The Effects of Strained Multiple Quantum Well on a Spatial Chirped DFB SOA-Based Flip-Flop

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Abstract: In this paper, based on the coupled-mode and carrier rate equations, derivation of a dynamic model for a MQW chirped DFB SOA-based flip-flop is performed precisely. Then we have analyzed the effects of strains of quantum wells, multiple quantum wells and cross phase modulation on its dynamic response, such as and rise and fall times. We have shown that application of a strained MQW active region (under an optimized condition) into a distributed feedback semiconductor optical amplifier with chirped grating can improve the switching ON speed limitation significantly, while the fall time is increased. The value of the rise time for such an all-optical flip-flop has been obtained about 255 ps in an optimized condition.

Key words: Cross Phase Modulation (XPM) • All Optical Flip Flop (AO-FF) • Distributed feedback semiconductor optical amplifier (DFB-SOA) • Optical Bistability (OB) • Multi quantum well (MQW) • Continues Wave (CW)

INTRODUCTION

Optical networks have become an important part of the global telecommunication networks. Transmission technologies have been developed by great advances in dense wavelength division multiplexing (DWDM). A DWDM system allows that more than a hundred wavelengths to be simultaneously launched into a single optical fiber. However, the electronic packet routers in the cross-connects face challenges in terms of power consumption, cost and switching speed [1]. On the other hand, all optical switching appears as a promising technology, because it can overcome the challenges of its electronic counterpart. Gradually, more switching functions will be implemented in optical domain by using all optical integrated circuits. For this reason, advances in all-optical signal processing technologies are essential for the future of all-optical packet-switching nodes [1]. In an all-optical packet switch, first the optical label is taken from the receiving packet and converted to a parallel signal, then it is applied to an optical flip-flop and afterward the optical output from the flip-flop enters an all-optical switch. Thus, without any optoelectronic conversion, the optical packets are switched fully in optical domain. This configuration provides us an ultra fast switching due to high speed operation of both the optical flip-flop and all-optical switch [2]. Also, the latching capability of all optical flip-flops allows the output to be preserved for processing at a later time and can be used in sequential processes such as bit-length conversion, re-timing and data-format changing [3]. Recently, various all-optical flip-flops (AOFFs) have been proposed [3-10]. Such AOFFs are based on different structures such as a distributed feedback semiconductor optical amplifier (DFB SOA) [3], a SOA mutually connected to a DFB-laser diode [4-6], a single quarter wavelength shifted (QWS) DFB laser diode [7], an optically bistable integrated SOA and DFB-SOA [8], a bistable distributed coupling coefficient (DCC) DFB semiconductor optical amplifier [9] and a bistable DFB semiconductor laser amplifier [10].

When a distributed feedback semiconductor laser diode is biased below its oscillation threshold, it acts as a DFB-SOA and shows a dispersive optical bistability (OB) behavior [7]. This device suffers from low speed due to the high carrier life time. Although the intrinsic carrier life time is in the order of few hundred picoseconds, the effective carrier lifetime can be decreased by stimulated emission. Reducing effective carrier life time can be achieved by increasing the waveguide confinement (Γ)
and the material differential gain. This can be done through a thicker active region including a thick InGaAsP quaternary or a large number of quantum wells [11]. Increasing the photon number in the DFB-SOA is another way to reduce the effective carrier lifetime. Introduction of an additional holding beam (Assist light) creates a large number of photons in the DFB-SOA [12].

Previously Maywar et al. proposed the structure of non-uniform linear chirp grating DFB-SOA to improve the steady state behavior of a SOA [3]. Also we investigated the linear chirped DFB-SOA all optical flip flop (DFB-SOA-AOFF) switching based on cross phase modulation (XPM) and optimized the device parameters to gain minimum switching ON and OFF times [12]. Now in this work, we have numerically applied single and multiple strained quantum wells in the linear chirped DFB-SOA all optical flip flop switching based on XPM and investigate the effect of strained QW and MQW on the rise and fall times in the DFB-SOA-AOFF.

The paper is organized as follows. First, we explains the device structure and the parameters used in an all-optical flip flop. Next section describes the static and dynamic responses of DFB-SOA all optical flip based on XPM and the MQW effects on switching ON and OFF times. Finally, we summarizes the essential points of this investigation with the conclusion.

**DFB-SOA Structure:** The time-domain traveling wave approach based on the coupled wave equations is well established for simulating the dynamic behavior of DFB structures. In the spatial domain, however, such devices exhibit nonuniform carriers and photon distributions along the propagation direction. To treat such variations precisely, one need to discretize the behavioral equations along the DFB-SOA active layer. Obviously, such discretized equations can also be adopted to describe the processes designed in SOA [12]. DFB structures are normally designed for single-mode operation. Therefore, it is sufficient to solve the discretized behavioral equations just in a narrow spectral range around the lasing wavelength, where the phase information is preserved. The coupled wave equations which specify the lasing mode of the propagating field in the DFB-SOA active layer are as follows:

\[
\frac{1}{v_g} \frac{dF(z,t)}{dt} + \frac{\partial F(z,t)}{\partial z} = \left[ -j\beta_0 + \frac{1}{2} \left( \Gamma_{	ext{m}}(z,t) - \alpha_e \right) \right] F(z,t) + j\delta R(z,t) \tag{1a}
\]

\[
\frac{1}{v_g} \frac{dR(z,t)}{dt} - \frac{\partial R(z,t)}{\partial z} = \left[ -j\beta_0 + \frac{1}{2} \left( \Gamma_{	ext{m}}(z,t) - \alpha_e \right) \right] R(z,t) + j\delta F(z,t) \tag{1b}
\]

Where \( \beta_0 = \pi/\Lambda \) is the propagation constant at the Bragg wavelength, \( \Lambda \) is the grating period, \( \omega_s \) is the reference frequency and \( \varphi(x,y) \) is the transverse field profile. \( F(z,t) \) and \( R(z,t) \) represent the complex electrical field envelopes of forward and backward traveling waves and \( v_g \) is the group velocity, \( \alpha_e \) accounts for internal loss which is assumed to be negligible and \( \kappa \) denotes the grating coupling coefficient, respectively. The phase detuning factor from the Bragg wavelength is given as [12]:

\[
\delta_p = \beta(\lambda_s) + \frac{1}{2} \alpha_m \Gamma_{	ext{m},k}(z,t) - \beta_0 \tag{2}
\]

Where \( \beta(\lambda_s) = 2\pi n_g/\lambda_s \) is the signal wave propagation constant and \( \lambda_s \) is the signal wavelength, \( \alpha_m \) denotes the linewidth enhancement factor and \( \Gamma_{	ext{m},k}(z,t) \) is the material gain which depends on the carrier density, \( N(z,t) \) and wavelength. The subscript \( k \) represents \( s, r \) and \( h \), for the set, reset and CW holding beam respectively. In a nonuniform DFB-SOA, as long as the variations in the period of the grating are small, similar to that given in [12] under steady state condition, the coupled-mode equations (1a) and (1b) remain unchanged, though, the detuning parameter depends on \( z \). In a linear spatial chirp, it can be written as:

\[
\delta(z)L = \delta_L L - C(z - L/2)L \tag{3}
\]

Where \( C \) is the chirp parameter. Here we assumed that \( \delta_L \) is the average detuning factor according to the (2). In order to model the asymmetric gain profile, we use an active region with strain multi quantum well based on references [13] and [14]. In an active layer whose thickness, \( d \) and width, \( W \), are both far greater than the carrier diffusion length, the corresponding rate equation becomes,

\[
\frac{\partial N(z,t)}{\partial t} = \frac{J}{qd} - \frac{N(z,t)}{\tau_c} - \frac{\sigma}{h\omega d} \sum_r \left( \frac{\Gamma_{	ext{m},k}(z,t)|F(z,t)|^2}{\omega_k} \right) \tag{4}
\]

Where \( J=L/\omega_L \) is the current density, \( L \) is the active region length, \( \omega \) is the mode cross section and \( \tau_c \) is the carrier life time defined as [16],

\[
\tau_c = \left( A_{\text{rad}} + B_{\text{rad}} N(z,t) + C_{\text{Aug}} N^2(z,t) \right)^{-1} \tag{5}
\]

Where \( A_{\text{rad}} \) and \( C_{\text{Aug}} \) are the total nonradiative recombination rates due to Shockley-Read-Hall (SRH) and Auger processes, respectively and \( B_{\text{rad}} \) is the total radiative recombination rate.
Table 1: Device parameters used in simulation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Active region length</td>
<td>300</td>
<td>µm</td>
</tr>
<tr>
<td>W</td>
<td>Active region width</td>
<td>12</td>
<td>µm</td>
</tr>
<tr>
<td>d</td>
<td>Active region thickness</td>
<td>15</td>
<td>µm</td>
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<tr>
<td>Γ</td>
<td>Optical confinement factor</td>
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<tr>
<td>α&lt;sub&gt;η&lt;/sub&gt;</td>
<td>Linewidth enhancement factor</td>
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<td></td>
</tr>
<tr>
<td>N&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Carrier density at transparency</td>
<td>1.5 × 10&lt;sup&gt;21&lt;/sup&gt;</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>n</td>
<td>Model refractive index</td>
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<td></td>
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<tr>
<td>σ</td>
<td>Mode cross section</td>
<td>10&lt;sup&gt;−12&lt;/sup&gt;</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>κ</td>
<td>Coupling coefficient</td>
<td>10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>m&lt;sup&gt;−1&lt;/sup&gt;</td>
</tr>
<tr>
<td>R&lt;sub&gt;r&lt;/sub&gt; = R&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Facets Reflectivities</td>
<td>0</td>
<td></td>
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<tr>
<td>A&lt;sub&gt;nr&lt;/sub&gt;</td>
<td>Nonradiative recombination constant</td>
<td>1 × 10&lt;sup&gt;9&lt;/sup&gt;</td>
<td>S&lt;sup&gt;−1&lt;/sup&gt;</td>
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<tr>
<td>B&lt;sub&gt;nr&lt;/sub&gt;</td>
<td>Radiative recombination constant</td>
<td>2.5 × 10&lt;sup&gt;−17&lt;/sup&gt;</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;S&lt;sup&gt;−1&lt;/sup&gt;</td>
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<tr>
<td>C&lt;sub&gt;Auger&lt;/sub&gt;</td>
<td>Auger recombination constant</td>
<td>9.4 × 10&lt;sup&gt;−11&lt;/sup&gt;</td>
<td>m&lt;sup&gt;−3&lt;/sup&gt;</td>
</tr>
<tr>
<td>a&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Material gain constant</td>
<td>6 × 10&lt;sup&gt;−20&lt;/sup&gt;</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;</td>
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<td>a&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Material gain constant</td>
<td>7.4 × 10&lt;sup&gt;−10&lt;/sup&gt;</td>
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<td>Material gain constant</td>
<td>3.115 × 10&lt;sup&gt;−15&lt;/sup&gt;</td>
<td>m&lt;sup&gt;4&lt;/sup&gt;</td>
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<tr>
<td>a&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Material gain constant</td>
<td>3.0 × 10&lt;sup&gt;−12&lt;/sup&gt;</td>
<td>m&lt;sup&gt;−4&lt;/sup&gt;</td>
</tr>
<tr>
<td>λ&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Wavelength at transparency</td>
<td>1595</td>
<td>nm</td>
</tr>
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</table>

The model structure is assumed to be a traveling-wave type DFB-SOA with no facet reflections merely supporting a single transverse mode. Furthermore, the current is considered to be uniformly injected into the entire area of the device, while the local carrier densities vary with position in the active region. Thus, the carrier density in each section can be derived from the corresponding rate equations. As illustrated in Fig. 1, a continuous wave (CW) probe light with constant power, as well as a light set light signal are injected into the active region, from the left. Meanwhile, a reset light signal is injected from the right. When the set and rest pulses are injected separately, the injection scheme is known as XPM based switching [3].

**Simulation Results:** We have simulated the performance of DFB-SOAs with uniform and nonuniform gratings, using FDTD method. As a starting point, by solving the carrier density rate equation in each section, we have obtained N(z,t). This has allowed us to calculate the material gain coefficient, g<sub>z</sub>, in the corresponding section. Then, we have assumed that the duration of the input pulse is much longer than the round-trip time in the cavity. Such an assumption has enabled us to ignore the spatial derivative term in (1). Then, to solve the forward and backward waves by FDTD method, with an appropriate accuracy, we have divided the length, L, into M = 30 equal sections. We have also assumed that the distribution of carrier and photon densities in each section to be uniform and have applied Lax average technique to the time dependent coupled wave equations [12]. Thus, we obtain:

\[
F_{Z+1}^{T+1} = AF_{Z}^{T} + BR_{Z+1}^{T}
\]

\[
R_{Z+1}^{T+1} = DF_{Z}^{T} + ER_{Z+1}^{T}
\]

Where T and Z are the time and length steps, respectively, while the coefficients A, B, D and E are:
\[ A = E = \frac{1}{\Delta} \left( L^2 - \left( \frac{gL - j\delta L}{2} \right)^2 - \left( \frac{\kappa Ls}{2} \right)^2 \right) \]

\[ B = D = \frac{1}{\Delta} \left( L - \frac{gL - j\delta L}{2} \right) \left( \frac{j\kappa Ls}{2} \right) \left( L + \frac{gL - j\delta L}{2} \right) \]

Where \( s = L/M \) is the length of each section and

\[ \Delta = \left( L - \frac{s}{2}(gL - j\delta L) \right)^2 + \left( \frac{\kappa Ls}{2} \right)^2 \]

To compare the roles of chirp grating in a similar condition, we have assumed the control light pulses to be Gaussian wave forms of order of 16 with 90ps full width half maximums (FWHMs). Using the modified time dependent transfer matrix method (TMM) and finite difference time dependent (FDTD) method, we have numerically simulated the performance of a DFB-SOA as well as a MQW liner chirped DFB-SOA. To confirm the validity of the analysis, we have compared our simulation results for the conventional DFB-SOA with the results of TMM method [3].

**Quasi Static Response:** As mentioned above, QW and MQW with or without strained effects are used in the active layer in the DFB-SOA all-optical flip flop. In order to show the quantum well effects on the dynamic behavior of an all optical flip, the modal gain of a MQW region for different carrier densities is plotted in Fig. 2. To avoid confusion, the detailed definitions of the important basis functions and strains due to external stress and lattice mismatch aren’t given in this paper [15].

Since MQW as well as strained MQW region have higher differential gain than QW region, the dependence of the maximum modal gain, \( I_g \) on the carrier density calculated from Fig. 2 for an InGaAsP/InP MQW is shown in Fig. 3. In the same figure, the maximum modal gain versus carrier density for a strained MQW and a QW with and without strained effects are shown for comparison. As we have seen from these results, the curve slop as well as the differential gain value for the compression strained MQW with fraction mole \( x=0.37 \) is larger than those for the MQW and QW with and without strained. These results have good agreement with the results given in [15, 16]. Meanwhile, it is well known that the differential gain of tension strained MQW is less than that for the MQW and compression strained MQW, so we have ignored this type of region in our work [15].
To obtain the static responses, we have applied each input for 10.8 ns which is much longer than the round trip in a 300µm active region, satisfying the quasi static condition. In order to characterize the device behavior, we have needed to calculate the ratio of the output power to the small signal input power, known as the optical transmittivity, as a function of the wavelength. To trace out the transmittivity curve, a single CW light signal is injected into QW or MQW liner chirped DFB-SOA from the left. Then, after 10.8 ns, the output power is calculated as a function of wavelength. Figure 4 demonstrates the transmittivity curves for various active layer regions, QW and MQW with and without strained, while grating coupling coefficient, $\kappa L$ and the chirp coefficient, $C$ are kept constant; e.g. $\kappa L = 2$ and $C = 6$ for the chirped DFB-SOA.

To compare the effects of quantum well and strains on chirped DFB-SOA all-optical flip flop in Fig. 3, the current is set equal to 12.16 mA. As shown in Fig. 3, the chirped DFB-SOA all-optical flip flop with strained MQW layer in the active region give a larger transmittivity at Bragg resonance than the other types of active layer region. This is because the larger modal gain causes the larger amplification and therefore, the larger transmittivity is obtained. Also, the amounts of transmittivity in the shorter wavelengths are less than transmittivity in the longer wavelengths because the DFB-SOA experiences a non equal amplification for different wavelengths. Here we haven’t mentioned to the effects of grating coupling coefficient and chirp coefficient because these were explained in [12].

The peak of transmittivity at the Bragg resonance approaches infinity (in theory) when the bias current increases. The SOA reaches the threshold condition at which it produces output light without any input (i.e., SOA operates as a laser). As shown in Fig. 3, little perturbation occurs with strained MQW because the current of 12.16 mA causes the chirped DFB-SOA to operate below the threshold condition.

**Dynamic Response:** To obtain the dynamic responses, we have first calculated the bistability curves and then mention to the dynamic responses. To trace out the bistability curves, we have increased the input power and calculate the output power. Then, we have reduced the input power and recalculate the output power. To do this, we have applied each input for 10.8 ns which is much longer than the active region round-trip of ~3 ps. This choice ascertains the quasi static condition.

The two output states of an optical flip-flop are based on optical bistability in a DFB-SOA which are simply got when the input power (holding beam) intersects the two branches of the hysteresis curve. The output power can be switched between ON and OFF states by injecting the set and reset pulse signals, respectively. This behavior demonstrates that the switching action is based on XPM. The set pulse signal, like the holding beam, drops within the SOA gain spectrum and hence stimulates recombination of electron-hole pairs. Recombination makes the gain to saturate and the refractive index to increase. Thus, the set signal modulates the wave-number and phase of the holding beam along the structure. In our application, the increase in refractive index pushes the Bragg resonance to longer wavelengths. Upward switching occurs when the Bragg resonance is shifted sufficiently to initiate the positive feedback loop. In terms of the hysteresis curve, using XPM to shift the Bragg resonance toward the holding-beam wavelength corresponds to the case of pushing the switching threshold to a lower power. The sign of XPM for the reset signals is opposite to that of the set signals, whereas the reset signal wavelength drops out of the SOA gain spectrum and is absorbed in the active region of SOA. Here, it is supposed that the control signals (set and reset signals) travel in the DFB-SOA without any interaction with the grating. To investigate the flip flop operation in all figures, the set and reset signal wavelengths are tuned at $\lambda_s = 1555$ nm and $\lambda_r = 1310$ nm, respectively, where the holding beam wavelength is adjusted 0.3 nm larger than the Bragg wavelengths according to Fig. 4. The dynamic behavior of MQW chirp DFB-SOA all-optical flip flop based on XPM is illustrated in Fig. 5. The holding power is adjusted in the middle of the hysteresis loop. The set and reset signals with Gaussian shape are separately injected into the device from the left and right, respectively where the device operates as a flip flop. The reason is that the set signal from the left experiences a large amplification due to the high material gain, therefore large carrier density depletion occurs at the output end of the device. For the reset signals, injection from the right increases the carrier density and as a result, the flip flop speed increases. The energies of set and reset pulse signals with the same FWHM of 100 ps are $E_{set} = 265.6$ pJ and $E_{reset} = 11.63$ pJ, respectively. As shown in Fig. 6, the switch ON time decreases when the strain MQW active layers is chosen.
This is because the large differential gain reduces the effective carrier lifetime. Therefore, the carrier density experiences the shorter recovery time and as a result, the switching ON time improves. We have noted that the switching OFF time increases when the differential gain increases and limit the switching speed as shown in Fig. 5b.

CONCLUSION

In this paper, we have investigated the dynamic responses of a QW and MQW chirped DFB-SOA all optical flip flop based on XPM mechanism. In addition, the effects of strains on the rise and fall times are investigated. We have solved the coupled-mode and carrier rate equations in the time domain under low-intensity regime. We have found that the energy of set and reset pulses can be reduced by strained MQW active region. The rise time decreases to 250 ps with energy of set pulse 256.6 fJ. Unfortunately, the fall time can’t be improved with such an active region. Hence, using strained MQW active region gives good reduction in switching ON time but it can’t decrease the switching OFF time.

REFERENCES