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XPM Response of Multiple Quantum Well chirped DFB-SOA All Optical Flip-Flop Switching

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***Abstract*—**In this paper, based on the coupled-mode and carrier rate equations, derivation of a dynamic model and numerically analysis of a MQW chirped DFB-SOA all-optical flip-flop is done precisely. We have analyzed the effects of strains of QW and MQW and cross phase modulation (XPM) on the dynamic response, and rise and fall times of the DFB-SOA all optical flip flop. We have shown that strained MQW active region in under an optimized condition into a DFB-SOA with chirped grating can improve the switching ON speed limitation in such a of the device, significantly while the fall time is increased. The values of the rise times for such an all optical flip-flop, are obtained in an optimized condition, areas tr=255ps.

***Keywords*—**All-Optical Flip-Flop (AO-FF); Distributed feedback semiconductor optical amplifier (DFB-SOA); Optical Bistability; Multi quantum well (MQW).

I. Introduction

OPTICAL networks have become an important part of the global telecommunication networks. In such networks, signals are transmitted through optical fibers and are switched by cross-connects. Transmission technologies have been developed by great advances in dense wavelength division multiplexing (DWDM). A DWDM system allow 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]. However, all optical switching is appearing 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 future 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 (DFBSOA) [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 QWS-DFB semiconductor laser amplifier with tapered grating [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 bi-stability (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 life time. Introduction of an additional holding beam (Assist light) is creating a large number of photons in the DFB-SOA [12].

Previously Maywar *et al.* proposed the non uniform linear chirp grating DFB-SOA to improve the steady state behavior [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]. In this work, we numerically applied single and multiple strained

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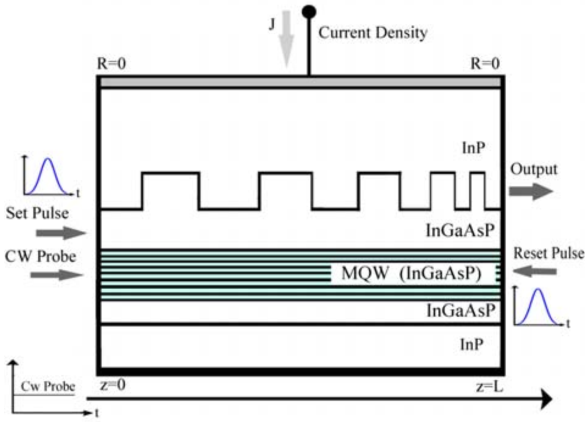


Fig. 1 Schematic diagram of a MQW liner chirped DFB-SOA

quantum wells in the linear chirped DFB-SOA all optical flip flop switching based on XPM and investigated the effect of strained QW and MQW on the rise and fall time in the DFB-SOA-AOFF.

The paper is organized as follows. Section II explains the device structure and the parameters that used in an all optical flip flop. Section III describes the static dynamic responses of DFB-SOA all optical flip flop switching based on XPM and the MQW effects on switching ON and OFF time. Finally, Section IV summarizes the essential points of this investigation with the Conclusion.

II. DFB-SOA Structure

In order to study the fundamental characteristics of an all-optical flip-flop, we consider a longitudinally multi quantum well linear chirped DFB-SOA operating at 1550nm [12]. The device structure and its parameters, used in our simulation, are shown in Fig. 1, and Table I, respectively. In the active layer, we used single or multiple quantum wells with or without strained effects. To show the effects of quantum well on the DFB-SOA all optical flip flops, we first used single quantum well with 75Ao and calculate the modal gain. Then we chose 14 well with compression strained MQW. All the other needed active layer parameters are in [13].

The model structure is assumed to be a traveling-wave type DFB-SOA with no facets 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 control light set signal are injected into the active region, from the left. Meanwhile, a reset 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].

TABLE I
Geometrical and Physical Parameters Used in the Device Simulation

Symbol	Description	Value	Unit
L	Active region length	300	μm
Γ_{MQW}	Optical confinement factor	0.344	-
Γ_{QW}	Optical confinement factor	0.125	-
α_m	Linewidth enhancement factor	2.5	-
C	Liner chirp coefficient	6	-
n	Modal refractive index	3.2353	-
σ	Mode cross section	10^{-12}	m^2
κL	Coupling coefficient	2	-
$R_1=R_2$	Facets Reflectivities	0	-
A_{nrad}	Nonradiative recombination constant	1×10^{8}	s^{-1}
B_{rad}	Radiative recombination constant	2.5×10^{-17}	m^3/s
C_{Aug}	Auger recombination constant	9.4×10^{-41}	m^6/s
L_{QW}	Quantum well length	75	A°
L_w	Multiple quantum well length	190	A°
L_b	Multiple quantum well barrier length	470	A°
$\Gamma_{L(MQW)}$	Broadening factor of MQW	30	meV
$\Gamma_{L(QW)}$	Broadening factor of QW	10	meV

III. Simulation Results

Using the modified time dependent TMM and 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]. As a starting point for the simulation, the carrier densities in each section are obtained by solving the carrier density rate equation. Finding N(z,t) allows us to calculate the modal gain, Γg, within the strained single and multiple quantum well layer in each section with finite difference method.

We have assumed that the duration of the input pulse is much longer than the round-trip time in the cavity. Thus, the solutions to the forward and backward propagating wave equations can be obtained by using TMM and FDTD method. Splitting the length L into M(=30) equal sections makes the computation speed and accuracy appropriate.

A. Quasi Static Response

As is mentioned before, QW or MQW with or without strained effects are used in the active layer in the DFB-SOA all optical flip flop. So, to show the quantum well effects on the dynamic behavior of an all optical flip, the modal gain of a MQW region is plotted in Fig. 2 for different carrier density. To avoid confusion, the detailed definitions of the important basis functions, and strains due to external stress and lattice mismatch aren't wrote in this paper [15]. We also tabulate the important parameters used in our work in the Table I.

Thus MQW as well as strained MQW region have the higher differential gain than QW region, the dependence of the maximum modal gain, Γg for TE polarization calculated from the Fig. 2 for an InGaAsP/InP MQW versus the carrier density is shown in Fig. 3. In the same figure, the maximum modal gain for a strained MQW and a QW with and without

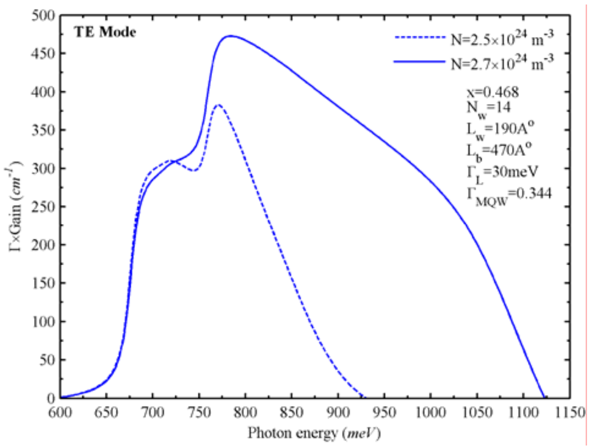


Fig. 2 Modal gain versus photon energy for different carrier density in a MQW region

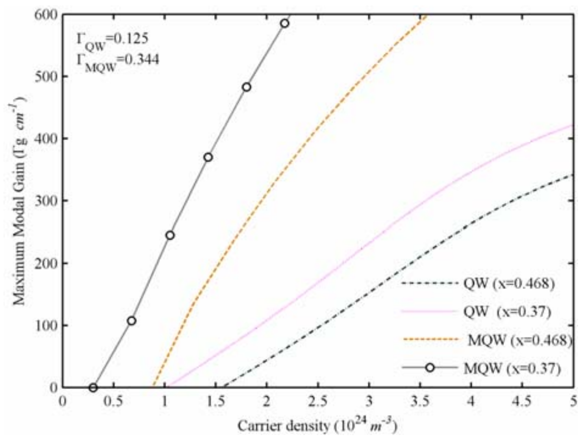


Fig. 3 Maximum modal gain versus carrier density for a different QW (x=0.68), compression strained QW (x=0.37), MQW (x=0.468) and compression strained MQW (x=0.37)

strained effects are shown for comparison, versus carrier density. As we see from these results, the slop as well as differential gain of compression strained MQW with fraction mole x=0.37 is larger than the MQW and QW with and without strained. These results have good agreement with the results of [15] and [16]. It is well known that the differential gain of tension strained MQW is less than the MQW and compression strained MQW, so we ignore these kind of region in our work [15].

To obtain the static responses, we apply each input for 10.8ns 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 need 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 10.8ns, the output power is calculated as a function of wavelength. Fig. 4 demonstrates the transmittivity curves for various active layer region, QW and MQW with

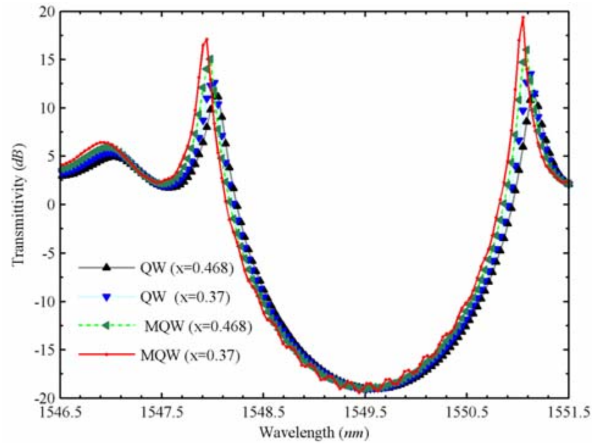


Fig. 4 Transmittivity versus wavelength for different active layer region

and without strained, while grating coupling coefficient, κL and the chirp coefficient (C) are kept constant; e.g. κL=2 and C =6 that corresponding to chirped DFB-SOA.

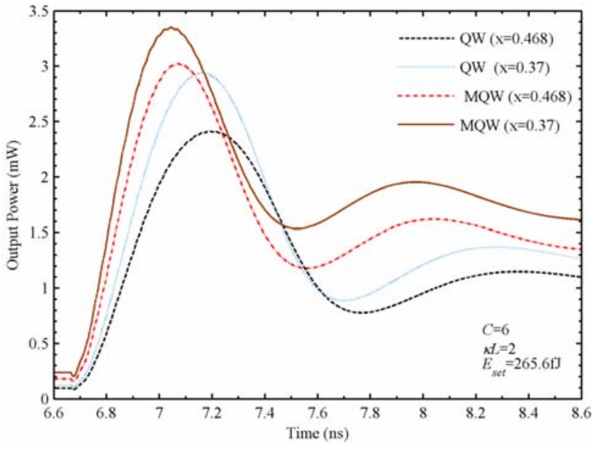
To compare the effects of quantum well and strains on chirped DFB-SOA all optical flip flop in Fig. 3, the current is adjust to 12.16mA. As shown in Fig. 3, the chirped DFB-SOA all optical flip flop with strained MQW layer in active region give a larger transmittivity at Bragg resonance than the other type 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 shorter wavelengths are less than transmittivity in the longer wavelengths because the DFB-SOA experiences a non equal amplification for different wavelengths. Here we don't mention to the effects of grating coupling coefficient and chirp coefficient because these are 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 the Fig. 3, little perturbation occurs with strained MQW because the current of 12.16mA cause the chirped DFB-SOA operate below the threshold condition.

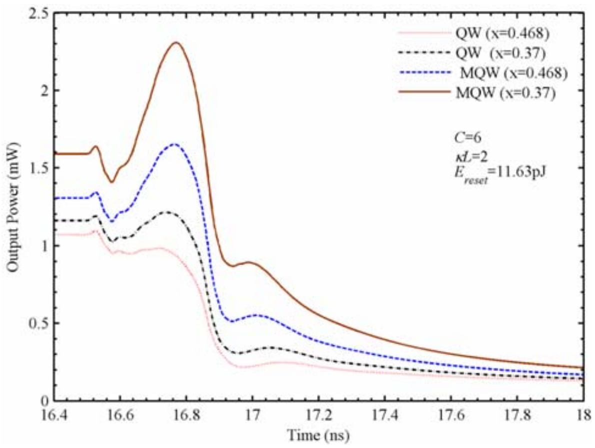
B. Dynamic Responses

To obtain the dynamic responses, first we give the bistability curves and the mention to the dynamic responses. To trace out the bistability curves, we first increase the input power and calculate the output power. Then, we decrease the input power and recalculate the output power. To do this, we apply each input for 10.8ns which is much longer than the active region round-trip of ~3ps. 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 where 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



(a)



(b)

Fig. 5 (a) Rise time and (b) fall time versus time with different active layer region

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 wavenumber and phase of the holding beam along the structure. In our application, the increase in refractive index pushes the Bragg resonances to longer wavelengths. Upward switching occurs when the Bragg resonance has been 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 λs=1555nm and λr=1310nm,

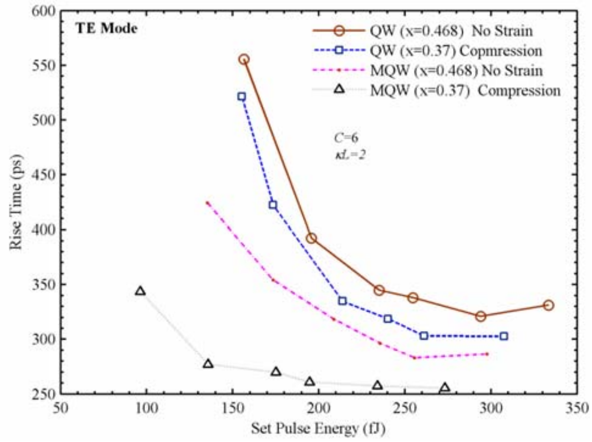


Fig. 6 Rise time versus set pulse energy for different active layer region

respectively, where the holding beam wavelength is adjusted 0.3nm larger than the Bragg wavelengths according to the 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 hysteresis loop. The control signals with Gaussian shape are separately injected into the device from the left and right where the device operates as a flip flop. The reason is that, the set signal from the left experience a large amplification due to the high material gain, therefore large carrier density depletion is occur in the output end of the device. So, to choose the appropriate injection direction of reset signals, injection from the right increase the carrier density and as a result the speed of flip flop rises. The energies of set and reset pulse signals with the same FWHM of 100ps are Eset=265.6fJ and Ereset=11.63pJ, respectively. As is shown in Fig. 5a, the switch ON time decreases when the strain MQW active layers is chose. This is because the large differential gain decreases the effective carrier lifetime. Therefore carrier density experiences the faster recovery time and as a result the switching ON time improves. We note that the switching OFF time increases when the differential gain increase and limit the switching speed as is shown in Fig. 5b.

IV. 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 solved the coupled-mode and carrier rate equations in the time domain under low-intensity regime. We found that the energy of set and reset pulses can be reducing by strained MQW active region. The rise time decrease to 250ps with energy of set pulse 256.6fJ. Unfortunately the fall time can't improve with such an active region. Hence using strained MQW active region give good reduction in switching ON time but can't decrease the switching OFF time.

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