FACET REFLECTIVITY OF WAVEGUIDES BURIED AT REALISTIC DEPTH

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ABSTRACT

The novel Half Space Radiation Mode (HSRM) method for modal analysis is extended to calculate the facet reflectivity of shallowly buried semiconductor slab and can be also used for 2D-waveguides. The impact of the dielectric corner on facet reflectivity is implicitly incorporated in this method via an iterative procedure. The end facet can be uncoated or coated with an arbitrary number of layers. The waveguide can also be incident normally to the facet or at an angle. The method can be presented for both the TE and TM polarizations.

1 INTRODUCTION

There is increasing interest in accurately calculating facet reflectivity for many devices in optoelectronics such as semiconductor optical amplifiers, lasers, couplers and switches. Moreover, reducing facet reflectivity is of vital interest for the proper function of many devices. Very low facet reflectivity ($< 10^{-4}$) is principal for achieving high gain (~ 30 dB) and good bandwidth (3-4 GHz) for coupling passive or active semiconductor waveguides and circuits to a fibre. There are several different ways for reducing facet reflectivity: terminating the wave- guide with the low refractive index waveguide region, [1], adding multilayered antireflection (AR) coatings at the end of the facet [2], or by angling the incidence of a guide on the facet [3]. However, accurate calculation of very low facet reflectivity ($\sim 10^{-4}$) requires consideration of several different factors such as: 2D nature of the waveguide; polarisation of the field; multilayered AR coatings, case of angled or tilted waveguides.

Well known numerical methods, such as the Finite Differences and Beam Propagation methods have the difficulty of avoiding non-physical reflections from the artificial open boundaries imposed around the problem space especially when facet reflectivity of order $< 10^{-4}$ are considered. [4].

In the following section a theory for the HSRM method for the slab waveguides is described. This method can be used also for 2D waveguides including the effects of the air-semiconductor plane and 3D semiconductor corner on the facet reflectivity and coatings in the facet plane and incidence of the guide at an angle to the facet.

2 HALF SPACE RADIATION MODE METHOD FOR FACET ANALYSIS

The HSRM method exploits two approximations. The first approximation models the penetration of the optical field into the air above the waveguide, by introducing the concept of a displaced boundary [5]. That means, that the original horizontal air-semiconductor boundary is displaced by a small distance in order to be $E = 0$ on it. The penetration depth depends upon the orientation of the principal field component on the air-semiconductor boundary and is different for the case of TE and TM polarisation. These penetration depths for the TE and TM polarisation are expressed as

$$\Delta_{TE} = \Delta_t = 1/\sqrt{\beta^2 - k_0^2}\,, \qquad \Delta_{TM} = \Delta_n = \sqrt{(n_0/n_2)^2/(\beta^2 - k_0^2)}\,. \qquad (1)$$

Here β is the slab mode propagation constant, $k_0 = 2\pi/\lambda$, where λ is the free space wavelength and n_0, n_1 and n_2 are the refractive indices of air, core and cladding, respectively.

The second approximation regards the radiation modes which are assumed to propagate through a medium of uniform refractive index, which restricts the range of applicability to waveguides with low refractive contrast. Longitudinal index contrasts in the transverse plane are unlimited.

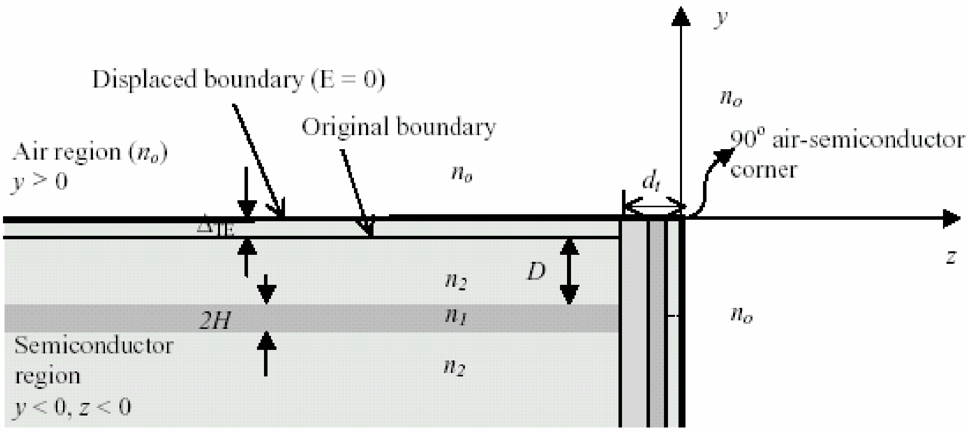

Fig. 1: *Waveguide facet in proximity to the semiconductor-air interface*

An analysis of the problem in Fourier space would thus normally involve different spectral variables on both sides of the facet, and hence convolution integrals on applying field boundary conditions on the facet plane $z = 0$. Evaluation of such integrals would significantly degrade the efficiency of the procedure, which is a feature of the FSRM method. To preserve the simplicity and the speed of the method, a new iterative solution approach is presented for facet analysis of slab waveguides.

Its core of thickness $2H$ is buried at a depth D below the air-semiconductor boundary. The facet can be a simple semiconductor to air facet or coated with an arbitrary number of layers. The configuration under consideration is two dimensional, in the sense that there is no variation in the x direction. The origin of the coordinate system is placed on the facet, as indicated in Fig.2.

The method is based on the HSRM method in which the field in the region $z < 0$, $y < 0$, Fig.2, is described as a summation of the incident and reflected slab guided modes and a radiation field $F(y,z)$, where this radiation field is allowed to propagate freely in a uniform half space $y < 0$. To account for the penetration of the radiation field into the air ($z < 0$, $y > 0$)

the new air-semiconductor interface is formed by extending the semiconductor to a fictitious surface just inside the air region ($y = \Delta_{TE}$) upon which the field is set to zero [6].

3 COATED WAVEGUIDE FACET

As discussed at the introduction the reflectivity can be reduced by using AR coatings.

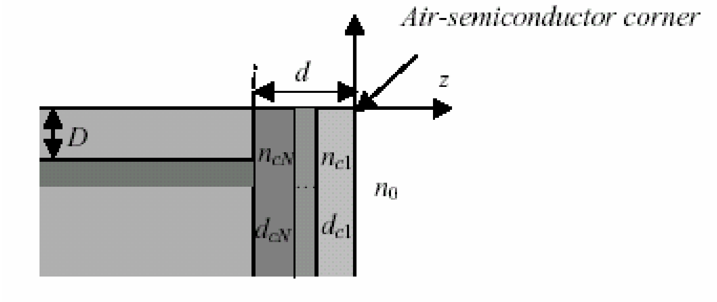

Fig. 2: *Schematic presentation of waveguide facet coated with* N *AR coatings*

In the case of an *N* layered AR coating at the end of the facet is considered, (Figs.3, 4). They are labelled from 1 to *N,* (air labelled zero). The refractive index and thickness of the *i*th coating layer are n_{ci} and d_{ci} respectively. The starting solution for the facet reflectivity is obtained by matching fields at the plane $z = - d$, (d is the total thickness of the AR coatings), where the admittance and impedance is the response function of the air and coatings, and is obtained using the recurrence relationship. The iterative procedure can be explained for the case of the TE polarisation or/and the TM polarisation.

The field just inside the buried waveguide can be found in the first step using the field, which is propagated to the plane $z = 0$ by use of the conventional ABCD matrix, (which relates voltages and currents), on different ends of the line and in the second one for the case of *N* cascaded transmission lines: the overall ABCD matrix is found by multiplication of ABCD matrices of each individual line.

4 RESULTS

In this section results for the facet reflectivity of a waveguide normally incident on a facet are presented in two parts, covering uncoated and coated facet respectively. A maximum of two AR coatings are considered. The effect of the air-semiconductor boundary and the diffractive corner is examined for waveguides with different refractive index contrasts and different thicknesses. Field profiles for shallowly buried waveguides with uncoated and coated facets are also given.

4.1 UNCOATED FACET

The set of structures analysed have core refractive index $n_1 = 3.6$ and cladding index given by $n_2 = n_1(1 - p/100)$, where p is the percentage difference from n_1. The operating wavelength is $\lambda = 0.86$ µm. Fig.3 shows that decreasing the buried depth generally increases the reflectivity and that the change is more drastic in case of weakly guiding structure (p = 3%, Fig.3a). In the case of the TE polarisation for the index contrast p=10 %, the curves for D = 0.5 µm and $D \to \infty$ overlap (Fig.3b), which clearly indicates that above a certain depth, D = 0.5 µm in this case, the effect of the air-semiconductor boundary and the diffracting corner disappears.

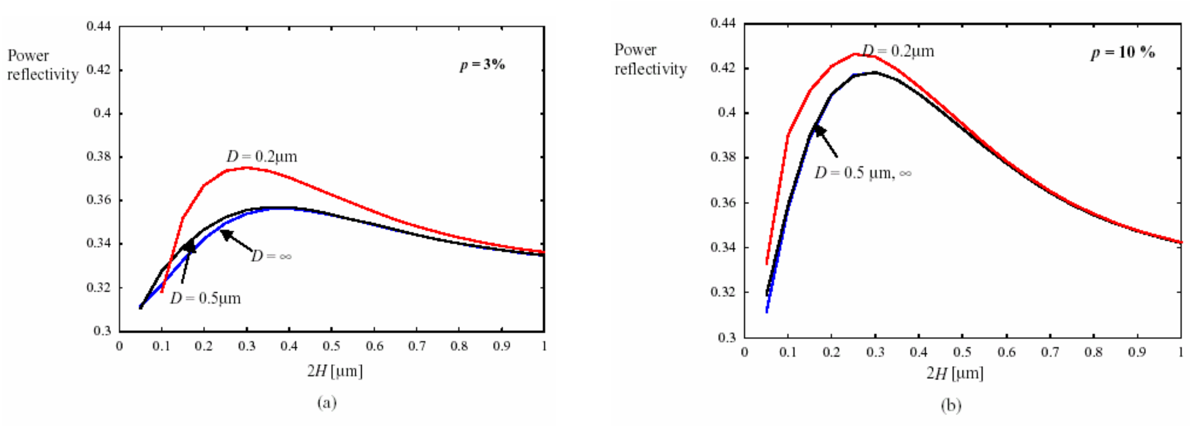

Fig. 3: *The TE power reflectivity vs. slab width for* D = *0.2 μm, 0.5 μm,* D → ∞*. The waveguide core refractive index* n_1*=3.6 and the index contrast a)* p = *3 % and b)* p = *10 %. The operating wavelength is* $\lambda = 0.86$ *μm.*

4.2 COATED FACET

The reflectivity can be reduced by using AR coatings. The illustrative example of a coated facet studied is the case of the facet with one AR coating of refractive index $n_{c1} = \sqrt{\beta / k_0}$. The waveguide is the same as in previous case. The refractive index and thickness of a single AR coating are $n_{c1} = \sqrt{\beta / k_0}$ and $d_{c1} = \lambda / 4 n_{c1}$, respectively. In order to distinguish between small reflectivities, the results are plotted with a logarithmic scale on the reflectivity axis. Comparing the results in Fig.4 with the results for the uncoated facet (Fig.3) it can be seen that the reflectivity of a coated facet changes much more and is more sensitive to the presence of the air-semiconductor boundary and diffracting corner. In the case of the coated facet, structures with smaller index difference (p = 3 %) are shown to be more sensitive to the proximity of the air-semiconductor boundary.

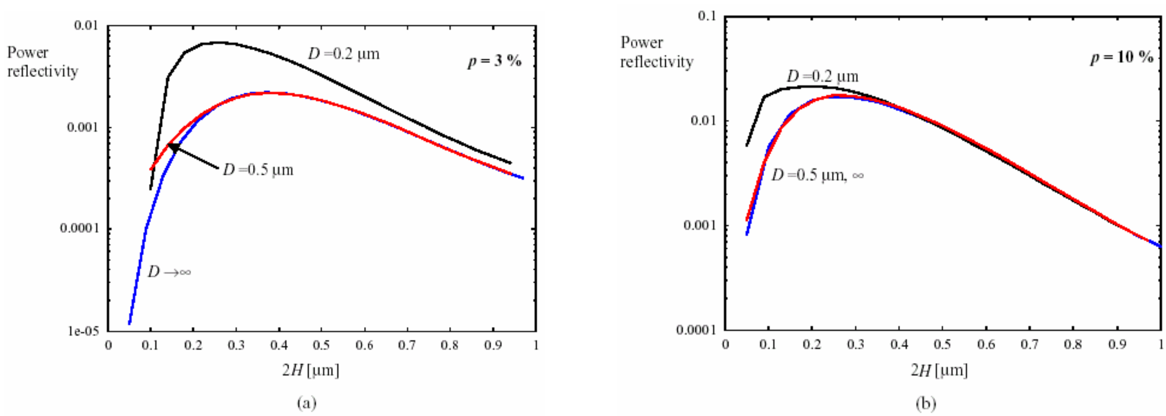

Fig. 4: *The TE power reflectivity of the coated facet vs. slab width for* D = *0.2 μm, 0.5 μm and* D → ∞*, for the index contrast of: a)* p = *3 % and b)* p=*10 %. The waveguide has core refractive index* n_1*=3.6 and the operating wavelength* λ = *0.86 μm.*

5 CONCLUSION

The HSRM method has been applied to the analysis of facet reflectivity of 2D waveguides in the presence of an air-semiconductor boundary and a diffractive corner. The power reflectivities of typical waveguide structures have been analysed for both uncoated and coated facets. In the case of a 1D waveguide normally incident on an uncoated facet, the air-semiconductor boundary has stronger impact on weakly confined fields (small slab thickness H) for both the TE and TM polarisations. The effect is also stronger for smaller buried depth D, but there is a certain depth for each polarisation after which the reflectivity equals that of a deeply buried guide ($D \to \infty$). This depth is smaller for the TE than for the TM polarisation, so that TM polarisation is more susceptible to the presence of the air-boundary.

Similar behaviour is noticed in the case of coated facets, but the presence of the air-semiconductor boundary and the diffractive corner now have much stronger effect on the modal reflectivity and field profiles. It also can be concluded that structures with smaller index contrasts are more susceptible to the presence of the air-semiconductor boundary, for both polarisations.

The novel HSRM method for the waveguide facet reflectivity analysis is very efficient and converges to solution only after a few iterations. For all results presented it was never necessary to use more than six iterations to achieve convergence to a final reflectivity with a high precision for waveguides. Calculation time for the facet reflectivity waveguide takes only seconds on a 600 MHz Pentium PC. When the waveguide facet is coated the analysis requires more iterations and hence slightly longer computation time then in the case of uncoated waveguide facet.

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REFERENCES

[1] Cha, M., Kitamura, H., Mito Honmou, I.: 1.5 m band travelling wave

[2] semiconductor optical amplifiers with window facet structure, Electron. Lett., 1989, vol. 25, No. 7, p. 1241-1242.

[3] Hubner, J., Zauner, D., Kristensen, M.: Strong sampled Bragg gratings for WDM applications, IEEE Photon. Technol. Lett., 1998, vol. 10, No. 4, p. 552- 556.

[4] Kuznetsova, T. I., Lebedev, V. S.: Concentration of light energy within a cone with a metal coating, Quantum Electron., 2003, vol. 33, No. 10, p. 931-937.

[5] Yamauchi, J., Mita, M., Aoki, S., Nakano, H.: Analysis of antireflection coatings using the FD-TD method with the PML absorbing boundary condition, IEEE Photon. Techn. Let , 1996, vol. 8, No. 2, p. 239-241.

[6] Košťálová, D., Dobis, P., Tománek, P.: Singular spectral index method for the local analysis of rib waveguide, In Frollo, I., Tyšler, M., Plačková, A. (Eds), Measurement 2003, 395-398, Slovak Acad. Sci Bratislava, 2003, ISBN 80-967402-6-1.

[7] Visser, T. D., Demeulenaere, B., Haes, J., Lenstra, D., Baets, R., Blok, H.: Confinement and modal gain in dielectric waveguides, IEEE J. of Lightwave Technol., 1996, vol. 14, No.5, p.885-887.