Polymer tapered pillar on a fiber end fabricated by UV irradiation using a high-NA fiber

Taiga Kurisawa,[*1] Yoshiki Kamiura,[1] Chiemi Fujikawa,[1] and Osamu Mikami[2]

[1]*Course of Electrical and Electronic Engineering, Graduate School of Engineering, Tokai University, 4-4-1, Kitakaname, Hiratsuka, Kanagawa, 259-1292, Japan*
[2]*Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, 54100 Jalan Sultan Yahya Petra, Kuala Lumpur, Malaysia*

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Abstract—The increasing need for single-mode fibers (SMFs) and advances in silicon photonics (SiPh) devices have led to the need for an efficient method of optical coupling between them. To achieve a higher coupling between them, a polymer tapered pillar was fabricated on the end face of the SMF by applying the optical diffraction effect and a self-written waveguide technology using a high numerical aperture (HiNA) fiber. The initial 10.4 µm spot size was reduced to 4.17 µm at 1.55 µm wavelength, and the greatest coupling efficiency of –1.01 dB was reached between an SMF with a tapered pillar and uncured resin cladding and a HiNA fiber.

Recently, a great deal of research has been conducted on silicon photonics (SiPh) for high-capacity data communication [1]. The increasing need for single-mode fibers (SMF) and advances in the fabrication technology of SiPh devices have led to the need for an efficient method of optical coupling between SMF and SiPh chips. The spot size of a beam propagating out of a SiPh chip is usually enlarged to approximately 4 µm using an integrated spot-size converter (SSC). On the other hand, the spot size of the SMF was approximately 10 µm. This difference in spot size is a significant factor in the lower coupling efficiency between them. To achieve high coupling between them, several approaches have been proposed, such as a polymer waveguide with curvature on the SMF core end face [2], polymer microtips at different types of optical fibers [3], a coupling device consisting of a pillar and microlens on the SMF end face [4–5], a self-written waveguide (SWW) using a resin that can be cured in the near-infrared region [6–7], a taper fabricated by 3D printing technology [8], a self-formed tapered waveguide by bilateral injection from a SiPh chip, and an SMF with a special waveguide fabricated [9–10]. Previously, our university team proposed a method for fabricating multiple tapered pillars using the photomask transfer method for UV-curable resin [11]. By using a small mask aperture with a diameter of 3 µm, UV light passing through the aperture of the mask was radiated owing to the diffraction effect, and a taper with predetermined form was produced on the glass substrate as a test. Although we could obtain numerous tapered pillars from a single dose of UV irradiation, it may be difficult to precisely adjust the position of the pillar and the SMF core.

In this study, a new method for fabricating a tapered pillar that matches the mode field diameter (MFD) of a SiPh chip on the end face of an SMF is proposed, as shown in Fig. 1. In the following section, the fabrication method of the tapered pillar on the end face of the SMF, optical characteristics, coupling efficiency with HiNA fibers, and the effect of cured resin cladding are introduced.

The tapered pillar was fabricated using UV-curable resin (SUNCONNECT®, Nissan Chemical Corp.) [12] and the SWW method [13–14].

First, we studied the effects of small apertures by using several fibers. The examined fibers were SMF, HiNA fibers UHNA1, UHNA3, and UHNA7 from NUFERN [15–16]. The data sheet for the HiNA fibers is summarized in Table1. Standard SMFs were set in front of these fibers [except for irradiation by SMF (a)] with a space gap of 80–100 µm in all cases. The gap between the SMF and irradiating fibers was filled with UV-curable resin. A 405 nm wavelength UV light of approximately 3 nW was carefully irradiated for several seconds from the fibers. The pillars grown from the irradiated fiber ends are summarized in Table 1. Taper pillars were fabricated for all cases except for the SMF irradiation in case (a). As expected, the angle of the tapers increased proportionally with the mode field size. From these preliminary studies, we decided that UHNA3 has a similar MFD to the conventional SSC of the SiPh chip and would be the best for our target.

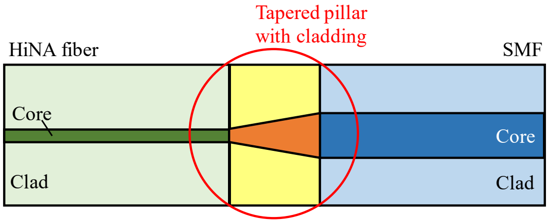
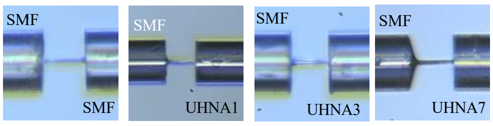


Fig. 1. Proposed coupling device.

Table 1. The pillar grown from irradiating each HiNA fiber end.

* E-mail: 1ceim021@mail.u-tokai.ac.jp



	SMF	**UHNA1**	**UHNA3**	**UHNA7**
NA	0.14	0.28	0.35	0.41
Core diameter	8.2μm	2.5μm	1.8μm	2.4μm
Mode field diameter (λ=1.55μm)	10.4 ± 0.5μm	4.8 ± 0.3μm	4.1 ± 0.3μm	3.2 ± 0.3μm

The tapered pillar was fabricated using a HiNA fiber, UHNA3, and NUFERN with an MFD similar to that of the conventional SSC of the SiPh chip. The data sheet of UHNA3 indicates that the cladding diameter is 125.0 ± 1.5 μm, the core diameter is 1.8 μm, the MFD is approximately 4.1 ± 0.3 μm at a wavelength of 1.55 μm, and the NA is 0.35 [15–16].

A schematic diagram of the final fabrication method is shown in Fig. 2.

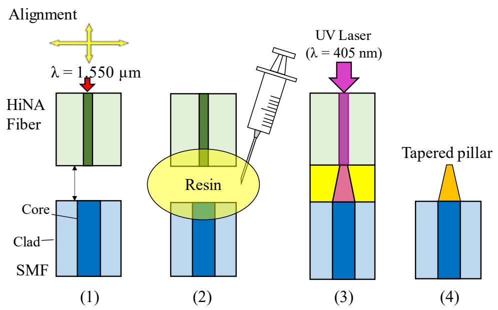


Fig. 2. Fabrication process of taper pillar with cladding. In (3), taper was fabricated using the diffraction phenomenon.

(1) The SMF and HiNA fibers were aligned using a light source with a wavelength of 1.55 μm. A gap with a target taper length of approximately 80 μm was established between the SMF and HiNA fiber.

(2) The spacing gap was filled with a UV-curable resin (SUNCONNECT® [12]) having a refractive index of 1.573 at 1.55 μm.

(3) A 405 nm UV laser was irradiated from the other end of the HiNA fiber to form a tapered pillar. The diameters of the bottom and tip of the tapered pillar may be controlled by varying the irradiation power and exposure time.

(4) The uncured resin is removed to expose the fabricated tapered pillar.

The scanning electron microscopy (SEM) image of the fabricated tapered pillar is shown in Fig. 3(a). Light with a wavelength of 405 nm was irradiated from a HiNA fiber at a power of approximately 3 nW and an irradiation time of 3 s. The tapered pillar measures 2.55 μm in diameter at the tip, 9.36 μm in diameter at the root, and has a taper length of 76.59 μm.

The optical properties of the tapered pillars were evaluated using near-field pattern (NFP) measurements. The NFP of the tapered pillar output beam at a 1.55 μm wavelength is shown in Fig. 3(b). The spot size was determined from the $1/e^2$ intensity distribution of the peak value. The spot size of the tapered pillar was converted from its original 10.4 μm to 4.17 μm of spot size.

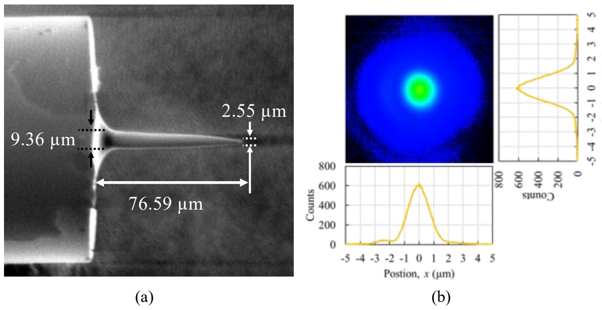


Fig. 3. SEM photograph of fabricated tapered pillar on a SMF end face (a) and observed NFP at 1.55 μm wavelength (b).

The coupling efficiency measurement was conducted using a beam with a wavelength of 1.55 μm emitted from an SMF/HiNA fiber and received by a HiNA fiber/SMF, as schematically shown in Fig. 4. Instead of a SiPh chip with an integrated SSC, a HiNA fiber, UNHA3 of NUFERN [15–16], was used. Unfortunately, a valuable SiPh chip is not very easy to obtain in university laboratories.

The coupling efficiency was obtained from the ratio of the incident power of the 1.55 μm wavelength light input from the HiNA fiber/SMF and propagated through the SMF/HiNA fiber via an FC connector or tapered pillar.

The coupling efficiency between the tapered pillars fabricated on the SMF and HiNA fiber is summarized in Table 2. The coupling efficiency was measured under the following conditions.

Step #1 Butt coupling without tapered pillar
Step #2 Using the tapered pillar without a cladding
Step #3 Using the tapered pillars with uncured resin cladding

The coupling efficiency of the tapered pillar without cladding (Step #2) was –9.30 dB and –4.69 dB for both directions. The lower coupling efficiency of the tapered pillars without cladding may be due to the safety gap that was introduced to prevent physical contact with the HiNA fibers. In the case of taper pillars with uncured resin cladding (Step #3), the coupling efficiency was –1.67 dB or –1.02 dB. In contrast, the butt coupling efficiency between the SMF and HiNA fiber was –3.14 dB or –2.87 dB. The tapered pillars with uncured resin cladding were found to be effective in improving the coupling efficiency by –1.47 dB or –1.85 dB compared to butt coupling.

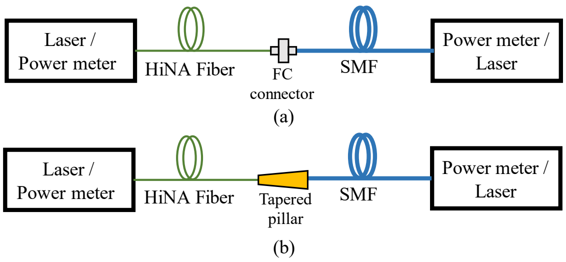


Fig. 4. Measurement systems for coupling efficiency.

Table 2. Coupling efficiency in each step.

		HiNA fiber → SMF
Step #1	Butt coupling between SMF and HiNA fiber	–2.87 dB
Step #2	Taper pillar without cladding	–4.69 dB
Step #3	Taper pillar with uncured cladding	–1.02 dB

During the fiber implementation stage, tapered pillars with uncured resin cladding are difficult to install. Therefore, a cured resin cladding was fabricated around the fabricated taper pillars. After fabricating the tapered pillar and washing the uncured resin, as shown in Fig. 3, cladding resin (SUNCONNECT® [12]) with a refractive index of 1.544 at 1.55 µm was filled around the tapered pillar and cured using a UV-LED with a wavelength of 365 nm. At this point, the tip of the tapered pillar was in contact with the HiNA fiber. A photograph of the fabricated tapered pillar with the cladding is shown in Fig. 5(a).

The optical properties of the tapered pillar with the cured resin cladding were evaluated using NFP measurements. The NFP of the tapered pillar with a cured resin cladding output beam at the 1.55 µm wavelength is shown in Fig. 5(b). The spot size was determined from the $1/e^2$ intensity distribution of the peak value. The spot size of the tapered pillar with the cured resin cladding was 4.12 µm. As a result, the spot size was reduced from the SMF spot size when cladding was applied around the tapered pillar.

In conclusion, a polymer tapered pillar was fabricated on the end face of an SMF by the diffraction effect and a self-written waveguide technology using a HiNA fiber. The spot size of the beam emitted from the taper pillar was determined to be 4.17 µm using the NFP. The coupling efficiency of –1.67 dB or –1.02 dB between tapered pillars with uncured resin cladding and HiNA fiber was achieved. In addition, a preliminary study of tapered pillars with hard cladding was conducted. It was found that the resin cladding had a diameter similar to that of the SMF and a flat end face.

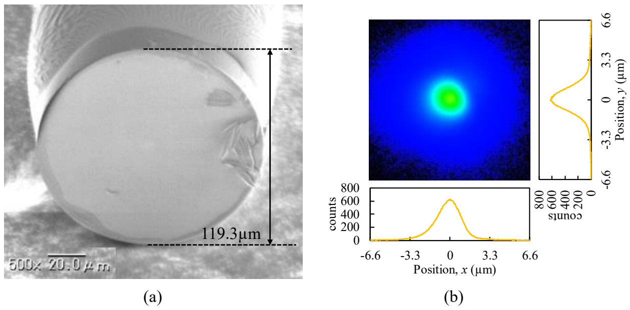


Fig. 5. SEM photograph of SMF with cladding. Fabricated taper is cannot seen in the front view (a). the near-field pattern at 1.55 µm wavelength indicates a little bit larger spot-size compared with taper pillar without cladding.

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