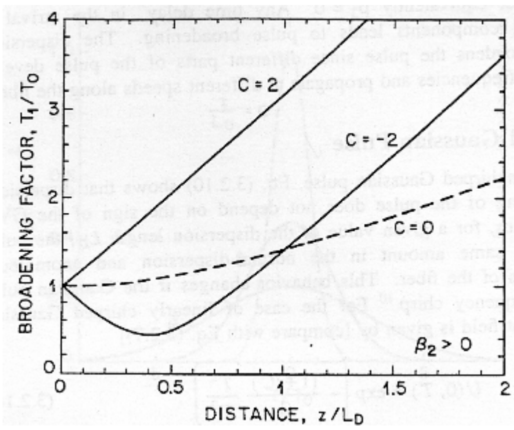

Figure 2.2.3.1 Variation of broadeningfactor with propagated dis ance for a chirped Gaussian pulse. *From: G. P. Agrawal, **Nonlinear Fiber Optics.** (Academic New York, 1989)*

When the pulse is initially chirped and the condition $\beta_2 C<0$ is satisfied, the dispersion-induced chirp is in opposite direction to that of the initial chirp. As a result the net chirp is reduced leading to pulse narrowing. The minimum pulse width occurs at a point at which the two chirps cancel each other. With a further increase in the propagation distance, the dispersion-induced chirp starts to dominate over the initial chirp, and the pulse begins to broaden.

2.2.4 Fiber Compression

Due to the nature of red-shift chirping, compression of this negatively chirped pulse in the time domain is possible if a fiber with normal dispersion ($\beta_2 = d^2\beta/d\omega^2 > 0$, β: propagation constant, ω: carrier angular frequency) is provided. In such a fiber, the group velocity $\left(v_g^{-1} = \dfrac{d\beta}{d\omega} \right)$ of a shorter wavelength signal will be less than that of a longer wavelength signal. Thus, if we mentally break up the chirped pulse into a number of segments, each with a slightly different group velocity, the leading edge of the negatively chirped pulse will travel slower than the trailing edge, resulting in temporal compression. In order to establish a semi-quantitative understanding of the optimum compression condition, we analyzed the propagation of a chirped pulse in a dispersive fiber by assuming the optical output from the SOAFL to be with a Gaussian profile and linear chirping [10]. We found, at the first-order approximation, an explicit expression for the optimum compression condition as follows [11]:

$$-DL = \frac{\Delta t}{\Delta \lambda} \tag{2.2.4-1}$$

where $D = -2\pi c\beta_2/\lambda^2$ is the fiber dispersion parameter in ps/km/nm, L is the fiber length, Δt is the FWHM of the input pulse, and $\Delta\lambda$ is the chirped spectral width.

2.3 Theoretical Model of Soliton Compression

2.3.1 Brief Introduction

Pulse compression is achieved, in this scheme by taking advantage of a non-linear phenomenon in optical fibers known as SPM [20]. This nonlinear phenomenon is responsible for the spectral broadening of optical pulses in fibers, and will interact with GVD in the anomalous dispersion regime to produce optical solitons. In the case of a fundamental or first-order soliton, the effects of SPM cancel the effects of anomalous GVD perfectly, and the soliton propagates whilst preserving its sec h^2 shape in a loss less optical fiber. A higher order soliton, on the other hand, changes its shape periodically as it propagates in a fiber. Such a soliton always experiences an initial pulses narrowing phase before recovering its original sec h^2 profile at integral multiples of the soliton period z_0 , and this behavior is exploited to achieve pulse compression. Optimum compression is achieved when the higher order soliton leave the fiber just as it attains its narrowest width.

2.3.2 SPM-Induced Spectral Broadening

The propagation in the limit $\beta_2 = 0$ becomes

$$\frac{\partial U}{\partial z} = \frac{i}{L_{NL}} \exp(-\alpha z)|U|^2 U \qquad (2.3.2\text{-}1)$$

where α accounts for the fiber loss. The non-linear length

$$L_{NL} = (\gamma P_0)^{-1} \qquad (2.3.2\text{-}2)$$

where P_0 is the peak power and γ is related to the nonlinear-index coefficient n_2. Equation (2.4.8-1) is readily solved to obtain

$$U(z,T) = U(0,T)\exp[i\phi_{NL}(z,T)] \qquad (2.3.2\text{-}3)$$

Equation (2.3.2-1) shows that SPM gives rise to an intensity-dependent phase shift while the pulse shape governed by $|U(z,T)|^2$ remains unchanged. The maximum phase shift ϕ_{max} occurs at the pulse center located at T = 0. Since U is normalized such that $|U(0,0)| = 1$, it's given by

$$\phi_{\max} = z_{eff} / L_{NL} = \gamma P_0 z_{eff} \qquad (2.3.2\text{-}4)$$

The physical meaning of the nonlinear length L_{NL} is evident from Equation (2.4.8-4); it is the effective propagation distance at which ϕ_{max} =1. SPM-induced spectral broadening is a consequence of the time dependence of $\phi_{NL}(z,T)$. This can be understood by noting that a temporally varying phase implies that the instantaneous optical frequency differs across the pulse from its central value ω_0. The difference $\delta\omega$ is given by

$$\delta\omega(t) = -\frac{\partial \phi_{NL}}{\partial T} = -\frac{\partial}{\partial T}\left(\left|U(0,T)\right|^2\right)\frac{z_{eff}}{L_{NL}} \qquad (2.3.2\text{-}5)$$

The chirp is induced by SPM and increases in magnitude with the propagated distance. In other words, new frequency components are continuously generated as the pulse propagates down the fiber.

2.3.3 Soliton-Effect Pulse Compression

In practice, soliton-effect compression is carried out by initially amplifying optical pulses up to power level required for the formation of higher order solitons. The peak optical power of the initial pulse required for the formation of an *Nth* -order soliton is given by

$$P_N = 3.11 N^2 \frac{D\lambda^2}{2\pi c \gamma \tau^2} = 3.11 \frac{|\beta_2| N^2}{\gamma \tau^2} \qquad (2.3.3\text{-}1)$$

where β_2 is the GVD parameter in units of ps^2/Km, γ is the fiber non-linearity coefficient associated with SPM in units of $W^{-1}Km^{-1}$, τ is the Full-Width at Half-Maximum (FWHM) of the initial optical pulse, *N* is the soliton order, *D* is the fiber dispersion parameter, λ is the optical wavelength, *c* is the velocity, and P_N is the peak power required to excite the *Nth* -order soliton in the fiber. These *Nth* -order solitons are then passed through the correct length of optical fiber to finally yield highly compressed pulses. In general, the higher the order *N*, the shorter the length of fiber required for the compression process [13]. The optical soliton is the result of interaction betweenthe group velocity dispersion (GVD) and the self-phasebmodulation (SPM) effects in a fiber with anomalous dispersion. The soliton theory shows that for pulses with a $sech^2$ profile and appropriate peak power, the two effects can cooperate in such a way that the fundamental solitons will travel in a lossless fiber without any temporal and spectral changes due to the balanced effects, and the higher order solitons will follow a periodic evolution patter, with the original shape recurring at multiples of the soliton period Z_0 [14]. During the propagation of higher order solitons, SPM generates a frequency chirp such that the leading edge is red shifted and the trailing edge is blue shifted from the central frequency, while at the same time, the anomalous GVD will compensate for such frequency chirping at a certain propagation distance, resulting in a pulse compression over the central part of the pulse. The soliton-effect compression is due to the initial narrowing phase through which all higher order solitons go before the initial shape is restored after one soliton period. A crucial point for the successful realization of the soliton-effect compression is the appropriate choice of the fiber length to obtain optimum compression because the higher order solitons follow a periodic evolution pattern such that they go through an initial narrowing phase at the beginning of each period. The optimum fiber length Z_{opt} corresponds to the location at which the width of the central spike is minimum. From the theoretical analysis in [15], we found that the optimum soliton effects, the pulse narrowing is defined about z_0 where

$$Z_0 = 0.332\frac{c}{D}\left(\frac{\tau\pi}{\lambda}\right)^2 \qquad (2.3.3\text{-}2)$$

is the soliton period.

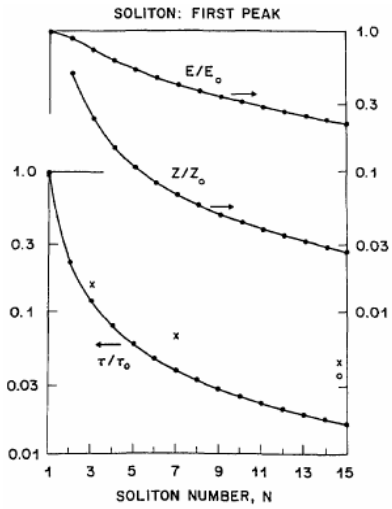

Figure 2.4.3.3 Calculated properties of the first optimal narrowing by means of the soliton effect in single-mode fibers and some related experimental data as a function of soliton number N. *From: G. P. Agrawal,* ***Nonlinear Fiber Optics.*** *(Academic New York, 1989)*

The optimum length (for $10 \le N \le 50$) can be estimated from the following empirical relation

$$Z_{opt} \approx Z_0\left(\frac{0.32}{N} + \frac{1.1}{N^2}\right) \tag{2.3.3-3}$$

where N is the soliton order and Z_0 is the soliton period. Z_0 can be elated back to the initial pulse width and GVD by the equation:

$$Z_0 \approx 0.332\frac{\pi\tau^2}{2|\beta_2|} \tag{2.3.3-4}$$

The optimum pulse compression factor, which is the ratio of the width of an optimally compressed pulse to its initial width, can also be estimated (for $N \le 50$) from the following empirical formula:

$$F_{opt} \approx 4.1N \tag{2.3.3-5}$$

One difficulty faced when using the soliton-effect compression scheme, as alluded to previously, is pulses with high peak power are required for the formation of high-order solitons in conventional optical fibers.

2.3.4 Remove Pedestal From Nonlinear Pulse Compression

We already know an inherent drawback of soliton-effect compression that the compressed pulses always consist of a sharp narrow spike centered on a broad low intensity pedestal that carries a large proportion of the pulse energy. This is undesirable because the broad pedestal will overlap with adjacent pulses, resulting in unacceptably high levels of crosstalk in a TDM system and limiting the achievable bit rates. One method of eliminating the pedestal is to use the intensity dependent birefringence effect in optical fibers to realize intensity discrimination [16]. In this work, we demonstrate that by using the fiber birefringence advantageously in conjunction with a wave plate, a polarizer and a polarization controller, the soliton-effect pulse compression can be realized with simultaneous suppression of the low intensity pedestal. The wave plate is used to compensate for the phase shift and to reconstruct linear polarization states from circular or elliptical polarization states. Subsequent use of the polarizer then ensured that light in only one polarization state is produced at the output. The polarization state of the input light and its launching angle with respect to the optic axes (also referred to as the fast and slow axes) of the fiber are also very crucial. Therefore, a polarization controller is used at the fiber input to control the input polarization state of the light and launching angle into the fiber. Intensity discrimination relies upon the intensity dependent polarization state of light in the fiber. As the optical pulses propagate in the fiber, the narrowing process caused by the soliton-effect commences and the peak power of the pulse increases. At the optimum length (also called the point of optimum compression), each compressed pulse consists of an extremely high intensity peak and a low intensity pedestal. A schematic diagram in Figure 2.3.4.1 provides a qualitative description of the intensity discrimination.

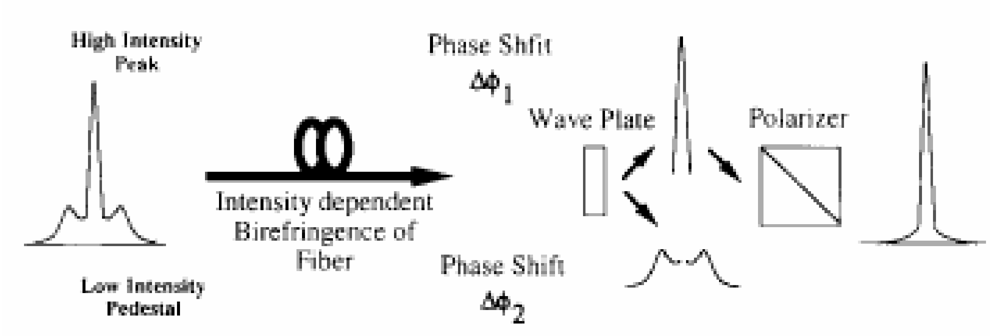

Figure 2.3.4.1 mechanism in a birefringent fiber. Schematic diagram qualitatively explaining the pulse reshaping. *From:* ***IEEE J. Quantum Electronics 1,*** *592 June 1995*

As the pulses are launched into the fiber, their electric field can be considered as the result of the two orthogonal fields aligned along the two optic axes. Due to the intensity-dependent nonlinear birefringence, the intense central peak and the weak pedestal experience different phase shifts, $\Delta\Phi_1$ and $\Delta\Phi_2$ respectively, as shown in the diagram. Consequently, the high intensity peak and the low intensity pedestal will have different polarization states at the fiber output. By rotating the wave plate at appropriate power levels, the phase shift of the intense central peak can be fully compensated for and changed to a linear polarization state while leaving the pedestal components in a different polarization state. Subsequently, intensity discrimination against the pedestal can be realized with the help of a polarizer.

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