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A novel scheme of optical pulse width compression using a feedback optical phase modulator

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ABSTRACT This paper presents a scheme for the compression of optical pulse widths by using a feedback optical phase modulator. In the first part of the proposed circuit, the carrier and two fourth-order sidebands on either side of the carrier are amplified and phase shifted before getting combined by an optical power combiner to generate a picosecond optical pulse. The optical pulse generated by this part of the circuit has a calculated width of 3.5 ps. This optical pulse when passed through a feedback optical phase modulator produces a compressed optical pulse at the output. By making the drive frequency of the feedback optical phase modulator equal to 100 GHz, we found the output optical pulse to have a calculated width of 1.0 ps.

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1 Introduction

High-repetition rate subpicosecond optical pulse generation [1–17] is an important theme of modern research. These short optical pulses find application as a source of optical clock signal. They are also used in high-capacity optical time division multiplexed (OTDM) [18, 19] communication system. In order to achieve a high bit rate optical modulation, we not only require a high-speed modulator, but also a high repetition rate short optical pulse train. In OTDM communication, the optical pulse train undergoes high-speed modulation and the modulated pulse trains are subjected to incremental delay so that they can be distinguished in the time domain. These pulse trains are combined in a multiplexer to generate the OTDM signal. A conventional source of picosecond optical pulses is a mode-locked laser [20]. In a mode-locked laser, resonant modes are coupled in phases through gain modulation of the resonator cavity. It is, however, difficult to generate high-frequency ultra-short pulse trains by conventional methods.

In this paper, we propose a method of optical pulse width compression using a feedback-type optical phase modulator (FOPM). At the first stage, we propose generating optical pulses by injection locking three laser diodes to three specific frequency components of a phase modulated (PM) light wave. The resultant pulse has a width of several picosecond. At the second stage, we propose reducing the optical pulse width by passing the optical pulse through a feedback optical phase modulator (FOPM). Calculations show that a 1.0 ps pulse train at 100 GHz repetition frequency can by generated by using an feedback optical phase modulator (FOPM). The drive frequency of the feedback optical phase modulator (FOPM) is 100 GHz.

2 Proposed scheme of optical pulse generation

In this section, we describe a novel circuit for the generation of picosecond optical pulse train and analyze the same for the calculation of the pulse width.

2.1 *Circuit description*

The pulse generation circuit is shown in Fig. 1. The DFB laser diode (LD) at the input is the master laser which emits light of wavelength λ. This light is then phase modulated in an optical phase modulator (OPM). The PM light wave is then coupled to the arrayed waveguide grating (AWG) having a channel spacing equal to the modulation frequency f_m. The AWG demultiplexes the sidebands of the optical PM light wave. We select three light waves from the output of the AWG that have the frequencies $f_c - nf_m$, f_c, $f_c + nf_m$. Here, f_c is the master laser frequency and n has a typical value of four. These three light waves are then amplified by injection-locked [21] DFB LDs – LD2, LD0, and LD1, respectively. The free-running oscillation frequencies of these LDs are made equal to $f_c - nf_m$, f_c, $f_c + nf_m$ respectively. The phases of these amplified light waves can be adjusted by placing a voltage-tunable electro-optic phase shifter (OPS) after each injection-locked LD. The three light waves are then combined in an optical power combiner to generate an optical pulse.

2.2 *Analysis*

The light wave output from the master DFB laser is expressed as

$$a(t) = a_0 \, e^{j2\pi f_c t} \,. \tag{1}$$

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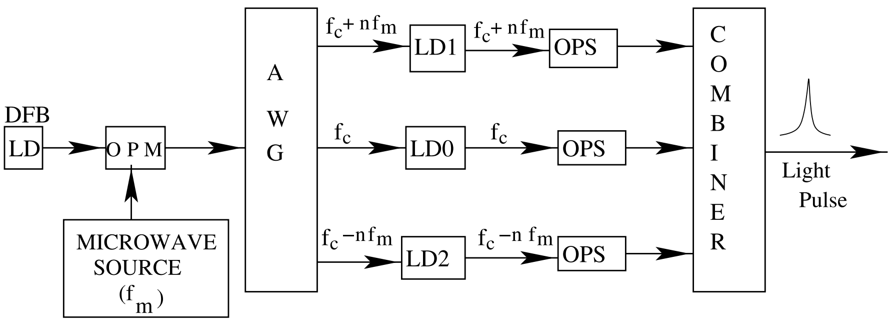

FIGURE 1 Schematic circuit diagram of the high repetition-rate optical pulse generator. LD: Laser diode; OPM: Optical phase modulator; AWG: Arrayed waveguide grating; OPS: Optical phase shifter

The actual electric field of the light wave is the real part of this complex representation. The output light wave from the kth LD is expressed as

$$a_k(t) = a_{k_0}\,\mathrm{e}^{j[(\omega_c + kn\omega_m)t + \varphi_k]}\,, \tag{2}$$

where $k = 1$ indicates LD1, $k = 0$ indicates LD0, and $k = -1$ indicates LD2. a_{k_0} is the amplitude of the output light from the injection-locked kth LD, ω_c is carrier frequency, ω_m is the optical phase modulator drive frequency, all in radian, and φ_k is the phase angle of the output of the kth LD. The output light wave from the combiner can be written as

$$Y(t) = \sum_{k=-1}^{k=1} a_k(t)\,. \tag{3}$$

Putting $a_{-10} = a_{20}$, we get,

$$\begin{aligned}|Y(t)|^2 &= Y(t)Y^*(t)\\ &= a_{00}^2 + a_{10}^2 + a_{20}^2 + 2a_{00}a_{10}\cos(n\omega_m t + \varphi_1 - \varphi_0)\\ &\quad + 2a_{00}a_{20}\cos(n\omega_m t + \varphi_0 - \varphi_2)\\ &\quad + 2a_{10}a_{20}\cos(2n\omega_m t - \varphi_2 + \varphi_1)\,.\end{aligned}$$

Adjusting the phases $(\varphi_0, \varphi_1, \varphi_2)$ of the combining light waves, we can generate different kinds of optical pulses. For getting a good pulse shape, we put $a_{10} = a_{00}$ and $a_{20} = \frac{a_{00}}{2}$. Also, we put $\varphi_0 = \varphi_1 = \varphi_2$.Then,

$$\frac{|Y(t)|^2}{|Y(0)|^2} = \frac{1}{25}(9 + 12\cos n\omega_m t + 4\cos 2n\omega_m t)\,. \tag{4}$$

Taking $n = 4$ and $f_m = \frac{\omega_m}{2\pi} = 25$ GHz, we plot the normalized intensity of the output light wave from this circuit in Fig. 2.

This is a train of pulses having a calculated pulse width of 3.5 ps. The repetition frequency of this pulse train is $n f_m = 100$ GHz in this case. The time width-frequency bandwidth product of this pulse is 0.7.

3 Optical pulse compression

In this section, we describe a method of reducing the pulse width from its original several picosecond level to 1.0 ps level by using a feedback optical phase modulator.

We consider the phase modulation produced in a travelling-wave feedback modulator. The modulator is assumed to be fabricated on an X-cut $LiNbO_3$ substrate with its optic axis in the Z-direction. The modulator is Y-propagating and the input

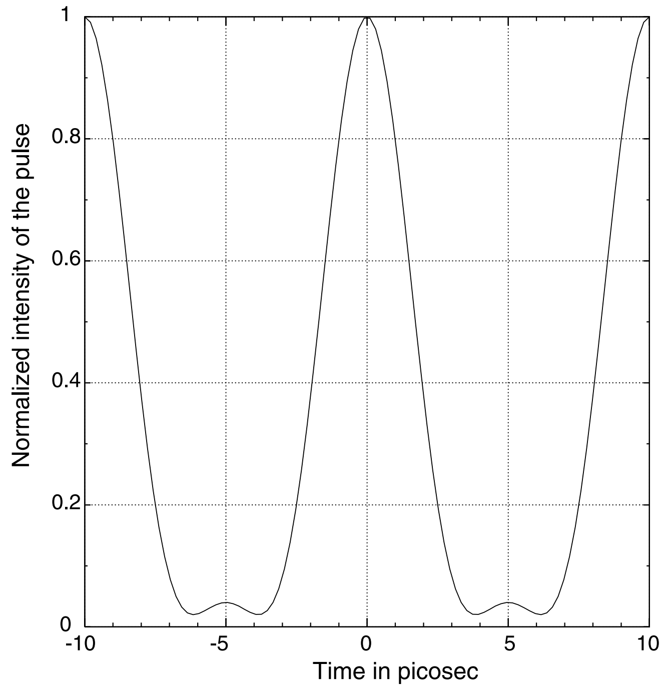

FIGURE 2 Calculated intensity profile of the optical pulse. $f_m = 25$ GHz and $n = 4$

light has polarization along the Z-direction. We will calculate the length of the planar electrodes of the feedback modulator.

We consider an electro-optic optical phase modulator with reflectors at its ends. The reflectors reflect the modulated light back into the phase modulator (PM). Let R_1 and R_2 be the reflectivities of the reflectors attached with the input and output ports of the feedback optical phase modulator (FOPM). A schematic diagram of the optical feedback modulator is shown in Fig. 3.

The coordinate system and the light propagation inside the modulator is shown in Fig. 4. The microwave field is also in the Z-direction.

The microwave drive signal propagates down the electrodes with a smaller velocity than that of the light-wave. So, it gradually lags behind the light wave as it travels down the electrode. Let v_m be the microwave velocity and v_{op} be the light wave velocity. Microwave and light wave start at the same time at $y = 0$. So, at time t after start, the microwave lags behind the light wave by a distance $(v_{op} - v_m)t$. This corresponds to a phase lag $\Delta\varphi_1(t) = \frac{n\omega_m}{v_m}(v_{op} - v_m)t$, where $n\omega_m$ is the radian frequency of the microwave signal. The phase of the microwave field seen by the light wave at (y, t) is $(n\omega_m t -$

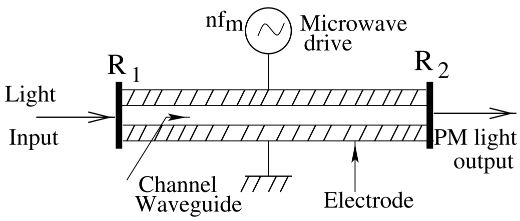

FIGURE 3 Schematic diagram of the optical phase modulator with end reflectors. R_1 and R_2 are reflectivities

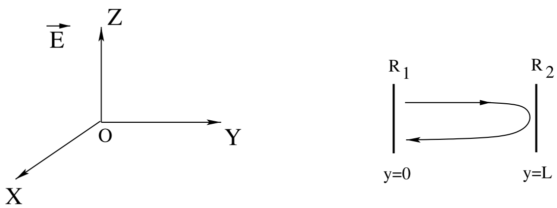

FIGURE 4 Coordinate system and light propagation in the feedback modulator

$\Delta\varphi_1$). Since light travels a distance y in time t, we have $t = \frac{y}{v_{\mathrm{op}}}$. Then,

$$\Delta\varphi_1 = n\omega_{\mathrm{m}} \left(\frac{1}{v_{\mathrm{m}}} - \frac{1}{v_{\mathrm{op}}} \right) y \, . \tag{5}$$

The spatial average of the microwave field seen by the light wave in propagating from $y = 0$ to $y = L$ is

$$\begin{aligned} E_{\mathrm{av}} &= \frac{1}{L} \int_0^L E_0 \, \mathrm{e}^{j(n\omega_{\mathrm{m}} t - \Delta\varphi_1)} \, \mathrm{d}y \\ &= E_0 \frac{\sin\left(\frac{k_0 L}{2}\right)}{\left(\frac{k_0 L}{2}\right)} \mathrm{e}^{j\left(n\omega_{\mathrm{m}} t - \frac{k_0 L}{2}\right)} \, , \end{aligned} \tag{6}$$

where E_0 is the microwave electric field amplitude at the input of the modulator. Here, $k_0 = n\omega_{\mathrm{m}} \left(\frac{1}{v_{\mathrm{m}}} - \frac{1}{v_{\mathrm{op}}} \right)$.

The corresponding average microwave voltage seen by the light wave is given by

$$V_{\mathrm{av}} = V_{\mathrm{m}_0} \frac{\sin\left(\frac{k_0 L}{2}\right)}{\left(\frac{k_0 L}{2}\right)} \mathrm{e}^{j\left(n\omega_{\mathrm{m}} t - \frac{k_0 L}{2}\right)} \, , \tag{7}$$

where V_{m_0} is the voltage amplitude of the input microwave signal. This follows from (6). Similarly, the spatial average of the microwave field seen by the reflected light wave in propagating from $y = L$ to $y = 0$ is

$$E'_{\mathrm{av}} = \frac{1}{L} \int_L^0 E_0 \, \mathrm{e}^{j(n\omega_{\mathrm{m}} t + \Delta\varphi_2)} \, \mathrm{d}y \, ,$$

where $\Delta\varphi_2 = n\omega_{\mathrm{m}} \left(\frac{1}{v_{\mathrm{m}}} + \frac{1}{v_{\mathrm{op}}} \right) y - n\omega_{\mathrm{m}} \frac{L}{v_{\mathrm{op}}}$. Now,

$$E'_{\mathrm{av}} = -E_0 \frac{\sin\left(\frac{k'_0 L}{2}\right)}{\left(\frac{k'_0 L}{2}\right)} \mathrm{e}^{j\left(n\omega_{\mathrm{m}} t + \frac{k_0 L}{2}\right)} \, , \tag{8}$$

where $k'_0 = n\omega_{\mathrm{m}} \left(\frac{1}{v_{\mathrm{m}}} + \frac{1}{v_{\mathrm{op}}} \right)$. The corresponding average microwave voltage seen by the reflected light wave is given by

$$V'_{\mathrm{av}} = -V_{\mathrm{m}_0} \frac{\sin\left(\frac{k'_0 L}{2}\right)}{\left(\frac{k'_0 L}{2}\right)} \mathrm{e}^{j\left(n\omega_{\mathrm{m}} t + \frac{k_0 L}{2}\right)} \, . \tag{9}$$

This follows from (8). Let

$$k_0 L = \pi \tag{10}$$

then,

$$\begin{aligned} \frac{E'_{\mathrm{av}}}{E_{\mathrm{av}}} &= \frac{\sin\left(\frac{k'_0 L}{2}\right)}{\sin\left(\frac{k_0 L}{2}\right)} \left(\frac{k_0}{k'_0} \right) \\ &= \frac{n_{\mathrm{m}} - n_{\mathrm{op}}}{n_{\mathrm{m}} + n_{\mathrm{op}}} \sin\left(\frac{k'_0 L}{2} \right) \, , \end{aligned} \tag{11}$$

where n_{m} and n_{op} are the refractive indices of the microwave and light wave, respectively.

So, the phase modulation produced in forward motion is greater than that in backward motion of the light wave. The length of the electrode of the feedback modulator will be obtained from (10) as

$$L = \frac{\lambda_{\mathrm{m}}}{2(n_{\mathrm{m}} - n_{\mathrm{op}})} \, . \tag{12}$$

λ_{m} is the vacuum wavelength of the microwave signal of frequency $n\omega_{\mathrm{m}}$. Here, we have assumed $n_{\mathrm{m}} > n_{\mathrm{op}}$. In some polymer, $n_{\mathrm{m}} < n_{\mathrm{op}}$. Then, we have

$$L = \frac{\lambda_{\mathrm{m}}}{2(n_{\mathrm{op}} - n_{\mathrm{m}})} \, . \tag{13}$$

Now, $\lambda_{\mathrm{m}} = \frac{c}{n f_{\mathrm{m}}}$ where $c = 3 \times 10^8\,\mathrm{m/s}$ and $n f_{\mathrm{m}} = 100\,\mathrm{GHz}$. c is the vacuum velocity of light. For a polymer modulator [22, 23] using SU-8 electro-optic polymer which is a negative photoresist, we take $n_{\mathrm{m}} = 1.5$ and $n_{\mathrm{op}} = 1.565$ at the operating wavelength of $1.55\,\mu\mathrm{m}$. This yields a value of electrode length, $L = 23$ mm.

If l be the length of the $R_1 - R_2$ cavity then the optical round-trip time is $\left(\frac{2 l n_{\mathrm{op}}}{c} \right)$ and for the reinforcement of the output waves, we must have

$$n\omega_{\mathrm{m}} \left(\frac{2 l n_{\mathrm{op}}}{c} \right) = 2p\pi \, , \tag{14}$$

where $p = 1, 2, 3, ...$ is an integer. This principle is analogous with the principle of mode-locking [20]. Therefore,

$$l = \frac{2p\pi c}{n\omega_{\mathrm{m}} 2 n_{\mathrm{op}}} = \frac{pc}{n f_{\mathrm{m}} 2 n_{\mathrm{op}}} \, , \tag{15}$$

Taking $c = 3 \times 10^8\,\mathrm{m/s}$, $n f_{\mathrm{m}} = 100\,\mathrm{GHz}$ and, $n_{\mathrm{op}} = 1.565$, we have the cavity length $l = 0.96p$ mm, where the integer p must be such that $l \geq L$. Any imbalance in the cavity length l determined by the condition (14) can be compensated by applying a dc voltage to the phase modulator.

The output light wave from the feedback OPM is given by

$$a_{pm}(t) = a(t)\left(1-\sqrt{R_2}\right) \mathrm{e}^{j\Delta\psi_1(t)}\left[1+\sqrt{R_1 R_2}\,\mathrm{e}^{j(\Delta\psi_1+\Delta\psi_2)} + R_1 R_2\,\mathrm{e}^{j2(\Delta\psi_1+\Delta\psi_2)} + (R_1 R_2)^{\frac{3}{2}}\,\mathrm{e}^{j3(\Delta\psi_1+\Delta\psi_2)} + \ldots\right], \tag{16}$$

where

$$\Delta\psi_1(t) = \frac{\pi}{V_\pi} V_{\mathrm{av}} = \frac{\pi V_{\mathrm{m}_0}}{V_\pi} \frac{\sin\left(\frac{k_0 L}{2}\right)}{\left(\frac{k_0 L}{2}\right)} \cos\left(n\omega_{\mathrm{m}} t - \frac{k_0 L}{2}\right) = \frac{2V_{\mathrm{m}_0}}{V_\pi} \sin n\omega_{\mathrm{m}} t \tag{17}$$

and

$$\Delta\psi_2(t) = \frac{\pi V'_{\mathrm{av}}}{V_\pi} = \Delta\psi_1(t)\frac{V'_{\mathrm{av}}}{V_{\mathrm{av}}} = \Delta\psi_1(t)\frac{n_{\mathrm{m}}-n_{\mathrm{op}}}{n_{\mathrm{m}}+n_{\mathrm{op}}}\sin\left(\frac{k'_0 L}{2}\right) = \frac{2V_{\mathrm{m}_0}}{V_\pi}\frac{n_{\mathrm{m}}-n_{\mathrm{op}}}{n_{\mathrm{m}}+n_{\mathrm{op}}}\sin\left(\frac{k'_0 L}{2}\right)\sin n\omega_{\mathrm{m}} t\,. \tag{18}$$

Thus,

$$\Delta\psi_1(t)+\Delta\psi_2(t) = \frac{2V_{\mathrm{m}_0}}{V_\pi}\left[1+\frac{n_{\mathrm{m}}-n_{\mathrm{op}}}{n_{\mathrm{m}}+n_{\mathrm{op}}}\sin\left(\frac{k'_0 L}{2}\right)\right]\sin n\omega_{\mathrm{m}} t \tag{19}$$

$$= \beta \sin n\omega_{\mathrm{m}} t\,, \tag{20}$$

where

$$\beta = \frac{2V_{\mathrm{m}_0}}{V_\pi}\left[1+\frac{n_{\mathrm{m}}-n_{\mathrm{op}}}{n_{\mathrm{m}}+n_{\mathrm{op}}}\sin\left(\frac{k'_0 L}{2}\right)\right]. \tag{21}$$

Here , we have taken $n_{\mathrm{m}} > n_{\mathrm{op}}$. If $n_{\mathrm{m}} < n_{\mathrm{op}}$ for any polymer, the expression for β will be given by

$$\beta = \frac{2V_{\mathrm{m}_0}}{V_\pi}\left[1+\frac{n_{\mathrm{op}}-n_{\mathrm{m}}}{n_{\mathrm{op}}+n_{\mathrm{m}}}\sin\left(\frac{k'_0 L}{2}\right)\right]. \tag{22}$$

Here, V_π is the half-wave voltage of the feedback OPM and $V_{\mathrm{m}_0}\cos n\omega_{\mathrm{m}} t$ is the microwave modulating signal voltage of amplitude V_{m_0} and angular frequency $n\omega_{\mathrm{m}}$. The value of V_π of the 40 Gb/s $LiNbO_3$ modulator has been reported [24] to go down to 0.9 V. The value of V_π for a polymer modulator [25] less than 1 V has also been reported to be achieved. Now,

$$|a_{pm}(t)|^2 = |a(t)|^2\frac{\left(1-\sqrt{R_2}\right)^2}{1-R_1 R_2}\left[1+2\sqrt{R_1 R_2}\cos(\beta\sin n\omega_{\mathrm{m}} t) + 2R_1 R_2\cos(2\beta\sin n\omega_{\mathrm{m}} t) + 2(R_1 R_2)^{\frac{3}{2}}\cos(3\beta\sin n\omega_{\mathrm{m}} t)+\ldots\right]. \tag{23}$$

We take $\beta = 2$ in numerical calculation. This corresponds to the case $V_{\mathrm{m}_0} < V_\pi$ and the modulator is underdriven. We have considered Bessel functions with argument $2r\beta$ for $r = 1, 2, 3, 4$ and having an order up to 8 in numerical calculations. The feedback modulator drive frequency is $n f_{\mathrm{m}}$ which is 100 GHz for $n = 4$ and $f_{\mathrm{m}} = 25$ GHz. The FOPM drive signal can be generated through a nonlinear harmonic generator by using the fundamental microwave signal of frequency f_{m}. Recently, polymer electro-optic modulators [26] have been realized with a bandwidth of 113 GHz. The shape and the width of the optical pulse generated by the feedback optical phase modulator is shown in Fig. 5.

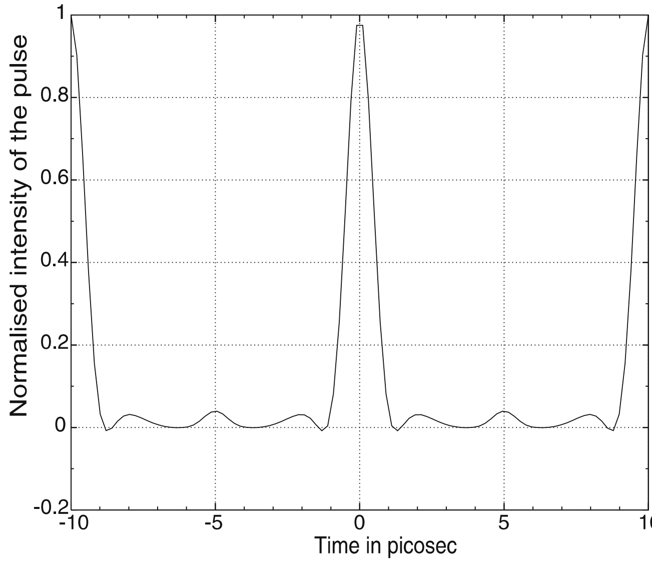

FIGURE 5 Calculated intensity profile of the optical pulse. $f_{\mathrm{m}} = 25$ GHz and $n = 4$

The calculated pulse width is 1.0 ps taking $R_1 = 1$, $R_2 = 0.5$, $L = 23$ mm, $n_{\mathrm{m}} = 1.5$ and $n_{\mathrm{op}} = 1.565$. The repetition rate of the generated pulse train is $n f_{\mathrm{m}}$. Taking $n = 4$ and $f_{\mathrm{m}} = 25$ GHz, we find that the repetition rate is 100 GHz.

We have selected three light waves with a frequency separation of $n f_{\mathrm{m}}$ between adjacent waves from the output of the AWG. This is because this results in a pulse train having a repetition frequency of $n f_{\mathrm{m}}$. If we select more light waves from the output of the AWG having an interwave frequency separation less than $n f_{\mathrm{m}}$, the repetition frequency of the pulse train would accordingly be less than $n f_{\mathrm{m}}$. But, the pulse would be shorter. So, for generating high repetition frequency pulse trains, we have selected three light waves with the interwave spacing of $n f_{\mathrm{m}}$.

The optical sideband power at $f_{\mathrm{c}} + n f_{\mathrm{m}}$ frequency decreases with increasing n. In order to accomplish injection locking of the laser diode (LD), the locking light wave power must be typically ≥ -30 dB relative to the free-running power of the locked laser. The integer n in $n f_{\mathrm{m}}$ should be as large as possible subject to the condition that the light wave power at the frequency $(f_{\mathrm{c}} \pm n f_{\mathrm{m}})$ is sufficient to injection lock the slave laser diode (LD). This gives rise to a trade-off between the high repetition frequency of the pulse train and the occurrence of injection locking.

The feedback optical phase modulator (FOPM) is used instead of a single optical phase modulator in order to produce a greater effective phase modulation index which, in turn, produces many sidebands and hence broadens the spectrum of the pulse. This results in a shorter pulse. If we try to achieve this result with a single optical phase modulator, it would require much higher modulator drive power.

The response of the optical cavity of the FOPM is exponential in nature. This is seen from the basic definition of the

Q-factor of the cavity. The ring-down time (T_r) is defined as the time taken by the light pulse intensity to fall to $\frac{1}{e}$ of its maximum value. Simple calculations given an expression for T_r as

$$T_r = \frac{Q}{2\pi}\frac{\lambda}{c}\,, \tag{24}$$

where λ is the central wavelength of the light pulse in vacuum. Taking $Q = 100$, $\lambda = 1.55\ \mu$m and $c = 3 \times 10^8$ m/s, we get $T_r = 0.08$ ps. T_r must be much less than the pulse width in order that the effect of the cavity response on the pulse width may be neglected. A similar conclusion can be drawn for the build-up time of the cavity.

4 Conclusion

A method of optical pulse width compression has been proposed in this paper by using a feedback optical phase modulator. Typical full-width at half maximum (FWHM) of the pulse has a calculated value of 1.0 ps. The method uses the technique of spreading the frequency spectrum of the optical pulse by the use of a feedback optical phase modulator which leads to a compression in the time domain.

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