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Design High Efficient Reflectivity of Distributed Bragg Reflectors

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Abstract: Bragg Reflectors consist of periodic dielectric layers having an optical path length of quarter wavelength for each layer giving them important properties and makes them suitable for optoelectronics applications. The reflectivity can be increased by increasing the number of layers of the mirror to get the required value. For example for an 8 layers Bragg mirror (two layers for each dielectric pair), the contrast of the refractive index has to be equal to 0.275 for reaching reflectivity > 99%. Doubling the number of layers results in a reflectivity of 99.99%. The high reflectivity is purely caused by multiple-interference effects. It can be analyzed by using different matrix methods such as the transfer matrix method (TMM) which is the simplest method to study the characteristic of devices with different alternating layers.

Introduction

Bragg mirrors (also called *distributed Bragg reflector*) (DBR) are composed of multiple layered alternating dielectric pairs. Each pair consists of two materials having different refractive indices. The reflectivity of these devices can be tuned from 0% to nearly 100% by changing the number of the stacks of the mirror and for certain required wavelength (total wavelength) [1].

Bragg mirrors have small intrinsic absorption coefficient. The high reflectivity of light is because of the constructive interference between the incident light and the reflected light due to Fresnel reflection. Highly efficient Bragg mirrors can be produced by using high purity dielectric material to suppress absorption, and by controlling accurately the thickness of layers during fabrication to select the desired reflection wavelength. Also it requires smooth interfaces and surfaces to prevent scattering [2].

DBRs is made of the low absorption and high reflectivity semiconductor material. DBR mirrors are fabricated by repeatedly growing epitaxial pairs of semiconductor layers with low refractive indices. The thickness of each layer equals to quarter of the desired wavelength. So, when a pattern of high to low refractive indices of several quarter wavelengths layers combination will maximize the reflectivity for higher than 99% [3-4]. A simple equation can be used to calculate the single DBR reflectivity at normal light incidence as follows [4].

$$R = \left[\frac{1-\left(\frac{n_1}{n_2}\right)^{2m}}{1+\left(\frac{n_1}{n_2}\right)^{2m}}\right]^2 \qquad (1)$$

Where m is the index number of the quarter wave DBR pairs, n_1 and n_2 are the refractive indices of the two layers of DBR.

DBR mirrors have wide range of applications in optoelectronics such as Novalux Extended Cavity Surface Emitting Lasers (NECSEL), [5] Vertical Cavity Surface Emitting Lasers (VCSELs) [6], and Resonant Cavity Light Emitting Diodes (RCLED) [7].

These types of mirrors are also named as quarter wavelength mirrors because the thickness of each layer equals to the quarter wavelength the light travelling inside the mirror material.

The principle of operation is explained as follows. Fresnel reflection at the interface between the two material layers occurs. For the desired wavelength, the difference in optical path length between subsequent interfaces equals to half wavelength (quarter wavelength for each layer). Moreover, the amplitude coefficients of the reflected light from the interfaces have opposite signs [8]. As a result, constructive interference occurs between all reflected components from the interfaces results in strong reflection. The reflectivity of the mirror is determined by the contrast of the refractive index between the materials and the number of alternating pairs. The bandwidth of reflection is mainly determined by the contrast of the refractive index. Figure 1 shows the DBR mirror in a semiconductor laser structure in which the light is confined within the active medium by the alternating pairs of the upper and lower DBR mirrors [9].

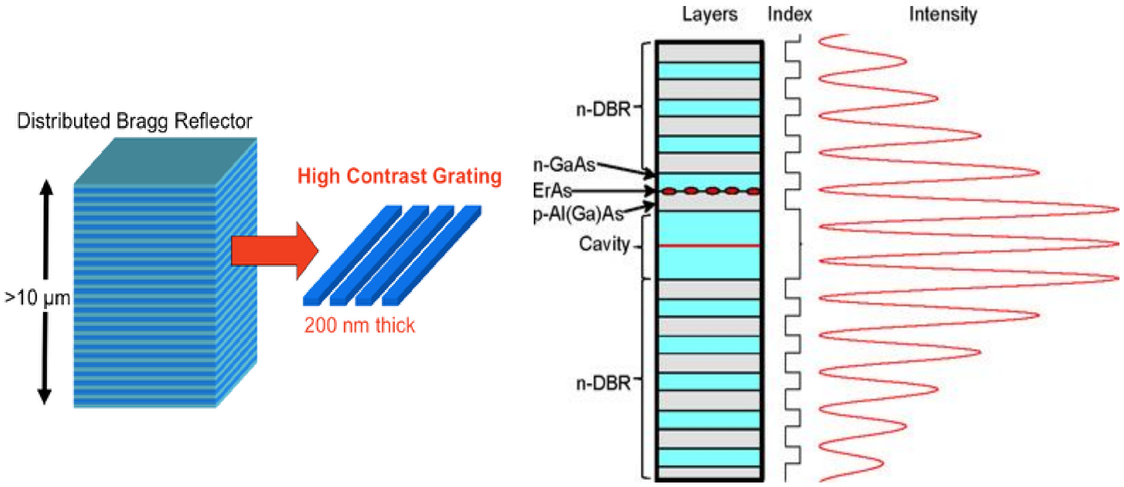

Fig.(1): Simple DBR structure in Semiconductor laser [9]

Transmission matrix method (TMM)

Consider the light waves show in Fig.2 which are travelling in z-direction . Their electric fields representations are formulated by Eqs. (2&3) ,

$$A_j(z_1) = e^{-j\beta L}(z_2 - z_1).A_i(z_2) \ \ldots \qquad (2)$$

$$B_j(z_2) = e^{j\beta L}(z_2 - z_1).B_i(z_2)\ldots\ldots\ldots \qquad (3)$$

$$B_i = k_o n_i = k_o\left(n_{i,re} + n_{i.im}\right) = \frac{2\pi}{\lambda} \ \ldots (4)$$

Where:

n_i: complex refraction index

k_0: wave number

$n_{i,im}$: extinction coefficient

$n_{i,re}$: refraction index

B_i is propagation constant

Equations (2) and (3) can be written in matrix form as follows:

$$\begin{bmatrix} A_j(z_2) \\ B_j(z_2) \end{bmatrix} = \begin{bmatrix} e^{-j\beta L} & 0 \\ 0 & e^{j\beta L} \end{bmatrix} \begin{bmatrix} A_i(z_1) \\ A_i(z_1) \end{bmatrix}$$

$$= P_i \begin{bmatrix} A_i(z_1) \\ A_i(z_2) \end{bmatrix}$$

Where B_i is the light propagation matrix, and L $=z_2$- z_1

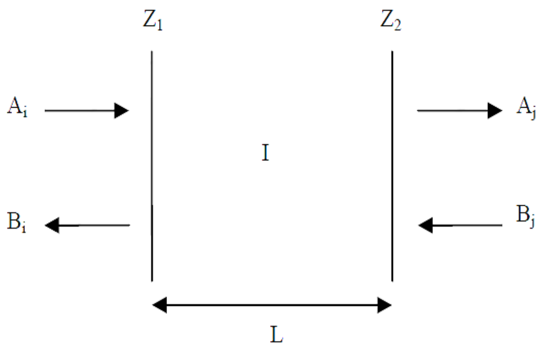

Fig. (2): A schematic diagram of the wave propagation in region I

The light waves travelling through different material interface ,as shown in Fig. 3, can be extracted using the boundary conditions as below:

$$A_j + B_j = A_i + B_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$-n_jA_j + n_jB_j = -n_iA_i + n_i + B_i \ldots\ldots \ (6)$$

Equations (5) and (6) can be written in matrix form,

$$\begin{bmatrix} A_j \\ B_j \end{bmatrix} = \begin{bmatrix} \frac{n_j + n_i}{2n_j} & \frac{n_j - n_i}{2n_j} \\ \frac{n_j - n_i}{2n_j} & \frac{n_j + n_i}{2n_j} \end{bmatrix} \begin{bmatrix} A_i \\ B_i \end{bmatrix} = T_{j,i} \begin{bmatrix} A_i \\ B_i \end{bmatrix}$$

Where $T_{j,i}$ is the light propagation coefficient between the mediums i and j in matrix form.

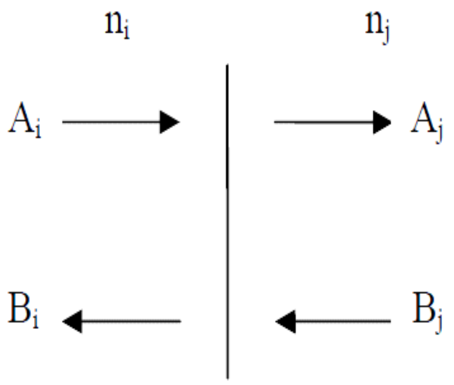

Fig. (3): A Schematic diagram of the Wave propagation inside the interface between $n_i$and n_j

The structure of multilayered stacks is shown in Fig. 4, then the wave propagation scheme, can be presented in matrix propagation type.

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = T_P \begin{bmatrix} A_1 \\ B_1 \end{bmatrix}$$

$$T_P = T_{1,2}P_2T_{2,1}P_1 = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}$$

Assuming A_2= 0, the coefficient of reflection can be expressed as:

$$R_1 = \frac{A_1}{B_1}$$

$$R = |R_1|^2$$

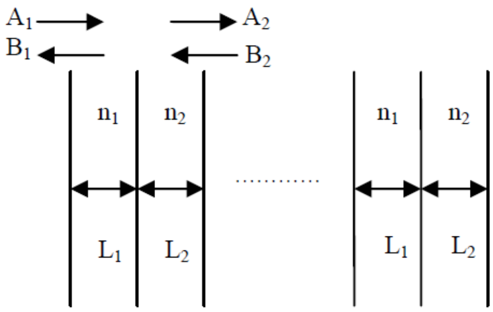

Fig. (4): The $n_1$and n_2 mediums of the multiplayer structures

Simulation Results

Several materials can be used for constructing DBR structures. Each pair differs in thickness and refractive index. In this work, a simulation is done to compare the reflectivity of different semiconductor materials (AlAs, GaAs, GaSb, InAs, InP, and InSb) for wavelength of 2 µm.

Reflectance

The reflectance of eight types of DBR layers is compared at 20 alternating pairs. The results are shown in Table 1.

Figure 5 shows the reflectance of GaAs/InAs DBR mirror for 20 alternating pairs. It can be seen that the mirror has 99% reflectivity at a wavelength of 2 µm. Figure 6 shows the reflectivity of GaSb/InSb alternating pairs. It can be seen that the reflectivity is 37% at a wavelength of 2µm which means that it requires more layers to achieve high reflectivity. The reflectance on GaSb/InSb DBR has less sidelobs compared to the GaAs/InAs DBR mirror.

Table (1): The reflectivity of different DBR Mirrors

DBR Mirror	Reflectivity at 20 layers
GaAs/AlAs	99%
AlAs/InAs	90%
GaAs/InAs	73%
GaAs/GaSb	96%
GaSb/InSb	37%
InAs/InSb	99%
InAs/InP	2%
InSb/InP	99%

The results showed that the three types of DBR mirrors have high reflectivities at 20 pairs as below:

1-GaAs/AlAs (99%).

2-InAs/InSb (99%).

3-InSb/InP (99%).

4-GaAs/GaSb (96%).

5- AlAs/InAs (90%).

The pairs mentioned above are the best suitable to be used in the fabrication of mirrors in VCSEL lasers or other DBR required devices.

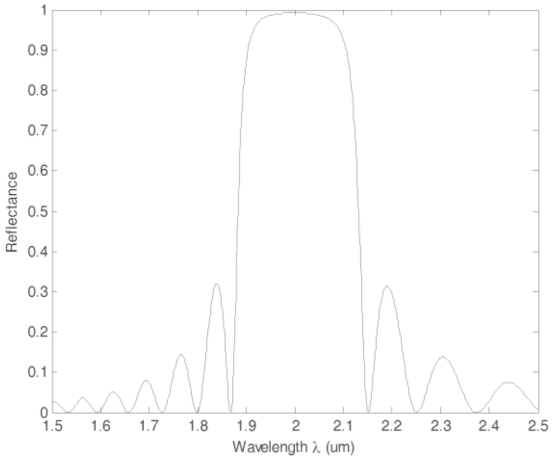

Fig. (5): Reflectance vs Wavelength for GaAs/InAs with linewidth of 250nm

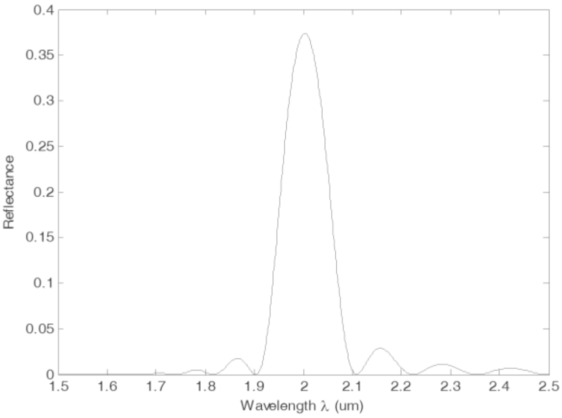

Fig. (6): Reflectance vs Wavelength for GaSb/InSb with linewidth of 200nm

Thickness:

The thickness is also an important parameter that must be taken in consideration when designing semiconductor DBR devices. High thickness devices may lead to loss of carriers and require excessive cooling. Table 2 shows a comparison between the thicknesses required of each alternating pair. For a GaAs/AlAs pairs, the thickness of a 20 pair of DBR mirror is $1.22*10^{-5}$ meters. On the other hand, to achieve the same reflectivity in InAs/InSb the thickness has to be of $5.54 * 10^{-6}$ meters.

Table (2): Thickness of different types of DBR mirrors

DBR Mirror	Thickness Layer1/Layer2	Single Layer Thickness	20 Layer Thickness
GaAs/AlAs	2.6726e-007 / 3.4675e-007	6.1401E-07	1.22802E-05
AlAs/InAs	3.4675e-007 / 1.5008e-007	4.9683E-07	9.9366E-06
GaAs/InAs	2.6726e-007 / 1.5008e-007	4.1734E-07	8.3468E-06
GaAs/GaSb	2.6726e-007 / 1.3817e-007	4.05E-07	8.1086E-06
GaSb/InSb	1.3817e-007 / 1.2741e-007	2.6558E-07	5.3116E-06
InAs/InSb	1.5008e-007 / 1.2741e-007	2.7749E-07	5.5498E-06
InAs/InP	1.5008e-007 / 1.8563e-007	3.36E-07	6.7142E-06
InSb/InP	1.2741e-007 / 1.8563e-007	3.13E-07	6.2608E-06

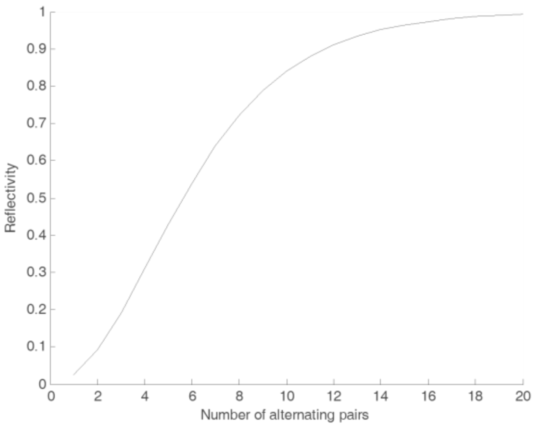

Fig. (7): Number of alternating pairs vs. reflectivity for GaAs/AlAs DBR

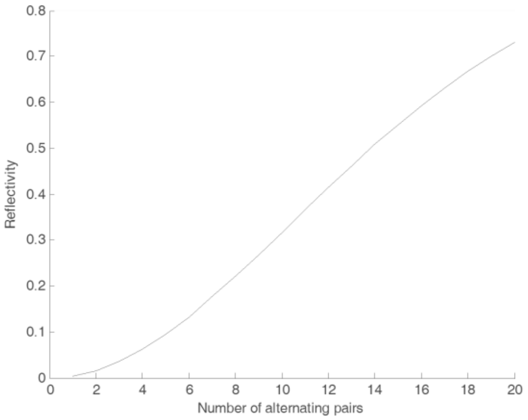

Fig. (8): Number of alternating pairs vs. reflectivity for GaAs/InAs DBR

Conclusions

The main idea of the paper is to study the characteristic of distributed Bragg reflector (DBR) for wavelength of 2 μm by using different types of materials and study the effect of change the number of layers on reflectivity by using transfer matrix method (TMM) analysis. DBRs are used in a wide range of optoelectronics applications so this paper is useful for knowing the best type of DBR. From our result, it is shown that the maximum achievable reflectivity of GaAs/InAs DBR for 20 alternating pairs was 99.99%. While the reflectivity of GaSb/InSb is 37% at 2μm wavelength. This means it requires more than 20 pairs of layers to achieve high reflectivity. In addition, the thickness is an important parameter and suitable thickness must be selected in order to avoid loss and easily cooling.

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تصميم مرايا DBR عالية الكفاءة

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الخلاصة: تتكون مرايا براغ من عدة طبقات عازلة مع سمك يعادل ربع الطول الموجي ولها أهمية في تطبيقات أجهزة الالكترونيات البصرية، يمكن زيادة الانعكاسية عن طريق زيادة عدد الطبقات من المرآة حتى الحصول على القيم المطلوبة، على سبيل المثال عندما نستخدم مرايا مكونة من أربعة طبقات براغ مزدوجة مع ضرورة ان يكون التباين في معامل الانكسار بمقدار 0.275 للحصول على انعكاسية اعلى من 99٪، وعند استخدام ثمانية طبقات مزدوجة مع نفس التباين في معامل الانكسار نحصل على انعكاسية عالية بمقدار 99.99٪. تم حساب أفضل سمك للزوج من طبقات المادة المزدوجة InAs/InSb بمقدار 2.7749×10^{-7} متر. تم تحليل الانعكاسية لمواد مختلفة باستخدام طريقة (TMM) للمصفوفات وتعتبر اسهل طريقة لدراسة الخصائص لعدة طبقات متناوبة مختلفة.