

Article

Design of Silicon Photonics Metasurface Enabling Optical Interfacing for Co-Packaged Optics

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Abstract

The exponential growth of AI-driven data traffic necessitates the evolution of Data Center Networks toward high bandwidths and sub-microsecond latency. While co-packaged optics (CPO) offer a pathway to reduced energy consumption and increased capacity, they introduce significant challenges in optical chip coupling and packaging complexity. This study explores monolithically integrated metasurfaces as an alternative for optical interfaces, potentially reducing the need for bulky external microlens arrays or extremely precise mechanical alignment. We design an amorphous silicon (a-Si) metasurface on a Silicon-On-Insulator (SOI) platform operating at 1310 nm. By spatially mapping nanopillar radii to satisfy a spherical phase profile, we achieved near-vertical beam emission with an emission angle of 0.88° focused at a focal length of $98.99\ \mu\text{m}$. Broadband characterization across a 20 nm band confirms stable focusing and a confined spot size with moderate roll-off toward the band edges. The sensitivity of the emission profile of the device to fabrication imperfections in pillar radius, height, and sidewall taper is quantified. The coupling to a polymer-based optical redistribution layer (ORDL) is also studied, and the corresponding modal analysis demonstrates a maximum coupling efficiency of 68.2% into an SU-8 polymer waveguide. Tolerance analysis results reveal deterioration of 0.9 dB and 0.4 dB for $\pm 0.6\ \mu\text{m}$ horizontal and $\pm 1.5\ \mu\text{m}$ vertical misalignment respectively, making the interface compatible with relaxed alignment assembly assumptions, although experimental packaging validation remains required. The methodology is further validated at 1550 nm, demonstrating its applicability across telecom bands. These results suggest that integrated metasurfaces may simplify the packaging stack and enhance density for next-generation CPO links by providing precise, on-chip wavefront manipulation.

Keywords: optical interconnects; co-packaged optics; chip coupling; metasurfaces; Silicon Photonics; beam shaping



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1. Introduction

Data centers (DCs) face unprecedented demand driven by global data traffic growth and, in particular, the rapid advancement of Artificial Intelligence (AI), with internet-connected devices and AI agents both projected to grow steeply over the coming decade [1]. Within this landscape, Data Center Networks (DCNs) must evolve to meet AI's requirements—bandwidths scaling from 800 Gbps to 1.6 Tbps, low latency, and dynamic adaptability—while operating under increasingly stringent energy constraints, as DC electricity demand is projected to roughly double by 2030 [2–4].

The convergence of these significant bandwidth requirements and stringent energy constraints constitute the need for high-efficiency optical interconnects within DCN architectures. Currently, optical solutions are utilized for rack-to-rack communication and are increasingly being explored for intra-rack links [5], with the capacity of optical modules having already reached 400 Gb/s and research progressing towards 800 Gb/s [6].

In current architectures, optical modules are pluggable at the front plate of the switch Application-Specific Integrated Circuit (ASIC), relying on relatively long electrical channels that compromise signal integrity at the required transmission rates. This necessitates high-power Serializer/Deserializer (SerDes) circuits to compensate, increasing link power consumption, while scaling the number of pluggable modules per switch raises rack-level power density and thermal management challenges that ultimately cap bandwidth density [6]. To overcome these limitations, co-packaged optics (CPO) architectures integrate the optical engine into the same package as the ASIC, minimizing electrical line length; CPO has been shown to double network capacity while reducing energy consumption by 50% compared to pluggable optics [7].

CPO introduces new challenges in optical chip coupling (chip-to-fiber, chip-to-chip) to meet high-density requirements, prompting a shift toward wafer-level packaging using optical redistribution layers (ORDLs). In [8] a co-packaged optical chiplet (TeraPHY) demonstrates in-package optical I/O by directly coupling fiber arrays to the photonic die, illustrating the packaging challenge of interfacing optical signals between fiber and photonic components. While vertical architectures provide a dense interconnection fabric that reduces latency, they introduce new bottlenecks in thermal management and manufacturing complexity [9], motivating the exploration of alternative ORDL materials with better mechanical and thermal resilience.

IBM utilizes polymer waveguides (PWGs), potentially increasing beachfront density by $6\times$ [10]. Flexible polymer interfaces absorb thermo-mechanical stress between the fiber array and the silicon chip, ensuring reliability during temperature cycling [10,11]. Current implementations interface with these ORDLs via adiabatic coupling [12,13]. IBM has demonstrated polymer interfaces that relax alignment tolerances to $\pm 2\ \mu\text{m}$ while maintaining high transmission efficiency through lithographically defined adiabatic tapers [11], and heterogeneous integration techniques using adiabatic coupling between on-chip silicon nitride (SiN) waveguides and package-level polymer waveguides have also been developed [14]. Such adiabatic silicon- and SiN-to-polymer couplers achieve sub-1 dB coupling with lateral 1 dB tolerances of several micrometers [13,14]. In parallel, glass-based solutions such as angled 3D glass-to-silicon interfaces achieve $< 1\ \text{dB}$ loss [15], and a SiN-assisted interface has been proposed in which a thin silicon nitride layer enhances mode overlap between the silicon chip and the glass or polymer interposer, theoretically reducing coupling loss to $< 0.1\ \text{dB}$ [16,17].

To achieve efficient optical coupling in packaged systems, common solutions often rely on precise mechanical alignment for edge coupling like Intel's Optical Computing Interconnect (OCI) chiplet in [18] or insert discrete Microlens Arrays (MLAs) or use expanded beam connectors to focus light across the interface [19,20]. In [21] an MLA is used to implement a connector between the fiber array and the PIC. While these external optical elements successfully relax alignment tolerances, they increase packaging complexity (like the vertical package height) and introduce new points of mechanical error [22].

Monolithically integrated metasurfaces directly onto the photonic chip can be explored as a versatile alternative for the optical interface. Amorphous silicon (a-Si) metasurfaces can be fabricated directly on silicon waveguides using standard CMOS processes. Optimized Bosch deep-reactive-ion-etch (DRIE) techniques have been demonstrated to realize silicon pillar structures with aspect ratios up to $\sim 20:1$ and near-vertical sidewall profiles, with

the approach noted to be applicable to infrared and visible regimes with smaller feature sizes [23]. These structures offer on-chip wavefront manipulation, capable of focusing light directly into the cores of polymer or glass ORDLS without external lenses or extremely precise alignment. Gratings can also achieve focusing; focusing or inverse-designed grating couplers reach -1 to -1.7 dB with 1 dB bandwidths of roughly 20–35 nm in footprints of a few hundred μm^2 [24,25]. Compared to these, metasurfaces leverage sub-wavelength phase manipulation to provide more flexible wavefront control and can be designed for high numerical aperture (NA) in compact footprints. In this way, a monolithic metasurface occupies a distinct point in the design space as it performs the out-of-plane focusing function in the device layer that is otherwise provided by discrete free-space optics [19–21,26] and can relax the vertical standoff tolerance that contact-based adiabatic coupling controls most tightly. This suggests that metasurfaces can serve as compact, monolithic elements to simplify the packaging stack and further enhance density in CPO links.

In this paper, we present a design framework and numerical feasibility study for a metasurface-based optical interface solution for CPO architectures. We design a metasurface integrated on a Silicon-On-Insulator (SOI) platform waveguide operating at the O-band (~ 1310 nm), which achieves the emission of the fundamental TE guided mode at a 0.88° angle and focuses the beam at a focal length of $98.99 \mu\text{m}$ above its surface. The design process utilizes FDE, FDTD and RCWA simulations as well as a spatial phase profile discretization and geometry-based mapping method. A broadband characterization is performed at wavelength offsets of -10 , -5 , $+5$, and $+10$ from the design wavelength to assess the spectral stability of the emission profile. We then calculate the coupling efficiency of the device with an SU-8 polymer waveguide, by performing mode overlap analysis obtained from FDE simulation solvers. The calculations show a maximum efficiency of 68.2% for a $3.5 \mu\text{m} \times 14 \mu\text{m}$ waveguide, with alignment tolerance $\pm 0.6 \mu\text{m}$ horizontally with less than 0.9 dB loss, and $\pm 1.5 \mu\text{m}$ vertically with less than 0.4 dB loss. While the design framework applies to photonic packaging in general, this study demonstrates the metasurface's potential as an optical coupling element capable of providing out-of-plane beam focusing to support CPO architectures.

2. Materials and Methods

The proposed methodology for the development of the optical interconnect is as follows: (i) phase profile extraction of the metasurface, (ii) spatial mapping and design of the meta-atoms (sub-wavelength scattering elements) based on extracted phase library, (iii) polymer waveguide mode simulation, and (iv) coupling efficiency calculation.

The metasurface is designed as a periodic array of amorphous silicon (a-Si) cylindrical nanopillars. The refractive index of amorphous silicon at the design wavelength is 3.81. These meta-atoms are integrated onto a Silicon-On-Insulator (SOI) stack, which comprises a 220 nm silicon waveguide layer with an index of $n_{1310\text{nm}}^{\text{Si}} = 3.503$. It is simulated to be on top of a 300 nm buried oxide (BOX) layer, while it is cladded by an 80 nm silicon oxide layer (hardmask) with $n_{1310\text{nm}}^{\text{SiO}_2} = 1.447$. An SU-8 polymer waveguide is placed above the silicon chip, to couple the emission from the metasurface.

The waveguide is oriented in the xy-plane, with light injected from a source along the x-direction to excite the fundamental guided mode. The component is designed to emit the power of the TE guided mode, focusing it at the targeted focal length F , where the ORDLS is placed, as shown in Figure 1. To achieve this, the emitted wavefront must satisfy a spherical phase profile:

$$\phi(x, y) = \frac{-2\pi}{\lambda} \left(\sqrt{x^2 + y^2 + F^2} - F \right)$$

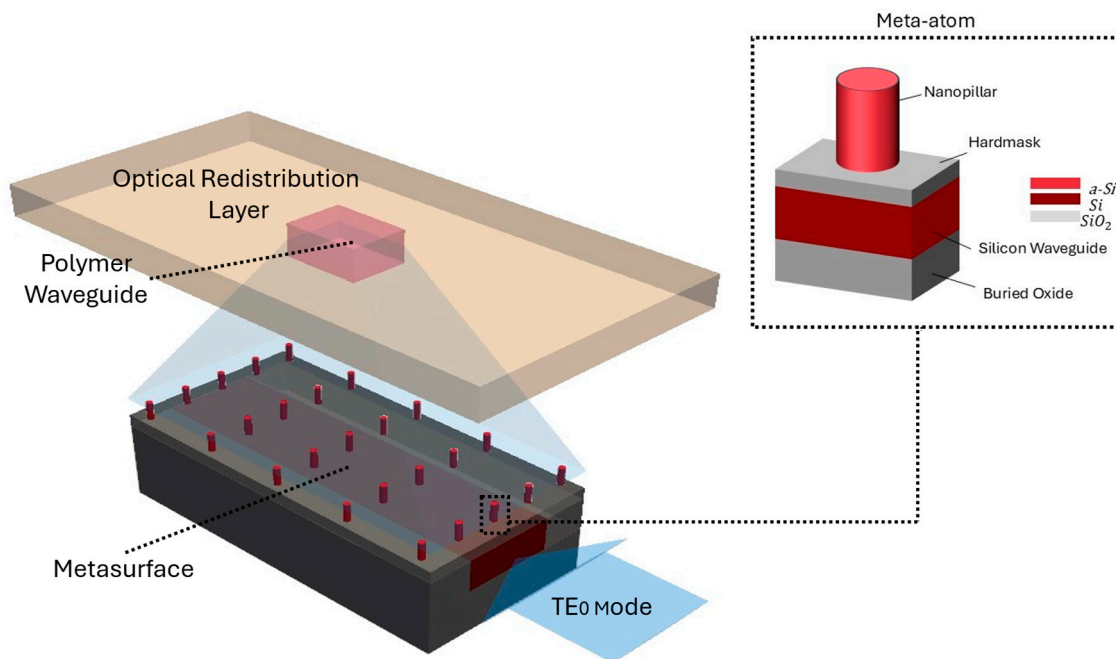


Figure 1. Conceptual view of the designed integrated metasurface, with polymer ORDL above the chip. (Inset) geometry and layerstack of the meta-atoms (nanopillars) on SOI platform.

To implement this component phase profile, the metasurface must impart a phase shift that introduces the required spherical behavior while simultaneously compensating for the phase accumulation $\phi_{wav} = \beta x$ of the guided mode along the propagation direction. That means that the metasurface must provide a phase profile defined by

$$\phi(x, y) = \frac{-2\pi}{\lambda} \left(\sqrt{x^2 + y^2 + F} - F \right) - \beta x$$

To calculate the propagation constant $\beta = n_{eff}k_0$, we first obtained the effective refractive index $n_{eff} = 2.983$ of the mode of the silicon waveguide with the meta-atoms on top, by executing a Finite-Difference Eigenmode (FDE) simulation of a uniform array of nanopillars with a selected lattice period $\Lambda = 452$ nm.

We performed an iterative selection process for the lattice period utilizing the grating equation $\sin \theta_d = n_{eff} - \frac{\lambda}{\Lambda}$ and aiming for a small diffraction angle θ_d for a near-vertical emission profile to simplify far-field alignment and integration with subsequent optical components.

To realize the phase profile of the metasurface we first developed a phase library that maps the meta-atom geometry to its corresponding phase response. This library was generated by performing a series of Rigorous coupled-wave analysis (RCWA) simulations of a single nanopillar, sweeping across heights in a range of 0.5 to 1.5 μm and radii in a range of 0.05 to 0.25 μm to calculate the phase shift introduced by the meta-atom for each geometrical configuration (radii and height). A fixed-height geometry is employed, utilizing the nanopillar radius as the sole parameter for the phase mapping, to achieve low-complexity fabrication and compatibility with established CMOS fabrication processes.

The analysis of the phase library revealed that meta-atoms with a height of 1.3 μm , varying the radius, provide a phase coverage of 2π radians. The resulting aspect ratios (AR), spanning approximately 5.4:1 to 13:1, fall well within the fabricable scope of optimized processes [23]. The metasurface was then constructed by spatially mapping the radii of the selected nanopillars onto the coordinates of a 60×20 μm grid with the lattice of 452 nm. As a result the SOI waveguide cross-section (width $\times$ height) at the metasurface region is

$20 \times 0.22 \mu\text{m}$. At each lattice position, we assigned the specific radius from our library that best approximated the analytical phase value required by the design equation as shown in Figures 2 and 3.

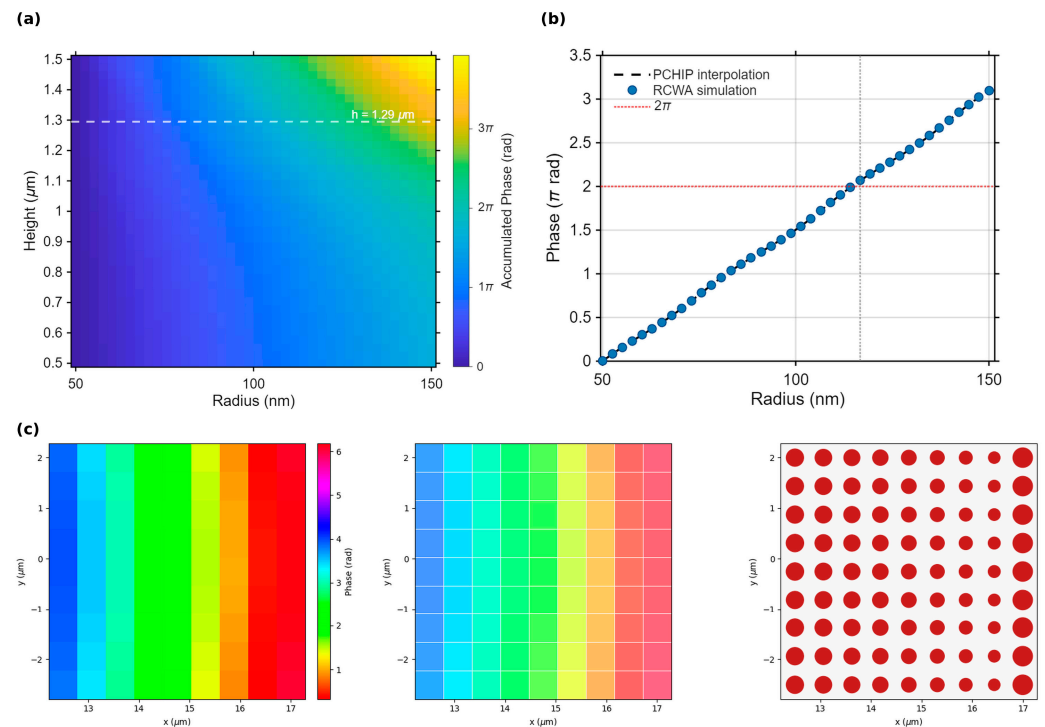


Figure 2. Design process of the metasurface. (a) Simulated phase library of the meta-atoms. (b) Radius vs. phase curve for a fixed nanopillar height $1.3 \mu\text{m}$. (c) Phase mapping process. (I) Target continuous phase profile calculated for the desired wavefront shaping. (II) Spatial discretization of the phase onto a square lattice with a subwavelength period. (III) Mapping of physical nanopillars onto the grid based on the phase-radius library.

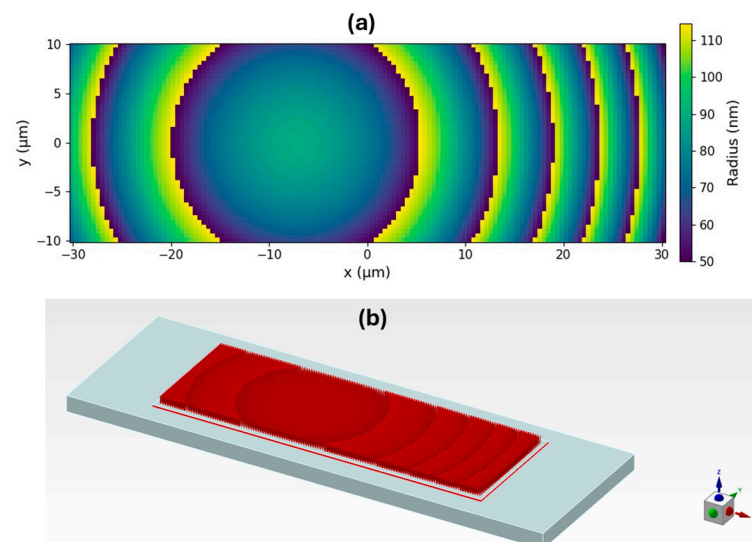


Figure 3. Final implementation of the integrated metasurface. (a) Final mapping of the required meta-atom radii on the $60 \times 20 \mu\text{m}$ grid. (b) 3D model of the simulated metasurface.

The optical redistribution layer (ORDL) consists of a waveguide with an SU-8 polymer core, with refractive index $n_{1310\text{nm}}^{\text{SU-8}} = 1.57$, embedded in a Low-Temperature Oxide (LTO) with $n_{1310\text{nm}}^{\text{LTO}} = 1.44$. The ORDL schematic is shown Figure 4a,b, while the FDE

calculated polymer waveguide TE fundamental propagation mode at 1310 nm is presented in Figure 4c.

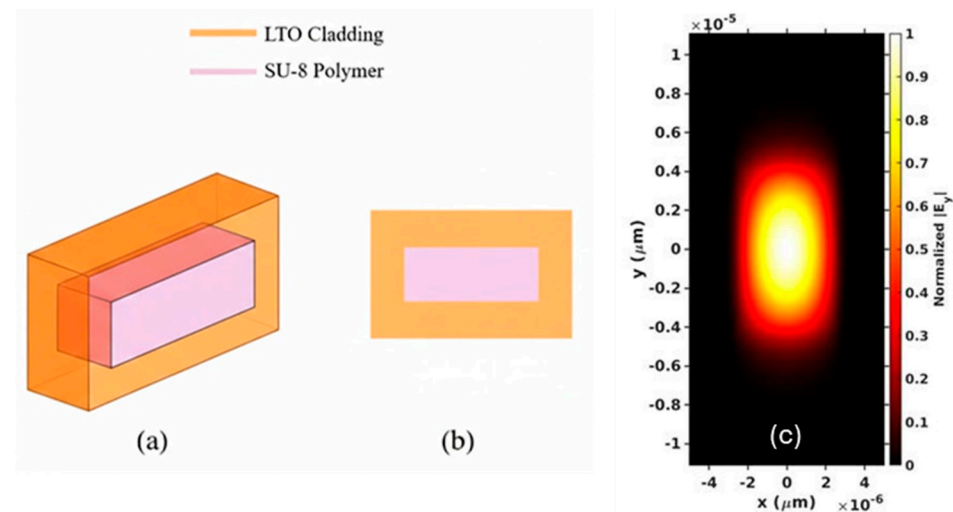


Figure 4. The SU-8 polymer waveguide embedded in an Low-Temperature Oxide (LTO) cladding. (a) 3D view, (b) 2D cut, and (c) polymer waveguide TE fundamental propagation mode.

The fundamental mode of the polymer waveguide was calculated via FDE simulation solver. Next, we calculate the coupling efficiency by overlapping the fundamental mode of the polymer waveguide with the emission profile of the metasurface using the overlap integral equation and the full complex fields acquired from the simulations, as shown below:

$$\text{overlap} = \left| \text{Re} \left\{ \frac{\int E_1 \times H_2^* \cdot dS \int E_2 \times H_1^* \cdot dS}{\int E_1 \times H_1^* \cdot dS} \right\} \frac{1}{\text{Re} \left\{ \int E_2 \times H_2^* \cdot dS \right\}} \right|$$

All simulations were performed using the commercial software Ansys Lumerical (Ansys Inc., Canonsburg, PA, USA), v2023 R2.

3. Results

In this section we present the simulation results after the phase profile extraction. First, we calculate the emission profile of the metasurface. Next, the coupling efficiency of the radiated mode with the polymer waveguide mode is calculated. Finally, a tolerance analysis on the assembly misalignments is carried out.

The theoretical performance of the device is studied employing 3D-FDTD simulation solver. The wavelength was selected to be 1310 nm, using a mesh accuracy of 200 nm for the z-axis and 25 nm for the x and y grid and design focal length of 100 μm. The radiation power is found to be focused at the focal length of $z = 98.99 \mu\text{m}$, representing a focal shift of only 1.01%. The electric field intensity distributions, visualized in Figure 5, exhibit a focal spot with a Full-Width at Half-Maximum (FWHM) of 2.42 μm in the x-direction (FWHM_x) and 7.27 μm in the y-direction (FWHM_y). The simulation also yielded an emission angle of 0.88°.

To assess the spectral stability of the emission profile, the metasurface was characterized across the 1300–1320 nm band at 2.5 nm intervals. The resulting emission metrics are summarized in Figure 6.

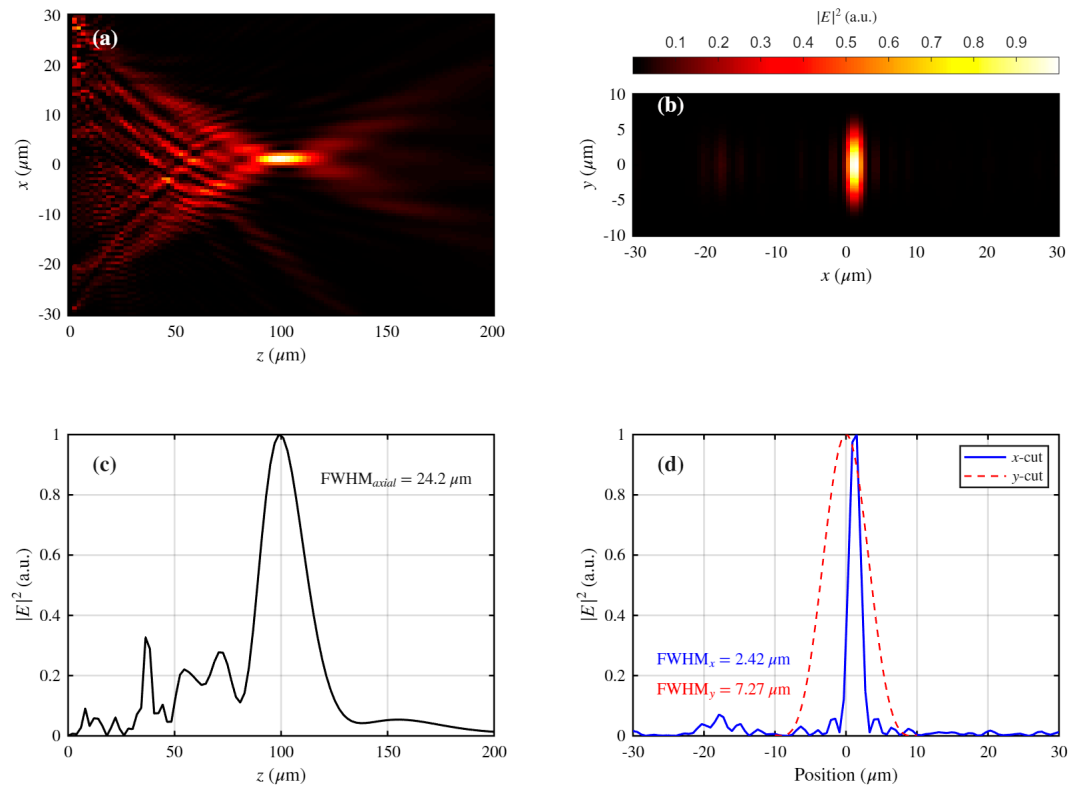


Figure 5. FDTD simulation results for the metasurface emission profile. (a) Intensity distribution in the longitudinal propagation (xz -plane) showing focusing at $z = 98.99 \mu\text{m}$. (b) Transverse intensity distribution at the focal plane (xy -plane). (c) Axial intensity profile along the propagation direction (z -axis). (d) Transverse intensity cross-sections (x and y cuts) at the focal plane.

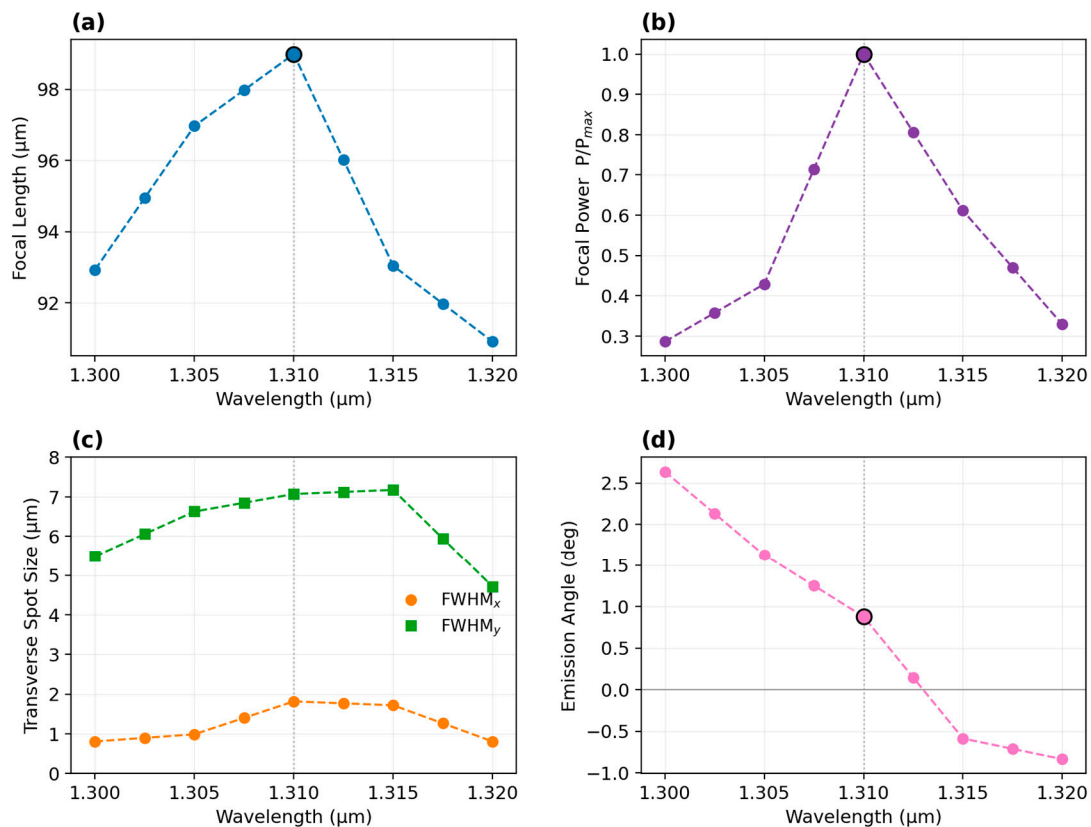


Figure 6. Broadband characterization of the metasurface across 1300–1320 nm. (a) Focal length, (b) focal power fraction, (c) transverse spot sizes (FWHM_x , FWHM_y), (d) emission angle.

This broadband characterization shows that both focal length and focal power (quantified as the fraction of the power in the focal plane within the FWHM footprint) peak at the 1310 nm design wavelength, with performance roll-off at neighboring wavelengths due to spectral detuning of the phase profile. The emission angle exhibits a monotonic shift from $+2.64^\circ$ to -0.84° across the 20 nm band. Meanwhile, the transverse spot size remains tightly confined, with FWHM_x and FWHM_y maintained within 0.8–1.8 μm and 4.7–7.3 μm , respectively.

Next, robustness to fabrication imperfections is studied by evaluating three perturbation cases: pillar radius errors arising from lithographic dose variations, sidewall taper from non-vertical etch profiles in the RIE/ICP process, and pillar height variation from etch depth non-uniformity.

Radius errors are modeled as independent Gaussian perturbations ($3\sigma = 10\%$ of nominal radius), yielding focal length, emission angle and FWHM_y deviations below 1%, while FWHM_x is narrowed to 0.84 μm . Sidewall taper leaves the focal length unchanged (98.99 μm), shifts the emission angle to 1.97° ($+1.09^\circ$) and narrows FWHM_x to 1.01 μm . Height variation shifts the focal length to 101.01 μm ($+2.02 \mu\text{m}$) and emission angle to 1.04° ($+0.16^\circ$), with FWHM_x broadening to 1.62 μm . FWHM_y remains stable in both cases ($\sim 7.5 \mu\text{m}$). Across these perturbations, focused power deviations remain within 3.4 dB of nominal. Figure 7 displays the effect on the intensity distribution of the focal plane. While the profile remains relatively stable, small shifts and side lobes occur as the geometry variations degrade phase control and the cancelation of accumulated phase across the waveguide's excitation direction.

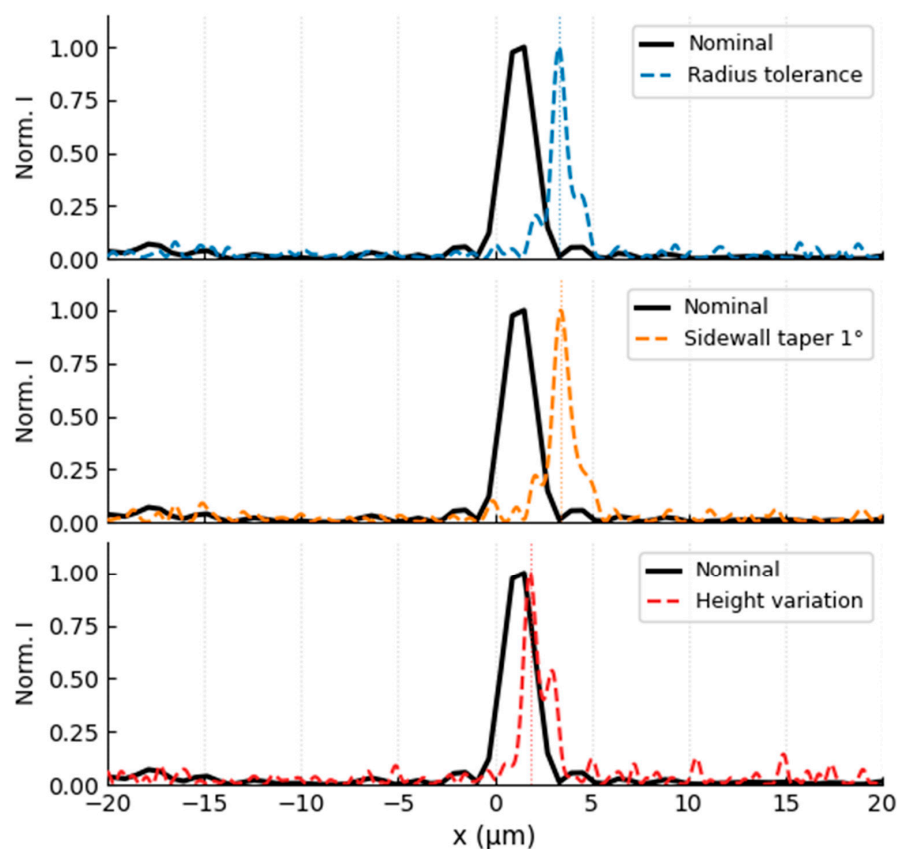


Figure 7. Impact of geometric variations on the focal plane intensity distribution along the excitation direction (x-axis). The shifts in peak position and profile highlight the degradation of phase control and the incomplete cancelation of waveguide phase accumulation as the parameters deviate from the nominal design library.

Finally, the coupling efficiency of the radiation mode with the polymer waveguide is extracted. This is quantified by calculating the overlap of the emission profile with the fundamental TE mode of the polymer waveguide, varying the width and height dimensions of the waveguide to discover the optimal power overlap which turned out to be 65.6% for a $3.5 \times 14 \mu\text{m}$ waveguide as shown in Figure 8. In case the use case requires smaller dimension of the polymer waveguide, alternative waveguide cross-section geometries can be selected, with the efficiency standing beyond 60%, such as $3.0 \times 12.0 \mu\text{m}$ at 64.1% and $2.5 \times 12.0 \mu\text{m}$ at 62.5%, and beyond 50%, such as $3.0 \times 8.0 \mu\text{m}$ at 54.0% and $2.5 \times 8.0 \mu\text{m}$ at 52.7%.

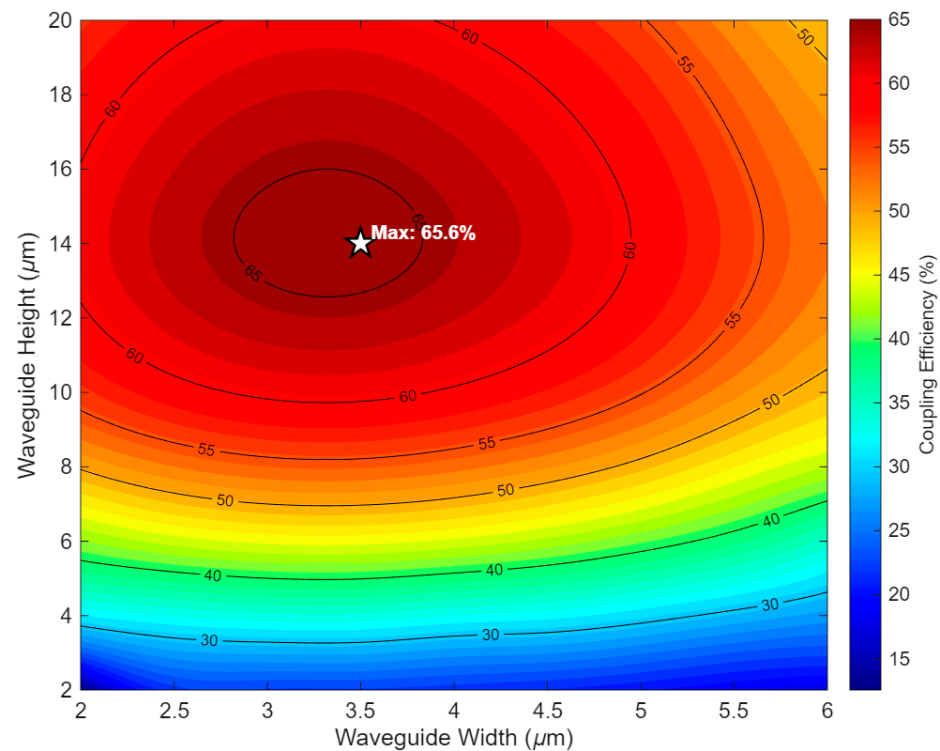


Figure 8. Coupling efficiency for different geometric configurations of the SU-8 polymer waveguide.

Upon finding the optimal configuration we performed an alignment sweep and discovered the optimal alignment is with a horizontal offset of 300 nm and a vertical offset of 100 nm compared to the initial centered position, improving efficiency to 68.2%. We then performed an alignment tolerance analysis around that optimal position, visualized in Figure 9. The 1 dB tolerance region extends to $0.64 \mu\text{m}$ horizontally and $2.4 \mu\text{m}$ vertically, while the 2 dB and 3 dB regions reach $\pm 0.91/\pm 3.47$ and $\pm 1.11 \mu\text{m}/\pm 4.23 \mu\text{m}$ respectively. The most robust operating regime is defined by a rectangular displacement area of $\pm 0.6 \mu\text{m}$ horizontally and $\pm 1.5 \mu\text{m}$ vertically, as indicated by the solid white lines in Figure 9. Within this region, the maximum loss at the horizontal limits is only 0.9 dB, while the vertical loss is restricted to 0.4 dB, resulting in a worst-case combined misalignment loss of 1.3 dB. These tolerance margins are sufficiently large to enable passive alignment of silicon photonic chips using standard pick-and-place assembly, eliminating the need for active alignment while maintaining acceptable coupling loss. This robustness makes the proposed approach particularly well suited for co-packaged optics (CPO) interfaces, where relaxed alignment tolerances are critical for scalable, low-cost, and high-yield integration of optical engines with electronic ASICs.

The tolerance of the interface to the longitudinal position of the polymer facet was also evaluated. Keeping the waveguide at its optimal in-plane alignment, the coupling efficiency was computed as the facet was displaced along the propagation axis relative to

the focal plane. As shown in Figure 10, the coupling remains within 1 dB of its peak over a longitudinal range from $-5.98\ \mu\text{m}$ to $+11.26\ \mu\text{m}$, a total window of approximately $17\ \mu\text{m}$, reflecting the extended depth of focus of the emitted beam (axial FWHM $\approx 24\ \mu\text{m}$). The response is asymmetric, with a more relaxed tolerance on the far side of the focal plane, and the maximum coupling is in fact obtained slightly beyond the nominal focal plane (69.4% at $\Delta z \approx +2\ \mu\text{m}$). This relaxed z -tolerance indicates that the polymer facet standoff is not a critical alignment dimension for this interface.

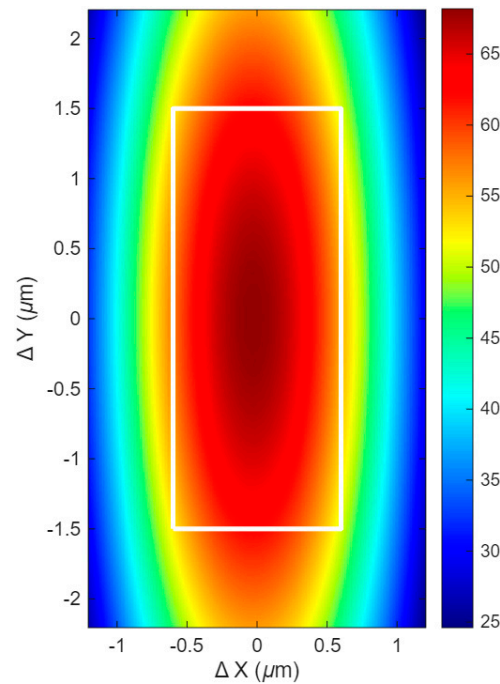


Figure 9. Metasurface-waveguide alignment tolerance analysis for the optimal waveguide configuration around the optimal position.

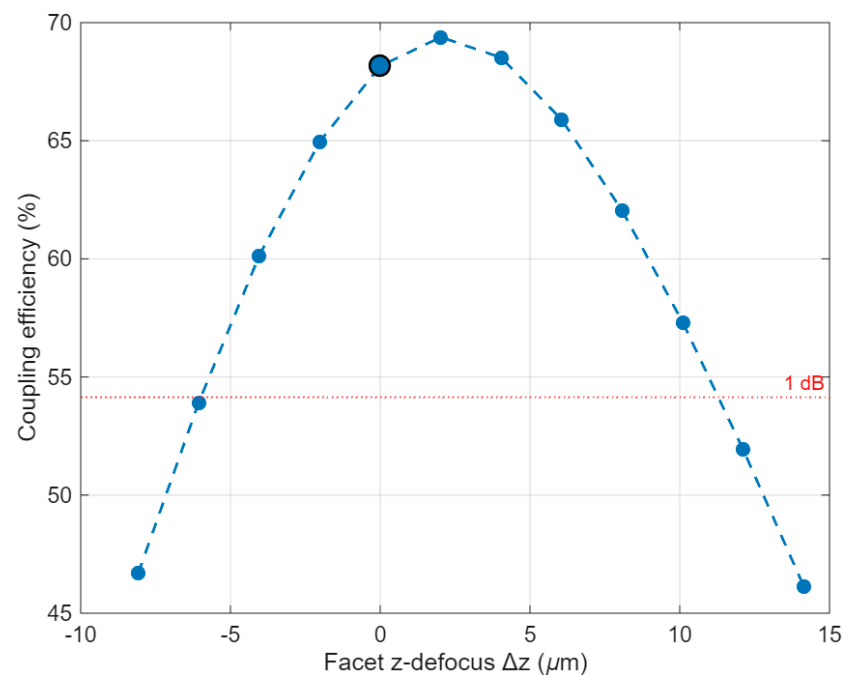


Figure 10. Coupling efficiency as a function of the polymer facet position along the emitted beam (z -defocus), with the waveguide held at its optimal in-plane alignment.

The broadband coupling efficiency was calculated with the polymer waveguide fixed at its optimized spatial alignment, as shown in Figure 11. As expected, the normalized coupling efficiency decreases as the operating wavelength deviates from 1310 nm. This behavior is primarily governed by the refractive-index-dependent phase matching and the spatial mode matching at the focal plane, both of which are highly sensitive to wavelength shifts. The efficiency decreases more rapidly for wavelengths below the design target, whereas the response for longer wavelengths is more gradual, remaining within a 3 dB penalty up to 1320 nm. By linearly interpolating the simulated data points, the 1 dB coupling bandwidth of the device was determined to be approximately 2.57 nm.

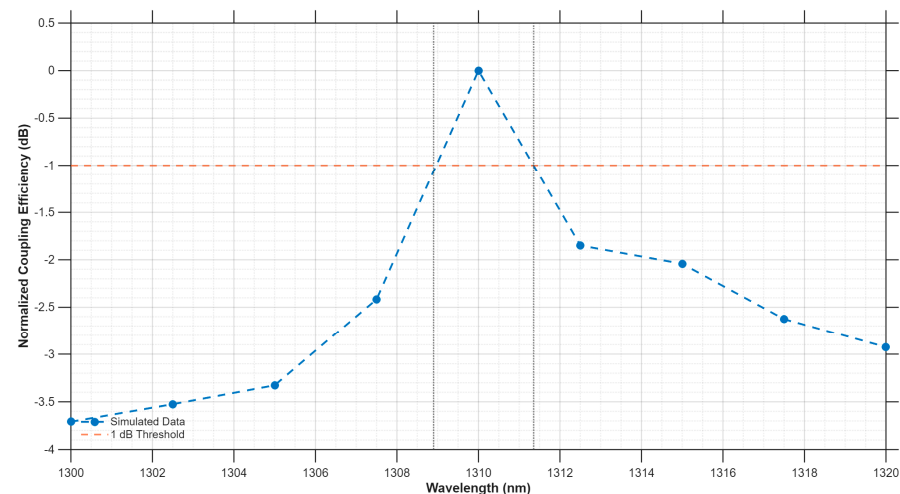


Figure 11. Broadband study of the coupling efficiency of the optical interface.

To demonstrate the generality of the proposed methodology, an independent metasurface was designed and simulated at 1550 nm, targeting applications in the C-band where integrated focusing and coupling may also be required. The design follows the same spatial phase mapping process and SOI platform, with meta-atom geometry and lattice period re-optimized for the target wavelength.

The FDTD simulation yields a focal length of 98.75 μm , an emission angle of 0.53° , and a focused spot with $\text{FWHM}_x = 2.42 \mu\text{m}$ and $\text{FWHM}_y = 8.16 \mu\text{m}$ at the focal plane, consistent with the near-vertical, tightly focused emission behavior obtained at 1310 nm. The coupling efficiency to an SU-8 polymer waveguide is evaluated via the same mode overlap analysis and optimization (introducing a 600 nm horizontal shift after the optimal cross-section was identified), yielding a maximum efficiency of 65.5% for a $3.8 \times 16.6 \mu\text{m}$ waveguide cross-section. Alignment tolerance analysis indicates a worst-case loss of 1.35 dB and 0.68 dB for $\pm 1 \mu\text{m}$ horizontal and $\pm 2 \mu\text{m}$ vertical misalignments, respectively. The results are summarized in Figure 12.

These results confirm that the design framework is wavelength-agnostic and can be readily adapted to the C-band, broadening the scope of the proposed interface to use cases that require integrated focusing and coupling at 1550 nm.

The present implementation is polarization-specific. The phase library and spatial phase mapping were generated for TE excitation, and the design should therefore be interpreted as a TE optical interface. For TM excitation, the modal effective index and meta-atom phase response differ, so the encoded phase profile would not produce the same focused emission. A receiver-side implementation would require polarization diversity, for example through a polarization splitting front end or separate TE/TM-optimized metasurfaces. This extension is outside the scope of the present numerical feasibility study.

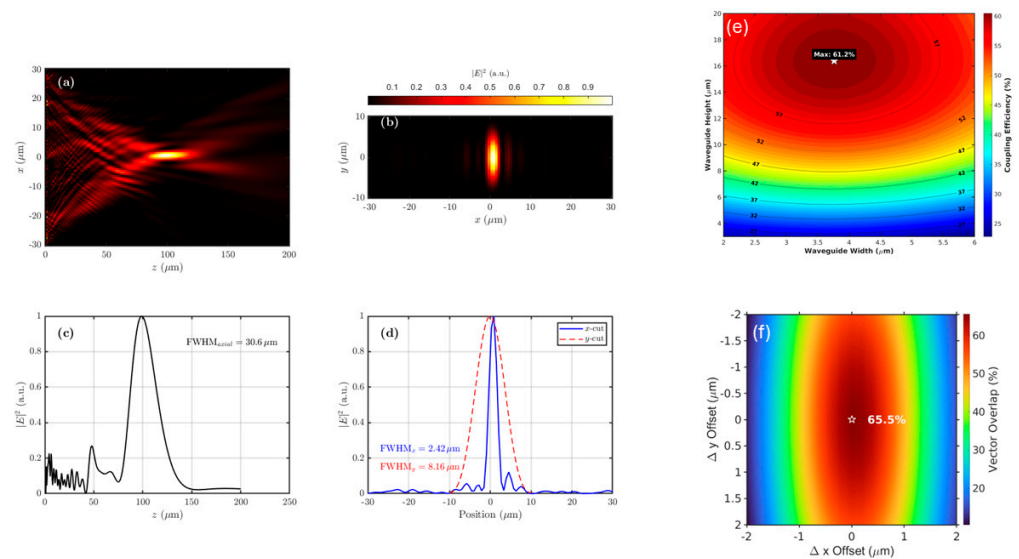


Figure 12. FDTD simulation results and coupling analysis for the 1550 nm metasurface design. (a) Longitudinal intensity distribution (xz-plane). (b) Transverse intensity distribution at the focal plane (xy-plane). (c) Axial intensity profile. (d) Transverse cross-sections at the focal plane (e) Coupling efficiency as a function of SU-8 polymer waveguide dimensions, with a maximum of 61.2% (prior to the alignment optimization). (f) Alignment tolerance map showing vector overlap as a function of lateral offset, with 65.5% at the centered position.

4. Discussion

The integrated a-Si metasurface, monolithically integrated on SOI, enables the realization of a tunable optical interface for next-gen chip interconnects in future CPO architectures. The fabrication tolerance analysis indicates robustness to manufacturing non-idealities, supporting the viability of the proposed design. This methodology uses a spatial phase mapping approach to convert a guided TE mode into a focused beam, bridging the gap between high-index silicon waveguides and larger polymer ORDL waveguides. The device has a degree of versatility since the designer can efficiently control the focal length. Compared to methods usually deployed for optical interfaces in packaged systems, like external lenses or precise edge or adiabatic coupling, this metasurface reduces packaging complexity and volume while meeting the alignment tolerance requirements for high-density co-packaged optics. The near-vertical emission architecture could target established out-of-plane polymer waveguide assembly flows. These include architectures where a 45° total-internal-reflection facet redirects the beam [27], as well as modern 3D Co-Packaged Optics (CPO) frameworks such as Fan-Out Wafer-Level Packaging (FOWLP). In these stacked 3D configurations, polymer optical redistribution layers are integrated directly above the face-up silicon chip, allowing the vertically emitted beam to couple straight into the overlaying waveguide [14,28]. Furthermore, continued advances in fabrication processes, particularly in aspect ratio control and lithographic resolution, are expected to enable more precise and customizable emission profiles, further improving coupling efficiency and overall interface performance.

A complete theoretical coupling efficiency budget must account for the 68.2% mode overlap upper bound, a mitigable Fresnel reflection loss of approximately 0.22 dB at the polymer facet, and the fundamental free-space radiation efficiency of the metasurface. The analysis of this radiation efficiency reveals that 60.3% of the radiated power is emitted upwards toward the waveguide, while the remaining 39.7% leaks downwards into the substrate. While the current implementation prioritizes a compact footprint and a specific phase profile, future designs could optimize insertion loss by utilizing sparser meta-atom

distributions to enhance upward scattering at the cost of larger footprint and integrating bottom reflectors to break the emission symmetry.

5. Conclusions

We present an amorphous silicon (a-Si) metasurface integrated on a Silicon-On-Insulator (SOI) platform at 1310 nm, enabling near-vertical beam emission with a diffraction angle of 0.88° and a focal length of $98.99\ \mu\text{m}$ via spatial phase mapping of nanopillar radii. Efficient coupling to the polymer ORDL is achieved, with a maximum coupling efficiency of 68.2% into an SU-8 waveguide. Alignment tolerance analysis indicates limited performance degradation of 0.9 dB and 0.4 dB for $\pm 0.6\ \mu\text{m}$ horizontal and $\pm 1.5\ \mu\text{m}$ vertical misalignments, respectively. This study demonstrates a monolithically integrated a-Si metasurface that transforms guided modes into focused beams, providing a compact, high-tolerance interface between silicon and polymer waveguides for CPO architectures.

Next steps could target a further enhancement of the coupling efficiency, by optimizing the emission profile to match the polymer waveguide assembly. Future iterations could employ more complex meta-atom geometries or dual-layer stacks to allow for more precise phase modulation and broaden the spectral response. Experimental fabrication and optical characterization of the device would constitute a natural next step toward validating the proposed design in practice.

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