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

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Direct UV writing provides an attractive route towards low-cost integrated optical components in photosensitive glasses. The technique may be applied to a wide range of different geometries including silica-on-silicon wafers, compound oxide glasses, directly bonded glass composites and GLS. This presentation will review research in this area and present an overview of the activities in Southampton in this field. Recent developments of the UV writing technique 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.

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

1. Introduction

In recent years Direct UV writing has emerged as a viable route for the fabrication of low-cost integrated optical components in photosensitive silica-on-silicon wafers. The technique has a number of significant advantages over conventional techniques for fabricating waveguides. In particular the process requires only 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, including silica on silicon[1], ion exchanged bulk glasses[2], directly bonded glass composites[3], polymers[4] and even lithium niobate[5].

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 can 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 index differences while others exhibit negative index changes.

The mechanism for index change varies between materials, but can largely be characterised as either photosensitive or thermal. The classic 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. Thermal mechanisms involve heating and then rapid quenching of the material. The photosensitive responding materials have certain advantages, especially that it is possible to have an index that varies over the short length scales needed to define Bragg gratings. Materials exhibiting thermal responses are not generally suitable for Bragg gratings because thermal diffusion typically occurs over micron length scales 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.
A recent application of UV writing has been the development 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 gratings. The new approach that will be described in this paper provides a uniquely powerful and flexible solution to the provision of Bragg gratings in a planar format. Combining closely packed channel waveguides with a versatile Bragg grating tailored spectral response would allow the creation of compact systems for wavelength division multiplexing on a single optical chip. To this end 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 geometry and Bragg grating superstructure, with the potential for implementing many aspects of advanced grating design, such as chirp and apodisation, without the need for a phase mask.

Here, we review the latest developments in UV writing, firstly for 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 describe the technique for controlling the grating response is defined through computer software, and as such requires no modifications to our experimental setup to create Bragg gratings with responses spanning 490nm, providing an almost unparallel 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 is a fabrication technique based on the motion of a tightly focused writing spot relative to a 'blank' photosensitive sample. The photosensitive material exhibits a refractive index increase only in the regions exposed to the UV irradiation, leaving the remaining areas of the sample unaffected. When the writing spot is traced relative to the sample, 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.

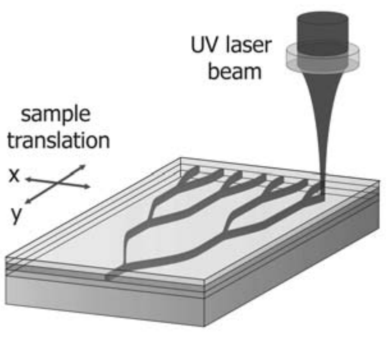

Figure 1: Showing the concept of Direct UV writing

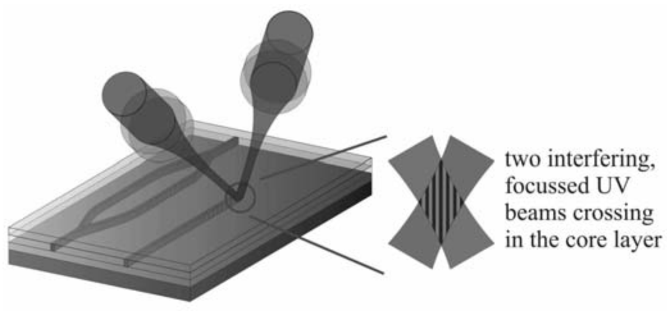

Figure 2: Concept of Direct Grating Writing

In our variant of Direct UV writing, throughout the remainder of this paper referred to as Direct Grating Writing (DGW), two focussed beams 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 an overall refractive index increase with the same physical dimensions as the writing spot, but with a periodic modulation corresponding to the inference pattern. By exposing multiple ‘snap-spots’, each offset by the period of the interference pattern, the index modulation structure 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 focussed spot can be used to write standard channel waveguide structures, including the curves and junctions that form the basic building blocks of many larger integrated optical systems [7].

The combination of these two techniques allows planar Bragg gratings to be inserted into complex all-UV-written devices in a single processing step, and is achievable as a direct result of the small writing spot fundamental to this process. Structurally, 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.

By contrast, in DGW the Bragg grating modulation is not superimposed, but generated at the same time as the channel structure, with the index modulation oscillating either side of the average index of the channel. Thus, the contrast of the grating is independent of the strength of the channel waveguide within the limit of the average index of the channel structure. This is an important feature of the process allowing the optimization of the channel waveguide and Bragg grating properties independently without detrimental effects to the other structure. As the photosensitivity of the sample is no longer shared between the two processing steps, the risk of saturation of 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 optimal device performance. An additional advantage of the small interference spot is the very accurate location and short lead-in/out distance (distance of varying grating contrast, in this case the width of the writing spot) to the grating structure.

2. Experimental

Fabrication of direct-written gratings was 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 was used to create two separate beam paths at an intersection angle of 29 degrees, and both beams were individually focussed and aligned to give a single ~4µm interfering spot.

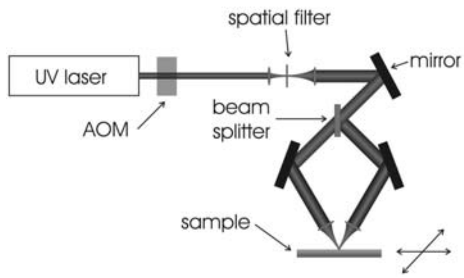

Figure 3: Schematic diagram of the Direct Grating Writing setup

The samples used throughout these experiments were three-layer silica-on-silicon wafers produced through flame hydrolysis deposition. In each case the core layer was co-doped with germanium, seeding the sites that are potential hosts for the UV absorbing defect centers, whilst raising the refractive index thus defining a planar waveguide structure. The photosensitivity of the germanosilicate core layer was enhanced by 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

A typical mode profile of a channel waveguide containing a Bragg grating structure is shown in figure 4 (at 633nm) and figure 5 (at 1.55µm). The guided modes have near symmetrical profiles comparable to that of standard single mode telecoms' fibres, providing a high degree of compatibility between the planar channels and fibre. The channel waveguides are clearly visible by eye, with an NA = 0.17± 0.02 measured using a multiple far field imaging technique.

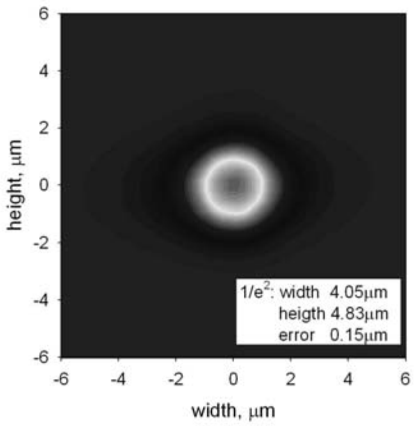

Figure 4: Mode profile of a DGW channel waveguide at 633nm

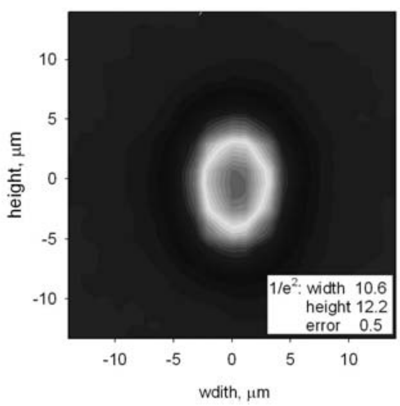

Figure 5: Mode profile of a DGW channel waveguide at 1.5µm

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 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 Bragg wavelength, dependant in this case on the strength of the channel waveguide, remains at the same wavelength of the two structures confirming the contrast of the grating and the channel strength can be controlled independently.

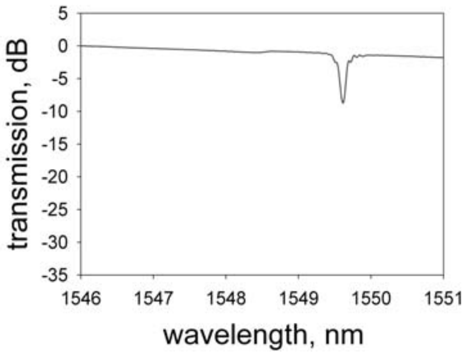

Figure 6: Spectral response of a 'weak' 8mm long Bragg grating

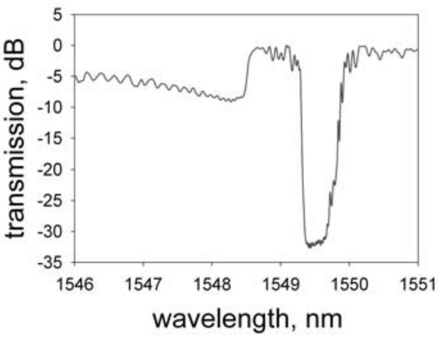

Figure 7: Spectral response of a 'strong' 8mm long Bragg grating

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.

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].

$$F = \frac{I_{UV} \times a}{v_{scan}} \tag{1}$$

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 against the writing fluence used, 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.

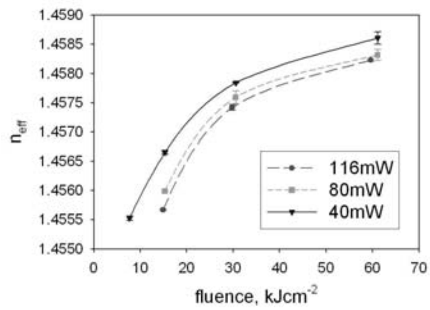

Figure 8: Difference on the strength of the waveguide with writing conditions

Directional Couplers

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 guided mode extending into the cladding structure surrounding the waveguide. If there is a second waveguide close enough that the evanescent fields interact 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 dependant, 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.

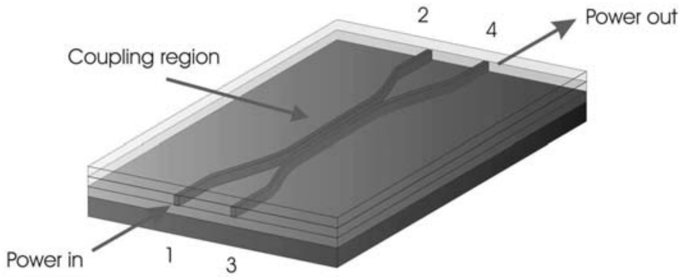

Figure 9: Schematic of a directional coupler, providing wavelength dependant power splitting between the output ports with a Bragg grating structure written in the coupling region.

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.

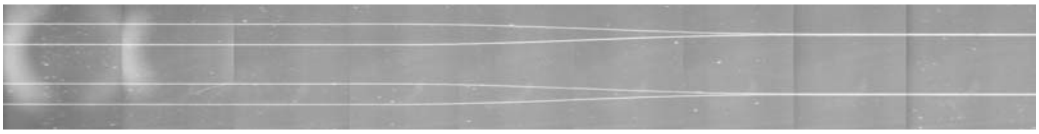

Figure 10: Overhead view (half) of two directional couplers as illustrated in figure 14

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 dependant response to the structure. The presence of the second waveguide affects the performance of the Bragg grating during the writing process, however the process is currently being optimized to eliminate this effect.

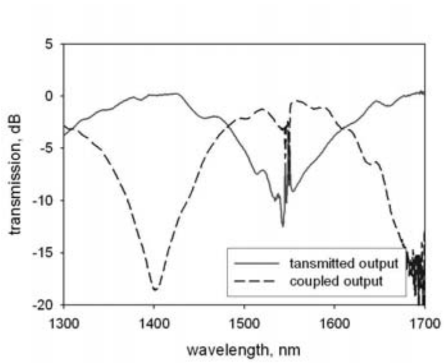

Figure 11: Wavelength dependence of the power distribution between the output arms of the coupler with a Bragg grating response at 1550nm

Ultra-wide detuning

With the absolute period of our small-spot interference pattern defined by the refractive index of the host material and 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 an image of the interference pattern as in many of the existing techniques [7, 9, 10]. This distinction permits fine tuning of the final grating structure, allowing a specific spectral response that is different from a grating containing an index modulation matching the image of the interference pattern.

In the centre-wavelength detuning process, each exposure of the writing spot is displaced by the period of the interference pattern (Λ) plus an additional constant offset (Δ). With the summation effect of the multiple exposures the resultant index modulation period is defined by the displacement between each exposure (Λ + Δ), not the period of the interference pattern. In systems using phase masks to generate an interference pattern the spot size is typically >200μm, 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, an effect dramatically demonstrated in the graph of figure 12, where an effective detuning range of 490nm, spanning 1.23μm to 1.72μm, and encompassing all of the O, E, S, C, L, and U wavelength bands used in optical communication systems is presented.

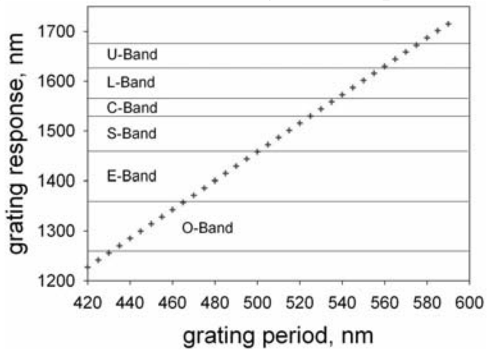

Figure 12: Bragg gratings produced through the computer controlled detuning process. Gratings with responses covering the entire ITU grid were produced in a single fabrication run with no alteration to the fabrication setup.

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.

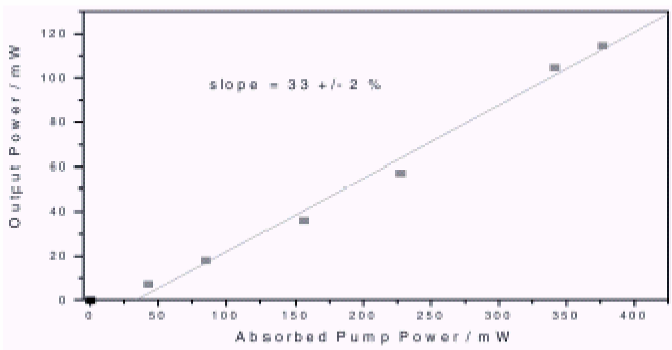

Figure 13 showing the threshold characteristic for a directly UV written Nd doped silica on silicon laser

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.

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