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Picosecond Pulse Compression to Femtosecond Level by the Combined Action of a Highly Nonlinear Fiber and an Optical Time Lens

Taraprasad Chattopadhyay, Prosenjit Bhattacharyya and Chiranjib Ghosh

Student Member IEEE Department of Physics, Visva-Bharati University, Santiniketan-731235, W.B., India.

Abstract

In this paper, we propose and analyze a novel method of picoseconds optical pulse compression down to femtosecond level by the combined action of a highly nonlinear fiber and an optical time lens. Typical pulse width ~ 300 femtosecond can be achieved with pulse repetition period of 2 picosecond.

Keywords: Highly nonlinear fiber, Optical time lens, Optical pulse compression, Pulse width, Pulse repetition period.

1. Introduction:

Generation of high repetition rate, narrow optical pulses [1, 4-19] 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 [2-3, 20-25] is necessary. Applications of high repetition rate, narrow optical pulses lie in optical time division multiplexing (OTDM) [26-27], light detection and ranging (LIDAR), 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 system can utilize the super wide bandwidth of the low loss optical fiber.

This paper proposes and analyses a novel method of optical pulse compression where picoseconds input optical pulse 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 the lightwave in space whereas the time lens compresses the optical pulse in the time domain.

2. System Description:

A mode-locked laser diode (MLLD) operating at a central wavelength λ_c produces optical pulses with a repetition frequency f_m. This pulse train contains many optical frequency components 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 η^2 times those of LDs lasing at $f_c \pm nf_m$. Here, η is a constant fraction, less than unity. These four lightwaves when combined in an optical (4×1) power combiner we get a train of optical pulses. The scheme is shown in Fig. 1.

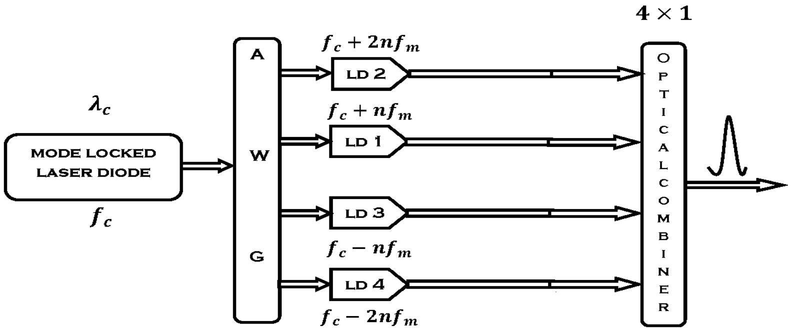

Figure 1. Schematic diagram of optical pulse synthesizer.

The intensity of the light pulse thus generated is described as

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

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 Fig. 2. The pulse has a width of 5 ps and a repetition frequency of 100 GHz with $\eta^2 = 0.01$.

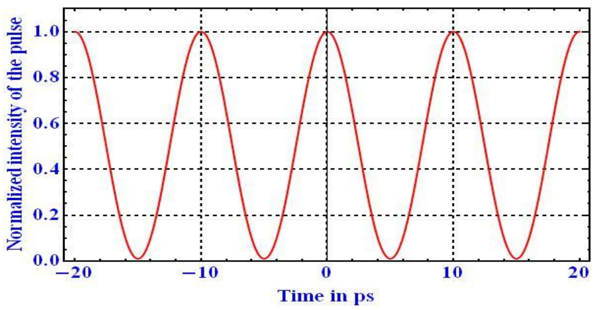

Figure 2. **Normalized intensity of the pulse as a function of time. Pulse width 5 ps. Pulse repetition frequency = 100 GHz.**

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 ω in propagating through the HNLF is

$$t = \frac{L_H}{v_g} \tag{2}$$

where $v_g = \dfrac{d\omega}{d\beta_p}$ (3)

is the group velocity of the lightwave and β_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

$$t(\omega_c + \Delta\omega) = t_c + \left.\frac{dt}{d\omega}\right|_{\omega_c} \Delta\omega + \frac{1}{2}\left.\frac{d^2t}{d\omega^2}\right|_{\omega_c} (\Delta\omega)^2 + ... \tag{4}$$

where t_c is the time taken by light of angular frequency ω_c. Taking $\Delta\omega = kn\omega_m$ (for $k = \pm 1,\ \pm 2$), the phase shift $\varphi(t)$ is given by

$$\begin{aligned}\varphi(t) &= (\omega_c + kn\omega_m)t \\ &\approx \omega_c\left[t_c + \left.\frac{dt}{d\omega}\right|_{\omega_c} \Delta\omega + \frac{1}{2}\left.\frac{d^2t}{d\omega^2}\right|_{\omega_c} (kn\omega_m)^2 + kn\omega_m t_c\right]\end{aligned} \tag{5}$$

neglecting second order small terms in (5). Now,

$$\varphi(t) = \varphi_0 - kn\omega_m\tau_0 + (kn\omega_m)^2\tau_1^2 + kn\omega_m\frac{\varphi_0}{\omega_c} \tag{6}$$

where $\varphi_0 = \omega_c\dfrac{L_H}{v_{g0}}$, $\tau_0 = L_H\lambda_c D_H$ and $\tau_1^2 = \dfrac{1}{2}\omega_c L_H\beta_{3H}$. Here, v_{g0} is the group velocity of lightwave of frequency ω_c. The corresponding wavelength is λ_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

$$n' = n_0 + n_2 I(t) \tag{7}$$

where n_2 is the Kerr nonlinearity constant and $I(t)$ is the optical pulse intensity. The nonlinear coefficient (γ) is related to Kerr nonlinearity as

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{8}$$

where λ 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

$$\varphi_{NL} = (\omega_c + kn\omega_m)\tau_{NLH} \tag{9}$$

where $$\tau_{NLH} = \frac{1}{2}\tau_{NLH0}\left[1+\frac{1}{1+\eta^2}\cos 2n\omega_m t+\frac{\eta^2}{1+\eta^2}\cos 4n\omega_m t\right] \quad (10)$$

and $$\tau_{NLH0} = \frac{n_2 L_H I_0}{c} \quad (11)$$

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 modulation frequency applied to the OPM is

$$H_{PM}(jn\omega_m) = e^{-j\psi(t)} \quad (12)$$

where $$\psi(t) = m\pi \cos n\omega_m t \quad (13)$$

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

$$\frac{d\psi(t)}{dt} = -m\pi\, n\omega_m \sin(n\omega_m t) \quad (14)$$

The output lightwave from the OPM passes through a SMF of length L which is dispersive.

The transfer function of the SMF is

$$\begin{aligned} H_{SM}(j\omega) &= e^{-j[(\omega_c+kn\omega_m)t_0'+L\beta_2 kn\omega_m(\omega_c+kn\omega_m)]} \\ &\approx e^{-j[(\omega_c+kn\omega_m)t_0'+\theta_k]} \end{aligned} \quad (15)$$

where $t_0' = \frac{L}{v_{g0}}$ and $k = \pm 1, \pm 2$. β_2 is the group velocity dispersion (GVD) parameter. Here, $\theta_k = L\beta_2 k\, n\omega_m \omega_c$. We have neglected terms proportional to ω_m^2 since $\omega_m << \omega_c$.

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

$$Y(t) = A\begin{bmatrix} e^{j\{(\omega_c+n\omega_m)t-\varphi_{T1}-\psi-(\omega_c+n\omega_m-m\pi 2n\omega_m \sin 2n\omega_m t)(t_0'+L\beta_2 n\omega_m)\}} \\ +e^{j\{(\omega_c-n\omega_m)t-\varphi_{T1}'-\psi-(\omega_c-n\omega_m-m\pi 2n\omega_m \sin 2n\omega_m t)(t_0'-L\beta_2 n\omega_m)\}} \\ +\eta e^{j\{(\omega_c+2n\omega_m)t-\varphi_{T2}-\psi-(\omega_c+2n\omega_m-m\pi 2n\omega_m \sin 2n\omega_m t)(t_0'+2L\beta_2 n\omega_m)\}} \\ +\eta e^{j\{(\omega_c-2n\omega_m)t-\varphi_{T2}'-\psi-(\omega_c-2n\omega_m-m\pi 2n\omega_m \sin 2n\omega_m t)(t_0'-2L\beta_2 n\omega_m)\}} \end{bmatrix} \quad (16)$$

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

$$\varphi_{T1} = \varphi_0 - n\omega_m\tau_0 + (n\omega_m)^2\tau_1^2 + n\omega_m\frac{L_H}{v_{g0}} + (\omega_c + n\omega_m)\tau_{NLH} \quad (17)$$

$$\varphi_{T1}' = \varphi_0 + n\omega_m\tau_0 + (n\omega_m)^2\tau_1^2 - n\omega_m\frac{L_H}{v_{g0}} + (\omega_c - n\omega_m)\tau_{NLH} \quad (18)$$

$$\varphi_{T2} = \varphi_0 - 2n\omega_m\tau_0 + (2n\omega_m)^2\tau_1^2 + 2n\omega_m\frac{L_H}{v_{g0}} + (\omega_c + 2n\omega_m)\tau_{NLH} \quad (19)$$

$$\varphi_{T2}' = \varphi_0 + 2n\omega_m\tau_0 + (2n\omega_m)^2\tau_1^2 - 2n\omega_m\frac{L_H}{v_{g0}} + (\omega_c - 2n\omega_m)\tau_{NLH} \quad (20)$$

Then,

$$\left|Y(t)\right|^2 = 4A^2\left[\frac{1+\eta^2}{2}+\frac{1}{2}\cos(2\varphi_1)+\frac{\eta^2}{2}\cos(4\varphi_1)+\eta\cos\varphi_1\cos 2\varphi_1\cos\varphi_3\right] \quad (21)$$

where, $$\varphi_1 = n\omega_m(t-t_0')-n\omega_m\tau'-\omega_c L\beta_2 n\omega_m + m\pi L\beta_2^2(n\omega_m)^2\sin(2n\omega_m t) \quad (22)$$

$$\varphi_3 = 3(n\omega_m)^2 L\beta_2 \quad (23)$$

$$\tau' = \frac{L_H}{v_{g0}}+\tau_{NLH}-\tau_0 \quad (24)$$

The normalized intensity of the resultant optical pulse is given by

$$\frac{I(t)}{I(0)} = \frac{\left|Y(t)\right|^2}{\left|Y(0)\right|^2} \quad (22)$$

When solved numerically, the pulse waveforms obtained are shown in Figs. 3, 4, 5 and 6 for a value of drive parameter $m=0.1$. Other parameters have values as mentioned in the caption. The pulses are compressed relative to the input pulses and have calculated widths in the range of 303 fs to 327 fs.

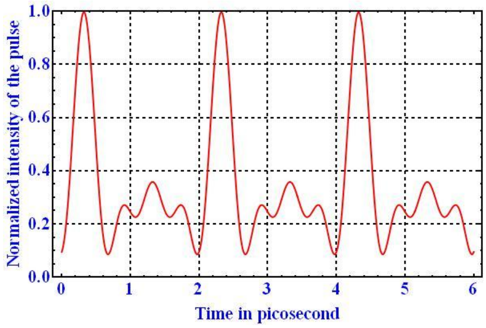

Figure 3. $m=0.1$, $L_H=1\,m$, $L=1\,m$, $\eta^2=0.5$, $f_m=10\,GHz$, **Pulsewidth = 315 fs**

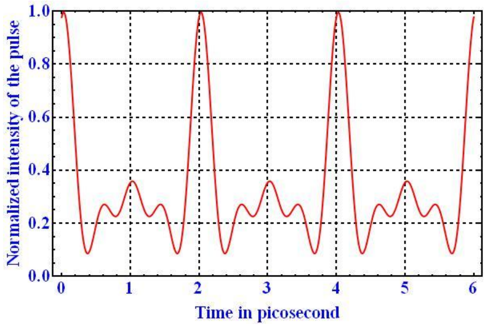

Figure 4. $m=0.1$, $L_H=1\,m$, $L=10\,m$, $\eta^2=0.5$, $f_m=10\,GHz$, **Pulsewidth = 303 fs**

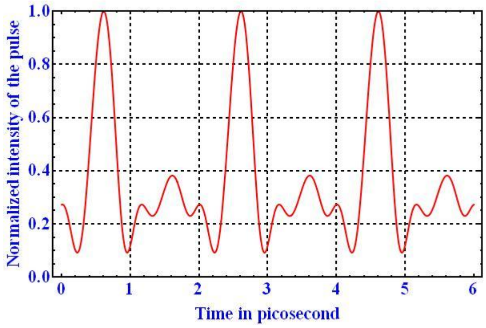

Figure 5. $m = 0.1$, $L_H = 10\,m$, $L = 1\,m$, $\eta^2 = 0.5$, $f_m = 10\,GHz$, **Pulsewidth = 327 fs**

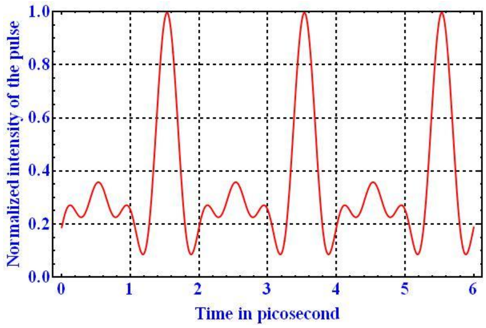

Figure 6. $m = 0.1$, $L_H = 10\,m$, $L = 10\,m$, $\eta^2 = 0.5$, $f_m = 10\,GHz$, **Pulsewidth = 315 fs**

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

Table I

1	n	5
2	f_m	$10\,GHz$
3	η^2	0.5
4	c	$3\times10^8\ m/s$
5	λ_c	$1.55\,\mu m$
6	n_0	1.458
7	n_2	$2.9\times10^{-20}\,m^2/W$
8	A_{eff} for HNLF	$9.7\ \mu m^2$
9	γ for HNLF	$12.11\ W^{-1}km^{-1}$
1	v_{g0}	$c/n_0 = 2\times10^8$ m/sec
1	L_H	10m, 1m
1	L	$1\,m$, 10m
1	m	0.1
1	τ_0	$3.1\times L_H$

1	τ_1	0
1	β_2	2.167×10^{-2} ps^2/m
1	t_0' for L=10 m	5×10^{-8} sec
1	P_0	$10\,mW$

4. Conclusion:

In this paper, we have 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 ps pulse can be compressed down to fs domain by the HNLF-time lens combination. The OPM is underdriven, the drive parameter m being only 10%.

5. Acknowledgement:

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