On-chip beam shaping using lateral leakage

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A beam-shaping mechanism based on lateral leakage of TM modes is proposed, using a waveguide as an on-chip tunable antenna element, combining this with a phase-shifting section and a large-scale grating coupler for coupling out of the chip.

Introduction

Silicon photonics offer high-contrast compact waveguides, where mostly TE polarized light is used because of higher effective index values, leading to smaller footprints of devices (shorter interaction lengths and bend radii). For TE polarization the use of rib waveguides considerably lowers losses, because the sidewall surface defects cover a smaller area in this case. When using TM polarized light however, rib waveguides do not decrease losses compared to wires, because of the occurrence of a peculiar phenomenon called *lateral leakage,* where the light is radiated into the silicon slab next to the waveguide as an on-chip beam as shown in Figure 1 below. The propagation loss due to lateral leakage depends on the width of the waveguide and can for some *magic* widths cancel out almost entirely [1,2].

The control of the lateral leakage rate [3] enables on-chip beam generation with controllable width. In this work we want to exploit the lateral leakage to shape the profile of the on-chip beam. In optical beam forming, a waveguide circuit is used to create an optical beam and then steer it in a certain direction. This is attracting a lot of attention for applications in *light detection and ranging* (LiDAR) and free-space communication. One of the challenges is to define a high-quality, large-area beam starting from high-contrast sub-micrometer waveguides.

In this paper an experimental study of the relation between waveguide width and beam shape of the lateral leakage is investigated.

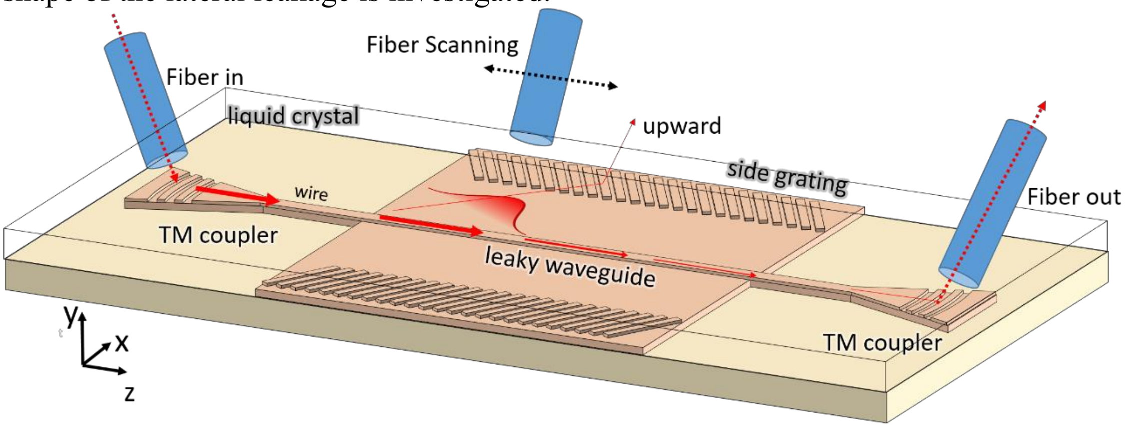

Figure 1 Drawing of a beam shaping device showing leaking of TM polarized light in the lateral direction. The setups for measurement of the transmisison response and the lateral leakage through side gratings are also depicted.

Lateral Leakage of a guided TM mode in rib waveguides

In the silicon photonics platform, the effective index of the 'guided' TM waveguide mode for a ridge waveguide turns out to have a smaller values than the TE slab modes in the thinner silicon side cladding (Figure 1(a)). This fact allows phase matching of the guided TM mode with a laterally propagating TE slab mode under a certain in-plane angle θ, as shown in Figure 1(b) below[1].

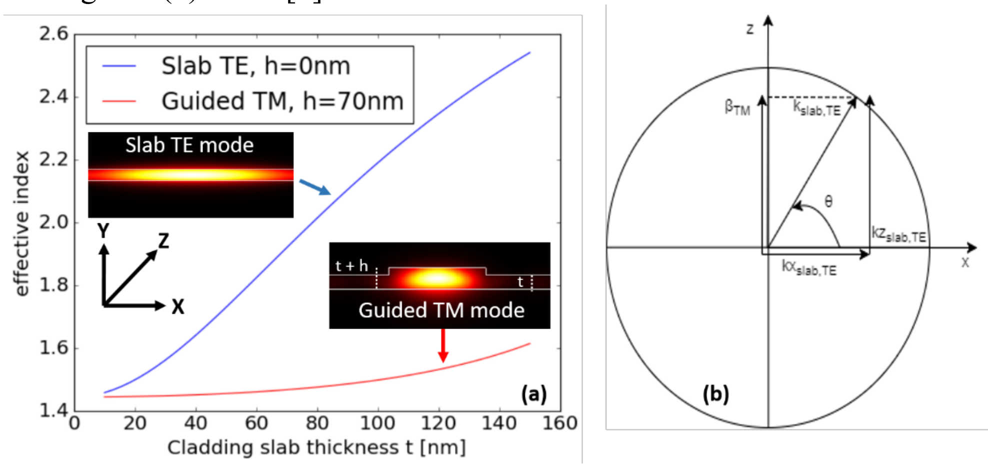

Figure 2 (a) The blue line in the plot shows the calculated effective index of the fundamental TE slab mode for varying thicknesses of the silicon slab. The red line in the plot shows the caldculated effective index of the fundamental guided TM ridge waveguide mode for varying thicknesses of the slab. The insets show the respective modes. (b) The phase matching diagram in the k space.

The high index contrast causes a large field overlap between the guided TM mode and the slab TE mode facilitating coupling at the waveguide edge. Because a waveguide consists of two edges, it can be seen as two emitting radiators, and the emitted beams will interfere. Therefore, the distance between the waveguide edges governs either constructive or destructive interference. As a result, the radiated pattern from the two edges forms an on-chip beam with an exponentially decaying power profile, as the waveguide loses power while it radiates [2].

Beam-shaping with lateral leakage

Six lateral leakage beam shaping devices with waveguide core widths varying from 740 nm to 840 nm were fabricated using the IMEC standard silicon photonics. Standard TM grating couplers were used for coupling from and to the chip, and a photonic wire (which had no leakage) was used to couple to the leaky rib waveguide. The rib waveguide has a very wide side cladding, leading to large slab areas on the chip. These areas propagate the TE slab mode at a certain angle towards two rows of gratings on the side of the slab. These side gratings are periodic lines of un-etched and partly etched silicon, designed to diffract 1550 nm wavelengths upward, radiating the power out of the chip.

The exponential decay of the beam is depicted on top of the microscope image of the fabricated device in Figure 3. As the core width moves away from the magic width of 720 nm for wavelength of 1550 nm, the leakage (slab coupling) becomes stronger and coupling length for core-slab coupling decreases. As the power is radiated out of the slab via side gratings, some power is never coupled back in to the waveguide.

In future experiments, we will tune the leakage strength and thus the beam width by depositing a liquid crystal cladding and locally tuning the voltage over the liquid crystal [3].

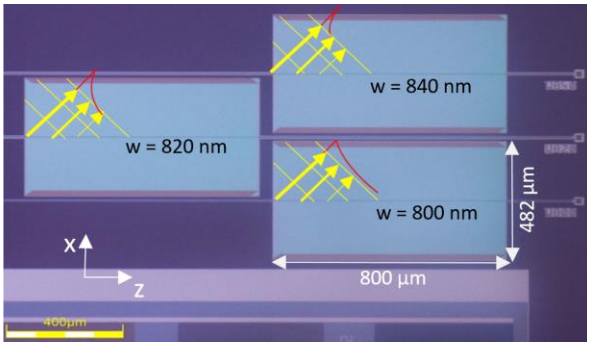

Figure 3 Beam profiles for waveguides of different widths are plotted on top a microscope image of the fabricated devices. It can be noticed in the figure that stronger leakage leads to a smaller beam width (power is concentrated in a smaller area) and the angle of the beam stays more or less same in all cases.

Characterization of the devices

Transmission spectra of the devices were measured for the air clad devices using a tunable laser as input and a photodetector on the output grating coupler. Measured spectra are shown in Figure 4(a) below.

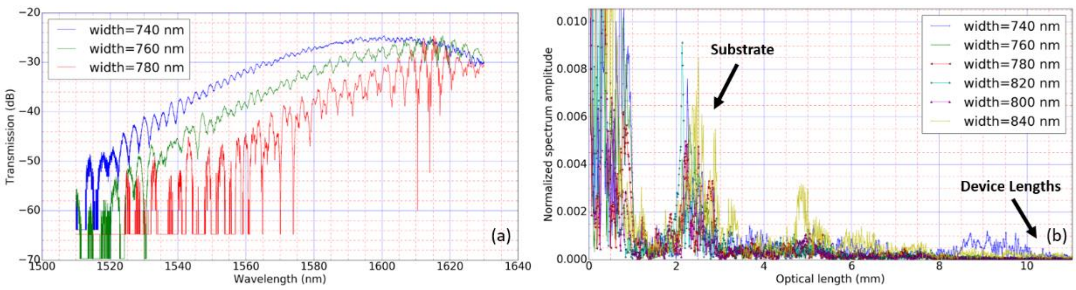

Figure 4 (a) Plot showing the measured transmission speactra for 740, 760 and 780 nm wide waveguides. (b) The plot shows the calculated fast fourier transform (FFT) over the optical transmission. The peaks due to device lengths and underlying silicon sunbstrate are marked in the plot.

It has been shown in an earlier research [2] that magic width value for such waveguides is 720 nm for a wavelength of 1550 nm. Thus, increasing core width will result in a decreasing transmission which can be noticed in the measured spectra. Also, the point of maximum transmission will shift to larger wavelengths, as the magic wavelength for larger core widths also increases [2]. Strong ripples in the transmisison curves can be noticed which are due to the strong cavity effects present in the devices. The hypothesis is that the strongest cavities are formed in the discrete slab area, where the leaked power in TE polarisation forms standing waves. This would be consistent with the fact that for increasing core width, there is an increasing ripple, while the point of minimal ripple is situated at magic wavelength, where least power is present in the slab.
In an attempt to identify the most prominent cavity lengths Fourier analysis was performed on the measured spectra. Figure 4(b) shows the peaked response corresponding with the optical cavity lengths. To compare all devices pure in respect of cavities (thus variations in spectrum) all power spectra are normalized.
The Fourier analysis shows that for increasing core width (and thus increasing leakage, or power present in the slab), the cavities close to device length become weaker and other peaks become more prominent. Reflection off the substrate can be found at around 2.5 mm optical length. This confirms that the cavity effects scale with the amount of lateral leakage, and thus power present in the discrete slab area.

Measurements of the beam profiles

The beam profiles at the side gratings of the devices were all measured by scanning a fibre in discrete steps of 250 nm over the side gratings in a 2D pattern.[2] In a later stadium the far field will also be measured using an infrared camera.

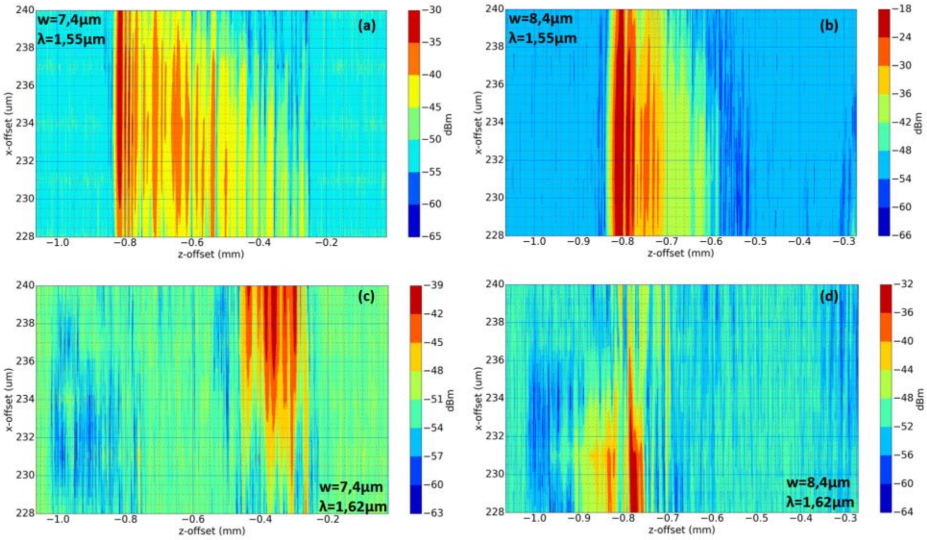

Figure 5 Measured outcoupled lateral leakage at 1550 nm wavelengths for (a) 740nm and (b) 840 nm wide waveguides. Measured outcoupled lateral leakage at 1620 nm wavelength for (c)740 nm and (d) 840 nm waveguides.

In Figure 5 spatial beam profiles of two devices (least leaking and most leaking device) at two wavelengths (strong leaking wavelength and weak leaking wavelength) are shown. One can see that for a given wavelength a stronger leaking core width leads to a smaller beam width, while varying the wavelength for a given core width significantly changes the power and position of the beam as well. Fringes are present in the beam indicating standing wave patterns emerging in the slab cavity, thus confirming that the slab area acts as a large cavity. At 1550 nm wavelength the side-gratings are more efficient, thus here highest output beam can be achieved if the waveguide core has a significant leakage for this wavelength. At other strong leaking wavelengths power can be seen to shift to areas with smaller angle not reachable with direct leakage paths, also indicating the cavity effects in the slab.

Conclusions

First explorative measurements were performed on a new device concept for optical beam forming, where the first difficulties such as cavity effects and grating bandwidth are explored. These measurements form a benchmark in the investigation of the tuning potential using a liquid crystal cladding and difficulties arising in lateral leakage devices.

References

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