Two Photon Absorption Effect on Nonlinear SOA-MZI Switching

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Abstract: *The dynamic performance of differential Symmetric Mach Zehnder Interferometer (SMZI) switch based on semiconductor optical amplifier (SOA) phase shifter is analyzed. For the first time, we investigate the effect of two photon absorption (TPA) as a nonlinear effect of SOA on the push-pull MZ switching scheme where SOAs are placed in each arm. It is shown that our switch is easily affected by TPA phenomena in SOA-SMZI. We use finite difference beam propagation (FD-BPM) method for analysis and solve nonlinear modified Schrödinger equation. In our results we take into account all nonlinear effects relevant to subpicosecond regime in SOA such as group velocity dispersion (GVD), Kerr effect, carrier heating and spectral hole burning (SHB).*

Keywords: nonlinear switching, push-pull MZI, SOA, TPA

1 Introduction

SOA as a key component in high-speed optical communication networks has been attracting a great interest in the recent years. SOA-MZI plays an essential role in such a network. With the help of rate equation model (REM), we can describe the nonlinear gain and phase dynamics in a phenomenological way [1, 2]. Two common techniques to exploit the SOA nonlinearities as switching component are cross phase modulation (XPM) and self-phase modulation (SPM). Among interferometric structures the MZI based SOA using XPM is the promising candidate due to its attractive features of low energy requirement, simplicity, compactness and stability [3]. Another switching technique is based on SPM phenomena. We use XPM by the control pulses injecting in each SOA. If the input and control signals are split unequally over the interferometer arms, two SOAs are operating in different regimes, yielding a phase difference between the signals which are propagated in each arm [4]. In this technique, TPA will change the pulse shape as well as its switching window. In this paper, for the first time, we analyze the TPA effect in SOA-MZI switch using FD-BPM.

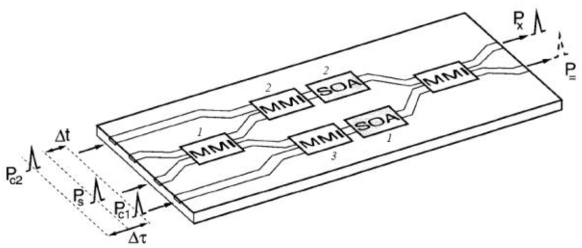

Figure 1: Structure of monolithically integrated MZI switch with two SOAs and four multimode interference coupler (MMIs). Signal (P_s) and control pulses ($P_{c1,2}$) are used in the co propagation arrangement.

2 Theory

2.1 SOA-MZI Principle

In our study, all optical switch modelling consist of a SMZI with two SOA located in the same relative position of each arm as shown in Fig. 1[5]. Data signal enters the structure and split symmetrically into each arm by the first coupler. Two further control signals also are lunched to each SOA via second and third couplers. The mechanism of switching is based on time differential between two control pulses. Data signal is injected between two control pulses. Control 1 as shown in Fig. 1 is presented in the lower arm and changes the refractive index of lower SOA before the signal pulse enters. Control 2 is injected to the upper arm after data signal and saturates upper SOA. In the switched state, the control pulse P_{c1} saturates the lower SOA, inducing phase shift of $\Delta\varphi_{NL}$ between two arms and switched data signal from bar $(P_{out,=})$ to cross $(P_{out,\times})$ output port. Maximum transmission signal can be obtained if the induced nonlinear phase shift between the arms is equal to π. Control pulse P_{c2} switches back the SOA-SMZI from constructive to destructive interference and so reseat switch for the next set of pulses arrive. Output powers can be written as [6]

$$P_{out,=} = \frac{P_{in}}{8}\left\{G_1 + G_2 - 2\sqrt{G_1G_2}\cos\left[\Delta\varphi_1 - \Delta\varphi_2\right]\right\} \qquad (1)$$

$$P_{out,\times} = \frac{P_{in}}{8}\left\{G_1 + G_2 + 2\sqrt{G_1G_2}\cos\left[\Delta\varphi_1 - \Delta\varphi_2\right]\right\} \qquad (2)$$

$$\Delta\varphi_{NL}(t) = \Delta\varphi_1(t) - \Delta\varphi_2(t) = -(\alpha/2).\ln(G_2/G_1) \qquad (3)$$

$P_{in}(t)$ is input power and $G_1(t)$, $\Delta\varphi_1$ and $G_2(t)$, $\Delta\varphi_2$ are gain and phase difference of SOA1 and SOA2, respectively and $\Delta\varphi_{NL}$ is total phase difference accumulated by the optical signals given by Eq. (3). Finally, the switching window of the proposed switch can be expressed as Eq. (4), (5). In the differential scheme the switching window width is determined by the time- delay between the two control pulses [6].

$$T^{\times} = \frac{1}{4}\left\{G_1(t) + G_2(t) - 2\sqrt{G_1G_2}.\cos(\Delta\varphi_{NL})\right\} \qquad (4)$$

$$T^{=} = \frac{1}{4}\left\{G_1(t) + G_2(t) + 2\sqrt{G_1G_2}.\cos(\Delta\varphi_{NL})\right\} \qquad (5)$$

2.2 SOA Model

The following modified nonlinear Schrödinger equation [7] is used for analysis of SOAs and the characteristics of MZI switch.

$$\left[\frac{\partial}{\partial z} - \frac{i}{2}\beta_2\frac{\partial^2}{\partial\tau^2} + \frac{\gamma}{2} + \left(\frac{\gamma_{2P}}{2} + ib_2\right)\left|V(\tau,z)\right|^2\right]V(\tau,z) =$$
$$\left\{\begin{array}{l}\frac{1}{2}g_N(\tau)\left[\frac{1}{f(\tau)} + i\alpha_N\right] + \frac{1}{2}\Delta g_T(\tau)(1 + i\alpha_T) \\ -i\frac{1}{2}\frac{\partial g(\tau,\omega)}{\partial\omega}\Big|_{\omega_0}\frac{\partial}{\partial\tau} - \frac{1}{4}\frac{\partial^2 g(\tau,\omega)}{\partial\omega^2}\Big|_{\omega_0}\frac{\partial^2}{\partial\tau^2}\end{array}\right\}V(\tau,z). \qquad (6)$$

$$g_N(\tau) = g_0\exp\left(-\frac{1}{W_s}\int_{-\infty}^{\tau} e^{-s/\tau_s}\left|V(s)\right|^2 ds\right) \qquad (7)$$

$$f(\tau) = 1 + \frac{1}{\tau_{shb}P_{shb}}\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{shb}}\left|V(\tau - s)\right|^2 ds \qquad (8)$$

$$\Delta g_T(\tau) = -h_1\int_{-\infty}^{+\infty} u(s)e^{-s/\tau_{ch}}(1 - e^{-s/\tau_{shb}})\left|V(\tau - s)\right|^2$$
$$- h_2\int_{-\infty}^{\infty} u(s)e^{-s/\tau_{ch}}(1 - e^{-s/\tau_{shb}})\left|V(\tau - s)\right|^4 ds \qquad (9)$$

$$\frac{\partial g(\tau,\omega)}{\partial\omega}\Big|_{\omega_0} = A_1 + B_1[g_0 - g(\tau,\omega_0)] \qquad (10)$$

$$\frac{\partial^2 g(\tau,\omega)}{\partial\omega^2}\Big|_{\omega_0} = A_2 + B_2[g_0 - g(\tau,\omega_0)] \qquad (11)$$

$$g(\tau,\omega_0) = g_N(\tau,\omega_0)/f(\tau) + \Delta g_T(\tau,\omega_0) \qquad (12)$$

Here, $V(\tau,z)$ is the envelope function of an optical pulse, $|V(\tau,z)|^2$ corresponds to the optical power, β_2 is the group velocity dispersion, γ is linear loss, γ_{2P} is the two-photon absorption coefficient, $b_2(=\omega_0 n_2/cA)$ is the instantaneous SPM term due to the instantaneous nonlinear Kerr effect n_2, $\omega_0(=2\pi f_0)$ is the center angular frequency of the pulse, *c* is the velocity of light in a vacuum, *A* is the effective area of the active region, $g_N(\tau)$ is the saturated gain due to carrier depletion (Eq. (7)), g_0 is the linear gain, W_s is the saturation energy, τ_s is the carrier lifetime, $f(\tau)$ is the SHB function (Eq. (8)), P_{shb} is the SHB saturation power, τ_{shb} is the SHB relaxation time, α_N and α_T are the linewidth enhancement factors associated with the gain changes due to carrier depletion and CH, $\Delta g_T(\tau)$ is the resulting gain change due to CH and TPA (Eq. (9)), $u(s)$ is the unit step function, τ_{ch} is the CH relaxation time, h_1 is the contribution of stimulated emission and free carrier absorption to CH gain reduction, h_2 is the contribution of two-photon absorption, A_1 and A_2 are the slope and curvature of linear gain at ω_0, and B_1 and B_2 are constants describing changes in these quantities with saturation (Eq. (10) and (11)). The gain spectrum of an SOA can be approximated by the following second-order Taylor expansion in ω.

$$g(\tau,\omega) = g(\tau,\omega_0) + \Delta\omega \frac{\partial g(\tau,\omega)}{\partial \omega}|_{\omega_0} + \frac{(\Delta\omega)^2}{2} \frac{\partial^2 g(\tau,\omega)}{\partial \omega^2}|_{\omega_0} \qquad (13)$$

The coefficients $\frac{\partial g(\tau,\omega)}{\partial \omega}|_{\omega_0}$ and $\frac{\partial^2 g(\tau,\omega)}{\partial \omega^2}|_{\omega_0}$ are related to A_1, B_1, A_2 and B_2 by Eq. (10) and (11).

3 Results

In this paper we concentrate on switching window (SW by Eq. (4)) and switch output (SO) of the nonlinear SOA-SMZI. Delay-time between two control pulses and each of them with data input pulse are equal to $\Delta\tau$ and Δt , respectively. SOAs have a 500 μm length and operate in 1.55 μm. The input pulses are $sech^2$ with 180fs full width at half maximum (FWHM). The input energy for data, control 1 and control 2 signals are equal to1fJ, 250fJ and 100fJ, respectively.

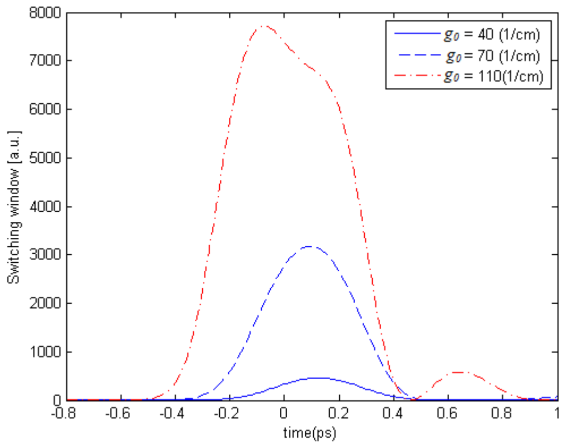

Figure 2: Switching window for different values of $g_0 = 40,70,110\ cm^{-1}$. $\Delta\tau$ =0.45ps.

Fig. 2 shows variation of SW regarding three different value of unsaturated gain for $\Delta\tau$ of 0.45ps. Output peak of SW increases for larger g_0 and also for $g_0 = 110(cm^{-1})$ has a rectangular shape. By increasing of g_0 for a fixed delay time, output SW pulse becomes broader; moreover its shape turns into rectangular shape. For more rectangular SW pulse, SO pulse shape becomes more similar to input pulse shape. It is because of the coverage increase of rectangular SW pulse shape as compared with triangle SW pulse shape. This results in patterning effect decrease in the output. Furthermore, for $g_0 = 110(cm^{-1})$ we have optimal phase difference (π) in MZI. In Fig. 2 for $g_0 = 110(cm^{-1})$ we have satellite pulse in the end of the SW. The satellite pulses may present a problem during transmission because they are chirped differently from the main pulse [8]. Fig. 3 shows the effects of TPA on SW pulse shape. The central value (around t=0.1ps) pick of SW pulse

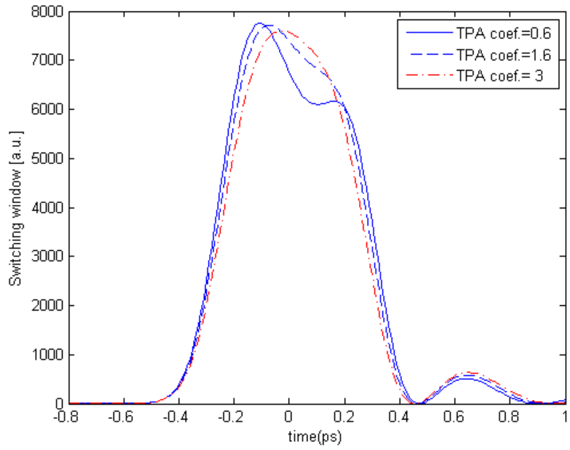

Figure 3: switching window for different value of TPA coefficient, 0.6, 1.6 and 3 $cm^{-1}W^{-1}$. g_0 = 110 and $\Delta\tau$ = 0.45 ps.

increases with increase of TPA and furthermore SW pulse shape becomes rectangular and its FWHM decreases. This phenomenon originates from phase difference between MZI arms so that optimal phase difference is for TPA coefficient of 1.6. TPA coefficients of 3 and 0.6 cause to minus and plus deviation of phase difference (Eq. (3)) from optimal value of π, respectively. As depicted in Fig. 4, output pulse pick decreases in SO for larger values of TPA. To make it more clearly, we show the SOA's gain in each arm as a function of TPA in Fig. 5. As TPA coefficient increases, each SOA experiences lower saturation effect due to decrease of the carrier depletion rate with respect to the entrance photon rate. As the lower energy control pulse is used for SOA2, its corresponding dynamic gain variation is lower in comparison to SOA1 (as shown in Fig. 5).

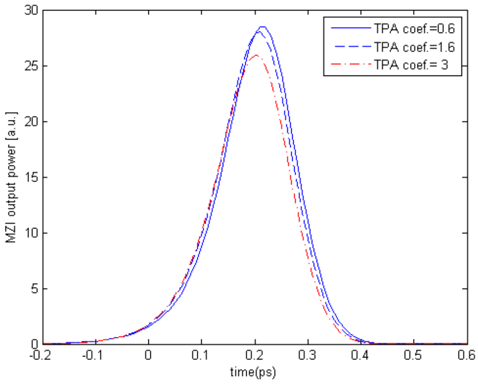

Figure 4: MZI switch output power for different values of TPA, 0.6, 1.6 and $3\,cm^{-1}W^{-1}$. g_0 = 110 and $\Delta\tau$ = 0.45ps.

In Fig. 5, the gain difference between minimum point of SOA1 and corresponding gain of SOA2 at the same time (around t= 0.1ps) causes the main pick of SW and has positive chirp but the gain difference between minimum point of SOA2 and corresponding gain of SOA1(around t=0.64ps) causes the pick of satellite pulse with negative chirp. As can be observed in Fig. 5, there is a smaller gain difference between minimum points of SOA2 and SOA1 gain at the same temporal point around 0.6ps and therefore we can explain the reason of increasing satellite pulse in Fig. 3 by increase TPA coefficient.

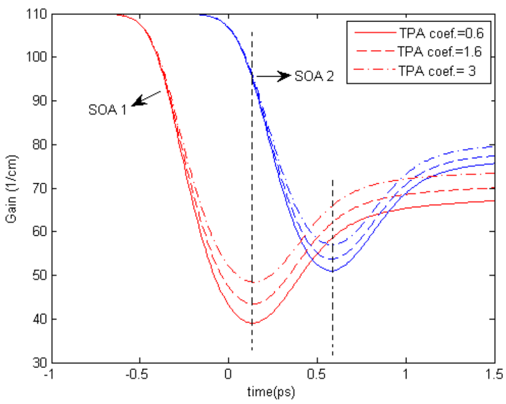

Figure 5: Variation of each SOA gain for different values of TPA coefficient, 0.6, 1.6 and $3\,cm^{-1}W^{-1}$. g_0 = 110 and $\Delta\tau$ =0.45ps

4 Conclusion

We numerically analyzed MZI switching based on SOA with equal distribution of input optical signal in each arm. Using 500 μm SOAs, and FD-BPM scheme, it was shown that nonlinear parameters such as TPA have a great effect on output pulse shape and should not be neglected. We show that increase of TPA coefficient causes decrease of switch output and increase of satellite pulse power.

Acknowledgements

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