Optical Coupling Technique Based on Fiber Side-Polishing Without Service Interruption

Takui Uematsu, Kazutaka Noto, Hiroyuki Iida, Hidenobu Hirota, and Kazunori Katayama

***Abstract*— We propose an optical coupler insertion technique based on fiber side-polishing that does not interrupt service. We clarify that fiber side-polishing with an insertion loss of 0.64 dB or less is possible by polishing while monitoring the loss and halting the polishing when the loss reaches the target value. Experiments on fabricated couplers confirm coupling efficiencies of up to 95% when another side-polished fiber is set close to the polished in-service fiber.**

***Index Terms*— Optical fiber coupling, optical fiber coupler, optical fiber side-polishing.**

I. Introduction

OPTICAL access networks (NWs) based on the passive double star (tree-and-branch) type passive optical architecture have been put into wide use. In recent years, a bus-type optical access NW using distributed Raman amplification and asymmetric couplers was proposed to efficiently accommodate users scattered over wide areas such as the countryside [1]. The configuration of the bus-type NW connects multiple branch fibers to a single trunk fiber by using optical couplers, so the coupler is a key device. Traditionally, couplers are inserted by cutting the trunk fiber, which interrupts communication service or by installing more couplers than initially needed when constructing the NW. However, adding more couplers degrades the loss budget, i.e., reach of the NW and the number of accommodated users, due to the insertion loss of each coupler. This problem can be solved if couplers can be connected to the trunk fiber after NW construction as needed without interrupting the communication service. One solution is to bend the fiber [2], but this yields coupling values of only -15 dB (3%) at most with an insertion loss of 2 dB because of its high excess loss. Fiber coupling techniques based on side-polishing have been proposed and commercialized because they can realize fiber couplers that provide high coupling efficiency with low excess loss; two side-polished fibers are simply brought close to each other [3], [4], [5]. The technique also achieves easy adjustment of coupling efficiency of up to 100% by simply moving the side-polished fibers relative to each other. Since it is necessary to polish the fiber several micro meters into the core to obtain high coupling efficiency, the remaining cladding thickness (RCT) is an important parameter. In order to estimate whether the desired RCT has been obtained, liquid drop tests [6], [7], [8] are conventionally used. In the conventional test, the RCT is estimated by measuring the insertion loss when a liquid with a higher refractive index than the core is applied to the polished surface. However, it is difficult to apply such tests to an in-service fiber because they create high insertion loss of several tens of dB. A method that can estimate RCT and finish polishing at the desired RCT without service interruption is required.

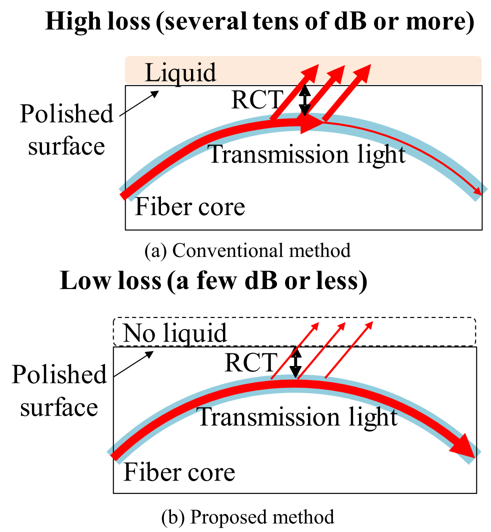


Fig. 1. Comparison of conventional and proposed methods of RCT estimation.

In this letter, we propose a method to determine whether the desired RCT has been achieved and when the polishing can be terminated as shown in Fig. 1. First, the target loss that yields the desired RCT is clarified by simulations and experiments. Next, it is confirmed that the RCT can be monitored while maintaining a low insertion loss by polishing while monitoring the loss and ending the polishing when the loss reaches the target value. Finally, experiments confirm that a coupling efficiency of up to 95% can be obtained by bringing and aligning another side-polished fiber, the branch fiber, close to the polished optical fiber.

II. Proposed Optical Coupling Technique Based On Fiber Side-Polishing Without Service Interruption

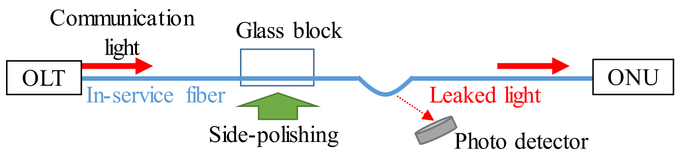
Fig. 2 shows the proposed coupler insertion technique based on fiber side-polishing without service interruption. The target

Manuscript received 1 July 2022; revised 2 August 2022; accepted 9 August 2022. Date of publication 17 August 2022; date of current version 30 August 2022. *(Corresponding author: Takui Uematsu.)*

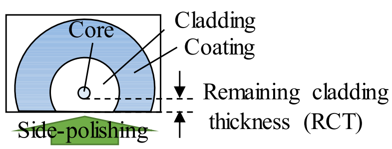
The authors are with the Access Network Service Systems Laboratories, Nippon Telegraph and Telephone Corporation, Tsukuba, Ibaraki 305-0805, Japan (e-mail: takui.uematsu.vk@hco.ntt.co.jp; kazutaka.noto.bn@hco.ntt.co.jp; hiroyuki.iida.hr@hco.ntt.co.jp; hidenobu.hirota.ft@hco.ntt.co.jp; kazunori.katayama.xt@hco.ntt.co.jp).

Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2022.3199456.

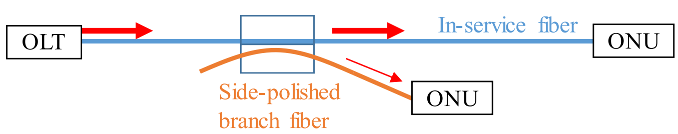
Digital Object Identifier 10.1109/LPT.2022.3199456



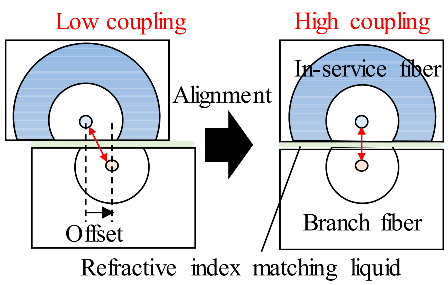
(a) Side-polishing of in-service fiber



(b) Cross-section view of the side-polished in-service fiber

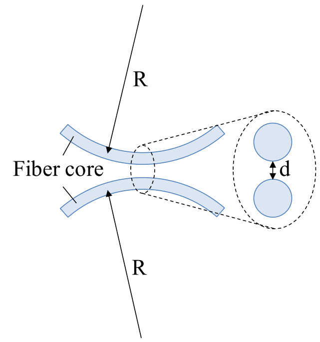


(c) Insertion of the coupler to in-service fiber

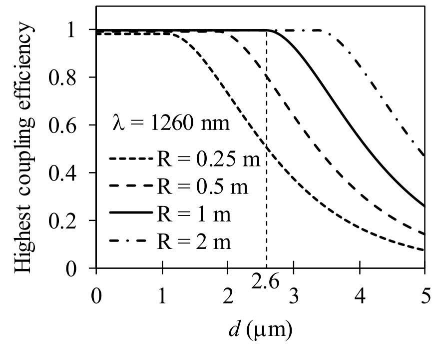


(d) Cross-section view of alignment for adjusting coupling efficiency

Fig. 2. Proposed optical coupling technique based on fiber side-polishing. OLT: optical line terminal, ONU: optical network unit.



(a) Structure of a curved fiber coupler for 3-D BPM calculation



(b) Highest coupling efficiency as a function of the closest core distance d when R changes

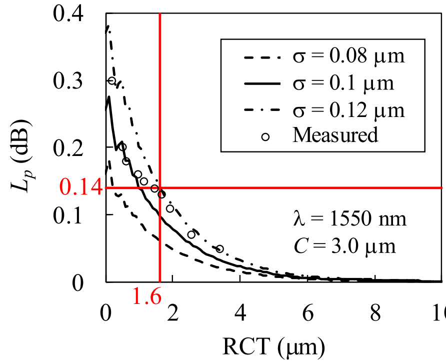
Fig. 3. Calculated relationship between coupling efficiency and core-to-core distance d.

optical fiber with diameter of 0.25 mm is held in a V-groove with radius of curvature of R cut into a glass block. Side-polishing is performed while monitoring insertion loss using the communication light that leaks from the fiber bend as shown in Fig. 2 (a). Since the insertion loss L_p increases as the polishing surface approaches the core, i.e. RCT decreases [9], the polishing ends when the loss reaches desired value. After polishing, the polished surface is coated with refractive index matching liquid, and bought into contact with another side-polished fiber prepared in advance (referred to as the branch fiber) as shown in Fig. 2 (b) and (d). The in-service and the branch fibers are adequately separated to prevent evanescent-coupling. The refractive index of the matching liquid should be smaller than that of the cladding to avoid an increase in insertion loss [6], [7], [8]. Finally, the in-service and branch fibers are moved relative to each other to bring the cores close to each other, and fixed at the position that yields the desired coupling efficiency as shown in Fig. 2 (d).

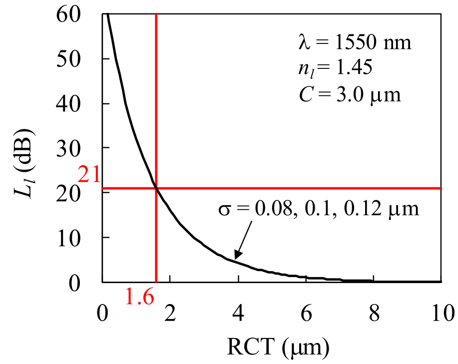
L_p should be carefully determined so as to obtain the desired RCT and thus high coupling efficiency with low loss insertion. First, we calculated the highest coupling efficiency as a function of core distance d assuming the structure shown in Fig. 3 (a). The three-dimensional beam propagation method (3-D BPM) was used in the calculation, and the cores of two identical ITU-T G. 652 compliant fibers with a radius of curvature of R were moved to approach each other with the closest distance $d = \text{RCT} + \text{RCT}_{\text{branch}}$, where $\text{RCT}_{\text{branch}}$ is RCT of the branch fiber. The wavelength used was 1260 nm, assuming service frequencies from 1260 to 1650 nm. From Fig. 3 (b), the highest coupling efficiency increases as d decreases, and it first reaches about 100% at d_c. Larger R values yield larger d_c values, namely larger RCT and so lower L_p because the effective interaction length of the curved fiber coupler is proportional to R [5]. On the other hand, when R is too large, the polished surface becomes long, which makes it difficult to realize a flat polished surface. R should be carefully chosen, making more detailed study necessary. In this letter, we choose $R = 1$ m, which means the polished surface has a length of around 31 mm, and $d_c = 2.6$ μm. $\text{RCT}_{\text{branch}}$ can be assumed no more than 1 μm because the branch fiber can be polished with high accuracy in advance using the conventional liquid drop test. Therefore, 100% coupling is achieved when RCT is 1.6 μm or less.

Next, Fig. 4 (a) and (b) show L_p and the conventional liquid drop loss L_l as a function of RCT. The refractive index of the liquid was 1.45 at the wavelength of 1550 nm. L_p can be considered to be scattering loss caused by roughness of the polished surface, as previously determined for planar optical waveguides [10]. We calculated L_p with the 3-D BPM by applying the commonly used roughness model [10] to the polished surface. The surface roughness is characterized by the following autocorrelation function of the distribution function with zero mean $f(z)$

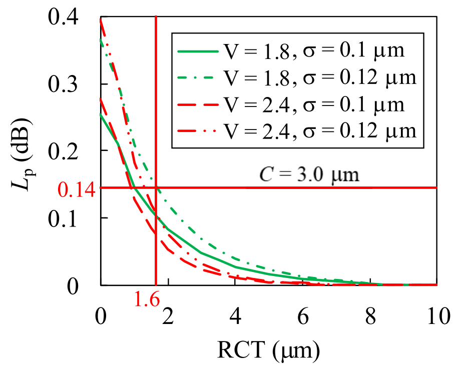
$$R(u) = \langle f(z) f(z+u) \rangle \approx \sigma^2 \exp\left(-\frac{|u|}{C}\right) \qquad (1)$$



(a) Polishing loss L_p as a function of RCT for various surface roughnesses



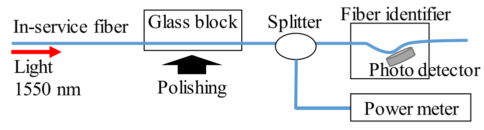
(b) Liquid drop loss L_l as a function of RCT for various surface roughnesses



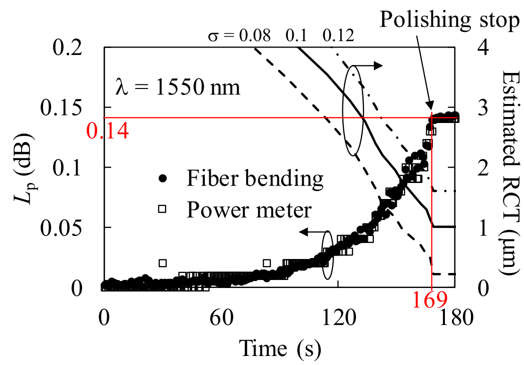
(c) L_p as a function of RCT for various V-parameters

Fig. 4. Relationship between L_p and RCT.

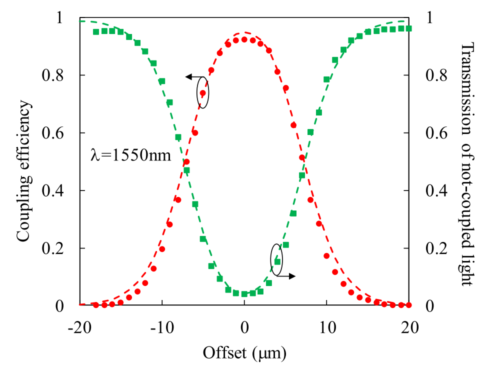
where the brackets represent the ensemble average, σ^2 is the roughness variance, and C is the correlation length. From Fig. 4 (a) and (b), L_p increases as RCT decreases and depends on the root-mean-square (rms) roughness σ, whereas L_l does not depend on σ. The calculated L_p and L_l were almost independent of C of a few micrometers. We measured L_p, σ, and C by using a commercially available polishing machine for optical connectors and a polishing film with a particle size of 5 μm. The polishing pressure and speed were optimized so that polishing could be completed in as a short time as possible without breaking the fiber. The measured σ and C yielded average values of 0.1 μm and 3.0 μm, respectively. The measured relationship between L_p and RCT was derived from the measured L_p for various L_l and Fig. 4 (b). The measured L_p values, plotted as open circles in Fig. 4 (a), agree with the calculated results for σ = 0.08 to 0.12 μm.



(a) Experimental setup for measuring insertion loss during side-polishing



(b) Measured L_p and estimated RCT during side-polishing



(c) Coupling efficiency and transmission of uncoupled light as a function of offset of the two fiber-cores

Fig. 5. Measured results.

RCT is less than 1.6 μm (namely 100% coupling) when L_p exceeds 0.14 dB.

Fig. 4 (c) shows the calculated relationship between L_p and RCT for various V-parameters, which are defined by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_{core}^2 - n_{clad}^2} \tag{2}$$

where a is the core diameter, λ is the wavelength, and n_{core} and n_{clad} are the refractive indices of the fiber-core and cladding. V of the fiber used in the experiment is 1.9 at a wavelength of 1550 nm. V changes from 1.8 to 2.4, when the wavelength changes from 1260 to 1650 nm. Although L_p depends slightly on V, we obtain RCT of 1.5 to 1.6 when L_p = 0.14 dB even if V changes from 1.8 to 2.4. Thus, we may stop the polishing when L_p = 0.14 dB and still achieve 100% coupling.

III. Experimental Results

Fig. 5 (a) shows the experimental setup used for measuring L_p. We used a fiber identifier with a bending loss of around 0.5 dB. To confirm that L_p can be monitored by fiber bending, we also monitored the signal power by a power

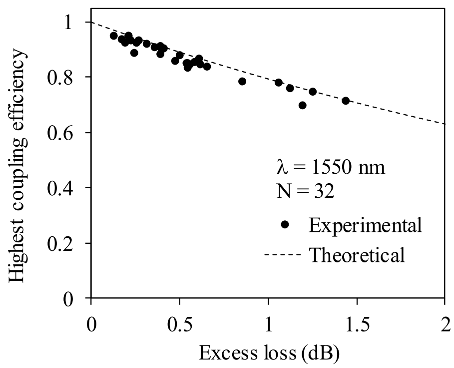


Fig. 6. The highest coupling efficiencies as a function of the excess loss.

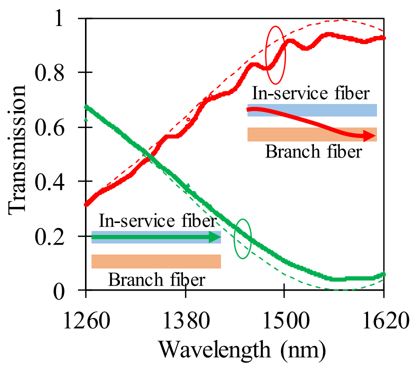


Fig. 7. Wavelength dependence of the fabricated coupler.

meter. Fig. 5 (b) shows the measured L_p and estimated RCT during polishing. We stopped the polishing at 169 seconds when $L_p = 0.14$ dB; that is, the estimated RCT $= 0.22$ to 1.6 μm. The agreement between the monitored L_p given by fiber bending and power meter values indicates that the fiber bending approach is valid. Even when the bending loss of the fiber identifier is added, polishing was performed while suppressing the insertion loss to 0.64 dB or less. Therefore, it was confirmed that the polishing is possible without interruption of communication service [2]. Fig. 5 (c) shows the measured results of the coupling efficiency and transmission of uncoupled light as a function of the offset between the cores of the in-service and branch fibers by moving these fibers relative to each other as shown in Fig. 2 (d). The dashed lines show the calculated results for $d = 5.0$ μm with the structure shown in Fig. 3 (a). The wavelength in the experiment and calculation is 1550 nm. Coupling efficiencies of up to 0.92 were obtained, and the measured values were consistent with the calculated results. We measured minimum value of d estimated in the same way as above at a wavelength of 1310 nm and obtained $d = 3.3$ μm. The difference between the estimated minimum value and the target d_c of 2.6 μm can be decreased by aligning the two fibers more accurately and flattening the polishing surface by reducing the particle size of the polishing sheet or R. Fig. 6 shows the highest coupling efficiencies as a function of the excess loss. We measured 32 samples and obtained coupling efficiencies from 0.7 to 0.95 with an average value of 0.87. As shown by the dashed theoretical curve in Fig. 6, the highest coupling efficiency decreases as the excess loss increases. The measured results agree with the theoretical curve. The variation in the coupling efficiencies can be reduced by reducing the excess losses. Fig. 7 shows wavelength dependence of the transmission of uncoupled light and coupling efficiency when the branch fiber was aligned to realize the highest coupling efficiency at the wavelength of 1550 nm. The dashed lines show the simulation results when $d = 5.0$ μm. It was confirmed that the calculated and measured results agreed.

IV. Conclusion

We proposed an optical coupler insertion technique based on fiber side-polishing that does not interrupt service. It was clarified that the desired degree of side-polishing could be attained by using our RCT estimation method based on fiber bend monitoring while holding the insertion loss to 0.64 dB or better. Experiments on a fabricated coupler yielded coupling efficiencies from 0.7 to 0.95 with an average value of 0.87 by bringing the side-polished branch fiber close to the polished in-service fiber. The coupling efficiencies can be improved by reducing the excess losses.

References

[1] R. Igarashi *et al.*, "Network design for bus-type optical access using distributed Raman amplification with asymmetric power splitter," *J. Lightw. Technol.*, vol. 39, no. 21, pp. 6814–6823, Nov. 1, 2021.

[2] T. Uematsu, T. Kiyokura, H. Hirota, H. Iida, T. Kawano, and T. Manabe, "Temporary optical coupler for optical cable re-routing without service interruption," *IEEE Photon. J.*, vol. 10, no. 3, pp. 1–11, Jun. 2018.

[3] R. A. Bergh, G. Kotler, and H. J. Shaw, "Single-mode fiber optic directional coupler," *Electron. Lett.*, vol. 16, pp. 260–261, Mar. 1980.

[4] O. Parriaux, S. Gidon, and A. A. Kuznetsov, "Distributed coupling on polished single-mode optical fibers," *Appl. Opt.*, vol. 20, pp. 2420–2423, Jul. 1981.

[5] M. Digonnet and H. Shaw, "Analysis of a tunable single mode optical fiber coupler," *IEEE J. Quantum Electron.*, vol. QE-18, no. 4, pp. 746–754, Apr. 1982.

[6] M. J. F. Digonnet, J. R. Feth, and L. F. Stokes, "Measurement of the core proximity in polished fiber substrates and couplers," *Opt. Lett.*, vol. 10, no. 9, pp. 463–465, Sep. 1985.

[7] A. K. Das, M. A. Mondal, A. Mukherjee, and A. K. Mandal, "Automatic determination of the remaining cladding thickness of a single-mode fiber half-coupler," *Opt. Lett.*, vol. 19, no. 6, pp. 384–386, Mar. 1994.

[8] S. Tseng and C. Chen, "Side-polished fibers," *Appl Opt.*, vol. 31, no. 18, pp. 3438–3447, Jun. 1992.

[9] J. Zhao *et al.*, "Rough side-polished fiber with surface scratches for sensing applications," *IEEE Photon. J.*, vol. 7, no. 3, pp. 1–7, Jun. 2015.

[10] F. P. Payne and J. P. R. Lacey, "A theoretical analysis of scattering loss from planar optical waveguides," *Opt. Quantum Electron.*, vol. 26, no. 10, pp. 977–986, Oct. 1994.