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ULTRA-WIDE PLANAR BRAGG GRATING DETUNING AND 2D CHANNEL WAVEGUIDE INTEGRATION THROUGH DIRECT GRATING WRITING

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Abstract *We present a technique for defining 2D channel waveguide structures with internal Bragg gratings in photosensitive germanosilica-on-silicon using two interfering focussed UV beams. Grating detuning across the S, C, L and U bands is demonstrated.*

Introduction

Direct UV writing provides an attractive route towards low-cost integrated optical components in photosensitive silica-on-silicon wafers. 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 presented the first demonstration of simultaneously defined channel waveguides with integral Bragg gratings based on the interference of two focussed UV-writing beams [1]. 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 present two refinements unique to the small writing spot used during this process, extending the UV-written channel waveguide geometry to two dimensions, while also demonstrating an unprecedented ultra-wide grating detuning response across the S, C, L and U wavelength bands - a technique controlled entirely through computer software and requiring no modifications to our experimental setup.

Direct Grating Writing

Like Direct UV writing, our technique is based on the motion of a tightly focused writing spot relative to a 'blank' photosensitive sample [2, 3, 4]. The photo-sensitive material exhibits a refractive index increase only in the regions exposed to the UV irradiation, leaving the remaining areas of the sample unaffected. As 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. 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.

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 1). 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 [5].

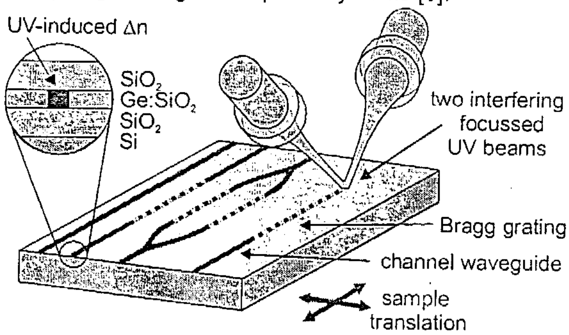

Figure 1:
Single-step definition of channel waveguides and Bragg gratings by Direct Grating Writing

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.

Experimental: 2D integration

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.

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 centres 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.

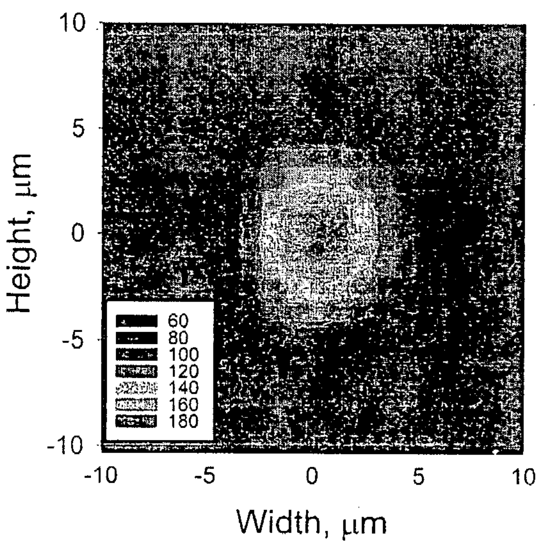

Figure 2:
Typical mode profile of channel waveguide containing a Bragg grating structure at 1.55μm

A typical mode profile of a channel waveguide containing a Bragg grating structure is shown in figure 2. 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.

Transmission spectra from straight channel waveguides containing an integral Bragg grating section are presented in figures 3a and 3b. Through control of the writing conditions and grating parameters the strength of the wavelength specific response can be readily tailored to range from <5dB to >30dB, with the bandwidth scaling as expected.

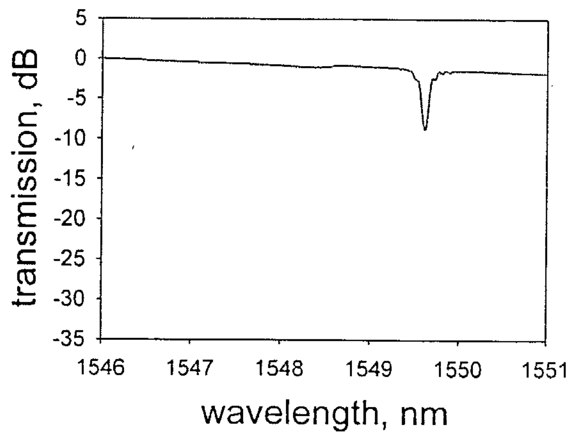

Figure 3a:
Typical transmission spectra for a straight channel waveguide with 10mm long 'weak' integral Bragg grating

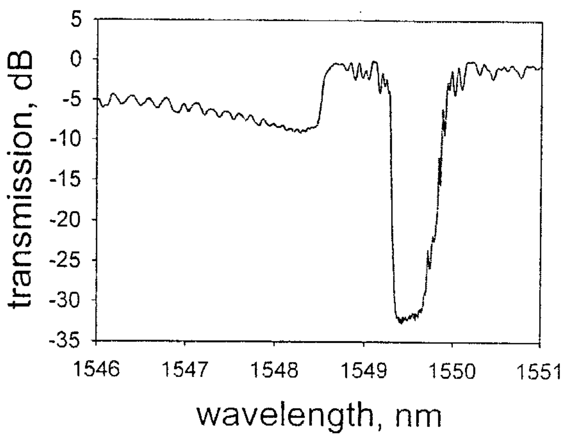

Figure 3b:
Typical strong grating response from a 10mm long Bragg grating with the cladding modes clearly displayed

Due to the nature of the three-layer samples used during this experiment, each incorporating an existing slab waveguide, there is an inherent birefringence observed in the UV-written structures. This is readily observable through control of the polarisation of the light used to interrogate the grating. In these samples the Bragg grating channel waveguide structures have a typical measured characteristic birefringence of ~$1.2x10^{-4}$ (figure 4). When used to characterise 'weak' grating structures this interrogation technique provides a rapid and accurate insight into the characteristics of the host channel waveguides themselves, such as birefringence, Δn, etc.

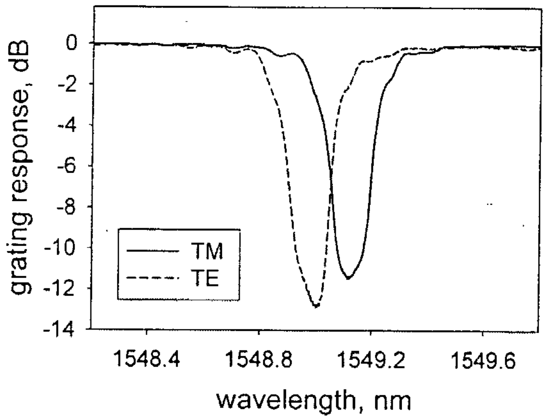

Figure 4:
Interrogation of grating response with respect to polarisation yielding a birefringence of $1.2x10^{-4}$.

In order to demonstrate the 2D capabilities of our Direct Grating Writing technique, Mach-Zender structures were written based on the arrangement illustrated in figure 1. For each device, two 5mm-long cosine-style y-splitter sections were used to separate the two central arms of the structure by 200μm, corresponding to s-bend radii of ~ 60mm (figure 5).

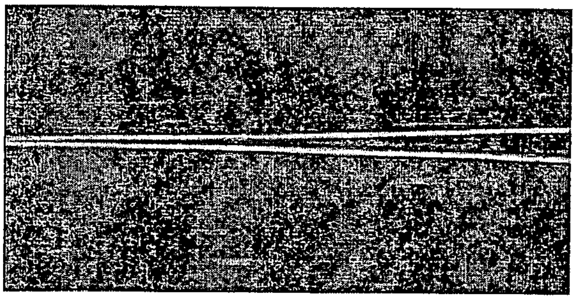

Figure 5:
Overhead photograph of a splitter section in a silica-on-silicon sample written using the DGW technique. The channel waveguides are clearly visible indicating the strong index change occurring in the writing process.

For these initial experiments two 8mm long planar Bragg gratings with periods of 532 and 532.4nm respectively (defined using a process known as centre-wavelength detuning [4,5], as described in the following section) were incorporated into the two arms of each device, resulting in dual-peak spectral responses typical of that given in figure 6. The two grating reflection responses are clearly defined, and future work will be aimed at integrating such gratings into larger optical systems.

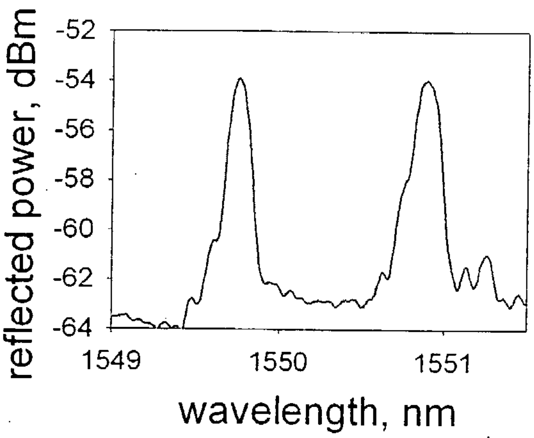

Figure 6:
Reflection spectra for a 2D Mach-Zender channel waveguide structure with 8mm long integral Bragg grating sections on each of the two arms.

Ultra-wide grating 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 focussed 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 [5, 8, 9]. 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 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 ($\Lambda + \Delta$), not the period of the interference pattern (figure 7).

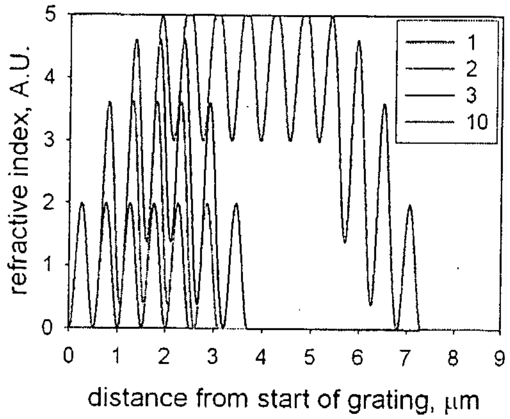

Figure 7:
Demonstration of refractive index modulation build-up over 1-10 small-spot exposures of a 2.5μm wide writing spot with an interference pattern period of 500μm and stepped exposure displacement of 600μm.

Unlike the period of the interference pattern, the distance between subsequent exposures is readily defined through control software, and thus does not require the angle of intersection or any of the optical train to be adjusted. However, an important consequence of the detuning process is that the contrast of a grating structure decreases as the magnitude of the offset Δ increases. In a simple case the limit of detuning before minimal index modulation is reached can be expressed as;

$$\Delta = \pm \frac{\Lambda}{N} \qquad (1)$$

where N is the number of interference fringes contained within the writing spot. It is important to note that the magnitude of the detuning range possible is inversely proportional to the number of grating planes contained in the writing spot. As the interference period is fixed this relates directly to the size of the writing spot.

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 arraignment 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 8, where an effective detuning range of ~300nm, spanning 1.4μm to 1.7μm, encompassing the majority of the E, S, C, L, and U wavelength bands is presented.

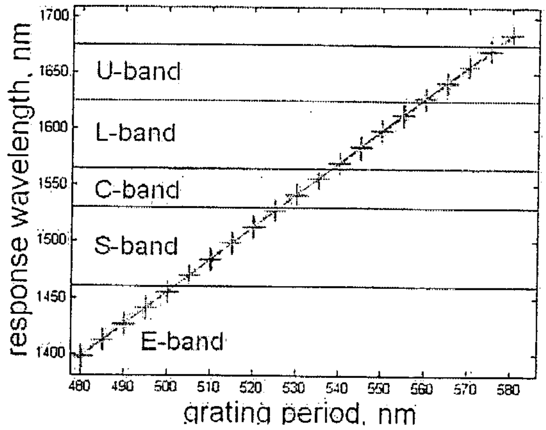

Figure 8:
Demonstration of ultra-wide grating detuning with grating responses ranging from 1.4μm to 1.7μm. This wide range of grating periods was achieved entirely through software controlled Direct Grating Writing with a fixed two-beam interference setup.

Conclusions

In conclusion, we have presented two refinements to our recently reported Direct Grating Writing process, each specifically derived from our unique use of a micron-order circular writing spot. Using these processes we have demonstrated single-step integration of planar Bragg gratings into 2D Mach-Zender structures and an unprecedented ~300nm ultra-wide grating detuning response encompassing most of the E, S, C, L and U wavelength bands, results achieved entirely through software control of the modulated writing spot. 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.

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