Chapter – 7

Picosecond pulse compression to femtosecond level by the combined action of a highly nonlinear fiber and an optical time lens

7.1. Introduction:

Generation of high repetition rate, narrow optical pulses [7.1, 7.4-7.19] is a topic of current research in optical engineering all over the globe. Conventional techniques of optical pulse generation produce pulses of widths typically in the picosecond range. In order to generate optical pulses in the femtosecond domain, pulse compression [7.2-7.3, 7.20-7.25] is necessary. Applications of high repetition rate, narrow optical pulses lie in optical time division multiplexing (OTDM) [7.26-7.27], light detection and ranging (LIDAR) systems, chemical sensing of poisonous gases, high speed optical data transmission, etc. The maximum number of channels in wavelength division multiplexing (WDM) is limited by fiber dispersion. OTDM-WDM communication systems can utilize the super-wide bandwidth of the low loss optical fiber.

In this chapter, a novel method of optical pulse compression is proposed and analyzed where picosecond input optical pulses can be compressed down to femtosecond domain by using a moderate length of highly nonlinear fiber (HNLF) followed by an optical time lens. Normal geometrical optical lens compresses lightwave in space whereas the optical time lens compresses the optical pulse in the time domain.

7.2. System description:

A mode-locked laser diode (MLLD) operating at a central wavelength $\lambda_c$ produces optical pulses with a repetition frequency $f_m$. This pulse train contains many optical frequency components in multiples of $f_m$ which when demultiplexed by an arrayed waveguide grating (AWG), we can get different optical frequency components. We select four lightwaves having frequencies $f_c \pm nf_m$ and $f_c \pm 2nf_m$ where $n$ is a fixed integer and $f_c$ is the central frequency of the MLLD. These four lightwaves are amplified by four laser diodes in the injection-locked mode. The free-running frequencies of these LDs are identical with the injection lightwave frequencies (viz. $f_c \pm nf_m$ and $f_c \pm 2nf_m$). The free-running powers of LDs
Lasing at \( f_c \pm 2nf_m \) are \( \eta^2 \) times those of LDs lasing at \( f_c \pm nf_m \). Here, \( \eta \) is a constant fraction, less than unity. These four lightwaves when combined in an optical \((4 \times 1)\) power combiner we get a train of optical pulses. The scheme is shown in figure 7.1.

The electric field of the lightwaves from LD1, LD2, LD3 and LD4, in complex representation, can be written as

\[
E_1(t) = E_0 e^{j(\omega_c + n\omega_m)t} \quad (7.1)
\]

\[
E_2(t) = \eta E_0 e^{j(\omega_c + 2n\omega_m)t} \quad (7.2)
\]

\[
E_3(t) = E_0 e^{j(\omega_c - n\omega_m)t} \quad (7.3)
\]

\[
E_4(t) = \eta E_0 e^{j(\omega_c - 2n\omega_m)t} \quad (7.4)
\]

where \( E_0 \) is the amplitude of the electric field. The total electric field at the input of the optical power combiner is given by

\[
E_T(t) = \sum_{i=1}^{4} E_i(t) \quad (7.5)
\]

The resultant intensity is

\[
I(t) \propto E_T(t)E_T^*(t) \quad (7.6)
\]

Again, the peak intensity of the resultant pulse is

\[
I_0 \propto E_0^2 \quad (7.7)
\]

The intensity of the light pulse thus generated is described as

\[
I(t) = \frac{1}{2}I_0 \left[ 1 + \frac{1}{1+\eta^2} \cos 2n\omega_m t + \frac{\eta^2}{1+\eta^2} \cos 4n\omega_m t \right] \quad (7.8)
\]

Here, \( I_0 \) is the peak intensity of the pulse at \( t = 0 \). The normalized intensity \( I(t)/I_0 \) of the pulse as a function of time is plotted in figure 7.2. The pulse has a width of 5 ps and a repetition frequency of 100 GHz with \( \eta^2 = 0.01 \).
Figure 7.1: Schematic diagram of optical pulse synthesizer.
Figure 7.2: Normalized intensity of the pulse as a function of time. Pulse width 5 ps.
Pulse repetition frequency = 100 GHz.
7.3. Analysis:

The input optical pulse is passed through a highly nonlinear fiber of length $L_{H}$ and then it propagates through an optical time lens. The time taken by light of angular frequency $\omega$ in propagating through the HNLF is

$$
t = \frac{L_{H}}{v_{g}}
$$

(7.9)

where

$$
v_{g} = \frac{d\omega}{d\beta_{p}}
$$

(7.10)

is the group velocity of the lightwave and $\beta_{p}$ is the phase constant of the lightwave. The time taken by light of angular frequency $(\omega_{c} + \Delta \omega)$ can be expanded in Taylor’s series as

$$
t(\omega_{c} + \Delta \omega) = t_{c} + \left. \frac{dt}{d\omega_{c}} \right|_{\omega_{c}} \Delta \omega + \frac{1}{2} \left. \frac{d^{2}t}{d\omega^{2}} \right|_{\omega_{c}} (\Delta \omega)^{2} + ...
$$

(7.11)

where $t_{c}$ is the time taken by light of angular frequency $\omega_{c}$. Taking $\Delta \omega = k \omega_{m}$ (for $k = \pm 1$, $\pm 2$), the phase shift $\varphi(t)$ is given by

$$
\varphi(t) = (\omega_{c} + k \omega_{m}) t
$$

$$
\approx \omega_{c} \left[ t_{c} + \left. \frac{dt}{d\omega_{c}} \right|_{\omega_{c}} \Delta \omega + \frac{1}{2} \left. \frac{d^{2}t}{d\omega^{2}} \right|_{\omega_{c}} (k \omega_{m})^{2} + k \omega_{m} t_{c} \right]
$$

$$
= \omega_{c} \left[ t_{c} + k n \omega_{m} L_{H} \beta_{2H} + \frac{1}{2} (k n \omega_{m})^{2} L_{H} \beta_{3H} + k n \omega_{m} t_{c} \right]
$$

(7.12)

Neglecting second order small terms in (7.12). Here, $\beta_{2H} = \left. \frac{d^{2} \beta_{p}}{d\omega^{2}} \right|_{\omega_{c}}$ and $\beta_{3H} = \left. \frac{d \beta_{2H}}{d\omega} \right|_{\omega_{c}}$.

Now,

$$
\varphi(t) = \varphi_{0} - k \omega_{m} r_{0} + (k \omega_{m})^{2} \tau_{1}^{2} + k \omega_{m} \frac{\varphi_{0}}{\omega_{c}}
$$

(7.13)

where $\varphi_{0} = \omega_{c} L_{H}^{\prime} / v_{g0}$, $r_{0} = L_{H} \lambda_{c} D_{H}$ and $\tau_{1}^{2} = \frac{1}{2} \omega_{c} L_{H} \beta_{3H}$. Here, $v_{g0}$ is the group velocity of lightwave of frequency $\omega_{c}$. The corresponding wavelength is $\lambda_{c}$. $D_{H}$ is the dispersion.
parameters of the HNLF. We consider zero dispersion slope of HNLF so that $\beta_{3H} = 0$ and hence, $\tau_1 = 0$.

The intensity-dependent refractive index of the highly nonlinear fiber is written as

$$n' = n_0 + n_z I(t) \quad (7.14)$$

where $n_z$ is the Kerr nonlinearity constant and $I(t)$ is the optical pulse intensity. The nonlinear coefficient ($\gamma$) is related to Kerr nonlinearity as

$$\gamma = \frac{2\pi n_z}{\lambda A_{eff}} \quad (7.15)$$

where $\lambda$ is the wavelength of light and $A_{eff}$ is the effective cross-sectional area of the core of the HNLF. The phase shift of the lightwave due to nonlinear refractive index is given by

$$\varphi_{NL} = (\omega_c + k n_0 \omega_m) \tau_{NLH} \quad (7.16)$$

where

$$\tau_{NLH} = \frac{1}{2} \tau_{NLH0} \left[ 1 + \frac{1}{1 + \eta^2} \cos 2n m \omega_m t + \frac{\eta^2}{1 + \eta^2} \cos 4n m \omega_m t \right] \quad (7.17)$$

and

$$\tau_{NLH0} = \frac{n_z L_H I_0}{c} \quad (7.18)$$

Here, the subscript $H$ indicates HNLF.

After the HNLF, there is an optical time lens consisting of an optical phase modulator (OPM) followed by a single mode fiber (SMF).

The transfer function of the OPM is written as

$$H_{PM}(j \omega_m) = e^{-j\psi(t)} \quad (7.19)$$

where

$$\psi(t) = m\pi \cos n \omega_m t \quad (7.20)$$

and $m = \frac{V_{m0}}{V_x}$, where $V_{m0}$ is the voltage amplitude of the modulator drive signal and $V_x$ is the half-wave voltage of the modulator. The instantaneous frequency change generated due to phase modulation is calculated as

$$\frac{d\psi(t)}{dt} = -m \pi n \omega_m \sin(n \omega_m t) \quad (7.21)$$
The output lightwave from the OPM passes through a SMF of length $L$ which is dispersive.

The transfer function of the SMF is

$$H_{SM}(j\omega) = e^{-j[(\omega_0 + k\omega_0)\tau_0 + L\beta_2k\omega_0(\omega_0 + k\omega_0)]} \approx e^{-j[(\omega_0 + k\omega_0)\tau_0 + \theta_1]}$$ (7.22)

where $\tau_0' = \frac{L}{v_{g0}}$ and $k = \pm 1, \pm 2$. $\beta_2$ is the group velocity dispersion (GVD) parameter. Here, $\theta_1 = L\beta_2k\omega_0\omega_0$. We have neglected terms proportional to $\omega_0^2$ since $\omega_0 \ll \omega_c$.

The composite lightwave output from the HNLF and time lens combination is expressed as

$$Y(t) = A \left[ e^{j[(\omega_0 + 2\omega_m)\tau_{r1} - \varphi_{r1} - \omega_c - 2\omega_m - m\pi n_2\omega_m \sin(2\omega_m t)]} (t_0' + L\beta_2n_2\omega_m) } \right] + \right)$$

$$+ e^{j[(\omega_0 - 2\omega_m)\tau_{r1} - \varphi_{r1} + \omega_c - 2\omega_m - m\pi n_2\omega_m \sin(2\omega_m t)]} (t_0' - L\beta_2n_2\omega_m) } \right] \right)$$

where $A$ = amplitude constant of a single wave with frequency $\omega_c \pm \omega_m$,

$$\varphi_{r1} = \varphi_0 - n_2\omega_m \tau_0 + (\omega_2m) \frac{L}{Vg0} + (\omega_c + n_2\omega_m) \tau_{NLH} \quad (7.24)$$

$$\varphi_{r1}' = \varphi_0 + n_2\omega_m \tau_0 + (\omega_2m) \frac{L}{Vg0} + (\omega_c + n_2\omega_m) \tau_{NLH} \quad (7.25)$$

$$\varphi_{r2} = \varphi_0 - 2n_2\omega_m \tau_0 + (2\omega_m) \frac{L}{Vg0} + (\omega_c + 2\omega_m) \tau_{NLH} \quad (7.26)$$

$$\varphi_{r2}' = \varphi_0 + 2n_2\omega_m \tau_0 + (2\omega_m) \frac{L}{Vg0} + (\omega_c - 2\omega_m) \tau_{NLH} \quad (7.27)$$

Then, $|Y(t)|^2 = 4A^2 \left[ \frac{1 + \eta^2}{2} + \frac{1}{2} \cos(2\varphi_1) + \frac{\eta^2}{2} \cos(4\varphi_1) + \eta \cos \varphi_1 \cos 2\varphi_1 \cos \varphi_3 \right]$ (7.28)

where,

$$\varphi_1 = n_2\omega_m (t - t_0') - n_2\omega_m \tau' - \omega_c L\beta_2n_2\omega_m + m\pi L\beta_2^2 (n_2\omega_m)^2 \sin(2n_2\omega_m t) \quad (7.29)$$

$$\varphi_3 = 3(n_2\omega_m)^2 L\beta_2 \quad (7.30)$$
The normalized intensity of the resultant optical pulse is given by

\[
\frac{I(t)}{I(0)} = \frac{|Y(t)|^2}{|Y(0)|^2}
\]  

(7.32)

When solved numerically, the pulse waveforms obtained are shown in figures 7.3, 7.4, 7.5 and 7.6 for a value of drive parameter \( m = 0.1 \). Other parameters have values as mentioned in the captions of figures. The pulses are compressed relative to the input pulses and have calculated widths in the range of 303 fs to 327 fs. Thus, the HNLF and time lens combination acts a good optical pulse width compressor.

The values of parameters used in numerical calculation are given in Table 7.1.

### Table 7.1

|   |   |   | 1.  |   | 2.  |   | 3.  |   | 4.  |   | 5.  |   | 6.  |   | 7.  |   | 8.  |   | 9.  |   | 10. |   | 11. |   | 12. |   | 13. |   | 14. |   | 15. |   | 16. |   | 17. |   | 18. |   |
|---|---|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|
|   |   |   | \( n \) | 5 | \( f_m \) | 10 GHz | \( \eta^2 \) | 0.5 | \( c \) | \( 3 \times 10^8 \) m/s | \( \lambda_c \) | 1.55 \( \mu \)m | \( n_0 \) | 1.458 | \( n_2 \) | \( 2.9 \times 10^{-20} \) m\(^2\)/W | \( A_{\text{eff}} \) for HNLF | 9.7 \( \mu \)m\(^2\) | \( \gamma \) for HNLF | 12.11 W\(^{-1}\) km\(^{-1}\) | \( v_{g0} = c/n_0 \) | \( 2 \times 10^8 \) m/sec | \( L_H \) | 1m, 10m | \( L \) | 1m, 10m | \( m \) | 0.1 | \( \tau_0 \) | \( 3.1 \times L_H \) | \( \tau_1 \) | 0 | \( \beta_2 \) | \( 2.167 \times 10^{-26} \) m\(^2\)/s\(^2\) | \( t_0' \) for L=10 m | \( 5 \times 10^{-8} \) sec | \( P_0 \) | 10 mW |
Figure 7.3: Normalized pulse intensity waveform. $m = 0.1$, $L_{ff} = 1 \text{ m}$, $L = 1 \text{ m}$, $\eta^2 = 0.5$, $f_w = 10 \text{ GHz}$, Pulsewidth = 315 fs.
Figure 7.4: Normalized pulse intensity waveform. \( m = 0.1 \), \( L_m = 1 \, \text{m} \), \( L = 10 \, \text{m} \), \( \eta^2 = 0.5 \),
\[ f_m = 10 \, \text{GHz}, \quad \text{Pulsewidth} = 303 \, \text{fs}. \]
Figure 7.5: Normalized pulse intensity waveform. $m = 0.1$, $L_H = 10 \text{ m}$, $L = 1 \text{ m}$, $\eta^2 = 0.5$, $f_m = 10 \text{ GHz}$, Pulsewidth = 327 fs.
Figure 7.6: Normalized pulse intensity waveform. $m = 0.1$, $L_H = 10 \, m$, $L = 10 \, m$, $\eta^2 = 0.5$, $f_s = 10 \, GHz$, Pulsewidth = 315 fs.
7.4. Conclusion:

In this chapter, the author has proposed and analyzed the possibility of optical pulse compression produced by the combined action of a highly nonlinear fiber and an optical time lens. The dependence of optical pulse compression on various physical parameters such as highly nonlinear fiber length and SMF length have been presented. The picosecond optical pulse can be compressed down to femtosecond domain by the HNLF-time lens combination which acts as a good optical pulse compressor. The OPM is underdriven, the value of the drive parameter, $m$, is only 10%.

The scheme proposed in this chapter for optical pulse compression is simple in circuitry in the sense that it requires only a certain length of HNLF followed by an optical time lens. The degree of pulse compression which can be achieved by this technique is fairly high in which picoseconds pulses are compressed to femtosecond pulses.

References:


