

A Comparison of Top Distributed Bragg Reflector for 1300 nm Vertical Cavity Semiconductor Optical Amplifiers Based on III–V Compound

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Abstract—In this work, the design of GaAs/AlGaAs distributed Bragg reflector (DBR) has been implemented for 1300 nm vertical cavity semiconductor optical amplifiers (VC SOAs) for optical fiber communication applications. The top DBR period and Al concentration are varied, the peak reflectivity of the DBR is increasing from 50% to 97.5% for 13 periods with increasing Al concentration, whereas the reflectivity bandwidth is increased to almost 190 nm. The relation between wavelength and incidence angle variation on DBR reflectivity is increasing with the incident angle (0° , 20° , 30° , and 50°), the resonant wavelength and bandwidth of the measured reflectance spectra shifts to shorter wavelength and wider bandwidth, respectively. In addition, a comparison between the linear, the graded, and the parabolic DBRs has been achieved with transfer matrix method using MATLAB software to show the influence of layer in DBRs and its effect on lasing wavelength. It is shown that using grading DBR mirror is much more beneficial compared to abrupt DBR, whereas it has lower reflectivity of almost 10% due to VC SOAs device which needs less number of top layers until prevent reaching lasing threshold.

Index Terms — Vertical cavity semiconductor optical amplifiers; distributed Bragg reflector; abrupt and grading distributed Bragg reflector.

I. INTRODUCTION

III–V compound semiconductors have played a critical role in modern electronic and optoelectronic device technologies. They have many potential applications, pervading our everyday lives in optical communication systems, computing, entertainment, lighting, and medicine (Tu and Paul, 2003; Kuech, 2016; Hasnayeem, Othman and Faidz, 2008). Recently, vertical cavity semiconductor optical amplifier (VC SOA) has been developed, for applications including optical communications and optical interconnection systems (Bjorlin et al., 2001;

Chaqmaqchee, 2015). Reports and data have shown that VC SOAs at 1300 nm have focused on DBRs and multi-quantum well active regions, structures such as GaInNAs/GaAs were optically pumped through the GaAs substrate (Chaqmaqchee et al., 2012; Chaqmaqchee, Salh and Sabri, 2020). Nevertheless, incorporation antimony GaInNAsSb/GaAs to the active regions provides important advantages for developing 1300 nm vertical cavity devices, such as monolithic integration with the GaAs/AlGaAs distributed Bragg reflectors (DBR) and improved optical behavior (Chaqmaqchee, Salh and Sabri, 2020). VC SOA consists of a vertical cavity mode formed by placing an active region between two DBRs, the operation of the surface emitting semiconductor optical amplifier depends heavily on the performance and design of Bragg mirror. As its particular vertical structure, the VC SOA has a very small active region, small length of the cavity, therefore, the top and bottom DBRs should have high reflectivity, to be able to obtain a long wavelength VC SOAs (Chen, et al., 2020; Hurtado, Gonzalez-Marcos and Martin-Pereda, 2005). DBRs, which consist of a periodic quarter-wave layers with alternating high and low refractive index materials that work as a highly reflecting mirror for optical as well as electrical confinement in the active region, have an important role in optoelectronic devices. DBRs are a set of two highly reflecting mirrors of semiconductor compounds, generally III–V materials, these mirrors are named as quarter wavelength mirrors because the thickness of each layer equals to the one-quarter wavelength of the light travelling inside the mirror material (Mishkat-Ul-Masabih, et al., 2019; Choquette and Hou, 1997; Winston and Hayes, 1998). This study will report and analyze the influence of Al composition, number of layers in the DBR, effects of thickness layers, and incident angle variation due to optical properties through reflectivity.

II. DESIGN AND SIMULATION MODELING METHOD

The VC SOAs structure is modified version of vertical cavity surface emitting lasers (VCSELs) (Pipek, Bjorlin and Bowers, 2001; Chaqmaqchee, 2016) that driven below threshold current. In this paper, the VC SOA design is modified as shown in Fig. 1. The structure consists of



13 pairs of top and 24.5 pairs of bottom DBR mirrors. The active region consists of three QW $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.027}\text{As}_{0.9605}\text{Sb}_{0.0125}/\text{GaAs}$. The reflectance R and transmittance T are calculated according to transfer matrix method (Sanchez, Cerutti and Tournié, 2013, Karim, et al., 2000, Yu, 2003):

Eqs. 1 and 2 are used to determine the reflectivity (R) and transmittance (T) of the DBR.

$$R = \left| \frac{\mu_{0B-C}}{\mu_{0B+C}} \right|^2 \quad (1)$$

$$T = \frac{4\mu_0 \mu_m}{|\mu_{0B+C}|^2} \quad (2)$$

Where, μ_o is incident admittance, μ_m is optical admittance of the substrate, B and C are the total electric and magnetic field amplitude method (Karim, et al., 2000).

The VCSOAs with variation of DBR composition are studied with different samples studies for DBR of surface-emitting lasers. Each pair differs in refractive index and thickness, GaAs as a high refractive index layer $\text{Al}_x\text{Ga}_{1-x}\text{As}$, and AlAs as a low refractive index of layer, with different x composition. Details of the parameters for each sample are shown in Table 1. In the DBRs structure, the top and the bottom DBRs are designed with 13 periods and 24.5 periods, respectively. In this work, a simulation was done to compare the reflectivity of different semiconductor materials each one of these samples reflectivity and bandwidth is varies according

TABLE I
DBR MIRROR WITH VARIOUS Al COMPOSITION

Sample	Materials	Al composition (wt.%)
1	GaAs/AlAs	1
2	GaAs/ $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$	0.9
3	GaAs/ $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$	0.7
4	GaAs/ $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$	0.5
5	GaAs/ $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	0.3
6	GaAs/ $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$	0.2

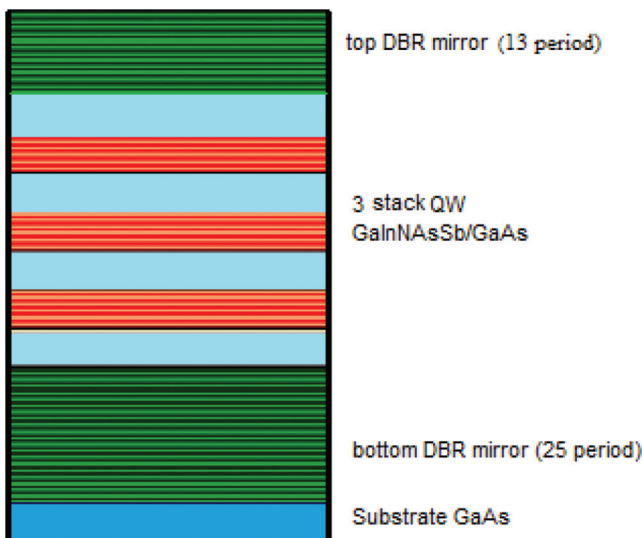


Fig. 1: The structure of vertical cavity semiconductor optical amplifiers.

to the number of alternating layer pairs and refractive index contrast between layers. In performing VCSOAs DBR, refractive index and lack of GaAs lattice matched in DBR material are critical properties that need to be considered.

In this paper, two types of DBRs were studied, the first one is called linear (abrupt) DBRs and the second is graded DBRs, as shown in Fig. 2. Table 2 shows the design of p-type for linear and graded DBRs. Table 2a shows the design of abrupt (linear) DBR with 13 periods of GaAs and $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ p-doped layers, beryllium doped with concentration of $3 \times 10^{18} \text{ cm}^{-3}$. Abrupt (linear) DBR was used to achieve a high index contrast as well as provide good thermal conductivity, which is also one of the necessary requirements for material used to design a VCSEA structure. Table 2 shows the design of graded DBR, which made by inserting an intermediate layer $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ between GaAs and $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$. The DBR composition ramped continuously from $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ to $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$. In addition, the layer thickness of 10 nm doped GaAs cap is used in DBR to protect the sample and to make the electrical contact between the DBRs structure and the metal contact much easier.

III. RESULTS AND DISCUSSION

The reflectivity spectrum of different Al composition of top DBR is shown in Fig. 3, whereas the reflectivity of GaAs/AlGaAs with different periods (10, 13, and 16) is shown in Fig. 4. The result shows that reflectivity increases when Al concentration

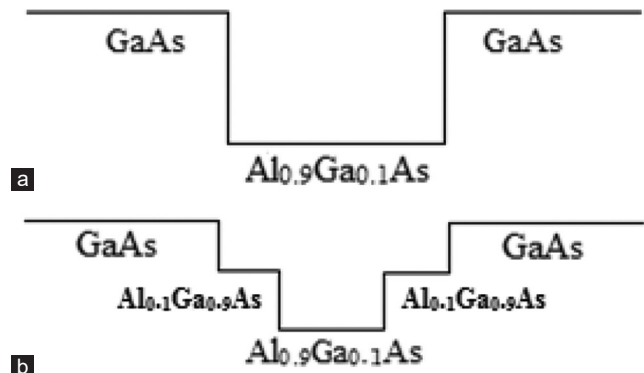


Fig. 2: GaAs/AlGaAs DBR structure : a) the basic reflector design (abrupt), and b) addition of intermediate layer (graded).

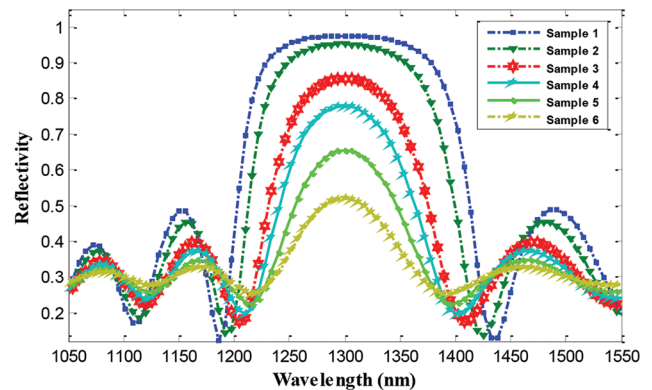


Fig. 3: Reflectivity spectrum of DBR for various Al composition of 13 top layers.

increases. Sample 1, GaAs/AlAs exhibits the highest reflectivity and the largest stopband width which is around 200 nm due to the highest refractive index between low and high refractive index materials of DBR followed by the sample 2 to the last one sample 6 which is GaAs/Al_{0.2}Ga_{0.8}As. Nevertheless, reflectivity of the DBR increases with increasing number of DBR layers. These graphs show that the peak maximum increase with increasing the number of layers also with increasing refractive index contrast for 13 periods of DBR AlAs/GaAs have the higher reflectivity of 97.5% at 1300 nm, whereas reflectivity at 1300 nm for Al_{0.9}Ga_{0.1}As/GaAs DBR is 95.1%.

Fig. 5 shows the reflectivity spectra of DBR under various incident angles of 0°, 15°, 30°, and 50°. From the dependent angle results, we can obtain the wavelength of the stopband center of the DBRs. It can be seen that with increasing incident angle, the stopband center shifts toward the shorter wavelength. However, the reflectivity becomes high, and in Fig. 6, several interests can be seen that at angle of 0° for AlGaAs/GaAs layers, the bandwidth of the stopband is narrowed and the resonant wavelength shifts toward longer wavelength with lower reflectivity compared to AlAs/GaAs DBRs. Thus, the phase of a DBR is zero or pi response in

TABLE II
P-TYPE DBRS STRUCTURES: (A) LINEAR DBR (B) GRADED DBR

(a)	
Material	Layer thickness (nm)
GaAs cap	10
GaAs	94
Al _{0.9} Ga _{0.1} As	109
GaAs substrate	
Total layers thickness=2852 nm (for 13 periods)	
(B)	
Material	Layer thickness (nm)
GaAs cap	10
GaAs	94
Al _{0.1} Ga _{0.9} As	92
Al _{0.9} Ga _{0.1} As	109
Al _{0.1} Ga _{0.9} As	92
GaAs substrate	
Total layers thickness=5041 nm (for 13 periods)	

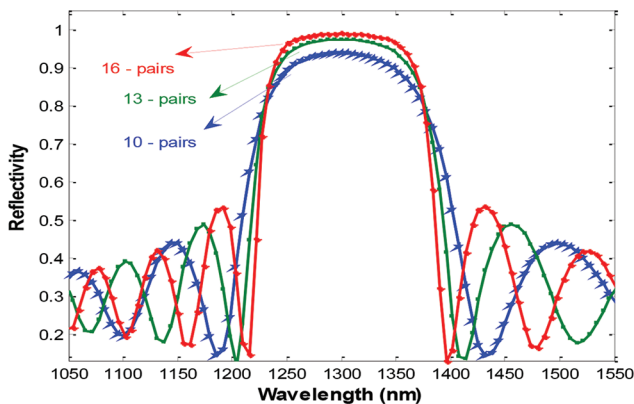


Fig. 4. Reflectivity spectrum of distributed Bragg reflector for three different layers of Al_{0.9}Ga_{0.1}As.

the center wavelength of the reflection stopband. As the angle of incidence increased, the resonant wavelength decreased.

Fig. 7 displays the variation of reflectivity as a function of wavelength for abrupt and graded DBR with using different material was determined. It can be seen that the reflectivity of graded DBR for both of them GaAs/AlAs and GaAs/AlGaAs is lower compared to the abrupt DBR GaAs/Al_{0.2}Ga_{0.8}As/AlAs and GaAs/Al_{0.1}Ga_{0.9}As/Al_{0.1}Ga_{0.9}As with increasing the intermediate layer for graded DBR reduce the potential energy barriers for majority carriers, hence reducing the resistance and self-heating nevertheless influence the reflectivity of the

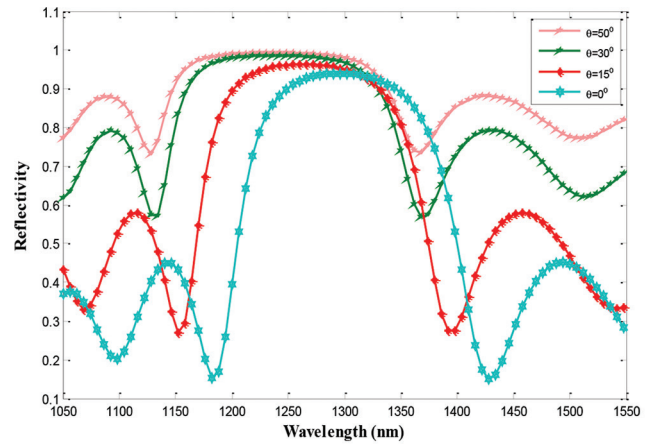


Fig. 5: Reflectivity of a distributed Bragg reflector calculated for a different incident angle.

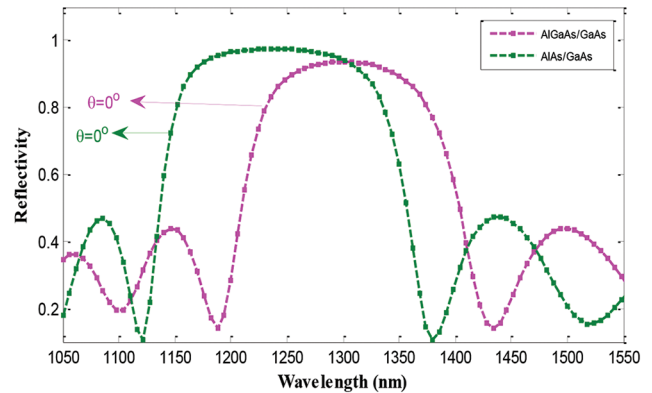


Fig. 6: Reflectivity of a DBR calculated for different materials at same angle

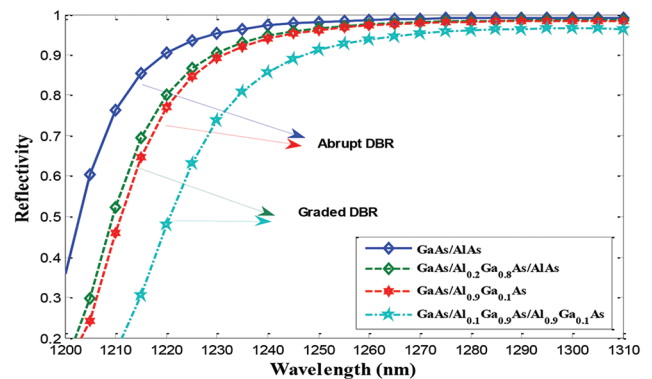


Fig. 7: Comparison of the abrupt and the graded reflectivity spectra for different materials with fixed 13 pairs top distributed Bragg reflector.

device. This variation in Al composition causes the decreasing reflectivity spectrum and bandwidth of graded DBR is more suitable for operating VCSEA devices, compared to the VCSELs which require the higher reflectivity of the top DBR until it gets to the lasing wavelength. To reach the reflectivity of more than 99%, more than 13 pairs of DBRs are required for graded DBR compared to the linear DBR. However, using AIAs in DBR mirrors the reflectivity of the device increased either in linear and graded DBR compared to the AlGaAs, this is due to decreasing the refractive index contrast between layers and the intermediate layer being more prominent with the structure which influence the relative barrier high.

IV. CONCLUSION

An analytical simulation method for the change of reflectivity, wavelength of DBR, and VCSEAs reflective mode operation, stopband, and incidence angle variation for DBR-based VCSEAs has been studied. High reflective mirror was obtained which are 97.5% for GaAs/AlAs, $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}$ DBR is 95.1% decreased with decreasing Al concentration to almost 50%. With increasing incident angle of light beam, the band center shifts toward shorter wavelength, also its depend on the material. It was observed that increasing intermediate layers using grading junction DBR resulting in a decreasing reflectivity due to decreasing the potential barriers which is more suitable for performance of VCSEAs. The simulation results show that the higher refractive indices contrast, incident angle and periodic number of DBR layer will cause an increase in reflectivity, and decrease the depth of cavity mode (resonant cavity).

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