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Integrated optical differential pressure transducers achieved using thin buckled silica membranes and direct UV written planar Bragg gratings

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ABSTRACT

Direct UV written differential pressure sensors have been fabricated in a silica-on-silicon platform. The reported components achieve physical sensitivity through actuating planar Bragg gratings defined within a thin (<40 μm) silica membrane. The optimised transducer exploits the condition of static membrane buckling to resolve both positive and negative pressure differentials, either side of the membrane. The fabricated device has demonstrated operation over a 202 kPa range with a 0.36 kPa resolution.

1. Introduction

Recent developments of miniaturised membrane transducers have allowed differential pressure sensing capabilities to be integrated upon a single compact chip [1]. The technique by which these components operate can broadly be classified into optical [2,3] or electrical [4–6] methods. Optical methods generally have advantages over electrical methods as they possess inherent immunity to electromagnetic interference and the ability to operate in flammable environments. The reported developments of such optical techniques can, in turn be further classified into intensity modulation [7,8], polarisation modulation [9,10] and phase modulation [9,10] approaches. The use of Bragg grating waveguides is yet another direct optical approach [14,15], the specific advantages of which include a relative insensitivity to intensity variation and an inherent ability to be multiplexed.

The majority of reported differential pressure sensors, based on Bragg grating waveguides, have generally been confined to optical fibre based gratings [14–16]. In these reported structures the fibre Bragg grating is anchored to at least one locations on a membrane and is stretched as the membrane deforms. Whilst this indicates deflection between two points, information about stress across the membrane is lost, as the gratings are not structurally contained. Also in terms of compact chip fabrication, it must be noted that optical fibre is not a platform inherently suited to planar integration. Recent publications reporting silica micro-cantilever transducers have used a direct UV writing (DUW) technique to physically define Bragg gratings within a planar integrated structure. This technique allows the local characterisation of stress within an integrated optical chip [17]. Using such DUW technology, this paper reports the fabrication of planar Bragg gratings structurally integrated into a silica membrane, illustrated in Fig. 1. This novel design allows stress information across the membrane to be accessed through multiplexing, in addition to providing a platform inherently suited to planar integration.

Two DUW membrane devices are reported in this paper. The first demonstrates stress mapping of a buckled silica membrane. The second device contains a single, optimally placed Bragg grating and exploits static buckling to maximise positive and negative pressure differential sensing.

2. Concept and theory of device operation

A membrane can be buckled by applying a pressure differential between both of its surfaces. This buckling induces strain within the structure of the membrane. If a Bragg grating is inherently defined within the membrane it shall be affected by this strain. The effect of straining a Bragg grating is to spectrally shift its Bragg condition. The following section formulates the theoretical spectral shift expected for a Bragg grating in an arbitrary location of a membrane undergoing buckling.

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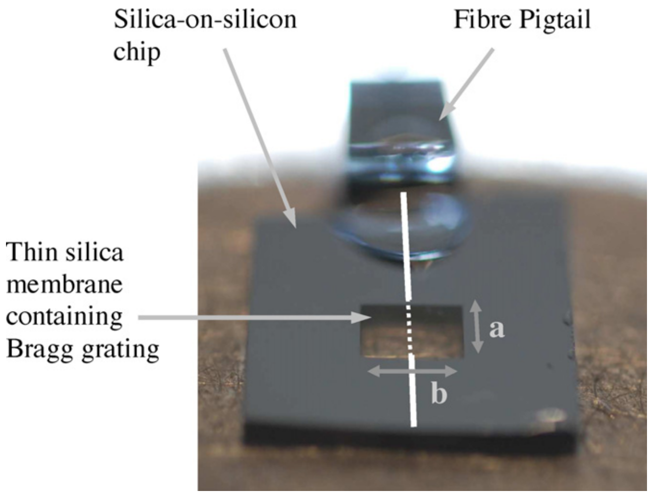

Fig. 1. Image of fabricated silica-on-silicon chip, indicating waveguide (solid line) and Bragg grating (dashed line) locations with respect to the thin square silica membrane.

2.1. Membrane buckling

The form of the first order buckling for an arbitrary rectangular membrane with clamped edges and of dimension a (along the x-axis) by b (along the y-axis), is understood to be of the form [18].

$$w(x,y)=\frac{w_0}{4}\left(1-\cos\left(\frac{2\pi x}{a}\right)\right)\left(1-\cos\left(\frac{2\pi y}{b}\right)\right) \quad (1)$$

where w_0 is a maximum vertical displacement at the centre of the membrane. It must be noted that in this coordinate system the origin is located at a particular corner of the membrane.

When a membrane buckles it induces strain. The strain at particular locations on the membrane can be calculated using [18].

$$\varepsilon_x=\left(1+\left(\frac{\partial w}{\partial x}\right)^2\right)^{1/2}-1 \quad (2)$$

$$\varepsilon_y=\left(1+\left(\frac{\partial w}{\partial y}\right)^2\right)^{1/2}-1 \quad (3)$$

where ε_x and ε_y are the strains along the x-axis and y-axis respectively. It must be noted that strain along the z-axis ε_z can be inferred using the Poisson phenomenon and the calculated values of ε_x and ε_y.

2.2. Optical response to strain

The fabricated devices reported consist of planar Bragg gratings that are structurally part of a thin silica membrane. When strain is induced in the membrane, it results in a fractional change in the grating's pitch and a change in the refractive index of the silica membrane due to the strain-optic effect [19]. Thus the induced strain can be monitored from the spectral response, $\Delta\lambda$, of the grating. It is understood that for a Bragg grating orientated normal to the x-axis, the spectral response of TE and TM polarisations to physical strain is [20]

$$\frac{\Delta\lambda_z}{\lambda_z}=\varepsilon_x-\frac{n_z^2}{2}(p_{11}\varepsilon_z+p_{12}(\varepsilon_y+\varepsilon_x))+\eta\ \Delta T \quad (4)$$

$$\frac{\Delta\lambda_y}{\lambda_y}=\varepsilon_x-\frac{n_y^2}{2}(p_{11}\varepsilon_y+p_{12}(\varepsilon_z+\varepsilon_x))+\eta\ \Delta T \quad (5)$$

where λ_z and λ_y are TE and TM polarisations, ε_i, represent the strain components acting along the spatial directions, p_{11} and p_{12} are the strain optic coefficients [21] and n_x and n_y are the unstrained effective refractive indices of TE and TM modes respectively. The final term $\eta\ \Delta T$ is the thermal response, which we have separately measured to be ~10 pm °C^{-1}. From Eqs. (4) and (5) the birefringence can be calculated as

$$\Delta(n_x-n_z)=\frac{n^3}{2}((p_{11}-p_{12})(\varepsilon_x-\varepsilon_z)) \quad (6)$$

The following section describes the steps implemented to achieve device fabrication.

3. Fabrication

The device fabrication process is illustrated in Fig. 2. The first stage involves the consolidation of two individual silica layers that have a total combined thickness of 21 μm upon a 0.986 mm thick silicon wafer that has a 16 μm of thermally grown oxide. The silica layers are formed using flame hydrolysis deposition (FHD) and consolidated at ~1200–1300 °C. After consolidation they form, with the thermally grown oxide, a combined silica thickness of 37 μm. The silica layer sandwiched between the thermal oxide and the final FHD silica layer is 6.5 μm thick. This central core layer is doped with germanium which makes it photosensitive to UV radiation.

The second stage of fabrication involves using a direct UV writing technique to define both channels and Bragg gratings [22]. This process focuses two coherent UV laser beams into the central photosensitive germanium doped layer resulting in a refractive index change of approximately 5×10^{-3}. The focused spot has a diameter of 7 μm and consists of a series of interference fringes at the approximate Bragg period. Waveguides are produced by traversing the interference spot across the sample. Bragg gratings are produced by modulating the beams in synchronisation with the sample translation. All gratings in this work have been Gaussian apodised and have a length of millimetre order.

In the third stage of fabrication an area of thermal oxide and silicon is selectively removed (~500 μm depth) on the underside of the device using a micro-grinder (Dremel tipped milling bit) and a xyz-translation stage. This exposes an area of the underlying silicon whilst the rest of the silicon remains masked by the oxide.

In the final stage the exposed silicon is etched in a 5.0 M solution of potassium hydroxide (KOH) for ~48 h at 90 °C, which anisotropically etches the exposed silicon. To account for the anisotropic etch a ~1 mm border offset is made around the area of the desired membrane in the third stage of fabrication, e.g. a 10 mm × 10 mm membrane has a 12 mm × 12 mm exposed area.

The reflection spectra of the gratings are observed using an Optical Spectrum Analyser (OSA) at a resolution of 10 pm, the resulting spectral data was curve fitted to a Gaussian model to match the apodisation. The thermo-optic coefficient of the Bragg gratings are 10 pm °C^{-1} and thermal variations in the laboratory during data collection was ~3 °C. For all data sets taken a temperature reference grating is located in the bulk of the chip. This allows the data to be thermally compensated. With thermal compensation and curve fitting algorithms an absolute ~0.1 pm spectral shift resolution can be achieved.

4. Stress map characterisation

To investigate the theoretical model constructed in Section 2 a thin silica membrane with 1 0 0 evenly distributed Bragg gratings was characterised. This evenly distributed array of multiplexed sensors acted as a stress map for the membrane, characterising the stress at particular positions.

The fabricated membrane was centrally located upon a 20 mm by 20 mm silica-on-silicon chip. The size of each Bragg grating in this membrane was 1 mm long, so to evenly distribute the Bragg