Design and numerical simulation of novel DBRs

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In this paper, a numerical simulation of the traditional graded distributed Bragg reflector (DBR) and a design of the novel DBR with short period superlattices (SPSs DBR) used by vertical cavity surface emitting laser (VCSEL) are reported. First, the optical characteristic matrix of the graded DBRs is derived using the theories of thin film optics. Second, its reflective spectrum is numerical simulated and it is found that the simulative results are similar with the experimental data. The difference of the cavity mode position between the experimental and simulative data is discussed. Finally, based on the simulative results of graded DBR, a novel DBR with 4.5-pair GaAs/AlAs SPSs is designed, and its reflective spectrum is numerical simulated and analyzed.

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Since the vertical cavity surface emitting laser (VCSEL) was developed by Soda and Iga *et al.* in 1979[1], the VCSELs have made good progress, and in the 21st century, the VCSELs are playing an important role in the IT field. There must be a great challenge for the VCSEL researchers. Many new types of VCSELs have been developed by the researchers to improve their optical, electrical and thermal performances[2−4]. The numerical simulation of VCSELs was also employed to shorten the research cycle and enhance the research efficiency of the devices. Many cases indicate that it is an effective method for the device development.

In the 1990's, Osinski's research group did a series of numerical simulation researches about the VCSELs[5−7], and Wenzel *et al.* presented the effective frequency method (EFM) for analyzing the VCSELs[8]. In these papers, however, the numerical simulation of the distributed Bragg reflectors (DBRs) was not involved. The performance of the DBRs is so important for the VCSEL that, in some cases, it may dominate the performance of VCSEL. Therefore, the numerical simulation of the DBR is particularly studied in this paper.

The fundamental principle of the DBR is similar with the optical thin film. The $\lambda_0/4$ thin film stacks are employed for obtaining the high reflectivity in the DBRs. For simulating the DBRs, the model of $\lambda_0/4$ thin film stacks will be analyzed. Its reflectivity is derived by the characteristic matrix method as follows. For the q layers DBR, the light injects from the top, its characteristic matrix is written as

$$\begin{bmatrix} B \\ C \end{bmatrix} = \prod_{r=1}^{q} \begin{bmatrix} \cos\delta_r & \frac{i}{n_r}\sin\delta_r \\ in_r\sin\delta_r & \cos\delta_4 \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix}, \quad (1)$$

where δ_r is the phase thickness of the r-th layer of DBR, and $\delta_r = \frac{2\pi}{\lambda} N_r d_r \cos\theta_r$, $N_r d_r \cos\theta_r$ is the optical thickness of the r-th layer for the designed wavelength λ_0. As the light vertically injects into the VCSEL, the value of θ_r is 0. $N_r = n_r - ik_r$ is the complex refractivity of the material consisting of DBR, n_r is the real refractivity, and k_r is the extinction coefficient. For the dielectric material used in DBR, $k_r = 0$, λ is the wavelength of injected light. d_r is the geometrical thickness of the r-th layer. n_s is the refractive index of the substrate of VCSEL. The reflectivity of DBR R can be derived according to the characteristic matrix

$$R = \frac{(n_0 B - C)(n_0 B - C)^*}{(n_0 B + C)(n_0 B + C)^*}, \quad (2)$$

where n_0 is the refractive index of the incident medium, $(n_0 B - C)^*$ is the conjugative part of $(n_0 B - C)$.

The VCSEL with graded DBR is grown by MOVPE. Its optical cavity is consisted of three quantum GaAs wells and two $Al_{0.3}Ga_{0.7}As$ barriers with two $Al_xGa_{1-x}As$ graded spacers, and the optical thickness of the cavity is 1λ. One oxide layer of $Al_{0.98}Ga_{0.02}As$ is laid above the optical cavity. The top DBR is consisted of 22 pairs of $Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As$ with the 20-nm graded layer following every layer, its optical thickness is $\lambda/4$. The bottom DBR is laid above the GaAs buffer and substrate, it is consisted of 34 pairs of $Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As$ with the 20-nm graded layer following every layer, and its optical thickness is also $\lambda/4$. The reflective spectrum of this VCSEL is measured and shown with the solid line in Fig. 1.

The numerical simulation of this device is performed by the characteristic matrix method, the reflective spectrum is drawn in Fig. 1 with dashed line. In Fig. 1, the reflectivity, the width of stop band and the position of the stop band fit with the experimental data, but the significant difference of cavity mode position between the experimental data and the simulative data is found. Why is there the difference? We deduce that it is caused by the change of refractive index of materials consisting of the active region. According to Refs. [9] and [10], there are higher refractive index and absorption coefficient in quantum well than in the bulk materials. Based on this viewpoint, the numerical simulation is performed with

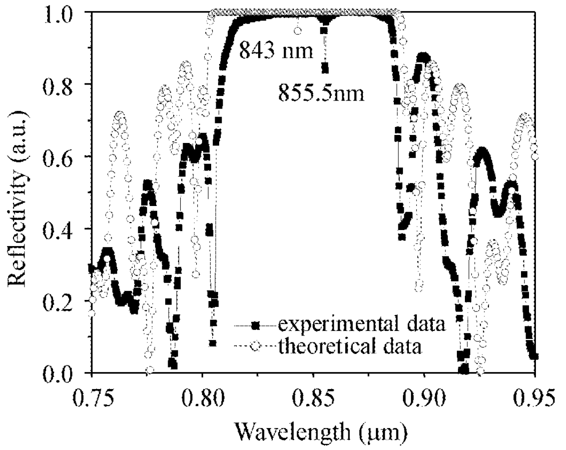

Fig. 1. The theoretical and experimental reflective spectra of graded DBR.

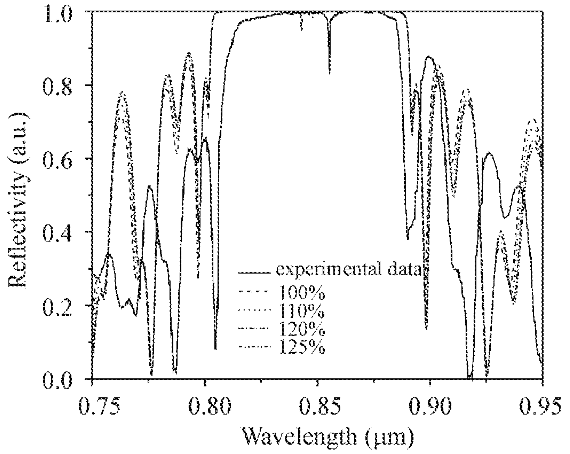

Fig. 2. The cavity mode position of VCSEL shifts with the increasing of the refractive index of the active region multiple quantum well (MQW), the refractive index increases from original data to its 1.25 times.

our simulation program. The refractive indices of the active region materials are increased to 110%, 120% and 125% respectively, and the reflective spectrum is drawn in Figs. 2 and 3. The experimental data are also drawn in Figs. 2 and 3 with solid line. Increasing the refractive indices, the red shift of cavity mode increases. The cavity mode position increases to 856 nm when the refractive index is increased to 125%, it is almost the same as the experimental data (855.5 nm). This confirms our deduction.

Based on the above analysis, this method is found to be available to simulate the reflective spectrum. So it is used to design and simulate the novel DBR. In Ref. [2], the authors presented the novel DBR for VCSEL where the GaAs/AlAs short period superlattices (SPSs) are used for replacing of traditional high refractive index semiconductor dielectric materials for the DBR layers. The 18.5-pair GaAs/AlAs SPSs are used in their structure. The thickness of GaAs is 3 nm and that of AlAs is 0.7 nm. But it is too thin for growing the high-quality epilayer. For obtaining high-quality epilayer, we designed a kind of novel DBR with 4.5-pair GaAs/AlAs SPSs. The

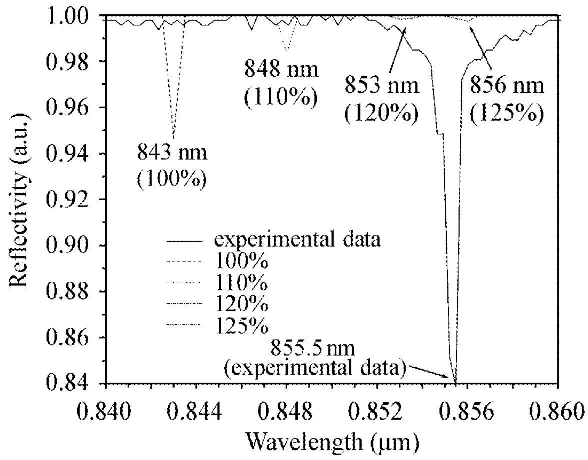

Fig. 3. The partial enlargement of Fig. 2.

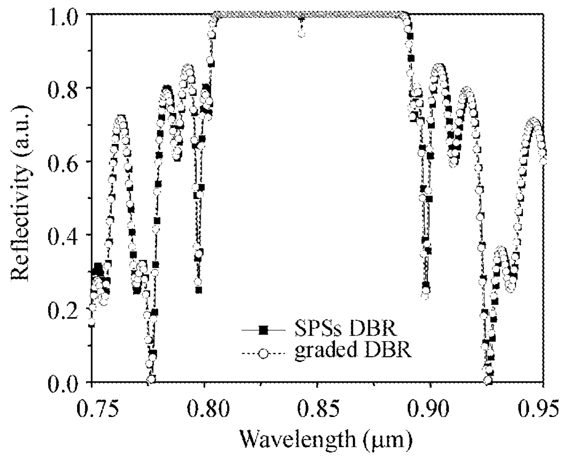

Fig. 4. The reflective spectrum of 4.5-pair SPSs DBR, and it is almost the same as the graded DBR.

thickness of GaAs is 10 nm and that of AlAs is 1.9 nm in our SPS. The layers with high refractive indices are replaced by the 4.5-pair GaAs/AlAs SPSs, and the other parts are the same as the VCSEL with graded DBR. The reflective spectrum of our device with SPSs DBR is simulated by above method. The reflective spectrum is drawn in Fig. 4 and the change of the refractive indices of superlattices and active region is neglected. The simulative result indicates that the optical performance of VCSEL with the newly designed 4.5-pair SPSs DBR is almost the same as that with graded DBR. According to Ref. [2], using the SPSs DBR can decrease significantly the series resistance of VCSELs.

In summary, the reflective spectrum of the graded DBR is simulated and compared with the experimental data. The difference of cavity mode between the simulative data and the experimental data is analyzed, it is caused by the increase of the refractive indices of the quantum wells and barriers in active region. Finally, a novel DBR with 4.5-pair GaAs/AlAs SPSs is designed. The reflective spectrum of the SPSs DBR is simulated and it is almost the same as the graded DBR. It will become a promising method for decreasing the series resistance of VCSELs.

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