

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

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SAFELOC: Self-Aligned Fiber Entry Low-loss Optical Coupler

1. CHARACTERIZATION OF IP-DIP2 REFRACTIVE INDEX THROUGH EXPERIMENT

The refractive index of IP-Dip2 photoresin has been reported in several studies across the visible to mid-IR range [1, 2]. However, the refractive index of two-photon polymerized (TPP) IP-Dip2, which exhibits similar properties to IP-Dip2 photoresin, has not been comprehensively characterized near 1550 nm [3, 4]. In this work, we use $n_{\text{IP-Dip2}} = 1.5318$ at 1550 nm, extrapolated from manufacturer-provided data in the 400–900 nm range [5]. We also experimentally determine the refractive index near 1550 nm using a Mach-Zehnder interferometer (MZI). This involves comparing the spectral response of MZIs with and without IP-Dip2 cladding on a fraction of the longer arm. Multiple devices with different arm length differences (ΔL) were fabricated (MZI1–MZI4), where a portion of the longer arm was clad with IP-Dip2 and polymerized via two-photon polymerization, with a fractional coverage $dL/\Delta L$, as illustrated in Fig. S1(a).

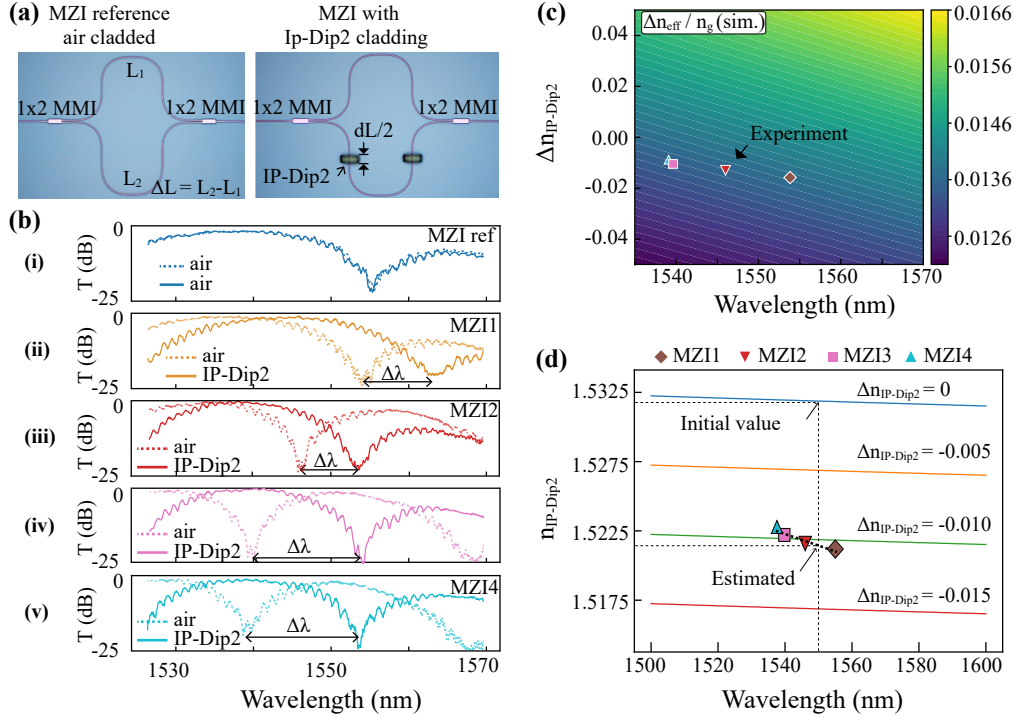


Fig. S1. (a) Optical microscope images of a reference MZI with air cladding and an MZI in which a fraction (dL) of the longer arm is clad with IP-Dip2. (b) Measured spectral shifts for different device configurations: (i) reference MZI without cladding, (ii) MZI1 with $dL/\Delta L = 7/15$, (iii) MZI2 with $dL/\Delta L = 7/20$, and (iv) MZI3 and MZI4 with $dL/\Delta L = 14/20$. (c) Simulated $\Delta n_g/n_g$ as a function of small changes in the IP-Dip2 refractive index near 1550 nm, along with experimentally obtained $\Delta n_g/n_g$ values. (d) Experimentally estimated $n_{\text{IP-Dip2}}$ values and corresponding simulated values for $-0.015 < \Delta n_{\text{IP-Dip2}} < 0$.

The length ΔL is chosen such that the maximum spectral shift ($\Delta\lambda$) due to IP-Dip2 cladding over ΔL (i.e., $dL/\Delta L = 1$) is less than one free spectral range (FSR), for the given initial assumption of $n_{\text{IP-Dip2}}$. The spectral shift upon cladding deposition follows the relationship

$$\frac{\Delta\lambda}{\lambda_0} \approx \frac{\Delta n_{\text{eff}} \cdot dL}{n_g \cdot \Delta L}, \quad (\text{S1})$$

which can be rearranged as

$$\frac{\Delta\lambda \cdot \Delta L}{\lambda_0 \cdot dL} = \frac{\Delta n_{\text{eff}}}{n_g}, \quad (\text{S2})$$

where the left-hand side is experimentally measured and compared with simulated values on the right-hand side. Figures S1(b)(ii)–(v) show measured spectral shifts for different device configurations: (c) $dL/\Delta L = 7/15$, (d) $dL/\Delta L = 7/20$, (e) and (f) $dL/\Delta L = 14/20$. A reference MZI without IP-Dip2 cladding on the arm is used to measure and compensate for spectral shifts due to ambient changes, as shown in Fig. S1(b)(i). For simulation, the cladding index was swept around an initial assumption of $n_{\text{IP-Dip2}} = 1.5318$ at $\lambda_0 = 1550$ nm. The color contour plot in Fig. S1(c) shows $\Delta n_{\text{eff}}/n_g$ as a function of small changes in the cladding index ($\Delta n_{\text{IP-Dip2}}$), calculated near 1550 nm, with experimental data points overlaid for comparison. Fig. S1(d) shows the experimentally extracted $n_{\text{IP-Dip2}}$ values and corresponding simulated values for $-0.015 < \Delta n_{\text{IP-Dip2}} < 0$. The results indicate that the refractive index of IP-Dip2 is approximately

$$n_{\text{IP-Dip2}} \approx 1.5225 \pm 0.0025 \quad (\text{S3})$$

at 1550 nm, compared to the initial assumption of 1.5318, with measured values converging consistently across different MZI devices.

2. METHOD FOR TAPERING FIBERS WITH HYDROFLUORIC ACID ETCHING

The single-ended fiber tapers used in this work were fabricated using two distinct approaches: thermal stretching and hydrofluoric acid (HF) etching. In the thermal stretching method, a micro-heater-based fiber pulling system [6] was used to taper a standard SMF-28 fiber down to a diameter of 15 μm . The fiber was then cleaved at the taper waist to produce two single-ended fiber tapers. Thermal tapering typically yields long, gradually tapered fibers with an extended evanescent field in the cladding region as the diameter decreases, which can lead to substrate leakage when placed in close proximity to the chip surface.

Here, we describe our HF tapering method, which differs from previous work [7] in that we aim to reduce the outer diameter of the tip of the fiber to a specific, relatively large value ($\approx 15 \mu\text{m}$) while also maintaining a smooth output facet. A composite image of a full taper is shown in Fig. S2(a).

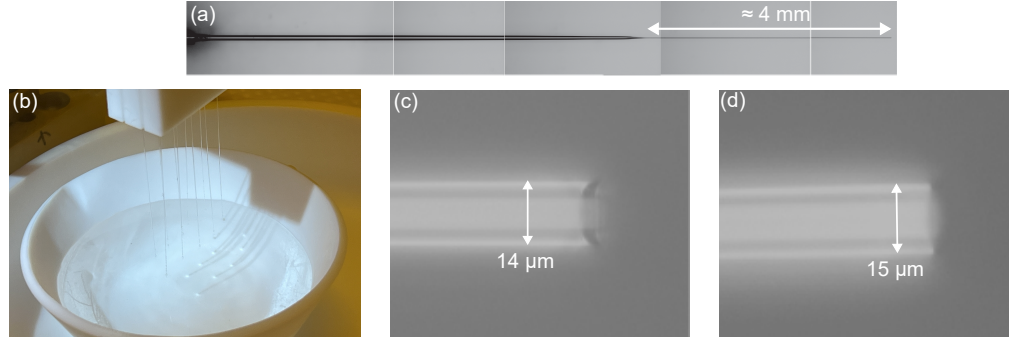


Fig. S2. Fig. 2. (a) A composite of optical microscope images showing an HF-etched fiber taper with final measured tip diameter of 14 μm . (b) Ten optical fibers mounted vertically with the cleaved tips inserted into a beaker of 49 % HF. The bright spots on the bottom of the beaker show that the fibers have penetrated the surface of the HF, forming menisci. (c) Optical microscope image of the side of a fiber taper, etched in 49 % HF. The tip facet is concave, with a depression around 5 μm at the center. (d) Optical microscope image of the side of a fiber taper, etched in 1.35:1 $\text{NH}_4\text{F}:\text{HF}$. The tip facet is very slightly convex, with a protrusion around 1 μm at the center..

We first strip the coating from the end of an SMF-28 optical fiber and cleave it. It is important that this is a high quality cleave because it will affect the quality of the final etched facet. Then, under a fume hood, we mount the fiber vertically on a mechanical stage. We slowly lower the fiber into a small polytetrafluoroethylene (PTFE) beaker of 49 % HF. In order to determine precisely when the fiber contacts the surface of the HF, we shine a flashlight on the surface. The

meniscus that is formed when the fiber touches the surface focuses the light onto the bottom of the beaker as an easily-visible bright spot (Fig. S2(b)). Once the fiber is in contact with the surface, we lower it an additional 3 mm. Measuring this value ensures consistency in the etch rate. With this technique, we measure the etch rate of the cladding to be $\approx 1.5 \mu\text{m}/\text{min}$.

Optical microscope images show that the etch rate of the core is somewhat faster than the cladding (see Fig. S2(c)), thus forming a concavity of around $5 \mu\text{m}$ at the tip. Measurements (see next section) show that the facet concavity introduces a coupling loss at the fiber-polymer interface, which can be modified by adjusting the HF concentration through dilution with NH_4F and water [8]. The measurements presented in this work were taken using tapered fibers etched with 49 % HF, but we have since etched fibers using 1.35:1 $\text{NH}_4\text{F}:\text{HF}$, which have nearly flat facets (Fig. 2(d)) and significantly improved optical transmission, as detailed in the next section.

This simple HF tapering technique can be used to taper several fibers simultaneously and consistently, making it more easily scalable than typical thermal tapering. Fig. S3(a) shows a photograph of several single-ended tapered fibers and a fiber loop tapered at its midpoint. The tapering loss, measured during the etching process, is below 0.5 dB for the target diameter of $15 \mu\text{m}$.

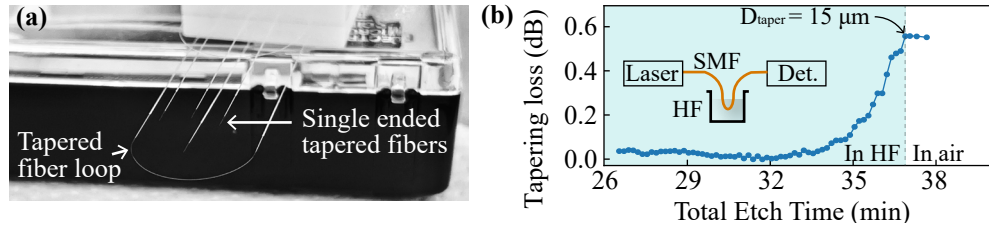


Fig. S3. a) Photograph showing multiple single-ended tapered fibers and a loop fiber tapered at the midpoint. (b) Measured tapering loss as a function of etching time during the HF process.

3. TAPERED FIBER-TO-FIBER TRANSMISSION

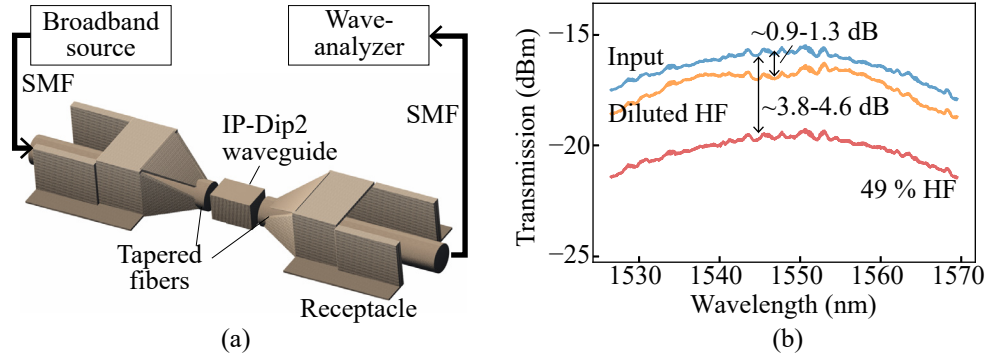


Fig. S4. (a) Schematic of the tapered-fiber-to-fiber (TF-TF) loss measurement setup. (b) Measured transmission spectra ($\sim 1550 \text{ nm}$) for the reference (SMF-SMF), 49% HF-etched, and diluted HF (1.35:1 $\text{NH}_4\text{F}:\text{HF}$) -etched tapered fibers.

Figure S4(a) shows the tapered fiber-to-fiber (TF-TF) transmission measurement setup, where self-centering clamps (see section S5 for details) secure the input/output fibers in the receptacle. The insertion loss measured through a $20 \mu\text{m}$ long IP-Dip2 waveguide for diluted-HF (1.35:1 $\text{NH}_4\text{F}:\text{HF}$) etched tapered fibers is $0.45\text{--}0.65 \text{ dB}$ per facet relative to the input SMF-SMF transmission (Fig. S4(b)). This represents a significant improvement over the $1.9\text{--}2.3 \text{ dB}$ per facet loss observed for 49% HF-etched tapered fibers.

4. TWO-PHOTON POLYMERIZATION FABRICATION PARAMETERS

The SAFELOC structures were fabricated using a Nanoscribe Photonic Professional GT2 direct laser writing system. The system operates at a center wavelength of 780 nm using a mode-locked femtosecond laser with a pulse duration of ~ 100 fs and a repetition rate of ~ 80 MHz. Printing was performed in dip-in lithography (DiLL) mode using IP-Dip2 photoresin with a high numerical aperture ($NA = 1.4$) 63 $\times$ objective, enabling submicron voxel resolution and smooth sidewall definition.

The laser power and scan parameters were set independently for the taper and receptacle sections to balance resolution and structural integrity. For the polymer taper, a laser power of 11 mW and a scan speed of 9,000 $\mu\text{m/s}$ were used, with slicing and hatching distances of 0.05 μm to achieve fine feature resolution. For the receptacle, a laser power of 15 mW was used with slicing/hatching distances of 0.2 μm , which is sufficient for the larger structural features while reducing print time. The taper and receptacle sections are printed as two independent structures, to avoid stitching artifacts that would otherwise arise if the combined structure were to exceed the write-field boundary (200 $\mu\text{m} \times 200 \mu\text{m}$). The total write time for a single SAFELOC structure (taper + receptacle) is approximately 15 minutes under these settings.

Following exposure, uncured resist was removed by immersion in PGMEA (propylene glycol monomethyl ether acetate) for 20 minutes, followed by a 5-minute rinse in isopropanol (IPA). No additional UV flood exposure or thermal post-cure was required, as the two-photon cross-linking process sufficiently hardens the IP-Dip2 structures for subsequent optical and mechanical use.

5. SELF-CENTERING CLAMP RECEPTACLE DESIGN

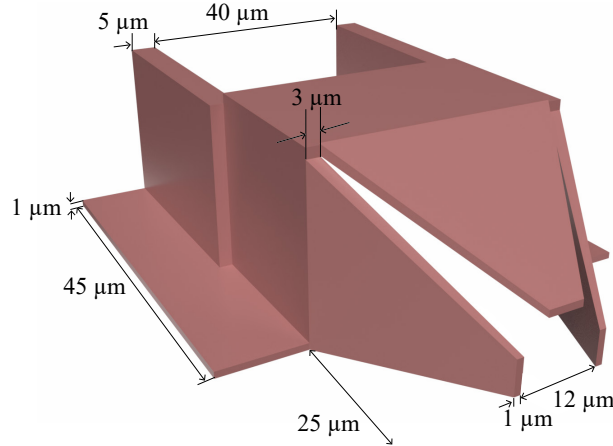


Fig. S5. 3D CAD illustration of the self-centering clamp receptacle. Pairs of flexible IP-Dip2 polymer arms are arranged symmetrically about the fiber axis at the receptacle entrance. Upon fiber insertion, the arms deflect elastically and exert a restoring force that centers the fiber, accommodating diameter variations of ± 3 μm from the nominal 15 μm target.

The self-centering clamps shown in Fig. S5 consist of pairs of flexible IP-Dip2 polymer arms arranged symmetrically about the fiber axis at the receptacle entrance. As the fiber is inserted, the arms deflect elastically and exert a restoring force that centers the fiber regardless of small diameter variations ($\sim \pm 3$ μm from the nominal 15 μm target). The clamp geometry — including arm length, width, and spacing — can be readily customized in the CAD model to suit different fiber diameters or contact force requirements, and the TPP process faithfully reproduces these features without additional process steps. The design presented here was chosen to provide sufficient restoring force to maintain lateral and vertical alignment while remaining compliant enough to avoid mechanical damage to the tapered tip.

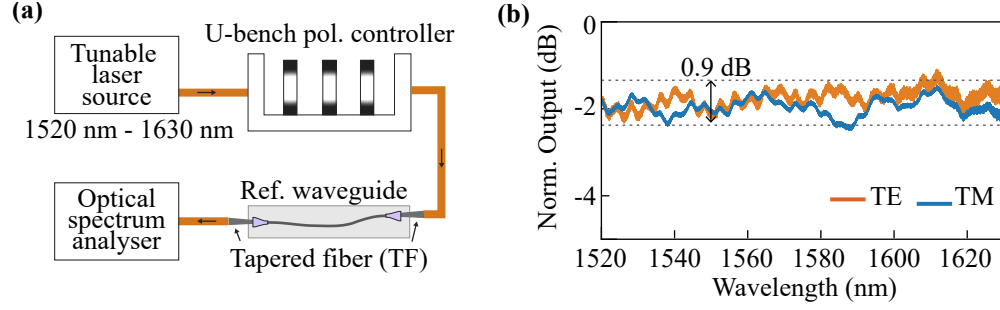


Fig. S6. (a) Experimental setup for broadband optical characterization and (b) transmission spectrum of a 3 mm-long reference waveguide across 1520-1630 nm wavelength range.

6. BROADBAND SAFELOC CHARACTERIZATION

Broadband performance of the SAFELOC coupler (on $\text{Si}_3\text{N}_4/\text{SiO}_2$) was characterized using an independent measurement setup. A tunable laser source (TLS) together with an optical spectrum analyzer (OSA) was used to measure the wavelength response over the extended range of 1520 nm - 1630 nm as shown in Fig. S6.

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