Compact lens-assisted focusing tapers fabricated on Silicon-On-Insulator

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***Abstract*—Efficient tapering is one of the basic functions one needs in photonic integrated circuits. While adiabatic tapers are relatively long, we propose an in-plane lensing technology to make efficient compact tapers on silicon-on-insulator.**

I. Introduction

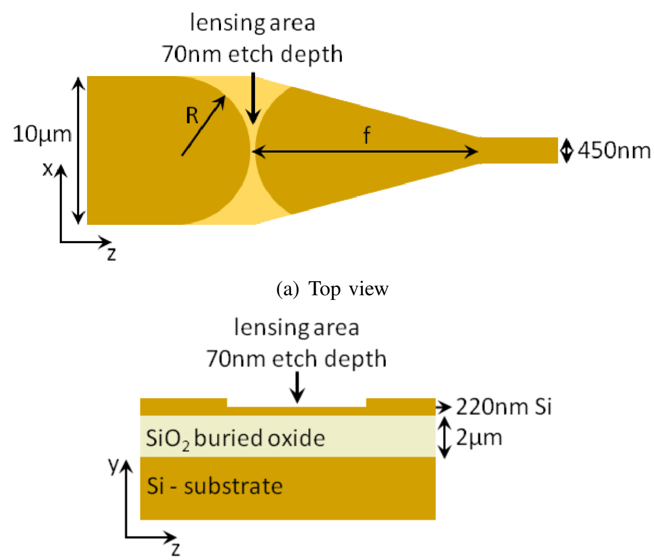
As photonic integration continues to scale down, there is a need to efficiently use the chip area one has available. Tapering is one of the important chip area consuming functions. When light is coupled into a photonic integrated circuit from an optical fiber, we usually want to taper down to a single mode waveguide. When vertical coupling is used, the grating can act as a focusing element, focusing the light immediately into a single mode waveguide [1]. This alleviates the need for a long adiabatic taper. However, when tapering inside the photonic circuit is necessary, such an approach can not be used.

In this paper, we propose a lens-assisted focusing taper consisting of an in-plane lens. We therefore use the silicon photonics platform using silicon-on-insulator (SOI). Due to the high index contrast, this platform allows dense integration of photonic functions using CMOS (Complementary Metal Oxide Semiconductor) compatible processes. When we have two areas with different effective indices, we can create a lens that focuses light in-plane. This is put into practice to fabricate a compact taper. First the proposed component was simulated using an FDTD (Finite Difference Time Domain) approach, next we fabricated and measured our designs. While these in-plane lenses are used here in a simple taper design, one might think of more complicated functions performed by lensing setups that can now be integrated on chip.

Next, we discuss the design and fabrication of the component. In Section 3 the measurement results are given. Finally, Section 4 gives a conclusion.

II. Design and Fabrication

A top and side view of the focusing taper is shown in Fig. 1. The tapers were fabricated on SOI at *imec*, Leuven using standard CMOS (Complementary Metal Oxide Semiconductor) processes [2]. The buried oxide layer layer is 2μm thick and the silicon top layer is 220nm high. A deep etch of 220nm is used to etch the waveguides and a shallow etch of 70nm to etch the lensing area. This is a standard process available through [3].



(a) Top view

(b) Side view

Fig. 1. Top and side view of the focusing taper structure. The etched area has a lower effective index and acts as a focusing lens.

Due to the 70nm etch, we have a way to change the effective index of the slab which gives us the possibility to create in-plane lenses. A 220nm and 150nm thick slab will have different effective indices, which are also dependent on the used polarization. Due to the asymmetry of the slab region (silica and air), there are not two orthogonal TE- and TM-modes, but we can still split them up in quasi-orthogonal TE- and TM-like modes.

We now design an in-plane lens to focus the light from a 10μm slab waveguide into a 450nm single mode waveguide. As a 150nm slab has a lower effective index, the lens has a concave shape to focus the light. In Table I, the effective indices of the slabs are given for the TE- and TM-like mode. The structures are then simulated using an FDTD approach [4]. In a first instance, a 2D FDTD optimization run is performed using the effective index method to find the optimum focal length of our taper for different radii of curvature R of the lens interface. Next a 3D FDTD simulation is performed to verify this optimum and the validity of our effective index method.

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slab thickness (nm)	TE-like	TM-like
150	2.50	1.49
220	2.83	1.89

TABLE I
EFFECTIVE SLAB INDICES AT λ=1550NM OF THE TE- AND TM-LIKE MODE IN SOI FOR DIFFERENT SLAB THICKNESSES.

First of all, using the indices of Table I we can using basic lensing theory to find the focal distance of our lens. The focal distance f of a symmetric bi-concave thin lens can be approximated by:

$$f = \frac{n_{bg} R}{2(n_l - n_{bg})} \quad (1)$$

with n_{bg}, the index of the background – the 220nm slab –, n_l the index of the lens – the 150nm slab – and R the radius of curvature of the two interfaces of the symmetric bi-concave lens. For a radius of curvature of 5μm and the effective indices in Table I this would results in a focal distance of 21.4μm for the TE-like mode and 11.8μm for the TM-like mode.

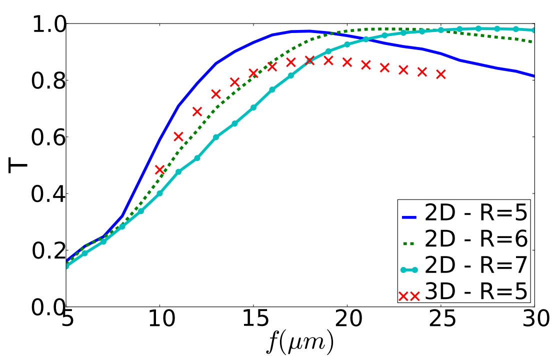

Fig. 2. FDTD simulation of the transmission of the lens-assisted taper as a function of taper length f for different radii of curvature R for the fundamental TE-like mode at λ=1550nm.

In Fig. 2 the simulated transmission of the fundamental TE-like mode of the taper as a function of taper length f with a symmetric bi-concave lens (as shown in Fig. 1(a)) at 1550nm is given for different radii of curvature R. When starting from a 10μm waveguide, the minimal radius of curvature to avoid discontinuities is 5μm. A very broad optimum is found with a transmission of more than 95% for a taper length f of 16 to 20μm for R=5μm. This number corresponds relatively well to the geometrical approach. When R becomes larger, the lens becomes weaker and we see the optimum shifting to larger f and broadening. The main part of the loss is now just the reflection at the lens interfaces. The 3D simulation shows an optimum near the same f, but the maximum transmission is now about 87% as the etch step of 70nm will result in extra scatter losses.

In Fig. 3, a similar simulation result for the fundamental TM-like mode is given. We now have a stronger lens, which was already predicted by the geometrical approach. The optimum in 2D now reaches up to 90%. For R=5μm, the lens becomes too strong and the numerical aperture (NA) of the lens is too large to match the single mode waveguide NA resulting a a decrease of efficiency to 85%. The 3D simulation shows huge decrease in transmission to about 34%. We attribute this loss due to the fact that the TM mode is very sensitive to irregularities at the interfaces in the y-direction (Fig. 1(b)) as the main E-field component E_y makes large jumps at these interfaces on contrary to the TE-like mode. This is clearly visible in Fig. 4, where the electric field profile of both the TE- and TM-like mode of a 220nm slab are given in the y-direction. It is just at this silicon-air interface, an etch step of 70nm happens and thus a large amount of light gets lost for the TM-like mode. Using refractive index engineering as in [5], we can avoid this abrupt step and this problem can be overcome.

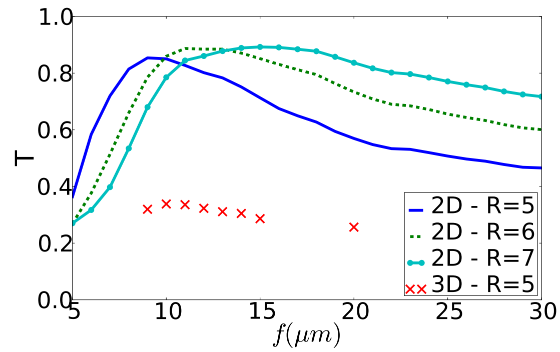

Fig. 3. FDTD simulation of the transmission of the lens-assisted taper as a function of taper length f for different radii of curvature R for the fundamental TM-like mode at λ=1550nm.

From lensing theory we know that a plano-convex lens would reduce aberrations in this configuration. However this will reduce the strength of the lens for a given radius of curvature R, increasing the taper length. Simulations have shown that there is no significant improvement in efficiency, as we already reach a near optimum with the symmetric bi-concave lenses. The losses for the 2D FDTD simulation are mainly attributed to the Fresnel reflection losses. The tapers are furthermore relatively wavelength independent, with only a few percent of change in transmission over a 100nm range around 1550nm.

III. MEASUREMENT RESULTS

To measure the tapers for the TE-like mode, we excite the structure using a grating coupler for near vertical coupling of the TE-like mode [1]. The waveguide is then adiabatically tapered to a 450nm wide photonic wire to eliminate higher order mode incoupling. Then we adiabatically taper back to a 10μm width which is the input of our focusing taper. The focusing taper tapers to a 450nm wide waveguide which is again connected to a vertical grating coupler. Using a reference waveguide without intermediate lensing taper, we cancel out all the coupling and waveguide losses effects. Different lens-assisted focusing tapers were measured, all symmetric bi-concave, with a radius of curvature of R=5μm. The taper

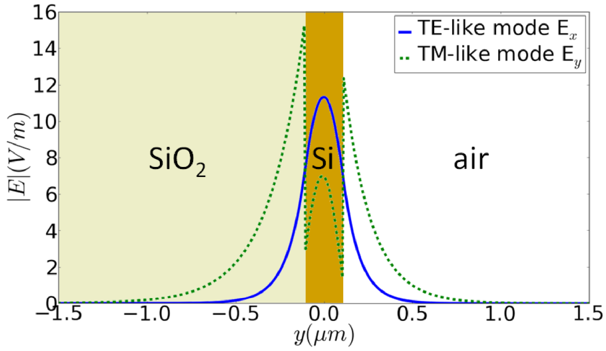

Fig. 4. Mode profile of the fundamental TE- and TM-like mode in a 220nm Si slab on SOI.

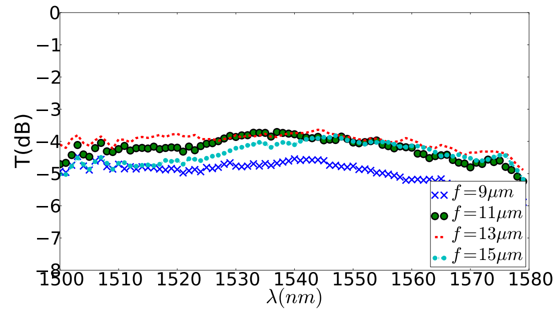

Fig. 6. Measured transmission of lens-assisted tapers for the TM-like mode for different taper lengths f as a function of wavelength.

length f varies from 16μm to 22μm. The results are given in Fig. 5. We see a total loss ranging between 0.5-2dB and independent of wavelength. The difference in transmission for the different structures is not clearly visible due to the measurement error. A decrease in efficiency can be seen for the longer taper lengths of about 1dB.

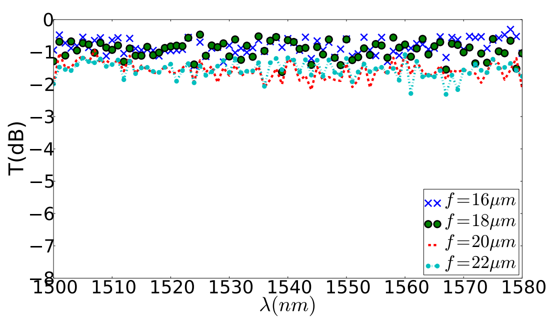

Fig. 5. Measured transmission of lens-assisted tapers for the TE-like mode for different taper lengths f as a function of wavelength.

When working with TM-light, the light is coupled in using a vertical grating coupler optimized for the fundamental TM-like mode. As reference waveguide, we now take a broad 12μm waveguide as we cannot taper TM light easily in an asymmetric cladding as shown in [6]. To test the efficiency of the lensed tapers, we put two of these identical tapers in between the 12μm waveguide to taper to a 500nm waveguide and then back to a 12μm waveguide. All lensed tapers have a symmetric bi-concave lens with a radius of curvature of 6μm. The measurement results are given in Fig. 6. We have a good wavelength independence and a large loss per taper of about 4-5dB, which corresponds well to our 3D simulation. The difference of different taper lengths f is again not clearly visible, although we see that a 9μm taper length has a larger loss which is due to the fact that this lens is too strong to effectively couple into the 500nm wire.

IV. Conclusion

A novel approach to taper light in photonic integrated circuits has been shown. By using in-plane lensing using refractive index engineering, we can make compact focusing tapers, with taper lengths between 10μm to 20μm. This can greatly reduce the amount of needed chip area compared to adiabatic tapers, which easily extend up to several tens of micrometers. This approach furthermore allows to fabricate efficient tapers of the TM-like mode in an asymmetrical background cladding. A loss of about 1dB and 5dB for tapers of the TE- and TM-like mode has been shown, respectively. These numbers can be increased by efficient refractive index engineering. While these tapers are the most basic component of this in-plane lensing technology, free-space optical setups could possibly be integrated on-chip using the same approach.

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