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Silicon Nanophotonics and Its Applications in Sensing

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Abstract: We present photonic wire waveguides and basic components in Silicon-on-Insulator (SOI). A large number of these compact SOI devices fit on a single chip. We describe possible applications in biochemical sensing and strain sensing.

OCIS codes: (230.3120) Integrated optics Devices; (250.5300) Photonic integrated circuits; (230.7370) Waveguides;

1. Introduction

Silicon-on-Insulator (SOI) is a very interesting material system for highly integrated photonic circuits. The high refractive index contrast allows photonic waveguides and waveguide components with submicron dimensions to guide, bend and control light on a very small scale so that various functions can be integrated on a chip. Moreover, the photonic circuits can be fabricated using the existing manufacturing equipment that is used for CMOS electronics, allowing inexpensive mass fabrication [1]. Ultimately photonic and electronic circuitry can be integrated on a single chip [2]. However, silicon photonics also poses a lot of challenges. The required accuracy on the waveguide dimensions is 1 to 10 nm, also the refractive index is sensitive to temperature variations. In this paper we first present SOI waveguides and ring resonators, followed by sensor applications of these components.

2. SOI photonic wires and ring resonators

Photonic wires are optical waveguides with a submicron core and a high index contrast. We use a core thickness of 220nm with a width smaller than 580nm for single-mode operation a 1.55μm wavelength (TE-polarized light). In straight photonic wires, we have demonstrated propagation losses as low a 2.4dB/cm [1][3]. We have also studied bend losses using large spiral waveguides (inset in Fig. 1b) with sufficient length (up to 50mm) and number of bends (up to 550 bends). From Fig. 1a, which shows the transmission for spirals with a 3μm bend radius we can extract the propagation loss and the excess loss per bend. As can be seen in Fig. 1b the excess bend losses increase dramatically for sharper bends. For a 5μm bend, the losses are lower than 0.01dB/bend

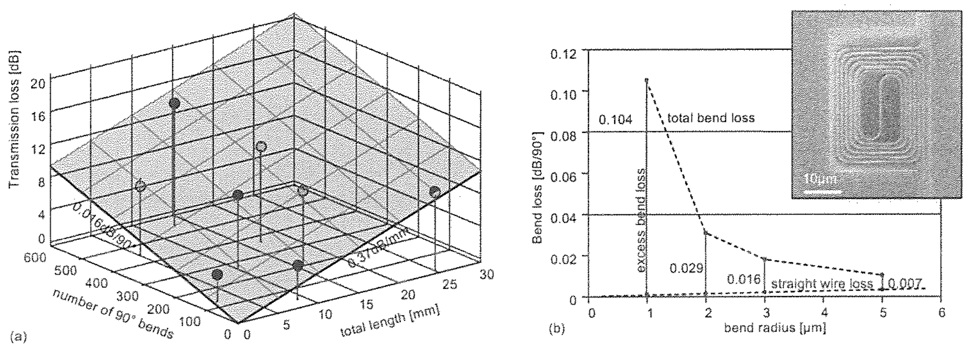

Fig. 1. Bend losses in photonic wire waveguides. (a) transmission of various spiral waveguides with a 3μm bend radius (SEM picture in inset). (b) extrapolated bend losses of spirals with different bend radius.

Thanks to the low bend losses, microring resonators with a small radius and consequently a large free spectral range (FSR) can be achieved in SOI. To obtain sufficient coupling between the ring and the input and output waveguides, we use racetrack resonators with a straight coupling section (Fig. 2). With a 2μm radius, Q-factors of 5000-9000 can be achieved. Because the resonance wavelength is strongly dependent on the effective index, these microring resonators can be used a sensor elements or as (tunable) wavelength filters. Thanks to the small size, many structures fit on one small chip. If one succeeds in integrating photodetectors and electronics on the same chip, then a system on a chip with both sensors and spectrometers becomes feasible. We will now discuss three possible applications of (passive) SOI circuits as sensors.

3. Microring resonator biosensor

In label-free biosensors, a receptor layer is located on top of the silicon. These receptors bind to specific biomolecules and consequently the refractive index changes. In response to this change, the resonance wavelength of the ring shifts. Thanks to the large Q factor and the fact that a substantial part of the optical mode is outside the silicon core, a large sensitivity can be achieved . Using salt concentrations with a well known refractive index, we measured that a wavelength change of 1pm corresponds to a refractive index change of 1.3 10^{-5}. Using biotin/avidin as a model of receptor/ligand interaction, a wavelength change of 1pm corresponds to a concentration of 6 ng/ml.

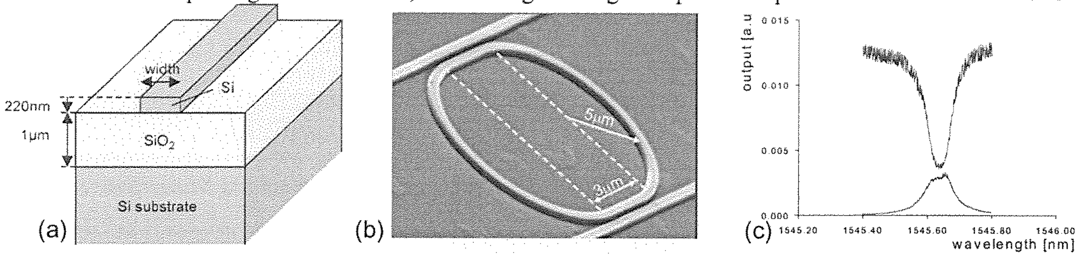

Fig. 2. a) photonic wire waveguide, b) racetrack resonator, c) add/drop spectrum

4. Surface plasmon interferometer

The use of surface plasmon resonance (SPR) for biological and chemical sensing is well established. The high sensitivity of this technique to surface phenomena makes it ideal for use in real-time and label-free biosensors. In [4], we have proposed a novel configuration for a biosensor in SOI. The basic element is a thin layer of gold embedded in the silicon waveguide layer (fig. 3). Two surface plasmon modes are excited at the beginning of the gold layer. As they propagate through the structure, the phase of the top surface plasmon mode is influenced by the refractive index of the environment, while the phase of the bottom surface plasmon mode is insensitive to any refractive index changes. At the end of the gold layer, both surface plasmon modes will interfere constructively or destructively, depending on the relative phase. The calculated transmission vs. refractive index is shown in fig. 3b.

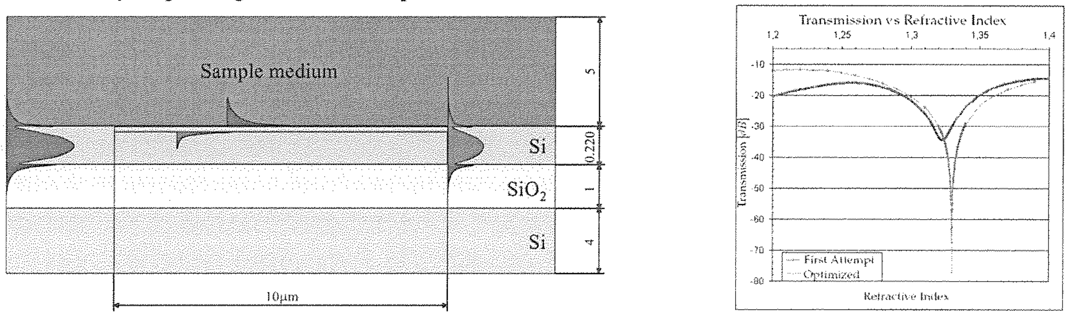

Fig. 3. a) Sketch of surface plasmon interferometer on SOI. Dimensions are indicated in μm. b)Calculated transmission for this structure.

5. Strain sensors

A different type of sensor is a strain gage. Strain is expressed as $\varepsilon=\Delta L/L$ and strain gages are used in mechanics research and structural health monitoring. A well known optical strain sensor is the Fiber Bragg Grating, where the wavelength shift of the reflection peak is a measure of strain. In a similar way, the resonance wavelength of a racetrack resonator is dependent on strain. Thanks to the use of SOI, the FSR of the ring resonators can be tens of nanometers and several sensors can be put in series (wavelength multiplexing). To use it as a strain gage, the SOI circuit is transfered from a thick silicon substrate to a thin flexible foil. First, non optimized devices had a sensitivity of 0.65 pm wavelength shift per $\mu\varepsilon$, measured on a sensor bonded to an Al plate. The main advantages compared to electrical gages are immunity to electromagnetic interference and the absolute wavelength measurement.

6. References

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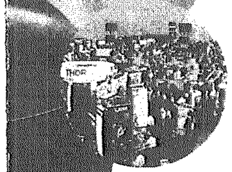

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