Direct UV written waveguides and Bragg gratings in doped planar silica using a 213 nm laser

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In this paper, the first demonstration of simultaneous UV written Bragg gratings and waveguides in germanium and boron-doped planar silica is presented using a 5th harmonic solid-state nanosecond laser operating at 213 nm wavelength. The fabrication of high-quality gratings by using a high peak power density, yielding sufficient uniformity and without any surface damage is demonstrated. The photostimulation of the doped silica layer is investigated by measuring the local effective refractive index of the optical modes. The written gratings are used to measure grating refractive index modulation, grating detuning bandwidth and the waveguide propagation loss with a minimum value of 0.28 ± 0.07 dB cm⁻¹. This paper shows that this new generation of pulsed UV lasers is a promising alternative for conventional longer wavelength CW laser sources used in small spot direct grating writing in doped silica.

Introduction: Bragg gratings in planar silica provide functionality for various integrated devices such as optical sensors [1], grating stabilized semiconductor lasers [2], and add-drop filter components [3]. Bragg grating based devices are usually fabricated using conventional lithography and etching to form both the waveguide and grating structures. Etched grating components typically require a precise definition of the waveguide dimensions and the grating period—demanding extremely high fabrication accuracy. The limitations of lithography and etching have led researchers to look to alternative approaches such as phase mask [4] and direct writing techniques, including femtosecond [5] and UV laser writing [1]. Femtosecond writing provides a unique ability to fabricate 3D photonic structures [6] but has its challenges due to nonuniformity originating from nonlinear laser interaction.

Direct UV writing (DUW) has unique benefits for defining both channel waveguides and Bragg gratings in doped planar silica with minimal losses [7, 8]. Typically, DUW and direct grating writing (DGW) employ a 244 nm frequency-doubled argon-ion laser and rely on the photosensitivity of planar silica achieved by doping with germanium and boron to induce a change in refractive index. Additionally, the doped silica layers often require in-diffusion of hydrogen or deuterium before UV writing to ensure adequate refractive index change [9].

For commercial implementation, there is a need to reduce the manufacturing and maintenance cost of direct UV writing setups. Conventional laser sources for UV writing are usually costly to run and maintain; therefore, new high-efficiency, low-maintenance sources are desirable. The first use of a 213 nm quintupled Nd:YAG laser source to induce a refractive index change in planar silica was by Schenker et al. [10], with further studies exploring the use of picosecond pulses to UV trim fibre Bragg gratings [11]. More recently, fifth harmonic solid-state Nd: YVO4 lasers, operating at a wavelength of 213 nm, have become commercially available, providing nanosecond pulses with high peak power. Compared with conventional lasers, these sources are compact, cost-effective, and efficient in terms of footprint, power consumption and maintenance. These laser sources have been employed to fabricate Bragg gratings in hydrogen-free SMF-28 fibre using a phase mask technique [4]. The relatively long coherence lengths available from such commercial systems permit the flexibility of the dual-beam interferometer arrangement [12] suggesting such systems may be suitable for DGW.

Recently single-mode waveguides have been fabricated in hydrogen-loaded and non-hydrogen loaded planar silica by single-beam 213 nm inscription [13, 14]. Some preliminary results on simultaneously produced Bragg gratings and waveguides by 213 nm light were reported in [15], however the high peak power densities of the source led to significant undesirable surface damage. Figure 1 is an optical microscope image of a chip that contains 213 nm UV written waveguides showing induced surface damage. The inset shows a higher magnification image of a waveguide, clearly showing the high peak power density causing ablation of the silica.

In such a case, implementation of direct grating writing becomes more challenging due to stability issues of the interferometer over a longer period of time. Therefore, to employ such high energy sources for small spot grating writing, it is essential to find the optimum values of fluence and average power of the laser to obtain stable gratings without damaging the surface, especially for non-hydrogen loaded samples [16].

Here we report the first successful fabrication of both channel waveguides and Bragg gratings simultaneously produced in doped planar silica by 213 nm dual-beam laser interferometry at a peak power density exceeding 1000 times higher than previously used with a 244 nm CW laser. We demonstrate high-quality gratings can be fabricated with such high peak powers, yielding sufficient uniformity and low defects, while still achieving a reasonable speed for fabrication. To the best of our knowledge, this is the highest UV written peak power density experiments in the literature. Thereby confirming the suitability of such 213 nm solid-state laser systems for DGW, we fully calibrate this new system for grating writing using the dual-beam technique, where one arm of an interferometer is phase modulated using an EOM. We also characterise the various properties of our UV written devices, including; the fluence dependence of the induced effective refractive index change (Δn_eff), the reflectivity of the gratings and thus refractive index modulation (Δn_m), grating detuning bandwidth, and waveguide propagation loss.

Experimental method and results: The DGW system operates with the same principle as prior work using 244 nm [17]. However, the geometry and components have been modified to account for the change in UV operating wavelength, i.e. CaF2 lenses to replace fused silica. Figure 2 is a schematic of the phase-controlled DGW technique, which relies on a precision air-bearing stage system (Aerotech) and the UV laser system. The grating inscription pattern was generated by the interference of two UV beams from a fifth harmonic solid-state Nd: YVO4 laser operating at a wavelength of 213 nm (Xiton Photonics, Impress 213). The laser beam was spatially filtered and expanded prior to splitting by a beam splitter to supply the two arms of the interferometer. One beam of the interferometer passed through a bespoke KD*P electro-optic modulator (EOM)(Leslyopt Ltd.) to provide phase control of the interference pattern. A pair of planoconvex CaF2 lenses was used to focus both laser beams at the same point in space, where the UV inscription pattern is formed. The period of the fringes is related to the crossing angle of the beams. In this work, the target wavelength of operation is in the telecommunication C-band. A Bragg grating with the peak reflectivity at 1550 nm equates to a
period of 535.6 nm and a crossing angle of 22.6° (half angle 11.3°). This angle is achieved through alignment of the interferometer. However, as we will discuss later, the bandwidth of the system is such that accurate alignment is not critical. Via applied voltage to the EOM, it is possible to control the position of the fringe pattern within the foci of the two beams. Precise modulation of the EOM voltage can, therefore, be used to translate the interference pattern in-phase with the translation speed of the sample [17]. This technique allows the simultaneous fabrication of channel waveguide and grating structures during constant sample translation.

In this work, three-layer silica-on-silicon was used as the photosensitive platform. Flame Hydrolysis Deposition (FHD) was employed to deposit a 4.2 µm thick core layer of germanium and boron-doped silica onto a silicon wafer with a 15 µm thermal oxide acting as an underclad. The peak germanium and boron concentrations are estimated from time-of-flight mass spectroscopy to be ≈3% and 3% respectively. This core layer was capped with an index-matched 15.1 µm thick boron and phosphorous doped over-clad layer, also produced by FHD. Individual chips measuring 10 × 20 mm were diced from this wafer using a Loadpoint Microcne 3 dicing machine and loaded in a hydrogen cell at a pressure of 120 bar for 5 days, before writing, to improve photosensitivity. To achieve the highest grating refractive index modulation, we first calibrated the 213 nm direct grating writing system in a similar approach as given in [17]. In the 213 nm system, the EOM requires a slightly lower voltage (3.8 kV) as compared to 244 nm operation [17] to get the peak voltage (3.8 kV) as compared to 244 nm operation [17] to get the highest grating index modulation; the phase change due to applied voltage is directly related with the writing wavelength. As in the previous work, the duty cycle of the control signal defines the strength of grating index modulation [18].

For grating characterisation, an Er-doped fibre ASE source was launched into the UV written waveguides by using a polariser and polarising maintaining fibre V-groove coupling to ensure a single polarisation (TE) was coupled into the device. A 3 dB fused fibre coupler was used to collect the reflected light, and the grating spectra were measured on an optical spectrum analyser [8, 18]. Figure 3 shows the normalised reflectivity of the 1 mm long uniform grating written with a fluence of 1 kJ cm⁻² and 100% duty cycle. The reflectivity of this grating was normalised by referencing to the 3.3% reflection of the polished connector facet prior to the V-groove assembly. This reference provides an approximate estimate of the absolute reflectivity of the grating and does not consider the coupling and propagation loss. Surprisingly, the spectrum shows a peak reflectivity of 86%, despite the grating only being 1 mm in length. The plot also shows the reflection spectra of an ideal uniform Bragg reflector calculated using coupled mode theory. Both experimental and theoretical plots show good agreement.

Prior DUW with 213 nm light suggests a linear trend followed by saturation of the photosensitivity mechanism [13]. Previously the fluence response was estimated from the waveguide mode size and numerical aperture measurements. The ability to write Bragg gratings allows a precise measurement of the induced refractive index change. In order to investigate the fluence response, a planar chip was UV written with a series of integrated waveguides and Bragg gratings at a fluence range of 0.5 to 15 kJ cm⁻² by manipulating the stage translation speed. The writing beam at average power of 4 mW was focused using a pair of 100 mm focal length lens to a 1/e² spot diameter of 5.1 µm determined by knife edge measurements. For this experiment, the duty cycle was reduced to 50% to reduce the reflectivity of the gratings, as strong gratings provide a poor regime for interrogating the properties of the grating. Figure 4 plots the effective refractive index (n_eff) of the waveguide against the laser fluence. n_eff is calculated from the central Bragg wavelength and fabricated grating period. At fluences below 4 kJ cm⁻², a near linear trend is observed, after which the photosensitivity begins to saturate. Beyond fluences of 10 kJ cm⁻² no appreciable change is noted, this corresponds to a maximum UV induced effective refractive index change of 3.3 × 10⁻³.

Compared to other UV grating writing techniques, such as phase mask approaches, the small spot DWG technique allows for wide detuning of the grating wavelength over hundreds of nanometers without altering the interferometer [17]. In order to quantify the detuning of this system, a chip was fabricated with a 20 mm long waveguide containing ten 1 mm long uniform gratings. The written gratings were targeted from 1450 to 1648 nm with a wavelength interval of 22 nm. The writing was performed at a fluence of 0.9 kJ cm⁻² and duty cycle of 40% to avoid saturation of the gratings. As previous devices, fabricated with 4 mW of average power, did not show evidence of surface damage, the writing power of the laser was increased to 12 mW. The reflection spectrum of the waveguide is presented in Figure 5(a) shows a normalised peak reflectivity of 54% for the Bragg grating at 1560 nm and corresponds to an estimated grating refractive index modulation (Δn_eff) of 0.49 × 10⁻³. As previously, the reflectivity is normalised using the back-reflection from the fibre facet. Despite the number of gratings within the waveguide the spectrum has > 25 dB of noise floor suppression. Figure 4(b) displays the Δn_eff of each grating plotted against the central Bragg wavelength. The value of Δn_eff is estimated both analytically and numerically using a Bragg grating model. Analytical values are calculated by using the peak reflectivity from each grating [19], while Roard's method [20] was used to fit a model to the reflection spectrum of each peak. The results from both methods are presented in Figure 4(b) and show good agreement. The data is fitted with a Gaussian curve in the frequency domain, which again exhibits excellent agreement and yields a 3 dB bandwidth (FWHM) of the Bragg grating index modulation of 17.7 THz (142 nm).

Bragg gratings also provide a route to precisely and non-destructively measure propagation loss [8]. To investigate the propagation loss, a chip
was UV written with series of integrated waveguides at various fluences. The waveguides were each 20 mm in length and contained ten 1 mm long Gaussian apodised gratings. The gratings had central Bragg wavelengths from 1520 to 1590 nm with 7.5 nm spectral spacing. The gratings were written in pseudo-random wavelength order with a 0.5 mm inter-grating spacing. Reflection spectra were collected from both facets of the waveguides. Propagation losses and associated errors were calculated for each waveguide using the technique outlined in [8]. The lowest propagation loss of 0.28 ± 0.07 dB cm⁻¹ was observed at the fluence of 0.8 kJ cm⁻². This measured propagation loss is lower compared to previous work, in which the cutback method was used for loss estimation [13]. However, the work here does not consider the optimisation of the mode size as previously [13], which led to the use of higher fluences to achieve the best mode matching to single-mode fibres.

**Conclusion:** In this work, we have demonstrated the first 213 nm direct UV written waveguides containing Bragg gratings. The waveguides and gratings are formed in hydrogen-loaded planar doped silica and display high consistency and reproducibility. In all these experiments, the grating parameters were controlled through software, without altering the crossing angle of the UV interferometer. This work also presents and discusses the use of Bragg gratings to characterise device propagation losses. Key highlights of this work include high reflectivity up to 86% from 1 mm uniform gratings and propagation loss of 0.28 ± 0.07 dB cm⁻¹ from a pulsed 213 nm laser written waveguide. Conclusively this paper confirms that this new generation of pulsed UV lasers are suitable for small spot direct grating writing. Further work will explore the effects of average writing power of laser with fluence and core layer thickness on properties of the waveguide, namely mode size and propagation loss. Extensive work will be required to quantitatively compare the performance of pulsed 213 nm and CW 244 written devices. Nonlinear effects of 213 nm laser writing have been previously suggested in boron and germanium co-doped optical fibre [4]. However, this work did not identify any nonlinearities. A greater range of applied UV power will be required to verify these effects in DUW structures.

The data that support the findings of this study are openly available in the University of Southampton repository at https://doi.org/10.5258/SOTON/D1539.

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