Mode-field Matching Down-Tapers on Single-Mode Optical Fibers for Edge Coupling Towards Generic Photonic Integrated Circuit Platforms

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***Abstract*—Connections between standard single-mode fibers and waveguides in photonic integrated circuits tend to have relatively high coupling losses due to a difference in mode size and mode profile between both light guiding media. Edge coupling strategies involving specialty fibers are frequently used to obtain the best performance in terms of coupling efficiency, bandwidth and polarization independence. We propose the fabrication of free-standing down-taper structures on top of cleaved fiber facets by two-photon direct laser writing and show their performance for silicon, silicon nitride and indium phosphide generic chip platforms. We present a comprehensive analysis of the design of such taper structures that show unprecedented flexibility. We demonstrate their fabrication and fully characterize them in terms of output modal fields and coupling efficiencies. Furthermore, we experimentally compare the fabricated down-tapers with commercially available lensed fibers and demonstrate equal or better coupling efficiency for four out of the five investigated photonic integrated circuit platforms, with a measured improvement in coupling efficiency up to 1.43 dB.**

***Index Terms*—3D direct laser writing, fiber-to-chip coupling, fiber taper, generic platforms, mode-matching, optical interconnects, photonic integrated circuits, two-photon polymerization.**

I. Introduction

The integration of many different optical components and functionalities into a compact device or chip has been actively investigated for many years. Research into these so-called Photonic Integrated Circuits (PIC) has led to three main material platforms, being silicon (Si), silicon nitride (SiN) and indium phosphide (InP). All of these platforms have intrinsic merits and challenges, and have their usefulness for specific components and applications [1]. The Si-platform can make use of high-yield optimized processing techniques compatible with the complementary metal-oxide-semiconductor (CMOS) manufacturing industry for the fabrication of high-volume and small-footprint chips with tight light confinement within the waveguides [2], [3], whereas SiN is showing better performance for passive components in terms of propagation loss and transparency at visible wavelengths, at the expense of a larger footprint [4], [5]. Finally, the InP-platform allows monolithic integration of active components and hence is the platform-of-choice for optical amplifiers and lasers [6], [7].

Whereas the many developments in chip-level components bring various fascinating opportunities and applications, one of the limiting factors in the widespread adoption of PICs is their packaging, and in particular their connection to the outside world [8]–[10]. As the optical modes in integrated waveguides tend to be an order of magnitude smaller than those in standard single-mode fibers (SMF), creating a highly efficient, robust and alignment-tolerant fiber-to-chip interface remains a challenge and therefore a much-investigated research topic.

The two main coupling strategies being investigated are grating couplers [11] and edge couplers [12]–[19]. The latter approach (also called in-plane coupling) generally offers the best optical performance in terms of coupling efficiency, spectral transmission bandwidth and polarization independency [20], [21]. This approach often relies on an intermediate coupling scheme that transforms and matches the modal field of the waveguide to that of the SMF. This can be achieved with a combination of on-chip taper features and specialty fibers.

As many different types of on-chip coupling schemes are still being actively explored for the various material platforms, our design strategy is to optimize the fiber's side of the fiber-to-chip connection and tailor the design of the fiber taper to the on-chip waveguide schemes being employed by generic PIC foundries and research centers.

The most frequently used types of specialty fibers for fiber-to-chip coupling are lensed fibers [22]. These end-shaped fibertips (usually conical) can be micro-polished or laser-ablated out of

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standard optical fibers to produce a focal spot down to about $> 1.6\ \mu$m ($1/e^2$ intensity at 1550 nm). This free-space approach of coupling will always be affected by Fresnel reflections at the optical interfaces. Anti-reflection coatings can improve the coupling efficiency, but they also introduce a wavelength dependency, thereby counteracting one of the important advantages of edge coupling over grating coupling. Secondly, the lensed approach is limited in its design freedom on the shape and size of the focused spot, making it hard to exactly match the chip's modal fields.

As an alternative, ultra-high numerical aperture (UHNA) fibers allow to create a true butt-coupled (physical contact) fiber-to-chip connection [23]. This technique permits the use of an index-matching medium to minimize reflections and is more suitable for mutual alignment of an array of fibers in multifiber edge coupling [21]. On the other hand, these UHNA fibers do not come in a large variety. As such, there is little freedom of choice in the mode-field diameter (MFD) which is usually between 3 and 5 μm, and consequently it requires thermal core expansion to achieve an efficient coupling to standard SMFs. The latter process is not straightforward with respect to achieving excellent manufacturing.

One of the technologies that has proven to have a lot of potential to functionalize SMF end-facets is two-photon polymerization (2PP)-based direct laser writing. This fabrication technology allows the creation of 3D structures with full design freedom and submicrometer resolution [24]. The technique has already been used in the development of a microstructured antireflective coating [25], phase masks [26], lenses [27], [28] and mode-field expansion up-taper structures [29] on optical fiber tips. In the latter, we demonstrated the fabrication method for use in physical contact expanded beam fiber-to-fiber connections to relax the alignment tolerances.

Recently, next to the 2PP printed free-space fiber-to-chip configurations targeted by Dietrich et al. [30], photonic wire bonds developed at the Karlsruhe Institute of Technology (KIT) have shown a lot of opportunities with the demonstration of hybrid photonic integration using 2PP-printed permanent interconnections. As such, permanent single-core and multi-core optical fiber connections towards Si-chips [31] and connections between InP-based lasers and Si-chips [32] have been established. Such permanent connections have very high potential in reducing the cost of active alignment strategies, but still have several challenges to overcome. Indeed, visual computer detection of on-chip alignment markers is used to calculate the 3D path for the wire bonds between the connection-joints. Whereas this fabrication methodology works well for ridge-type waveguides, it is not straighforward to make such joints to other types of waveguides, like for example buried waveguides. Moreover, fiber-to-chip and chip-to-chip connections often have very tight (submicrometer) alignment tolerances, for which optimal coupling in a passive way is very hard to obtain due to the combination of computer vision errors and mechanical alignment accuracy of galvanometric mirrors and translation stages. Finally, a damage in the permanent link between components can cause the whole device to become unserviceable with higher difficulty for repair and part-replacement.

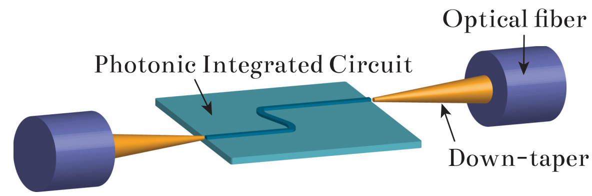

Fig. 1. Schematic view of down-taper structures directly printed on single-mode optical fibers for edge coupling towards photonic integrated circuits. In this approach, the down-taper is not permanently connected to the chip, though such a permanent connection can easily be obtained through a packaging process. Dimensions are not to scale.

In this paper, we propose to use the 2PP additive manufacturing technique to print down-taper structures on the end-facet of SMFs. A taper structure with excellent modal match in terms of shape and size can therefore be fabricated directly on top of the optical fiber, such that it can be butt-coupled with the photonic chip to minimize reflections. This can be done without the need for physical changes to the PIC. Furthermore, the obtained design flexibility at the fiber side does not put extra constraints on the design of the on-chip coupling structures, which can further develop independently from the limited availability of matching specialty fibers. A schematic visualization of the proposed coupling approach is given in Fig. 1.

An extensive analysis of the taper design is given in Section II for the coupling to 3 generic PIC material platforms with 5 different configurations in terms of input/output waveguide cross sections and mode sizes. As such, we demonstrate the effectiveness of our solution for the most relevant waveguide materials and different waveguide cross sections. In Section III the fabrication process and characterization towards taper positioning accuracy, geometry and output modal field are explained. Here, we also demonstrate the potential of the fabrication method for photonic packaging by printing a down-taper structure on a fiber inserted in a glass block component. Finally, we experimentally measure the coupling losses for the 5 different PICs and discuss the results in Section IV.

II. Design and Analysis of Down-Tapered Fiber-to-Chip Coupling Structures

The performance of an edge coupling structure for fiber-to-chip coupling in terms of coupling efficiency mainly depends on three different aspects: 1) Modal field matching and transformation, 2) Fresnel reflections at the interfaces (end-facets), and 3) Misalignment tolerances. These design aspects are described and analyzed in the following subsections. The last subsection describes the addition of a cladding material to the proposed coupling structures.

A. Modal Field Matching and Transformation

A first implementation of the proposed down-tapers fabricated on SMFs consists of a 3D printed polymer core with an air-cladding around it. We used the commercially available and optimized IP-DIP photoresist formulation from Nanoscribe GmbH to achieve the highest 2PP resolution [33]. The taper

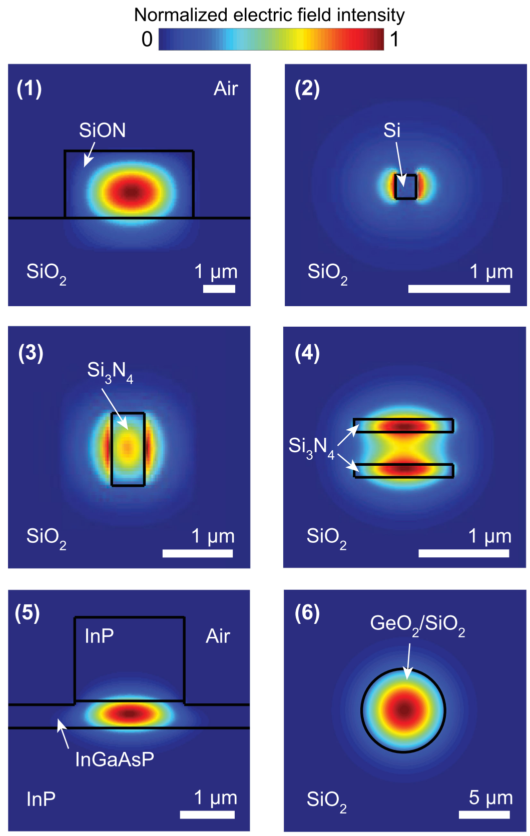

Fig. 2. Overview of the simulated TE modal field intensities of the estimated input/output waveguides of the different material platforms. (1) SiON SSC, (2) inverted Si-taper, (3) inverted SiN-taper, (4) SiN symmetric double-strip, (5) InP waveguide, and (6) G.652 standard SMF.

surrounded by an air cladding has a large refractive index difference of about 0.53 between core and cladding, and as a result supports multiple modes. However, excitation and mode coupling to these higher order modes and radiative modes can be avoided by careful design of the taper structure, such that a maximal transmission of the fundamental mode is obtained. In order to transmit light efficiently, the coupling structure should create a good overlap between the electromagnetic modal fields of the taper and the on-chip waveguide.

We used the eigenmode solver from the Lumerical Mode Solutions software [34] to model the fiber and waveguides. All simulations are performed at a wavelength of 1550 nm, which is one of the main wavelengths used in SMF and PIC technology due to low material absorption in that spectral range and the many telecom-related applications that come with it.

At the chip side of the down-taper structure, the polymer core should be mode-matched with the desired PIC mode profile. In this study, we therefore analyzed the modal fields of 5 different types of PICs, consisting of 3 different material platforms. Fig. 2 gives an overview of the estimated waveguide layouts at the chip facets and their simulated mode profiles, including also the mode profile of a standard telecom SMF.

For the Si-platform, 2 different chips with different input/output waveguide strategies were examined. The first having

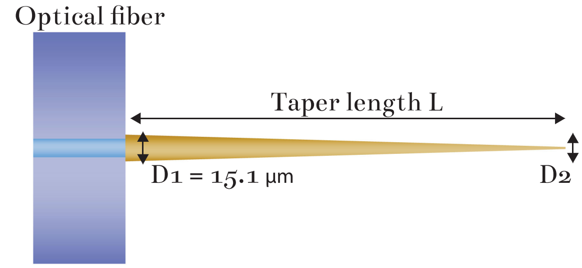

Fig. 3. Design parameters of the air-clad taper structure to be printed on top of a single-mode optical fiber tip.

a silicon oxynitride (SiON) spot-size converter (SSC), whereas the second is using an inverted Si-taper scheme. For the SiN-platform, we used 2 chips from different foundries using different waveguide geometries. The first has a single buried tapered waveguide and the second has a symmetric double-strip geometry. A chip with InGaAsP rib-waveguides represents the InP-platform. Finally, as we will use a G.652 [35] standard telecom fiber in the down-taper fabrication process, a model of such a fiber was used at the input port of the simulations.

The Transverse Electric (TE) and Transverse Magnetic (TM) polarization states are found to be very similar for most of the input/output waveguide schemes. We choose the down-taper design to be targeted towards the TE-polarization state. Nevertheless, a completely analog methodology can be used to find an optimal coupling design towards the TM-polarization states.

An eigenmode analysis and optimization makes it possible to find the optimal taper input and output diameters for maximal mode overlap with respectively the optical fiber and the photonic chips. The optimal input polymer waveguide diameter at the fiber side is found to be about 15.1 μm. At the output side, the optimal coupling diameter strongly depends on the exact PIC waveguide cross section at the chip facets, which is often kept confidential by the foundries and research centers. We therefore decided to further investigate the down-taper design for 7 different output diameters D_2, going from 1 μm to 7 μm in steps of 1 μm.

It is often found that waveguide geometries have strongly elliptical mode profiles. The fully optimized design would therefore need an elliptic shape and could further increase the coupling efficiency. Such an elliptic taper design could also be fabricated with the 3D printing technique, but in this paper we only consider rotationally symmetric down-tapers.

We used the Lumerical Mode Solutions software to model the light propagation through the down-tapered fiber models, for which a visualization of the structure is given in Fig. 3. A sweep of the taper length allows us to find a (local) maximum in transmission for the fundamental mode. In general, a larger taper length, which corresponds to a more gradual change in cross section, will give better transmission of the fundamental mode [36]. We found that a taper length of 250 μm is sufficiently adiabatic, giving more than 90% fundamental mode transmission for all output diameters D_2. In addition, this taper length limit is convenient to prevent the need for stitching of writing fields in the fabrication process.

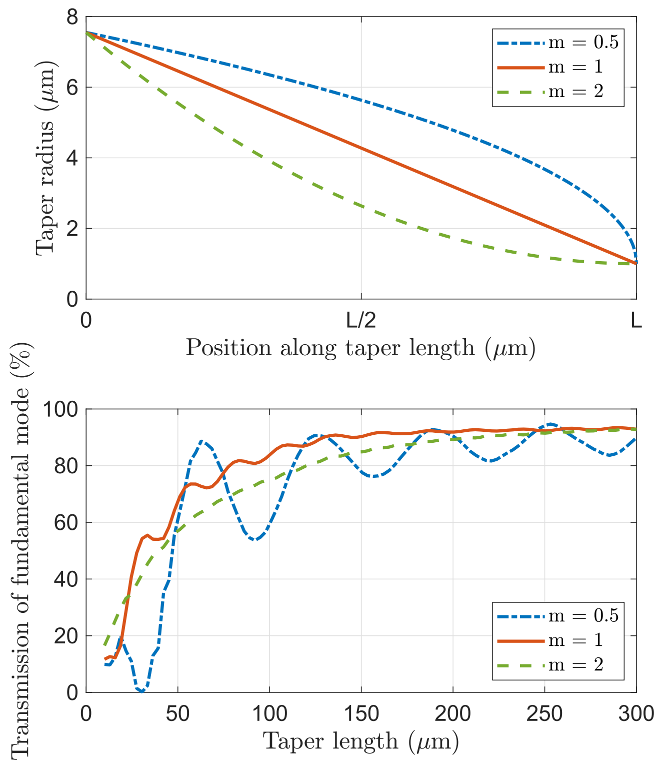

Fig. 4. Top: taper radius as a function of position along the taper length for nonlinear taper shapes with nonlinear exponent m equal to 0.5, 1 (linear) and 2. Bottom: simulation results for these down-tapers at 1550 nm: transmission of the fundamental mode as a function of the taper length.

As the linear taper length is relatively long, it is prone to mechanical damage and increasing propagation loss. Nonlinear taper shapes can bring a solution. Such nonlinearly shaped taper structures can decrease the total taper length, while keeping the radiation loss from mode-field conversion low [12], [37]. To investigate their usefulness in down-tapered fiber structures, we extended our simulations with a nonlinear shape function described as follows:

$$D(z) = D_2 + (D_1 - D_2) \cdot (1 - z/L)^m, \tag{1}$$

where L is the length of the taper, m is the nonlinear exponent, and D_1 and D_2 are the taper input and output diameters respectively.

The shape of nonlinear tapers with m equal to 0.5, 1 (linear) and 2 is shown in Fig. 4 for a taper with input diameter mode-matched with the SMF and an output diameter of 2 μm, together with the evolution of the fundamental mode's tranmission as a function of taper length. It is clear that a shape corresponding to an exponent of 2 gives less efficient transmission. On the other hand, a shape with an exponent of 0.5 will reach a point of 89% transmission at a length of 62.7 μm, whereas a linear taper shape would only get such high transmission for lengths larger than 127 μm. Therefore, a nonlinear structure can lead to smaller taper lengths with the trade-off of achieving a slightly higher coupling loss. The case of a 62.7 μm-long nonlinear taper is also fabricated and tested for verification and comparison.

Finally, it has to be mentioned that material absorption is not taken into account in the transmission simulations. Cured IP-DIP polymer has an absorption loss of less than 1 dB/cm at 1550 nm [30]. As the light will only propagate through a relatively small length, material absorption can be neglected.

B. Fresnel Reflections at Interfaces (End-Facets)

Reflection of the incoming light at an interface of media with different refractive indices can considerably impair the coupling efficiency. Even when two waveguides are perfectly butt-coupled, without having any air-gap between them, a mismatch between the effective indices of both waveguides will generate back-reflections. The reflectance for a normally incident light beam passing an interface from medium 1 to medium 2 is given by [38]

$$R = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2}, \tag{2}$$

where n_1 and n_2 represent the refractive or effective indices of the two media or waveguides.

As for every chip platform an optimal mode overlap is targeted, the difference in effective indices between the tapered fiber and the chip will be relatively small and leads to an estimated reflectance of $<3\%$ per facet, which corresponds to a loss of <0.26 dB for the input and output facets combined. An exception holds for the high-index InP-platform, which would give a Fresnel reflection of about 15% per facet for a total of about 1.4 dB reflection loss.

Next to losses from modal field matching and transformation, these reflection losses will contribute to the total coupling efficiency, where a higher loss for the InP-platform can already be anticipated.

C. Misalignment Tolerances

When investigating the coupling between (sub)micrometer-scale structures, a misalignment tolerance analysis gives many insights into the realistically achievable coupling efficiency of the designed structure in practice. A good understanding of alignment tolerances will help in making decisions in the design phase, in analyzing experimental results, and in defining packaging strategies.

In a butt-coupled connection, lateral misalignments will have a higher impact on the loss than axial and angular misalignments [39]. The consequences from misalignments are found to be bigger with decreasing mode-fields. Our simulations show that a submicrometer accurate alignment is needed for all chip platforms in order to achieve <1 dB misalignment losses. Because of this, it is clear that efficient coupling is hard to obtain with passive packaging techniques.

In general, a larger misalignment tolerance can be achieved by making use of wider taper tips, at the cost of higher coupling losses. In that sense, the proposed tapered fibers experience the same misalignment tolerance as traditional lensed fibers with the same MFD.

Finally, when using the 2PP technology for the fabrication of taper structures on cleaved fiber tips, a small misalignment

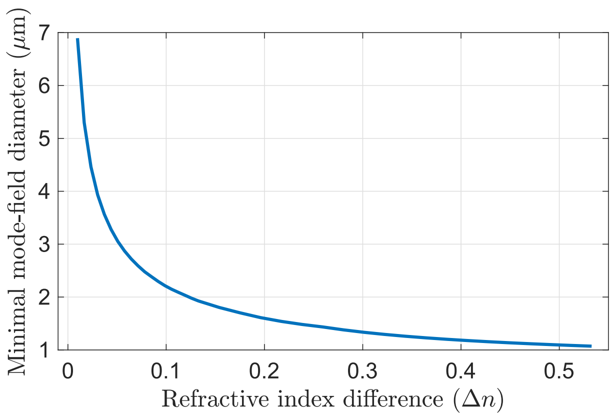

Fig. 5. Minimally obtainable MFD as a function of the waveguide's core-cladding refractive index difference Δn. The core is chosen to be the polymer IP-DIP. Simulated at 1550 nm.

between the taper and fiber core can also occur. Nevertheless, by using high-magnification real-time imaging of the fiber end-facet during the printing process, submicrometer positioning control can be achieved.

D. Impact of Adding a Cladding Material

Up to now, the down-taper design was based on an air-clad waveguide. However, index matching materials play an important role in photonic chip packaging [21]. Such materials usually come in the form of gels or UV curable epoxies and will fill the air-gap between the chip and the tapered fiber, therefore strongly reducing unwanted reflections at the optical interfaces.

In our down-taper coupling scheme, this index matching material can at the same time be used as an effective cladding for the down-tapered waveguide. This cladding would also prevent contamination of the taper interface that could lead to undesired radiation losses and could also decrease possible scattering due to roughness at the taper's side wall.

An important consideration here is that a decrease in refractive index difference between core and cladding (Δn) lowers the light confinement of the waveguide, therefore increasing its mode-field. As such, the minimal MFD that is possible to obtain increases with decreasing index contrast, as can be seen in Fig. 5.

Therefore, the choice of cladding material will be a compromise between fiber-to-taper and taper-to-chip coupling losses, and Fresnel reflection losses. Though, for the first implementation of the down-taper approach we only consider air-cladded tapers in this paper.

III. Taper Fabrication and Characterization

We used the commercial IP-DIP photoresist material with the Photonic Professional GT+ system from Nanoscribe [33] in the dip-in configuration to fabricate our designed down-taper structures directly on the end-facet of cleaved G.652 SMFs. By sending red laser light through the fiber and careful active alignment of the core position with the printer axes, the full structure can be printed in a matter of minutes using the built-in galvo scanner. All processing steps are done without any specific environmental restrictions, e.g. temperature or humidity control, other than processing the undeveloped material in a room with UV-filtered lighting conditions to prevent undesired single-photon polymerization of the resist.

Good adhesion of the polymer taper to the fused silica (SiO_2) end-facet of the cleaved fiber is crucial. For this reason, we perform a silanization process to the fiber facet before printing. This chemical surface treatment will form covalent bonds between the organic polymer and the inorganic fiber silica glass upon laser exposure, effectively connecting both materials. Additionally, we are adding a base plate layer with a thickness of about 6 μm to the taper design, which increases the effective contact area between the taper and fiber. Simulations show that such a thin base layer has negligible impact on the light transmission.

With the 2PP direct laser writing system submicrometer fabrication tolerances are obtained, which is quantitatively verified using a Hirox SNE-4500M scanning electron microscope (SEM), a Bruker Contour GT-I white-light interferometer, and a Werth VideoCheck UA400 coordinate measurement machine. SEM images of the linear and nonlinear down-taper structures printed on SMF end-facets are shown in Fig. 6.

We characterized the output modal fields with a Bobcat SWIR camera from Xenics accompanied by a Zeiss 100x NA0.9 microscope objective, allowing us to make high-magnification and high-resolution images of the modes at telecom wavelengths. Such an experimentally obtained mode-field image from the end-facet of a down-taper with a tip diameter of 3 μm is shown in Fig. 7, together with the measured MFDs for the different taper designs. This near-field measurement technique allows to image MFDs down to about 1.8 μm, limited by the microscope's resolving power. It is found that the MFD of the nonlinear taper structure is only slightly larger than that of its linear counterpart. This can be caused by the fact that the change in nonlinear taper diameter is more abrupt at the taper's end (see Fig. 4), making it more sensitive to the layered fabrication approach inherent to the 3D printing process.

Next, we demonstrate the use of this fabrication process to print taper structures on fiber glass blocks, as shown in Fig. 6(c), that are frequently used in packaging processes. All previous considerations can be applied to these components as well. Moreover, it is possible to scale up the fabrication process and print taper structures on multi-fiber array glass blocks to increase the fiber count and density [29].

IV. Coupling Experiments

We investigated the coupling losses between the fabricated down-tapered fibers and the 5 PICs mentioned in Section II, and compared the results to the coupling losses obtained with commercial lensed fibers. The measurement set-up is shown in Fig. 8 (a), where a fiber-coupled continuous-wave tunable WDM8-C-27A-20-NM source, at a wavelength of 1549.36 nm and at a power of 1 mW, combined with a Thorlabs Pro 8000 controller is used to send light to the chip. A polarization controller allows aligning the polarization of the fiber mode to the desired TE mode of the PIC waveguide. The tapered or lensed fibers are

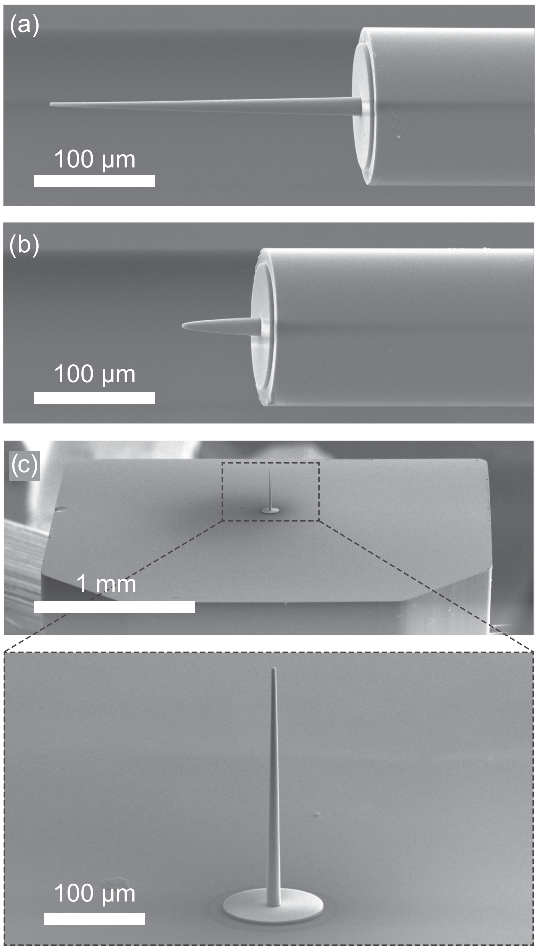

Fig. 6. Scanning electron microscope images of the 3D printed taper structures on top of cleaved optical fiber tips. (a) Linear down-taper with tip diameter of 3 μm and length of 250 μm printed on a bare SMF, (b) nonlinear down-taper with tip diameter of 2 μm and length of 62.7 μm printed on a bare SMF, (c) linear down-taper printed on a single-fiber glass block.

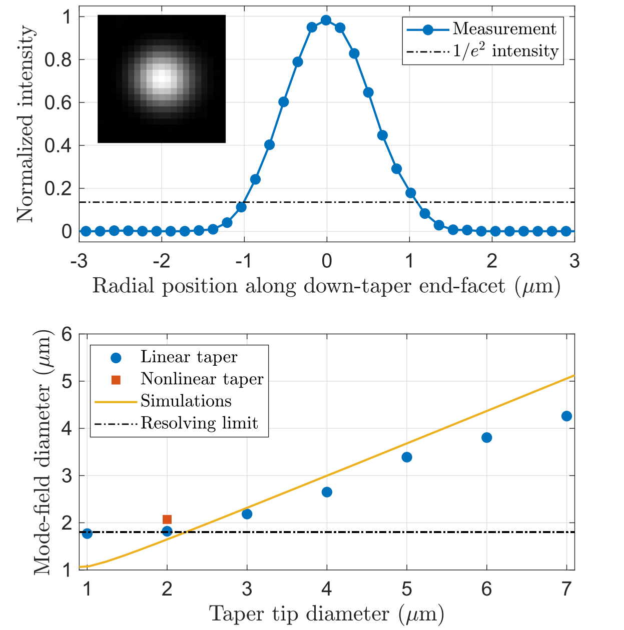

Fig. 7. Top: Experimentally visualized modal field at the end-facet of a down-taper with a tip diameter of 3 μm. Bottom: Measured and simulated MFDs for down-tapers with tip diameters ranging from 1 μm to 7 μm. All measured at a wavelength of 1550 nm.

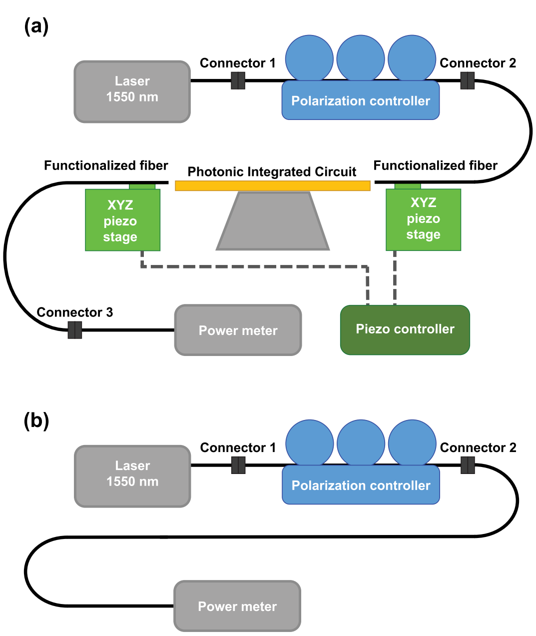

Fig. 8. (a) Set-up for the measurement of the coupling losses of the fabricated down-tapered fibers and lensed fibers towards different PIC chips. (b) Set-up for the reference measurement.

positioned on piezo stages and can be accurately aligned to the chip with the use of a piezo controller. Finally, the transmitted light is captured by a Thorlabs S122C power detector coupled to a PM320E power meter.

A reference measurement, where the chip and functionalized fibers are removed (as schematically represented in Fig. 8 (b)) is subtracted from the transmitted power (obtained with the set-up in Fig. 8 (a)) together with the known waveguide loss to obtain a value for the coupling loss per facet. A reference measurement defined as such, takes into account one FC connector less than the measurement itself and will therefore lead to a worst-case coupling loss estimate. This way, the obtained coupling loss includes Fresnel reflections and the loss due to absorption, mode conversion and mode mismatch from both the on-chip coupling structures and the fiber down-tapers. We can then easily compare the performance of the tapered fibers with that of commercial lensed fibers by measuring the losses in the same way.

Fig. 9 shows the experimentally obtained coupling losses for all linear down-taper and chip combinations. For every PIC platform a minimum in coupling loss was found as a function of taper tip diameter, which shows the strength of this flexible design and fabrication strategy in order to find the optimal coupling efficiency to a given on-chip structure.

To compare with a state-of-the-art and widely used coupling method, we performed the same measurements with a pair of commercially available lensed fibers, which are anti-reflection coated and are measured to have an MFD of about 2.7 μm. An overview of the achieved coupling losses for each of the PIC platforms is given in Table I. For three out of the five

TABLE I

Overview of the Experimentally Obtained Coupling Losses Per Facet for the Commercial Lensed Fibers and 2PP Linear and Nonlinear Down-Tapers, for All Investigated Chip Platforms (Referring to the PICs Shown in Fig. 2). D_2 Gives the Taper Tip Diameter for Which a Minimum in Loss is Obtained. The Improvement in Coupling Loss Between the Linear Taper and Lensed Fiber Connections is Given, as Well as the Difference in Loss Between the Linear and Nonlinear Taper Connections. The Measurement Repeatability is Better Than 0.1 dB

PIC platform	Lensed (dB)	Linear taper (dB)	D_2 (μm)	Nonlinear taper (dB)	Linear taper vs. Lensed (dB)	Linear vs. Nonlinear (dB)
(1) SiON	-2.31	-1.34	6	n/a	0.97	n/a
(2) Si	-2.10	-2.69	3	-2.78	-0.59	0.09
(3) SiN	-2.09	-1.65	6	n/a	0.44	n/a
(4) SiN	-2.58	-2.55	4	n/a	0.03	n/a
(5) InP	-5.61	-4.18	2	-4.27	1.43	0.09

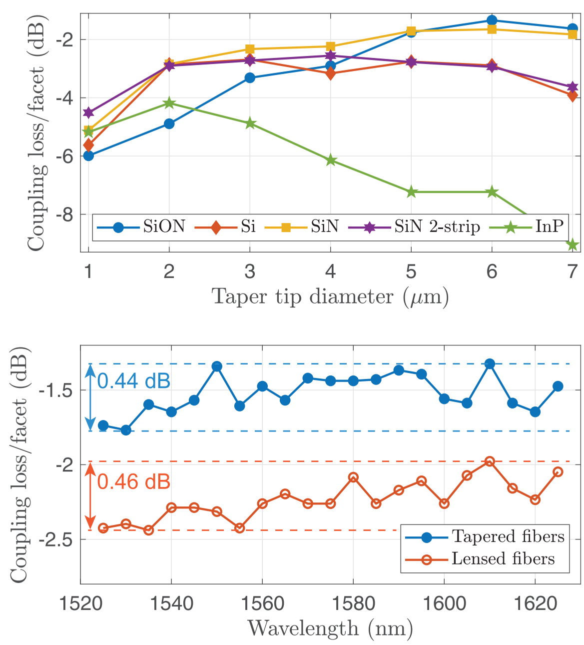

Fig. 9. Top: Comparison of the coupling loss per facet measurements between the different PIC platforms as a function of the down-taper tip diameter. Bottom: Comparison between the wavelength dependency in the C and L telecom bands for the connection between the linear down-tapers with tip diameter of 6 μm and the SiON chip, and the connection with lensed fibers.

PIC platforms we found that the down-taper approach produces lower losses than the lensed counterpart, with an improvement in coupling loss of respectively 0.97 dB, 0.44 dB and 1.43 dB for the SiON, SiN, and InP-platforms. The measured loss for the double-strip SiN chip is on par with lensed fiber losses. For the Si-platform however, we achieved a 0.59 dB higher loss than for the lensed approach. Whereas the trend in the relation between the coupling loss and taper tip diameter is well within the expectations from simulation results, the reason for this higher loss compared with lensed fibers is not fully clear yet.

From these observations it is clear that an optimized mode-matching design is very beneficial to reduce the overall coupling losses in fiber-to-chip connections. An additional advantage of the down-taper approach over lensed fibers is that a physical contact through butt coupling can be used, which would facilitate a robust packaging of the PIC.

In addition to the linear taper structures, we also designed and fabricated nonlinear down-tapers on SMFs. As can be seen from Fig. 6(b), a nonlinear taper has the advantage that it can be much shorter than its linear equivalent. These nonlinear tapers were made to have a taper tip diameter of about 2 μm, and were therefore tested with the Si and InP platforms, which have shown to have a minimum in coupling loss around the same taper tip diameter for the linear tapers. As such, the coupling between the Si-chip and nonlinear down-taper produces a coupling loss of -2.78 dB per facet, compared to the -2.69 dB per facet with the linear tapers. For the InP-chip a loss of -4.27 dB per facet was achieved with the nonlinear tapers, compared with -4.18 dB when we used the linear tapers. These results show that the taper length can be strongly decreased with only a small penalty in terms of coupling loss.

To be considered as an efficient and practical edge coupling method, the proposed coupling scheme should be wavelength independent over a broad range (e.g. within the C and L telecom bands). We therefore experimentally examined the coupling between the SiON chip and its optimal taper combination with 6 μm tip diameter for wavelengths ranging from 1525 nm to 1625 nm (using a Tunics T100S-HP continuous-wave tunable laser from Yenista Optics with 1 mW output power). The results are shown in Fig. 9. We found that the maximal change in coupling loss for the tapered approach is about 0.44 dB, compared to 0.46 dB for the lensed fiber method.

Finally, as the proposed coupling scheme makes use of a true butt-coupled approach, it is important to ensure that no damage will occur to both the chip and tapers upon physical contact. When using translation stages, under practical and realistic circumstances, we found that the polymer down-taper structures are sufficiently soft while robust, such that the taper is not causing any damage upon physical contact. Unless excessive force is applied, the taper returns to its original straight shape when it is withdrawn from the chip facet, and no degradation in coupling loss is observed.

V. Conclusion

We have demonstrated the design and 2PP fabrication of linear and nonlinear down-taper structures on top of cleaved single-mode optical fiber tips with the aim of matching the mode profile of the fiber to that of on-chip waveguides in different generic photonic integrated circuit platforms. The 2PP fabrication method allows for rapid prototyping and can create functional components with unprecedented flexibility. Our tapered fibers show better optical performance in terms of coupling loss compared to state-of-the-art lensed fibers for three out of the five investigated PIC platforms, with a measured improvement in coupling loss up to 1.43 dB (for the InP-platform). This can be attributed to both the efficient modal matching between the optical fibers and chips, and to the physical contact that is enabled by this approach, which reduces Fresnel reflections at the optical interfaces. At the same time the wavelength dependency, across the C and L telecom bands, of the coupling loss for the tapered couplers is found to be very similar to that of the lensed fibers. Finally, we have shown that using a nonlinear taper profile over a linear one allows to strongly reduce the length of the down-taper with a minimal ($<$0.1 dB) penalty in coupling loss.

The investigated tapers have shown to be able to produce tailored mode-fields down to 1.8 μm and smaller (measurement of smaller dimensions is limited by the resolving power of the used microscope system). As such, it can remove restrictions on the complex design and hard-to-fabricate on-chip coupling features that are being investigated for their use with commercially available specialty fibers. These on-chip mode conversion structures take up a lot of chip real estate that could be used for other means. The obtained flexibility of our down-tapered fibers makes it possible for the development of the on-chip features to be further pursued independently from the available fiber components.

In addition, we have shown that our approach permits to print down-tapers on fiber glass blocks that are often used in practical packaging processes. As opposed to a lensed fiber coupling approach, the down-tapers allow epoxies or gels to be used in these packaging processes since they can act as an effective cladding for the taper structure.

Future work will include the design and implementation of such cladded down-tapers, as well as a more in-depth exploration of nonlinear taper structures and an optimization of the taper shape towards elliptical profiles.

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