Thorough experimental testing of Multimode interference couplers and expected nulls thereof; for exoplanet detection

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Abstract: In exoplanet interferometry a null of 40 dB is a large step in achieving the ability to directly image an Earth-like planet that is in the habitable zone around a star like our own. Based on the standard procedure at the Australian National University we have created a nulling interferometer that has achieved a 25 dB null in the astronomical L band under laboratory conditions. The device has been constructed on a 2-dimensional platform of chalcogenide glass: a three layered structure of Ge11.5As24S64.5 undercladding, 2 µm of Ge11.5As24Se64.5 core and an angled deposition of Ge11.5As24S64.5 as a complete overcladding. Matching simulation from Rsoft and individual results of the MMIs the expected null should produce a null of 40 dB over a bandwidth of 400 nm but due to limitations in mask design and light contamination only a 25 dB extinction can be reliably achieved.

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1. Introduction

Direct imaging of exoplanets is vital for the future of exoplanet research. Most exoplanets have been discovered with indirect detection techniques, like the transit detection method (exemplified by the Kepler space telescope) and radial velocity detection method. These methods, however, cannot produce an image of the exoplanet and are limited to star systems where the exoplanets make a transit, or the star is Doppler shifted towards the sun. Direct detection methods work for any star system and are only limited by the amount of light emitted by the exoplanet and host star.

Direct imaging methods include chronography, placing a physical block over the host star, and interferometry, interfering multiple images of the object to form an image. At present chronography has detected an exoplanet in the early stages of forming [1] and a few exoplanets that are larger than Jupiter and further away from their host star than that of any planet in the solar system [2–4]. Direct imaging through interferometry has yet to detect an exoplanet but may outperform chronography in the future. This is due to an interferometer not relying on a physical block to null out star light, rather using destructive interference to force the light from the star to null and leaving only light from radiating or reflecting objects orbiting the star. The method for a bulk optic, space faring, apparatus was proposed by Bracewell [5]. Photonic equivalents have been tested in Silicon at a wavelength of 1550 nm [6] and recently in the mid-infrared (MIR) at 3.7 µm [7].

The astronomical L band (3.7 µm-4.2 µm) is within the atmospheric window of the Earth which makes it the key area of research for Earth bound instruments. Current technology in this area includes a three dimensional direct write systems of laser inscription. This method requires evanescent couplers in a Chalcogenide glass [7] to provide a 50:50 splitting ratio for a single input with work towards a four beam combiner as per envisioned by Bracewell [5]. Multimode interference couplers (MMIs) have also achieved the 50:50 splitting [8], in a two dimensional arrangement, with preliminary results of the components in [9,10]. The two dimensional approach provides a higher index contrast between the core and cladding material which implies the devices can be manufactured to much smaller lengths than the evanescent coupler equivalent. This is in addition to providing a larger bandwidth where the coupling is closer to a 50:50 split [9].

Both the direct write system and three dimensional technology use a combination of Chalcogenide glasses (ChGs). This is due to silica being opaque in the MIR. Photonic devices often use materials such as Silicon on Sapphire [11], Silicon Germanium [12], Indium Phospohide [13], Aluminum Gallium Arsenide [14], Lithium Niobate [15] and Chalcogenide glass [16] in the MIR regime. ChG has a low refractive index, has shown to have a loss down to 0.5 dB/cm [16] for ideal processing conditions and is transparent as far as 10 µm, which is ideal for astronomy purposes.

In this paper we will describe the deposition of the two dimensional method and describe the results of the MMIs produced to have a 50:50 splitting ratio at 4 µm. This will lead into the construction of a Mach-Zehnder interferometer and the first measurement of a mid infrared null.
2. Deposition

The layers of ChG were deposited using evaporation methods. The initial wafer had a substrate of silicon (Si) with 5 µm of SiO2 grown on top to segregate the two high index materials (Si and the ChG) and stop absorption into the substrate. 3 µm of Ge\textsubscript{11.5}As\textsubscript{24}S\textsubscript{64.5} was deposited as an undercladding layer, 2 µm of Ge\textsubscript{11.5}As\textsubscript{24}S\textsubscript{64.5} was used as a core layer to provide the 0.33 index contrast and 1 µm of Ge\textsubscript{11.5}As\textsubscript{24}S\textsubscript{64.5} was deposited as an extra protective layer against the plasma etching. A layer of Su-8 was used to protect the top layer from atmosphere contamination. Standard photoresist was spun onto the Su-8 before a one-to-one imaging system was used to harden the photoresist. An ICP was used to plasma etch the soft resist and the uncovered ChG down to the Ge\textsubscript{11.5}As\textsubscript{24}S\textsubscript{64.5} undercladding, creating full etched waveguides. The Su-8 was also plasma etched away once the ChG etch was complete. The wafer is then put back into the chamber for an angled deposition to overclad the remaining structures with Ge\textsubscript{11.5}As\textsubscript{24}S\textsubscript{64.5}.

Testing of the chips used the Australian National University’s high-power Nd : YVO\textsubscript{4} picosecond laser at 1064 nm [17] as a pump and was seeded with a standard CW tunable laser. This provided a testing bandwidth of 3.7 µm to 4.7 µm with a gap between 4.25 µm and 4.65 µm due to the limitations of the LiNb crystal that was used.

3. Simulation & Lab results

3.1. Multimode interference coupler

The loss through the 2 µm waveguide was much higher than expected by [16]. As shown in Fig. 1 the best loss was 1 dB/cm. The expected increase in loss at 4 µm due to the S-H absorption in the cladding material is also shown in Fig. 1.

![Fig. 1. Loss of the on chip cutback](image)

Following from work in [8, 9] the light split by a multimode interference coupler (MMI) was measured to test whether the imbalance follows the simulation. The imbalance in this case is the normalized value of the cross and bar port subtraction. From this the expected extinction from the equivalent 2 beam combiner is derived.

The simulation and experimental results of the imbalance are displayed in Fig. 2 for a taper width of 8 µm (a) and 13.5 µm (b). Note that both Fig. 2 (a) and (b) required an 8% correction to account for an additional loss in one arm. Once corrected the measured imbalance matches the
Fig. 2. Imbalance from an MMI of width 45 μm as per [8] and taper width of (a) 13.5 μm (b) 8 μm waveguide.
simulation for both taper widths over the bandwidth 3700 nm to 4150 nm. At larger wavelengths the wavelengths dependence of the MMI appears to differ from the simulation. This is likely due to a minor defect in the MMI making the real device differ from the simulated equivalent.

To detect the signals through the MMI simultaneously a Xenics Onca camera was used. This enabled much higher precision than that in [10] which only used pyroelectric detectors.

At a closer inspection of Fig. 2 the extinction can be derived, using the same method as [9]: fitting an extinction curve to the imbalance data.

\[-20 \times \log(0.71|\text{Imbalance}|) = \text{Extinction}\]  

was used to generate the points in Fig. 3, and a threshold of 40 dB was applied for greater clarity. Figure 3 shows that using an MMI, as a two beam combiner, with taper widths of 13.5 µm has a 40 dB bandwidth of 150 nm and that the MMI with a taper width of 8 µm has a wider bandwidth of 400 nm. The expected bandwidth at this level of extinction by [9] was 250 nm and 400 nm respectively which implies that there may be an issue in the fabrication process for the 13.5 µm MMIs. One potential issue was raised in [8] where the gap between the taper widths at the interface into the MMI would not fill. This will need further investigation.

3.2. Mach-Zehnder Interferometer

A Mach-Zehnder interferometer (MZI) using two MMIs - the first MMI is the 3 dB splitter and the second used as the combiner - was constructed to measure the extinction of the MMI directly.

Initial simulations in Rsoft are shown in Fig. 4 and show that a null depth of 60 dB should be achievable. The limitations of this simulations are obvious with an inability to take into account scattered light from minor defects through the core material of the waveguide and MMIs. However from [9] it is clear that this type of simulation is accurate.

The measured MZI, using the same MMI as above and a taper width of 8 µm, is shown in Fig. 5. The maximum null achieved for this MZI was ~ 25 dB, however a reversed null was also seen. Comparing figure 5 to figure 4 it is clear that the inherent shape of the MZI with a taper width of 8 µm is not retained. From Fig. 4 the null should be at ~ 4000 nm but from Fig. 5 the null is either at 3700 nm or 4150 nm. It is possible that the shape mismatch is due to scattered light from both MMIs used in the MZI but it does not explain the null reversal nor does it explain the shift in where the null is supposed to form.
Fig. 4. The extinction from a simulated Mach-Zehnder interferometer for MMI with a taper width of 13.5 \( \mu \)m (orange) and 8 \( \mu \)m (blue).

Fig. 5. Measured light through a MZI with the MMIs used have a width of 45 \( \mu \)m and taper width of 8 \( \mu \)m.

The two nulls in Fig. 5 provide information on the free spectral range of the measured system. To reproduce the range in an MZI an MZI model with a variable Optical Path Length (OPL) difference and the same coupling ratios as Fig. 2 was used. This model estimates an OPL difference of 18.5 \( \mu \)m between the connecting waveguides, corresponding to a 25 nm difference in width. The implication of which is that the fabrication tolerance is drastically lower than anticipated by [8]. The optical mask write used to create the lithography mask has a critical dimension uniformity greater than 50 nm which encompass the error we have calculated.

It is possible that the scattered light from the two MMIs, or a mismatch in the overlap of the fundamental mode in the input waveguide, is the limiting factor in measuring the null depth. As
Fig. 6. A cross section of the best case extinction by only illuminating a single waveguide.

an example Fig. 6 shows an extinction calculation from a single illuminated waveguide as a best case scenario. It shows that even when no MMIs are used the scattered light provides a 25 dB limit to the null (averaged over the entire band) we can measure. This can also be seen in 5 where both extinctions are limited to 25 dB.

4. Conclusion

Chalcogenide glass was used to create a Mach-Zehnder interferometer. The glass transmission was only as good as 1 dB/cm and an absorption of S-H increased the loss to 5.5 dB/cm at 4 μm. The multimode interference couplers used to construct the MZI behaved as predicted, with the optical path length difference between the two arms of the MZI being a catastrophic impediment to the expected null.

During the measurements of the multimode interference couplers it has been shown that the imbalance should lead to a 400 nm of bandwidth at an extinction level of 40 dB. This is the first time, to our knowledge, that the imbalance from a 3 dB coupler has been used experimentally to prove that such a level of extinction can be reached.

To actually reach the 40 dB extinction the limitation of the OPL difference must be overcome. Future iterations of the MZI will require connecting waveguides with larger widths so that a fabrication error of 25 nm is negligible. In addition, it would be pertinent to have the ends of the MMI facing perpendicular to the direction of the input and output waveguides to reduce the scattered light. This would likely allow a greater null than the 25 dB allowed by the level of scattered light.

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