Mach-Zehnder-Interferometer realized with silicon-oxynitride waveguides for optoelectronics

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Introduction

In optical signal processing, for example in the field of optical sensing, optical quantum computing and high-capacity optical networks, are often used Mach-Zehnder interferometers (MZI) for preparing difference signals, and optical routing-switching. Furthermore the combination of optical and electronic functions manufactured with low-cost technologies is needed. Silicon technology is of special interest because of the unique properties of the substrate material silicon: the availability of large-area substrate, good thermal conductivity and chemical stability, high surface quality, and low cost.

Silicon-oxynitride is a suitable material [1] for passive optical components like branching waveguides, couplers, interferometers, power splitters and filters. The minimum allowable bending radius for our high-index-contrast material is one order of magnitude smaller than for commonly used silica technology. This enables the realization of very compact integrated optoelectronic circuits at low cost. We demonstrate basic integrated MZI's fabricated in the high refractive index material system silicon-oxynitride on silicon.

Waveguide design and fabrication

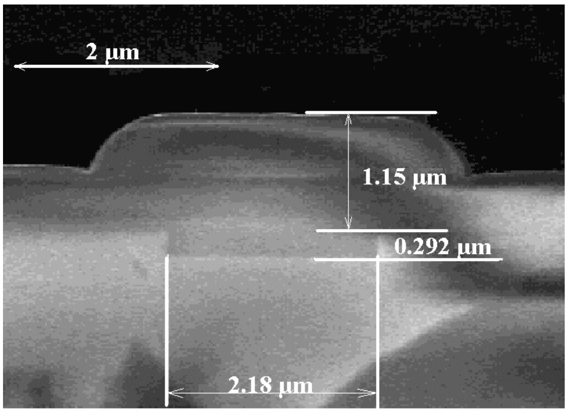

Fig. 1 Face of an embedded waveguide structure (design for λ = 850 nm)

The waveguide design is based on planar optical waveguide technology with core to cladding layer refractive index step Δn = 5.7%. This high Δn system was chosen to allow small waveguide bending radii down to 1 mm. The embedded channel waveguide is 0.3 µm in height and 1.3 µm to 2.1 µm in width (depending on the wavelength). For the fabrication of the buffer and cladding layer a process with very low N_2 content was chosen resulting in $n_B = n_C = 1.49$. For the core layer a process with higher N_2 content was used resulting in $n_f = 1.57$. The refractive indices were measured at a wavelength of λ = 633 nm. A layer thickness uniformity of better than 1% and a refractive index uniformity across the 4'' wafers better than 0.5% was obtained. After deposition, annealing of the $Si_xO_yN_z$ layers was not necessary. The waveguide loss is < 1.9 dB/cm measured at a wavelength of 633 nm. For further manufacturing details see [1].

Waveguide structures

Integrated MZI's consist of two directional couplers and and two different optical waveguides (Fig. 3).

- *Directional couplers*

Directional couplers are basic elements in splitters, modulators, switches or wavelength filters. Their coupling efficiency depends strongly on the distance s between the waveguides (Fig. 2).

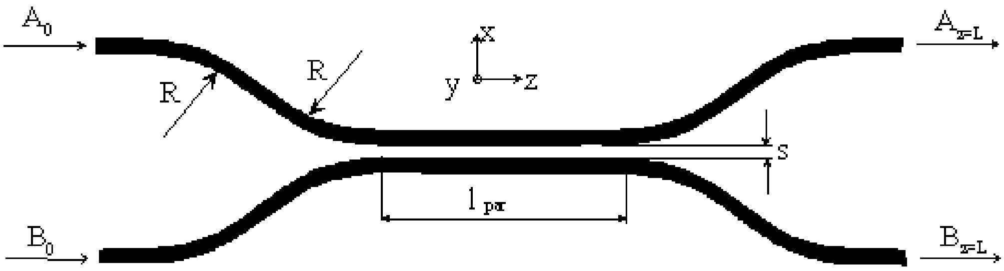

Fig. 2 Layout of a directional coupler

Optical power launched into one input port of a directional coupler is in general distributed to the two output ports of the device. The power splitting ratio depends on the effective coupler length

$$L = l_{par} + l_{bends} \tag{1}$$

with l_{par} the contribution of the parallel waveguide region and l_{bends} equivalent to an extra length in the parallel coupling region caused by the coupling contribution at the gradual approximation in the input and output bends region (called as "S-bends" because of the S-shaped bend of the waveguide with the radius R, Fig. 2). Total power transfer to the opposite output port (first cross state) is given for an effective coupling length $L_c = 1/2 * L_{beat}$ and any odd multiple of this value. The contribution of the parallel waveguides to the coupling length can be described as

$$L_c = \pi/2\kappa \tag{2}$$

where the coupling coefficient κ decreases exponentially with waveguide distance s.

In the limiting case of zero gap ($s = 0$) between the two coupler waveguides a multi-mode waveguide is formed. The resulting multi mode interference (MMI) couplers are much more insensitive to fabrication tolerances than directional couplers. For our devices we have especially used two mode interference (TMI) couplers. We have fabricated such coupler devices for 785 nm working wavelength with 2.5 µm wide TMI section, 1.6 µm wide input and output waveguides in the S-bend sections which have R = 2500 µm bending radius. Details and measurements about 3-dB TMI couplers are to found in [1].

- *Mach-Zehnder Interferometer*

The basic configuration of Mach-Zehnder Interferometers is shown in Fig. 3. It has two input ports, two output ports, two 3-dB couplers and between them two waveguide arms with a length difference ΔL. The transmission coefficients T_1 and T_2 of the MZI can easily be described using the transfer matrix method [2]:

$$T_1(\lambda) = \cos^2\left(\frac{n_{eff} \cdot \pi \cdot \Delta L}{\lambda}\right) \quad \text{and} \quad T_2(\lambda) = \sin^2\left(\frac{n_{eff} \cdot \pi \cdot \Delta L}{\lambda}\right) \tag{3}$$

The wavelength spacing $\Delta\lambda$ of transmitted peak intensity between the two output ports results in

$$\Delta\lambda = \frac{\lambda^2}{2n_{eff} \cdot \Delta L} \tag{4}$$

where n_{eff} is the effective refractive index of the waveguides, λ is wavelength, and ΔL is the length difference between arm I and II.

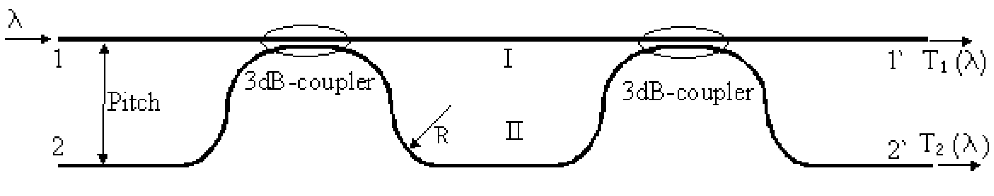

Fig. 3 Basic configuration of a MZI

We used a length difference of 60 µm between the two arms, a monomode waveguide width of 1.6 µm, and 3-dB TMI-couplers as described above. The coupler was designed for a power coupling ratio of 50/50 at 785 nm. The device was characterized by a tunable Ti:sapphire laser with calibrated wavelength reading. Light was launched into the device input waveguides by a high NA microscope objective. The output light was picked up with a multi-mode fiber and guided into a photo-spectrometer. The wavelength was tuned over a range of about 5 nm. We achieved a spectral resolution of 0.2 nm. The measured wavelength spacing between the two outputs was 3.5 nm in accordance with the design. A sufficient correlation between calculated and measured transmittance of this MZI was achieved as shown in Fig. 4.

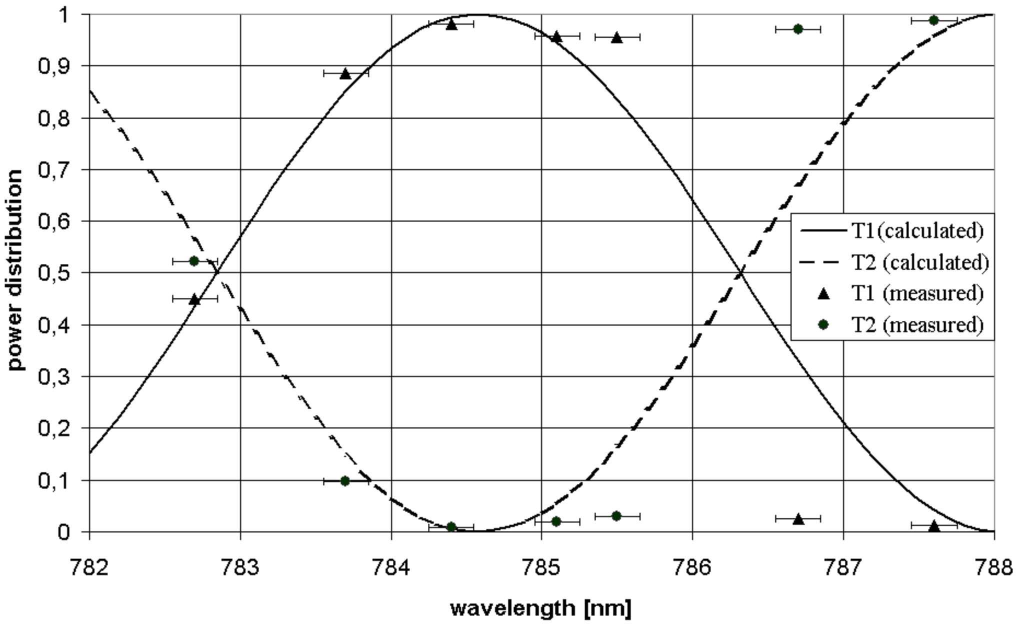

Fig. 4 Transmittance of a MZI with ΔL of 60 µm over wavelength

Conclusion

Based on a high *Δn* waveguide layer system of silicon-oxynitride we have manufactured directional couplers and MZI. which showed good agreement in the calculated and measured wavelength dependence. The chosen silicon-oxynitride material system is compatible with silicon technology. It offers the feasibility of the integration of MZI and electronics in silicon. Further, the visible and near infrared wavelength region enables the use of low cost laser diodes and also offers an application potential for integrated optical sensors.

References

[1] **Schauwecker, B.; Arnold, M.; Przyrembel, G.; Kuhlow, B.; Radehaus, C.:** “Optical waveguide components with high refractive index difference in silicon-oxynitride for application in integrated optoelectronics”, Opt. Eng. 41(1), p. 237 - 243 (2002).

[2] **Verbeek, B.H.; Henry, C.H.; Olsson, N.A.; Orlowsky, K.J.; Kazarinov, R.F.; Johnson, B.H.:** “Integrated four-channel Mach-Zehnder multi/demultiplexer fabricated with phosphorous-doped SiO_2 waveguides on Si” *Journal of Lightwave Technology* 6(6), p. 1011–1015 (1988).

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