Integrated Computer Generated Waveguide Hologram for Versatile Free-Space Beam Projection

(Student paper)

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We present integrated Computer Generated Waveguide Hologram couplers that can emit or receive free-space optical beams at an ultra-long working distance. Single wavelength waveguide holograms for 1300, 1450 and 1600 nm have been designed, fabricated and characterized. We demonstrate the focusing of optical beams 10 mm above the optical chip's surface with beam waists closely approaching the diffraction limit in one dimension.

Keywords: *integrated photonics, free-space radiation, hologram, photonic-free-space coupling, sensing*

INTRODUCTION

Monolithically integrating a coupler on a photonic integrated circuit that can emit or receive free-space beams focussed at an ultra-long working distance, enables further miniaturization of optical devices by reducing the need for external optics such as lenses or gratings. Small area grating couplers ($\sim 10x10\ \mu m^2$) are widely used to couple light out to an optical fiber near the chip. For focusing at ultra-long distances ($\sim 1\ cm$), which is useful in e.g. optical sensing or free-space optical communication, diffraction makes that much larger couplers ($\sim 400x400\ \mu m^2$) are required. Furthermore, both the phase and intensity profile of the emitted beam - the coupler's near-field - need to be accurately controlled. Backlund et al [1] designed and demonstrated a Computer-Generated Waveguide Hologram (CGWH) consisting of a 2D array of grating lines. They engineered the offset of each grating line to obtain the required phase profile. Additionally, apodizing the filling factor of the grating lines allows to uniformly distribute the intensity over the surface of the coupler [2]. A limitation of the modelling used in [1-2] is the assumption that the optical behaviour of the pixels is independent of each other, i.e. changing the scattering properties of one pixel does not affect its neighbours. This limited the performance that could be demonstrated.

In previous work, we have shown that the neighbouring pixels do affect each other and that this has a large influence on the far-field pattern [3]. Therefore, we have developed a new model and design tool for waveguide holograms that incorporates the effects of neighbouring pixels [3]. By designing and demonstrating three single wavelength CGWH couplers for 1300, 1450 and 1600 nm with an ultra-long working distance of 1 cm, we prove that our model is highly flexible and suited for broadband applications. We have fabricated these couplers on the InP Membrane on Silicon (IMOS) platform that allows for dense monolithic integration of lasers and other building blocks [4]. In this paper, we present an overview of the design and the performance of the realised devices.

DESIGN

The conversion of the light field from the regular single-mode IMOS waveguide to free space occurs in three stages as shown in Figure 1. In the first stage, an 80 µm long taper expands the waveguide mode from 400 nm to 5 µm. In the second stage, the mode is expanded further in a 1 mm long slab waveguide. In the third stage, this wave enters the hologram, formed by a 2D array of subwavelength grating lines made in a Si_3N_4 layer above the InP slab waveguide. Each grating line scatters a small part of the light outward and induces a phase shift on the remaining propagating light in the slab waveguide.

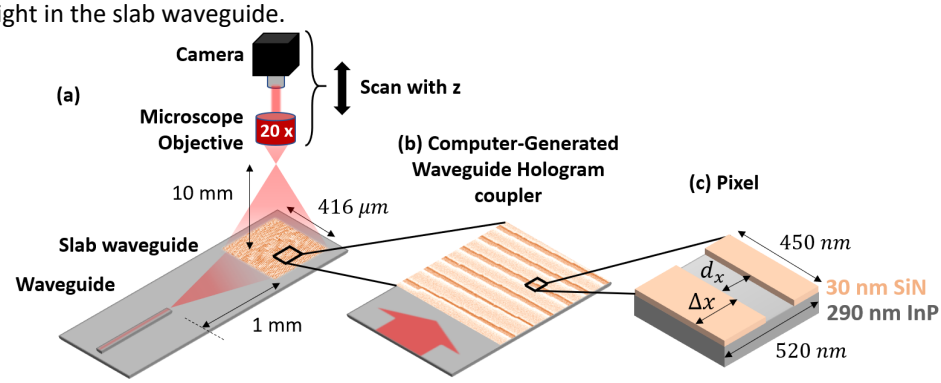

Fig. 1 ***(a)*** *Schematic of the integrated chip and the measurement set-up.* ***(b)*** *Zoomed view of the CGWH and* ***(c)*** *one of its pixels.*

We engineer the thickness of each grating line and its offset Δx from the edge of the pixel (i.e. the distance between them) to carefully control the upward coupling strength and phase shift at each pixel in the array. First, we linearly apodize the grating lines' thickness from 104 to $208\ nm$ at $x = 0$ and $416\ \mu m$, respectively. Then, we simulate using 2D FDTD in Lumerical the effects of neighbouring grating lines in the xz-plane on the far-field emission. This simulation includes an input beam confined in a waveguide, three consecutive grating lines etched in this waveguide and a field-profile monitor $700\ nm$ above the grating lines. For different thicknesses and positions of the grating lines, we calculate the far-field profile of the monitor to determine which percentage of the scattered light will arrive at the target location. A 3D FDTD simulation can also analyse the effects from neighbouring pixels in the y-direction, however, this would highly increase the simulation time (currently 2-3 hours). Finally, we use a similar algorithm as described in [1] to optimize the offsets of the different grating lines [3].

To focus a 50 µm spot at an ultra-long distance of 10 mm, we need a large area coupler of at least 416 µm due to diffraction. Based on our algorithm, we have designed three single wavelength $CGWH_\lambda$ couplers for wavelengths λ of 1300, 1450 and 1600 nm. We have fabricated the holograms monolithically in a 30 nm-thin Si_3N_4 layer deposited on top of a 290 nm-thick InP slab waveguide. By using a different material for the hologram, we can exploit the high dry etch selectivity between Si_3N_4 and InP. Our fabrication process is similar to [5], except that we do not use a metallic mirror and opt for Si_3N_4 instead of SiO_2 as it provides a higher coupling strength.

PERFORMANCE

In the experimental set-up, we use three fiber-coupled tunable lasers at 1300, 1450 and 1600 nm, respectively, and couple them via a side-fire fiber into on-chip grating couplers. A 20x microscope objective (Mitutoyo Plan APO NIR using a tube lens with a focal length of 200 mm) captures the light emitted by the CGWHs (Fig. 1). We mounted the objective and the camera on a motorized stage (CONEX-MFACC - Newport) to measure the far-field at different distances.

Figures 2(a-c) show the measured near- and far-field patterns of the different couplers. We notice that $CGWH_{1300}$ already couples a large part of its light at the start of the hologram (Fig 2ab). This reduces the confinement of the light at the focusing plane in the x-direction (Fig. 2c).

The near-filed pattern of $CGWH_{1300}$ indicates that the current apodization is not strong enough as most of its light still couples out at the start of the coupler (Fig. 2a). Thus we need to reduce the thickness of the first grating line further. From the far-field pattern of $CGWH_{1300}$, we notice that its strongest spot in the focal plane lies on a line with an angle of 0.02° from the normal. On the other hand, $CGWH_{1450}$ and $CGWH_{1600}$ both uniformly couple the light out of the hologram (Fig. 2b) and focus it with nearly an identical incident angle of -0.65° and -0.70°, respectively, at the focusing plane (Fig. 2a).

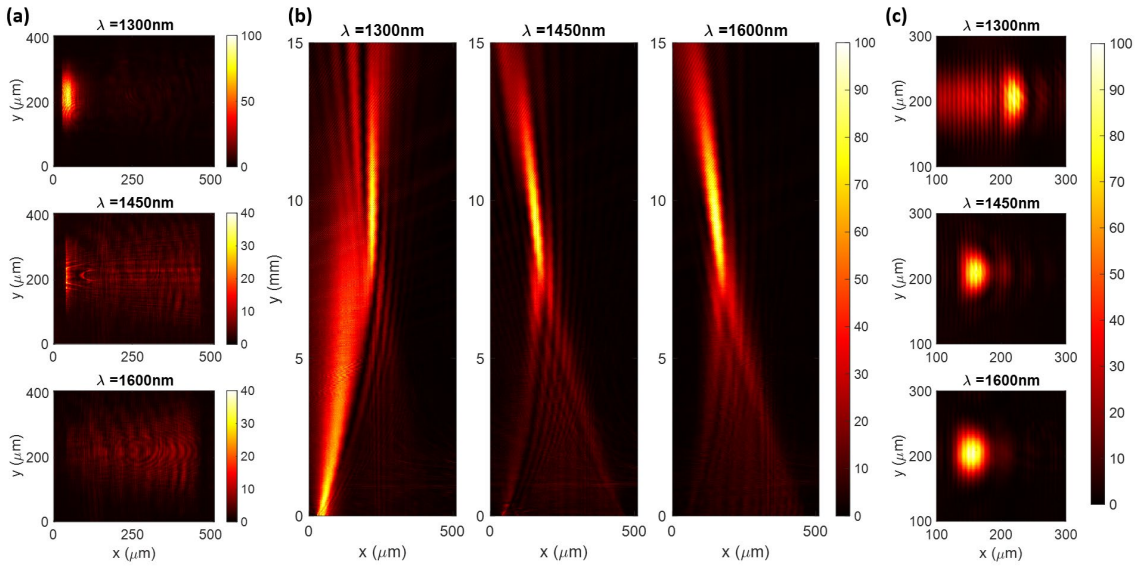

Fig. 2 ***(a)*** *Measured near-field and* ***(b)*** *far-field intensity distributions in the axial and* ***(c)*** *focal plane of the different $CGWH_i$ operating at wavelengths of 1300, 1450 and 1600 nm. The colour bars indicate the normalized intensity for each $CGWH_i$.*

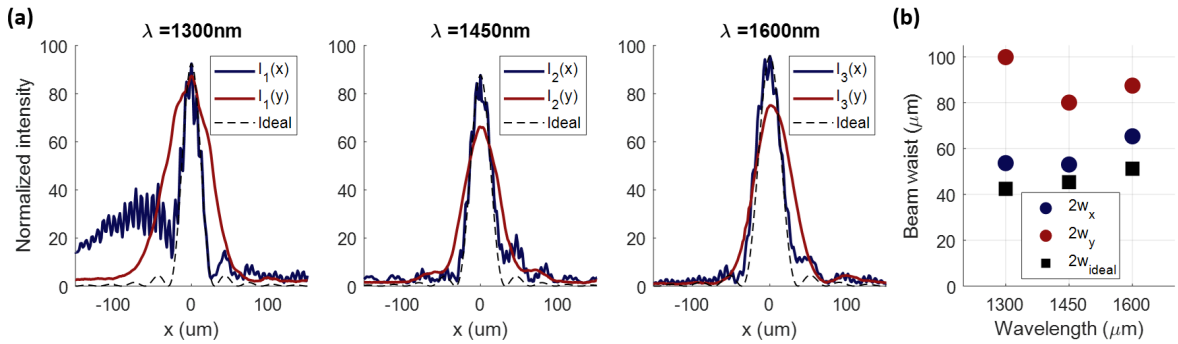

Figure 3 ***(a)*** *Intensity of the x- (blue) and y-profile (red) across the measured focal spots of the different CGWH$_i$ operating at wavelengths of 1300, 1450 and 1600 nm compared to the diffraction-limited case of a uniformly illuminated flat-lens (ideal). The x-axis represents the relative position to the centre of the peak.* ***(b)*** *Beam waists (1/e^2) after fitting the measured intensity at the focal plane with a 2D Gaussian and for the diffraction-limited case without fitting (ideal).*

Figure 3(a) shows the intensity profile of the horizontal $I_\lambda(x)$ and vertical cut $I_\lambda(y)$ of the measured focal spot of CGWH$_\lambda$ compared to the diffraction-limited case of a uniformly illuminated flat lens with focus $f = 10\ mm$ having the same area as the coupler. We calculate the intensity profile of the diffraction-limited case to be proportional to

$$I_{diffr.\ limit}(x,y) \sim\ sinc^2\left(\frac{\pi l_x x}{\lambda f}\right) sinc^2\left(\frac{\pi l_y y}{\lambda f}\right) \qquad (1)$$

where l_x and l_y represent the dimensions of the coupler. We notice that the central peak of the different $I_\lambda(x)$ closely resembles with $I_{diffr.\ limit}$. We observe strong sidelobes for $I_\lambda(x)$ as expected since they approach the diffraction limit. Even the location of the sidelobes matches with those of $I_{diffr.\ limit}$. Moreover, we detect a fringe pattern for $I_\lambda(x)$ with a periodicity of several micrometres. Potentially, other functional devices or fabrication inaccuracies – e.g. particles or roughness – on the chip scatter part of the incident light which interferes with the coupler's signal.

Figure 3(b) displays the beam waists after fitting the measured intensity at the focal plane with a 2D Gaussian fit and for $I_{diffr.\ limit}$. While the beam waists in the x-direction are equal to 53-66 µm, they are 81-100 µm in the y-direction, an increase of $34 - 86\%$. The fact that the near-fields of CGWH$_{1450}$ and CGWH$_{1600}$ show a lower uniformity in the y-direction as opposed to the x-direction can explain this effect (Fig. 2b). This is not evidently noticeable for CGWH$_{1300}$. In general, apodizing the structures also in the y-direction will ensure higher uniformity of the near-field.

CONCLUSION

We have realized three monolithic integrated couplers that can focus light at an ultra-long working distance of 10 mm above the chip plane at respective wavelengths of 1300, 1450 and 1600 nm. The CGWH couplers achieve near-vertical focusing ($\theta < 0.7\,°$) with beam waists (1/e^2) in the x-direction (53-66 µm) closely approaching the diffraction limit. Apodizing the structures in the y-direction will reduce these beam waists (81-100 µm) as well. Further research will focus on multiwavelength CGWH couplers and integration with other on-chip components to demonstrate its potential for gas sensing or compact position sensors.

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