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Planar waveguide to vertical mode couplers covering the visible to IR spectral range

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Abstract: Planar 45° turning mirrors with metal coating embedded in SU8 polymer waveguides enable waveguide to vertical mode coupling across a broad range of wavelengths from the visible to IR. The fabrication of these 2.5D structures is achieved using relatively simple grayscale lithography in thin film resists, compatible with standard planar lithography methods. Mirror losses of <1 dB are measured from 516 -1630 nm, and direct coupling to single mode fibre is achieved.

1. Introduction

The rapid maturation of Photonic Integrated Circuit technology has been enabled by the creation of Process Design Kits [1] from foundry suppliers and the standardisation of basic on-chip components including waveguides, power splitters and mode-convertors. However, the basic requirement of many passive PIC platforms for coupling light on and off chip has resulted in a wide variety of optical mode couplers, driven by a range of considerations including optical bandwidth, efficiency, material refractive index, compatibility with packaging and fabrication methods. For example, grating assisted vertical mode couplers enable wafer scale testing and intra-PIC monitoring, but are limited in bandwidth due to the resonant coupling operation [2]. Facet edge couplers can have broad spectral coverage, but are limited to the perimeter of diced chips and mode-mismatch to optical fibre can lead to coupling losses or strict alignment tolerances [3]. Each of these forms of coupler have been advanced with variations in geometry, materials and external optics to improve performance metrics, for example using mode-spot size convertors for edge couplers [4], or optimised grating designs for output efficiency [5]. Recently, a form of waveguide to vertical mode couplers using turning mirrors has been demonstrated, aimed at combining the wafer-scale coupling benefits of surface grating couplers with the broadband performance of edge coupler geometries. Notably, by making use of etched trenches in the PIC surface and two-photon polymerisation (TPP) lithography, waveguide to vertical mode convertors have been designed with mode-shaping reflective surfaces to match to single mode fibre with low insertion loss at telecommunications wavelengths [6]. In this work we demonstrate a waveguide to vertical mode coupler that can be fabricated with standard planar photo-resists using grayscale lithography and without requirement for modification of the PIC substrate. SU8 is a well established polymer material for waveguide fabrication with low propagation losses [7], compatibility with simple lithographic processing [7,8] and interfacing to high-index waveguide platforms including silicon and silicon nitride [4]. SU8 waveguides have also been employed for applications in biomedical sensing [9,10] and telecommunications [8,11,12], due to the material's large transparency range. Here we fabricate and characterise an on-chip method of light coupling

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using SU8 optical waveguides and metal coated 45-degree turning mirrors for broadband, low optical loss applications.

2. 2.5 D turning mirror device design

The operating principle for the polymer turning mirrors is based on use of a 45^o angled slope relative to the waveguide axis, shown schematically in Fig. 1(a). This geometry allows for the total internal reflection of guided light at the mirror interface to couple to a vertically radiated mode coupled through the waveguide top surface. To enable a short optical path length from the mirror to the free-space mode the waveguide facet should be undercut with respect to the sample surface. Demonstration of external 45^o surfaces at waveguide facets have been previously demonstrated, but are limited by the divergence of the optical mode from the horizontal waveguide facet to mirror area [13].

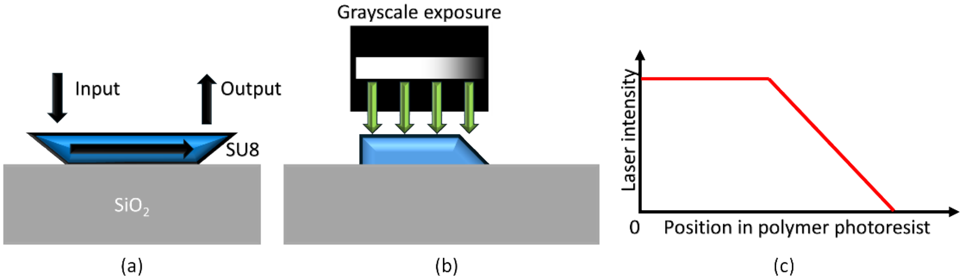

Fig. 1. (a) Schematic of a polymer waveguide with 45^o undercut facets, (b) positive surface 45^o facet geometry achievable with 2.5D grayscale lithography and (c) laser intensity profile variation to induce grayscale topology.

Creating such an undercut profile, embedded in a waveguide, through planar lithography techniques is difficult, though it can be achieved directly using TPP. In this work we have employed a 2-stage technique that enables an effective undercut mirror facet using standard positive geometry grayscale lithography patterning. First, a 2.5D positive geometry in the photoresist film can be fabricated using variable local dose density of the exposure field either through UV mask density techniques [13] or by control of a direct write laser exposure dose [14], which we employ here, shown schematically in Fig. 1(b). As shown in Fig. 1(c) the local laser intensity at any point in the exposed structure can be directly controlled, resulting in a variable height in the developed resist structure. A variety of surface topologies can then be achieved through design of the exposure dose pattern, for example linear gradients as in this work, or curved topologies for micro-lens fabrication [15].

The process flow for the vertically coupled mirrors is shown in Fig. 2(a). The first stage lithography defines the positive 45^o angled surface and supporting block in SU8 resist. After metal deposition onto the mirror facet, a second SU8 resist coating and lithography process is used to define waveguides terminating at the mirror facet. This second lithographically defined waveguide layer then terminates at an effectively undercut mirror facet, as shown in Fig. 2(b).

In fact, if waveguides are defined in both lithography stages, the turning mirror could be used to couple guided light vertically upwards from the chip or, in the case of transparent substrates or multi-layer structures, down into the substrate direction, as shown in Fig. 2(b).

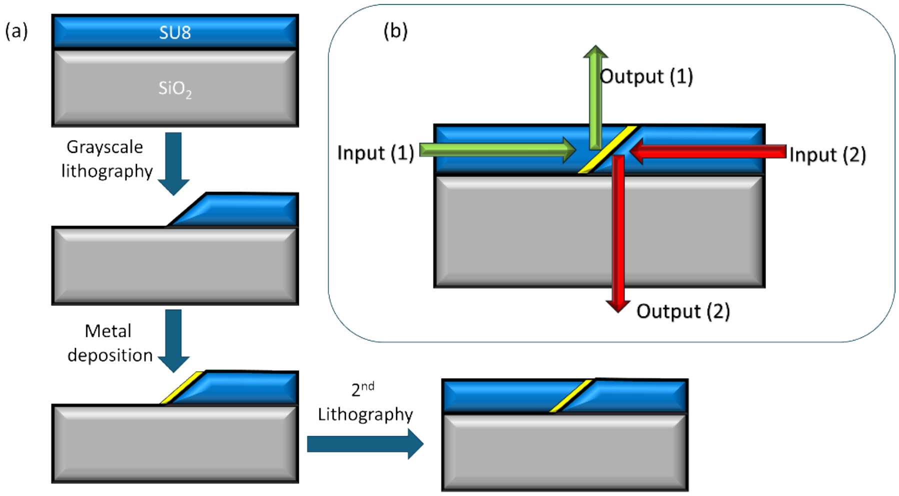

Fig. 2. (a) Schematic of fabrication process with grayscale 45° surface definition, metal deposition and liftoff, and second stage waveguide lithography. (b) Optical paths providing top surface and through substrate waveguide to free space coupling.

3. Microfabrication

SU8-6005 is used as the waveguide layer and spin-coated onto a glass coverslip substrate for production of the waveguide and mirror devices. The substrates are cleaned using organic solvents followed by a dehydration stage at $150^{O}C$ for 5 minutes on a hot-plate. Finally, the substrates are exposed to an O_2 plasma ash at $200^{O}C$ for 10 minutes to promote resist adhesion. A uniform layer of SU8-6005 is spin-coated onto the substrate at 4000 rpm to achieve a target thickness of $4\mu m$. The positive gradient 45° surface and support block are defined via grayscale lithography using a Heidelberg DWL66 + direct write laser system. The 45° surface is defined with a width 12.5 µm to provide an increased tolerance for the overlay alignment of the second waveguide layer. A layer of SPR-220-7.0 is spin-coated over the developed SU8 structures as a mask for the metal deposition process. Windows in this resist layer, aligned with the 45° mirror surfaces, are opened using laser lithography and development. A 50 nm thick layer of titanium is deposited by e-beam evaporation onto the sample, followed by a 200 nm layer of gold. The gold layer then acts as the reflective surface for the mirror. For shorter wavelength applications other metals, for example Aluminium, could be used. The metal lift-off was carried out using Microposit 1165 solvent to remove the SPR resist layer and excess metal. A microscope image of the processed mirrors at this stage are shown in Fig. 3(a).

For the final fabrication stage, a second layer of SU8-6005 was spin-coated onto the substrate, covering the pre-fabricated structures. This layer is used to define the waveguides terminating at the mirror surface as shown in Fig. 3(b). The waveguides are fabricated with a width of 10 µm which is substantially multi-mode through the visible spectral range and can support up to 4 modes at a wavelength of 1630 nm. Notably, spin-coating of the SU8 resist over pre-defined structures results in film thickness variations between the substrate areas and existing topology. If a simple uniform exposure of the SU8 resist is used to define the waveguide structures, with sections overlapping the mirror region, then the final developed structure can have significant height variations over the mirror due to additional resist thickness and dose variation due to mirror reflections during exposure. In simply exposed structures a bulge is formed over the mirror section as shown schematically in Fig. 4. This can be in the order of a few hundred nanometres in thickness, providing distortion of vertically coupled light and paths for loss through guiding

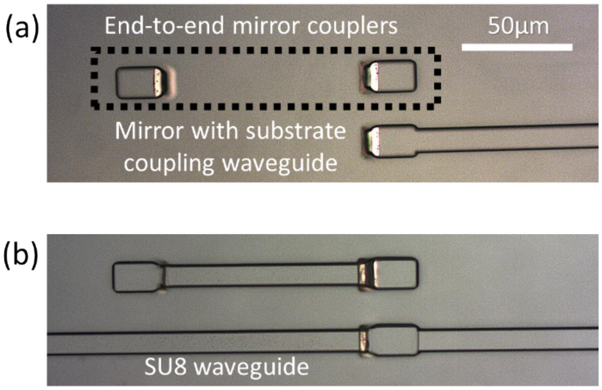

Fig. 3. (a) Microscope image of grayscale lithography defined 45° surfaces after TiAu metal layer deposition. (b) Devices after the 2nd stage lithography with waveguides aligned to the mirror sections for vertical off-chip coupling.

past the mirror section. In order to minimise the excess SU8 over the mirror, the lithography exposure at this mirror section can be tuned using grayscale processing to reduce the effective dose and therefore the developed SU8 resist deformations. Figure 4(c) shows a comparison of resist profiles over the mirror section with and without grayscale dose correction, with the uncompensated process producing an excess resist bulge in the order of 500 nm, compared with 150 nm in the grayscale lithography case. Measurements of the mirror loss, detailed below, show that the grayscale compensated process improves mirror loss from 4.4 dB to 0.5 dB. All further mirror loss results presented relate to the grayscale compensated overlap geometry.

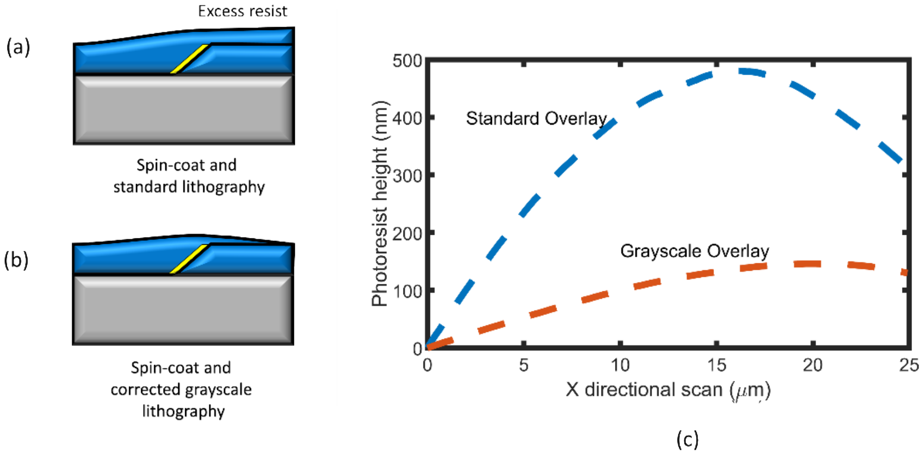

Fig. 4. (a) Schematic of 2nd lithography stage showing excess resist over mirror region and (b) excess resist minimisation using grayscale lithography correction. (c) AFM measurements of waveguide top surface profile over the mirror region where the data level is taken as the top surface of the adjoining waveguide.

4. Optical characterisation

To characterise the efficiency of the waveguide coupler devices, a simple transmission setup was used with optical sources coupled through a lensed fibre to the waveguide in an edge facet configuration with the potential to collect out coupled light either vertically from the mirror sections or from the second chip facet on a power meter or imaging camera, as shown in Fig. 5. A set of 5 fibre coupled optical sources were used to cover the spectral range from 516–1630 nm, including fixed wavelength lasers at 516 and 850 nm and swept wavelength tuneable sources around 635, 1250 and 1550 nm. Using the edge to edge facet coupled arrangement, cut-back loss measurements were carried out on end-end SU8 waveguides to extract the propagation and facet coupling losses across the wavelength spectrum. Facet losses were approximately 0.4-0.5 dB across the full wavelength range and the waveguide propagation losses were between 1.5-2.5 dB/cm as detailed in Table 1.

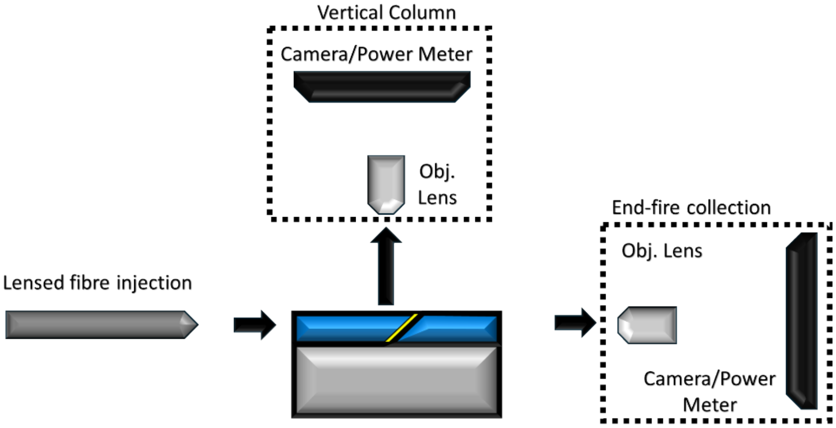

Fig. 5. Free space optical setup to characterise waveguide and waveguide coupler devices with a SMF injection and vertical plus end-fire collection.

Table 1. Propagation losses for wavelengths and wavelength bands.

Wavelength (nm)	*Propagation Losses (dB/cm)*
516	2.21
635	2.09
850	1.87
1250	1.66
1550	1.56

The mirror losses were then measured using the vertical collection setup. The total loss from optical source to detector was measured and then the fibre facet coupling loss and waveguide propagation losses were subtracted to leave the loss of the waveguide-vertical mode mirror. Camera images of the out-coupled light for each of the optical sources are shown in Fig. 6, where the 516, 635 and 850 nm sources were imaged using an ArduCam silicon camera, and the 1250 and 1550 nm sources were captured on a Xenics XS-320 InGaAs camera. Figure 6(a) shows an image of the light collected from the waveguide facet where light was coupled into the waveguide via the vertical coupling mirror from the microscope system.

Figure 7 shows the measured mirror transmission across the broadband spectral range, with <1 dB loss across the full range. Losses increase towards the shorter range of the spectrum, corresponding to the reflectivity reduction in the TiAu mirror coating as expected. For the longer wavelength scans around 1250 and 1550 nm, the facet coupling was optimised at the mid-spectral

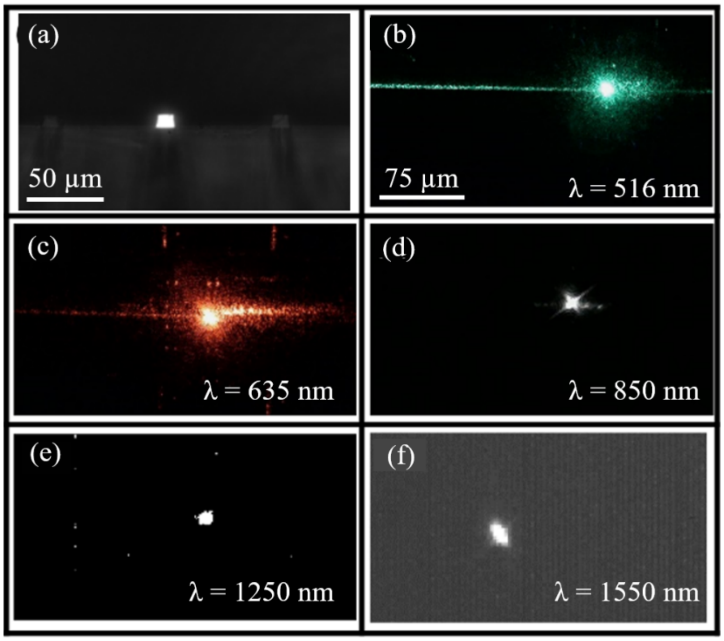

Fig. 6. (a) Image of the waveguide facet where the light was coupled onto the chip via the mirror. Images of the mirror coupler when injecting through the waveguide facet at (b) 516 nm (c) 635 nm (d) 850 nm (e) 1250 nm and (f) 1550 nm respectively.

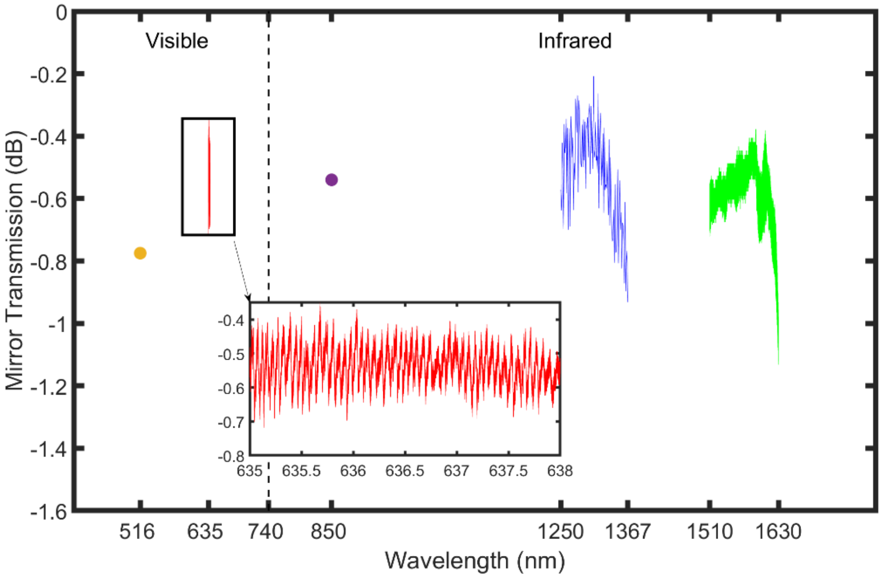

Fig. 7. Mirror transmission as a function of injection wavelength across visible and IR spectral regions.

range point and so degradation in coupling towards the edges of the scans are due to defocussing effects from the lensed fibre injection.

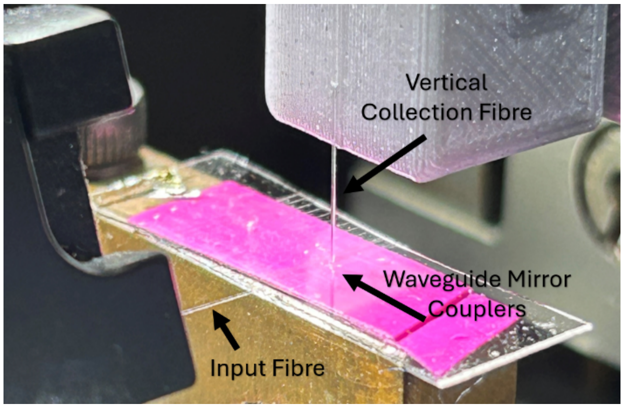

Fig. 8. Experimental setup of waveguide mirror couplers with vertically mounted lensed fibre collection.

Finally, a lensed SM28 fibre was mounted vertically over the mirror and the collected light was measured at 1550 nm (Fig. 8). The direct fibre collection exhibited a measured mirror loss of 0.8 dB, exhibiting good mode overlap between the mirror out-coupled mode and single-mode fibre. Measurements of 20 nominally identical individual devices showed consistent mirror losses of <1 dB. This demonstration shows the potential for these vertical mode couplers in wafer scale testing setups.

5. Conclusion

We have shown the design fabrication, and optical characterisation of waveguide to vertical mode couplers fabricated in SU8 polymer material. By using standard photo-resist and a 2-stage 2.5D planar grayscale lithography process these devices can be easily integrated with other PIC components and are compatible with surface coupled testing protocols. The broadband performance of the mirror couplers has been shown across a wavelength range from 516 nm to 1630 nm with mirror loss < 1 dB. By using a grayscale lithography correction for the second stage waveguide fabrication film thickness variations and increased mirror loss can be counteracted. Direct coupling from the mirror components to fibre was demonstrated, showing their compatibility with common surface coupled measurement schemes.

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Disclosures. The authors declare that there are no conflicts of interest related to this article.

Data availability. Data underlying the results in Figs. 4 & 7 are available in Ref. [16].

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