Cascaded Mach-Zehnder Filters in Silicon-on-Insulator Photonic Wires fabricated with deep UV lithography

Pieter Dumon (1), Wim Bogaerts (1), Dries Van Thourhout (1), Dirk Taillaert (1),
Vincent Wiaux (2), Stephan Beckx (2), Johan Wouters (2) and Roel Baets (1)
1 : Ghent University – IMEC, Department of Information Technology
Sint-Pietersnieuwstraat 41, 9000 Gent, BELGIUM
Email: pieter.dumon@intec.UGent.be
2 : IMEC v.z.w., Silicon Process Technology Division
Kapeldreef 75, 3001 Leuven, BELGIUM

Abstract *We present filters based on cascaded Mach-Zehnder sections, using single-mode photonic wires (high-contrast submicron waveguides) in Silicon-on-Insulator. We show a 2.6nm-bandwidth filter with 17nm FSR and near to 100% coupling drop efficiency.*

Introduction

In long-range optical communication, signals are transmitted using a number of channels with different carrier wavelengths. This Wavelength Division Multiplexing (WDM) requires components to combine and/or separate the wavelength channels at the input and output of the fibre. There are several approaches to such wavelength-selective functions. Filters can extract a single channel from an optical waveguide and/or insert another signal. These filters are often based on resonant structures. Alternatively, an Arrayed Waveguide Grating (AWG) uses a distributed circuit of various delay lines to separate or combine different wavelength channels.

Today's mainstream wavelength (de)multiplexer PLCs are implemented in silica on Silicon and have footprints of tens of cm^2, mainly because the low-index-contrast waveguides require large bend radii to keep light confined and suppress radiation losses. To reduce the chip area and increase integration, waveguides with sharp bends are a necessity. The confinement can be increased by using a higher refractive index contrast between core and (side) cladding, but to keep the waveguide single-mode, it has to be narrower. In semiconductor waveguides, with a refractive index contrast of 2 to 1 or larger, the threshold width is of the order of 600nm. Such high-contrast, submicron waveguides are called photonic wires. With photonic wires, low-loss bends with radii of a few µm are possible, dramatically reducing the footprint of photonic components.

Here, we present a cascaded Mach-Zehnder [1, 2] wavelength-selective filter in Silicon-on-insulator (SOI) photonic wires. In SOI, the Silicon core is shielded from the Silicon substrate by a SiO_2 cladding (buffer) layer. An advantage of SOI is its compatibility with CMOS fabrication, which allowed us to use advanced CMOS technology, including deep UV lithography.

Cascaded Mach-Zehnder (CMZ)

A CMZ [1, 2] is basically a 2 x 2 port device consisting of a weighted cascade of directional couplers, separated by delay sections with equal delay length. The power transfer to both output ports depends on the phase relation between both arms, which is defined by the physical length difference of the arms, the propagation constant in the waveguides and the wavelength of the light. A single-stage (first order) CMZ reduces to the well-known Mach-Zehnder interferometer. The transmission to the pass and drop ports varies in a sinusoidal way with the wavelength. Cascading such filter stages renders a higher order filter with higher finesse. The principle is illustrated in figure 1. By using an appropriate coupler weight function, a low sidelobe level can be obtained.

The spectral distance between wavelength channels in the drop port (free spectral range or FSR) depends on the group index of the waveguide. The larger the group index (read: the stronger the wavelength-dependence of the propagation constant), the smaller the delay length needs to be and the smaller the footprint of the filter. Photonic wires have a relatively large group index (>4). In combination with the possibility to make sharp bend, compact filter functions are possible.

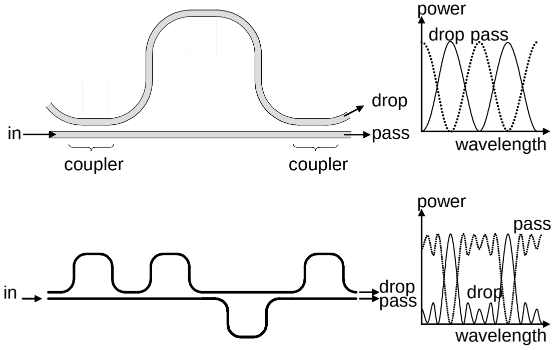

Figure 1: Principle of a CMZ filter. Top: MZI (first order CMZ), Bottom: a 4-stage CMZ.

Fabrication

For our high-contrast waveguides, we used Silicon-on-Insulator (SOI) purchased from SOITEC. The top Silicon layer has a thickness of 220nm and the oxide layer is 1µm thick. The actual processing was carried out in the advanced CMOS research environment of IMEC, Belgium. The fabrication process is described in detail in [3, 4]. After applying and baking the

Shipley UV3 photoresist, a deep UV stepper with an illumination wavelength of 248nm is used to define the patterns. After another baking step the resist is developed. To smooth the resist patterns and decrease the line width of the waveguides, a “resist hardening” plasma treatment is applied to the developed photoresist. This is then used directly as an etch mask for the Silicon etch, which uses an ICP-RIE etch technique with a $Cl_2/HBr/He/O_2$ chemistry. Finally, the remainder of the resist is removed.

Because in the coupling sections the waveguides are close together, optical proximity effects (OPE) will occur during the lithography, changing the waveguide width with respect to the isolated waveguide. For the coupling sections we studied, we found a negative OPE, i.e. the waveguides in the coupling sections were narrower than the isolated waveguides.

Results

Figure 2 shows an example of a 5-stage CMZ, consisting of 6 directional couplers and 5 delay sections. The physical delay length in each stage is 32.8µm, and to determine the length of the coupling sections we used a Chebychev type I filter synthesis. To minimize the effect of bends on the group index of the waveguides, the bend radius was chosen relatively large: 10µm. The isolated waveguides have a width of 565nm while the waveguides in the coupling sections are only 535nm wide due to optical proximity effects. The gap width itself is 220nm. The propagation losses are lower than 0.3dB/mm [4, 6].

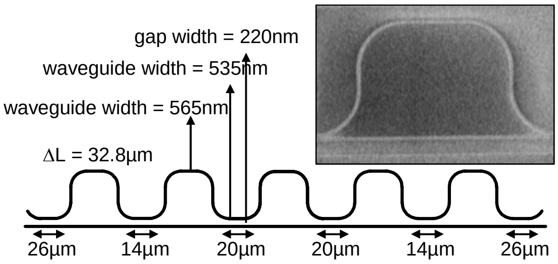

Figure 2: Design of a 5-stage CMZ

For the measurements we coupled light from a tuneable laser into a broad waveguide using a surface grating coupler [4, 5]. Using a linear taper the light is then focused into a photonic wire and coupled into the filter component. At the output side, a similar grating coupler is used.

Figure 3 shows the transmission characteristic (in dB) of this component in both the pass and the drop port normalized to the transmission of a simple straight waveguide. We can see a well-defined filter characteristic with a bandwidth of 2.6nm, a free spectral range of 17nm and a coupling efficiency of almost 100%. The crosstalk is still approximately -10dB. This somewhat high crosstalk is probably due to inaccuracies in the fabrication of the directional couplers.

The group index of the straight waveguides is 4.3. For the 10µm bends the group index is somewhat higher, around 4.5.

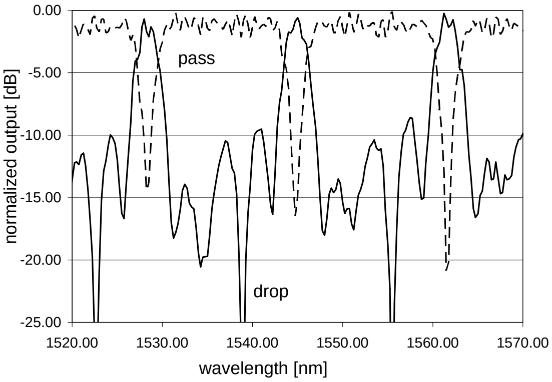

Figure 3: Transmission characteristic of the five-stage CMZ from figure 3.

Conclusion

We have fabricated a cascaded Mach-Zehnder filter based on high-contrast nanophotonic waveguides in SOI. First experiments show a filter with 2.6nm bandwidth, 17nm FSR and near to 100% coupling drop efficiency to the drop port.

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