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Improved simulation of VCSEL distributed Bragg reflectors

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Abstract In this paper, the Floquet-Bloch theory (FBT) has been applied to the accurate simulation of distributed Bragg reflectors in vertical cavity surface emitting lasers (VCSELs). A number of comparisons with other methods largely used in commercial CAD tools is presented. Performance predictions for long-wavelength GaInAsP VCSELs are derived.

Keywords Distributed Bragg reflectors · Vertical cavity surface emitting laser · Numerical modeling

1 Introduction

Long wavelength Vertical Cavity Surface Emitting Lasers (VCSEL) are of great interest as low-cost, efficient light sources for optical communication systems (at wavelengths around 1.55 μm). They are attractive for high density applications, because of their wafer-scale manufacturability, on-wafer testing and easy packaging due to their vertical orientation, allowing 2D array fabrication and efficient coupling to optical fibers [1].

One critical issue for VCSELs is connected to the very short optical gain region as compared to edge-emitting lasers, hence requiring very high (>99%) reflectivity mirrors to achieve lasing action. This is realized by distributed Bragg reflectors (DBRs), whose design criteria are related to maximum optical reflectivity, thermal and electrical conductivity, material index contrast and optical absorption. DBR analysis is critical in VCSEL design, because their reflectivity strongly affects all laser fundamental properties.

Long wavelength VCSELs require ternary or quaternary semiconductor alloys, having substantially lower thermal conductivities than binary counterpart due to alloy scattering [2]. Heat conduction is one of the most recurrent problem arising in long-wavelength VCSEL DBRs. Thermal heating and consequent deterioration of laser performance is connected with the high series resistance of DBR stacks, due to the large band gap difference at the hetero-interfaces, resulting in carrier flow impediment. Therefore, it is evident that an accurate investigation of optimized distributed Bragg reflectors is still a fundamental task in VCSEL design [3]. Numerical calculations of multilayered mirrors are generally carried out by the transfer matrix method (TMM) [1] or the coupled mode theory (CMT) [4]. TMM is commonly used to analyse the multilayered mirrors with abrupt interfaces. By this method it is possible to analytically formulate the reflectivity, provided the thickness of each quarter wavelength dielectric layer. However, the losses due to scattering at layer interfaces are not taken into account and the numerical implementation is often computationally onerous. CMT provides simple analytical expressions, also for mirrors having graded interfaces. This is simply done by modifying the coupling constant with the introduction of some approximations, so the applicability of the method is limited to DBR structures with small index contrast, where the perturbation induced by the index periodicity (grating) can be considered weak. Corzine et al. [5] developed a *Tanh* substitution technique to find the reflectivity of abrupt and graded multilayered mirrors, that does not introduce any advantage in terms of accuracy, but only in terms of simplicity.

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In this paper the rigorous method based on Floquet-Bloch theory (FBT) is applied to calculate the reflectivity of VCSEL DBRs. Although this method has already been presented in literature to investigate various devices, such as grating-assisted directional couplers [6] and fiber Bragg gratings, its application to the study of DBRs is novel. FBT approach provides accurate results because it calculates the grating profile as a Fourier series and considers the leaky modes really travelling in the periodic region, taking into account the scattering losses in DBR periodic structure. Each leaky mode is described as the sum of a number of space harmonics, whose phases are related by Floquet's theorem. This approach allows very good accuracy for high index contrast structures to be achieved. Then, FBT does not introduce any numerical or conceptual approximation, apart from the inevitable truncation of the Fourier-series expansion of the periodic medium permittivity in real finite-length structures. In general, the results very well agree with those obtained by TMM or CMT for structures with abrupt interfaces or rapidly varying profiles with moderate index contrast. However, significant discrepancies for some index profiles, such as sinusoidal or triangular profiles, or in case of high index contrast structures have been found, where other approaches (TMM or CMT) are too approximated. Differently from other methods, FBT derives the reflectivity spectra by calculating the energy band diagram of the structure, thus allowing a complete view of DBR physical and geometrical features.

2 Reflectivity numerical results

In order to compare the proposed method with well known TMM, CMT, and *Tanh* methods, the VCSEL test structure presented in [7] and sketched in Fig. 1 has been considered. It employs InP/$Al_{0.05}Ga_{0.42}In_{0.53}As$ DBRs, with an index contrast $\Delta n = 0.63$ between different layers. The calculations have been carried out for the bottom n-doped DBR, consisting of $N = 22$ periods. The structure is optimized for lasing at the wavelength of 1546 nm. DBRs with several refractive index profiles, i.e. step index (square), sinusoidal, triangular and trapezoidal, have been considered. Accurate results by FBT have been found by using five space harmonics, as a best trade-off between accuracy and calculation time. Typically, five/seven space harmonics are enough in the truncated series to obtain accurate results by FBT. Figure 2 shows the DBR reflectivity spectra in case of abrupt interfaces (square profile). The central lobe is clearly similar for the three analysed methods. However, 3 dB stop-bands are slightly different (207.5 nm for FBT, 210.8 nm for CMT and 210.5 nm for TMM, respectively) and centred at different wavelengths (1.5325 μm, 1.5475 μm and 1.5531 μm, respectively). This is related to rigorous evaluation of leaky modes by FBT, whose interference shifts a little the band center and its width. Peak values are given in Table 1.

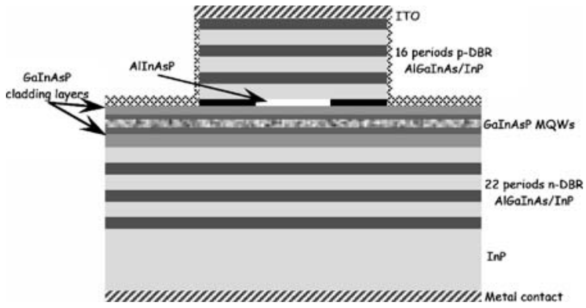

Fig. 1 VCSEL structure under investigation

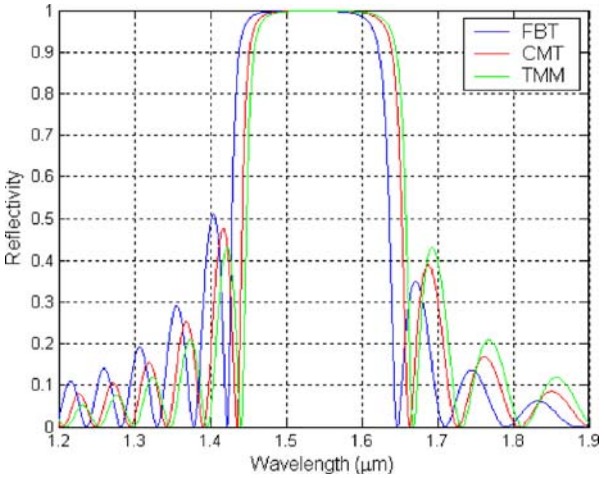

Fig. 2 Reflectivity spectra for a 22 periods DBR with refractive index square profile

Table 1 Peak reflectivity for 22 periods (square profile)

Method	Peak reflectivity
FBT (this paper)	0.99834
TMM [1]	0.99864
CMT [4]	0.99868
Tanh [5]	0.99861

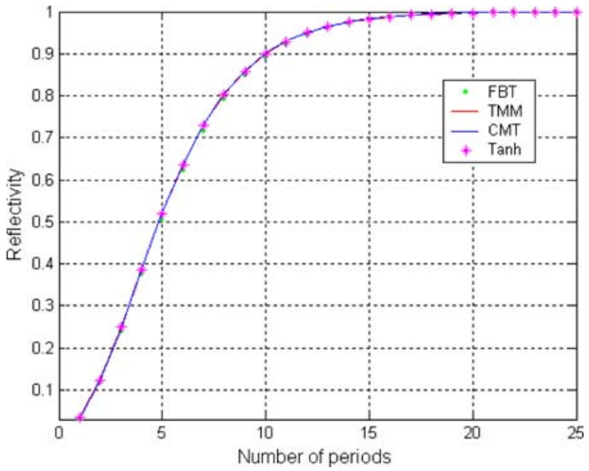

Fig. 3 Peak reflectivity versus number of periods (square profile)

Table 2 Number of periods for 99% reflectivity for various DBR system materials (square profile)

DBR composition	n_2	n_1	Δn	This work	Loss by FBT (dB/μm)	Ref. [8]
GaAs/AlAs	3.37	2.89	0.48	20	2.657	16
InGaAsP/InP	3.45	3.17	0.28	36	1.568	28
AlGaAsSb/AlAsSb	3.50	3.10	0.40	25	2.228	16
AlInGaAs/AlInAs	3.47	3.21	0.26	39	1.457	30
a-Si/SiO_2	3.60	1.45	1.15	4	9.512	4
a-Si/Al_2O_3	3.60	1.74	1.86	4	9.457	5

Table 3 Number of periods for 99% reflectivity for various DBR system materials and index profiles

DBR materials	Square	Sinusoidal	Triangular	Trapez. rapidly varying	Trapez. slowly varying
GaAs/AlAs	20	26	32	21	25
InGaAsP/InP	36	46	58	38	44
AlGaAsSb/AlAsSb	25	32	40	26	31
AlInGaAs/AlInAs	39	50	63	41	48
a-Si/SiO_2	4	23 for 89.7%	37 for 74.5%	7	26 for 92.3%
a-Si/Al_2O_3	4	8	21 for 98.8%	6	7

Table 4 Comparison of reflectivity and laser performance for various calculation methods (square profile)

	Reflectivity (%)		Laser performance		
Method	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d
FBT (this work)	99.834	98.624	221.158	716.025	0.545
CMT [4]	99.869	98.835	205.802	709.078	0.507
TMM [1]	99.864	98.808	207.732	709.947	0.513
Tanh [5]	99.861	98.790	209.062	710.547	0.516

Table 5 Comparison of reflectivity and laser performance for various calculation methods (sinusoidal profile)

	Reflectivity (%)		Laser performance		
Method	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d
FBT (this work)	99.136	95.563	460.026	833.286	0.759
CMT [4]	99.267	95.984	424.578	814.741	0.745
Tanh [5]	99.265	96.028	421.850	813.331	0.744

Table 6 Comparison of reflectivity and laser performance for various calculation methods (triangular profile)

	Reflectivity (%)		Laser performance		
Method	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d
FBT (this work)	88.115	72.245	2923.68	3982.26	0.880
CMT [4]	97.604	90.698	880.294	1088.13	0.831
Tanh [5]	97.683	91.091	848.501	1066.38	0.828

Table 7 Comparison of reflectivity and laser performance for various calculation methods (rapidly varying trapezoidal profile)

	Reflectivity (%)		Laser performance		
Method	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d
FBT (this work)	99.797	98.430	235.609	722.625	0.575
CMT [4]	99.824	98.559	225.872	718.171	0.556
Tanh [5]	99.815	98.517	229.073	719.632	0.562

Table 8 Comparison of reflectivity and laser performance for various calculation methods (slowly varying trapezoidal profile)

	Reflectivity (%)		Laser performance		
Method	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d
FBT (this work)	99.323	96.263	403.122	803.717	0.735
CMT [4]	99.400	96.518	381.939	792.980	0.724
Tanh [5]	99.394	96.537	381.043	792.529	0.723

Figure 3 shows the peak reflectivity as a function of DBR number of periods in case of abrupt interfaces, for the four analyzed methods.

We have calculated by FBT the number of periods N as required for obtaining 99% reflectivity (square profile), for six different 1550 nm DBR materials.

These results have been compared with those obtained by using a different TMM approach [8]. Table 2 summarizes this interesting comparison.

We can observe that the number of periods predicted by FBT is smaller than in [8], because our method takes into account the scattering losses (in Table 2), not considered in other approaches. This influence tends to increase with the number of periods. Table 3 shows a comparison by FBT among five examined index profiles, again for the material systems given in [8].

There are clear analogies between square and rapidly varying trapezoidal profiles and between sinusoidal and slowly varying trapezoidal profiles. Moreover, 99% reflectivity could not be achieved for silicon-based structures in some cases, since the relevant losses should be too high (see Table 2).

3 Laser performance

In this section we illustrate how the various DBR reflectivity values calculated by means of different methods affect the VCSEL fundamental properties. In particular, we have investigated the influence on threshold gain g_{th}, threshold current density J_{th} and external quantum efficiency η_d, calculated respectively as:

$$N_w \Gamma_w \Gamma_z g_{\text{th}} = \alpha_{\text{cav}} + \frac{1}{2L_{\text{cav}}} \ln \frac{1}{R_1 R_2} \tag{1}$$

$$J_{\text{th}} = \frac{N_w J_0}{\eta_{\text{int}}} \exp\left(\frac{\alpha_{\text{cav}} + \frac{1}{2L_{\text{cav}}} \ln \frac{1}{R_1 R_2}}{N_w \Gamma_w \Gamma_z g_0} \right) \tag{2}$$

$$\eta_d = \eta_{\text{int}} \frac{\ln \frac{1}{\sqrt{R_1 R_2}}}{\alpha_{\text{cav}} L_{\text{cav}} + \ln \frac{1}{\sqrt{R_1 R_2}}} \tag{3}$$

R_1 and R_2 are the reflectivity of bottom ($N = 22$) and top ($N = 16$) DBR mirror, respectively, N_w is the number of active region quantum wells, and Γ_w and Γ_z are lateral and longitudinal confinement factors, respectively. Moreover, L_{cav} is the laser cavity length, α_{cav} is the optical cavity loss, g_0 is the material gain coefficient, J_0 is the transparency current density and η_{int} is the internal quantum efficiency. Numerical values are taken from [7].

Tables 4–8 show the comparisons among different numerical methods in terms of reflectivity, threshold gain, threshold current density and external quantum efficiency. It is clear that even moderate differences in the calculated reflectivity (for example by FBT as compared with CMT) could induce significant changes in the predicted laser performance.

These examples well demonstrate the importance of rigorous evaluations of any DBR system material. Therefore, FBT approach could be included in a number of available and sophisticated (even commercial) CAD tools for accurate optical analysis and simulation of VCSEL lasers.

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