Microlens Coupler from Integrated Photonic Circuit to Fiber Design for Space Application

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***Abstract*—This study presents a novel design for a microlens coupler to transfer light from a straight waveguide to a single-mode fiber (SMF). Our design combines improved mode matching and enhanced alignment tolerance compared to edge coupling. An investigation of the alignment tolerance is done by assessing coupling efficiency under various degrees of manufacturing-induced misalignment. Singlet and diffractive lenses are incorporated into our design to focus the light into the fiber precisely. Comprehensive simulations demonstrate that the diffractive lens outperforms edge coupling and singlet lens in coupling efficiency. Fabrication methods such as additive manufacturing are discussed for future works. Our findings underscore the potential of innovative microlens coupler design in advancing free space optical communication (FSOC) systems.**

***Index Terms*—Microlens Coupler, DOE, Waveguide, Fiber to Chip Coupling, Optical Packaging**

I. INTRODUCTION

Free Space Optics (FSO) hardware for space applications, encompassing components such as optical transmitters, receivers, telescopes, modulators, and adaptive optics, is crucial for efficient signal transmission and reception in space communication systems. Key to this is fiber-to-waveguide coupling, which facilitates light transfer from a fiber optic cable into an integrated photonic device, enhancing system stability, alignment, and radiation resistance in space environment. Efficient coupling minimizes signal loss (from mode mismatch, polarization, insertion loss, etc.) between the two components. Coupling fiber with PIC enables the functions of signal multiplexing, filtering, and branching on PIC.

The microlens is a small coupling interface that can focus light from single-mode fiber (SMF) to waveguide. Microlens offer better alignment tolerances than edge coupling techniques such as facet mirrors [1]. Meanwhile, grating couplers [2] provide even better alignment tolerances compared to microlens-based coupling. However, microlens, depending on their design, can provide better coupling efficiencies while maintaining polarization and mode match between fiber and PIC. Furthermore, the back reflection of microlens can be mitigated by using an anti-reflection coating layer to the microlens [3]. The additive manufacturing method, such as two-photon polymerization (2PP), can reduce the complexity of such a fabrication process.

In [4], the authors proposed a DLW-printed micro-lens for efficient collection of radiation into a single-mode optical fiber, which is attached to the required surfaces with a micro-connector made by Direct Laser Writing (DLW). The use of DLW lithography as a single technological process to create all optical elements of the kit solves the key problem of the precise alignment of optical elements. [5] demonstrates a low-cost scheme for non-permanent optical signal coupling using polymer kinoform microlenses. This solution provides a significant geometrical separation between integrated waveguides and single-mode fibers.

The major contribution of this paper is concluded as follows:

- We propose the design of a micro diffraction lens and singlet lens coupler for coupling lights from straight waveguide to SMF, which improves the misalignment tolerance with enhanced mode matching, and reduced power loss compared to conventional edge coupling.
- Misalignment tolerance and coupling efficiency of the singlet and diffraction lenses are compared in terms of different levels of deviation of light propagation.

The rest of the paper is organized as follows. 2 different types of microlens design in term of singlet lens and diffraction lens is shown in section II. Simulation results and discussion are provided in section III. In section IV, the paper concludes with the future research direction in additive manufactured microlens.

II. PIC TO SMF COUPLING

Light coupling from optical fiber to chip-integrated waveguide is difficult because of the major difference in the dimensions between the fiber core and optical waveguide. The fiber core ranges from 8-10 um, but the width and height of the Silicon waveguide is typically 400nm and 200nm, respectively. This directly leads to the difference in the mode field diameter of two devices if the light is confined within the core.

The power coupling efficiency, in this case, is a measure of the optical power transmitted from the fiber to the waveguide, or vice versa, which is given as follows:

$$\eta = \frac{\left(\iint_{-\infty}^{\infty} E_1(x,y)E_2^*(x,y)dxdy\right)^2}{\iint_{-\infty}^{\infty} E_1(x,y)E_1^*(x,y)dxdy \iint_{-\infty}^{\infty} E_2(x,y)E_2^*(x,y)dxdy} \tag{1}$$

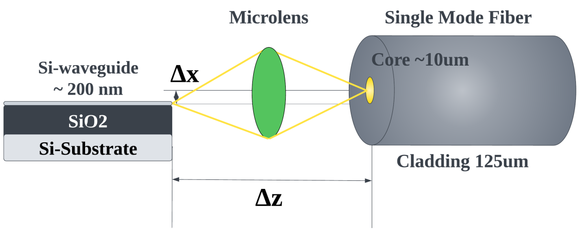


Fig. 1. Straight Waveguide to Straight SMF Coupling

The field integration includes both the intensity and phase profile of the optical beam. It can be solved numerically, and analytic solutions exist for Gaussian field profile. In Lumerical FDE solvers, the structure of interest (Fiber, waveguide) is discretized into a grid, and Maxwell's equations are solved on this grid to find the modes [6]. The size of the grid depends on the wavelength chosen. Maxwell's Equations are solved to find the Electric field distribution for each grid, and then the overlap between any part of the structure can be calculated [7].

E1 and E2 are the electric fields of two grid elements, respectively. Then, the overlap between the fundamental optical beam and the propagated beam can be calculated as,

$$O = \left| \int \int E_F(x,y) E_p(x,y) dx dy \right|^2 \tag{2}$$

This is usually used to quantify the similarity or match between two mode profiles. The absolute square of this integral gives the overlap coefficient (a number between 0 and 1). A value of 1 indicates perfect overlap or match between the modes, while 0 indicates no overlap. On the other hand, power coupling measures the power from the fiber that is successfully transferred to the waveguide. Power coupling can be affected by various factors, including not just the overlap of the modes but also things like the alignment of the optical components, phase matching, polarization matching, and reflections at the interface between the components (such as reflection of microlens).

The coupling efficiency between fiber and waveguide depends on the corresponding mode field diameters (MFDs) and offsets between the core of optical equipment. Using the Gaussian beam to approximate the fundamental mode of the optical beam from Fiber and the E field of it can be denoted as

$$E(x,y) = E_0 e^{\frac{-4(x-\Delta x)^2}{MFD_x^2} - \frac{4(y-\Delta y)^2}{MFD_y^2}} \tag{3}$$

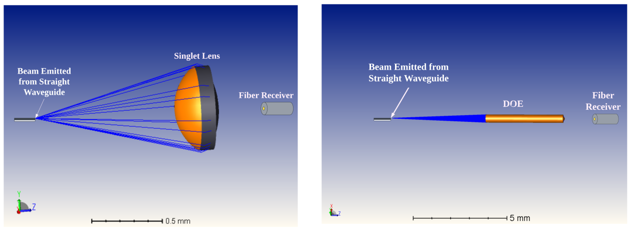
where Δx and Δy denote the transverse offsets between the core of fiber and waveguide as shown in figure 1. Δz denotes the axial offset or light propagation distance between the cores. For example, $\Delta z = 0$ in butt coupling.

III. MICROLENS DESIGN AND SIMULATION SETUP

The waist of the waveguide beam profile after physical optics propagation (POP) is 1.45 um with 6.2 um Rayleigh distance. Beam width after propagation is 1.85 mm at x axis and 3.4 mm at y axis, which the skew Gaussian beam profile can approximate. For POP simulation, the aperture type is a 0.3 object space numerical aperture with the Gaussian apodization type. The wavelength is 1550 nm with 1.0 Jx polarization. The image plane, which serves as the input end of the optical fiber, has been set with a material that has a refractive index of 1.43 and an anti-reflective (AR) coating, COAT I.99, with a reflectance of 1% and a transmittance of 99%.

A. Singlet Lens

The singlet lens is the simplest optical system with one element. It can focus or collimate light into a small field and the end of the waveguide. Singlet lenses can be designed with a specific numerical aperture (NA) that matches the NA of the waveguide, which can further improve the coupling efficiency. Singlet lenses are easier to fabricate compared to complex multi-lens systems. However, chromatic aberration, spherical aberration, and astigmatism can occur when light is focused through a single lens. These phenomena happen because different wavelengths of light refract, or bend, differently when they pass through a lens, resulting in a divergence of the light rather than a single focused point. This can result in reduced efficiency of fiber light coupled into the waveguide efficiently.



(a)

(b)

Fig. 2. (a) Singlet Lens Shaded Model (b) Diffraction Lens Model

As shown in 2 (a), the singlet lens design is with 100 um propagation distance. The radius of the STOP surface is -0.378 with 2.9 mm thickness. The second surface is 0.385 with 1 mm thickness. The semi-diameter is chosen to be 0.227 mm and 0.115 mm respectively.

B. Diffraction Lens

Diffraction lenses (also known as diffractive optical elements or DOEs) are designed to harness the wave nature of light rather than its particle properties, which allows for precise control over the phase of the light wavefront. When a single-mode light is collimated from a fiber through a diffraction lens, the lens is able to maintain the light's single mode, thus preventing it from diverging or spreading out. Depending on the design, diffraction lenses can offer decent performance over various wavelengths. This can be particularly beneficial for broadband applications or systems using multiple wavelengths. Compared to singlet lenses, diffraction lenses possess higher alignment tolerance. Thus, it reduces the need for precise mechanical alignment, which will be verified in section IV.

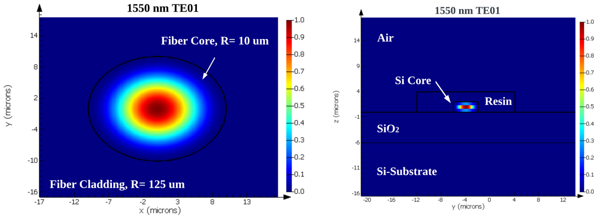
In the design shown in figure 2 (b), the light propagation is 5 mm. The radius of the first surface is 1.468 with 4.237

mm. The binary two surface has a -0.14 radius and 4.577 mm thickness. The semi-diameter is 0.201 and 0.104 respectively. Both surfaces use polymer material with a 1.55 refraction index and Vd = 0. Coeffient on p^2 and p^4 are -2700.824 and 7.444E7, respectively.

IV. SIMULATION RESULTS

In this section, a simulation setup in Lumerical and Zemax is presented. The mode 1 profile of optical fiber is obtained on the FDE solver since single-mode fiber (SMF) coupling behavior is investigated. The cladding is chosen with a 1.44 refractive index and 125 um radius, which is close to the typical polymer material. The 10 um core of fiber is with Si3N4 (RI: 1.9). Silicon (RI: 3.42) is used as the core material of the straight waveguide with a cover of resin layer on top of the waveguide, which provides the protective insulation to increase the mechanical durability and potentially offer a way to precisely adjust the effective refractive index (RI: 1.55) of the Si waveguide and improve the control over light propagation. SiO2 (RI: 1.46) is used as the substrate layer of the waveguide to prevent internal reflection and confine the light within the higher refractive index silicon core of the waveguide. Both fiber and straight waveguide are set to have 200 um length. The wavelength of the simulation is 1550 nm (193.414 THz). The number of trial modes is set to 10. The mode 1 profile is presented below.

A. Mode Plot



(a) (b)

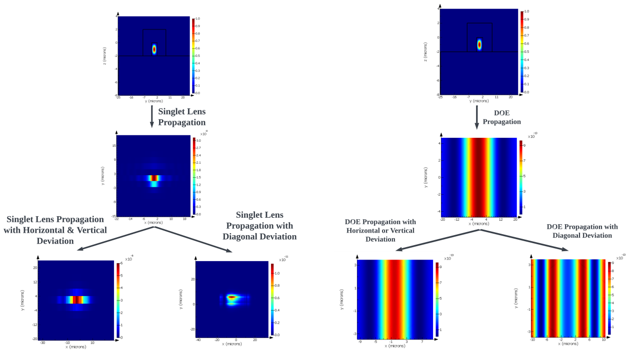
Fig. 3. (a) Fiber Mode 1 Beam Profile (b) Straight Waveguide Mode 1 Beam Profile

1) Single Mode Fiber: Single-mode fibers only allow one mode (or path) of light to propagate along the length of the fiber. It allows a near-perfect spatial coherence, meaning the light exiting the fiber has a well-defined phase relationship over its cross-section. This is beneficial for coupling light into a waveguide or other optical systems that require a highly coherent input beam. Single-mode fibers have a smaller core diameter (usually 8 to 10 micrometers) than multi-mode fibers. A smaller beam diameter can provide better spatial resolution and increased coupling efficiency since the mode field diameter is easier to match with the designed lens, where the light can be matched with the mode size of the waveguide. Although the design of lens couplers for small beam diameters can be more challenging due to the tighter focus requiring shorter focal lengths and higher numerical apertures, a diffraction lens can be used to mitigate these effects because of its high tolerance to alignment issues.

The simulation on eigensolver shows the loss of mode 1 in this SMF is 10.566 dB/cm and 100% TE polarization with effective are of 152.216 um^2. As shown in figure 3 (a), the mode shape of a single mode fiber is a typical Gaussian beam, which is dome-like and radially symmetric. the intensity distribution is the same in all directions perpendicular to the light's propagation direction. The mode field size is approximately 16 micrometers in the FDE simulation results.

In the straight waveguide structure under consideration, light propagates primarily in a fundamental mode (Mode 1), as demonstrated in Fig. 3 (b). This configuration, comprising a silicon (Si) core encapsulated by a resin layer and silicon dioxide (SiO2) substrate (shown as black contours), allows the mode-1 beam to exhibit a waist dimension of approximately 2 μm. Utilizing Finite Difference Eigenmode (FDE) simulations, it is determined that the resin layer effectively confines the Mode 1 light within the Si core. Furthermore, besides shielding the underlying waveguide core from possible physical damage or contamination during packaging or assembly, the resin layer also diminishes optical interference or crosstalk. This is significant in densely packed photonic integrated circuits (PICs), ensuring superior thermal stability, notably concerning the effective refractive index. The latter aspect is critical in space applications where maintenance or repairs are practically impossible. Eigenmode analysis reveals that this Mode 1 propagation experiences virtually no loss (0 dB/cm) and exhibits a high TE polarization proportion (99.68%). Additionally, the effective area of Mode 1 is determined to be $3.87436 um^2$.

The comparative efficacy of edge coupling, singlet lens, and diffractive lens in regard to coupling efficiency is rigorously examined in this section. Table I delineates the overlap and power coupling metrics for each of these coupling modalities premised on the assumption of zero misalignment between optical constituents within the simulation environment.



(a) (b)

Fig. 4. (a) Optical Beam Propagation with Singlet Lens (b) Optical Beam Propagation with Diffraction Microlens

Edge coupling, without light focusing mechanisms, aligns the fiber's core to the waveguide center, resulting in a beam waist exceeding the fiber core diameter of 10 m, demonstrating inferior coupling performance. The singlet lens exhibits superior focusing for mode 1 light, resulting in a smaller beam waist than the edge coupler. Figure 4 (a) shows the skew Gaussian beam propagation via a singlet lens. The singlet lens system is compromised by optical aberrations, such as spherical aberration, coma, and chromatic aberration, reducing its coupling efficiency.

In contrast, the diffractive lens showcases superior performance among microlens-based coupling modalities. Figure 4 (b) shows the skew Gaussian beam propagation via a diffraction lens. Post optimization maintains the Gaussian beam profile following the singlet lens surface, primarily attributing to the Directional Optical Element (DOE) that channels most incident light into the desired diffraction order. Moreover, the DOE's aberration correction capacity improves various optical aberrations introduced by a singlet lens, thereby retaining the mode shape emanating from the waveguide and consequently enhancing the coupling efficiency. Note that the line irradiance distribution can be introduced by the skew Gaussian beam encountering diffractive optical elements, where the optical beam diffracts into multiple orders, creating interference patterns.

TABLE I
COUPLING EFFICIENCY OF MICROLENS COUPLER

Methods	Beam Waist	Overlap	Power Coupling
Edging Coupling	2.83mm	6.41 %	5.97 %
Singlet Lens	0.005mm	19.52 %	16.03 %
DOE	0.021mm	68.65 %	63.93 %

The simulation employs field data to set the initial conditions of light as it traverses from the waveguide into the coupling system. Misalignment, simulated by varying the field angle (2.29°) in the X, Y, or diagonal directions, exhibits distinct influences on coupling efficiency. The coupling efficiency remains uniform for angular deviations in the X and Y directions. However, a more pronounced loss in coupling efficiency is observed when the light deviates diagonally.

TABLE II
COUPLING EFFICIENCY VARIATION VS LIGHT DEVIATION

Misalignment Type	Overlap	Power Coupling
Singlet Lens X / Y	2.41 %	2.25 %
Singlet Lens Diagonal	1.04 %	0.97 %
DOE X / Y	43.88 %	40.87 %
DOE Diagonal	39.58 %	36.86 %

As delineated in Table II, misalignment incurs a reduction in coupling efficiency for the singlet lens by approximately 19%, and for Diffractive Optical Elements (DOEs) by about 25% in the X and Y directions. The diagonal misalignment yields a steeper decrease in coupling efficiency, approximately 20% for singlet lens and 26% for DOE, attributable to the larger light deviation in this direction.

The DOE shows a heightened sensitivity to the angle of incidence, underlining its inherent characteristic. This sensitivity arises because the diffraction pattern on a DOE is designed for a specific angle of incidence, and deviations from this angle can induce unwanted diffraction orders, consequently undermining the efficiency of desired order.

V. CONCLUSION

In conclusion, this study proposes a micro diffraction lens coupler that transfers light from a single-mode fiber to a straight waveguide. Our design offers improved mode matching and enhanced alignment tolerance. We also provide an investigation of the alignment tolerance and demonstrate superior performance in terms of power coupling efficiency. The simulation results show that the design outperforms the traditional edge coupling method. Our proposed design has the potential for use in single-use photonic integrated chips and other optical components.

For future works, the structure, encompassing microlens can be fabricated on a Silicon wafer through additive manufacturing techniques utilizing the Nanoscribe's Photonic Professional GT2 microfabrication machine, which employs Two-Photon Polymerization (2PP) for high-precision 3D printing of intricate structures directly from CAD models. The selected manufacturing resin is IP-n162 photoresin due to its high refractive index and suitability for 2PP, ensuring minimal absorption losses crucial for the design. Additionally, the structure will undergo an optical cementing process using Norland Optical Adhesive (NOA) 1369, a UV-curable adhesive with a refractive index close to that of the IP-n162 resin, to safeguard the waveguide's integrity and enhance light transmission without compromising its performance.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. 2018853. The opinions, findings, and conclusions, or recommendations expressed are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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