Efficient vertical coupling between a silicon waveguide and an InP-based microdisk

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***Abstract*—Vertical coupling between a silicon waveguide and an InP-based microdisk structure is investigated and optimized using 3D coupled mode theory simulations. The results are verified with 3D FDTD simulations.**

Keywords-microdisk; vertical coupling; silicon-on-insulator; CMT; FDTD

I. INTRODUCTION

Microdisks have been proven to be useful as ultra-compact high Q passive filters [1], but also several active devices have been successfully demonstrated [2]. One of the most important design parameters in these structures is the coupling between the access waveguide and the microdisk. However, optimization of the coupling efficiency is not trivial as microdisks are inherently multimode in the radial direction. In active microdisk structures this can become even worse when additional vertical modes come into play due to the increased thickness resulting from the extra layers for electrical injection. Especially in more complex configurations when multiple disks are coupled to the same waveguide, such as e.g. a microdisk based multiwavelength laser [3], it is important that the coupling is mainly into the desired mode as otherwise the performance might severely degrade. Here, we investigate the coupling between a silicon waveguide and a heterogeneously integrated InP-based microdisk laser, using both 3D CMT and 3D FDTD methods and present optimum coupling conditions.

II. THEORY AND DESIGN

The results discussed here are for 7.5 µm diameter microdisks with a height of 580 nm and a 100 nm thin slab as shown in Fig.1(a). The gap between the waveguide and the disk is 100 nm. More details about this structure can be found in [2]. Microdisks support the so-called whispering gallery modes (WGM) which propagate at the periphery of the disk cavity. The different WGMs modes can be distinguished by the number of nodes in the azimuthal, radial and vertical direction. The modes with only 1 node in both the radial and vertical direction have the highest Q factor and are therefore the modes of interest and denoted here as fundamental modes. The azimuthal mode number depends on the frequency range of interest and the diameter of the disk. Fig. 1(b-d) shows the mode profiles of a fundamental, first order radial and first order vertical mode respectively. Although, a quite high coupling efficiency can be reached for this microdisk laser structure when using standard 450 nm wide silicon waveguides and a thin bonding layer, it was experimentally found that under these conditions there will also be significant coupling to higher order disk modes. Furthermore, when the waveguide is very close to the disk, the modes in the disk might be perturbed which can result in undesired coupling between higher order disk modes. Therefore, a detailed analysis of the coupling conditions is required.

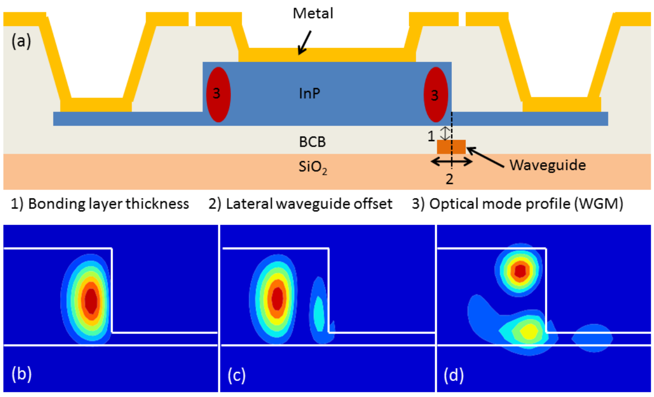

Figure 1. (a) Schematic representation of the cross-section of a microdisk laser. Modeprofile of (b) the fundamental, (c) the first order radial and (d) the first order vertical disk mode.

III. SIMULATION

Typically when simulating vertical coupling conditions between a straight and a bend structure one needs to use 3D FDTD simulations which are very intensive in terms of computational power and time. To investigate the coupling between the microdisk structure and the waveguide we made use of the 3D ring resonator module from Phoenix software [4]. This module is an add-on of their FieldDesigner mode solver and uses a 3D CMT algorithm for the analysis of coupling efficiency. An initial guess for optimal waveguide width can be made by comparing the effective indices of the fundamental mode of both the microdisk and the waveguide. Starting from this initial guess CMT simulation runs are performed where in every run the lateral offset is varied. Over the various runs, which only take up to a few minutes, waveguide dimensions and gap are swept.

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A. *Simulation results using 3D CMT method*

Fig. 2(a) shows the coupling efficiency for a 500 nm wide waveguide versus lateral offset for both the fundamental and the first order radial disk mode. It can be seen that the coupling is maximum for a negative offset of 200 nm. However, for this waveguide width the coupling to the fundamental and first order radial disk mode is in the same order, which is not desirable. In Fig. 2(b) the waveguide width is 750 nm and maximum coupling occurs at a negative offset of 300 nm. One can see that this situation is more desirable as practically all the light couples directly in the fundamental waveguide mode. However, because a 750 nm wide waveguide is already multimode, one needs to be careful that there is no significant coupling between the fundamental disk mode and the first order waveguide mode. It was found that in the case of a 750 nm wide waveguide the coupling to the first order waveguide mode is still sufficiently low. When the waveguide width is increased further the coupling to the first order waveguide mode starts to increase, while the coupling to the fundamental waveguide mode remains the same. Therefore a waveguide width of 750 nm with a 300 nm negative offset seems to be optimal in this situation.

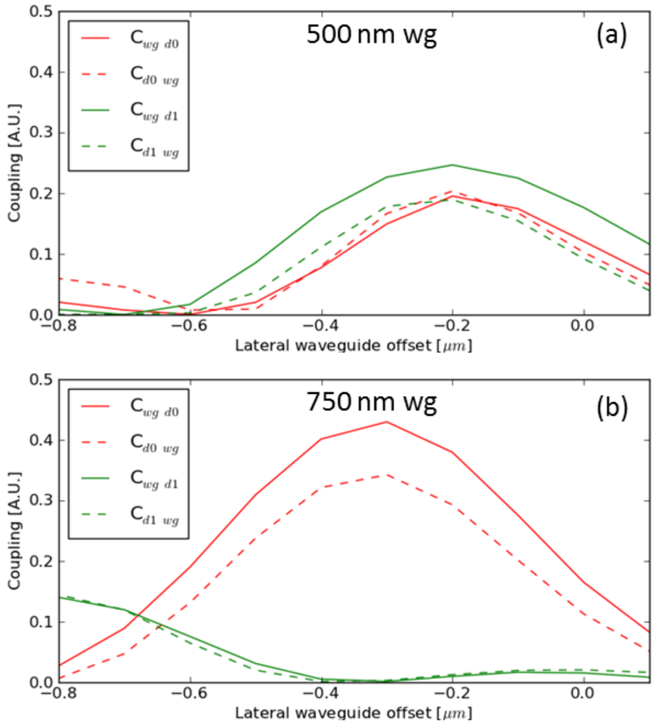

Figure 2. Coupling efficiency between fundamental waveguide mode and fundamental and first order radial disk mode for a (a) 500 nm and (b) 750 nm wide access waveguide. The solid lines represent the coupling from disk to waveguide and the dashed lines the reciprocal.

B. *Simulation results using 3D FDTD*

The bending radii considered here are very small, and results from the CMT simulations were not always perfectly reciprocal as can be seen in Fig. 2. Therefore, the results obtained with the 3D CMT simulations were verified with 3D FDTD using Meep. Fig. 3 shows the field profile of the disk when a CW source is excited in a 500 nm (a) or 750 nm (b) wide waveguide. From this figure it can already be seen that indeed for a waveguide width of 750 nm the coupling is mainly to the fundamental disk mode, while in the case of a 500 nm wide waveguide there is clearly a beating between different modes. To find out what modes are beating, the overlap of the field with the disk mode profiles was calculated. To be able to do this, the time window in the FDTD simulation was kept short such that the light that is coupled from the waveguide into the disk will not make a full roundtrip. The fields were sampled over one period at a cross-section in the waveguide before the disk and a cross-section in the disk as indicated by the red lines in Fig. 3. A Fourier transform was performed on these fields in order to get the frequency dependent field components. From these field components the Poynting vector was calculated for the fields in the waveguide and in the disk. The total amount of power coupled from the waveguide to the disk was calculated and finally, the overlap of mode profiles simulated with FieldDesigner and the field profile simulated with Meep was calculated. For the 500 nm wide waveguide it was found that 22% coupled to the fundamental disk mode and 12% coupled to the first order radial mode, while coupling to other higher order disk modes was negligible. For the 750 nm wide waveguide it was found that 36% was coupled to the fundamental disk mode, while coupling to other higher order modes was negligible. The results obtained with the 3D CMT simulations are thus in good agreement with the 3D FDTD results although the coupling to the first order mode is slightly overestimated in the case of a 500 nm wide waveguide.

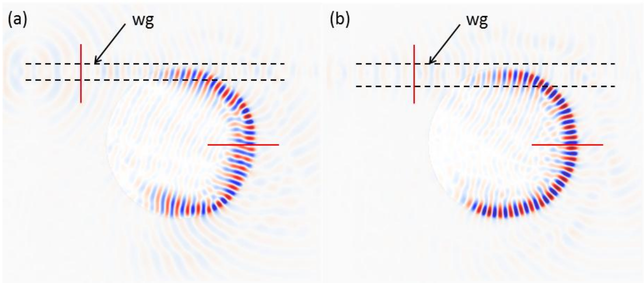

Figure 3. Field profiles of the microdisk for (a) a 500 nm access waveguide with -200 nm offset and (b) a 750 nm access waveguide with -300 nm offset.

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