Proceedings Symposium IEEE/LEOS Benelux Chapter, 2006, Eindhoven

A nanophotonic NEMS-modulator in Silicon-on-Insulator

J. Roels(1), I. De Vlaminck(2), D. van Thourhout(1), L. Lagae(2), D. Taillaert(1), R.Baets(1)

(1) Ghent University -IMEC, Department of Information Technology (INTEC),

St-Pietersnieuwstraat 41, 9000 Ghent - Belgium

Contact = joris.roels@intec.ugent.be

(2) IMEC, Kapeldreef 75, B-3001 Leuven, Belgium,
also at ESAT/INSYS, KULEUVEN, Belgium

In order to achieve fast all optical switching in communication networks, a compact, low cost, integrated optical switch is needed. Nanophotonic integrated circuits in silicon-on-insulator (high-index contrast) are well-suited for this purpose. Nevertheless it is hard to obtain a strong light modulation effect in silicon.

In this paper we demonstrate light modulation by moving a nanophotonic waveguide (NEMS = nano-electromechanical system). We also fabricated and characterized passive directional couplers. Both achievements are an important step towards a 2x2 nanophotonic NEMS-switch.

I. Introduction

Optical signal processing components need to be down-scaled to the size of electrical components in order to be economically competitive. However current photonic integrated circuits (PIC) are fairly large compared to their electronic counterparts. This is because the on-chip optical waveguides typically have a low index contrast, and therefore the light is weakly confined in the large waveguide core (core diameter >> 1µm). As a result waveguides need a large bend radius and signal processing components typically consume lots of valuable (expensive) chip area. Nanophotonic waveguides confine light into a submicron core area by using a very high refractive index contrast. Therefore the size of the PICS can be reduced by an order of magnitude.

Silicon-on-Insulator (SOI) is an attractive material system for such nanophotonic waveguides because of the high refractive index contrast between the silicon top layer ($n=3.48$) and the silica ($=SiO_2$) cladding ($n=1.45$). Moreover SOI makes it possible to integrate photonic components with electronics and offers CMOS-compatible, cost reducing fabrication.

The last 5 years many compact passive optical components in SOI have been successfully demonstrated [1,2]. However it is hard to obtain compact active optical components in SOI since the refractive index of silicon does not exhibit a strong electro-optic or thermo-optic modulation effect [3]. In this paper we discuss a concept for a waveguide switch based on an optical directional coupler with moving arms.. Moving on-chip structures with submicron size are often called NEMS (Nano-electro mechanical Systems). Optical NEMS are a new and exciting research domain that requires the combination of several engineering fields like electromagnetism, mechanical engineering and nanophotonics.

Electrostatic actuation

We will make the waveguide move by the principle of electrostatic actuation (Figure 1). A voltage is applied between a silicon waveguide and an electrode. The waveguide is partially suspended in air so that a stringlike structure is created. The electrode and string from electrical point of view act like the plates of a capacitor and electrical charges with opposite signs are formed upon them. These charges cause an attractive Coulomb force F_{elek} between the string and the electrode. The balance between F_{elek} and the counteracting mechanical spring force F_{elek} finally results in a translation of the waveguide string. When the translation exceeds a critical value (approximately one third of the original gap between string and electrode) instability occurs and the string irreversibly snaps down to the electrode (pull-in), which should be avoided.

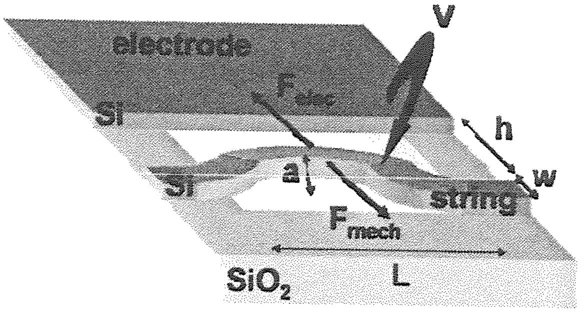

Figure 1: principle of electrostatic actuation

Switching principle

The waveguide switch is based on the principle of a passive directional coupler. The physical behavior of such a directional coupler is described by the theory of supermodes or a coupled mode theory [4]. When two waveguides are brought in sufficiently close proximity the mode profiles of their guided eigenmodes will have an overlap. Under that conditions a periodical exchange of light power between the two waveguides will take place. When we excite one waveguide with unity power (P_{in}=1) the power that is coupled into the not-excited waveguide (P_{cross}) is given by (with L the length of the coupling section, see Figure 2, right):

$$P_{cross} = \sin^2(\frac{\pi L}{2L_c})$$

Lc is a parameter that is called the “effective coupling length” and it is defined as the length of the coupling section that is needed to couple all light into the not-excited waveguide (P_{cross} =1). Lc can be calculated from the theory of supermodes when the effective mode indices of the supermodes are known [4].

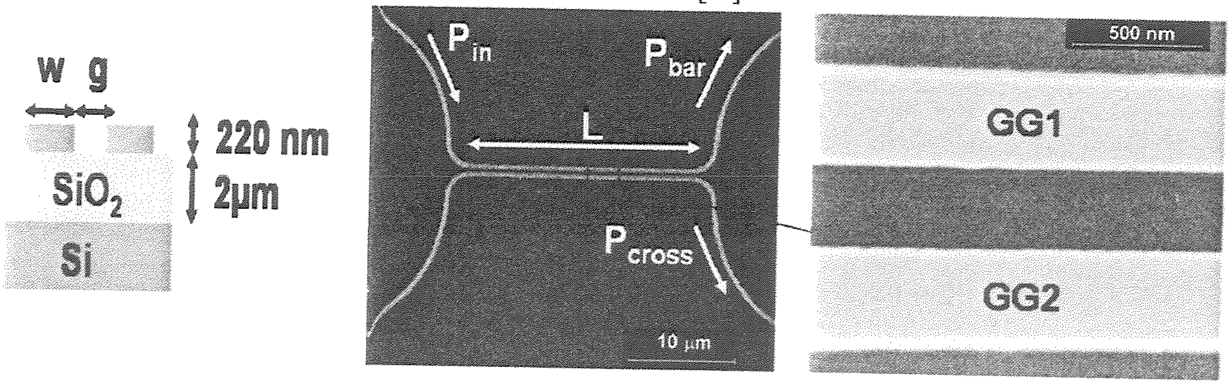

Figure 2: directional coupler: cross-section (left), SEM-picture + detail (right)

In a high-index contrast material system the parameter Lc is very sensitive to small changes in the gap distance g. Figure 3 (left) shows a simulation of Lc in function of the gap distance g for some typical design parameters. The simulation was performed with the help of a full vectorial 3D-mode solver. It is clear from the picture that changes as small as 100nm cause a doubling of Lc and therefore cause a full switch of the light from one waveguide to another.

In order to verify the above described theory we fabricated and characterized some passive directional couplers in SOI with coupling sections L varying from 0 to 28μm with an interval of 3.5 μm. The results are shown in Figure 3 (right). We found an excellent agreement between our measurements and the sine square dependency predicted by the theory of supermodes and the coupling mode theory.

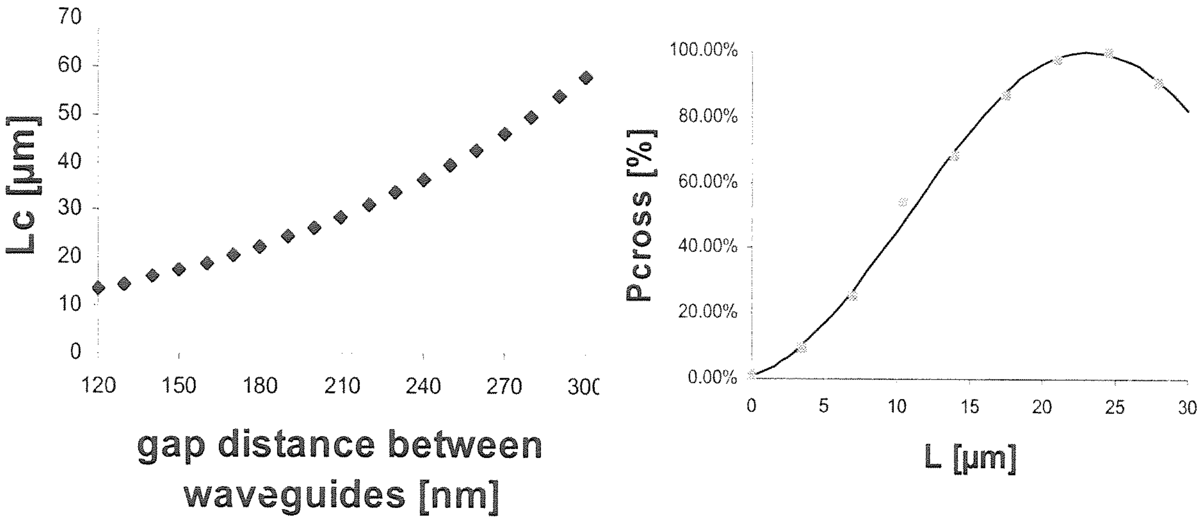

Figure 3: Simulation of Lc in function of g with w=400nm at λ=1.55μm (left); Measurement of P_{cross} (squares, right) + theoretical fitting (full line, right) at λ=1.57 μm

It should be stressed that for high-index contrast material systems it is not trivial to find such a good agreement between theory and measurements since slight aberrations in the fabrication generally cause uncomplete coupling (P_{cross} max < 1). To our knowledge it is the first time that such matching results are reported in literature for directional couplers fabricated with DUV (Deep Ultra Violet, see Fabrication) in SOI.

Fabrication

A DUV-process (Deep Ultra Violet) with submicron resolution was developed using the CMOS-facilities of IMEC to define the required patterns in the top silicon layer. This process is described in detail elsewhere [1]. To create an active NEMS-device in a second step the waveguides need to be partially underetched so that a suspended structure is created. This was done using a resist mask and buffered HF which provides a selective silica etch. Finally aluminium was evaporated to define electrical contact areas.

An optical NEMS-modulator

In order to demonstrate modulation by moving waveguides we fabricated the device shown in Figure 4 (left). Both the electrode and waveguide are suspended in air. By applying a voltage between the electrode and the waveguide they move closer to each other and more light will leak out of the waveguide so we expect a drop of the measured transmission P_{out}/P_{in}. Indeed we measured a decrease of 20% when a voltage of 15V was applied.

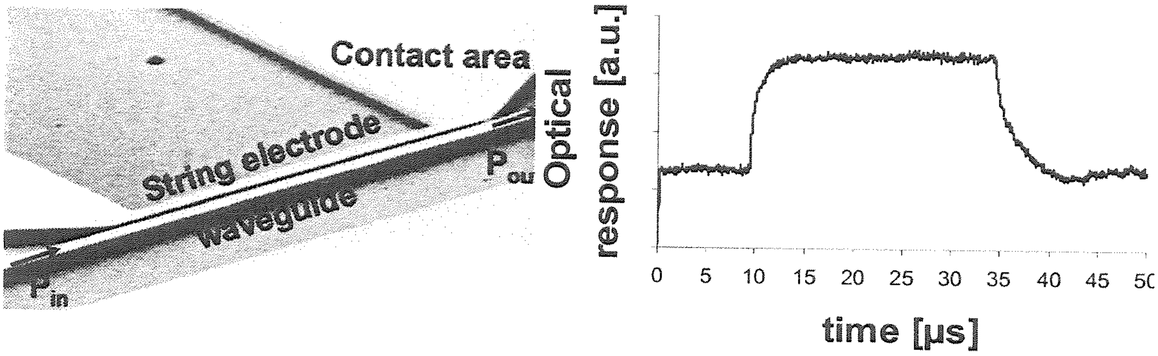

Figure 4: SEM-picture NEMS-device (left) + measurement dynamic optical response (right)

We also did experiments on the dynamic behavior. Figure 4 (right) shows the dynamical optical response when a square voltage wave is applied to the device. We can clearly see that switching times are in the order of 3-5µs. A SEM-analysis has shown that during the experiments pull-in has taken place which complicates the analysis of the results. Nevertheless we believe that the measured switching times are dominated by (purely) electrical charging effects and that the measured shape of the optical response corresponds to the typical exponential shape with RC-time constant that is found when a capacitor C is loaded over a resistor R. We can conclude from this experiment that for our future devices we need a better control of the contact resistance (lower the resistance to decrease the RC-time constant) and the driving voltage (to avoid pull-in). That way we expect to measure subµs switching times.

Conclusion

In this paper we discussed on-chip optical switching using a NEMS-approach in a high-index contrast material system. We have fabricated and characterized passive directional couplers and found an excellent agreement between theory and measurements. We also fabricated a NEMS-device and discussed the observed dynamics. Both results are important steps towards compact NEMS-switches in Silicon-on-Insulator that we will demonstrate in the near future.

References

[1] W. Bogaerts, Nanofotonische golfgeleiders en Fotonische Kristallen in Silicium-op-Isolator, PhD-thesis, 2004 University of Ghent

[2] Dumon, P., et al., Compact wavelength router based on a Silicon-on-insulator arrayed waveguide grating pigtailed to a fiber array, Optics Express, 2006. **14**(2): p. 664-669.

[3] R.S. Jacobsen, Strained silicon as a new electro-optic material, Nature 2006, **441**(7090): p. 199-202.

[4] Märtz R, Integrated Optics, Design and Modeling, 1995, Boston, London: Artech House

TU/e technische universiteit eindhoven

2006 Annual Symposium of the IEEE LEOS

Benelux Chapter

IEEE LEOS
LASERS & ELECTRO-OPTICS SOCIETY

Editors

A.M.J. Koonen, X.J.M. Leijtens,
H.P.A. van den Boom, E.J.M. Verdurmen,
J. Molina Vázquez

November 30 | December 1 | 2006

COBRA Institute

Eindhoven University of Technology

The Netherlands

Supported by

Materials Devices Systems COBRA

Genexis
fiber to the home

Ocean Optics
First in Photonics

BFi OPTiLAS

Newport
Experience | Solutions

Spectra-Physics
A Division of Newport Corporation

LASER 2000
THE FUTURE of PHOTONICS

simac

ISBN: 90-6144-989-8

Eindhoven University of **Technology**

Department of **Electrical Engineering**

Division of **Telecommunication Technology** and **Electromagnetics**

http://tte.ele.tue.nl