



SAFELOC: self-aligned fiber entry low-loss optical coupler

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Abstract: We present self-aligned fiber entry low-loss optical couplers (SAFELOCs), three-dimensionally tapered polymer waveguides that efficiently couple tapered optical fibers to on-chip waveguides across multiple material platforms with low insertion loss ($\lesssim 1$ dB) over the C and L-bands. SAFELOCs incorporate 3D fiber receptacles for passive, mechanical alignment, enabling broadband coupling without precision stages or active feedback. Experimental measurements confirm low insertion loss consistent with simulations, and the design can achieve minimal polarization dependence. The tapered fiber receptacle also allows permanent fiber attachment while expanding alignment tolerance, facilitating simultaneous coupling of fiber arrays for multi-port photonic circuits. While demonstrated in the C and L bands on Si_3N_4 , Si, and SU-8, the two-photon lithography fabrication process can be applied to other materials, and the polymer's broad transparency window suggests compatibility down to 400 nm, highlighting the versatility and scalability of SAFELOCs.

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1. Introduction

Photonic integrated circuits (PICs) are poised to revolutionize a number of applications, including sensing [1], microwave photonics [2], high performance computing [3–5], and quantum technologies [6]. While on-chip performance can exceed that of bulk fiber-optic components, the optical signal in most cases must eventually couple to an optical fiber. This interface remains a performance bottleneck [7] because the mode size and shape in the fiber are dramatically larger than that of on-chip waveguides. There are several demonstrations of fiber-to-chip couplers in the literature, including inverse-taper edge couplers, grating couplers, and evanescent couplers [8–13]. However, for practical applications, a fiber-to-chip coupler must have significant spatial tolerance to enable long-term alignment or permanent fixation of the fiber. Current solutions generally require precise stages and active alignment to maintain low insertion loss. Additionally, fiber-to-chip couplers must exhibit broad optical bandwidth to accommodate WDM systems. Polarization-independent coupling is critical, since many integrated photonic circuits are designed to operate with low loss for both polarizations, rather than assuming a single polarization. Furthermore, temperature stability and fabrication tolerance are essential for practical deployment.

Recently, three-dimensional polymer structures have emerged as a potential enabling technology for fiber-to-chip coupling [8,14–16]. In particular, two-photon-polymerized (TPP) “plug-and-play” structures have been used to mechanically align fibers to polymer waveguides [17,18]. In the first case [17], the light was redirected into a grating coupler, thereby limiting the performance to that of the grating coupler, but the mechanical receptacle allowed the fiber to be held robustly in alignment without ultra-precise stages or active feedback. In the second [18], alignment is

based on the precision of a V-groove fiber array mated at near normal incidence with macro-scale mechanical alignment bumps, and light is redirected into the waveguides by TPP-defined microlenses and mirrors.

In this work, we build on these concepts with our self-aligned fiber entry low-loss optical coupler (SAFELOC). Our three-dimensional structure comprises an entry receptacle and a low-loss tapered evanescent mode adapter. The entry receptacle serves as a precision alignment fixture for individual input/output tapered fibers in plane with the chip, ensuring stable positioning for long-term measurements or incorporation into packaged, connectorized assemblies. The large opening of the receptacle obviates the need for precision alignment stages and can enable the simultaneous insertion of fiber arrays. The tapered coupler is designed for low insertion loss over a wide wavelength range and can be optimized for a single polarization or for dual-polarization operation. Here, we present general design principles for the SAFELOC and experimentally demonstrate its performance on three different material platforms: Si_3N_4 on SiO_2 , Si on SiO_2 , and SU-8 on SiO_2 . In all cases, the measured insertion loss is less than 1 dB (i.e., coupling efficiency over 80 % per connection) over at least the C-band, and we show that these couplers can be made polarization-independent.

2. Device layout and design considerations

Figure 1 presents the conceptual design of a SAFELOC device. The coupler comprises four key components: a tapered single-mode fiber, a fiber receptacle for guided alignment, a 3D tapered polymer waveguide, and a 3D tapered polymer waveguide that surrounds an inverse-tapered single-mode waveguide on the substrate. The self-aligning functionality of the SAFELOC is realized through the fiber receptacle that provides mechanical support for the tapered fiber at the coupler interface [17,19]. Both the fiber receptacle and the 3D polymer waveguide are fabricated via two-photon polymerization (TPP) nano-printing directly onto the substrate. The entrance aperture of the receptacle is intentionally widened to facilitate insertion of the fiber, and the interior opening is tapered to precisely mate the tapered fiber endface to the input facet of the tapered 3D photoresin, ensuring optical alignment of the two. The receptacles can be customized in shape to accommodate different fiber geometries. The polymer waveguide is a multistage taper that gradually reduces the optical mode size while simultaneously translating the mode center downward toward the substrate, ultimately enabling adiabatic coupling into the underlying inverse tapered waveguide. In this manuscript, we present a hierarchical design approach that enables integration across various standard photonic platforms without platform-specific modifications.

The coupler design optimization targets maximum coupling efficiency and controlled polarization dependence within the specified wavelength range while constraining device footprint. Achieving these performance objectives requires systematic consideration of several interdependent design parameters and boundary conditions, including: photo-resin material selection, tapered fiber dimensions and input aperture geometry, TPP printing field constraints and resolution limits, and allowable misalignment tolerances—each of which is addressed in the subsequent analysis.

2.1. Material and fabrication considerations

We selected IP-Dip2 photoresin (supplied by Nanoscribe [20]) for two-photon polymerization (TPP) because of its submicron printing resolution, strong substrate adhesion, mechanical stability for photonic applications, high shape fidelity, and minimal post-processing requirements. TPP-processed IP-Dip2 is particularly suitable for telecom-wavelength devices [16,21]. A key constraint enabling this approach is the compatibility between the photoresin refractive index and that of the underlying cladding or substrate. We measured the refractive index of polymerized IP-Dip2 near 1550 nm to be 1.5225 ± 0.0025 (measurement method is described in Supplement 1), which is consistent with the dispersion data provided by the manufacturer, extrapolated to the NIR.

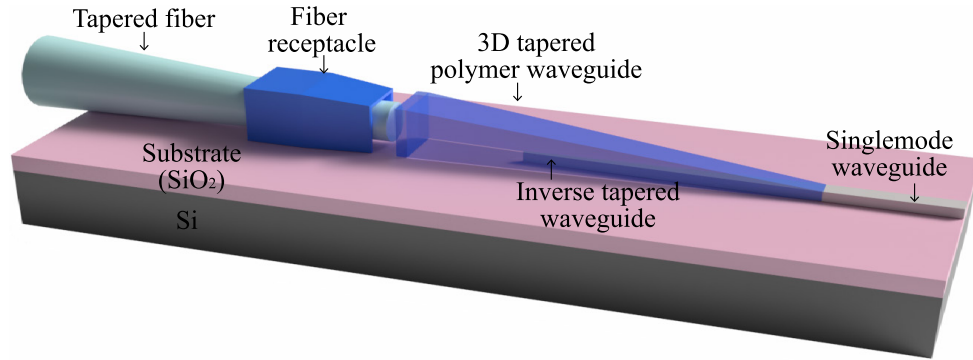


Fig. 1. Schematic of a self-aligned tapered fiber coupler. Light is transferred from a tapered optical fiber to a single-mode waveguide via a nano-printed 3D tapered polymer waveguide. The fiber receptacle ensures precise alignment of the tapered fiber.

In a majority of integrated photonics platforms (including those demonstrated here), the lower cladding layer is SiO_2 . This provides a sufficient index contrast ($\Delta n \approx 0.086$) to support optical confinement in the IP-Dip2 waveguide. Additionally, IP-Dip2 exhibits negligible absorption at 1550 nm and its index closely matches that of standard fused silica fiber, resulting in a Fresnel reflection loss of only about -0.036 dB, making it ideal for low-loss optical coupling.

In nanoscale 3D printing, resolution and scalability are influenced by the print field size and choice of objective lens. We used a high-numerical-aperture ($\text{NA} = 1.4$), $63\times$ objective, enabling smooth sidewalls and fine feature definition. Depending on the total device length, two printing strategies were employed: for compact designs that fit within a single write field ($200\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$), the fiber receptacle and 3D polymer taper were printed as a monolithic structure to avoid stitching artifacts (e.g., the Si_3N_4 platform in Section 3.1); for designs requiring greater length or flexibility, the receptacle and taper were printed as two independent structures within separate write fields (e.g., the SU-8 platform, Section 3.3). Full details of the fabrication parameters — including laser settings, scan speed, slicing/hatching distances, write time, and post-development procedure — are provided in [Supplement 1](#) Section 4.

2.2. Size of tapered fiber and input cross-section

We employ a tapered input fiber to avoid initiating the on-chip 3D polymer taper from macroscopic dimensions, which would otherwise require an excessively long taper and occupy a large chip footprint. Tapered fiber coupling is a well-established technique, and such fibers are typically fabricated either by thermal tapering — controlled heating and pulling of standard single-mode fiber (SMF-28) [22–25] — or by wet chemical tapering [26,27], achieved via hydrofluoric acid (HF) etching. The former method generally produces long, gradual tapers (extending over several millimeters), whereas HF etching results in shorter tapers.

Figure 2(a) shows a schematic of the fiber-to-polymer coupler interface. We consider a standard SMF-28 fiber with a core diameter of $D_{\text{core}} = 8.2\text{ }\mu\text{m}$, cladding diameter of $D_{\text{clad}} = 125\text{ }\mu\text{m}$, and a numerical aperture of $\text{NA} \approx 0.14$. The fundamental LP_{01} mode profiles for various taper diameters are shown in Fig. 2(b). During the tapering process, as the fiber diameter (D_{taper}) decreases, the guided mode gradually expands beyond the core region: in thermal tapering both the core and cladding shrink together, while in wet chemical tapering, significant mode expansion occurs once the cladding is fully removed (i.e., $D_{\text{core}} = D_{\text{clad}}$ for $D_{\text{taper}} \leq 8.2\text{ }\mu\text{m}$), potentially leading to evanescent and substrate leakage when the fiber is in contact with the chip surface. The variation of core diameter with cladding diameter for both methods is summarized in Fig. 2(c), while the simulated power confinement at $\lambda = 1550\text{ nm}$ as a function of fiber

diameter is shown in Fig. 2(d). As seen, confinement degrades sharply when $D_{\text{taper}} < 15 \mu\text{m}$ due to increased substrate interaction. Notably, for small diameters, HF-tapered fibers exhibit slightly better power confinement compared to thermally tapered fibers, owing to a larger fraction of the optical power remaining in the higher-index core, whereas thermal tapering leads to significant power residing in the lower-index cladding region of the tapered fiber.

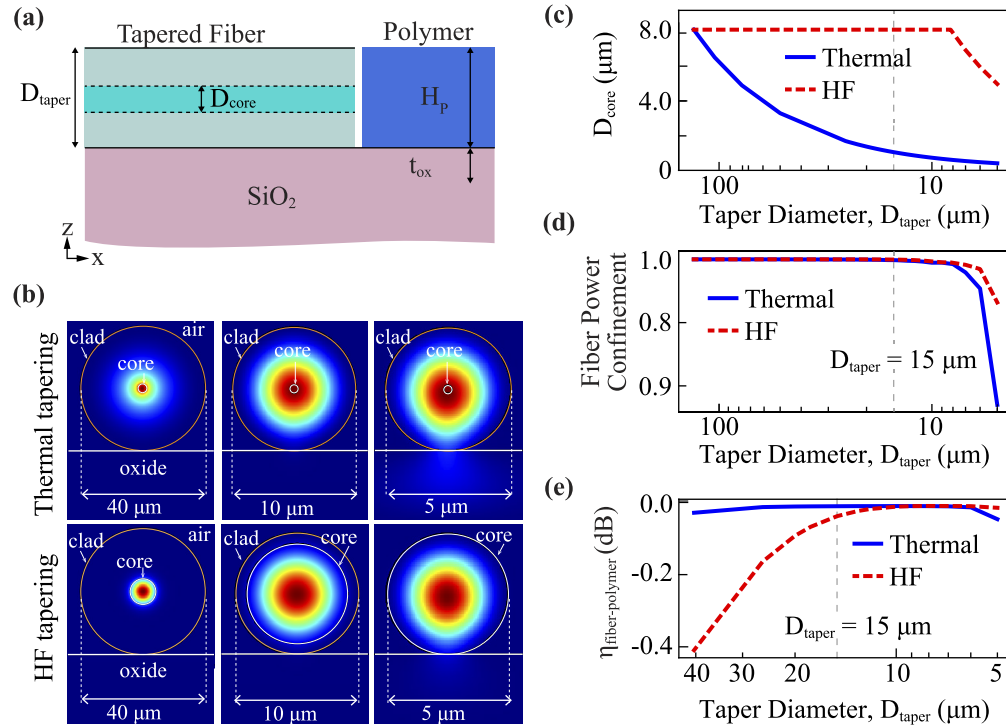


Fig. 2. (a) Longitudinal cross-section schematic of the fiber–polymer coupler interface. (b) Simulated LP_{01} mode profiles for different taper diameters in thermally tapered (top) and HF-etched (bottom) fibers. (c) Extracted effective core diameter D_{core} , (d) simulated optical power confinement in the tapered fiber, and (e) mode-overlap ($\eta_{\text{fiber-polymer}}$) between the tapered-fiber mode and the square polymer-coupler mode ($W_p = H_p = D_{\text{taper}}$), all evaluated as a function of the taper diameter D_{taper} . All simulations assume $\lambda = 1550 \text{ nm}$ and a bottom SiO_2 cladding thickness of $t_{\text{ox}} > 3 \mu\text{m}$.

At the fiber–polymer interface, coupling performance is primarily governed by the mode-field overlap between the tapered fiber mode and the polymer coupler mode. The overlap integral is evaluated assuming a polymer cross-section of $W_p = H_p = D_{\text{core}}$. The mode overlap (Fig. 2(e)) exceeds 98% (−0.05 dB) within the range $7 \mu\text{m} < D_{\text{taper}} < 15 \mu\text{m}$ for both tapering techniques. HF-tapered fibers exhibit reduced overlap at larger diameters because the optical mode remains strongly confined within the untapered core for $D_{\text{taper}} > 15 \mu\text{m}$. Further reduction of the diameter results in a reduced confinement in the core, which is correlated with loss through leakage to the substrate. Considering these trade-offs, we selected a fiber taper diameter of $D_{\text{taper}} = 15 \mu\text{m}$.

2.3. Misalignment tolerance

Although the tapered fiber is generally self-aligned within the entrance receptacle, minor misalignments can occur between the fiber and the coupler input due to variations in fiber diameter or receptacle dimensions. The color plots in Fig. 3(a)–(d) illustrate the coupling

efficiency from fiber to polymer for both tapering techniques under TE and TM polarizations. The coupling efficiency is calculated from the fundamental mode overlap between the fiber mode and polymer mode, assuming $D_{\text{taper}} = W_{P0} = H_{P0}$. For thermal tapering (Fig. 3(a)), the coupling efficiency decreases below -0.3 dB ($\approx 93\%$) when $|dy|$ or dz exceeds 1 μm , whereas for HF tapering, it drops below -0.5 dB ($\approx 89\%$) under the same conditions.

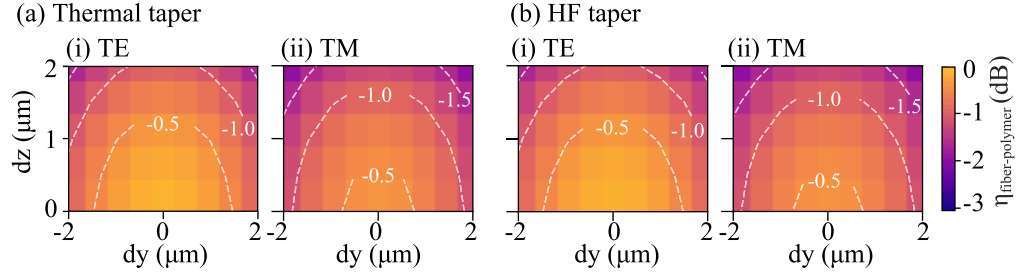


Fig. 3. Calculated coupling efficiency ($\eta_{\text{fiber-polymer}}$) versus fiber displacement along the y and z axes relative to the polymer input. (a) thermal tapering, (b) HF tapering. For simulation, we assume $D_{\text{clad}} = W_{P0} = H_{P0}$.

Additional misalignment may occur between the 3D-printed polymer structure and the underlying photonic waveguide due to printing inaccuracies. Achieving a misalignment-tolerant coupler therefore requires optimization of the taper profile and fabrication parameters. The impact of printing-induced misalignment on coupling performance is discussed in Section 3.1.2.

3. Device demonstrations

This section presents the simulation and experimental results of SAFELOC devices fabricated on three representative photonic platforms: Si_3N_4 on SiO_2 , Si on SiO_2 , and SU-8 on SiO_2 . These platforms were chosen to highlight the versatility of the SAFELOC concept across different material systems.

3.1. Polarization independent SAFELOC on silicon nitride-on-oxide platform

Silicon nitride offers low optical losses, a wide transparency window from visible to mid-infrared, and high power handling. Its compatibility with CMOS fabrication also makes it ideal for scalable, integrated photonic circuits used in communications, sensing, and nonlinear optics. For this demonstration, we employed a 500 nm thick Si_3N_4 -on- SiO_2 platform with a 3 μm buried oxide layer. The SAFELOC design parameters were optimized for low insertion loss and polarization-independent operation across the telecommunication C and L bands (1500–1630 nm). Figure 4(a) presents the initial design architecture.

The coupling structure employs a four-stage design consisting of an untapered polymer (IP-Dip2) section of length L_0 , followed by three successive 3D linear tapers with lengths L_1 , L_2 , and L_3 . Because the transverse dimensions evolve continuously throughout the structure, no abrupt index or geometry discontinuities are introduced. The role of the first taper stage is to gradually shrink the polymer mode size while simultaneously shifting the optical mode downward toward the substrate. This controlled evolution improves adiabaticity and minimizes coupling to higher-order or radiation modes in the subsequent taper sections, rather than relying on discrete modal overlap transitions. The second and third taper stages facilitate efficient transfer of optical power from the polymer waveguide into the underlying inverse tapered Si_3N_4 waveguide. The geometric parameters are defined as follows: W_{pi} and H_{pi} (where $i = 0, 1, 2, 3$) represent the widths and heights of the polymer waveguide cross-sections, while w_{wi} (where $i = 1, 2, 3$) denotes the widths of the Si_3N_4 waveguide with fixed height $h_w = 500$ nm at different cross-sectional

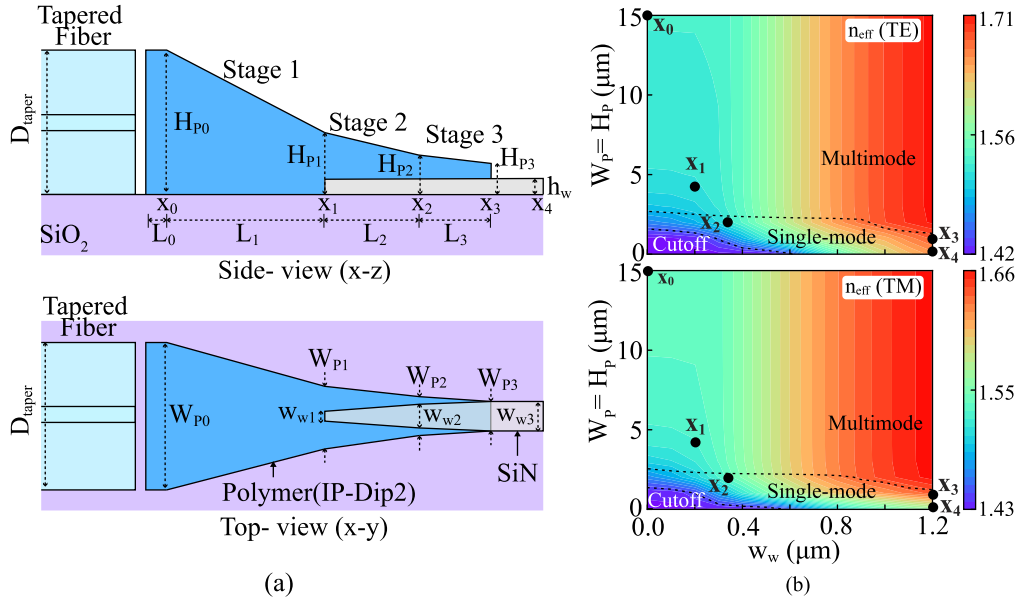


Fig. 4. (a) Design layout and dimensions of the coupler with three-stage taper. (b) 2D color map of the effective index (n_{eff}) of the fundamental mode in the combined structure as a function of polymer width $W_p (=H_p)$ and Si₃N₄ waveguide width w_w , calculated for (top) TE and (bottom) TM polarizations. Cut-off, single-mode, and multi-mode regions for TE and TM polarizations are explicitly marked. x_i ($i = 0, 1, 2, 3, 4$) represent the coordinates of the optimized cross-sections along the coupler length.

positions as indicated in the figure. To maintain design simplicity and ensure polarization-independent performance, we employed square cross-sections throughout the polymer waveguide taper profile. The design begins with a fixed tapered fiber diameter (D_{taper}) and corresponding input cross-section dimensions for the IP-Dip2 polymer waveguide ($W_{p0} = H_{p0} = D_{\text{taper}}$). Based on the analysis in Section 2, to minimize substrate leakage and ensure negligible fiber-to-polymer coupling loss, we selected a tapered fiber diameter of $D_{\text{taper}} = 15 \mu\text{m}$. For this tapered fiber diameter, we have confirmed that fiber tapering loss—i.e., insertion loss within the fiber taper itself—is below 0.5 dB (see Section 2 of Supplement 1).

Figure 4(b) shows a 2D color map of the effective index (n_{eff}) of the fundamental mode in the combined structure, calculated using an eigenmode solver and plotted over waveguide widths (w_w) from 0 to 1.2 μm and polymer widths (W_p) from 0 to 15 μm . The plot also indicates the cut-off, single-mode, and multi-mode regions for both TE and TM polarizations. For the simulations, the refractive indices used were $n_{\text{SiN}} = 1.9973$ [28] and $n_p = 1.5318$ for the polymer (IP-Dip2) at 1550 nm [20].

The optimization focused on three primary objectives: achieving a smooth transition in the effective refractive index to minimize Fresnel reflections, maximizing mode overlap for efficient power transfer, and minimizing the overall coupler length. As described earlier, the initial taper gradually reduces the mode size and effective index, matching the input of the second taper at $x = x_1$ with a polymer cross section of $W_{p1} \times H_{p1}$ and a waveguide width of w_{w1} . Ideally, the effective index at x_1 is continuous across the interface between the two tapers, yielding a mode overlap of unity. In practice, fabrication constraints limit the minimum realizable waveguide dimensions, and a feature size of 0.2 μm introduces a small effective-index discontinuity at this interface. Mode-overlap calculations were employed to optimize the taper geometry at x_1 , as shown in Fig. 5(a). To minimize the effective-index mismatch and maximize coupling between

the polymer mode and the polymer-clad waveguide, the polymer and waveguide dimensions were set to $4\ \mu\text{m}$ and $0.2\ \mu\text{m}$, respectively. A two-stage taper was employed between x_1 and x_3 , with the cross section chosen to maintain single-mode operation (see Fig. 4). For the first stage at x_2 , the polymer and waveguide dimensions were set to $W_{p2} = 2\ \mu\text{m}$ and $w_{w2} = 0.4\ \mu\text{m}$. Fabrication constraints limit the minimum realizable polymer dimension at x_3 to $1\ \mu\text{m}$, resulting in an unavoidable cross-sectional discontinuity between the polymer-clad coupler and the uncladded output waveguide. To mitigate this discontinuity, mode-overlap calculations were performed between the coupler geometry at x_3 and the uncladded output waveguide of width w_{w3} , as shown in Fig. 5(b). The calculated mode overlap approaches unity for polymer dimensions of $1\ \mu\text{m}$ or smaller. Accordingly, a polymer dimension of $W_{p2} = 1\ \mu\text{m}$ was selected, together with a final Si_3N_4 waveguide width of $w_{w3} = 1.2\ \mu\text{m}$.

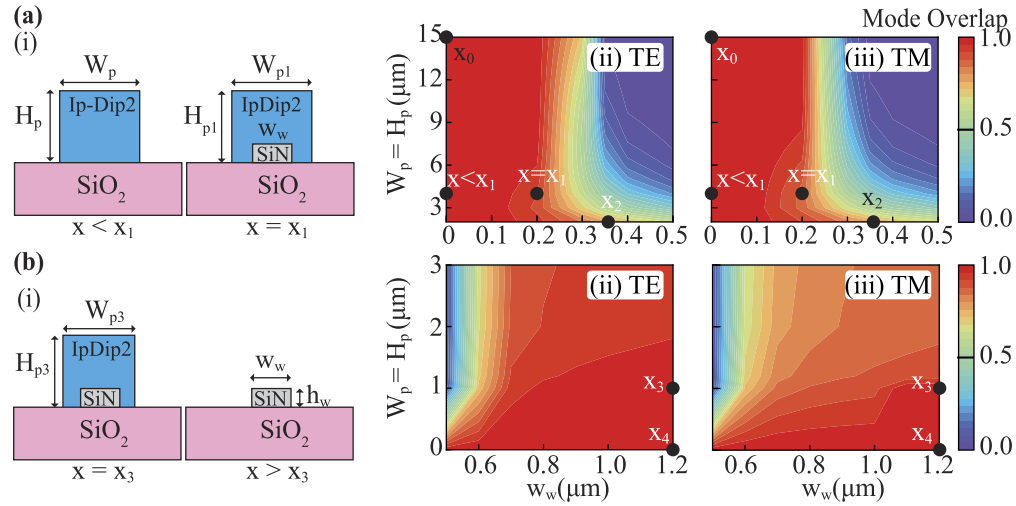


Fig. 5. Fundamental mode overlap calculation at the interfaces between (a) the first and second stages ($x = x_1$) and (b) the third stage and the output waveguide ($x = x_3$). (i) Corresponding waveguide cross-sections, (ii) and (iii) fundamental mode-overlap calculated for TE and TM polarizations, respectively.

Next, we employed eigenmode-expansion (EME) simulations to optimize the taper section lengths for both TE and TM polarizations. The terminal sections were fixed at $L_0 = 5\ \mu\text{m}$ and $L_4 = 5\ \mu\text{m}$, and the full bidirectional scattering matrix of the coupler was computed while sweeping the intermediate taper lengths L_1 , L_2 , and L_3 . For each polarization, the taper lengths were optimized to maximize the power-transfer coefficient $|S_{21}|^2$ at the output port.

The total taper length, $L_{\text{total}} = L_1 + L_2 + L_3$, was constrained to be less than $200\ \mu\text{m}$ to ensure that the coupler remains within the print-field size and enables high-resolution, stitch-free direct-write lithography. Figures 6(a) and (b) show colormaps of the calculated $|S_{21}|^2$ for TE and TM polarizations, respectively, as functions of L_2 and L_3 , where $L_1 \leq L_{\text{total}} - L_2 - L_3$. Contour lines corresponding to $L_1 = 50\ \mu\text{m}$, $100\ \mu\text{m}$, and $150\ \mu\text{m}$ are overlaid. Based on these results, taper lengths yielding transmission exceeding 85% for both polarizations were identified as $L_1 = 156\ \mu\text{m}$, $L_2 = 20\ \mu\text{m}$, and $L_3 = 8\ \mu\text{m}$.

While EME simulations were used to efficiently evaluate the mode evolution and optimize the coupler geometry, the final design was validated using finite-difference time-domain (FDTD) simulations. Figure 6(c) shows the FDTD-simulated coupling efficiency, defined as $\eta_c = 10 \log_{10}(|S_{21}|^2)$, for the finalized device. The results confirm a nearly uniform coupling response

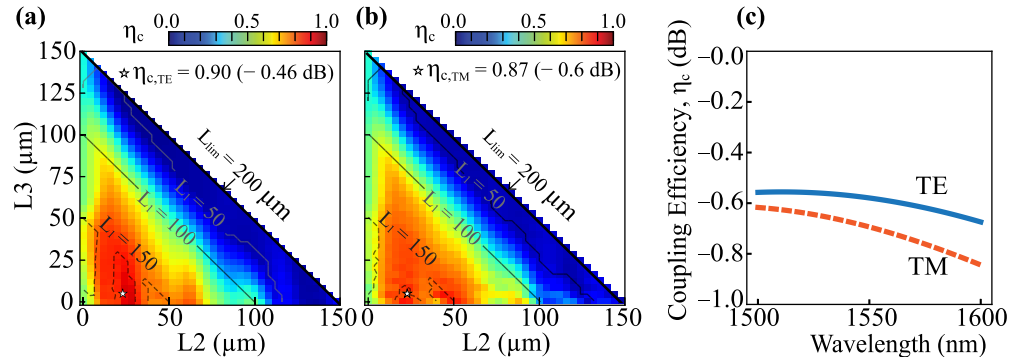


Fig. 6. Colormaps of the calculated $|S_{21}|^2$ for (a) TE and (b) TM polarizations as functions of L_2 and L_3 . The optimal value of L_1 is overlaid. The total device length $L_1 + L_2 + L_3$ is fixed at 200 μm for the simulations. (c) FDTD-simulated spectral response of the optimized three-stage coupler for TE and TM polarizations.

across the C and L bands for both TE and TM polarizations and show excellent agreement with the EME predictions.

Although the coupling efficiency can be further improved by increasing L_{total} , longer tapers—when combined with the input receptacle—would exceed the available print-field size and reduce the throughput of the high-resolution direct-write lithography system. Alternatively, the taper lengths can be shortened by subdividing it into multiple segments, or adopting a nonlinear taper profile. In the following sections, we present the simulation and experimental results of an optimized multi-stage (seven-stage) linear taper design, in which the first stage is subdivided into multiple subsections.

3.1.1. Compact multistage 3D coupler

To reduce the length and fit inside the single write field of the TPP printer, we subdivided the first stage into multiple sections while maintaining the parameters of the subsequent stages. This approach effectively reduced the polymer taper length without compromising performance. Through iterative simulations and design adjustments, we determined that a 5-stage subdivision of the first taper stage yielded a total coupler length of 120 μm with a simulated minimum transmission exceeding 80%. The calculated design parameters are summarized in Table 1.

Table 1. Calculated design parameters of the multi-stage SAFELOC shown in Fig. 7(a) on a 500 nm thick Si_3N_4 -on-3 μm SiO_2 platform.

Position along x (μm)	$x_0 = 0$	$x_{0a} = 5$	$x_{0b} = 56$	$x_{0c} = 69$	$x_{0d} = 83$	$x_1 = 108$	$x_2 = 115$	$x_3 = 120$
$W_p = H_p$ (μm)	15	12	9	8	6	4	2	1
w_w (μm)	—	—	—	—	—	0.2	0.4	1.2

The Si_3N_4 waveguide dimensions for stage 2 and stage 3 (w_{w1} , w_{w2} , and w_{w3}) remain the same as discussed in previous sections, while the lengths of each stage were determined through EME simulations. The optimized total length of the multi-stage coupler, obtained using EME simulations, is $L_{\text{total}} = 120 \mu\text{m}$. Figure 7(a) shows the FDTD-simulated field profile (x - z) along the coupler length for (i) TE and (ii) TM polarizations, and Fig. 7(b) presents the simulated spectral response of the finalized device. This design achieves nearly identical coupling efficiencies (>80%) for both polarizations near 1550 nm, while remaining within the print-field limitation of the direct laser writing system (200 μm $\times$ 200 μm).

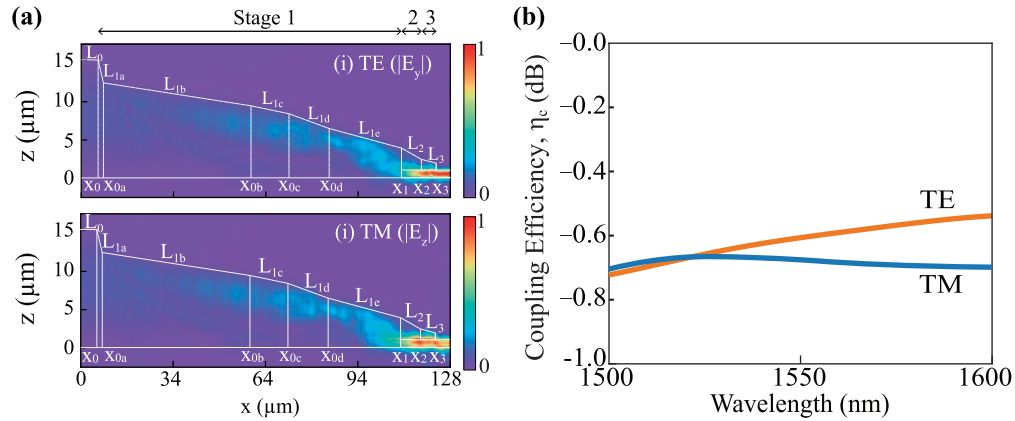


Fig. 7. FDTD simulation of the optimized seven-stage taper. (a) Electric field profile along the length of the coupler, and (b) spectral response for TE and TM polarizations.

3.1.2. Impact of material index and fabrication variation

We simulated the sensitivity of TE and TM mode transmission to index and alignment variations in the adiabatic coupler. Figure 8(a) presents the effect of refractive index change in IP-Dip2 (Δn), while (b)–(d) show the impact of coupler displacement—corresponding to lithographic misalignment of the polymer coupler relative to the waveguide—along the x (longitudinal), y (in-plane transverse), and z (out-of-plane) directions, respectively. We only consider negative values of Δz , corresponding to displacements into the substrate; positive Δz would imply a polymer waveguide detached from the substrate and is therefore not physically relevant. In practice, a small negative Δz offset is intentionally applied during fabrication to ensure that the bottom voxel layers of the printed taper overlap with the substrate surface, guaranteeing reliable adhesion. The focus-finding routine of the direct laser writing system allows the print origin to be set with sub-voxel repeatability, enabling us to target a slight negative offset of $\Delta z \approx -100$ to -200 nm—well within the range where the coupling efficiency penalty remains negligible, as confirmed by the simulations in Fig. 8(d). Each data point represents the transmission at $\lambda = 1550$ nm and the error bars show the wavelength dependence over ± 50 nm wavelength range. Overall, the results indicate that both TE and TM modes exhibit good tolerance to small index fluctuations and misalignments, with TM transmission showing slightly higher sensitivity, particularly to z -displacement and index variations. With perfect alignment, the adiabatic taper design ensures negligible polarization cross-talk (< -40 dB) throughout the coupler, consistent with the expected behavior of an adiabatic waveguide transition. Even with an in-plane misalignment of $\Delta y = -0.5$ μm, the polarization cross-talk remains lower than -30 dB.

3.1.3. Experimental results

We first fabricated Si_3N_4 waveguides comprising reference straight waveguides (3 mm long), Sagnac loop reflectors, and microring resonators (radius = 150 μm) on 500 nm-thick LPCVD Si_3N_4 deposited over 3 μm of thermally grown SiO_2 . The Sagnac loop reflectors were implemented using 1×2 multimode interference (MMI) couplers with waveguide loops of length ~ 2 mm. The device patterns were defined by electron-beam lithography and transferred using inductively coupled plasma reactive-ion etching. Subsequently, multistage SAFELOC structures were patterned on the input and output waveguides using TPP (see Supplement 1 Section 4), as illustrated in the micrograph in Fig. 9(a). A magnified view in Fig. 9(b) highlights the precise alignment of the coupler on the Si_3N_4 waveguide. An optical microscope image of the fiber-coupled SAFELOC device is presented in Fig. 9(c).

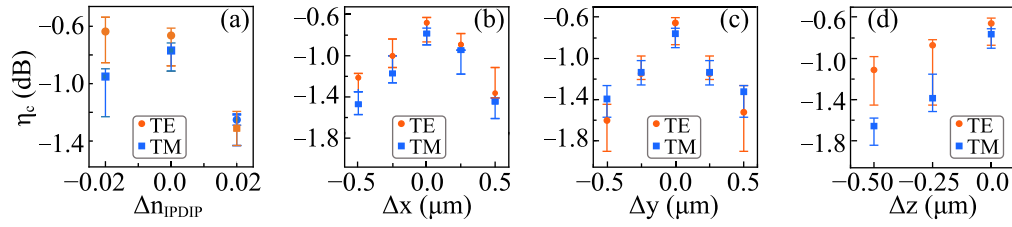


Fig. 8. Simulated tolerance of TE and TM transmission to (a) refractive-index variations in IP-Dip2 ($\Delta n_{\text{IP-Dip2}}$), and (b)–(d) spatial misalignments of the 3D coupler relative to the underlying Si_3N_4 waveguide. Misalignment sensitivities are evaluated along the (b) x -axis (longitudinal), (c) y -axis (in-plane transverse), and (d) z -axis (out-of-plane transverse). The markers and error bars denote the transmission at $\lambda = 1550$ nm and the corresponding variation over a ± 50 nm spectral window.

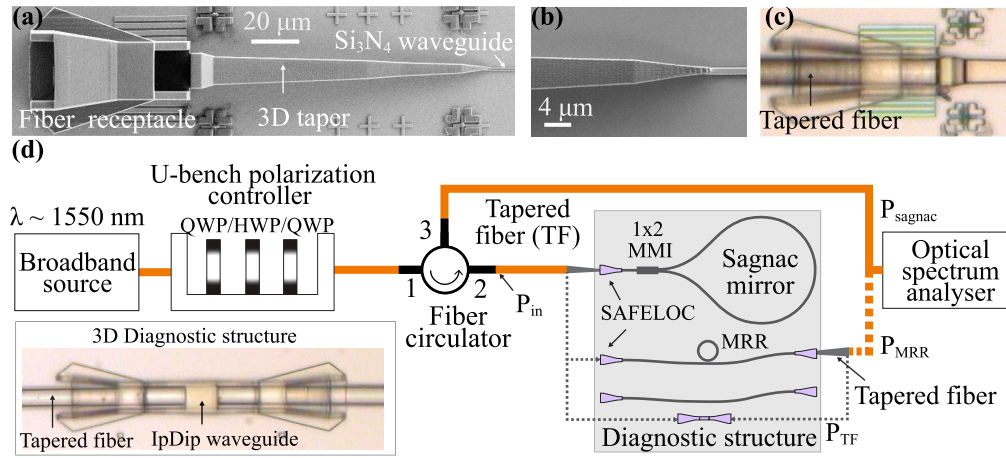


Fig. 9. Experimental demonstration multi-stage SAFELOC on Si_3N_4 platform. (a) SEM image of the SAFELOC structure. (b) Zoomed-in SEM view of the waveguide–polymer interface. (c) Optical microscope image of the tapered fiber self-aligned in the receptacle. (d) Schematic of the measurement setup. P_{in} denotes the input power launched into the tapered fiber and measured at Port 2 of the circulator, while P_{Sagnac} represents the reflected power from the Sagnac loop mirror measured at Port 3. P_{TF} corresponds to the back-to-back tapered-fiber transmission, and P_{MRR} refers to the transmitted power at the output port of the microring resonator, measured through the output tapered fiber.

Figure 9(d) illustrates the optical characterization setup. Single-ended tapered fibers with diameters of approximately $15\ \mu\text{m}$ were fabricated by HF etching (see Supplement 1). The tapered fibers were inserted into the corresponding input and output ports of the SAFELOC couplers. Although the tapered fiber is mechanically fragile, the receptacle geometry holds it in the correct position throughout insertion without requiring active feedback. The tapered receptacle walls act as a passive funnel that guides the fiber laterally and vertically to the correct transverse position at the polymer taper entrance without a hard mechanical stop — the fiber self-centers as it advances into the narrowing opening and comes to rest naturally, with no risk of damaging the fiber tip or the printed taper during insertion. Owing to this 3D-printed receptacle geometry, the configuration required no high-precision active alignment. The TPP-printed structure adheres robustly to the substrate through the bonding of IP-Dip2 to the underlying cladding surface and has shown no detachment under normal handling in our experiments. If permanent fixation is

required, a low-refractive-index UV-curable optical adhesive (e.g., NOA 1348 or equivalent) can be applied adjacent to the receptacle entrance — deliberately positioned away from the taper tip — to permanently secure the fiber without disturbing the alignment or interacting with the optically active taper region, making the assembly suitable for long-term or packaged operation.

A super-luminescent diode (SLD) centered at 1550 nm was connected to the input tapered fiber through a free-space U-bench polarization controller and a fiber-based circulator. The U-bench, comprising two quarter-waveplates (QWPs) and one half-waveplate (HWP), was configured to set the desired polarization state at the coupler input. Port 2 of the circulator was connected to the input tapered fiber, and Port 3 was connected to a C-band optical spectrum analyzer (OSA) for reflection measurements of the Sagnac loop reflectors. The transmissions of the ring resonator and reference waveguides were measured through the output tapered fiber using the same OSA.

Since the Si_3N_4 waveguides support both TE and TM polarizations, the microring resonator spectrum was used as a polarization reference, exhibiting distinct TE and TM resonances with different free spectral ranges (FSRs). The input polarization was adjusted by rotating the waveplates to selectively suppress either the TE or TM resonance, as shown in Fig. 10(a), with the magnified spectra in Fig. 10(b) near 1550 nm demonstrating that $\text{FSR}_{\text{TE}} \neq \text{FSR}_{\text{TM}}$. The total transmission loss of the microring resonator for both polarizations was measured to be in the range of 5.5–6 dB with respect to the input, P_{in} (Port 2 of the fiber circulator), including the losses from the two tapered fibers, the input/output SAFELOC couplers, and the Si_3N_4 waveguide propagation.

To quantify fiber coupling losses, 3D diagnostic structures incorporating 10 μm -long IP-Dip2 waveguides were fabricated to measure the back-to-back transmission of a pair of tapered fibers, as shown in the inset of Fig. 9(d). The insertion loss of the tapered fiber pair, $\text{IL}_{\text{TF-TF}}$, was found to be in the range of 4–4.6 dB (Fig. 10(c)), considerably higher than that of a single fiber tapered at the middle (<0.5 dB) with a similar taper diameter (see Section 2 of Supplement 1). The excess loss of the HF-tapered fibers are attributed to the concave tip profile produced by the HF-tapering process (see Section 3 of Supplement 1).

To accurately determine the coupling efficiency of a single SAFELOC coupler (η_c), we employed an integrated Sagnac loop reflector configuration incorporating a 50/50 MMI splitter and a fiber circulator, as illustrated in Fig. 9(d). The corresponding reflected power, P_{Sagnac} , for TE and TM polarizations are shown in Fig. 10(c). Considering an independently measured propagation loss (α_{wg}) of approximately 1 dB/cm in the straight waveguide, and assuming negligible MMI loss (thus slightly overestimating the coupler loss), the coupling efficiency of a single SAFELOC coupler was estimated to be $\eta_c = -(0.9 \pm 0.15)$ dB across the C-band for both polarizations, after accounting for the tapered fiber loss ($\text{IL}_{\text{TF-TF}} = 4.2$ dB) and the circulator insertion loss ($\text{IL}_{\text{circ}} = 0.85$ dB near 1550 nm). Three identical devices were characterized across the C-band to assess reproducibility and wavelength dependence. The wavelength-dependent coupling efficiency of the SAFELOC coupler is extracted as the median of three devices (D1, D2 and D3) for both polarizations, is shown in Fig. 10(d). The coupler exhibits a 1-dB bandwidth exceeding the entire C-band (1530–1565 nm). Detailed broadband characterization over an extended wavelength range (1520–1630) nm is provided in the Supplement 1 (Section 6).

3.2. Silicon-on-insulator (SOI) platform

A similar multistage design strategy was employed to design a SAFELOC for the 220 nm SOI platform with 2 μm SiO_2 bottom cladding. The design was optimized for TE polarization using silicon waveguides with a height of 220 nm and width of 550 nm. The initial tapering stage dimensions, where no overlapping waveguides are present, were maintained as in the Si_3N_4 design (see Table 1), while the final stage dimensions were optimized using EME and finite-difference time-domain FDTD simulations. The design parameters are summarized in Table 2.

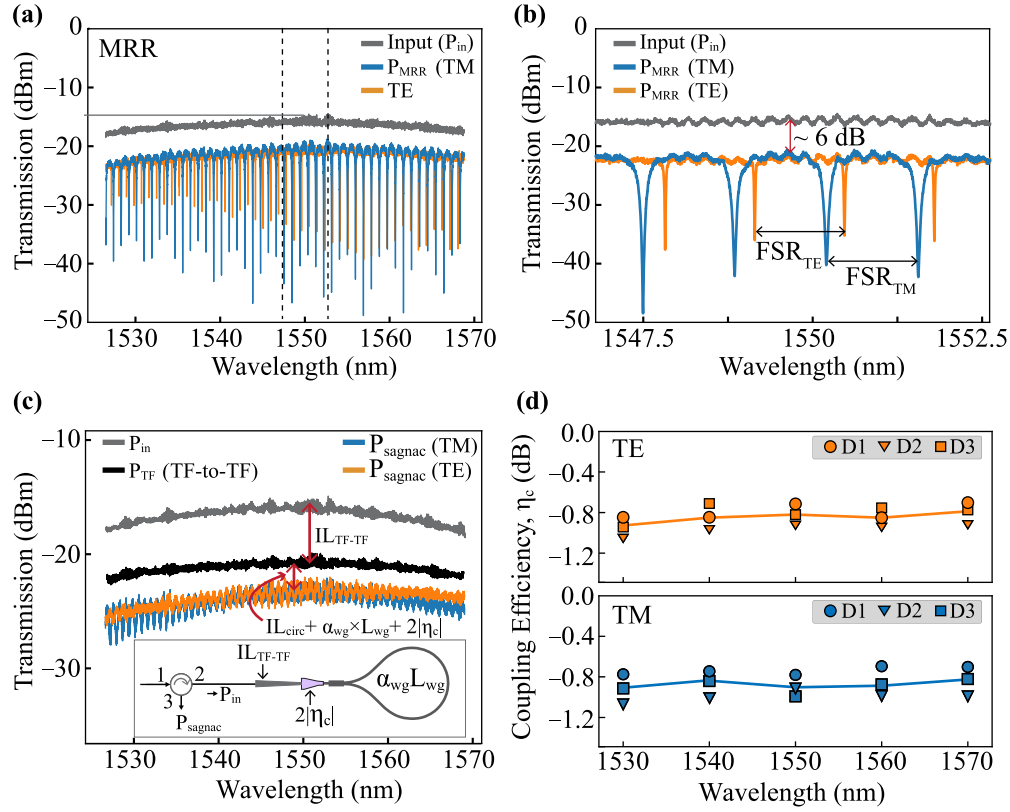


Fig. 10. (a) The input (P_{in}) and output transmission spectra of the microring resonator (MRR) for TE and TM polarizations, showing polarization-independent coupling efficiencies of the SAFELOCs. (b) Magnified view near 1550 nm highlighting the difference between the free spectral ranges ($FSR_{TE} \neq FSR_{TM}$). (c) Input (P_{in}) and reflection spectra (P_{Sagnac}) of the Sagnac loop mirror measured at Port 2 and Port 3 of the fiber circulator. The back-to-back tapered-fiber transmission (P_{TF}) obtained from the 3D diagnostic structure is also included for reference. (d) Coupling efficiency, η_c extracted from three nominally identical devices (D1, D2 and D3). Individual measurements with median value indicated by the line.

Table 2. Calculated design parameters of the multi-stage SAFELOC shown in Fig. 11(a) on a 220 nm thick Si-on-3 μm SiO₂ platform.

Position along x (μm)	$x_0 = 0$	$x_{0a} = 5$	$x_{0b} = 56$	$x_{0c} = 69$	$x_{0d} = 83$	$x_1 = 108$	$x_2 = 134$	$x_3 = 144$
$W_p = H_p$ (μm)	15	12	9	8	6	4	2	1
w_w (μm)	—	—	—	—	—	0.1	0.35	0.55

For the optimized coupler, the final two stages consist of silicon tapers with dimensions $L_6 = 26 \mu\text{m}$ (waveguide width tapering from $0.1 \mu\text{m}$ to $0.35 \mu\text{m}$) and $L_7 = 10 \mu\text{m}$ (width tapering from $0.35 \mu\text{m}$ to $0.55 \mu\text{m}$). FDTD simulations predict a transmission greater than -1 dB , as shown in Fig. 11(d).

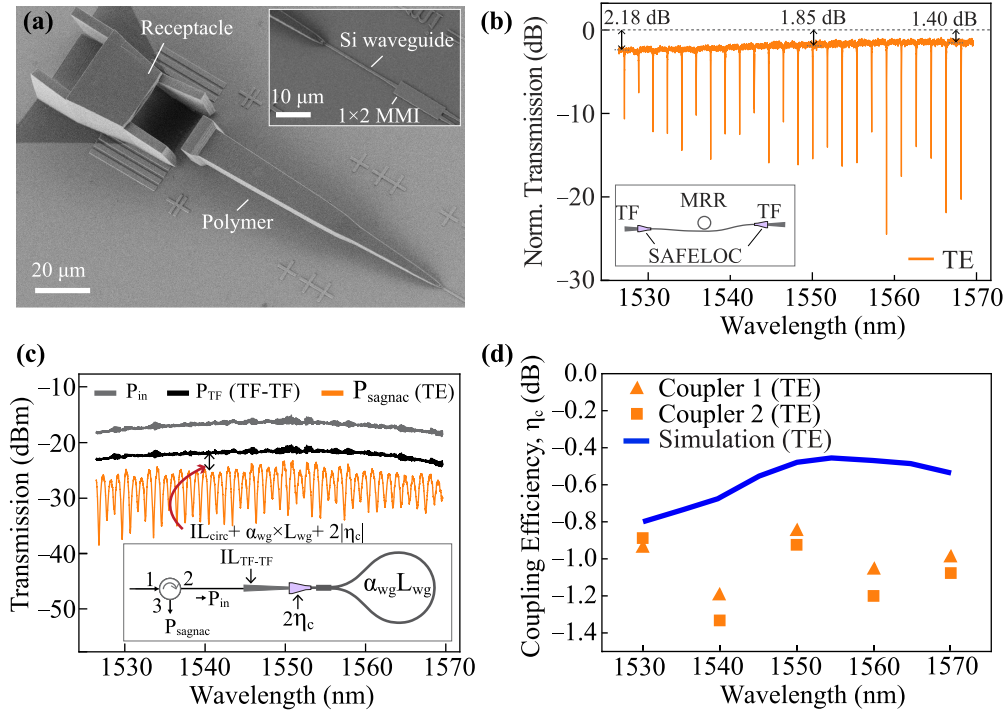


Fig. 11. Multi-stage SAFELOC on SOI platform. (a) SEM image with zoomed-in view of waveguide-polymer interface in the inset. (b) Transmission spectrum of the microring resonator for TE polarization normalized with the back-to-back tapered fiber transmission. (c) Input and reflection spectra of the Sagnac loop mirror measured at Port 2 (P_{in}) and Port 3 (P_{sagnac}) of the fiber circulator. The back-to-back tapered-fiber transmission (P_{TF}) obtained from the 3D diagnostic structure is also included for reference. (d) SAFELOC coupling efficiency (η_c) extracted from two nominally identical devices.

Figure 11(a) shows an SEM image of the fabricated coupler printed using IP-Dip2 resist on the SOI platform. The measured transmission spectrum at the output of a $50 \mu\text{m}$ -radius microring resonator is presented in Fig. 11(b), normalized to the back-to-back tapered fiber transmission. The results indicate a coupling efficiency exceeding -1.2 dB (76%) per coupler across the C-band.

To obtain a more accurate estimate of the SAFELOC coupling efficiency, we also characterized Sagnac loop mirrors incorporating 1×2 MMIs, following the same procedure as described previously. Figure 11(c) shows the measured input and reflected spectra of the mirror, collected at ports 2 and 3 of the fiber circulator, as illustrated in the inset. The back-to-back tapered fiber transmission, measured using 3D diagnostic structures, is also plotted for reference, exhibiting an insertion loss of approximately 4.2 dB relative to the input. As discussed before, this excess loss is attributed to the concave tip profile of the HF-tapered fiber (see Section 3 of Supplement 1). The SAFELOC efficiency was extracted relative to the tapered fiber transmission (P_{TF}).

Figure 11(d) summarizes the average SAFELOC coupling efficiency obtained from two identical devices. FDTD-simulated transmission spectra of the coupler are also included for

comparison. In both the microring resonator and Sagnac loop mirror measurements, the estimated coupling efficiency is approximately $-(1.0 \pm 0.2 \text{ dB})$ (75 – 83%) across the C-band.

3.3. SU-8 on oxide platform

Polymer-integrated photonic waveguides have attracted increasing interest due to their cost-effectiveness, fabrication flexibility, and ease of integration with other photonic components. Among polymer materials, SU-8 is particularly attractive for photonic applications because of its excellent mechanical stability and low optical loss [29–32]. SU-8 is a negative-tone electron-beam resist that can be patterned directly by exposure and development, without the need for dry etching or additional masking steps. In this section, we present the design, fabrication, and experimental performance of a SAFELOC implemented on SU-8 waveguides.

The SU-8 waveguide height was fixed at $2.2 \mu\text{m}$, with a $3 \mu\text{m}$ -thick SiO_2 lower cladding. The refractive index of SU-8 was assumed to be $n_{\text{SU-8}} = 1.571$ at 1550 nm and 300 K [33]. Device simulations followed the same methodology described in Section 3.1, EME and FDTD techniques, and a three-stage SAFELOC was optimized for TE polarization [34]. The optimized geometrical parameters are summarized in Table 3, with the total device length constrained to $200 \mu\text{m}$. The corresponding FDTD-simulated transmission spectrum is shown in Fig. 12(d).

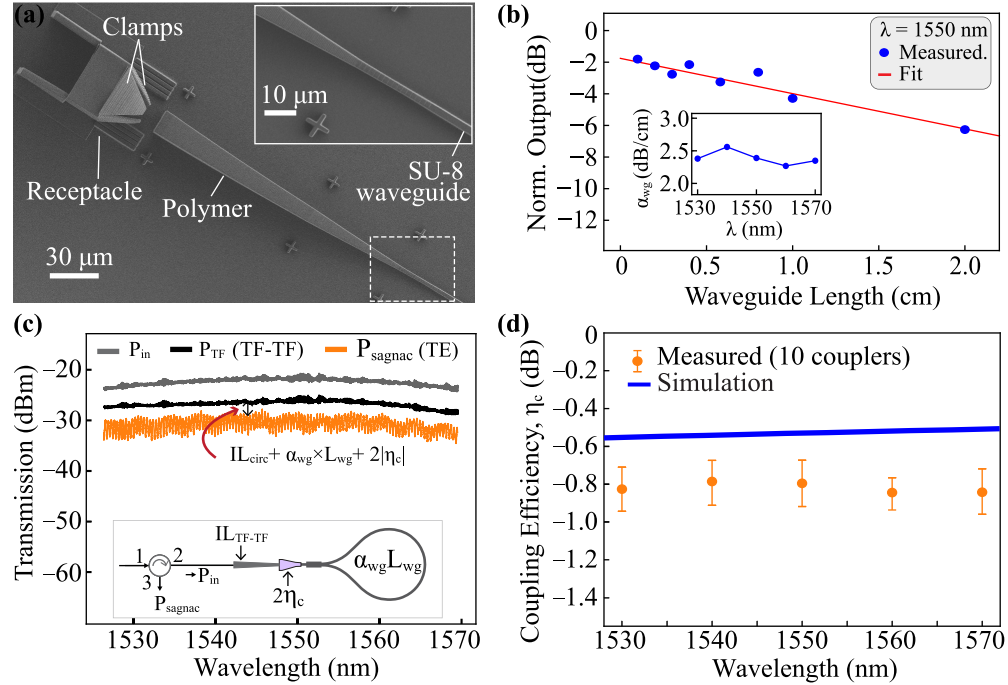


Fig. 12. Three stage SAFELOC printed on SU-8 waveguide on oxide platform (a) SEM image, (b) Normalized transmission measured loss for different length waveguides. Inset shows the wavelength dependent propagation loss. (c) Input and reflection spectra of the Sagnac loop mirror measured at Port 2 (P_{in}) and Port 3 (P_{sagnac}) of the fiber circulator. The back-to-back tapered-fiber transmission (P_{TF}) obtained from the 3D diagnostic structure is also included for reference. (d) SAFELOC coupling efficiency (η_c) extracted from ten nominally identical devices. The error bars indicate the standard deviation from the mean.

For fabrication, SU-8 2002 was spin-coated to a thickness of $2.2 \mu\text{m}$ on a $3 \mu\text{m}$ -thick thermally grown SiO_2 layer. Reference straight waveguides and Sagnac loop reflectors were patterned using electron-beam lithography followed by solvent development. The cross-linked polymer

Table 3. Calculated design parameters of the three-stage SAFELOC shown in Fig. 12(a) on a 2.2- μm -thick SU-8-on-3- μm SiO₂ platform.

Position along x (μm)	$x_0 = 0$	$x_1 = 108.5$	$x_2 = 172.5$	$x_3 = 200$
W_p, H_p (μm)	15, 15	9, 9	3, 3	2, 2.2
w_w (μm)	—	—	0.75	2

was subsequently hard-baked for final curing. Input and output SAFELOC structures were fabricated using two-photon polymerization. The hardened SU-8 waveguides are compatible with subsequent processing of the IP-Dip2 photoresin: the IP-Dip host solvent does not dissolve or degrade the cross-linked SU-8, and the two-photon exposure does not measurably alter the SU-8 structures.

Figure 12(a) shows an SEM image of the fabricated SAFELOC structure integrated with an SU-8 waveguide. In contrast to the previous design, this receptacle employs self-centering clamps that keep the fiber centered despite minor diameter variations. Propagation loss extracted from cutback measurements of waveguides with different lengths is shown in Fig. 12(b), yielding an estimated loss of ~ 2.25 dB/cm at 1550 nm. The SAFELOC coupling efficiency was extracted using 1 $\times$ 2 MMI-based Sagnac loop reflectors, following the procedure described in the previous sections. Figure 12(c) shows the measured input and reflected spectra of the mirror, collected at ports 2 and 3 of a fiber circulator, as illustrated in the inset. The coupling efficiency was estimated relative to the tapered fiber-to-fiber transmission (see Section 3 of the Supplement 1).

Figure 12(d) summarizes the average SAFELOC coupling efficiency extracted from ten nominally identical devices. For comparison, the FDTD-simulated transmission spectrum of the coupler is also included. The experimentally estimated coupling efficiency is approximately -0.85 ± 0.15 dB (79–85 %) across the C-band.

4. Simultaneous fiber-array-to-chip coupling

The locally self-aligned nature of SAFELOCs provides a key advantage for simultaneously coupling multiple fibers in an array without being limited by imprecision in the array itself. To evaluate this capability, we measured the performance of SAFELOCs using simultaneous fiber-array-to-chip coupling. The demonstration was carried out on the SU-8-on-oxide SAFELOC platform (see Section 3.2), where eight fibers were coupled to the chip in parallel.

Eight tapered fibers ($D_{\text{taper}} \sim 15$ μm) were mounted into a standard V-groove array with 250 μm pitch. The fibers extending from the V-groove array were adjusted to the same length to enable simultaneous coupling with the SAFELOC structures. A photograph of the fiber-array-to-chip coupling setup is shown in Fig. 13(a). Figure 13(b) shows an optical microscope image of eight tapered fibers simultaneously coupled to the eight different SAFELOCs, with each waveguide interfaced to a Sagnac loop reflector.

Figure 13(c) compares the coupling efficiency (η_c) of the SAFELOCs measured at $\lambda = 1550$ nm under simultaneous fiber-array coupling with measurements obtained using individual single-fiber coupling. The increased loss observed for the fifth SAFELOC is due to damage to the corresponding fiber tip during handling. The negligible difference in coupling efficiency compared to individual single-fiber coupling indicates that SAFELOCs maintain high performance under simultaneous multi-fiber operation.

5. Conclusion

We designed 3D tapered polymer waveguides to adapt the mode of an optical fiber taper to that of an on-chip waveguide in a variety of materials while maintaining low ($\lesssim 1$ dB) insertion loss

across at least the C-band. We have fabricated these polymer tapers using two-photon lithography on Si_3N_4 , Si, and SU-8 and included three-dimensional fiber receptacles to mechanically align the fiber taper to the input of the tapered polymer waveguide. In all of these cases, we measured low insertion loss comparable to the simulated values while also demonstrating a bandwidth exceeding the C-band.

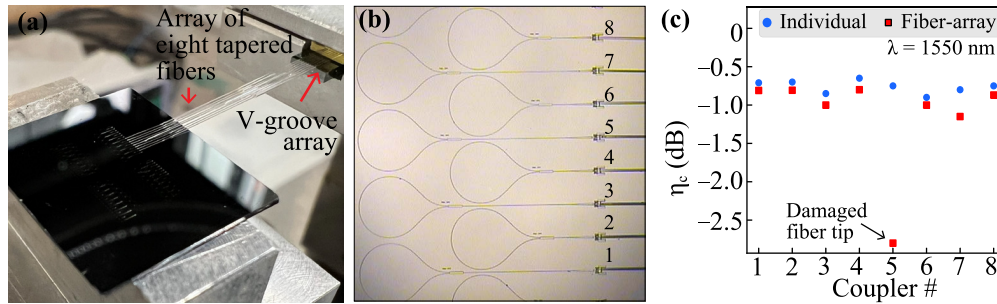


Fig. 13. Fiber-array-to-chip coupling. (a) Photograph of the fiber-array-to-chip coupling setup, where eight tapered fibers are arranged in a V-groove array and coupled to the SAFELOCs on the chip (SU-8/ SiO_2). (b) Optical microscope image showing simultaneous coupling of the eight fibers to the SAFELOCs. (c) Coupling efficiency of the SAFELOCs measured (at $\lambda = 1550$ nm) under simultaneous fiber-array coupling, compared with individual single-fiber coupling measurements. The increased loss observed for the fifth fiber is attributed to the damage at the fiber tip during handling.

Because these self-aligned fiber entry low-loss optical coupler (SAFELOC) structures exhibit low insertion loss over a broad wavelength range without the need for precision stages or active feedback, we see them as a promising alternative to traditional coupling strategies, such as grating couplers and edge couplers, especially in environments, such as cryostats [33], where alignment can be more challenging. In addition, the on-chip receptacle that mechanically aligns the fibers provides a straightforward path to permanently affix fibers without having to compensate for adhesive shrinkage [35]. The tapered nature of the receptacle further expands the positional tolerance during alignment, enabling the simultaneous coupling of multiple fibers and facilitating scalable, multi-port photonic integrated circuits.

While we demonstrated SAFELOCs on three different material platforms, the two-photon lithography fabrication process could additively manufacture these structures on an even wider range of material stacks. Although the SAFELOCs demonstrated here targeted the telecom C-band, the wide transparency window of the polymer material suggests that similar structures could be compatible with wavelengths as short as 400 nm [36].

These versatile SAFELOCs offer mechanically robust and efficient coupling across a broad range of wavelengths and photonic material platforms, while also supporting simultaneous multi-fiber coupling. Their long-term stability makes them well suited for applications ranging from quantum photonics to bio-sensing and microwave photonics.

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Data availability. All data needed to evaluate the conclusions in the paper are presented in the paper and/or the Supplemental document.

Supplemental document. See Supplement 1 for supporting content.

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