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# Direct UV written integrated planar waveguides using a 213 nm laser

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**Abstract:** We present the first demonstration of integrated waveguides in planar silica devices fabricated using direct UV writing with 213 nm laser light. Waveguides were produced with different writing fluences and the NA and MFD of each were measured. Single mode waveguides were achieved at fluence values one-tenth that typically required when operating with a 244 nm laser, allowing for more rapid fabrication. A maximum in-plane index change of 2.4 $\times 10^{-3}$ for a writing fluence of 5 kJ cm$^{-2}$ was estimated from NA measurements. Finally cutback measurements were performed and a propagation loss of 0.42 ± 0.07 dB cm$^{-1}$ was directly measured, though losses as low as 0.2 ± 0.03 dB/cm are indicated through calculations.



## 1. Introduction

Integrated optics is an enabling technology for fields such as sensing, communications and quantum technologies [1–3]. In particular passive devices made in silica are useful as they are compatible with the existing telecommunications infrastructure, enabling many benefits such as lower coupling losses. Silica photonics also offers reduced optical losses over other techniques for transmission in the visible and near infrared, and possesses other optical properties including non-linear attributes [4, 5]. Direct Ultra-Violet Writing (DUW) commonly employs a 244 nm frequency doubled Argon Ion or 248 nm Excimer UV laser to induce a refractive index change [6]. Using this approach photonic structures - such as beam splitters, couplers and Bragg gratings - can be achieved in germanium and boron doped silica. To successfully scale DUW of planar photonics towards commercial goals it is important to reduce manufacturing costs and improve fabrication consistency. Traditional laser sources for DUW are costly to run and maintain, therefore new sources with better efficiency and low maintenance requirements are desirable.

Here we present the first planar silica waveguides fabricated through the DUW technique by using a 213 nm UV laser. We characterise the numerical aperture (NA) and mode field diameter (MFD) of each waveguide, as a means of inferring the maximum index change induced by the UV light. We also measure propagation loss through cutback measurements.

## 2. Background

Direct UV written planar waveguides in silica have been explored for over two decades [7, 8]. The technique is capable of fabricating low-loss channel waveguides, couplers, Bragg gratings and polarisers [9] within a photosensitive silica layer by translating an appropriate substrate through a focused UV beam. Typically a photosensitive Ge-doped silica layer is deposited on a thermally oxidised silicon wafer and is then capped with another layer of doped silica containing boron and phosphorus. This capping layer and the thermal oxide on the substrate have low intrinsic photosensitivity and act as optical cladding for waveguides written into the photosensitive core layer. To date direct UV written waveguides have been primarily formed by using 244 or 248 nm laser light, relying on the photosensitivity provided by doping with germanium to induce a

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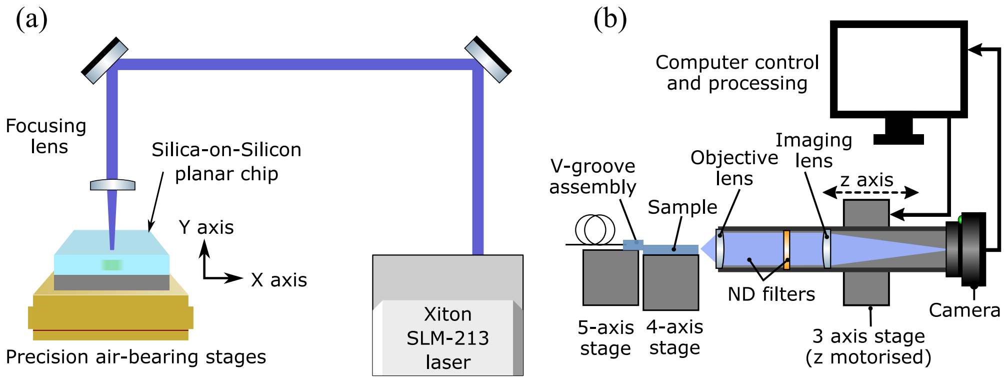


Fig. 1. (a) 213 nm wavelength light from a fifth harmonic laser is focused onto a planar silica-on-silicon chip. A set of precision air-bearing stages translate the chip through the beam focus to write waveguides into the Ge-doped silica core layer. Fluence is manipulated through translation speed. This is a measure of photon exposure and thus directly relates to refractive index change. (b) broadband light from an erbium-doped fiber ASE source was coupled into the waveguides via a fiber V-groove assembly. The waveguide facets were imaged directly onto an InGaAs camera interfaced with computer software. The camera and imaging lens were translated away from the waveguide facet and the software measured the divergence of the beam. The data were fitted using a second moment technique (ISO11146) allowing the extraction of NA, beam waist and $M^2$ parameters.

refractive index change. For a refractive index change sufficient to form waveguides the substrates also typically include boron co-doping and hydrogenation prior to UV writing [10].

Bragg gratings in Ge-doped optical fibre have been achieved without the need for hydrogenation by using a deep UV laser operating at 213 nm [11]. These gratings were produced through the phase mask technique and were shown to generate a higher photosensitivity than 248 nm light [12]. In our work the source used for UV writing was a fifth-harmonic solid state Nd:$YVO_4$ laser operating at a wavelength of 213 nm supplied by Xiton Photonics. The Xiton laser exhibits a typical power consumption of 800 W through a standard 240 V wall-plug supply and is cooled by a closed-loop chiller system. This is in contrast to other coherent UV sources, for example; a frequency-doubled Argon Ion laser cooled via a heat exchanger, drawing up to 50 Amps and typically consuming over 10 kW of power. To scale DUW of planar photonics it is important to reduce manufacturing costs and improve fabrication consistency.

## 3. Experimental method and results

In this section the characterisation of waveguides written with 213 nm UV light is discussed. The NA and MFD of each waveguide written with different fluences are compared and the resulting index change induced by the UV light is inferred. The propagation losses are determined through cutback measurements.

### *3.1. Fluence characterisation of waveguides*

Flame Hydrolysis Deposition (FHD) was used to deposit a 7.1 µm silica core layer, doped with germanium and boron, onto a silicon wafer with a 15 µm thermal oxide. A 7.3 µm thick overclad layer doped with phosphorus and boron was formed on top of the core layer. The core and cladding layers were fabricated to have similar refractive indices, so that the index change of the core region exposed to the 213 nm UV light could be directly quantified. Some guiding in the unwritten core was observed, suggesting a slightly increased refractive index in the core compared to the cladding, possibly induced during consolidation of the cladding through diffusion

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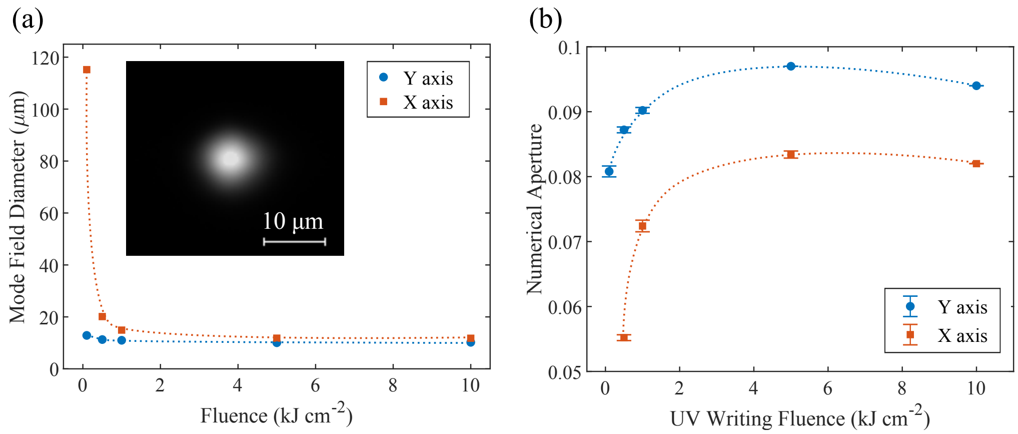


Fig. 2. (a) shows the resulting MFD of the waveguides in relation to the fluence they were written with. Higher fluences induce a larger index change and so better confine the mode. Inset: An image of the mode of the waveguide written with 10 kJ cm$^{-2}$. (b) shows the measured NA of the waveguides in relation to writing fluence. Higher fluences cause a greater index difference between the written core and surrounding material, leading to higher waveguide NA. The light was not well confined for the waveguide written with a fluence of 0.1 kJ cm$^{-2}$ and gave an anomalous NA result. For this reason the data point has been excluded from the plot. Dashed lines are provided to guide the eye.

or stresses. Individual planar chips were then diced from this wafer using a Loadpoint, MicroAce, Series 3 dicing machine. The chips were diced in the ductile regime [13] which negated the need for an additional facet polishing process. The chips were then placed inside a cell pressurised with hydrogen at 120 bar for four days to allow in-diffusion prior to writing.

The planar chip was removed from the hydrogen cell, mounted on a set of Aerotech precision air bearing stages. The beam was focused by a 100 mm focal length $CaF_2$ lens to a $1/e^2$ spot diameter of ~5 μm, which was determined through knife edge measurements, and the chip was translated through the focus to write waveguides into the core layer (Fig. 1(a)). In order to maximize exposure but avoid the damage threshold of FHD glass, a repetition rate of 30 kHz and 5 mW average power was selected.

For each waveguide the writing fluence was manipulated through stage translation speed, therefore varying the induced refractive index change of each waveguide. Waveguides were UV written into the chip with a range of fluences from 0.01 to 10 kJ cm$^{-2}$, resulting in stage speeds from 382 to 0.382 mm min$^{-1}$. It took a total time of 23 minutes to write all 7 waveguides into a chip measuring 10 mm in length. To ensure laser stability for this length of writing time, the average power of the laser was measured over 3 hours and found to be stable to within 10 percent.

The MFD and NA characterisation setup is shown in Fig.1(b). Broadband light from an erbium-doped fiber ASE source was coupled into the waveguides via a fiber V-groove assembly. The waveguides were characterised by imaging the waveguide facets directly onto an InGaAs camera interfaced with computer software. The camera and imaging lens were translated away from the waveguide facet and the software measured the divergence of the beam. The data were fitted using a second moment technique based on the standard detailed in ISO11146:2000 [14], which allowed the extraction of the NA, beam waist and $M^2$ parameters of both axes (the orientation is indicated in Fig. 1(a)), where the X axis is defined as being perpendicular to the waveguide direction in the plane of the core layer, and the Y axis is perpendicular to the planar core layer. The waveguides were realigned and measured 5 times each to provide mean and standard deviation information. The chip was initially characterised soon after writing and then

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stored for 12 months. The chip was then re-measured and found to have no temporal degradation of the waveguides. All the data presented here are from this secondary characterisation.

The mean MFD results for these chips are shown in Fig. 2(a). The change in index of the photosensitive silica is proportional to the fluence used to UV write [15], therefore higher fluence leads to stronger mode confinement in the waveguide. The MFD in the Y axis shows little variation compared to the X axis, and achieves a consistent value of around 10.4 µm for fluences over 1 kJ $cm^{-2}$. This is because the MFD in this axis is primarily dictated by the thickness of the deposited photosensitive layer. The MFD in the X axis decreases with increasing fluence until it reaches a consistent X axis MFD of ~11.8 µm for fluences above 1 kJ $cm^{-2}$. Fluences below 0.1 kJ $cm^{-2}$ did not produce observable waveguides. This is due to the fluence being too low to induce an index change sufficient to produce a waveguide. Waveguides with fluences at and above 0.1 kJ $cm^{-2}$ were written with at least 40 pulses per micron, ensuring continuous waveguides. The typical writing fluence used for a system operating with a 244 nm laser is around 12 kJ $cm^{-2}$. It is therefore possible to write much faster and with lower fluences using 213 nm light. This would allow devices to be written quickly before outgassing of hydrogen could cause significant feature variation.

### 3.2. Estimate for index change

Figure 2(b) shows the resulting mean NA measurements for the waveguides as a function of fluence. The induced refractive index change of the UV written waveguides can be estimated by the NA of the waveguide through $\Delta n \approx NA^2/2n_{clad}$, where $\Delta n$ is the index change induced by UV exposure. $n_{clad}$ is the index of the cladding layer and is equivalent to the index of the core layer prior to UV writing.

The FHD glasses were measured on a Metricon prism coupler system to determine the refractive index of the unwritten silica. This was determined to be 1.4474 for the core and top cladding layers, both individually measured at 1553 nm. The NA measurements were then used to determine the induced index change of the waveguides through UV writing. The maximum NA's achieved were 0.0834 and 0.097 in X and Y respectively, both for a fluence of 5 kJ $cm^{-2}$. Therefore the maximum index change achieved can be approximated as 2.4 x$10^{-3}$ in the X axis and 3.25 x$10^{-3}$ in the Y axis. However, the index change achieved in the Y axis cannot be attributed to UV exposure alone due to the slight guiding in the core layer prior to writing. This calculation is designed to predict the $\Delta n$ of a step-index change. The waveguides here are defined by UV writing with a Gaussian spot, so this calculation simply serves as an estimate of index change.

### 3.3. Propagation loss

To measure the propagation loss of 213 nm written waveguides a 9 cm long chip was diced, hydrogenated and written with the 213 nm laser with a fluence of 2 kJ $cm^{-2}$ and a $1/e^2$ spot diameter of ~2 µm. The smaller spot size and fluence was used to decrease the writing time of the long chip, whilst ensuring a good resulting MFD. The chip was aligned with a fiber V-groove assembly and attached with UV cured glue. It was then aligned in the cutback measurement setup shown in Fig.3(a). The chip was abutted against a glass coverslip with refractive index matched oil to ensure consistent alignment position between dicing. Transmitted light was collimated and passed through an iris to remove stray and scattered light. The light was directed on to a detector to determine transmitted power, and the chip was removed, cleaned, and remeasured three times to eliminate further alignment discrepancies. The chip was then diced back sequentially in increments of 1 cm using the Loadpoint dicing machine, and the transmitted power measured as above. The transmission data is plotted in Fig.3(b) and the gradient of the weighted fit was used to determine the propagation loss and error. The propagation loss measured for the chip gave a value of 0.42 ± 0.07 dB $cm^{-1}$. This loss value is larger compared to the 0.235 ± 0.006

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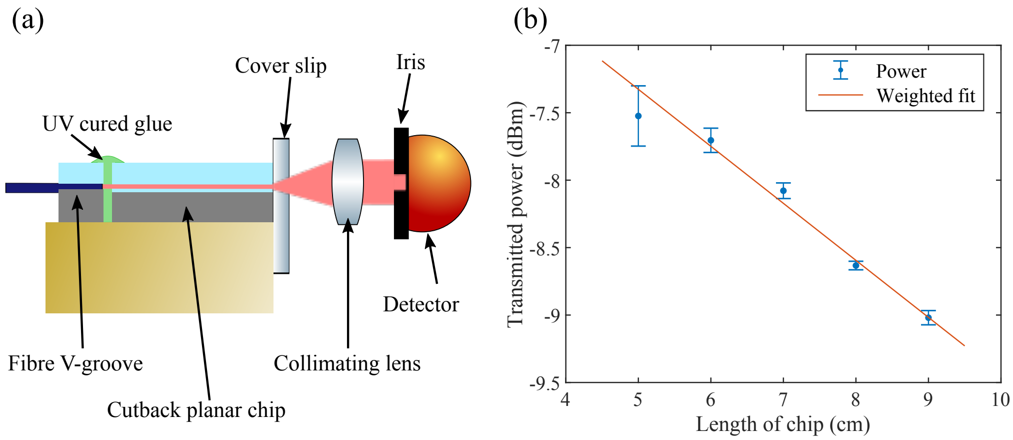


Fig. 3. (a) The characterisation setup for the cutback measurements is shown. A fiber pigtail is attached to a long waveguide chip with UV curing glue. The chip is aligned against a glass coverslip with refractive index matched oil to ensure consistent alignment position. Transmitted light is collimated and passed through an iris, to remove stray and scattered light, onto a detector to determine transmitted power. (b) Transmitted power measured against chip length for cutback measurements performed on the 9 cm long chip written with 5 kJ $cm^{-2}$. The standard deviations of the measurements are plotted as error bars. The loss of $0.42 \pm 0.07$ dB $cm^{-1}$ is taken from the gradient and error in the gradient of the weighted fit.

dB/cm achieved previously with 244 nm written waveguides measured using a Bragg grating technique [16]. This difference in loss may be due to the thinner cladding layer used in this work, or could indicate damage caused by the pulsed 213 nm light during writing causing scattering.

To investigate coupling losses a PM fibre V-groove assembly was measured in the NA setup to image its mode. An overlap integral was performed between this data and the modes of all of the waveguides to determine coupling efficiencies. This gave an estimate of losses due to coupling between the V-groove and the written waveguides. The best value of coupling losses achieved was $0.608 \pm 0.001$ dB for the waveguide written with 10 kJ $cm^{-2}$, and the inset of Fig. 2(a) shows an image of the mode profile of this waveguide. This coupling efficiency could be improved by mode matching of the wavegides through control of the UV writing spot size and FHD layer thickness.

A second V-groove assembly was aligned along the opposite side of the chip to measure the power transmitted by the waveguide. Both V-grooves were then aligned to each other and the transmitted power was measured. This gave a total loss (propagation + coupling losses) of $1.42 \pm 0.03$ dB for the 10 kJ $cm^{-2}$ waveguide. Using the coupling losses computed by the overlap integral for this waveguide, we can estimate a propagation loss of $0.2 \pm 0.03$ dB/cm. This is much closer to the value stated in [16], however this value is calculated and future work will aim to determine losses more accurately through the Bragg grating technique.

## 4. Conclusion

Planar photonic waveguides were written in silica using a UV laser operating at 213 nm. Writing fluences over 1 kJ $cm^{-2}$ produced consistent waveguides with an MFD of approximately $11.8\mu m$ in the X axis. The NA of the waveguides was measured and gave an estimated maximum index change in the X axis of 2.4 $x10^{-3}$ for a fluence of 5 kJ $cm^{-2}$. A 9 cm chip was written with a smaller spot size and a fluence of 2 kJ $cm^{-2}$ to reduce writing time. Cutback measurements were performed to find a propagation loss of $0.42 \pm 0.07$ dB $cm^{-1}$, though losses as low as $0.2 \pm 0.03$ dB/cm are indicated through calculations. The best coupling loss calculated through an overlap integral was 0.608 ± 0.001 dB for the 10 kJ $cm^{-2}$ waveguide, and could be improved through fabrication. Comparing with a system employing a 244 nm laser, it is possible to write with more than ten times lower fluence with 213 nm light into a hydrogenated chip. Future work will be to investigate the writing of Bragg gratings with and without hydrogenation using 213 nm light, and to investigate the effects of this in comparison to writing with a 244 nm laser.

(All data supporting this study are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D1022)

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