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Improved Simulation of VCSEL Distributed Bragg Reflectors

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INTRODUCTION

In this paper, the Floquet-Bloch theory (FBT) [1] has been applied to the accurate simulation of distributed Bragg reflectors (DBRs) in vertical cavity surface emitting lasers (VCSELs). A number of comparisons with other largely used methods are presented. Performance predictions for long-wavelength VCSELs with GaInAsP active region are derived.

VCSEL STRUCTURE

The VCSEL structure (see Fig. 1) under investigation employs InP/$Al_{0.05}Ga_{0.42}In_{0.53}As$ DBRs, having a layer index difference $\Delta n = 0.63$ [2]. The structure is optimized for lasing at the wavelength of 1546 nm. The calculations have been carried out for the bottom n-DBR, consisting of $N = 22$ periods. DBRs with various refractive index profiles have been examined, i.e. step index (square), sinusoidal and trapezoidal. Accurate results by FBT have been found by using five space harmonics, as the best trade-off between accuracy and calculation time. Reflectivity calculations have been compared as obtained by FBT, modified transfer matrix method (TMM) [2], coupled mode theory (CMT) [3], *tanh* [4] and TMM [5].

NUMERICAL RESULTS

Fig. 2 shows the DBR reflectivity spectra in case of abrupt interfaces (square profile). The central lobe is clearly similar for the three analysed methods, as they exhibit the same value of peak reflectivity. However, the 3dB stopbands 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), because of the rigorous evaluation of leaky modes by FBT, whose interference shifts the band a little. Other DBR system compositions have been also considered, and results are summarized in Table I. It clearly shows the advantage of using FBT, including scattering losses, instead of other approaches [6]. Increasing approximations are given by CMT and TMM when the index profiles become more trapezoidal and the index contrast larger.

Finally, Tables II-IV show the comparison among various methods in terms of DBR reflectivity, VCSEL threshold gain, threshold current density and external quantum efficiency, being $B = \Lambda/2$ and Λ the DBR layer period. Accurate predictions by FBT are clearly shown.

CONCLUSION

Rigorous simulations of DBR reflectivity and VCSEL performance by Floquet-Bloch theory are presented in this work.

ACKNOWLEDGEMENT

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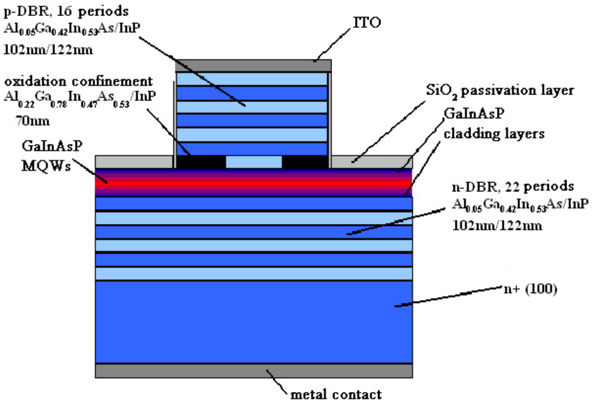

Fig. 1. VCSEL structure under investigation.

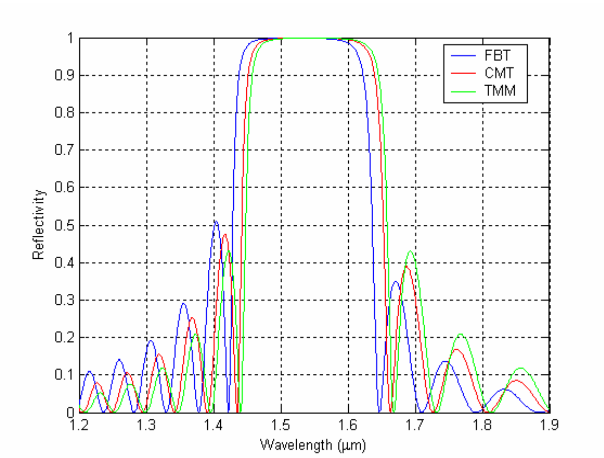

Fig. 2. Reflectivity spectra for 22 periods (square profile).

Table I. 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. [6]
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	3.5	3.1	0.40	25	2.228	16
AlInGaAs/AlInAs	3.47	3.21	0.26	39	1.457	30
a-Si/SiO_2	3.6	1.45	1.15	4	9.512	4
a-Si/Al_2O_3	3.6	1.74	1.86	4	9.457	5

Table II. Comparison of reflectivity and laser performance with various calculation methods (square profile, A = 0).

Method	DBR Reflectivity (%)		VCSEL performance		
	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d (%)
FBT (this work)	99.8338	98.6241	172.7136	694.3365	24.86
modified TMM [2]	92.3076	79.7471	481.5607	844.7579	76.58
CMT [3]	99.8685	98.8345	155.3526	686.7250	17.58
tanh [4]	99.8610	98.7899	140.7890	680.4043	18.15
TMM [5]	99.8639	98.8082	156.0793	687.0419	17.92

Table III. Comparison of reflectivity and laser performance for various calculation methods ("abrupt" trapezoidal, A=0.3B).

Method	DBR Reflectivity (%)		VCSEL performance		
	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d (%)
FBT (this work)	99.7974	98.4303	166.5497	691.6245	22.45
modified TMM [2]	91.1234	77.6109	528.1910	870.1422	77.92
CMT [3]	99.8237	98.5591	162.8924	690.0203	20.94
tanh [4]	99.8153	98.5165	144.5473	682.0298	21.44
TMM [5]	99.8639	98.8082	156.0781	687.0414	17.92

Table IV. Comparison of reflectivity and laser performance for various calculation methods ("smooth" trapezoidal, A=0.7B).

Method	DBR Reflectivity (%)		VCSEL performance		
	R_1	R_2	g_{th} (cm^{-1})	J_{th} (A/cm^2)	η_d (%)
FBT (this work)	99.3225	96.2632	229.4754	719.8163	40.98
modified TMM [2]	85.1038	68.5485	752.2500	1003.1661	81.84
CMT [3]	99.3995	96.5180	221.5182	716.1888	39.21
tanh [4]	99.3942	96.5371	173.0909	694.5029	39.14
TMM [5]	99.8639	98.8082	156.0781	687.0414	17.92