Towards a photonic mid-infrared nulling interferometer in chalcogenide glass

THOMAS GRETZINGER,* SIMON GROSS, ALEXANDER ARRIOLA, AND MICHAEL J. WITHFORD

MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia
*thomas.gretzinger@mq.edu.au

Abstract: Nulling interferometry enables astronomers to advance beyond the resolving power of ground-based telescopes with the goal of directly detecting exo-planets. By diminishing the overwhelming emission of the host star through destructive interference, radiation from young companions can be observed. The atmospheric transmission window centered around 4 µm wavelength is of particular interest because it has a favorable contrast between star and planet as well as a reduced atmospheric disturbance. For robustness and high stability, it is desirable to employ integrated devices based on optical waveguide technology. Their development is hindered at this wavelength range due to the lack of suitable host materials and compatible fabrication techniques to create low-loss photonic devices. This paper details our work on femtosecond laser direct-written optical waveguides and key components for an on-chip nulling interferometer inside gallium lanthanum sulphur glass. By combining cumulative heating fabrication with the multiscan technique, single-mode optical waveguides with propagation losses as low as 0.22 ± 0.02 dB/cm at 4 µm and polarization-dependent losses of < 0.1 dB/cm were realized. Furthermore, S-bends with negligible bending loss and broadband Y splitters with 50/50 power division across a 600 nm wavelength window (3.6 - 4.2 µm) and low losses of < 0.5 dB are demonstrated. Directional couplers with an equal splitting ratio complement these main building blocks to create a future compact nulling interferometer with a total projected intrinsic loss of < 1 dB, a value that is sufficient to perform future on-sky experiments in relatively short observation runs on ground-based telescopes.

Published by The Optical Society under the terms of the Creative Commons Attribution 4.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

1. Introduction

Integrated optical circuits are indispensable components of modern optical communication networks. Initially developed for telecommunication purposes, integrated optics have successfully been introduced into the field of astronomy as a serious alternative to classical bulk optics. This new field of astrophotonics has the capability to reduce the complexity of astronomical instruments by implementing a wide range of optical functions on a single chip [1, 2]. Bracewell’s nulling interferometry technique [3] for exo-planet detection benefits in particular from modal filtering [4] of single-mode photonics. In contrast to the bulk optic and fiber based nulling interferometer at the Palomar [5] and Large Binocular Telescope [6], an integrated phonic analogue is compact and inherently more resistant to environmental influences such as temperature and vibration.

Exo-planets are more likely to be found in the mid-infrared spectrum due to a favourable contrast between the high photon emission of the host star and a relatively low flux of its companion [7]. So far, the limited choice of materials and fabrication techniques has hampered the transition of such integrated devices into the mid-infrared wavelength range. But it has recently been shown that the gallium lanthanum sulphur glass, produced at the University of Southampton, is an excellent material for mid-infrared waveguide circuits [8] with high transmission of up to 10 µm wavelength [9]. GLS is a non-toxic glass which is well compatible with the femtosecond...
laser direct-write technique which is, compared to the lithographic approach, simple, fast and permits 3-dimensional fabrication of waveguide-based photonics [10]. GLS responds with a positive refractive index change to femtosecond laser irradiation. The result is usually a shorter fabrication time compared to negative refractive index-based depressed cladding waveguides in other chalcogenide glasses [8] since less material has to be exposed to the femtosecond laser. Only a few basic components for mid-infrared astronomical purposes have been reported [11–13] and to the best of our knowledge the devices reported were not tested on-sky due to high losses.

![Fig. 1. Layout of an on-chip two-port nulling interferometer chip in GLS glass. Two Y-splitters at the front-end feed the starlight into two outer power monitoring lines and two inner interferometric channels. The channels fan into the broadband 50:50 coupling region designed for 4 µm center wavelength where the starlight is nulled by means of destructive interference. Evidence of additional light in the null of the star will be detected at the output of the coupler and is associated with a possible exo-planet near the star.](image)

We designed an integrated nulling interferometer for exo-planet detection similar to Hague-nauer’s [14] and Benisty’s [15] beam combiners. Our aim was to build a device with an internal instrument loss of < 1 dB that makes it compatible with future on-sky operations. To achieve this, we have taken a novel hybrid waveguide fabrication approach between cumulative heating and multiscan technique to reduce propagation losses to a minimum.

The design layout in Fig. 1 shows two single-mode input waveguides spaced 500 µm apart to allow for the use of a commercially available silicon based micro-lens array (MLA) or a 1-dimensional V-groove fiber array for light injection. These input waveguides act as spatial filters that remove all phase variations associated with the collected starlight [4]. The waveguides evolve into S-bend based asymmetric Y-splitters that direct 50% of the light to the outer photometric channels while the remaining light is directed into the two inner channels for interferometric interaction. The principle of this two-port interferometer is to recombine on-axis stellar light destructively which had been half-wave shifted on one of the inputs. Thereby faint off-axis companions are revealed at the null channel while the starlight is detected at the anti-null channel. All four outputs are spaced 250 µm apart to match an aforementioned V-groove array that connects the chip to a mid-infrared detector via optical fibers.

This paper first gives an overview of the experimental methods used for fabrication and characterisation of low propagation loss waveguides in GLS glass at 3.39 µm and 4 µm wavelength. Afterwards the design and fabrication of the main components of the photonic nulling interferometer are discussed: S-bends, Y-splitters and directional couplers at 4 µm center wavelength. These building blocks of the proposed device are introduced individually and their performance is characterised.
2. Experimental methods

A mode-locked Ti:sapphire femtosecond oscillator (Femtosource XL500, 800 nm, <50 fs, 5.1 MHz) was used for waveguide inscription. Details on the inscription setup can be found in our previous work [16]. In brief, waveguides were fabricated with an oil immersion objective (Olympus Plan N 100 ×, 1.25 NA, 0.9 effective NA) focusing the laser pulses 180 µm below the surface of the GLS glass sample. The glass was kindly provided by ChG Southampton.

Two inscription methods were studied to assess the most suitable technique for this particular type of glass. Firstly, the multiscan technique [17] in the athermal regime was investigated using four different repetition rates: 425, 510, 728 and 1020 kHz, each of which was studied with translation stage velocities between 100 and 1125 mm/min and pulse energies varying from 30 to 120 nJ. Each waveguide consists of 15 passes across the sample where each was transversely offset by 400 nm to create a nominally 6 µm wide structure similar to previous femtosecond laser direct-written studies in GLS glass [18]. Secondly, the cumulative heating in the thermal regime was explored by utilising the laser’s native repetition rate of 5.1 MHz. The pulse energy was varied between 8 and 13 nJ while the translation stage velocity was set to a fixed value of 100 mm/min, which delivered the best results in our previous near-infrared studies of GLS [16].

The propagation losses of the single-mode waveguides were measured using the Fabry-Perot method [19]. The polished end-faces of the chip form an etalon at the air-glass interface due to the high refractive index contrast. This technique is independent of the coupling efficiency and relies on the periodically varying transmittance of monochromatic light when changing the optical path length by heating the sample. The contrast of the resulting fringes is a function of the propagation loss. A 3.39 µm Helium-Neon laser (REO-4018) and a 4 µm Quantum Cascade laser (Daylight Solutions - 21040), both featuring a narrow linewidth and thus a long coherence length [20], were used to interrogate the waveguides.

![Fig. 2. Left: Fabry-Perot measurement test-bed. Monochromatic light (3.39 or 4 µm) was coupled into a single-mode GLS waveguide and the output monitored on a mid-infrared camera while the glass was heated. The contrast of the periodically changing transmitted light was used to precisely derive the propagation loss of the waveguide. Right: Broadband measurement test-bed. Light from both, a broadband tungsten as well as the reference helium-neon source was simultaneously focused into a GLS Y-splitter or directional coupler input while the output was spatially dispersed after passing through the prism. The two detected spectra of each arm were used to determine the power splitting ratio at different wavelengths (3 - 5 µm).](image-url)
to ensure high resolution. The propagation loss was calculated with the averaged value across consecutive minima and maxima. The measurement was repeated before the sample’s end-faces were cleaned and flipped to measure the loss in the opposite direction. The presented loss values reflect the average of these four measurements that ensure reproducibility of the results. Angular deviations from the perpendicularity between waveguides and sample end-faces [21] of less than 0.5° were measured using an optical microscope. The loss values therefore indicate the upper boundary and are thus potentially overestimated.

A broadband CaF$_2$ beam-splitter plate (BS) was installed after the second objective followed by a set of mirrors (M1 - M3) and a plano convex lens ($L_2 = 150$ mm) to redirect part of the laser light directly onto the camera. This light served as a reference to compensate for any laser power fluctuation. The $1/e^2$ mode-field diameter was extracted from the recorded frames by applying a Gaussian fit using a MATLAB script. A polariser was inserted before the beam-splitter to measure polarisation dependent losses, while the waveguide size was measured on a Differential Interference Contrast (DIC) microscope. The refractive index contrast was determined by feeding a bright field image of the waveguide’s cross-section into a photonics device modelling software (RSoft BeamProp). The refractive index contrast was adjusted until the simulated mode-field diameters matched the experimentally measured mode-field diameters.

Figure 2 (right) shows the setup for determining the power splitting ratio and chromaticity of Y-splitters and directional couplers. Light from a tungsten emitter (Thorlabs SLS202, 0.45 - 5.5 µm) and a helium-neon laser were transmitted through individual optical fibers (InF$_3$ and ZrF$_4$) and combined in a pellicle beam splitter plate (3 - 5 µm) after collimation by off-axis parabolas (OAP2 and OAP1, respectively). Both beams were simultaneously focused before and collimated after the chip by aspheric lenses. The output light was dispersed by a prism and calibrated using the lasers sharp peak at 3.39 µm and the CO$_2$ absorption dip at 4.26 µm. This resulted in a spectral resolution of $\sim 19$ nm/pixel on the detector.

3. Waveguide characterization

3.1. Athermal regime - multiscan

The Fabry-Perot measurements at 3.39 µm showed that the lowest propagation loss at each repetition rate (425, 510, 728 and 1020 kHz) was achieved with the highest pulse energy and pulse density used (Fig. 3). Sample translation velocities between 100 - 1025 mm/min were chosen to ensure a similar pulse density (41, 61, 122 and 255 pulses/µm) at all laser repetition rates. Lowering the repetition rate enabled the use of higher pulse energies to fabricate single-mode waveguides, where Kerr self-focusing created largely elongated cross-sections.

Comparing waveguides fabricated with the same pulse energy and density shown in Fig. 3, reveals a reduction in propagation loss when increasing the repetition rate (e.g. the same colour coded plots). This increase led to a higher deposition of energy inside the material per unit time and thus stronger thermal diffusion up to an intermediate state of cumulative heating. The cross-section of the lowest loss waveguide at each repetition rate (Fig. 3(a)–(d) insets) underpins the growing cumulative heating effect, distinguishable by the expanding tear-drop shape when increasing the repetition rate. The mode-field diameter increased along with the physical size keeping the confinement and index contrast consistent.

The best waveguide performance in the athermal regime of $1.5 \pm 0.03$ dB/cm was achieved at 425 kHz, 100 nJ and 61 pulses/µm with a mode-field diameter of 23.5 ± 0.5 µm in the horizontal and 25.1 ± 0.5 µm in the vertical, with a peak index change of $\Delta n = 0.005$. We remeasured the propagation losses for this waveguide with a polariser inserted and found a polarisation dependent loss of 0.24 ± 0.02 dB/cm (higher loss for horizontally polarised light). Waveguides inscribed with pulse energies larger than 50, 70, 90 and 100 nJ for 1020, 728, 510 and 425 kHz, respectively, supported more than one mode in the vertical dimension at 3.39 µm. Fabrication parameters tested below 425 kHz were insufficient to guide light at 3.39 µm due to a weak
Fig. 3. Sets of multiscan waveguides were written with 10 nJ pulse energy increments between 30 and 120 nJ at four different repetition rates (425, 510, 728 and 1020 kHz), where each waveguide consists of 15 partially overlapping passes. The four insets show the cross-section of the lowest loss waveguide fabricated with the highest pulse energy and density for each repetition rate. We observed increasing heat diffusion effects with rising repetition rate but similar pulse density. The lowest propagation loss of 1.5 ± 0.03 dB/cm was found for 425 kHz and 100 nJ pulse energy. This waveguide exhibits a $\Delta n = 0.005$. 

modification of the glass. The positive correlation between an escalating cumulative heating effect and the decrease in propagation loss due to the higher energy deposition inside the material will be further examined in the next section.

### 3.2. Thermal regime - cumulative heating

In order to allow heat diffusion to be the primary source of material index change, a higher repetition rate of 5.1 MHz was chosen to transition into the cumulative heating regime [22], compared to the kHz region associated with the multiscan regime. Single track waveguides were fabricated with a translation stage velocity of 100 mm/min and pulse energies between 8 and 13 nJ resulting in 5.5 to 9.8 µm wide waveguides. We found that the width of the single-mode waveguide was the benchmark for precisely replicating propagation loss and mode-field diameter values. A 7.5 µm width led to the lowest propagation loss of 0.47 ± 0.01 dB/cm at 3.39 µm with a mode-field diameter of $22.9 \times 24.7 \mu m \pm 0.05 \mu m$ (Fig. 4(a)). Single tracks with an approximate aspect ratio of 1:3 in the horizontal:vertical showed elliptical mode-field ratios of 0.83 - 0.93, potentially causing coupling loss from round apertures and increased bending loss. To increase the symmetry, a set of parallel double tracks with different spacing were inscribed (inset in Fig. 4(b)) using the lowest loss single track fabrication parameters. A further reduction in propagation loss to 0.33 ± 0.02 dB/cm indicated a stronger mode confinement with a mode-field diameter of $19.7 \times 22.1 \mu m \pm 0.05 \mu m$ in the horizontal and vertical (Fig. 4(b)). This loss value is similar to other reports of 0.25 dB/cm in GLS at 3.39 µm using the multiscan technique [23]. The reported waveguide width of 12 µm was decisive for a low-loss performance which is of
Fig. 4. Propagation losses for waveguides written in the cumulative heating regime as a function of structure width at 3.39 $\mu$m wavelength. The insets show the cross-section and the mode-field of the lowest propagation loss single track waveguide (a) with $0.47 \pm 0.01$ dB/cm while the lowest propagation loss double track waveguide (b) exhibited $0.33 \pm 0.02$ dB/cm. These waveguides show a significantly lower loss than waveguides fabricated with the multiscan method.

The same order of magnitude of the demonstrated cumulative heating waveguide with a width of 12.3 $\mu$m. These low-loss values remained consistently low until a structure width of 15 $\mu$m where the parallel tracks stopped overlapping. The unmodified center region between the tracks likely contributed to imperfect guidance and thus to a higher propagation loss.

At 4 $\mu$m, single tracks showed an improved guidance for structures between 8.3 and 9.8 $\mu$m (Fig. 5(a)) compared to 3.39 $\mu$m (Fig. 4(a)). While the natural glass attenuation for both wavelengths is negligibly small (<0.3 dB/m) [9], Rayleigh scattering decreases at longer wavelengths. In order to create cross-sections equal in the vertical and horizontal and thus round mode-fields, three single tracks were inscribed sequentially with the same center-to-center spacing of 2.55 to 6.05 $\mu$m at 0.7 $\mu$m increments. An almost linear decline in propagation loss with increasing waveguide width was observed for both single and triple structures, resulting in a propagation loss as low as $0.29 \pm 0.06$ dB/cm (Fig. 5(a)) and $0.22 \pm 0.02$ dB/cm (Fig. 5(b)), respectively, at the threshold to multi-mode behaviour. The error bars in Fig. 5(b) reflect the minimum and maximum deviation of subsequent inscriptions in two additional glass samples within a 4-week interval, resulting in reasonable replicas. Remeasuring the properties of the waveguides after several months under the same experimental conditions showed an unaltered behaviour which reflects a great long-term stability.

Fig. 5. Propagation losses for cumulative heating waveguides at 4 $\mu$m for single (a) and triple structures (b) where the bottom left inset shows the fringe pattern of the Fabry-Perot loss measurement with $0.22 \pm 0.02$ dB/cm while the top right insets show the cross-section and mode-field of the lowest loss waveguide with $\Delta n = 0.012$. 
The findings are consistent with those of Gross et al. [24] who achieved propagation loss values of $0.29 \pm 0.03$ dB/cm in fluorozirconate glass at 4 $\mu$m. The bottom left inset in Fig. 5(b) shows the fringe pattern of the Fabry-Perot resonance measurement for the lowest loss waveguide. The insets in the top right show the cross-section of the best triple structure with a physical size of $19.4 \times 19.8$ $\mu$m, and a round mode profile of $22.3 \times 22.6$ $\mu$m. The retrieved peak index contrast change of $\Delta n = 0.012$ matches the index contrast Rodenas et al. [13] reported for multiscan GLS waveguides at 10.6 $\mu$m and is twofold larger than the approximated index contrast change for athermally inscribed waveguides described in the previous section. The hybrid approach between multiscan and cumulative heating with two and three tracks featured a lower polarisation dependent loss of $< 0.1$ dB/cm (lowest propagation loss for vertical polarisation) compared to the multiscan waveguides while no polarisation dependent loss was found for single track waveguides.

McCarthy et al. [25] and Hughes et al. [26] demonstrated waveguides in this regime with a tear-drop shaped cross-section in GLS and distinguished between a dark inner region and a surrounding, positive outer halo. This resulted in an overall positive refractive index contrast leading to a guided fundamental mode that spans across the whole structure. Further investigations on these structures and material changes have been undertaken in Ref. [27]. The tear-drop shape of the cross-section was attributed to the nonlinear absorption of the femtosecond laser pulses in the elongated region along the irradiated axis and internal melting of the glass due to cumulative heating, investigated in more detail by Miyamoto et al. [28], as well as Hughes et al. [29]. Cumulative heating waveguides in GLS feature a great thermal stability where a temperature of $>580^\circ$C is required to annealed out the waveguides [16].

4. Photonic chip components

This section shows that the approach of combining cumulative heating inscription with the multiscan technique is well suited to creating the main building blocks of the proposed nulling interferometer chip (Fig. 1). S-bend shaped waveguides with a low bending loss are indispensable for the overall device performance and play an important role in optical Y-splitters and directional couplers. In Y-splitters, they branch from one into two single-mode waveguides, dividing the power equally, while S-bends in 3-dB directional couplers bring single-mode waveguides in close proximity for interferometric interaction.

4.1. S-bends

The cosine S-bend design has a lower transition loss than two inverted radial arcs while a raised-sine shape experiences a higher radial loss [30]. More importantly, the latter has a higher potential for premature power transfers at the end of two S-bends fanning into the coupling region of a directional coupler due to their close vicinity. The cosine S-bend has a minimum radius at the start and end of the bend, while the curvature changes gradually with a monotonically change in the center (Fig. 6 right).

We investigated a wide range of minimum radii by fabricating cosine S-bends of varying lengths (2 - 12 mm) for two different lateral offsets of 125 and 250 $\mu$m. The S-bend excess loss was determined by measuring the S-bends propagation loss on the Fabry-Perot test bed and subtracting the corresponding propagation loss value of straight reference waveguides inscribed before and after the set of S-bends. Both sets of S-bends with different lateral offset showed identical loss behaviour (Fig. 6 left) with negligible bending losses for bend radii $> 40$ mm. The resulting S-bend lengths were $\sim 5$ and $\sim 7$ mm for offsets of 125 and 250 $\mu$m, respectively. Achieving short S-bends leads to an overall shorter chip design and reduces the loss for light propagating through the waveguides.
Fig. 6. Left: The inset shows the top view of the cosine S-bend waveguides fabricated in the cumulative heating regime (triple modification) featuring negligible bending loss for bending radii larger than 40 mm. This resulted in S-bend lengths of $\sim 5$ and $\sim 7$ mm for 125 and 250 $\mu$m lateral offset S-bends, respectively. Right: Comparison of calculated radii of curvature for three S-bend designs with a length of 5 mm and 125 $\mu$m lateral offset. Two inverted arcs offer the highest bending radii but in turn suffer from high transition loss at the inflection point. The cosine design shows the best compromise between low transition loss and high bending radii.

4.2. Y-splitters

The single-mode Y-splitter consists of a stem and a tapered waveguide section with two diverging arms [31]. In symmetric splitters, the fundamental mode in the stem equally excites the fundamental modes in both arms. This behaviour is difficult to achieve employing femtosecond laser direct-writing due to the overlap of waveguide tracks in the splitting area [32]. The two arms of our asymmetric Y-splitter designs (Fig. 7 left) differ significantly in refractive indices due to different changes in bending radii, resulting in mismatching propagation constants [31,33]. The fundamental mode in the stem evolves across the junction stronger into the fundamental mode of the branch with a more similar effective index and thus leads to an unbalanced power splitting [34].

Fig. 7. Left: Design of 6 different Y-splitters. The number at the end of each line indicates the writing order of the 6 tracks. Green lines indicate the overpassing tracks which influence the power splitting ratio. Right: Power splitting ratios between the two arms (left/(left+right)) of the Y-splitters. The best spectral response in terms of equal power splitting over a 600 nm wavelength window was found for design 6.
For an equal power splitting ratio, the imbalance was countered by the inscription order of the six tracks forming the Y-splitter, indicated by the numbers on top of each design in Fig. 7 (left). Since the fabrication of the tracks is sequential, the first three tracks (blue) were overpassed a second time (green) up to the branching point, forming a more dominant light guiding pathway than the previous tracks. The splitting ratios of six different designs were measured across a 600 nm wavelength window, showing a gradually transition of transmission efficiency from one arm into the other (Fig. 7 right). Designs 1 - 3 have a higher power ratio towards the left arm with 125 µm lateral offsets, while designs 4 - 6 distribute more light into the right arm with 250 µm lateral offsets. The orientation of the last two tracks decisively directs significantly more light to either arm. The left arm receives more light from the evolved mode in the stem but receives less light due to the waveguide writing order, resulting in an almost equal power splitting. Design 6 is closest to achromaticity and equal power splitting between 3.6 - 4.2 µm where the last three tracks inscribed lead into the arm with the larger lateral offset of 250 µm. A polarisation dependency was not found when characterising the Y-splitters with vertically or horizontally polarised light. The excess loss of the Y-splitters due to the branching point and overpassing of the stem was measured to be less than 0.5 dB by subtracting the waveguide propagation loss and coupling loss from the total measured throughput under broadband illumination.

### 4.3. Directional couplers

The heart of the photonic nulling interferometer is a 2 × 2 directional coupler that requires an equal power splitting to achieve efficient destructive interference. The power splitting ratio is wavelength dependent and changes with the length of the two parallel waveguides in the coupling region (Fig. 1). The sinusoidal power transfer between these waveguides through evanescent coupling can be calculated by [35]

\[
\frac{P_{\text{cross}}}{P_{\text{cross}} + P_{\text{bar}}} = \sigma^2 \sin^2 \left( \frac{\kappa}{\sigma} L + \phi \right)
\]

(1)

with \(P_{\text{bar}}\) being the power output at the light injected waveguide, and \(P_{\text{cross}}\) the power output at the cross coupled waveguide. The coupling coefficient for length \(L\) is given by \(\kappa\) while the power transfer contribution of the S-bends at the start and end of the coupling region is taken into account by the bending phase \(\phi\) [36]. The dephasing term

\[
\sigma = \left[ 1 + \left( \frac{\Delta \beta}{2 \kappa} \right)^2 \right]^{-1/2}
\]

(2)

restricts the cross coupling ratio relative to the difference in propagation constants \(\Delta \beta = |\beta_2 - \beta_1|\) of the two adjacent waveguides. A difference can arise from the sequential fabrication of the parallel waveguides where the second waveguide is inscribed into a pre-modified stress region caused by previously applied femtosecond laser irradiation [37].

As similarly demonstrated by Arriola et al. [12] using GLS glass, we fabricated couplers with a fixed center-to-center separation of 21 and 26 µm and varied the interaction length between 0 - 7.5 mm. To avoid Fabry-Perot resonances, we characterised these devices using broadband light as described in Section 2 and extracted their splitting ratios at three different wavelengths (3.75, 4 and 4.25 µm). The experimental data is fitted with Eq. (1) for all three wavelengths with a root mean square error (RMSE) of 3.4% - 4.8% for 21 µm separation and with a RMSE of 2.7 - 2.8% for a 26 µm separation, as summarised in Fig. 8.

Couplers with a 21 µm separation show strong premature coupling in the S-bends where more than 70% light is transferred before the coupling region. Despite the very small separation between the 19.4 µm wide waveguides, the couplers show a relatively small asymmetry indicated
by a $\Delta \beta$ of 0.32 - 0.43 rad/mm between 3.75 and 4.25 $\mu$m wavelengths. The small propagation constant offsets for thermally inscribed couplers are similar to the values for couplers presented by Diener et al. [37] also fabricated in GLS but using the multiscan method in the athermal regime. This indicates a similarly small stress field surrounding the waveguides. The couplers feature a maximum cross coupling of 91.6 - 95% and a small coupling coefficient $\kappa$ of 0.69 - 0.71 rad/mm compared to reported values of 1 - 2.5 rad/mm [35]. These values underpin the strong mode confinement achieved with cumulative heating waveguides discussed in Section 3.2 and as a result, a generally small overlap of the evanescent tails.

For longer wavelengths, however, the electric field amplitude of the guided mode reaches further into the bulk [38] resulting in a slightly larger overlap of the evanescent tails. This fosters the energy transfer illustrated by the uniform decrease of the oscillatory period.

A similar dephasing for both coupler separations of 21 $\mu$m and 26 $\mu$m at 4.25 $\mu$m wavelength (red graph) results in a similar maximum cross coupling, but also shows that the dephasing has a larger influence on the dispersion when $\kappa$ remains low. Hence, it is beneficial to increase the coupling coefficient as high as possible by simply reducing the distance between the waveguides in the coupling region. For the larger separation of 26 $\mu$m the power transfer proceeds more slowly [39] as a consequence of smaller coupling coefficients $\kappa = 0.23 - 0.29$, reflected in a long periodicity of the power exchange. Equal power splitting ratios can be found at beat lengths of 0.5 $\times$ n + 0.25 ($n \in \mathbb{N}_0$) where one beat length is needed to gradually transfer light into the opposite waveguide and back. We identified two 3-dB couplers at 26 $\mu$m separation at 4 $\mu$m wavelength at 0.25 (L = 1.5 mm) and 0.75 (L = 6.5 mm) beat lengths, respectively (Fig. 8 right). The comparison between the slopes shows how the dispersion at longer interaction lengths leads to an increased chromaticity from 23.8% to 29.5% over the investigated 500 nm wavelength window. Therefore, shorter interaction lengths are preferred to achieve a more broadband device. In comparison, as reported by Tepper et al. [40] the directional couplers inscribed into GLS glass using athermal multiscanning featured a chromaticity of 40% across a similar wavelength range.

With $\pi$ relative phase shift between the two inputs and 50% power transfer from both input modes into the adjacent waveguide, it will be possible to obtain efficient destructive interference in one output and constructive interference in the other for nulling interferometry.
5. Conclusion

Single-mode waveguides were inscribed in gallium lanthanum sulphur glass employing femtosecond laser direct-writing. High heat diffusion in the cumulative heating regime led to tear-drop shaped cross-sections with a strong mode confinement. Despite strong guidance of the mode in the vertical direction, poor guiding was shown in the horizontal dimension due to an asymmetric physical aspect ratio. By forming a hybrid waveguide comprising multiscanned cumulative heating modifications, we extended the horizontal dimension and reduced the propagation loss to $0.22 \pm 0.02$ dB/cm at 4 $\mu$m. This result outperformed the athermal multiscan waveguides where we achieved a minimal propagation loss of $1.5 \pm 0.03$ dB/cm at 3.39 $\mu$m.

Using these low-loss waveguides, the key components of an integrated nulling interferometer, waveguide S-bends, Y-splitters and directional couplers were fabricated and characterised. We found negligible bending losses for cosine S-bend shaped waveguides when keeping the minimum bending radius above 40 mm. These S-bends were used to fabricate Y-splitters exhibiting close to a 50/50 power division over a wavelength window of 3.6 - 4.2 $\mu$m. Furthermore, cosine S-bends formed symmetric directional couplers with different separations of the coupling region and a series of different interaction lengths, allowing precise control over the desired splitting ratio. The demonstrated couplers feature lower losses and less chromaticity than previously reported devices in GLS. These basic components will enable the fabrication of an integrated nulling interferometer with a length of $\sim 14$ mm in less than 2 minutes. The sum of propagation loss ($\sim 0.3$ dB/cm) and the loss associated with Y-splitters ($< 0.5$ dB) is expected to deliver a nulling interferometer with an internal loss of $\sim 0.8$ dB, which is compatible with on-sky telescope operations.

It has previously been shown that interference from unguided stray light can compromise measurements in a stellar interferometer. The issue originates from coupling light into the device with a micro lens array (MLA) and can be mitigated by integrating a side-step at the front end of the chip [41]. A cosine side-step has to be $\sim 22.4$ mm long to stay within bend radii limit when injecting light with an MLA with a NA of $\sim 0.19$. An additional loss of 0.5 dB applies and amounts to 1.3 dB total intrinsic loss.

Fresnel reflection of 15.3% at 4 $\mu$m occurs at the input as well as the output of the photonic chip at the glass-air interface and 4.5% if coupled to mid-infrared fluoride glass fibres. A dielectric anti-reflection coating is required and has been demonstrated on laser written waveguides in a mid-infrared transparent soft glass [42]. The integration of these components is work in progress and detailed characterisation will be subject of another publication.

Funding

International Macquarie University Research Excellence Scholarship (iMQRES) (2016078); Australian Research Council DECRA fellowship (DE160100714); Engineering and Physical Sciences Research Council (UK) (EP/M015130/1).

Acknowledgments

This work was performed in-part at the OptoFab node of the Australian National Fabrication Facility, utilising NCRIS and NSW state government funding. Thomas Gretzinger gratefully acknowledges Dan Hewak and the University of Southampton for kindly providing the GLS glass samples. Chalcogenide glasses were provided through the support of the Engineering and Physical Sciences Research Council (UK) through Manufacturing and Application of Next Generation Chalcogenides.
References

29. M. A. Hughes, W. Yang, and D. W. Hewak, "Spectral broadening in femtosecond laser written waveguides in