Chapter 3

Picosecond Pulse Generation for High-Speed Optical Time Division Multiplexing Systems

3.1 Introduction

In an ultrahigh speed OTDM system, picosecond or subpicosecond optical data pulses are transmitted through a fibre link. The optical pulses used in such OTDM systems should have the following characteristics: narrow pulsewidth, high extinction ratio, small timing jitter, repetition-rate tunability, and long term stability.

Up to now, several techniques have been developed to produce optical pulses suitable for high-speed optical communication systems, including mode-locking [61, 62], gain-switching of DFB lasers [63, 64], external pulse carving using electroabsorption modulators [65-68], and super-continuum generation [69].

Among these techniques, active mode-locking of a fibre ring laser is capable of directly generating high-quality transform limited pulses on the timescale of several hundred femtoseconds to several picoseconds [70, 71]. However, such lasers usually need complex feedback control to maintain the operating stability and the pulse repetition rate is always determined by the laser cavity parameters. Another widely used approach to get picosecond pulses is to use a fast optical modulator such as an EAM to get a train of somewhat longer pulses, usually between 10 to 30ps (when driven by a 10GHz RF signal), and then to use some type of pulse compression scheme to obtain the shorter pulse width required [72]. Although in terms of
repetition-rate tunability, this approach is quite advantageous, the resulting pulse quality is often compromised in the compression process and this can lead to severe problems in the transmission performance especially when ultra-high speed OTDM systems are considered. So a carefully designed pulse compression scheme is essential to control the timing jitter and pedestal level of the compressed pulses using this external pulse carving scheme.

In this chapter, a practical picosecond pulse generator employing external pulse carving and a double-stage pulse compressor based on self-phase modulation (SPM) induced spectral broadening is demonstrated. The compressed pulse width is 1.2 ps and the ratio of the peak power to background level is about 17 dB. In section 3.2 theoretical analyses and numerical simulations of various pulse compression approaches are given. Section 3.3 describes the picosecond pulse generation experiment. Finally, a brief summary is made in Section 3.4.

3.2 Optical pulse compression

3.2.1 Pulse compression using Self-Phase Modulation

3.2.1.1 Self-Phase Modulation

Self-phase modulation is a third order nonlinear process caused by an intensity dependent nonlinear index of refraction [73]. In fibre optics this process arises from the third order susceptibility term in the expansion of the fibre material’s polarization. This intensity dependence of refractive index is called the Kerr effect and can be described by

$$n(I) = n_0 + n_2 I$$  \hspace{1cm} \text{Equation 3.1}

where $n_0$ represents the usual, weak-field refractive index of the fibre, $n_2$ is the nonlinear refraction coefficient of the fibre and $I$ the light intensity. The nonlinear phase change due to SPM can be written as:

$$\phi_{nl} = \gamma P_0 L$$  \hspace{1cm} \text{Equation 3.2}
where \( L \) is the fibre length and \( P_0 \) is the optical pulse’s peak power and the nonlinear coefficient \( \gamma \) is governed by:
\[
\gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}}
\]
\[\text{Equation 3.3}\]

where \( A_{\text{eff}} \) is the effective area of the fibre, \( \omega_0 \) is the center frequency. Normally the small value of nonlinear refraction coefficient \( n_2 \) (~2.2-3.4 x 10^{-20} m^2/W) would lead to a negligible nonlinear phase change. However, when a long fibre length is combined with a high pulse peak power the nonlinear phase change due to SPM can become significant and must be taken into account.

3.2.1.2 SPM-induced Spectral Broadening

One of the features about SPM is its ability to introduce frequency chirp across the transmitted pulses. This chirp is related to nonlinear phase change by [73]:
\[
\delta \omega(T) = -\frac{\partial \phi_{\text{NL}}}{\partial T}
\]
\[\text{Equation 3.4}\]

It can be seen from Eq. 3.4 that the SPM induced chirp increases with the transmitted distance, where new frequency components are continuously generated while the pulse travels along the fibre. Due to these newly generated frequency components the pulse’s optical spectrum is broadened over its initial width at the transmitter end. Fig. 3.1 shows the SPM-induced chirp on an initially unchirped Gaussian pulse after propagation through 2.5km DSF (peak power=1W). An almost linear up-chirp can be observed across the central part of the pulse which can be exploited in optical pulse compression.

When the maximum nonlinear phase change induced by SPM is large enough (greater than \( \pi \)), the spectrum broadening exhibits oscillatory structure across the whole frequency range and the empirical relationship between the maximum nonlinear phase shift \( \phi_{\text{max}} \) and the number of peaks \( M \) is given by:
\[
\phi_{\text{max}} \approx (M - 1/2)\pi
\]
\[\text{Equation 3.5}\]
Fig. 3.2 shows the optical spectrum’s change with the maximum nonlinear phase shift $\phi_{\text{max}}$ when $\phi_{\text{max}} = \pi, 1.5\pi, 2.5\pi, \text{and } 3.5\pi$.

Figure 3.1- Self-phase modulation induced frequency chirp (blue) for a Gaussian pulse after propagation through 2.5km DSF (red)

Figure 3.2- Simulated SPM-induced spectral broadening of unchirped Gaussian pulses
3.2.1.3 Pulse compression based on SPM-induced Spectral Broadening

In the last subsection, the frequency chirp and spectral broadening brought about by SPM have been discussed. This is one of the most commonly used ways to compress pulses using optical fibre [74]. The basic principle is to use a span of fibre with negative group velocity dispersion (GVD) to cancel the up chirp induced by SPM to get chirp-free pulses, in other words, to align the different spectral components in time domain so that the fast and slow components will overlap each other to give shorter pulses.

In practice this is often implemented by amplifying an initial chirp-free pulse to a peak power of several Watts and then launching it into an appropriate length of fibre to induce SPM. In order to maintain an approximately linear chirp and a high SPM efficiency, DSF with a small normal dispersion coefficient is often used. The highly chirped pulse obtained after the DSF is often broadened in time domain and can be compressed using another span of fibre with anomalous dispersion, normally SMF is used. When the initial pulse width, peak power and the span lengths are chosen properly, a near transform-limited pulse with shorter pulse width can be obtained. This process is schematically shown in Fig. 3.10.

![Figure 3.3- Pulse compression scheme based on SPM-induced spectral broadening](image)

The compression factor using this scheme is given by

\[ K_c \approx \frac{\Delta \omega_2}{\Delta \omega_1} \]

Equation 3.6
Although pulse compression based on SPM-induced spectral broadening and subsequent chirp compensation is an easy and effective way to get picosecond optical pulses, the fact that SPM-induced chirp is not linear across the entire pulse duration has limited the resultant pulse’s quality. In most of the cases, a short pulse with a relatively wide pedestal is obtained. Thus, an additional pulse shaping stage is always required for this kind of pulse compressor. In the next section, we will review another widely used pulse compression scheme based on the co-effects of SPM and anomalous dispersion, namely the soliton effect compressor.

3.2.2 Soliton and soliton-effect compression

3.2.2.1 Solitons

As is widely known, the propagation of the slowly varying envelope \( A(z, T) \) of a light pulse along an optical fibre is governed by the nonlinear Schrödinger equation (NLSE).

\[
\frac{i}{\beta_2} \frac{\partial A}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} - \gamma |A|^2 A \tag{3.7}
\]

where \( z \) is distance, \( \beta_2 \) is the second-order dispersion coefficient, and \( \gamma \) is the nonlinear coefficient. The quantity \( T \) is defined in a moving frame of reference by

\[
T = t - \frac{z}{\nu_g} \tag{3.8}
\]

where \( \nu_g \) is the group delay and \( t \) is the physical time. From the NLSE one can derive length scales relevant to linear dispersion and nonlinearity according to:

\[
L_D = \frac{T_0^2}{|\beta_2|}, \quad L_{NL} = \frac{1}{\gamma P_0} \tag{3.9}
\]

where \( T_0 \) is the pulse’s half-width at 1/e-intensity, and \( P_0 \) is the pulse peak power.

The parameter \( N \), which is defined by

\[
N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|}, \tag{3.10}
\]

is closely related to the soliton order. Although Eq. 3.7 does not incorporate all the physical phenomena in the optical fibre medium, it is the basis for modeling optical communication systems. To obtain a more realistic description of an optical fibre
transmission, one usually has to modify the nonlinear Schrödinger equation by inserting certain nonlinear or higher-order dispersion terms. When the condition $\beta_2 < 0$ is satisfied, Eq. 3.7 has a well-known ‘soliton’ solution of the form [73]

$$u(\xi, \tau) = \eta \sec h(\eta \tau) \exp(i\xi / 2)$$  \hspace{1cm} \text{Equation 3.11}

where

$$u = \sqrt{\gamma L_D} A \quad \xi = \frac{z}{L_D} \quad \tau = \frac{T}{T_0}$$  \hspace{1cm} \text{Equation 3.12}

and $\eta$ is a non-physical parameter. The name ‘soliton’ comes from the fact that the pulse-like intensity profile of the resultant field solution doesn’t change with distance, and numerical simulations and experiments have suggested that these solitons are robust in the presence of various perturbations such as non-perfect launch conditions, loss, filtering and so on.

If $N=1$, the resultant soliton is called a fundamental soliton, whose temporal intensity profile and spectrum doesn’t change during the course of propagation. If $N$ is equal to a positive integer other than 1, the resultant soliton is often referred to as a higher-order soliton, the energy of which is higher than that of a fundamental soliton by a factor of $N$ squared. The temporal intensity profile of such a pulse is not constant, but rather varies periodically during propagation. This period is called the soliton period and is simply defined as

$$z_0 = \frac{\pi}{2} L_D = \frac{\pi}{2} \frac{T_0^2}{|\beta_2|} \approx \frac{T_{\text{FWHM}}^2}{2|\beta_2|}$$  \hspace{1cm} \text{Equation 3.13}

The NLSE, like most nonlinear partial differential equations, is not amenable to analytical solution except in certain special cases where the inverse scattering transform can be used [75]. Thus various numerical simulation schemes [76-80] have been proposed to assist the study of soliton propagation problems. Fig. 3.4 shows the fundamental soliton’s evolution along transmission fibre using the Split Step Fourier Method (SSFM, refer to Appendix A). The simulation parameters are listed in the following table:
Table 3.1 Simulation parameter for fundamental soliton

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>4 ps</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>-2 ps$^2$/km</td>
</tr>
<tr>
<td>$L_D$</td>
<td>8 km</td>
</tr>
<tr>
<td>$P_0$</td>
<td>62.5 mW</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>2 (km x W)$^{-1}$</td>
</tr>
<tr>
<td>$L_{NL}$</td>
<td>8 km</td>
</tr>
</tbody>
</table>

By boosting the peak power of the optical pulses to 562.5 mW, a fundamental soliton is transformed into a 3rd order soliton as can be seen from Fig. 3.5. It is clearly shown that higher order solitons behave very differently from fundamental solitons. Their pulse shapes change quite dramatically within one soliton period, and at certain points, it may “break up”, and multipeak structure can be observed. It should also be noted that while a fundamental soliton’s spectrum remains the same along the transmission medium, the frequency spectrum of the higher-order soliton does not. It also varies periodically along the transmission link. The unique transmission features of fundamental solitons and higher-order solitons have found many applications in the area of pulse compression, which will be discussed in the next subsection.

![Figure 3.4- Fundamental Soliton Propagation](image-url)
3.2.2.2 Pulse compressor based on nonlinear soliton effect

1) Higher-order soliton compression

Higher-order soliton compression is achieved by initially amplifying the power of the injected pulses to a level that is higher than a fundamental soliton would require. Thus the pulse evolves into a soliton of higher order. If the length of the fibre is chosen so that the central part of the pulse is at its shortest, picosecond or even sub-picosecond pulse can be generated [81-83]. Unlike the compression scheme based on SPM-induced spectral broadening, where a separate chirp compensation stage is used, higher-order soliton compression is normally achieved through a single span of fibre. Numerical simulation indicates that for large soliton order N, the compression factor and the optimal fibre length satisfy [84]:

\[
F_c \approx \frac{N}{1.6} \quad Z_{opt} \approx \sqrt{6L_D L_{SL}} \quad \text{when} \quad N = \sqrt{\frac{L_D}{L_{SL}}} > 5
\]

Although it is a practical way to get very short pulses, the resultant pulses always suffer from a broad side-pedestal; hence a further stage to reduce the pedestal is
always needed. From Eq. 3.11 we can see a large value of $N$ implies a stronger impact from Self-Phase Modulation, so SPM is also the underlying pulse compression mechanism for higher-order soliton compression.

2) Adiabatic soliton compression

Adiabatic soliton compression is the process by which a fundamental soliton pulse compresses itself when propagating through a dispersion decreasing fibre (DDF). It has long been thought of as a promising pulse compressing technique due to its ability to generate extremely short pulses (~20fs) and its relatively high compression quality [85]. However the required DDF length for adiabatic soliton compression is proportional to the input pulse width squared and this makes the compression of relatively long pulses (~20ps) impractical due to the hundreds of kilometres of DDF needed. An alternative approach is to use a counter-propagating Raman pump to create an increasing gain profile along the compression fibre. This distributed Raman amplification (DRA) based approach not only eliminates the requirement of DDF, but also provides the possibility of duration tunability [86]. Fig. 3.6 shows the two basic configurations for adiabatic soliton compression and simulated soliton pulse evolution inside a dispersion-decreasing fibre is shown in Fig. 3.7.

![Figure 3.6 - Adiabatic soliton compression setups (a) using DDF (b) using DRA](image)
Figure 3.7 - Adiabatic soliton compression in Dispersion Decreasing fibre (a) pulse evolution in DDF (b) Dispersion Decreasing fibre Dispersion distribution along fibre length
3.3 Picosecond pulse generation Experiment

3.3.1 Experimental Setup

The experimental setup of the picosecond pulse generation scheme is shown in Fig. 3.8. An external cavity tunable laser is used as the continuous wave (CW) light source. The electroabsorption modulator, provided by CIP, is driven by an amplified sinusoidal RF signal at 10 GHz. The RF amplifier has a small signal gain of 30 dB for an input power below 5 dBm. A polarization controller (PC) is placed between the tunable laser and the EAM to control the incident light’s State of Polarization (SOP).

The measured insertion loss versus reverse bias of the EAM is shown in Fig. 3.9. In this experiment, the operating wavelength is chosen to be 1550 nm, since the EAM used in this setup has its optimal pulse carving performance near this wavelength (steep slope of the extinction curve and wide dynamic range). From the green curve, the optimal reverse bias and driving RF amplitude for high extinction ratio pulse carving are estimated to be 4.5 V and 6 V_{pp} (26 dBm) respectively.

The output from the EAM is first amplified by an EDFA and the negative chirp induced by the pulse carving in the EAM is compensated by choosing an appropriate span of Dispersion Compensating Fibre (DCF). By adjusting the length of DCF used in this linear compression stage, a transform limited pulse with a FWHM width of 16.6ps is obtained.
After the initial chirp compensation stage, the compressed pulse is amplified to 21dBm using a high-power EDFA and then launched into a double-stage nonlinear pulse compressor. In each stage, a DSF with small normal dispersion is first used to induce spectral broadening through SPM. The residual chirp is compensated using an appropriate length of SMF, after which a transform-limited pulse can be obtained. After this two stage compressor, a 1.2 ps transform-limited pulse with 17 dB extinction ratio is obtained.

In this experiment, the pulse traces are recorded using an Agilent Infiniium Scope with an optical bandwidth of 50 GHz. The pulse width and spectrum are measured using an inrad 5-14-LDA SHG autocorrelator and HP 86140A Optical Spectrum Analyzer respectively.
3.3.2 External pulse carving using EAM

In the last section, the optimal pulse carving conditions for the EAM were estimated based on the measured insertion loss versus reverse bias curve. While this provides us with very useful information, in practice several more factors have to be taken into account such as the incident light’s SOP and input power. By varying the input power within the range -2~3 dBm, we found the pulse carving operation is nearly independent of the input power. Fig. 3.10 shows the EAM output pulses at different reverse bias levels at an RF level of 26 dBm (polarization state optimized), it can be seen from the figure that the optimal reverse bias is around -4 V.

Figure 3.10- EAM output at different reverse bias voltages

In this experiment, it is obvious that the RF level will have a direct impact on the pulse carving performance of the EAM. This is evaluated by inserting RF attenuators with different values after the high-power RF amplifier as well as controlling the amplifier gain by tuning the amplifier’s DC supply. The best performance in terms of
extinction ratio and pulse shape is obtained when the level is set to 26 dBm which agrees well with the value predicted from the insertion loss versus reverse bias curve. The optical spectrum of the pulses after EAM under optimal carving conditions is shown in Fig. 3.11. From the Gaussian fit, a FWHM spectrum width of 0.21 nm (27 GHz in frequency) can be inferred.

![Optical Spectrum of Pulses](image)

Figure 3.11- Optical spectrum of pulses carved by EAM, measured at RF level=26 dBm and EAM reverse bias=-4.25 V. (blue)spectrum (red) Gaussian fit

The corresponding autocorrelation traces of the EAM output are shown in Fig. 3.12, which indicates a FWHM pulse width of 21 ps (Gaussian approximation), the extinction ratio is estimated to be 16 dB. Also it should be noted that the time-bandwidth product of the output pulses is 0.57, which means the pulse is chirped instead of transform-limited.

![Autocorrelation Traces](image)

Figure 3.12- Autocorrelation traces measured at RF level=26 dBm and EAM reverse bias=-4.25V. Pulse width=21 ps A) linear scale B) log scale
3.3.3 Pulse compression results

3.3.3.1 Linear compression using DCF

As was mentioned in the last subsection, the output pulses from the EAM are not transform-limited but chirped. This frequency chirping is an inherent problem of EA modulators and can be resolved by propagating the pulses inside a chirp compensation medium. Since EAM induced chirp is negative (short wavelength is leading long wavelength), we need to use a span of fibre with normal dispersion (long wavelength travels faster than short wavelength) to satisfy the condition $\beta_2 C < 0$ for linear pulse compression [73]. Fig. 3.13 shows the pulsewidth evolution of the EAM output as a function of the DCF length. Initially the pulse is linearly compressed because the negative chirp is continuously being cancelled by the DCF’s normal dispersion. When the pulse reaches its minimum width, 16.7 ps, after 330m of transmission inside the DCF, different frequency components are overlapping in time, so chirp is eliminated. The time-bandwidth product at this point is 0.449, which indicates an almost chirp-free pulse. After that point, however, the DCF induced chirp begins to dominate and the pulse broadens with positive chirp.

![Figure 3.13- Pulse width as a function of length of DCF.](image-url)
In this experiment, in order to maximize the SPM-induced spectral broadening, a transform-limited pulse in this linear compression stage is desirable because this will enhance the SPM effects by a higher pulse peak power.

3.3.3.2 Nonlinear pulse compression

The double-stage nonlinear pulse compressor is shown in Fig. 3.14. In each stage, DSF (D=-0.5 ps/nm/km) is first used to allow SPM to broaden the optical spectrum. A subsequent span of SMF (D=-16 ps/nm/km) is used to compensate the near linear chirp across the center of the pulse induced by SPM.

![Figure 3.14- nonlinear pulse compression scheme](image)

**Stage 1**

The 16.7 ps output pulses from the linear compression stage are first amplified to 21 dBm using a high-power EDFA. Assuming a Gaussian pulse shape, this corresponds to a peak power of 0.68 W at 10 GHz repetition rate. After DSF1 (DSF fibre in the first stage), the pulse is broadened to 20.79 ps due to the normal dispersion in DSF and the optical spectrum is expanded to 1.2 nm (150 GHz in frequency) owing mainly to SPM. The autocorrelation trace and the corresponding optical spectrum of the pulses after DSF1 are shown in Fig. 3.15.

As was described in section 3.2.1.3, the output from DSF is up-chirped and can be compressed by transmitting it through a span of SMF. Just like the case where DCF is employed to compensate the EAM chirp, (when SPM induced chirp is cancelled by the anomalous dispersion of SMF) a transform-limited pulse can be obtained. Fig.
3.16 shows the autocorrelation traces when different lengths of SMF are used. The minimum pulse width of 2.71 ps (as shown in Fig. 3.16d) is observed at $L_{\text{SMF}}=600\,\text{m}$. This corresponds to a time-bandwidth product of 0.40. The deviation from the theoretically predicted 0.33 is mainly due to the nonlinear chirp characteristics induced by SPM. A compression factor of 6.2 is obtained in this first stage which is in good agreement with Eq.3.6 where a theoretical value of 6 can be deduced. As was mentioned earlier, a disadvantage of pulse compression based on SPM-induced spectral broadening is the relatively poor pulse quality. This is manifest in the resultant pulse’s wide pedestal. The extinction ratio of the pulse obtained in this stage is 13 dB. Without further reduction or removal of the pedestal, this will greatly limit the practicality of such pulse sources.

![Figure 3.15- Pulse (a) autocorrelation trace and (b) spectrum after propagation in DSF1]
Figure 3.16- Autocorrelation traces after different lengths of SMF in stage1’s chirp compensation

(a) LSMF=0m, TFWHM=20.79ps
(b) LSMF=200m, TFWHM=10.23ps
(c) LSMF=400m, TFWHM=4.71ps
(d) LSMF=600m, TFWHM=2.71ps
(e) LSMF=800m, TFWHM=3.86ps
(f) LSMF=1000m, TFWHM=5.31ps
To better illustrate the pulse broadening inside the first stage’s DSF and the following compression process in the SMF, a numerical simulation was carried out. The initial 16.7 ps pulse is assumed to have a Gaussian shape (T0=10 ps) and the peak power is set to 0.68 W (as used in experiments). To ensure accuracy, a step size of 10m is chosen. The fibres are modeled as lossless media and their dispersion and nonlinear parameters are configured as shown in Table 3.2, the results are illustrated in Fig. 3.17 and Fig. 3.18.

<table>
<thead>
<tr>
<th></th>
<th>β₂ (ps²/km)</th>
<th>β₃ (ps³/km)</th>
<th>γ (W·km)⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSF</td>
<td>0.64</td>
<td>0.09</td>
<td>2</td>
</tr>
<tr>
<td>SMF</td>
<td>-20.5</td>
<td>0.09</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.2 Fibre parameters in the simulation

From Fig. 3.17 and Fig. 3.18, an excellent agreement between simulation results and experimental data can be observed. Because the initial pulse width is quite wide, the SPM effect in stage1 DSF is relatively moderate. Combined with the small normal dispersion in the DSF, the pulse shape remains almost unchanged. From the simulated spectrum in Fig. 3.17, the maximum nonlinear phase shift introduced in DSF1 is estimated to be around $2\pi$ and this leads to a linear up-chirp across the center of the resultant output pulse. Due to this chirp characteristic, the subsequent pulse compression in the SMF follows theory well, and the minimum pulse width of 2 ps in the simulation is obtained at $L_{SMF}=640$m. Fig. 3.18 presents the simulated pulsewidth evolution inside the SMF1. For comparison, the experimental data is shown in the same figure. The two curves are in good agreement when $L_{SMF}<900$m. Around $L_{SMF}=940$m however the simulated curve exhibits a steep slope. This is mainly caused by the multipeak structure as can be observed in the upper plot. It should also be noted that, when the pulse’s temporal intensity profile deviates from $Sech^2(t)$, the autocorrelation output is no longer accurate, so the calculated data after $L_{SMF}=900$m shouldn’t be taken seriously.
Pulse evolution in stage 1 DSF

Initial and output Pulses in stage 1 DSF

Input width = 16.7
Output width = 20.6

Chirp characteristic of the output pulse from stage 1 DSF

Pulse width evolution in stage 1 DSF

Normalized optical power

Initial and output spectrum in stage 1 DSF

Figure 3.17 - Simulation results for pulse propagation in stage 1 DSF
Figure 3.18- Simulation and experimental results for pulse propagation in stage 1 SMF
Stage 2

The 2.7 ps pulse obtained in the first stage has an average power of 18 dBm. Assuming a \( Sech^2(t) \) intensity profile, this corresponds to a peak power of 2 W at 10 GHz repetition rate. Owing to this increased peak power, SPM in DSF2 is more dominant than in the last span, and the enhanced chirp combined with the normal dispersion of DSF leads to a pronounced temporal broadening (output 14 ps). Spectral and temporal broadening of the pulses in DSF2 are investigated by varying the launch power; the results are shown in Fig 3.19, and the output spectrum from DSF2 is also shown.

Figure 3.19- (a) Output pulse width, spectra width as a function of DSF2 input power  
(b) DSF2 output spectrum when \( P_{\text{input}} \) is 18 dBm

From the above figure, it can be clearly seen that the input power of DSF2 directly affects the spectral broadening efficiency. The initial 1.2 nm spectrum expanded to 2.9 nm (362 GHz in frequency) with 18 dBm input power, from which a compression factor of 2.4 is estimated. In the chirp compensation stage, the best compression is obtained when 200m SMF is used and the resulted pulse width is 1.2 ps (corresponding a compression factor of 2.3). Fig. 3.20 shows the autocorrelation traces of the output pulses from both stages, besides the reduction in pulse width, a 4 dB improvement in the pulse’s extinction ratio can also be obtained. The small compression factor in the second compression stage is mainly due to the relatively low input power (\( N \approx 4 \)), and this is the major difference between our experiment and some of the other experiments employing super-continuum generation [87, 88].
Fig. 3.21 shows the compression results when different lengths of SMF are used in the second stage’s chirp compensation. Another numerical simulation assuming the input to be a 2.7 ps soliton pulse with a peak power of 2 W is performed and the results are shown in Fig. 3.22-3.23.

![Autocorrelation traces after different lengths of SMF in stage 2’s chirp compensation](image-url)

Figure 3.20- Output pulses from both stages (a) linear scale (b) log scale

(a) $L_{\text{SMF}} = 50\text{m}$, $T_{\text{FWHM}} = 9.35\text{ps}$

(b) $L_{\text{SMF}} = 100\text{m}$, $T_{\text{FWHM}} = 5.78\text{ps}$

(c) $L_{\text{SMF}} = 250\text{m}$, $T_{\text{FWHM}} = 1.96\text{ps}$

(d) $L_{\text{SMF}} = 300\text{m}$, $T_{\text{FWHM}} = 4.65\text{ps}$

Figure 3.21- Autocorrelation traces after different lengths of SMF in stage 2’s chirp compensation
Figure 3.22- Simulation results for pulse propagation in stage 2 DSF
Figure 3.23- Simulation and experimental results for pulse propagation in stage 2 SMF

In general, the simulation results are in good agreement with the experimental data. A stronger SPM effect in DSF2 is manifest through the enhanced chirp around the edges of the broadened pulse. The calculated pulse width and spectral structure almost exactly match those obtained from experiment. The asymmetric spectral structure observed both in the experiment and numerical simulations is caused by the widened spectral width which gives rise to a more pronounced impact from
higher-order dispersion effects. A clear discrepancy occurs in Fig. 3.23b, where the optimal compensation lengths exhibit a difference of 80 m and the numerical simulation supports a minimum pulse width of 900 fs (simulation time resolution: 100 fs). This mismatch can be explained by the input pulse’s deviation from the ideal soliton shape in our experiment. Also it should be noted that the steep transition in the calculated plot in Fig. 3.18b is caused by the temporal oscillatory structure which appeared after about 60 m of transmission in the SMF. Fig. 3.23c shows the calculated pulse intensity profile after 50 m, 60 m, 70 m and 80 m SMF. This clearly shows the dynamics of the pulse compression in the SMF when strong chirp is present. Because of the strong chirp, the pulse’s leading and trailing edges have a wide range of frequency components. When the trailing edge catches up with the leading one in SMF, matching frequency components within them interfere with each other causing this oscillatory structure.

Finally, the compressed 1.2 ps pulse is found to have a time-bandwidth product of 0.43. The large deviation from the theoretically predicted value is due to two facts: first, the chirp caused by SPM inside stage2 DSF is nonlinear, so chirp compensation using optical fibre is unlikely to give completely transform-limited pulses; second, the resultant pulse’s spectrum is not of $Sech^2(t)$ shape. This latter feature is further utilized in our experiment to improve the pulse quality by spectral filtering. This will be discussed in more detail in the next section.

3.3.4 Pulse shaping by spectral filtering

After the double-stage nonlinear compressor the original output pulse from EAM (21 ps) has been compressed down to 1.2 ps, however the relatively low extinction ratio (17 dB) limits its applications in high speed transmission systems, where a minimum extinction ratio of 20 dB is required. The wide pedestal observed in the resultant 1.2 ps pulse (Fig. 3.20a) is mainly caused by the intense peaks (located at the carrier frequency) in the optical spectrum as can be identified in Fig. 3.21b. Various experiments have been carried out to suppress this pulse pedestal, and most of them
are based on spectral filtering using NOLM and its variants such as NALM and DILM [89-92]. In this experiment, considering the spectral structure of the obtained 1.2 ps pulses and our projected OTDM transmission systems, a pulse shaping scheme based on spectral filtering using bandpass filter is adopted [93-95]. Compared to methods employing fibre loop mirrors, this scheme features simple configuration and high stability. The operating principle is relatively straightforward. The improvement of pulse extinction ratio is obtained by blocking the carrier-component using a BPF. In this experiment, carrier-suppression is realized by aligning a tunable bandpass filter with a 3 dB bandwidth of 1nm to the wings of the SPM spectrum. To further illustrate this, Fig. 3.24a shows the extinction ratio of the BPF output pulse when the BPF is tuned from 1547.5 nm to 1552.5 nm. On the same figure, the output spectrum from the nonlinear compression stage is also shown.

![Figure 3.24](image)

Figure 3.24- (a) Optical spectrum after nonlinear pulse compressor and pulse extinction ratio at different filter pass band center. (b) Optical spectrum when filter pass band centered at 1548 nm (blue), 1552 nm (red)

Fig. 3.24b shows the optical spectrum when the 1 nm BPF is aligned to 1548 nm and 1552 nm respectively. These filter centers give the best case extinction ratio of 20 dB. The corresponding autocorrelation traces of these two channels together with the “worst case” results (when BPF is aligned to the central peaks) are shown in Fig. 3.25.

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The pulse widths corresponding to the best extinction ratio performance are found to be 2.5 ps and 2.8 ps for the two filtered signals at 1548 nm and 1552 nm. The increase in the pulse width is due to the limited bandwidth of the filter. As can be seen from the above figure, the wide pedestal associated with the 1.2 ps pulses (Fig. 3.20) after the double-stage nonlinear compressor is effectively suppressed. The resulting time-bandwidth products for 1548 nm and 1552 nm channels are 0.31 and 0.35 respectively, indicating almost transform-limited pulses. The slightly wider pulse width at the longer wavelength channel is due to the dispersion tilt caused by the relatively large channel spacing.
3.4 Summary

In this chapter, a picosecond pulse generator is demonstrated based on external pulse carving and a double-stage pulse compressor employing SPM-induced spectral broadening. The initial 21 ps pulse from an EAM is successfully compressed down to 1.2 ps with an extinction ratio of 17 dB, giving an overall compression factor of 18. Numerical simulations are carried out and agreement between the experimental results and simulations is excellent for both stages of the nonlinear pulse compressor. Moreover, based on the resulting pulse’s spectral structure, a pulse shaping scheme employing spectral filtering is investigated. Effective suppression of pedestal level has been achieved. This scheme will be further employed in Chapter 5 to realize a carrier-suppressed single sideband modulation format for a 4×10Gb/s OTDM systems.