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Research paper

Micro-fabricated all optical pressure sensors

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ABSTRACT

Optical pressure sensors can operate in certain harsh application areas where the electrical pressure sensors cannot. However, the sensitivity is often not as good for the optical sensors. This work presents an all optical pressure sensor, which is fabricated by micro fabrication techniques, where the sensitivity can be tuned in the fabrication process. The developed sensor design, simplifies the fabrication process leading to a lower fabrication cost, which can make the all optical pressure sensors more competitive towards their electrical counterpart. The sensor has shown promising results and a linear pressure response has been measured with a sensitivity of 0.6nm/bar.

1. Introduction

Sensing using Micro Electro Mechanical Systems (MEMS) is employed in many different applications, where pressure, acceleration and temperature sensing are most common [1–3]. MEMS sensors are electrical devices which is a disadvantage in some special cases. Electrical and magnetic fields can perturb the current flow in a MEMS device. Hence, reliable sensing in strong fields can be difficult. Another disadvantage is the risk of sparks during a short circuit. This can lead to dangerous situations if the sensing application is within flammable environments. For sensing in such environments optical sensors will be the obvious choice, since they are immune to electromagnetic interference, and have no risk of generating sparks.

Optical sensing can be divided into several subgroups, where amplitude-modulated (AM) and frequency-modulated (FM) are the most common ones. The AM optical sensors measure changes in the amplitude of a given optical signal. Hence, AM sensors are not suited for remote sensing. The readout, of FM optical sensors, is not affected by small reductions in the intensity, since it measures changes in frequency. This property makes it ideal for remote sensing, where the optical signal is transmitted in an optical fiber. FM optical sensors, like Fiber Bragg Gratings (FBG), are already commercialized and used in many sensing areas [4–6] . FBGs are optical fibers with a Bragg grating written in the core. They are easily fabricated by few process steps. By using optical fibers the final design has low weight, becomes flexible and has high temperature tolerance. The challenge for FBG based sensors is to transform a sensing input into longitudinal strain, since FBGs essentially measure strain, due to changes in the grating period. In order to determine other properties e.g. pressure, the input signal has to be converted into strain, which usually requires additional mechanical structures to surround the FBG. Several papers have been written with ideas on how to convert pressure into strain in an efficient way [7–11] . These structures can be tedious to fabricate, large in size and can have limited degrees of freedom regarding sensitivity.

The sensor, presented in this paper, is a Micro Optical Electro Mechanical System (MOEMS) that combines the best properties from optical fibers and MEMS fabrication. The sensor design is a metal free on-chip optical system, where an optical fiber is glued to a $6 \times 6\ \text{mm}^2$ micro-fabricated chip as shown in Fig. 1.

The presented sensor possesses all the features from FM sensors and can be used in similar application areas. The fact that the sensor is completely metal free opens up for new applications e.g. in the wind turbine industry. The pressure sensor can be mounted on wind turbine blades, where metal-based sensors would act as a lightning rod, which can lead to damage of the electronics in the wind turbine, or the blades during a thunder storm.

2. Design

The principle of the device is to guide light in an optical fiber into a micro-fabricated chip with a confining $10\ \mu\text{m}$ tall cavity, wherein a Bragg grating is defined as illustrated in Fig. 2. The Bragg grating reflects a specific wavelength, which gives rise to a Bragg peak in the reflected spectrum. The measured quantity is the position of the Bragg peak. The cavity is defined between a diaphragm and a thick

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bottom substrate. The 3D sketch of the device in Fig. 1 has a partly removed silicon diaphragm (top part) to illustrate the encapsulated structures. The chip is made of silicon, dielectric thin films and the polymer Bisbenzocyclobutene (BCB). The rectangular SiO_2 region in the sketch is the Bragg grating. The light has to propagate inside an air core (cavity), which introduces large losses compared with the propagation inside an optical fiber. SiO_2 and Si_3N_4 thin films are deposited on the cavity surface in order to minimize propagation losses. This specific combination allows wave guiding properties inside the air-filled cavity. The waveguide effect is known from literature as an anti-resonant reflecting optical waveguide (ARROW) [12–14] . An ARROW is, opposite to conventional Total Internal Reflection waveguides, able to guide light in a core with a lower refractive index than the surroundings. The thickness and refractive indices, of the SiO_2 and Si_3N_4 thin films, are chosen such that the optical loss is minimized for light with a wavelength of approximately 1550 nm.

The lower image in Fig. 1 shows the final device consisting of an optical fiber, a V-groove and a MEMS sensor. The V-groove is a bulk piece of glass that surrounds the end of the optical fiber, it is used to ease the gluing process between fiber and chip and to give mechanical stability.

3. Theory

The sensing principle of the presented sensor is similar to traditional FBGs, where a wavelength shift is measured in the reflected spectrum. This measuring technique utilizes the linearity in the Bragg equation given by:

$$\lambda_B = 2n_{\mathrm{eff}}\Lambda \tag{1}$$

where λ_B is the Bragg wavelength or reflected wavelength, n_{eff} the effective refractive index and Λ is the Bragg grating period. FBGs measure strain by detecting changes in the grating period, where the presented sensor measures changes in the effective refractive index. The sensitivity of the sensor is determined by the thickness of a silicon diaphragm, which can easily be controlled in an etch process. Hence, the sensitivity is tunable for both low and high pressure applications.

The concept of the sensor is shown in Fig. 2. Light emitted from the optical fiber gets confined inside the cavity. The confinement and refractive index depend on the cavity height. By introducing a Bragg grating on the bottom substrate it is possible to perturb the cavity height periodically and thereby effectively make up a Bragg reflector. The fiber geometry is cylindrical and the cavity has a slab waveguide geometry, a mismatch in the mode profiles is thus unavoidable. For this reason significant coupling losses is expected, however, quantitative values are not known.

Sub-figure A shows the initial state where the Bragg wavelength is λ_B. The diaphragm is flat due to an identical pressure inside,p_0, and outside, p_1, of the cavity ($p_1 = p_0$). If a pressure difference is present the diaphragm deflects (scenario $p_1 > p_0$) as seen in sub-figure B. The deflection leads to a higher confinement of the light, resulting in a change in the effective refractive index, hence a measurable wavelength shift of $\Delta\lambda_B$. The diaphragm deflection is thus correlated with the wavelength shift. The corresponding reflected spectrum is shown in sub-figure C.

The increased confinement reduces the effective refractive index [15]. The measured quantity is the Bragg wavelength shift, and it is expected to go towards lower wavelengths when pressure is applied. Experiments have shown the sensor should be dimensioned such the center deflection w_0 is maximum 20% of the cavity height, H. Larger deflections will gives rise to undesired nonlinearities in the reflected spectrum. In order to dimension the sensor the following

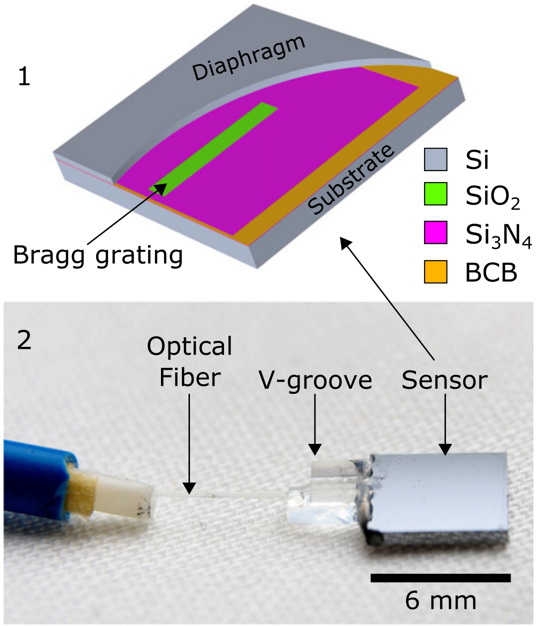

Fig. 1. Pictures of the presented pressure sensor. 1) 3D schematics of the sensor, for an illustrative purpose the majority of the diaphragm is removed such that the encapsulated part becomes visible e.g the Bragg grating. 2) Image of the final sensor, showing the sensor chip coupled to an optical fiber using a V-groove.

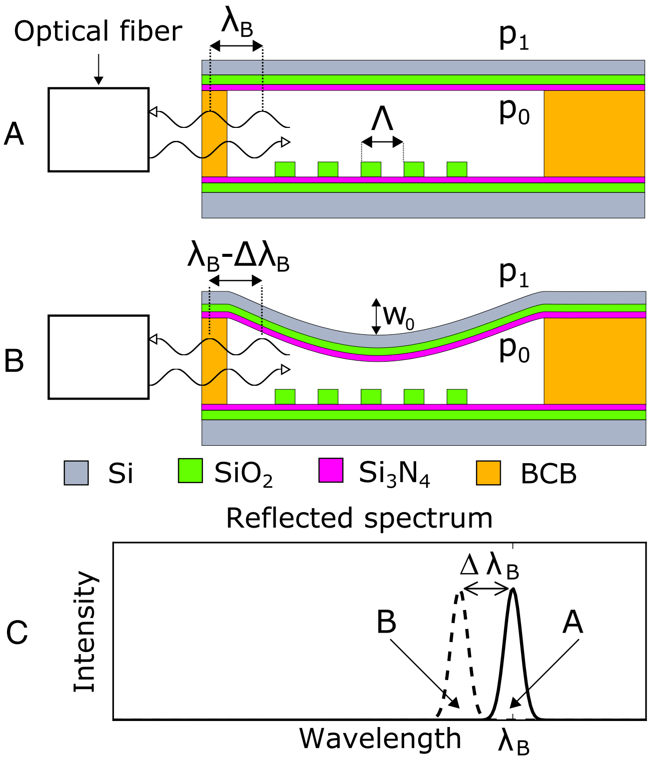

Fig. 2. A concept sketch of the presented sensor design. A: Cross-sectional view of the sensor at its equilibrium state, with a reflected wavelength of λ_B. In this case, the pressure is identical inside and outside of the cavity ($p_1 = p_0$). B: The sensor when a pressure is applied ($p_1 > p_0$). The diaphragm is deflected due to a pressure difference, which alters the effective refractive index such that changes in the wavelength $\Delta\lambda_B$ can be measured. C: The reflected spectrum for the sensor in both the equilibrium state and the state where pressure is applied (sub-figures A and B). A shift towards lower wavelength is observed. Sub-figures A and B are not to scale.