Reflow-Solderable Optical Fibers for Low Loss Coupling in Silicon Photonics

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Silicon Photonics-based devices are attractive owing to their advantages such as compactness, high functionality, and low-cost fabrication. One of the challenges is the optical coupling loss due to the spot size mismatch between the silicon waveguides and standard optical fibers. We have developed low-loss coupling fibers between them. This study reports the improvements in their splice losses with standard optical fibers by optimizing the fiber structure. Moreover, the fibers developed in this study show reflow-soldering resistance upon application of a high-temperature resistant coating.

1. Introduction

The field of information technology is steadily expanding with the advances in various technologies such as cloud communications, data centers, and the Internet of Things. The field of optical communication networks is also evolving. Photonic waveguide devices have made remarkable progress. Among them, Silicon Photonics (SiPh) is one of the most attractive technologies. Its research and development for application to optical transceivers are accelerating. There is a constant demand for optical transceivers to become more compact and consume less power. Co-packaging is a notable solution 1) 2). This approach requires mounting an optical transceiver directly on board by reflow-soldering. Reflow-soldering, where the peak temperature reaches 260 °C, results in repeated application of heat to the optical fibers connected to the SiPh devices. Therefore, high heat resistance is required not only for devices but also for optical fibers.

Optical fiber coupling with SiPh is an important issue hindering its practical use 3). The spot size of silicon waveguides is sub-micron owing to its strong confinement effect. A large coupling loss due to spot size mismatch occurs when standard optical fibers having spot sizes of approximately 10 μm are directly connected to silicon waveguides. Spot size converters (SSC) are usually formed at the edge of the silicon waveguides to reduce the fiber coupling loss. However, there are many challenges to design or manufacture SSC when expanding the spot size to approximately 10 μm. The other fiber coupling method involves using thermally expanded core (TEC) fiber and is shown in Fig. 1. Here, the expansion of spot size by SSC is limited to 4 μm 4) 5); spot size conversion on the optical fiber side, from 10 μm to 4 μm, is possible by TEC fiber 6). The germanium inside the core is diffused due to the heat generated by the arc discharging during splicing, causing the mode field diameters (MFD) in the heated region of the TEC fiber to expand from 4 μm to 10 μm. This allows low-loss splicing between fibers having different MFDs. Figure 2 shows the internal structure of the TEC fiber. Three types of dopants, Ge, P, and F, are co-doped in the inner cladding region adjacent to the core to assist the thermal diffusion of Ge in the core. This co-doping in the inner cladding can result in a lower splicing loss with a shorter splicing time compared to that without co-doping. We have developed both single-mode fibers

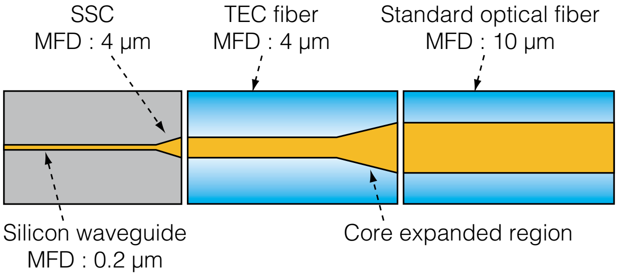

Fig. 1. Coupling structure for SiPh using TEC fiber. The MFDs are approximate values at a wavelength of 1550 nm.

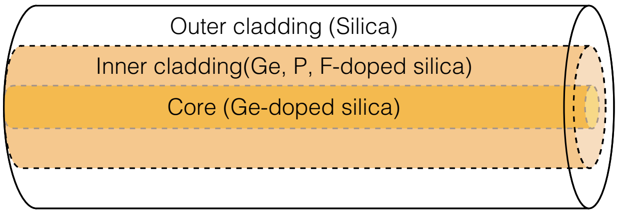

Fig. 2. Internal structure of TEC fiber.

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Panel 1. Abbreviations, Acronyms, and Terms.

SiPh—Silicon Photonics
MFD—Mode Field Diameter
SSC—Spot Size Converter
TEC—Thermally Expanded Core
SMF—Single-Mode Fiber
PMF—Polarization-Maintaining Fiber
SAP—Stress Applying Part

(SMF) and polarization-maintaining fibers (PMF) using the TEC technique, referred to as TEC-SMF and TEC-PMF. In our previous study, we showed a low coupling loss of 2.5 dB/2 facets, including splice loss using these TEC fibers [7]. The remaining issue was that the splice loss between the TEC-PMF and the standard PMF was higher than that between the TEC-SMF and the standard fiber, owing to the trade-off relationship between splice loss and polarization-maintaining property in TEC-PMF.

We developed reflow-solderable TEC fibers with lower splicing loss. We determined the optimized glass structure of TEC-PMF to satisfy both low splicing loss and high polarization-maintaining property. Moreover, we confirmed that applying high-temperature resistant acrylate coating to the TEC fibers showed minimal changes in optical properties while maintaining good mechanical reliability even when exposed to reflow-soldering several times.

2. Fabrication and evaluation of TEC fibers

Table 1 shows the properties of the fabricated TEC fiber samples. We prepared one TEC-SMF sample and three TEC-PMF samples. The optimized structure of TEC-PMF was decided through experimetns using these TEC-PMF samples (details are described later). All fibers had higher attenuation compared to the standard optical fibers. This is due to the Rayleigh scattering caused by both high concentration of Ge added to core and multiple dopants added to the inner cladding layer. However, we believe that this attenuation is unlikely to cause a problem. The insertion loss values of TEC fibers are very small because they are expected to be used only a few meters in transceiver applications.

Table 1. Typical properties of TEC fiber samples.

[1] Measurement wavelength：1550 nm

Item	Unit	SMF-A	PMF-A	PMF-B	PMF-C
Fiber type	-	TEC-SMF	TEC-PMF	TEC-PMF	TEC-PMF
Cladding diameter	μm	125	125	125	125
MFD[1]	μm	4.0	4.2	4.0	4.1
Cut-off wavelength	nm	1170	1310	1230	1200
Attenuation[1]	dB/km	26	14	27	17

Figure 3 shows the experimental setup for splice loss evaluation between the TEC fibers and standard optical fibers. We measured the reference power by connecting the light source and power meter by a standard optical fiber. After placing a TEC fiber on the power meter side, we investigated the change in splice loss between a TEC fiber and a standard optical fiber over time during the arc discharge. Figure 4 shows an example of the splice time transition of the splice loss between SMF-A and a standard SMF of Fujikura FutureGuide®-SR15. The splice loss decreased starting from 3 dB, and reached a minimum of 0.1 dB, 25 s after the start of arc discharging. Figure 5 shows the histogram of the minimum splice loss when the same experiment was repeated 20 times. The values were

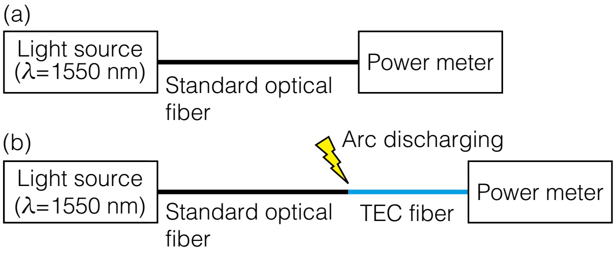

Fig. 3. Evaluation setup for splice loss of TEC fiber. (a) Reference power measurement (b) Splice loss measurement during arc discharging.

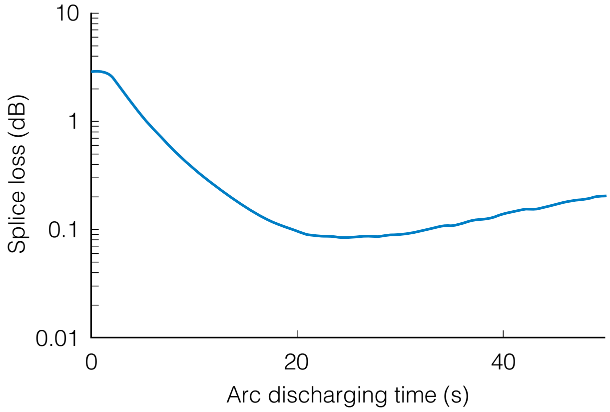

Fig. 4. Splice loss transition of SMF-A during arc discharging, at a wavelength of 1550 nm.

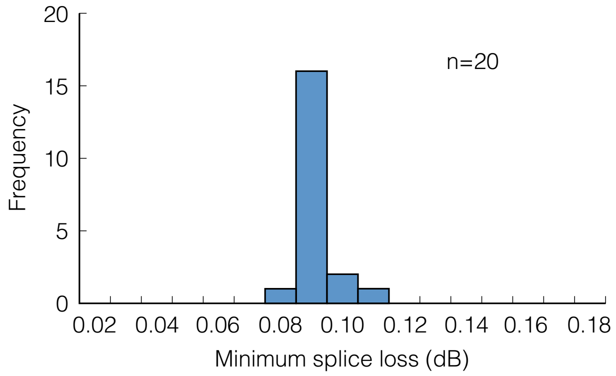

Fig. 5. Measurement result of the minimum splice loss of SMF-A, at a wavelength of 1550 nm.

very stable at 0.10 ± 0.02 dB.

We prepared three TEC-PMFs with different structural parameters, which are the diameter of the stress-applying parts (SAP), the distance between the SAPs, and the inner cladding diameter, as indicated in Fig. 6(a). PMFs have two SAPs, which induce stress to the core, generating polarization-maintaining properties. There are dimensional constraints for the coexistence of SAPs and inner cladding. They create a trade-off relationship between splice loss and polarization-maintaining property. Figure 6(b) shows the relative degree of change in these parameters for each TEC-PMF. PMF-A is expected to show the best polarization-maintaining property owing to its largest diameter of SAPs with the closest distance among them. However, since PMF-A has the smallest inner cladding diameter, the thermal diffusion region of the core is expected to be limited and its MFD cannot be expanded sufficiently, resulting in a higher splice loss than other TEC-PMFs. In contrast, PMF-C is expected to show the best splice loss because it has the largest inner cladding diameter; whereas its polarization-maintaining property may be the worst because its SAP diameter is the smallest and they are farthest away. PMF-B is expected to show intermediate properties. We measured the splice loss and polarization crosstalk for each TEC-PMF. We set the target values to less than 0.3 dB for splice loss and less than −25 dB for polarization crosstalk, taking into account the application to SiPh devices for coherent transmission. Polarization crosstalk was measured with the TEC-PMFs bent for 10 turns with a 5-mm radius, assuming a small bend within a compact optical module housing. TEC-PMFs were spliced with a standard PMF of Fujikura SM15-PS-U25D (MFD: 10.4 μm at a wavelength of 1550 nm) to measure the splice loss. Figure 7 summarizes the results with the target upper limits. A clear trade-off relationship between the splice loss and polarization crosstalk was observed, as expected. Only PMF-B satisfied both target values.

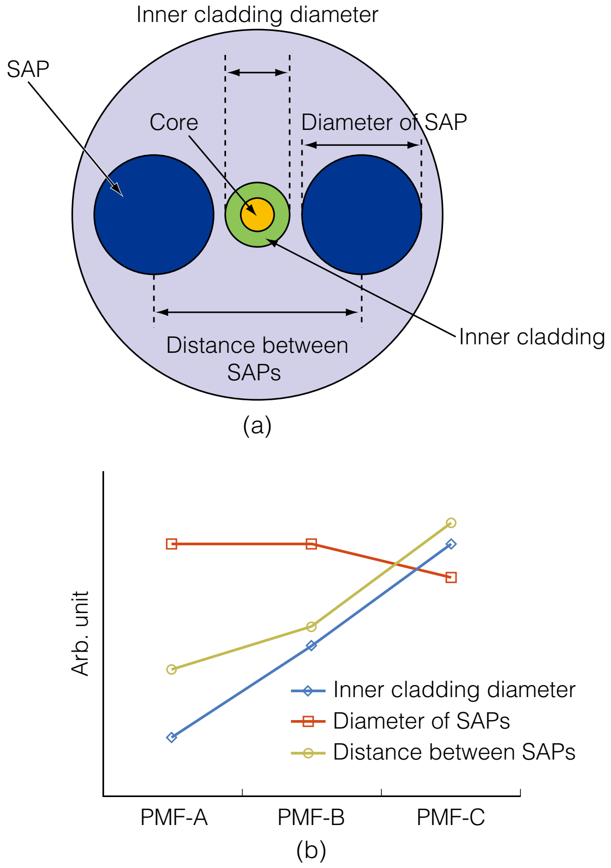

Fig. 6. Structural parameters of TEC-PMF (a) Overview diagram (b) Degree of change in structural parameters for each sample.

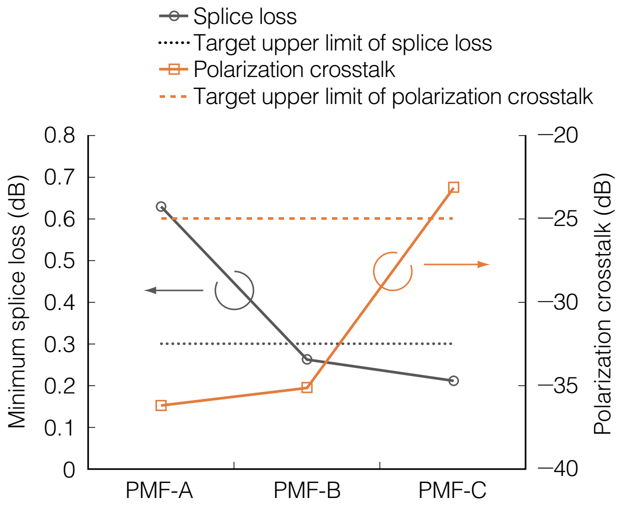

Fig. 7. Measurement result of the minimum splice loss and polarization crosstalk for each TEC-PMF sample, at a wavelength of 1550 nm.

Furthermore, we compared the splice characteristics using the bend-insensitive PMF (BI-PMF) of Fujikura BISM15-PX-U25D-H (MFD: 9.0 μm at a wavelength of

1550 nm) as a standard PMF instead of SM15-PS-U25D. Figure 8 compares the results of their splice losses. The splice loss reached as low as 0.1 dB when BI-PMF was used. Thus, the difference in splice losses was caused by the difference in standard fibers. This implies that the expansion of the MFD is saturated at approximately 9 µm in PMF-B. Therefore, the MFD gap between PMF-B and SM15-PS-U25D may remain, causing excess loss. The combination of PMF-B and BI-PMF is a suitable solution for showing not only low splice loss but also high polarization-maintaining property. The polarization crosstalk must have a sufficient margin because the PMFs are degraded by receiving external pressure, such as connectorization or assembling on the fiber array.

3. Investigation for resistance to reflow-soldering

Two characteristics of TEC fibers need to be studied against the heating effect by the reflow-soldering. The first is the change in optical properties due to the thermal diffusion of the core. The second is the degradation of mechanical reliability due to the thermal damage of the coating material. The heat-resistance temperature of general coating material is limited to 85 °C, which is not suitable for reflow-soldering. In this study, we investigated the applicability of Acrylate resin, which has been previously employed in a high-temperature environment in the temperature range of 150 °C to 200 °C [8]. Figure 9 shows the typical temperature profile for reflow-soldering. Its peak temperature of 260 °C is above the originally assumed temperature range of use of the Acrylate resin. Therefore, we investigated the changes in optical properties and mechanical reliabilities of TEC fibers coated with Acrylate resin.

In this experiment, reflow-soldering was applied five times, assuming a practical situation. Besides, we conducted additional experiments under harsh conditions of applying reflow ten times, and even more severe conditions in which the fiber was heated to 280 °C and held at that temperature for 20 min. Figure 10 shows the changes in appearance after the application of heat. Although the coating turned yellow with increasing the number of heat treatments, there were no issues in workabilities such as splicing, handling, and jacket removal. The change in MFD was evaluated for TEC fibers, and the changes in the splice loss and polarization crosstalk were evaluated for spliced fibers. Table 2 shows the changes in these optical properties before and after heat application. There

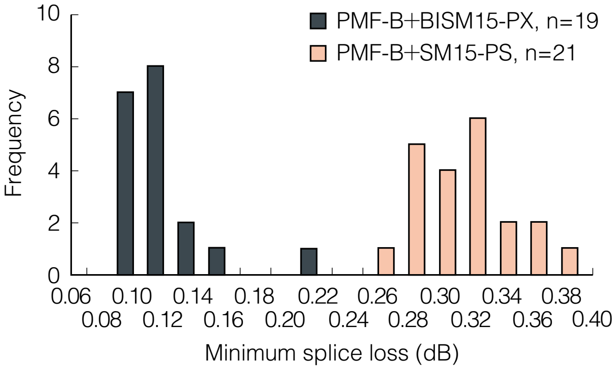

Fig. 8. Comparison of minimum splice losses between PMF-B and two standard PMFs, at a wavelength of 1550 nm.

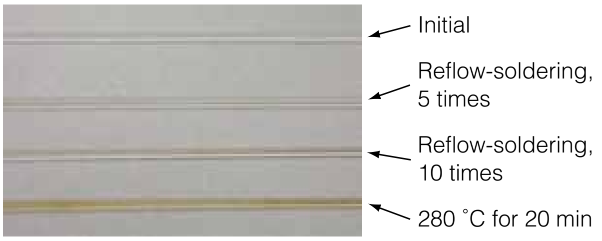

Fig. 10. Appearance of TEC fiber before and after heat application.

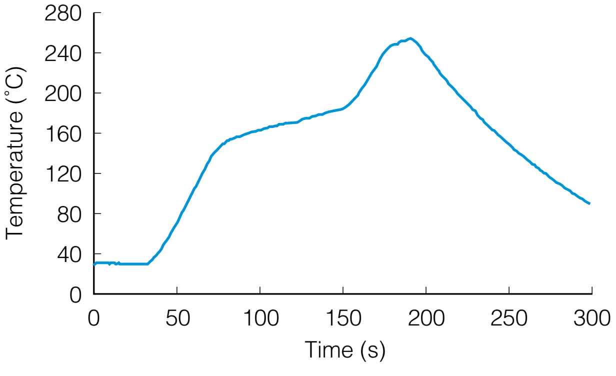

Fig. 9. Reflow profile for lead-free solder.

Table. 2. Changes in optical properties of TEC fibers before and after heat application.

Measurement wavelength: 1550 nm

Item	Sample name	Initial	Reflow-soldering, 5 times	Reflow-soldering, 10 times	280 °C for 20 min
MFD (µm)	SMF-A	4.1	4.1	4.0	4.0
	PMF-B	4.1	4.0	4.0	4.1
Minimum splice loss (dB)	SMF-A	0.08 to 0.09	0.08	0.09	0.08 to 0.09
	PMF-B	0.11 to 0.15	0.12	0.13 to 0.15	0.13 to 0.15
Polarization crosstalk (dB)	PMF-B	−37 to −42	−37 to −39	−36	−36 to −40

Table 3. Reliability test result of PMF-B

Item	Initial	280 °C for 20 min	Criteria
Tensile strength (GPa)	4.82	4.56	>3.80 (Unaged) >3.03 (Aged)
Dynamic fatigue value	26.8	18.9	> 18

were minimal changes in MFDs and splice losses. Although the polarization crosstalk looks slightly degraded, it is still much lower than −30 dB and there is little impact in practical use. Table 3 lists the results of the change in mechanical reliability. We measured the tensile strength and dynamic fatigue value based on Telcordia GR-20 9) before and after applying heat of 280 °C for 20 min to PMF-B. It satisfied GR-20 for both of the parameters despite the harsh thermal environment compared to reflow-soldering multiple times.

4. Conclusion

Low-loss coupling fibers for SiPh with two features have been developed. One is low loss splicing with standard fibers, and the other is resistant to reflow-soldering. A low splicing loss of TEC-PMF while maintaining good polarization is achieved by optimizing the fiber structure. We confirmed that the TEC fibers can withstand reflow-soldering multiple times by applying a heat-resistant coating.

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