Freeform optical arrays for free-space coupling into photonic integrated circuits

(Student paper)

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Photonic integrated circuits are versatile technology to transport and process light. However, one challenge for these chips is the effective optical coupling from external environments, especially in free-space settings. We have designed a freeform optical array that can focus and tilt normally incident free-space beam to efficiently couple into grating couplers at 12° with a gain factor of 3.14 over normal coupling using a traditional plano-convex lens.
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INTRODUCTION

Photonic integrated circuits (PIC) are an emerging technology that have drawn wide attention over the past years due to their ability to transport and process light in a compact, versatile, and programmable form. These circuits have a vast potential to be exploited in a wide range of applications such as communication, sensing, nanophotonics, and quantum information processing [1]. One long-standing challenge for photonic integrated circuits is the optical interface between the chip and the external world, mainly due to the requirement of the incident field to be matched to that accepted by the chip, where multiple coupling mechanisms have been explored over the years to facilitate such coupling [2]. Grating coupler is perhaps the most preferred solution to bridge the coupling gap in photonic chips due to their increased design flexibility, integration density, and testing feasibility [2–4]. However, one common challenge for these grating couplers is the efficient optical coupling from external sources. This is mainly due to the fact that grating couplers are usually optimised to collect and radiate optical fields at a specific angular tilt that fulfils the diffraction directionality requirement for a maximum transmission and minimum back-reflection [5].

The diffraction directionality in grating couplers require the incident beam to be tilted, e.g. be optimised for 10° tilt [6] off vertical, to minimise back reflection and break the grating bidirectional symmetry [3]. This requirement is attributed to the second-order diffraction back reflections and the fact that normally incident light onto the grating would symmetrically couple and split into both diffraction directions along the grating, resulting in only 50% of the coupled light being radiated toward the waveguide. This is usually addressed by tilting the incident field (or the chip) to break such symmetry. Additionally, there have been considerable investigations to enhance true vertical coupling [7–9], however, such alignment would generally induce additional losses and result in relatively lower coupling efficiency than the tilted geometries [3]. Even though the use of tilted optical fibres have been sufficient for many static applications, the desire to exploit photonic integrated circuits in future deployable, dynamic, and readily packaged platforms, such as imaging and sensing technologies, raise a considerable demand for solutions that allow efficient vertical coupling.

In this work, we present the design of a compound freeform element that can potentially be interfaced with photonic chips for efficient vertical free-space optical coupling. This element consists of a lens on one side and freeform surface on the other to readily focus and tilt normally incident beam at an angle of 12° for use on top of standard angle-sensitive grating couplers. The novelty of this design is not only due to its optical compound, but also due to the freeform structure, see Figure. 1(a), that was numerically optimised to allow for mode match the field to that accepted by on-chip surface gratings. Through the modelling of this design on top of standard grating coupler at normal incidence, we expect a coupling efficiency that is 3.14 times greater than a beam normally coupled through traditional plano-convex lens at a central wavelength of 1550 nm. This element can readily be arranged in an array to allow a seamless mapping of a single input field onto an array of couplers for chips with higher dimensionality and improved resolution, see Figure. 1(b).

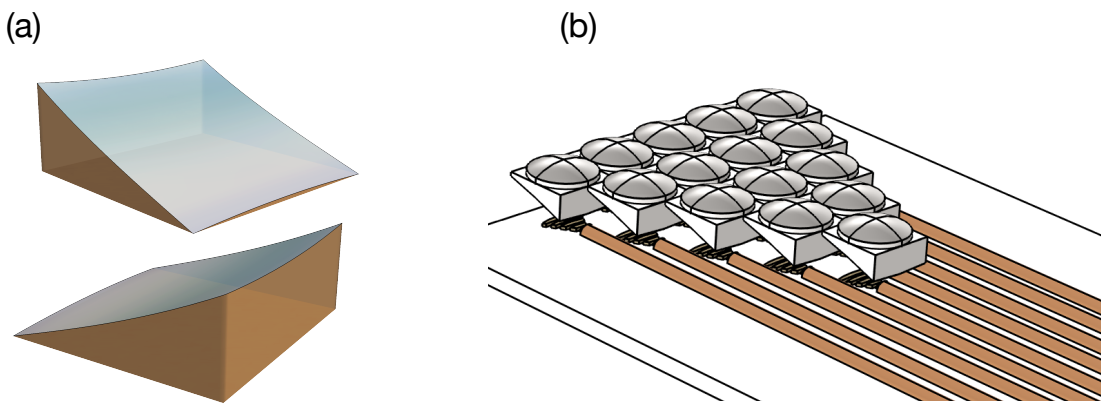

Figure. 1 (a) Illustrations of a prism-like freeform surface that can tilt the focused beam while accounting for the phase variations of the focused beam for equivalent deflection (b) Illustration of an array of our freeform element on top of an array of grating couplers, where such approach could potentially allow efficient free-space interface with integrated photonic circuits and facilitate their use in various optical applications.

Freeform Element Design and Modelling with Grating Coupler

Given the requirement for incident fields to match the numerical aperture and angular tilt accepted by grating coupler for efficient beam coupling, the first design step to address these optical requirements was to model the optical fields accepted by the grating couplers and subsequently optimise an optical surface to meet these requirements. For a standard grating couplers with a grating pitch of 630 nm, etch length of 315 nm, and etch depth of 70 nm; we modelled the field that can be efficiently collected by these grating couplers to have an optimum angular tilt of 12° in free-space. To match such optical field and address the challenge of performing two optical functions with minimum optical losses, a compound freeform element was derived through numerical optimisation to simultaneously focus and tilt normally incident field using a plano-convex lens and a wedge-like freeform surface. This was initially derived using a lens only, where the expected ray positions and distributions at its focal plane were calculated. These positions are then compared to the positions of a beam transmitted through a wedge prism only with a deflection angle that matches the tilt of standard grating couplers of 12° in free-space, providing the associated radial ray displacement for the given angular shift and allow for 2D mapping from the initial spots position to the 'target' tilted position. This is a crucial step to create a geometrical map to optimise the prism surface from a wedge to a freeform surface that accounts for phase shifts induced by the lens and closely map the beam to the desired target positions. Once this map is calculated, a finite number of evenly spaced hexahedrons, with initial overall dimensions similar to the 12° wedge prism, are attached to the two central axes of the flat surface of the lens. These hexahedrons are then optimised using a gradient-free Nelder-Mead algorithm in Comsol Multiphysics to map the incident rays from the initial to the target positions. Using this optimisation method, a control constraints function was applied to ensure that each adjacent hexahedrons have at least two connected points at the edge to avoid any surface discontinuity that can reduce surface quality and ensure seamless surface manufacturability. The final design of this freeform surface have an overall side thicknesses of 3 um and 19.2 um with its flat surface bonded to a convex lens with an NA of 0.3, radius of curvature of 46.3 um, equivalent focal length of 91 um; where this single element can be formed in triangular array for use with a triangle array of grating couplers with an increased effective fill factor of over 95%, see Figure. 1(b).

Upon the design and optimisation of the freeform element, theoretical modelling of its performance was investigated in terms of transmission efficiency and coupling efficiency into grating couplers. The first transmission efficiency model looked into how much of the optical power is transmitted through the compound element, which results in transmission efficiency of 91.8% at normal incidence, which is almost consistent with the traditional 4% back-reflection losses per surface for uncoated elements, see Figure. 2(a). As the incident beam might vary from a perfect normal incidence, we further examined the angular acceptance of this lens over 20° field of view and the transmission efficiency is expected to fall to a minimum of 89.7% at -10°, see Figure. 2(a). Although this is still relatively high coupling efficiency, the mode profile at such angles is expected to not be maintained due to off-axis distortion and the axial symmetry in the element. To further investigate the functionality of our optical design that potentially satisfies the focus and tilt requirements of grating couplers with minimum optical losses, we utilised numerical modelling based on a finite element method (FEM) to quantify the free-space coupling performance onto a standard surface coupler. We simulated both the freeform element and grating design in a single modelling environment to quantify the percentage of power that can be directed by the element and coupled by the grating

toward the waveguide, and potentially onto the chip. With our freeform element placed one focal length away from the grating coupler, an excitation port was used to release a Gaussian beam in free-space to be normally incident onto the full aperture of our element and then propagated and inputted onto the grating coupler. The transmitted power by this grating is then computed using a detection port located along the direction of the waveguide for c-band wavelengths between 1520-1570 nm in steps of 5 nm, see Figure. 2(b). To directly compare the coupling efficiency of our freeform element to traditional vertical coupling techniques, a normally incidence beam propagating from a fibre port as well as a normally incidence beam focused by the plano-convex lens in free space were modelled in place of our element and the power coupled by the grating for both cases was also calculated, see Figure. 2(b). These numerical results show that our freeform element outperforms the other normally incident reference optics and improve the coupling efficiency onto the grating coupler, with a coupling efficiency increase factor of 3.14 and 55 times greater than a beam normally coupled through traditional plano-convex lens and an optical fibre at a central wavelength of 1550 nm, respectively. This is expected to largely be due to the angular tilt induce by our element that matches the NA and angle of the grating. It is important to note that such coupling efficiency is dependent on the position of illuminating beam with respect to the grating coupler, where such position was optimised in our model for maximum coupling.

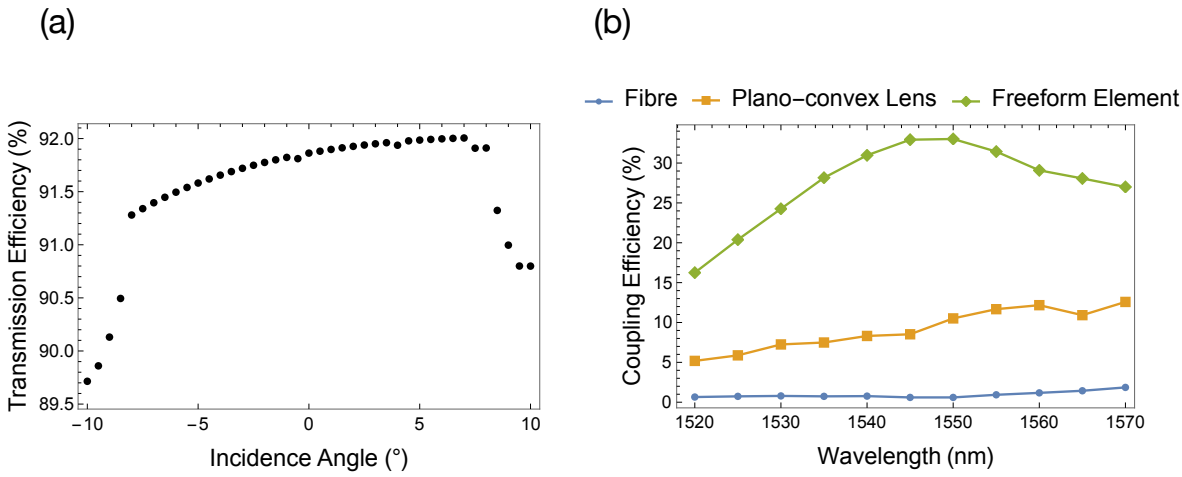

Figure. 2 (a) Simulation of the angular transmission efficiency of the freeform element for incident angles of ±10°. The difference in efficiency between the minus incidence angles and the plus incidence angles is due to the asymmetrical behaviour of the freeform surface along one of its geometrical axis. (b) Simulation of the coupling efficiency of a grating coupler when our freeform element is placed on top of the coupler for different wavelengths with a normal incident beam. This model is compared to the use of a plano-convex lens or optical fibre instead of our element for different wavelengths with normally incident beams.

Discussion

We designed a novel freeform element that can simultaneously focus and deflect a normally incident beam to match the coupling requirements of standard surface grating couplers. This element consists of three compounded elements; convex lens to focus the light and a freeform prism-like structure to mode match to the angled couplers on photonic chip. Although our design is optimised for 12 degrees tilt angle that matches the free-space incident angle of standard grating couplers and increases the effective fill factor to almost over 95%, this method provides a ray mapping process that can be applied to develop different angular specs, transformations, and functions.

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