Low Polarization Dependent MQW Semiconductor Optical Amplifier with Tensile-Strained-Barrier Design for Optical Datacom and Telecom Networks

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ABSTRACT

We present for the first time an in-depth numerical analyses on a strained-barrier InGaAs/InGaAs multi-quantum well (MQW) structure suitable to realize polarization insensitive semiconductor optical amplifier. The proposed active layer consists of ternary InGaAs/InGaAs MQW structure with lattice-matched well layers surrounded by tensile-strained barriers. Using ternary materials makes the MQW epitaxial growth more straightforward compared to quaternary system. Additionally the advantage of this structure with respect to other types of MQW SOAs, is the use of matched well which makes it easier to adjust the operating wavelength of the SOA. By proper designing the strain level on the barrier one could achieve low PDG SOA for broadband communication wavelengths including C- and S-band. The polarization dependent gain (PDG) of SOA depends on the bias current level and signal wavelength. An MQW SOA with low PDG is designed for optical telecom and Datacom applications in the wavelength range of 1490 nm to 1550 nm. Results show that at biased current of 80 mA and 50 mA, a signal gain of 16 dB and 7 dB is achieved at 1500 nm wavelength, respectively, with a polarization sensitivity below 3-dB. These characteristics make this MQW SOA suitable candidate to be used in photonic integrated circuits.

Keywords: semiconductor optical amplifier, low polarization sensitive SOA, multi quantum well active layer, amplifying characteristics.

1. INTRODUCTION

Due to the high gain and small footprint of Semiconductor optical amplifiers (SOAs), they play a significant role in the optical telecom and datacom and switching systems. Polarization insensitivity, low power consumption, and high optical output power are essential requirements for SOAs.

Among these attributes, polarization insensitive operation of SOAs is critical in enabling transparent operation of optical communication networks. The net gain of input optical field propagating through SOA depends on two factors; the active layer material gain and the confinement factor of corresponding polarized field propagating through SOA. For SOAs based on bulk active layers [1-3], the bulk material has isotropic gain which means the material gain for both polarizations are the same, thus the main design parameter for bulk SOAs to make polarization insensitive operation is the confinement factor. Thus, one should devise and consider square shape buried heterostructure cross section which could realize optical equality between thickness and width of the active region. However, it needs tapering and window regions to improve the coupling loss and facet reflectivity, which make co-integration with integrated passive circuits even harder. Moreover, well-defined submicron stripe width needs sophisticated epitaxial technology [1,2].

A different approach which relaxes the technology issue discussed above is to use MQW InGaAs(P) strained active layer. Generally, in MQW structure without any strain the TE-mode gain is predominant compared to TM-mode gain, because of the heavy- and light-hole band-structures. Three main types of strained structures which have been proposed for polarization insensitive MQW SOAs are: (1) InGasAs/InGaAsP strained compensated MQW, (2) InGaAs/InGaAsP well compressive MQW, and (3) InGaAs/InGaAs barrier tensile MQW structure [4, 5]. Among them we focus on the latter approach because of two main reasons: first, in ternary material (InGaAs) system only mole fraction of one atom (Ga) should be determined to achieve the needed strain. Second reason is that although applying biaxial tension to the well is straightforward, in practice it is difficult to achieve since the well composition couldn't be adjusted to the wavelength of interest [4,5]. There are few experimental papers on this type of MQW structures, while they seem very interesting. As far as we know, for the first time, we focus on theoretical and numerical study and simulation of InGaAs/InGaAs barrier tensile MQW SOAs which incorporate tensile strain in the barrier to enhance TM-mode gain.

2. DESIGN OF MULTI QUANTUM WELL (MQW) SOA

In conventional MQW semiconductor amplifiers, the TM-mode gain is lower than TE-mode gain. Thus, to realize polarization insensitive (low PDG) SOA, enhancement of TM-mode gain is required. In order to obtain polarization insensitive MQW SOA, tensile and compressive strain is applied to the active layer (barrier/well). Here, to design the active layer system, we consider ternary system InGaAs/InGaAs for both quantum well and barrier material. The barrier is tensile-strained (Ga mole fraction > 0.47) while the well layer is lattice-matched

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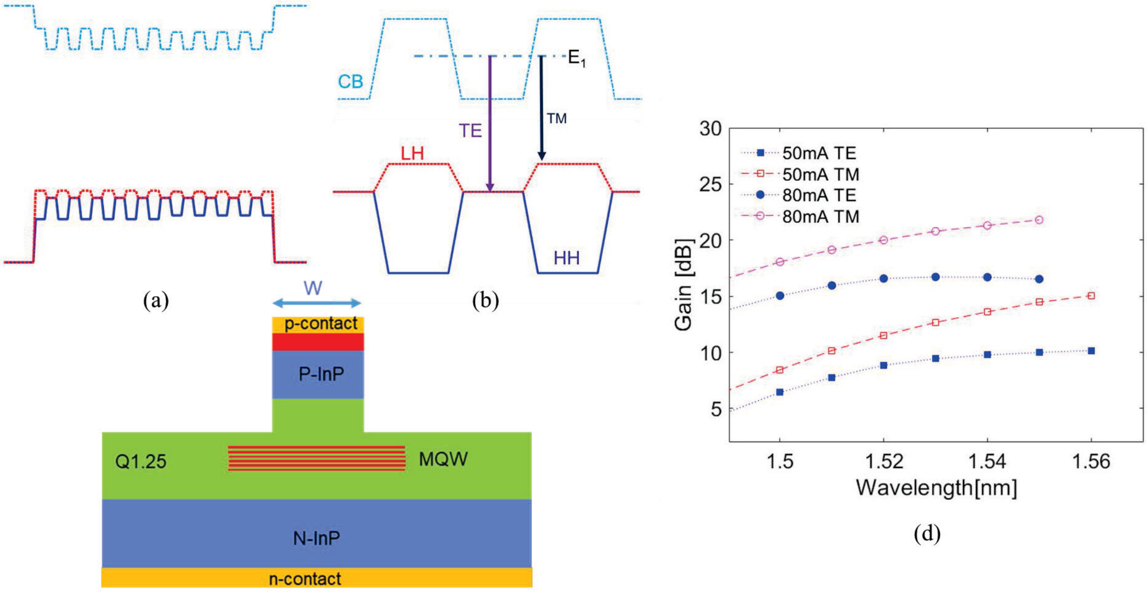
to the InP substrate ($In_{0.53}Ga_{0.47}As$). It is worth noting that the introduction of strain in the ternary system is easier compared to the quaternary system because in quaternary material system to apply strain one should adjust two parameters, Ga (or In) and As (or P). While using ternary system makes it comparatively easier to apply strain as well as epitaxial growth [4, 5].

Figure 1(a) shows the energy band diagram of the investigated MQW structure which is used as active layer. The active layer structure of strained-barrier MQW semiconductor optical amplifier consists of 10 quantum wells surrounded by 11 barriers. The barrier contains $In_{0.28}Ga_{0.72}As$ ternary material with 1.68% – 1.7% tensile strain (four barriers have 1.7% tensile-strain and the remaining barriers have 1.68% tensile-strain). Two wide bandgap InGaAsP layers (with 1.25 μm) sandwiches the MQW active layers. By applying tensile strain on the barrier, the heavy- and light-hole band-edges split [c.f. Fig. 1(b)]. In the barrier, the light-hole band-edge moves to decrease the bandgap. However, the heavy-hole in the barrier shifts toward increasing the bandgap. In the well, the heavy-hole band, like a normal MQW structure, forms a quantum level. Correspondingly, the peak of TE-mode gain (transition from conduction band to heavy-hole state) occurs at shorter wavelengths compared to the TM-mode gain (transition from conduction band to light-hole state) which is in line with energy bands shown in Fig. 1(b) for TM- and TE-mode transitions. Furthermore, since the light-hole energy level is higher compared to the heavy-hole energy band, the material gains for TM-mode is higher than the TE-mode which effectively compensate the difference between confinement factor for TE- and TM-mode polarization (Γ_{TE}/Γ_{TM}).

Moreover, the waveguide geometry of the designed MQW SOA is illustrated in Fig. 1(c). The SOA length and stripe width are assumed 600μm and 2μm. To avoid lasing we assume the two facets of SOA were coated with antireflection coating (AR) films (TiO_2/SiO_2), resulting in a negligible reflectivity.



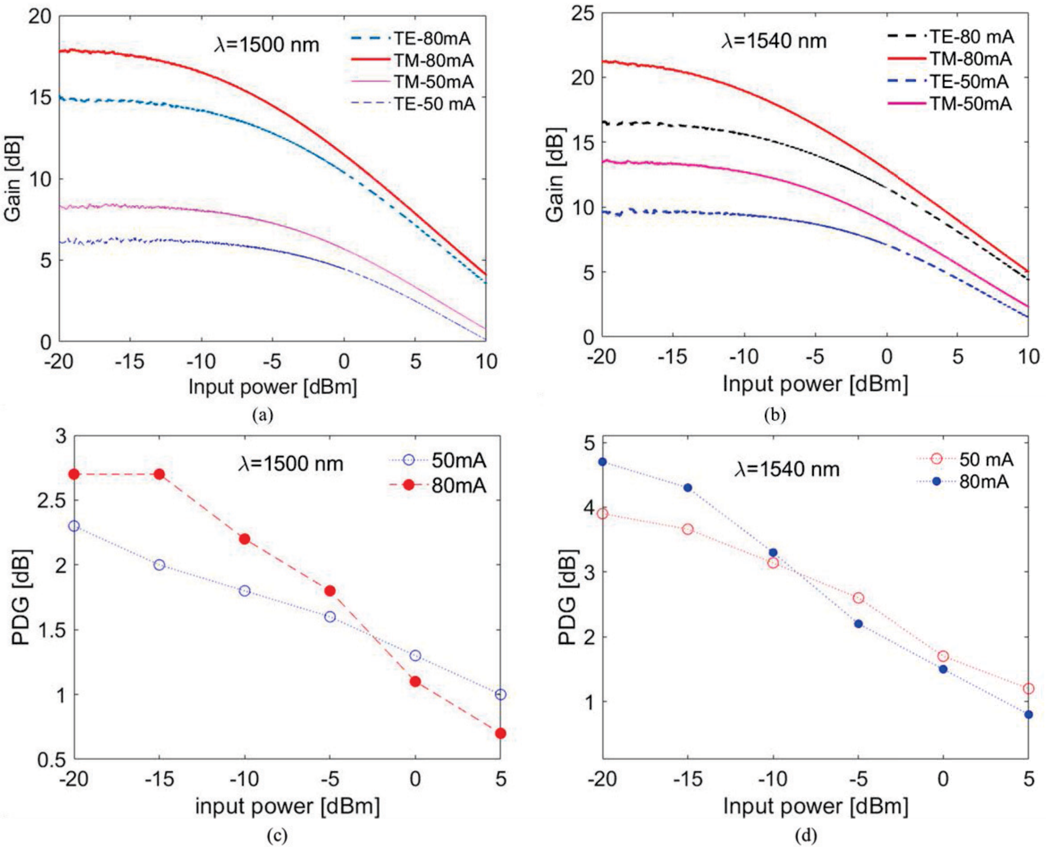
(a) (b) (c) (d)

Figure 1: (a) Active layer energy band diagram which includes 10-strained multi quantum well (MQW) layers with 1.68%-1.7% tensile strain on barriers; (b) Zoomed two QWs to show electrons allowed transitions for TE- and TM- modes. LH, HH, CB, and E_1 indicate light-hole, heavy-hole, electron well potential, and first energy level of electron in well, respectively; (c) Travelling waveguide structure of SOA with QW active layers. W shows the width of the stripe which is assumed 2 μm and the length of SOA is 600 μm; (d) Gain vs. wavelength for two different bias currents of 50mA and 80mA.

Figure 1(d) shows the SOA net gain spectra for both TE- and TM-mode polarizations for two biased currents of 50 mA and 80 mA. The peak of TE-mode gain (transition from conduction band to heavy-hole state) occurs at shorter wavelength (at 1.54 μm) compared to the TM- mode gain, which occurs at around 1590 nm, which is in line with the band structure shown in Fig. 1(b). Moreover, the TM-mode gain is higher than that of TE-mode. This is because the material gain for TM-mode is more than that of TE-mode. Moreover, the PDG level for shorter wavelengths is lower. It is because the peak of material gain for TM-mode occurs at longer wavelength. Thus, the TM-mode gain is more than compensated for longer wavelengths which makes the TM-mode gain more than TE-mode gain. It is worth mentioning that to achieve the low PDG SOA around required wavelength, the strain level on the barriers should be optimized.

2.1 Gain Characteristics

In normal MQW structure without any strain, the TE-mode gain is higher than TM-mode gain. By applying tensile strain the bandgap between conduction band and light-hole shrinks which means that the transition of electrons from conduction to light-hole band increases which increase the TM mode gain. Thus. by introducing more tensile strain, the TM-mode gain enhances. As a result, at certain stress condition and operating points, one could make an SOA with approximately the same TE- and TM-mode gain. The SOA sample under study consists of well and barrier layers with thickness of 5 nm. The wavelength corresponding to the TE and TM transitions [c.f. Fig. 1(b)] determines the peak of amplified spontaneous emission (ASE) and corresponding net gain of SOA. We designed MQW SOA works around S- and C-band of communication wavelengths which is interesting for fibre communication applications and optical network and Datacom.



(a) (b) (c) (d)

Figure 2. Gain saturation (gain vs. input power) properties of MQW SOA at (a) 1500 nm and (b) 1540 nm. The Polarization dependent gain (PDG) vs. input power for two biased currents of 50 mA and 80 mA at two corresponding wavelengths, (c) 1500 nm and (d) 1540 nm.

The gain saturation characteristics of the proposed MQW SOA are shown in Fig. 2(a) and 2(b) where the gain is plotted as a function of the input power. The SOA starts saturating around -10 dBm and its gain decreases rapidly around 0 dBm. For low input power from -20 dBm to -10 dBm the gain of MQW SOA is approximately constant. At 1500 nm, the average gain of SOA for bias current of 50 mA and 80 mA is 7 dB and 16 dB respectively. Additionally, at wavelength of 1540 nm, the average gain is 12 dB and 20 dB for bias currents of 50 mA and 80 mA respectively. Figure 2(c) and 2(d) shows the polarization dependent gain (PDG) of the MQW SOA, which is defined as the absolute value of the difference of the chip gain for the TE- and TM-mode polarization $\left|\mathrm{TE}_{\mathrm{gain}} - \mathrm{TM}_{\mathrm{gain}}\right| = \left|\Gamma_{\mathrm{TE}} g_{\mathrm{mat,TE}} - \Gamma_{\mathrm{TM}} g_{\mathrm{mat,TM}}\right|$ where g_{mat} stands for the material gain of QW active layer. Since $\Gamma_{\mathrm{TE}} > \Gamma_{\mathrm{TM}}$ and $g_{\mathrm{mat,TE}} < g_{\mathrm{mat,TM}}$, one could expect that the TM material gain could compensate the TE confinement factor to have a low polarization dependant SOA. As shown in Fig. 2(c) and 2(d), the PDG for an input optical power range from -20 dBm to 5 dBm) is less than 3 dB which make this SOA suitable to be used as optical gate and booster SOA in wavelength selective switches [6]. The PDG level for 1540 nm wavelength is higher compared to that of 1500nm, because the gain of TE-mode is higher for shorter wavelengths. As depicted in this figure, by increasing the input power at a fixed current the PDG also decreases. This result is in agreement with theoretical and experimental results of other types of SOAs (bulk and MQW SOAs) [3-5]. Furthermore, by increasing the bias current of SOA, the gain increases and the PDG increases correspondingly. At wavelength of 1500 nm, the PDG is less than 3dB for both 50 mA and 80 mA currents and input range [c.f. Fig. 2(c)]. However, at 1540 nm wavelength, numerical simulation shows that the PDG level is higher (less than 4.7 dB). By increasing the operating wavelength from 1490 nm to 1550 nm the PDG level increases to around 5 dB.

Actually by proper design of strain level, one could modify the PDG to achieve the lowest PDG at wavelength of interest around 1500 – 1550 nm.

3. CONCLUSIONS

Tensile strained-barrier MQW SOA based on InGaAs/InGaAs system is designed and simulated. The enhancement of TM-mode gain is achieved by introducing strain on the barriers. This approach from experimental point of view relaxes the fabrication challenges by changing the mole fraction ratio of only one atom (Ga) during epitaxial growth. Thus, the SOA module exhibits low polarization dependent gain less than 3-dB depending on the input power level for a broad spectrum operation. The proposed QW ridge-type low PDG SOA is well suited for integration with passive waveguides which allows to utilize these active components in more sophisticated circuits such as wavelength selective switches (WSS) where the integration of actives and passive components (arrayed waveguide gratings which act as multiplexers and de-multiplexers) on-chip are needed.

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REFERENCES

[1] Itoh, Masayuki *et al*. “Amplifying characteristics or 1.55-µm polarization-insensitive SOAs with MQW and strained-bulk active layers for device application,” *Journal of Lightwave Technology*, vol. 24. 3, p. 1478, 2006.

[2] K. Morito *et al*., “High-output-power polarization-insensitive semiconductor optical amplifier,” *Journal of Lightwave Technology*, vol. 21, no. 1, pp. 176-181, 2003.

[3] A. R. Zali *et al.,* “Low polarization sensitive semiconductor optical amplifier co-integrated with passive waveguides for optical datacom and telecom networks,” in *Proc. 22nd European Conference on Integrated Optics*, Paris, France 2020, accepted to be published.

[4] P. Cinguino *et al*., “InGaA/InGaAs tensile-strained barrier MQW structures for optical amplifiers,” in *Proc. 8th International Conference on Indium Phosphide and Related Materials, IEEE*, 1996.

[5] K. Magari *et al*., “Polarization-insensitive optical amplifier with tensile-strained-barrier MQW structure,” *IEEE Journal of Quantum Electronics*, vol. 30, no. 3, Mar. 1994.

[6] A. R. Zali *et al*., “Analysis of the 1×8 monolithically integrated InP based wavelength selective switch,” in *Proc. 24th Annual Symposium of the IEEE Photonics Benelux Chapter*, Vrije University, Amsterdam, The Netherlands.