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RESEARCH PAPER

# Optical Analysis of 1300 nm GaInNAsSb/GaAs Vertical Cavity Semiconductor Optical Amplifier

*Faten Adel Ismael Chaqmaqchee, Shawbo Abdulsamad Abubekr Salh, Mohammed Faeq Mohammed Sabri

Department of Physics, Faculty of Science and Health, Koya University, University Park, Danielle Mitterrand Boulevard, Koya KOY45, Kurdistan Region-F.R. Iraq

**A B S T R A C T:**

Vertical cavity semiconductor optical amplifiers (VCSOAs) based on GaInNAsSb active region is designed to operate in reflection mode at wavelength of 1300 nm. Addition of antimony Sb to the GaInNAs has dramatically improve the performance of VCSOAs, where the wavelength shifts to longer wavelength. This study is aimed to design GaInNAsSb/GaAs quantum wells (QWs) enclosed between various periods of front and 25-periods of back of AlGaAs/GaAs distributed Bragg mirrors (DBRs) by using MATLAB. GaInNAsSb can be grown and lattice matched to GaAs with a very small band gap and it can be grown monolithically on high quality GaAs/AlGaAs distributed Bragg reflector. Peak reflection gain at around of 53.2 dB at single pass gain of 1.076 is observed. In addition, amplifier bandwidth at various front back mirrors reflectivities is simulated to achieve high gain and wide optical bandwidth at low reflectivity of front mirrors.

KEY WORDS: Vertical cavity semiconductor optical amplifier (VCSOA), distributed Bragg reflectors (DBRs), quantum wells (QWs), gain, amplifier bandwidth, mirror reflectivity.
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## 1. INTRODUCTION:

Dilute nitride III-V-N materials have been successfully employed in optoelectronic devices. The first optically pumped was demonstrated in 1972 under using III-nitride materials (Pankove *et al.* 1972). In 1996, the InGaAs was discovered by Kondow and co-workers (Kondow *et al.* 1997).
gap. Additionally, incorporating antimony (Sb) into GaInNAs/GaAs is pushing the vertical cavity surface emitting lasers VCSEL/VCSOA devices to the longer wavelengths ranges between 1300 to 1500 nm (Wistey *et al.* 2006; Aho *et al.* 2016).

* **Corresponding Author:**
Faten Adel Ismael Chaqmaqchee
E-mail: faten.chaqmaqchee@koyauniversity.org
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decrease the lattice constant and decrease the band

Antimony controls atom diffusion length and allows more nitrogen incorporation that lowers the band gap and improves material and optical quality (Braza *et al.* 2017; Rahman *et al.* 2018). Therefore, Sb affects the valence band and likely the quinary of five component alloy will not only control of band gap and lattice match, but also affect the band offset ratio (Yang *et al.* 1999; Gambin *et al.* 2002; Harris Jr 2005; Yuen *et al.* 2006).

The first surface emitting laser was demonstrated in 1979 (Soda *et al.* 1979), which then led to the development of the vertical cavity surface emitting lasers VCSELs (Haghighi *et al.* 2018, Chaqmaqchee 2019, Liu *et al.* 2019). Since then, extensive work has been done on both types of the devices. Thus, the first VCSOAs was demonstrated in 1991 by koyama, Kubota and Iga at Tokyo institute of technology that present the first VCSEL (Koyama *et al.* 1991). The vertical geometry of VCSOAs are essentially VCSELs are operated below lasing threshold, and the design for VCSELs can be directly applied in VCSOA devices. The main difference is that strong feedback is desired in VCSELs in order to minimize the threshold current. While in VCSOAs, reduced feedback is useful so as to allow high gain. VCSOAs can be operated in reflection mode, depending on the reflectivity from the DBR mirrors, therefore VCSOAs require higher single pass gain and lower mirror reflectivity than VCSELs (Karim *et al.* 2000; Song *et al.* 2007; Chaqmaqchee and Balkan, 2014; Spiewak 2018).

Vertical cavity semiconductor optical amplifiers (VCSOAs) are an interesting alternative to conventional amplifier technologies for long wavelengths optical fiber communications systems, data storage and access network applications. Furthermore, VCSOA devices have been used as optical preamplifiers, and interconnect in applications such as optical routing, signal regeneration, and wavelength shifting. Such devices have a number of advantages over edge emitting lasers (EEL) and semiconductor optical amplifier (SOA), including low cost manufacturing, compact size, wafer scale fabrication and testing processes (Bjorlin *et al.* 2001).

In this article, VCSOA are designed using Fabry Perot (FP) models. The cavity of $3\lambda/2n_c$ long is based on GaInNAsSb/GaAs multi quantum wells (MQWs), where a recombination process occurs to produce photons of light. The model includes reflectivity spectra, material gain, optical gain and amplifier bandwidth in reflection mode.

## 2. VCSOA Design and modelling

To improve the performance of present vertical cavity semiconductor optical amplifiers (VCSOAs), several extensive researches have been done and still under investigation (Piprek *et al.* 2001; Chaqmaqchee 2015). VCSOAs are usually made by a thin layer of quantum well (QW) lying between two DBRs to improve the recombination efficiency of the active region and to obtain high optical gain. The electrons and holes can be trapped near each other by using a QW structure. The most important device aspect in VCSOAs is the choice of gain material, which affect all device parameter and defines achievable wavelength range (Ilroy *et al.* 1985; Li and Chua 2010).

In this study, the VCSOA device consist of an active region of nine $Ga_{0.61}In_{0.39}N_{0.0033}As_{0.9876}Sb_{0.016}$ QWs bounded between 9-periods of front and 25-periods of back DBRs mirrors to make a VCSOA amplifying, and the layers structure is depicted in Table 1. The QWs are grouped together in three sets of three wells each positioned on standing wave of $3\lambda/2n_c$ with the total layer thickness of 10 µm QWs to provide high periodic gain and matches the standing wave pattern within the cavity as indicated in Fig.1. However, using the large number of QWs in active region leads to the lack of uniform carrier distribution over each well due to energy barriers of adjacent QWs in the device, whereas the gain enhancement increases with decreasing the number of QWs per standing wave peak (Chaqmaqchee and Balkan, 2012).

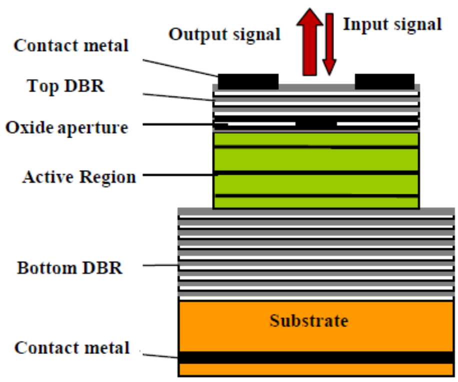


**Figure 1:** Typical VCSOA structures of top emitting mesa. To make a VCSOA amplifying, it requires mirrors with less reflectivity typically less than 99 % using DBRs.

**Table (1)** Design of VCSOA structure with GaInNAsSb QWs.

| Materials | Thickness (nm) | Notes |
|---|---|---|
| GaAs cap | 10 | |
| GaAs | 94.4 | 9 pairs top DBR with total layer thickness 1837 nm |
| $Al_{0.9}Ga_{0.1}As$ | 108.6 | |
| AlAs | 20000 | Oxide aperture |
| GaAs | 566.9 | Active region 3 QWs per three stuck with total layer thickness 10092.4 nm |
| $Ga_{0.61}In_{0.39}N_{0.0033}As_{0.9876}Sb_{0.016}$ | 554 | |
| GaAs | 566.9 | |
| $Al_{0.9}Ga_{0.1}As$ | 108.6 | 25 pairs bottom DBR with total layer thickness 5075 nm |
| GaAs | 94.4 | |
| GaAs substrate | | |

The gain and bandwidth spectrum of a VCSOA can be modeled using equations namely

Fabry- Perot (FP) and photon rate equations. The amplifier gain in reflection mode ($G_r$) can be calculated using (Adams *et al.*1985):

$$G_r = \frac{(\sqrt{R_f}-\sqrt{R_b}g_s)^2+4\sqrt{R_fR_b}g_s sin^2\emptyset}{(1-\sqrt{R_fR_b}g_s)^2+4\sqrt{R_fR_bb}g_s sin^2\emptyset} \quad (1)$$

where $R_b, R_f$ and $g_s$ are the back mirror reflectivity, the front mirror reflectivity, and the single pass gain, respectively. The maximum amplification gain is achieved when $\emptyset = 0°$ whereas the minimum gain occurs when $\emptyset = 90°$.

The DBR peak reflectivities can also stimulated as a fixed mirror positioned at a distance from the boundary with the incident medium and given by (Karim *et al.* 2000):

$$R = \left(\frac{1-qap^{N-1}}{1+qap^{N-1}}\right)^2 \quad (2)$$

where $q$, $a$, and $p$ are refractive indices that characterize the incident and exist media. Factor q is the ratio of the first medium and first DBR section refractive indices. Factor $a$ is the ratio of exist medium and final DBR section refractive indices. Factor $p$ is the ratio of low and high index mirror period refractive indexes and finally $N$ is the number of mirror layer for bottom DBR or top DBRs.

The material gain provided dependence carrier density $N$ can be modelled as (Coldren and Corzine, 1995):

$$g = g_o \ln\left(\frac{N+N_s}{N_{tr}+N_s}\right) \quad (3)$$

where $N_{tr}$ is the transparence carrier density, fitting parameters, and $g_o$ and $N_s$ can be taken from the calculated results.

The gain bandwidth is mainly measured by the line width of Fabry Perod (FP) modes. Additionally, an optical amplifier in reflection mode can be obtained using (Piprek *et al.* 2001; Connelly, 2002):

$$\Delta f_r = \frac{c}{\pi n_c L_c} \times arcsin\left\{4\sqrt{R_fR_b}g_s[(1-\sqrt{R_fR_b}g_s)^{-2} - 2\sqrt{R_f} - \sqrt{R_b}\, g_s)^{-2}]\right\}^{-1/2} \quad (4)$$

where c, $L_c$, $n_c$, $g_s$, $R_f$, $R_b$ are the velocity of light in vacuum, the effective cavity length, the cavity refractive index, the single pass gain, the top mirror and bottom mirror reflectivities, respectively.

## 3. RESULTS AND DISCUSSION

The structure of VCSOAs is optically designed (Piprek 2002, Chaqmaqchee 2016, Karim *et al.* 2017) to operate at wavelength of 1300 nm using many important simulation steps. Eq. 2 has been used for plotting Fig. 2 by Matlab program. The mirror reflectivity of $Al_xGa_{1-x}As$ increases as a result of increasing the number of front of back distributed brag mirrors layers, and the mirror reflectivity increases with the concentration of aluminum (Al).

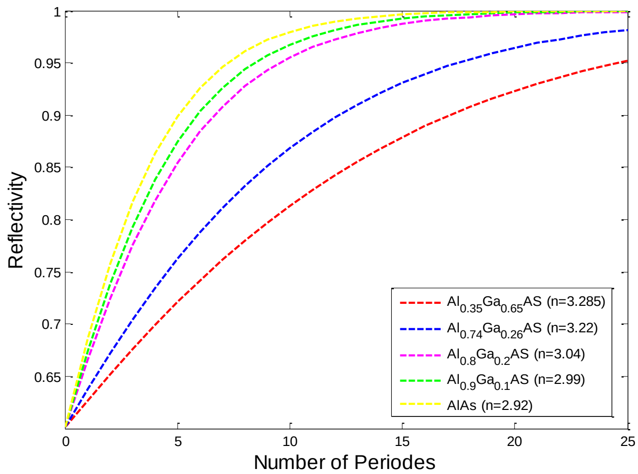


**Figure 2:** Distributed Bragg reflectors versus number of periods for different concentration of Al.

Figure 3, shows the reflectivity spectrum of the GaInNAsSb VCSOA structure versus wavelength for different front mirrors of 9, 12, 14 and 16 periods and fixed back mirrors of 25 periods along with the assumed refractive index values used for the various layers within the structure. The center dip of the mirror stop band represents the position of cavity resonance at emission wavelength of 1300 nm. This increase in transmissivity at the resonance frequency helps to couple light out of the structure, as the number of front mirror increased, the reflectivity of the mirrors increased greater than 99% for high gain bandwidth, while low mirror reflectivity causes a lower gain, and high saturation power.

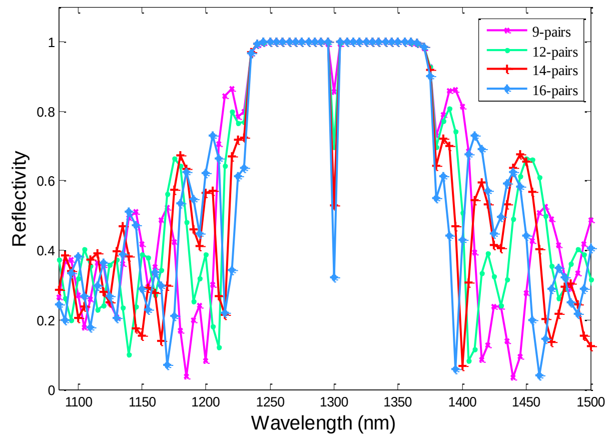


**Figure 3:** Reflectivity spectra for a cavity GaInNAsSb/GaAs VCSOAs placed between varied periods of front DBRs and 25-periods of back DBRs.

The relationship between material gain and carrier density is illustrated in Fig. 4. The material gain can be calculated using Eq. 3. The material gain was calculated according to a parameter transparency of carrier density of $1.8 \times 10^{18}\ cm^{-3}$, and fitting parameters of $4200\ cm^{-1}$ $and - 0.21 \times 10^{18}\ cm^{-3}$ (Björlin *et al.* 2003; Laurand *et al.* 2005). The material gain depends on carrier density of QW and their precise description at low carrier densities.

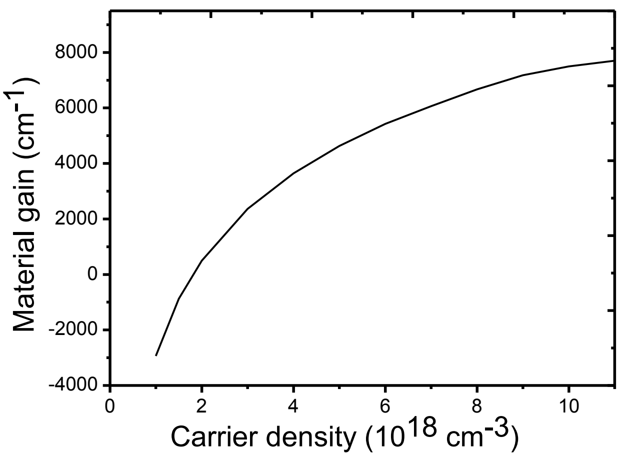


**Figure 4:** Material gain versus carrier density modeled using a three-parameter logarithmic function.

Equation 1 was used to calculate the peak gain of the VCSOAs in reflection mode. The peak gain depends on the front mirrors, the back mirrors and the single pass gains. Fig. 5 shows the gain spectra of GaInNAsSb/GaAs in reflection mode by using various single pass gains. The single pass gain $G_s$ required achieving high amplifier gain. When the single pass gain $G_s$ values are increased from 1.064 to 1.076, the peak gain values are also increased from 22.17 to 53.2 dB, while the bandwidth decreased with increased peak gain spectra. The narrow bandwidth of VCSOA reduces bad noise that making it ideal for signal amplifying optical filter (Lisesivdin *et al.*, 2014).

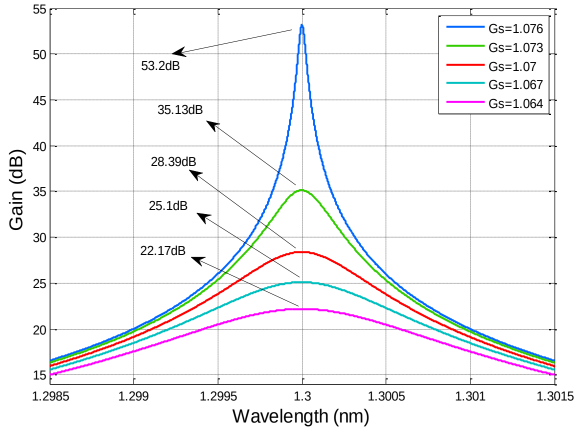


**Figure 5:** VCSOAs gain spectra in Reflection mode with different value of $G_s$ and fixed $R_b$=99.9% and $R_f$=86.6%.

Figure 6 illustrates amplifier bandwidth against peak reflection gain according to Eq.4 with 25- periods of 0.999 back mirrors reflectivity and 9, 10, 11, 12 and 15-periods of 0.939, 0.957, 0.969, 0.978 and 0.985 front mirrors reflectivities, respectively. The amplifier bandwidth in reflection mode for GaInNAsSb/GaAs VCSOA decreases as the peak reflection gain increases. Besides, by reducing the reflectivity of the front Bragg mirror from 0.985 to 0.939 allows for further gain and for wide optical bandwidth. As well as, the reflectivity of the front mirror is decreased to achieve wide optical bandwidth. The narrow bandwidths reduce the signal noise as in filtering application, while the wider bandwidths used in applications with multiple channels (Bjorlin and Bowers, 2002).

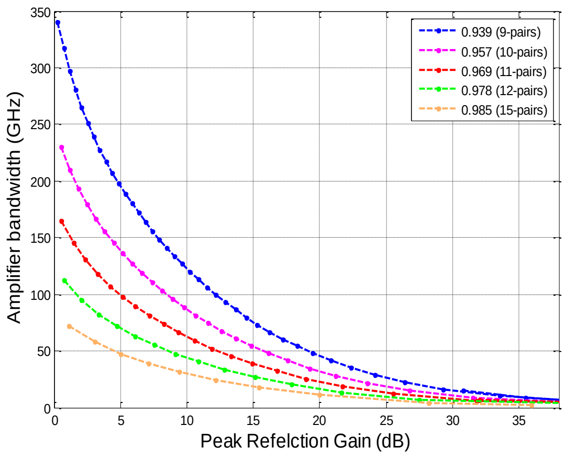


**Figure 6:** Amplifier bandwidth vs. peak reflection gain for back DBR of 0.999 (25-peiods) and different number of top DBR.

## 4. CONCLUSIONS

The study was focused on the design, and demonstration of the optically design of VCSOAs devices. The theoretical model had based on Fabry-Perot (FP) SOAs equations and earliest theoretical analysis of the VCSOA design, in which have a potential applications in fiber optic communication systems. GaInNAsSb used as an active region of VCSOAs on GaAs substrate it can be grown monolithically on GaAs/AlGaAs distributed Bragg reflector mirrors with high reflectivity for operation in the 1.3 µm wavelength range. Peak reflection gain at around of 53.2 dB is observed. Moreover, high amplifier bandwidth is achieved at 0.939 front mirrors reflectivity. The optical design of the layer thickness DBRs should redesigned to regulate the emission at 1300 nm and using materials have enough reflectivity for the light to be amplified via internal reflection. The construction of DBR layers essentially governs the operation features of VCSOAs. Therefore, it is very important to select appropriate material system.

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