Resonance characteristics of rib-type slot waveguides

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Abstract - *We numerically investigate the lateral leakage behavior of horizontal rib-type slot waveguides at $\lambda = 1.55\mu m$. We focus on resonance effects, which can be exploited to achieve waveguide structures ensuring high power confinement in the slot and low loss operation at the same time.*

Introduction

While the horizontal wire-type slot waveguide structure [1, 2] offers several important advantages over the vertical structure [3] such as better layer thickness control, smoother interfaces and larger waveguide width-to-height ratios, it lacks the possibilities of electric wiring and self-suspension. Horizontal rib-type slot waveguides (see Fig. 1 (a)) offer these features but can suffer from lateral leakage loss due to TM-TE mode conversion [4, 5, 6]. This lateral leakage can be effectively suppressed by taking advantage of resonance effects occurring for certain rib widths. The wire/slab-type slot waveguide shown in Fig. 1 (b) is another interesting structure. It could offer better lateral confinement compared to the rib type and therefore would be particularly attractive for waveguide sections in active photonic devices where no direct electrical wiring is necessary. However, also for this structure lateral leakage is a critical issue. In this study, we investigate the resonance characteristics of rib-type and wire/slab-type slot waveguides in detail employing the variable mode-matching (VMM) method [7].

The lateral leakage & resonance effect

Lateral leakage in rib-type structures occurs due to coupling of the minor TE field components of a TM-like rib mode to a TE slab mode outside the rib that has a higher effective index than the TM-like rib mode [4, 5]. In principle, the slot waveguide structure supports two first order modes for each polarization, an even and an odd one [8]. The highly

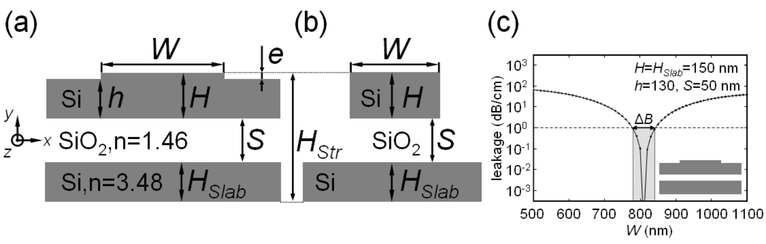

Figure 1: Cross sections of (a) rib-type and (b) wire/slab-type slot waveguide structures. (c) Typical width dependent resonance behavior of a rib-type slot waveguide; ΔB defines the range of width within which lateral leakage losses are below 1 dB/cm.

confined slot mode corresponds to the TM-polarized even mode.

Except for vertical fully symmetric systems, coupling to both the even and odd TE slab mode takes place [6]. The coupling to the even TE slab mode is always more critical because it has a higher effective index than the odd TE slab mode. For all rib-type slot waveguide structures this coupling can be avoided by decreasing the effective index of both TE slab modes below that of the TM rib mode, which is achieved by choosing a geometry with $H \gg H_{\mathrm{Slab}}$. Unfortunately, this measure leads to a severe reduction of the maximum power confined in the slot to well below 20% [9].

By exploiting resonance effects for otherwise leaky geometries, low loss operation becomes possible without sacrificing optical power confinement in the slot. These resonance effects are related to TE waves generated through mode-conversion of the TM rib mode at the rib side walls. While one part of these TE waves propagates into the slab region the other part is reflected at the side wall and traverses inside the rib to the other side wall, where it interferes with newly generated TE waves. For certain rib widths (see Fig. 1 (c)) this results in a cancellation of TE waves leaking into the slab region thus suppressing the leakage loss.

Influence of imperfections

With respect to deviations of the geometry caused by fabrication processes the rib width is the most critical parameter. Thus, the width range for which leakage losses are small has to be maximized to ensure low loss operation for waveguides with slightly fluctuating width. For this purpose, we define ΔB as the width range for which losses are below 1 dB/cm (see Fig. 1 (c)) and study this parameter in dependence of the geometry parameters. The etch depth e has a major impact on ΔB as Fig. 2 (a) shows. For shallow etch depths, ΔB significantly increases and the influence of the slot thickness is small. However, for rib-type slot waveguides the applicable range of S is limited by the effective index of the odd TE slab mode outside of the rib [8]. If the effective index of the odd TE slab mode becomes higher than that of the TM-like slot mode leakage occurs again because the resonance condition can only be fulfilled for one of the two TE slab modes at the same time. In the example shown in Fig. 2 (a) this situation occurs for $e = 0.07H_{\mathrm{Str}}$ at $S \approx 70$ nm. With increasing etch depth this effect diminishes and for the slab/wire-type,

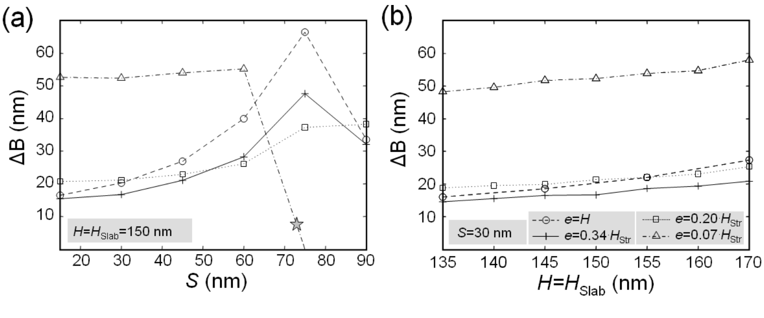

Figure 2: Dependence of ΔB on (a) the slot thickness S and on (b) the waveguide thicknesses $H = H_{\mathrm{Slab}}$ for different etch depths e. The star indicates the slot thickness where coupling to the odd TE slab mode occurs.

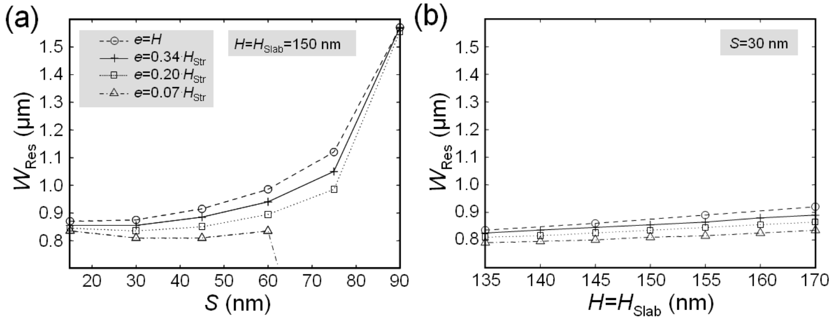

Figure 3: Width W_{Res} for which the resonance occurs as a function of (a) the slot thickness S and (b) the waveguide thickness $H = H_{\mathrm{Slab}}$ for different etch depths e.

i.e., for $e = H$ the effective index of the even and odd TE slab mode outside the rib become identical. Deeply etched structures, on the other hand, show a strong dependence of ΔB on the slot thickness. For $e = H$ the width range ΔB reaches its maximum at $S \approx 75$ nm. In contrast, the dependence of ΔB on the thicknesses H and H_{Slab} is almost negligible (see Fig. 2 (b)) while the etch depth again has a strong influence. Asymmetries in the amount of $H_{Slab} = H \pm 15$ nm do not affect the ΔB as well.

Apart from the width range ΔB also the shift of the rib width W_{Res} at which the resonance occurs is of high importance. Figure 3 (a) and (b) reveal that the slot thickness has a major impact on W_{Res} for $S > 70$ nm, whereas the influence of the waveguide thickness $H = H_{\mathrm{Slab}}$ is small.

Not only the deviating width also the variations of the other geometry parameters due to fabrication processes have to be taken into account. In order to study this influence we varied all geometry parameters, *i.e.*, H, H_{Slab}, e and S by ± 5 nm resulting in sixteen different geometries. As an example, Fig. 4 (a) shows the leakage losses of all these geometries for a structure centered at $H = H_{\mathrm{Slab}} = 135$ nm, $e = 0.081 H_{\mathrm{Str}}$ and $S = 50$ nm. The envelope of these curves (solid line) represents the maximum losses that can occur considering all possible variations. This envelope is a result of the shift of the resonant minimum W_{Res} for each geometry which leads to a reduction of the width range ΔB compared to 50 nm for a perfect system.

Next, we studied the envelope characteristic for rib-type slot waveguides with different $H = H_{\mathrm{Slab}}$, e and S (Fig. 4). As for the perfect system, also for the rib-type slot waveguides with variations the etch depth e and the slot thickness S have a major impact on the lateral leakage losses. Interestingly, smaller waveguide thicknesses H and H_{Slab} result in lower losses. For a rib-type slot waveguide with $H = H_{\mathrm{Slab}} = 135$ nm, $e = 0.081 H_{\mathrm{Str}}$ and $S = 30$ nm the width range of operation is larger than 20 nm.

Taken together, the results show that small slot thicknesses of $S < 50$ nm, shallow etch depths and thin waveguides are beneficial for maximizing ΔB. For a wire/slab system these optimizations are not sufficient and accordingly no low loss width range for geometries with variations of ± 5 nm can be obtained.

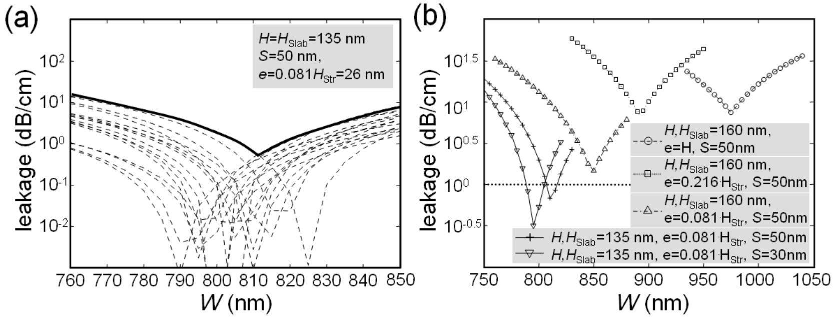

Figure 4: (a) Lateral leakage losses of a typical rib-type slot waveguide structure taking into account the variations of all geometry parameters by ± 5 nm. The envelope of these loss curves (solid line) indicates the maximum losses that can occur; (b) dependence of the maximum losses on the etch depth, waveguide thicknesses and slot thickness.

Conclusion

As our studies reveal, geometry parameters for rib-type slot waveguides can be found which ensure both low loss operation and high optical power confinement in the slot. Moreover, the results show that they can be designed to be sufficiently tolerant against variations of all geometry parameters. Therefore, rib-type slot waveguides have the potential to be utilized for applications were electric wiring or self-suspension are required without foregoing the inherent advantages of the horizontal configuration.

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