# Temperature-Independent Temporary Optical Coupler Using Fiber Bending Technique

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

***Abstract*—This paper shows how to reduce the temperature dependence of a temporary optical coupler that enables us to output a signal light from a bent fiber by aligning a probe fiber in the path of the light leaked from the bent fiber and input a signal light from the probe fiber to the bent fiber. We experimentally demonstrate that the temperature dependence of the coupling efficiency between the bent and probe fibers is significantly improved by reducing the misalignment between these fibers created by temperature changes. First, we confirm by comparing calculation results to measured values that the temperature dependence of the conventional structure is caused by misalignment between the bent and probe fibers created by the difference in the thermal expansion of the components. Next, we demonstrate that the temperature dependence of the coupling efficiency is suppressed by using a structure that reduces the misalignment, and the proposed temperature-independent temporary optical coupler provides the coupling efficiency required to support its application over the wide temperature range of -10 to 50 degrees Celsius (equivalent to a fusion splicer) for fibers compliant with ITU-T G. 652 and G. 657.**

***Index Terms*—Fiber bending, temperature dependence, temporary optical coupler.**

## I. Introduction

FIBER-TO-THE-HOME (FTTH) services are widely used all over the world, and the number of FTTH subscribers will continue to increase. The importance of continuous FTTH service continues to strengthen. However, since the number of optical fiber cables continues to increase significantly, their maintenance and operation of them will become a tough work.

Temporary optical couplers (TOCs) employing non-destructive fiber bending techniques have been proposed to realize highly efficient maintenance and operation [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. The TOC enables us to output a signal light from a bent fiber by setting a probe fiber in the path of the light leaked from the bent fiber and input a signal light from the probe fiber to the bent fiber. The TOC realizes insertion of a temporary optical coupler at any point without cutting the target fibers and can be applied to fiber identification [1], [2], [3], [4], detour route formation [5], [6], [7], [8], [9], and temporary test instrument connection [10], [11], [12]. The TOC is usually applied outdoors in a variety of weather conditions and so should be independent of weather conditions. However, components constituting the TOC expand or contract due to environmental temperature changes. This degrades the coupling efficiency between the bent and probe fibers due to their misalignment. No previous research has, to the best of our knowledge examined or solved this problem.

In this paper, we experimentally demonstrate that the temperature dependence of the coupling efficiency can be significantly reduced by suppressing the misalignment by careful design of the TOC components. First, we confirm by comparing calculation and measurement results that the temperature dependence of the conventional TOC is caused by the misalignment between the bent and probe fibers due to the difference in the thermal expansion/contraction of the components. Next, we demonstrate that the temperature dependence of the coupling efficiency is reduced by using a structure that resists the misalignment. Our proposed TOC yields coupling efficiencies better than $-20$ dB required to support the application over the wide temperature range of $-10$ to 50 °C (equivalent to commonly used fusion splicers [13]) for fibers compliant with ITU-T G. 652 [14] and G. 657 [15].

## II. Temperature Dependence of Conventional Structure

The conventional structure of the TOC is shown in Fig. 1. Convex and concave clamps are used to bend a fiber with the correct bending radius of 2 mm and angle of 90 degrees [12]. The concave clamp is made of optically transparent plastic and the refractive index of the plastic is the same as that of coating of the bent fiber to avoid any reflection of the leaked light at the boundary between the coating and the clamp. The convex clamp has a V-groove to set the fiber in the correct position. The probe fiber is used to input/output light into/from the bent fiber, and it is aligned and fixed so that the highest coupling efficiency between the bent and probe fibers is obtained. A graded-index (GRIN) lens is spliced to the tip of the probe fiber to improve the coupling efficiency. In this paper, we use a single-mode fiber as the probe fiber so that it can be connected to conventional repeater and test instruments such as an optical time domain reflectometer (OTDR) [6], [11], [12]. The GRIN lens is designed to obtain a beam waist diameter of 25 $\mu$m at a focal length of about 1 mm. Magnets are employed to bend the fiber within the

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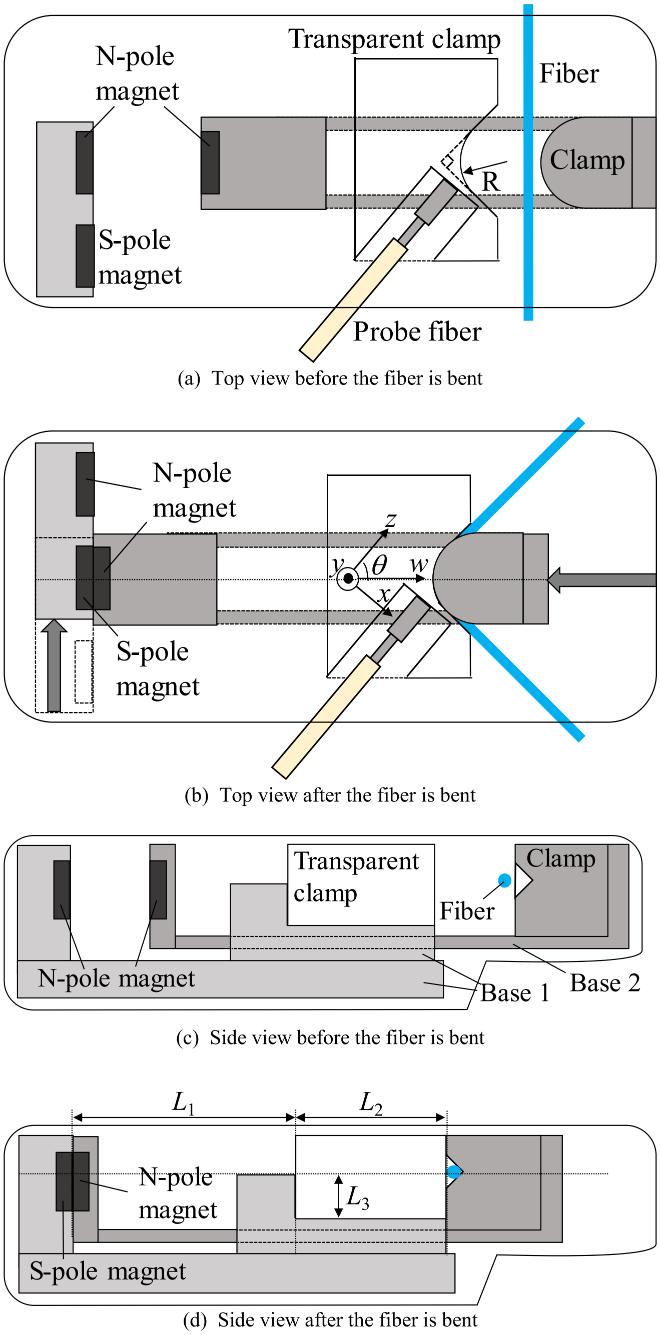



Fig. 1. Structure of the conventional TOC.

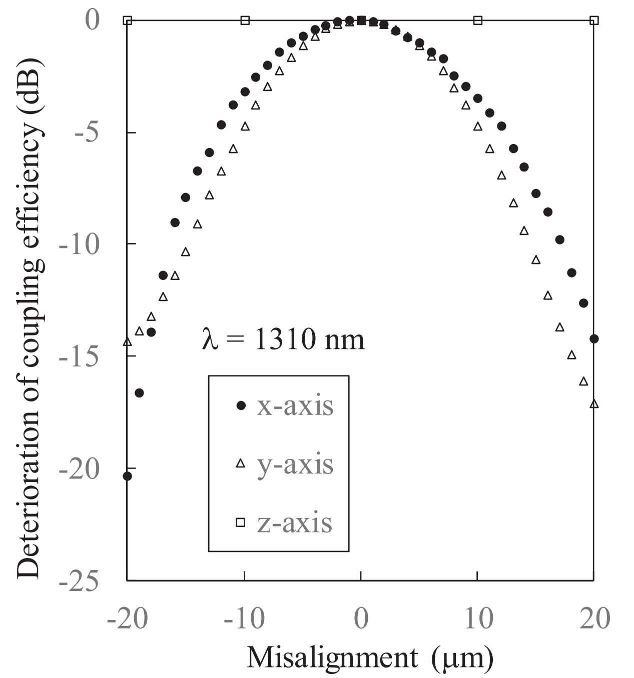



Fig. 2. The deterioration of the coupling efficiency as a function of *x*-, *y*-, and *z*-axis misalignment.

short switching time of several tens of milliseconds. The clamps touch to bend the fiber when N-pole and S-pole magnets face each other, and in other cases, the clamps separate to release the fiber.

The concave clamp, the convex clamp, the base 1, and base 2 are made of materials that have different coefficients of thermal expansion. This results in a drop in coupling efficiency due to misalignment between the bent and probe fibers when environmental temperature changes from the temperature at the time at which the probe fiber was aligned and fixed. Fig. 2 shows the measured deterioration in the coupling efficiency as a function of *x*-, *y*-, and *z*-axis misalignment. The coupling efficiency decreases exponentially with *x*- and *y*-axis misalignment, but only slightly dependent on *z*-axis misalignment.

The *y*-axis misalignment is derived from the difference between the thermal expansions of the convex and concave clamps and is given by

$$(\alpha_1 - \alpha_2)\, L_3 \Delta T \tag{1}$$

where $\alpha_1$, $\alpha_2$, $L_3$, and $\Delta T$ are, respectively, the coefficients of thermal expansion of the convex and concave clamps, the length shown in Fig. 1(d), and the temperature change. The *x*-axis misalignment is given by

$$f\,(\Delta S) \sin\theta \tag{2}$$

where $\Delta S$, $f(\Delta S)$, and $\theta$ are, respectively, the amount of change in the distance between the convex and concave clamps due to temperature change $\Delta T$, displacement of the core of the bent fiber relative to the probe fiber as a function of $\Delta S$, and the angle between *w*- and *z*-axis. $\Delta S$ is derived from the difference of the thermal expansions of the components and is expressed by the following equation,

$$\Delta S = \begin{cases} k\Delta T & (k\Delta T > 0) \\ 0 & (k\Delta T \le 0) \end{cases} \tag{3}$$

$$k = (\alpha_1 - \alpha_3)\, L_1 + (\alpha_1 - \alpha_2)\, L_2 \tag{4}$$

where $\alpha_3$, $L_1$, and $L_2$ are, respectively, the coefficient of thermal expansion of base 1, and the lengths shown in Fig. 1(d). The first term of (4) represents the change in $L_1$ due to the difference between the thermal expansions of the base 1 and base 2, while the second term expresses the change in $L_2$ caused by the thermal

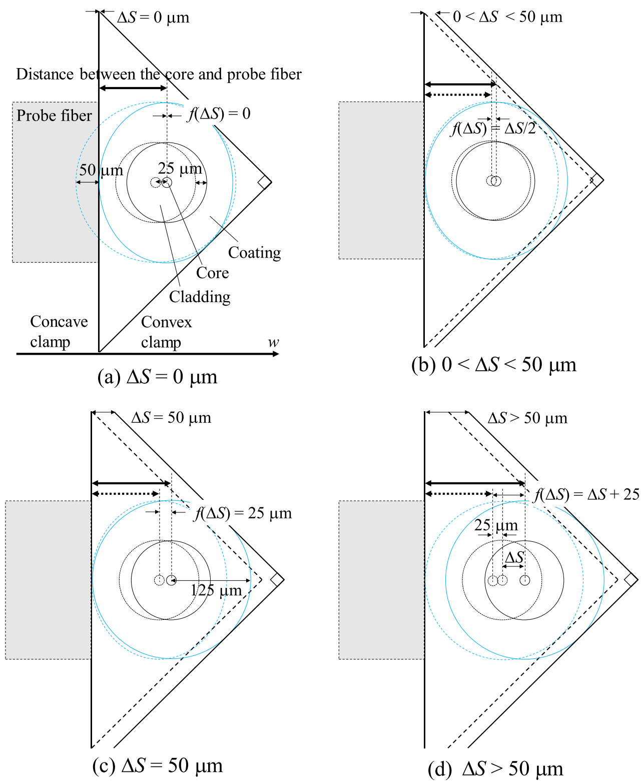



Fig. 3. The movement of the fiber-core position in $w$-axis direction.

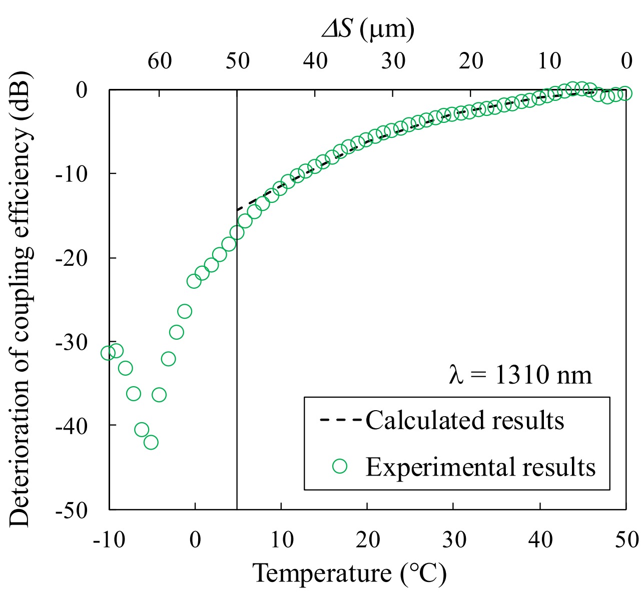



Fig. 4. The temperature dependence of the conventional structure.

expansion differences of the base 1 and transparent clamp. Fig. 3 shows the movement of the fiber-core position in $w$-axis direction due to temperature change. The V-groove is designed to crush the bent fiber by 50 $\mu$m when the convex and concave clamps touch each other. For the case of $\Delta S < 50$ $\mu$m, the fiber is crushed while deforming into an ellipse as shown in Fig. 3(b). It is intended to give the fiber an elliptical surface shape in

TABLE I
CALCULATION SPECIFICATIONS

| Symbol | Parameter |
|---|---|
| $\alpha_1$ | $17.3\times10^{-6}$ (/K) |
| $\alpha_1$ | $66.0\times10^{-6}$ (/K) |
| $\alpha_1$ | $23.6\times10^{-6}$ (/K) |
| $L_1$ | 60 (mm) |
| $L_2$ | 15 (mm) |
| $L_3$ | 5 (mm) |
| $\theta$ | $2\pi/9$ (rad) |

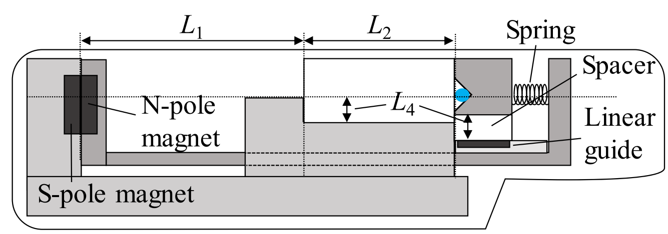



Fig. 5. Proposed structure of temperature-independent TOC.

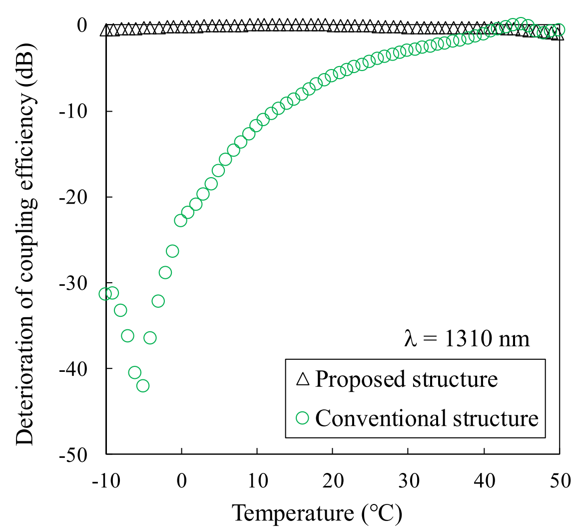
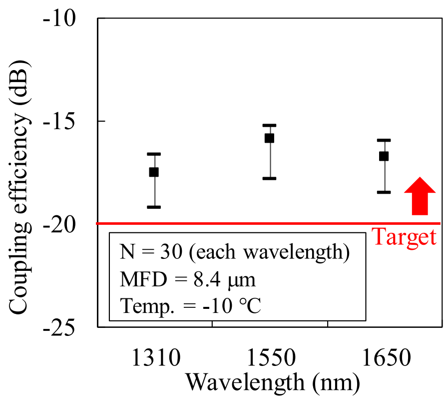



Fig. 6. Measured temperature dependence of the proposed and conventional structures.

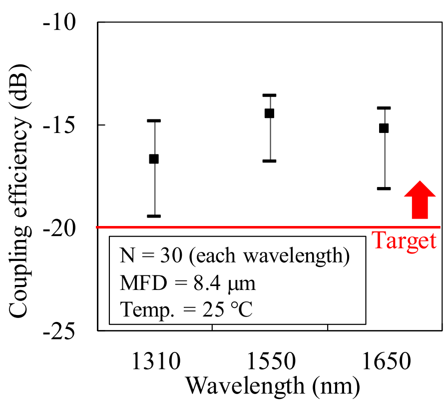
order to increase the loss and coupling efficiency. For the case of $\Delta S > 50$ $\mu$m, the fiber is not in contact with the concave clamp as shown in Fig. 3(d). Thus, we assume that the movement of the core position can be expressed by

$$f(\Delta S) = \begin{cases} \frac{\Delta S}{2} & (0 \leq \Delta S \leq 50\,\mu\text{m}) \\ \Delta S + 25 & (50\,\mu\text{m} < \Delta S) \end{cases} . \quad (5)$$

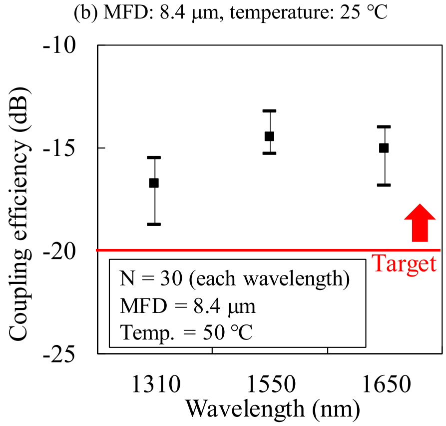
Fig. 4 plots the temperature dependence of the conventional structure over the temperature range from $-10$ to 50 °C. The calculated result was obtained from the deterioration of the coupling efficiency shown in Fig. 2 and the misalignments in the $x$- and $y$-axis direction derived from (1) to (5) with the calculation



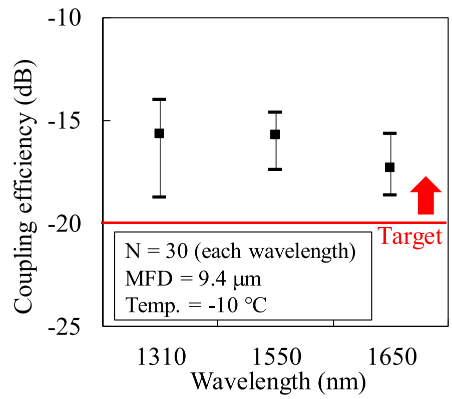

(a) MFD: 8.4 μm, temperature: -10 °C



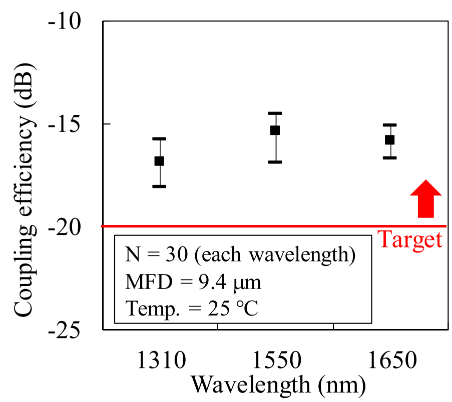

(b) MFD: 8.4 μm, temperature: 25 °C



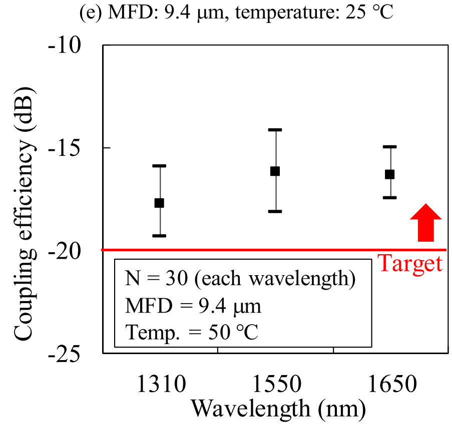

(c) MFD: 8.4 μm, temperature: 50 °C




(d) MFD: 9.4 μm, temperature: -10 °C




(e) MFD: 9.4 μm, temperature: 25 °C




(f) MFD: 9.4 μm, temperature: 50 °C

Fig. 7. Measured coupling efficiency for wavelengths of 1310, 1550, and 1650 nm at temperatures of −10, 25, and 50 °C.

parameters shown in Table I. $\alpha_1$, $\alpha_2$, and $\alpha_3$ were respectively set to the thermal expansion coefficients of stainless steel 304, polycarbonate, and aluminum provided by the manufacturers. These coefficients are in agreement with widely used typical values [16], [17], [18], [19], [20]. The TOC was held in a thermostatic chamber and the bent fiber had a mode-field diameter (MFD) of 8.4 $\mu$m (compliant with ITU-T G. 657). The temperature was decreased by 10°C per hour from 50 to -10°C. The probe fiber was aligned and fixed so that the highest coupling efficiency was obtained at a temperature of 50°C. The experimental result is in agreement with the calculated one except for temperatures below 5°C. It is considered that the divergence below 5°C is mainly due to the formation of an air layer in the path between the bent and probe fibers because the concave clamp completely separates from the bent fiber at a temperature of 5°C. The light output from the bent fiber is reflected at the boundary between the coating of fiber and the air layer. The light input from the probe fiber is also reflected at the boundary between the air layer and concave clamp. This causes a significant reduction in the coupling efficiency as shown in Fig. 4. It is confirmed from Fig. 4 that the temperature dependence is caused by the misalignment between the bent and probe fibers due to the difference in the thermal expansion of the components. The coupling efficiency must be improved to meet our target value of −20 dB for actual real-world application [5], [6], [7], [8], [9], [10], [11], [12].

## III. Proposed Temperature Independent Structure

Fig. 5 shows the proposed TOC with temperature compensation configuration. There are two advances over the conventional structure. The first is that a spacer made of the same material as the concave clamp is installed under the convex clamp to suppress the y-axis misalignment. The second is to install a spring so that the concave and convex clamps remain in contact with each other to suppress the x-axis misalignment. The thickness of the spacer, $L_4$, is 3 mm. The spring is selected so that a force of 20 N is applied at a temperature of 25 °C to crush the bent fiber by 50 mm when the convex and concave clamps are in contact as illustrated in Fig. 3(a). The force fluctuates by less than 2 N in the temperature range of $-10$ to 50 °C, and so does not contribute to changes in the coupling efficiency.

## IV. Experimental Results

Fig. 6 shows measured temperature dependence of the proposed and conventional structures over the temperature range from $-10$ to 50 °C. The TOC was held in the thermostatic chamber and the bent fiber had MFD of 8.4 $\mu$m. The temperature was decreased by 10 °C per hour from 50 to $-10$ °C. The deterioration in the coupling efficiency was no more than 1.1 dB for the proposed structure, which is a significant improvement over the conventional structure.

Finally, we confirm that the proposed structure achieves the target coupling efficiency of better than $-20$ dB. Fig. 7 shows the measured coupling efficiency for wavelengths of 1310, 1550, and 1650 nm at temperatures of $-10$, 25, and 50 °C. The sample fibers were compatible with ITU-T G. 652 (minimum bending radius = 30 mm) and G. 657 (minimum bending radius = 15 mm). These fibers had MFDs of 9.4 and 8.4 $\mu$m, respectively. From Fig. 7, the coupling efficiency for the three wavelengths achieved the target of over $-20$ dB at all temperatures. The highest coupling efficiency was obtained at 1550 nm, because we aligned the probe fiber at 1550 nm. We confirmed that the proposed structure attained the target coupling efficiency, and is suitable for real-world application [5], [6], [7], [8], [9], [10], [11], [12].

## V. Conclusion

Experiments demonstrated that the temperature dependence of temporary optical coupling efficiency was significantly reduced by countering the misalignment due to temperature change. First, the temperature dependence of the conventional structure was measured, and indeed the coupling efficiency was shown to significantly degrade with temperature change. Next, the validity of the assumption that the temperature dependence was caused by misalignment between the bent and probe fibers due to the difference in the thermal expansion/contraction of the coupler's components was confirmed by comparing calculation and experimental results. Finally, we elucidated which coupler structures were responsible for the misalignment. Our proposed temperature-independent TOC provides the coupling efficiency required to support application in the wide temperature range of $-10$ to 50 °C (equivalent to a fusion splicer [13]).

## References


[1] M. D. Feuer and V. A. Vaishampayan, "Clip-on fiber identifier using digital lightpath labels," *Proc. SPIE*, vol. 7632, 2009, Art. no. 763220.

[2] T. Matsui, K. Nakajima, K. Toge, T. Kurashima, and M. Tsubokawa, "Fiber identification technique based on mechanically-induced long-period grating for bending-loss insensitive fibers," *J. Lightw. Technol.*, vol. 28, no. 24, pp. 3556–3561, Dec. 2010.

[3] K. Matsuoka, S. Niimi, M. Miyamoto, and H. Sugawara, "New optical fiber identifier," in *Proc. 64th Int. Cable Connectivity Symp.*, 2015, pp. 704–708.

[4] M. Shimizu, S. Takashima, and H. Kobayashi, "Identification system for optical fiber transmission operation lines with local-light injection and detection coupling system," *J. Lightw. Technol.*, vol. 10, no. 5, pp. 686–692, May 1992.

[5] Go4Fiber, "Passive fiber clip-on coupler." 2017. [Online]. Available: https://www.go4fiber.com/spec/PFC%201000.pdf

[6] H. Hirota et al., "Optical cable changeover tool with light injection and detection technology," *J. Lightw. Technol.*, vol. 34, no. 14, pp. 3379–3388, Jul. 2016.

[7] T. Manabe, T. Kawano, T. Kiyokura, T. Uematsu, and H. Hirota, "Optical cable re-routing operation support system with a short service interruption," in *Proc. UL Int. Cable Connectivity Symp.*, 2017, pp. 10–11.

[8] T. Manabe, K. Noto, M. Inoue, H. Watanabe, and Y. Koshikiya, "Optical cable re-routing operation support system without service interruption," in *Proc. 66th Int. Cable Connectivity Symp.*, 2017, pp. 733–738.

[9] 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, Jun. 2018, Art. no. 7102611.

[10] T. Uematsu, H. Hirota, T. Kawano, T. Kiyokura, and T. Tetsuya, "Design of temporary optical coupler using fiber bending for traffic monitoring," *IEEE Photon. J.*, vol. 9, no. 6, Dec. 2017, Art. no. 7106013.

[11] H. Iida, H. Hirota, T. Uematsu, and N. Ambe., "Novel fibre termination identification employing local light injection and detection and 1.31/1.55-Pm-band coherent OTDR," in *Proc. Eur. Conf. Opt. Commun.*, 2019, pp. 1–4.

[12] H. Iida, H. Hirota, T. Uematsu, and K. Noto, "Fresnel reflection analysis for optical fibre identification employing with three-wavelength OTDR," in *Proc. Eur. Conf. Opt. Commun.*, 2020, pp. 1–8.

[13] K. Ito, M. Miyamori, R. Sato, H. Takayanagi, H. Yusa, and T. Homma, "History and vision of optical fiber fusion splicing technology," *SEI Tech. Rev.*, no. 86, pp. 51–54, Apr. 2018. [Online]. Available: https://global-sei.com/technology/tr/bn86/pdf/86-10.pdf

[14] *Characteristics of a Single-Mode Optical Fibre and Cable*, Rec. ITU-T G.652, International Telecommunication Union (ITU), Nov. 2009.

[15] *Characteristics of a Bending-Loss Insensitive Single-Mode Optical Fibre and Cable*, Rec. ITU-T G.657, International Telecommunication Union (ITU), Nov. 2016.

[16] M. Zahedul, H. Khandkar, J. A. Khan, A. P. Reynolds, and M. A. Sutton, "Predicting residual thermal stresses in friction stir welded metals," *J. Mater. Process. Technol.*, vol. 174, no. 1-3, pp. 195–203, May 2006.

[17] Y. G. Jung, S. C. Choi, and C. S. Oh, "Residual stress and thermal properties of zirconia/metal (nickel, stainless steel 304) functionally graded materials fabricated by hot pressing," *J. Mater. Sci.*, vol. 32, no. 14, pp. 3841–3850, Jul. 1997.

[18] A. Miyagawa, S. Nobukawa, and M. Yamaguchi, "Thermal expansion behavior of antiplasticized polycarbonate," *J. Soc. Rheol.*, vol. 42, no. 4, pp. 255–260, May 2014.

[19] I. W. Gilmour, A. Trainor, and R. N. Haward, "The thermoelastic effect in glassy polymers," *J. Polym. Sci., Part B: Polym. Phys.*, vol. 16, no. 7, pp. 1277–1290, Jul. 1978.

[20] F. C. Nix and D. MacNair, "The thermal expansion of pure metals: Copper, gold, aluminum, nickel, and iron," *Phys. Rev.*, vol. 60, no. 8, pp. 597–605, Oct. 1941.



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