Semi-Analytic Models for Photonic Circuits

T. M. Benson, A. Vukovic, P. Sewell

Abstract - **In this paper we review a suite of highly accurate, yet extremely efficient, simulation techniques based upon semi-analytical approaches that we have successfully developed. In these approaches, physically appropriate approximations are made that significantly simplify the analyses, without compromising accuracy. Up to date applications of the techniques in photonic circuits analysis, synthesis and as a part of hybrid numerical: semi-analytic design tools are discussed.**

Keywords - **Photonic circuits, modelling methods**

I. INTRODUCTION

Computer simulations are now firmly established as an integral part of the design cycle amongst the photonics community. Both researchers of completely novel device concepts as well industrial engineers developing commercial products, recognise that an accurate and efficient simulation capability has a substantial impact on performance, development costs and the time to market. Over the years, many methods have been proposed and exploited for modelling the optical behaviour of photonics devices, although a number of commonly occurring limitations are encountered in practice. Foremost amongst these is computational intensity, which either restricts the accuracy that can be achieved or else the complexity of the geometry that can be dealt with. This causes severe problems when designers need to consider the behaviour of a particular device within a sub-system, especially when stringent performance specifications mean that the subtle characteristics of the device must be taken into account. Furthermore, systematic, or preferably automated, optimisation of components becomes highly unwieldy. To address this situation, we have successfully developed a suite of highly accurate, yet extremely efficient, simulation techniques based upon semi-analytical approaches. In these approaches, physically appropriate approximations are made that significantly simplify the analysis, without compromising the utility of the results. For example, the Free Space Radiation Mode (FSRM) method [1-3] applies when transverse index contrasts are less than 10% (with no restriction on longitudinal index contrasts), the Spectral Index (SI) [4] and Half Space Radiation Mode (HSRM) methods [5-8] to configurations with an upper medium of air. Within the remit of these physical approximations the semi-analytical analyses embrace general problems (including those involving loss, gain, radiation and reflections) and have consistently provided extraordinary speed and accuracy advantages over alternative approaches or unique solutions.

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II. THE EFFECTIVE INDEX METHOD

The internal refractive index of many photonic structures may be assumed to be of low contrast. In the specific case of III-V semiconductor devices this would imply that the interface with air is taken to lie at a sufficiently large distance from the waveguide core that its influence may be ignored. The scalar wave equation

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + (k^2 - \beta^2)E = 0 \qquad (1)$$

is then a good first approximation. Here E is the electric field with E and its spatial derivatives assumed continuous everywhere, $k = k_o\, n(x,y)$ with n(x,y) the refractive index profile in the cross section and k_o the free space wave-number. Propagation is for present purposes assumed to be along a z-invariant waveguide with propagation constant β. The simplification to (1) is very attractive and, if k(x,y) varies slowly along the x axis, say, then the well known approximate Effective Index solution can be found through a function G(x,y) which, for each x, satisfies a local 1D (slab) equation

$$\frac{\partial^2 G}{\partial y^2} + (k^2 - \beta_x^2)G = 0 \qquad (2)$$

with a local propagation constant β_x. Both G(x, y) and β_x are assumed to vary slowly with x so that we can nearly separate the variables with

$$E = F(x)\, G(x, y) \qquad (3)$$

and

$$\frac{\partial^2 F}{\partial x^2} + (\beta_x^2 - \beta^2)F = 0 \qquad (4)$$

Equation (4) is one-dimensional and can be used to find the approximate propagation constant β for any slowly varying configuration. Thus the Effective Index method has enabled us to reduce the 2D problem defined by (1) to two 2D ones given by (2) and (4).

In this Special Session of TELSIKS celebrating the 70th birthday of Professor Aleksandar Marinčić, it is worth noting that the Effective Index method was used by one of the authors (TB), Marinčić and co-workers in the very successful development of a short focus microwave horn antenna based upon a graded 1D refractive medium of hyperbolic secant type [10-11]. In this work the graded effective refractive index profile was obtained by varying the plate separation of a planar waveguide supporting the TE_{01} mode. Horns fabricated with both smooth and discretised effective index profiles were characterised experimentally. This same concept has been recently used and developed further by the present authors and others at Nottingham in the design of a 980 nm short-cavity high-brightness, laterally graded-index (GRIN) laser diode with distributed phase correction [12]. The laser consists of a feed waveguide section coupled to a GRIN waveguide region with a discretised hyperbolic-secant index profile. Detailed wide-angle two-dimensional finite-difference beam propagation method (FD-BPM) simulations, based on an effective index reduction of the structure, predict that this lateral laser will exhibit significant performance improvements over comparable tapered lasers. In particular, in spite of its short cavity length of ~1000 µm (i.e., 300µm feed waveguide plus a 700µm power amplifier section), the GRIN laser is expected to have a considerably flatter output phase front, significantly lower beam divergence and better beam quality parameter M^2 than comparable tapered lasers with taper lengths over 2000 µm. Thus, the GRIN laser is expected to exhibit extremely good beam quality with a nearly diffraction-limited Gaussian beam, which can be focused to a small, high-power, high-brightness spot using simple optics. The GRIN laser's low output divergence angle is expected to permit the independent optical manipulation of the individual beams, while permitting an acceptable bar filling factor.

Notwithstanding the success of the Effective Index method in this and other contexts, modern photonic components such as the arrayed waveguide grating (AWG) are highly sensitive to many subtle phenomena (e.g. attenuation, phase, cross-coupling, polarisation rotation, radiation), which must be accurately modelled to predict their behaviour. It almost goes without saying that models such as the Effective Index method, which reduce the dimensionality of the problem, are inadequate for the advanced design of such components. The cutting-edge need for robust 3D tools is contrary to the fact that the relative computational simplicity of reduced dimensionality approaches mean that they still tend to dominate the published literature.

III. The Spectral Index (SI) Method

The Spectral Index (SI) method is a fast and accurate semi-analytic technique introduced in 1989 to analyse multiple layered air-clad rib and ridge waveguides, in particular those formed from planar semiconductor substrates [4]. The method relies on the low refractive index of the air cladding in comparison to those of the (semiconductor) guiding layers. It takes advantage of the high index contrast by approximating the open waveguide system by one that is completely enclosed by a surface defined as a small displacement of the the air/semiconductor boundary, as shown in Figure 1. The displacements $\Delta_{t,n}$ are

$$\Delta_t = 1/\sqrt{\beta^2 - k_o^2 n_1^2}\ , \quad \Delta_n = \left(\frac{n_1}{n_2}\right)^2 \Delta_t \qquad (5)$$

for electric field components tangential (t) and normal (n) to the air interface. These expressions involve the value of β being sought and which may be updated in an iterative manner. However, for the study of semiconductor rib waveguides in air n_3k_o or n_2k_o may be substituted for β in these expressions with negligible error. The method then proceeds by finding a simple solution to the wave equation inside the rib, finding a Fourier transform of the solution in the layered region under the rib and matching the two solutions using a variational principle. In this way the cross-sectional analysis of a z-invariant waveguide is reduced to the solution of a transcendental equation.

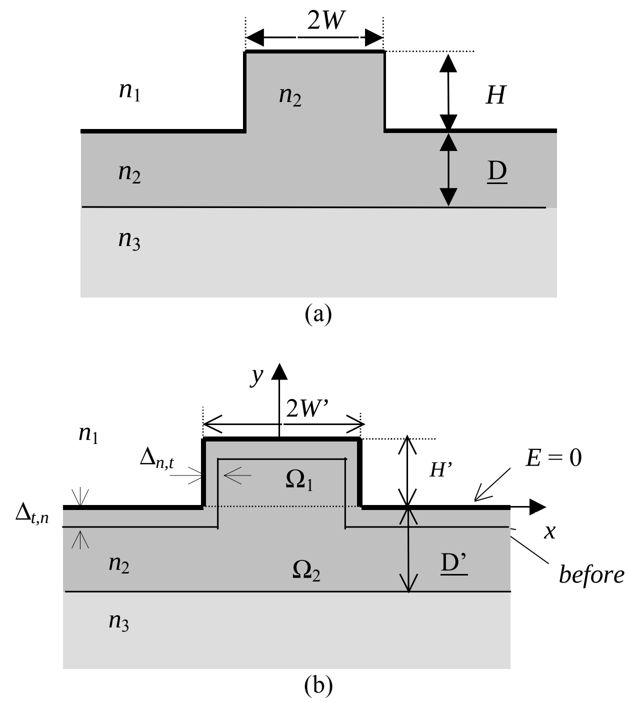


Fig.1 (a) The dimensions and refractive index distribution of a simple rib waveguide cross-section, (b) The SI representation where the position of the rib is moved outwards to a new position on which $E = 0$.

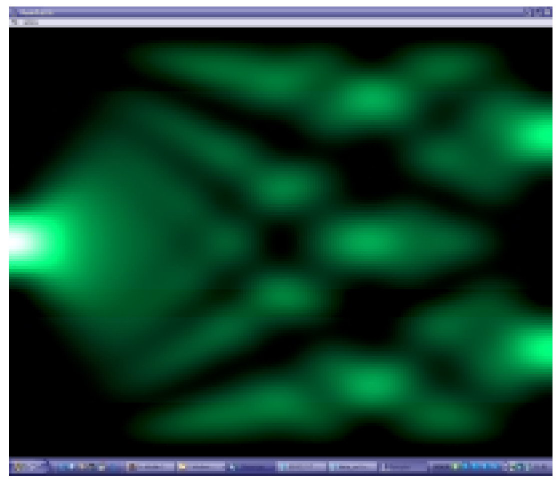
Subsequent developments have included an SI analysis of a mode spot size converter in which an air-clad tapered rib sits on a mesa having a constant wider width. Multiple expansions terms were included in the rib and mesa regions and careful consideration given to the coupling between the top and bottom of the large area mesa in terms of accessible modes, to provide a numerically robust algorithm. An additional feature of these geometries is that the outer slab section formed by the mesa typically permits many slab modes to propagate. This means that all modes of the total cross section are leaky in nature and it is the extent of this leakage that determines the apparent single mode behaviour of the coupler. Thus, slab mode leakage effects were taken into account in the method, a highly important feature given that enhanced transmission efficiency is the motivation for mode spot converters. The large mode profile supported by the large rib section of this device made its analysis by a numerical FD technique extremely laborious whereas the new method was able to produce accurate design curves in seconds on a PC. A further application of the SI method is the simulation of optical detectors based upon pillbox resonators directly fed by a rib waveguide, [13]. In this work, a novel SI algorithm in cylindrical coordinates was developed to characterise the high Q whispering gallery modes of the resonators. Again, the algorithm proved extremely accurate and incredibly fast. Excellent agreement was obtained with results from both FD and full wave vectorial integral equation approaches. Finally, since optical detectors often have sloped walls to improve their electrical characteristics, we developed an SI technique for the case of sloped walled ribs, which was then extended to arbitrary profiles, [14].

A. SI Propagation

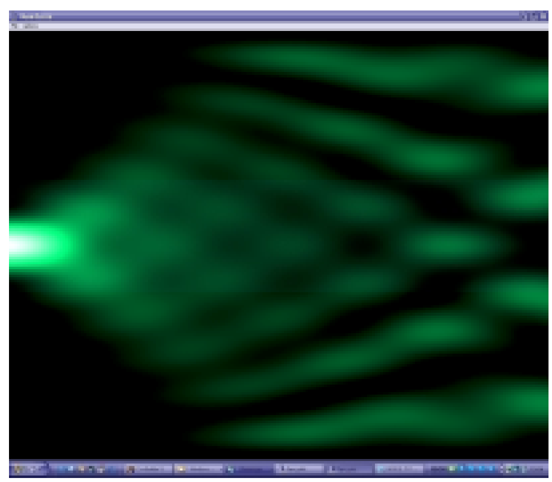
An SI approach to simulating air-clad rib waveguide circuits, including the effect of facets was developed in [15]. In this approach, the SI method is applied in the full 2D plane separating the rib from the underlying substrate to yield a full 3D analysis. The usual SI approximations of neglecting radiation through air-semiconductor interfaces and accounting for the evanescent penetration by slightly displacing the interfaces are made. This provides a simple integral equation, relating all fields to those at the base of the ribProjecting the latter onto a numerically robust basis set; the transverse behaviour of the local guided mode and overlapping piecewise constant terms along the axis of the local guide, again yields a very rapid algorithm. The algorithm features truly piecewise linear models of tapered rib geometries and it was shown that the size of the linear equation set that is necessary to solve is very small compared to a numerical approach such as FD-BPM. Typically, a discretisation length along the axis of a tapered GaAs rib waveguide of 10µm gave comparable accuracy to FD-BPM using steps of 1µm. Importantly, the algorithm is not only fast, but does not demand the large quantities of memory used for 3D FD-BPM.

B. SI Based Circuit Analysis

Coupling between optical components takes place via guided modes and radiation modes. The optical components may be considered as individual blocks connected to each other at well-defined ports. The complete circuit may then be described by an S-matrix approach [16]. Essential to the development of the S-matrix is the accurate calculation of the modal propagation constants of the optical circuit's constituent blocks. The SI method is well suited to this task when dealing with polarized modes in semiconductor rib waveguides. The method accounts for both substrate radiation as well as the slab mode leakage. The sufficiently complete leaky mode spectrum of the resulting waveguide system can then be obtained to high accuracy in a matter of seconds. Once the properties of each block have been calculated they are joined using a scattering matrix, allowing a relatively simple representation of a complex circuit. Such circuits may have high aspect ratios, i.e. microns wide and millimetres in length and would prove prohibitive for 3D numerical methods, such as the FD-BPM, for which discretisation of the problem space would require significant computational resources. Conventional mode matching would never succeed in this task as identifying the true modes of all the rib guides would be unreliable and incredibly slow. We successfully validated the SI approach by comparing extinction ratios, transmission losses and field profiles of RF modulators based on this geometry with experiments. The agreement was excellent. Given that these devices are several centimetres long this really proves the strength of our techniques, [17]. Figure 2 presents some illustrative results for (a) 1 x 2 and (b) 1 x 4 multi-mode interference splitters formed using deeply etched GaAs/GaAlAs rib waveguides. The single mode input and output waveguides are of width 4.4µm. In (a) the multi-mode region is 17.6µm wide and 502µm long. In (b) this region is 26.4µm wide and 564.5µm long. The operating wavelength is 1.064µm.



(a)



(b)

Fig. 2 Illustrative results from a 3D SI simulation of (a) a 1x2 and (b) a 1x4 MMI splitter. The single mode input waveguide is on the left and the output waveguides on the right.

IV. The Free and Half Space Radiation Mode Methods

A. The Free Space Radiation Mode Method (FSRM)

The essence of the important Free Space Radiation Mode (FSRM) method is that the guided modes are treated rigorously but that the radiation modes are assumed to propagate in a uniform medium. The approximation is, as expected, more reliable when studying structures of low transverse refractive index contrast. The method was first established to solve facet reflectivity problems and subsequently extended to the analysis of dielectric waveguide discontinuities and propagation in 3D structures. As we have seen, propagation methods are in constant demand for the modelling of photonic components such as tapers and interacting step discontinuities. Unlike beam propagation methods, (BPMs), the FSRM method intrinsically incorporates continuous reflections and is inherently wide-angled in nature. Strictly speaking, BPM formulations should only be applied with confidence to structures where index variations in the propagation direction are small, although the flexibility of these methods makes them popular with designers who then ignore the constraints. A key feature of the FSRM method is that the analysis is unbounded and deals naturally with radiation, i.e. there is no need to impose artificial boundary conditions. FSRM studies have been reported for a range of practical structures [18], including a dual waveguide buried InP-based spot size converter [19]. In this device the dimensions of the upper waveguide correspond to those of the integrated device, for example a laser or optical amplifier, whilst those of the lower waveguide are chosen so that the fundamental mode it supports closely resembles the optical field profile of the fibre. The width of one of the waveguides is varied so as to force light to transfer from one guide to the other. Once again the 3D FSRM simulations were extremely efficient, particularly as it was found that long longitudinal step sizes could be used. Thus a full 3D analysis of this complicated structure can be readily performed on a PC, taking full account of reflections.

We have recently developed a fully vectorial FSRM algorithm for optical fibres, making extensive efforts to maximise the efficiency by deriving closed form expressions for numerical integrals wherever possible, [20]. Finally, we have also used FSRM to model periodic waveguide structures, recent work here being the analysis of gratings in optical fibres [21]. The large dimensions of periodic structures, particularly in the longitudinal directions where the number of periods can be as large as 10000, once again preclude their efficient study using purely numerical methods.

B. The Half Space Radiation Mode Method (HSRM)

The FSRM method is accurate only for those configurations of planar technology in which the refractive index changes are small in directions orthogonal to the direction of propagation. In cases where such small index changes occur in a semiconductor but in the presence of the horizontal air/semiconductor planar interface, we might consider taking a horizontal Fourier Transform (FT), as in the SI method. However, it is simpler, and much faster computationally, to reduce the number of intermediate interfaces by choosing the most favourable direction for the FT. For a symmetric waveguide of rectangular cross-section, buried at a distance below an air/semiconductor interface, the simplest FT direction is vertical. Using the symmetry or antisymmetry of solutions, only one vertical discontinuity is encountered. Therefore the HSRM approach was developed by (1) moving the air semiconductor interface upwards into the air by the Goos-Hanchen penetration depth, (2) applying the boundary condition $E = 0$ there, (3) taking the Fourier sine transform in the vertical direction with the moved upper interface as origin, (4) using the FSRM method by propagating the guided mode or modes and Free Space Radiation Modes horizontally, (5) forming the transcendental equation for the waveguide propagation constants by using the orthogonality of the guided mode to the assembly of all radiation modes and then (6) solving the transcendental equation. This procedure is simple to carry out in practice. A cross-sectional HSRM analysis for buried waveguides was first developed and scalar and polarised mode solutions were reported in [7]. It was shown that the HSRM method gave excellent agreement with benchmark numerical results for both propagation constant and field profile. The HSRM method maintains all the speed and memory advantages of the FSRM method. The HSRM technique was then developed for facet reflectivity analysis, driven by the knowledge that, although the output waveguide of a spot size converter is a buried one, the burial may be shallow because of design or manufacturing (re-growth) cost constraints. The presence of the semiconductor-air diffracting corner was shown to be particularly influential when the facet was anti-reflection (AR) coated. Indeed the presence of this corner can change reflectivity to such an extent that an AR coating designed for an infinitely buried waveguide may not in fact meet systems requirements. Because the 2D geometry of the waveguide and the presence of the semiconductor-air corner are both highly significant, considerable effort was expended to implement an analysis of a HSRM facet for 2D waveguides and applied to the design of AR coatings for SOAs [22]. This facet work was later extended to a 3D HSRM propagation method.

V. Combined Spectral Methods

Consider a mode spot-size converter based on a semiconductor rib waveguide in air coupled to a buried waveguide. A novel spectral method combining the SI and FSRM methods is needed to analyse this type of problem. Although each method is useful in its own right neither can be used on its own to model the composite spot-size converter structure. A new approach is needed which uses the SI method to develop an expression for the field in the rib waveguide region and the FSRM method to develop an expression for the field in the buried waveguide region under the rib. These two expressions may then be linked using a variational principle. This approach yields a system of equations, the non-trivial solutions to which yield the propagation constants of the modes of the composite structure. The method proved relatively simple to implement, as both SI and FSRM methods are spectral in nature, and yielded results for field profiles and propagation constant in excellent agreement with benchmark numerical solutions, [23]. The theoretical basis of the novel method together with design curves for a typical air-semiconductor mode spot-size converting taper were presented in [24].

VI. Combinations of Spectral and Numerical Methods

There are certain configurations where the complexity of the structure precludes the development of semi-analytical techniques. Moreover, the size and complexity of modern photonic integrated circuits and the high accuracy required of simulations place great demands on computational resource when using purely numerical methods. Whilst increasing computer power will increase the application of numerical methods to such complex problems a combination of semi-analytical and numerical methods in hybrid tools seems a very attractive way forward. A good example is that the coupling of air-clad rib waveguides to optical fibres. FDTD and fully reflective wide angled FDBPM are not only very intensive, but investigating designs specifying facet reflections <-50dB with FDTD places immense pressure on accurate PMLs to terminate the simulation space. A hybrid technique is therefore most appropriate. In this, FSRM is employed to model the fields in the fibre and this is self-consistently coupled with a 3D FD-BPM model of the fields in the rib. An iterative approach can be used to perform the required linking of these diverse methods, [25]. This is important as it shows that FSRM can be applied as part of a simulation based upon the philosophy of using the most appropriate technique for each part of the circuit. This work was completely validated against full mode matching in 2D and was rigorously developed in 3D where virtually no other technique can compete. Figure 3 compares various results obtained for the power transmission into a single mode fibre from a silicon-on-insulator rib waveguide fabricated from a silicon layer of thickness 10μm, etched to give a rib height of 6μm. The fibre has core and cladding indices of 1.4516 and 1,4473 and a core diameter of 8.7μm. The operating wavelength is 1.55μm and the waveguide width W is used as the variable parameter. It can be seen from the figure that a 2D version of the present hybrid method gives results in excellent agreement with ‘benchmark’ mode matching results. However, the 2D results in general differ noticeably from 3D ones, indicating that a 2D approximation is not sufficiently accurate in this case. Furthermore an overlap calculation does not take into account all the coupling mechanisms and overestimates the actual transmission. Results obtained are in good agreement with experimental observations, [25].

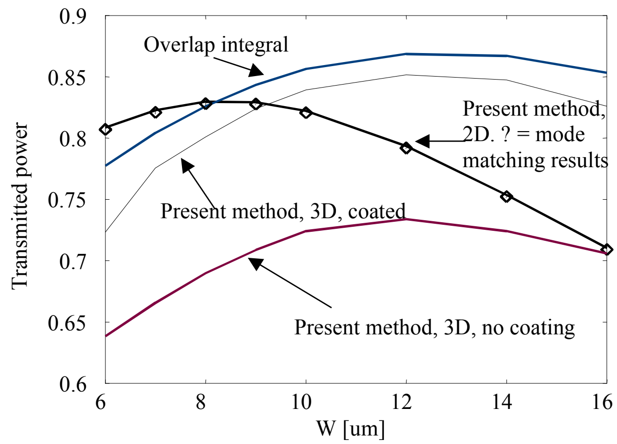
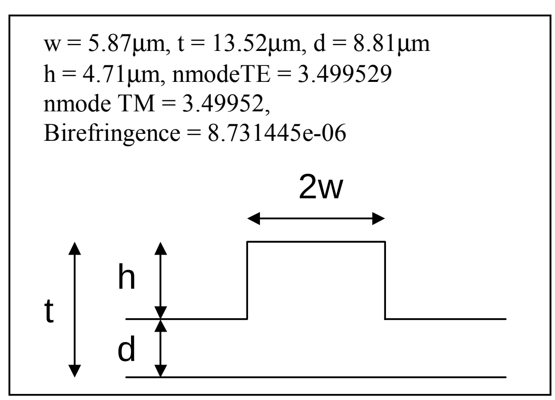


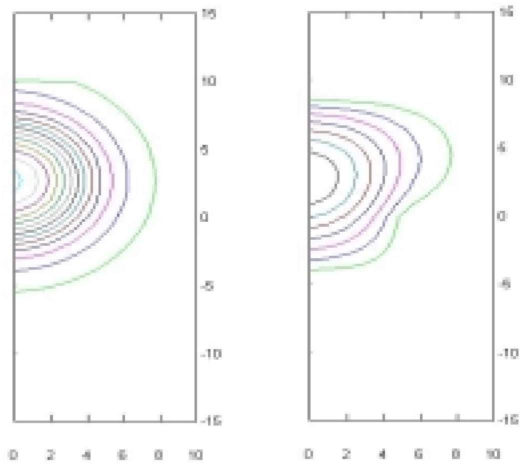
Fig. 3 Power transmission between a single mode fibre and SOI waveguides of different widths calculated using a 2D FSRM-FD: BPM hybrid method, a 2D mode matching method, a 3D FSRM: FD-BPM hybrid method and as an overlap integral between fibre and rib waveguide modes.

VII. Synthesis and Optimization

Besides conventional design investigations the computational efficiency and robustness of the semi-analytic methods lends themselves to use within an automated design optimisation context [26]. To this end we have been developing at Nottingham an exciting combination of genetic algorithms, fast optimisers and a control strategy that allows adaptive use of different simulation techniques to provide truly optimal solutions in the minimum time. This has already yielded optimal birefringent waveguide designs using SI, which are also optimised for coupling with fibres, [27]. Figure 4 illustrates this for a silicon-on-insulator rib waveguides whose dimensions are optimised to couple into a single mode fibre. The coupling loss, quantified as the overlap integral between fibre and rib modes in this example, is required to be insensitive to vertical misalignment. When aligned the calculated loss is 0.134 dB. The coupling loss increases by 0.863 dB when the guide is moved up by 2μm and by 0.206dB when it is moved down by a similar amount. Presently, optimised taper profiles are being investigated.



(a)



(b)

Fig 4. Schematic of: (a) an SOI rib waveguide whose geometry is adjusted to obtain optimum coupling to an optical fibre together with field profiles of fibre, and (b) optimised rib. Dimensions are in μm.

VIII. CONCLUSIONS

The application of the Effective Index method in previous work by one of the authors (TB) and Professor Aleksandar Marinčić in the development of a short focus microwave horn antenna was briefly reviewed, together with the recent use of this concept in the design of a 980 nm short-cavity high-brightness, laterally graded-index (GRIN) laser diode with distributed phase correction. The accurate, and extremely efficient, Spectral Index, Free Space Radiation Mode and Half Space Radiation Mode methods were then discussed. Finally, recent applications of these techniques in photonic circuit design, analysis, synthesis and optimisation and as a part of hybrid numerical: semi-analytic design tools were discussed.

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