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# All-UV written integrated glass devices including planar Bragg gratings and lasers

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One attractive route to low-cost integrated optical components is the use of direct UV writing. This technique may be applied to a wide range of materials including silica-on-silicon wafers, compound oxide glasses, directly bonded glass composites and GLS. This presentation will focus on the first of these material systems – silica-on-silicon. This has a number of attractive features including fibre compatibility, industrial acceptance, stability and most importantly for our work a photosensitivity depends light intensity and not the thermal effects found in many materials. Recent developments of the UV writing technique at Southampton have allowed the realisation of high quality Bragg gratings in silica-on-silicon by simultaneous writing of the channel waveguides and gratings (the direct grating writing technique). This approach together with wavelength detuning, allows an unprecedented range of wavelengths to be written under software control. Latest results will be presented covering laser operation in Neodymium doped channels, small angle couplers, sensors based on planar gratings and liquid crystal tunable devices.

(Key words: integrated optics, Bragg gratings, silica on silicon, UV writing, waveguide lasers)

## 1. INTRODUCTION

Direct UV writing is an emerging technology for the fabrication of low-cost integrated optical components. It makes use of photosensitive materials and UV laser exposure to create a waveguide channel. The process can use a range of materials, including silica on silicon[1], ion exchanged bulk glasses[2], directly bonded glass composites[3], polymers[4] and even lithium niobate[5]. Arguably the most significant opportunity is silica-on-silicon due to its integrability with silica fibres and the potential for planar integration with silicon technology. This approach has advantages over conventional techniques for fabricating waveguides. In particular this route only requires layer depositions and has does not make use of either etching or photolithography. The starting point is a buried photosensitive layer into which the waveguide circuit is "drawn" by translating the sample under a tightly focused laser spot. The technique may be applied to a wide range of materials

UV writing works by altering the refractive index of the material, normally increasing the index, but also sometimes by reducing the index of the areas adjacent to the channels. The UV laser light is used to modify the refractive index of the material to create a waveguide. In some application the UV writing is carried out in an existing layered structure to define vertical confinement, while in others the short absorption depth of the UV can create a waveguide in a homogeneous substrate. The results are strongly dependent on the material, with some materials showing positive and some negative refractive index changes.

The UV induced change in different materials can largely be characterised as either photosensitive or thermal. A good example of a photosensitive material is germania doped silica in which the mechanisms are generally well understood and UV written waveguides have been demonstrated by a number of groups. The alternative to a photosensitive response is a thermal mechanism involving rapid heating and then quenching of the material. The materials with photosensitive responses have certain advantages, especially that it is possible to have an index that varies over the short length scales needed to define first-order Bragg gratings. The materials exhibiting thermal responses are not generally suitable for first-order Bragg gratings because thermal diffusion prevents significant temperature differences over length scales shorter than about one micron so in general these melting and quenching phenomena are incapable of defining the 500nm scale structures needed for gratings. Although not suitable for writing gratings the length scales of thermal diffusion are ideal for defining channel waveguides and the heating/rapid quenching mechanisms provide a powerful means of making waveguides in soft glasses. It should be stressed that these conclusions apply only to continuous wave exposure, for pulsed sources in the nanosecond or shorter regimes, the melting and quenching can occur over short length scales, however this paper concerns only UV writing with cw lasers.

A recent development in UV writing in photosensitive silica-on-silicon has been made at the ORC, University of Southampton, of a technique for the simultaneous definition of Bragg gratings and channels waveguides. While the fibre Bragg grating has undoubtedly been one of the most important developments in optics over the last 20 years, there is a growing need to see this technology applied to planar geometries. We recently demonstrated the first simultaneous definition of channel waveguides with integral Bragg gratings based on the interference of two focused UV-writing beams [6]. This single-step approach was developed to promote optimal use of sample photosensitivity for both the waveguide and the Bragg grating superstructure. The new approach has the potential for implementing many aspects of advanced grating design, such as chirp and apodisation, without the need for a phase mask.

In this publication we will report on the latest developments at the ORC in UV writing of devices, firstly on the Direct Grating Writing process, extending the UV-written channel waveguide geometry towards two-dimensional devices, which also demonstrating an unprecedented ultra-wide grating detuning response across the entire ITU grid, the spectral wavelengths commonly used in optical communication systems. We will show how the technique for controlling the grating response is defined through computer software, and requires no modifications in our experimental setup to create Bragg gratings with responses spanning a 490nm span in the telecomm bands, providing an almost unparalleled flexibility as a fabrication process. Having reviewed the UV writing technique, we will then cover recent results on all UV written planar laser operation and the use of gratings to characterize materials.

Direct UV writing works by translating a 'blank' photosensitive sample under a tightly focused writing spot. The photosensitive material shows a refractive index increase in the regions exposed to the UV irradiation, leaving the remaining areas of the sample unaffected. When the sample is moved relative to the writing spot , the paths of motion define the structures of the planar channel waveguides, and thus ultimately the devices written (figure 1). Through accurate control of the location of the writing spot, complex multi-channelled overlapping structures (for example splitters, couplers, etc.) can be written, with the structure design controlled entirely through computer software. This approach provides the significant advantage that no photolithographic or subsequent clean-room processing steps are required. The waveguides formed in this way are naturally smooth and continuous, and may merge continuously into each other without the 'blinds' formed in conventional etched waveguides.

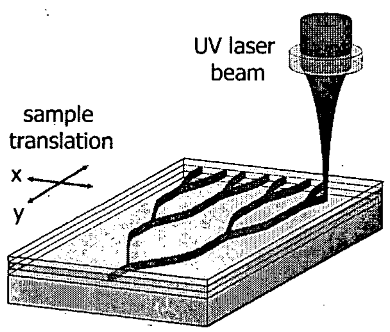



Figure 1: Showing the concept of Direct UV writing

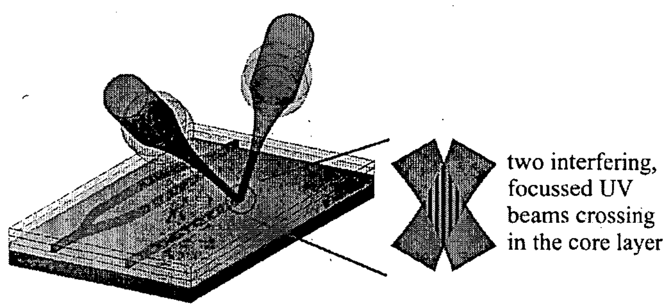



Figure 2: Concept of Direct Grating Writing

Unlike standard UV writing in which a single beam is used, our Direct Grating Writing technique (DGW) uses two focused beams that are overlapped to give a micron-order near-circular spot with an inherent linear interference pattern in one dimension (figure 2). Exposure of this intensity pattern onto a photosensitive sample results in a refractive index increase with the same physical dimensions as the writing spot, but with a periodic modulation corresponding to the interference pattern. By strobing the exposure as the sample is moved multiple 'snap-spots', each offset by the period of the interference pattern are added to create an index modulation structure that can be extended, plane by plane, into a grating structure much longer than the size of the spot. As the interference pattern is contained within the writing spot, the width of the induced grating is by definition the same as a channel waveguide. When the sample is translated under a constant power writing beam, the intra-spot interference pattern is averaged out and the focused spot can be used to write standard channel waveguide structures, including the curves and branches that make up the basic building blocks of larger integrated optical systems [7].

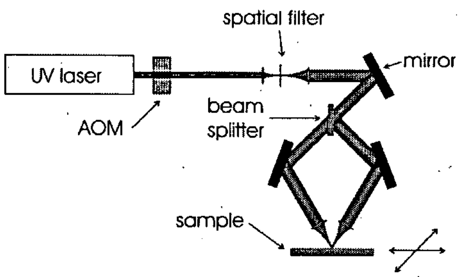
Our news approach allows planar Bragg gratings to be inserted into complex all-UV-written devices in a single processing step, and its success is a direct result of the small writing spot fundamental to this process. The Bragg gratings produced using the new Direct Grating Writing technique differ in a significant manner to planar Bragg structures defined in a conventional two step process. This is because traditional two-step Bragg grating fabrication requires the Bragg grating structure to be superimposed over an existing channel waveguide, typically by exposing a UV interference pattern onto a photosensitive channel [8]. As the interference pattern is superimposed onto the existing waveguide structure the index modulation is always added to the index of the channel, and thus the average index of the channel is increased by the addition of the Bragg grating structure. This average index increase causes ringing in the grating response, and must be compensated by using apodisation techniques.

By contrast, to additive index gratings, in DGW the Bragg grating modulation is not superimposed, but generated at the same time as the channel structure, with the index modulation sinusoidal either side of the average index of the channel. Thus, the local contrast of the grating is independent of the local strength of the channel waveguide within the limit of the average index of the channel structure. This feature is important as it allows for independent optimization of the channel waveguide and Bragg grating. The photosensitivity of the sample is no longer shared between the two processing steps, and the risk of saturating the photosensitive effect is reduced, often a limiting factor in the traditional two-step techniques. Additionally, this allows the matching of channel strengths and the seamless interconnection between channel waveguides and Bragg grating structures resulting in improved device performance.

## 2. EXPERIMENTAL

In our technique fabrication of direct-written gratings is performed using a frequency-doubled 244nm argon-ion laser, a high precision 3-dimensional translation stage, and an interferometrically-controlled acousto-optic modulator. A beam splitter is used to form two separate beam paths at an intersection angle of around 29 degrees, and both beams are individually focussed and aligned to give a single ~4μm interfering spot.

Figure 3: Schematic diagram of the Direct Grating Writing setup




The samples used throughout the experiments reported in this paper were three-layer silica-on-silicon wafers produced through flame hydrolysis deposition. In each case the core layer was co-doped with germanium the best known photosensitive dopant, which also raises the refractive index thus defining a planar waveguide structure. The photosensitivity of the germanosilicate core layer was enhanced by hydrogen or deuterium loading at 100-150bar for one week, following which the samples were UV-written immediately at room temperature. A range of planar gratings based on variations of period, length, channel waveguide structure, and UV-writing conditions (speed, power, etc.) have been written and subsequently characterised using an optical spectrum analyser.

## 3. RESULTS

### 3.1 UV written waveguides

A mode profile of a typical channel waveguide containing a Bragg grating structure is shown in figure 4 (at 633nm) and figure 5 (at 1.55μm). It can be seen that the guided modes have near symmetrical profiles comparable to that of standard single mode telecoms fibre, providing a high degree of compatibility between the planar channels and fibre. When viewed from above the resulting channel waveguides are clearly visible by the naked-eye. These guides had an NA = 0.17± 0.02 measured using a multiple far field imaging technique.

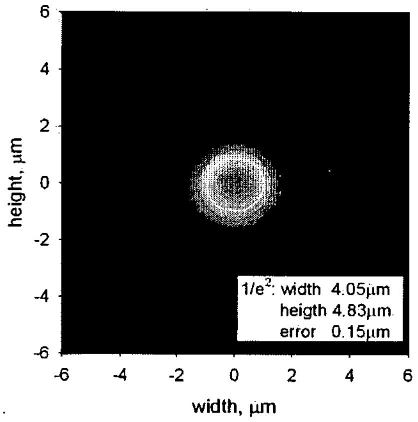



Figure 4: Mode profile of a DGW channel waveguide at 633nm

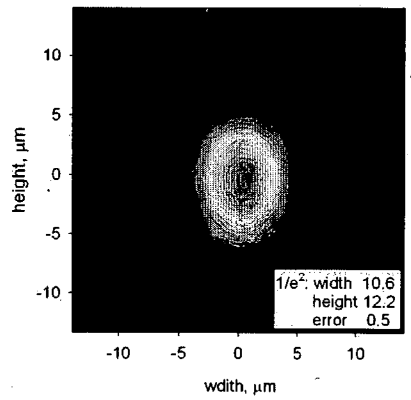



Figure 5: Mode profile of a DGW channel waveguide at 1.5μm

The transmission spectra from two straight channel waveguides containing integral Bragg grating sections are presented in figures 6 and 7. Both Bragg grating gratings were written over the same length and width and had the same period, however through control of the writing conditions the strength of the wavelength specific response can be readily tailored to range from <5dB to >30dB, with the bandwidth scaling as expected. The exact Bragg wavelength, which is dependent on the strength of the channel waveguide, remains at the same wavelength in the two structures confirming the contrast of the grating and the channel strength can be controlled independently.

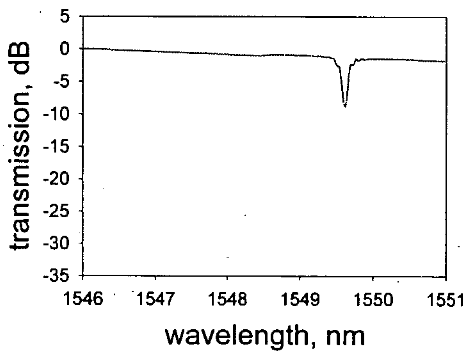



Figure 6: Spectral response of a 'weak' 8mm long Bragg grating

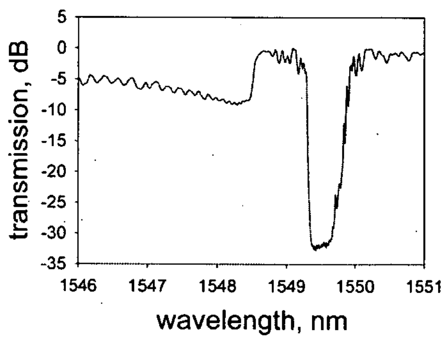



Figure 7: Spectral response of a 'strong' 8mm long Bragg grating

As the DGW technique is used to define the channel waveguide and grating structures at the same time, the resultant characteristics of the structures are a direct consequence of the writing conditions. Since the only difference between the fabrication of the channel waveguides and Bragg grating sections is the modulation of the laser, the power and writing conditions can be very closely matched for both structures. Thus, by interrogating the response of the grating section, accurate information about both the channel waveguide and Bragg structure can be obtained, providing direct insight into the characteristics of the channel waveguides. Using the Bragg relation ( $\lambda_b = 2\Lambda n_{eff}$ ) and accurate knowledge of the grating period, these gratings offer an ideal method of accurately and efficiently determining the effective index of a guided mode in the waveguide, and hence the strength of the UV induced channel index. By using gratings with different periods this approach may be extended further to determine the dispersion properties of the waveguide.

The UV-induced index change of the material and its relationship with the writing beam power depends greatly on the processing history of the sample. Using the convention typically applied in Direct UV writing, the writing conditions have been expressed in terms of fluence (equation 1)[1].

$$F = \frac{I_{UV} \times a}{v_{scan}} \qquad (1)$$

where F is the fluence (kJcm$^{-2}$), $I_{UV}$ is the average power density in the writing spot (kJcm$^{-2}$s$^{-1}$), a is the writing spot diameter (cm) and vscan is the translation velocity (cms$^{-1}$). Fluence is an expression of the energy exposed to the material in the writing process and is a common parameter used in direct UV writing.

Figure 8 is a plot of the variation of effective index in a channel waveguide plotted versus the writing fluence, with the data also separated in terms of the power of the writing spot. The data presented in figure 8 is derived from a deuterium loaded sample written immediately after removal from cold storage. It is clear that fluence alone is not an accurate means of describing refractive index change during the UV writing process. Instead it should be noted that, counter-intuitively, the strength of the channel waveguide increases as the writing power is reduced for exposures of the same fluence (corresponding to a slower translation velocity). This effect is consistent throughout the range of fluences used, becoming more pronounced in the low fluence regime. Freshly loaded samples exhibit a distinct threshold effect around fluences below 10kJcm$^{-2}$ where channels are no longer written. The exact point where this threshold occurs varies with the power of the writing beam, again with slower translation speeds crossing the threshold effect at lower fluences.

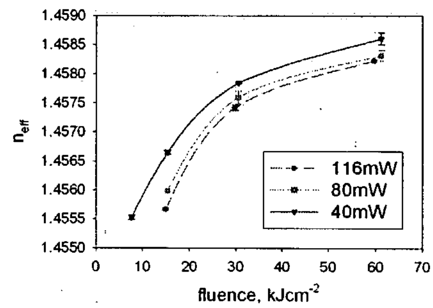



Figure 8: Difference on the strength of the waveguide with writing conditions

### 3.2 Directional Couplers

As an example of a specific device, directional couplers are devices ideally suited to a planar geometry, forming the guided wave equivalent of a beam splitter. Such devices rely on the extension of the evanescent field from the guided mode extending into the cladding structure surrounding the waveguide. If there is a second waveguide such that the evanescent fields overlap then power can be coupled between the two structures. The structures can be used for power splitting, coarse wavelength splitting, sensors etc.

In a planar geometry cross coupled directional coupler devices generally [12] comprise of two channel waveguide structures brought very close together (typically of the order 10µm) for a fixed interaction length before separation (figure 9). In the coupling region the power oscillates back and forth between the two channel waveguides. The length of the coupling region required to couple maximum power from one waveguide to another is wavelength dependent, thus for any given coupling length, with a range of wavelengths launched into port 1 (figure 9) there are specific wavelengths where all the power is coupled into port 2 and other wavelengths into port 4 with various combinations between.

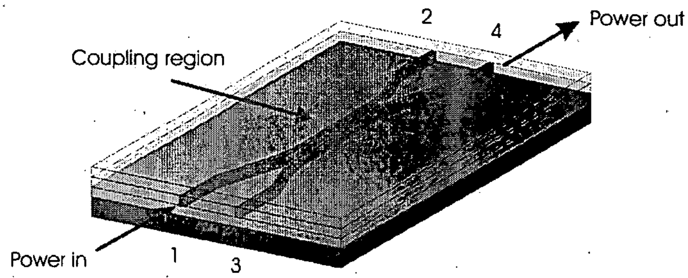



Figure 9: Schematic of a directional coupler, providing wavelength dependent power splitting between the output ports with a Bragg grating structure written in the coupling region.

Based on the crossed coupler architecture, the inclusion of a Bragg grating structure in the coupling region allows the coupling of power into a counter-propagating mode. Coupler structures were produced with an over-head view of half such a device shown in figure 10, the other half of the structure is a symmetrical image.

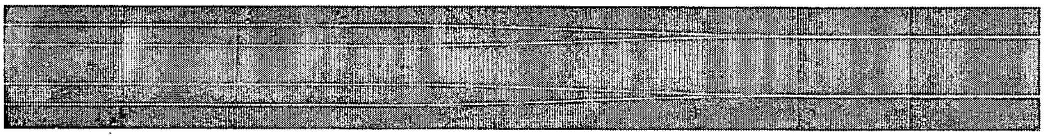


Figure 10: Overhead view (half) of two directional couplers as illustrated in figure 9

In the coupling region, the waveguide spacing is 10μm with various coupling lengths ranging from 8mm to 8.9mm and the power slitting ratio between the two arms for a given coupling length was monitored. A typical broadband output profile of the two output ports is shown in figure 11. The wide-wavelength dependence of the coupling structure is apparent with the power ratio coupling between the two output arms of the device. A Bragg grating was written within the coupling region with a response around 1550nm, providing a narrow, highly wavelength dependent response to the structure.

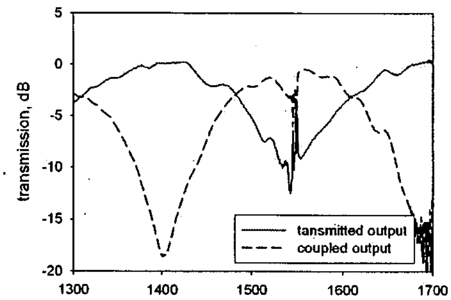



Figure 11: Wavelength dependence of the power distribution between the output arms of the coupler with a Bragg grating response at 1550nm

### 3.3 Ultra-wide detuning

While the absolute period of our small-spot interference pattern is defined by intersection angle of the two focused beams, the process of centre-wavelength detuning can be applied to allow gratings of different periods to be defined via computer-controlled modulation of the writing beam, with no alteration to our optical arrangement. As stated earlier, the

DGW process builds up a grating structure through successive exposures of a small spot interference pattern, with each single snapshot only contributing to a fraction of the overall exposure at any given point in the grating structure. Therefore the final grating structure defined in the material is not a perfect clone of the interference pattern as in many of the existing techniques [7, 9, 10]. This distinction permits fine-tuning of the final grating period.

In the centre-wavelength detuning process, each exposure of the writing spot is displaced by the period of the interference pattern ($\Lambda$) plus an additional constant offset ($\Delta$). With the summation effect of the multiple exposures the resultant index modulation period is defined by the displacement between each exposure ($\Lambda + \Delta$), not the period of the interference pattern. In systems using phase masks to generate an interference pattern the spot size is typically >200$\mu$m wide, resulting in a narrow detuning range. In our system a spot diameter of 4µm with a 532nm period interference pattern results in approximately 8 interference fringes written per exposure. This extremely small writing spot allows a much greater range of detuning from the native interference pattern than has traditionally been possible, allowing our arrangement of a single writing spot formed through the fixed intersection of two writing beams to generate a wide range of grating periods. Using this concept, the process has been demonstrated as a highly flexible fabrication technique capable of producing a wide range grating periods from a single experimental setup. This is dramatically demonstrated in the graph of figure 12, where an effective detuning range of 490nm, spanning 1.23$\mu$m to 1.72$\mu$m, and encompassing all of the O, E, S, C, L, and U wavelength bands used in optical communication systems is presented.

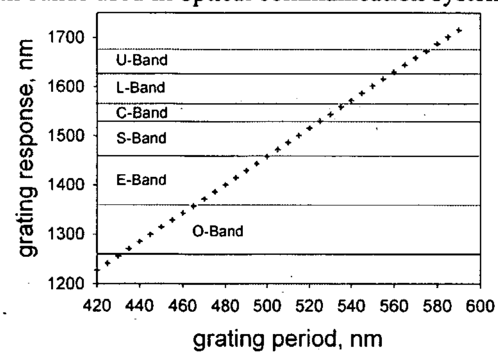



Figure 12: Bragg gratings produced through the computer controlled detuning process. Gratings with responses covering the entire ITU grid were produced in a single fabrication run with no alteration to the fabrication setup.

### 3.4 UV written lasers

Recently the addition of rare earths by solution doping of a partially consolidated soot has also been achieved. These substrates have found application in the first UV written waveguide laser in Nd doped silica on silicon[13]. This latter result is particularly important as it showed both low threshold and high efficiency for such a system, and proves that the UV writing technique is suitable for high power operation. The realisation of solution doping and UV writing is an important proof of concept for UV writing as it shows that low loss waveguides may be obtained in rare earth doped silica.

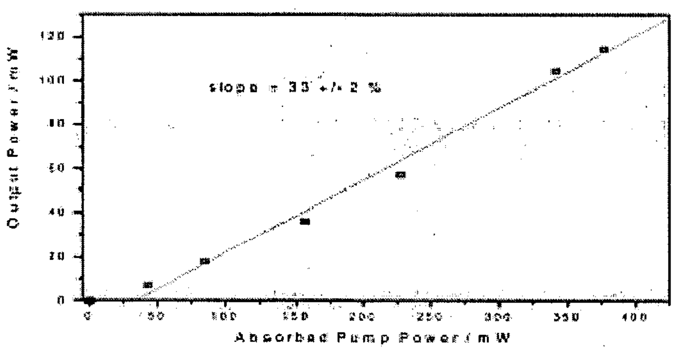



Figure 13 showing the threshold characteristic for a directly UV written Nd doped silica on silicon laser

**3.5 Planar Grating Sensors**

Planar Bragg gratings may also be used to create sensor devices. Recent work[14] has shown that by removing the cladding from the waveguide, and then placing a liquid in contact with the grating it is possible to make a sensitive refractive index sensor. Such sensors have been used to detect phase changes in water/ice and in liquid crystals. An example of a phase detection is shown in figure 14, showing measured effective index data determinted by Bragg reflection wavelength for water melting on a sensor chip. Planar Bragg grating sensors have a number of key advantages, primarily in making it easy to make a reference measurement on chip (on a separate grating) to allow temperature and drift compensation. Further work has demonstrated tunable Bragg gratings by using a liquid crystal overlay and applying an electric field.

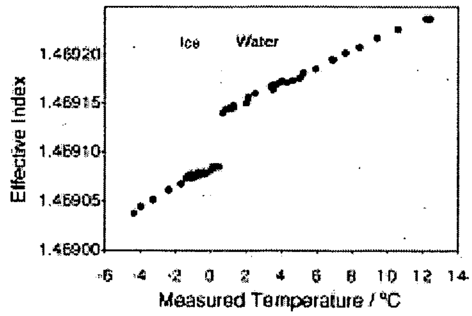



Figure 14 showing index differences from the melting transition of water on a planar Bragg grating sensor.

# 4. CONCLUSIONS

In conclusion, we have presented several refinements to our recently reported Direct Grating Writing process, each specifically derived from our unique use of a micron-order circular writing spot. We have demonstrated the independent control over both the channel waveguide and the Bragg grating structures that is achieved through defining both structures simultaneously, producing two gratings of significantly different strengths but the same average strength as a channel waveguide. The use of the DGW process as a characterising tool has been demonstrated, using the process to observe the birefringence of the structures and the subtleties in the writing conditions.

We have demonstrated single-step integration of different planar Bragg gratings into 2D Mach-Zehnder structures and the production of directional coupler structures with integral Bragg gratings. One of the strongest advantages of DGW is the ability to define a wide range of Bragg grating periods from a single setup. To demonstrate this we have produced an unprecedented 490nm wide grating detuning response encompassing the entirety of the ITU grid (O, E, S, C, L, and U wavelength bands), results achieved entirely through software control of the modulated writing spot. Through control of the various writing conditions allowing the contrast of the grating to be controlled, gratings over this entire span were demonstrated with approximately normalised grating responses. Based on these early results it is hoped that further optimisation of channel waveguide and Bragg grating characteristics will lead to highly efficient integrated optical devices for use in wavelength-selective planar systems. By adding rare-earth ions into the glass layers we have demonstrated a UV written planar waveguide laser. Further applications of planar Bragg gratings are being researched in sensing where refractive index sensors have been demonstrated.

# 5. ACKNOWLEDGMENTS

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## 6. REFERENCES


1. M.Svalgaard et al., "Directly UV written silica-on-silicon planar waveguides with low loss", Elect. Lett. 33, p.861-863, 1997
2. A.K.Sheridan, C.B.E.Gawith, G.D.Emmerson, P.G.R.Smith, J.S.Wilkinson "UV-written channel waveguides in ion-exchanged Pyrex", ECIO 2003 Prague 2-4 Apr 2003 WeA1.3
3. C.B.E.Gawith et al, "Direct-UV-written buried channel waveguide lasers in direct-bonded intersubstrate ion-exchanged neodymium-doped germano-borosilicate glass", Appl. Phys. Lett. 81, p. 3522-3524, 2002
4. J.S.Koo et al, "UV written waveguide devices using crosslinkable PMMA-based copolymers", Elect. Lett. 39, p. 394-395, 2003
5. S.Mailis, C.Riziotis, I.T.Wellington, P.G.R.Smith, C.B.E.Gawith, R.W.Eason, "Direct UV writing of channel waveguides in congruent lithium niobate single crystals", Optics Letters 2003 Vol.28(16) pp.1433-5
6. G.D.Emmerson et al, "Fabrication of directly UV-written channel waveguides with simultaneously defined integral Bragg gratings", Elec. Lett. 38, p.1531-1532, 2002
7. M.Y.Park et. al., "Fabrication of low-cost planar wavelength-selective optical add-drop multiplexer by employing UV photosensitivity", Elect. Lett. 38, p.1532-1533, 2002
8. K.O.Hill et. al., "Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication", Appl. Phys. Lett. 32, p.647-649, 1978
9. M.Cole et. al., "Moving fibre/phase mask-scanning beam technique for enhanced flexibility in producing fiber gratings with uniform phase mask", Elect. Lett. 31, p.1488-1490, 1995
10. M.Ibsen et al, "Sinc-sampled fiber Bragg gratings for identical multiple wavelength operation", IEEE Photon. Tech. Lett. 10, p.842-844, 1998
11. M.Svalgaard, "Optical waveguides and gratings made by UV- photogeneration", ECIO, p.333-338, 1999
12. A. Ghatak, K. Thyagarajan, *Introduction to Fiber Optics*, Ch 17, Cambridge University Press, 2000
13. D.A. Guilhot et al., "Single-mode direct-ultraviolet-written channel waveguide laser in neodymium-doped silica on silicon"Opt. Lett. 29 (9): 947-949 May 2004
14. I.J.G. Sparrow, G.D. Emmerson, C.B.E. Gawith and P.G.R. Smith, "Planar waveguide hygrometer and state sensor demonstrating supercooled water recognition", Sensors and Actuators B, 107, 856-860.