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Topical Review

Direct UV-written planar Bragg grating sensors

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Abstract

Integrated photonics is a proven platform for physical and chemical sensing. It offers miniaturised solutions that are suited for use in extreme environments, including strong EM-fields, EM-pulses and contact with flammable materials, often far exceeding electronic sensors in this regard. This review looks into direct UV-written planar Bragg grating technology and its application to integrated photonic sensors. The platform has been demonstrated widely for measurement of physical properties such as temperature, pressure and strain. In addition, by using an evanescent interaction, refractive index can be measured allowing for chemical and biochemical detection. Further to this, the platform has recently been utilised in quantum information processing, where quantum gate operations and single photon detection has been shown.

Keywords: Bragg gratings, sensors, direct writing

(Some figures may appear in colour only in the online journal)

1. Introduction

Optical fibres provide an ideal platform for sensor technology, offering unique capabilities in terms of distributed sensing, freedom from EM interference, and the ability to make use of technology developed within the telecommunications arena. They are widely deployed for applications ranging from structural monitoring through to oil and gas. There is extensive literature on the use of fibres for sensing and many recent books [1, 2]. One particular class of fibre sensor makes use of Bragg gratings, which have distinct advantages over other optical sensors, including spectral multiplexing and the ability for self-referencing. These again have been recently reviewed [3–5], with more detail on the underlying properties of Bragg gratings also present in the literature [6, 7]. While fibre based Bragg gratings have advantages for monitoring over large physical distances (several km’s), the newly developing field of planar Bragg gratings offers miniaturised dimension scales, compact multi-parameter sensing and the scope for microfluidic and MEMS (microelectromechanical systems) interfacing. The integrated platform offers lab-on-a-chip capability where refractive index, pressure, flow and temperature can be monitored [8–14]. Furthermore, through spectral multiplexing both platforms are compatible meaning integrated optical planar chips can distributed over larger distances as part of a fibre based sensing network.

The purpose of this report is to review one field of planar Bragg grating development that uses direct UV writing (DUW) in the fabrication of sensor components. The DUW sensors reviewed in this paper (illustrated in figure 1, as a lab-based prototype (left) and a commercialised packaged sensor (right) [9]) are based within the industry standard silica-on-silicon
platform, although recent work has seen the demonstration of an all UV written planar Bragg grating device in polymer (PMMA) for measuring static strain [15].

The review is structured as follows: section 2 describes the fabrication principles behind DUW and grating responses. Section 3 describes the physical sensing regimes and section 4 describes the refractive index sensing regimes.

Bragg gratings are ideally suited to indicate either a physical and/or an external refractive index change in the environment. This is principally achieved through monitoring spectral shifts in the Bragg condition defined as

$$\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda_{\text{Bragg}}$$  \hspace{1cm} (1)

Where $\lambda_{\text{Bragg}}$ is the Bragg wavelength, $n_{\text{eff}}$ is the effective refractive index of the waveguide and $\Lambda_{\text{Bragg}}$ is the period of the Bragg grating. Through device design the Bragg response can be optimised for physical and/or refractive index sensing. Physical strain monitoring is enhanced through manipulating the moment of area and position of the neutral axis with respect to the grating. Components can be miniaturised through the fabrication of on-chip micromechanical elements. Refractive index monitoring can be achieved using evanescent field exposure, in which case sensitivity is enhanced through modal manipulation and selectivity through surface functionalization. Through a combination of physical and refractive index sensor components, chips can be tailored using selected combinations thereof to address multi-parameter detection.

2. Direct UV writing

In contrast to alternative direct writing techniques that typically use femtosecond pulsed lasers [16, 17], DUW uses a continuous-wave UV laser to define waveguides. The technique is inherently conducive to rapid prototyping and can produce high quality waveguides and Bragg gratings with propagation losses as low 0.24 dB cm$^{-1}$ [18], and mode profiles tailored to match those of coupling fibres (for low coupling losses).

The development of DUW began with developments made in the 1990s by Svalgaard et al [19, 20]. In this work a ‘single-beam’ approach was implemented, which allowed the fabrication of waveguides in a silica-on-silicon planar substrate. Further development at the University of Southampton led to the ability to simultaneously write Bragg gratings and waveguides in a single fabrication step, using a ‘dual-beam’ approach. This dual-beam approach uses two focused coherent UV beams to fabricate both waveguides and Bragg gratings [21] and shall be the attention of this review.

The dual-beam approach requires two coherent laser beams, focused and overlapping to a small spot size (~7 $\mu$m). Due to their coherence the beams form an interference pattern, with an inherent periodicity, $\Lambda$, that can be defined as

$$\Lambda = \frac{\lambda_{\text{UV}} \sin 2\theta}{2}$$  \hspace{1cm} (2)

Where $\lambda_{\text{UV}}$ is the laser wavelength (typically an argon-ion frequency doubled laser, of 244 nm wavelength) and $\theta$ is the intersecting angle, as illustrated in figure 2.

The principle behind Bragg grating fabrication is to synchronise translation and modulation of the interference pattern with respect to a UV photosensitive doped silica layer. It must be noted that the periodicity of the interference pattern is set by the convergence angle of the beams $\theta$. However, due to the small focused spot (~7 $\mu$m diameter) there are typically only a few interference fringes established, meaning that through detuned modulation, the period of interference pattern can be used to produce a range of Bragg gratings that have grating pitches that do not exactly match that of the initial interference fringe period. In the region of the C-band this detuning concept can typically access a 3 dB bandwidth of at least 250 nm [22, 23].

Development of DUW components has typically been made in silica-on-silicon substrates. The composition of which is formed from three silica layers; an underclad, a core layer and an overclad. The core layer being doped with germanium and boron, such to be photosensitive to UV-light [6, 24]. This sensitivity can be further enhanced through hydrogenation [6, 25]. All the silica layers are typically fabricated onto a thick (650 $\mu$m—1 mm) silicon wafer as illustrated in figure 3.

Chip composition is similar to traditional silica-based photolithography and as such has similar material benefits including low coupling loss to optical fibres, low propagation loss in telecommunication bands and potential for integration with semiconductor components such as lasers. Furthermore, DUW has additional benefits of rapid prototyping and removes the dependency for cleanroom processing to define waveguide
structure. Planar DUW has also been demonstrated in germanosilicate flat fibre [26] which has similar properties to silica-based optical fibres, for completeness this review shall also cover the structures developed in this platform.

Upon exposure to UV the photosensitive core layer undergoes a refractive index increase, the magnitude of which is dependent upon the photosensitivity of the substrate and total number of UV photons incident upon a point during the writing process quantified as the fluence parameter, $F$:

$$F = \frac{I_{UV}d}{v}$$

Where $I_{UV}$ is average power intensity, $d$ is the diameter of the spot in the core layer and $v$ is the translation or writing speed. The focused beams generate a small writing spot of the order ~7 μm and have typical writing fluences range from 10 kJ cm$^{-2}$ to 25 kJ cm$^{-2}$, meaning a typical translation speed (for incident UV laser power of 50 mW) of ~3.5 mm min$^{-1}$.

The arrangement of the DUW system is illustrated in figure 4. It consists of a pair of focused coherent UV laser beams in an interferometric arrangement. Waveguides are defined in the core layer through translating the sample on a stage system beneath the interferometer.

2.1. Amplitude modulation

Amplitude modulation synchronises translation speed with single-shot exposures (the dual beams are either on or off), principally achieved using an acousto-optic modulator (AOM) [27]. The coordination of amplitude modulation with respect to positional movement to define a Bragg grating is illustrated in figure 5. Here multiple exposures build up the physical grating profile.

As figure 5 illustrates the sample undergoes a set translation whilst the beams are in an ‘on-state’ $\Delta x_1$ and a set translation $\Delta x_2$ when the beams are in an ‘off-state’. This defines the period and can be arbitrarily set to give a desired Bragg period. The ratio of the set translation during exposure time $\Delta x_1$, to total translation made between the initiation...
of multiple exposures ($\Delta x_1 + \Delta x_2$), is termed duty cycle. Through manipulating duty cycle, fluence and period a range of Bragg grating structures can be fabricated all through computer controlled software, as shall be described later in section 2.3.

A limitation of amplitude modulation is its inefficient use of available laser power. The inefficiency arises as exposure has an ‘off-state’ compounded by the use of the relatively inefficient first diffracted order through the AOM. This unnecessarily increases writing time, compared to the alternative approach of a phase modulation in which the chip is constantly exposed.

2.2. Phase modulation

Phase modulation acts through modulating the phase of one of the two arms in the dual beam interferometer arrangement. This has been demonstrated through using an electro-optic modulator (EOM) as reported by Sima et al [28]. In this method phase manipulation of one path in the interferometer is used to control the fringe pattern as the sample is translated. Figure 6 illustrates the optical set-up of the EOM and a schematic of this operational mode.

During the fabrication process the beam continually illuminates the sample. As illustrated in figure 6, the interference pattern varies with translation such that it translates...
synchronously with the sample, allowing continual exposure. Detuning is accomplished by allowing appropriate phase slippage between the grating movement and sample translation.

The technique provides a unique ability to control grating apodisation and achieve ultrawide Bragg wavelength detuning ranging from 1200 to 1900 nm, which can be written on a single chip. Since there is neither laser power reduction nor writing speed variation, the method offers significantly faster writing speeds, as well as allowing for simplified fluence matching between the input waveguide and grating sections.

The following section reports some of the grating responses achieved using both of these grating writing methods.

### 2.3. Grating responses

Figure 7 shows example grating structures fabricated using DUW. These include gratings with different windowing functions including uniform (figure 7(a)) and Gaussian apodised (figure 7(b)) as well physically structured gratings that give beneficial spectral features for sensing including Fabry–Perot Bragg gratings (figure 7(c)) and tilted planar Bragg gratings (figure 7(d)).

The spectral signature of a Bragg grating can be tailored through manipulating the duty cycle of the defined grating period. To a first approximation the spectral reflection of a weak Bragg grating is a Fourier Transform of the periodic structure [4, 29]. Thus a weak grating whose duty cycle varies with a Gaussian profile over its length will approximate a Gaussian spectral response. The physical form of the grating is thus said to have a Gaussian windowing function. However, in the general case this can be tailored to take any arbitrary function. Figure 8 considers a Gaussian windowing function for an amplitude modulation approach (not to scale). In this instance the duty cycle of the period varies as a (Gaussian) function of grating length, starting at a duty cycle of 1.0 reaching a maximum at the middle of the grating (in this example 0.5) and then retuning to 1.0. To avoid variation in effective refractive index (over/under exposure) the writing speed is in turn varied, also illustrated in figure 8. For the phase modulation approach, writing speed does not need to be compensated for as the laser is always set to an on state and duty cycle is defined through phase slippage.

Detuning can also be used to fabricate multiple gratings at different wavelengths, as illustrated in figure 9. Here we observe 15 Bragg gratings ranging from 1275 nm to 1625 nm, all fabricated in a single fabrication step.

DUW gratings can be used alongside power splitting components to attain specific spectral characteristics, such as Hilbert Transformers [28]. Power splitting components are also a useful tool to combine multiplexed sensor components and distribute components over chip. For example using powers splitters, multiplexed Bragg gratings can be physically distributed over a chip and used in combination. In the following section routes to creating splitters will be discussed.

### 2.4. Power splitting

Low loss power splitting components demonstrated with DUW have included Y-splitters [20], directional couplers [30] and X-couplers [26]. In particular, X-couplers offer the combined advantages of lowest coupling loss, broadest bandwidth, minimal proximity effects [31–34] and tuneable power.
A further advantage of DUW X-couplers is that they have relatively broad band spectra over a large wavelength range [26], illustrated in figure 10(b). The following section describes how the fabrication toolbox is implemented in the development of sensor components.

3. Sensor components

This section is split to describe in detail the developed physical and chemical sensors. Collectively these can be multiplexed into a network of sensor chips or on a single chip allowing multiparameter multiplexed measurements. The platform is fully compatible with fibre Bragg gratings (FBGs) and could form part of a networked arrangement of optical sensors.

3.1. Physical sensing

The most common application for Bragg grating based sensors is in the field of civil engineering, where FBGs have been used over the past 20 years for structural health monitoring [36]. As optical fibres are small and lightweight they can be easily attached to the surface of a structure or embedded inside it, whilst having little impact on the structure itself [36, 37]. Compared to fibre Bragg gratings, one obvious technical complexity is the inherent rigid nature of planar optics,
meaning it is less suited for monitoring torsional and tensile stress. However, through adopting processing similar to that used to fabricate MEMS components it is possible to develop miniaturised mechanical structures on an integrated optical chip [14].

The spectral response of a Bragg grating to strain is readily understood. The relationship is a combination of the stress-optic effect and a physical change in length. Considering three orthogonal components of linear strain this is expressed in equation (4) [1].

\[
\Delta \lambda_{2,3} = \varepsilon_1 - \frac{n_{2,3}^2}{2} [p_{11} \varepsilon_2 + p_{12} (\varepsilon_1 + \varepsilon_2)] + \eta \Delta T
\]  

(4)

Where strain, \( \varepsilon_{1,2,3} \) acts in \( x_1, x_2 \) and \( x_3 \) components, \( p_{11} \) and \( p_{12} \) are elements of the stress-optic tensor and \( \eta \) is the thermo-optic constant, dependent upon thermal variations \( \Delta T \). This notation considers a planar waveguide, whose propagation is in the \( x_3 \) component and supports TE (effective modal index \( n_{23} \)) and TM (effective modal index \( n_{33} \)) modes.

Thermal expansion is usually summarised in the third term of equation (4), rather than consider the strain terms individually. In the case of silica-on-silicon the thermo-optic coefficient typically takes values in the range of 9 pm K\(^{-1}\) to 11 pm K\(^{-1}\) at 1550nm and is approximately linear over a large operational range [38]. It is important to note that all gratings are subject to thermal variation and therefore by including an on-chip temperature reference grating, the accuracy of all other gratings can be enhanced.

Physical strain can be induced through simple bending, including three-point and four-point bending regimes illustrated in figures 11(a) and (b) respectively and demonstrated in DUW silica-on-silicon [39] and DUW flat fibre [40].

In this bending regime there exists an axis of maximum tensile strain and an axis of maximum compressive strain. Between these exists an axis of zero strain, the so called neutral axis \( N \). It is essential that the neutral axis be considered when optimise strain sensor design. The location of \( N \) is determined by the Young’s Modulus \( E \) and cross-sectional area \( A \) of the composite, calculated through a null resultant stress argument given in equation (5).

\[
\sum F_i = 0 = \int \sigma dA
\]  

(5)

Typically the silica-on-silicon platform used for this work has a silicon substrate thickness of ~1 mm. This means that the silica core layer is inherently located far from the neutral axis.

The spectral response of a Bragg grating in a bulk substrate under three-point and four-point bending is illustrated in figures 12 and 13 respectively. In both arrangements the spectral signature deteriorates under tensile and compressive actuation as can be seen inserted spectra. In the instance of three-point bending the spectrum is chirped due to a linear variation in strain between the three pivot points. In four-point bending a general bandwidth broadens due to pivot point form. However, both bending arrangements result in a comparable sensitivity to applied force.

The thick silicon substrate of the composite in these bending regimes is the main limiting factor to device performance. Compared to an optical fibre the chip is less compliant as the second moment of area \( I \) is comparably large, defined in equation (6):

\[
I = \int y^2 dA
\]  

(6)

where \( A \) is a thin section of the area taken as a slice parallel to the neutral axis, and \( y \) is the distance separating that slice from the neutral axis. The chip also has another limitation that cannot be accounted for by altering the moment of area that is the inherent mechanical weakness of silicon. At sufficiently large applied force silicon will shear along its crystal planes.

Flat Fibre is an alternative all silicate based planar substrate in which DUW structures have been demonstrated [41]. The technique uses optical fibre fabrication techniques (namely MCVD and fibre drawing [42]) to produce long lengths of flexible substrate, as illustrated in figure 14. Unlike silica-on-silicon the platform does not have an inherent mechanical weakness brought about by the silicon substrate.

Flat fibre is typically more flexible than silica-on-silicon. However, as the core is located at the neutral axis it is inherently insensitive to bending along that axis. This can be improved by removing the cladding on one side of the core.
layer. This acts to shift the neutral axis away from core layer and typically leads to a forty times improvement in sensitivity as demonstrated by Ambran et al [40]. Bending can also be made along the axis perpendicular to the core. Through distributing gratings throughout the span of the core layer both horizontal and vertical displacement can be distinguished [40]. A similar concept using D-shaped fibres has also been reported by Zhao [43], to obtain vectorised detection.

Having discussed strain monitoring in bulk structures, we will now move on to more complex micro-structured devices. Micro-structured devices can be fabricated with far smaller dimensions than bulk chips allowing for significant reduction in stiffness, and allowing for far greater sensitivity. Additionally, multiple microstructured components can be integrated upon a single chip.

3.2. Microstructures

Recent years have seen significant industrial uptake of microstructured sensors, in particular MEMS technology [44]. These miniaturised electronic components have a wide range of applications from sensors in smart phone technology to the automotive industry [45]. These micro-electronic devices have utilised micro- and nano-scale physical structures to achieve sensitivity. Typically, these components have associated limitations, which prevent them from being deployed in harsh environments. For example they can be a spark source for flammable materials, suffer EM interference and be susceptible to large EM pulses. Micromechanical components that use an optical mode of operation are immune to these limitations and thus have become of increasing interest for certain application in harsh environments [46, 47].

Work on DUW micromechanical structures has focused upon the development of three basic physical building blocks namely cantilevers, membranes and bridges, illustrated in figure 15. These physical structures are silica based and contain waveguides and Bragg gratings to monitor actuation.

The three micromechanical structures described in this review are fabricated using a four-stage process. Namely silica
layer deposition (step 1), DUW (step 2), selective removal of silica using physical micromachining (step 3) and a silicon wet etch using potassium hydroxide (step 4). Figure 16 depicts this four-stage fabrication process, for a membrane component. The following subsections summarise work done to develop these three individual microstructure components.

3.2.1. Micro-cantilevers. Cantilevers are ubiquitously employed as MEMS components to monitor either physical or chemical changes. DUW micro-cantilevers \cite{48–50} typically have dimensions $<1 \text{ mm}^2$ in cross-section and millimetres in length, with the cantilever body consisting only of silica. Figure 17 illustrates how the selective removal of silica is made to expose the silicon. This is achieved through physically micromachining the top of the chip \cite{51}, with a subsequent wet etch using potassium hydroxide partially releases the cantilever from the silicon, illustrated in figure 15(a).

Typically upon release the micro-cantilevers deflect out of plane, as illustrated in figure 15(a). This is due to residual stress between the silica layers. For a silica-on-silicon substrate fabricated through flame hydrolysis deposition (FHD), the difference in thermal expansion coefficients can vary from $-5.5 \times 10^{-7} \text{ K}^{-1}$ for pure silica up to $4.3 \times 10^{-6} \text{ K}^{-1}$ for borophosphosilicate \cite{52, 53}. Therefore, it is possible to control cantilever curvature through a combination of layer thicknesses, cross-sectional form and dopant concentration.

The location of maximum strain sensitivity occurs where moment is a maximum. For a silica-on-silicon substrate fabricated through flame hydrolysis deposition (FHD), the difference in thermal expansion coefficients can vary from $-5.5 \times 10^{-7} \text{ K}^{-1}$ for pure silica up to $4.3 \times 10^{-6} \text{ K}^{-1}$ for borophosphosilicate \cite{52, 53}. Therefore, it is possible to control cantilever curvature through a combination of layer thicknesses, cross-sectional form and dopant concentration.

The location of maximum strain sensitivity occurs where moment is a maximum. For a cantilever of uniform cross-section this is at the root of the structure. Sensitivity can be further enhanced through manipulation of the cantilever’s neutral axis \cite{48} or physical stiffness.

To quantify sensitivity the Tai and Muller technique \cite{54} has been used, which calibrates point force using a scanning stylus profiler. For each scan the stylus begins at the root of the cantilever and traverses along the top to the tip. Calibration is achieved through simultaneously monitoring cantilever deflection and spectral shift. Figure 18(b) illustrates the spectral response of an optimally placed Bragg grating at the root of the cantilever, subject to a 50 mg (491 $\mu$N) point load. The technique has been used characterise sub-micro-Newton sensitivities \cite{48}.

Applying point-load to a cantilever is a ‘static-mode’ (or non-resonance) scheme of operation. Optical detection of the mechanical resonance is another form of operation. In this ‘dynamic-mode’ (or resonance mode) rapid varying changes in the Bragg condition are monitored by using a fixed wavelength laser tuned to sit on the edge of the Bragg peak, which converts grating shift into amplitude modulation. It should be noted that in contrast to atomic force microscopy (AFM) the environmental stability of deflection monitoring using this technique is greater, as light is guided in a waveguide as opposed to free space (as in the case for AFM). This means it is not alignment critical and therefore more robust in its operation.

Through using dynamic-mode, physical parameters such as external pressure can be monitored. This is enabled as...
external pressure results in the damping of the mechanical resonance. Figure 19 illustrates the mechanical resonance of a silica micro-cantilever. In this arrangement a Gaussian apodised Bragg grating is optimally placed near the cantilever root [50].

Figure 20 illustrates work undertaken to monitor the damping coefficient with respect to air pressure, with the ability to distinguish molecular and viscous flow regimes [50, 55]. It was previously reasoned that the optimum location of a grating in order to detect the physical actuation of a cantilever is at the root. As this is the location of maximum moment, and thus strain. However, for a cantilever of uniform cross-section the moment linearly varies with length. This means that strain linearly varies and thus a linear change in the Bragg condition which results in grating chirp. This can make spectral interrogation in both static and dynamic (resonant) modes difficult, especially for larger physical displacements. Two schemes have been developed in order to overcome this.

Figure 16. The fabrication of a micro-membrane device combining DUW alongside micromachining.

Figure 17. Image of trenches, physically diced into the chip to expose the silicon beneath.

Figure 18. The Tai and Muller approach to calibrate micro-cantilevers, showing the spectral response of a Bragg grating placed near the root of a 1.5 mm cantilever under a translated load of 491 μN.
two gratings (or a grating and a broadband reflector). Such structures and referred to as a FPBGs (Fabry–Perot Bragg gratings). In the case of a cantilever the FPBG is typically made over the root, with one grating set back from the root and another reflector set at the tip. As the tip of the cantilever observes minimal strain the integrity of the optical spectral response is maintained. Actuation acts to modify the optical cavity only and not the spectral signature of the grating. FPBG have advantages over regular FP-cavity sensors as they can also inherently temperature reference and thus can compensate for thermal fluctuations, which would otherwise be difficult to distinguish using solely the spectral signature of a FP-cavity [14]. Furthermore fluctuations in source power do not effect measurement.

The calibrated sensitivity of silica-on-silicon cantilevers (using the Tai and Muller measurement technique) has been shown to be 450 nm N$^{-1}$ for a grating placed at the root [14] and 330 nm N$^{-1}$ for FPBG interrogation [49], in a comparable cantilever. The difference is related to the shift in FPBG integrating over a longer length rather than being positioned at the location of maximum strain. The reduction in static sensitivity is compensated by an improvement in dynamic sensitivity, of up to eleven times [49].

3.2.2. Micro-membranes. The first true MEMS devices developed in the 1960s were membrane based pressure sensors [56, 57]. Today almost all industrial sectors use MEMS components for pressure sensing, e.g. in the medical, aerospace, process control, automation and automotive industries [44]. Optically interrogated membranes have the additional advantage of harsh environment operation (e.g. flammable, high EM-interference) enabling greater application and monitoring of engineered systems.

Figure 21 shows a conceptual image of a silica micro-membrane forming part of a silica-on-silicon chip. As the membrane can form a seal between two environments a pressure differential can result in deflection of the membrane. Placing a DUW Bragg grating within the membrane this deflection can be monitored and the pressure differential quantified.

Fabrication of these components has previously been illustrated in figure 16. For membranes in this report the silicon substrate is removed through KOH-etchant. Due to the anisotropic etching of silicon (with potassium hydroxide) and the use of [99] silicon wafers, the resulting silica membranes are rectangular in form.

As the membranes are anchored on all sides they are generally less compliant than cantilevers of similar dimension. However, upon deflection their neutral axis remains in plane with the bulk silica-on-silicon chip. This means that greater strains in the core are observed for a comparable deflection.

Inherent stresses existing in the silica layers [14, 58] have been understood to deflect cantilevers out of plane. Similarly, these stresses can cause membranes to buckle out of plane. The phenomena of static buckling can be understood in terms of energy minimisation [59] and occurs when the inherent (total) compressive stress $\sigma$ in the silica is greater than a critical stress $\sigma_{cr}$. For first order buckling of an arbitrary rectangular membrane this is related by [60].

$$\sigma_{cr} = \frac{1}{9} \frac{\pi^2 Eh a^2}{1 - \nu^2} \left( \frac{3}{a^2} + \frac{3}{b^2} + \frac{2}{a^2b^2} \right) \left( 1 + \frac{a^2}{b^2} \right)^{-1}$$

where $a$ and $b$ are the dimensions of the membrane side (in $x$ and $y$ axis respectively), $h$ is the thickness of the silica and $\nu$ is the Poisson ratio. The membrane undergoes static buckling when the resultant inherent stress in the silica is greater than
the critical stress. For first-order buckling the membrane is understood to take the form [61].

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

(8)

There are typically two first order buckling states, one into and the other out of plane. Both states have locally minimised energy. However, due to stress mismatch in the layers, one buckled state has a lower minimum energy. Typically this means that fabricated membranes buckle into the body of the chip. Through stress manipulation of the layers [62, 63] these parameters can be controlled.

The local stress for a buckled membrane can be quantified through the use of Bragg gratings. (a) illustrates the use of 100 Bragg gratings distributed over a 100 mm² membrane [58]. The spectral response of a central waveguide in this arrangement is illustrated in (b) (note: the physical concatenation of gratings

Figure 22. (a) Schematic of the Bragg grating locations with respect to the thin square silica membrane (b) the spectral response from 11 gratings in the central waveguide [58].

Figure 23. (a) the deflection of a membrane (b) theoretical Bragg shift map using deflected data (c) the measured Bragg shift acquired from one hundred 1 mm long Bragg gratings distributed over the cantilever [58].
Membrane buckling can be advantageous in the design of differential pressure sensors, for two reasons. Firstly it breaks the symmetry of the device, which permits the distinction between positive and negative pressure differentials. Secondly, achieving an optimal buckling displacement will provide optimal sensitivity. To understand this consider the membrane buckling \( w_0 \) response subject to the pressure differential \( \Delta P \) across the membrane related by \[ \Delta P = \frac{4nw_0}{a^2} \left( C_1\sigma + C_2\frac{4Ew_0^5}{a^2} \right) \tag{9} \]

Where \( t \) is the thickness of the membrane and \( C_1 \) and \( C_2 \) are constants dependent upon the dimensions of the membrane and Poisson ratio. Figure 24 illustrates a theoretical pressure sensitivity for square membranes whose closed form expression is principally derived from equation (9) and considering a Bragg grating optimally located on a membrane [58]. From equation (8) this is understood to be maximum for a grating running along location 0.25a and symmetric 0.75a length position.

Figure 24 highlights the pressure sensitivity with respect to an initial deflection point, which can be tailored by introducing inherent buckling (buckling when \( \Delta P = 0 \)). This means that sensitivity can be optimised for a \( \Delta P = 0 \) condition, or indeed an arbitrary differential pressure range of interest through manipulating stress in the thin glass layer. A further advantageous feature of inherent buckling is the distinction between positive and negative pressure differentials, arising due to the introduction of asymmetry (at the \( \Delta P = 0 \) condition). As it is noted that in the unbuckled state it is indistinguishable as to whether an induced spectral shift is a result of the membrane deflecting up or deflecting down. In both consideration optimal inherent buckling can be achieved through the manipulation of anisotropic stress [62, 63].

For small membrane dimensions the size of the membrane may become comparable to grating length. This results in the degradation of spectral integrity, as illustrated in figure 25. This is due to strain variation over the grating length. And can be compensated for through use of an oppositely chirped grating or through redesigning the sensor such that the grating does not lie within the membrane, such as in a FPBG configuration [14].

Figure 25 also shows a FPBG spanning the same membrane on which the single Bragg grating sits. In the FPBG arrangement equivalent Bragg gratings are situated either side of the membrane and the waveguide between them spans the membrane. Deflection in the membrane does not shift the central Bragg peak of the grating; rather it results in a spectral shift of the Fabry–Perot fringes situated on top of it. In typical Fabry–Perot cavities, thermal variations result in problematic spectral drift. However, this can be compensated for as thermal drift independently shifts the central Bragg wavelength only and so a thermal compensation can be made [14].

3.2.3. Micro-bridges. Micro-bridges are key structural building blocks in MEMS technology. Their main advantages come from use as structural girders and torsional hinges, which permit the construction of complex MEMS components, including digital micromirror devices such as that developed by Texas Instruments. Whilst the explicit use of optical waveguide based structural actuators have been suggested [65]. Bragg grating based micro-bridges are still in their infancy. One application that has been successfully demonstrated is thermo-optic tuning elements [66] and hot-wire anemometers [37]. These components are principally fabricated through physical micromachining [51] and subsequently deposited of...
a suitable metal to form a conducting filament. The microbridges are, to a large extent, thermally isolated from the bulk silicon chip making them energy efficient in comparison to alternative bulk monolithic filaments [38]. However, due to this thermal isolation they typically have a poor temporal response. The following subsection addresses the use of thermo-optic tuning elements for the application of tuneable diode laser spectroscopy (TDLS) of gas species.

3.3. Laser spectroscopy using DUW Bragg gratings

Wavelength tunable lasers have revolutionised optical gas sensing [67, 68]. TDLS in particular uses the narrow bandwidth of a laser for high resolution imaging of gas spectral lines, giving the ability for high specificity of gas species.

A variety of lasers for TDLS measurements exist and form part of a mature technology. Typically sources are targeted around the mid-IR region, where a high density of strong gas absorption lines exist. However, significant developments in detectors and sources in the telecommunications window have resulted in low noise and cost effective components [69], which in turn has made shorter wavelength regions gain an increased level of interest.

Recently the development of FBG stabilised lasers has been reported [70] from 1530–1560nm. Using DUW it has been possible to integrate Bragg stabilised external cavity lasers, into an integrated format. Tuning of which has been demonstrated around 1648nm [71], which is of particular interest for methane detection. The developed DUW integrated chip makes use of photolithographic processing to fabricate heating assemblies over the grating and cavity structure, to thermo-optically tune the output spectra [38]. The grating design has a super Gaussian windowing function to achieve desired reflectivity over a short length scale whilst still suppressing spectral side bands.

3.4. Refractive index sensing

Refractometry or refractive index sensing is used for many applications including industrial process monitoring, quality control in the food industry and biomedicine. Most refractometers are based on a classic Abbe total internal reflection design and can achieve refractive index resolution of 10⁻⁵. These systems have limitations due to size, power requirements and method of analyte delivery. Waveguide-based refractometers permit the miniaturisation of conventional spectroscopy in combination with small sample volume delivery systems, e.g. microfluidics. Typical operation is achieved through replacing all or part of the cladding with an analyte, such that the analyte is exposed to the evanescent field of a guided mode. Monitoring of modal effective index is generally monitored interferometrically [72–74], through Mach–Zehnder (MZ), Fabry–Perot (FP), Bragg grating or surface plasmon resonance (SPR). Fabry–Perot and Mach–Zehnder interferometers have refractive index resolution of the order 10⁻⁸ [75], whilst Bragg gratings [76] and surface plasmon resonance (SPR) [77] are other interferometric regimes with refractive index resolution of the order 10⁻⁶. Despite having a lower sensitivity they hold advantage in the fact that they have a large dynamic range and are less sensitive to variations in supplied optical power. As discussed, refractometry is the most well established use of UV-written planar Bragg sensors, and is being industrially commercialised by Stratophase Ltd.

Bragg grating based devices were first developed using fibre [78] and more recently planar [79, 80] platforms. The advantages of moving to a planar platform include multi-functionality of sensor components, dense array of sensors and integration with microfluidic delivery systems. Planar Bragg grating based refractometers using free space cavities are also a solution for refractive index/absorption sensing [81, 82], but have not yet been developed using DUW.

This section considers Bragg grating [83] and SPR based DUW planar devices, which through mode manipulation and thermal compensation have achieved refractive index resolutions down to 10⁻⁶. The platform has demonstrated detection of thin-film growth ranging from nanometers to micrometers [83] and higher integration of sensing regions is possible with multi-analyte detection through the use of integrated 2D patterning of agent-selective receptors [11]. Figure 26 illustrates the typical architecture for DUW planar Bragg grating refractometer. It consists of one ‘exposed’ grating and another ‘buried’. The exposed waveguide has a supported mode whose evanescent tail penetrates the external refractive index, as the buried waveguide is insensitive to this it serves as a temperature reference, able to resolve 0.01 K temperature variations [9]. Both gratings are located in proximity for effective thermal normalisation. Alternatively, temperature referencing can be made through use of a single grating by monitoring birefringence [84].

The use of Bragg gratings as a basis for chemical sensors is not a new concept [85] and has largely been demonstrated in D-shaped [86] and thinned core FBG's [87]. However, as the overclad thickness of a planar chip is typically 15 μm there is less material that needs to be removed compared to optical fibres with typically a 125 μm outer diameter. Material removal has been achieved through wet/dry etching and physical micromachining [88], with real-time grating feedback for reproducibility. The concept of optimised evanescent field exposure has also been used to resolve individual (and multiple) photons for quantum technology using the DUW platform [89].
Refractometers operating through evanescent field exposure can achieve enhanced sensitivity by manipulating the fraction of modal power that penetrates into the analyte. This can be achieved through either building a permeable/porous cladding [90] or through the addition of a thin layer of high refractive index material (between waveguide core and analyte) [91]. Demonstrated high index layers for DUW devices include titanium dioxide and tantalum pentoxide ($n \approx 1.90$–2.56 [92] and 2.08 [93] respectively). Tantalum pentoxide, in particular is well suited for sensor surface applications [94], as it has a similar morphology to silica providing excellent adhesion. Furthermore its surface is covered in hydrophilic hydroxyl groups allowing it to be functionalised analogously to silica.

Using surface functionalization selectivity can be targeted to specific biological or chemical agents. As the targeted species can typically be significantly smaller than the penetration depth of the evanescent field, it is important to quantify the absolute sensitivity to thin layer build-up. This has been demonstrated for DUW components using ultra-thin layers of sputtered silica [83], illustrated in figure 27. It must be noted that silica has a comparable refractive index ($n \approx 1.44$) at 1550 nm to that of a typical organic monolayer.

Figure 27 illustrates detectable changes in silica thicknesses, from which a resolution of 0.20 nm can be inferred. For detection in bulk medium this corresponds to a detection resolution of 0.035 nm. Sub-nanometre detectability is below that required for organic monolayers, thus making such components ideal for functionalization as demonstrated for chemical and small biological receptive surface layers [9, 11, 95].

Importantly both the silica-on-silicon platform and direct UV written structures can undergo steam sterilisation in an autoclave without degradation. This allows the chips to be re-functionalised and reused. The devices can also withstand different solvent-based flush throughs, e.g. isopropanol, acetone, methanol and water; strong acids and strong bases [8]. Cleaning processes using these solvents can prove problematic in competing microfluidic technologies. For example acetone can dissolve many polymer based material systems.

The tolerance of the DUW devices has enabled observation of subtle microfluidic responses that occur due to solvent mixing, as illustrated in figure 28. It was observed that transitioning between isopropanol and water within this microfluidic flow cell gives a square wave response in refractive index (inferred through wavelength shift), but with a small mixing transient [8]. In contrast, mixing water with alcohols, such as methanol or ethanol, produces a ‘spike’ in the measured refractive index during the transition [8]. This ‘spike’ was shown to be caused by the formation of intermediate binary liquids with higher refractive index than the constituent solvents, as can be seen in figure 29 for a methanol–water mixture. The surprising lifespan of such transient effects within the microfluidic flow cell was attributed to solvent dispersion within a laminar flow regime.

Thus far device geometry has considered evanescent field exposure through the removal of the overclad layer only. Another approach for exposure is through the removal of cladding to the side of the waveguide. This geometry has been demonstrated through use of a vertically machined trench, which can form part of an inherent microfluidic channel [96].

Tilted Bragg grating (TBG) refractometers have also been demonstrated, primarily in optical fibre [97–101], where the cladding width enables a finite number of cladding modes to be supported. In this arrangement the cladding modes have an evanescent field that propagates into the external environment. As the measured analyte is well separated from the waveguide core, these structures typically have an associated low cross
sensitivity between unwanted environmental perturbations, including temperature and strain.

A tilted Bragg grating consists of a refractive index modulation that is purposely blazed relative to the waveguide’s axis. The effect of this is to enhance coupling between the forward-propagating core mode and counter-propagating cladding modes. The counter-propagating cladding modes attenuate quickly and are not usually observed in reflection; however geometries do exist that exploit end-face reflection in order to achieve single-port interrogation [102]. Typically the supported cladding modes are observed in transmission. For a discreet number of modes these are observed as a series of narrow transmission dips (resonance features) seen at shorter wavelengths with respect to the main Bragg reflection peak. The effective index of $i^{th}$ cladding mode $n_{clad,i}$ is calculated from the resonance position $\lambda_i$ using the phase matching condition.

$$\lambda_i = \frac{\Lambda(n_{core} + n_{clad,i})}{\cos \theta}$$  \(10\)

where $n_{core}$ is the effective refractive index of the core mode, $\Lambda$ is the nominal grating period and $\theta$ is the angle of tilt, with respect to a perpendicular axis from the propagation direction. The finite set of distinguishable spectral resonances is dependent upon the width of the cladding. For fibre platforms this is determined by the diameter of the optical fibre.

The first TBG refractometer in a planar platform was fabricated using DUW [103]. A discreet set of optical modes was achieved through the fabrication of a pair of grooves as illustrated in figure 30 through physical micromachining. These grooves serve both for modal confinement and as inherent microfluidic delivery system that can control delivery of small sample volumes.

Figure 7(d) illustrates the transmission spectra of planar tilted Bragg grating, with a $10^\circ$ of tilt and a groove-to-groove width of $125 \, \mu m$. As with fibre-based tilted gratings external refractive index can be inferred through directly monitoring the cladding modes. This can be achieved by observing spectral shifts of individual resonances, or through monitoring cut-off by envelope analysis [104]. Figure 31 depicts the evolution of the cladding mode envelope with respect to different refractive indices in the fluidic channels. As the effective refractive index of shorter wavelength modes is lower these modes are observed to be cut-off at lower external refractive index values.

Refractometers based upon surface plasmon resonance (SPR) are commercially exploited for a range of biomedical and chemical analysis methods [105–107]. Detection arrangements include Otto but more predominantly Kretschmann configuration. Gold is a well-documented substrate for surface functionalization and as surface plasmons have modal power concentrated in the first few hundred nanometers [108], they are even further suited to optimal detection of surface functionalized layers.

Typically SPR sensor systems use bulk optic arrangements and so are susceptible to misalignment and ‘in-the-field’ rigours. The desire to overcome these limitations has sparked research into integrated approaches that use waveguides (both fibre and planar based solutions), with more recent activity using Bragg gratings to couple into plasmon modes [109, 110].

TBG are one efficient route for achieving plasmon mode coupling [104] as has been demonstrated in both fibre [111–113] and planar geometries. The first planar embodiment was demonstrated using DUW, showing added advantages over...
fibre solutions due to of planar integration and microfluidic compatibility.

It has been understood that if the surface plasmon wave and the guided mode are phase-matched, the light wave excites a surface plasmon. Using the Cauchy integral method [114] cladding mode solutions for a planar system can be solved [115]. The method requires consideration of both the dispersion and the 2D geometry of the waveguide and can obtain solutions for a system with complex (e.g. metal layers) and non-complex refractive indices. Figure 32 illustrates a typical solution for a ‘plasmon-hybrid’ cladding mode that can be supported in a TBG with ~30 nm gold layer deposited upon the side-walls.

Figure 33 depicts the evolution of cladding modes with respect to external refractive index for the same device illustrated in figure 31 but with the addition of a ~30 nm layer of gold deposited upon the side walls. Unlike figure 31, the cladding mode envelope effectively ‘reappears’ with increasing external refractive index.

This experimental feature is understood to be a result of pure-plasmon type modes shifting to a longer wavelength with increasing external refractive index. Figure 34 illustrates this by plotting the complex part (propagation loss) of the modal solutions. Those with greater complex part have a greater pure plasmon constituent. It is the propagation of this peak (pure-plasmon like mode) that results in the observed spectral feature observed in figure 33.

Benefits of extended surface functionalization exist through the use of a gold-enhancement layer. This is a direct result of gold-based surface chemistry, which permits the exploitation of pre-existing SPR chemistry based on ligands/receptors and gold/thiol.

4. Conclusions

This review has considered some of the most recent progress in DUW sensors. DUW is a proven technique for the fabrication of planar silica, through use of a dual beam UV writing system. The writing system has full computer control translation and modulation enabling Bragg gratings and complex integrated circuitry to be fabricated. Gratings designs of varying period, position (including tilt angle) and apodisation have been presented. These form the building blocks for larger multiplexed planar Bragg sensor chips.

The versatility of the planar Bragg grating platform allows for implementation of many techniques derived from areas such as Fibre sensing and Surface Plasmon Resonance devices. The ability to create compact components using MEMS techniques offers a high degree of miniaturisation as well some specific advantages such a chemical and thermal durability. Components for sensing have been demonstrated through optimising Bragg grating’s spectral response to particular measureands. This is achieved through evanescent field exposure in the case for refractometers or physical form in the instance of physical sensors. The technology is also compatible with a harsh environment operation and silica-based multiplexed Bragg gratings (such as FBGs). Spectral multiplexing also allows for multiple components to be present on a single chip, and the use of spectral measurement offers signal to noise ratio advantages, while ability to access devices over fibre allows for remote interrogation over distances comparable to telecommunication spans.

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