A thin foil optical strain gage based on silicon-on-insulator microresonators

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ABSTRACT

We present a novel type of optical strain gage. The strain gage consists of a thin polyimide foil with an integrated optical circuit. The strain sensing elements are optical microresonators. The optical response to strain of these microresonators is a wavelength shift of the resonance wavelength. The optical circuit includes several of these resonators to measure strain in different directions. The strain sensor is read-out using a single-mode optical fiber. Because the different microresonators in the optical circuit have different resonance wavelengths, they can be read out using the same fiber. Our strain sensor is some kind of a cross between electrical resistance foil gages and fiber Bragg grating (FBG) sensors. It is a thin foil device, with a thickness of a few tens of micrometers, but it is an optical device and can be read out in a similar way as FBG sensors. We present the working principle, fabrication and first experimental results.

Keywords: Strain sensor, silicon, integrated optics

1. INTRODUCTION

Optical fiber sensors based on FBGs are well known because of their immunity to electromagnetic interference, optical multiplexing and relatively high sensitivity. We report here on a new type of strain sensor that tries to implement these assets in a small, thin foil, strain gage. This strain sensor uses an optical circuit with several microresonators. In figure 1, a microresonator is shown with a typical transmission spectrum. In this example, the width of the resonance peak is 0.12 nm. Because of the nature of the resonator, there is not a single resonance peak, but the spectrum is periodic and the period is called the free spectral range (FSR). In [1], a polymer microresonator was demonstrated that can be used as a strain sensor, but this polymer structure had a very limited FSR. In high refractive index contrast silicon-on-insulator waveguides, microresonators with a much smaller diameter and hence larger free spectral range (several tens of nanometers) can be made [2]. In the silicon-on-insulator (SOI) material, the waveguide core is a crystalline silicon layer with n=3.45, and it is surrounded by SiO_2 (n=1.45) cladding layers. The shift of the resonance wavelength of a resonator is given by $\frac{\Delta\lambda}{\lambda} = \frac{\Delta L}{L} + \frac{\Delta n_{eff}}{n_{eff}}$ where L is the length of the resonator and n_{eff}, the effective index of the guided mode.

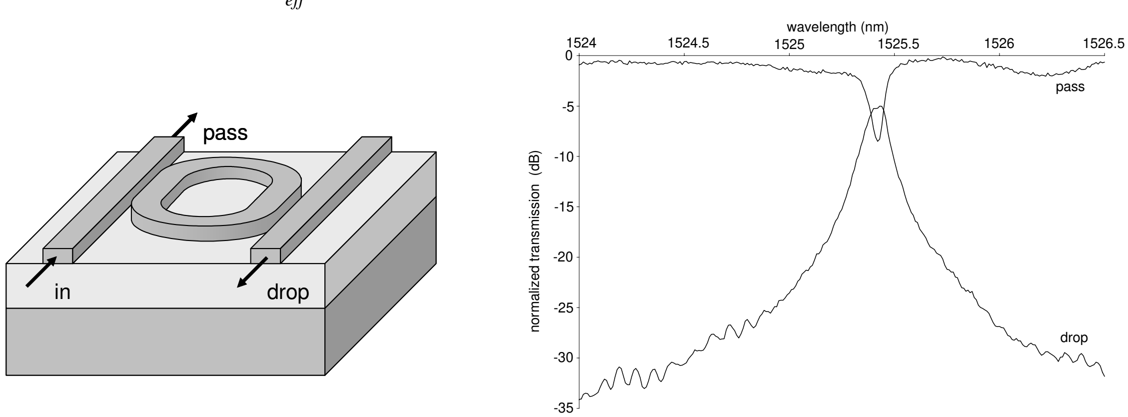

Fig. 1. Schematic drawing of microring resonator and experimental transmission characteristic of a SOI microresonator.

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A circular microresonator (ring resonator) is sensitive to strain in any in-plane direction. By adding two straight sections, a so-called racetrack resonator is created and a different sensitivity to strain in two orthogonal directions can be achieved. In table 1, the theoretical wavelength shift as a function of strain is shown for several SOI racetrack resonators. The geometrical parameters are chosen in such a way that the circumference of the resonator (and hence the FSR) is approximately the same. The wavelength shift $\Delta\lambda$ is expressed in pm and the strain ε in $\mu\varepsilon$.

Table 1. Calculated sensitivity of a SOI mircoresonator for different geometrical parameters. The sensitivity is expressed in pm/$\mu\varepsilon$.

y x		FSR ≈ 16 nm	ε_{xx}	ε_{yy}
R L	R=4µm L=6µm	L_{bend} ≈ 24µm $L_{straight}$ = 12µm	$\Delta\lambda=0.99\varepsilon_{xx}$	$\Delta\lambda=0.63\varepsilon_{yy}$
	R=3µm L=9µm	L_{bend} ≈ 18µm $L_{straight}$ = 18µm	$\Delta\lambda=1.18\varepsilon_{xx}$	$\Delta\lambda=0.45\varepsilon_{yy}$
	R=2µm L=12µm	L_{bend} ≈ 12µm $L_{straight}$ = 24µm	$\Delta\lambda=1.30\varepsilon_{xx}$	$\Delta\lambda=0.34\varepsilon_{yy}$

Experimental results on the microresonators with 4 µm radius, will be presented in this paper. It should be noted that the cross-sensitivity to strain in the transverse direction is still rather high for this structure. This can be improved by using longer straight sections and smaller bend radii. There is however a lower limit to the radius of the bend, because radiation losses will increase in the bend when the radius becomes to small. We expect that the smallest bend radius with acceptable losses will be around 2 to 2.5µm in practice.

2. FABRICATION OF THE SENSOR

First the optical circuit is made on a silicon-on-insulator (SOI) wafer. The fabrication of the optical circuit consists of several standard processing steps (lithography, reactive ion etching). This processing is performed in a fabrication line that is also used for the fabrication of CMOS electronics [3]. However the number of processing steps required for the optical circuit is much lower than for electronics circuits. A close up of the resonator structures is shown in figure 2. After the fabrication of the SOI circuit is completed, it is not yet suitable as strain sensor because it is made on a thick (approximately 700µm) silicon substrate. This silicon substrate can be thinned down by grinding to less than 50µm, but even then it is not suited as strain gage, because the silicon is brittle and has a high elastic modulus. Therefore we have transfered the SOI optical circuit to a flexible foil and completely removed the original silicon substrate.

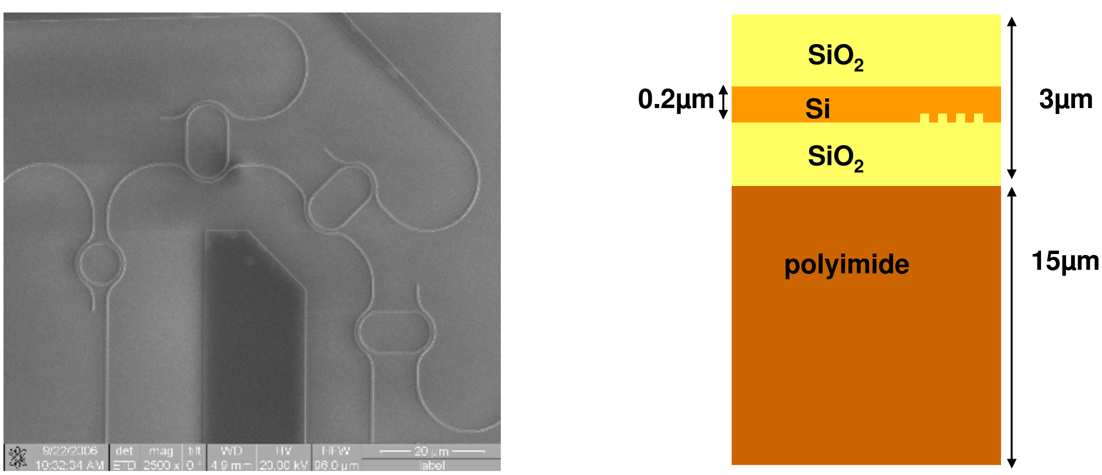

Fig. 2. Left : Top view of the optical integrated circuit consisting of several microresonators. The diameter of the bends in the resonators is 8 µm. Right : Layer stack of the thin foil optical strain sensor. The optical circuit is etched in the silicon layer. The oxide layers form the cladding of the optical waveguide.

On top of the SOI, a polyimide layer is created by spinning and thermal curing. The thickness of this polyimide layer can be chosen anywhere between 5 and 50 µm. Afterwards the original silicon substrate is completely removed by mechanical and chemical processing steps. The final step in removing the substrate is a wet etch using potassium hydroxide (KOH). This etchant has a very good selectivity $Si:SiO_2$ and consequently the silicon substrate can be completely removed while the SiO_2 layers remain intact. The resulting layer structure is shown in figure 2. This is a thin flexible foil, that can be handled and bent without damaging the integrated optical circuit.

It is also possible to spin a second polyimide layer on top of this structure to create a symmetric structure. Polyimide is used because it has good thermal stability, good resistance to solvents and corrosives, low moisture absorption and a relatively low elastic modulus (8.5 GPa in our case). Because polyimide is also used as backing material in electrical resistance strain gages, the bonding materials and procedures for bonding the gages to a workpiece are already well established.

3. EXPERIMENTAL RESULTS

To perform measurements, the strain sensor was bonded on an aluminum beam. A photo of the bonded strainsensor is shown in figure 3. The strain sensor was bonded using M-Bond 200 adhesive [4], a commercially available adhesive for bonding of thin foil strain gages. In our first experiments, we have bent the beam by fixing one end and moving the other end over a known distance using a micrometer srew. The bending induces tensile strain at the upper surface of the plate, that is measured by the strain sensor. To read out the sensor, light is coupled in and out of the optical circuit using single-mode optical fibers. A broadband light source (SLED) is connected to the input fiber and a spectrum analyzer to the output fiber. During our experiment, the fibers were mounted on translation stages to align them with the optical circuit, but in the future the fibers will be glued to to the strain gage.

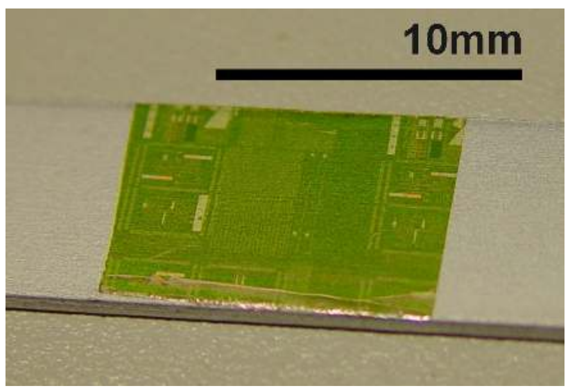

Fig. 3. Thin film optical strain sensor bonded on an aluminum test plate. The sensing circuit itself (microring resonator) is not visible with the naked eye, but some other alignment patterns are.

The measured shift of the resonance wavelength of the resonators, is plotted in figure 4, as a function of the deflection of the aluminum beam. The 4 curves correspond to 4 resonators with a different shape, as indicated on the figure. A linear relation between the deflection and the measured wavelength shift is obtained. From the deflection of the plate we can estimate the theoretical strain at the top surface. Qualitatively the experimental results agree well with the theoretical predictions. In the near future, a tensile test will be performed to more accurately characterize the sensitivity and make a quantitative comparison with the theoretical results.

The largest wavelength shift obtained was 1.7 nm, corresponding to approximately 1700 µε. This limit is due to our current measurement setup. In this range, the behaviour of the sensor was linear and reversible.

We have demonstrated a proof-of-principle device. It should be noted that the structures used are not yet optimized and that the sensitivity and cross-sensitivity can be improved. We have also not adressed the issue of temperature effects and compensation in this paper.

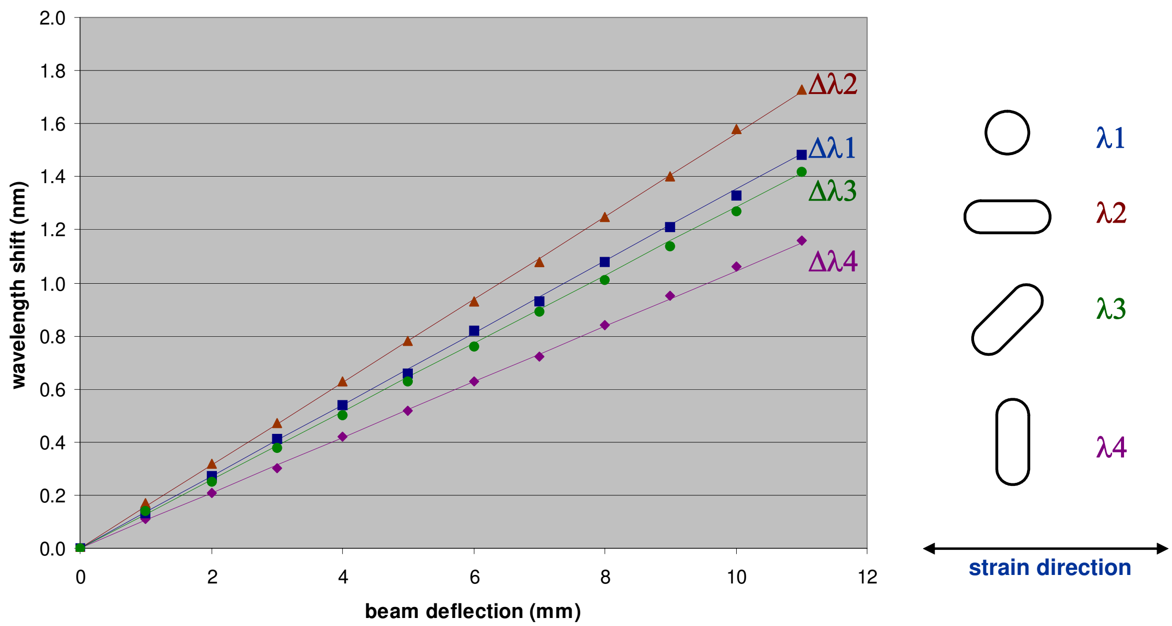

Fig. 4. Measured wavelength shift of the resonance wavelength as a function of the beam deflection. The 4 curves correspond to the 4 resonators with different shape (see also figure 2).

4. CONCLUSIONS

We have presented the principle, fabrication and first experimental validation of a new type type of optical strain sensor. Based on a theoretical calculation, we expect a sensitivity up to 1.3 pm wavelength shift per με using an optimized device design.

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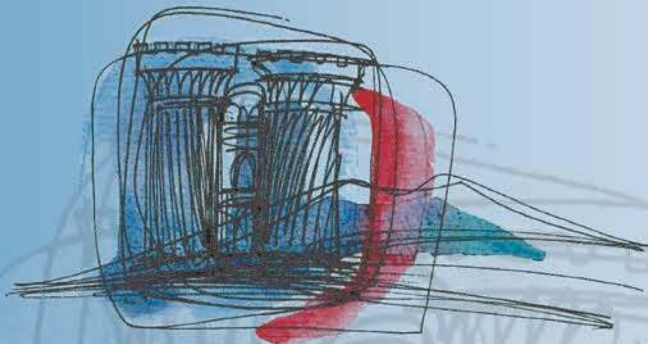

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